

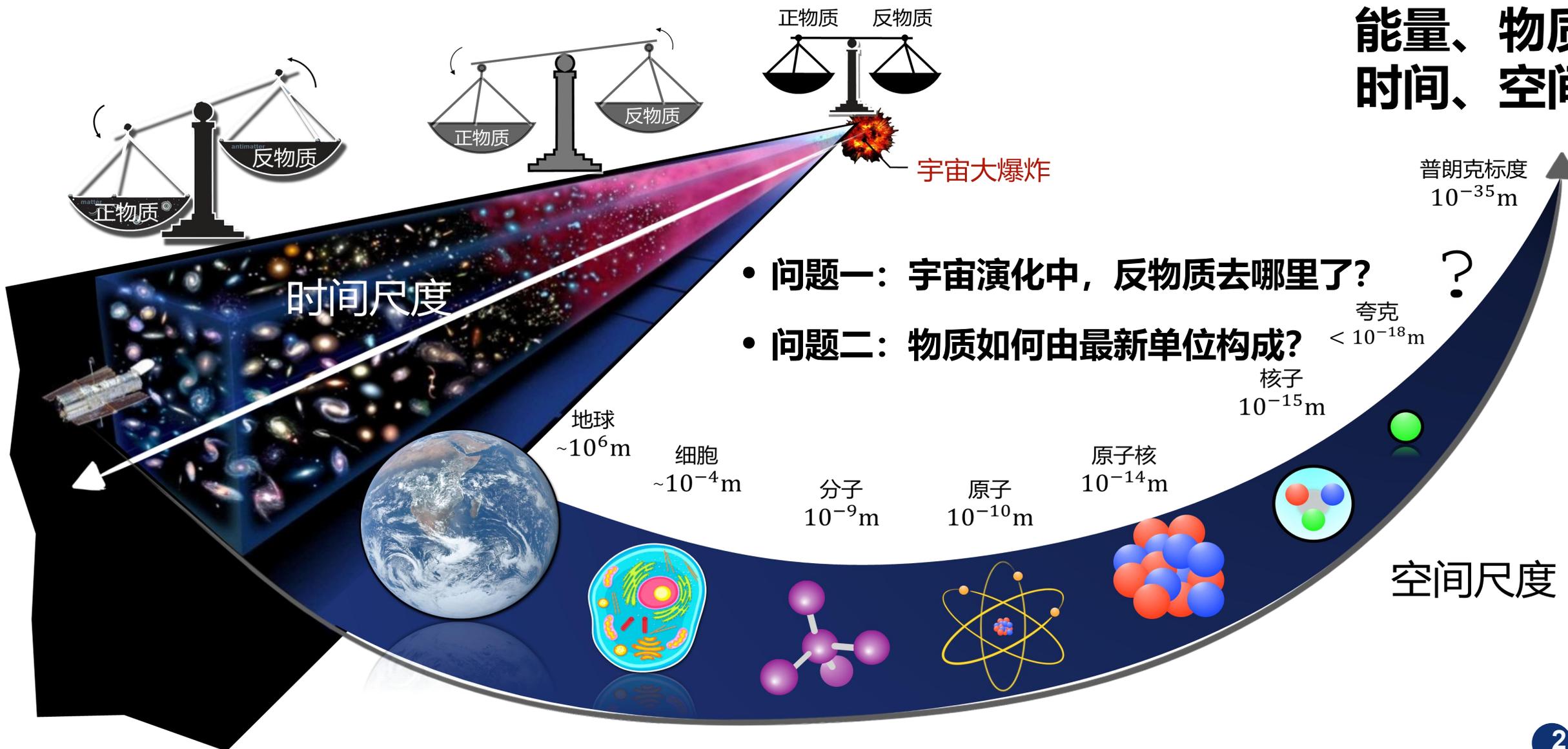
超级陶粲装置 (STCF) 研究进展 及强子物理研究展望

彭海平

中国科学技术大学

2025年8月20日 郑州大学

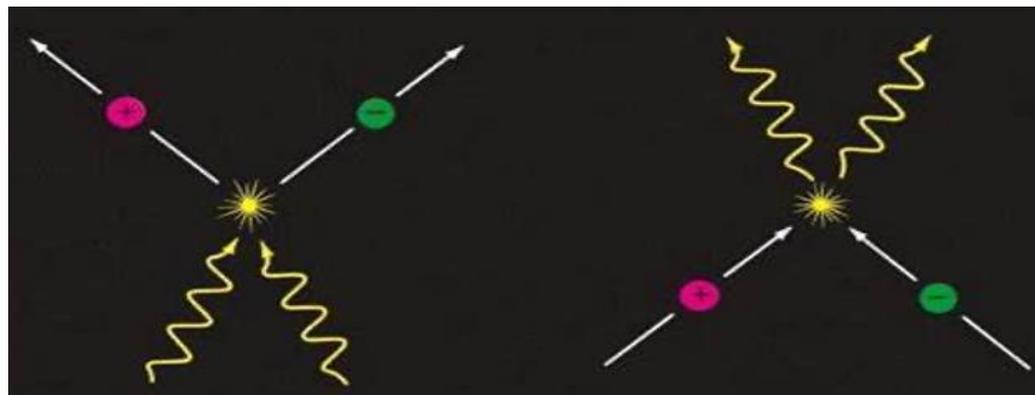
能量、物质 时间、空间



问题一：正反物质不对称性

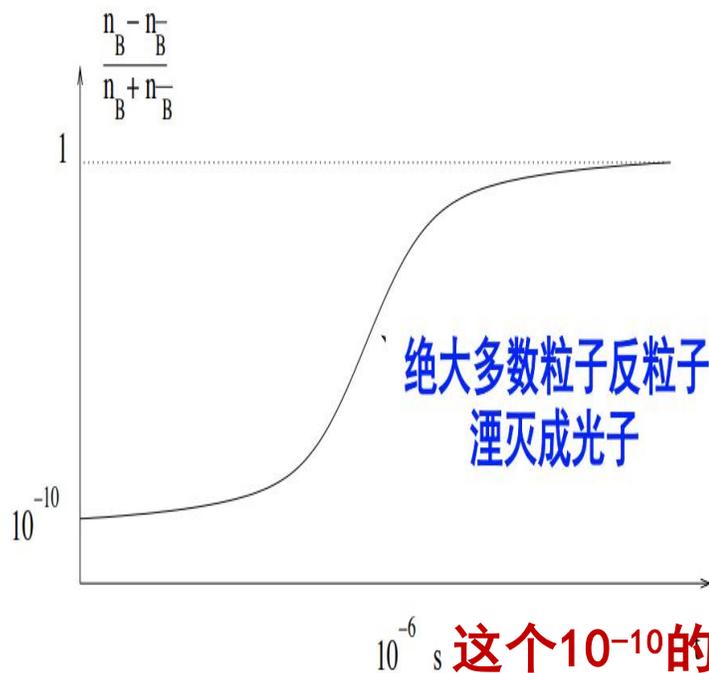
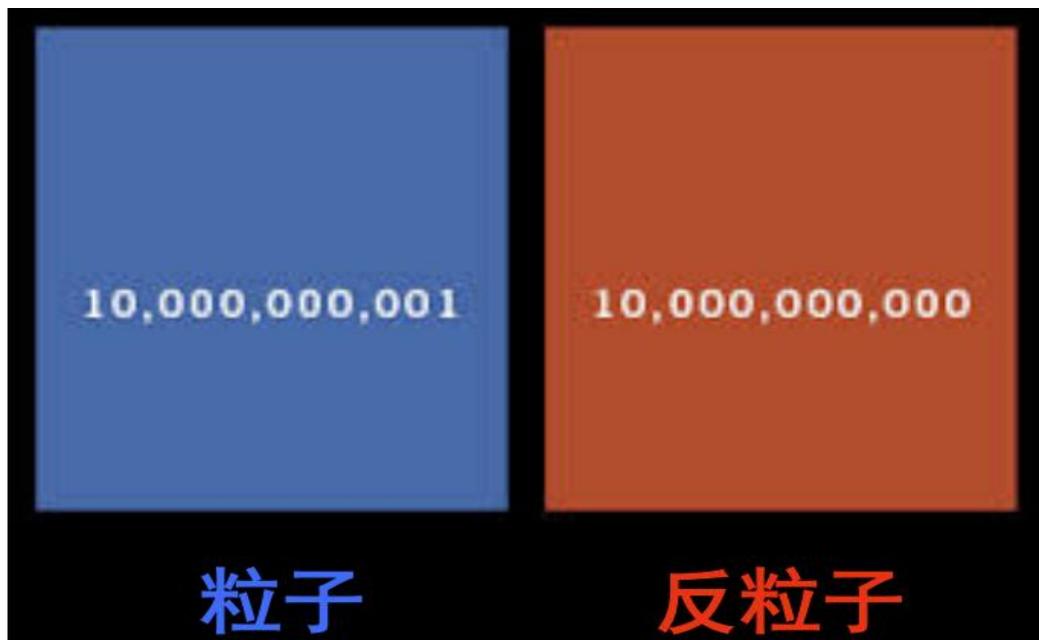


- 宇宙在大爆炸中产生，根据已知的物理规律，正反物质总量应该相同
- 宇宙在早期处于夸克胶子等离子体（QGP），发生正反物质湮灭形成光子对，正反物质平衡
- QGP在 10^{-6} 秒发生冷却，极少数正粒子幸存，组成重子，形成我们今天的正物质世界



能量转化为正-反物质对

正-反物质对发生湮灭转化为能量



当前宇宙早期大爆炸核合成以及微波背景辐射都对重子光子比有精确的测量，比值 $\sim 10^{-10}$

10^{-6} s 这个 10^{-10} 的差别最初是如何形成？

问题一：正反物质不对称性



正反物质不对称性形成（重子数产生(baryogenesis)机制)的三个条件(1967年)：

- 重子数不守恒：宇宙是从“什么都没有”开始
- 物质与反物质存在差异（C破坏和CP破坏）
否则产生的重子数不对称性会被C或CP变换抵消
- 早期的**宇宙**处热不平衡状态
否则产生的重子数不对称性会被逆过程抵消

尚未发现核子数守恒被破坏

已发现的CP破坏强度还远远不够



安德烈萨·哈罗洛夫

Andrey Sakharov

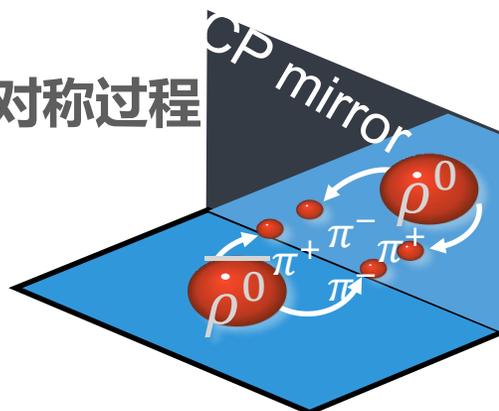
1921-1989

CP对称性：

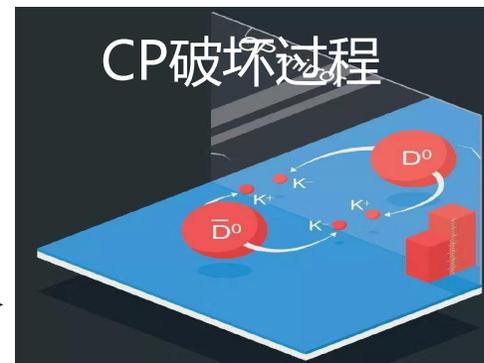
CP镜子两侧的物理规律相同，

物质 (x, y, z) || 反物质 $(-x, -y, -z)$

CP对称过程



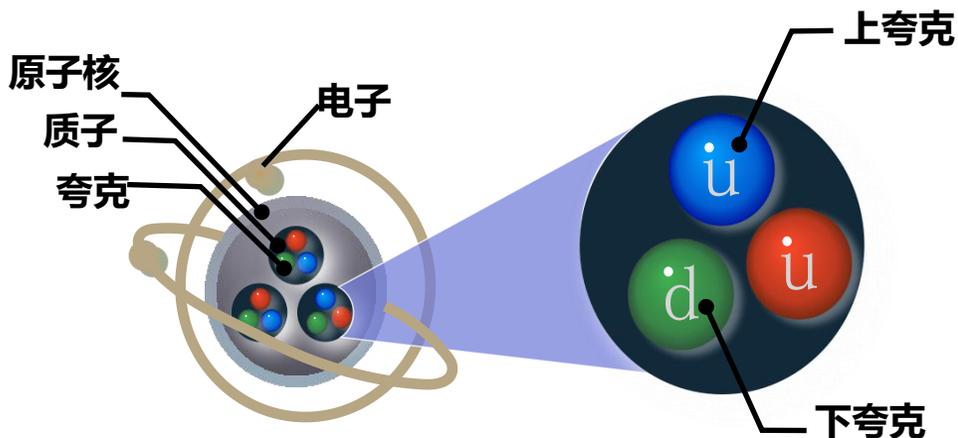
CP破坏过程



部分物理过程破坏CP对称性
计数率的差别可表示CP破坏程度

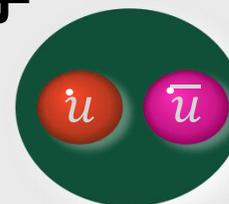
探索CP破坏机制以及寻找新的CP破坏源是当前研究正反物质不对称的核心

问题二：物质最小结构单元

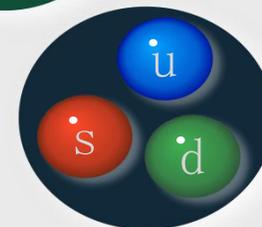
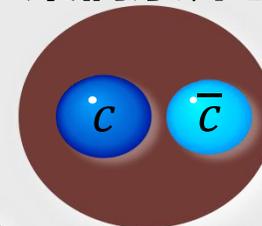


由胶子为媒介的**强相互作用力**束缚夸克成核子，也可以形成介子和重子

介子

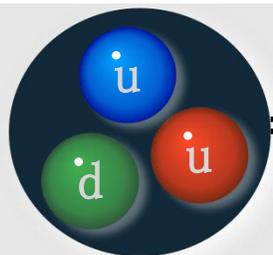


粲偶素介子

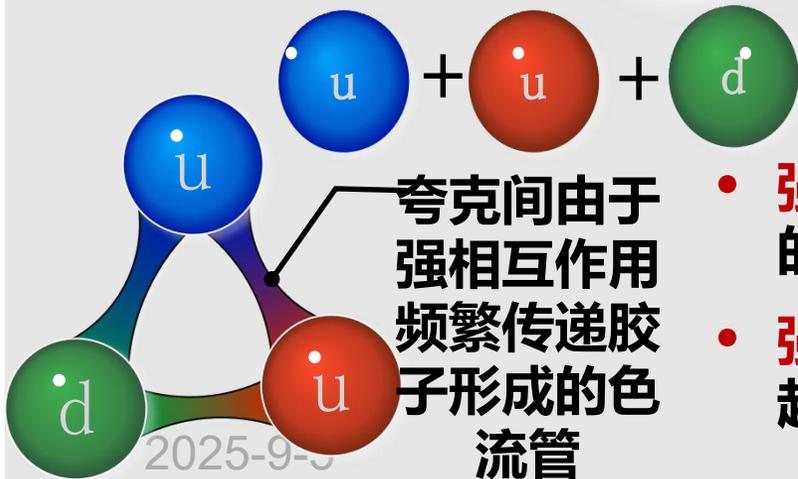


超子

强相互作用是可见物质质量的主要来源



= 938 MeV 测量到质子质量



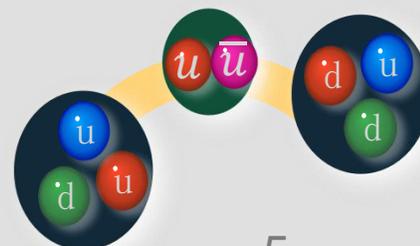
= 9.1 MeV 希格斯机制产生

夸克间由于强相互作用频繁传递胶子形成的色流管

- **强相互作用**赋予了质子99%的质量
- **强相互作用力**将夸克束缚在一起，自然界不存在自由夸克

中国科学院大学

强相互作用使质子、重子结合成为不同原子核，是**核能**的根本来源



5



问题二：强子谱学夸克如何形成强子？



强子结构规律——强子谱学，静态探针

原子结构规律——元素周期表

普通强子态

普通重子
普通介子

奇特强子态

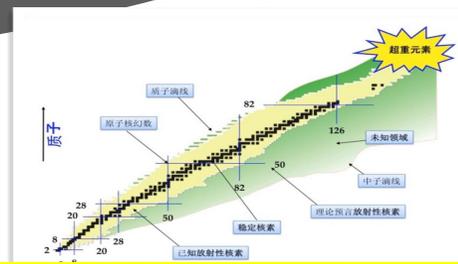
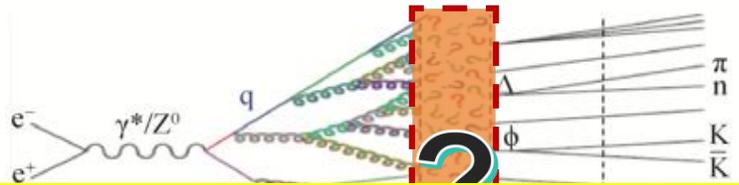
四夸克态
五夸克态
强子分子态
胶球
混杂态

绝大部分已发现强子内部夸克构型

理论上可能，但没有证实的夸克构型

原子核结构规律——核素表

元素的工业运用



Element	Isotope	Half-life	Decay Mode
Ac-225	Ac-225	10.0 days	α
	Ac-226	14.9 days	α
Pa-231	Pa-231	3.2765 years	α
	Pa-232	1.32 days	α
Th-230	Th-230	7540 years	α
	Th-231	25.52 hours	α
U-235	U-235	7.04e8 years	α
	U-236	2.34267e5 years	α
Np-236	Np-236	1.5365 years	β
	Np-237	2.1446e6 years	α

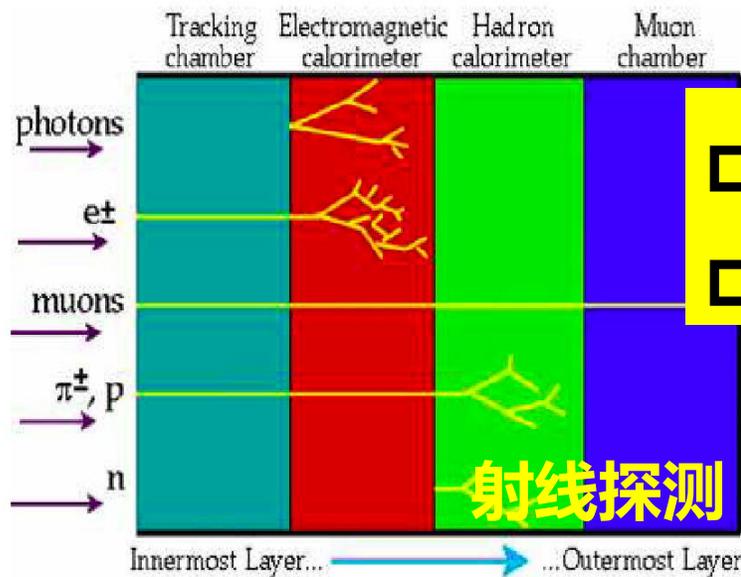
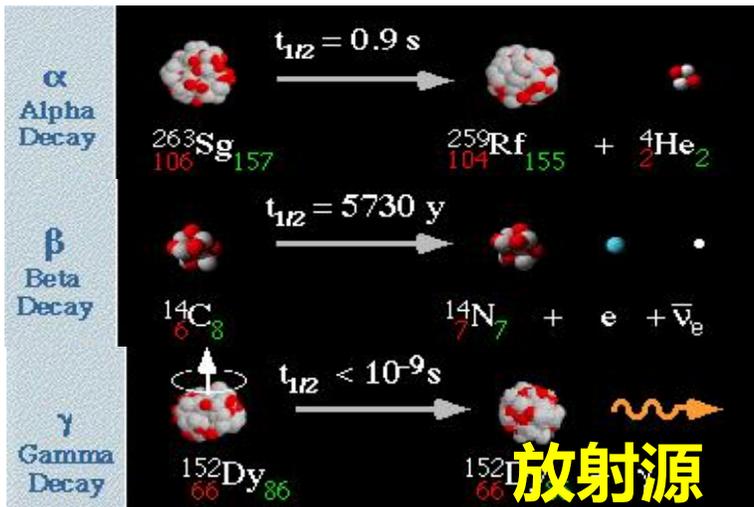
强相互作用涉及不同的前沿领域

然而，强相互作用力当前是四种相互作用力中我们认识最不清楚的

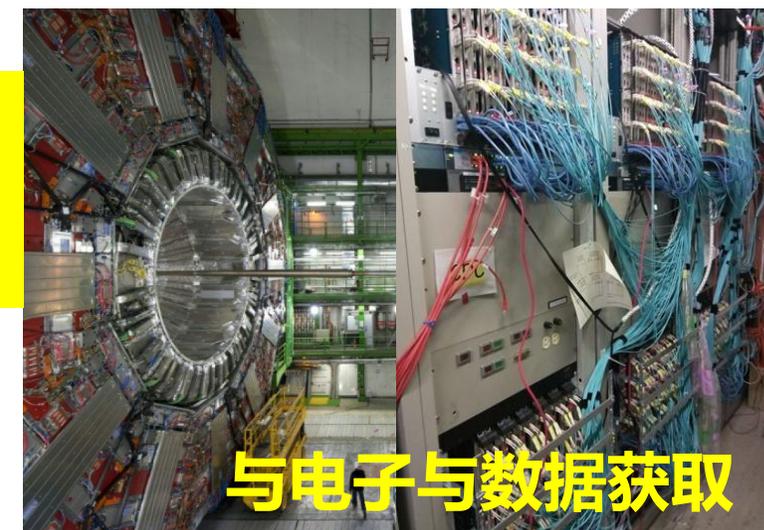
夸克/胶子如何形成强子——碎裂函数，动态探针

核素的工业运用

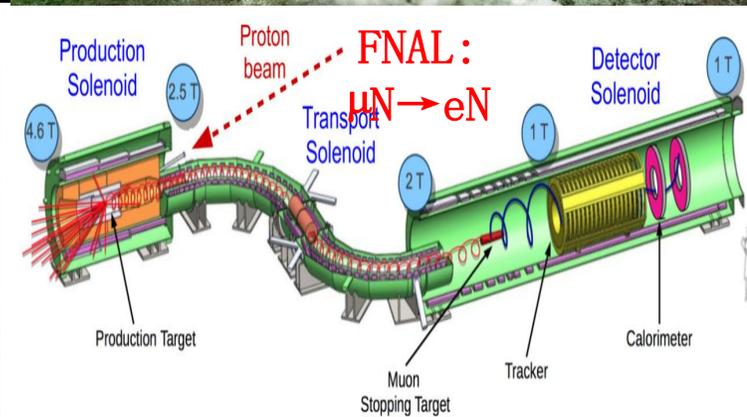
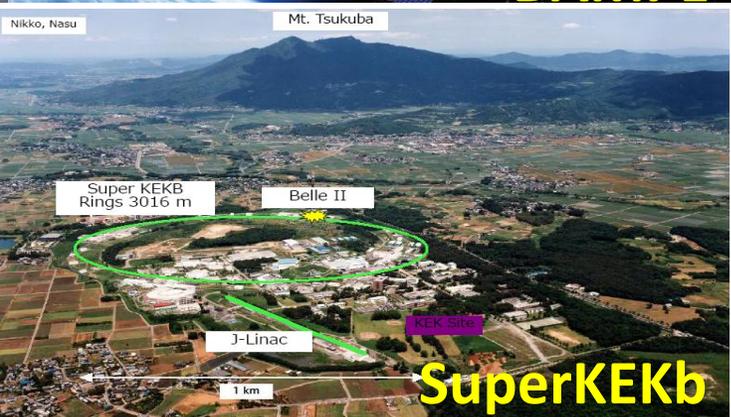
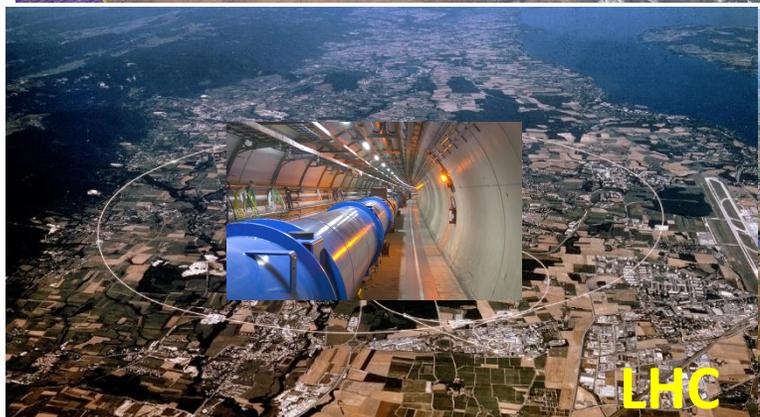
核与粒子物理研究基本方法



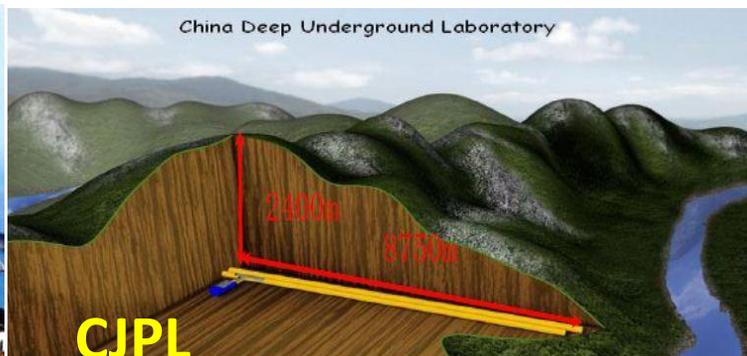
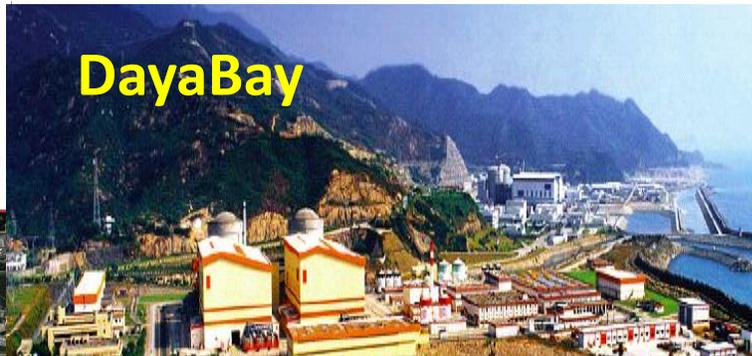
广泛运用不同领域的前沿技术
高新技术的驱动力和源泉



核与粒子物理实验



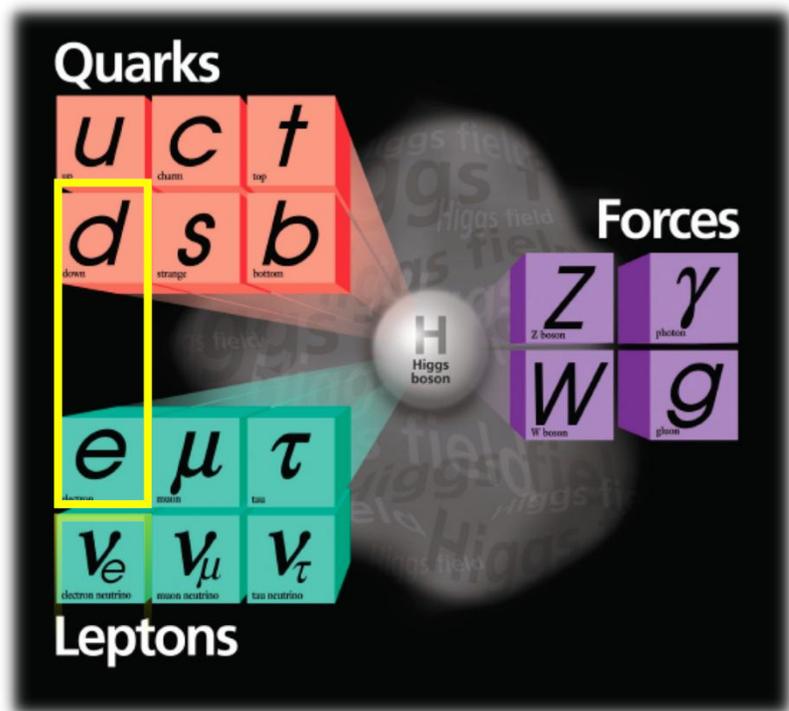
Super-Kamiokande (ICRR, Univ. Tokyo)



根据物理学目标，不同的实验空间、技术方案，非常丰富

自然界**最基本的**科学问题：构成宇宙万物**最基本的组分和规律**是什么？

基本粒子与宇宙起源及演化紧密相关，粒子物理的**标准模型**取得了巨大成功



质子和中子由**第一代夸克**构成，
与**电子**构成稳定的物质世界

标准模型面临的**重大挑战**：

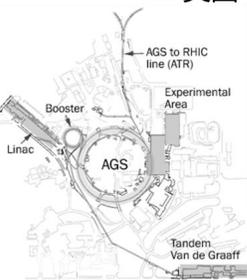
- 为什么宇宙**正反物质不对称**？
- 物质**质量的本质**是什么？
(强子产生机制和强子结构)
- 夸克为什么**囚禁**在物质中？
- 暗物质，暗能量是什么？
-

基于加速器粒子物理实验

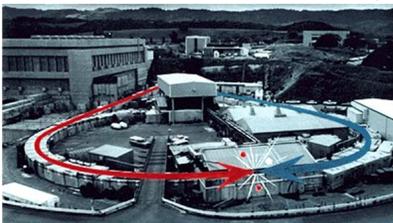


- 最有效的实验途径，一系列重大发现：重味夸克、陶轻子、W/Z传播子以及希格斯粒子等
- 针对物理目标，覆盖不同能区，人工产生海量基本粒子，研究相应的产生和衰变机制

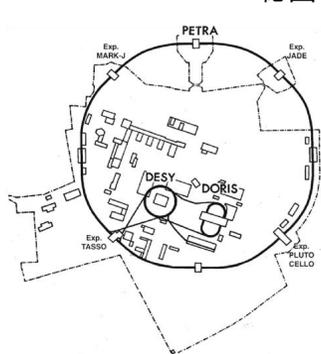
AGS 美国



SPEAR 美国



PETRA 德国



Tevatron 美国



LHC 瑞士



1974, 粲夸克发现

1979, 胶子发现

1995, 顶夸克发现

2012, 希格斯(Higgs)玻色子发现

1975, 陶轻子发现

1983, W, Z玻色子发现

2001, B介子CP破坏

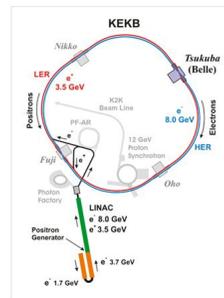
2013, $Z_c(3900)$ 发现



SLAC 美国



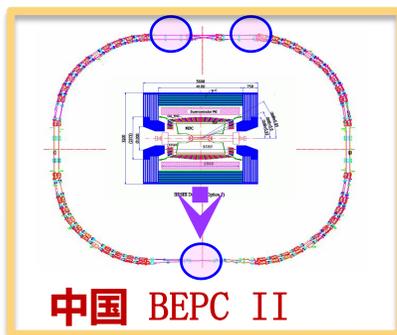
SPS 瑞士



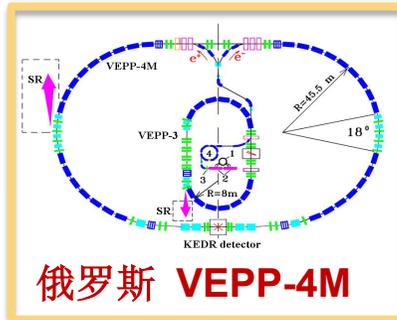
质心能量覆盖范围对应于产生基本粒子种类



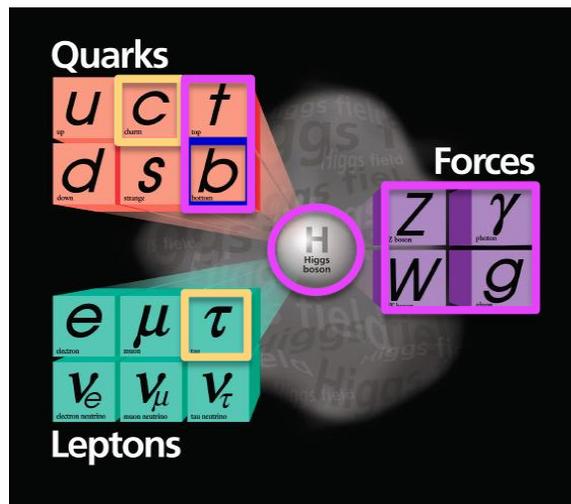
日本 SuperKEKB



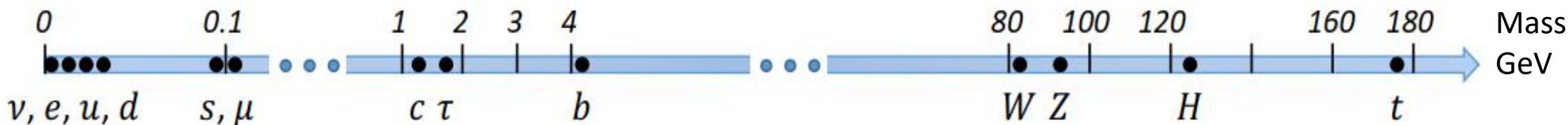
中国 BEPC II



俄罗斯 VEPP-4M



欧洲LHC



高亮度/精度前沿： 强子结构、奇特物质态、强相互作用本质、以 c/b 夸克和 τ 轻子为媒介寻找新物理

高能量前沿： 质量起源、电弱相互作用本质、通过希格斯粒子寻找新物理、第三代夸克的精确研究

基于加速器粒子物理实验

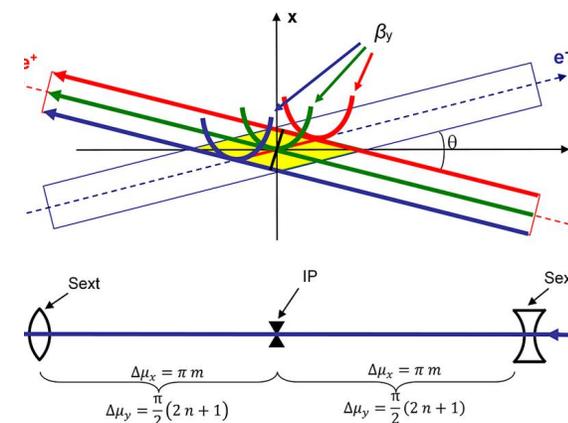
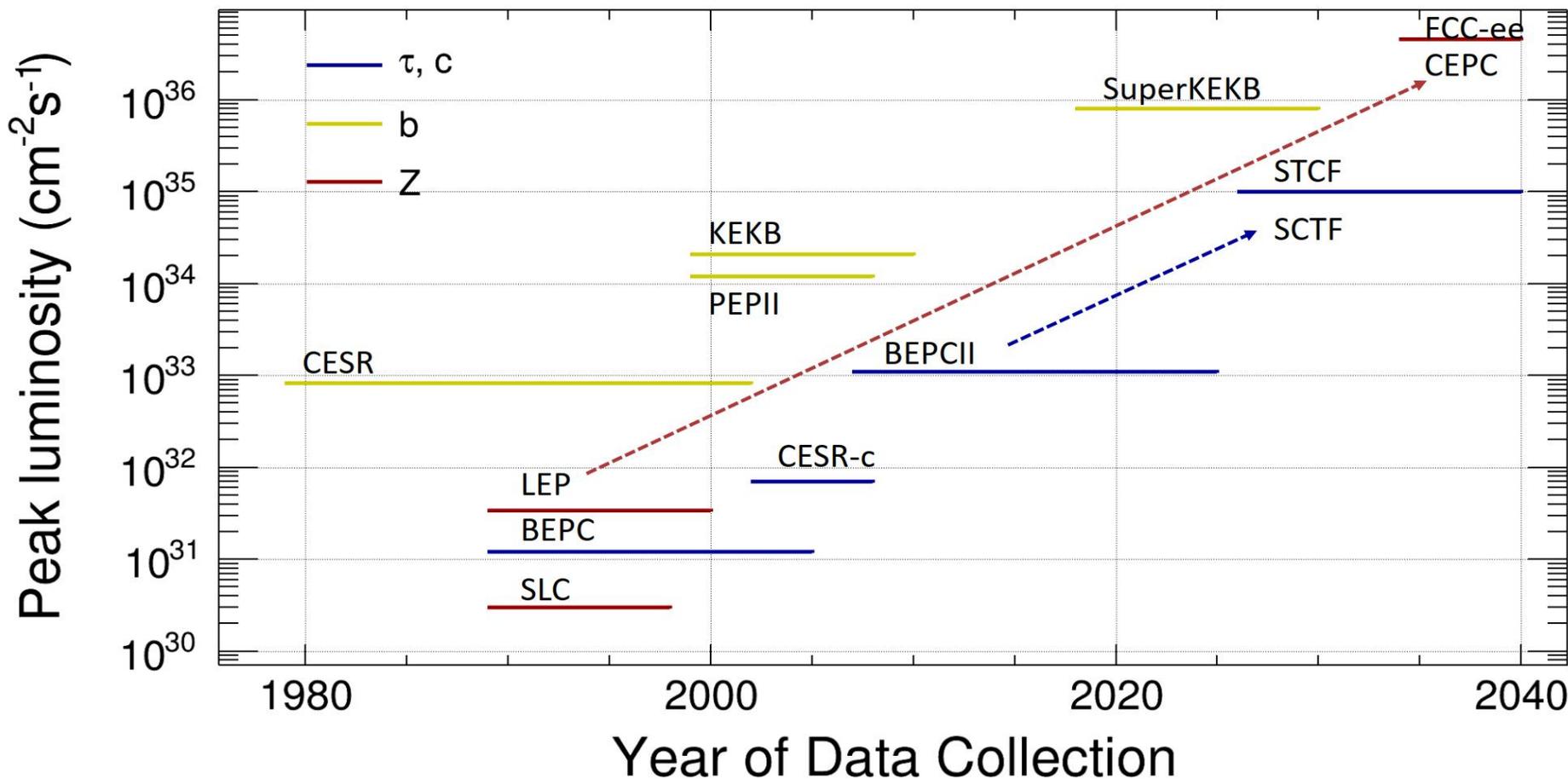


第一代
单环

第二代
双环
更多束团数
低 b_y @IP

第三代
双环
大流强,大交叉角
极低 b_y @IP

$$L = \frac{\gamma n_b I_b}{2e r_e \beta_y^*} \xi_y H$$



大Piwinski Angle
+ Crab Waist

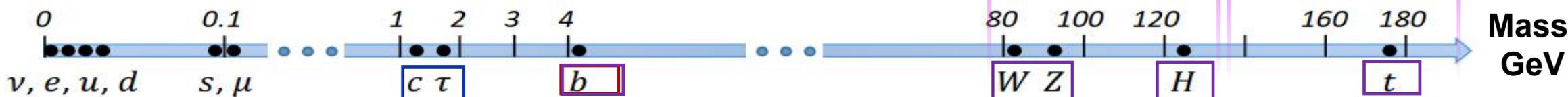
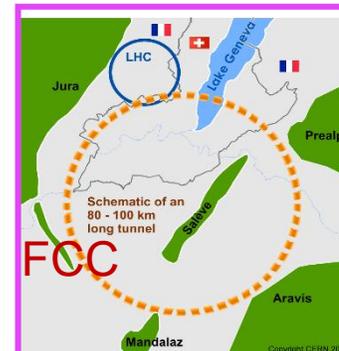
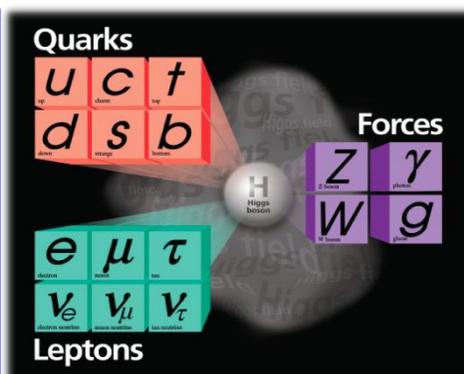
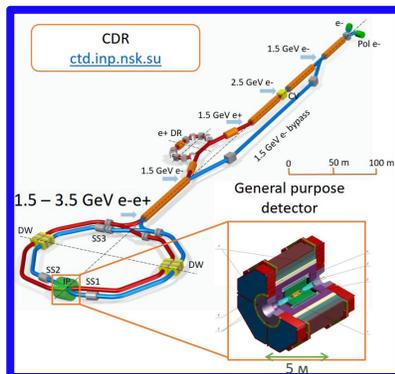
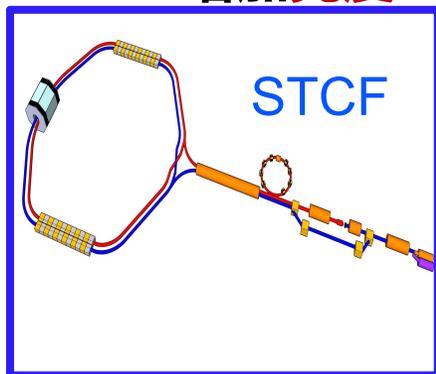
新一代加速器装置



新一代加速器实验装置，大幅度提高**能量**，**亮度和粒子探测精度**

增加**亮度** ~50-100

增加**能量** ~3-10 倍



高亮度前沿： 强子产生机制、
结构、奇特物质态、 强相互
作用本质、以 c, b 夸克和 τ
轻子为媒介寻找新物理

**互补
不可相互替代**

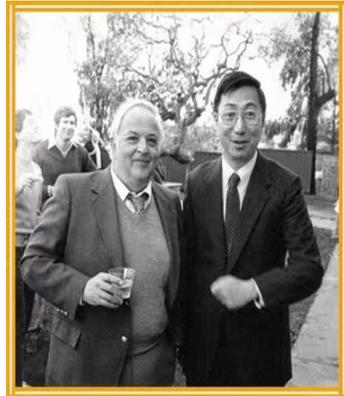
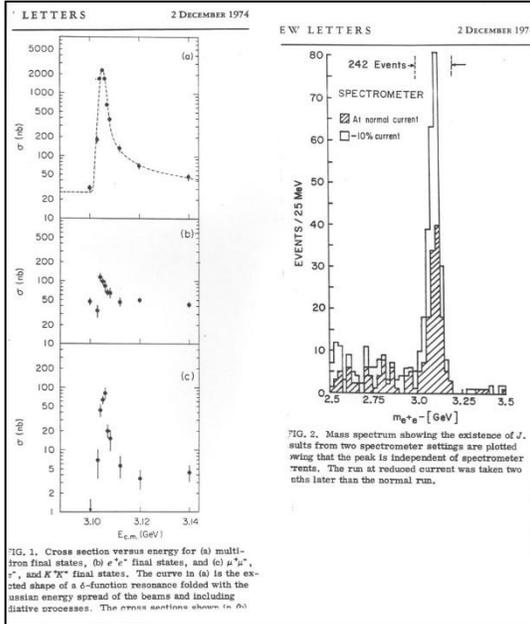
高能量前沿： 基本粒子质量
起源、电弱相互作用本质、
夸克胶子等离子体，通过希
格斯粒子寻找新物理

目录

CONTENTS

- 一、项目的提出和简介
- 二、项目科学目标
- 三、关键技术攻关项目
- 四、项目的组织和推动
- 五、总结

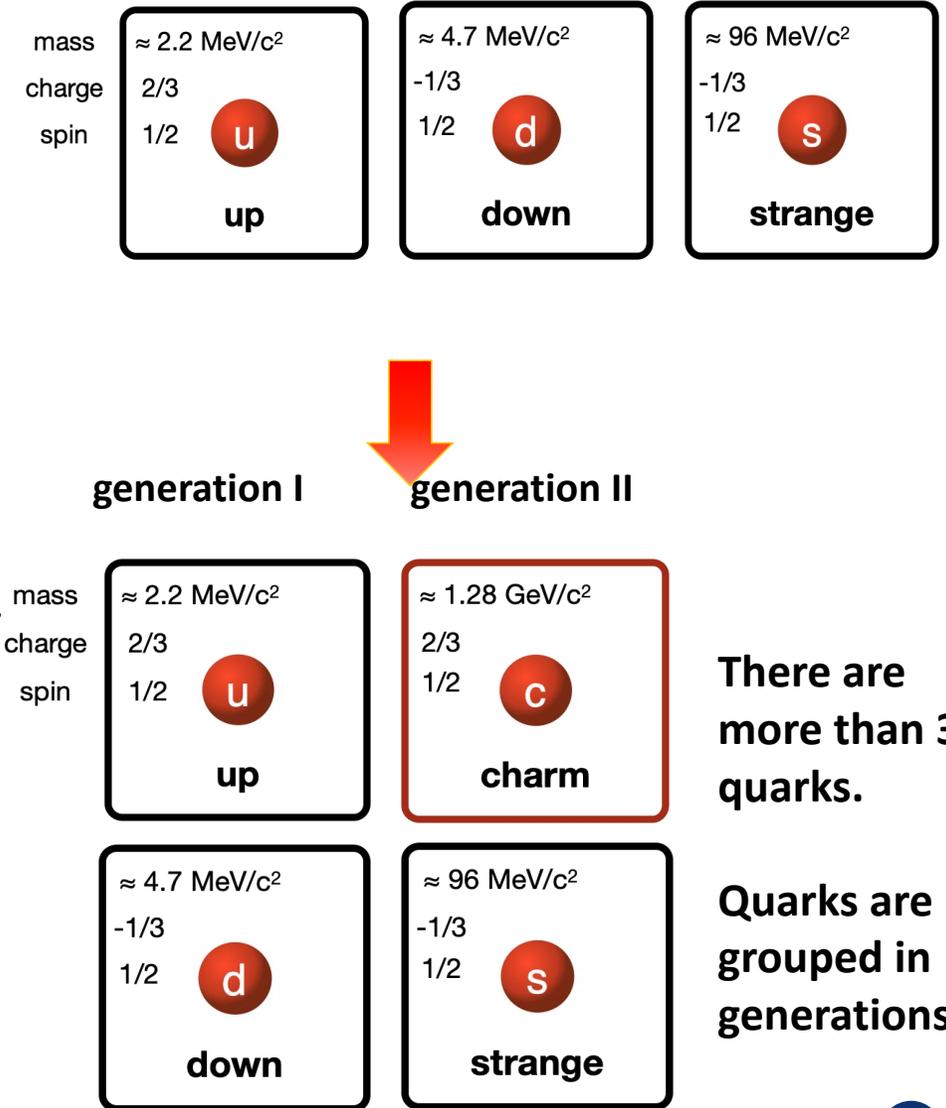
粲夸克的发现

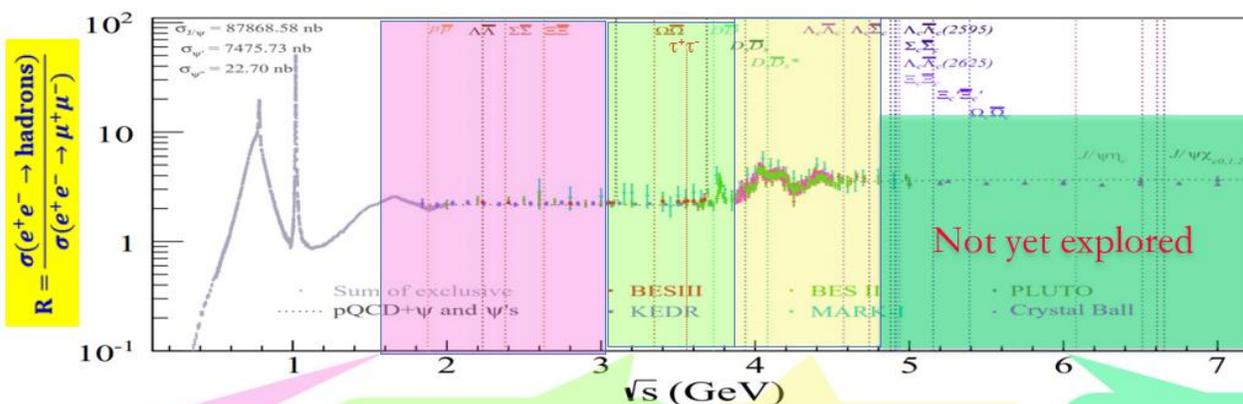
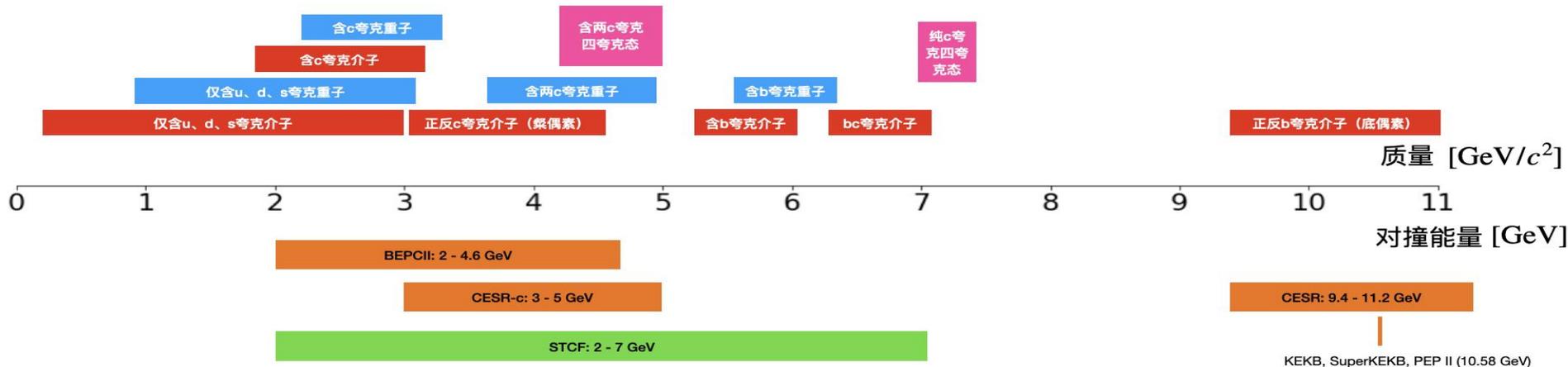


“November Revolution” in particle physics, a milestone of SM journey

Big impact on particle physics:

- Reoriented the theoretical community: confirmed **GIM mechanism**, extended **quark model**
- Reoriented the experimental community: led to the **constructions** of higher energy colliders





- 微扰与非微扰 QCD 的过渡能区
- 丰富的共振结构, 巨大的粲偶素态产生截面, 阈值产生强子对和 τ 轻子对
- 大量奇特量子数强子、胶子态、多夸克态、夸克胶子混合态

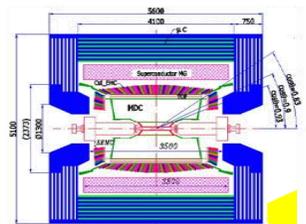
- Nucleon/Hadron form factors
- Y(2175) resonance
- Multiquark states with s quark
- MLLA/LPHD and QCD sum rule predictions

- LH spectroscopy
- Gluonic and exotic
- LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

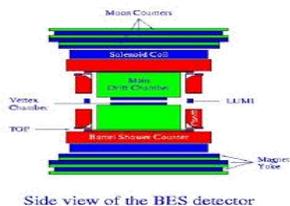
- XYZ particles
- Physics with D mesons
- f_D and f_{D_s}
- $D_0-\bar{D}_0$ mixing
- Charm baryons

- New XYZ particle
- Hidden-charm pentaquark
- Multiquark state
- Di-charmonium state
- Charm baryons
- Hadron fragmentation

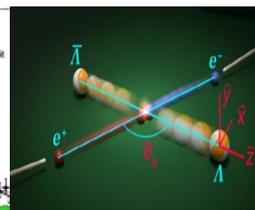
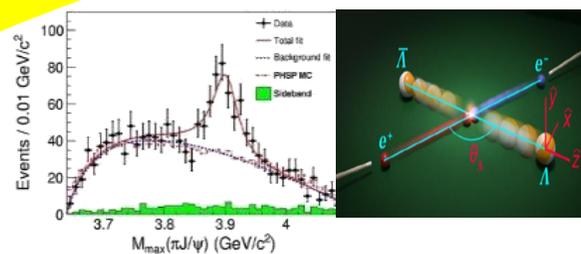
2010
BEPCII/BESIII ($10^{33}\text{cm}^{-2}\text{s}^{-1}$)



BEPCII/BESI-II
($10^{31}\text{cm}^{-2}\text{s}^{-1}$)

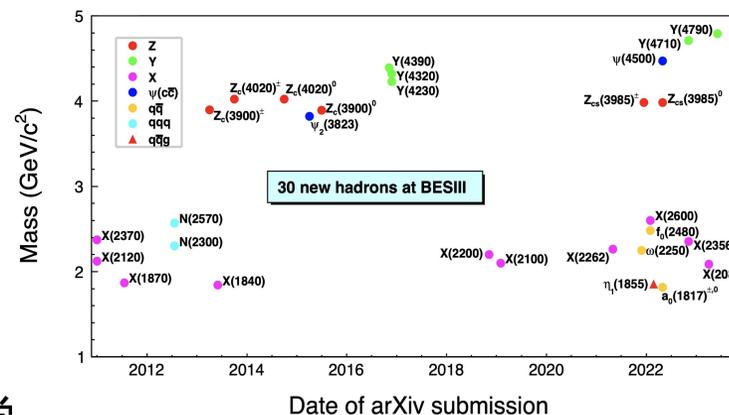
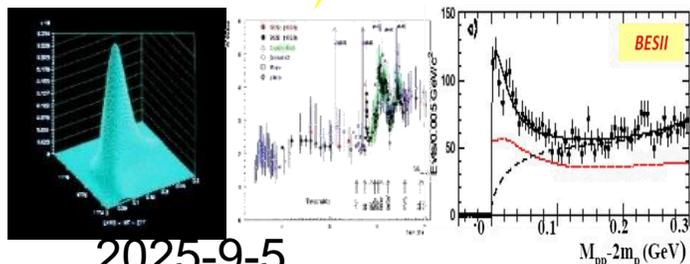


1990

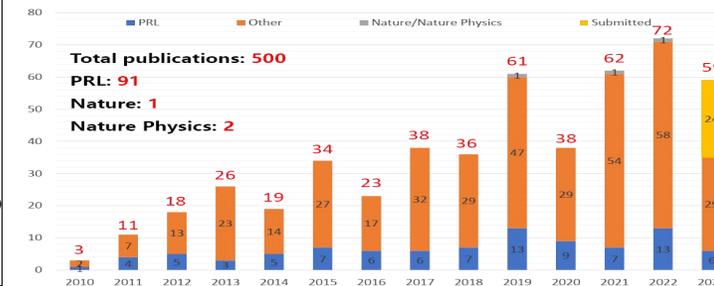


500 paper milestone

BESIII



BESIII publications
(May 9, 2023)

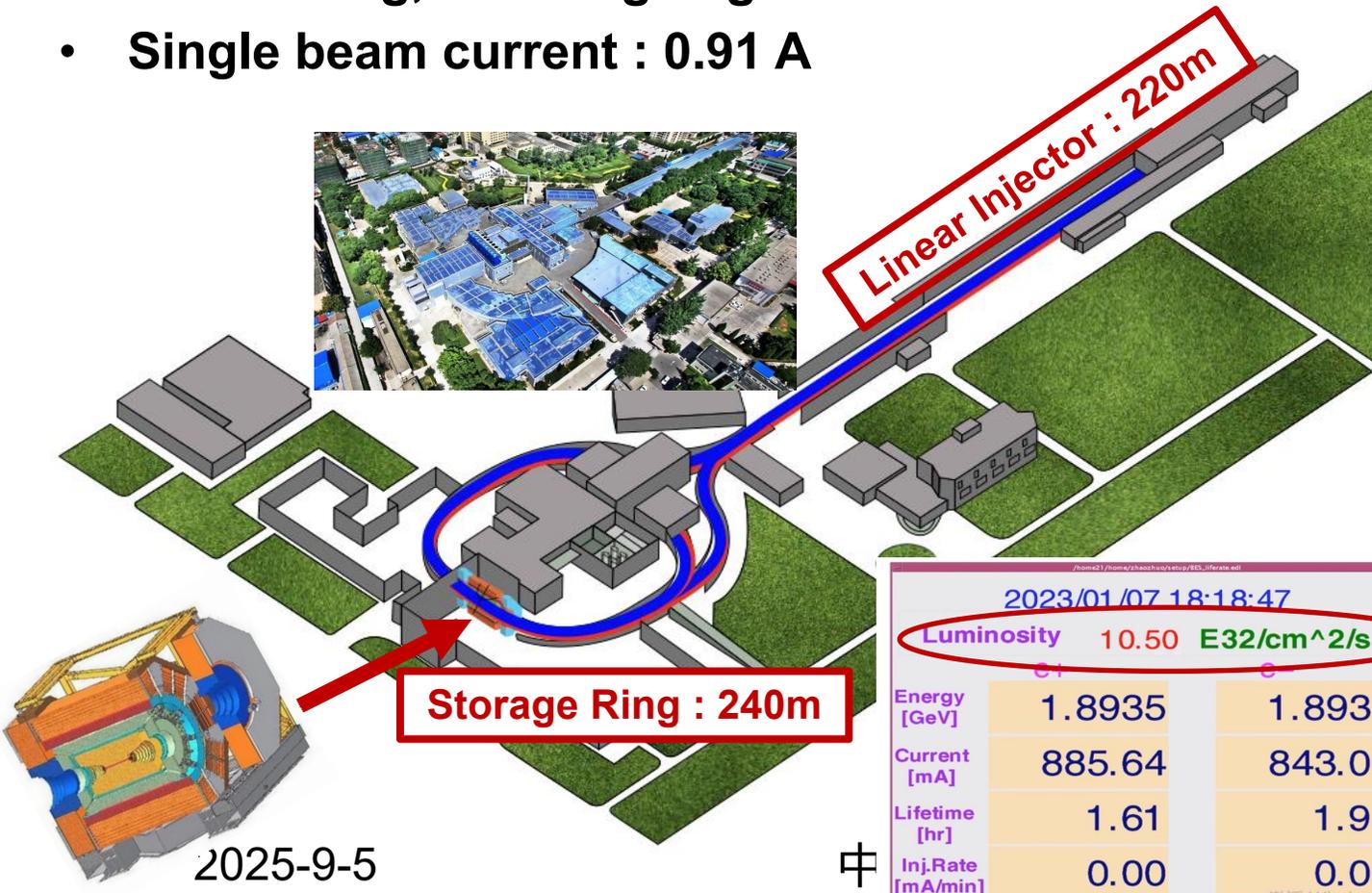


北京正负电子对撞机



BEPCII : A symmetric e⁺e⁻ collider in Beijing (IHEP) Upgrade of BEPCI accelerator

- Center of mass energy range : $\sqrt{s} = 2\sim 4.9$ GeV
- Peaking luminosity : $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- Double ring, crossing angle : 11 mrad
- Single beam current : 0.91 A



Double Ring Multi-Bunch : $kb=1 \rightarrow 93$

Large Emittance & Optimize Beam : $I_b=9.8\text{mA}, \xi_y=0.04$

$$L(\text{cm}^{-2}\text{s}^{-1}) = 2.17 \times 10^{34} (1+R) \xi_y \frac{E(\text{GeV}) k_b I_b (\text{A})}{\beta_y^* (\text{cm})}$$

Micro- β : $\beta_y^* = 5\text{cm} \rightarrow 1.5 \text{ cm}$
Superconductive quadrupole Magnet

$\sigma_z = 5\text{cm} \rightarrow < 1.5\text{cm}$
Reduce Impedance & Superconducting RF

$$(L_{\text{BEPCII}} / L_{\text{BEPC}})_{\text{D.R.}} = (5.5/1.5) \times 93 \times 9.8/35 = 96$$

$$L_{\text{BEPC}} = 1.0 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} \rightarrow L_{\text{BEPCII}} = 1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$$

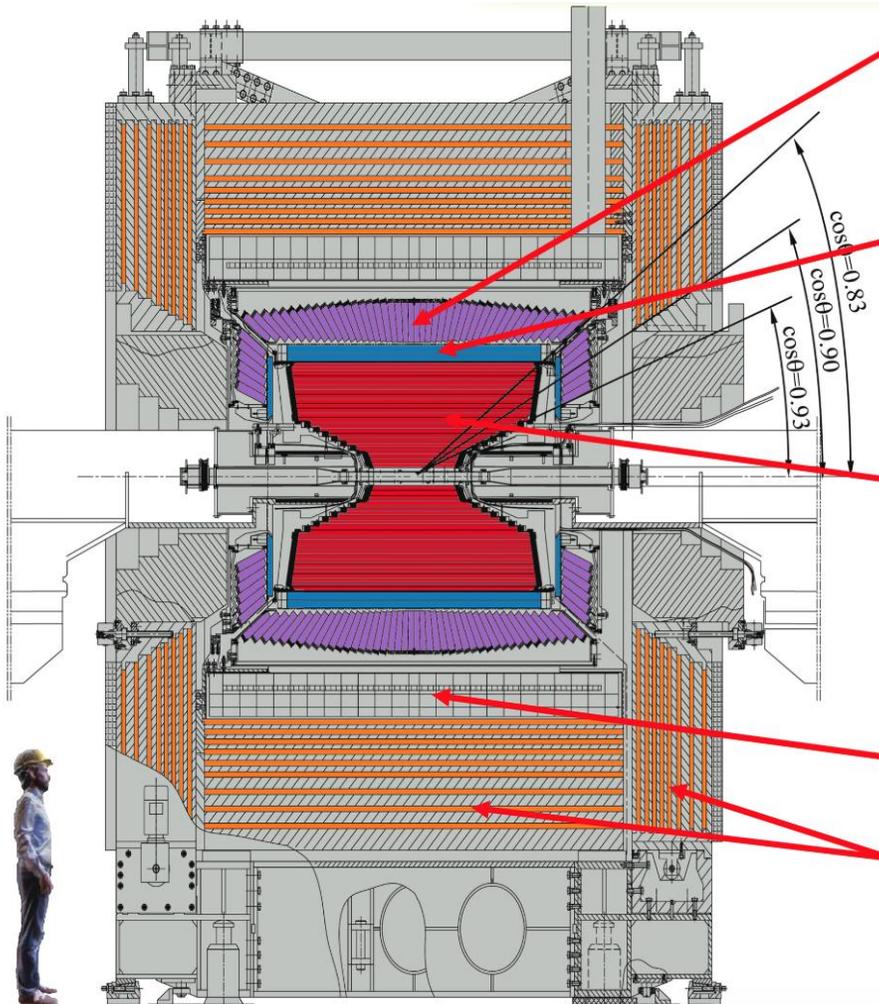
2023/01/07 18:18:47

Luminosity 10.50 E32/cm²/s

Energy [GeV]	1.8935	1.8935
Current [mA]	885.64	843.00
Lifetime [hr]	1.61	1.94
Inj. Rate [mA/min]	0.00	0.00

- 2004: Construction started
- 2008: First Collisions
- 2009: BESIII Physics Runs
- 2016: reached design luminosity
- 2020 : Energy upgrade & top-up mode

A **general purpose** detector with **excellent resolution** and **PID** for the neutral and charged particles, and large coverage.



EMC: CsI crystals

$\Delta E/E = 2.5\%$ @ 1 GeV - Barrel

$\Delta E/E = 5.0\%$ @ 1 GeV - Endcaps

TOF:

$\sigma_T = 80$ ps Barrel

$\sigma_T = 110$ (60) ps Endcap

MDC: small cell & He gas

$\sigma_{xy} = 130$ μm

$\sigma_p/p = 0.5\%$ @ 1 GeV

$dE/dx = 6\%$

Magnet: 1T Super conducting

Muon ID: 9 layer RPC

Trigger: Tracks & Showers

BESIII

Total weight 730 ton,
~40,000 readout channels,
Data rate: 5kHz, 50Mb/s

- Full operation since 2008,
- Very stable data-taking
- Good detector performance
- Aging effects under control

Political Map of the World, November 2011

AUSTRALIA Independent state
Bermuda Dependency or area of special sovereignty
Sicily / AZORES Island / island group

Scale: 1:35,000,000
Robinson Projection
standard parallels 38°N and 38°S



BESIII
~600 members
From 83 institutions in 16 countries

Europe (17/115)

- Germany (6):** Bochum University, GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, Universitaet Giessen, University of Münster
- Italy (3):** Ferrara University, INFN, University of Torino
- Netherlands (1):** KVI/University of Groningen
- Russia (2):** Budker Institute of Nuclear Physics, Dubna JINR
- Sweden (1):** Uppsala University
- Turkey (1):** Turkish Accelerator Center-Particle Factory Group
- UK (2):** University of Manchester, University of Oxford
- Poland (1):** National Centre for Nuclear Research

Asia (6/10)

- Pakistan (2):** COMSATS Institute of Information Technology, University of the Punjab, University of Lahore
- Mongolia (1):** Institute of Physics and Technology
- Korea (1):** Chung-Ang University
- India (1):** Indian Institute of Technology madras
- Thailand (1):** Suranaree University of Technology

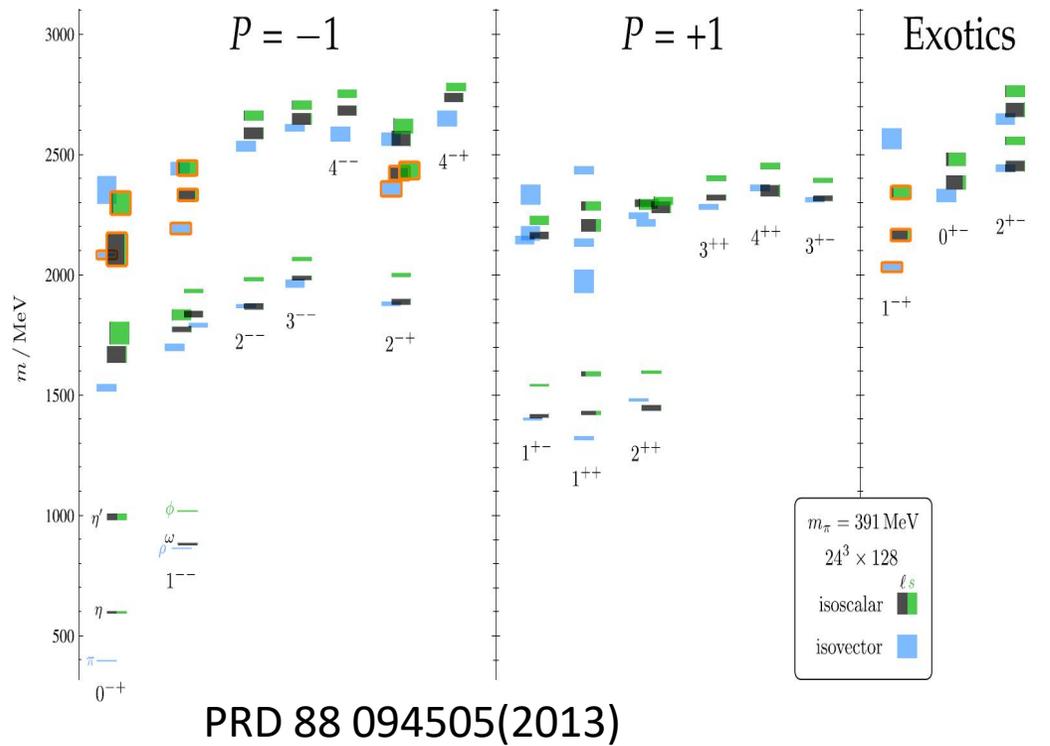
China (55/367)

- Institute of High Energy Physics (146), other units (221):** chemical Technology, Beihang University, China Center of Advanced Science and Technology, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Henan Normal University, Henan University of Science and Technology, Huazhong Normal University, Huangshan College, Hunan University, Hunan Normal University, Henan University of Technology, Institute of modern physics, Jilin University, Lanzhou University, Liaoning Normal University, Liaoning University, Nanjing Normal University, Nanjing University, Nankai University, North China Electric Power University, Peking University, Qufu normal university, Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, Shanghai Jiaotong University, Soochow University, South China Normal University, Southeast University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Sciences, University of Jinan, University of Science and Technology of China, University of Science and Technology Liaoning, University of South China, Wuhan University, Xinyang Normal University, Zhejiang University, Zhengzhou University, YunNan University, China University of Geosciences

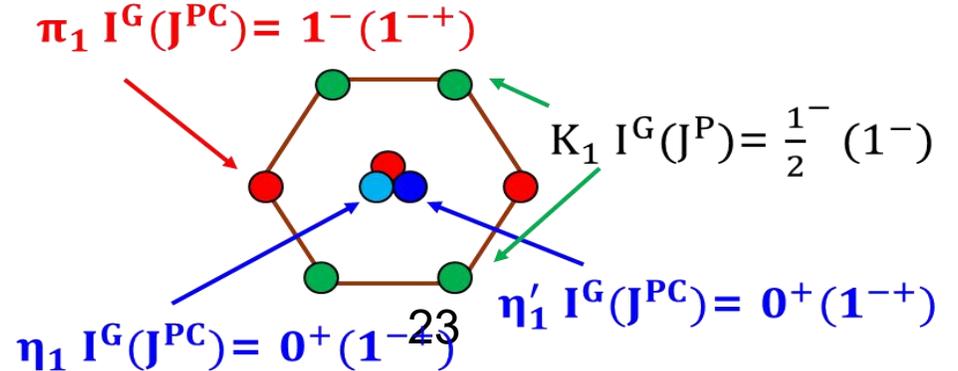
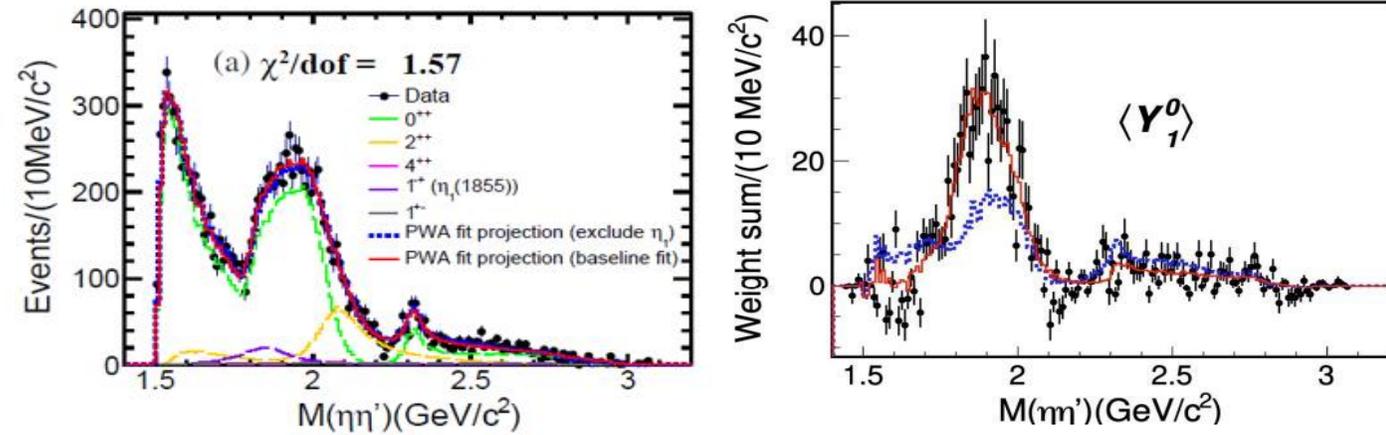
$\eta_1(1^{-+})$ 奇特态的发现

Studies of **Hadron Spectroscopy** and searching for the **exotic hadrons** are crucial to test QCD in the **confinement** region and reveal the **fundamental degrees of freedom**

Hybrids on Lattice



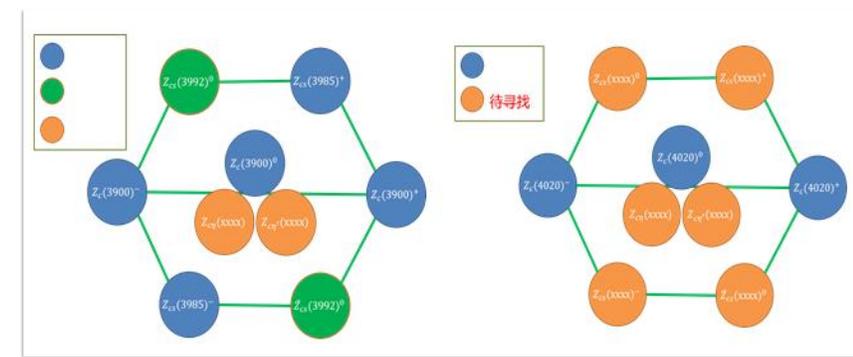
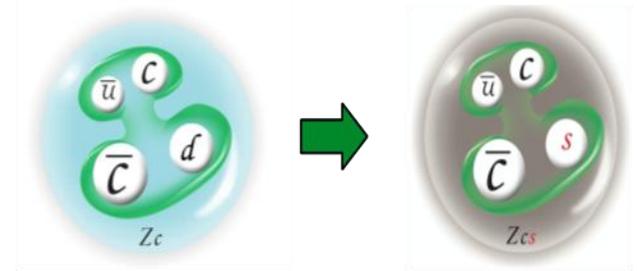
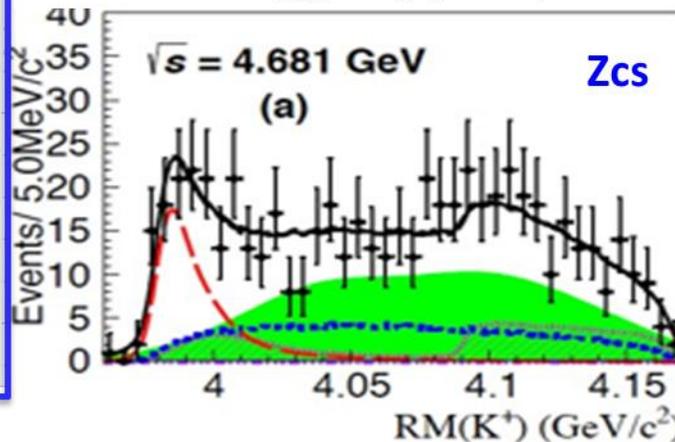
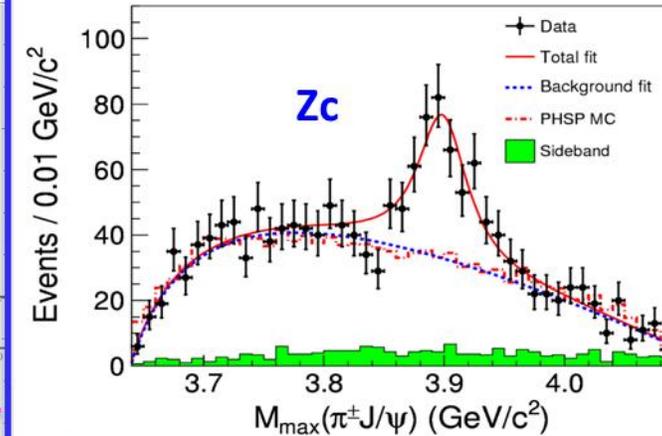
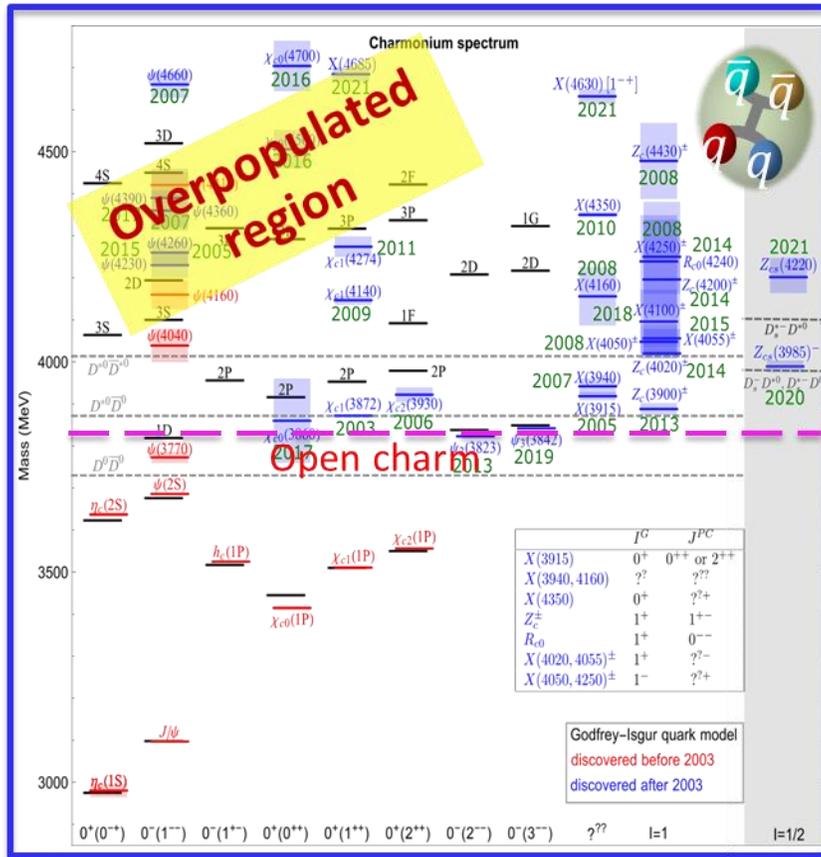
Only 3 Spin-exotic mesons candidates so far:
 $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$, all 1^{-+} isovectors



Lightest nonet of hybrids: 1^{-+} , 0^{++} , 1^{-+} , 2^{-+}

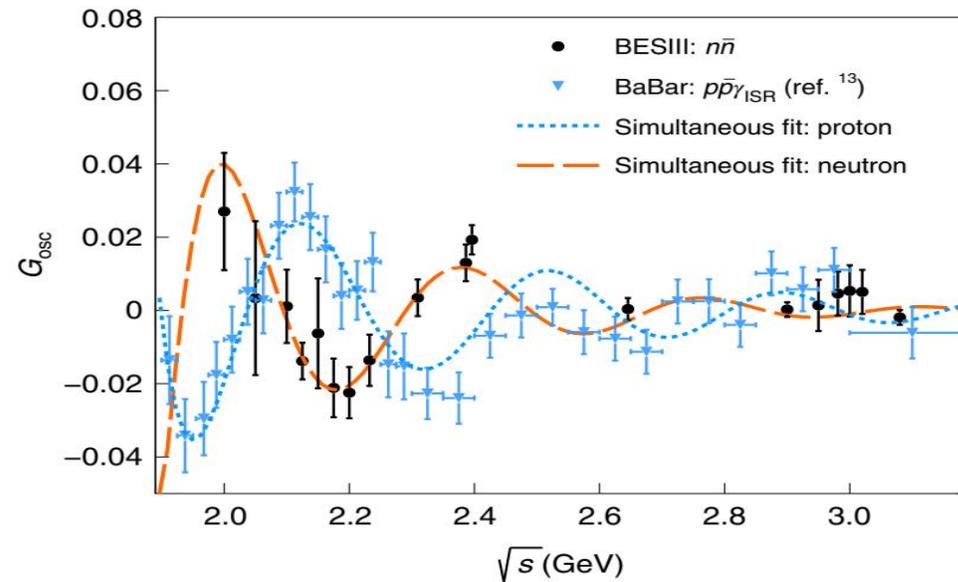
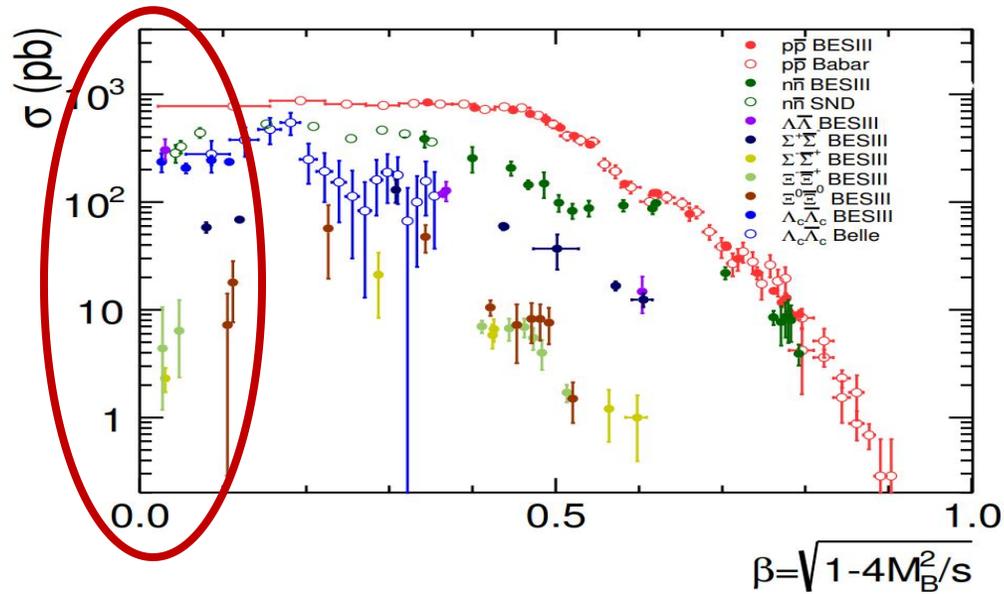
Zc(s) 态的发现

Charmonium(like) spectrometer provide an excellent platform to study exotic hadrons and pQCD, is very **attractive** and **fruitful** in past decade, but **controversy**



Zc and Zcs, the obvious tetra-quarks states, a nonet of the exotic hadrons?

Fundamental properties of the nucleon, connected to charge and magnetization distributions, crucial testing ground for models of the nucleon internal structure



- **Comparable precision** of cross section and form factor for ppbar between **time-like** and **space-like** regions
- **Abnormal** cross section at production threshold
- **Oscillation** as function of CME, **orthogonal** between neutron and proton

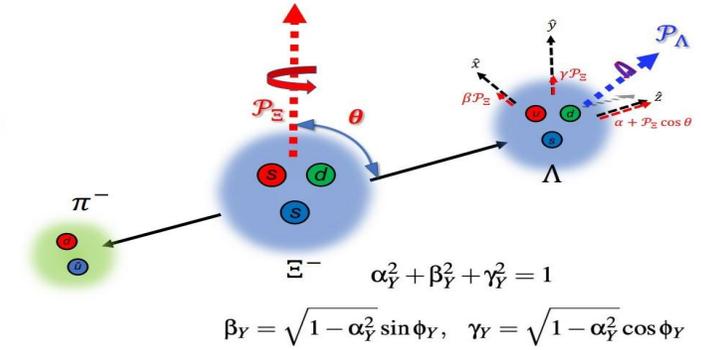
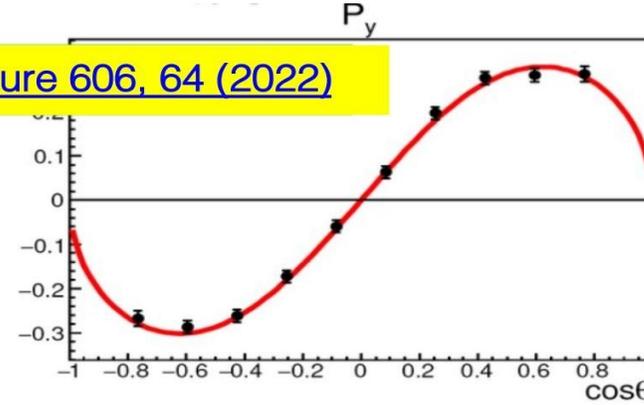
超子CPV?



CPV are found in B, S, and C meson sectors, consistent with SM, but can not explain matter and anti-matter asymmetry in universe. CPV in baryon sector is critical, not observed yet



Nature 606, 64 (2022)



PHYSICAL REVIEW D VOLUME 34, NUMBER 3 1 AUGUST 1986

PRD 34,833 1986

Hyperon decays and CP nonconservation

John F. Donoghue

Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003

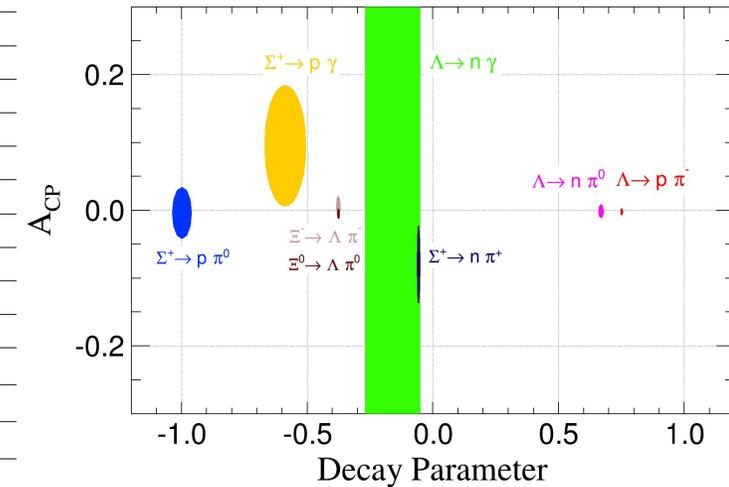
Xiao-Gang He and Sandip Pakvasa

Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822

(Received 7 March 1986)

We study all modes of hyperon nonleptonic decay and consider the CP-odd observables which result. Explicit calculations are provided in the Kobayashi-Maskawa, Weinberg-Higgs, and left-right-symmetric models of CP nonconservation.

Parameter	This work	Previous result
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016 \text{ rad}$	-
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009 \text{ rad}$	$-0.037 \pm 0.014 \text{ rad}$
$\bar{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	-
$\bar{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007 \text{ rad}$	-
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2} \text{ rad}$	-
$\bar{\delta}_P - \bar{\delta}_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2} \text{ rad}$	$(10.2 \pm 3.9) \times 10^{-2} \text{ rad}$
A_{CP}^Ξ	$(6 \pm 13 \pm 6) \times 10^{-3}$	-
$\Delta\phi_{CP}^\Xi$	$(-5 \pm 14 \pm 3) \times 10^{-3} \text{ rad}$	-
A_{CP}^Λ	$(-4 \pm 12 \pm 9) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007 \text{ rad}$	-

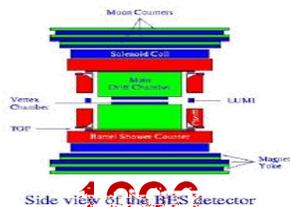


BESIII found the polarized hyperon pair provide unique opportunity to study CPV in hyperon sector

中国陶粲装置

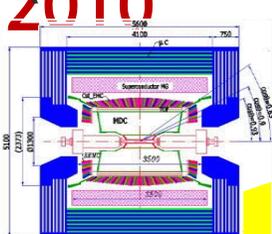


BEPCII/BESI-II
($10^{31} \text{cm}^{-2}\text{s}^{-1}$)



1996

BEPCII/BESIII ($10^{33} \text{cm}^{-2}\text{s}^{-1}$)



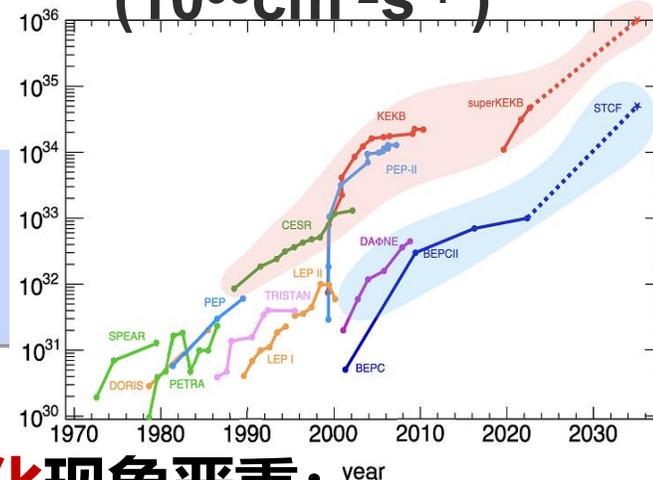
2010

203?

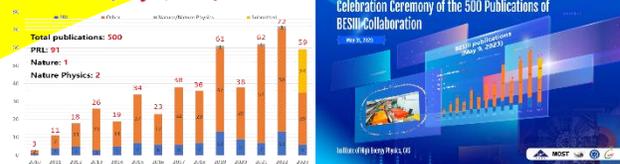


超级陶粲装置?

($10^{35} \text{cm}^{-2}\text{s}^{-1}$)



BESIII publications
(May 9, 2023)



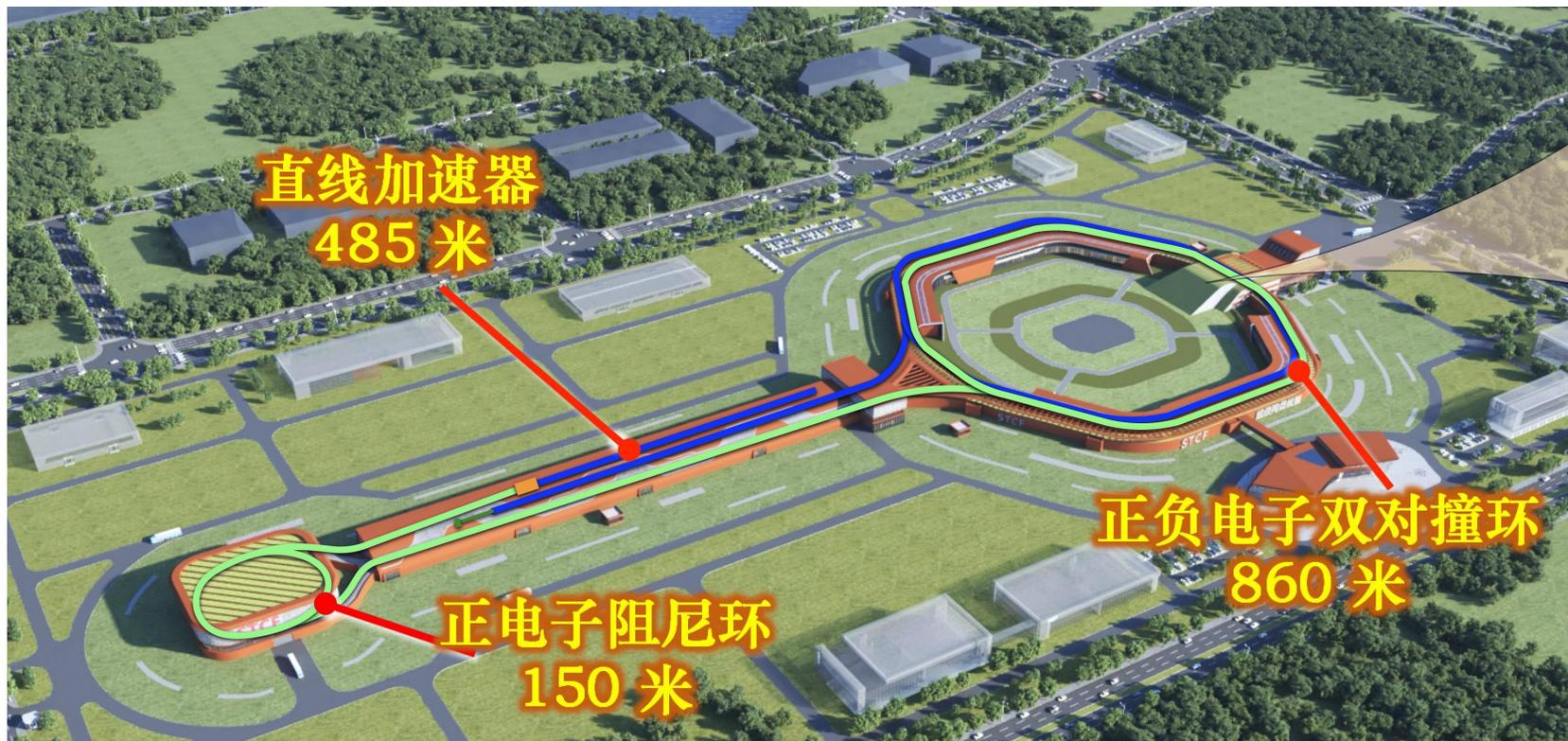
- BEPCII/BESIII取得**重大研究成果**,但**老化现象严重**;
- 解决了一系列问题,同时也提供了**更大机遇**,期待**更多的数据**:

数据量显著提升不只是测量重复和精度提升,同时带来了研究领域和课题的大幅度扩大

超级陶粲装置



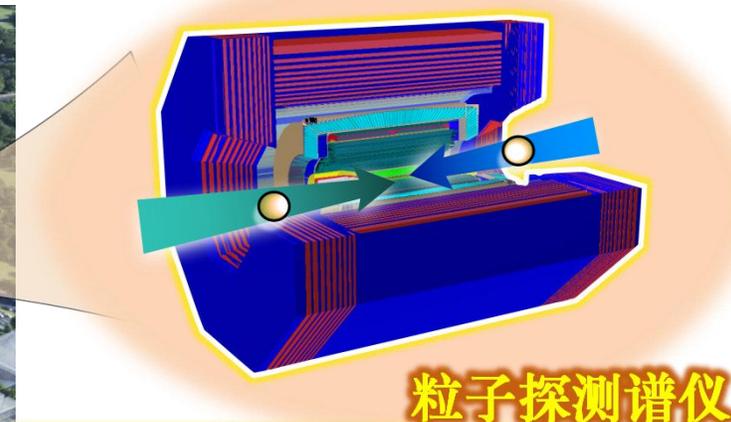
新一代GeV能区正负电子对撞机，国际粒子物理领域高亮度前沿核心装置，探索夸克如何构成物质和研究基本对称性的独特平台



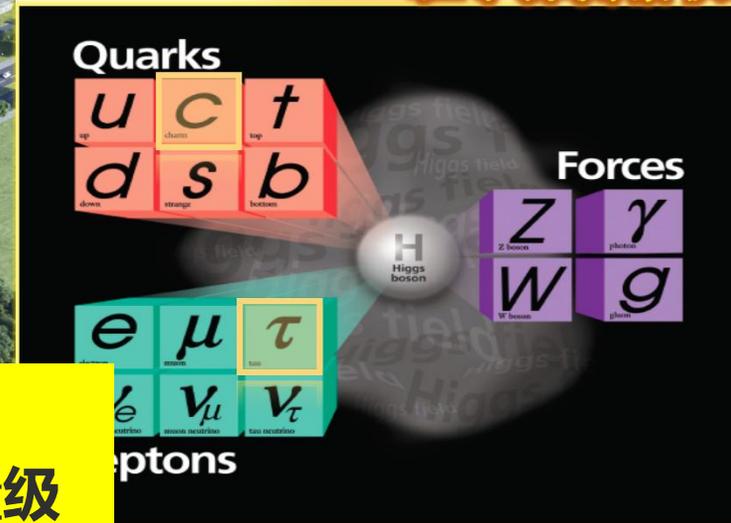
直线加速器
485 米

正负电子双对撞环
860 米

正电子阻尼环
150 米

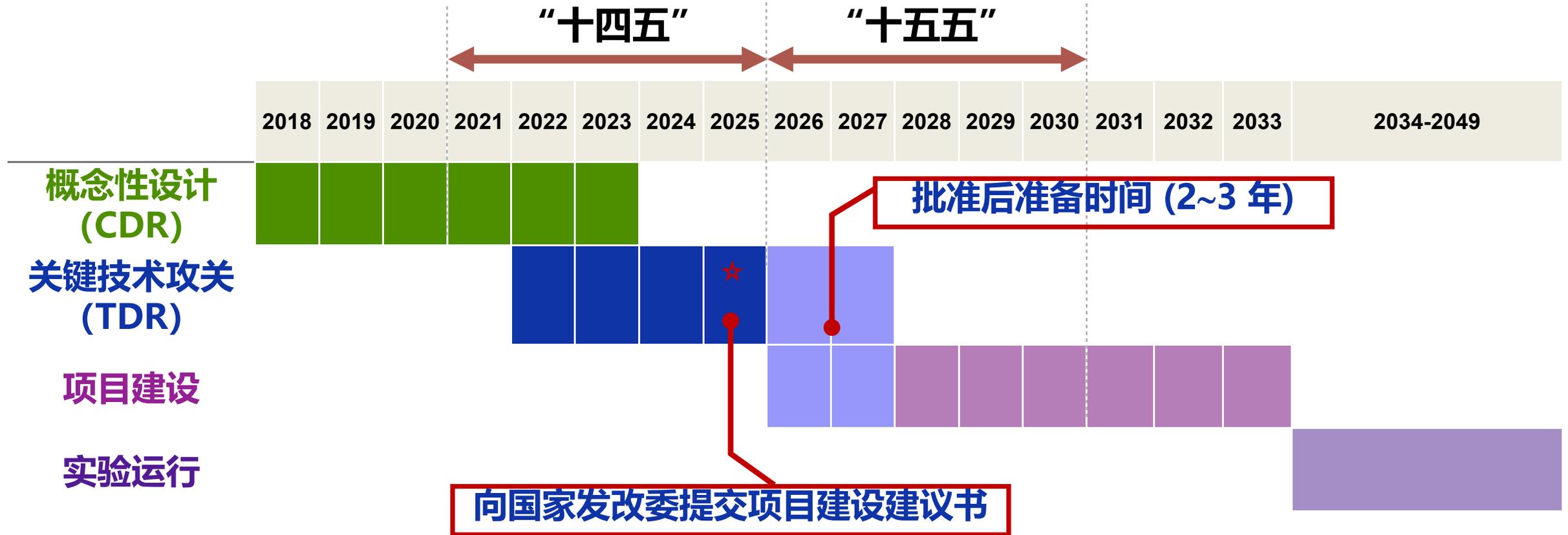


粒子探测谱仪



- 质心能量**2-7GeV**，亮度 **$0.5\sim 1\times 10^{35}\text{cm}^{-2}\text{s}^{-1}$** (提升100倍)
- 两天实验 **\approx** 当前装置一年，对物质深层次结构解析能力提高1-2量级
- 具备进一步**提升性能**的潜力

项目时间表

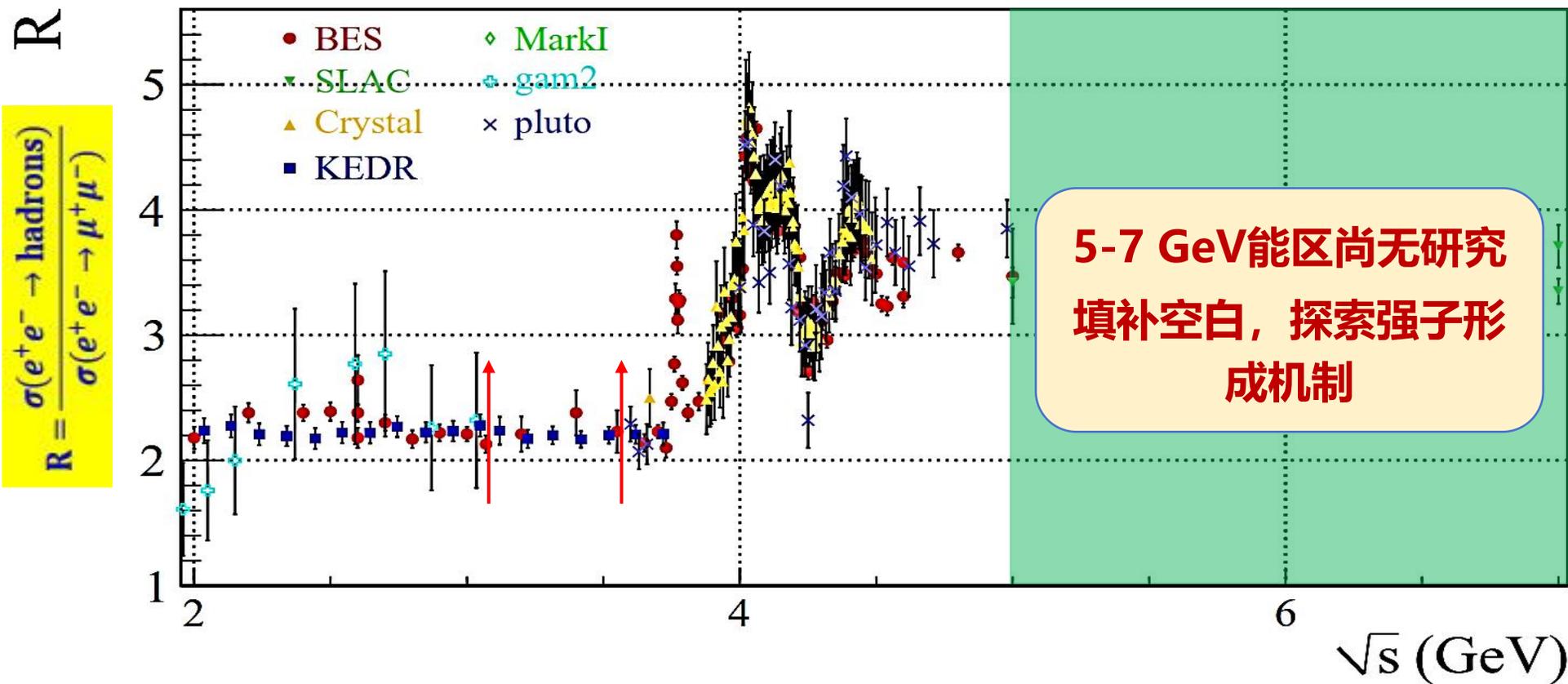


- 十四五期间：**概念性设计、关键技术攻关**, 3.64 亿
- 十五五期间：**开建前准备、建设**, 6 年, ~50亿
- 运行10-15年, 升级2-3年, 再运行10年

目录

CONTENTS

- 一、项目的提出和简介
- 二、项目科学目标**
- 三、关键技术攻关项目
- 四、项目的组织和推动
- 五、总结

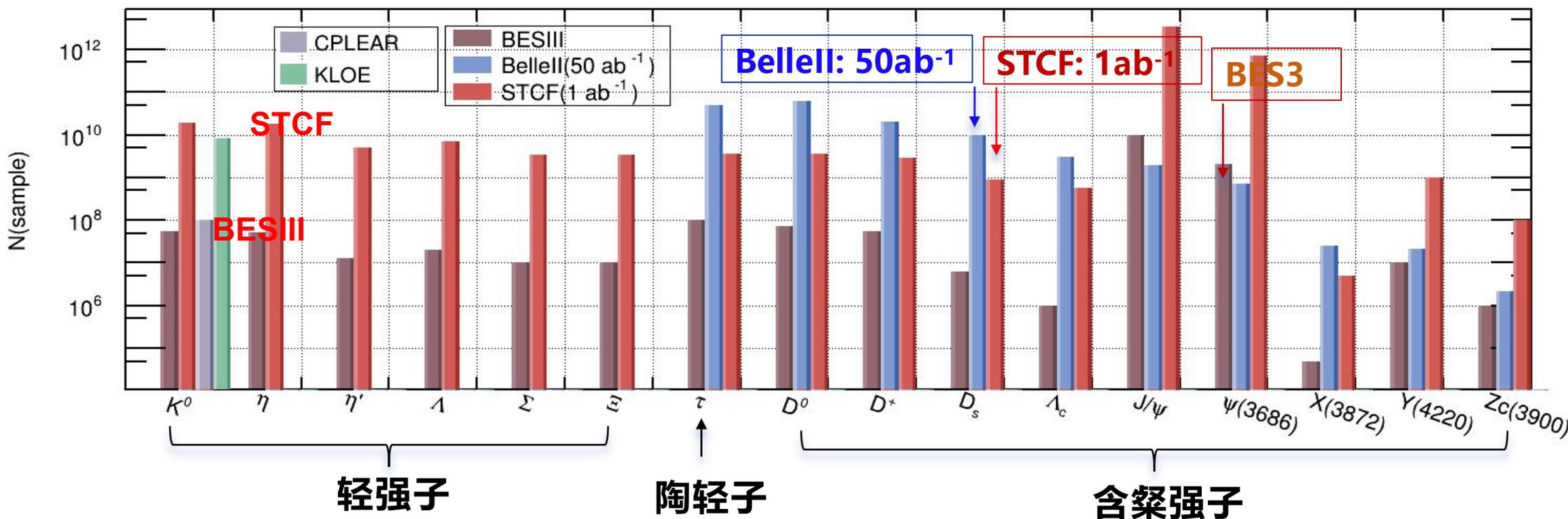


- 超高亮度
- 超宽能区连续可调
- 超高测量精度

独特的超大数据样本



STCF每年获取 $1ab^{-1}$ 数据，是**陶粲工厂**，同时也是**XYZ粒子、超子、轻介子工厂**



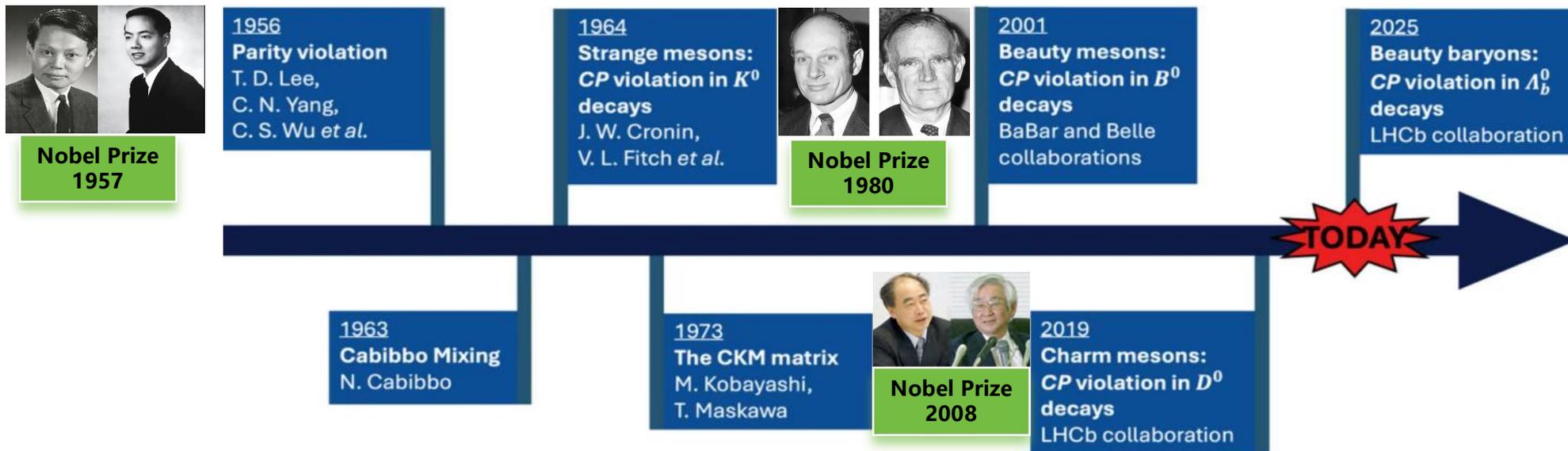
世界**独特**的超大数据样本 + **高分辨** + **低本底** → **高精度**测量 → **重大发现**

- 味物理和宇称不守恒
- 强子物理与色禁闭之谜
- 基本参数测量与新物理

超级陶粲装置将解开**夸克如何构成物质**和**基本相互作用对称性**的奥秘

物理机遇一：正反物质不对称

CP破坏是宇宙物质-反物质不对称性的必要条件，但当前实验观测的CP破坏效应远不足够



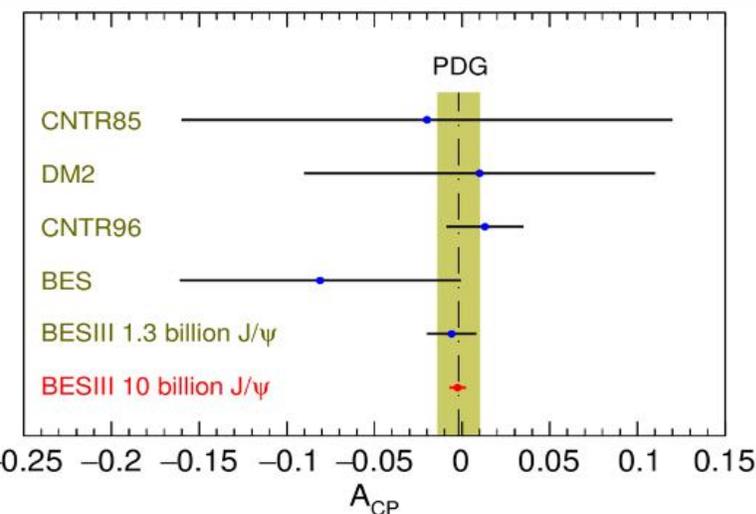
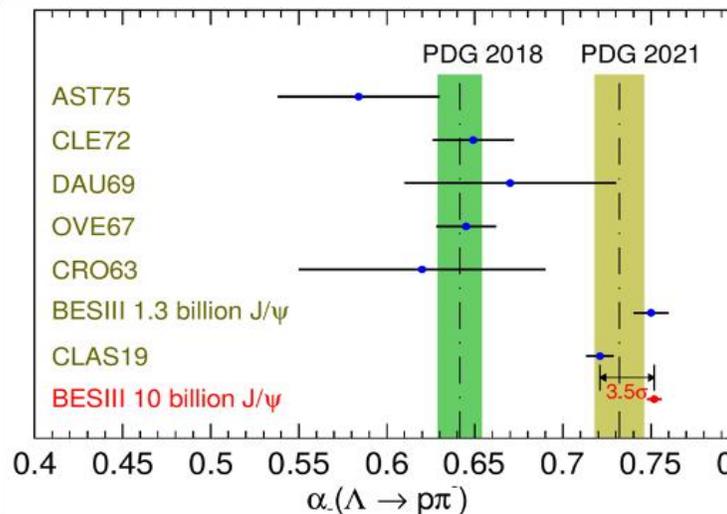
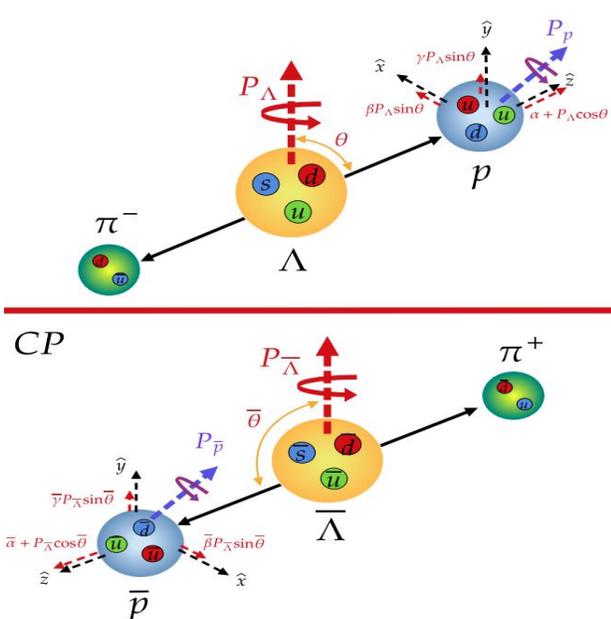
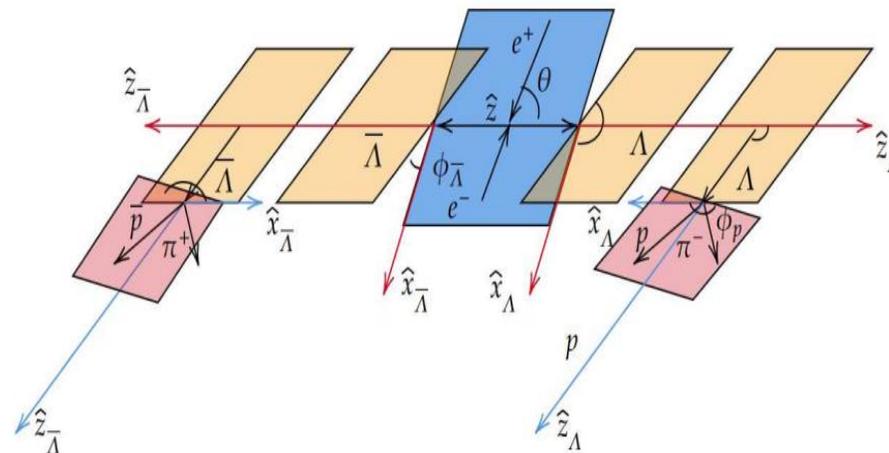
夸克层次的CP破坏研究现状

第一代	第二代	第三代
上夸克 (Up)	粲夸克 (Charm)	顶夸克 (Top)
第一代强子CP破坏预言远低于当前实验能力	粲介子: 2009年LHCb实验发现, CP破坏量级 $O(10^{-3})$, 标准模型预言范围内 粲重子: 实验 未发现CP破坏 , 标准模型预言 $O(10^{-4})$, 新物理 $O(10^{-3})$	寿命极短, 无法形成强子即发生衰变, 无“顶强子”CP不对称性。
下夸克 (Down)	奇异夸克 (Strange)	底夸克 (Bottom)
第一代强子CP破坏预言远低于当前实验能力	奇异介子: 1964年实验发现, CP破坏量级 $O(10^{-3})$, 标准模型预言范围内, 1974年诺奖 奇异重子: 实验 未发现CP破坏 , 标准模型预言 $O(10^{-4} - 10^{-5})$, 新物理 $O(10^{-3})$	底介子: 2001年Babar/Belle实验发现, CP破坏量级 $O(0.1)$, 标准模型预言范围内, 2008年诺奖 底重子: 2025年LHCb实验发现, CP破坏量级 $O(0.1)$, 标准模型预言范围内

目前仅剩**奇异重子**和**粲重子**的CP破坏没有发现, 存在**新物理空间**, 是**强子物理**最后未被开垦的前沿之一

超子极化与CP破坏

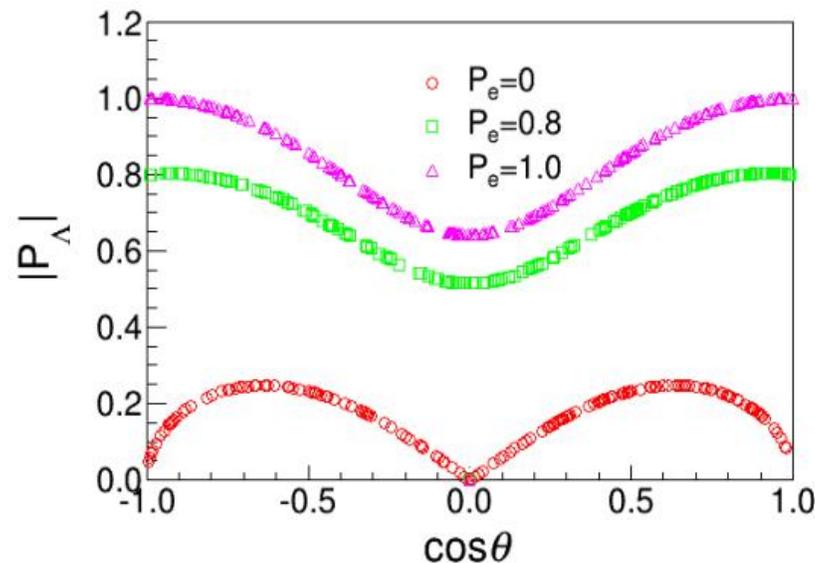
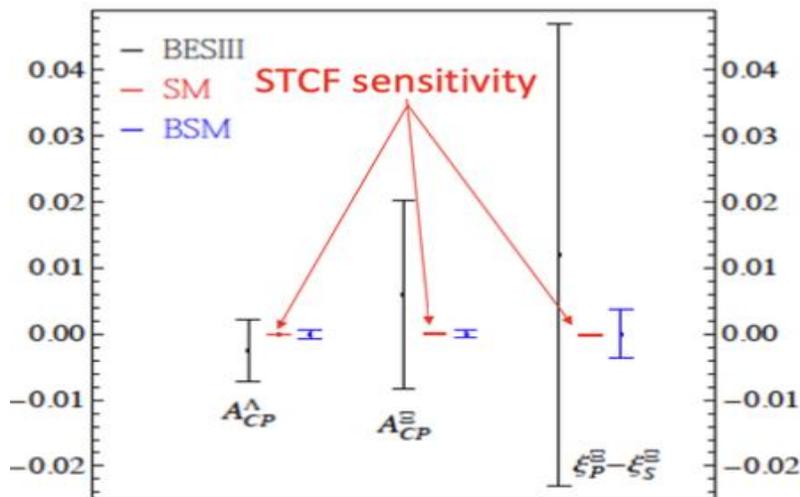
- BES3实验发现 J/ψ 衰变产生的超子对，具备量子纠缠和极化（最大30%）的特性，可构造多个CP破坏观测量，为测量超子CP破坏提供了重大机遇
- 多衰变角联合分析提升CP对称性检验敏感度（1500倍）
- BESIII获得世界上最精确的 Λ 衰变中的CP对称性检验敏感度，但和标准模型预言有一定差距



CP test
$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

**BESIII CPV 检验灵敏度0.5 %，
SM 预言:10⁻⁴~10⁻⁵**

X.G. He et al. Sci.Bull. 67 (2022) 1840-1843:



- 大量产生**各类超子-反超子对**，构造多个CP破坏观测，灵敏度可达 **10^{-4}**
- 极化束流**能够显著提高CP对称性检验敏感度
- 系统误差**可控制在与统计误差相当的量级

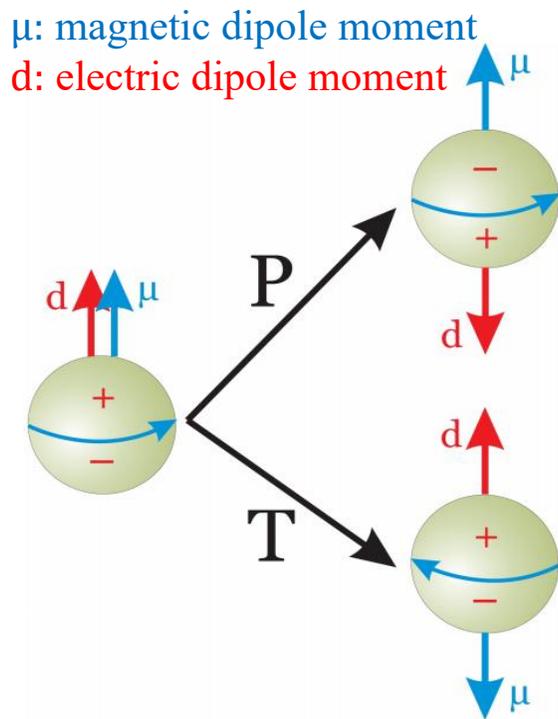
$$\sigma_{ACP} \approx \sqrt{\frac{3}{2}} \frac{1}{\alpha_1 \sqrt{N_{sig}} \sqrt{\langle P_B^2 \rangle}}$$

$$\frac{1 \times 10^9 \Lambda \bar{\Lambda}, \quad \langle P_B^2 \rangle = 0.1}{\implies} \sigma_{ACP} \sim 1.4 \times 10^{-4}$$

$$\frac{1 \times 10^9 \Lambda \bar{\Lambda}, \quad \langle P_B^2 \rangle = 0.8}{\implies} \sigma_{ACP} \sim 5 \times 10^{-5}$$

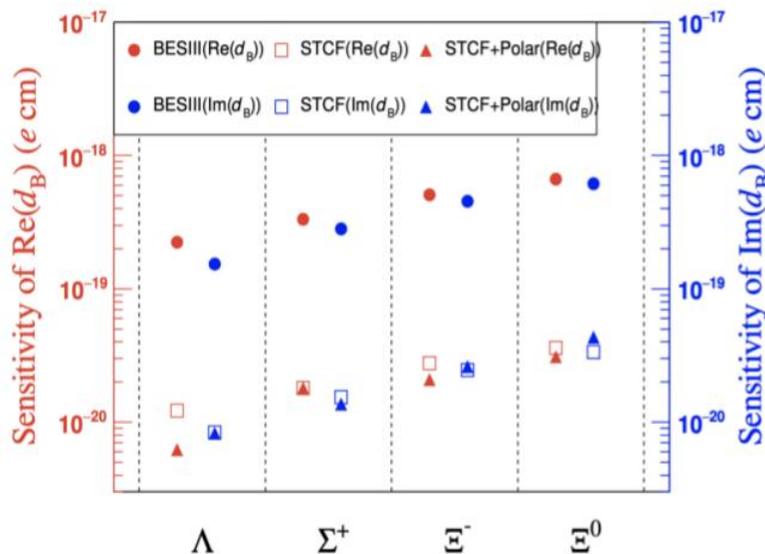
STCF 一年数据，将达到标准模型预期的CP破坏灵敏度，系统误差可控制

非零的电偶极矩破坏时间反演对称性，在CPT联合对称性守恒下，是CP破坏的间接证据



Detailed dynamics have been studied:

$$\mathcal{A} = \epsilon_{\mu}(\lambda) \bar{u}(\lambda_1) \left(F_V \gamma^{\mu} + \frac{i}{2M_{\Lambda}} \sigma^{\mu\nu} q_{\nu} H_{\sigma} + \gamma^{\mu} \gamma^5 F_A + \sigma^{\mu\nu} \gamma^5 q_{\nu} H_T \right) v(\lambda_2)$$



(a) Sensitivity of $Re(d_B)$ and $Im(d_B)$

SM: $\sim 10^{-26}$ e cm

BESIII: milestone for hyperon EDM measurement
 Λ 10^{-19} e cm (FermiLab 10^{-16} e cm)
 first achievement for Σ^+, Ξ^- and Ξ^0 at level of 10^{-19} e cm
 a litmus test for new physics

STCF: improved by 2 order of magnitude

STCF在超子的CP破坏和EDM将是国际实验的最高精度

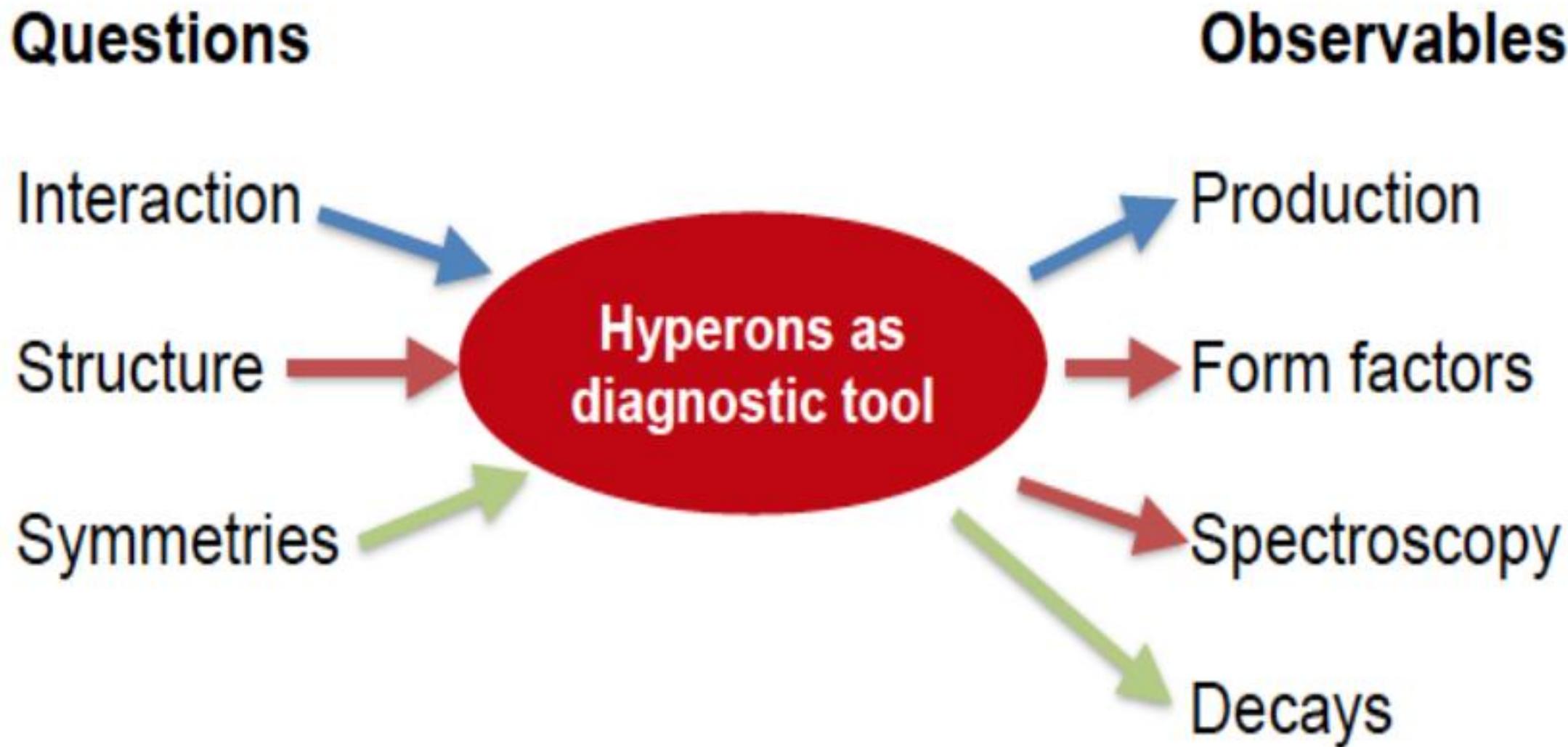
Questions

Interaction

Structure

Symmetries

Hyperons as
diagnostic tool



Observables

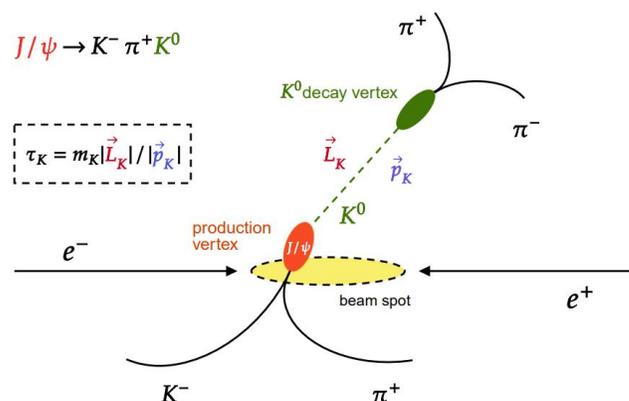
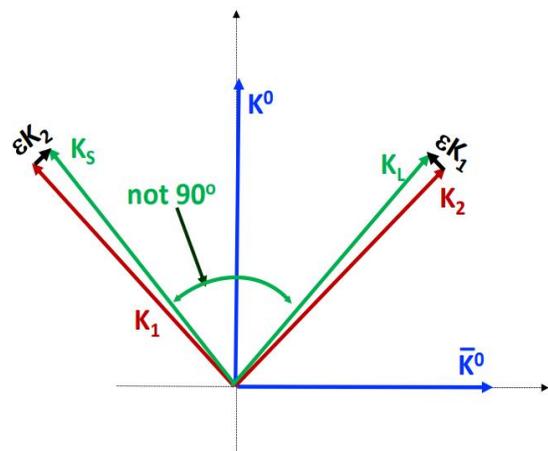
Production

Form factors

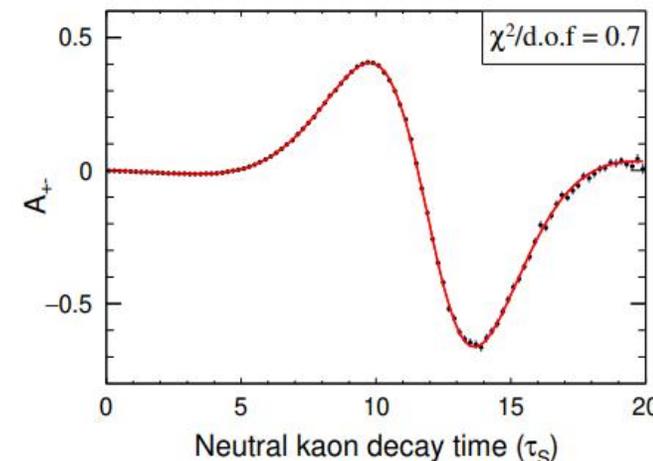
Spectroscopy

Decays

根据量子场论，洛伦兹不变的局域场论中CPT对称，CPT的对称性检验是对超出标准模型的新物理的直接寻找。



arXiv : 2209.12551



- $K^0 - \bar{K}^0$ **flavor tagging** via $J/\psi \rightarrow K^0 K^- \pi^+ / \bar{K}^0 K^+ \pi^-$
- $K_1 - K_2$ **CP tagging** by reconstructing $\pi^+ \pi^-$ or $\pi^+ \pi^- \pi^0$
- Precise determination of K^0 decay vertex \Rightarrow essential for time-distribution

- The phase in CP parameter ϕ_{+-} used to set limits on CPT violation
- sensitivity of ϕ_{+-} is $\mathcal{O}(10^{-3})$ at STCF \Rightarrow **one magnitude better than PDG average**

CP violation studies at Super tau-charm facility

Hai-Yang Cheng^a, Zhi-Hui Guo^b, Xiao-Gang He^c, Yingrui Hou^d, Xian-Wei Kang^e, Andrzej Kupsc^{f,g}, Ying-Ying Li^h, Liang Liu^h, Xiao-Rui Lyu^d, Jian-Ping Maⁱ, Stephen Lars Olsen^{j,k}, Haiping Peng^h, Qin Qin^q, Pablo Roig^{m,n}, Zhi-Zhong Xing^o, Fu-Sheng Yu^p, Yu Zhang^q, Jianyu Zhang^d, Xiaorong Zhou^h

^aInstitute of Physics, Academia Sinica, Taipei, 11529, China

^bHebei Normal University, Shijiazhuang, 050024, China

^cShanghai Jiao Tong University, Shanghai, 200250, China

^dUniversity of Chinese Academy of Sciences, Beijing, 100049, China

^eBeijing Normal University, Beijing, 100875, China

^fNational Centre for Nuclear Research, Warsaw, 02-093, Poland

^gUppsala University, Uppsala, SE-75120, Sweden

^hUniversity of Science and Technology of China, Address One, 230026, China

ⁱInstitute of Theoretical Physics, Chinese Academy of Sciences, Beijing, 100190, China

^jHigh Energy Physics Center, Chung-Ang University, Seoul, 06974, Korea

^kParticle and Nuclear Physics Institute, Institute for Basic Science, Daejeon, 34126, Korea

^lHuazhong University of Science and Technology, Wuhan, 430074, China

^mDepartamento de Física, Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional, Mexico City, AP 14740, CP 07000, Mexico

ⁿIFIC, Universitat de València – CSIC, Paterna, E-46980, Spain

^oInstitute of High Energy Physics, Chinese Academy of Sciences, Beijing, 100049, China

^pLanzhou University, Lanzhou, 730000, China

^qUniversity of South China, Hengyang, 421001, China

Abstract

Charge-parity (CP) violation in the tau-charm energy region is one of the promising areas to search for. The future tau-charm facility of next generation is designed to operate in a center-of-mass energy from 2.0 to 7.0 GeV with a peak luminosity of $0.5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$. Huge amount of hadrons and tau (τ) leptons will be collected with good kinematic constraint and low-background environment. In this report, possibilities of CP violation studies in tau-charm energy region and at the future tau-charm facility are discussed from various aspects, *i.e.* in the production and decay of hyperons and τ lepton; in the decay of charmed hadrons. The CPT invariance test in $K^0 - \bar{K}^0$ mixing is also presented.

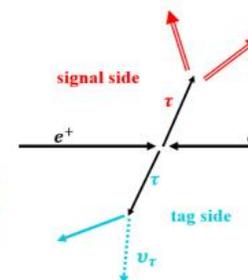
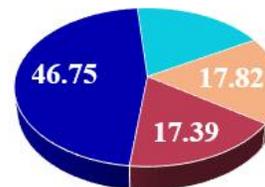
Contents

1	Introduction	4
2	CP-violation in hyperon sector	7
2.1	Direct CP violation in strange quark systems	7
2.2	Hyperon two-body hadronic weak decays	8
2.3	Spin entangled baryon-antibaryon systems	13
2.4	Radiative and semileptonic decays	18
2.5	CP violation in production via edm	22
2.6	CP violation in charmed baryon decays	22
2.7	Prospect of hyperon CP -violation study at STCF	24
2.7.1	Event selection	24
2.7.2	Sensitivity of CP -violation in hyperon decay	25
2.7.3	Comparison of hyperon CP sensitivity with different experiments	27
3	CP-violation in τ sector	30
3.1	Hadronic form factors in semileptonic τ decays	30
3.2	Structure functions in hadronic τ decays	33
3.3	CP -violation observables in hadronic τ decays	34
3.4	CP violating asymmetries in $\tau \rightarrow K_S \pi \nu$ decays: the BaBar anomaly and the Belle measurement	36
3.5	CP -violation proposal via EDM	39
3.6	Prospect of τ CP -violation study at STCF	40
3.6.1	MC simulation of $\tau^- \rightarrow K_S \pi^- \nu_\tau$	40
3.6.2	Optimization of event selection	41
3.6.3	Sensitivity of CP -violation in $\tau^- \rightarrow K_S \pi^- \nu_\tau$ at STCF	43
4	CP-violation in charm sector	45
4.1	The CKM matrix and its unitarity	45
4.2	Six types of CP violation	46
4.2.1	CP violation in the direct decays	46
4.2.2	CP violation from D^0 - \bar{D}^0 mixing	47
4.2.3	CP violation from the interplay between decay and mixing	48
4.2.4	CP violation in the CP -forbidden coherent $D^0 \bar{D}^0$ decays	50
4.2.5	CP violation due to the final-state K^0 - \bar{K}^0 mixing	51
4.2.6	CP violation due to $D^0 - \bar{D}^0$ and $K^0 - \bar{K}^0$ oscillating interference	52
4.3	Indirect CP violation associated with D^0 - \bar{D}^0 mixing	53
4.3.1	Formulas for incoherent neutral D meson decays	54
4.3.2	Formulas for coherent $(D^0 \bar{D}^0)_{C=\pm 1}$ decays	55
4.3.3	CP violation in $D^0 \rightarrow \pi^+ \pi^-$ and $K^+ K^-$ decays	59
4.3.4	CP violation in $D^0 \rightarrow K^{*+} K^-$ and $K^+ K^{*-}$ decays	62
4.4	Direct CP violation in the decays of charmed mesons and charmed baryons	64
4.5	Prospect of Charm CP violation studies at STCF	67
4.5.1	Measurements of the $D \rightarrow K^- \pi^+ \pi^+ \pi^-$ decay	67
4.5.2	Measurements of the $D \rightarrow K_S^0 \pi^+ \pi^-$ decay	68
4.5.3	Measurements of the $D \rightarrow K^- \pi^+ \pi^0$ decay	69
4.5.4	Overall prospects	69
5	Tests of the CPT invariance with J/ψ decays	70
5.1	CPT and the Theory of Everything	71
5.2	Neutral K mesons and tests of the CPT theorem	72
5.3	The neutral kaon mass eigenstates with no CPT -invariance related restrictions	73
5.3.1	Properties of ϵ and δ	75
5.4	Interference measurements of the ϕ_{+-} and ϕ_{00} phases	76
5.4.1	Estimated measurement sensitivity with $10^{12} J/\psi$ -decays	77
5.5	Comment on the Bell Steinberger relation	79
5.6	Comments	82
5.7	Prospects of Kaon CPT study at STCF	82
5.7.1	MC simulation of $J/\psi \rightarrow K^- \pi^+ K^0 + c.c.$	83
5.7.2	Event selection procedure	83
5.7.3	Expected sensitivity at STCF	83
5.7.4	Systematic uncertainty discussion	84
6	Summary	85
	Acknowledgement	87

- Signal side: $\tau \rightarrow 3 \text{ leptons}$
- Tag side: $\tau \rightarrow e\nu\bar{\nu}, \mu\nu\bar{\nu}, \pi\nu + n\pi^0$ ($Br = 82\%$)
- Almost background free, sensitivity: $\mathcal{B}_{UL}^{90}(\tau \rightarrow \mu\mu\mu) \sim 1/\mathcal{L}$
- Best efficiency ($\tau \rightarrow \mu\mu\mu$): 22.5% (including the tag \mathcal{BF})

$$\mathcal{B}_{UL}^{90}(\tau \rightarrow \mu\mu\mu) < \frac{N_{UL}^{90}}{2\epsilon N_{\tau\tau}} \sim 1.4 \times 10^{-9}$$

■ electronic ■ muonic
■ pionic 1-prong ■ others



Model	Ref.	$\tau \rightarrow \mu\gamma$	$\tau \rightarrow \mu\mu\mu$
SM + heavy majorana	PRD 66.034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547(3)252	10^{-9}	10^{-8}
SUSY + seesaw	PRL 89:241802	10^{-10}	10^{-7}
SM + 4 th generation	arXiv.1006.5306	10^{-8}	10^{-8}

- The cLFV decays of vector mesons $V \rightarrow l_i l_j$ are also predicted in various of extension models of SM^[1]:

$$\mathcal{B}_{UL}^{90}(J/\psi \rightarrow e\mu) < 10^{-13}$$

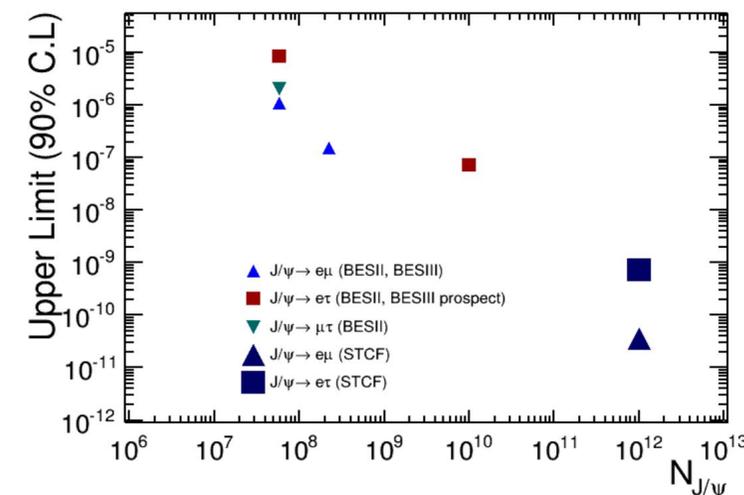
$$\mathcal{B}_{UL}^{90}(J/\psi \rightarrow e(\mu)\tau) < 10^{-9}$$

- At STCF, 1 trillion J/ψ can be obtained per year, taken efficiency from BESIII, the upper limit can be predicted to be:

$$\mathcal{B}_{UL}^{90}(J/\psi \rightarrow e\mu) < 3.6 \times 10^{-11}$$

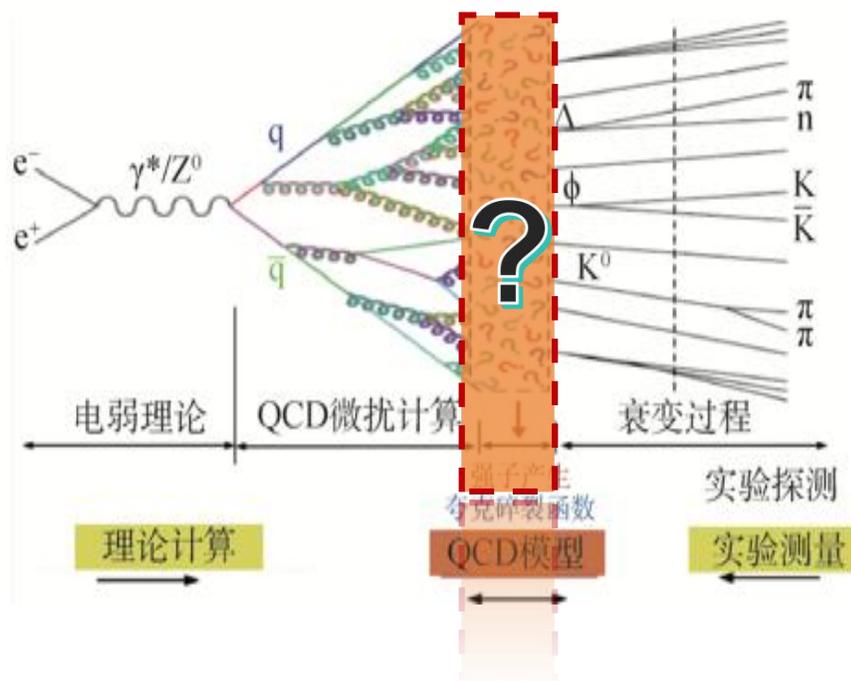
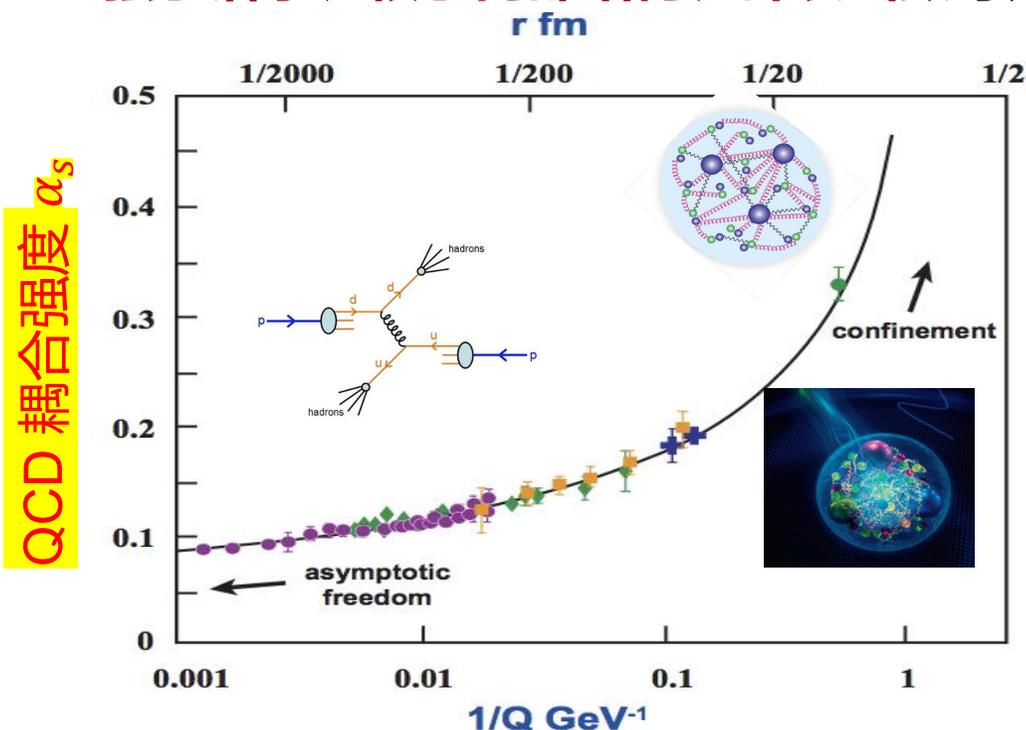
$$\mathcal{B}_{UL}^{90}(J/\psi \rightarrow e\tau) < 7.1 \times 10^{-10}$$

- The $\mathcal{B}_{UL}^{90}(J/\psi \rightarrow e\tau)$ can be further optimized with better PID.



物理机遇二：色禁闭之谜

- 在低能区QCD色禁闭和非微扰性质已逐渐发展为标准模型的重大挑战之一。
- 相应的不确定性已成为精确检验标准模型和探索新物理的瓶颈
- 强子谱学、核子内部结构、碎裂函数等是研究QCD色禁闭的天然场所。



□ 强子与核子是研究非微扰QCD的静态探针

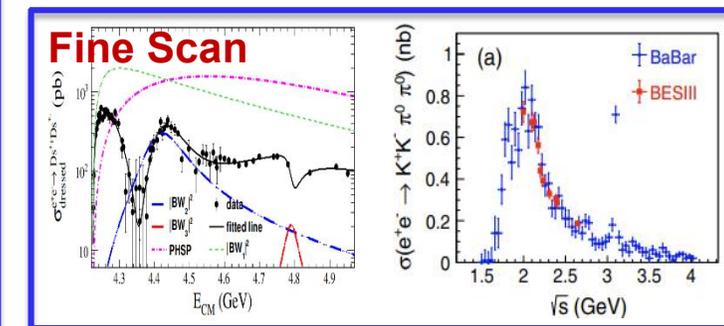
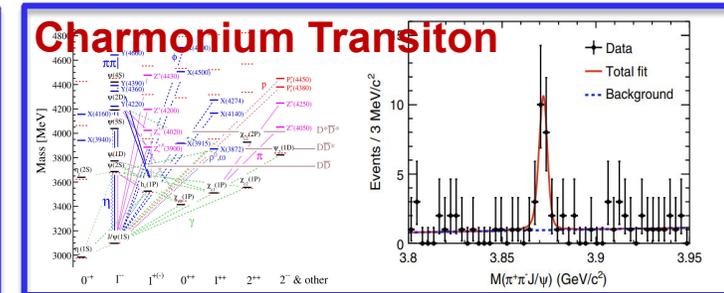
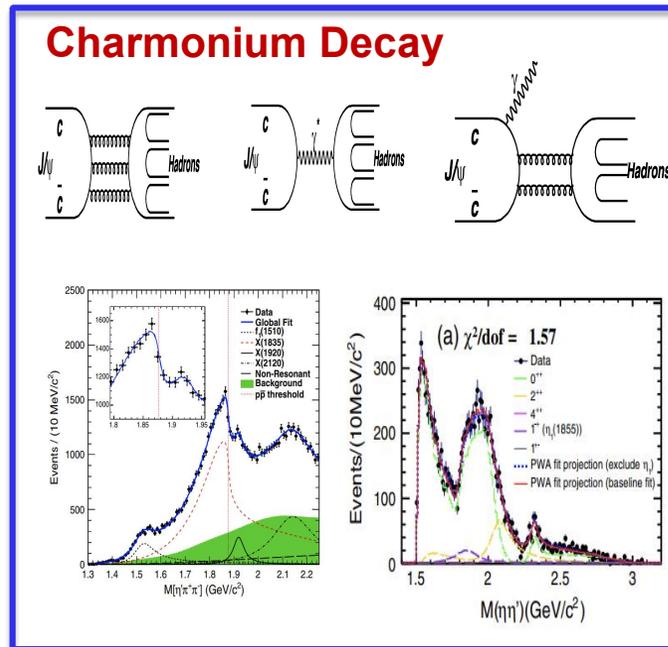
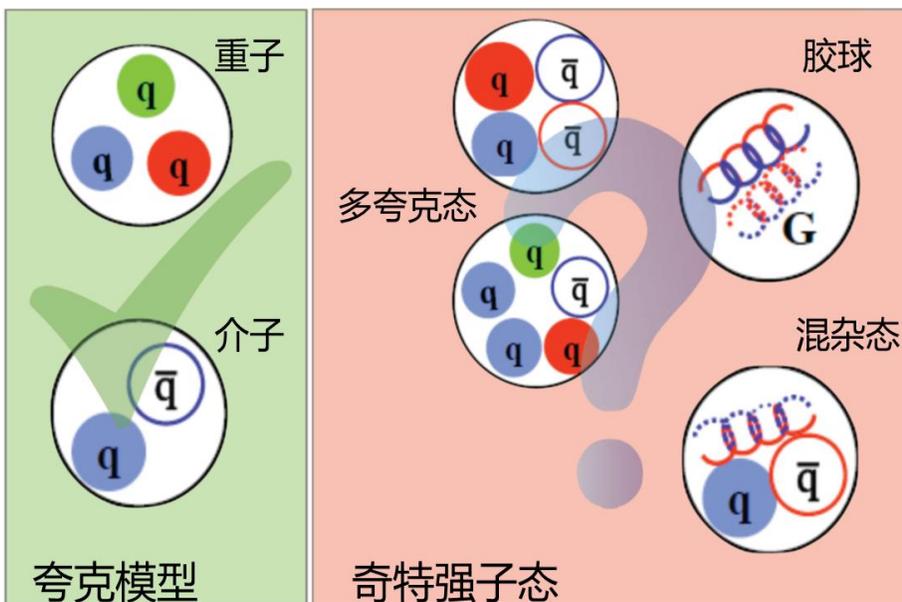
□ 碎裂函数是研究非微扰QCD的动态探针，理论无法计算必须依赖实验

强子谱学与奇特态



强子谱的研究是探索与认识强相互作用理论的重要手段

- 强子是物质世界基本组成单元：正反两个夸克构成的是介子，三个夸克构成的是重子。
- 理论预期存在胶球、混杂态、分子态、多夸克态等奇特强子态。



A Charmonium(-like) factory (per year):

- 3T J/ψ , 0.1T $\psi(3686)$, 1B $Y(4230)$, 100M $Z_c(3900)$ and 5M $X(3872)$

Physics opportunities :

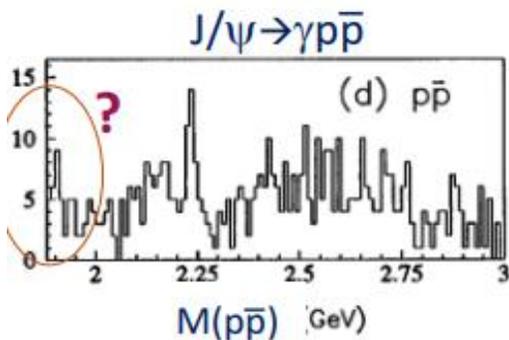
- Energy dependent structures of $Z_{c(s)}$
- More XYZ states \rightarrow Spectroscopy
- Missing charmonium states and their transitions
- Traces of glueballs and Hybrid states

STCF has an absolute advantage in studying hadron spectroscopy and exotic states, and is expected to achieve significant breakthroughs.

更多的数据，更精细的结构

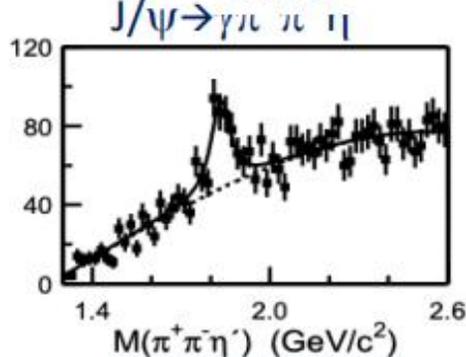
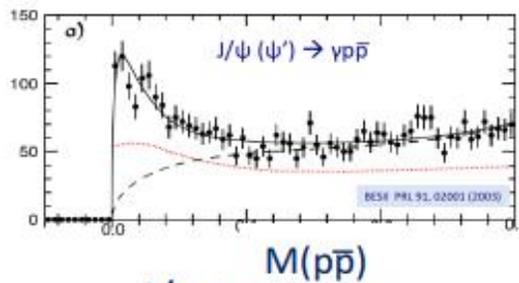


1996: 8 M J/ψ 's



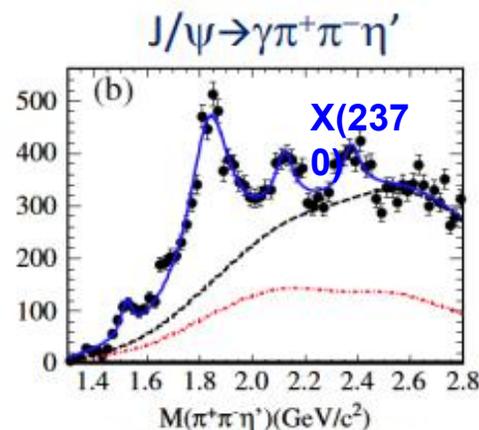
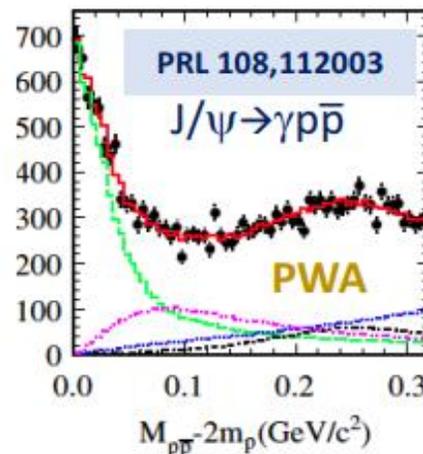
PRL 76, 3502

2002: 58 M J/ψ 's



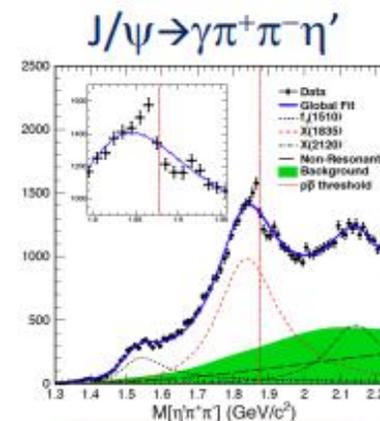
PRL 95, 262001

2011: 225 M J/ψ 's

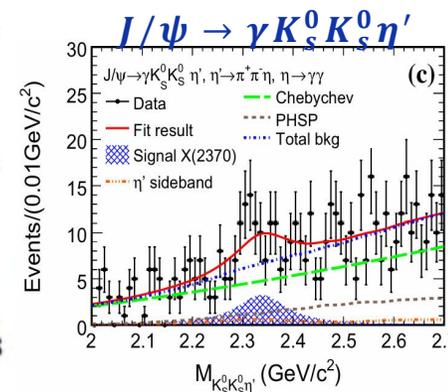


PRL 106, 072002

2016: 1.3 B J/ψ 's

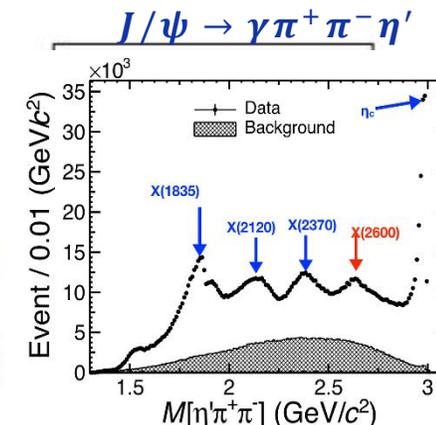


PRL 117, 042002

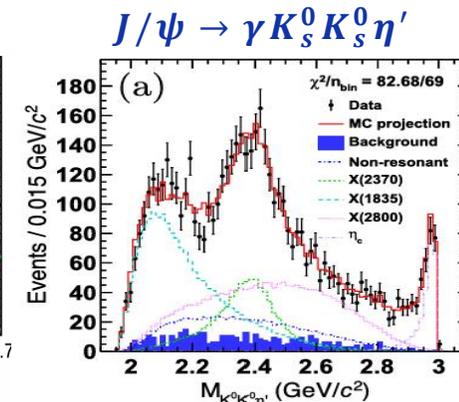


EPJC 80, 746

2022: 10 B J/ψ 's



PRL 129, 042001



PRL 132.181901

You never have enough J/ψ events!

— Stephen Lars Olsen

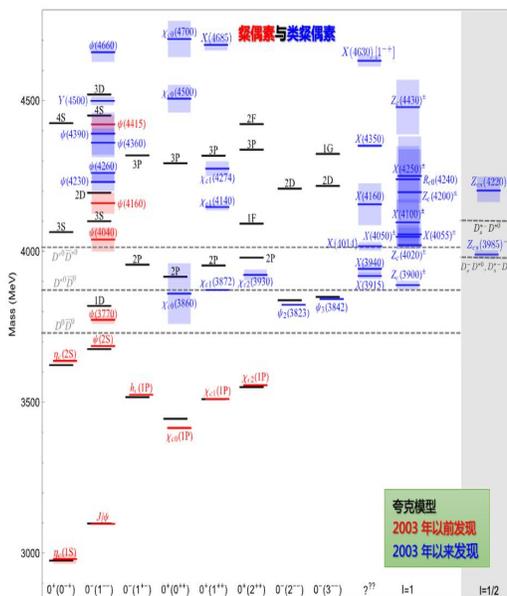
Talk on "Symposium on 30 years of BES Physics", (2019)

$0^- +$ Pseudoscalar Glueball-like

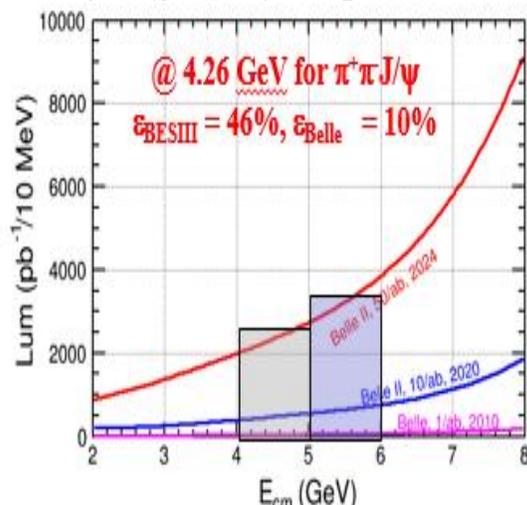
(类) 粲偶素研究

- **夸克如何形成强子**是未解决的千禧年难题，研究**夸克禁闭**的重要途径
- 粲偶素是粲夸克与反粲夸克的束缚态，是研究非微扰QCD的**独特平台**
- 近百个新强子的**发现**是研究“**强子周期表**”的新机遇
- STCF每年可以获取 1ab^{-1} 的数据，在研究类夸克偶素具有**绝对优势**，有望取得**重大突破**

夸克偶素谱

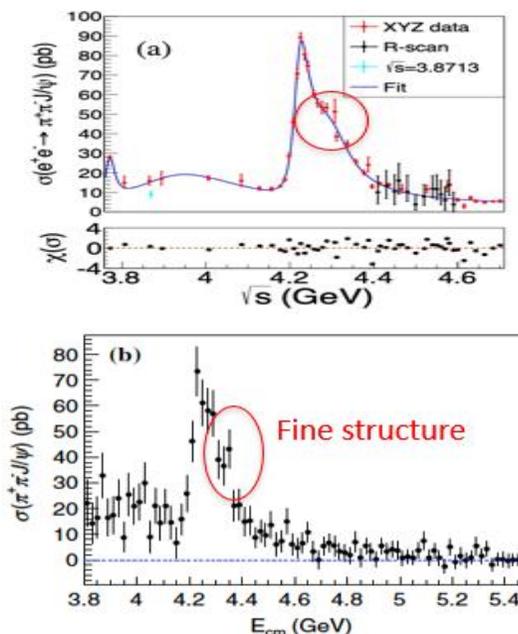


亮度/统计量



	XYZ	Y(4260)	Z _c (3900)	Z _c (4020)	X(3872)
No. of events		10^{10}	10^9	10^9	5×10^6

灵敏度/探测效率



全方位的研究:

- 寻找“缺失”粒子
- 探索XYZ强子谱学
- 风波分析、Argand相图分析
- 寻找稀有衰变模式
- 不同的产生与衰变机制
- ...

高精度超级陶粲装置在Y粒子产生阈值附近扫描，精确确定矢量Y粒子和X(3872)粒子的轻子分宽度，是理解这些奇特态粒子的内部结构的关键，是STCF独特的地方。

The Y(4230) state (1B/year)

- Too many vector states
- STCF can precisely determine their resonance parameters, partial widths of various decay modes

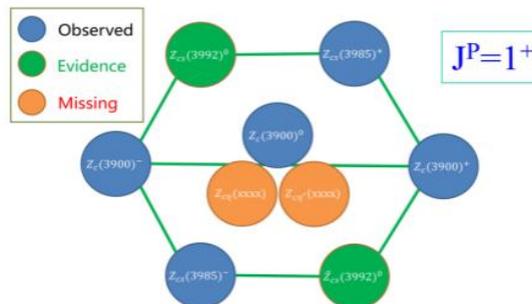
Partial decay width of Y(4230)	Expected precision
$B_{\omega\chi_{c0}} \times \Gamma_{ee}$	0.8% _{stat.}
$B_{\pi^+\pi^-\eta_c} \times \Gamma_{ee}$	2.0% _{stat.}
$B_{\pi^+\pi^-J/\psi} \times \Gamma_{ee}$	0.7% _{stat.}
$B_{D^0D^{*+}\pi^+c.c.} \times \Gamma_{ee}$	0.8% _{stat.}
$B_{\pi^+\pi^-\psi(3686)} \times \Gamma_{ee}$	3.5% _{stat.}
$B_{\pi^+\pi^-\psi(3686)} \times \Gamma_{ee}$	0.7% _{stat.}

Search for 1^{--} hybrids

$\sigma(e^+e^- \rightarrow Y_{ccg}) \sim \mathcal{O}(10 - 100)$ pb
 $\mathcal{O}(6 - 60)$ in $\gamma\eta_c/\gamma\chi_{c0}$ expected

The Z_c(3900) state (100M/year)

- Unprecedented data at STCF
 - Establish Z_c tetraquark family
- Z_c tetraquark family:**



State	Signif.	JP	Mass (MeV)	Width (MeV)
Z _{cs} (3985)	5.3σ	??	3982.5 ^{+1.8} _{-2.6} ± 2.1	12.8 ^{+5.3} _{-4.4} ± 3.0
Z _{cs} (4000)	15σ	1+	4003 ± 6 ⁺⁴ ₋₁₄	131 ± 15 ± 26
Z _{cs} (4220)	5.9σ	1+	4216 ± 24 ⁺⁴³ ₋₃₀	233 ± 52 ⁺⁹⁷ ₋₇₃

Are Z_{cs}(3985) and Z_{cs}(4000) the same or different states?

The X(3872) state (5M/year)

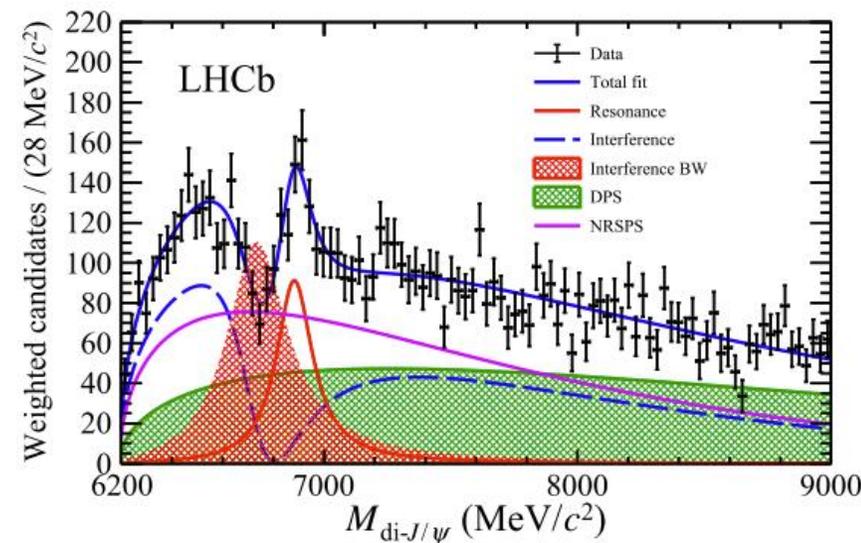
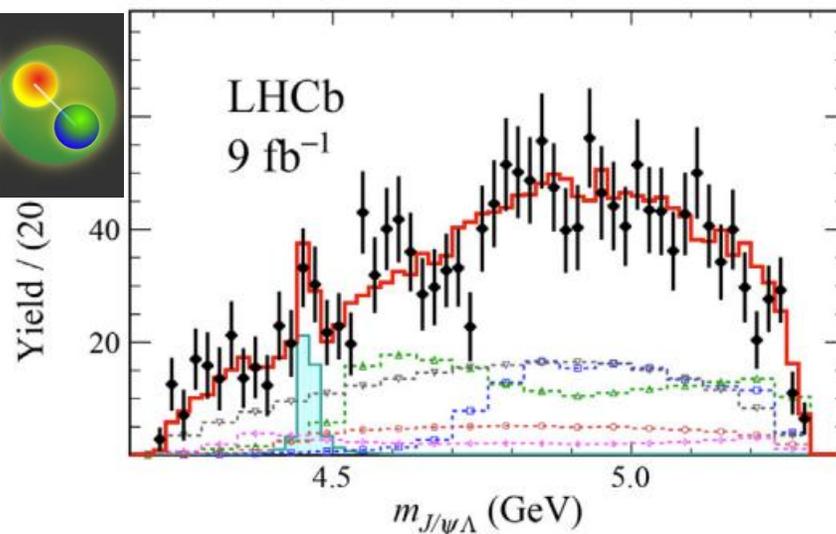
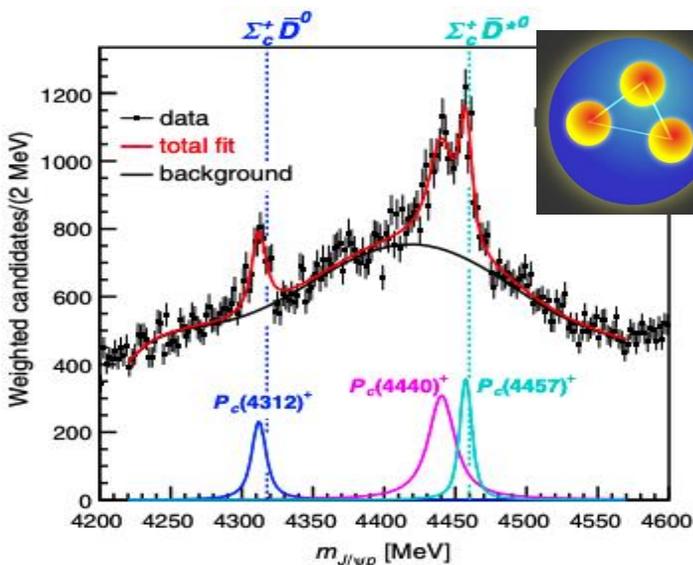
- STCF can precisely determine the branching fractions of various decay modes of X(3872) => proportion of DD^{*}
- Search for its partners

Decay channel	Expected precision
$X(3872) \rightarrow \pi^+\pi^-J/\psi$	4.5% _{stat.}
$X(3872) \rightarrow D^{*0}D^0 + c.c.$	5.0% _{stat.}
$X(3872) \rightarrow \gamma J/\psi$	5.5% _{stat.}
$X(3872) \rightarrow \gamma\psi(3686)$	5.0% _{stat.}
$X(3872) \rightarrow \pi^0\chi_{c1}$	6.0% _{stat.}
$X(3872) \rightarrow \omega J/\psi$	5.5% _{stat.}

X(3872) in direct e⁺e⁻ collisions

$\Gamma(X \rightarrow e^+e^-) \geq 0.03$ eV (VMD)
 $\mathcal{O}(60)$ in $\pi^+\pi^-J/\psi$ expected

超级陶粲装置是研究夸克和胶子形成奇特态强子的理想利器。



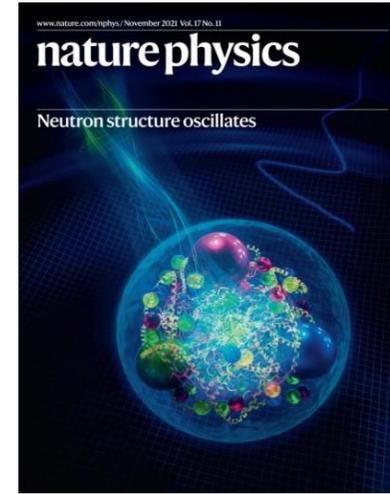
- **P_c pentaquarks** are good hadronic molecule candidates
- $e^+e^- \rightarrow J/\psi h\bar{h}$ are possible processes for studying hidden-charm pentaquarks
- More likely decay to **open-charm** final states: $e^+e^- \rightarrow \Lambda_c \bar{D}^* \bar{p}, \Sigma_c^+ \bar{D}^{(*)} \bar{p}$
- More pentaquark states? Cross-section lineshape ...

- Energy region above 6 GeV is ideal for **fully charmed tetraquark states**
- $e^+e^- \rightarrow J/\psi c\bar{c}$ has a production cross-section **on the order of tens of fb**
- **Low background** and **high efficiency** of reconstructing charged leptons at STCF

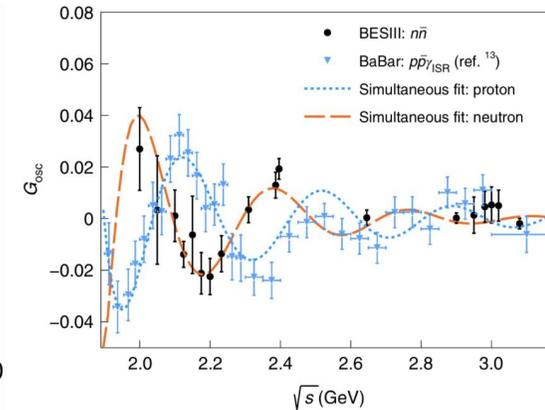
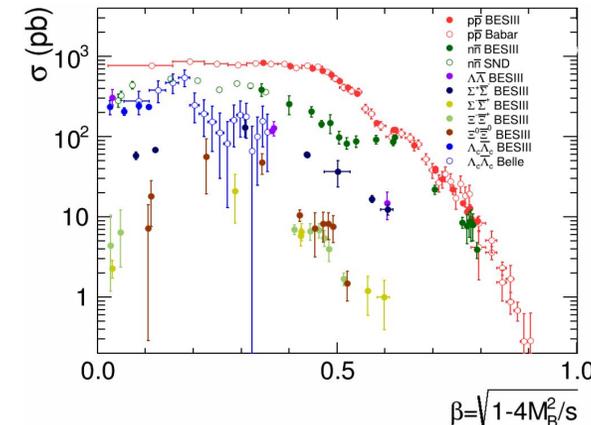
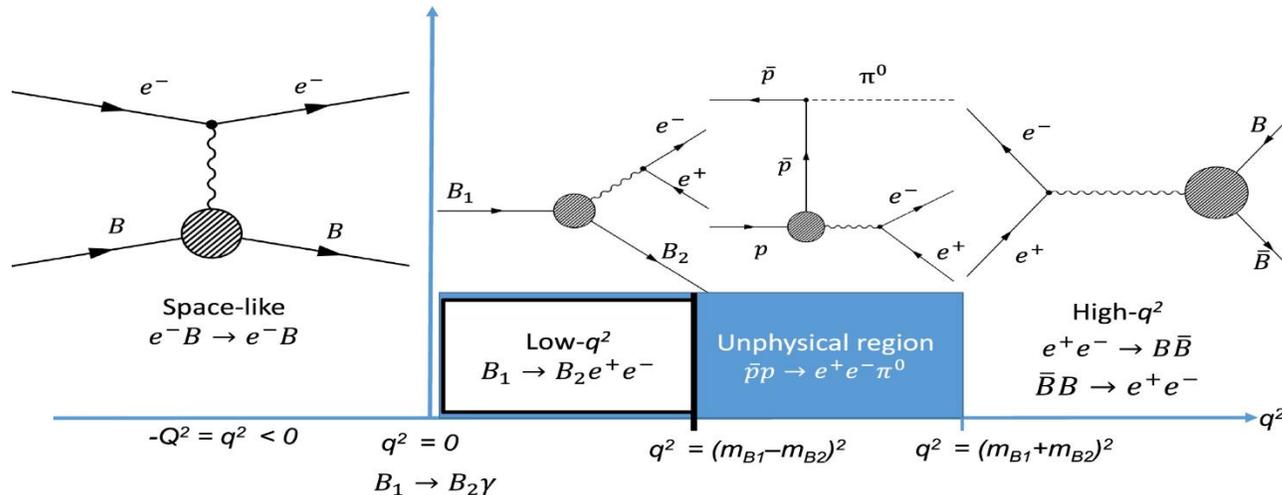
强子形状因子 (EMFF) 测量



- **电磁形状因子**是核子**最基本**的观测量之一，提供电和磁密度信息，并对强相互作用相关理论提供严格的验证。
- **由于超子和粲重子束流难以形成**，其内部结构研究只能通过类时空的电磁形状因子研究获得。
- 高四动量转移的电磁形状因子研究可以抽取核子的光锥波函数，从而确认质子中的夸克成分。



2021年
中子电磁结构精细测量，解决光子-核子耦合之谜，BESIII首篇《自然·物理》封面文章

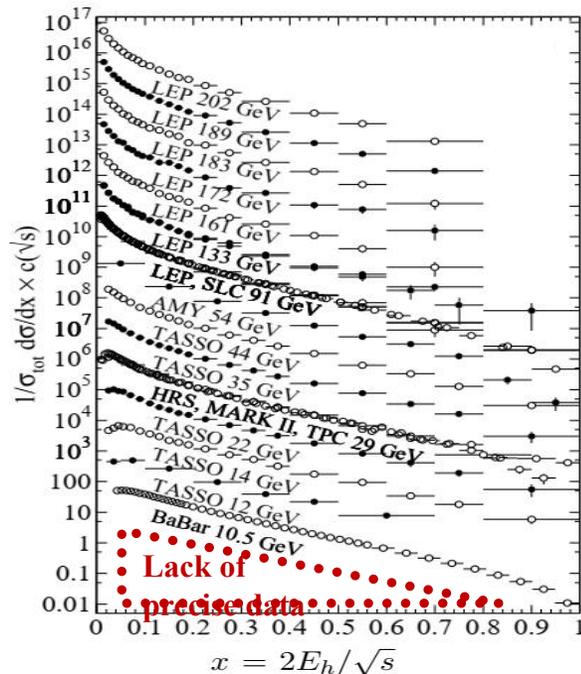
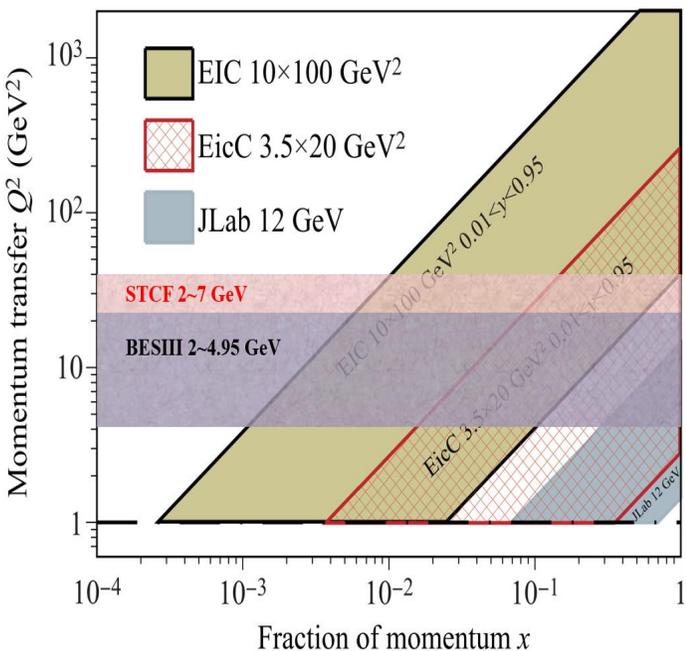
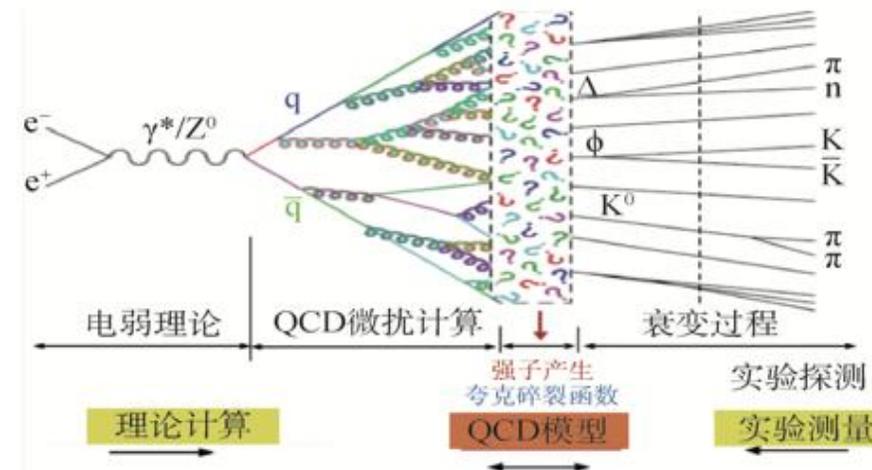


Natl.Sci.Rev. 8 (2021) 11, nwab187

碎裂函数 (FFs) 测量



- FFs 描述夸克/胶子的强子化过程，是理论计算和实验测量的桥梁，具有非微扰效应，无法精确理论计算
- 未来高能装置依赖的质子部分子分布函数 (PDFs) 的精确测量需要更精确的FFs输入
- 正负电子对撞机能够提供测量FFs最干净的数据样本



STCF研究潜力:

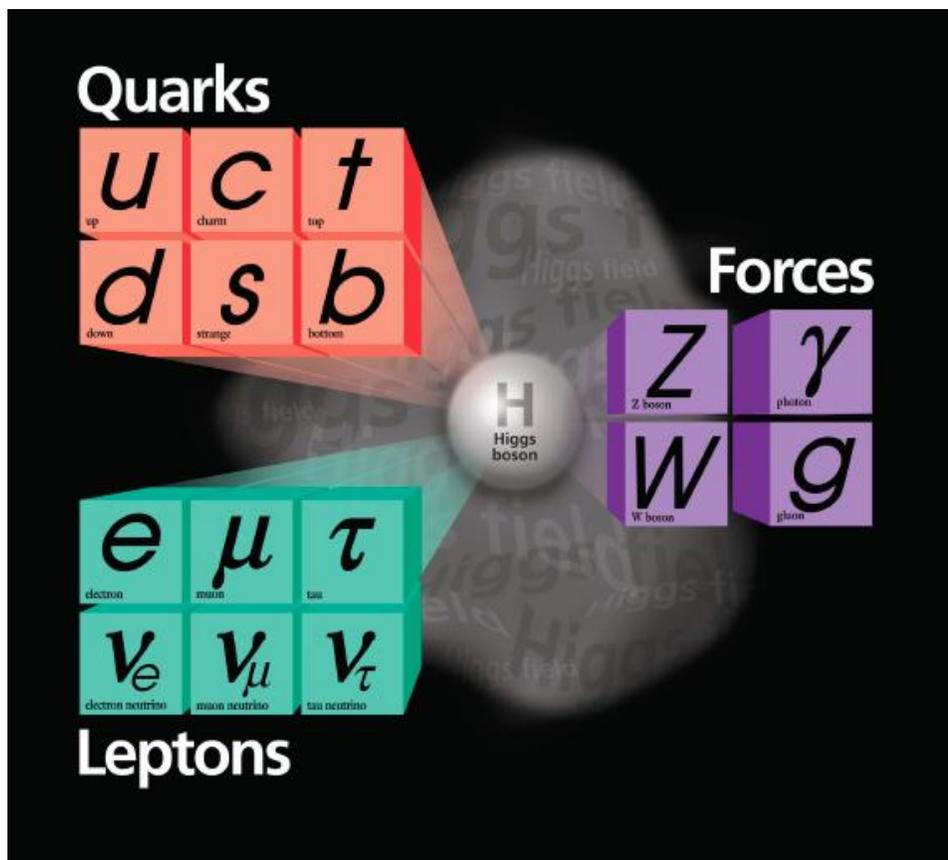
- 将在 $q^2 \sim 4-50 \text{ GeV}^2$ 范围内提供最精确的多维FFs分布函数，极化束流能够进一步提升测量精度和增加测量量
- 高精度验证FFs的普适性以及随 q^2 的演化过程
- 将为EIC、EicC、Jlab等实验提供关键输入

- **碎裂函数**（侧重于强子化过程中的纵向动量转移）和**能量关联**（侧重于强子化过程中的横向动量转移）构成了对强子过程的三维层析成像，提供了对强子化描述的最全面数据。
- 当前，**格点QCD**和**量子计算**均无法对强子化进行模拟。近年来QCD关于碎裂函数和能量关联的理论得到迅速发展，迫切需要一个在适当能区的对撞机对这些观测量进行全面精细测量。这些实验数据将成为未来一代代物理学家理解强子化本质的最根本出发点。
- 强子化的**特征时间标度是 10^{-23} 秒**，对比几个重要的高能对撞机装置：
 - STCF: 2-7 GeV, $\sim 10^{-23}$ 秒– 10^{-24} 秒
 - LEP: 10-200 GeV, $\sim 10^{-24}$ 秒– 10^{-25} 秒
 - LHC: 100-1000GeV, $\sim 10^{-25}$ 秒– 10^{-26} 秒
 - STCF的运行能区正好是**强子化效应最为显著能区**，相比其他对撞装置有不可比拟的优势。
- QCD在5-7 GeV能区会涌现出**喷注现象**（高能强子在动量空间的集体现象）。在该能区的对撞机为研究喷注涌现过程的动力学提供最最重要数据。
- 测量特定的**碎裂函数**（例如Collins函数）和**能量关联**提供了研究QCD手征对称性自发破缺的动力学手段。

重大问题三：精确测量与新物理



实验测量精度直接反映人类对自然的认知程度，精确实验测量是探索新物理的重要途径之一



Masses

Parameter	Value	Method
m_u	1.9 MeV	Lattice
m_d	4.4 MeV	Lattice
m_s	87 MeV	Lattice
m_c	1.3 MeV	Collider
m_b	4.24 MeV	Collider
m_t	173 GeV	Collider
m_e	511 keV	Non-collider
m_μ	106 MeV	Non-collider
m_τ	1.78 GeV	Collider
m_z	91.2 GeV	Collider
m_H	125 GeV	Collider

Couplings

Parameter	Value	Method
α	0.0073	non-collider + collider
G_F	1.17×10^{-5}	Non-collider
α_s	0.12	Lattice + collider

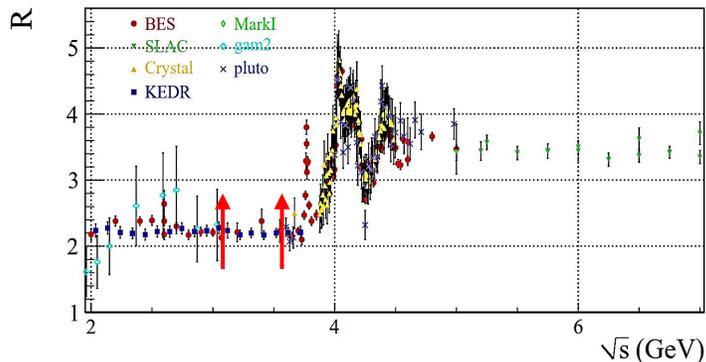
Flavour and CP violation

Parameter	Value	Method
θ_{12} (CKM)	13.1°	Collider
θ_{23} (CKM)	2.4°	Collider
θ_{13} (CKM)	0.2°	Collider
δ (CKM-CPV)	0.995	Collider
θ (strong CP)	~ 0	Non-collider

- 标准模型包含19个自由参数：夸克质量、轻子质量、相互作用常数、夸克味混合参数
- 基本物理观测量：R值等

R值是粒子物理中最基本的物理量之一，直接反映夸克的味道和颜色，检验夸克模型和QCD，发现新粒子，并对精细结构常数和**缪子反常磁矩**的理论计算提供实验输入dangqiuq

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$



● Running of **fine structure constant** $\Delta\alpha_{em}$

$$\Delta\alpha(s) = 1 - \alpha(0)/\alpha(s) = \Delta\alpha_{\text{lepton}}(s) + \Delta\alpha_{\text{had}}^{(5)}(s) + \Delta\alpha_{\text{top}}(s)$$

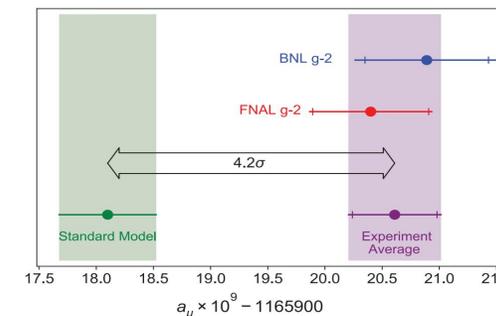
Eur. Phys. J. C 80, 241 (2020)

Source	Contribution ($\times 10^{-4}$)
$\Delta\alpha_{\text{lepton}}(M_Z^2)$	314.979 ± 0.002
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	276.0 ± 1.0
$\Delta\alpha_{\text{top}}(M_Z^2)$	-0.7180 ± 0.0054

● $\Delta\alpha_{had}^{(5)}(s)$ should be calculated with R value:

$$\Delta\alpha_{\text{had}}^{(5)}(s) = -\frac{\alpha s}{3\pi} \text{Re} \int_{E_{\text{th}}}^{\infty} ds' \frac{R(s')}{s'(s' - s - i\epsilon)}$$

● Muon **anomalous magnetic moment** a_μ



● SM : $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{Had}$

● Hadronic **Vacuum Polarization (HVP)** and Light-by-Light (HLbL) in a_μ^{Had} dominate uncertainty

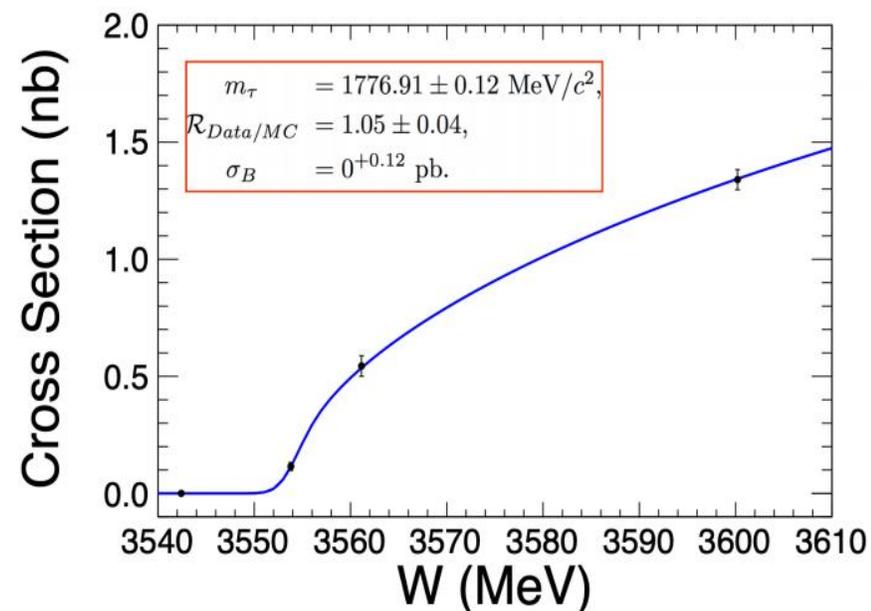
● HVP contribution is calculated with **R value** with **dispersion relation**:

$$a_\mu^{\text{LO-HVP}} = \left(\frac{\alpha m_\mu}{3\pi} \right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{R(s)K(s)}{s^2}$$

- The τ -lepton mass is a fundamental parameter of the Standard Model
- Lepton universality test:

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau} \left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B(\tau \rightarrow e\nu\bar{\nu})}{B(\mu \rightarrow e\nu\bar{\nu})}$$

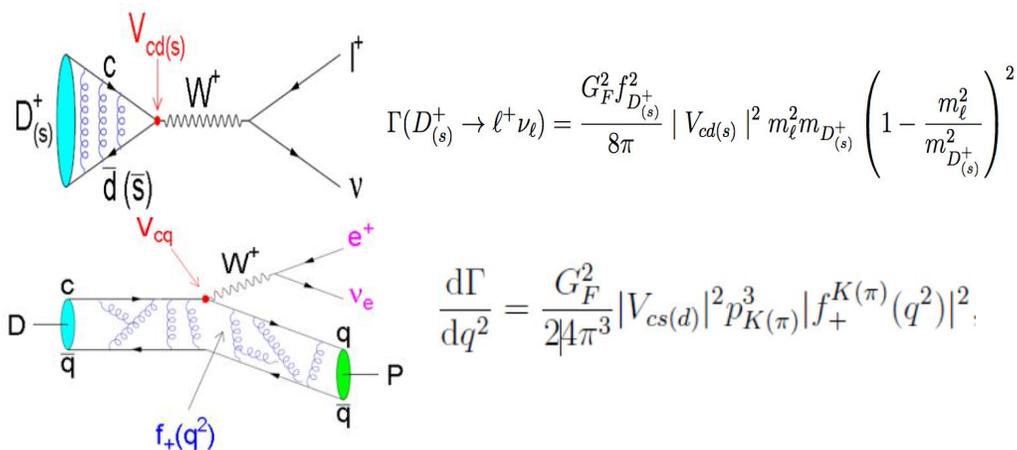
- Universality is sensitive to: m_τ^5
- For $e, \mu, \Delta m/m \sim 10^{-8}$, for $\tau, \Delta m/m \sim 10^{-4}$, need more measurements
- Methods
 - Pseudo-mass technique: ARGUS, OPAL, BELLE and BABAR
 - Threshold scan method : DELCO, BES (92, 96), KEDR and BESIII
 - Determination of **the beam energy** and the **beam energy spread** precisely is extremely important



$$\sigma(E_{\text{c.m.}}, m_\tau, \delta_w^{\text{BEMS}}) = \frac{1}{\sqrt{2\pi}\delta_w^{\text{BEMS}}} \int_{2m_\tau}^{\infty} dE'_{\text{c.m.}} e^{\frac{-(E_{\text{c.m.}} - E'_{\text{c.m.}})^2}{2(\delta_w^{\text{BEMS}})^2}} \int_0^{1 - \frac{4m^2}{E_{\text{c.m.}}^2}} dx F(x, E'_{\text{c.m.}}) \frac{\sigma_1(E'_{\text{c.m.}} \sqrt{1-x}, m_\tau)}{|1 - \prod(E_{\text{c.m.}})|^2}.$$

CKM矩阵元描述了夸克味道的混合，其么正性能够保证是否只有三代夸克，么正性的破坏意味着第四代夸克的存在！

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



	BESIII	STCF	Belle II
Luminosity	2.93 fb ⁻¹ at 3.773 GeV	1 ab ⁻¹ at 3.773 GeV	50 ab ⁻¹ at Υ(nS)
$\mathcal{B}(D^+ \rightarrow \mu^+ \nu_\mu)$	5.1% _{stat} 1.6% _{syst} [8]	0.28% _{stat}	-
f_{D^+} (MeV)	2.6% _{stat} 0.9% _{syst} [8]	0.15% _{stat}	-
$ V_{cd} $	2.6% _{stat} 1.0% _{syst} [8]	0.15% _{stat}	-
$\mathcal{B}(D^+ \rightarrow \tau^+ \nu_\tau)$	20% _{stat} 10% _{syst} [9]	0.41% _{stat}	-
$\mathcal{B}(D^+ \rightarrow \tau^+ \nu_\tau)$	21% _{stat} 13% _{syst} [9]	0.50% _{stat}	-
$\mathcal{B}(D^+ \rightarrow \mu^+ \nu_\mu)$	-	-	-
Luminosity	3.2 fb ⁻¹ at 4.178 GeV	1 ab ⁻¹ at 4.009 GeV	50 ab ⁻¹ at Υ(nS)
$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu)$	2.8% _{stat} 2.7% _{syst} [10]	0.30% _{stat}	0.1% _{stat} 0.8% _{syst}
$f_{D_s^+}$ (MeV)	1.5% _{stat} 1.6% _{syst} [10]	0.15% _{stat}	-
$ V_{cs} $	1.5% _{stat} 1.6% _{syst} [10]	0.15% _{stat}	-
$f_{D_s^+}/f_{D^+}$	3.0% _{stat} 1.5% _{syst} [10]	0.21% _{stat}	-
$\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau)$	1.9% _{stat} 2.3% _{syst}	0.24% _{stat}	0.6% _{stat} 2.7% _{syst}
$f_{D_s^+}$ (MeV)	0.9% _{stat} 1.2% _{syst}	0.11% _{stat}	-
$ V_{cs} $	0.9% _{stat} 1.2% _{syst}	0.11% _{stat}	-
$\overline{f}_{D_s^+}^{\mu\&\tau}$ (MeV)	0.9% _{stat} 1.0% _{syst}	0.09% _{stat}	0.3% _{stat} 1.0% _{syst}
$ \overline{V}_{cs}^{\mu\&\tau} $	0.9% _{stat} 1.0% _{syst}	0.09% _{stat}	-
$\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau)$	3.6% _{stat} 3.0% _{syst}	0.38% _{stat}	0.9% _{stat} 3.2% _{syst}
$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu)$	-	-	-

Theory : 0.2% (0.1% expected)

Theory : 0.2% (0.1% expected)

Theory : 0.2% (0.1% expected)

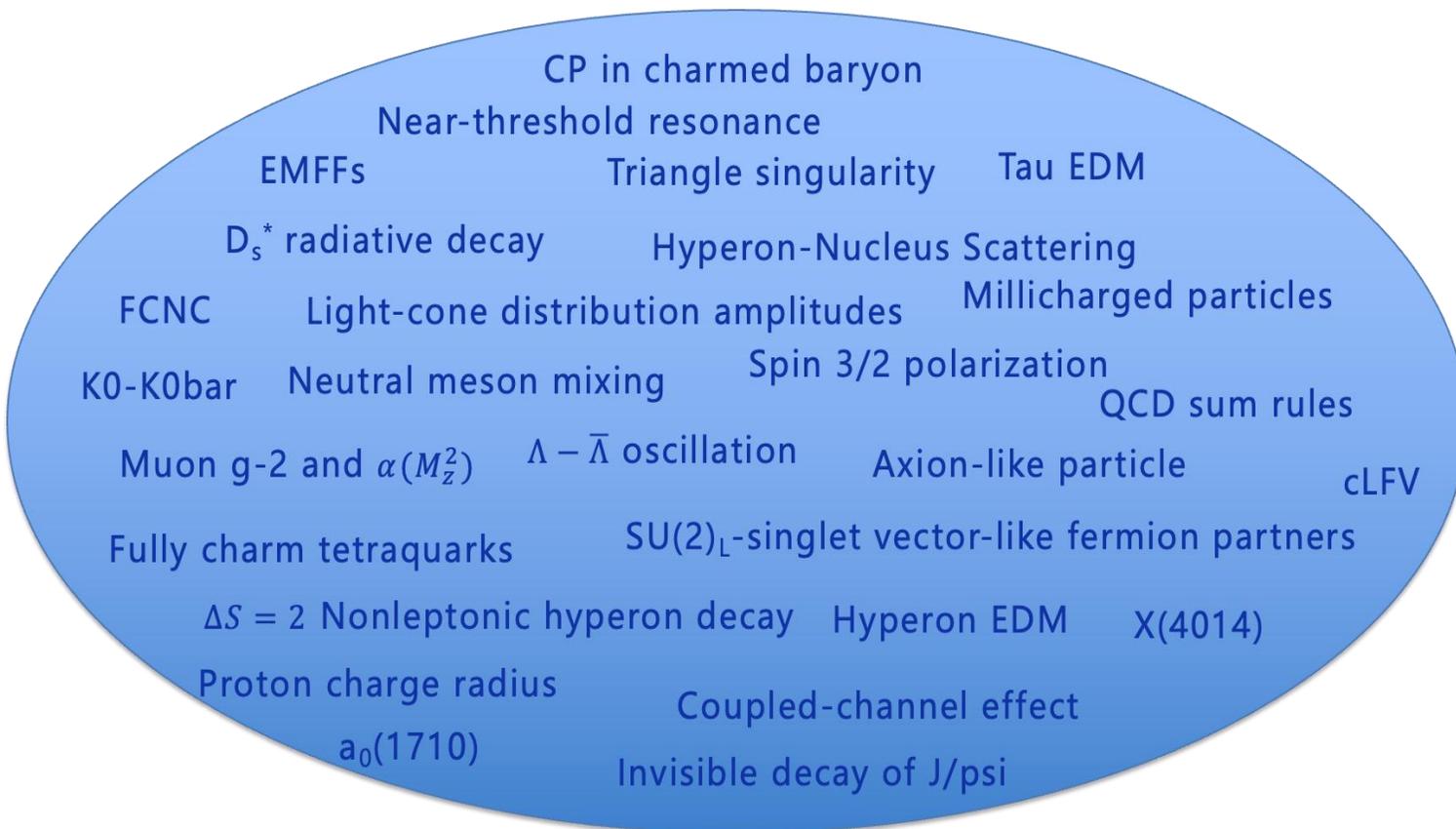
STCF的测量|Vcs|和|Vcd|的统计误差将达到理论预期水平，系统误差将成关键，同时通过陶轻子和超子衰变也为提升|Vus|和|Vud|测量精度提供重大机遇

Physics at STCF	Benchmark Processes	Key Parameters*	Physics at STCF	Benchmark Processes	Key Parameters*
XYZ properties	$e^+e^- \rightarrow Y \rightarrow \gamma X, \eta X, \phi X$ $e^+e^- \rightarrow Y \rightarrow \pi Z_c, KZ_{cs}$	$N_{Y(4260)/Z_c/X(3872)} \sim 10^{10}/10^9/10^6$	CKM matrix	$D_{(s)}^+ \rightarrow l^+ \nu_l, D \rightarrow Pl^+ \nu_l$	$\delta V_{cd/cs} \sim 0.15\%$; $\delta f_{D/D_s} \sim 0.15\%$
Pentaquarks, Di-charmonium	$e^+e^- \rightarrow J/\psi p \bar{p}, \Lambda_c \bar{D} \bar{p}, \Sigma_c \bar{D} \bar{p}$ $e^+e^- \rightarrow J/\psi \eta_c, J/\psi h_c$	$\sigma(e^+e^- \rightarrow J/\psi p \bar{p}) \sim 4 \text{ fb}$; $\sigma(e^+e^- \rightarrow J/\psi c \bar{c}) \sim 10 \text{ fb}$ (prediction)	γ/ϕ_3 measurement	$D^0 \rightarrow K_s \pi^+ \pi^-, K_s K^+ K^- \dots$	$\Delta(\cos \delta_{K\pi}) \sim 0.007$; $\Delta(\delta_{K\pi}) \sim 2^\circ$
Hadron Spectroscopy	Excited $c\bar{c}$ and their transition, Charmed hadron, Light hadron	$N_{J/\psi/\psi(3686)/\Lambda_c} \sim 10^{12}/10^{11}/10^8$	$D^0 - \bar{D}^0$ mixing	$\psi(3770) \rightarrow (D^0 \bar{D}^0)_{CP=-}$, $\psi(4140) \rightarrow \gamma(D^0 \bar{D}^0)_{CP=+}$	$\Delta x \sim 0.035\%$; $\Delta y \sim 0.023\%$
Muon g-2	$\pi^+ \pi^-, \pi^+ \pi^- \pi^0, K^+ K^-$ $\gamma\gamma \rightarrow \pi^0, \eta^{(\prime)}, \pi^+ \pi^-$	$\Delta a_\mu^{HVP} \ll 40 \times 10^{-11}$	Charm hadron decay	$D_{(s)}, \Lambda_c^+, \Sigma_c, \Xi_c, \Omega_c$ decay	$N_{D/D_s/\Lambda_c} \sim 10^9/10^8/10^8$
R value, τ mass	$e^+e^- \rightarrow \text{inclusive}$ $e^+e^- \rightarrow \tau^+ \tau^-$	$\Delta m_\tau \sim 0.012 \text{ MeV}$ (with 1 month scan)	γ polarization	$D^0 \rightarrow K_1 e^+ \nu_e$	$\Delta A'_{UD} \sim 0.015$
Fragmentation functions	$e^+e^- \rightarrow (\pi, K, p, \Lambda, D) + X$ $e^+e^- \rightarrow (\pi\pi, KK, \pi K) + X$	$\Delta A^{\text{Collins}} < 0.002$	CPV in Hyperons	$J/\psi \rightarrow \Lambda \bar{\Lambda}, \Sigma \bar{\Sigma}, \Xi^- \bar{\Xi}^-, \Xi^0 \bar{\Xi}^0$	$\Delta A_\Lambda \sim 10^{-4}$
Nucleon Form Factors	$e^+e^- \rightarrow B \bar{B}$ from threshold	$\delta R_{EM} \sim 1\%$	CPV in τ	$\tau \rightarrow K_s \pi \nu$, EDM of τ ,	$\Delta A_{\tau \rightarrow K_s \pi \nu} \sim 10^{-3}$; $\Delta d_\tau \sim 5 \times 10^{-19} \text{ (e cm)}$
FLV decays	$\tau \rightarrow \gamma l, ll, lP_1 P_2$ $J/\psi \rightarrow ll', D^0 \rightarrow ll' (l' \neq l) \dots$	$B(\tau \rightarrow \gamma \mu / \mu \mu \mu) < 12/1.5 \times 10^{-9}$; $B(J/\psi \rightarrow e\tau) < 0.71 \times 10^{-9}$	CPV in Charm	$D^0 \rightarrow K^+ K^- / \pi^+ \pi^-$, $\Lambda_c \rightarrow p K^- \pi^+ \pi^0 \dots$	$\Delta A_D \sim 10^{-3}$; $\Delta A_{\Lambda_c} \sim 10^{-3}$
LNV, BNV	$D_{(s)}^+ \rightarrow l^+ l^+ X^-, J/\psi \rightarrow \Lambda_c e^-$, $B \rightarrow \bar{B} \dots$	$B(J/\psi \rightarrow \Lambda_c e^-) < 10^{-11}$	FCNC	$D \rightarrow \gamma V, D^0 \rightarrow l^+ l^-, e^+ e^- \rightarrow D^*$, $\Sigma^+ \rightarrow pl^+ l^- \dots$	$B(D^0 \rightarrow e^+ e^- X) < 10^{-8}$
Symmetry violation	$\eta^{(\prime)} \rightarrow ll\pi^0, \eta' \rightarrow \eta ll \dots$	$B(\eta' \rightarrow ll/\pi^0 ll) < 1.5/2.4 \times 10^{-10}$	Dark photon, millicharged	$e^+e^- \rightarrow (J/\psi) \rightarrow \gamma A' (\rightarrow l^+ l^-) \dots$ $e^+e^- \rightarrow \chi \bar{\chi} \gamma \dots$	Mixing strength $\Delta \epsilon_{A'} \sim 10^{-4}$; $\Delta \epsilon_\chi \sim 10^{-4}$

Observable	BESIII (2020)	Belle II (50 ab ⁻¹)	STCF (1 ab ⁻¹)
<i>Charmonium(like) spectroscopy:</i>			
Luminosity between 4–5 GeV	20 fb ⁻¹	0.23 ab ⁻¹	1 ab ⁻¹
<i>Collins fragmentation functions:</i>			
Asymmetry in $e^+e^- \rightarrow KK + X$	0.3 [470]	–	< 0.002 [471]
<i>CP violations:</i>			
A_{cp} in hyperon	0.014 [26]	–	0.00023
A_{cp} in τ	–	$\mathcal{O}(10^{-3})/\sqrt{70}$ [251]	0.0009 [250]
<i>Leptonic decays of $D(s)$:</i>			
V_{cd}	0.03 [472]	–	0.0015
f_D	0.03	–	0.0015
$\frac{\mathcal{B}(D \rightarrow \tau \nu)}{\mathcal{B}(D \rightarrow \mu \nu)}$	0.2	–	0.005
V_{cs}	0.02 [473]	0.005	0.0015
f_{D_s}	0.02	0.005	0.0015
$\frac{\mathcal{B}(D_s \rightarrow \tau \nu)}{\mathcal{B}(D_s \rightarrow \mu \nu)}$	0.04	0.009	0.0038
<i>D mixing parameter:</i>			
x	–	0.03	0.05 [474]
y	–	0.02	0.05
<i>τ properties:</i>			
m_τ (MeV/ c^2)	0.12 [475]	–	0.012
d_τ (e cm)	–	2.02×10^{-19}	5.14×10^{-19}
<i>cLFV decays of τ (U.L at 90% C.L.):</i>			
$\tau \rightarrow lll$	–	1×10^{-9}	1.4×10^{-9}
$\tau \rightarrow \gamma \mu$	–	5×10^{-9}	1.8×10^{-8}
$J/\psi \rightarrow e\tau$	7.5×10^{-8}	–	7.1×10^{-10}



- 正在开展或者预期的研究可以更深入开展
- CDR广泛引用，一系列新的研究课题



目录

CONTENTS

- 一、STCF项目介绍
- 二、项目科学目标
- 三、项目的组织和推动**
- 四、关键技术攻关项目
- 五、总结

项目推进与进展



合肥综合性国家科学中心项目
资金申请报告
(科研项目)

项目类别: 合肥综合性国家科学中心项目
项目类型: 重大科技基础设施项目
申报单位: 中国科学院
申报地点: 中国科学院大学
申报日期: 2023年11月-2023年12月
负责人: 赵国瑞, 1505510460
联系人: 张宇, 1505512662

在合肥综合性国家科学中心建设规划中, 量子科技是重要组成部分。量子科技具有颠覆性、战略性、前瞻性, 是未来科技竞争的关键领域。量子科技的发展, 将深刻改变人类社会生产、生活和全球格局。量子科技的发展, 将深刻改变人类社会生产、生活和全球格局。量子科技的发展, 将深刻改变人类社会生产、生活和全球格局。

**关键技术攻关项目启动
2000万启动费**

**关键技术攻关项目经费评审
批准3.64亿总经费**

**第一届的咨询委员会会议
对关键技术攻关项目、项目
推动给出重要建议**

科学院第一次重大科技基础设施项目评议会



**关键技术攻关项目启动会和
战略研讨会
170位专家、学者及管理人
员30位院士**

**第一次国际顾问委员会
国际研讨会, 历时2天的评
审, 重要的建议和意见**

**第二次国际顾问委员会
给出重要的建议和意见,
指导项目的推动**

项目推进与进展



关键技术攻关项目中期考核
11位专家（包括财务）
重大进展、高度评价



第三次国际顾问委员会会议
重大进展、高度肯定

2025.01

2025.03

2025.05

2025.05



加速器CDR国内评审
13位国内加速器一线专家
重要的意见和建议



关键技术攻关项目中期考核
11位国际加速器专家
重大进展、高度评价

加速器研发单位 ●

探测器研发单位 ●

软件研发单位 ●

中国科学技术大学 ●●●

中国科学院合肥物质研究院 ●

安徽理工大学 ●●

郑州大学 ●●

河南师大 ●

清华大学 ●

中国科学院大学 ●●

北京科技大学 ●

中国科学院大连化物所 ●

山东大学 ●●

中国科学院上海高研院 ●

复旦大学 ●

浙江大学 ●

华中师范大学 ●

华中科技大学 ●

湖南科技大学 ●●

南华大学 ●

中山大学 ●

深圳技术大学 ●

深圳综合粒子设施研究院 ●

中国科学院近代物理所 ●●

中国科学院兰州化物所 ●

兰州大学 ●●

中国科学院西光所 ●

西北工业大学 ●

广西师范大学 ●

25 个研究所和大学直接参与关键技术攻关项目

240位研究人员+300名研究生

其他参与物理研究单位

- 北京大学
- 中国科学院高能所
- 中国科学院理论所
- 上海交通大学
- 北京师范大学
- 武汉大学
- 中国地质大学
- 辽宁大学
- 南京师范大学
- 南京大学
- 河北师范大学
- 南开大学
- 华南师范大学
- . . .

国际合作与交流



已与BINP、JINR、IJCLab、KEK签署了正式合作协议，与CERN DRD、LHCb等国际科研组织建立了良好的合作关系



与LHCb TORCH项目组合作



与CERN薄膜沉积实验室合作



与CERN气体探测器组合作



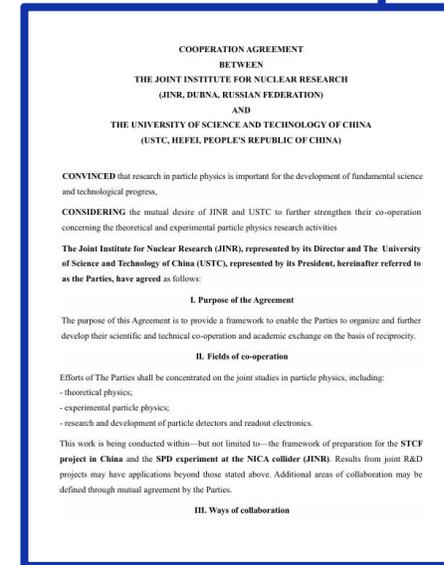
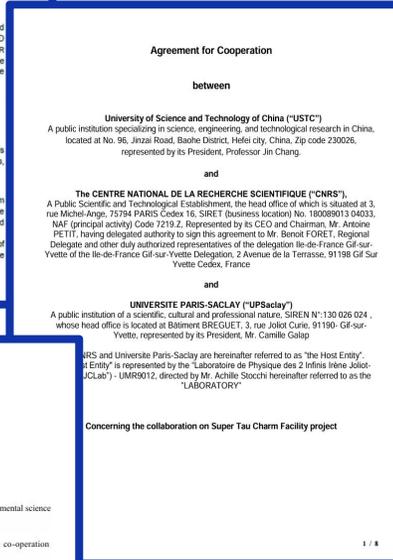
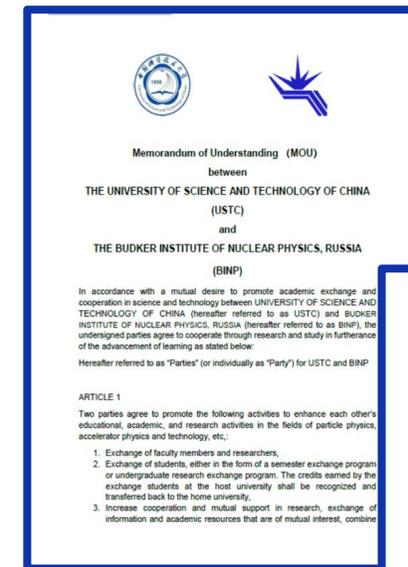
与BINP加速器专家合作



与JINR团队交流



与KEK专家合作研究



关键技术攻关项目中期检查 (11位)

评审专家组成员

赵红卫	中国科学院近代物理研究所 院士(专家组组长)
唐传祥	清华大学 教授
王九庆	中国科学院高能物理研究所 研究员
王 东	中国科学院上海高等研究院 研究员
李玉兰	清华大学 教授
王 萌	山东大学 教授
魏 微	中国科学院高能物理研究所 研究员
杨亚东	河南师范大学 教授
冒亚军	北京大学 教授
陈宗发	中国科学院合肥物质科学研究院 高级会计师
孟凡红	合肥工业大学 高级会计师

安徽省、合肥市地方领导

李 辰	合肥市发展改革委科学中心处 处长
胡 月	安徽省发展改革委科学中心处 一级主任科员



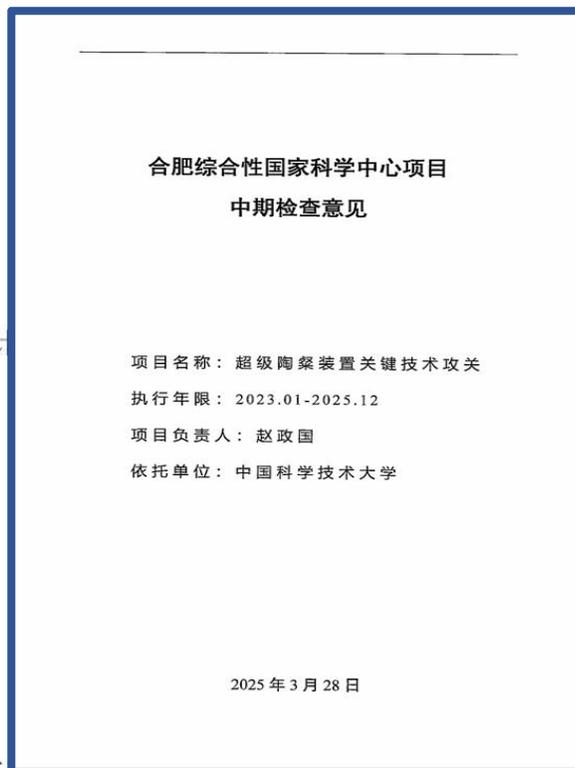
项目汇报→质询/讨论

专家组评审意见:

“专家组一致认为，项目组按照总体目标和计划开展关键技术攻关，**组织架构健全，管理规范，质量控制措施有效**，已完成中期目标任务，**建议通过中期检查**”

专家组建议:

- 加快加速器和探测器核心**样机研制进度**
- 加快**预算**执行力度，提前做好计划和招标任务
- 优化项目执行和**验收方案**，凝练**验收指标**



国际顾问委员会 (IAC, 22位)

主席	Guy Wilkinson	牛津大学	英国
副主席	Frank Zimmermann	欧洲核子中心	瑞士
成员	Marica Biagini	弗拉斯卡蒂国家实验室	意大利
	Ikaros Bigi	圣母大学	美国
	Alexander Bondar	布德科尔核物理研究所	俄罗斯
	Tom Browder	夏威夷大学	美国
	赵光达	北京大学	中国
	高原宁	北京大学	中国
	Wolfgang Gradl	美茵茨大学	德国
	David Hitlin	加州理工学院	美国
	Tord Johansson	乌普萨拉大学	瑞典
	Marek Karliner	特拉维夫大学	以色列
	Eugeny Levichev	布德科尔核物理研究所	俄罗斯
	马余刚	复旦大学	中国
	Mikihiko Nakao	高能加速器研究机构	日本
	Stephen Olsen	中央大学	韩国
	Alexey Petrov	南卡罗来纳大学	美国
Antonio Pich	瓦伦西亚大学	西班牙	
Makoto Tobiyama	高能加速器研究机构	日本	
赵红卫	中国科学院近代物理所	中国	
赵振堂	中国科学院上海高研院	中国	
邹冰松	中国科学院理论物理所	中国	



项目汇报→面对面质询/讨论→参观场地 (1.5天)

- 再次肯定项目的**科学意义、可行性、重要性**：“STCF将是一个独特的装置，具有广泛而卓越的物理研究能力，可在多个重要课题上实现世界领先的高精度测量，具有重大发现的潜力和机遇。它将与2030、2040年代预计建成或正在运行的其它装置形成互补，受到国际粒子物理界高度关注”
- 高度评价物理、探测器和加速器等方面的**显著进展**
- 提出物理、探测器、加速器具体**建议与意见**

Report of third meeting of International Advisory Committee for the Super Tau Charm Facility

Maria Enrica Biagini¹, Ikaros Bigi², Alex Bondar³, Tom Browder⁴, Kuang-Ta Chao⁵, Yuanming Gao⁶, Wolfgang Gradl⁷, David Hitlin⁸, Tord Johansson⁹, Marek Karliner¹⁰, Eugeny Levichev¹¹, Yugang Ma¹², Mikihiko Nakao¹³, Stephen Olsen¹⁴, Alexey Petrov¹⁵, Antonio Pich¹⁶, Makoto Tobiyama¹⁷, Guy Wilkinson¹⁸, Hongwei Zhao¹⁹, Zhentang Zhao²⁰, Frank Zimmermann¹⁸, Bingsong Zou¹⁹

¹ INFN - Frascati National Laboratories, ² University of Notre Dame, ³ Budker Institute of Nuclear Physics (BINP), ⁴ University of Hawaii, ⁵ Peking University, ⁶ Johannes Gutenberg University Mainz, ⁷ California Institute of Technology, ⁸ Uppsala University, ⁹ Tel Aviv University, ¹⁰ Padua University, ¹¹ High Energy Accelerator Research Organization (KEK), ¹² Cheng Ang University, ¹³ University of South Carolina, ¹⁴ University of Valencia, IREC, ¹⁵ University of Oxford, ¹⁶ Institute of Modern Physics, CAS, ¹⁷ Shanghai Advanced Research Institute, CAS, ¹⁸ European Organization for Nuclear Research (CERN), ¹⁹ Tsinghua University.

¹ Co-chair.

1 Introduction

The International Advisory Committee (IAC) for the Super Tau Charm Facility (STCF) met for the third time on 9th and 10th June 2025 at USTC, Hefei, with several members participating remotely. Members of the STCF project were in attendance, and presentations were given on the project as a whole, on the progress with the physics studies, the accelerator and the detector. Parallel discussion sessions followed on the physics and detector, and on the accelerator. A visit took place to the proposed site of STCF at the Hefei Future Big Science City. The second day concluded with further discussions in plenary, and then a wrap-up session.

The IAC meeting was preceded by a day-long review of the Conceptual Design Report (CDR) of the accelerator, which was conducted by a committee that included the machine experts of the IAC, plus additional experts from around the world. Several key recommendations on various parts of the accelerator design are presented in this report. A more complete set of observations and recommendations are provided in the separate report from the Accelerator CDR Review.

2 Executive summary

STCF will be a unique facility with a broad and impressive physics reach. It will allow for results of world-leading precision in many important topics, and has significant discovery potential. It will ideally complement the other facilities that are currently operational or are foreseen for the 2030s and 2040s, and will be of great interest to the international particle physics community. The principal challenge of the project lies in the accelerator. Here the intended luminosity will exceed by two orders of magnitude that previously achieved in the same energy regime.

The IAC is pleased to note the substantial progress made in physics, detector and accelerator studies since the last review in October 2024. An accelerator CDR has been written, which was reviewed immediately prior to the IAC meeting. Progress on both the accelerator and the detector has been aided by a growth in the number of Chinese institutes involved in the project

国内、国际研讨会



Time	Place	Content
2018.10	Hengyang (USC)	STCF
2019.03	Beijing (UCAS)	STCF: Physics
2019.07	Hefei (USTC)	STCF: Accelerator
2019.08	Hefei (USTC)	STCF: Phys. & simulations
2019.11	Beijing (UCAS)	STCF: CDR
2020.08	Hefei (USTC)	STCF: From CDR to TDR
2022.12	Guangzhou (SYSU)	STCF: R&D kick-off
2023.07	Zhengzhou (ZZU)	STCF: Collaboration
2024.07	Lanzhou (LZU)	STCF: R&D progress
2025.07	Xiantan (HUST)	STCF: R&D progress

Hunan University of Science and Technology



2025 超级陶粲装置研讨会

会议时间: 7月2日-7月6日 (7月2日报到)
地点: 湖南科技大学

会议主办单位: 核程超核电子学物理重点实验室, 核程超核电子学物理研究中心
会议承办单位: 湖南科技大学物理与电子科学学院



- 200+ attendees from 20+ countries
- 125 talks: 20 plenary, 105 parallel
- Several other experiments

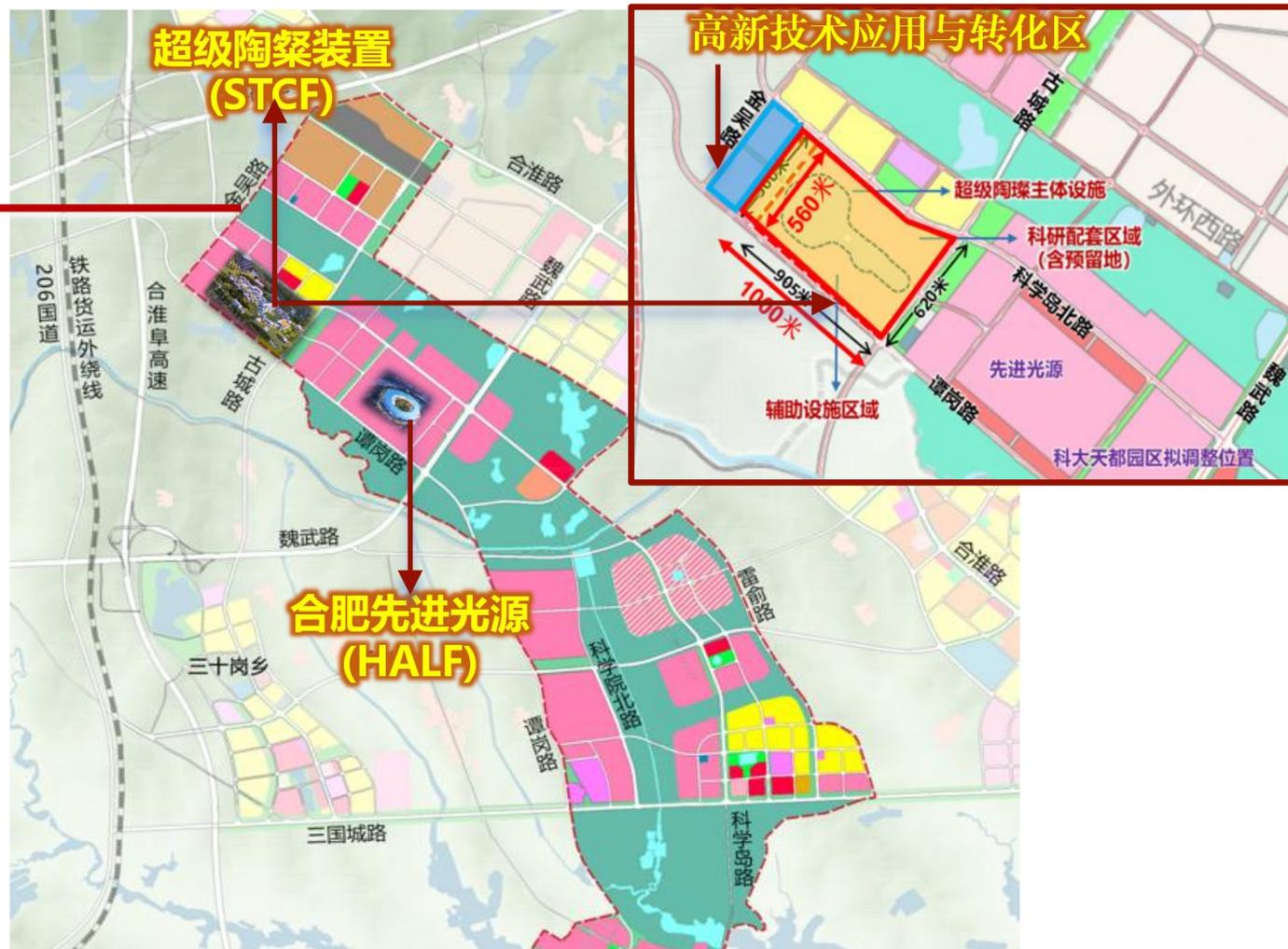
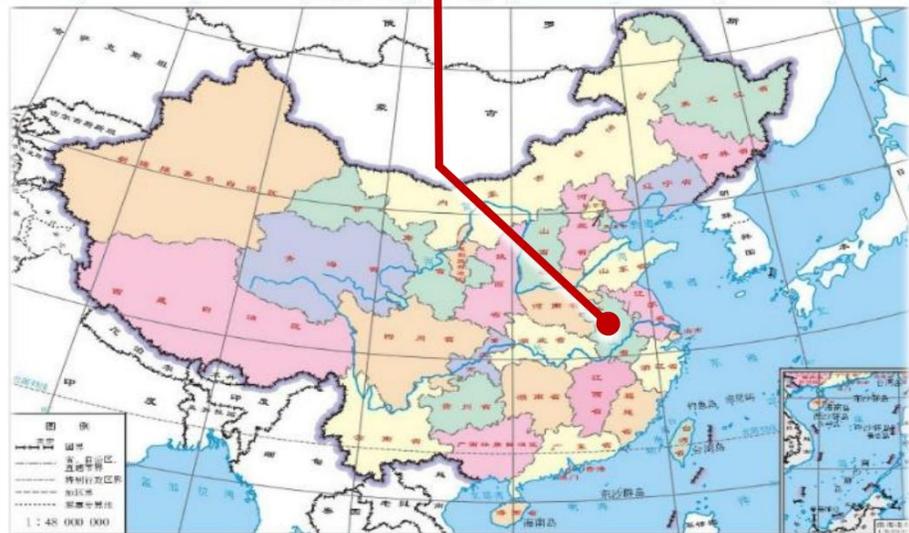
Intensively, fruitfully and impressively

Time	Place	Content
2015.01	Hefei, China	Workshop on Super tau-Charm Facility in China
2018.03	Beijing, China	Workshop on Super tau-Charm Facility in China
2018.05	Novosibirsk, Russia	Workshop on Super tau-Charm Facility in Russia
2018.12	Paris, France	1 st FTCF (Joint International Workshop)
2019.08	Moscow, Russia	2 nd FTCF
2020.11	Online, China	3 rd FTCF
2021.11	Online, Russia	4 th FTCF
2024.01	Hefei, China	5 th FTCF
2024.11	Guangzhou, China	6 th FTCF
2025.11	Huangshan, China	7 th FTCF

选址：合肥滨湖科学城

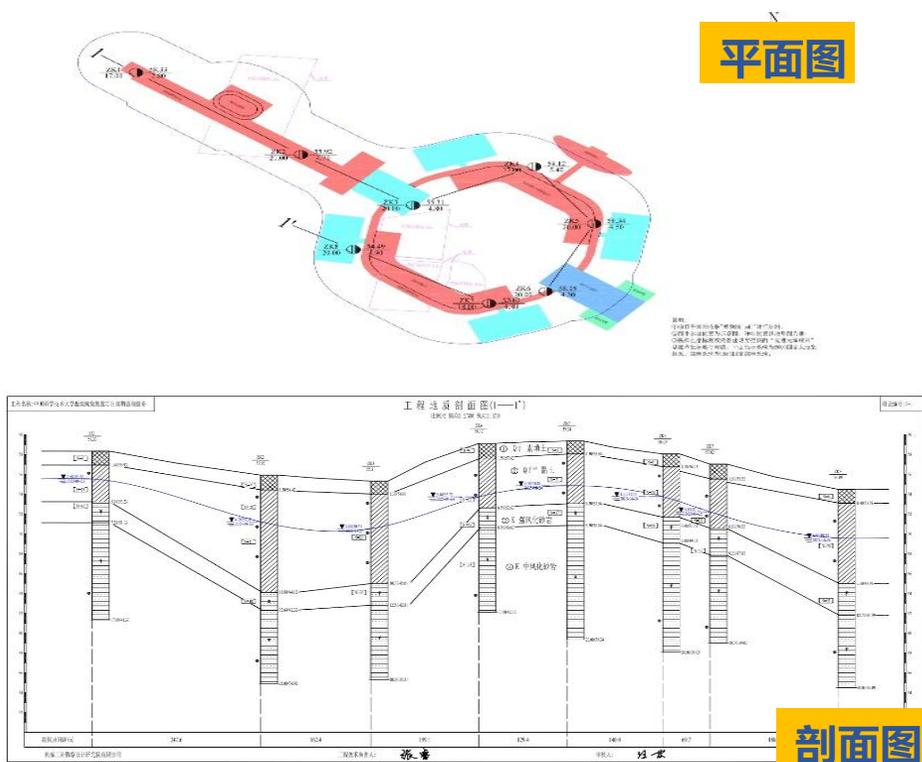


合肥滨湖科学城用地布局图

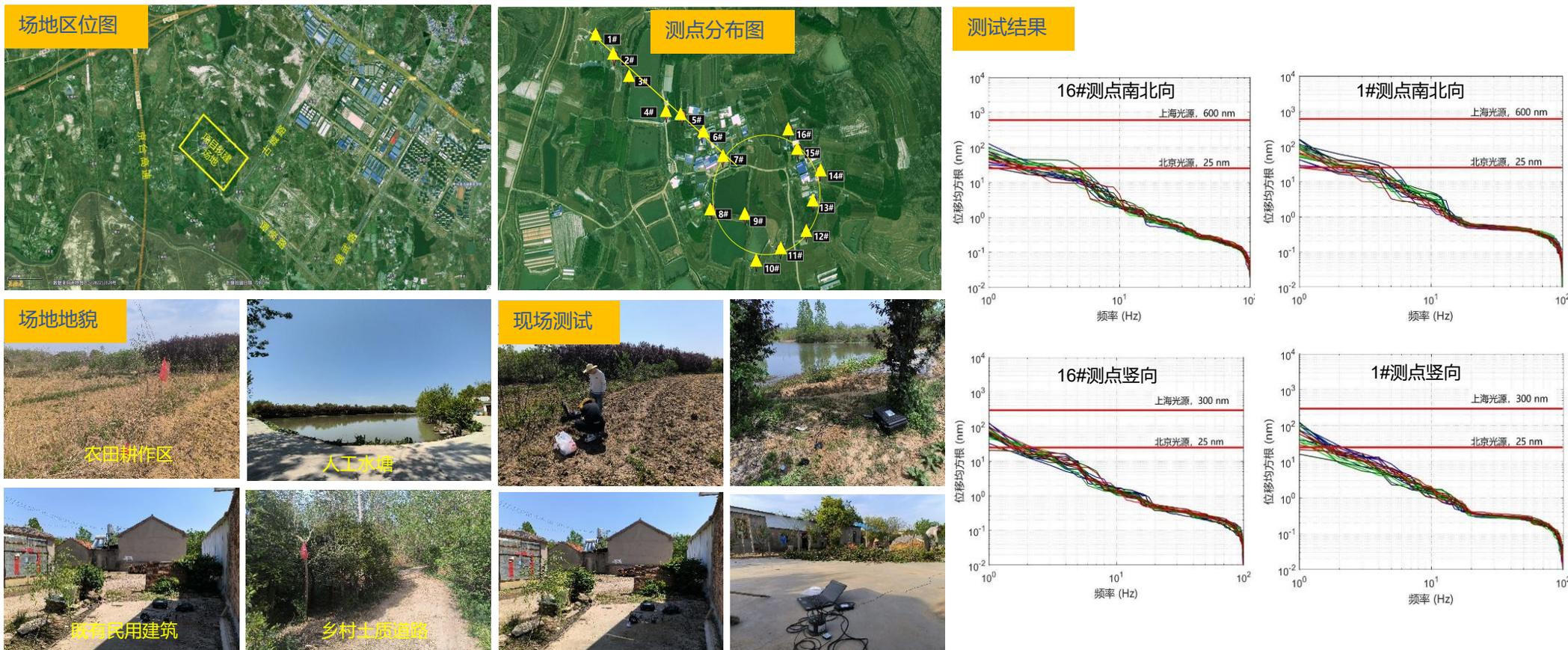


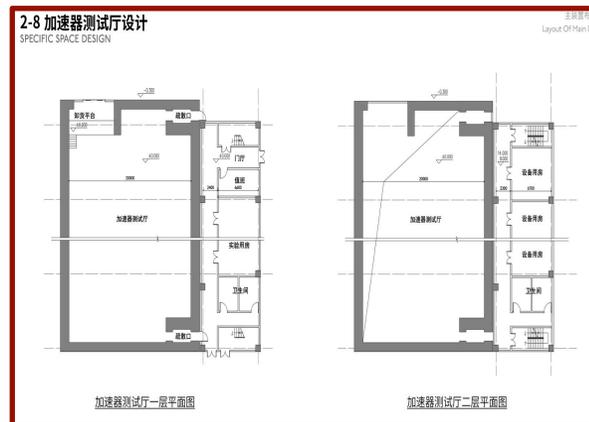
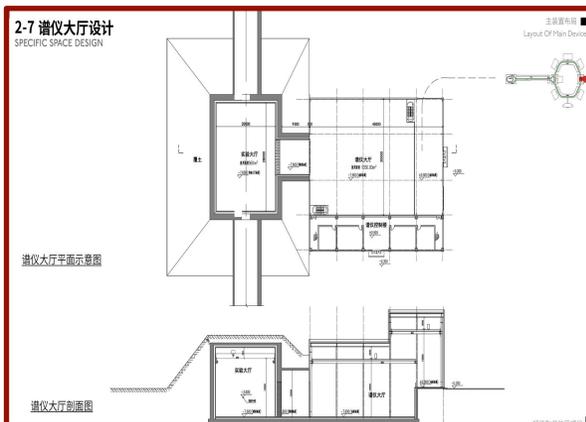
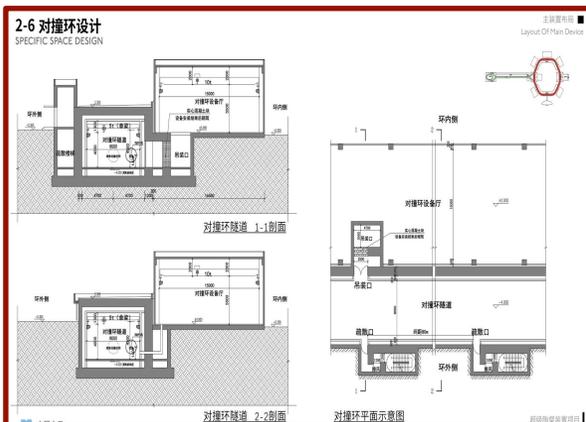
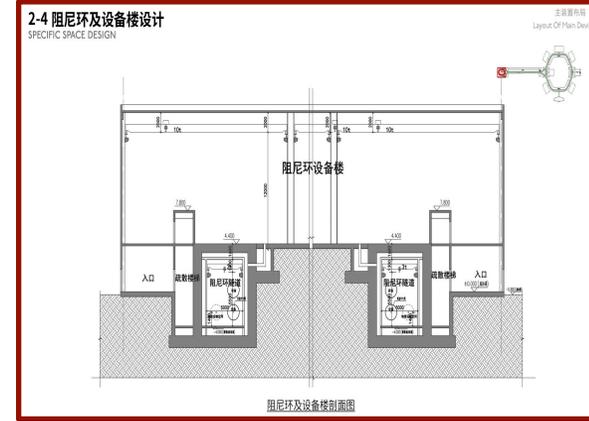
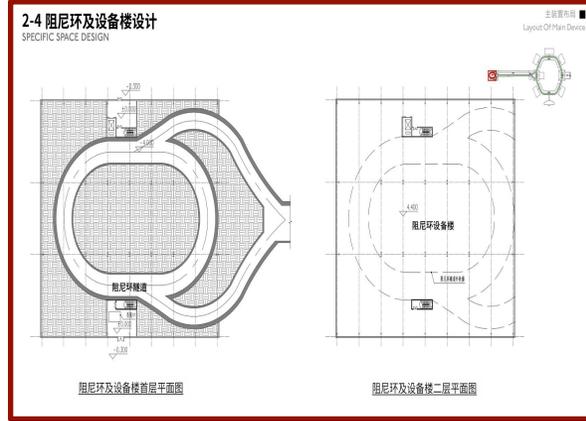
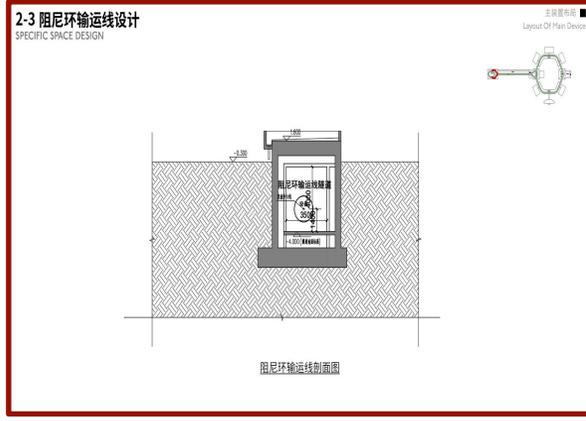
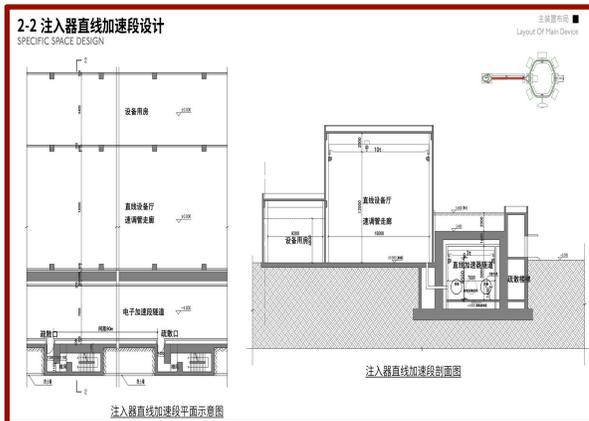
得到了安徽省、合肥市相关部分的大量支持，
多次多部门协调会议，确定选址

- 大科学装置的选址是一个涉及**多学科**、**多因素**的复杂决策过程。
- 需根据总体建设方案，综合考虑地理位置、地质条件、生态环境、科研需求、基础设施配套和社会经济条件等**多方面因素**。
- 根据区域地质资料及本次钻探结果，场地范围内及周边亦未发现影响场地稳定的滑坡、崩塌、泥石流等不良地质作用，场地稳定，工程地质及水文地质条件简单，**适宜工程建设**。



- 现阶段对STCF拟建场地开展了振动测试评估，加速器区域布置6个测点，对撞圆环区域布置10个测点
- 参考北京光源（HELPS）与上海光源（SSRF）振动控制标准，对每个测点取多个时间段，分析1~100Hz位移均方根的频域分布图，得出：
 - a) 现有场地振动水平**高于北京光源限值，低于上海光源限值**；
 - b) 后续结合装置运营及使用需求确定具体**振动控制辅助措施**，以确保满足工艺使用需求。





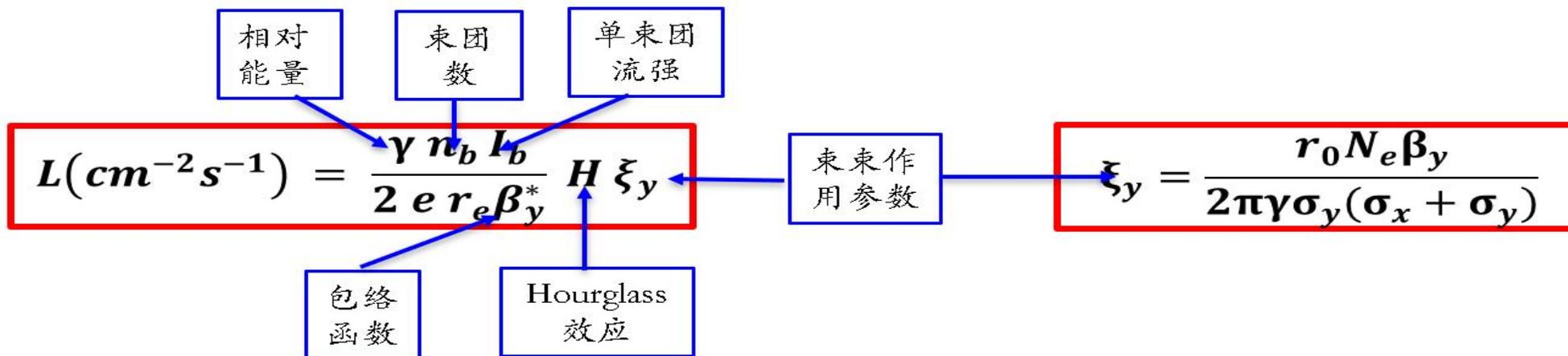
目录

CONTENTS

- 一、STCF项目介绍
- 二、项目科学目标
- 三、项目的组织和推动
- 四、关键技术攻关项目**
- 五、总结

STCF 挑战: 质心能量: 2-7 GeV, 峰值亮度: $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

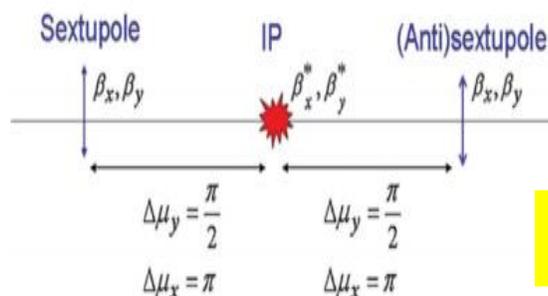
- 能量越高单束团流强越高 (近似 $\propto E^3$) , 因此**总亮度** $\propto E^4$, 难度不亚于SuperKEKB
- 束流大能量范围 (1-3.5GeV) 下, 磁铁等元器件在极大动态范围保持**稳定**和**精确**



“超级粒子工厂” : 受集体效应限制, 流强很难极大改善, 进一步压缩 β_y^* 到**亚毫米**量级?

大 Piwinski Angle

$$\phi = \tan \frac{\theta}{2} \cdot \frac{\sigma_z}{\sigma_x}$$



crab六极铁
抑制束-束共振

INFN实验验证(2009)

1. 对撞环和对撞区设计

要求: 高流强、低发射度、大能量范围, 对撞点极小 β 函数, 稳定运行与精确控制

挑战: 小动力学孔径和动量孔径, 强束束作用和束流集体效应, 极短束流寿命等

3. 加速器-谱仪交接面 探测谱仪设计

要求: 接口强聚焦和低本底, 谱仪探测谱仪精确探测粒子

挑战: MDI结构复杂, 空间极其紧张, 超导组合磁铁; 探测谱仪所处极强辐照高本底环境

2. 注入器设计

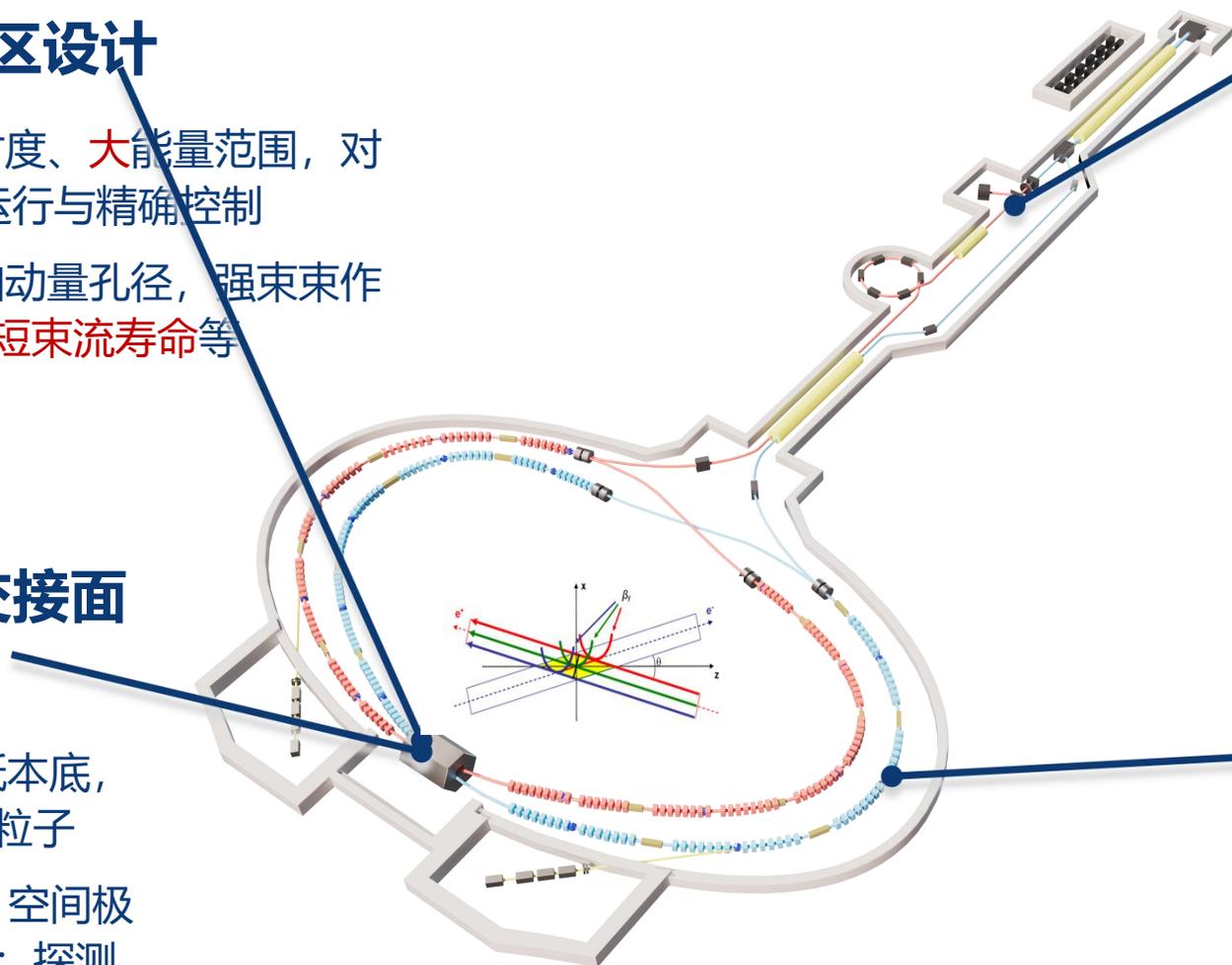
要求: 高重频注入、高电荷量、低发射度正负电子束

挑战: 大电荷量束团加速过程中的发射度和能散控制, 大电荷量正电子的产生和俘获、累积环中的累积和发射度阻尼等

4. 核心关键技术

要求: 先进技术与成熟技术结合, 满足物理设计和未来实验要求

挑战: 极端环境、极高参数需求



序号	关键设计或关键技术	重要性	备注
1	对撞环物理设计	A+	尤其是对撞区设计，是保证亮度的关键所在
2	对撞区超导磁铁技术	A+	结构复杂、场强高、空间受限，缺少经验
3	对撞环高频技术	A+	高功率、高次模深度抑制，缺少经验
4	对撞区结构	A+	空间极为紧凑、兼顾加速器和谱仪要求、机械结构复杂
5	对撞环束流测量技术	A	束团高精度和快速测量，快速反馈控制
6	注入器物理设计	A	为对撞环提供高品质束流，针对不同注入方案
7	对撞环注入技术	A	束团置换注入需要ns级超快冲击磁铁
8	正电子源技术	A	正电子转换靶、收集磁号，难度大于BEPCII
9	对撞环真空技术	A-	大流强、高辐射功率、对撞区高真空度
10	电子源技术	A-	大束团电荷量光阴极电子枪，要求大于现已掌握的
11	直线微波技术	A-	大孔径S波段加速管，缺少经验
12	直线功率源和低电平技术	A-	大功率固态调制器，低电平保证注入束流的高稳定性

加速器核心技术指标



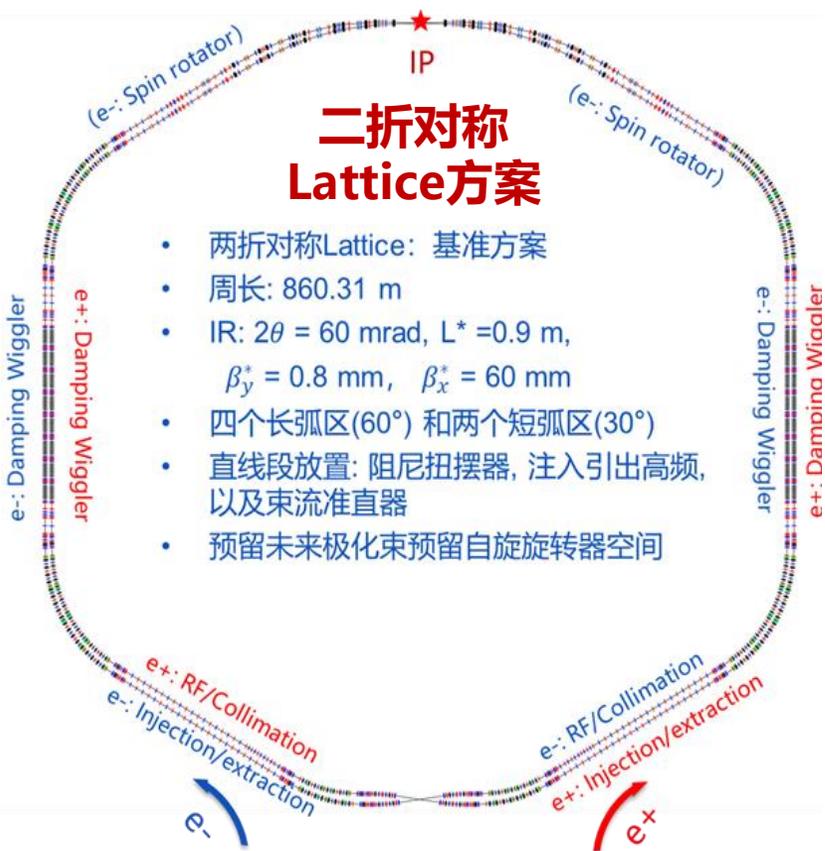
核心技术	STCF加速器设计指标和要求	国内现状	国际现状
对撞环物理设计	大交叉角+Crab Waist对撞 大流强/低发射度: 2A / 5 nm·rad 超高亮度 $> 5 \times 10^{34}$, 限制 : 束流寿命极短 < 300 s	BEPCII: 小交叉角; 0.9 A /150 nm·rad; 亮度 10^{33} ; 寿命2小时	SuperKEKB: 设计(2.6A/3.6A), 目前(1.1A/1.4A) 设计亮度 6×10^{35} , 目前 5×10^{34} ; 寿命 > 600 s
对撞区磁铁技术	对撞区 双孔径超导 四极铁 磁场梯度高 > 50 T/m	BEPCII: 单孔径超导磁铁, 25 T/m	SuperKEKB和BINP: 都研制了对撞区 双孔径超导 四极铁
环高频系统	耦合器功率 > 300 kW 高次模深度抑制常温腔	耦合器功率 ~ 150 kW, 无HOM抑制常温腔	SuperKEKB: 耦合器功率 > 500 kW
超快脉冲冲击磁铁	上升/下降时间 < 2 ns	HEPS: ~ 6 ns	KEK-ATF: $2\sim 3$ ns
对撞环束流精确测量和反馈控制	逐束团 横向位置分辨率好于 $5 \mu\text{m}$ 、纵向相位分辨率好于 0.2 ps; 快速反馈阻尼时间 0.1 ms、纵向阻尼时间 0.5 ms	BEPCII: 位置分辨率好于 $5 \mu\text{m}$; 反馈 0.7 ms	SuperKEKB: 逐圈横向位置分辨 $50\text{-}100 \mu\text{m}$, 逐圈纵向相位分辨 0.033 ps
正电子源	2.5 GeV 电子束能量驱动条件下, 累积单束团电荷量 8.5 nC	BEPCII: 仅满足上一代装置要求;	SuperKEKB: 采用 3.3GeV (目标 4nC 当前 1.5nC)

各项核心技术要求均达到或超过世界先进水平

对撞环总体物理设计

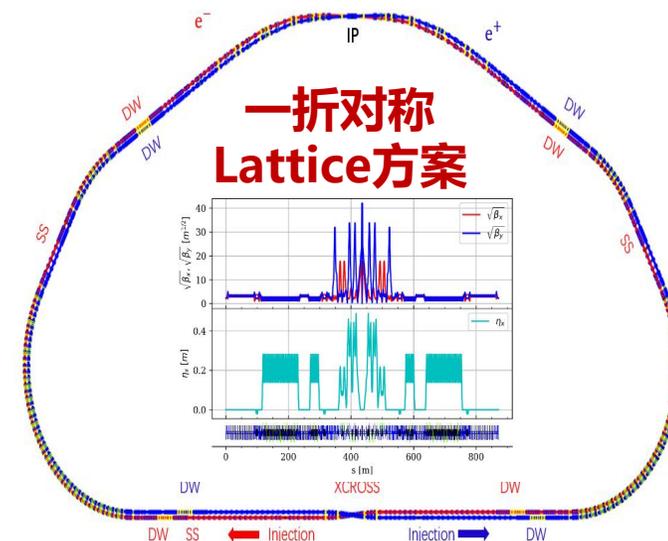


- 两折对称Lattice作为主方案，完整物理设计和技术设计；为未来极化束预留自旋旋转器(spin rotators)空间。



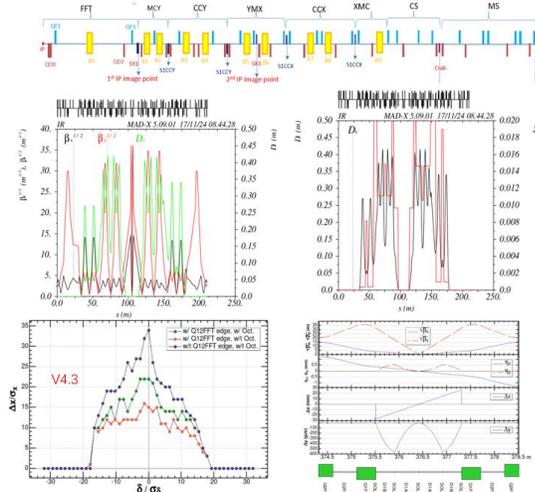
Parameters	Units	2 GeV
Circumference, C	m	860.321
Crossing angle, 2θ	mrad	60
Hor./Ver. beta function at IP, β_x^*/β_y^*	mm	60/0.8
Hor./Ver. betatron tune		30.543/34.58
Beam current, I	A	2
Hor. Emittance (SR/DW+IBS)	nm	8.79/4.63
Ver. Emittance (SR/DW+IBS)	pm	87.9/46.3
Ratio, ϵ_y/ϵ_x	%	1
Momentum compaction factor, α_p	10^{-3}	1.35
Energy spread (DW+IBS)	10^{-4}	7.8
Energy loss per turn (SR+DW), U_0	keV	543
SR power per beam (SR+DW), P	MW	1.086
RF voltage	MV	2.5
Synchrotron tune, ν_s		0.0194
δ_{RF}	%	1.68
Bunch length (Nature/ 0.1Ω +IBS)	mm	7.21/8.70
Hor./Ver. beam-beam parameter, ξ_x/ξ_y		0.005/0.095
Luminosity	$\text{cm}^{-2}\text{s}^{-1}$	9.4E+34

- 一折对称Lattice作为备选方案, 为未来极化束预留西伯利亚蛇 (Siberian Snakes)空间。



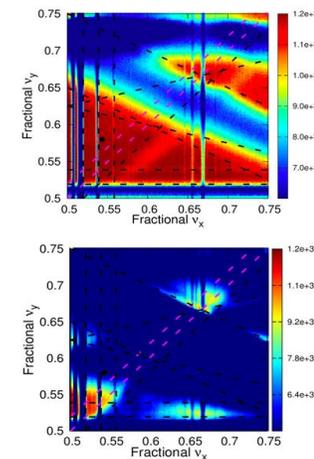
对撞区研究

- 模块化的对撞区设计→利于高阶色品校正和非线性优化
 - 最终聚焦望远镜、垂直/水平色品校正、Crab六极铁
 - CCY/CCX段实现精确的-I传输
 - 最小化色散不变量Hx函数以增大LMA
- 对撞区实现三阶局部色品校正
 - 增加动量带宽[-1.5%, 1.5%]
- FF超导四极铁的边缘场效应极大降低动力学孔径
 - 安装额外的八极磁铁来补偿动力学孔径
- 探测器螺线管场会带来垂直发射度增长
 - 理想补偿下，无发射度增长，光学函数和动力学孔径完全恢复



束-束作用问题

- 工作点与亮度
 - CW对稳定高亮度区域有显著帮助；在当前设计工作点下能达到设计亮度，但不能完全抑制SBRs
- 当前X-Z不稳定性对亮度的影响较大，其稳定区间宽度与SBRs 宽带正相关
- 束束效应与lattice非线性、空间电荷效应的相互作用
 - 在BBSCl下验证了当前设计lattice在考虑lattice非线性与空间电荷后仍能达到设计亮度
 - X-Z不稳定性的稳定工作点区间会发生偏移，需要在耦合情况下重新确定工作点
- 束束效应与阻抗的相互作用
 - 研究了加入简单阻抗模型之后对亮度的影响
 - 阻抗对亮度的影响比较复杂，需要进一步构建宽带纵向和横向阻抗模型以作全面评估
 - 计划后续结合lattice、空间电荷效应、阻抗进行进一步的模拟研究



Crab on and off

阻抗和不稳定性

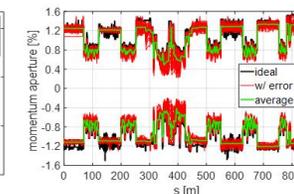
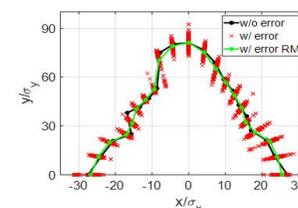
- 对于各种集体效应进行了初步研究
 - 束-腔相互作用-1模式不稳定性可通过PI反馈抑制
 - 电阻壁不稳定性可通过逐束团反馈系统抑制
 - 高次模(HOM)不稳定性及发热问题有待于元件的阻抗优化和冷却设计
 - 纵向微波不稳定依赖于阻抗建模，且需要严格控制阻抗预算
 - TMCI限制单束团流强阈值，主要受准直器阻抗和对撞区高β函数影响，需要进一步优化
 - 1 GeV时CWR不稳定性流强阈值可能小于1 mA，设计DW时需要同时统筹考虑
 - 离子效应和电子云效应：模拟程序已经部分掌握，未来还需与真空组配合推进
- 近期迫切任务：需要建立初步阻抗模型
 - 重点针对于阻抗贡献较大的元件
- 持续进行更细致的研究
 - 包括多物理效应的复合（束-束，阻抗，空间电荷效应，IBS，Feedback噪声等）

误差分析

	Δx (μm)	Δy (μm)	Δs (μm)	$\Delta\theta$ (mrad)	Field error
Dipole	100	100	100	0.1	0.02%
Quadrupole	50	50	100	0.1	0.02%
FFT doublet	30	30	100	0.1	0.02%
Arc/IR Sextupole	50/30	50/30	100	0.1	0.02%

- BPM与校正子布局
 - 四极铁旁放BPM和校正子；单环共405 BPM, 287 CORx, 254 CORy
 - 六极铁绑双向校正子和斜四极子
- 校正步骤与方法
 - 首圈轨迹校正：SVD+轨迹响应矩阵；
 - 轨道与色散校正：SVD + dispersion free steering (DFS) 方法；
 - 轨道和色散@IP: 加权重的SVD；
 - 光学函数与耦合校正：LOCO
 - β_y^* 校正: K-modulation

校正后	Global	@IP
轨道(x/y), MAX (μm)	371/328	0.52/0.10
轨道(x/y), RMS (μm)	48.3/47.6	0.17/0.034
色散畸变(x/y), MAX (mm)	7.0/1.8	0.81/0.04
色散畸变(x/y), RMS (mm)	0.48/0.17	0.35/0.014
β -beat (x/y), MAX (%)	3.0/3.8	0.12/0.86
β -beat (x/y), RMS (%)	0.13/0.17	0.04/0.29
耦合率, MAX/RMS ($\times 10^{-5}$)	7.9/2.8	
考虑边缘场的托歇克寿命 (s)	226	



注入器物理设计



两个不同的注入器设计方案，对应于对撞环的离轴注入方案和置换注入方案

● 离轴注入(Off-axis)方案:

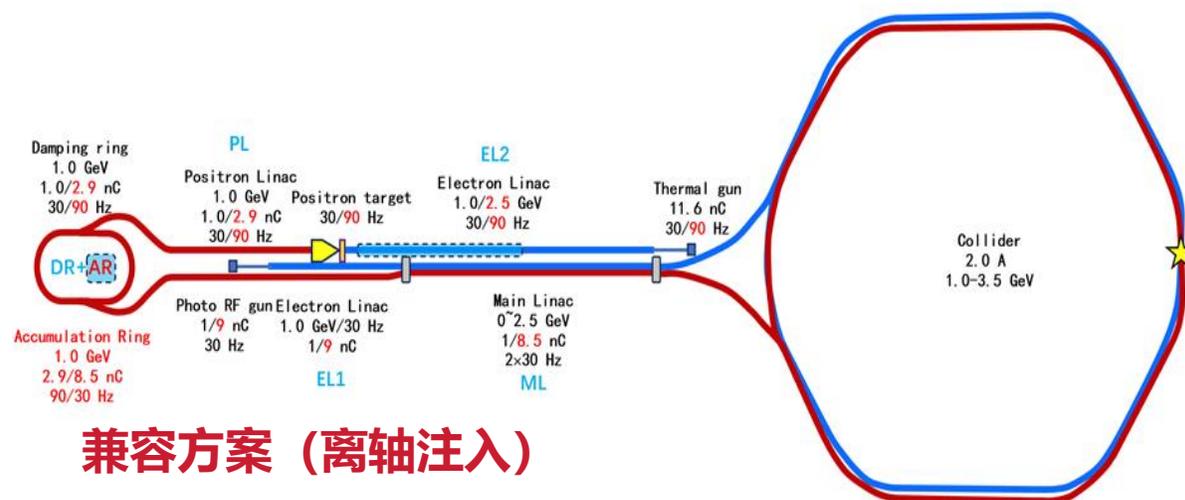
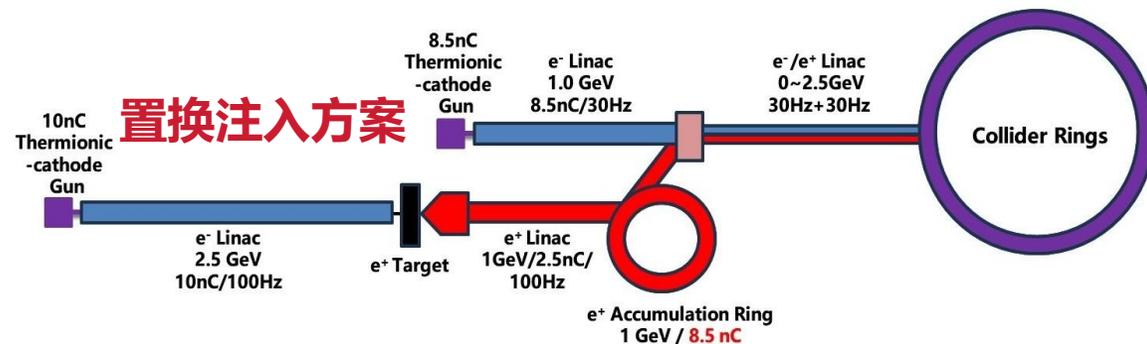
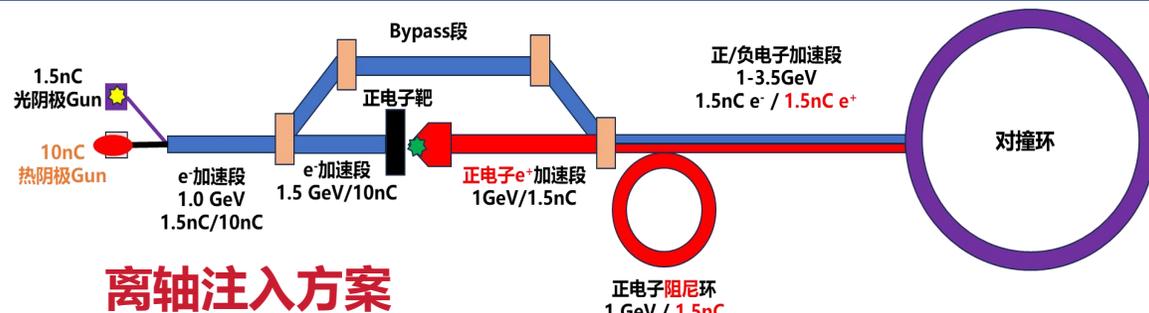
- 最大 $1.5\text{nC } e^+/e^-$ ，各30Hz注入
- e^+ 束流: $1.5\text{GeV}/10\text{nC}/30\text{Hz}$ e^- 直线, $1\text{GeV}/30\text{Hz}$ 阻尼环

● 置换注入(Swap-out)方案:

- $8.5\text{nC } e^+/e^-$ ，各30Hz注入
- e^+ 束流: $2.5\text{GeV}/10\text{nC}/90\text{Hz}$ e^- 直线, $1\text{GeV}/30\text{Hz}$ 累积环 (或阻尼环+累积环)

● 兼容方案 (专家评审建议)

- 布局采用置换注入，初期采用离轴注入 (降低造价)，后期可升级
- 离轴注入: 阻尼环; 置换注入: 叠加累积环



● 对撞区超导磁铁技术路线

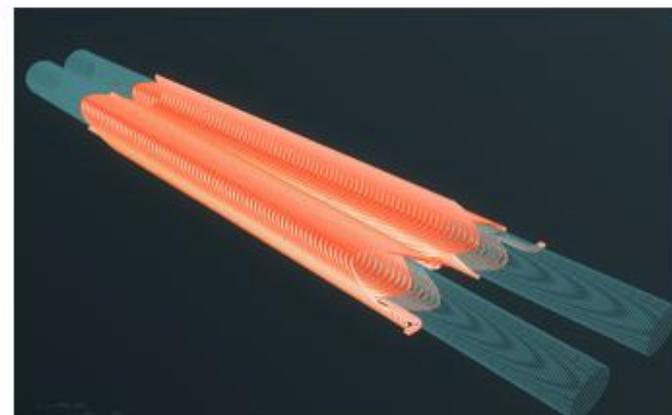
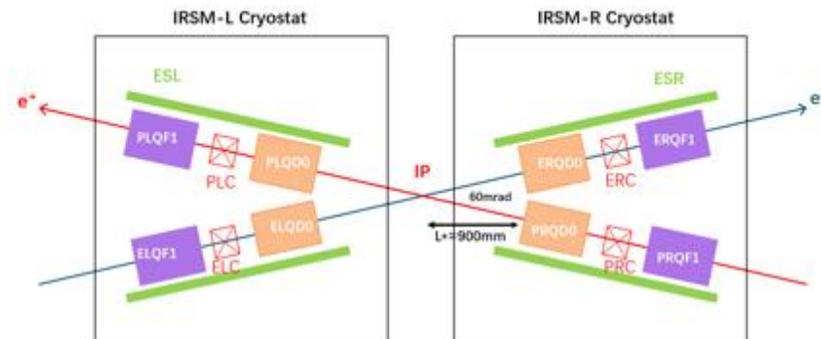
- 新一代对撞机最**具有挑战性的**技术
- 已有超导磁铁类型: CCT, Cos 2θ , DCT, 蛇形绕线
- 经概念设计和评审: 选择**CCT**作为样机研发技术路线

● 难点

- 物理设计和MDI要求 (苛刻)
- 极狭小的空间 (60mrad小分离角下的双孔径)
- 高场质量 (50T/m, 2×10^{-4} , Cross-talk: 2 Gs)
- 复合型磁铁: 屏蔽螺线管, 补偿螺张管, 校正磁铁和高阶场线圈

● 样机研制

- QD0 (最难) 的**电磁设计完成**; 线圈**骨干试加工**; 超导线材已购买
- **工艺试绕**即将开始



● 对撞环和阻尼环/累积环

- 对撞环：技术挑战，很高RF功率，深度高次模(HOM)抑制，低R/Q值
- 阻尼环/累积：频率相同但技术要求低

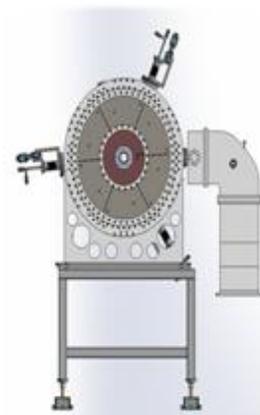
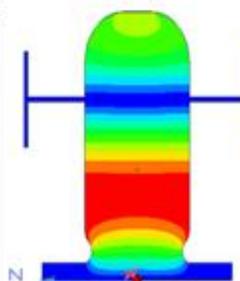
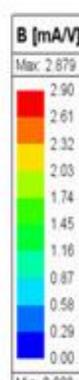
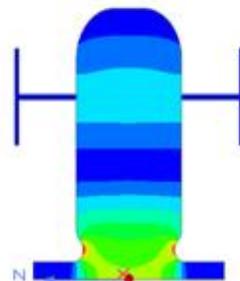
● 选择500MHz常温TM020模腔

- 具有技术优势：低腔耗，HOM抑制易实现，R/Q低
- 难点：加工工艺复杂，高功率耦合器(300kW)有难度
- 国内缺少经验，国际上可借鉴少（更高指标）

● R&D进展

- 已完成：方案设计，技术设计，腔体加工招标
- 2025年底：完成腔加工和装配
- 2026年上半年：高功率测试

RF parameters	
Working mode	TM020
Frequency [MHz]	499.7
R/Q [Ω]	95
Unloaded quality factor	63000
E_p/E_{acc}	2.48
B_p/E_{acc} [mA/V]	2.88



● 对束流测量的关键要求

- 对撞环：逐束团3D位置测量，横向位置测量 $< 5\mu\text{m}$ ，纵向相位 $< 0.2\text{ps}$ ；快速逐束团反馈；对撞点位置反馈
- 注入器：束团长度和电荷量精确测量
- 与物理设计进行迭代

● R&D进展

- 束团3D位置测量：完成系统设计，准备束流实验
- 逐束团快速反馈：完成自研反馈处理器设计，完成国产功率放大器的测试
- 注入器束团长度和电荷：完成第一版样机的离线和在线测试，分辨率满足要求



谐振腔
探头



在大连光源上进行的束长测量



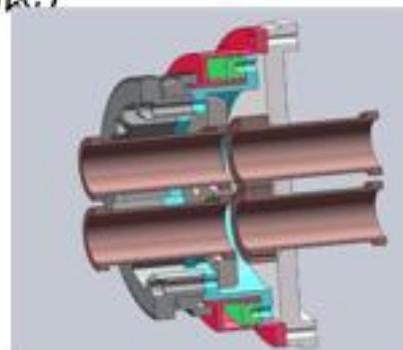
逐束团截面测量数据处理器：
光电探头, DAQ

● MDI相关的物理问题

- MDI关连：加速器（对撞区物理、超导磁铁、机械、束测、真空、准直）和谱仪（实验本底、内层探测器）
- 对撞区光学：元件布局 and 空间限制，孔径
- 实验本底抑制：束流损失和准直，真空韧致辐射
- 超导磁铁保护：束流损失和准直，真空韧致辐射
- 真空盒结构：耦合阻抗
- 同步辐射负载：同步光挡块和冷却

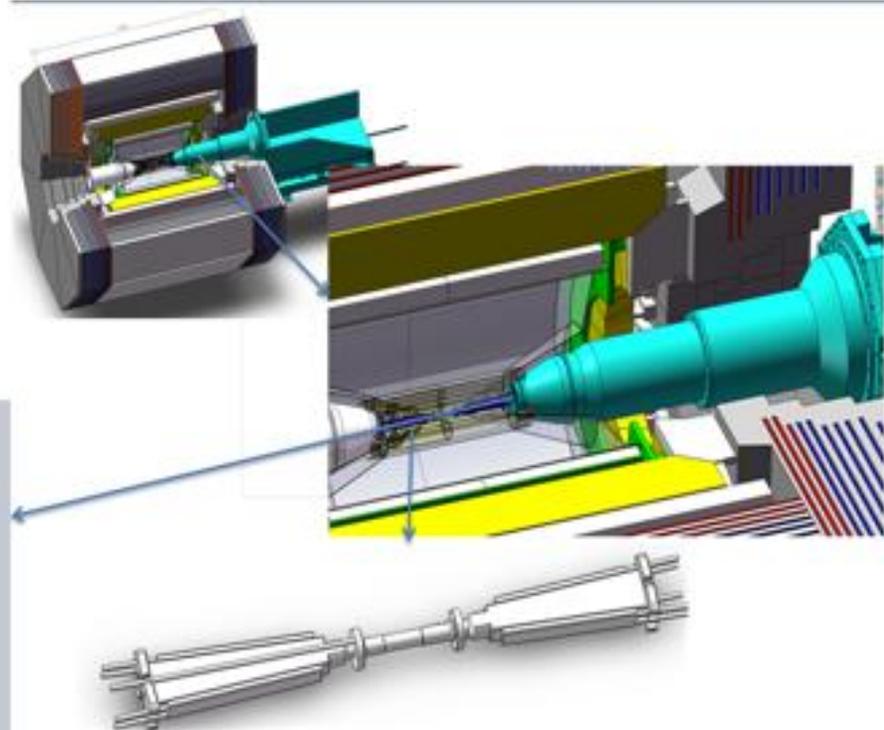
● MDI难点

- 结构复杂，涉及到多个系统（加速器物理、超导磁铁、机械、束测、真空、准直、谱仪探测器和实验本底）
- 空间极其受限
- 严格控制实验本底，亮度监测和反馈
- 中心束流管技术复杂（双层铍管，通冷却液）
- 真空抽气和连接困难
- 准直安装要求特殊（空间条件，低温）



● STCF正在采取的措施

- 加强多系统的沟通设计
- 对关键技术进行攻关
- MDI机械集成样机设计和制造



● 注入与引出系统

- 对撞环/累积环离轴注入：**非线性冲击磁铁**
- 对撞环置换注入：**超快冲击磁铁** (条带型, 底宽<6ns)

● 正电子源

- 对撞环**离轴注入**：常规固定靶正电子源
- 对撞环**置换注入**：摆动靶正电子源
- 绝热匹配设备(AMD：短脉冲大电流产生纵向快速下降磁场，最高6T)

● 微波

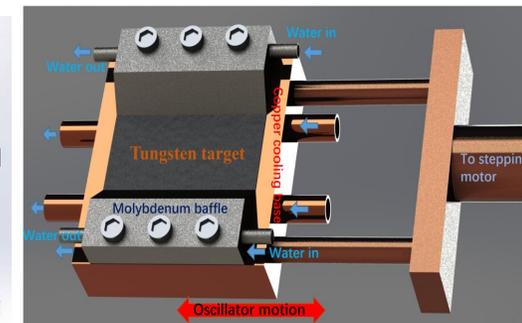
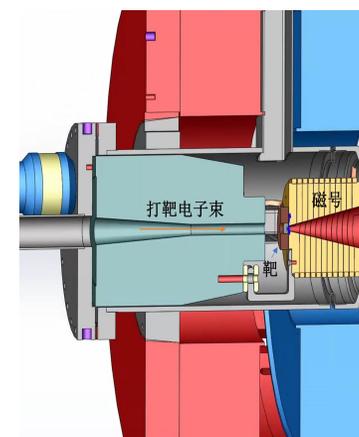
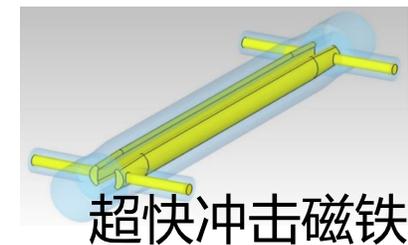
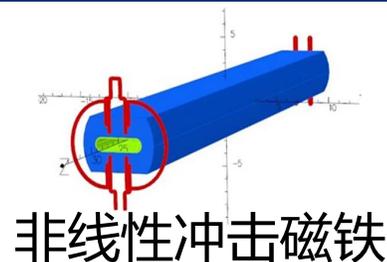
- **大孔径加速管**，正电子俘获和初加速需要，样机研制
- LLRF控制：样机研制

● 高重频速调管

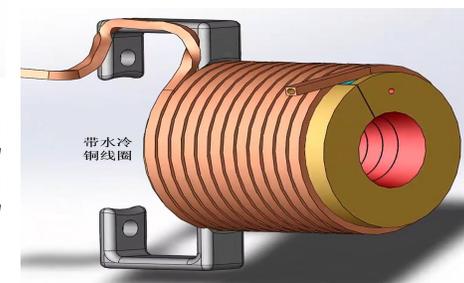
- 2998MHz, 45 MW, 30/60/90Hz (国产型号待提高)

● 高功率固态调制器

- 样机研制



上左：固定靶
上右：摆动靶
下右：AMD

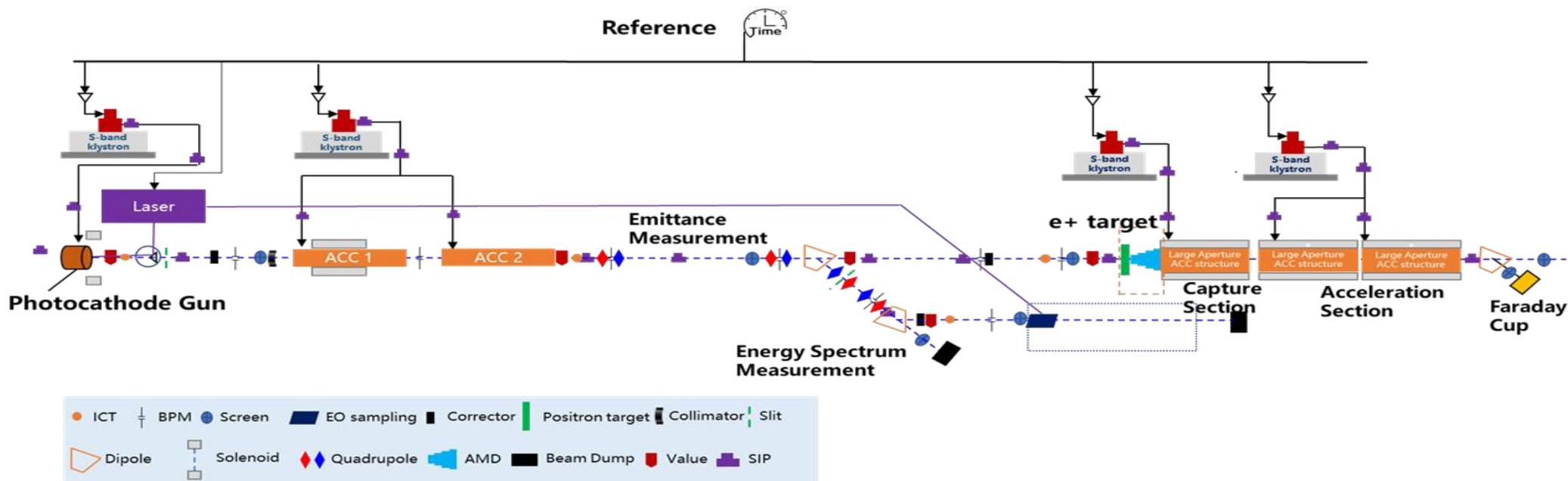


● 针对STCF注入器多个技术预研的测试平台

- 光阴极电子枪；高功率固态调制器；正电子靶；AMD；大孔径S波段加速管；束测元件

● 设计方案

- 100-MeV e-直线 + 正电子靶和AMD + 100-MeV e+直线
- 2024年物理设计和和技术设计；2025年设备加工和安装；2026年带束流调试





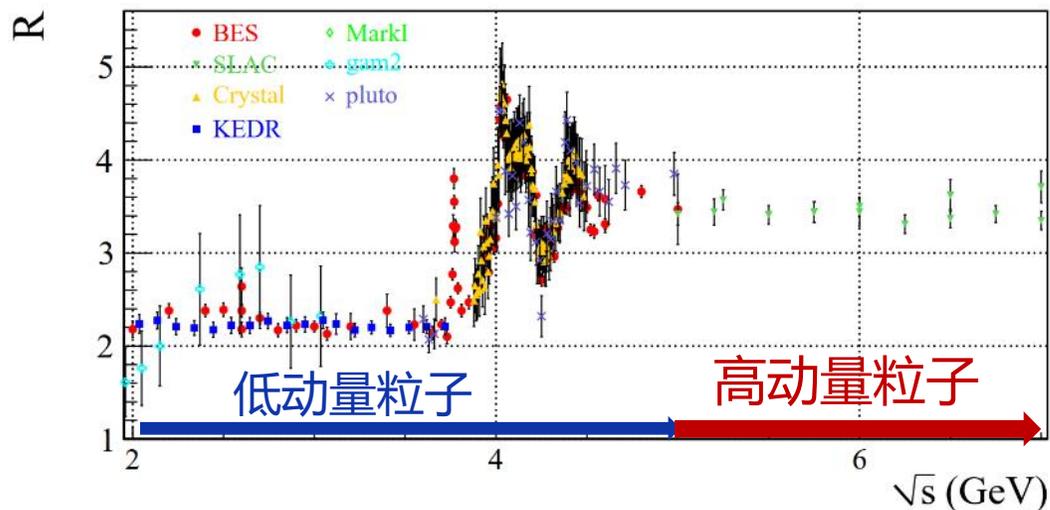
**Conceptual Design Report
Accelerator**

May 6, 2025

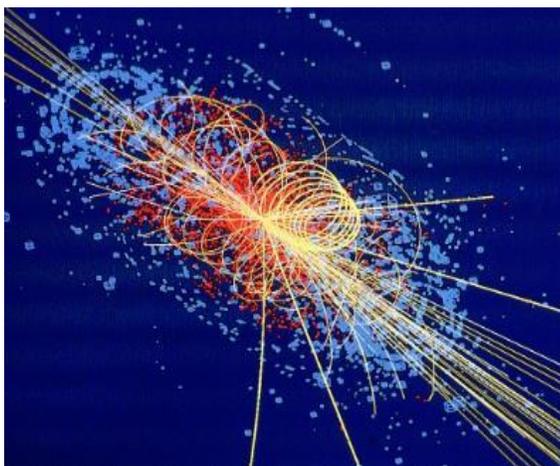
STCF Accelerator Team

6月份通过国际专家评审，正准备发表

宽能量范围 $E_{cm} : 2-7 \text{ GeV}$



峰值亮度 $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$



高物理事例率
~400 kHz
高计数率水平
~1 MHz/cm²
高数据率
~10 GB/s
高辐照本底
~4 kGy/y, ~ $2 \times 10^{11} n_{eq}/\text{cm}^2/\text{y}$

挑战: 强辐照、高本底、高事例率、宽能量范围精确测量和鉴别各种粒子

探测器

- 低质量、高计数率的径迹探测器
- 紧凑型、低质量的粒子鉴别探测器
- 快速发光和定时的闪烁晶体探测器
- 高计数率、大面积位敏探测器

电子学

- 超快微弱核脉冲信号的准确提取与处理
- 高精度时钟分发与同步
- 高效实时触发
- 高速数据传输与大容量数据获取
- 高密度物理事例分辨

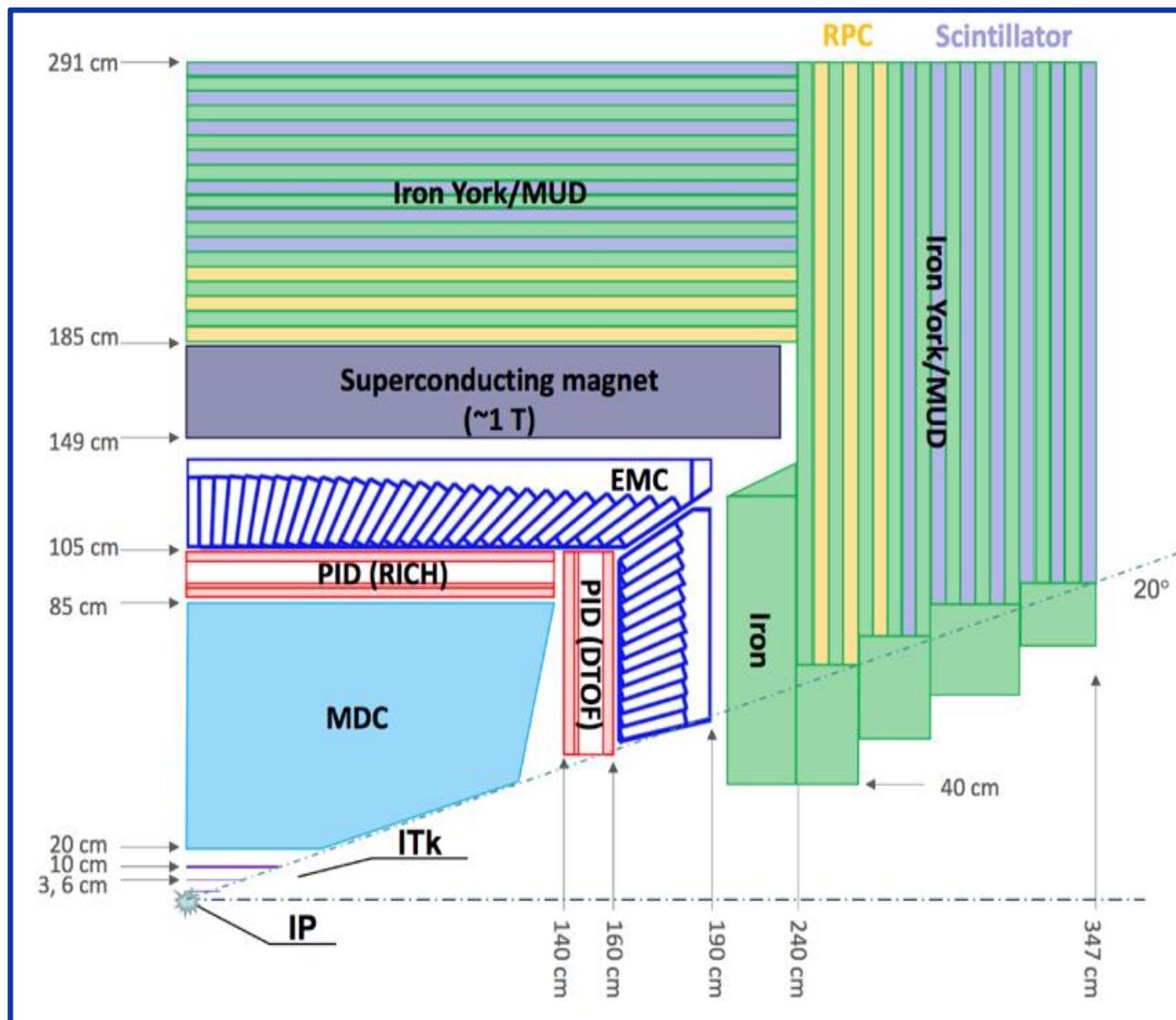
关键设计或关键技术	重要性	说明
单片有源 (MAPS) 像素芯片	A+	低质量、低功耗、集位置-时间-电荷测量功能于一体
专用集成电路 (ASIC) 芯片	A+	高集成度、高计数率、高精度、低功耗的核电子学
晶体量能器	A+	高计数率、高能量分辨、抗辐照、定时
单光子探测器	A+	(1) 高灵敏度、超高时间分辨、小死区、长寿命的多阳极微通道板光电倍增管 (2) 大面积、高计数率、高位置分辨的气体光电探测器
内反射契伦科夫 (DIRC) 飞行时间及粒子鉴别探测器	A	大面积、紧凑、超高分辨
微结构气体探测器 (MPG)	A	低质量、高计数率、大面积、圆柱形的单级放大
漂移室	A	低质量、高计数率、大型的超小单元
时钟分发和数据传输	A	高速、高精度、高可靠、抗辐
触发架构和处理技术	A	高效率、高吞吐率、低延迟、低功耗
数据获取技术	A-	高事例率、高数据率、高实时性、高性价比、易扩展
缪子探测器	A-	高计数率、具有强子鉴别能力

探测谱仪核心技术指标



核心技术	STCF探测器设计指标和要求	国内现状	国际现状
MAPS 内径迹探测器	时间分辨 < 30 ns; 位置分辨 < 20 μm 有能量测量, 单层物质质量 < 0.3% X/X_0	无	ALICE ITS2: 时间分辨 10 μs , 位置分辨 5 μm , 无能量测量, 单层物质质量 \sim 0.35% X/X_0
MPGD 内径迹探测器	时间分辨 < 10 ns; 位置分辨 < 100 μm 计数率能力 > 1 MHz/cm ² 圆柱形, 单层物质质量 < 0.3% X/X_0	无	KLOE CGEM: 位置分辨 \sim 200 μm , 单层物质质量 \sim 0.5% X/X_0
DIRC 粒子鉴别探测器	单元面积 \sim 0.6 m ² , 本底计数率 \sim 100 MHz条件下时间分辨 < 30 ps	无	研发中
pCsl 晶体量能器	在 \sim 1 MHz (\geq 0.5 MeV) 本底计数率条件下 能量分辨: \sim 5% @ 100 MeV, 2.5% @ 1 GeV 时间分辨: 300 ps @ 1 GeV	BESIII 在平均 \sim 20 kHz ($>$ 0.5 MeV) 本底 计数率条件下, 能量分辨: \sim 5% @ 100 MeV, 2.5% @ 1 GeV, 无时间分辨	Belle II 在平均 \sim 250 Hz ($>$ 100 MeV) 本底计数 率条件下, 能量分辨: \sim 8% @ 100 MeV, 2.2% @ 1 GeV, 无时间分辨
电子学读出 ASIC 芯片	全波形输出, 64通道, 电荷分辨 < 0.5 fC @ 48 fC & 20 pF, 时间分辨 < 1.0 ns @ 20 fC & 20 pF, 事例率 > 100 kHz	无	AGET芯片 事例率 < 1 kHz
	64通道, 时间分辨 < 10 ns @ 5fC, 事例率 > 4 MHz	无	VMM芯片 事例率 < 1 MHz

各项核心技术要求均达到或超过世界先进水平



谱仪主要性能设计指标

立体角覆盖: $94\% \times 4\pi$

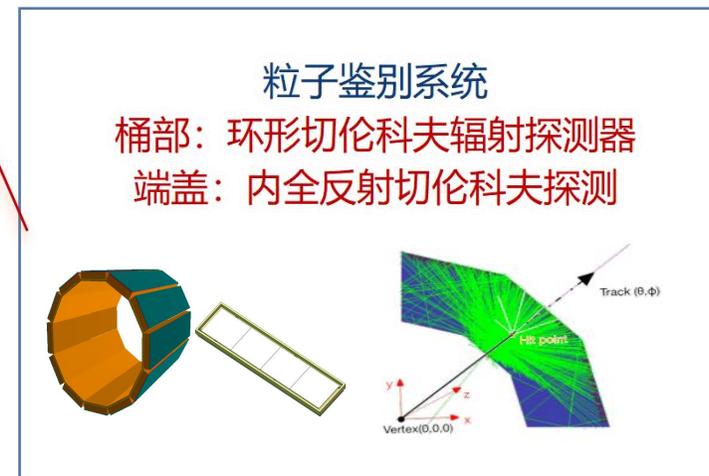
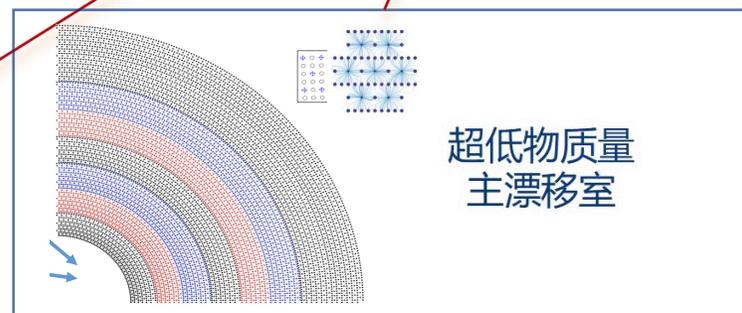
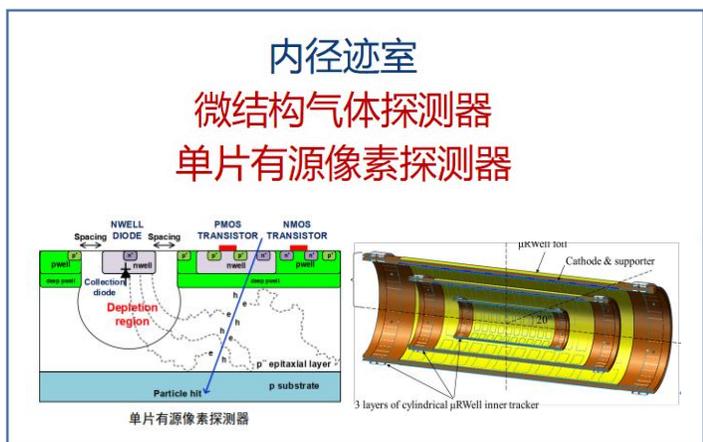
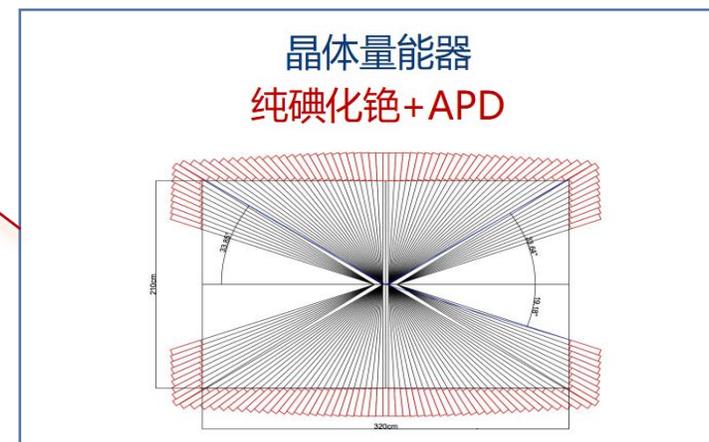
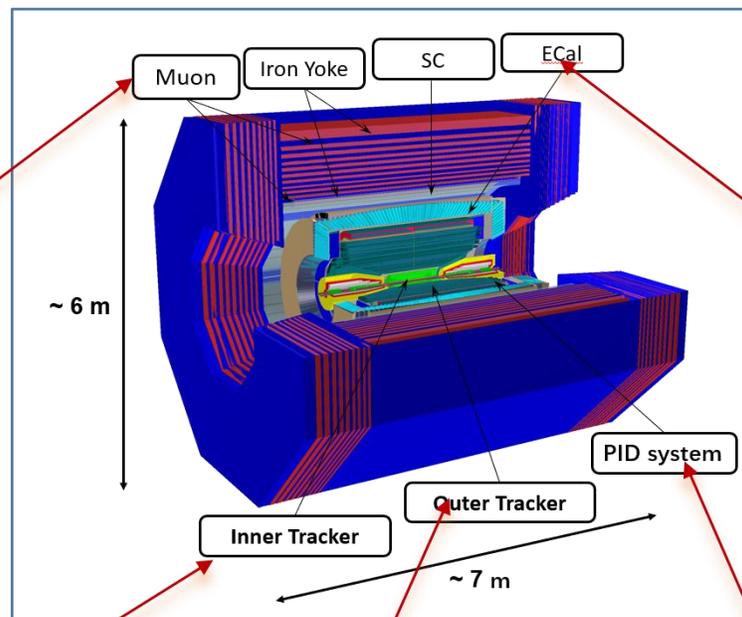
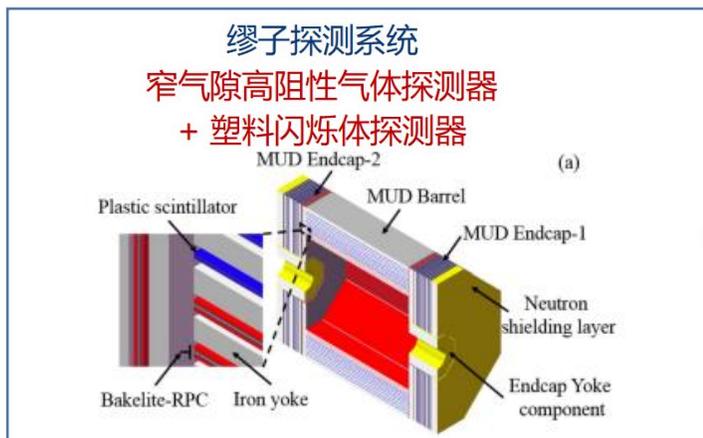
动量分辨率: $\sigma_p/p \sim 0.5\% @ 1\text{GeV}$

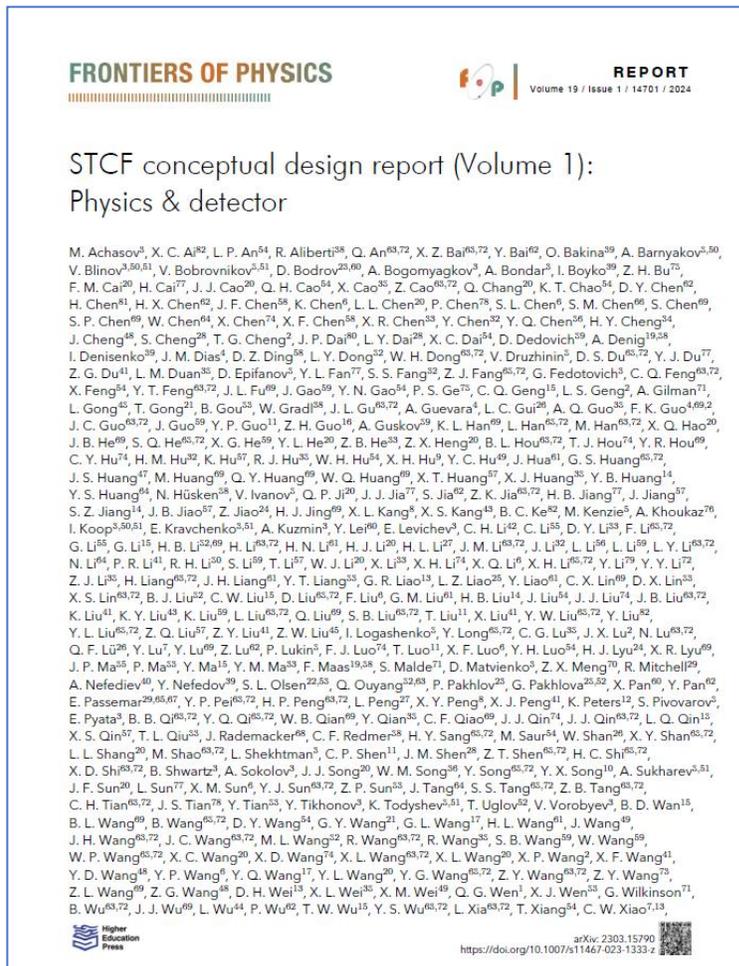
能量分辨率: $\sigma_E/E \sim 2.5\% @ 1\text{GeV}$

强子鉴别: π/K 分辨率 $\sim 4\sigma @ 2\text{GeV}$

缪子鉴别: 效率 $> 95\%$, 误判率 $< 3\% @ 1\text{GeV}$

探测谱仪设计目标：强辐照、高本底、高事例率、宽动态范围条件下的 粒子高精度测量和鉴别





REPORT		FRONTIERS OF PHYSICS	
3.7.2	DTOF conceptual design	81	lepton/baryon sector
3.7.3	DTOF performance simulation	82	4.2.3 Prospects of leptonic decay
3.7.4	DTOF structure optimization	86	$D_s^+ \rightarrow l^+ \nu_l$
3.7.5	Background simulation	88	4.2.4 Prospect of cLFV in τ decay
3.7.6	Readout electronics	89	4.3 Discussion of systematic uncertainties
3.7.7	Summary and outlook	90	4.3.1 Luminosity measurement
3.8	Electromagnetic calorimeter (EMC)	90	4.3.2 Tracking/PID uncertainty
3.8.1	Introduction	90	4.3.3 Radiative correction
3.8.2	EMC conceptual design	91	4.3.4 Vacuum polarization
3.8.3	Expected performance of the EMC	93	4.3.5 Others
3.8.4	Pileup mitigation	96	4.3.6 Conclusion
3.8.5	Readout electronics	100	5 Future plans
3.8.6	EMC R&D	101	5.1 Detector cost and project timeline
3.8.7	Summary	102	5.2 R&D prospects
3.9	Muon detector (MUD)	102	5.2.1 ITK
3.9.1	Introduction	102	5.2.2 MDC
3.9.2	MUD conceptual design	103	5.2.3 RICH
3.9.3	Expected performance	105	5.2.4 DTOF
3.9.4	Conclusion and outlook	108	5.2.5 EMC
3.10	Superconducting Solenoid (Solenoid)	108	5.2.6 MUD
3.10.1	Magnetic field design	108	5.2.7 Solenoid
3.10.2	Solenoid coil design	109	5.2.8 TDAQ
3.10.3	Iron yoke design	111	5.2.9 Software
3.10.4	Quench protection and power supply	112	5.2.10 Physics
3.10.5	Magnet cryogenics	112	Declarations
3.11	Iron yoke and mechanical structure	113	Acknowledgements
3.11.1	Mechanical structure of the iron yoke	113	References and notes
3.11.2	Mechanical movement of the iron yoke	114	
3.11.3	Detector hall and infrastructure	115	
3.12	Trigger, clock and data acquisition (TDAQ)	115	
3.12.1	Trigger	115	
3.12.2	Clock system for the readout electronics	117	
3.12.3	Data acquisition system	118	
3.12.4	Event start time (T_0) determination	121	
3.13	Offline software	121	
3.13.1	Introduction	121	
3.13.2	Architecture design	122	
3.13.3	Core software	122	
3.13.4	Detector simulation	123	
3.13.5	Reconstruction	125	
3.13.6	Validation system	125	
3.13.7	Summary	126	
4	Physics performance	126	
4.1	Fast simulation	126	
4.2	Selected physics performance	126	
4.2.1	Prospects of the collins fragmentation function	126	
4.2.2	Prospects of CP violations in the	126	

来自国内外82家科研单位和高校的453名研究人员署名了本报告

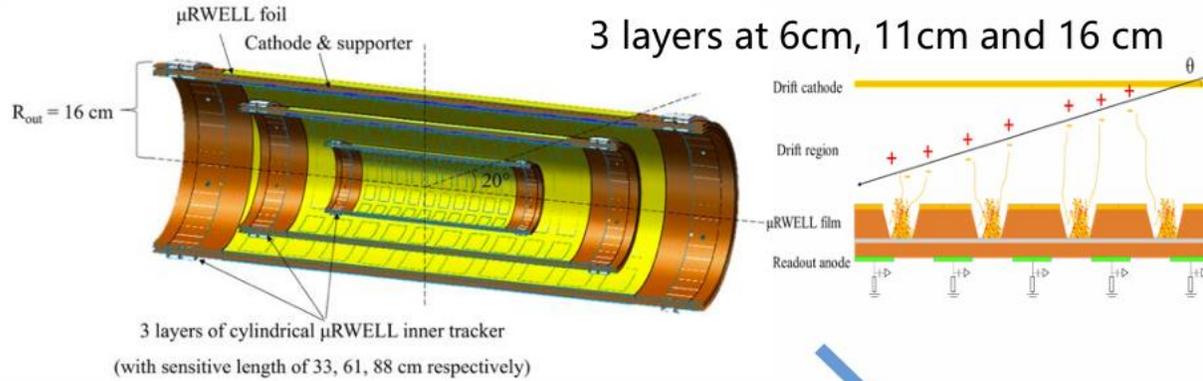
STCF项目建设中的一个里程碑

arXiv:2303.15790

径迹系统：ITK+MDC



ITK Gaseous option : MPGD

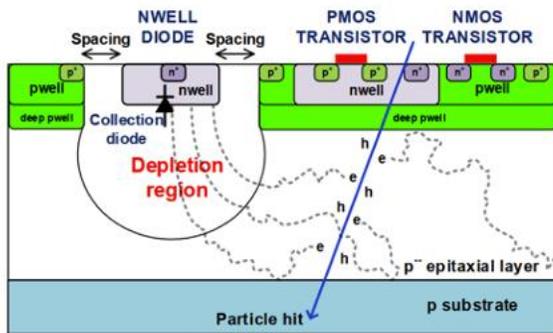


3 layers at 6cm, 11cm and 16 cm

3 layers of cylindrical μ RWELL inner tracker
(with sensitive length of 33, 61, 88 cm respectively)

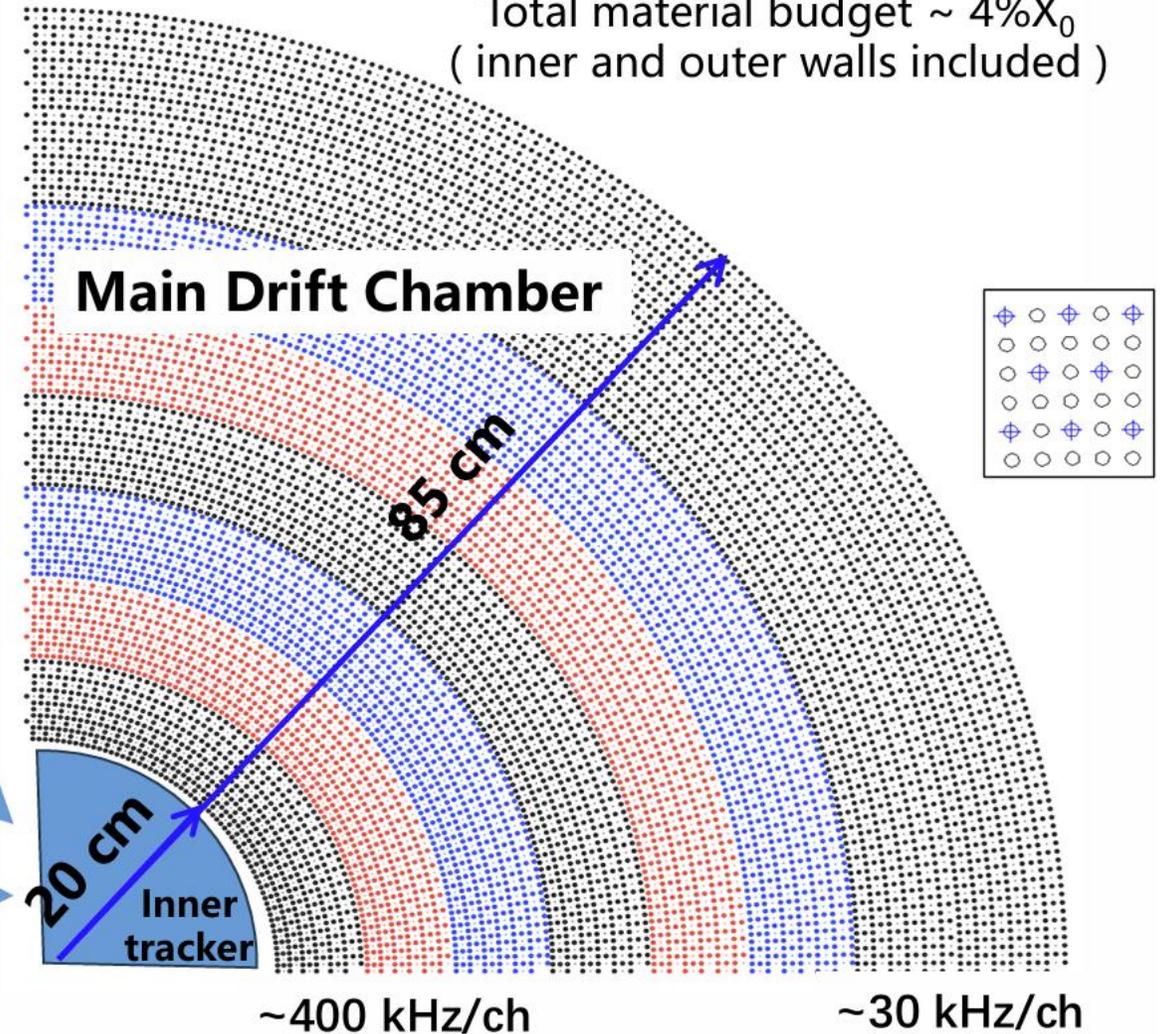
Material budget $\sim 0.3\%X_0$ /layer

ITK Silicon option: CMOS MAPS



3 layers at
3.6cm, 9.8cm and 16 cm

Total material budget $\sim 4\%X_0$
(inner and outer walls included)



Inner-outer separate designs to accommodate different levels of radiation background

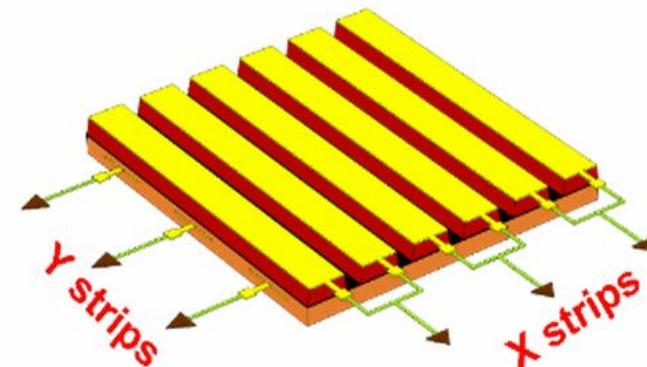
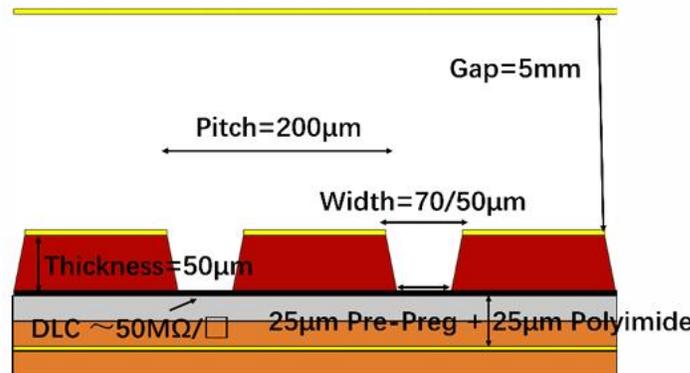
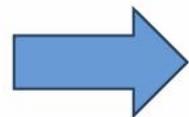
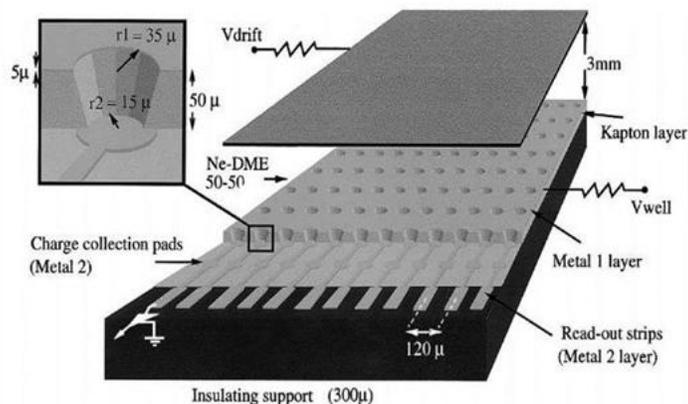
MPGD ITK: μ RGroove



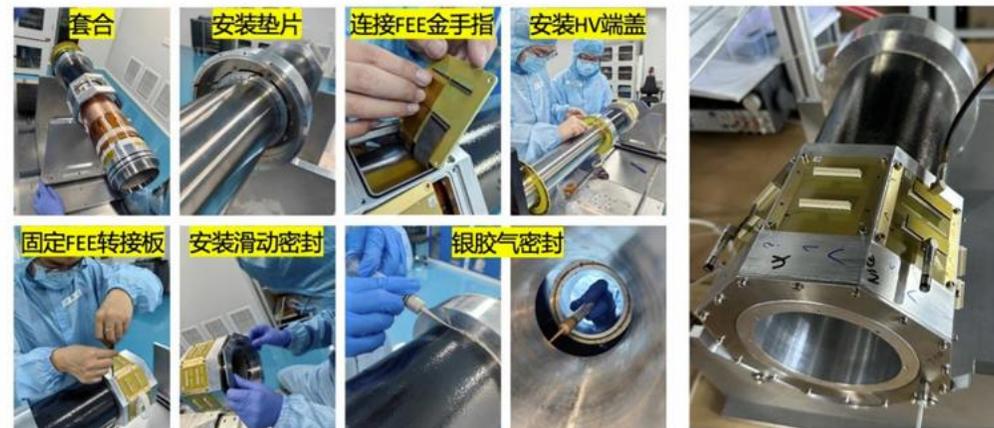
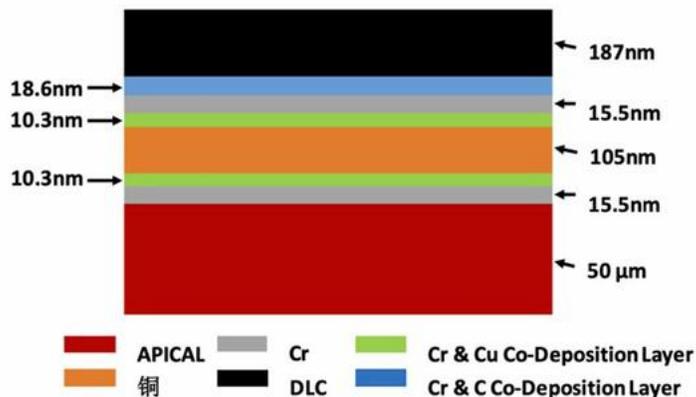
特点: 低物质量、成本低、抗辐照

挑战: 低物质量基材 \checkmark 、圆筒结构 \checkmark 、 μ TPC

WELL detector



μ RGroove provides larger signals and easier production compared to μ RWELL.

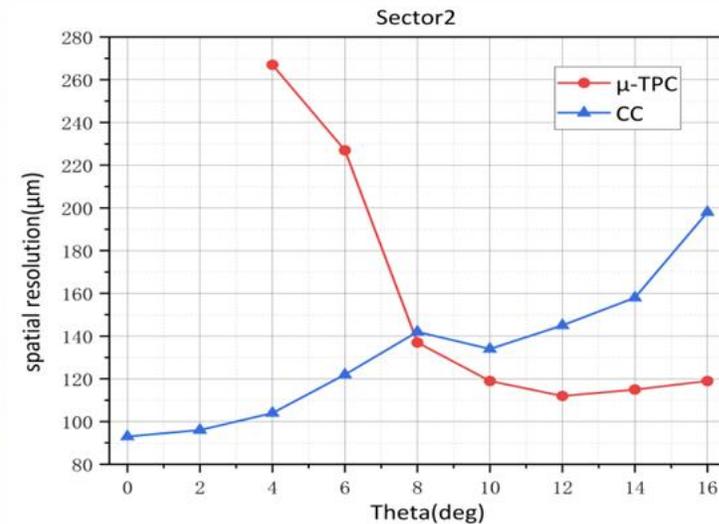
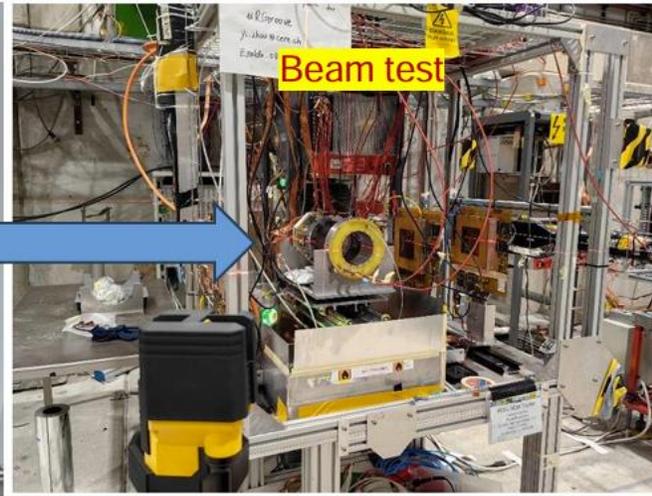
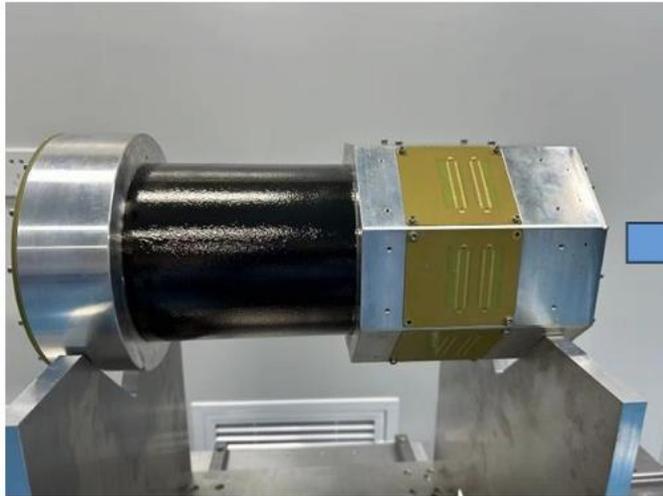
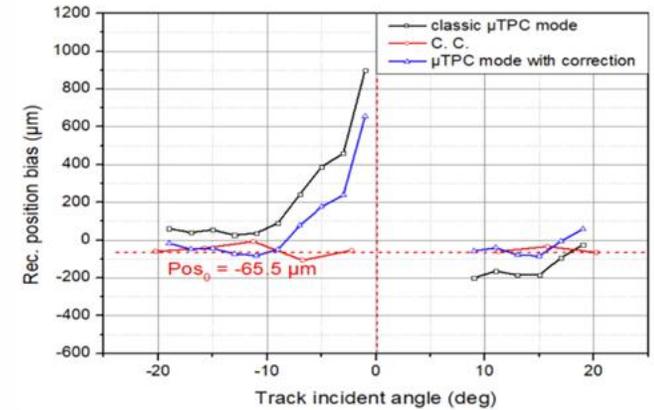
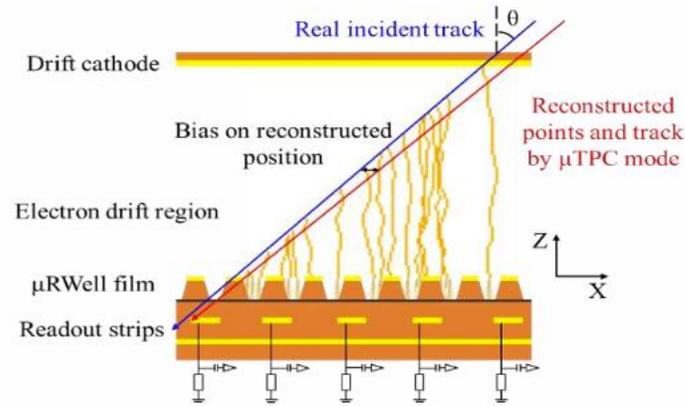


Fabricating the low mass μ RGroove prototype material budget: 0.22%/X0/layer

MPGD ITK : μ TPC mode

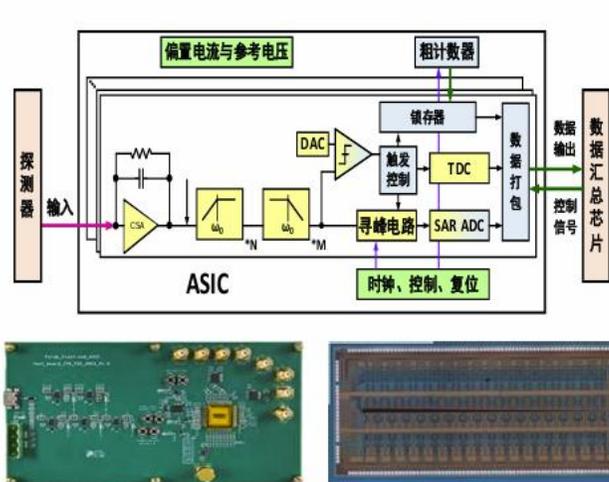


❖ Position reconstruction with μ TPC is the key to maintaining good position resolution in magnet field or for inclined tracks. The μ TPC method was thoroughly studied for systematic bias and its correction.

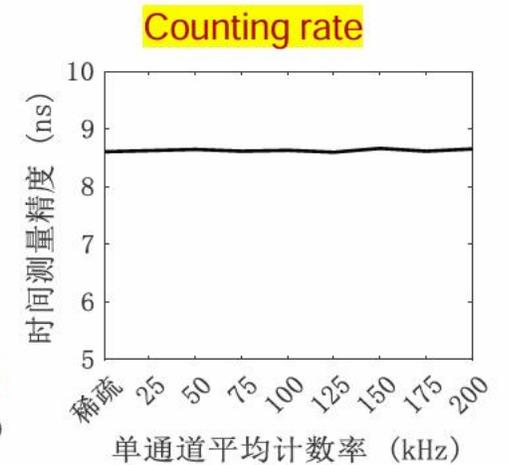
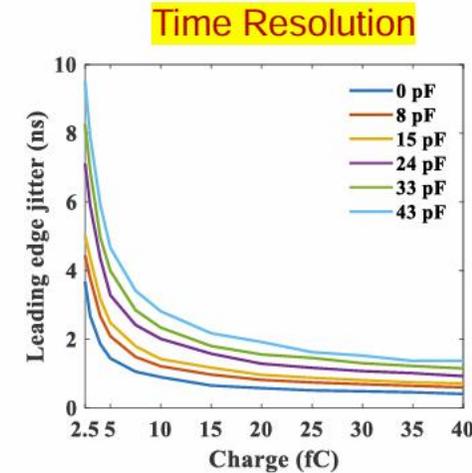


Beam test @ CERN, Position resolution better than $100\mu\text{m}$ for vertical tracks and $\sim 120\mu\text{m}$ for inclined tracks

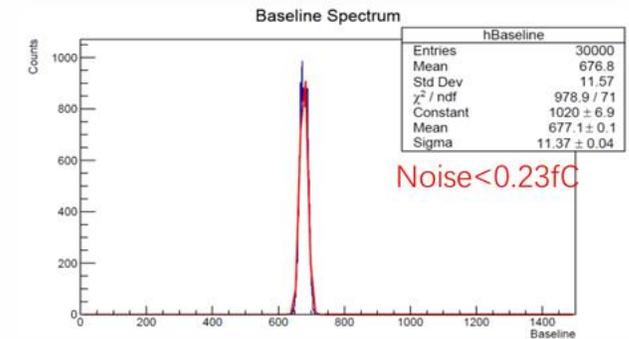
- ASIC is required for readout. Very challenging performance requirements (event rate much higher than VMM). Designed and produced a 32-channel prototype ASIC chip with full function.



ASIC Specs	Demands
Charge Range	40 fC
Charge precision	~ 1 fC RMS
Time precision	< 10 ns RMS
Max. event rate	4 MHz



- Designed and built a 1024-channel readout system based on APV25 for the purpose of testing and characterizing detector prototypes.



MAPSITK : MAPS Designs

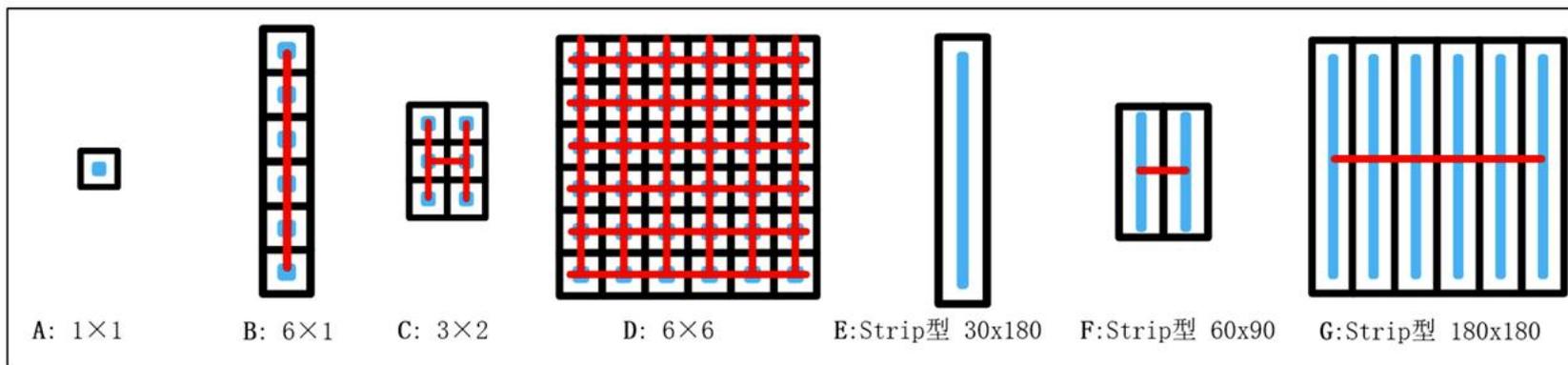


特点：抗辐照强、位置分辨率高

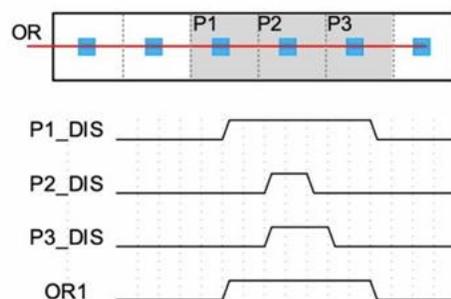
挑战：MAPS工艺、低功耗、定时等

Use larger pixel size to reduce the power consumption density

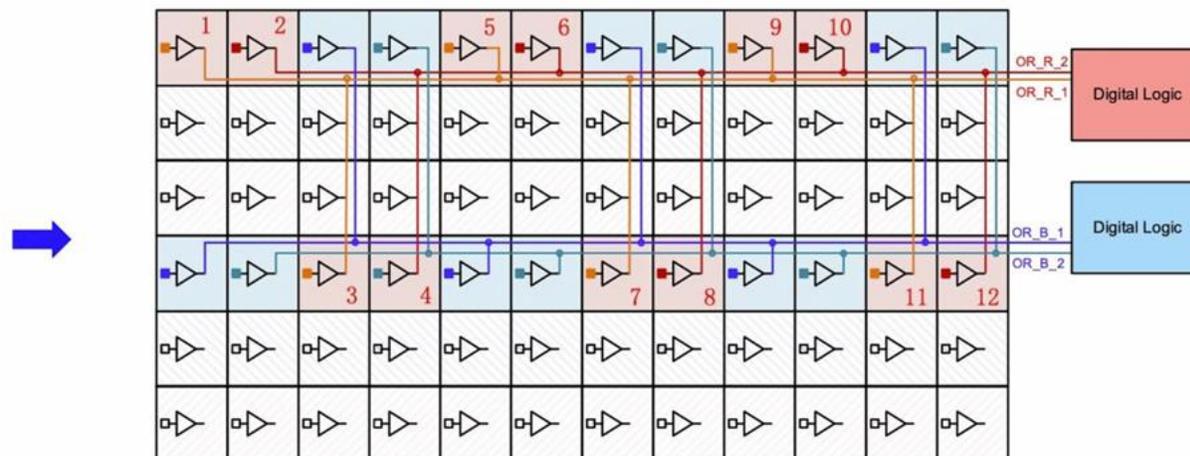
Aiming for a low-power chip design (required for a low-mass system) with timing and charge measurement capability



Combining non-adjacent pixels and designing a super-pixel design that can provide both high position and high time resolutions for low power consumption.



Combining adjacent pixels
→ ToT loss

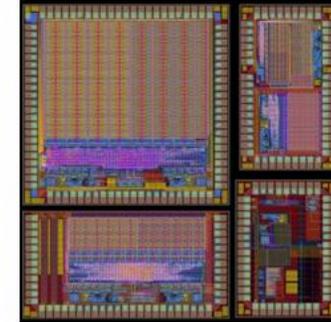


MAPSITK : MAPS Fabricating



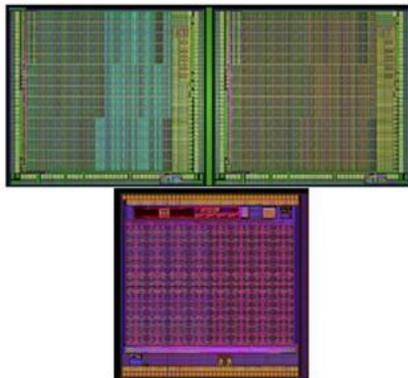
- Various CMOS processes being explored
 - Mature technology: TowerJazz 180nm (HR epi)

TowerJazz 180nm
Chips received,
testing underway

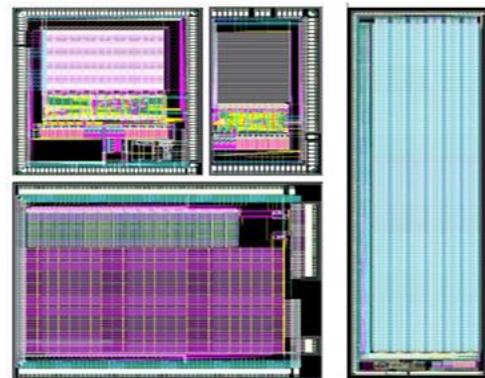


- Domestic foundries: NexChip BCIS 90nm (LR epi) , GSMC 130nm (HR substrate), IRAY 180nm (HR epi)

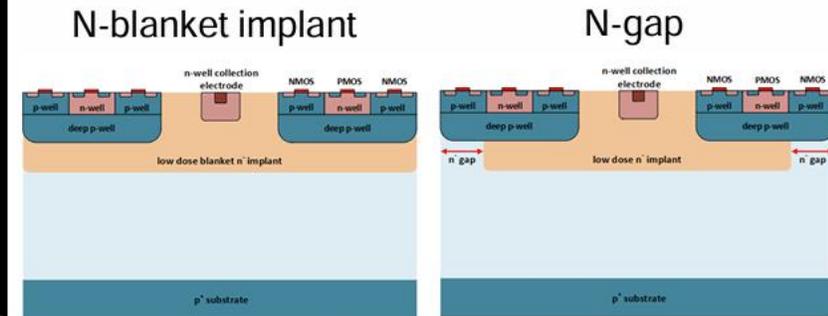
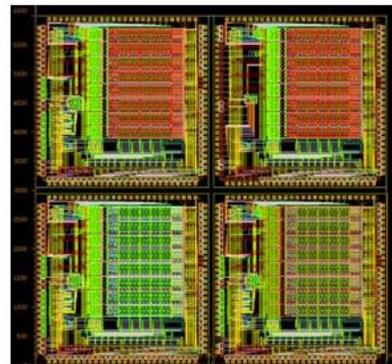
NexChip BCIS 90nm
Submitted in Jan. 2025



GSMC 130nm
Chips to be received



IRAY 180nm
Supporting quadruple-well with possibility of
N-blanket implant and N-gap. In the submission process



MAPSITK : MAPS Testing



❖ Characterized the TJ chips for threshold, noise, fake hit rate and capacitance. Tested the chips with laser and radioactive sources (Fe55 and Sr90) for detection efficiency, charge collection efficiency and time resolution.



TJ芯片

同尺寸芯片试粘接在绝缘胶上

未划片直接打线



子板背面(芯片+保护壳)

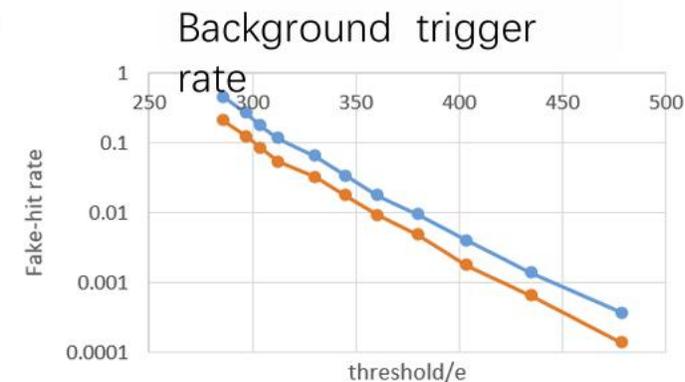


子板正面(绝缘胶挖洞)



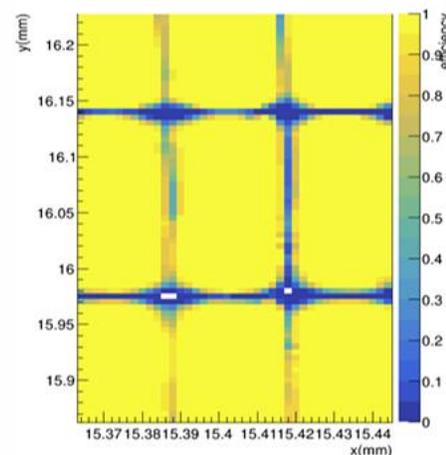
子板安装在测试转接板上

偏压/V	Threshold/e	FPN/e	TN/e	A_{OUT}/mV	基线 RMS/mV
-2	268.2	7.15	16.1	523	7.8
-3	234.7	2.75	15.3	477	9.2
-4	212.2	0.82	15.4	417	7.06
-5	178.1	5.32	11.3	348	5.92
-6	182.1	7.11	12.1	292	5.88

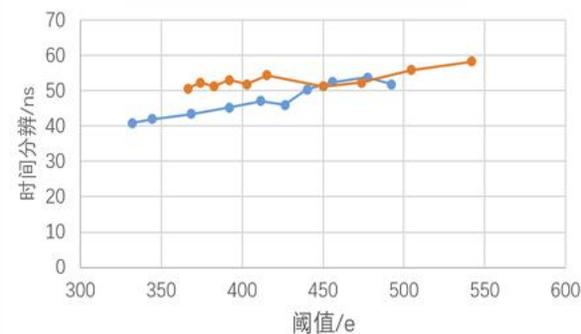


— Fake-hit unmasked(/pixel/s) — Fake-hit masked(/pixel/s)

Efficiency

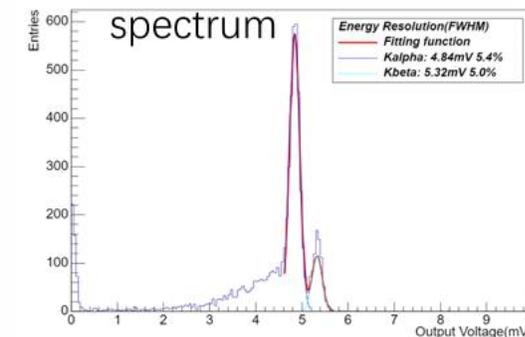


Time resolution



— pixel-based结果 — strip-based结果

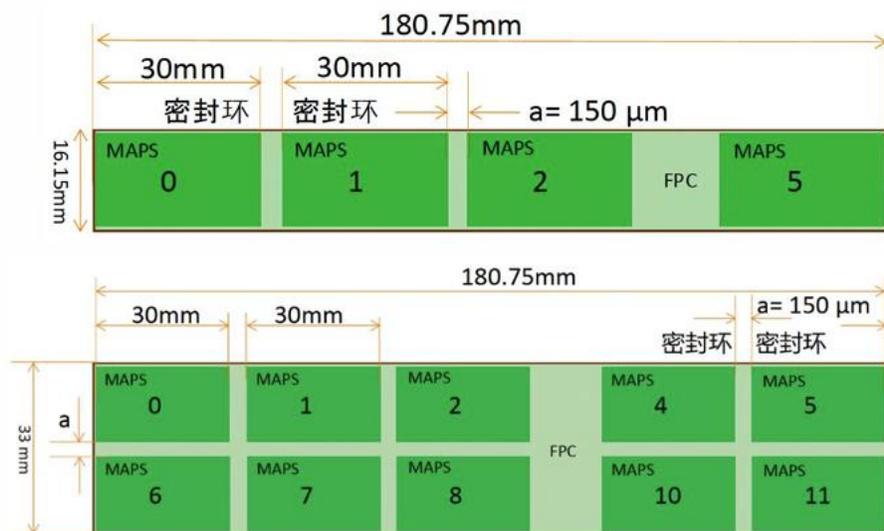
Fe55 energy spectrum



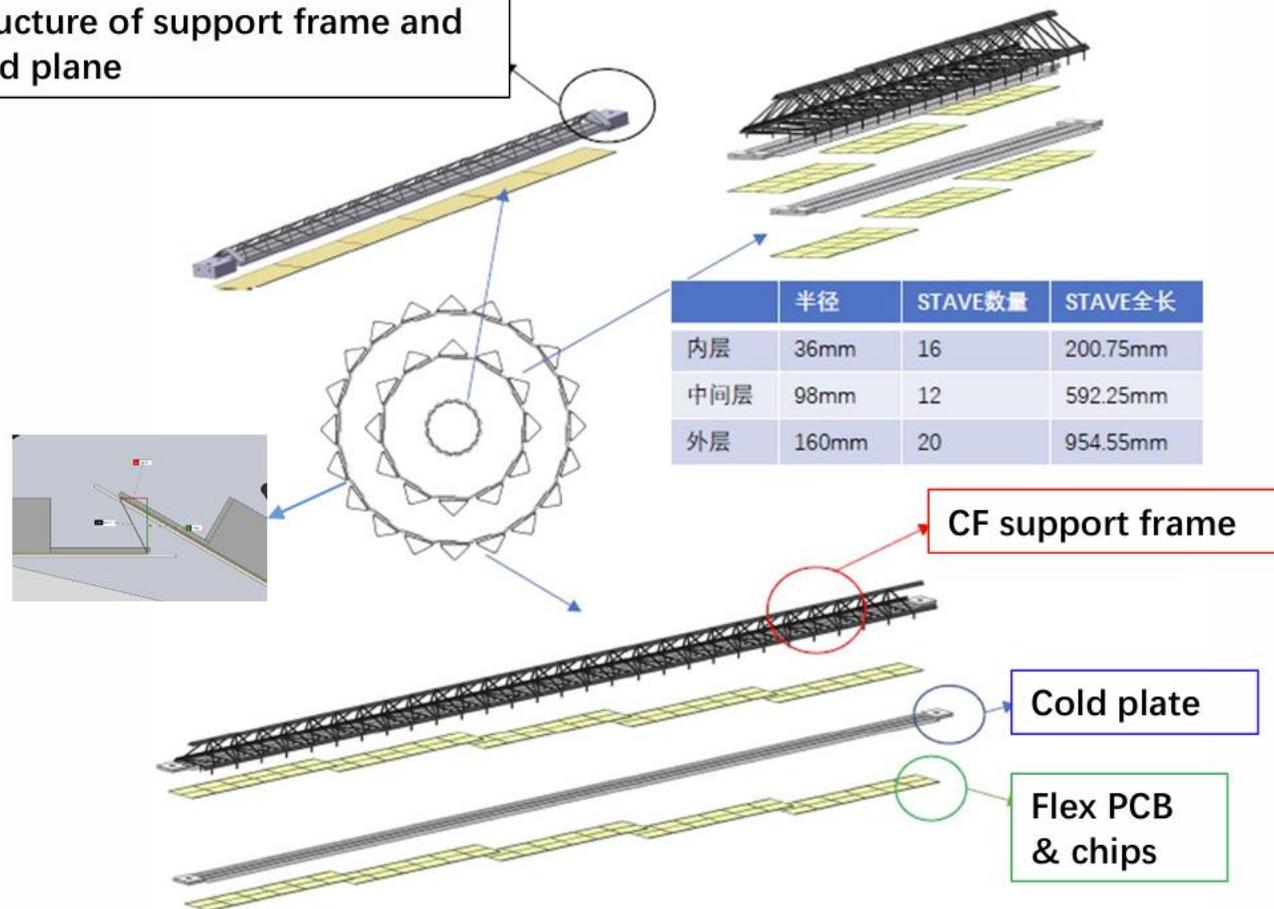
MAPSITK : Stave Design



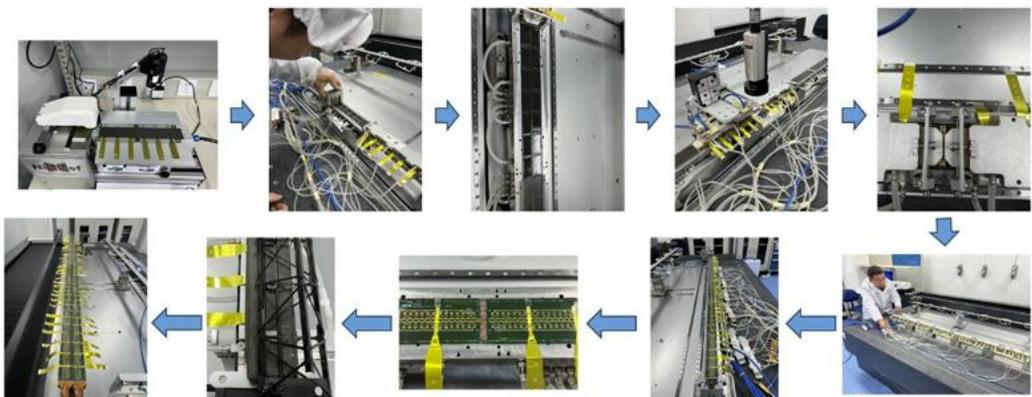
❖ Launched detector module (stave) mechanical design effort



The inner most layer: integrated structure of support frame and cold plane



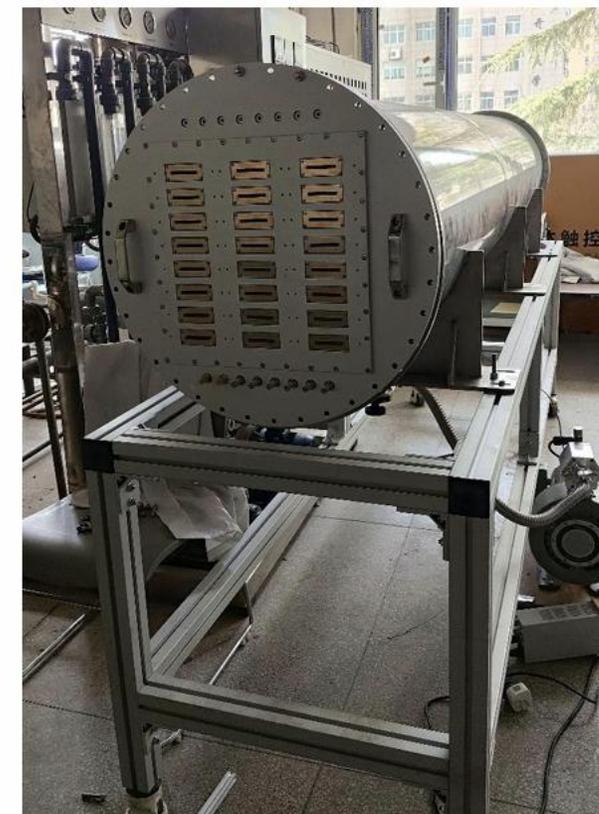
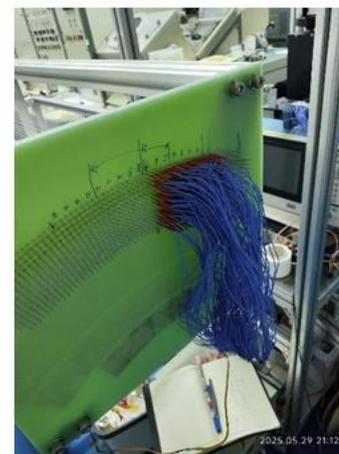
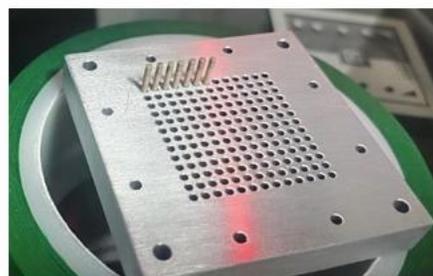
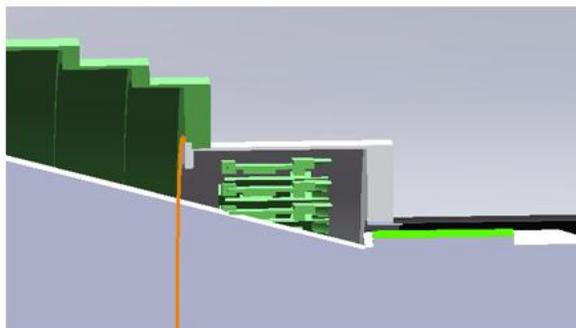
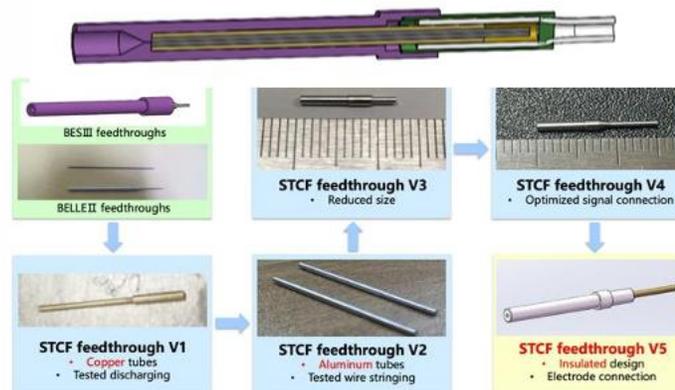
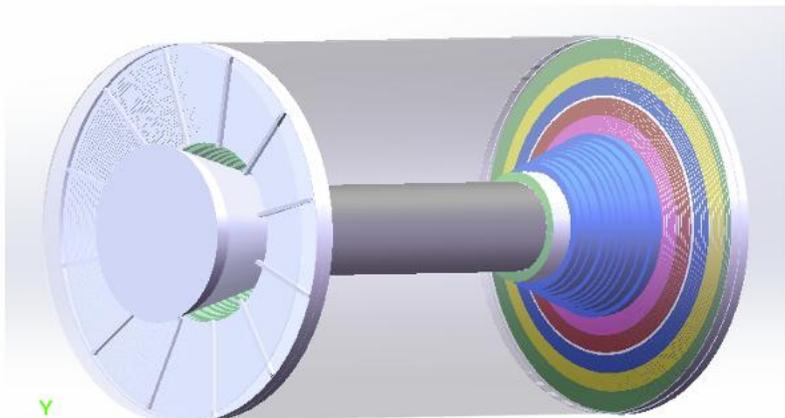
Stave assembly and integration infrastructure and experience



Main Drift Chamber : Detector

挑战：低质量、高计数率、小单元等

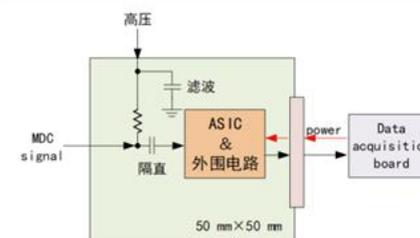
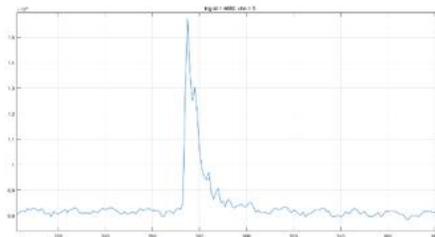
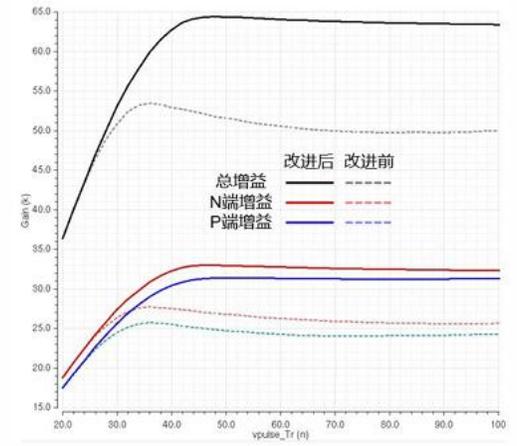
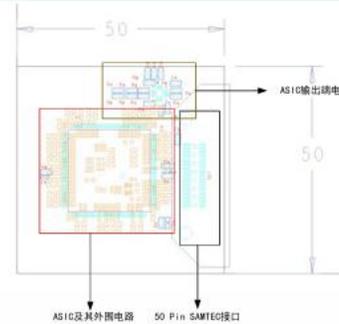
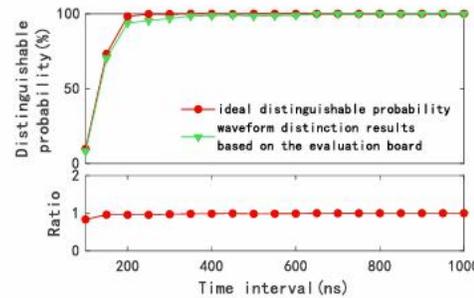
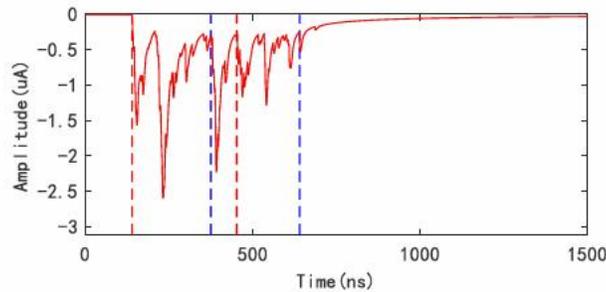
- ❖ Endplate structure optimized to simplify the assembly process
- ❖ Intensive ongoing R&D effort on feedthrough for super-small cells (~5 mm)
- ❖ A full-length super-small cell drift chamber prototype is under construction.



Main Drift Chamber : Electronics

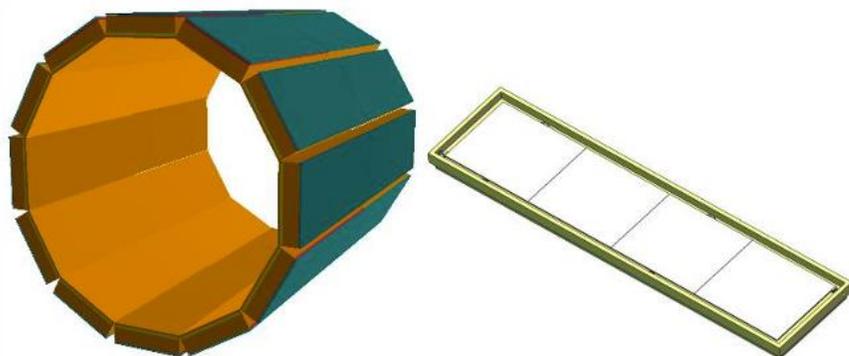


- ❖ A major challenge in MDC electronics: discriminating overlapping signal pulses (as a result of high counting rate) that are irregular in shape.
- ❖ Waveform digitizing electronics is used to allow online waveform discriminating algorithms that run on PFGA. Developed the electronics with discrete components (TIA + shaper + ADC) and tested with detector prototypes.
- ❖ ASIC design is underway. First version of the analogue part has been taped out. The chip prototype has been produced and is being tested.

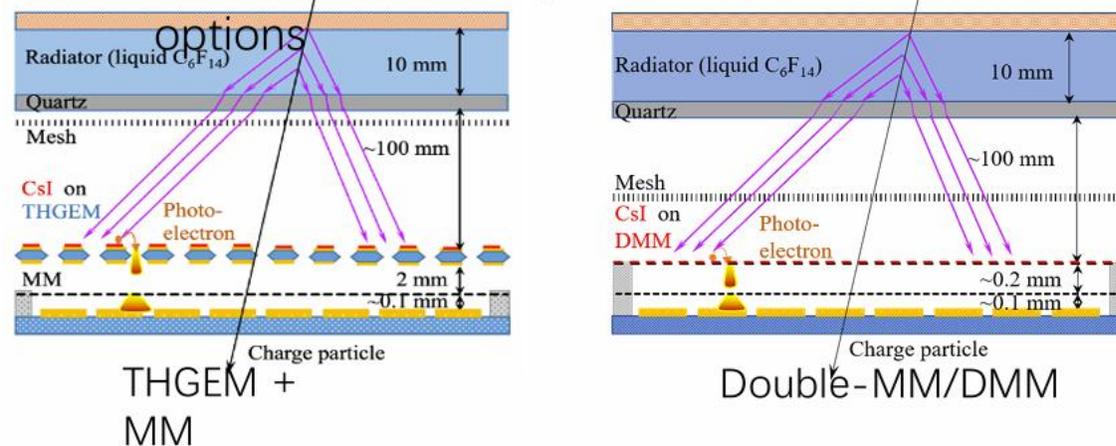


PID System

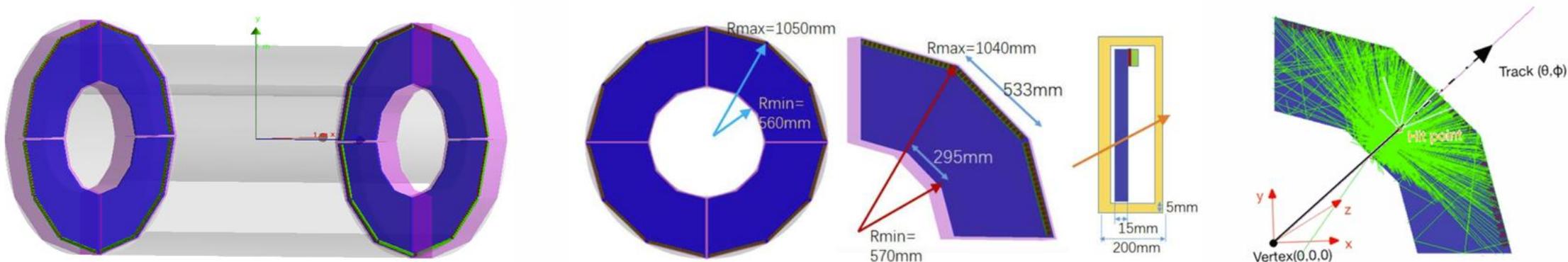
- PID system: thickness < 20cm, material budget < $0.3X_0$, $\pi/K \sim 4\sigma$ @ 2GeV
- ❖ Barrel PID: A RICH detector using MPGD with CsI for photon detection, $\sigma_\theta \sim 4$ mrad



Two MPGD-based photo detector options



- Endcap PID: A DIRC-like TOF detector, DTOF, quartz plate + MCP-maPMT, $\sigma_t \sim 30ps$



PID Barrel : RICH



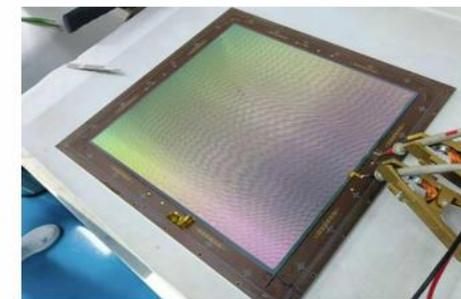
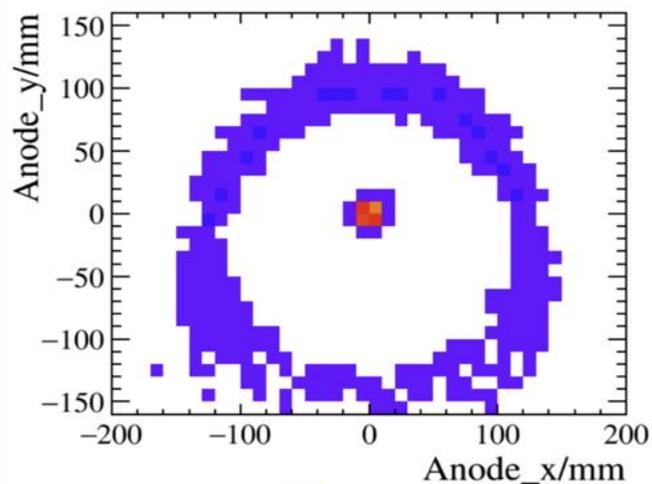
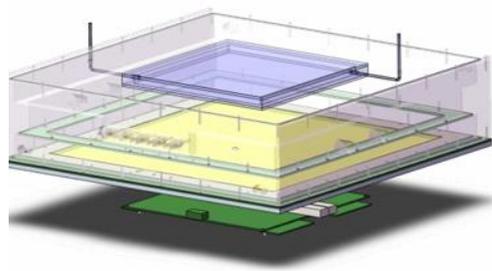
特点: 大面积单光电子探测 **挑战:** 大面积气体探测器、紫外单光电子探测、读出电子学等

Cosmic-ray test of a $32 \times 32 \text{ cm}^2$ RICH prototype with THGEM + MM



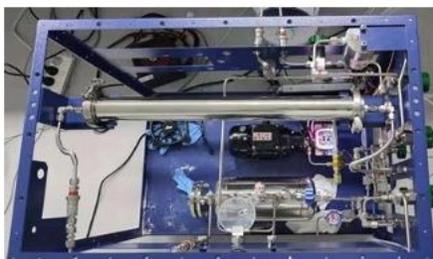
Moved to DMM option : DMM-RICH

- Compact structure
- High gain & good time resolution
- High electron collection efficiency & low ion backflow

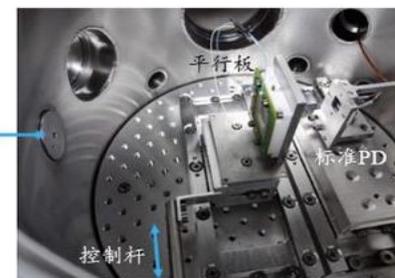
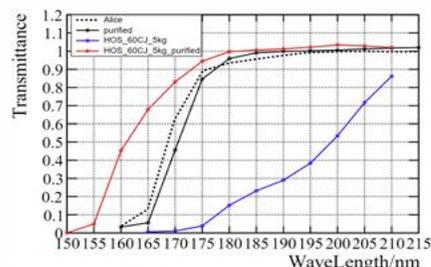


Ongoing test of a DMM-RICH prototype

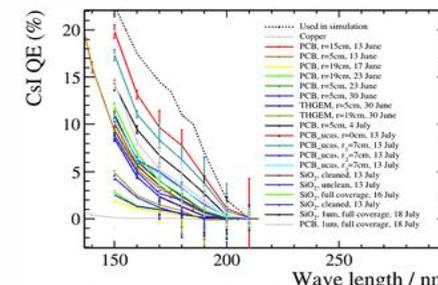
Ongoing efforts to bring up the photoelectron yield



Enhancing radiator transparency by purifying C_6F_{14}



Improving QE: CsI coating and QE measurement

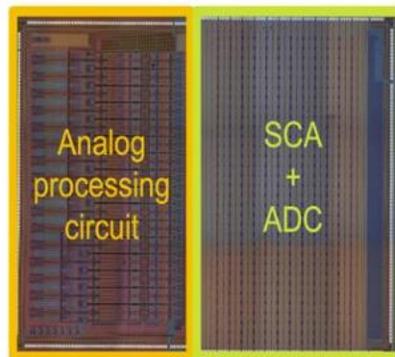
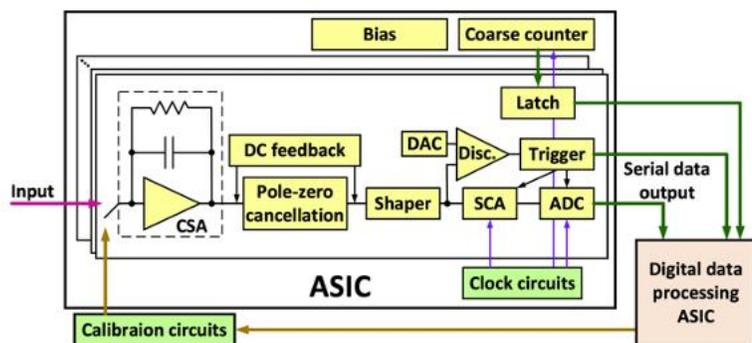


RICH Readout ASIC

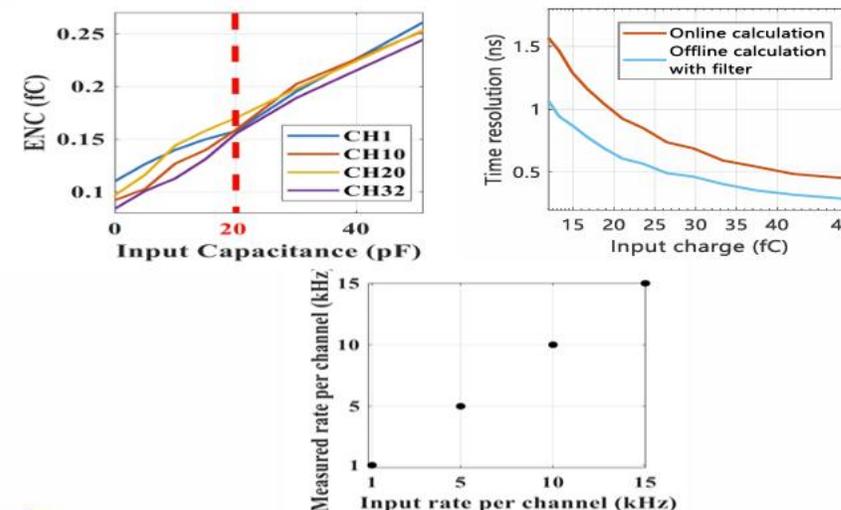


- A large number of readout channels in high density: ~500 k, 5×5 mm² granularity, requiring ASIC

Design specs: $\sigma_t < 1\text{ns}$ @20fC&20pF,
event rate ~ 30 kHz, 32-64 channels



Test results



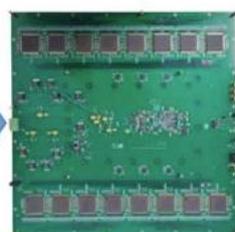
RICH ASIC design evolution

First version



32 channels/chip

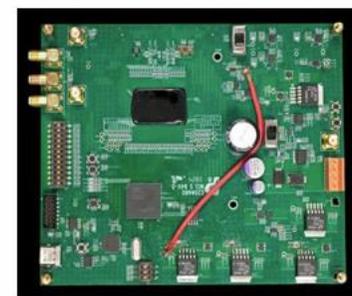
Second version



512-channel readout board
using the 32-ch ASIC



Third version



64 channels/chip



1024-channel readout board
being developed

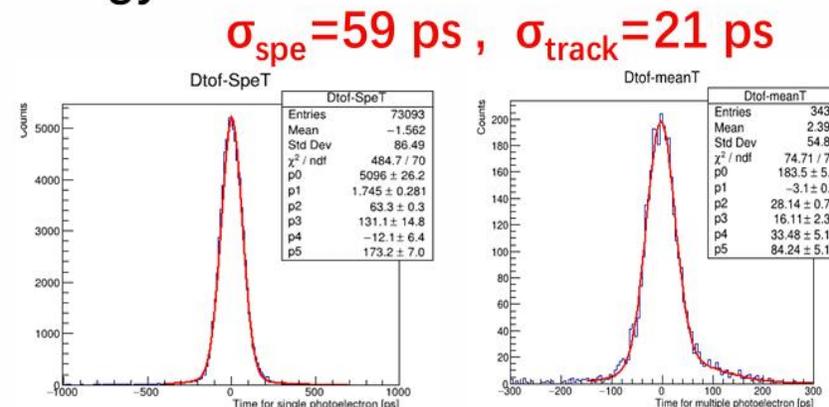
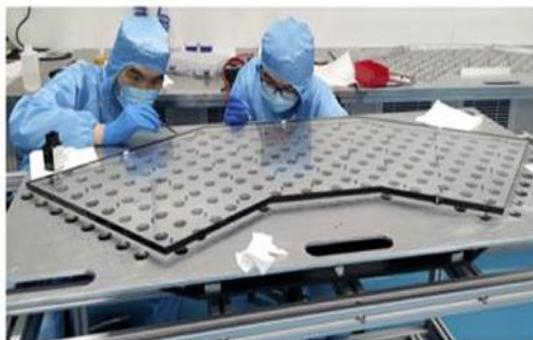
PID Endcap: DTOF



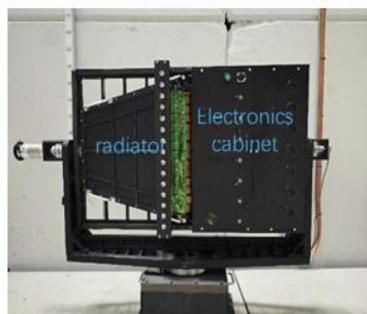
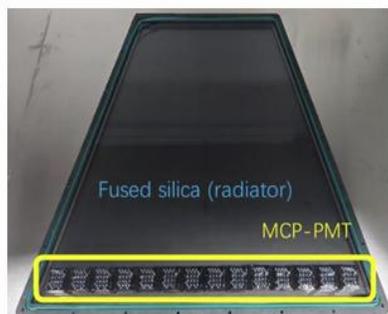
特点: 高精度时间探测

挑战: 大面积石英辐射体加工、多阳极光电倍增管等

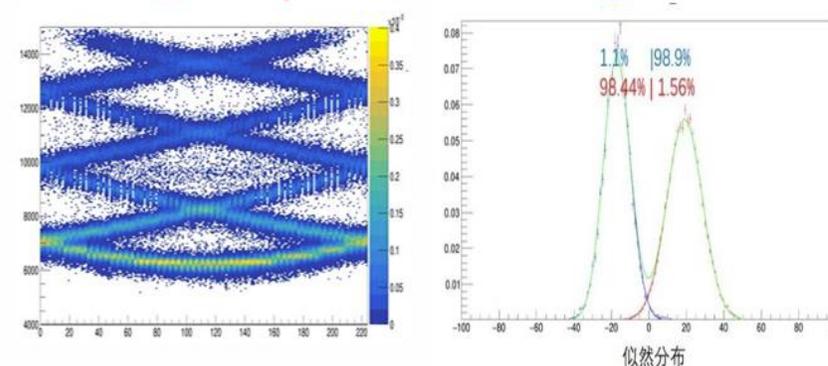
- A full-size DTOF prototype (a quadrant of STCF DTOF at one endcap) was built and tested with cosmic-rays to demonstrate the DTOF concept and technology on the full scale.



- A smaller DTOF prototype a third the size of the quadrant was built and tested with particle beams at CERN to demonstrate the PID capability of the DTOF detector



π/K separation $> 4\sigma$ @



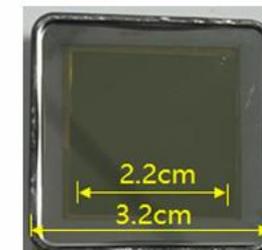
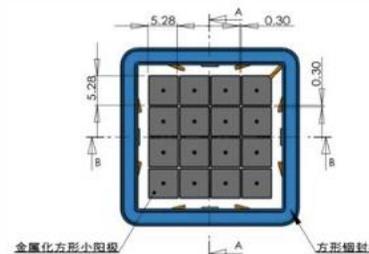
MCP-maPMT and Readout ASICs



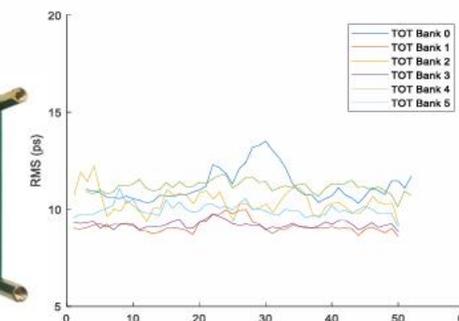
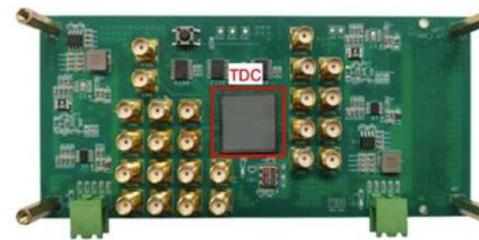
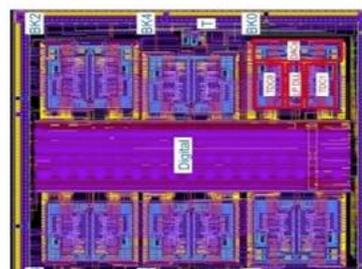
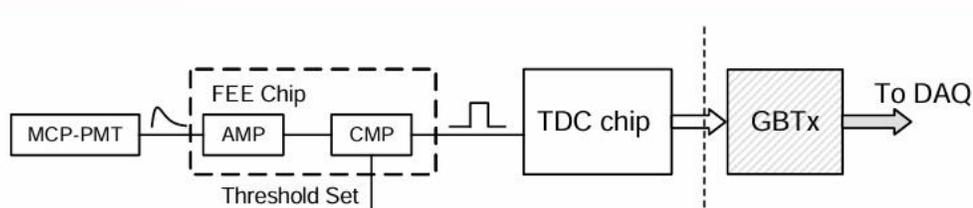
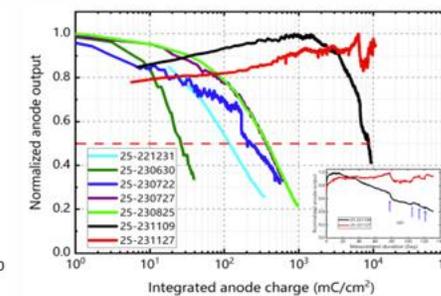
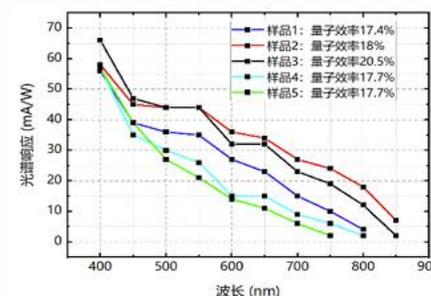
- MCP-maPMT: a critical component of the DTOF technology
- Intensive R&D on techniques (ALD and electron scrubbing) to produce long-life MCP-PMT (target $Q > 10 \text{ C/cm}^2$).
- Designed and produced 1-inch MCP-maPMT prototypes with 16 annodes each.
- Carried out various tests of the MCP-maPMT prototypes
 - $TTS < 40 \text{ ps}$, $QE > 20\%$, $G > 10^6$,
 - Aging : $< 10\%$ gain drop when $Q > 11 \text{ C/cm}^2$

Two ASICs designed for MCP-maPMT readout. Prototype chips produced and tested

- FET: target $\sim 15 \text{ ps}$, measured $\sim 15 \text{ ps}$
- TDC: target $\sim 15 \text{ ps}$, measured $\sim 10 \text{ ps}$



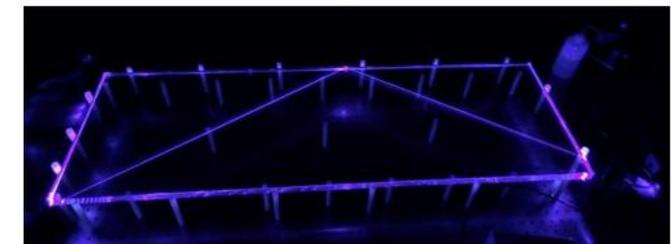
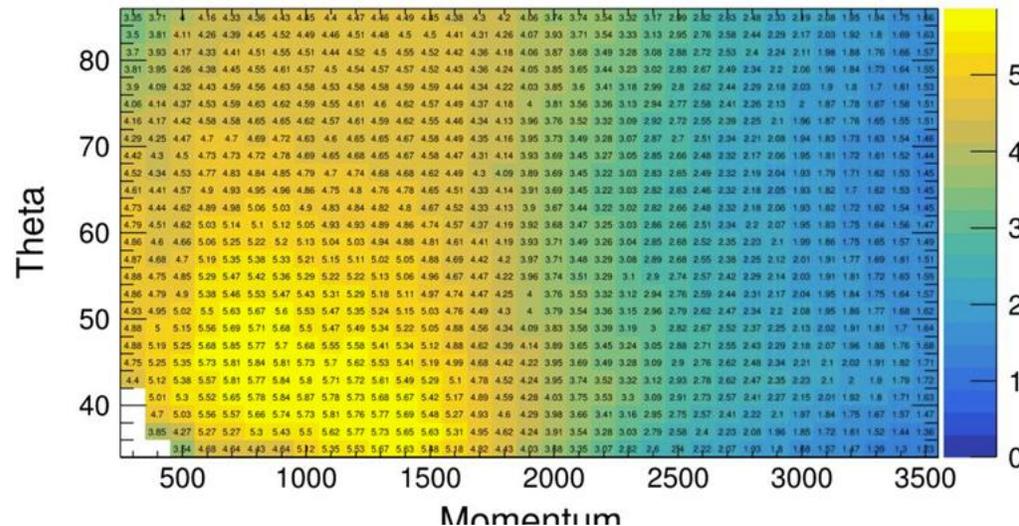
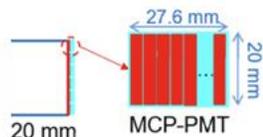
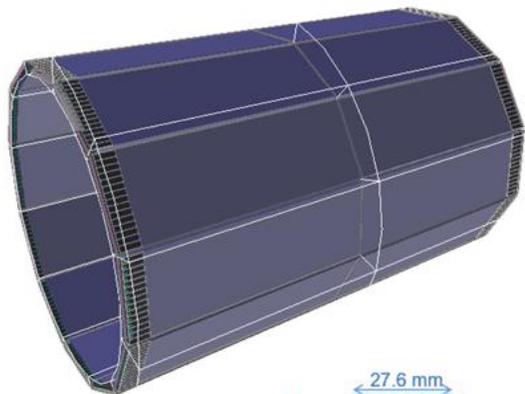
MCP-PMT编号	25-240507	25-240521	25-240605	25-240620
MCP类型	ALD-MCP, ALD镀膜厚度: D2			
MCP厂家	厂家1	厂家1	厂家2	厂家2
MCP电子清刷剂量	0.75 $\mu\text{A}\cdot\text{h}/\text{cm}^2$	0.87 $\mu\text{A}\cdot\text{h}/\text{cm}^2$	0.75 $\mu\text{A}\cdot\text{h}/\text{cm}^2$	0.87 $\mu\text{A}\cdot\text{h}/\text{cm}^2$



BTOF : DTOF in Barrel



- **Design of a barrel PID detector based on the DTOF technology is available (BTOF)**
 - 12 sectors with 2 modules placed longitudinally in each sector, 24 quartz plates in total
 - Quartz plate parameters : R = 875mm H = 20mm L = 1350mm D = 450mm
 - Inner side of a quartz plate is coated with light absorbing layer while the outer side is equipped with 15 SiPMs for readout
- **Performance with full simulation mostly meets PID requirements. Ongoing effort to optimize the design by scanning a variety of key parameters**
- **A full-length BTOF prototype is under construction and will undergo a beam test**



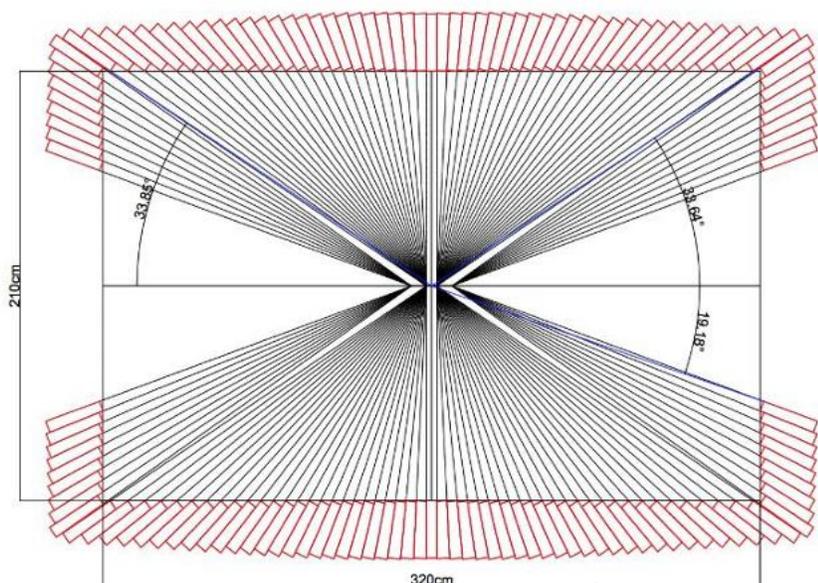
Electro-Magnetic Calorimeter



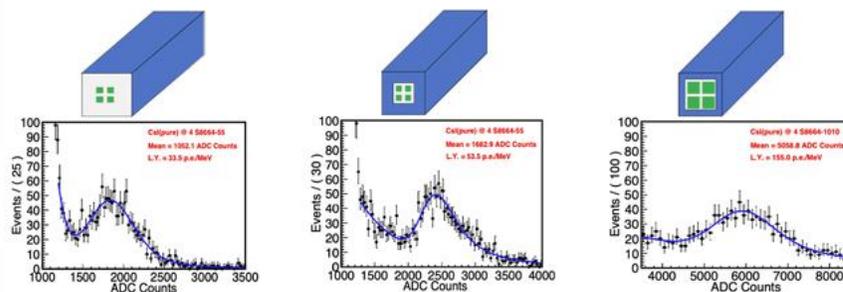
特点: 快时间响应, 高能量分辨 **挑战:** CsI光产额, 事例堆积及时间提取等

■ A crystal calorimeter using pCsI (short decay time of 30ns) to tackle the high background rate (~1 MHz/crystal)

- Crystal size: 28cm ($15X_0$), $5 \times 5 \text{cm}^2$
- Defocused layout: 6732 crystals in barrel, 1938 crystals in endcaps
- 4 large area APDs to address low light yield: $4 \times (1 \times 1 \text{cm}^2)$



A very low light yield of 3.6% for pCsI → a major R&D task : enhance the light yield of a pCsI unit

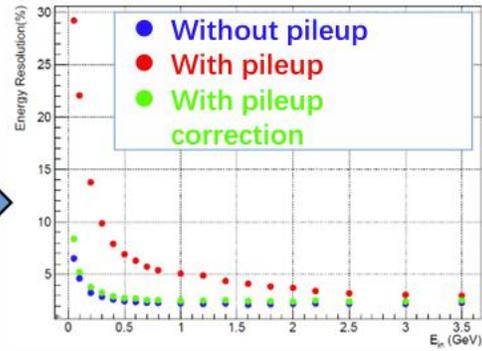
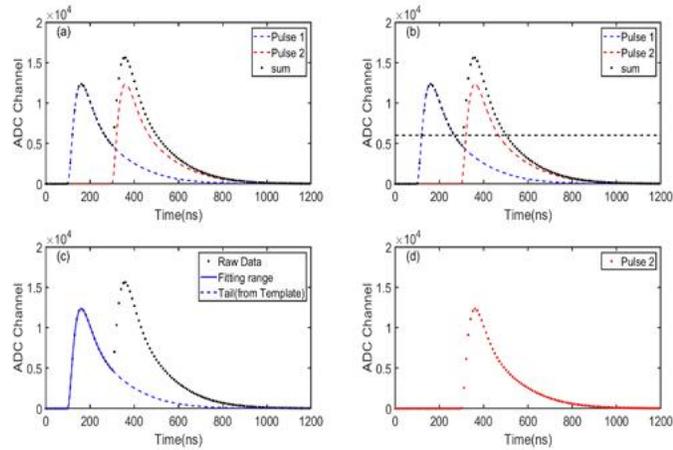


Light yield : 50 p.e./MeV → 300 p.e./MeV

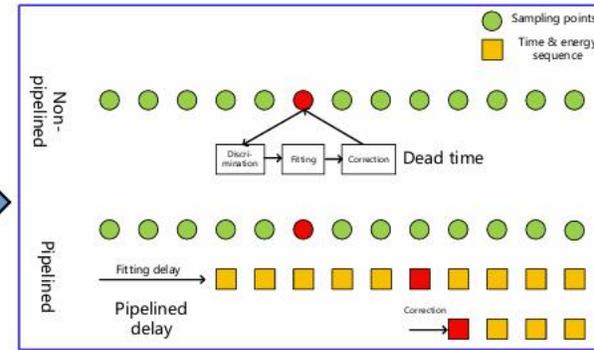


EMC : Pileup Mitigation and Electronics

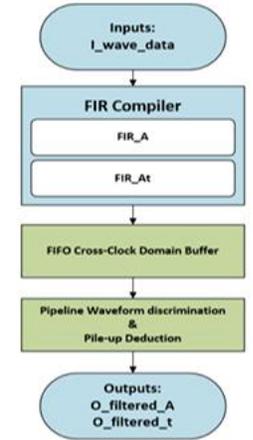
- Significant pileup in EMC in the presence of beam background (~ 1 MHz/ch). A dead-time free pileup correction algorithm involving waveform fitting based on pipelined optimal filtering has been developed and implemented in FPGA



Very effective in mitigating the pileup effect

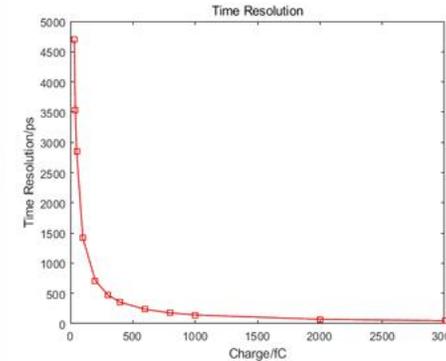
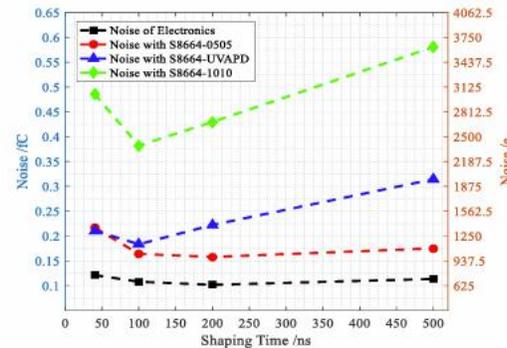


Pipelined correction algorithm



FPGA implementation

- Development of waveform digitization electronics (CSA + shaper + ADC)



Dynamic range
3 MeV \sim 3 GeV
ENE : \sim 0.5 MeV
Time resolution
< 150 ps@1GeV

5x5 pCsl EMC Prototype



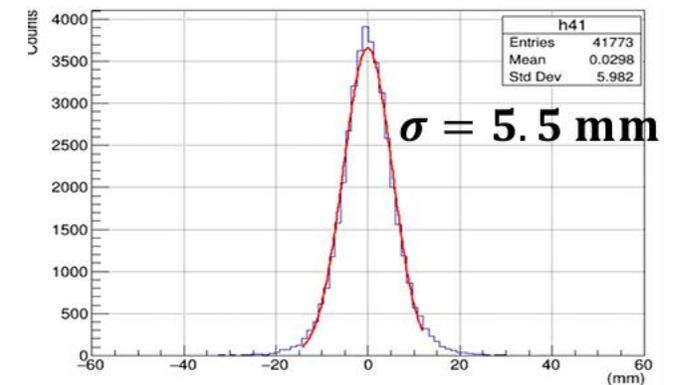
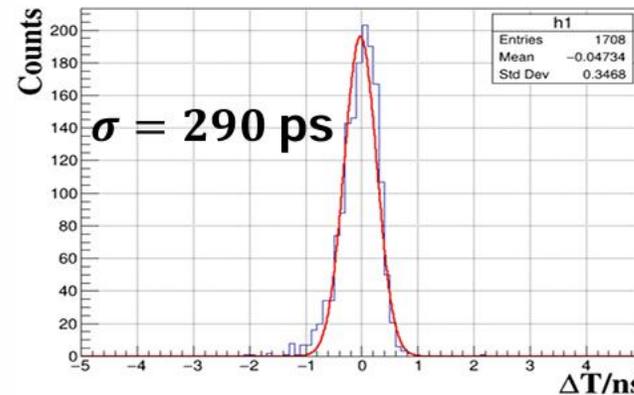
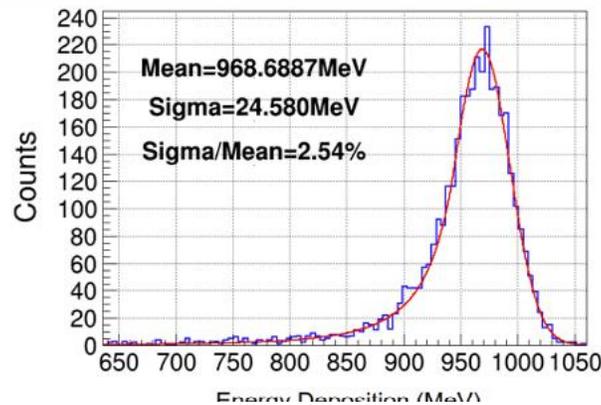
EMC prototype in the making



Beam test at CERN PS

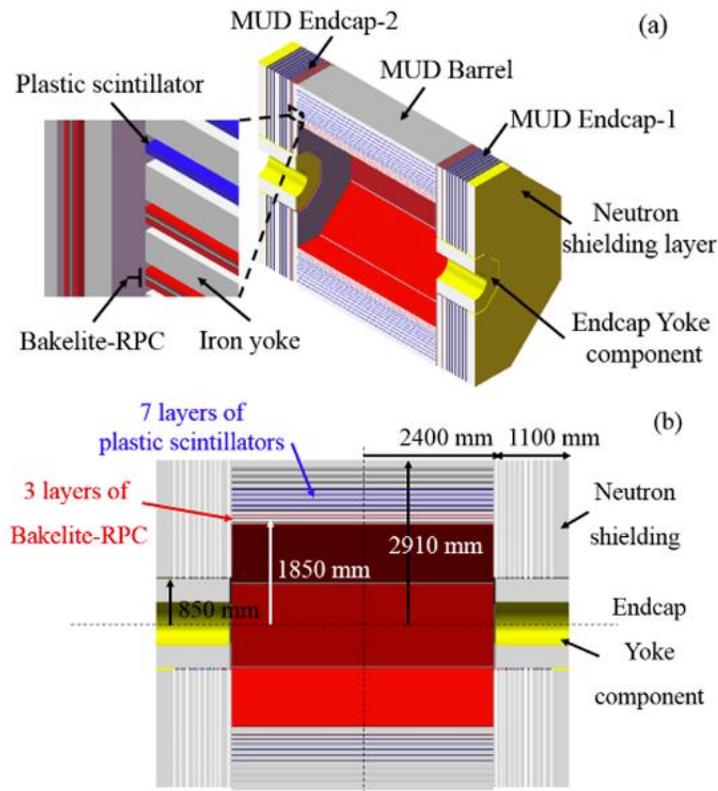


Performance from the beam test with 1 GeV/c electrons



特点: 提供muon和中性强子鉴别 **挑战:** 两种类型探测器的研发及优化

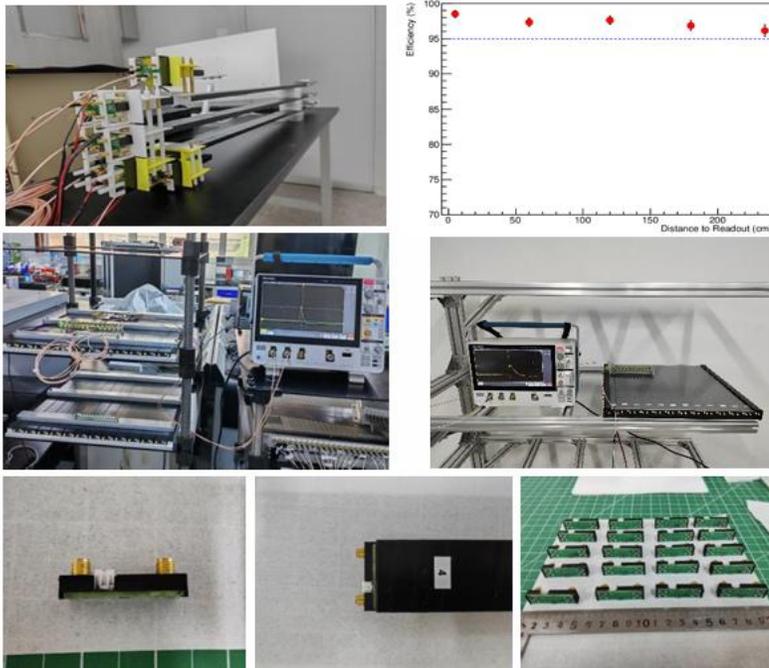
- A hybrid design with RPC and scintillator strips for optimal overall muon and neutral hadron identification performance
 - RPC for inner 3 layers : not sensitive to background
 - Scintillator for outer 7 layers: sensitive to hadrons



Parameter	Baseline design
R_{in} [cm]	185
R_{out} [cm]	291
R_e [cm]	85
L_{Barrel} [cm]	480
T_{Endcap} [cm]	107
Segmentation in ϕ	8
Number of detector layers	10
Iron yoke thickness [cm]	4/4/4.5/4.5/6/6/6/8/8 cm
	($\lambda=16.77$ cm)
Solid angle	Total: 51 cm, 3.04λ
	79.2% $\times 4\pi$ in barrel
	14.8% $\times 4\pi$ in endcap
	94% $\times 4\pi$ in total
Total area [m ²]	Barrel ~717
	Endcap ~520
	Total ~1237

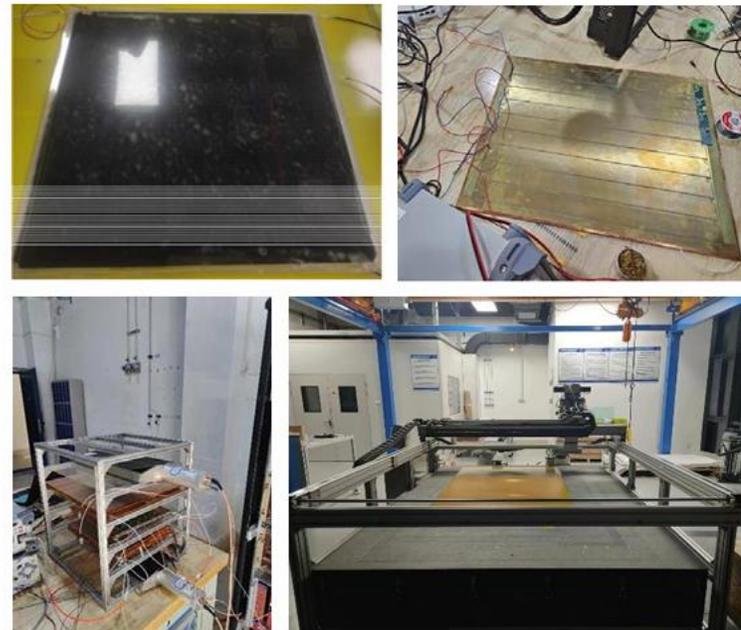
Scintillator strip + WLS + SiPM

- Design and fabrication of the scintillator unit : reflector, fiber groove, optical coupling, surface processing.
- Fabricated 2.4 long scintillator units (efficiency > 95%) and a 50×50 cm² scintillator strip array



Glass RPC

- Developed glass RPC fabrication techniques and built a 40×40 cm² glass prototype.
- Focusing on low-resistivity glass RPC for high count rate capabilities. Built some small prototypes.



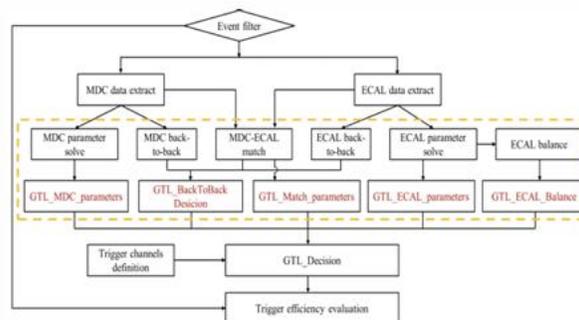
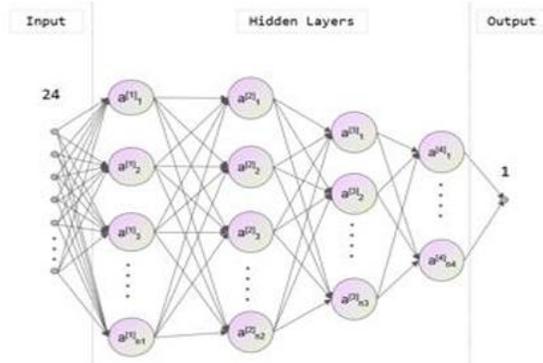
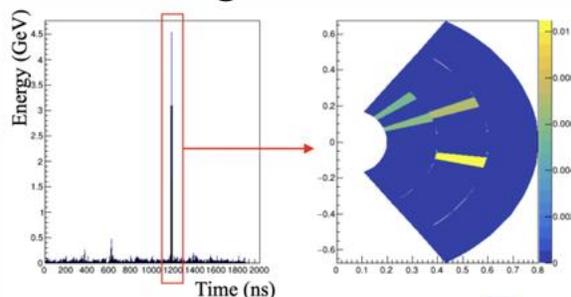
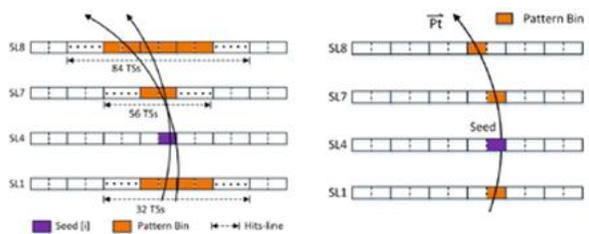
Readout Electronics

- Developed front-end amplifiers and readout boards. Tested with detector prototypes.
- Designed front-end ASICs for different input capacitance and gains. Prototype chips being tested



Trigger : Algorithms Studies and Development

- STCF trigger scheme : L1 (MDC, ECAL and global trigger) + HLT
- L1-MDC trigger algorithms: 2D track reconstruction (track finding and parameters (pt, θ , ϕ , t) estimation) , pattern matching , 2D short-track reconstruction incorporating stereo layers using NN, Z impact parameter estimation using NN
- L1-ECAL trigger algorithms : overlapping events resolving, cluster reconstruction and splitting (E, θ , ϕ , t)
- L1 global trigger : track and cluster matching, event T0 estimation, trigger menus for charged and neutral channels
- HLT : currently focusing on MDC HLT aiming to remove noise hits and reduce event size



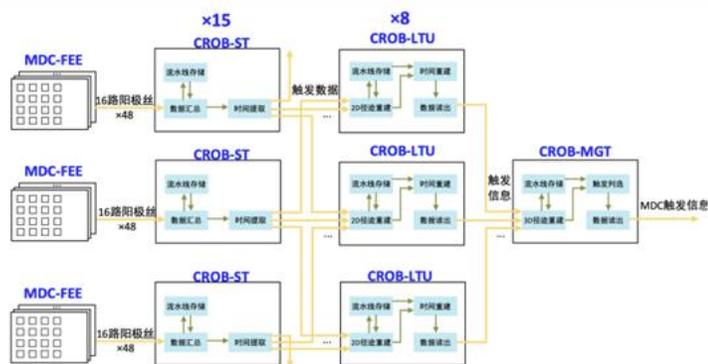
Background trigger rate < 50 kHz

Trigger channel	Physics signal	Energy point	Background trigger rate(kHz)	Signal trigger rate
带电道	$e^+e^- \rightarrow \pi^+\pi^-J/\psi; J/\psi \rightarrow e^+e^-$	4.26GeV		99.7%
	$e^+e^- \rightarrow \pi^+\pi^-J/\psi; J/\psi \rightarrow \mu^+\mu^-$	4.26GeV		99.8%
	$e^+e^- \rightarrow \tau^+\tau^-$	4.26GeV		98.2%
	$e^+e^- \rightarrow \pi^+\pi^-J/\psi; J/\psi \rightarrow \Lambda \bar{\Lambda}$	3.097GeV		99.0%
	$e^+e^- \rightarrow \pi^+\pi^-J/\psi; J/\psi \rightarrow \Xi \bar{\Xi}$	3.097GeV	43.3	99.1%
	$e^+e^- \rightarrow K^+K^-J/\psi; J/\psi \rightarrow l^+l^-$	4.682GeV		100%
	$e^+e^- \rightarrow D_s^+ D_s^-$	3.773GeV		100%
	$e^+e^- \rightarrow D^+ D^-$	3.773GeV		100%
	$e^+e^- \rightarrow D_s^+ D_s^-$	4.04GeV		100%
	$J/\psi \rightarrow$ inclusive	3.097GeV	46.6	97.7%
中性道	$J/\psi \rightarrow$ gam invisible	3.097GeV		99.7%
	$e^+e^- \rightarrow n \bar{n}$	3.097GeV	39.4	97.6%
	$e^+e^- \rightarrow$ gam n \bar{n}	3.097GeV		99.7%
亮度监测道	$e^+e^- \rightarrow$ gam n \bar{n} (ISR)	3.713GeV		93.1%
	RBB	4.26GeV		98.4%

Trigger : Hardware Development



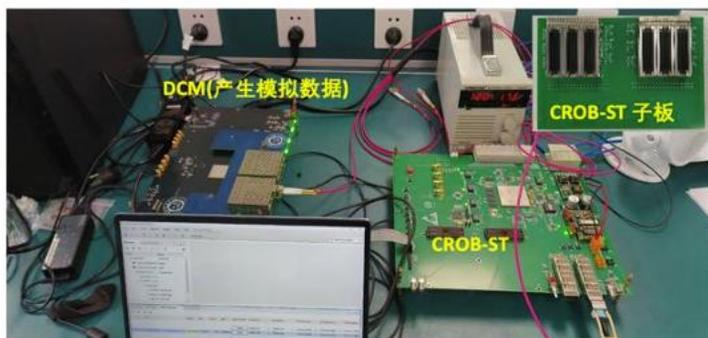
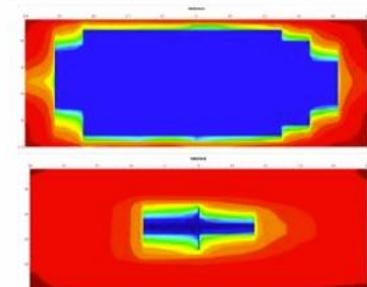
- Design of trigger hardware architecture. Development of various core trigger hardware components (CROB-ST, CROB-LTU, CROB-MGT/EGT, CTM, FMC ...). FPGA implementation of L1 trigger algorithms.
- A prototype L1 trigger system has been designed and is being built to demonstrate the trigger system design and its performance. An event simulator has been developed to generate pseudo data for the prototype trigger system.
- The prototype system will participate in the upcoming combined beam test.



CROB-LTU板卡调试及机箱测试



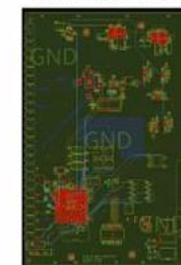
FMC 不同带宽眼图 (上: 5Gbps; 下: 10Gbps)



数据产生板机箱测试

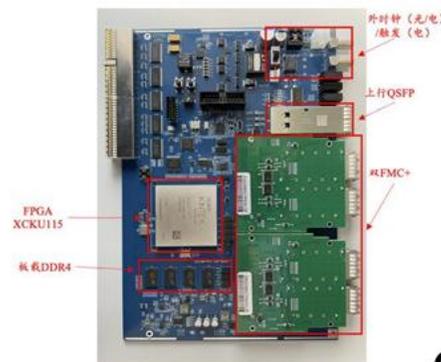


CTM板PCB图



- ❖ System architecture based on Data-Matrix: flow processing, hetero-computing, standard interfaces and protocols, global pipeline
- ❖ Software and firmware development
- ❖ Development of core electronics boards: CROB-PXI, CROB-PCIe, FMCP optical interface board
- ❖ System testing and performance evaluation using simulation data

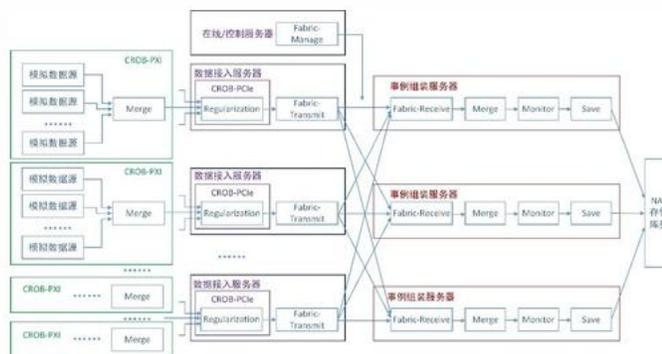
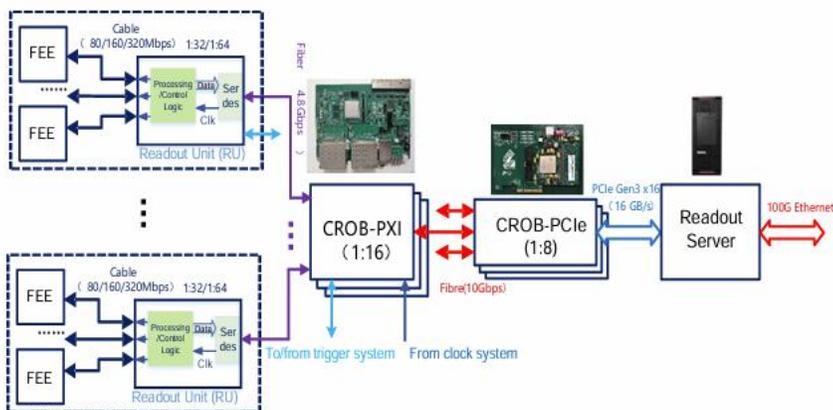
CROB-PXI board



FMCP optical interface board



CROB-PCIe board

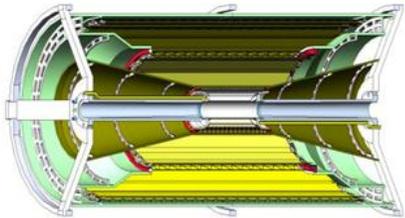


Test of event building

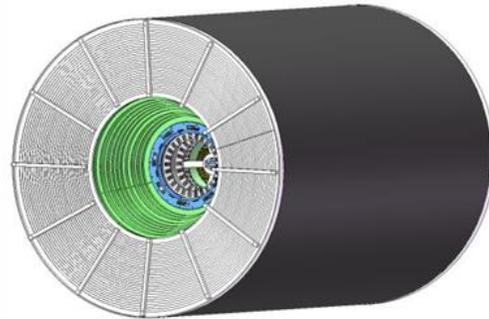
- 12 rack servers
 - 9 servers: readout+ 4 event builders
 - 3 servers: 4 event builders
- 33 simulated data sources
 - 17 big-frame sources: 20~32kB/frame
 - 16 small-frame source: 135 Byte/frame

- Detector conceptual design has been transferred into engineering drawings
- Engineering design available for each sub-detector or system
- Design studies on detector assembly and installation

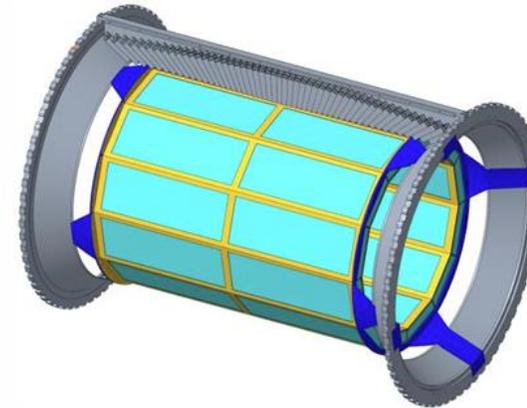
ITK-MAPS



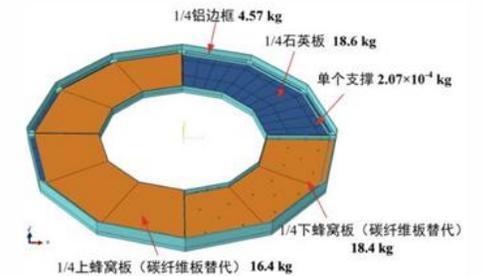
MDC



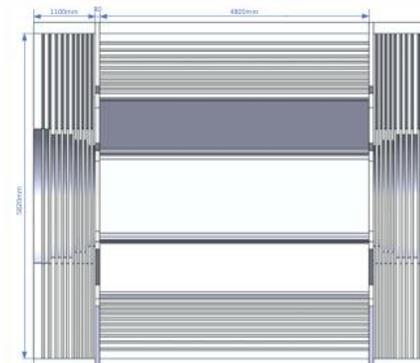
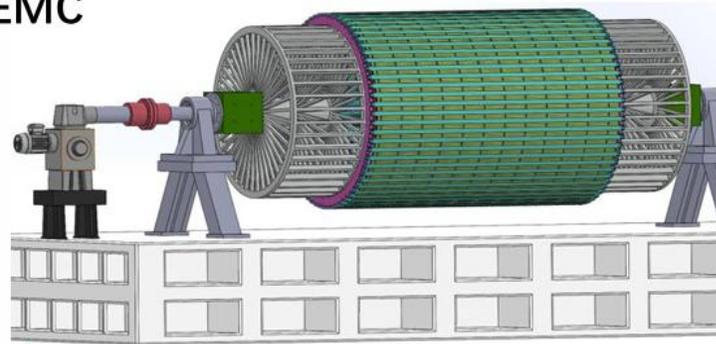
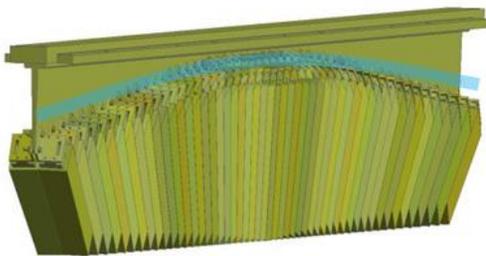
RICH



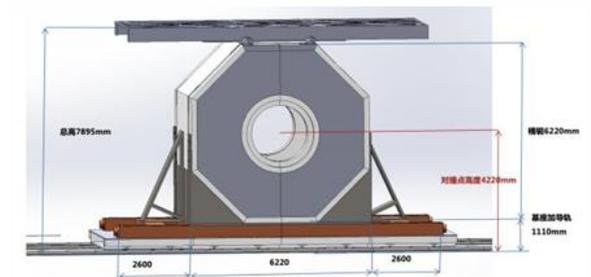
DTOF



EMC



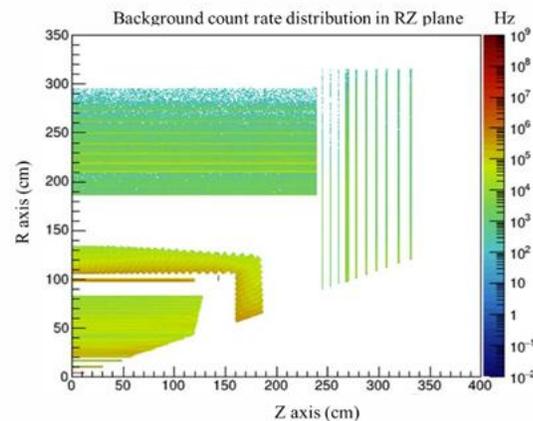
Iron Yoke



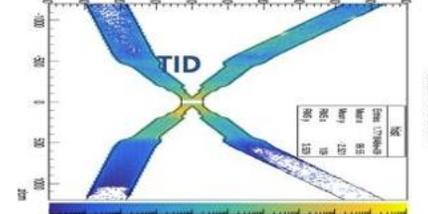
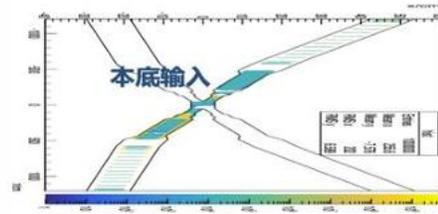
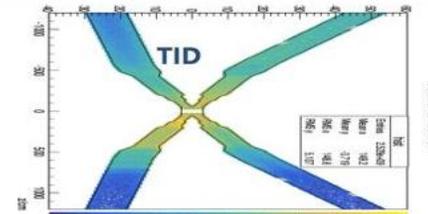
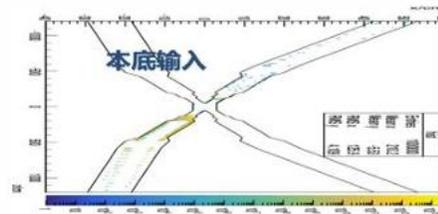
本底研究与前向探测器

- ❖ Keeping up with accelerator design evolution for beam background estimation. Working closely with MDI people to optimize the detector geometry and radiation shielding design in MDI region.
- ❖ Simulation studies on luminosity detectors (radiative Bhabha) and zero-degree detectors (ISR, two-photon process). Preliminary determination of the sites of these detectors at STCF from these studies.

Detector	TID value (Gy·y ⁻¹)	NIEL damage (1 MeV neutron·cm ⁻² ·y ⁻¹) (Hz)	Total count rate (Hz)	Average count rate (Hz/channel)	Highest count rate (Hz/channel)
ITKW-1	260	1.7×10 ¹⁰	1.1×10 ⁹	5.6×10 ⁵	7.2×10 ⁵
ITKW-2	25	8.3×10 ⁹	3.8×10 ⁸	1.1×10 ⁵	1.4×10 ⁵
ITKW-3	9.0	9.5×10 ⁹	2.4×10 ⁸	4.7×10 ⁴	7.3×10 ⁴
ITKM-1	4700	3.4×10 ¹⁰	2.0×10 ⁸	1.8×10 ¹	2.0×10 ¹
ITKM-2	47	7.9×10 ⁹	3.7×10 ⁷	0.52	0.57
ITKM-3	18	1.1×10 ¹⁰	3.3×10 ⁷	0.18	0.22
MDC	0.17	3.6×10 ¹³	3.3×10 ⁸	2.9×10 ⁴	1.8×10 ⁵
PID-Barrel (RICH)	0.90	1.1×10 ¹⁰	2.0×10 ⁸	3.0×10 ²	1.0×10 ⁴
PID-Endcap (DTOF)	1.0	1.6×10 ¹⁰	2.9×10 ⁸	4.5×10 ⁴	6.8×10 ⁴
ECAL-Barrel	0.36	1.6×10 ¹⁰	6.7×10 ⁸	1.2×10 ⁵	1.5×10 ⁵
ECAL-Endcap	0.69	1.7×10 ¹⁰	3.5×10 ⁸	1.9×10 ⁵	5.8×10 ⁵
MUD-Barrel-RPC	0.013	1.8×10 ⁹	1.0×10 ⁷	8.1×10 ²	3.7×10 ³
MUD-Barrel-Scintillator	0.0036	4.6×10 ¹⁰	6.1×10 ⁷	4.4×10 ³	2.2×10 ⁴
MUD-Endcap-RPC	0.0037	2.8×10 ⁸	1.9×10 ⁶	3.0×10 ²	3.5×10 ³
MUD-Endcap-Scintillator	0.0023	1.1×10 ¹⁰	7.1×10 ⁶	6.1×10 ²	1.2×10 ⁴



Electronic system	TID value (Gy·y ⁻¹)	NIEL damage (1 MeV neutron·cm ⁻² ·y ⁻¹)	Average SEEs (Hz/cm ²)	Highest SEEs (Hz/cm ²)
ITKW-1	34	5.4 × 10 ⁹	180	280
ITKW-2	11	6.3 × 10 ⁹	240	380
ITKW-3	5.7	1.0 × 10 ¹⁰	390	850
ITKM-1	1200	4.5 × 10 ¹⁰	220	310
ITKM-2	28	7.3 × 10 ⁹	320	660
ITKM-3	11	1.0 × 10 ¹⁰	410	980
MDC	1.3	6.7 × 10 ⁹	180	1230
PID-Barrel (RICH)	1.7	7.8 × 10 ⁹	350	450
PID-Endcap (DTOF)	1.1	1.5 × 10 ⁹	420	500
ECAL-Barrel	0.034	8.5 × 10 ⁸	36	100
ECAL-Endcap	0.1	1.5 × 10 ⁹	82	490
MUD	0.2	1.8 × 10 ⁹	16	80



Data Rates Estimation

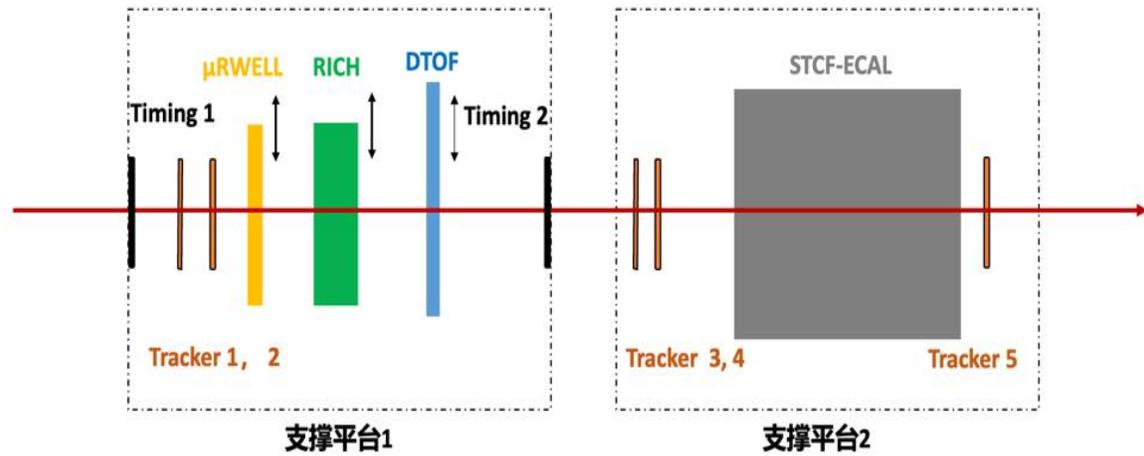


- ❖ Peak trigger rate : 400 kHz (physics @J/psi) + 50 kHz (background) = 450 kHz
- ❖ Raw event size : 18 kB/event (based on the updated beam background estimation)
- ❖ HLT data compression ratio was estimated based on preliminary HLT studies or experience from other experiments (e.g. BELLE2) .
- ❖ Final data rate to disk : 4 GB/s assuming HLT is in place.

Sub-detector	Raw data (GB/s)	L1 data rate (GB/s)	HLT data compression ratio	HLT data rate (GB/s)
ITK-MAPS	2.57	0.96	0.25	0.24
MDC (SSC)	4.34	1.40	0.45	0.63
BTOF	4.31	1.18	0.95	1.12
DTOF	2.78	0.72	0.95	0.68
ECAL	7.37	1.4	0.7	0.98
MUON	1.48	0.48	0.8	0.38
TOTAL	22.85	6.14		4.03

Redundant information e.g. data package head and tail is excluded from the estimation of L1 and HLT data rates

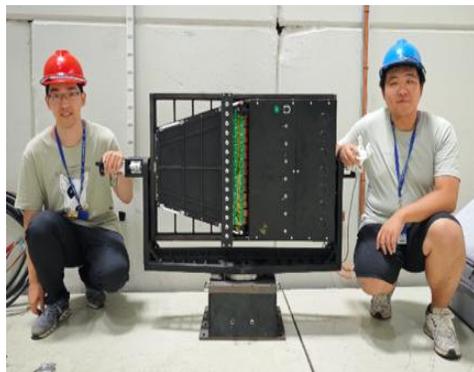
A test beam campaign for a combined system (DTOF, EMC, DAQ)



CERN PS T9 beam line (July 31 – August 14, 2024)



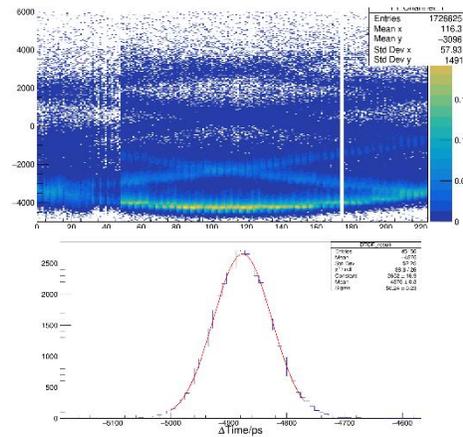
DTOF 样机



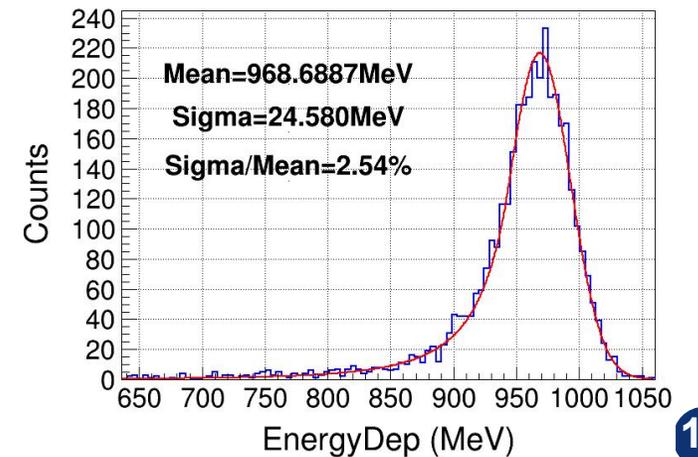
EMC 样机



DTOF: $\sigma_t \sim 25$ ps



EMC: $\sigma_E/E \sim 2.5\%$



Clock and Data Transmission



- Clock distribution system providing precise and stable clock signals with jitter < 5ps RMS
- High-speed serial data transmission: a GBTx-like ASIC, ADTC, uplink ~5Gbps

时钟主板

时钟从板

周期抖动 < 1 ps RMS @40 MHz

MultiView - Phase Noise

Signal Frequency	RISW	5%	Mean Phase
40.0 MHz	3.43 dBm	0.000000	0.000000

1 Noise Spectrum

Frequency	Power Spectral Density
10.000 MHz	-100.00 dBm/Hz
20.000 MHz	-110.00 dBm/Hz
30.000 MHz	-120.00 dBm/Hz
40.000 MHz	-130.00 dBm/Hz
50.000 MHz	-140.00 dBm/Hz
60.000 MHz	-150.00 dBm/Hz
70.000 MHz	-160.00 dBm/Hz
80.000 MHz	-170.00 dBm/Hz
90.000 MHz	-180.00 dBm/Hz
100.000 MHz	-190.00 dBm/Hz

激光收发芯片版图

并串转换芯片封装设计

高速并串转换+时钟管理芯片版图

并串转换芯片测试电路板

- Completed the design and test of clock distribution modules in a “master-slave” architecture
- Clock jitter tested ~1ps RMS
- Ready to join the upcoming combined beam test

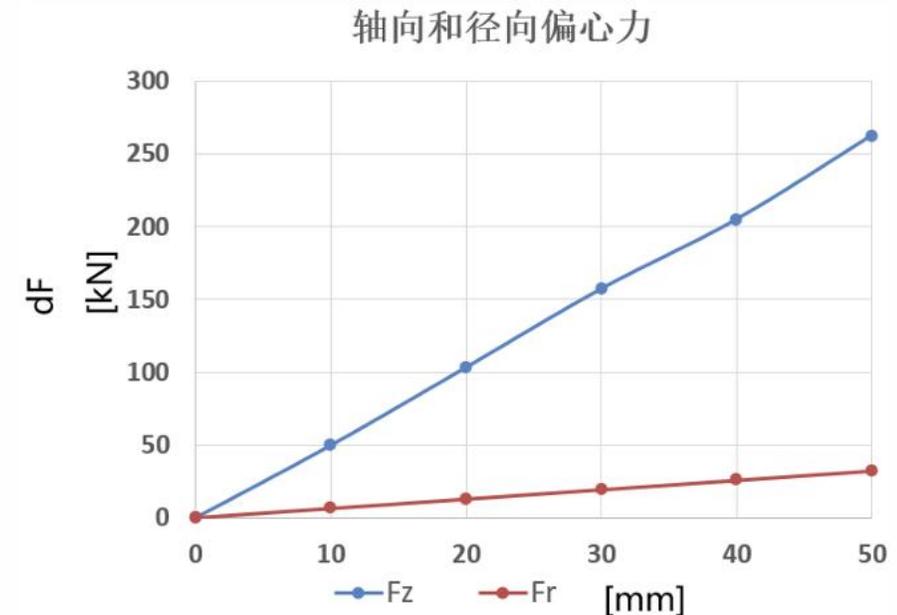
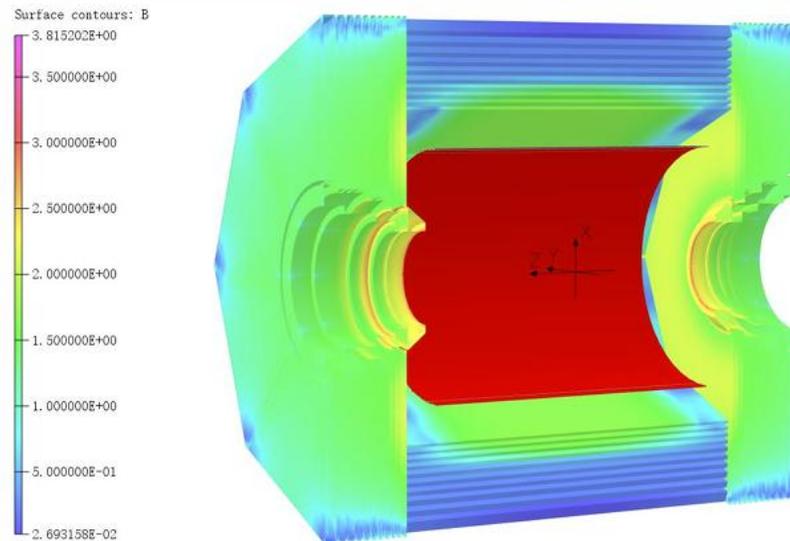
- Designed SerDes and clock managing modules in ADTC, and optical modules. Taped out the designs and received chips.
- Chips being packaged



Super-conducting Solenoid Magnet

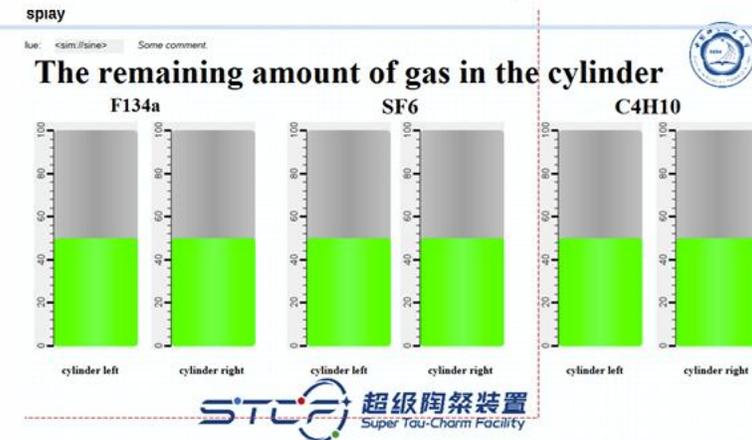


- ❖ Optimized the physics design of the magnet by performing FEA of magnet field and unbalanced forces.
- ❖ Studied impact of non-uniformity of the magnetic field on tracking performance and solutions to improve magnetic field homogeneity.
- ❖ Designing the magnet support structure using carbon fiber. Investigating heat leakage issue.
- ❖ Studying cryogenic forced circulation and thermosiphon schemes with FEA.



Detector Control System

- ❖ Finished conceptual design of the STCF detector control system.
- ❖ Designed and developed a control software framework.
- ❖ Developed a gas supplying and monitoring system in the framework as a technology demonstrator



Slow Control

Software() Database() Hardware()

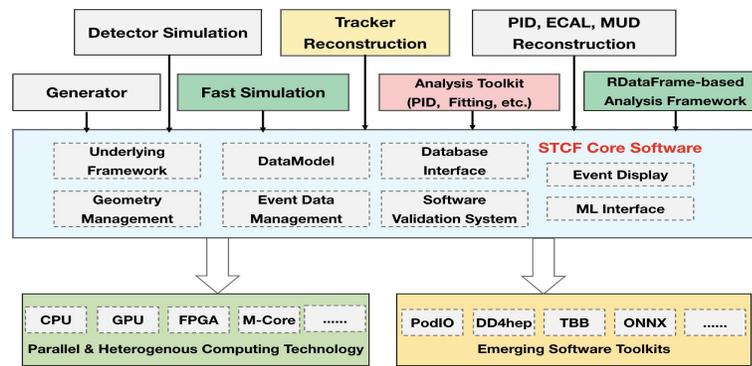
Core() EPICS IOC ROOT	GUI() JSGUI Pheobus	PostgreSQL/ TimescaleDB	Firmware() Device driver
-----------------------------	---------------------------	----------------------------	--------------------------------

JSGUI() JSROOT PyROOT	PLC Wiener series	CAEN series
	MFC series	vacuum gauge thermo meter

针对STCF探测器性能研究、方案优化和物理可行性研究需求，专门定制、设计和研发一套高性能的离线软件系统OSCAR (Offline Software of Super Tau Charm Facility)

采用国际先进技术：

- **PODIO**：国际上高效快速事例模型定义和管理工具
- **DD4hep**：国际上高效灵活探测器几何定义和管理工具
- **TBB**：因特尔多线程构建模块
- **OneAPI**：英特尔跨架构的编程模型
- **ONNX**：开源深度学习模型交换格式和生态系统
- **SNiPER**：我国自主研发全新软件框架
- **ACTS**：ATLAS实验开发径迹重建公用软件工具



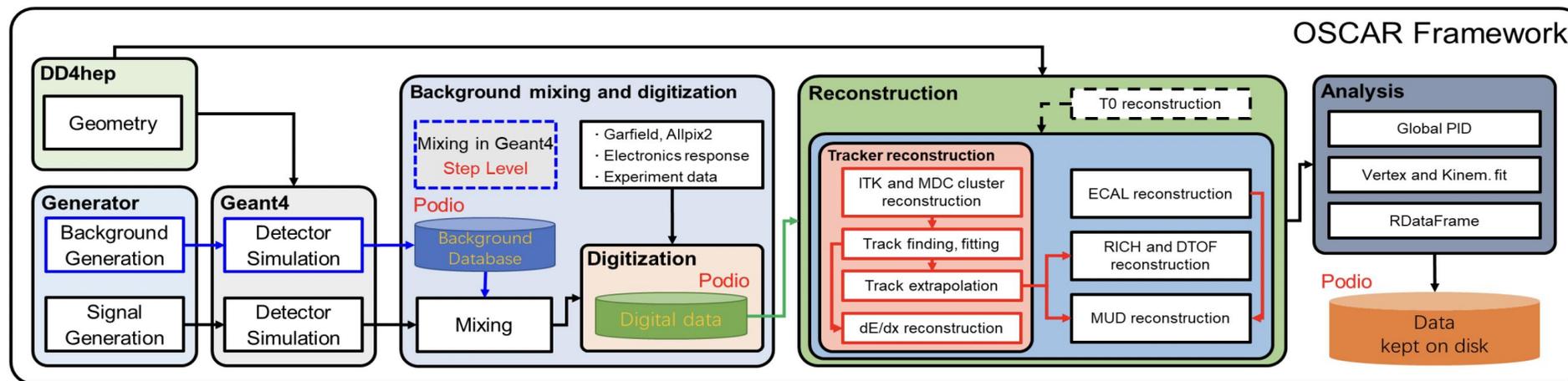
遵循国际软件开发规范：

- **C++**: 面向对象高级编程语言
- **Python**: 用户灵活的配置语言
- **CMake**: 跨平台编译工具
- **Git**: 协同软件开发工具
- **CentOS7/AlimaL9**: 国际高能物理软运行系统

研发了OSCAR重要组成软件系统，构建起完整的离线数据处理和物理分析流程，版本发布20余次，支撑探测器性能研究、设计优化和物理潜力研究。

核心组成部分：

- 核心软件
- 事例产生子软件
- 探测器模拟软件
- 本底混合软件
- 事例重建软件
- 物理分析软件
- 事例显示软件
- 性能检测软件



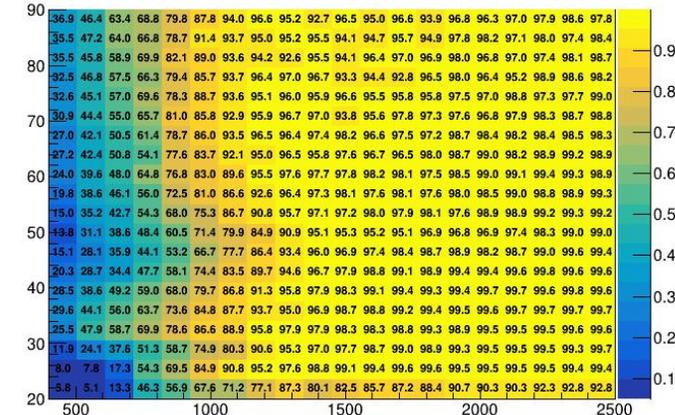
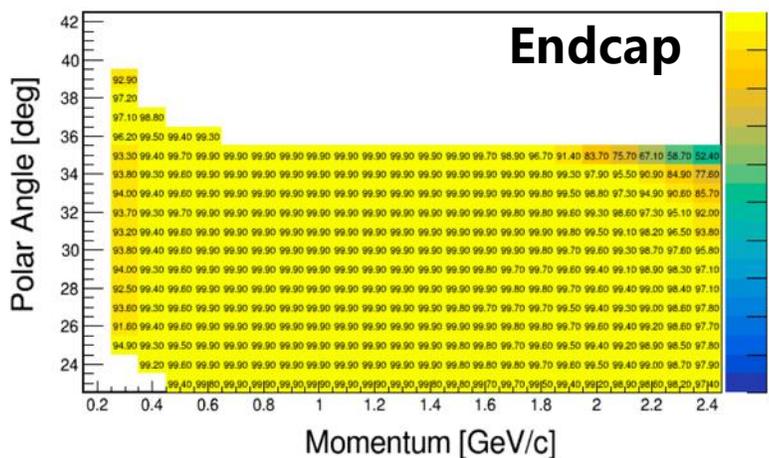
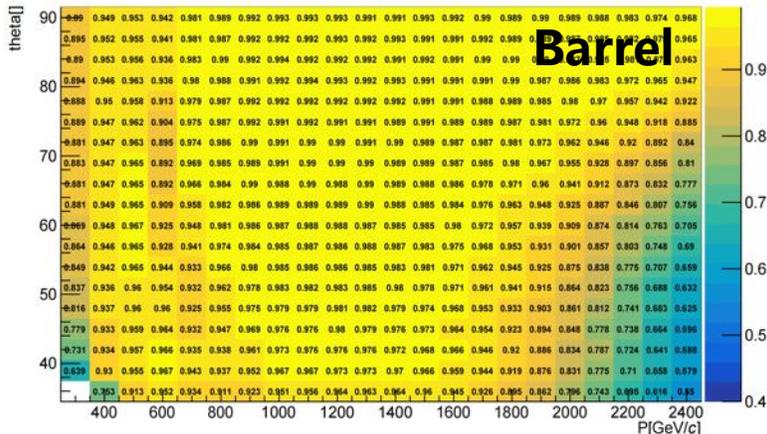
Detectors	Simulation	Digitization	Reconstruction	Analysis tools		
				Global PID	Traditional combined PID	Kinematic & Vertex Fit
ITK	✓	✓	✓	Charged tracks: ✓ Neutral tracks: ✓	✓	✓
MDC	✓	✓				
RICH	✓	✓				
DTOF	✓	✓				
BTOF	✓	✓				
EMC	✓	✓				
MUD	✓	✓				

基于全模拟的探测器预期性能

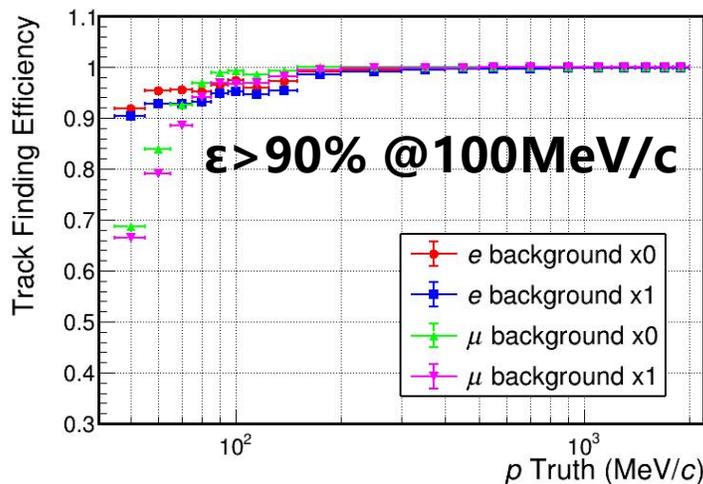


PID: Pion ID eff. >97% @ mis-ID (K->pi)=2%

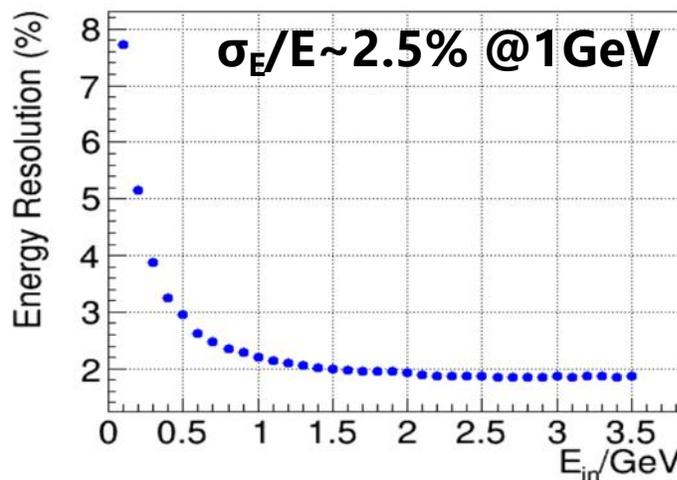
Muon ID eff. @ pi suppression=30



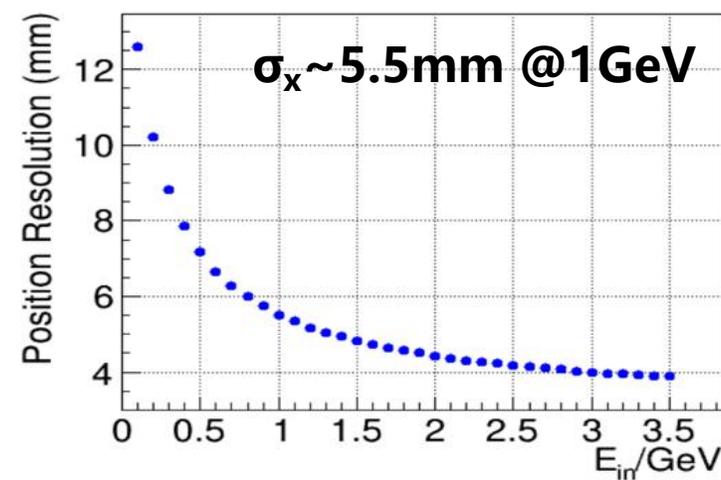
Tracking efficiency



EMC energy resolution



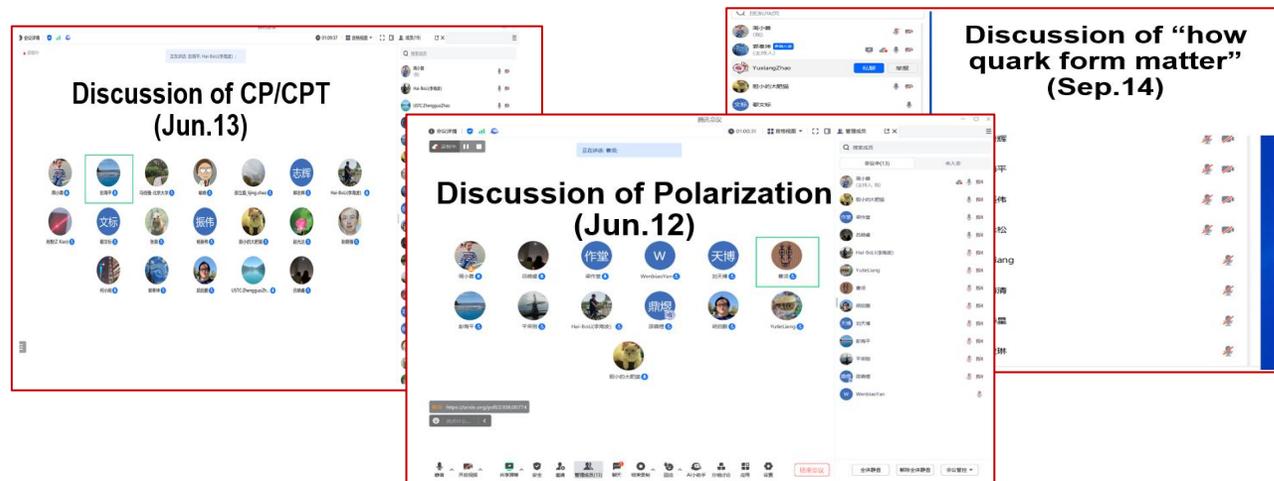
eff. ~> 90% when p ~> 1 GeV/c
EMC position resolution



研究内容	课题一	课题二	课题三	课题四	课题五	课题六	课题七
XYZ强子谱 理论 FastSimu OSCAR	Y(4260) parameters 郭奉坤、赵强、王倩 开展中(周杭, 中科大)	Zc(3900) parameters 陈云华、杜孟林、郭奉坤、郭志辉	X(3872) decay fractions 郭奉坤、	1-- hybrid production	X(3872) in e+e- production 郭奉坤、	Highly excited Y states (Baryon-antibaryon) 何军、董相坤	
多夸克态 理论 FastSimu OSCAR	双粲偶素eta J/psi, J/psi J/psi 张玉洁、邵华圣、张鸿飞 开展中(董焯娟, 张晋, 耿聪, 中山大学)	五夸克态ppbar J/psi 吴佳俊、郭奉坤 待开展(山大)	Lambdac D(*) pbar 吴佳俊、何军	Sigmac D(*) pbar 吴佳俊、何军	奇特量子数粲介子 董相坤、纪腾、郭奉坤	e+e- -> gam pipi J/psi 郭奉坤	ccbar的1-+, 0--的奇特量子数 邹冰松、郭奉坤
强子结构 理论 FastSimu OSCAR	7 GeV的Collins碎裂函数 已发表JUCAS (王滨龙, 国科大) 开展中(翟云聪, 山大)	极化下的碎裂函数 邢宏喜、刘天博、李阳 前期调研 (鄢文标, 中科大)	核子电磁形状因子 郭奉坤、林勇辉、周海青	能量关联函数 朱华星	sss激发态 邹冰松		
tau物理 理论 FastSimu OSCAR	tau->Ks pi nu 康现伟 已发表CPC (桑昊榆, 中科大)	tau EDM 郭志辉、李英英 已投稿(孙旭磊, 中科大, 吴永成, 南师大) 开展中(莫泓琨, 中科大)	tau-> gam pi nu 郭志辉, Pablo Roig 开展中(李昊霖、艾小聪, 郑大)	tau -> gam K nu 郭志辉, Pablo Roig	tau -> gam P nu 郭志辉, Pablo Roig	Quantum entanglement 开展中(刘明依, 陶昕中科大)	Vus measurement 开展中(蔡佳宇, 周小蓉 中科大)
粲物理 理论 FastSimu OSCAR	PV and CPV in Lambdac Ikaros Bigi, 康现伟 已发表PRD (师晓东, 中科大)	D -> KL e nu 王伟 已发表EPJC (范玉兰, 武大)	Ds->mu nu 已发表EPJC (刘佳俊, 南华) OSCAR	Ds->tau nu 已发表EPJC(李惠静, 河师大)	D+->pi mu nu 开展中(黄清源, 国科大)	D0-D0bar mixing and strong phase 郑海扬、于福升 开展中(王英豪, 张宇, 兰大/南华)	D0->K- pi+ pi0 开展中(王程, 兰大)
奇异强子物理 理论 FastSimu OSCAR	Lambda CPV Andrzej Kupsc、何小刚 已完成MPLA(徐月, 辽大) 系统误差 已发表JUST(徐明, 中科大) 开展中(于明玉, 山大)	极化下的Lambda CPV Andrzej Kupsc、何小刚 已完成CPC(曾胜, 南华) 待开展(山大)	K0-K0bar mixing Stephen Olsen 已提交PRD(张剑宇, 国科大) 开展中(张慧斌, 国科大)	K0-K0' oscillation	Ks->pi e nu Stephen Olsen	Lambda半轻衰变 Andrzej, Varavara 开展中(周俊贤, 复旦)	
电弱能标 理论 FastSimu OSCAR	Weinberg角测量 李阳 待开展(鄢文标、赵宇翔, 近物所)						
新物理 理论 FastSimu OSCAR	tau-> gam mu 已完成EPJC(相腾, 北大) 开展中(李昊霖, 郑州)	eta/eta' symmetry 郭志辉、Bastian Kubis 已完成PRD(康晓琳、向本后, 地质大学/高能所) generator update ongoing	D->pe 开展中(黄仪伟, 南开) 开展中(黄仪伟, 南开)	J/psi->Lambdac e 开展中(徐宇遥, 南开) 开展中(徐宇遥, 南开)	Lam-Lambar oscillation 开展中(薛又文, 南开) 开展中(薛又文)	Hyperon EDM 于福升 开展中(傅金林、张剑宇, 国科大)	CPV in J/psi/psip->KsKs以及 phi->KsKs 计划开展(张敬庆, 南师大)

OSCAR软件 (全模拟+快速模拟) 支撑开展物理模拟研究, 并在超子、tau轻子、粲重子、K介子的CP/CPT破坏、Collins碎裂函数、粲介子半轻衰变、cLFV等新物理过程发表物理模拟文章14篇。

- 多次专题会议凝练物理研究课题



- 三个物理组开展全模拟研究

- 召集人:

基本对称性检验：张宇(南华大学), 刘明依 (中科大)

QCD性质和色禁闭探索：耿聪 (中大), 罗涛(复旦), 康晓坤 (辽大)

基本物理量测量：康晓玲 (地质大学), 李惠静 (河师大)

- 周例会、月会

- 理论与实验联合会?

目录

CONTENTS

- 一、STCF项目介绍
- 二、项目科学目标
- 三、项目的组织和推动
- 四、关键技术攻关项目
- 五、总结**

- STCF 具有**丰富的前沿物理**，是研究物质深层次结构，探索宇宙正反物质不对称，寻找奇特物质和新物理的**独特装置**，具有**重大发现潜力**；将**引领世界陶粲物理的研究**，将取得重大科学突破，保持我国在该领域的**国际领先**；
- STCF 属于**高亮度/高精度前沿**：在加速器、粒子探测、数据获取和处理、计算和网络技术和方法等方面均**极具挑战**；这些关键技术的攻克将使我国在该领域处于**世界前列**，也具有广阔的**应用前景**
- STCF 符合当前国情，**性价比高**，是我国在**近中期能够实现**，能对中国高能物理发展起到**重要支撑**的关键装置，值得我国高能物理界同仁的共同努力；我国在STCF 项目**具有优势**，是国际公认建造 STCF 的**最佳场所**，得到国际的充分**支持和认可**
- STCF 项目得到安徽省和合肥市的**坚定支持**，也得到中国科学院、科技部、基金委等部门相关项目的支持，目标将是纳入“**十五五**”**国家重大科技基础设施项目**建设规划
- 关键技术攻关取得**重要进展**，国内多家**团队**参与攻关项目，希望能够得到进一步支持

衷心感谢大家的长期支持!

欢迎青年学生和研究人员参与!

谢谢!

Report of first meeting of International Advisory Committee for the Super Tau Charm Facility

Maria Enrica Biagini^{*1}, Ikaros Bigi^{*2}, Alex Bondar^{*3}, Tom Browder⁴, Kuang-Ta Chao^{*5}, Yuanning Gao⁵, Wolfgang Gradl⁶, David Hitlin^{*7}, Tord Johansson^{*8}, Marek Karliner^{*9}, Eugeny Levichev³, Yugang Ma^{*10}, Mikihiro Nakao^{*11}, Stephen Olsen^{*12}, Alexey Petrov^{*13}, Antonio Pich^{*14}, Makoto Tobiyama^{*11}, Guy Wilkinson^{†*15}, Hongwei Zhao¹⁶, Zhentang Zhao^{*17}, Frank Zimmermann^{†*18}, Bingsong Zou^{*19}

¹ INFN - Frascati National Laboratories, ² University of Notre Dame, ³ Budker Institute of Nuclear Physics (BINP), ⁴ University of Hawaii, ⁵ Peking University, ⁶ Johannes Gutenberg University Mainz, ⁷ California Institute of Technology, ⁸ Uppsala University, ⁹ Tel Aviv University, ¹⁰ Fudan University, ¹¹ High Energy Accelerator Research Organization (KEK), ¹² Chung Ang University, ¹³ University of South Carolina, ¹⁴ University of Valencia, IFIC, ¹⁵ University of Oxford, ¹⁶ Institute of Modern Physics, CAS, ¹⁷ Shanghai Advanced Research Institute, CAS, ¹⁸ European Organization for Nuclear Research (CERN), ¹⁹ Institute of Theoretical Physics, CAS.

† Co-chairs.

* Attended meeting.

2 Executive summary

STCF will be unique facility with a broad and impressive physics reach. It will allow for results of world-leading precision in many important topics, and has significant discovery potential. It will ideally complement the other facilities that are currently operational or are foreseen for the 2030s and 2040s, and will be of great interest to the international particle physics community. The principal challenge of the project lies in the accelerator. Here the intended luminosity will exceed by two orders of magnitude that previously achieved in the same energy regime. The IAC is pleased to recognise the significant progress on the STCF accelerator design that has occurred since the establishment of a dedicated Accelerator Division led by Prof. J.Y. Tang. The demands on the detector are less formidable, but should not be underestimated given the extreme event rate and size of data samples foreseen.

报告总结： STCF将是具有**丰富物理潜能**的独特装置，将在多个重要课题上获得**世界领先**的精确结果，并具有**重大的发现**的潜力。它将在未来20年中**完美**与其他设施**互补**，受到国际粒子物理界**极大关注**。项目的主要挑战在于加速器。其预期的亮度将比现有相同能量范围实验的亮度高出两个数量级。STCF 加速器设计和团队建设取得的显著进展。探测器的要求考虑到预期的极高事件率和数据样本的规模，挑战性也不容低估

物理与探测谱仪

3.2 Recommendations

The IAC has the following recommendations for the ongoing studies in the areas of physics studies and detector design.

- The breadth of physics that can be studied at STFC is impressive. However, a subset of flagship measurements should be identified to define more emphatically the uniqueness and importance of the project. It is suggested that these measurements should be predominantly related to the determination of fundamental parameters, or tests of the Standard Model.
- The IAC notes the great interest of the measurements that can be performed with polarized beams, currently foreseen for an upgrade phase, and recommends that equipping the machine with polarization remains a high-priority goal of the project. The design of the machine should, from the start, allow for the inclusion of this attribute at a later stage of the project.
- The STFC team must convince the wider community that it will be possible to attain the necessary level of systematic control to match the foreseen statistical precision. Strategies should be developed and described for meeting this challenge for the flagship measurements.
- Full simulation studies of the flagship measurements should be performed to demonstrate that the detector choices are well suited to the physics goals.
- The performance of the tracking system, in particular, is critical for the success of the physics programme. Metrics such as tracking efficiency (particularly at low momentum) and resolution should be used to demonstrate that the system meets the physics requirements and is robust against background. Particular attention should be paid to the design of the ITK, e.g. its inner radius, how many space points should it provide, does the proposed design have sufficiently low mass?
- The IAC is pleased by the preliminary studies on the DAQ system, given the challenge presented by the enormous event rate, particularly at the J/ψ , and recommends that this item continues to receive high attention.
- The foreseen data volume per year is very substantial. Where will this be stored and processed, and how will it be accessed? What are the Monte Carlo simulation needs? A detailed computing strategy must be formulated.
- Greater attention should be given to the Machine-Detector Interface, where there must be a careful optimisation between the needs of the physics and the constraints of the accelerator. The IAC recommends that all parameters, in particular the low-angle acceptance of the detector, be carefully considered in this respect.

加速器

4.2 Recommendations

The IAC issues the following recommendations for the accelerator:

- Stop working on the present lattice and immediately begin working on the 800-900 m-long lattice, for three different energies; also, a review of the latest and most modern lattices on the market, such as the HEPS optics and Pantaleo Raimondi's FCC-ee lattice could be considered;
- Complete the simulations of beam lifetime, beam instabilities, and high-current/collective effects — the high-current effects may relate to RF, injection, impedance, lifetime, vacuum, beam chamber issues, and lattice design;
- Determine and optimize the performance as a function of beam energy;
- Define a baseline for the collider 500 MHz RF system (normal conducting (NC) KEK type, NC SLAC type, or SC);
- Include detector solenoid field, and lattice errors, in the beam-beam and luminosity performance simulations
- Carry out more background simulations — Touschek, beam-beam and injection backgrounds will have a big impact on the luminosity performance; background suppression by collimators and masks should be studied;
- Pursue experimental checks of the Touschek lifetimes at existing 3rd and 4th generation light sources;
- Explore possible relaxation of bunch-length constraint from the detector (TOF); if the bunch length constraint can be relaxed, study the possible use of harmonic cavities to lengthen and shape the bunches for improved Touschek lifetime;
- Simulations should be performed as soon as possible to decide if the dynamic and momentum apertures are sufficient for off-axis injection, otherwise the swap-out option requiring accumulation rings will need further R&D funding and studies (probably this option would be challenging to finalize in the short time scale of 2–3 years); also compare the feasibility of the two injection schemes in beam-beam simulations;
- Pay much more attention to, and perform a preliminary technical design of, machine protection, collimation scheme, precise beam measurement system of bunch by bunch, and fast feedback systems;
- In the TDR, civil engineering, heating, ventilation, air conditioning, cooling, and power sources should be considered;
- Design the layout so as to allow for later polarization and/or monochromatization; the final lattice, at least the CDR one, should include space for Siberian Snakes, even if this option is only for a later upgrade;
- Enlarge the accelerator team to include more experienced accelerator physicists from USTC and elsewhere to guide the young team already working on the project;
- Strengthen collaboration with BINP, KEK, and if possible IHEP, and engage in SuperKEKB beam commissioning and operation.

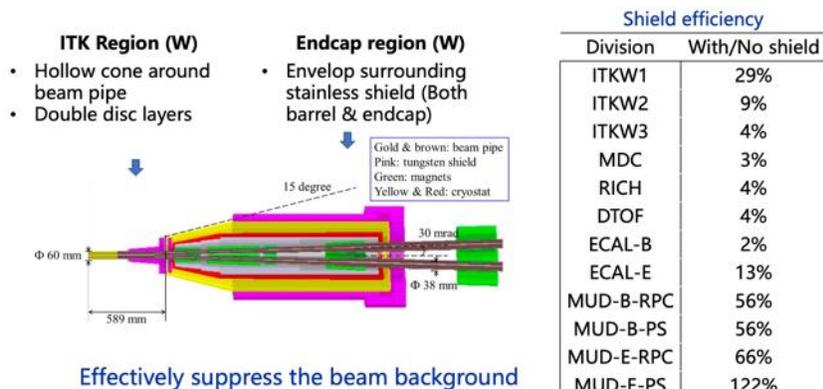
2 Executive summary

STCF will be unique facility with a broad and impressive physics reach. It will allow for results of world-leading precision in many important topics, and has significant discovery potential. It will ideally complement the other facilities that are currently operational or are foreseen for the 2030s and 2040s, and will be of great interest to the international particle physics community. The principal challenge of the project lies in the accelerator. Here the intended luminosity will exceed by two orders of magnitude that previously achieved in the same energy regime.

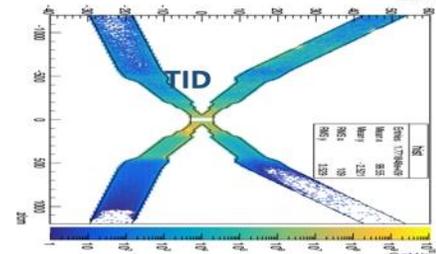
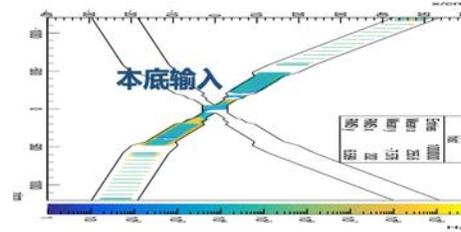
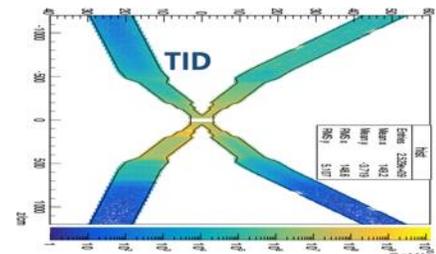
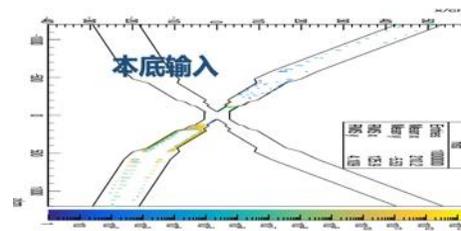
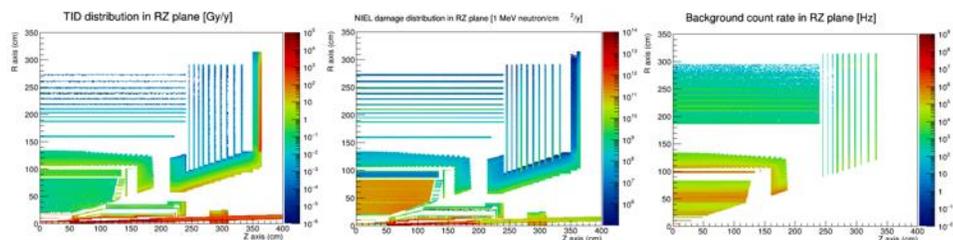
The IAC is pleased to note the significant progress made in physics, detector and accelerator studies since January. The STCF team intends to complete a Technical Design Report by the end of 2026. The IAC considers this an ambitious goal, but a feasible one, given the progress so far made. However, several critical items have been identified, which are discussed in the recommendations that follow.

报告总结： STCF将是具有**丰富物理潜能**的**独特装置**，将在多个重要课题上获得**世界领先**的精确结果，并具有重大的发现的潜力。它将在未来20年中完美与其他设施互补，受到国际粒子物理界**极大关注**。项目的主要挑战在于加速器。其预期的亮度将比现有相同能量范围实验的亮度高出两个数量级。IAC对项目在物理、探测器和加速器的**显著进展**表示高兴。项目组计划与2026年完成技术设计报告，有挑战性，也具有**可行性**。

- 优化束流本底屏蔽设计，有效压低束流本底。针对加速器设计更新，持续更新束流本底估计。
- 初步确定亮度监测探测器选址，开展亮度监测探测器方案模拟，评估了辐照和本底水平。



- The highest TID: 12000Gy/y (ITKM) 4300Gy/y (ITKW)
- Meets the requirement for a long-term run
- The Highest NIEL $\sim 1.7 \times 10^{13}$ (MDC)
- The other parts smaller than $1. \times 10^{11}$
- NIEL is not quite important for MDCs (gas chamber)
- Highest count rate per channel for ITK, MDC, ECAL $\sim 700 - 500\text{KHz}$



- 进行了谱仪超导磁体的物理设计，完成了有限元仿真（磁场、偏心力的计算）；
- 初步确定了谱仪超导磁体的磁场不均匀性对漂移室影响和后续解决方案；
- 初步设计了碳纤维材料悬挂结构方案。

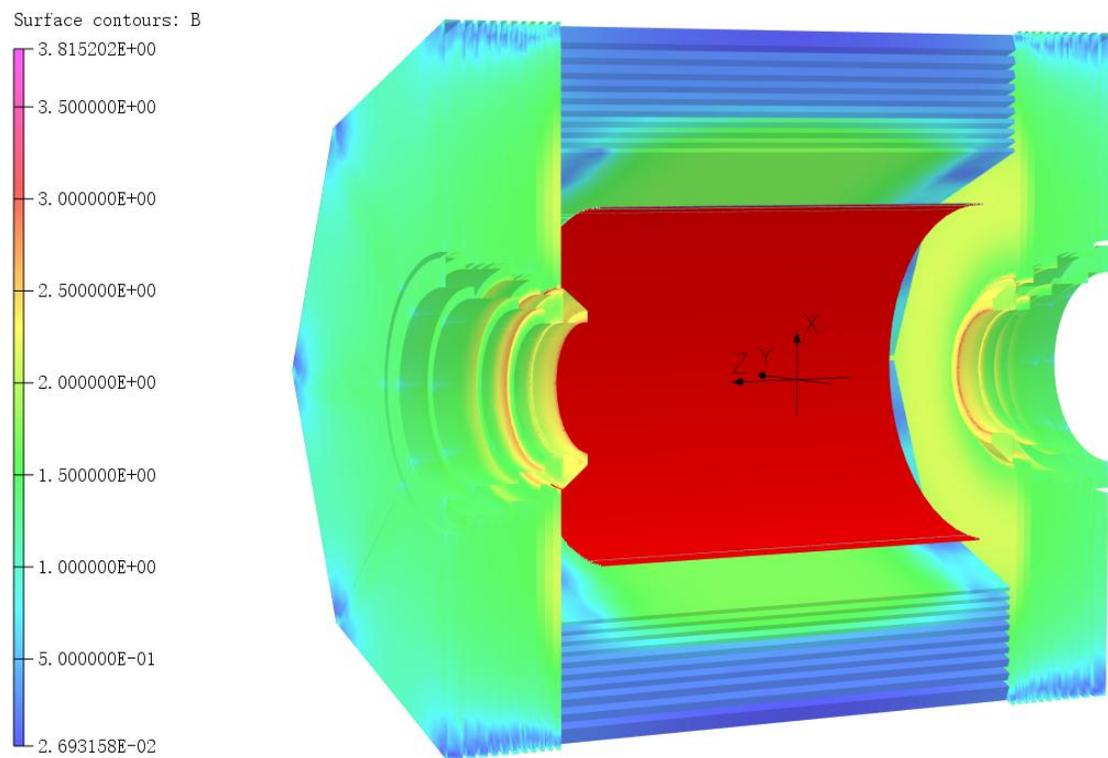


Fig.1 STCF 超导磁铁的三维磁场分布

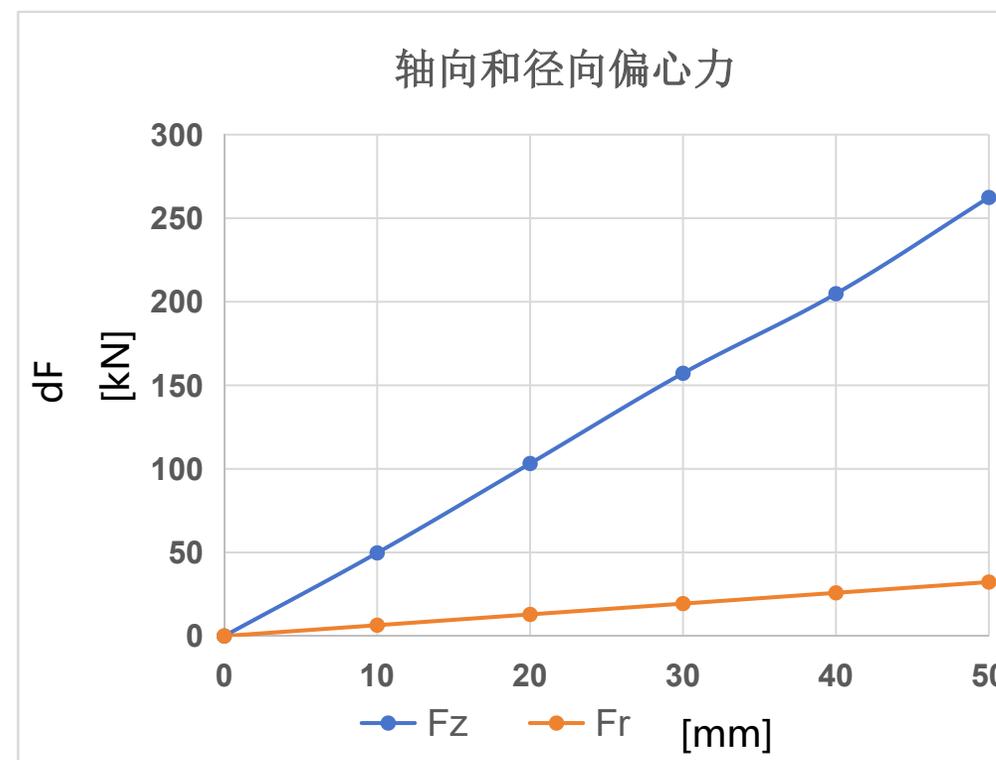
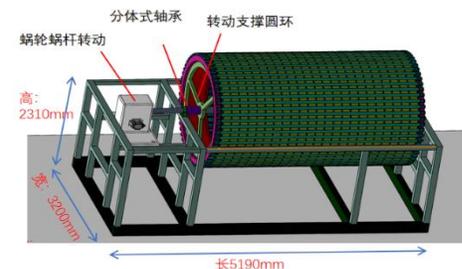
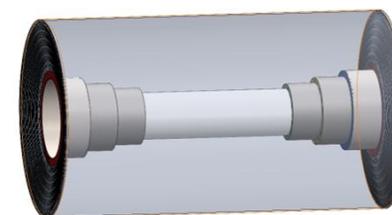
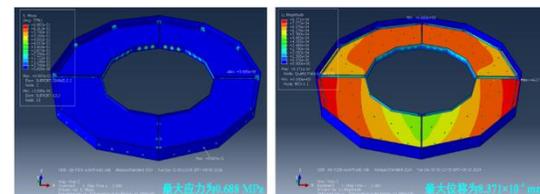
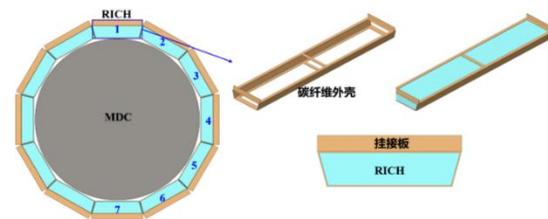
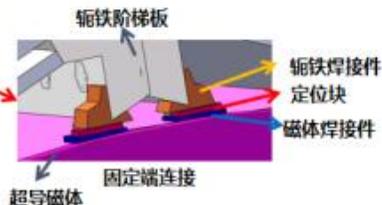
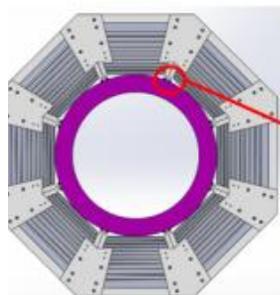
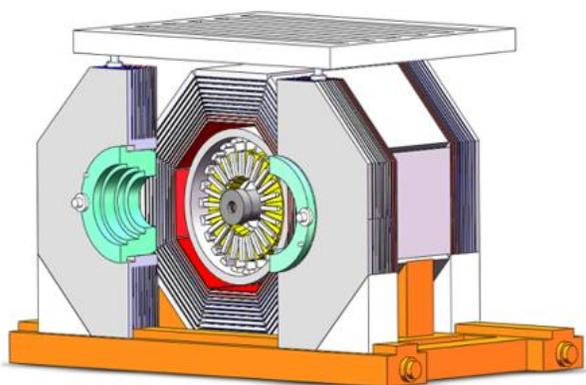


Fig.2 STCF 超导磁体偏心力计算结果

- 进行了谱仪机械的整体支撑和移动结构分析及优化；完成了整体轭铁机械结构的初步设计
- 完成了超导磁体支撑结构设计、与轭铁的连接定位结构设计，以及吊挂结构分析及优化；
- 完成了电磁量能器支撑结构设计及与轭铁的连接定位结构设计；
- 完成了 RICH探测器机械支撑结构的初步设计和DTOF探测器整体结构设计和优化；
- 完成了主漂移室机械结构的初步设计和关键部件强度的有限元分析；
- 完成了硅像素内径探测器整体结构和安装固定方案设计，对内、外服务桶结构、外部支撑框架结构以及工装方式进行了优化设计；
- 完成了气体径迹探测器整体机械结构和散热方案设计。



项目的组织



学术秘书组

组长: 杨振伟
成员: 吕晓睿、周小蓉、鄢文标、何吉波、郭奉坤、张艾霖、郭志辉、胡启鹏
职责: 项目宣传、学术会议、学术文档

项目建设领导小组

组长: 常进 (校长)
副组长: 傅尧
成员: 蒋一、王晓平、杨金龙、邓建松、薛天

项目建设工作小组

组长: 傅尧 (副校长)
副组长: 孙方稳、查正军、赵钢、封东来、陈宇翱
成员: 赵国飞、赵政国、姚子龙、龚流柱、梁宏飞、彭海平、薛永泉、瞿昆

项目办公室

主任: 邵明、刘建党
成员: 曾晖、胡东栋、李媛媛、王颖颖、王丽、鄢文标、胡启鹏、汪小庆
职责: 进度、质量、经费管理; 绩效考核, 文档与信息管理等, 采购与设备管理

项目总体

首席科学家: 赵政国
项目经理: 赵政国
项目副经理: 彭海平、冷用斌、郑阳恒
总工程师: 唐靖宇
副总工程师: 殷立新、刘树彬、刘建北
副总工艺师: 朱自安

国际顾问委员会

主席: Guy Wilkinson, Frank Zimmernan
共22位国际专家

咨询委员会

主席: 赵光达、高原宁、赵红卫、赵振堂
共24位院士和专家

加速器分总体

共含15个系统

主任: 唐靖宇
副主任: 罗箐

探测器分总体

共含14个系统

主任: 刘建北
副主任: 刘倩、赵雷

技术支持组

选址、场地、公共设施、通用技术

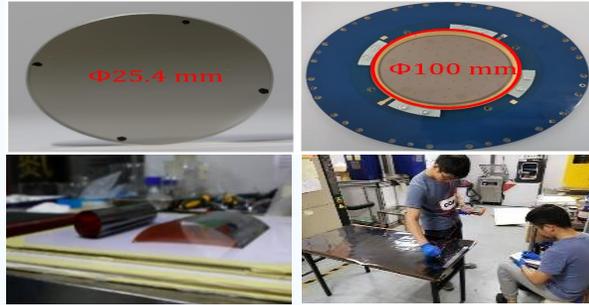
物理与软件组

组长: 黄性涛
副组长: 周小蓉、艾小聪、吕晓睿

关键技术攻关项目合作企业

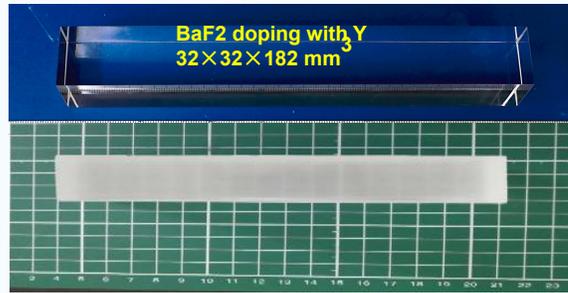


中国科学院兰州化物所



DLC电阻电极和MRPC研发

中国科学院上海硅酸盐所



闪烁体研制与生产

奕瑞科技公司



晶体生产、芯片研发

北京玻璃研究院有限公司



大面积石英玻璃表面加工

中国科学院西安光学和精密机械研究所



单、多阳极微通道板光电倍增管 MCP-PMT

合肥晶合集成电路股份有限公司

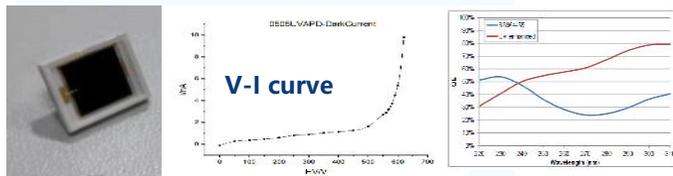
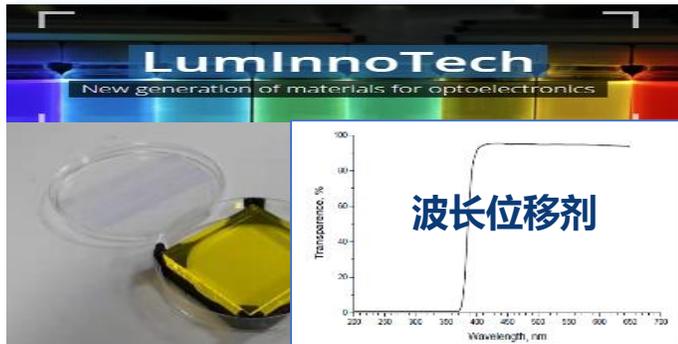


ASIC 设计与开发

合肥聚能电物理高技术开发有限公司



加速器磁铁设计与加工



紫外雪崩光电二极管(APD)

与CERN、俄罗斯BINP/JINR、日本KEK、法国IJCLab等单位 开展广泛而深入的技术交流和实质合作



与LHCb TORCH升级项目组合作



与CERN薄膜沉积实验室合作



与CERN气体探测器组合作



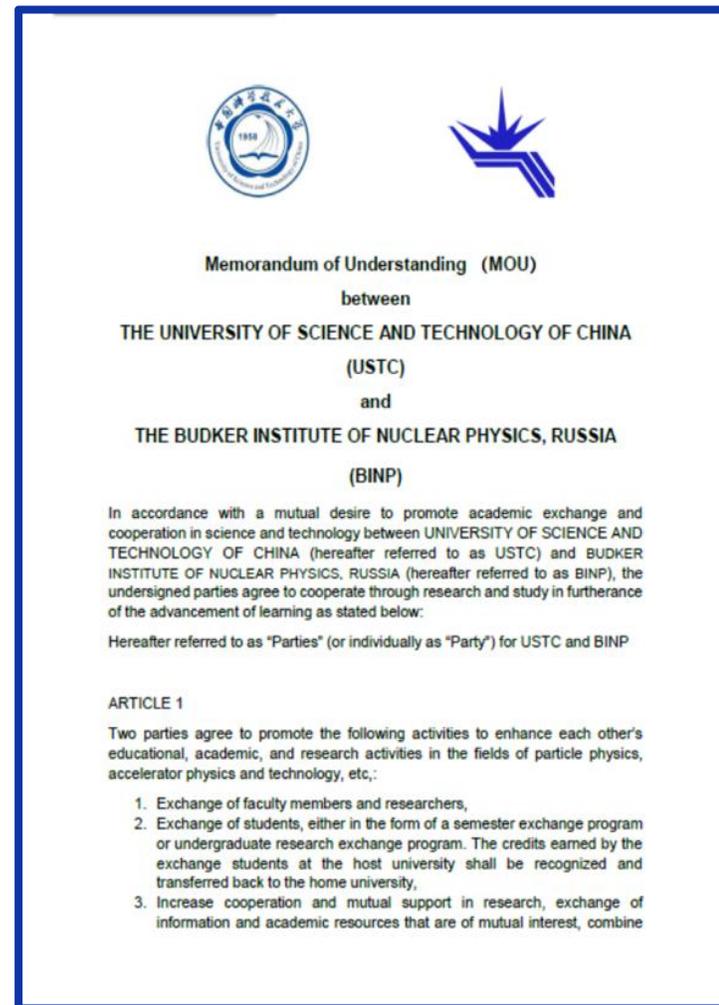
与BINP加速器专家合作



与JINR团队交流



与KEK加速器专家合作研究



已和BINP签完MOU，与其他单位的合作协议正在草拟中...

项目推动会议

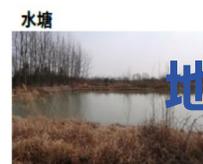
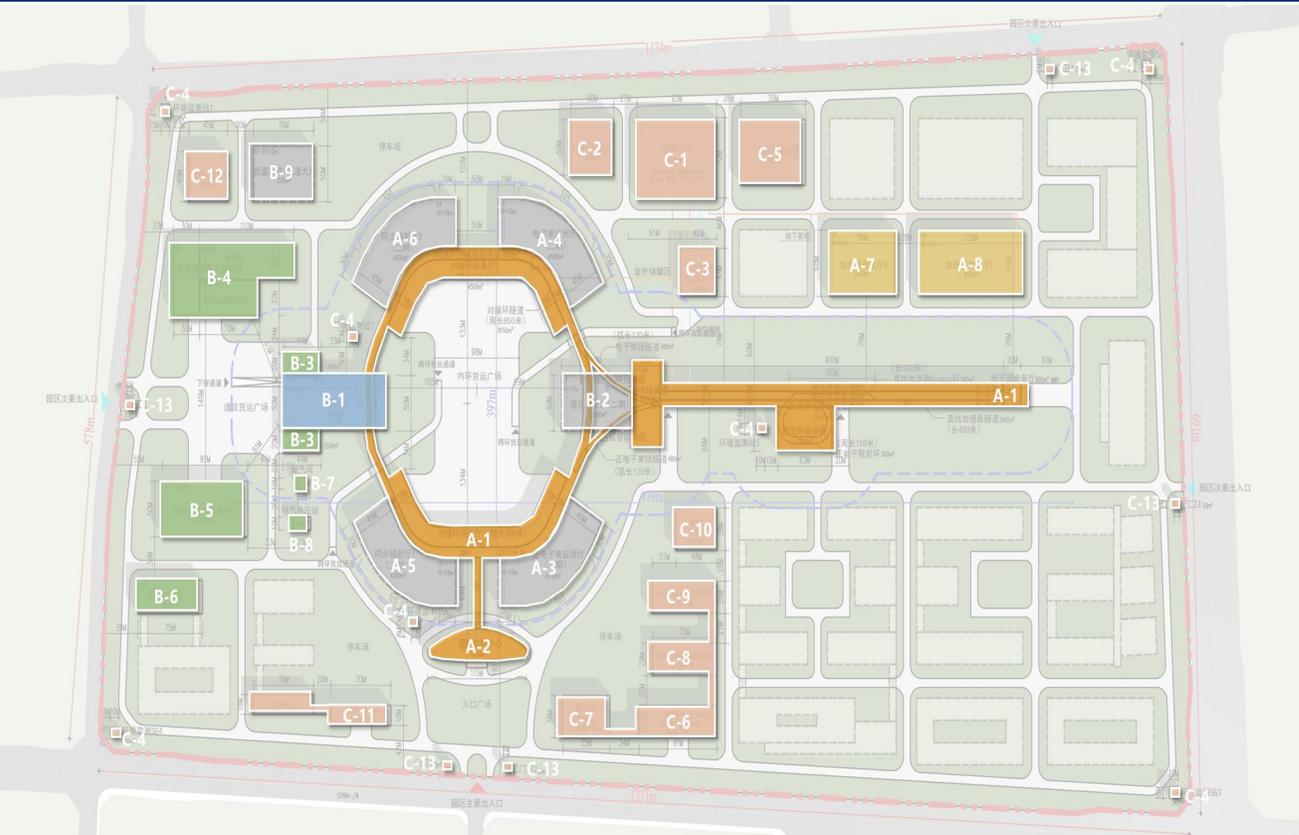


不同类型专家多形式参与，系统性评估和推动攻关项目的科学与技术，为建设项目立项奠定坚实基础 40

选址与园区规划



合肥市长丰县岗集镇，属于大科学装置集中区



加速器装置区

- A-1 主体建筑
- A-2 装置控制中心
- A-7 加速器测试厅1
- A-8 加速器测试厅2

谱仪主体装置区

- B-1 谱仪大厅
- B-3 谱仪控制楼
- B-4 探测器装配楼
- B-5 数据处理中心
- B-6 实验楼
- B-7 配气间
- B-8 气站

配套工程

- C-1 能源中心
- C-2 110kv变电站
- C-3 低温大厅
- C-4 环境监测站
- C-5 装配维修厅
- C-6 学科中心
- C-7 报告厅
- C-8/9 综合实验楼

国家重点科技基础设施建议书



为了STCF整体推进有利于国家立项，
项目组在积极推进《建议书》



国家重大科技基础设施项目需求建议书

名称: 超级陶粲装置

项目单位: 中国科学技术大学

姓名: 赵政国

联系人电话: 15505510490

电子邮箱: zhaozg@ustc.edu.cn

2024年9月29日

1

 **超级陶粲装置**
Super Tau-Charm Facility

超级陶粲装置 (STCF)

赵政国
中国科学技术大学
(代表STCF项目组)

2024年11月04日, 北京



“十五五”国家重大科技基础设施

超级陶粲装置 项目建议书

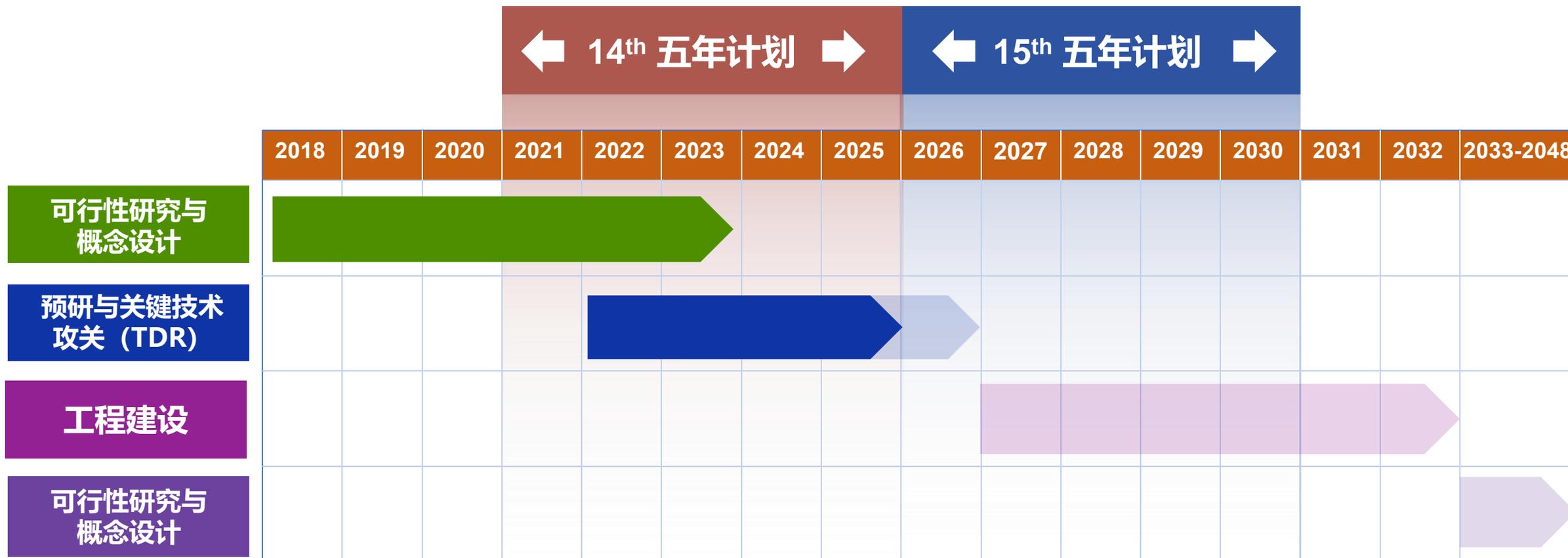
设施类型 面向世界科技前沿 面向经济主战场
 面向国家重大需求 综合交叉研究平台

主管部门: 中国科学院
项目法人单位: 中国科学技术大学
联系人: 赵政国
联系电话: 15505510490
E-mail 地址: zhaozg@ustc.edu.cn

版本号: V2.0.0108.0
二〇二五年六月

已经形成初稿 (约1200页), 正在优化

计划时间表



执行年份	基金部门	基金类型	金额 (万元)
2018-2021	中国科大	双一流重点项目	1500
2021-2026	中国科学院	国际伙伴项目	505
2022-2027	科技部	重点研发项目	1750
2023-2025	安徽省/合肥市/中科大	关键技术攻关项目	36400
2023-2027	基金委	重点项目群	1400
总和			41555

系统	建设经费 (亿人民币)
注入器	8.5
对撞环	25.0
探测谱仪	7.5
装置土建	8.8
合计	49.8

运行经费按照国家目前标准，预计是建设经费的8-10%。

项目规模、投资体量、运行经费与国家经济发展现状相契合

国际顾问委员会和咨询委员会



国际顾问委员会 (IAC, 22位)

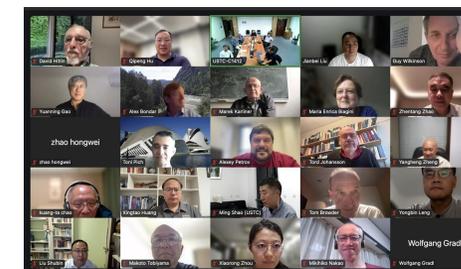
主席	Guy Wilkinson	牛津大学	英国
副主席	Frank Zimmermann	欧洲核子中心	瑞士
成员	Marica Biagini	弗拉斯卡蒂国家实验室	意大利
	Ikaros Bigi	圣母大学	美国
	Alexander Bondar	布德科尔核物理研究所	俄罗斯
	Tom Browder	夏威夷大学	美国
	赵光达	北京大学	中国
	高原宁	北京大学	中国
	Wolfgang Gradl	美茵茨大学	德国
	David Hitlin	加州理工学院	美国
	Tord Johansson	乌普萨拉大学	瑞典
	Marek Karliner	特拉维夫大学	以色列
	Eugeny Levichev	布德科尔核物理研究所	俄罗斯
	马余刚	复旦大学	中国
	Mikihiko Nakao	高能加速器研究机构	日本
	Stephen Olsen	中央大学	韩国
	Alexey Petrov	南卡罗来纳大学	美国
	Antonio Pich	瓦伦西亚大学	西班牙
	Makoto Tobiayama	高能加速器研究机构	日本
	赵红卫	中国科学院近代物理所	中国
	赵振堂	中国科学院上海高研院	中国
邹冰松	中国科学院理论物理所	中国	

咨询委员会 (24位)

组长	赵光达	北京大学
副组长	赵红卫	中国科学院近物所
	赵振堂	中国科学院上海高研院
成员	高原宁	北京大学
	蔡荣根	中国科学院理论所
	邓建军	中国工程物理研究院
	封东来	中国科学技术大学
	何多慧	中国科学技术大学
	何小刚	上海交通大学
	李建刚	中国科学院等离子体所
	柳卫平	南方科技大学
	罗民兴	北京计算科学研究中心
	马余刚	复旦大学
	欧阳晓平	西北核技术研究所
	欧阳钟灿	中国科学院理论所
	沈肖雁	中国科学院高能所
	史生才	中国科学院紫金山天文台
	万宝年	中国科学院等离子体所
	吴岳良	中国科学院大学
	夏佳文	中国科学院近物所
	向涛	中国科学院理论所
	许怒	中国科学院近物所
	詹文龙	中国科学院
张肇西	中国科学院理论所	



IAC第一次会议 2024年1月



IAC第二次会议 2024年10月



咨询委员会成立及第一次会议 2024年5月

Report of first meeting of International Advisory Committee for the Super Tau Charm Facility

Maria Enrica Biagini^{*1}, Ikaros Bigi^{*2}, Alex Bondar^{*3}, Tom Browder⁴, Kuang-Ta Chao^{*5}, Yuanning Gao⁵, Wolfgang Gradl⁶, David Hitlin^{*7}, Tord Johansson^{*8}, Marek Karliner^{*9}, Eugeny Levichev³, Yugang Ma^{*10}, Mikihiro Nakao^{*11}, Stephen Olsen^{*12}, Alexey Petrov^{*13}, Antonio Pich^{*14}, Makoto Tobiyama^{*11}, Guy Wilkinson^{†*15}, Hongwei Zhao¹⁶, Zhentang Zhao^{*17}, Frank Zimmermann^{†*18}, Bingsong Zou^{*19}

¹ INFN - Frascati National Laboratories, ² University of Notre Dame, ³ Budker Institute of Nuclear Physics (BINP), ⁴ University of Hawaii, ⁵ Peking University, ⁶ Johannes Gutenberg University Mainz, ⁷ California Institute of Technology, ⁸ Uppsala University, ⁹ Tel Aviv University, ¹⁰ Fudan University, ¹¹ High Energy Accelerator Research Organization (KEK), ¹² Chung Ang University, ¹³ University of South Carolina, ¹⁴ University of Valencia, IFIC, ¹⁵ University of Oxford, ¹⁶ Institute of Modern Physics, CAS, ¹⁷ Shanghai Advanced Research Institute, CAS, ¹⁸ European Organization for Nuclear Research (CERN), ¹⁹ Institute of Theoretical Physics, CAS.

† Co-chairs.

* Attended meeting.

2 Executive summary

STCF will be unique facility with a broad and impressive physics reach. It will allow for results of world-leading precision in many important topics, and has significant discovery potential. It will ideally complement the other facilities that are currently operational or are foreseen for the 2030s and 2040s, and will be of great interest to the international particle physics community. The principal challenge of the project lies in the accelerator. Here the intended luminosity will exceed by two orders of magnitude that previously achieved in the same energy regime. The IAC is pleased to recognise the significant progress on the STCF accelerator design that has occurred since the establishment of a dedicated Accelerator Division led by Prof. J.Y. Tang. The demands on the detector are less formidable, but should not be underestimated given the extreme event rate and size of data samples foreseen.

报告总结： STCF将是具有**丰富物理潜能**的独特装置，将在多个重要课题上获得**世界领先**的精确结果，并具有**重大的发现**的潜力。它将在未来20年中**完美**与其他设施**互补**，受到国际粒子物理界**极大关注**。项目的主要挑战在于加速器。其预期的亮度将比现有相同能量范围实验的亮度高出两个数量级。STCF 加速器设计和团队建设取得的显著进展。探测器的要求考虑到预期的极高事件率和数据样本的规模，挑战性也不容低估

物理与探测谱仪

3.2 Recommendations

The IAC has the following recommendations for the ongoing studies in the areas of physics studies and detector design.

- The breadth of physics that can be studied at STFC is impressive. However, a subset of flagship measurements should be identified to define more emphatically the uniqueness and importance of the project. It is suggested that these measurements should be predominantly related to the determination of fundamental parameters, or tests of the Standard Model.
- The IAC notes the great interest of the measurements that can be performed with polarized beams, currently foreseen for an upgrade phase, and recommends that equipping the machine with polarization remains a high-priority goal of the project. The design of the machine should, from the start, allow for the inclusion of this attribute at a later stage of the project.
- The STFC team must convince the wider community that it will be possible to attain the necessary level of systematic control to match the foreseen statistical precision. Strategies should be developed and described for meeting this challenge for the flagship measurements.
- Full simulation studies of the flagship measurements should be performed to demonstrate that the detector choices are well suited to the physics goals.
- The performance of the tracking system, in particular, is critical for the success of the physics programme. Metrics such as tracking efficiency (particularly at low momentum) and resolution should be used to demonstrate that the system meets the physics requirements and is robust against background. Particular attention should be paid to the design of the ITK, e.g. its inner radius, how many space points should it provide, does the proposed design have sufficiently low mass?
- The IAC is pleased by the preliminary studies on the DAQ system, given the challenge presented by the enormous event rate, particularly at the J/ψ , and recommends that this item continues to receive high attention.
- The foreseen data volume per year is very substantial. Where will this be stored and processed, and how will it be accessed? What are the Monte Carlo simulation needs? A detailed computing strategy must be formulated.
- Greater attention should be given to the Machine-Detector Interface, where there must be a careful optimisation between the needs of the physics and the constraints of the accelerator. The IAC recommends that all parameters, in particular the low-angle acceptance of the detector, be carefully considered in this respect.

加速器

4.2 Recommendations

The IAC issues the following recommendations for the accelerator:

- Stop working on the present lattice and immediately begin working on the 800-900 m-long lattice, for three different energies; also, a review of the latest and most modern lattices on the market, such as the HEPS optics and Pantaleo Raimondi's FCC-ee lattice could be considered;
- Complete the simulations of beam lifetime, beam instabilities, and high-current/collective effects — the high-current effects may relate to RF, injection, impedance, lifetime, vacuum, beam chamber issues, and lattice design;
- Determine and optimize the performance as a function of beam energy;
- Define a baseline for the collider 500 MHz RF system (normal conducting (NC) KEK type, NC SLAC type, or SC);
- Include detector solenoid field, and lattice errors, in the beam-beam and luminosity performance simulations
- Carry out more background simulations — Touschek, beam-beam and injection backgrounds will have a big impact on the luminosity performance; background suppression by collimators and masks should be studied;
- Pursue experimental checks of the Touschek lifetimes at existing 3rd and 4th generation light sources;
- Explore possible relaxation of bunch-length constraint from the detector (TOF); if the bunch length constraint can be relaxed, study the possible use of harmonic cavities to lengthen and shape the bunches for improved Touschek lifetime;
- Simulations should be performed as soon as possible to decide if the dynamic and momentum apertures are sufficient for off-axis injection, otherwise the swap-out option requiring accumulation rings will need further R&D funding and studies (probably this option would be challenging to finalize in the short time scale of 2–3 years); also compare the feasibility of the two injection schemes in beam-beam simulations;
- Pay much more attention to, and perform a preliminary technical design of, machine protection, collimation scheme, precise beam measurement system of bunch by bunch, and fast feedback systems;
- In the TDR, civil engineering, heating, ventilation, air conditioning, cooling, and power sources should be considered;
- Design the layout so as to allow for later polarization and/or monochromatization; the final lattice, at least the CDR one, should include space for Siberian Snakes, even if this option is only for a later upgrade;
- Enlarge the accelerator team to include more experienced accelerator physicists from USTC and elsewhere to guide the young team already working on the project;
- Strengthen collaboration with BINP, KEK, and if possible IHEP, and engage in SuperKEKB beam commissioning and operation.

2 Executive summary

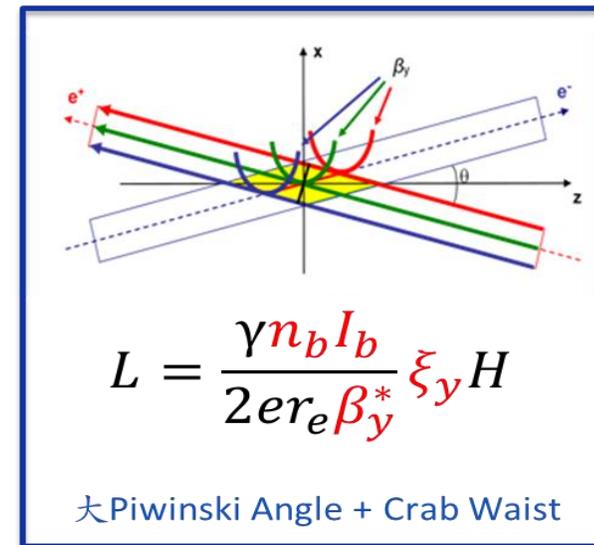
STCF will be unique facility with a broad and impressive physics reach. It will allow for results of world-leading precision in many important topics, and has significant discovery potential. It will ideally complement the other facilities that are currently operational or are foreseen for the 2030s and 2040s, and will be of great interest to the international particle physics community. The principal challenge of the project lies in the accelerator. Here the intended luminosity will exceed by two orders of magnitude that previously achieved in the same energy regime.

The IAC is pleased to note the significant progress made in physics, detector and accelerator studies since January. The STCF team intends to complete a Technical Design Report by the end of 2026. The IAC considers this an ambitious goal, but a feasible one, given the progress so far made. However, several critical items have been identified, which are discussed in the recommendations that follow.

报告总结： STCF将是具有**丰富物理潜能**的**独特装置**，将在多个重要课题上获得**世界领先**的精确结果，并具有重大的发现的潜力。它将在未来20年中完美与其他设施互补，受到国际粒子物理界**极大关注**。项目的主要挑战在于加速器。其预期的亮度将比现有相同能量范围实验的亮度高出两个数量级。IAC对项目在物理、探测器和加速器的**显著进展**表示高兴。项目组计划与2026年完成技术设计报告，有挑战性，也具有**可行性**。

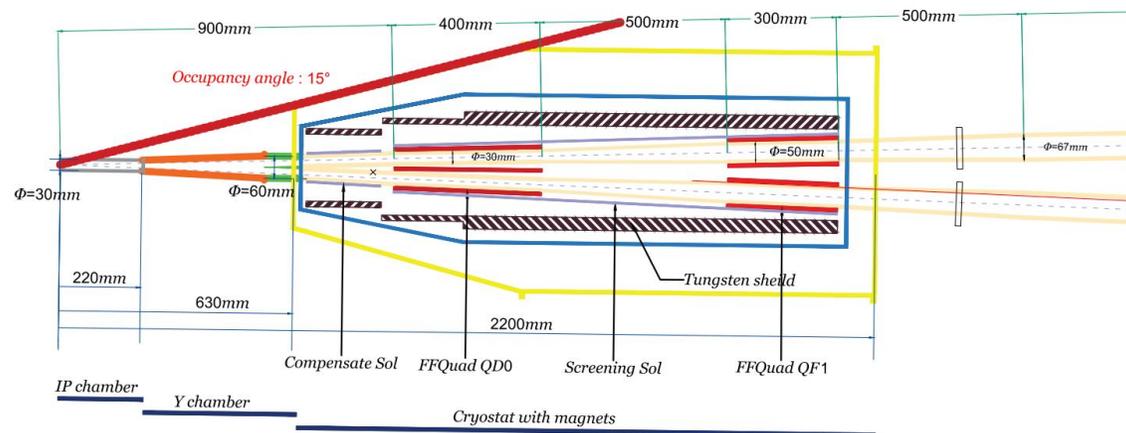
● 对撞环物理设计的主要挑战

- 第三代正负电子对撞机：亮度提升约**2个量级**（相对BEPcII），国际上无成熟经验，物理和技术上都**具有挑战**；
- **对撞区非常复杂**：双孔径强聚焦超导磁铁，严格的相移条件，强六极磁铁（色品校正和Crab-Waist），强边缘场，螺线管场，低本底要求
- 超强的**非线性效应**和**高阶效应**：动力学孔径很小，动量孔径很小
- **非常短的 Touschek 寿命**：目前做到约250 s（要求>200 s），是现有电子储存环中最低的（一般在小时量级）



● 主要关心的物理问题

- 增大**动力学孔径**和**动量孔径**（关键在对撞区）
- 提高**准直效率**，降低实验本底
- 大交叉角的**束束作用**及与其他物理过程的耦合
- 束流**集体不稳定性**（阻抗、快离子和电子云）
- **束流注入**（离轴注入和置换注入）
- **发射度阻尼**（大能量范围，阻尼扭摆磁铁）

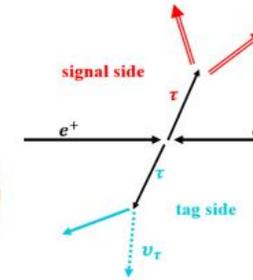
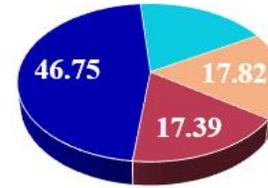


对撞区结构 (右侧)

- Signal side: $\tau \rightarrow 3 \text{ leptons}$
- Tag side: $\tau \rightarrow e\nu\bar{\nu}, \mu\nu\bar{\nu}, \pi\nu + n\pi^0$ ($\mathcal{B}r = 82\%$)
- Almost background free, sensitivity : $\mathcal{B}_{UL}^{90}(\tau \rightarrow \mu\mu\mu) \sim 1/\mathcal{L}$
- Best efficiency ($\tau \rightarrow \mu\mu\mu$): 22.5% (including the tag \mathcal{BF})

$$\mathcal{B}_{UL}^{90}(\tau \rightarrow \mu\mu\mu) < \frac{N_{UL}^{90}}{2\epsilon N_{\tau\tau}} \sim 1.4 \times 10^{-9}$$

■ electronic ■ muonic
■ pionic 1-prong ■ others



Model	Ref.	$\tau \rightarrow \mu\gamma$	$\tau \rightarrow \mu\mu\mu$
SM + heavy majorana	PRD 66.034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547(3)252	10^{-9}	10^{-8}
SUSY + seesaw	PRL 89:241802	10^{-10}	10^{-7}
SM + 4 th generation	arXiv.1006.5306	10^{-8}	10^{-8}

- The cLFV decays of vector mesons $V \rightarrow l_i l_j$ are also predicted in various of extension models of SM^[1]:

$$\mathcal{B}_{UL}^{90}(J/\psi \rightarrow e\mu) < 10^{-13}$$

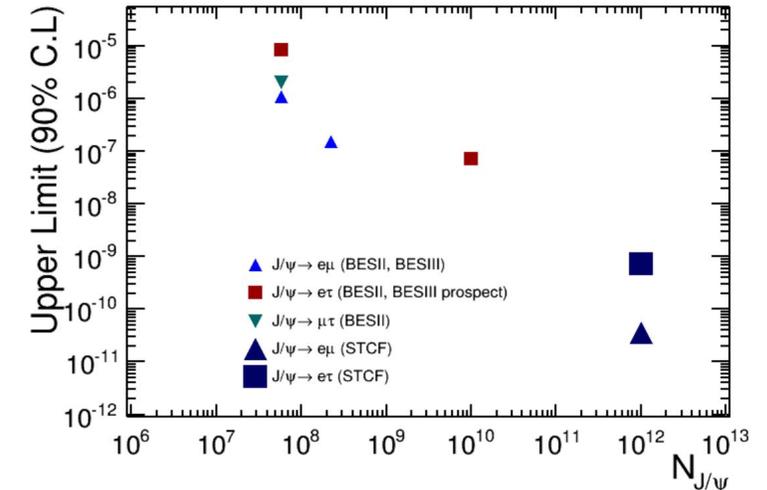
$$\mathcal{B}_{UL}^{90}(J/\psi \rightarrow e(\mu)\tau) < 10^{-9}$$

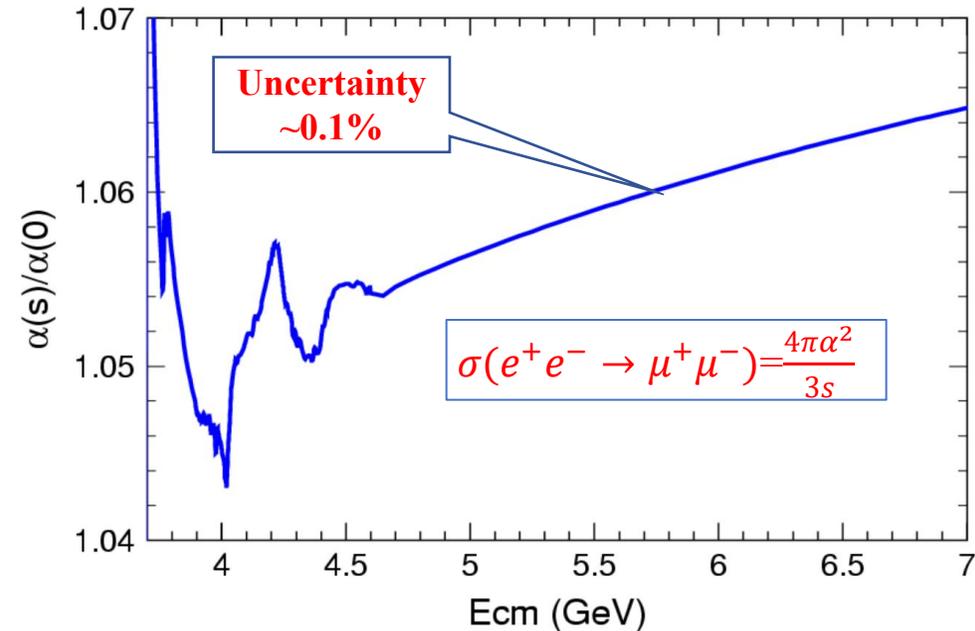
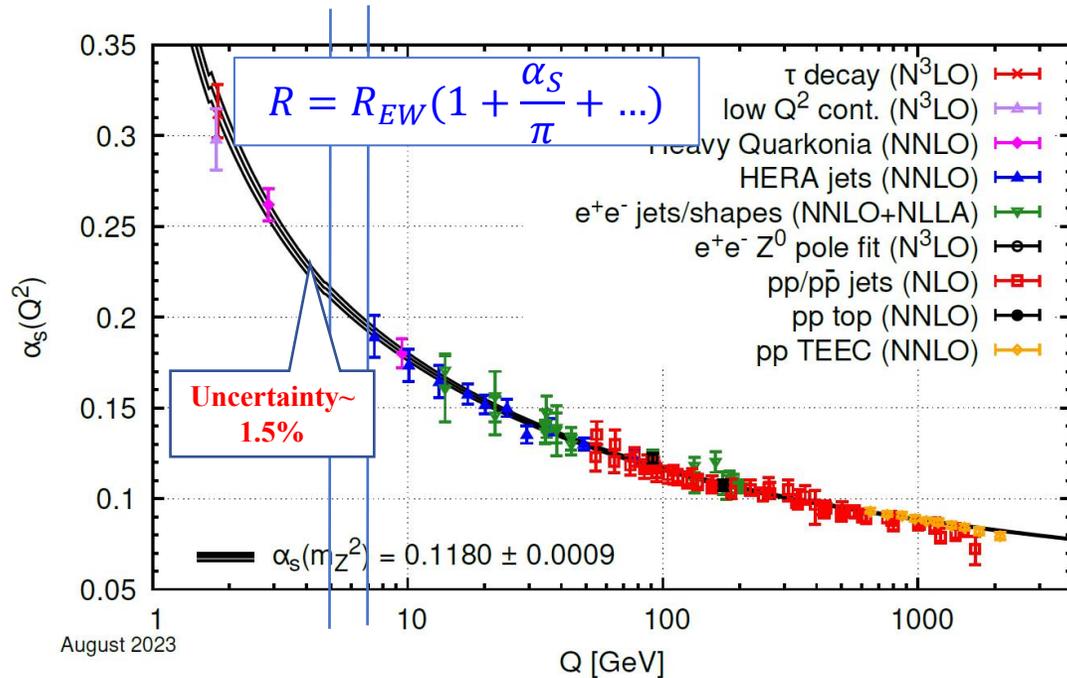
- At STCF, 1 trillion J/ψ can be obtained per year, taken efficiency from BESIII, the upper limit can be predicted to be:

$$\mathcal{B}_{UL}^{90}(J/\psi \rightarrow e\mu) < 3.6 \times 10^{-11}$$

$$\mathcal{B}_{UL}^{90}(J/\psi \rightarrow e\tau) < 7.1 \times 10^{-10}$$

- The $\mathcal{B}_{UL}^{90}(J/\psi \rightarrow e\tau)$ can be further optimized with better PID.





- finding invisible states in e^+e^- annihilation: Compare α_{QED} from $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ and that calculated from $\sigma(e^+e^- \rightarrow \text{hadrons})$
- $\sigma(e^+e^- \rightarrow \text{hadrons})$ & $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$
 - 100 fb⁻¹ data (~1 month @ $L_{\text{peak}} \sim 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$) \rightarrow
 - 2-4 x 10⁶ $e^+e^- \rightarrow \mu^+\mu^-$ events \rightarrow 0.2% or better precision?
 - 7-14 x 10⁶ $e^+e^- \rightarrow \text{hadrons}$ events \rightarrow 0.4% or better precision?
 - Bhabha or $e^+e^- \rightarrow \gamma\gamma$ for integrated luminosity measurements

● 对撞区超导磁铁技术路线

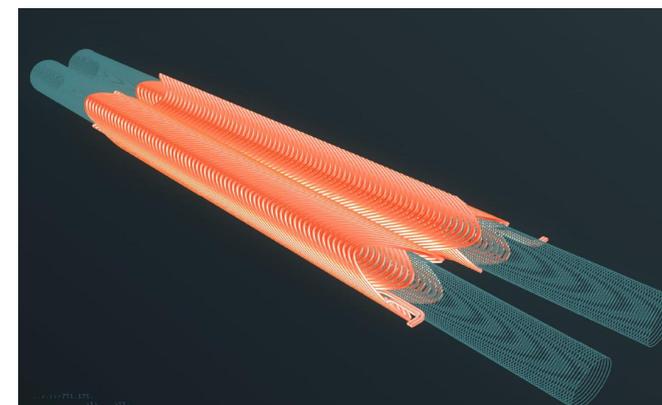
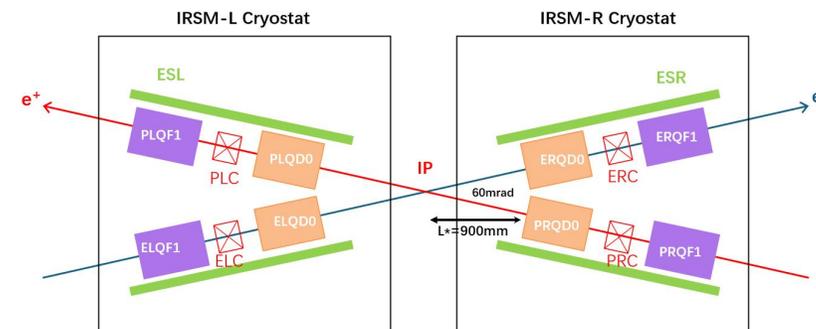
- 新一代对撞机最**具有挑战性的**技术
- 已有超导磁铁类型: CCT, Cos 2θ , DCT, 蛇形绕线
- 经概念设计和评审: 选择**CCT**作为样机研发技术路线

● 难点

- 物理设计和MDI要求 (苛刻)
- 极狭小的空间 (60mrad小分离角下的双孔径)
- 高场质量 (50T/m, 2×10^{-4} , Cross-talk: 2 Gs)
- 复合型磁铁: 屏蔽螺线管, 补偿螺张管, 校正磁铁和高阶场线圈

● 样机研制

- QD0 (最难) 的**电磁设计完成**; 线圈**骨干试加工**; 超导线材已购买
- **工艺试绕**即将开始



● 对撞环和阻尼环/累积环

- 对撞环：技术挑战，很高RF功率，深度高次模(HOM)抑制，低R/Q值
- 阻尼环/累积：频率相同但技术要求低

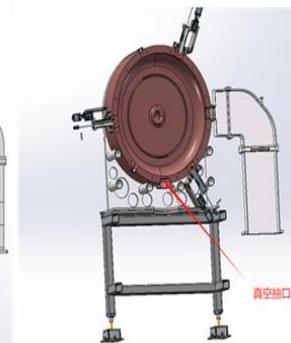
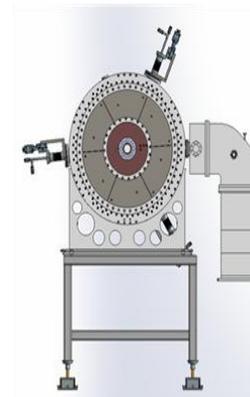
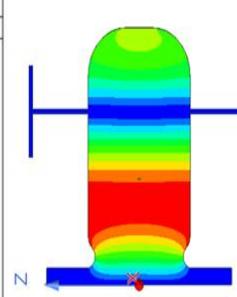
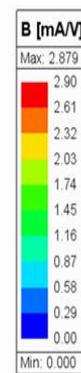
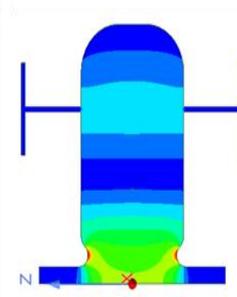
● 选择500MHz常温TM020模腔

- 具有技术优势：低腔耗，HOM抑制易实现，R/Q低
- 难点：加工工艺复杂，高功率耦合器(300kW)有难度
- 国内缺少经验，国际上可借鉴少（更高指标）

● R&D进展

- 已完成：方案设计，技术设计，腔体加工招标
- 2025年底：完成腔加工和装配
- 2026年上半年：高功率测试

RF parameters	
Working mode	TM020
Frequency [MHz]	499.7
R/Q [Ω]	95
Unloaded quality factor	63000
E_p/E_{acc}	2.48
B_p/E_{acc} [mA/V]	2.88

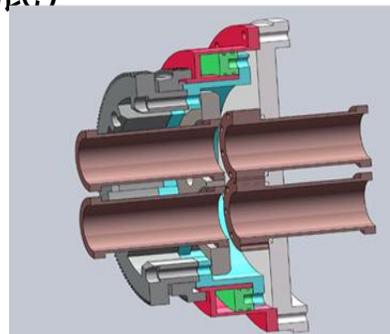


● MDI相关的物理问题

- MDI关连：加速器（对撞区物理、超导磁铁、机械、束测、真空、准直）和谱仪（实验本底、内层探测器）
- 对撞区光学：元件布局 and 空间限制，孔径
- 实验本底抑制：束流损失和准直，真空韧致辐射
- 超导磁铁保护：束流损失和准直，真空韧致辐射
- 真空盒结构：耦合阻抗
- 同步辐射负载：同步光挡块和冷却

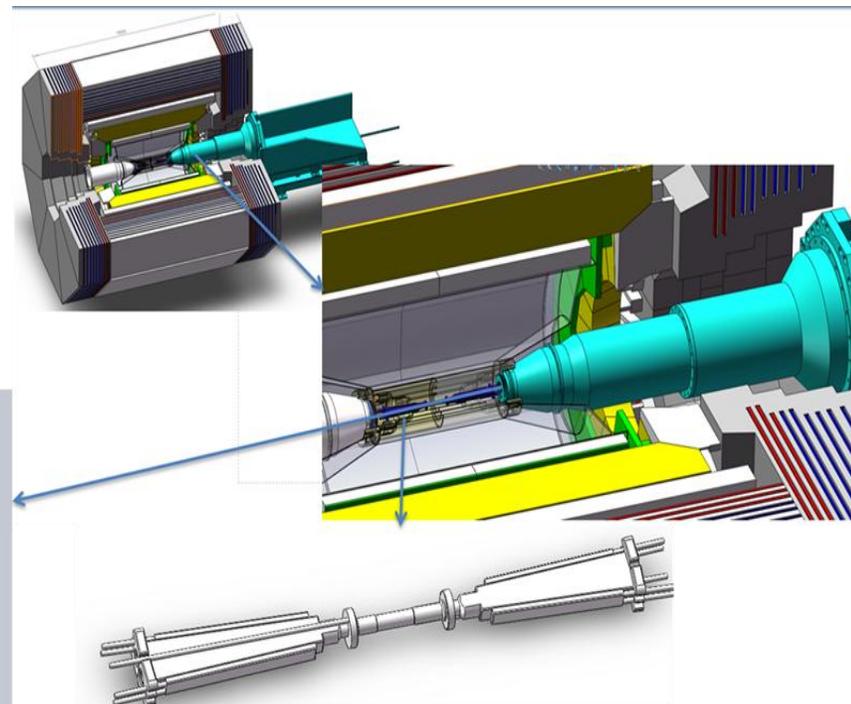
● MDI难点

- 结构复杂，涉及到多个系统（加速器物理、超导磁铁、机械、束测、真空、准直、谱仪探测器和实验本底）
- 空间极其受限
- 严格控制实验本底，亮度监测和反馈
- 中心束流管技术复杂（双层铍管，通冷却液）
- 真空抽气和连接困难
- 准直安装要求特殊（空间条件，低温）



● STCF正在采取的措施

- 加强多系统的沟通设计
- 对关键技术进行攻关
- MDI机械集成样机设计和制造

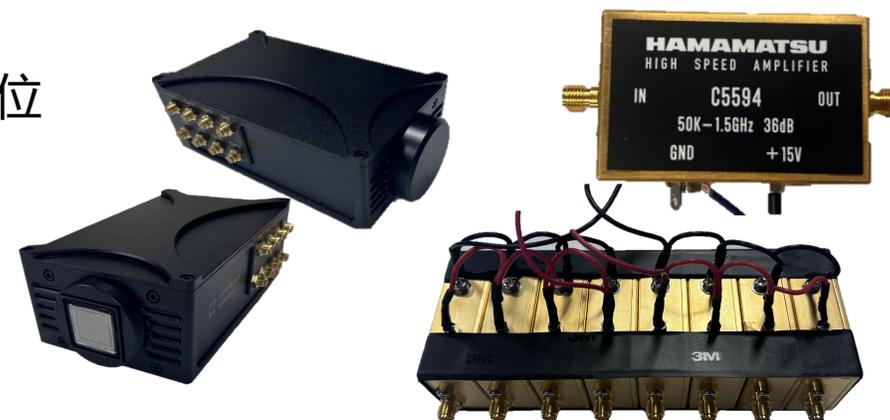


● 对束流测量的关键要求

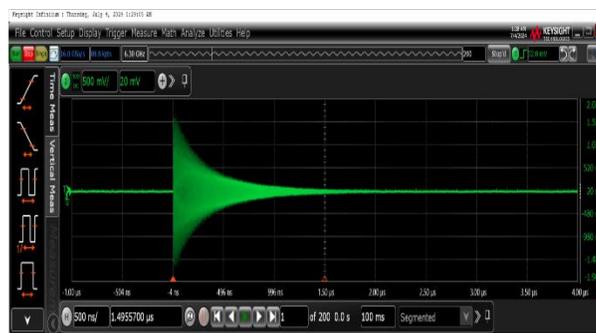
- 对撞环：逐束团3D位置测量，横向位置测量 $< 5\mu\text{m}$ ，纵向相位 $< 0.2\text{ps}$ ；快速逐束团反馈；对撞点位置反馈
- 注入器：束团长度和电荷量精确测量
- 与物理设计进行迭代

● R&D进展

- 束团3D位置测量：完成系统设计，准备束流实验
- 逐束团快速反馈：完成自研反馈处理器设计，完成国产功率放大器的测试
- 注入器束团长度和电荷：完成第一版样机的离线和在线测试，分辨率满足要求



谐振腔
探头



在大连光源上进行的束长测量



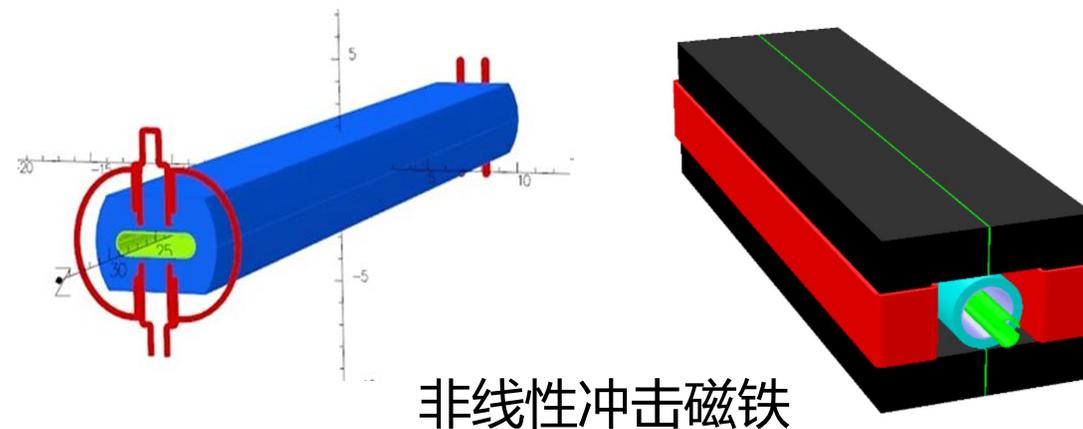
逐束团截面测量数据处理器：
光电探头, DAQ

● 技术设计与物理设计的迭代

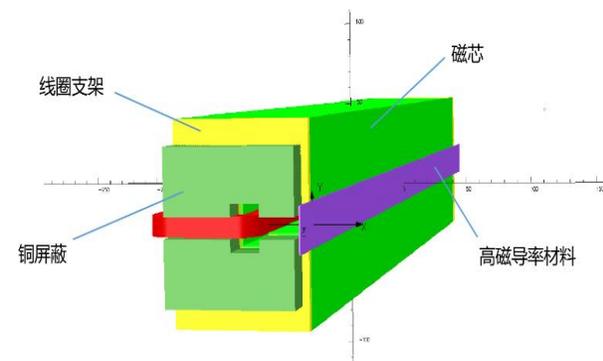
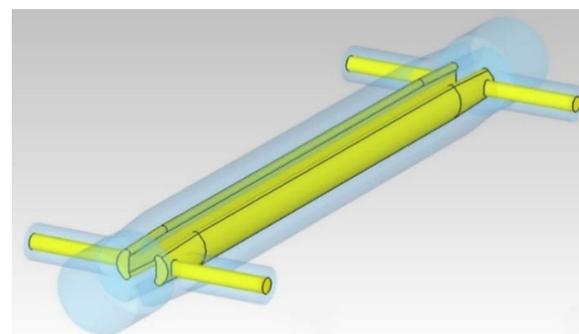
- 对撞环/累积环离轴注入：传统凸轨型冲击磁铁，**非线性冲击磁铁**
- 对撞环置换注入：**超快冲击磁铁** (条带型, 底宽<6ns)
- 引出：(对应置换注入)逐束团引出，机器保护全束团引出
- 注入切割磁铁：涡流型 (薄切割板)
- 反切割磁铁

● R&D进展

- **非线性冲击磁铁**和**超快冲击磁铁**的加工和采购进行中
- 2025年底进行测试



非线性冲击磁铁

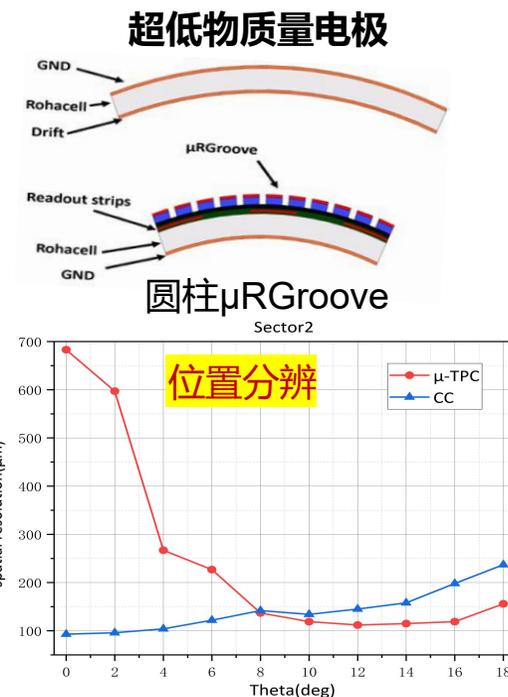
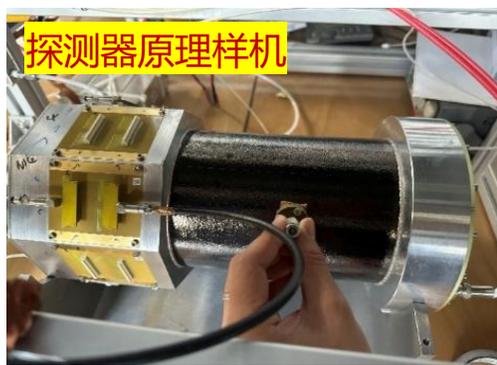
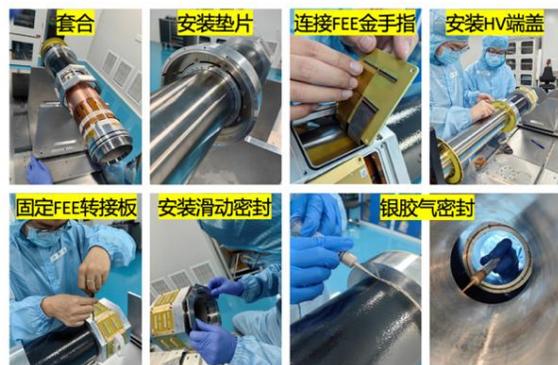


超快冲击磁铁

气体内径迹探测器

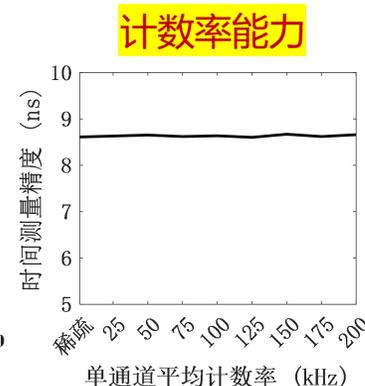
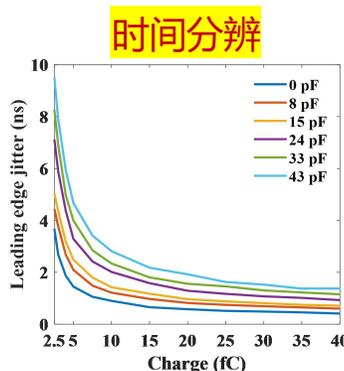
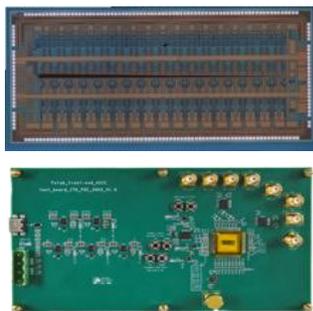


- 提出一种新型的单级放大微结构气体探测器：**阻性微槽型探测器** ($\mu\text{RGroove}$)，具有更好的加工性能和更强的信号，成为基准技术方案。
- 研制出了**圆柱形 $\mu\text{RGroove}$ 原理样机**：质量 $\sim 0.23\%X_0$ ，同类探测器最好水平；在CERN进行了束流测试，大角度入射下的位置分辨 $\sim 100\mu\text{m}$ 。

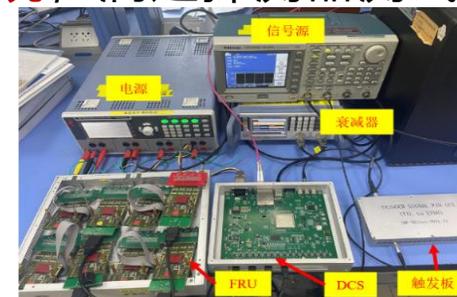


- 读出ASIC芯片：完成了32通道模数混合原型芯片设计和流片。

ASIC Specs	Demands
Charge Range	40 fC
Charge precision	~ 1 fC RMS
Time precision	< 10 ns RMS
Max. event rate	4 MHz



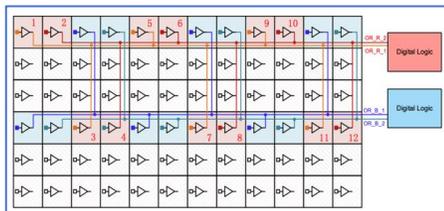
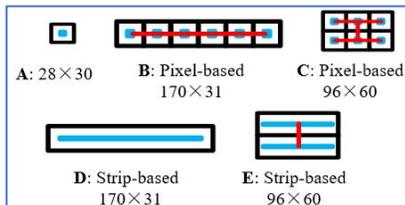
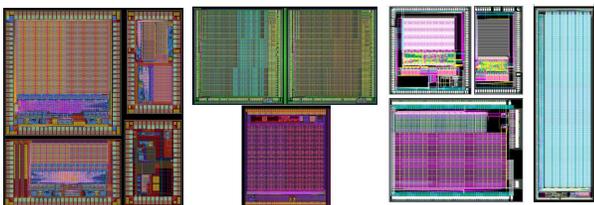
- 研制了基于APV25的**1024路读出系统**，满足探测器测试需求。



硅像素内径迹探测器

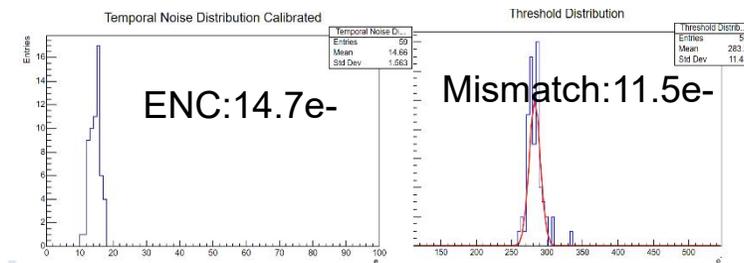
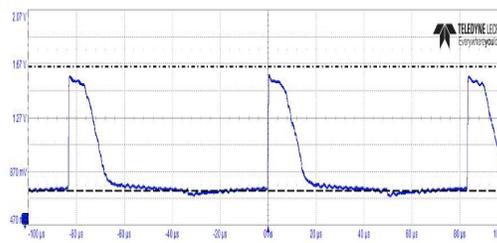
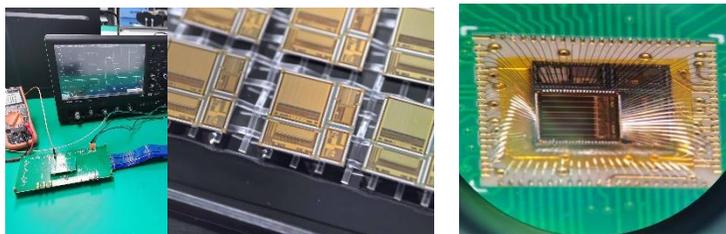


- 探索长条像素和超级像素设计，进行MAPS传感器的建模仿真，基于三种不同工艺完成了原理验证MAPS芯片的设计。要求：位置、时间和电荷测量；功耗 $<100\text{mW}/\text{cm}^2$ ；单层物质质量 $\sim 0.3\%X_0$

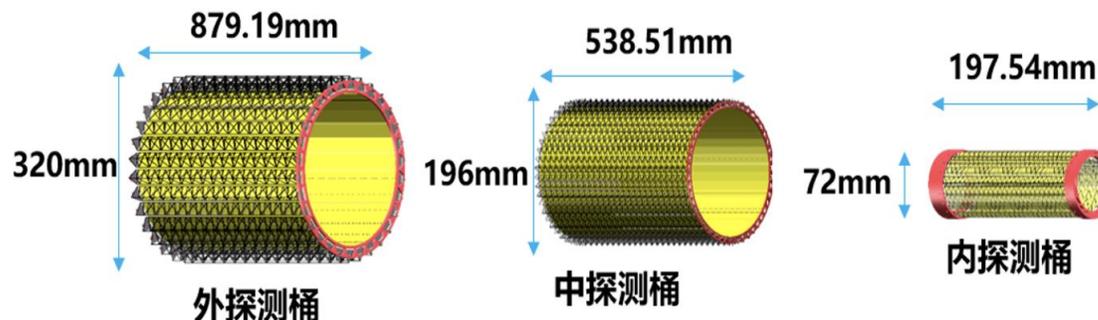


- 国外180nm工艺，四阱，高阻外延层
- 国内90nm CIS工艺，三阱，低阻外延层
- 国内130nm工艺，四阱，高阻衬底

- 均已投片。180nm国外工艺原型芯片已回片，经初步测试，芯片功能正常，性能基本符合预期。



- 开展了MAPS探测器模块结构设计与集成研究：模块的静态形变与散热仿真分析，探测器模块的组装试验。



- 完成了超小单元(2.5mm丝间距)漂移室设计方案, 初步机械结构与仿真, 超小单元**定位子**设计与试制, **拉丝**方法和丝张力测量技术, 丝的选型与张力蠕变效应测试。设计并加工了一个超小单元漂移室**全长(2.5m)样机**, 正在进行布丝工作; 此外正在开展小单元漂移室**老化实验**。

漂移室设计

Index	Super layers	the Cell number of per super layer	Cell size	locate
A	6	256	5.09~5.76	205
U	6	256	6.05~6.84	
V	6	256	7.16~8.09	
A	6	256	8.45~9.55	
U	6	256	10.44~11.80	420
V	6	320	9.77~10.78	
A	6	352	10.09~11.03	
U	6	400	9.97~10.78	
V	6	432	10.22~10.99	
A	6	464	10.46~11.35	833

定位子

- BESIII feedthroughs
- BELLEII feedthroughs
- STCF feedthrough V1: Copper tubes, Tested discharging
- STCF feedthrough V2: Aluminum tubes, Tested wire stringing
- STCF feedthrough V3: Reduced size
- STCF feedthrough V4: Optimized signal connection
- STCF feedthrough V5: Insulated design, Electrode connection

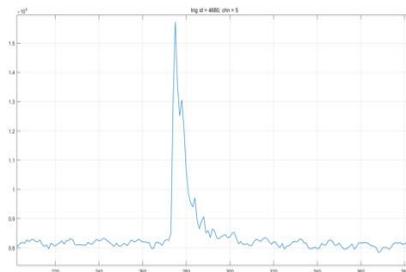
拉丝与全长样机

- 研制了基于分立元件的**波形采样原型读出电子学**, 与探测器开展了多次联合测试。提出并开发了基于波形积分曲线的**波形分辨算法**。完成了读出**ASIC芯片**前放部分的第一版设计和流片, 正在测试中。

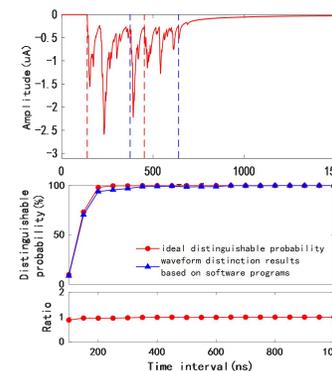
波形采样读出电子学



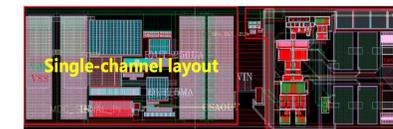
电子学与漂移室联测



波形分辨算法



读出ASIC设计与测试

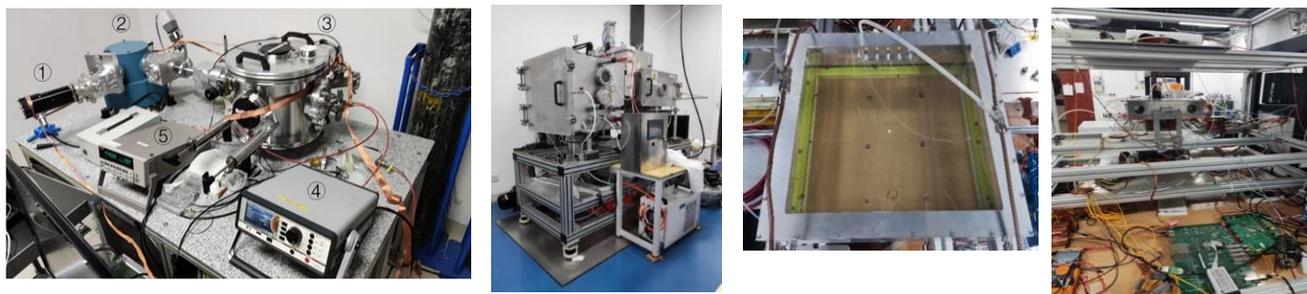


桶部粒子鉴别探测器

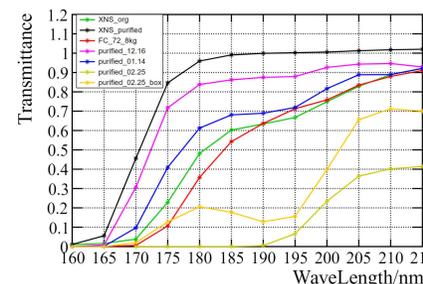


- 建立了液体**辐射体循环纯化**、透过率在线测试、封装及性能测试系统，**大面积CsI光阴极制备系统**，制备了大面积光阴极。建立了小面积光阴极测试系统，并正升级到大面积系统。研制了**大面积(32cm×32cm)RICH探测器原理样机**，并开展了宇宙线测试，但性能未达到预期，需进一步研究。与氟化物生产厂家合作，改进生产工艺，液体辐射体样品透过率基本达标，并在继续提升。

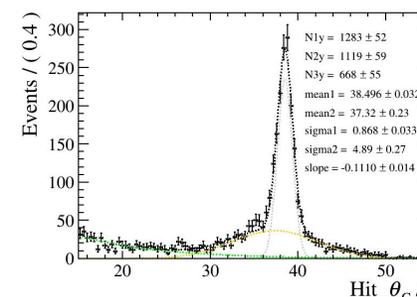
辐射体透过率和量子效率测试 CsI光阴极制备 大面积RICH样机及宇宙线测试



C₆F₁₄辐射体透过率

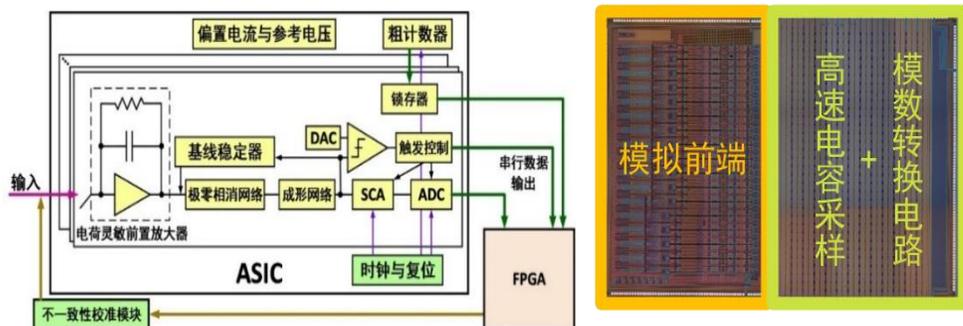


RICH样机单光子角分辨

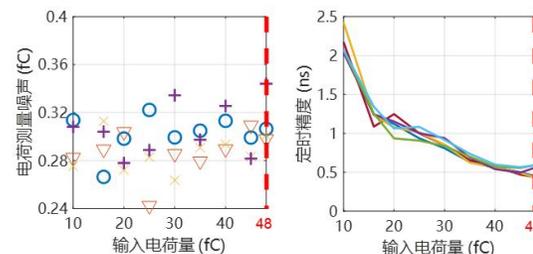


- 完成了**读出ASIC芯片一阶段(32通道)**和**二阶段(64通道)**的设计，完成了关键模块验证和原型**读出电子学系统(512路)**的设计与制作。原型芯片和电子学系统的测试性能满足设计指标。

读出ASIC芯片设计与测试



噪声~0.3 fC, 定时精度 ~1 ns @ 20 fC
(输入电容≤ 20 pF, 计数率>50kHz)



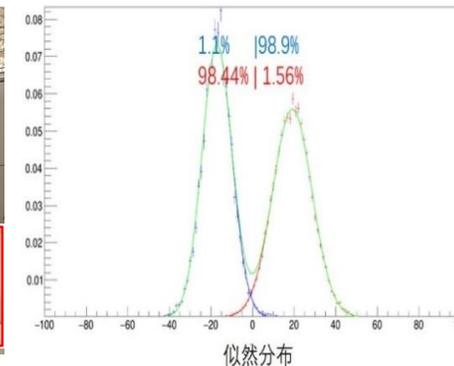
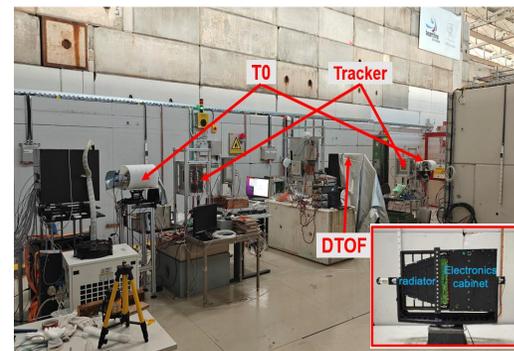
基于自研ASIC的读出电子学系统



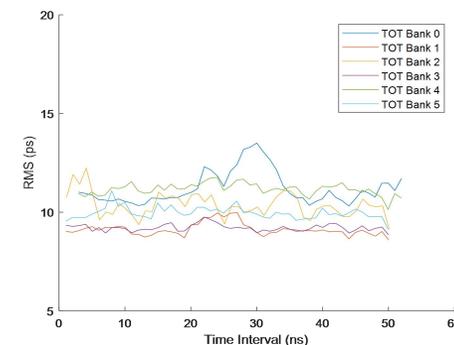
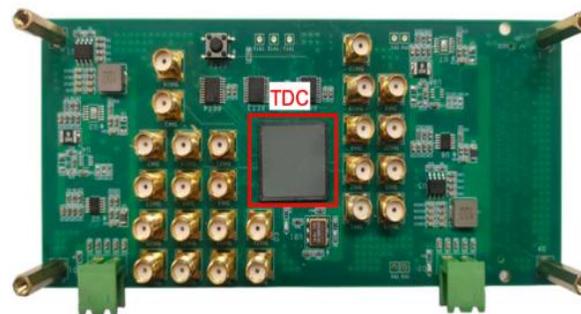
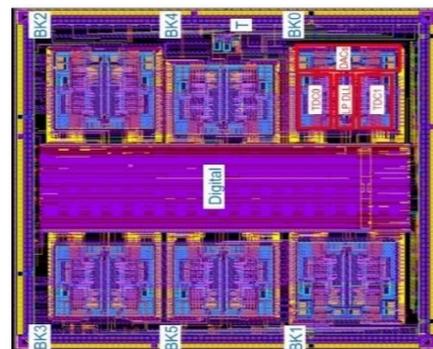
端盖粒子鉴别探测器



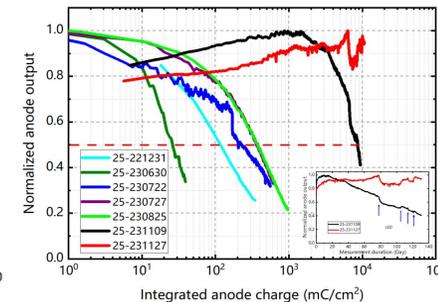
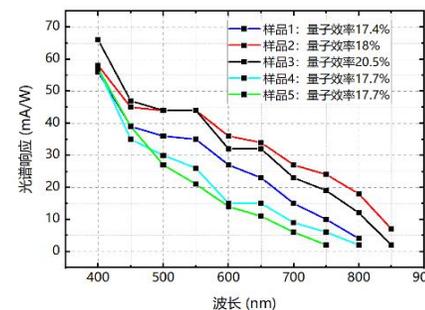
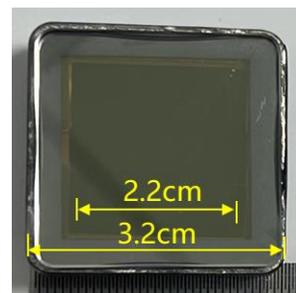
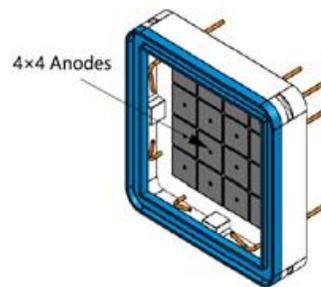
- 完成**DTOF全尺寸样机**的宇宙线测试和1/3样机的束流测试，单径迹时间分辨 $<25\text{ps}$ ，探测效率 $>95\%$ ，对 $4\text{GeV}/c$ 的 π/p （对应 $2\text{GeV}/c$ 的 π/K ）的鉴别能力 $>4\sigma$ ，满足需求。完成了**桶部DTOF方案**设计与模拟，预期性能满足要求。



- 完成**672通道**的分立元件**读出电子学系统**，定时精度 $<20\text{ps}$ ，实现了全尺寸样机的全读出。完成**TDCv1**和**FETv1**两款**ASIC**的设计、流片和测试，定时精度分别好于 15ps 和 10ps ，均实现预期指标。

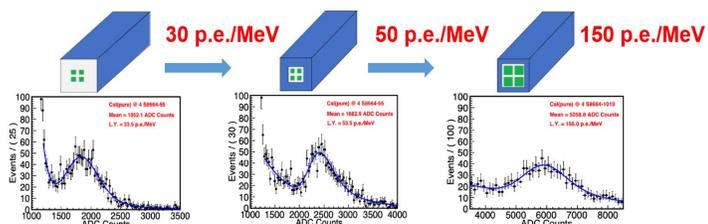


- **国产化微通道板光电倍增管** (MCP-PMT) 实现**长寿命突破**，累积阳极电荷 $>11\text{C}/\text{cm}^2$ 时量子效率损失 $<10\%$ ；**峰值量子效率** $>20\%$ ，单光子**平均增益** $>10^6$ 。

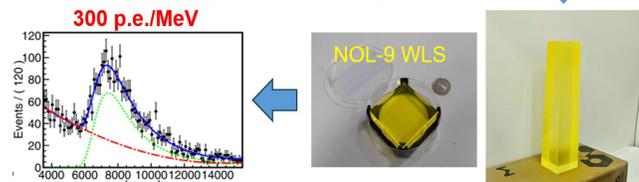


探测器研发

- pCsl晶体探测单元光输出产额优化：发射层材料、包装方式、喷涂波长位移剂。
比国际同类工作高2倍以上。



技术创新：用波长位移剂喷涂晶体表面

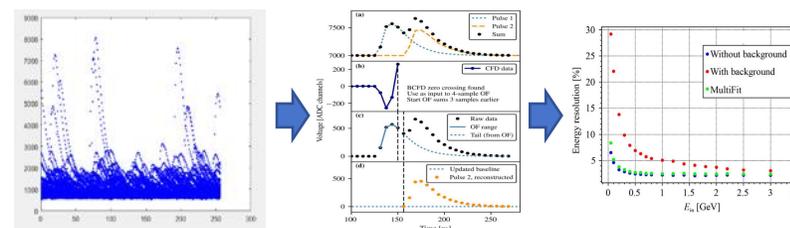
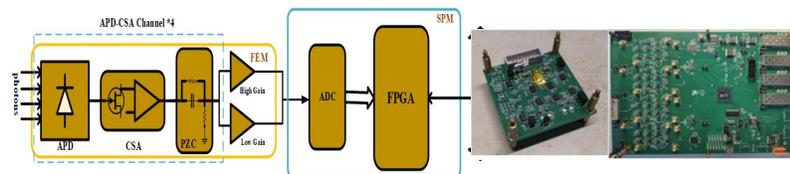


pCsl crystal & APD (S8864-1010)

光输出产额 > 200 pe/MeV

读出电子学研发

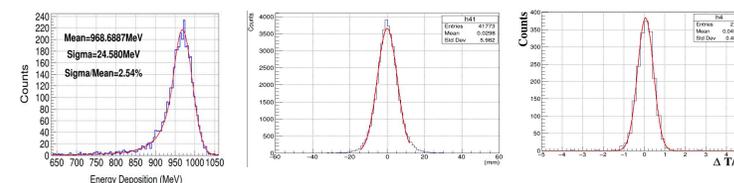
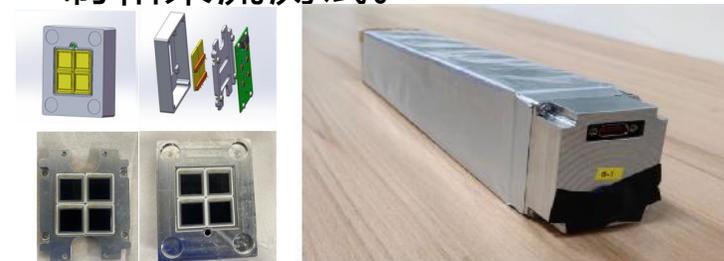
- 低噪声大动态范围读出电子学研制：电荷灵敏、双增益、舍去成形电路改用数字滤波、时幅信息在线提取
- ~MHz计数率下流水线式实时去堆积算法研究与成功实施。



噪声水平 < 1MeV, 动态范围 > 3000, 时间分辨 ~140ps @ 1pC

样机研制

- 5 × 5 晶体阵列量能器样机研制和束流测试。

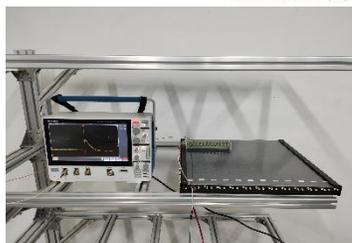
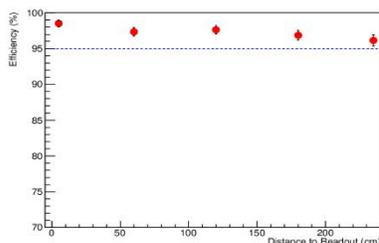
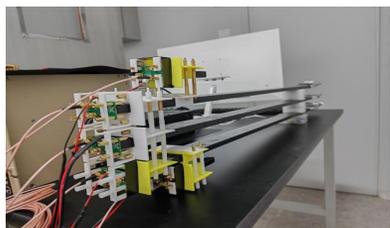


能量分辨率2.5%，位置分辨5.3mm，时间分辨390ps @ 1GeV电子

塑闪探测器

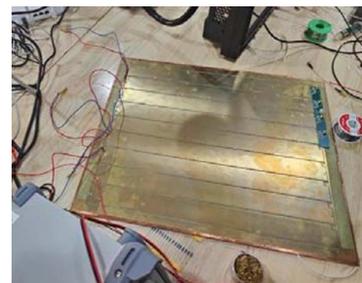
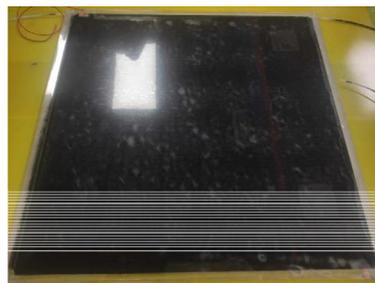
(塑闪条+内嵌光纤+SiPM)

- 探测单元设计与工艺研究：反射层、光纤槽、光学耦合、表面处理，研制2.4米长探测单元，效率>95%
- 研制了50cm*50cm平板样机



玻璃RPC探测器

- 研究了玻璃RPC制作工艺，制作了40cm*40cm的探测器原型。
- 开展基于新型低阻玻璃的RPC探测器研究，以提升计数率能力，成功试制了小面积探测器原型。



读出电子学

- 研制前端放大器及适配板，开发板级电子学，与探测器联调。
- 针对不同输入电容，设计了多款电荷增益不同的前端ASIC，并完成流片，正在测试。

