超级陶粲装置综述

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第三届“有道真论”理论物理前沿研究与教学研讨会
2025年12月5-8日，山东 济南

目录

- 超级陶粲装置
- 物理目标
- 关键技术预研
- 项目推进和现状
- 总结和展望

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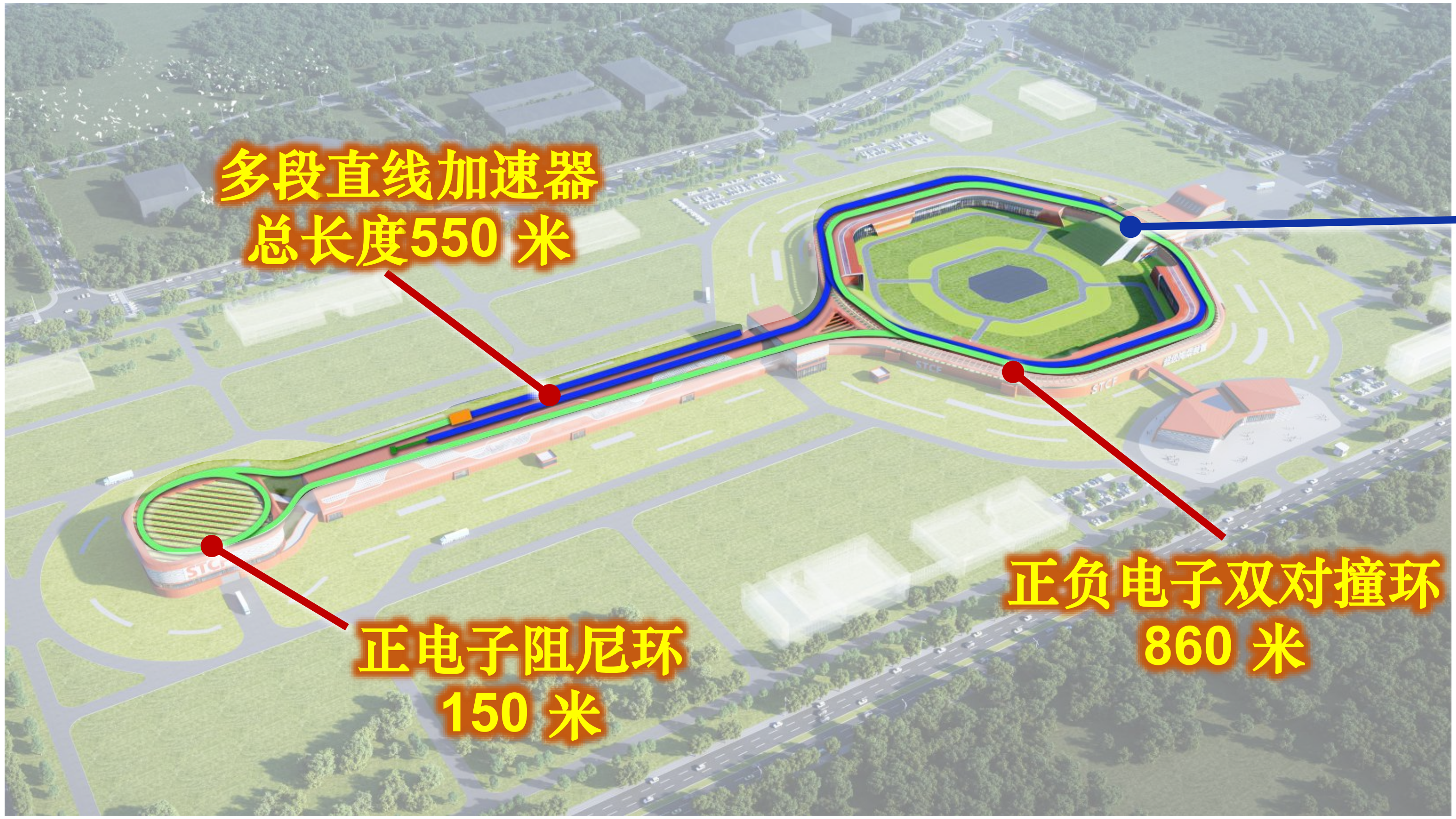
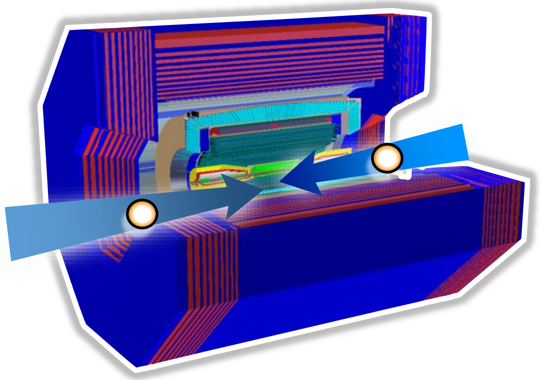
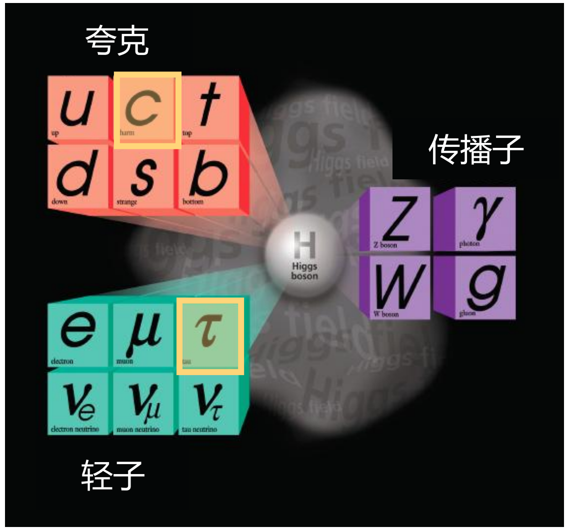
新一代大科学装置：超级陶粲装置

第三代正负电子对撞机，国际粒子物理领域高亮度前沿核心装置之一
研究夸克如何形成物质和基本相互作用对称性的独特平台





粒子探测谱仪

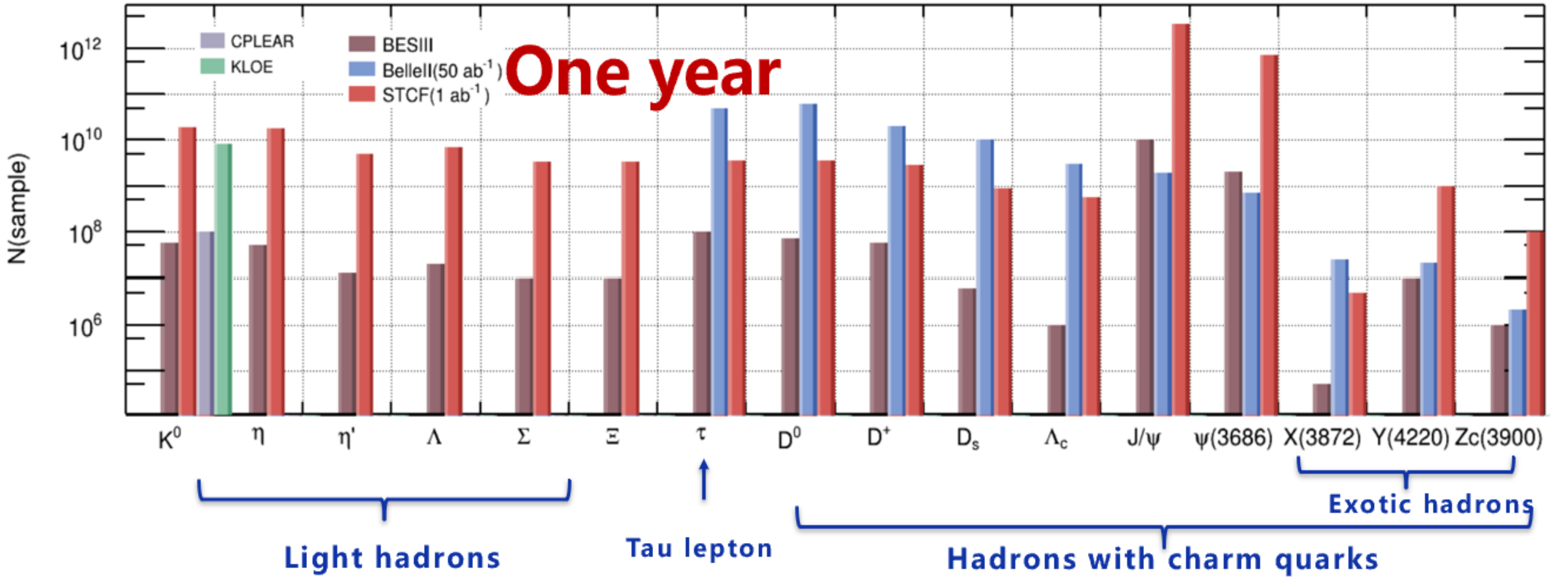


超宽连续可调能量：2 ~ 7 GeV，超高亮度：0.5×10^{35} cm^{-2} s^{-1}

强子化效应最为显著能区，相比其他对撞机有不可比拟的优势

STCF的预期事例数

- STCF能够产生**万亿级ψ样本**，**数十亿粲强子对和陶轻子对**，以及**大量的XYZ粒子**
- STCF具有**质心能量连续可调**，**成对阈值产生**，**量子关联**等独特性质



CME (GeV)	Lumi (ab^{-1})	Samples	σ(nb)	No. of Events	Remarks
3.097	1	J/ψ	3400	3.4×10^{12}	
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^{9}	
3.686	1	$\psi(3686)$	640	6.4×10^{11}	
		$\tau^+\tau^-$	2.5	2.5×10^{9}	
		$\psi(3686)\to\tau^+\tau^-$		2.0×10^{9}	
3.770	1	$D^0\bar{D}^0$	3.6	3.6×10^{9}	
		$D^+\bar{D}^-$	2.8	2.8×10^{9}	
		$D^0\bar{D}^0$		7.9×10^{8}	Single tag
		$D^+\bar{D}^-$		5.5×10^{8}	Single tag
		$\tau^+\tau^-$	2.9	2.9×10^{9}	
4.009	1	$D^{*0}\bar{D}^0 + c.c$	4.0	1.4×10^{9}	$CP_{D^0\bar{D}^0} = +$
		$D^{*0}\bar{D}^0 + c.c$	4.0	2.6×10^{9}	$CP_{D^0\bar{D}^0} = -$
		$D_s^+D_s^-$	0.20	2.0×10^{8}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.180	1	$D_s^{+*}D_s^-$+c.c.	0.90	9.0×10^{8}	
		$D_s^{+*}D_s^-$+c.c.		1.3×10^{8}	Single tag
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
4.230	1	$J/\psi\pi^+\pi^-$	0.085	8.5×10^{7}	
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
		$\gamma X(3872)$			
4.360	1	$\psi(3686)\pi^+\pi^-$	0.058	5.8×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.420	1	$\psi(3686)\pi^+\pi^-$	0.040	4.0×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.630	1	$\psi(3686)\pi^+\pi^-$	0.033	3.3×10^{7}	
		$\Lambda_c\bar{\Lambda}_c$	0.56	5.6×10^{8}	
		$\Lambda_c\bar{\Lambda}_c$		6.4×10^{7}	Single tag
		$\tau^+\tau^-$	3.4	3.4×10^{9}	
4.0–7.0	3	300-point scan with 10 MeV steps, 1 fb^{-1}/point			
> 5	2–7	Several ab^{-1} of high-energy data, details dependent on scan results			

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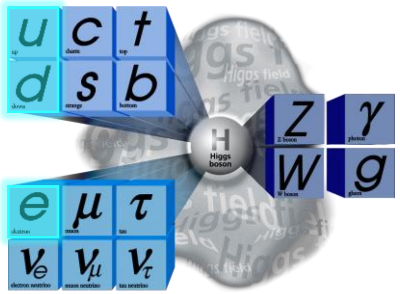
粒子物理重大科学问题

粒子物理的标准模型取得了巨大成功

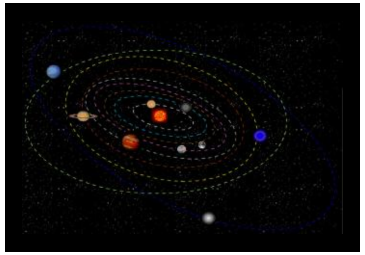
夸克



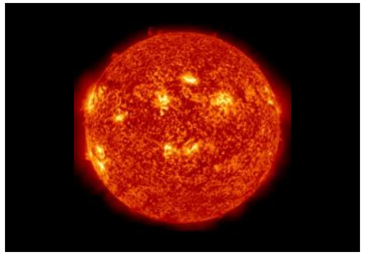
力传播子

轻子

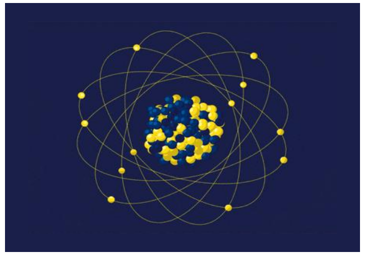
质子和中子由第一代夸克构成
与电子构成稳定的物质世界



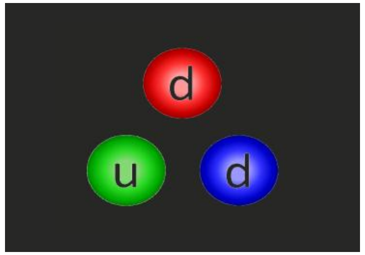
万有引力
Gravity
Magnitude = 1



弱相互作用力
Weak Force
Magnitude = 10^{25}



电磁力
Electromagnetism
Magnitude = 10



强相互作用力
Strong Force
Magnitude = 10^{38}

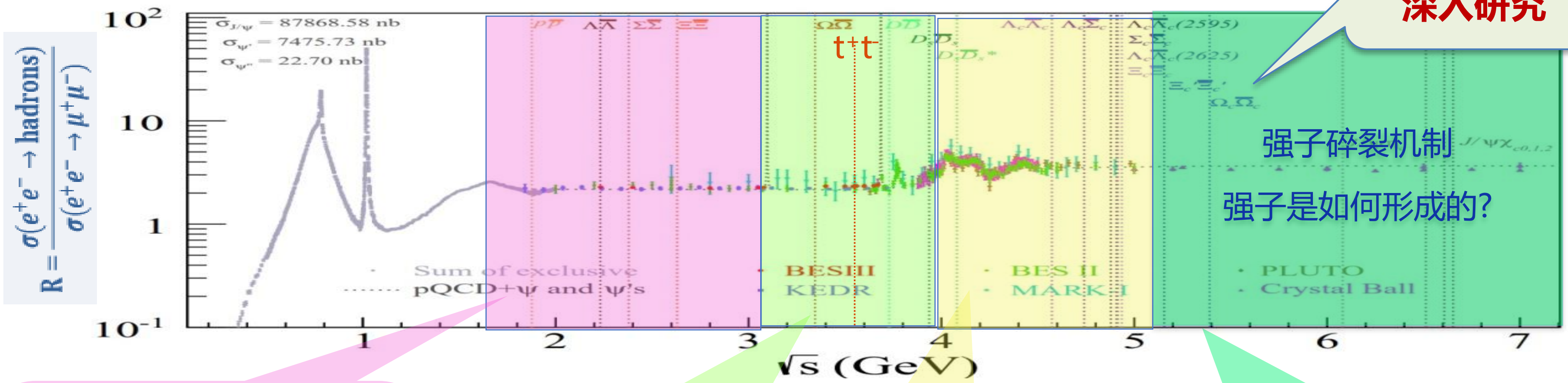
标准模型面临的重大挑战

- 为什么宇宙正反物质不对称?
- 夸克如何形成物质?
- 物质深层次结构是什么?
- 夸克为什么囚禁在物质中?

诺贝尔奖得主 David Gross:
夸克形成物质的过程（强子化）
是量子场论重大未解决难题

陶粲能区物理

- 微扰与非微扰**量子色动力学**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
- Mutltiquark states with s quark
- MLLA/LPHD and QCD sum rule predictions

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

- XYZ particles
- Physics with D mesons
- f_D and f_{Ds}
- D_0-D_0 mixing
- Charm baryons

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

基本对称性检验

超子和陶轻子CP破坏

$K^0 - \bar{K}^0$系统CPT对称性

轻子味破坏等

探索色禁闭之谜

强子谱和强子结构

碎裂函数和能量关联

基本物理量精确测量

R值、陶质量

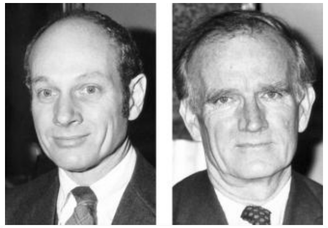
电磁、强跑动耦合常数

CKM矩阵元

基本对称性检验

- **时空分立对称性**的守恒和破坏在了解**宇宙演化和自然规律**中起着非常重要的作用。目前已知空间宇称P，时间反演宇称T，电荷宇称C以及CP联合变换对称性的**破缺已被实验证实**。
- **电荷宇称（CP）不对称性**是形成正反物质不对称的三大**必要条件**之一，历史上两次CP不对称性研究突破都**获得诺奖，但仍然**无法解释正物质多于反物质的谜团，亟需寻找超出标准模型CP不对称性的新来源。
- STCF将产生**高统计量**的J/ψ和ψ(2S)粲偶素粒子、粲强子、超子、陶轻子和轻介子 (K, *η*, *η*′)等，能够从**多个方面**对各种对称性进行精确检验。

*K*介子CP破坏[1]	*B* 介子CP破坏 [2,3]	*D*介子CP破坏 [4]	B重子CP破坏 [5]
1964实验发现K介子	1973理论预言，2001实验证实	2019实验发现	2025实验发现



Nobel Prize 1980

BELLE BABAR

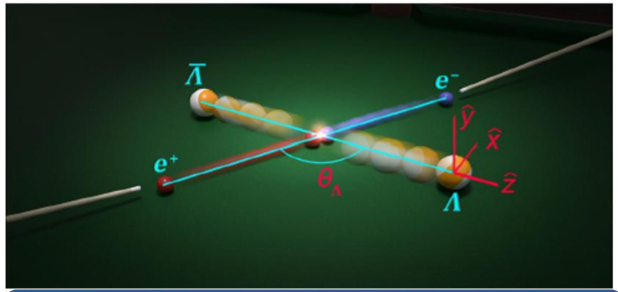
Nobel Prize 2008

LHCb

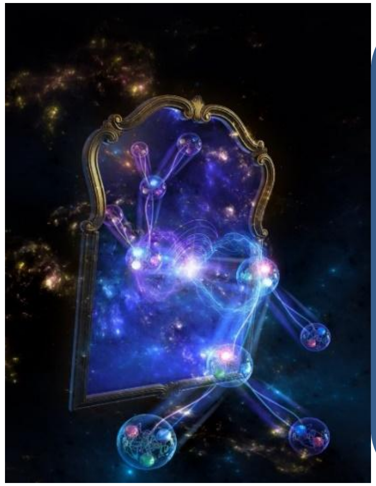
[1] Phys. Rev. Lett., 1964, 13: 138-140
[2] Phys. Rev. Lett., 2001, 87: 091801
[3] Phys. Rev. Lett., 2001, 87: 091802
[4] Phys. Rev. Lett., 2019, 122(21): 211803
[5] arXiv:2503.16954, 2025

STCF上超子CP对称性检验优势

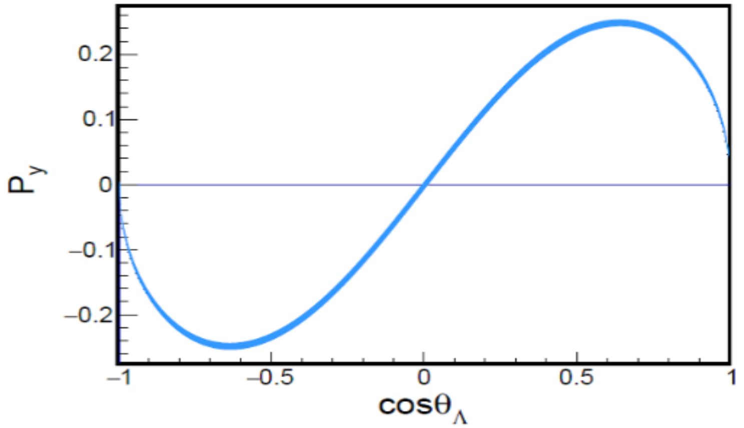
正负电子对撞机上的正反重子成对产生，利用**量子纠缠**和**极化**测量方法，相较于传统利用打靶实验的方法，重子CP研究精度能够大幅提高

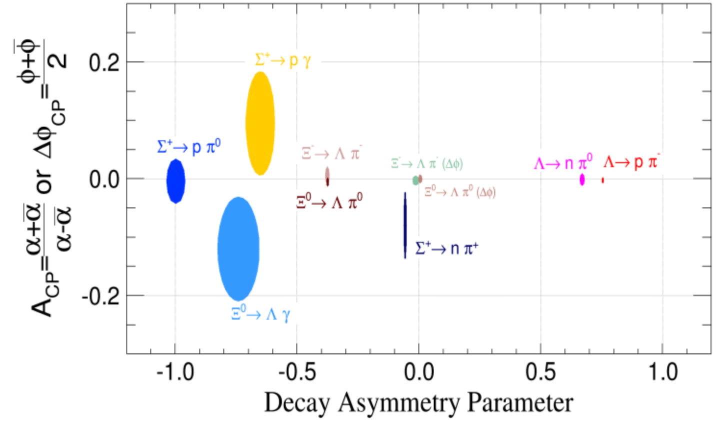


2019年
首次发现超子自旋极化，BESIII首篇《自然·物理》



2022年
重子CP不对称性世界最精确值，BESIII首篇《自然》





- **产生机制**已知，产生超子的**极化**和**运动学**精确确定，最大极化近30%
- **大量产生**各类超子-反超子对，构造**多个CP破坏观测量**，极化束流能够显著提高CP敏感度
- 系统误差**可控制**在与统计误差相当的量级

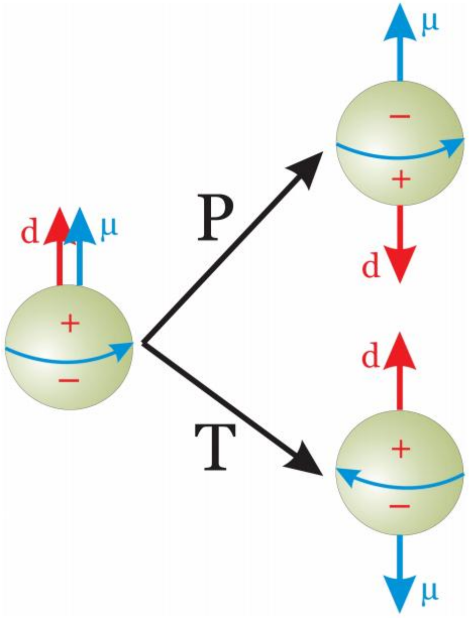
超子电偶极矩高精度研究

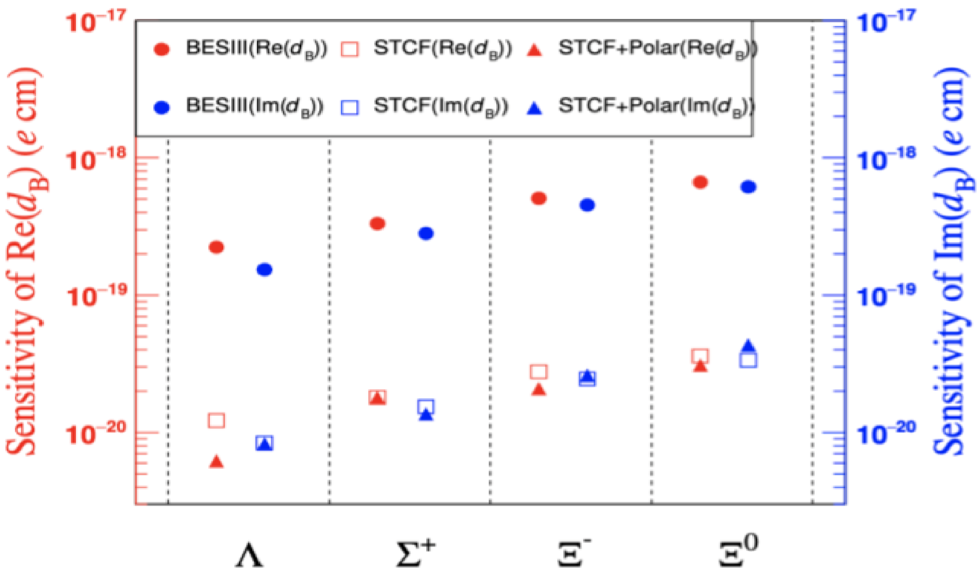
Detailed dynamics in J/ψ decay to hyperon pair have been studied:

μ: magnetic dipole moment
d: electric dipole moment

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

Systematic measurement of the EDMs of the hyperon family!





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

J.L. Fu et al.,*Phys.Rev.D* 108, 9 (2023)
X.G.He, J.P. Ma, Phys.Lett.B 839, 137834 (2023)

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

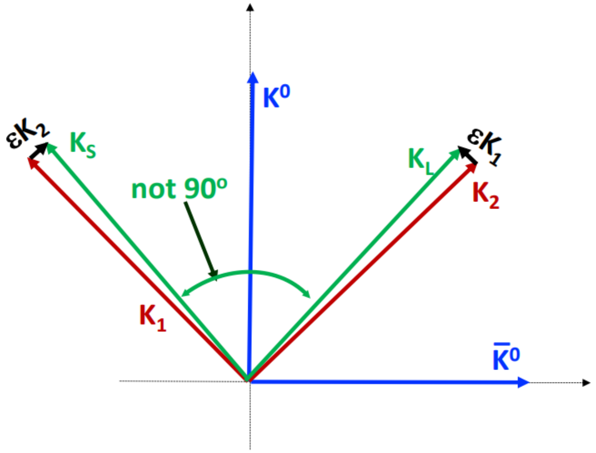
STCF: improved by 2 order of magnitude

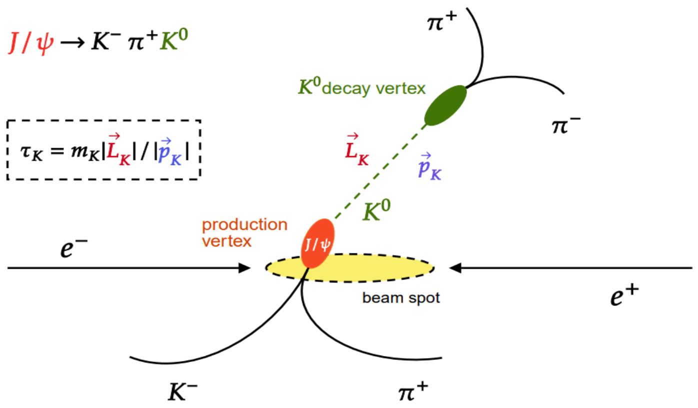
非零的电偶极矩破坏时间反演对称性T，在CPT联合对称性守恒下，是**CP破坏的间接证据**

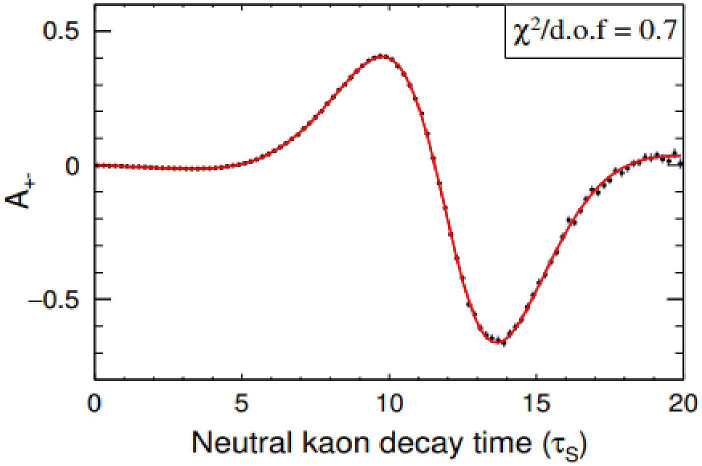
$K^0 - \bar{K}^0$ 系统中的CPT对称性检验

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







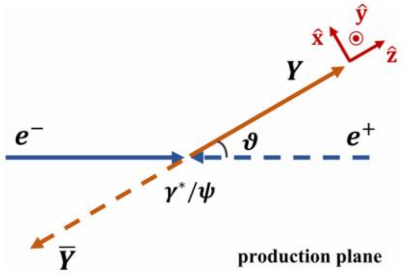
- $K^0 - \bar{K}^0$ **flavor tagging** via $J/\psi \to K^0K^-\pi^+/\bar{K}^0K^+\pi^-$
- $K_1 - K_2$ **CP tagging** by reconstructing $\pi^+\pi^-$ or $\pi^+\pi^-\pi^0$
- Precise determination of K^0 decay vertex ⇒ essential for time-distribution
- The phase in CP parameter ϕ_{+-} used to set limits on CPT violation
- sensitivity of ϕ_{+-} is $\mathcal{O}(10^{-3})$ at STCF ⇒ **one magnitude better than PDG average**

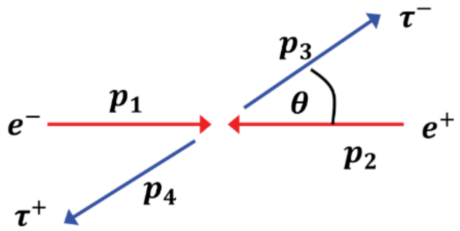
超子对、陶轻子对的量子纠缠系统

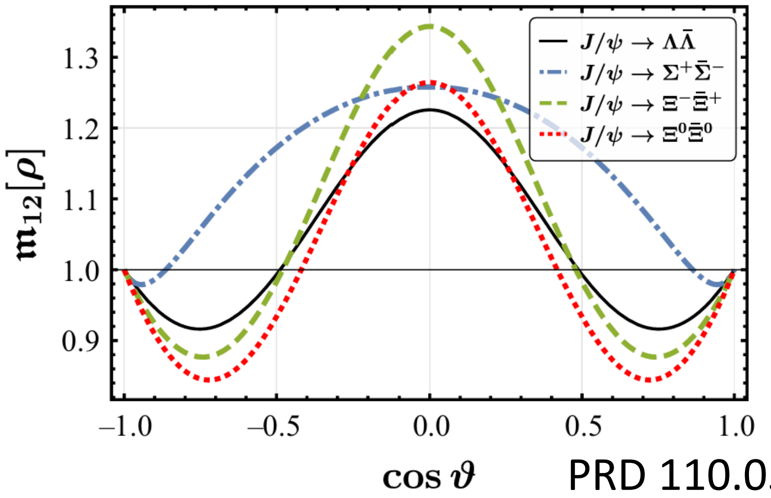
- **Quantum state tomography: reconstruct the spin density matrix (SDM) based on decay products.**

$$\rho = \frac{1}{4}\left[\mathbf{1}_2 \otimes \mathbf{1}_2 + \sum_{i=1}^{3} B_i^{+}(\sigma_i \otimes \mathbf{1}_2) + \sum_{j=1}^{3} B_j^{-}(\mathbf{1}_2 \otimes \sigma_j) + \sum_{i,j=1}^{3} C_{ij}(\sigma_i \otimes \sigma_j)\right],$$

$$\Theta_{\mu\nu} = \frac{1}{1+\alpha_\psi \cos^2\vartheta}\left[\begin{array}{c|ccc} 1+\alpha_\psi\cos^2\vartheta & 0 & \beta_\psi \sin\vartheta\cos\vartheta & 0 \\ \hline 0 & \sin^2\vartheta & 0 & \gamma_\psi \sin\vartheta\cos\vartheta \\ \beta_\psi \sin\vartheta\cos\vartheta & 0 & -\alpha_\psi \sin^2\vartheta & 0 \\ 0 & \gamma_\psi \sin\vartheta\cos\vartheta & 0 & \alpha_\psi + \cos^2\vartheta \end{array}\right]$$

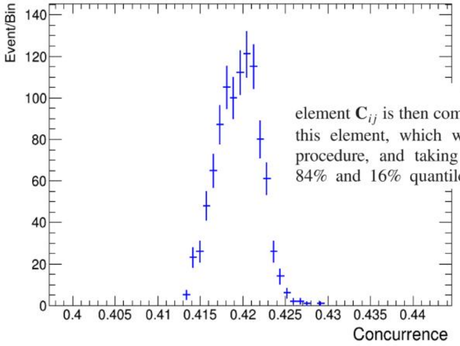




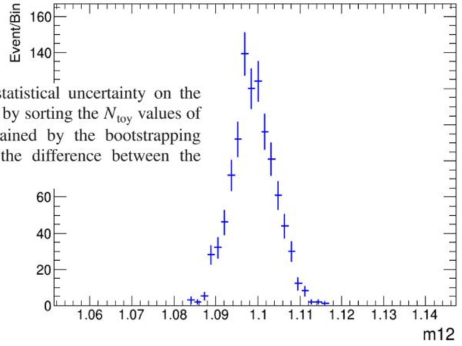


PRD 110.054012(2024)

TOY dist. Of concurrence



TOY dist. Of Bell inequality

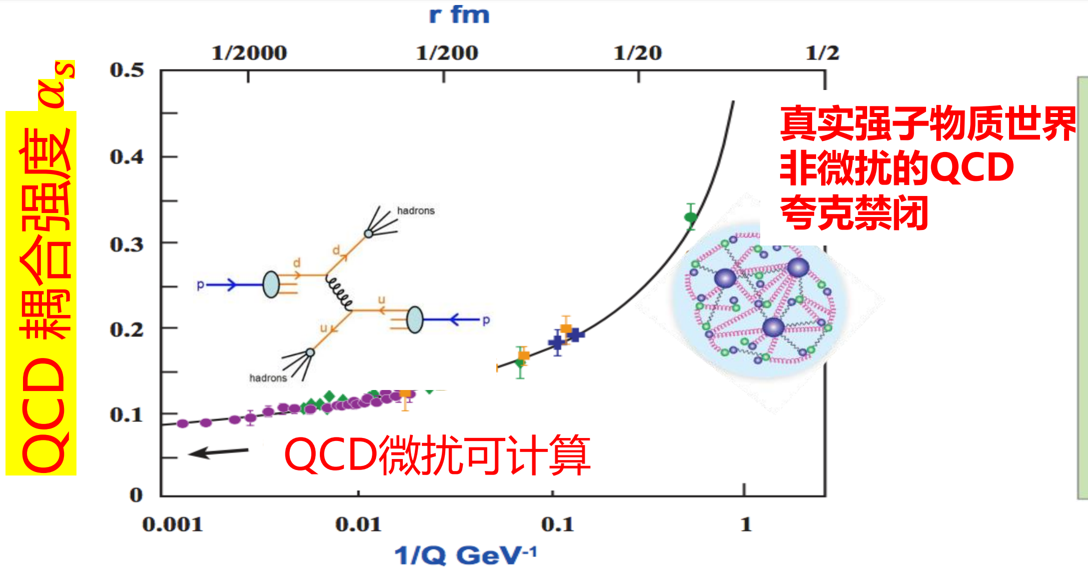


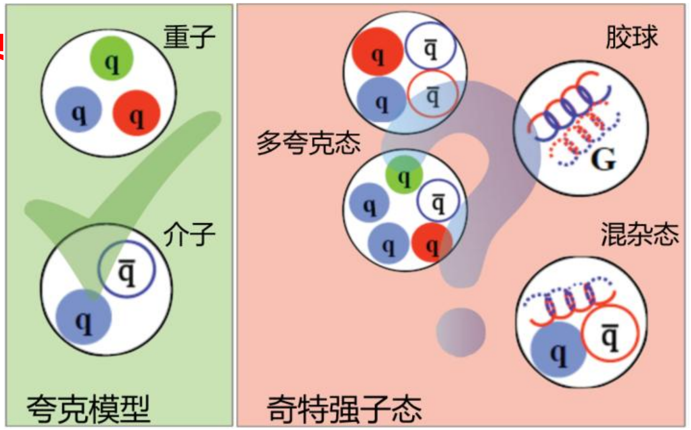
The statistical uncertainty on the element $\mathbf{C}_{ij}$ is then computed by sorting the $N_{\rm toy}$ values of this element, which we obtained by the bootstrapping procedure, and taking half the difference between the 84% and 16% quantiles.

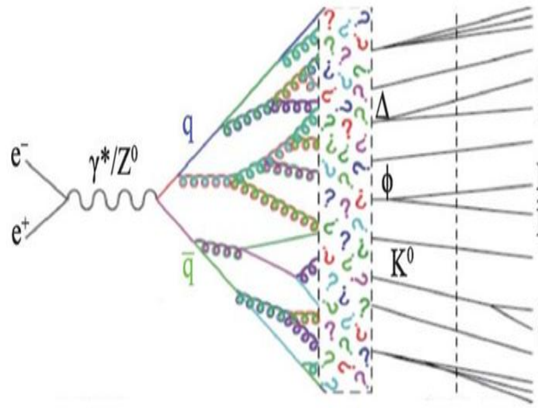
0.41945 +/- 0.00258 > 0

1.09852 +/- 0.00510 > 1

色禁闭之谜





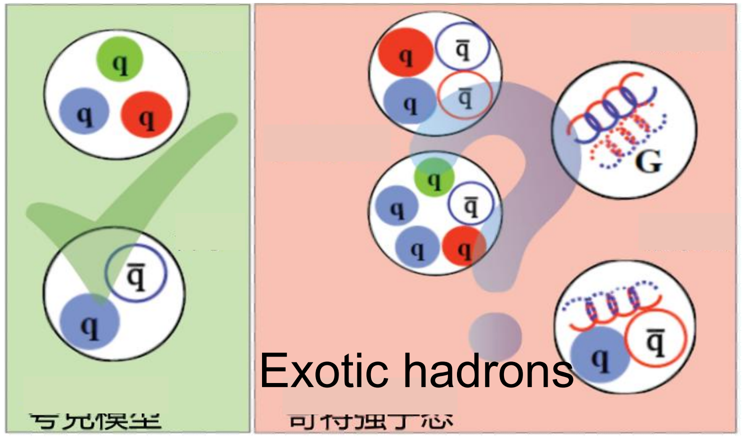


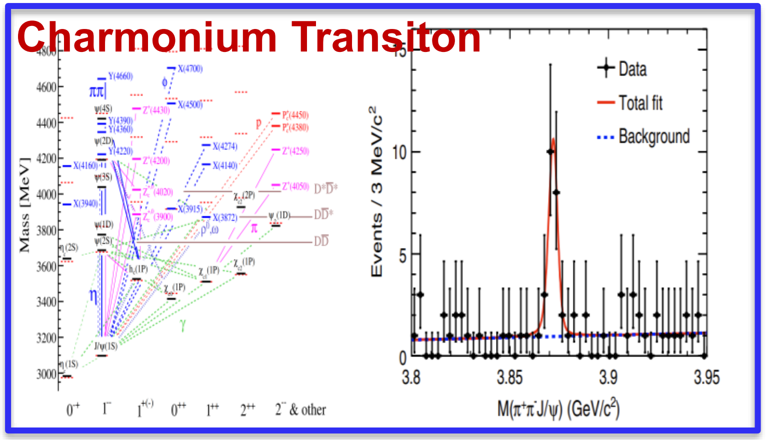
- **强子是物质世界基本组成单元**：理论预期存在胶球、混杂态、分子态、多夸克态等奇特强子态。强子谱的研究是探索与认识**强相互作用理论**的重要手段，STCF可以产生丰富的**奇特强子态**，在强子谱研究中具有**明显优势**。
- **夸克碎裂函数**描述夸克强子化的过程，正负电子对撞实验能够提供最干净的夸克碎了函数信息。**形状因子**是强子的**基本观测量**，能够探针其内部结构信息。

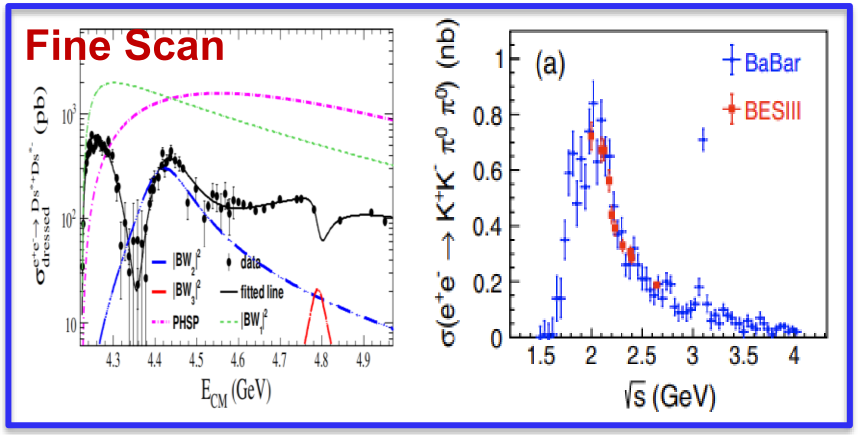
STCF上强子谱学和夸克碎裂函数及强子形状因子的精确测量将提供夸克塑造强子内部结构信息，从而破解色禁闭难题。

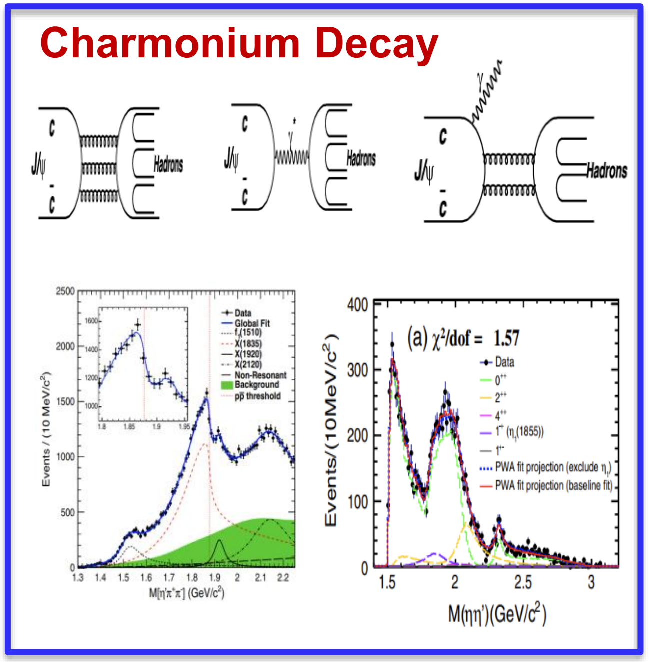
奇特强子态

- A **unique** territory for the QCD confinement









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

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

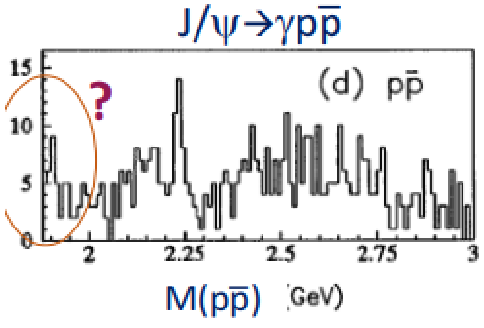
Physics opportunities :

- Energy dependent structures of $Z_{c(s)}$
- More XYZ states → 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.

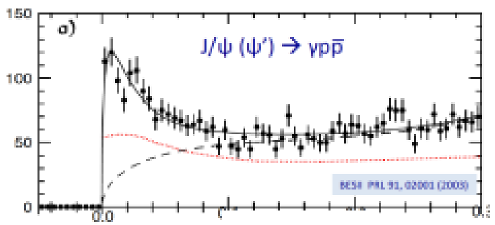
强子谱超精细结构

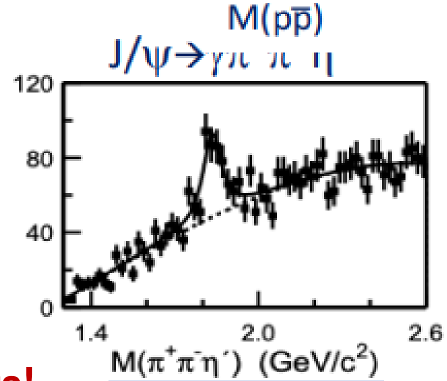
1996: 8 M J/ψ's



PRL 76, 3502

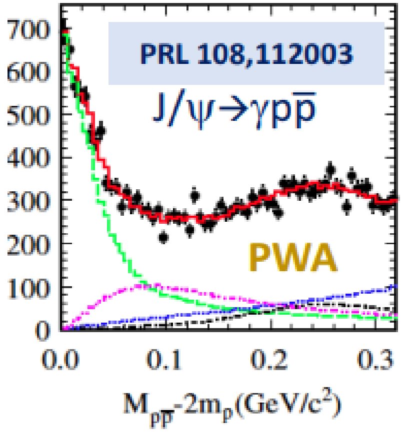
2002: 58 M J/ψ's

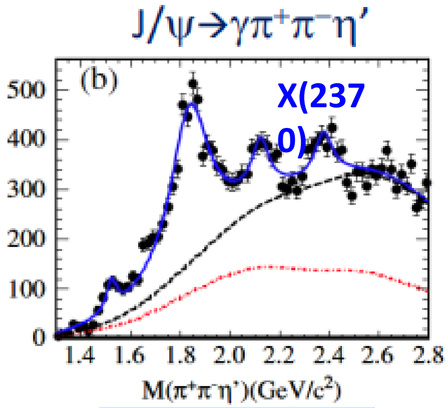




PRL 95,262001

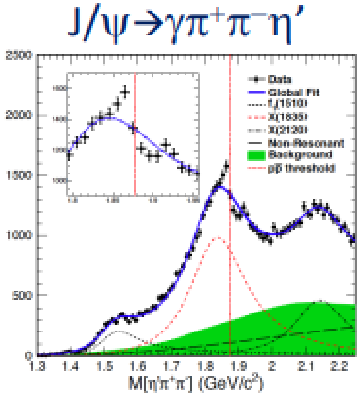
2011: 225 M J/ψ's



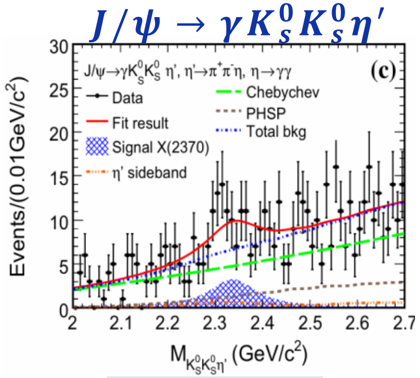


PRL 106,072002

2016: 1.3 B J/ψ's

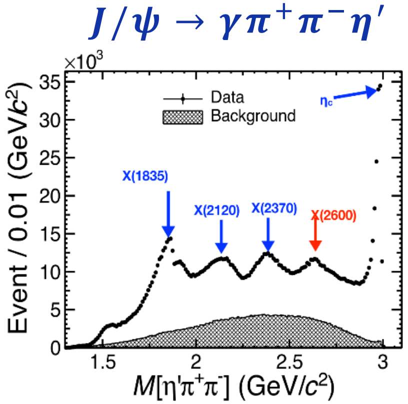


PRL 117,042002

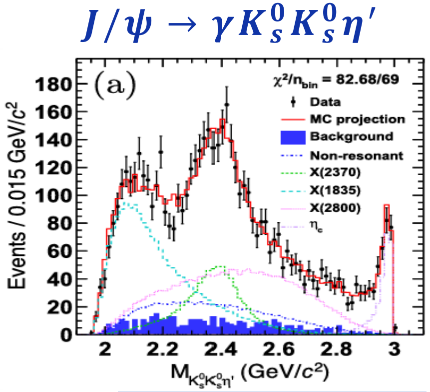


EPJC 80,746

2022: 10B J/ψ's



PRL 129, 042001



PRL 132.181901

0^{-+} Pseudoscalar Glueball-like

You never have enough J/ψ events!

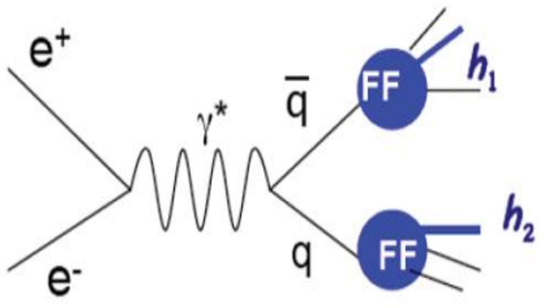
— Stephen Lars Olsen

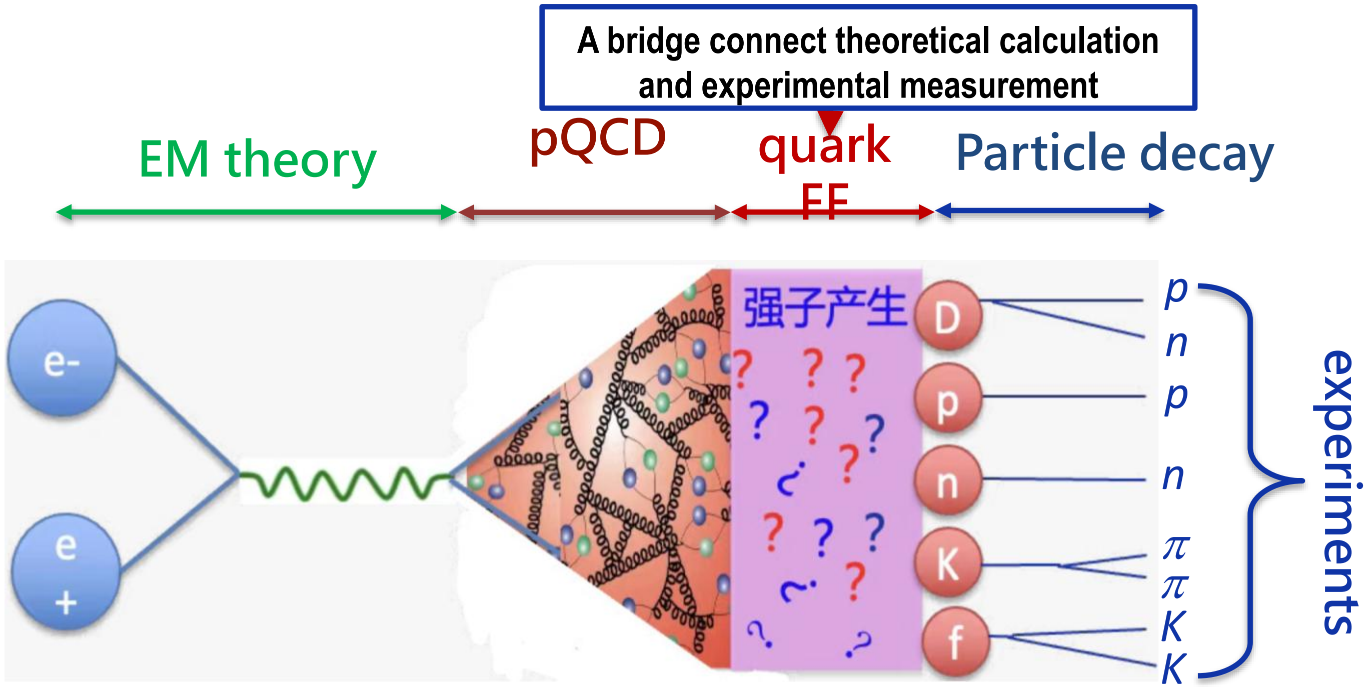
Talk on "Symposium on 30 years of BES Physics", (2019)

- Base on the large statistic and high precision data, STCF has an absolute advantage in the studying of hadron spectroscopy.
- STCF will study hadron spectroscopy comprehensively, and establish the "periodic table of hadron elements"

夸克碎裂函数

- Fragmentation function described the processes of quarks/gluon hadronization, is non-perturbative process, not be calculated theoretically.
- To accurately extract Parton Distribution Functions (PDFs), more precise FFs are required.
- e^+e^- collider experiment provides the cleanest input for fragmentation functions (FFs) fitting. With polarized electron beam, more FFs can be studied.



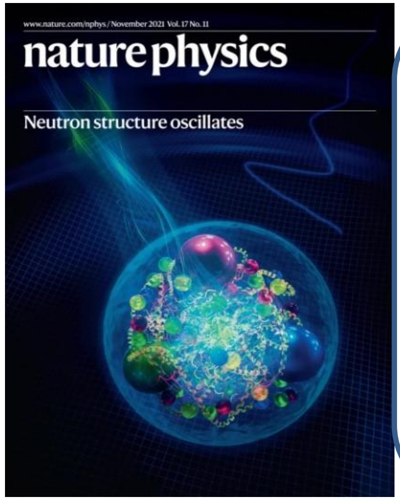


STCF prospects :

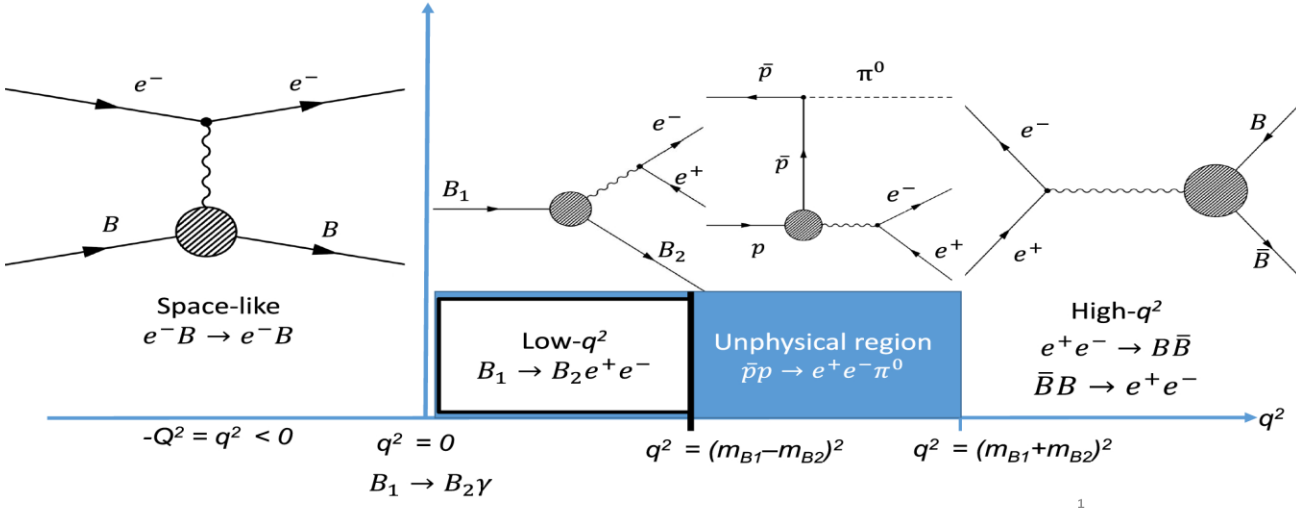
- will provide the most precise fragmentation function in q^2 range 4-50 GeV^2 with multi-dimensional binning
- Precise test the universality of fragmentation function in the different processes, and its evolution with q^2

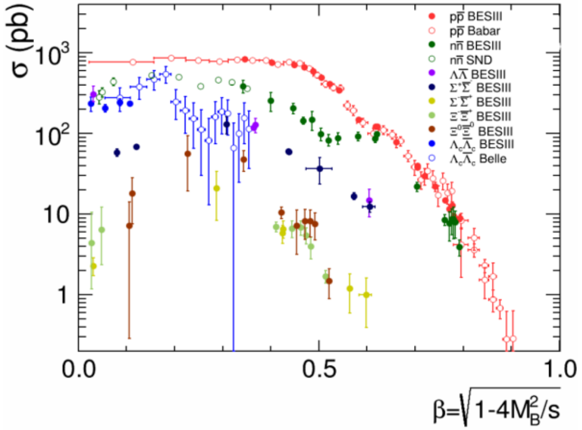
强子形状因子

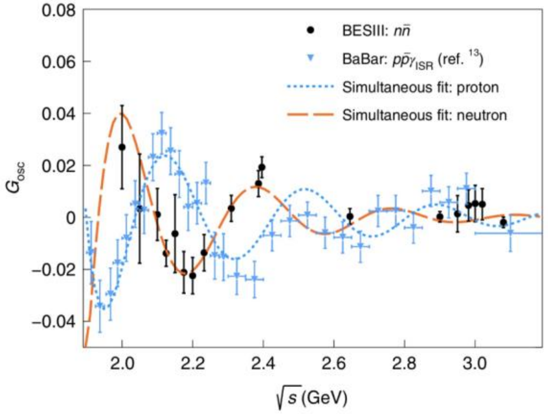
- **电磁形状因子**是核子**最基本**的观测量之一，提供电和磁密度信息，并对强相互作用相关理论提供严格的验证。
- **由于超子和粲重子束流难以形成**，其内部结构研究只能通过类时空间的电磁形状因子研究获得。
- 高四动量转移的电磁形状因子研究可以抽取核子的光锥波函数，从而确认质子中的夸克成分。



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



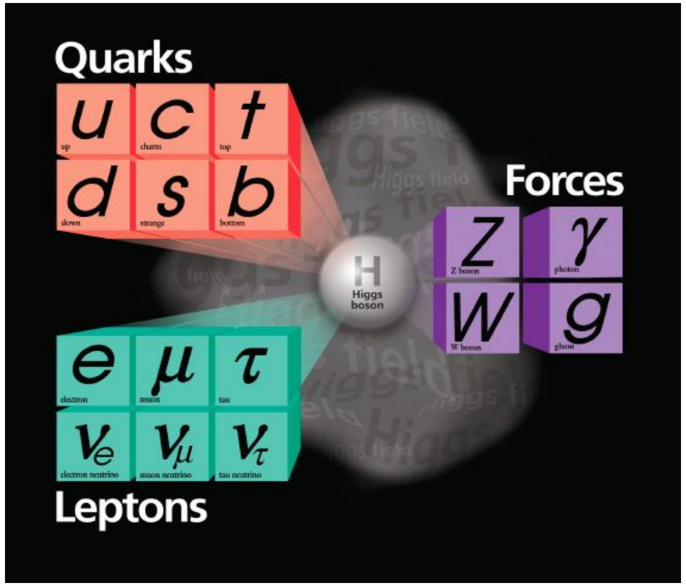




Natl.Sci.Rev. 8 (2021) 11, nwab187

基本物理量精确测量

- **基本物理量**或标准模型**基本参数**的精确测量，是**高精度检验标准模型**，**探索新物理**的重要途径。
- STCF能够对**R值**以及**陶轻子质量**、**CKM矩阵元**以及**强相互作用常数α_s**进行高精度测量：
  - **R值测量**：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**，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。
  - **陶轻子质量**精度对于**轻子普适性**的精确检验具有重要意义。
  - **CKM矩阵**幺正性能够保证是否只有三代夸克，幺正性的破坏意味着第四代夸克的存在！
  - **强耦合常数α_s**的精度会直接影响希格斯物理、电弱物理和顶夸克物理的理论预言，对理解电弱真空的稳定性具有重要意义。



标准模型自由参数：

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	1.17x10^{-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

R值定义：

$$R \equiv \frac{\sigma^0(e^+e^- \to \text{hadrons})}{\sigma^0(e^+e^- \to \mu^+\mu^-)} \equiv \frac{\sigma^0_{\text{had}}}{\sigma^0_{\mu\mu}} \approx N_c \sum_f Q_f^2$$

描述夸克味道的混合的CKM矩阵：

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

强子产生截面：R值

- **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

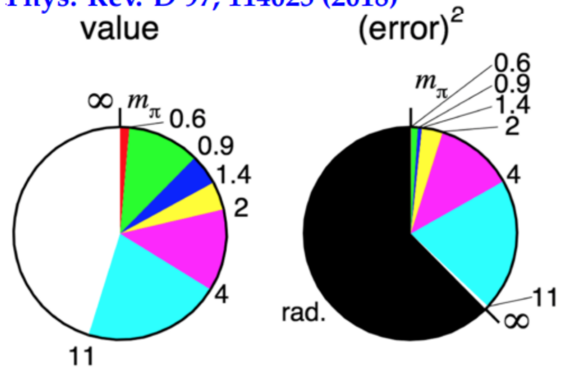
- Running of fine structure constant $\Delta\alpha_{\mathrm{em}}$

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

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

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

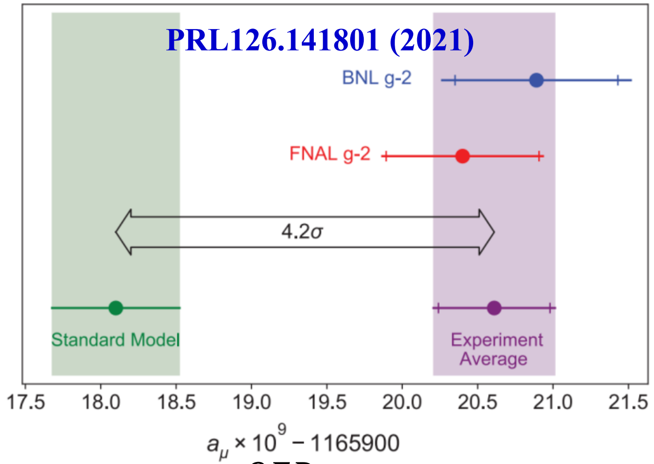
Fractional contribution to $\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$:
Phys. Rev. D 97, 114025 (2018)



$$\Delta\alpha^{(5)}_{\mathrm{had}}(s) = -\frac{\alpha s}{3\pi}\,\mathrm{Re}\int_{E_{\mathrm{th}}}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\varepsilon)}$$

- $\Delta\alpha^{(5)}_{had}(s)$ should be calculated with R value:

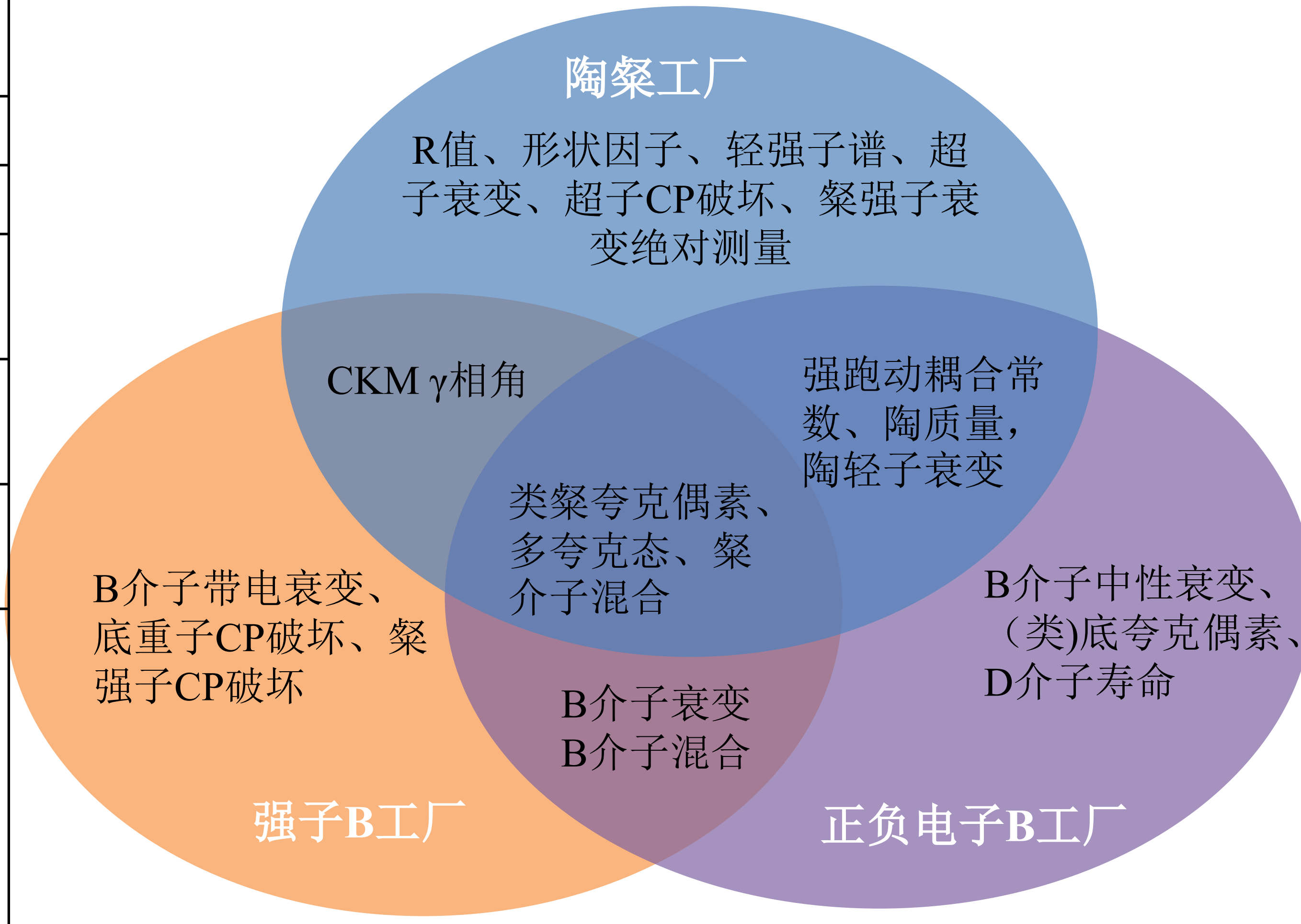
- Muon anomalous magnetic moment a_μ



- SM prediction: $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{Had}$
  - 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: $a_\mu^{\mathrm{LO\text{-}HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{R(s)K(s)}{s^2}$

STCF与Belle II, LHCb实验的协作和互补

装置名称	STCF	SuperKEKB/Belle II	LHC/LHCb upgrade I/II
对撞类型	e^+e^-	e^+e^-	pp
质心能量	2-7 GeV	10-11 GeV	13/14 TeV
峰值亮度	$0.5\times10^{35}\ cm^{-2}s^{-1}$	$8\times10^{35}\ cm^{-2}s^{-1}$	$(1.5\text{-}2.0)\times10^{33}\ cm^{-2}s^{-1}$
预计运行时间	2032-	2019-2043	2024-2033，2036-2041
预期积分亮度	$10\ ab^{-1}$	$50\ ab^{-1}$	$50/300\ fb^{-1}$
预期重要成果	确定奇特态强子谱结构；发现超子 CP 破坏；确定标准模型基本物理参数	底介子衰变性质和CKM相位角精确测量；粲物理和夸克偶素精确研究；新物理寻找	CKM矩阵参数精确测量；中性粲介子CP破坏参数精确测量；底强子中轻子普适性检验和稀有衰变寻找；奇特强子态研究



目录

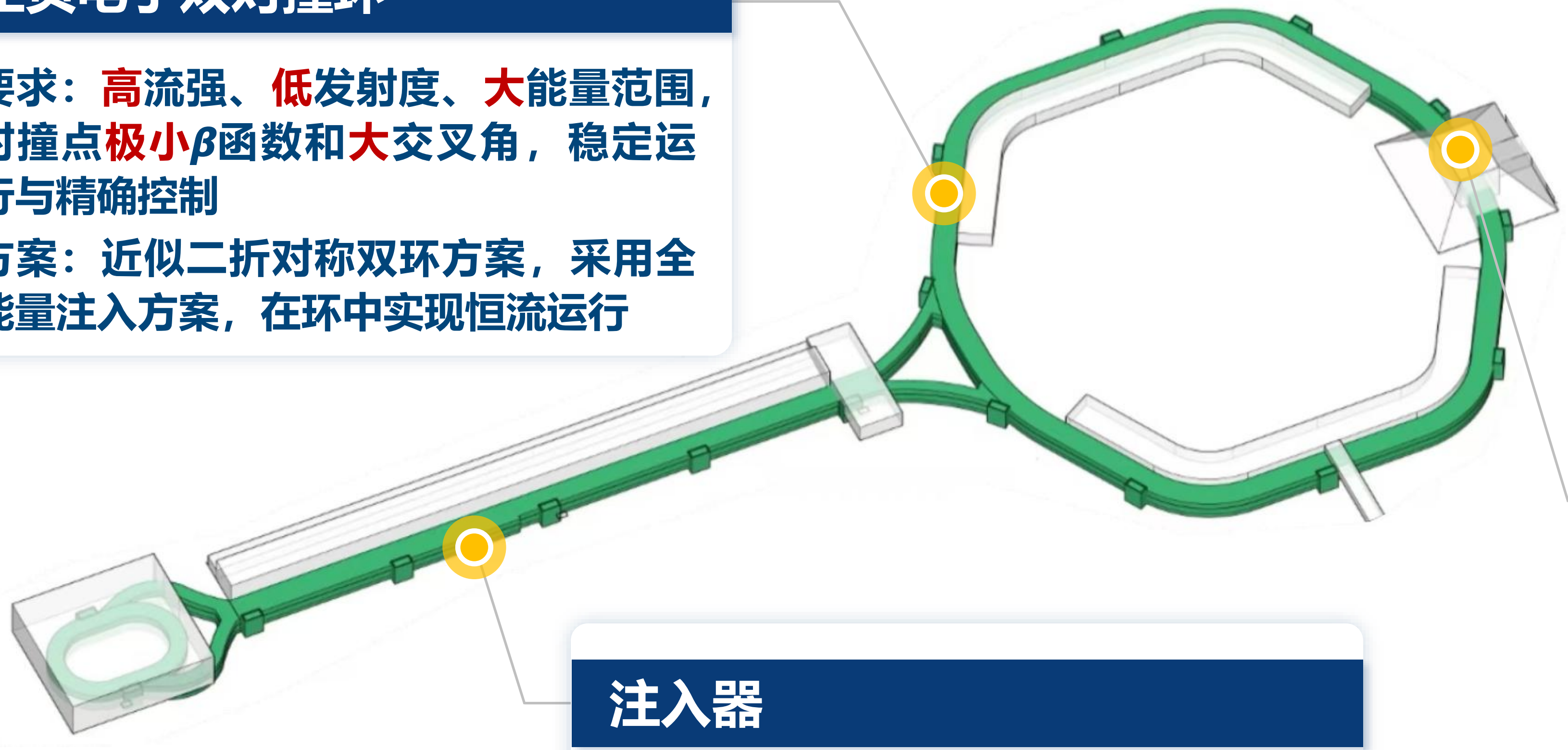
- 超级陶粲装置
- 物理目标
- **关键技术预研**
- 项目推进和现状
- 总结和展望

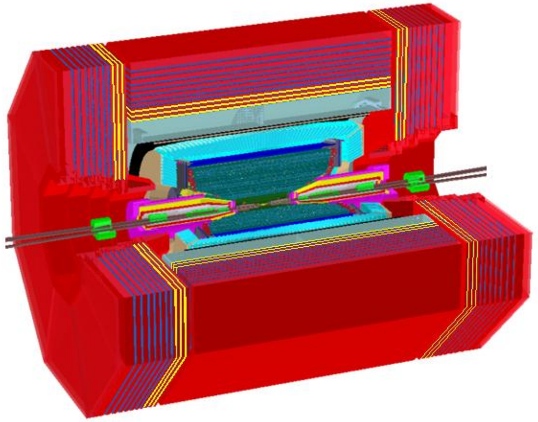
总体方案

正负电子双对撞环

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

方案：近似二折对称双环方案，采用全能量注入方案，在环中实现恒流运行





探测谱仪

要求：在强辐照、高本底、高事例率、宽动态范围条件下的超高精度粒子测量和鉴别

方案：多种粒子探测器+读出电子学系统+数据获取系统

注入器

要求：高重频注入、高电荷量、低发射度正负电子束

方案：多段直线加速器+正电子阻尼环，满能量注入对撞环

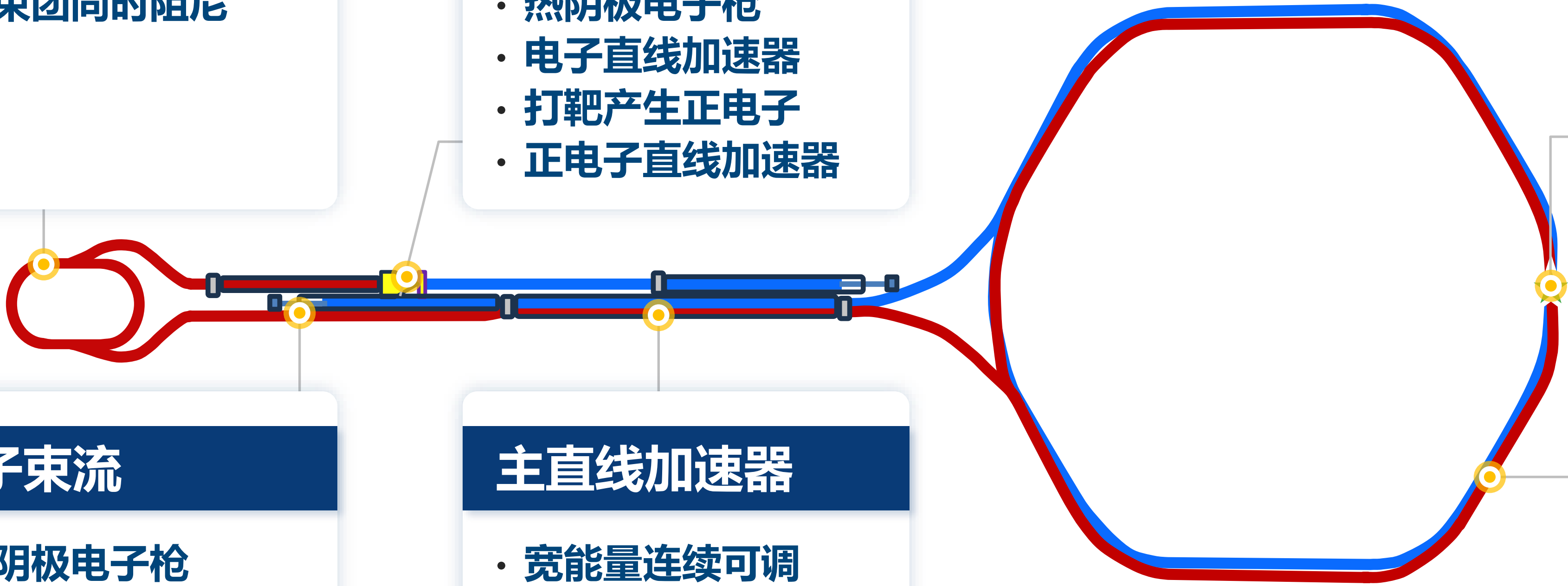
加速器系统方案

设计目标：亮度 ≥ 0.5×10^{35} $cm^{-2}s^{-1}$ @ 4 GeV，能区：2~7 GeV

正电子阻尼环
- 多束团同时阻尼

正电子束流
- 热阴极电子枪
- 电子直线加速器
- 打靶产生正电子
- 正电子直线加速器

第三代对撞机设计理念
- 大交叉角
- 低发射度
- Crab-Waist 对撞

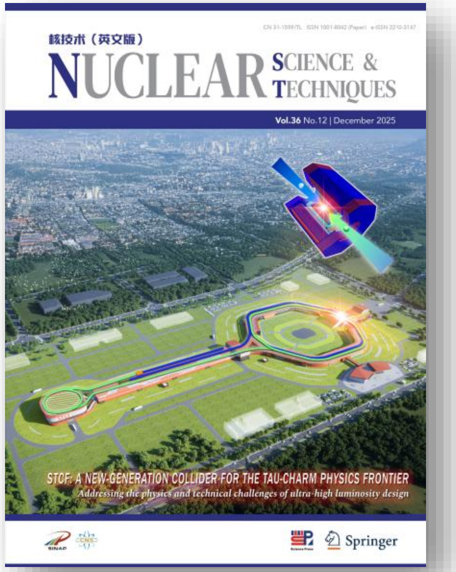


电子束流
- 光阴极电子枪
- 电子直线加速器

主直线加速器
- 宽能量连续可调
- 正负电子交替加速

对撞环关键硬件
- 对撞区超导磁铁组
- 高功率常温高频腔
- 强辐射下极高真空
- …

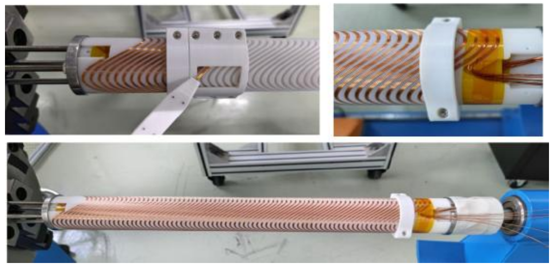
加速器预研进展



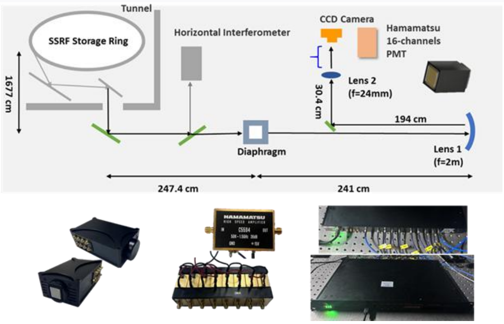
- **已完成概念设计**并通过国际国内评审，设计模拟亮度已达到**设计指标**
- 加速器部分关键技术系统正在进行**技术攻关和样机研制**

参数	单位	模拟数值			
对撞能量	GeV	4.0	2.0	3.0	7.0
亮度	$cm^{-2}s^{-1}$	9.4×10^{34}	6.2×10^{33}	2.1×10^{34}	4.5×10^{34}

对撞区超导磁体样机

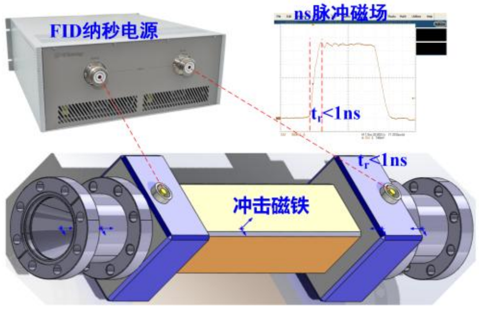


一体化测量技术发展



高功率常温高频腔样机

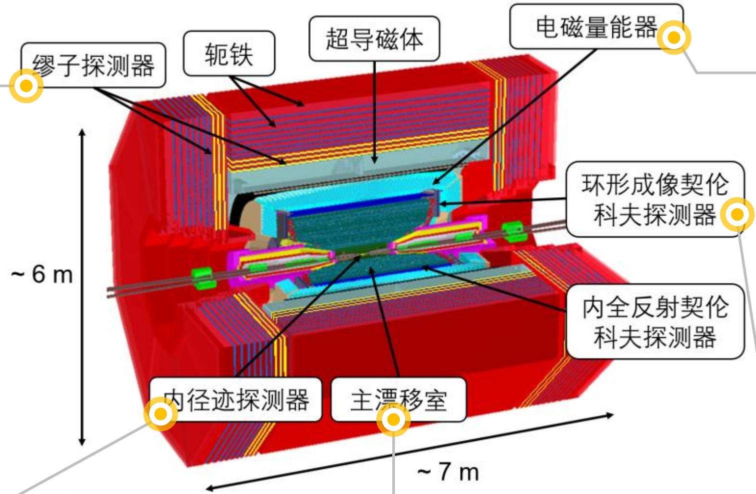
超快冲击磁铁样机



探测谱仪系统方案

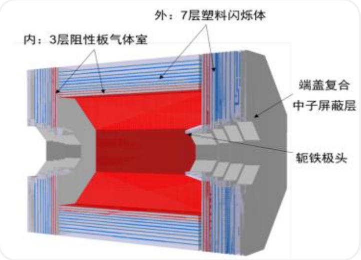
设计目标：强辐照、高本底、高事例率、大动态范围下的超高精度粒子测量和鉴别

$\sigma_P/P \leq 0.5\%$ @ 1 GeV/c，$\sigma_E/E \leq 2.5\%$ @ 1 GeV，$K/\pi \geq 4\sigma$ @ 2 GeV/c



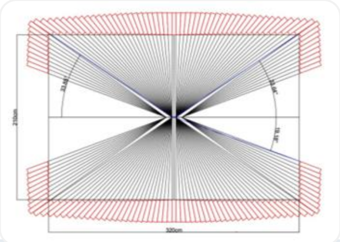
混合式缪子探测器

阻性板室 + 塑料闪烁体探测



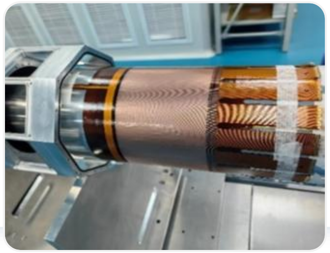
快响应晶体量能器

纯碘化铯+APD



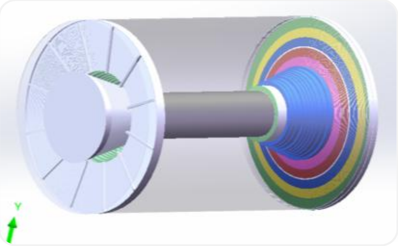
低物质量内径迹探测器

阻性微槽型气体探测器



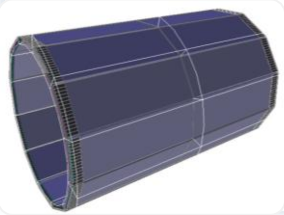
高计数率主漂移室

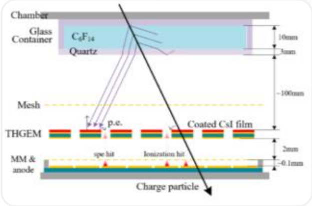
超小单元漂移室



契伦科夫粒子鉴别器

内全反射型　　环形成像





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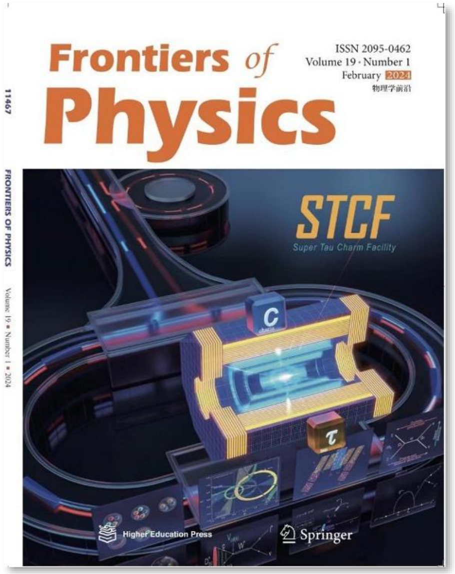
探测器预研进展

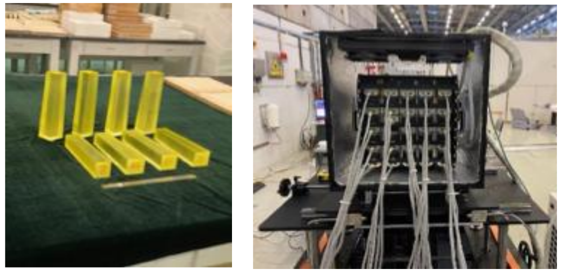


- 完成**全部五个**子探测器**样机研制**，其中**三个**已完成**束流测试**并**达到或超过**设计指标
- 完成**所有**关键部件的**技术设计**，研制出**大部分**的关键部件**原型**

内径迹探测器样机

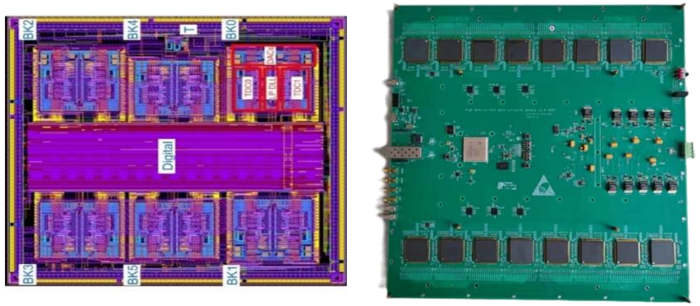
粒子鉴别器全尺寸样机

电磁量能器大阵列样机

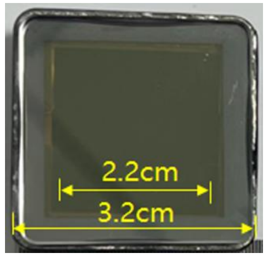


主漂移室全长样机

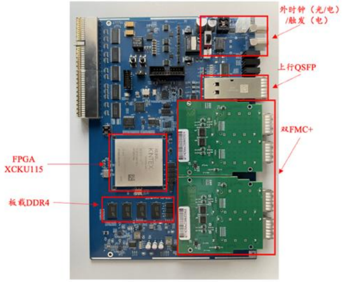
高性能专用集成电路读出芯片



超快多阳极微通道板光电器件



数据获取关键部件



物理概念设计报告和CP专题

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Spin 3/2 polarization
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Millicharged particles
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EMFFs
Light-cone distribution amplitudes
cLFV
baryogenesis
K0-K0bar
Two-pole
X(6200)
Neutral meson mixing
QCD sum rules
Muon g-2 and $\alpha(M_Z^2)$
$\Lambda-\bar{\Lambda}$ oscillation
Axion-like particle
Chiral theory
Fully charm tetraquarks
Tau EDM
$SU(2)_L$-signlet vector-like fermion partners
$\Delta S=2$ Nonleptonic hyperon decay
Hyperon EDM
X(4014)
Excited baryon
Axions
CPT
Proton charge radius
Coupled-channel effect
Hyperon-Nucleus Scattering
$a_0(1710)$
Invisible decay of J/psi
Phi meson photoproduction

Rich physics potential beyond the CDR content

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 Ma[i], 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]

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[b]Hebei Normal University, Shijiazhuang, 050024, China
[c]Shanghai Jiao Tong University, Shanghai, 200250, China
[d]University of Chinese Academy of Sciences, Beijing, 100049, China
[e]Beijing
[f]National Centr
[g]Uppsal
[h]University of Science
[i]Institute of Theoretical Ph
[j]High Energy Physic
[k]Particle and Nuclear Physic
[l]Huazhong Universi
[m]Departamento de Física, C
Politécnico Nac
[n]IFIC, Universi
[o]Institute of High Energy Pl
[p]Lanzh
[q]Universit

Abstract

Charge-parity (CP) vi
promising areas to search
is designed to operate in a c
luminosity of 0.5 × 10^{35} c
will be collected with goo
ment. In this report, poss
region and at the future tau
in the production and deca
hadrons. The CPT invaria

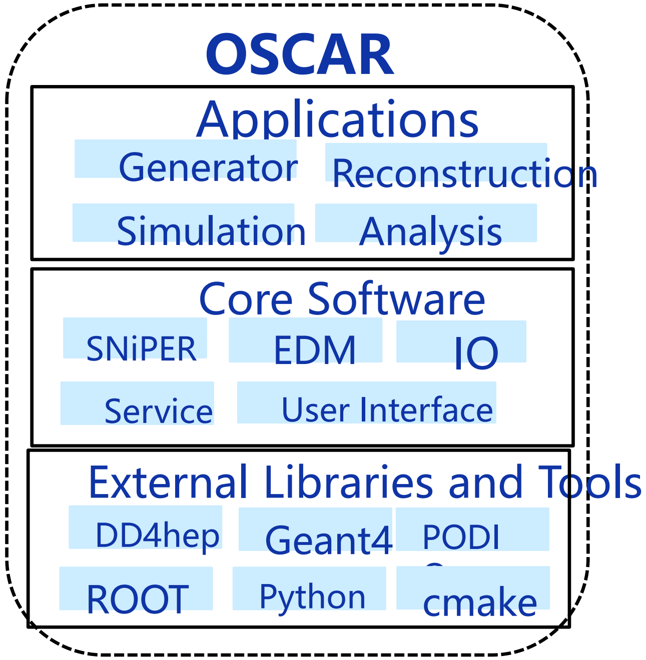
Preprint submitted to PHYSICS

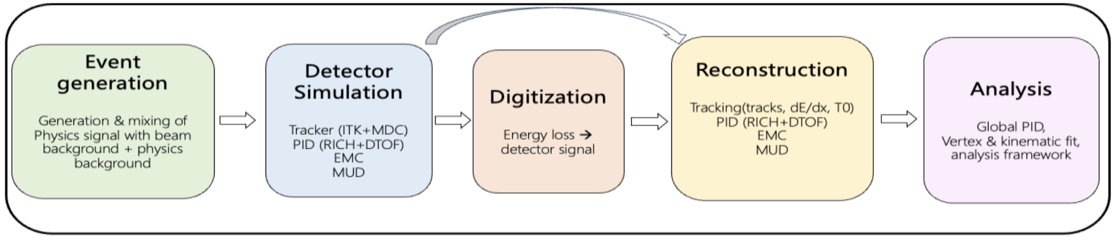
Contents

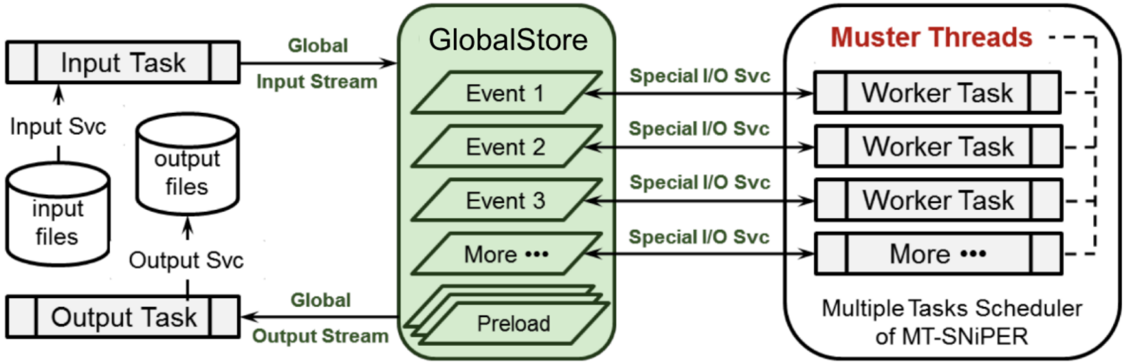
arXiv:2502.08907, submitted to Physics Reports

离线数据分析软件OSCAR

- Offline Software System of Super Tau-Charm Facility (OSCAR)
  - External Interface+ Framework +Offline
- SNiPER framework provides common functionalities for whole data processing
- Offline including Generator, Simulation, Calibration, Reconstruction and Analysis







W.H. Huang et al 2023 JINST 18 P03004

- Full simulation under OSCAR is undergoing: $e^+e^- \to \pi^+\pi^- J/\psi$, $\Lambda\bar{\Lambda}$, $\pi\pi/K\pi/KK + X$, $D^0\bar{D}^0$…

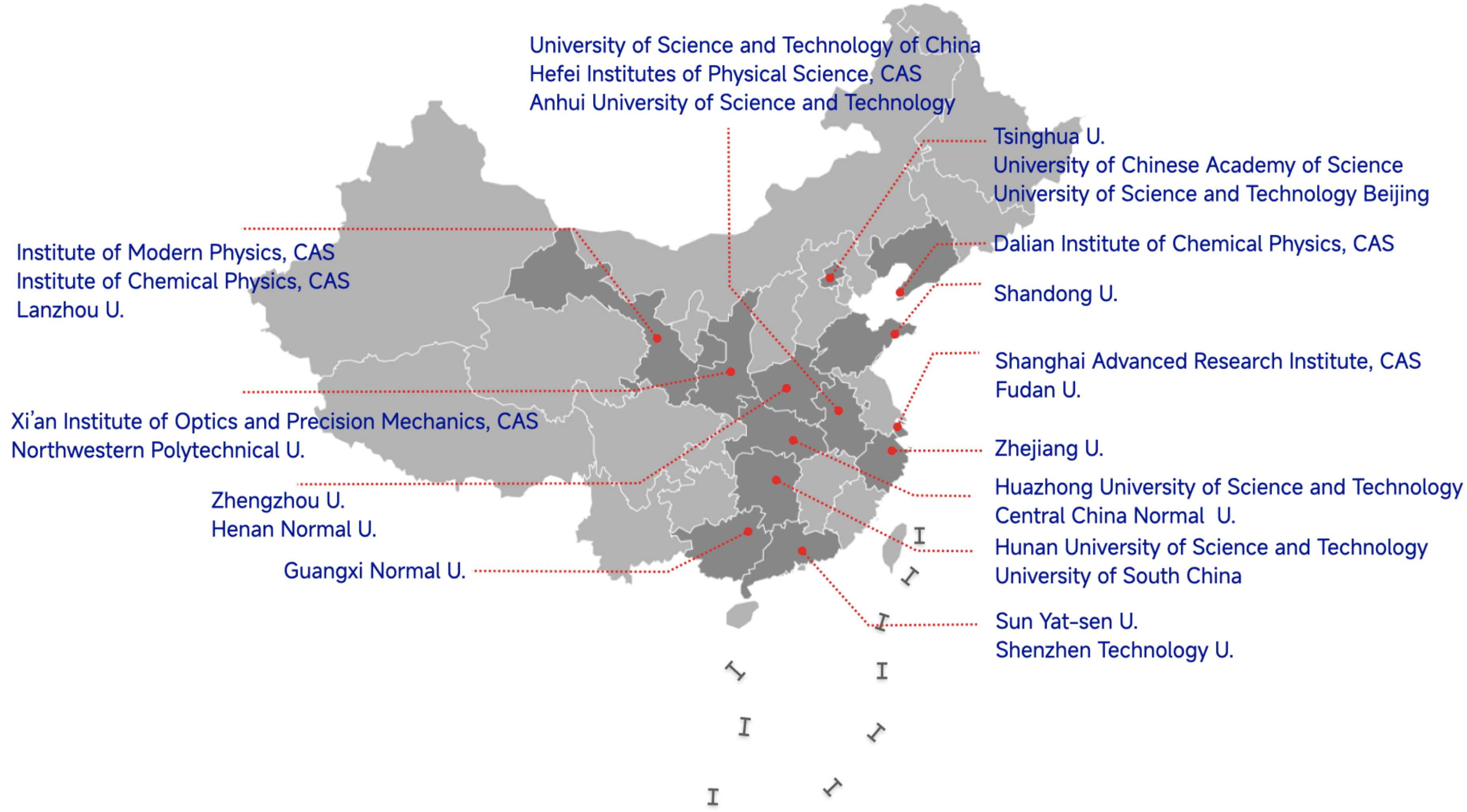
STCF上已开展的全模拟物理过程和性能检验

性能检验	物理过程
径迹重建和分辨	$J/\psi \to \Lambda\bar{\Lambda}$, $\Xi^{+}\bar{\Xi}^{-}$, $e^{+}e^{-} \to \pi Z_c(3900)$, $e^{+}e^{-} \to P_c\bar{p} \to J/\psi p\bar{p}$, $e^{+}e^{-} \to J/\psi\eta_c$
光子/π^0重建	C-even correlated $D\bar{D}$, $\Sigma^{+} \to \pi^{0}p$, $\Sigma^{+} \to \gamma p$, $\tau \to \pi(\pi\pi^{0})\nu$,陶轻子辐射衰变, $\Lambda_c^{+} \to \Lambda K^{+}, \Sigma^{0}K^{+}, \Sigma^{+}K_S^{0}$, $\eta_c \to \gamma\gamma$
低能质子重建	$e^{+}e^{-} \to P_c\bar{p} \to J/\psi p\bar{p}$
π/μ鉴别	$\tau \to 3\mu$, $\tau \to \pi(\pi\pi^{0})\nu$, $J/\psi \to l^{+}l^{-}\pi^{0}/\eta$, $D \to \pi\mu\nu$, $D \to \mu\nu$, $D \to inclusive$
π/K鉴别	$\Lambda_c^{+} \to \Lambda K^{+}, \Sigma^{0}K^{+}, \Sigma^{+}K_S^{0}$, $e^{+}e^{-} \to KK, \pi\pi, K\pi$, $\tau \to K\nu$, $\tau \to K\pi^{0}\nu_{\tau}$
轻子鉴别	$J/\psi \to \gamma ll'$, $\Lambda \to pe\nu$, $\Xi^{-} \to \Lambda e\nu$
质子鉴别	$e^{+}e^{-} \to p\bar{p}$
运动学拟合	$J/\psi \to \Lambda\bar{\Lambda}$, $\Xi^{+}\bar{\Xi}^{-}$, $J/\psi \to K_S^{0}K\pi$, $\Lambda \to pe\nu$, $\Xi^{-} \to \Lambda e\nu$
D介子标记	C-even correlated $D\bar{D}$, $D \to \pi\mu\nu$, $D \to \mu\nu$
能量刻度和分辨	$X(3872)$扫描, $e^{+}e^{-} \to \tau^{+}\tau^{-}$ near threshold
亮度测量	$e^{+}e^{-} \to hadrons$
前向区	$\gamma\gamma \to hadrons$

目录

STCF关键技术预研团队

25 universities/Institutes in R&D project:
170 faculties and 140 graduate students

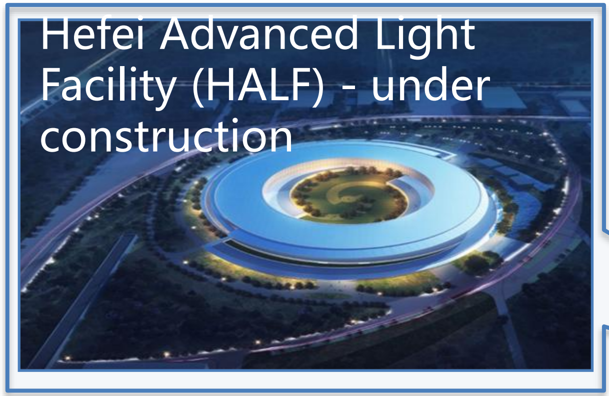


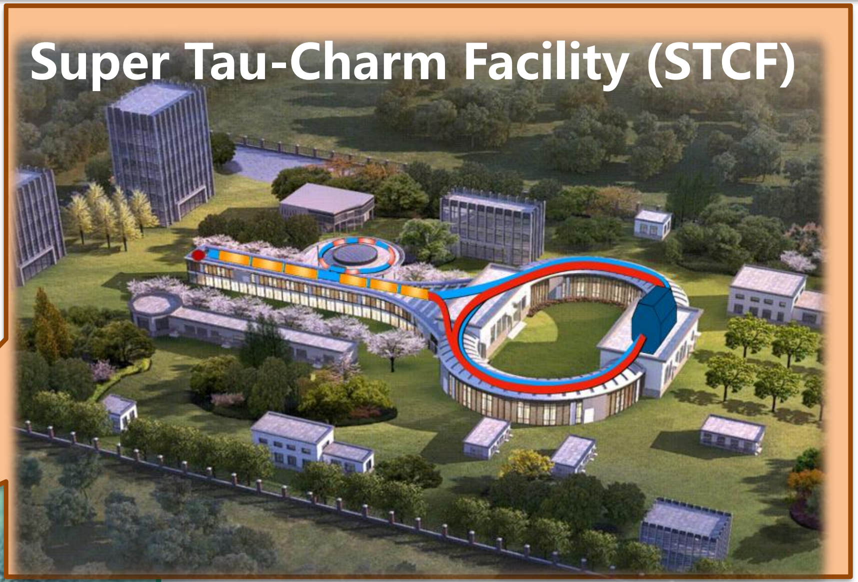
Physics Research

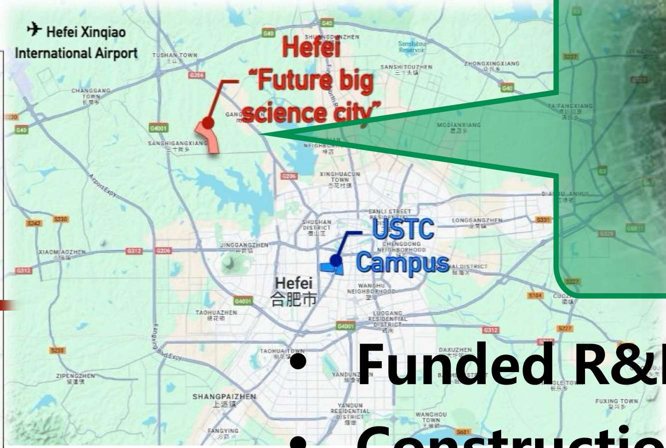
Institute of theoretical physics, CAS
Institute of High energy physics, CAS
Tsung-Dao Lee Institute
Perking University
Shanghai Jiao Tong University
Nanjing University
Wuhan University
Nankai University
South China Normal University
Beijing Normal University
China University of Geosciences
Liaoning University
Nanjing Normal University
Hebei Normal University
....

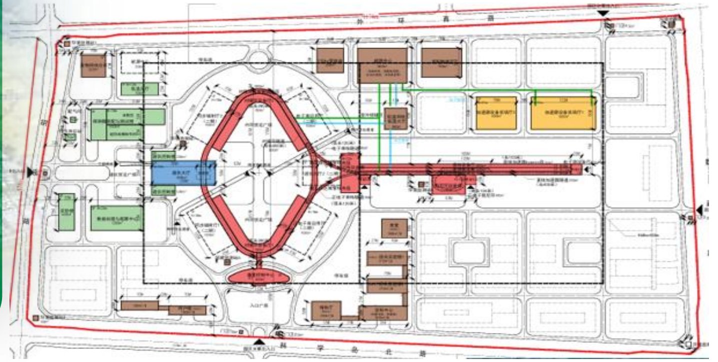
STCF项目选址

Hefei Comprehensive National Science Center
"Future Big Science City", Hefei, Anhui Province



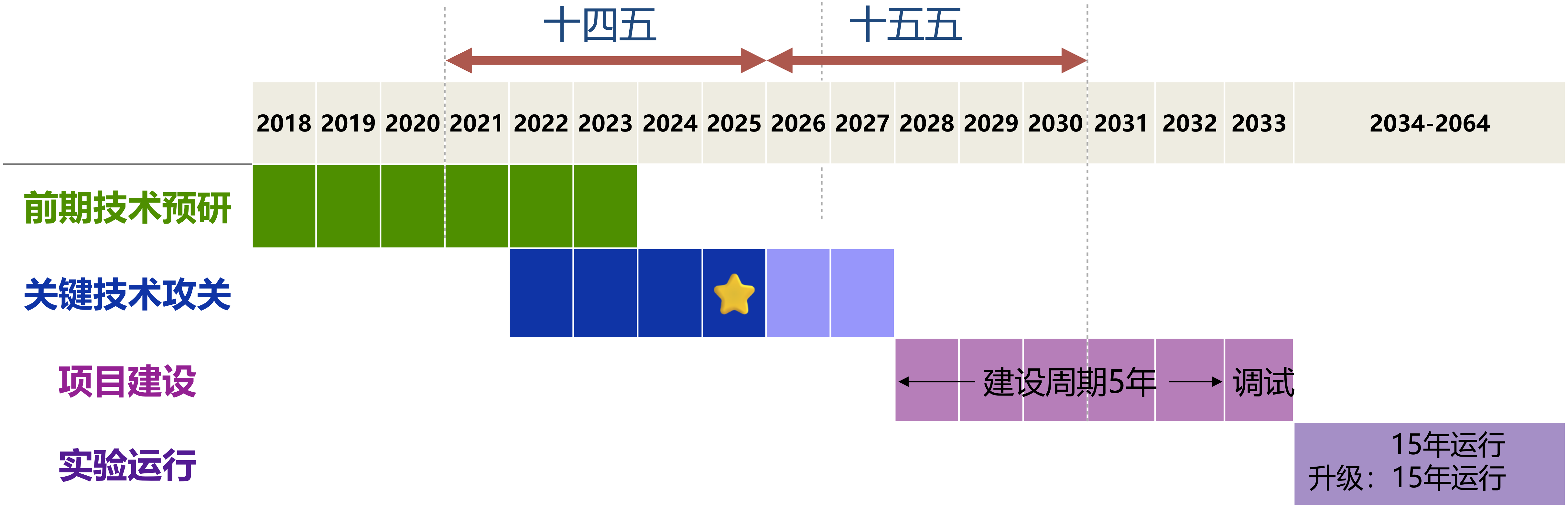






- **Funded R&D : 364 Million CNY by the Anhui government**
- **Construction budget : ~4.8 Billion CNY**
- **Geological prospecting, civil engineering design are ongoing**

STCF计划时间表



- 14th five-years plan : **Conceptual design** and **R&D of Key technology**, 364 M CNY
- 15th five-years plan : **Construction** 6 years, ~5 B CNY
- Operating for 10-15 years, upgrade for 3 years, operating again for ~10 years

STCF相关国际国内研讨会

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	Xiangtan (HUST)	STCF: R&D progress

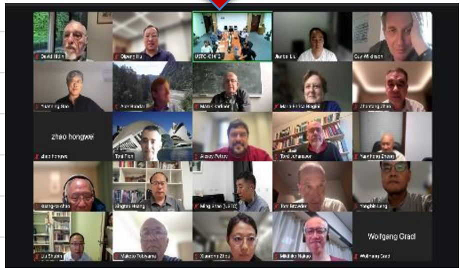
Time	Place	Content
2015.01	Hefei, China	Workshop on Super tau-Charm Facility in China
2018.03	Beijing, China	Workshop on Super tau-Charm Facility in China
2018.05	Novosibirsk, Russia	Workshop on Super tau-Charm Facility in Russia
2018.12	Paris, France	1st FTCF (Joint International Workshop)
2019.08	Moscow,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

国际顾问委员会会议

International Advisory Committee

主席	Guy Wilkinson	U. of Oxford	英国
副主席	Frank Zimmermann	CERN	瑞士
	Marica Biagini	INFN Frascati-National Lab.	意大利
	Ikaros Bigi	U. of Notre Dame	美国
	Alexander Bondar	BINP	俄罗斯
	Tom Browder	U. of Hawaii	美国
	赵光达	Perking U.	中国
	高原宁	Perking U.	中国
	Wolfgang Gradl	JGUM	德国
	David Hitlin	CIT	美国
	Tord Johansson	Uppsala U.	瑞典
	Marek Karliner	Tel Aviv U.	以色列
成员	Eugeny Levichev	BINP	俄罗斯
	马余刚	Fudan U.	中国
	Mikihiko Nakao	KEK	日本
	Stephen Olsen	Chung Ang U.	韩国
	Alexey Petrov	South Carolina U.	美国
	Antonio Pich	Valencia U. IFIC	西班牙
	Makoto Tobiyama	KEK	日本
	赵红卫	IMP, CAS	中国
	赵振堂	SARI, CAS	中国
	邹冰松	Tsinghua U.	中国

2024 Jan. 1st IAC meeting



2024 Oct. 2nd IAC meeting

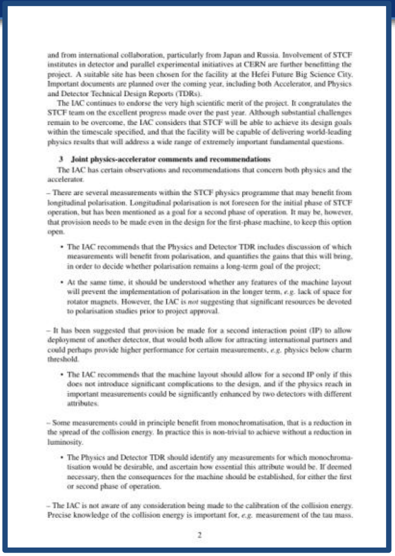
2025. May 3rd IAC me

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

Maria Enrica Biagini[1], Ikaros Bigi[2], Alex Bondar[3], Tom Browder[4], Kuang-Ta Chao[5], Yuanning Gao[5], Wolfgang Gradl[6], David Hitlin[7], Tord Johansson[8], Marek Karliner[9], Eugeny Levichev[3], Yugang Ma[10], Mikihiko Nakao[11], Stephen Olsen[12], Alexey Petrov[13], Antonio Pich[14], Makoto Tobiyama[11], Guy Wilkinson[†15] Hongwei Zhao[16], 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] Tsinghua University.

[†] Co-chairs.



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 IAC is pleased to note **the substantial progress made in physics, detector and accelerator studies** ………….

The IAC continues to **endorse the very high scientific merit of the project**. It congratulates the STCF team on **the excellent progress** made over the past year. Although substantial challenges remain to be overcome, the IAC considers that STCF will be able to **achieve its design goals within the timescale specified,……**

Very High rating, excellent comments and recommendations!

例行工作组会

项目官网 https://stcf.ustc.edu.cn/
会议信息 https://indico.pnp.ustc.edu.cn/category/10/

STCF 1,874 events

STCF公共信息	7 events
Accelerator	320 events
Detector	516 events
Physics & Software	670 events
Accelerator-Detector Joint meetings	empty
Conference Talk Review & Rehearsal	7 events
项目办公室	163 events
STCF项目总体例会	86 events
Management Meetings	77 events
建议书撰写小组	4 events
学术秘书组会议	4 events
园区规划和设计	2 events
国际顾问委员会（International Advisory Committee）	3 events
咨询委员会（National Consultative Committee ）	1 event
Steering Committee	1 event
Domestic Meeting	4 events
STCF publication	6 events
Event	2 events
Interviews	1 event

2025年秋季学期	周一	周二	周三	周四	周五
上午	每周（01） STCF基本对称性检验全模拟周会 周小蓉 10：00-11：00	每两周（01） 桶部粒子鉴别双周会 9：00~11：00 刘倩 每两周（01） 电磁量能器双周会 9：00~11：00 张云龙 每两周（02） 物理模拟双周会 09：00-11：00 周小蓉 每两周（03） 端盖粒子鉴别双周会 09：00-11：00 邵明	每周 （03） STCF项目办公室周会 9：00~11：00 邵明 每两周（01） 缪子探测器双周会 9：30~11：30 刘凯、李锋 双周（02） 数字化全模拟双周会 09：00-12：00 方竹君 双周（02） 触发与数据获取双周会 09：00-12：00 方竹君	每周（02） STCF管理周会 9：50~12：00 胡启鹏、彭海平	每两周（01） 时钟与数据传输双周会 10：00~12：00 王进红 每两周（02） 向前区双周会 10：30~12：30 陈海、刘明依 每周 （中大） STCF色禁闭全模拟周会 10：00-11：00 周小蓉 每两周 () 对撞区超导磁铁双周会 10：00-12：00 马文彬、魏绍清
下午		每周 （04） 注入器物理设计周会 14：00~16：00 原有进、谷端、张艾霖 每两周（03） 束流测试、微波联合双周会 15：30~17：30 罗箐、庞健 每两周（01） 软件框架双周会 16：00-17：00 李腾	每周（04） 对撞环物理设计周会 14：00~16：30 邹野 每两周（02） 硅内径迹探测器双周会 14：00~16：00 徐来林 每两周（01） 主漂移室、气体内径迹探测器双周会 14：00~16：00 周意、曹喆	每周 （04） 环高频系统周会 16：30-18：00 韦业龙 腾讯会议：552-8740-4576	每周 （01） 径迹与缪子重建周会 14：00~16：00 艾小聪 每周（05） STCF基本物理量精确测量全模拟周 16：00-17：30 周小蓉 每两周（02） STCF项目总体双周会 16：00~17：30 张艾霖、彭海平 每两周（03） 粒子鉴别器和电磁量能器重建双周会 14：00~16：00 齐斌斌
晚上	每周（01） 软件周会 19:00~21：00 艾小聪			每两周 （01） 月中&月底 谱仪机械双周会 19：00-22：30 康玲、沈刚	每两周（01） 超导螺线管磁体双周会 朱自安、张小涛 20：30-21：30

周会
双周

2025年秋季学期	九月	十月	十一月	十二月	26年一月	26年二月
下午	每月 9月22日 加速器分总体月例会 14：00-16：00 唐靖宇、罗箐	每月 10月27日 加速器分总体月例会 14：00-16：00 唐靖宇、罗箐	每月 11月24日 加速器分总体月例会 14：00-16：00 唐靖宇、罗箐	每月 12月29日 加速器分总体月例会 14：00-16：00 唐靖宇、罗箐	每月 最后一周 周一 加速器分总体月例会 14：00-16：00 唐靖宇、罗箐	每月 最后一周 周一 加速器分总体月例会 14：00-16：00 唐靖宇、罗箐
下午	每月（02） 谱仪分总体月例会 14：00~18：00 刘建北、赵雷	每月（02） 谱仪分总体月例会 14：00~18：00 刘建北、赵雷	每月（02） 谱仪分总体月例会 14：00~18：00 刘建北、赵雷	每月（02） 谱仪分总体月例会 14：00~18：00 刘建北、赵雷	每月（02） 谱仪分总体月例会 14：00~18：00 刘建北、赵雷	每月（02） 谱仪分总体月例会 14：00~18：00 刘建北、赵雷
晚上	每月（01） 9月4日 谱仪控制组月例会 19：00-22：30 胡东栋	每月（01） 第一周周四 谱仪控制组月例会 19：00-22：30 胡东栋	每月（01） 11月6日 谱仪控制组月例会 19：00-22：30 胡东栋	每月（01） 12月4日 谱仪控制组月例会 19：00-22：30 胡东栋	每月（01） 第一周周四 谱仪控制组月例会 19：00-22：30 胡东栋	每月（01） 第一周周四 谱仪控制组月例会 19：00-22：30 胡东栋

总结

- STCF是我国提出的**新一代**GeV能区高亮度正负电子对撞机， 致力于深入探索粒子物理中的独特能区——**陶粲能区**。它能够在阈值处产生大量粲偶素、粲强子、轻强子和陶轻子对。有望在**基本对称性检验**、**色禁闭之谜**、**基本物理量的基本测量**等前沿方向取得重要突破。

- STCF目前已完成加速器和探测器的概念设计，并在关键技术预研方面取得系列技术突破。当前，项目正积极推动国家重大科技基础设施的申请与立项。

- **诚挚欢迎更多专家加入，并期待开展更广泛的学术交流与合作！**

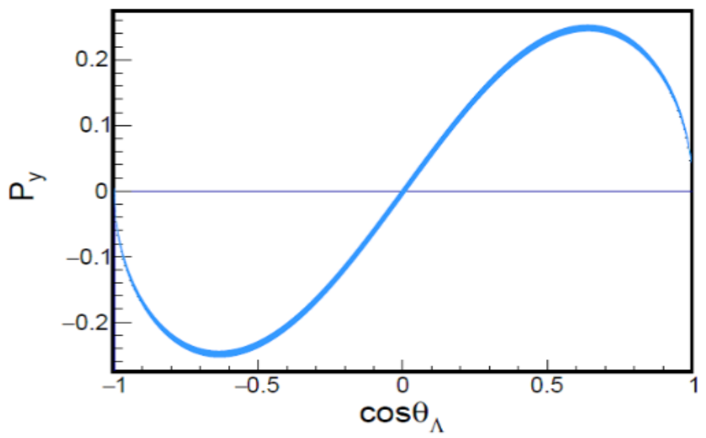
谢谢！

CP Tests in Hyperons Decays

★ *Certain analyses, such as the search for CP violation in hyperons, will require excellent* ***systematic control*** *in order to be sensitive to the very small size of signal expected and to match the foreseen statistical precision.*

Features of hyperon CP tests at STCF:

- Hyperon production, polarization and kinematics established
- Numerous CPV observables
- Systematic uncertainties control



Statistics related

- Data/MC difference in tracking, PID etc.→Two orders in magnitude improve of control sample→10^{-4} or better
- Input-output check → Larger MC statistics→ negligible

Theoretical calculation related

- NLO production → complete form factor function → negligible
- Procession in magnetic field/de-coherence → include the effects in MC → negligible

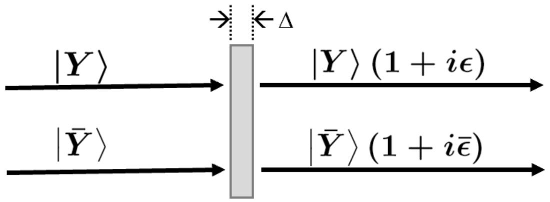
Detector and software related

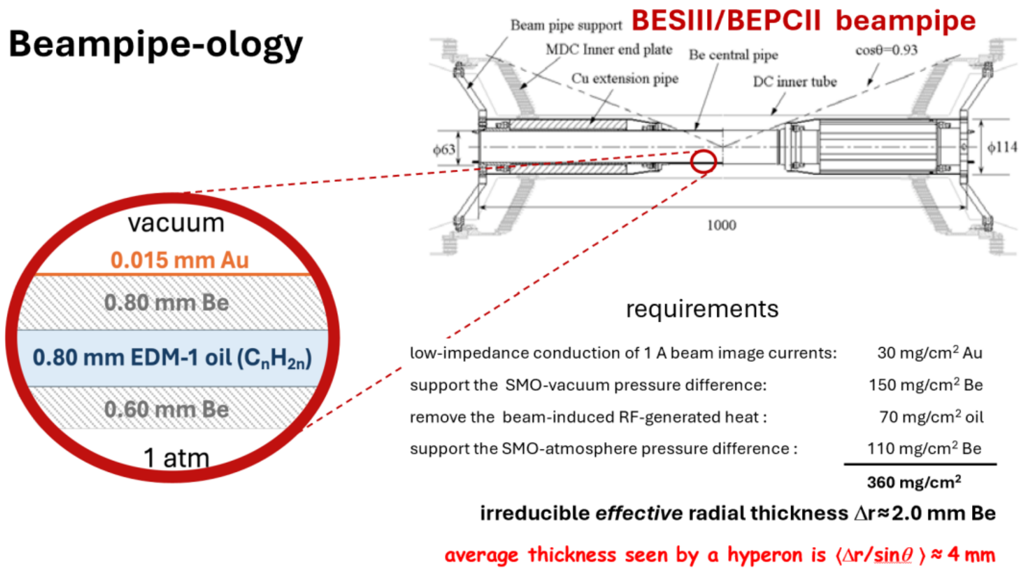
- Detection resolution effect → examine the decay parameter bin-by-bin → 10^{-4} or better
- Kinematic fits, photon noise, background etc.→ Novel MC tool and reconstruction→ 10^{-4} ?

CP Tests in Hyperons Decays

As the **detector resolution is a big issue in the uncertainty estimation**. A series of attempts are undergoing in the tracking recontribution, which include:

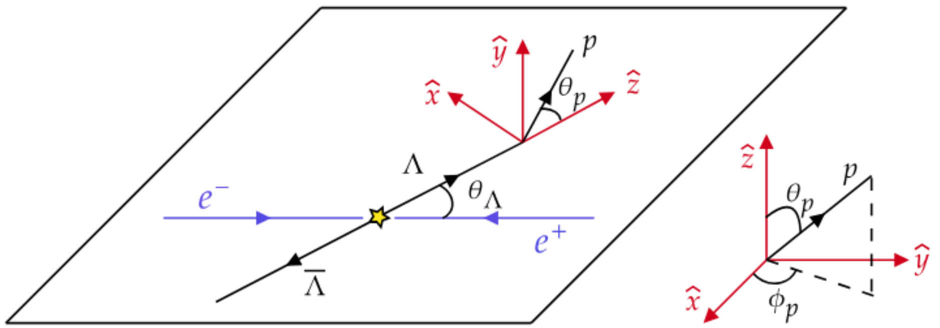
- Improve tracking efficiency from **long-life particle decay**
- Improve tracking efficiency for **low-momentum particles**
- Study the impact of electron **bremsstrahlung**
- Optimize of the **secondary vertex fitting**
- Impact of **magnetic field non-uniformity**
- Impact of **material budget**
- Impact of **background contamination**
- **How Y and $\bar{Y}$ affect $Y-\bar{Y}$ spin correlations?**





Talk in FTC2024-Guangzhou "CP studies with hyperons", by Stephen Olsen

Search for CPV and d_Λ in $J/\psi \to \Lambda\bar{\Lambda}$ decay



- **Angular distribution of hyperon production**
  - Described by EM form factors $G_{1,2}$

$$\alpha_\psi = \frac{s^2|G_1|^2-4m^2|G_2|^2}{s^2|G_1|^2+4m^2|G_2|^2},\quad \frac{G_1}{G_2} = \left|\frac{G_1}{G_2}\right| e^{-i\Delta\Phi}$$

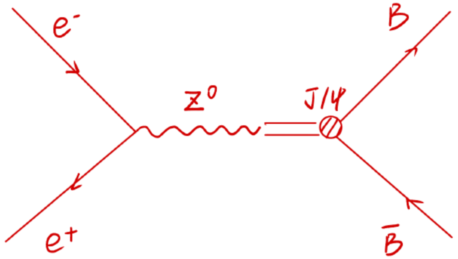
$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta$$

  - Non-zero sin(**ΔΦ**) signatures hyperon polarization

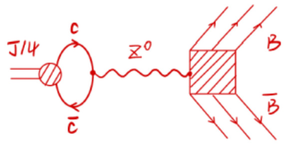
$$P_y(\cos\theta) = \frac{\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\cos\theta\sin\theta}{1+\alpha_\psi\cos^2\theta}$$

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

- ***P*, *CP* violating terms in J/ψ production and decay**
  - P_L: J/ψ longitudinal polarization induced by Z boson
  - F_A: P violating form factors
  - H_T: CP violating form factors associated with EDM

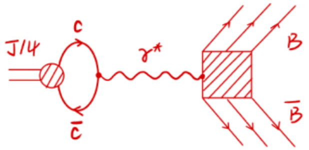


$$P_L = \frac{\rho_{++} - \rho_{--}}{\rho_{++} + \rho_{--}}$$



F_A : P violation term

Complex form factor, $F_A \neq 0$ indicate P violation



H_T: CP violation term

$$H_T(q^2) = \frac{2e}{3m_{J/\psi}^2} g_V d_B(q^2)$$

Assuming $d_B(q^2) \equiv d_B(0)$

$d_B(q^2)$: electric dipole form factor
$d_B(0)$: electric dipole moment
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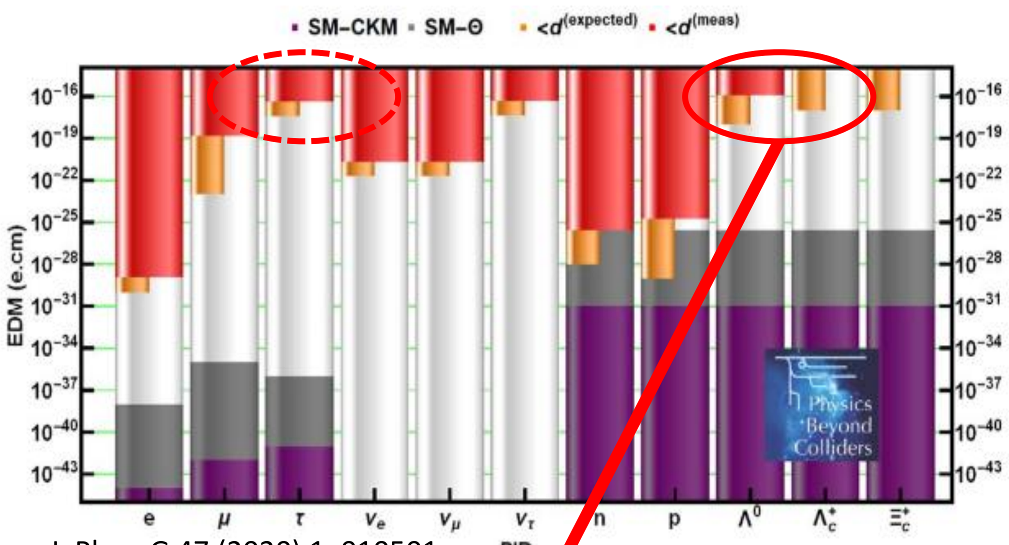
Search for CPV and d_Λ in $J/\psi \to \Lambda\bar{\Lambda}$ decay



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- EDM measurement only performed for Λ hyperon
- **d_Λ can be improved 10,000 in STCF**
- Search for EDM of the other strange and charmed baryons

- Based on OSCAR simulation, **statistical precision** improved by more than one order comparing to BESIII
- **Systematic uncertainty** dominated by **detector resolution effects**, could be improved by correcting resolution effect in MC with control samples, which is under study

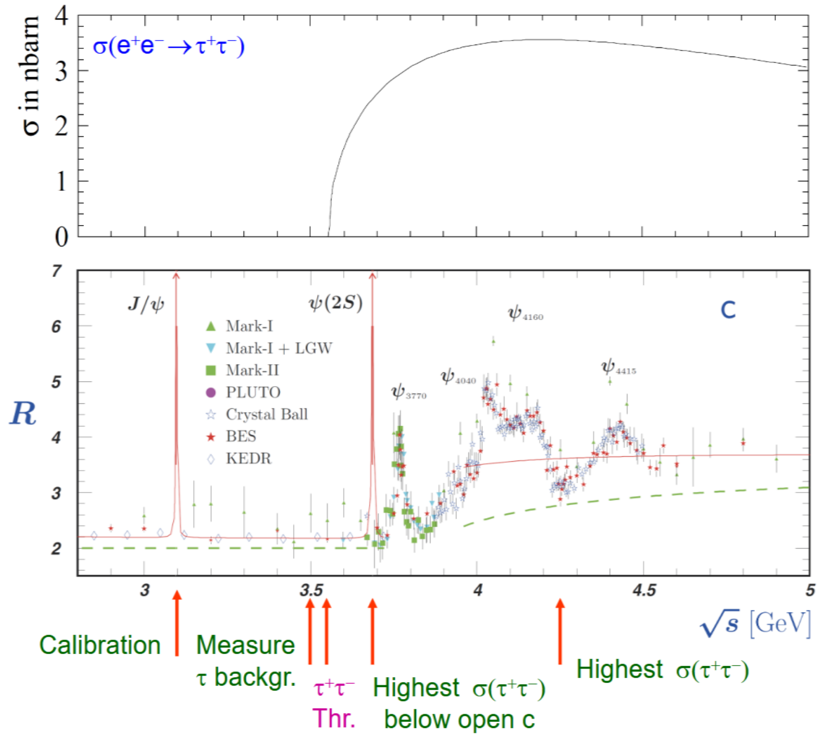
Parameter	**Stat.**	BESIII Stat.	BESIII Sys.
$\alpha_{J/\psi}$	$\mathbf{1.4\times10^{-4}}$	2.2×10^{-3}	1.7×10^{-3}
$\Delta\Phi$	$\mathbf{2.7\times10^{-4}}$	4.2×10^{-3}	1.3×10^{-3}
A_{cp}	$\mathbf{3.0\times10^{-4}}$	4.6×10^{-3}	1.1×10^{-3}
$\sin W^2$	$\mathbf{6.4\times10^{-4}}$	1.2×10^{-3}	2.6×10^{-3}
$Re(d_\Lambda)$	$\mathbf{2.1\times10^{-20}}$	3.2×10^{-19}	0.5×10^{-19}
$Im(d_\Lambda)$	$\mathbf{1.6\times10^{-20}}$	2.6×10^{-19}	0.6×10^{-19}

Tau physics at STCF

★ *The IAC notes and approves of the three physics topics that have been identified as flagship measurements, but suggests that the list could be extended to around five. In particular, it considers that it would be appropriate to include a* ***topic in tau physics****.*

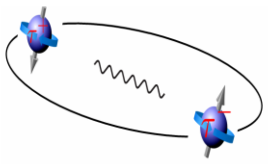
- Tau pairs in e^+e^- collider produced back-to-back in center-of-mass system
- At **tau-charm factory**: different energy region, different potential, runs near the tau pair threshold

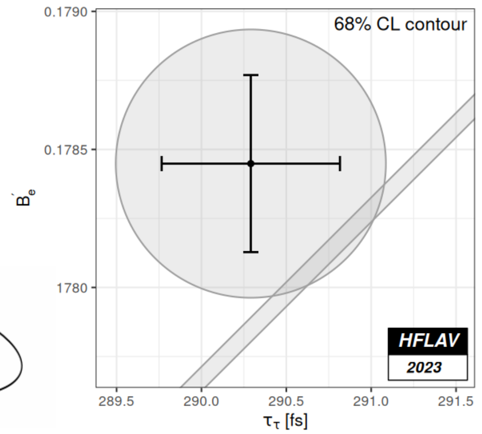
Exp.	Lum.	$\sqrt{q}$	Number of tau pairs
ALEPH	200 pb^{-1}	91.2 GeV	3.3×10^5 reconstructed
BaBar	467 fb^{-1}	~10.58 GeV	4.3×10^8
Belle	988 fb^{-1}	~10.58 GeV	9.12×10^8
Belle II (prospect)	50 ab^{-1}	~10.58 GeV	4.6×10^{10}
BESIII	~35 fb^{-1}	From threshold to 4.95 GeV	$\sim 1.2 \times 10^8$
STCF (prospect)	**1 ab^{-1} per year**	**From threshold to 7 GeV**	$\sim 3.5 \times 10^9$

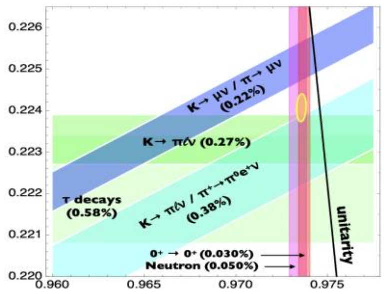


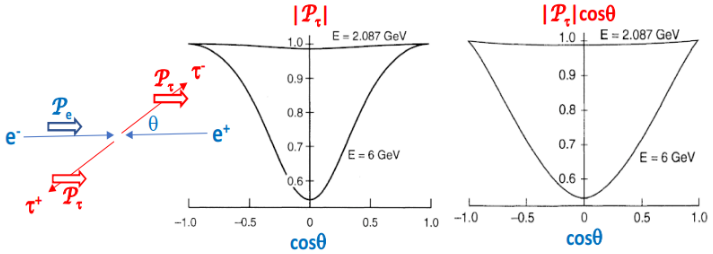
Tau physics potential at STCF

- **Properties of tau lepton**
  - **τ-lepton mass (Challenge from uncertainties in energy calibration and spread)**
  - **Tauonium** Enhanced significance with improved energy spread
  - **EDM** evolution of EDM form factors with energy
  - **Quantum entanglement**
- **Tau decay**
  - **cLFV** systematically studies via leptonic decays
  - **Cabibbo angle anomaly, CPV** studies via hadronic decays
  - **Amplitude/form factor** studies via many-body decays
  - **α_s and muon g-2**



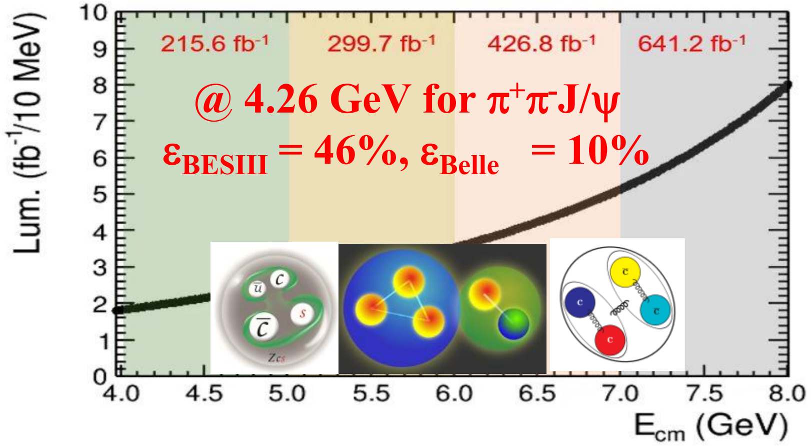


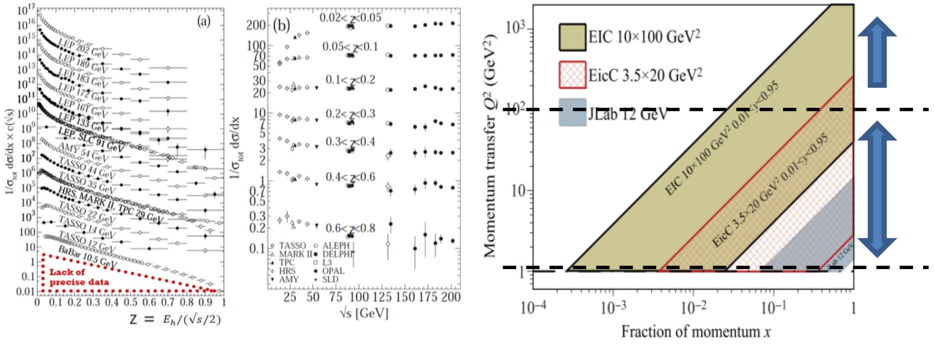


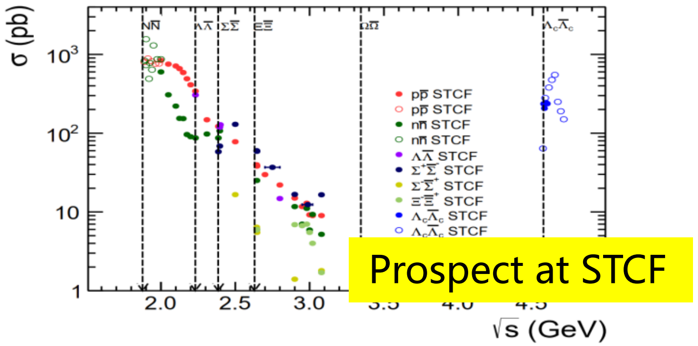


5-7 GeV physics potential at STCF

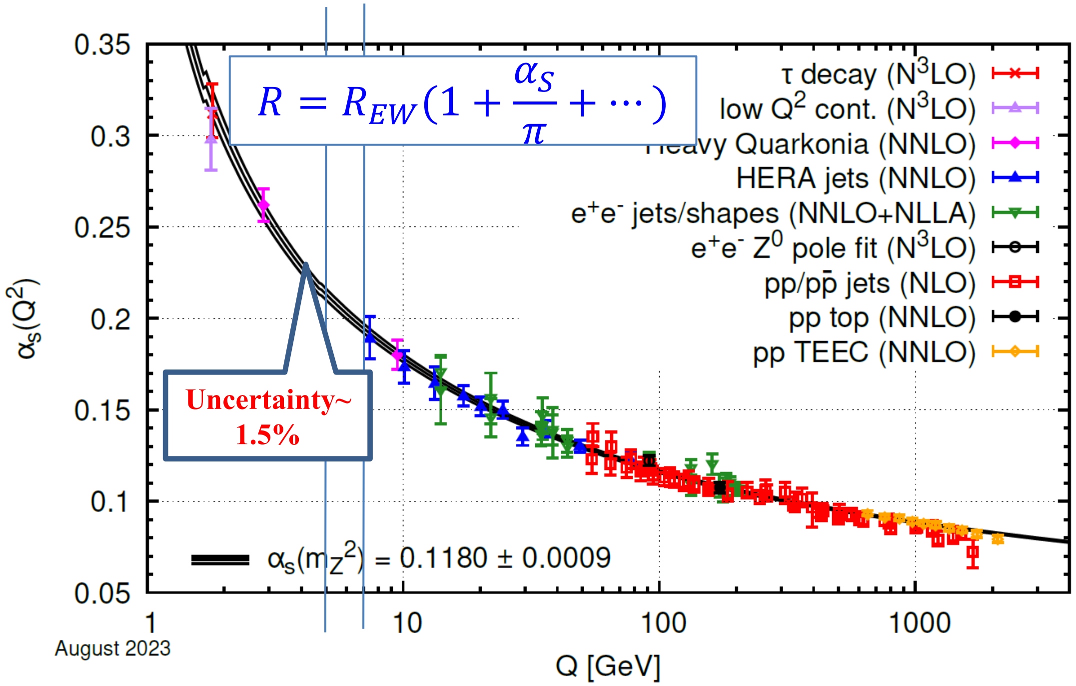
- **Hadron spectroscopy**
  - Many threshold opens in 5-7 GeV which yield more potentials for hadron studies
  - Structures in more channels for **XYZ physics**, with larger production rates above 5 GeV
  - **P_c pentaquarks** in $e^+e^- \to J/\psi h\bar{h}$ **for** hidden-charm and $e^+e^- \to \Lambda_c\bar{D}^*\bar{p}, \Sigma_c^*\bar{D}^{(*)}\bar{p}$ for open-charmed pentaquarks
  - Energy region above 6 GeV is ideal for **fully charmed tetraquark states** via $e^+e^- \to J/\psi c\bar{c}$ etc.
- **Hadronization and hadron structure**
  - **Fragmentation functions** for charmed quark is avaliable
  - Synergy with Eic(C) facilities for FF studies
  - A non-zero Pauli **Form factors** provides evidence for the existence of higher Fock states, that require higher energies

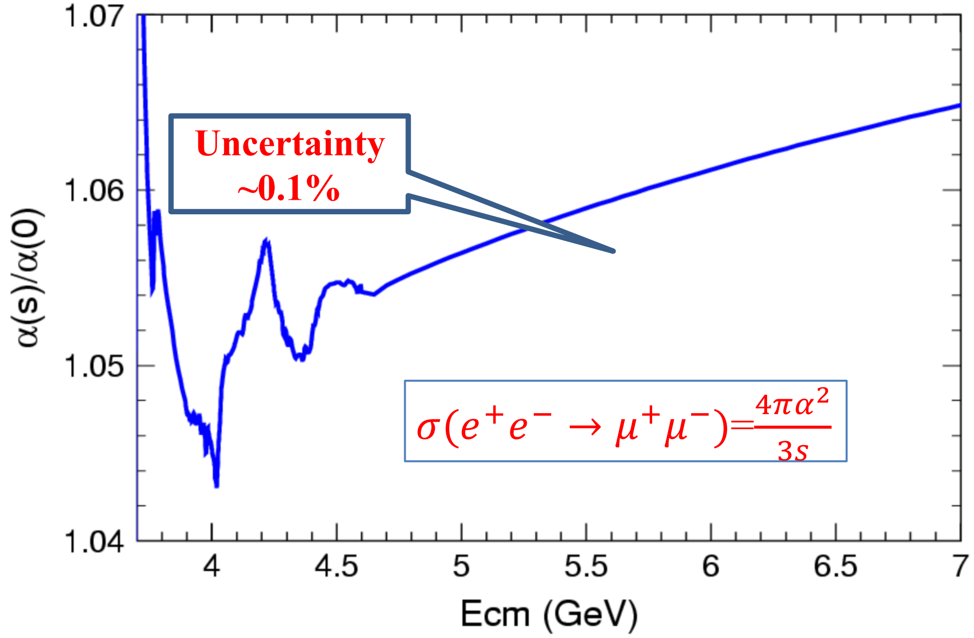






强相互作用耦合常数α_s





- Finding invisible states in e^+e^- annihilation：Compare α_{QED} from $\sigma(e^+e^- \to \mu^+\mu^-)$ and that calculated from $\sigma(e^+e^- \to \text{hadrons})$
- $\sigma(e^+e^- \to \text{hadrons})$ & $\sigma(e^+e^- \to \mu^+\mu^-)$
  - 100 fb^{-1} data (~1 month @ L_{peak}~$5\times10^{34} cm^{-2}s^{-1}$) ➔
    - 2-4 x 10^6 $e^+e^- \to \mu^+\mu^-$ events ➔ 0.2% or better precision?
    - 7-14 x 10^6 $e^+e^- \to$ *hadrons* events ➔ 0.4% or better precision?
  - Bhabha or $e^+e^- \to \gamma\gamma$ for integrated luminosity measurements