超子-核子谱仪(H-NS)

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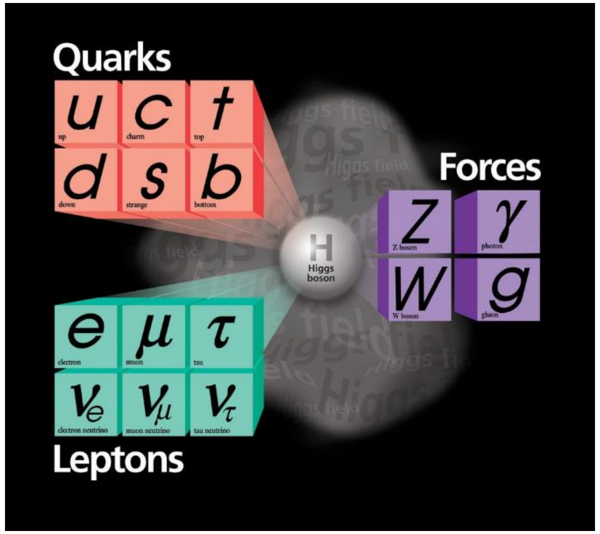
第一届强相互作用自旋物理会议
2026.07.29 青岛

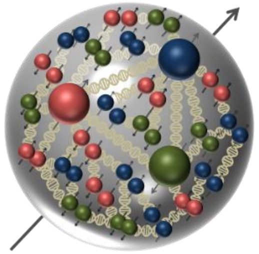
Phys. Rev. D 112, L031502
arXiv: 2512.02804, NST in press
arXiv: 2601.21325, NST in press
arXiv: 2606.06553, NST submitted
arXiv: 2607.19927

汇报内容

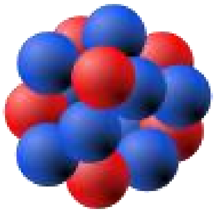
- 主要物理介绍
- H-NS谱仪设计
- 性能预期与物理潜力
- 发展规划
- 总结

21世纪基本物理谜题之一：核子内部结构





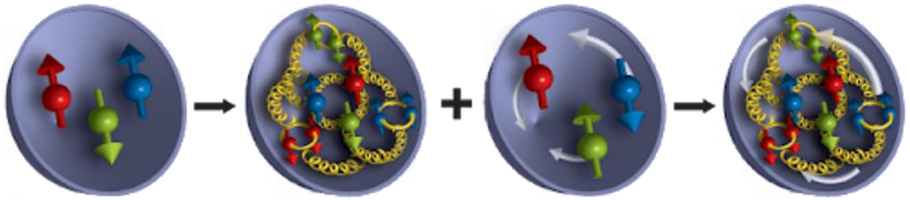
质子自旋结构?



质子质量来源?

自旋

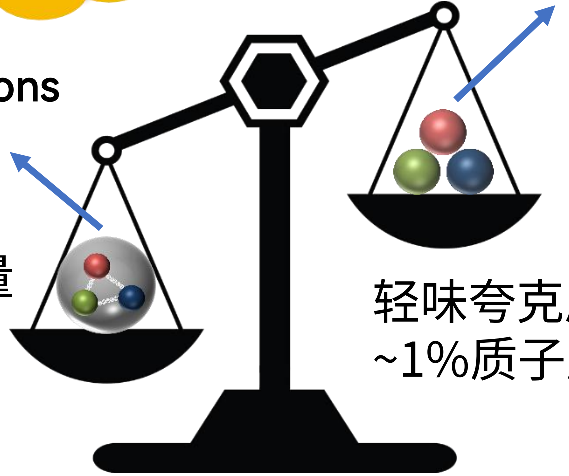
Gell-Mann
夸克模型



质量

Dynamics of gluons

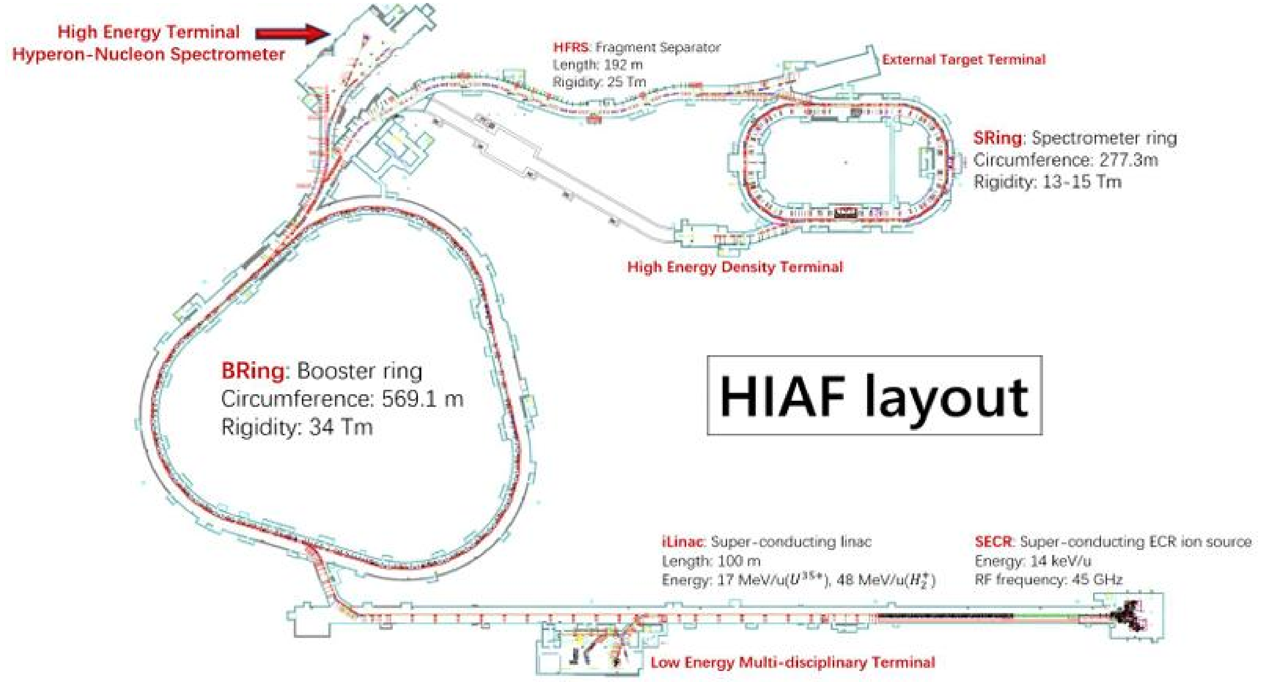
Higgs mechanism



~99%
质子质量

轻味夸克质量
~1%质子质量

基于HIAF的高能核物理研究



Ion species	Kinetic Energy (GeV/u)	Beam intensity (ppp)
p	9.3	6.0×10^{12}
$^{16}O^{8+}$	4.25	6.0×10^{11}
$^{18}O^{6+}$	2.6	6.0×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{35+}$	0.835	1.0×10^{11}
$^{238}U^{78+}$	2.6	1.0×10^{10}

- p 束流 → p 靶
- p 束流 → A 靶
- A 束流 → A 靶

- 电子离子对撞

长期规划：HIAF → HIAF-U → EicC

近期规划：利用HIAF束流开展高能核物理研究

两个基本问题：质子自旋与超子极化

核子自旋结构研究-1988年

质子自旋危机

EMC at CERN - J. Ashman et al., NPB 328, 1 (1989)

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\mathrm{stat}) \pm 14(\mathrm{syst})\%$$

A crisis in the parton model: where, oh where is the proton's spin?

E. Leader[1] and M. Anselmino[2]

Birkbeck College, University of London, London, UK
Dipartimento di Fisica Teorica, Università di Torino, I-10125 Torino, Italy

Received 18 March 1988

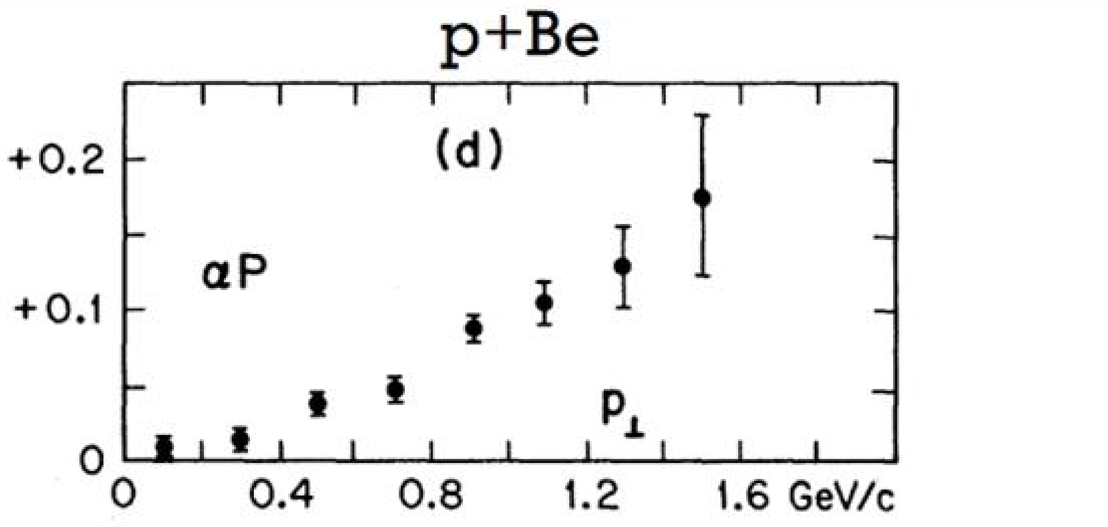
Z. Phys. C – Particles and Fields 41, 239–246 (1988)

Zeitschrift für Physik C Particles and Fields

Λ横向极化的首次观测-1976年

超子极化之谜

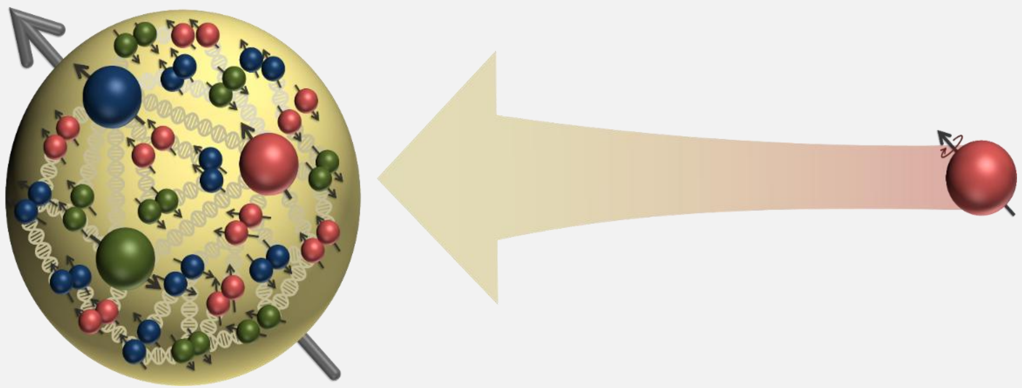
费米实验室：300 GeV质子打Be靶、初态均为非极化
末态产生的Λ观测到明显的横向极化现象



G.Bunce, *et al.*: Phys.Rev.Lett. 36, 1113-1116 (1976)

自旋结构与极化之间的内在联系

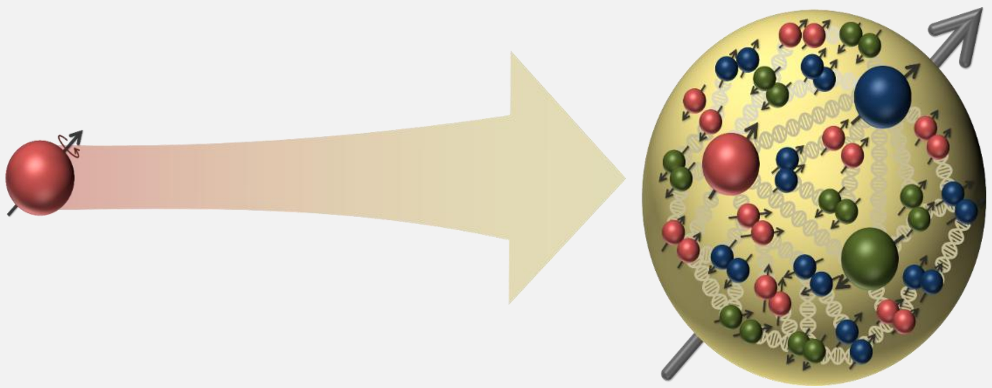
EIC: Initial state is polarized
-How do partons form up a polarized nucleon?



Initial state

Polarized by device

Λ polarization: Final state is polarized
-How do partons form up a polarized Λ / p?

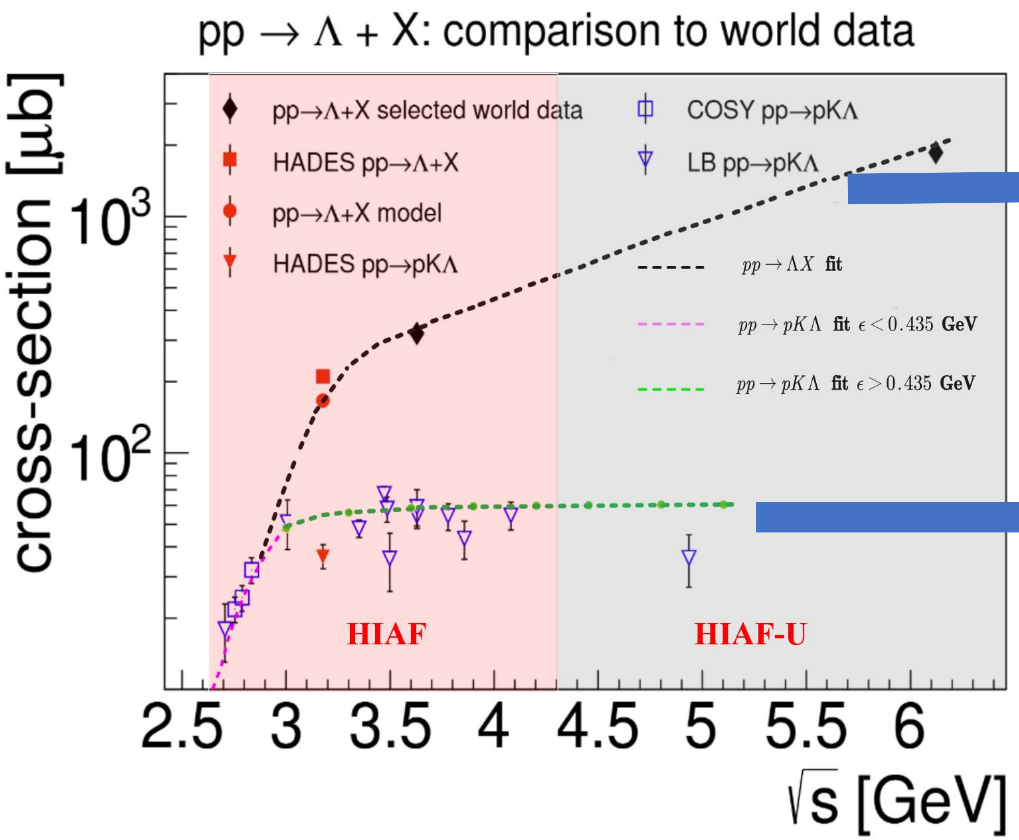


Final state

Λ serves as its own spin analyzer through the decay $\Lambda^0 \to p + \pi^-$

origin of nucleon spin VS origin of Λ or p polarization
物理上紧密相连

跨能区、跨反应过程研究

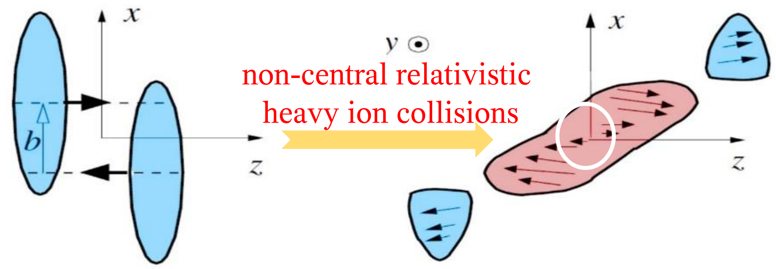


$$pp(A) \to \Lambda + X$$ polarization through hadronization

Zuo-tang Liang, and C. Boros, Phys. Rev. Lett. 79, 3608 (1997); PRD 61, 117503 (2000).
H. Dong and Zuo-tang Liang, PRD 70, 014019 (2004); PRD 72, 033006 (2005).

$$pp \to \mathrm{p} + \mathrm{K} + \Lambda$$ **Λ polarization in exclusive processes**

R. Machleidt, K. Holinde and C. Elster, Phys. Rept. 149, 1 (1987).
B. C. Liu, B. S. Zou, PRL 96, 042002 (2006).



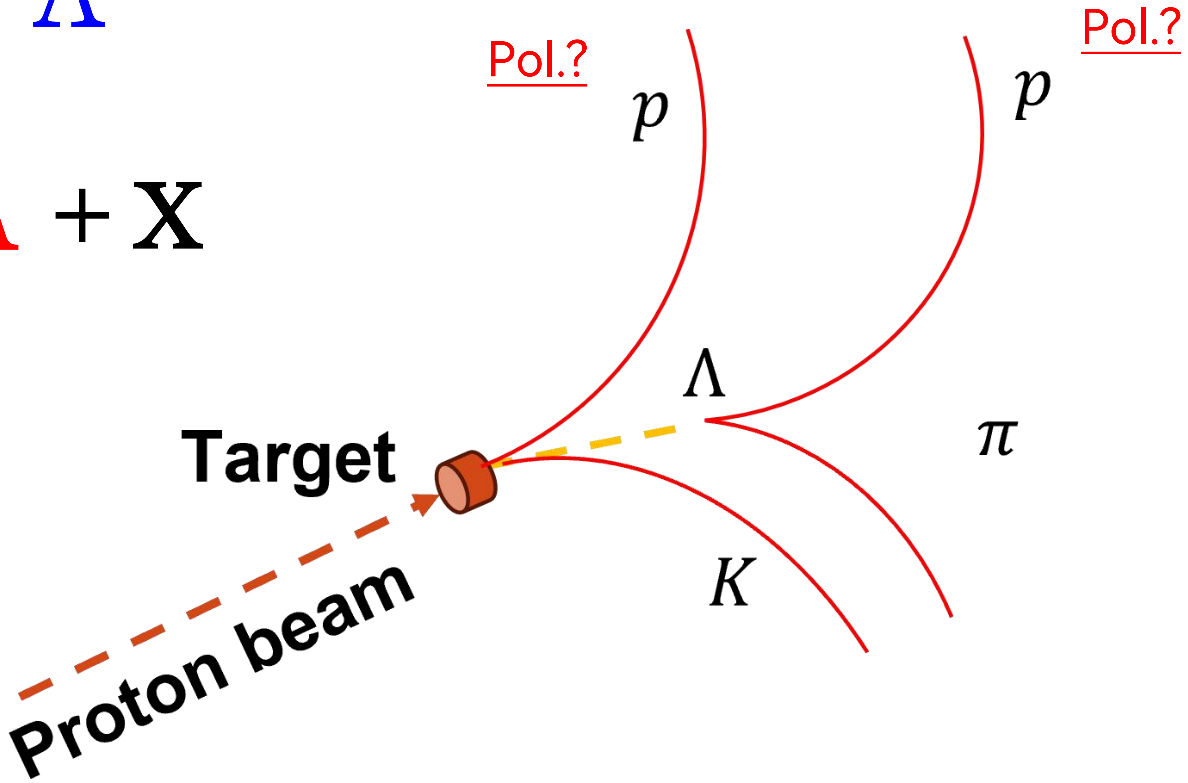
$$AA \to \Lambda + \mathrm{X}$$ **Global polarization**

Zuo-Tang Liang, Xin-Nian Wang, PRL 94,102301 (2005); PLB 629, 20 (2005).
Jian-Hua Gao, Shou-Wan Chen, Wei-tian Deng, Zuo-Tang Liang, Qun Wang, Xin-Nian Wang, PRC 77, 044902 (2008).

末态质子是否极化?

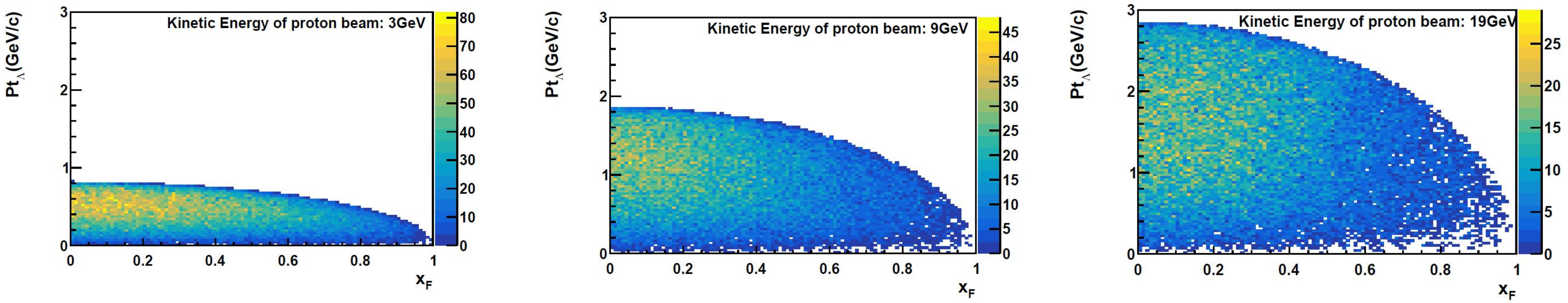
$pp \rightarrow p\,K\,\Lambda$

$pp \rightarrow p/\Lambda + X$



H-NS上专门设计了相关的探测器进行直接测量

HIAF超子产生相空间



3 GeV → 9 GeV → 20 GeV

Allow for a multi-dimensional mapping of the Λ^0 polarization and production

1. Beam energy scan
2. p → p, p → A, A → A data taking

H-NS谱仪设计

Hyperon-Nucleon Spectrometer (H-NS)

Mag. Field: 1.5 Tesla

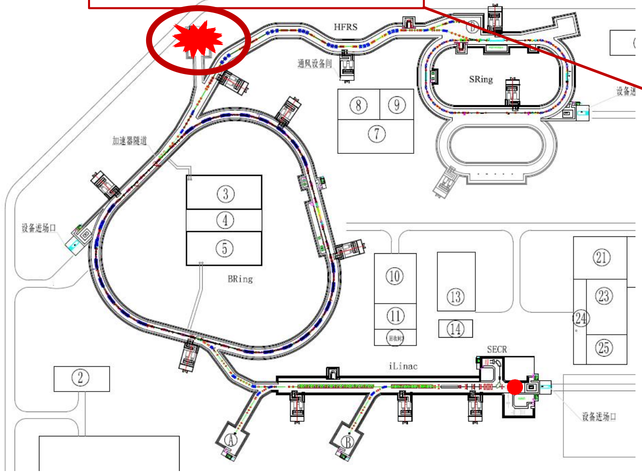
Tracker: MIC6, 30X30 μm², 0.8%X/X_0

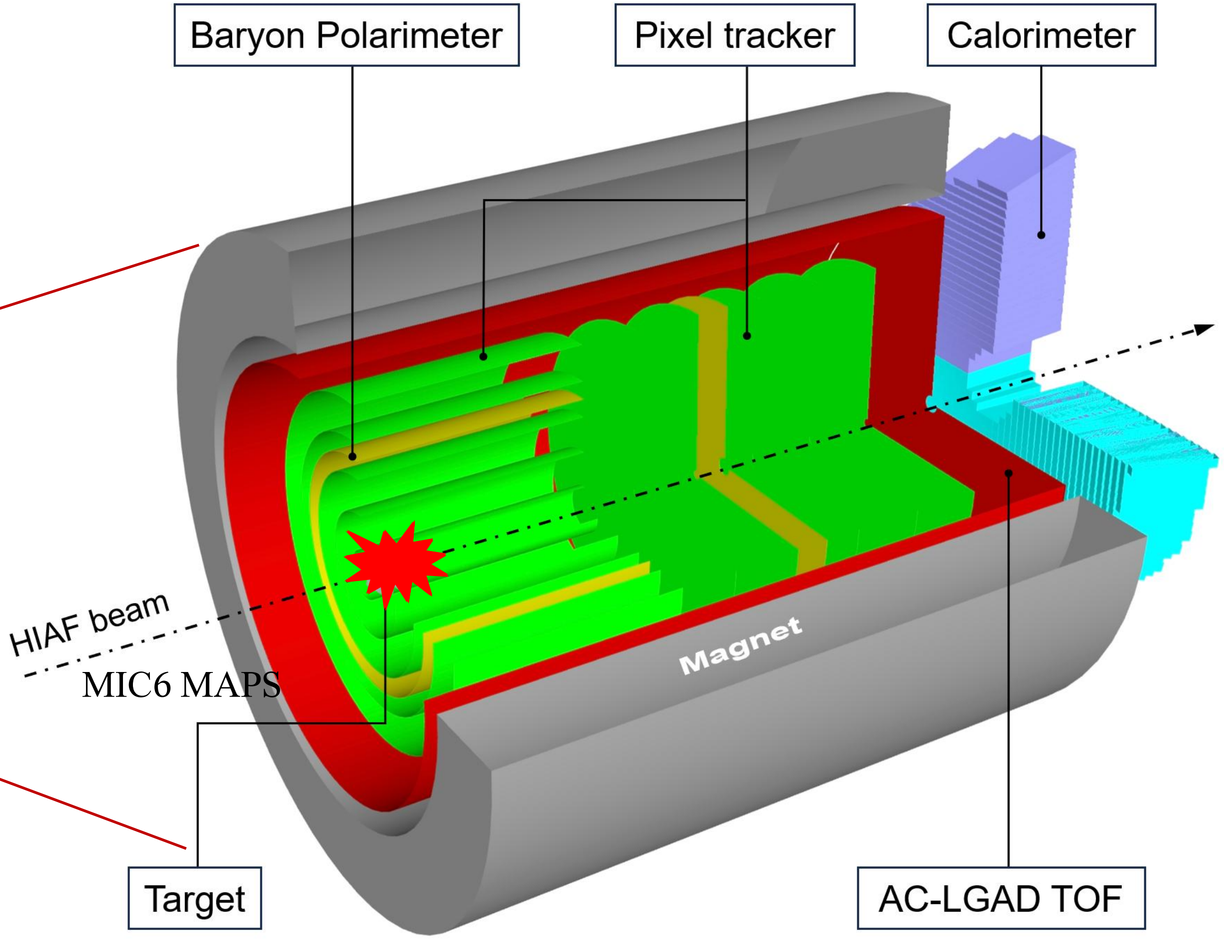
LGAD: $\sigma_t \sim 30$ ps , 300X300 μm²

Calorimeter: $\sigma_E \sim 3\%$ @ 1GeV

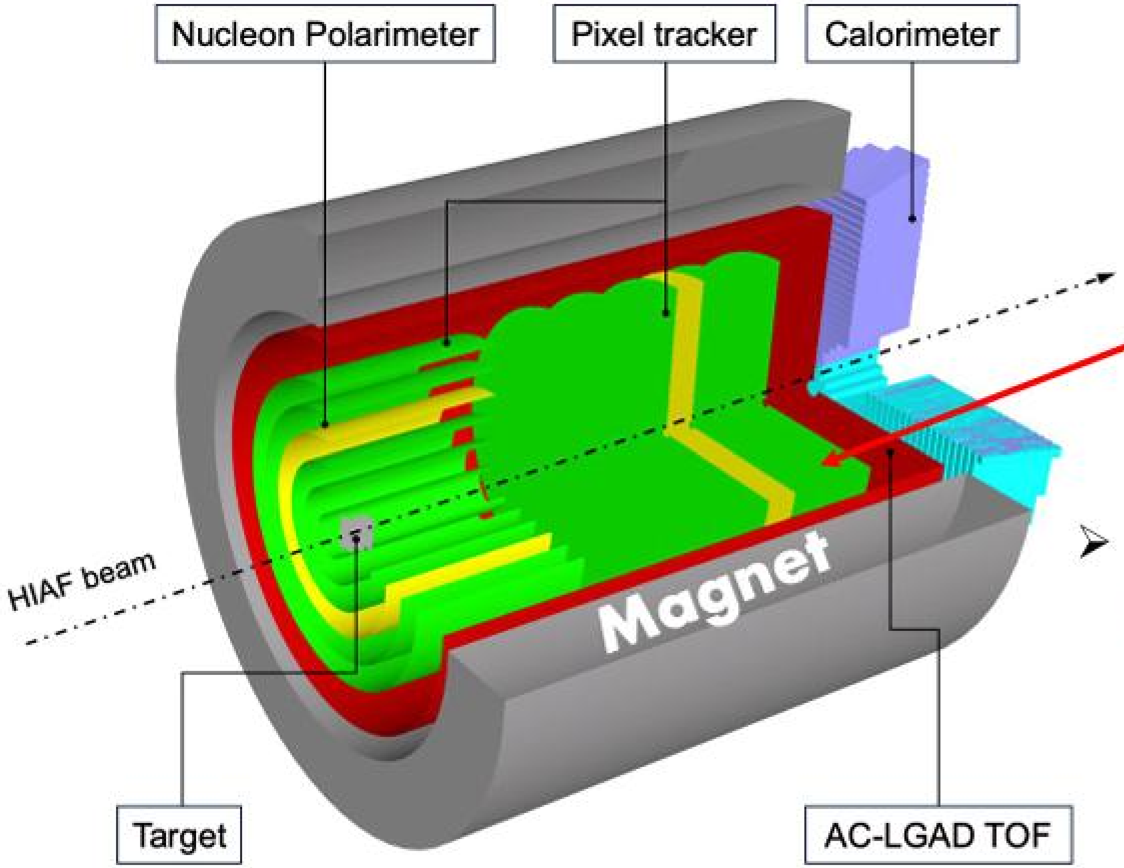
Polarimeter: nucleon and photon polarization

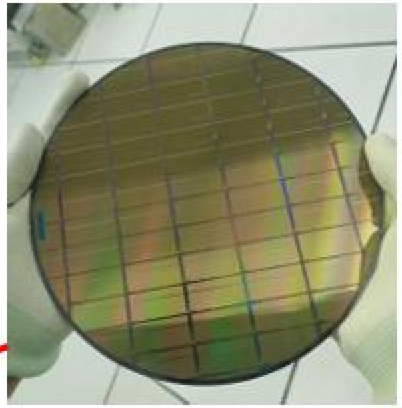
High Energy Nuclear Physics Terminal



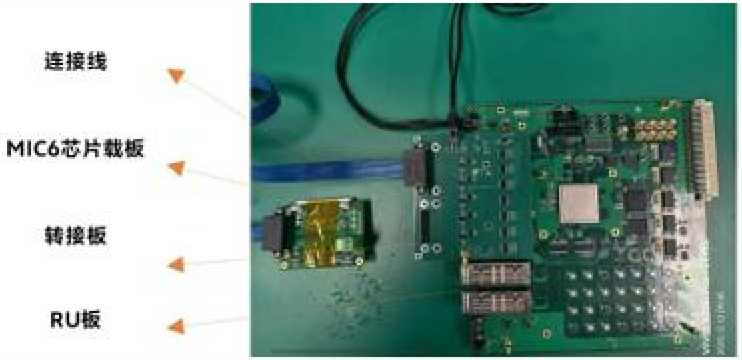


H-NS 径迹探测器系统

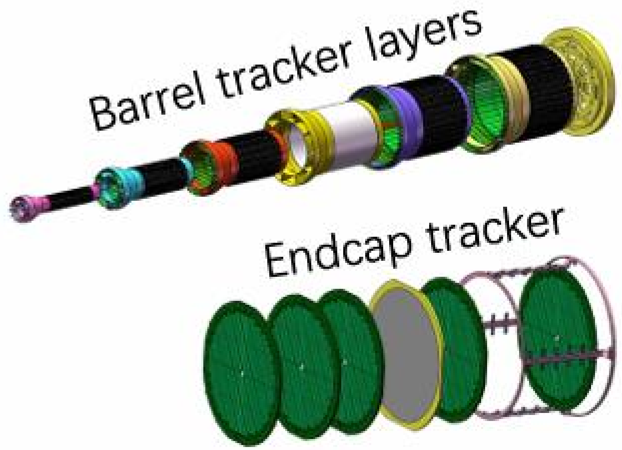




MIC6 V3测试系统

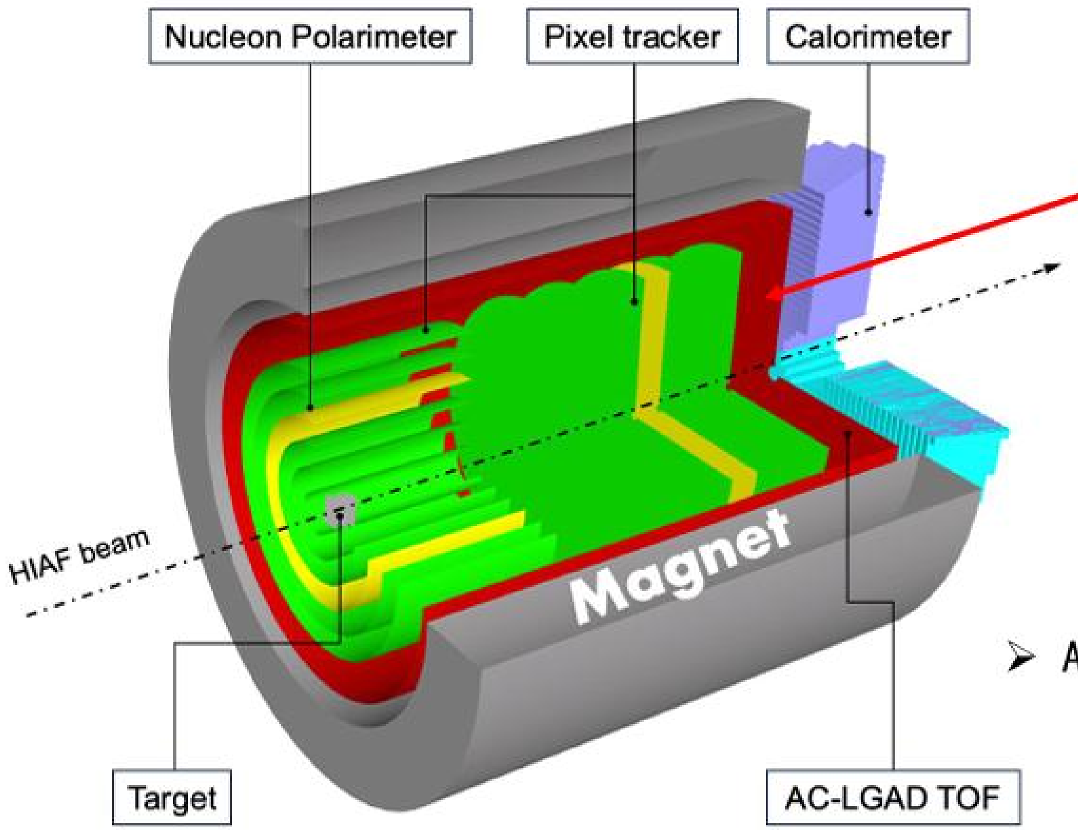


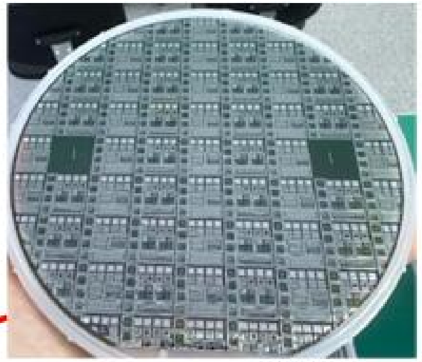
- MIC6 MAPS像素芯片：采用国产工艺开发与制造
  - 像素尺寸：30 μm
  - 物质量：0.8% X/X_0
  - 积分时间：5-10 μs

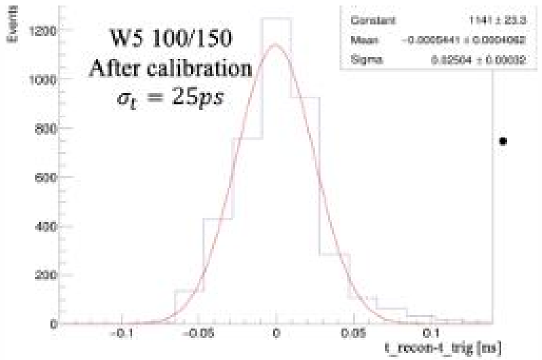


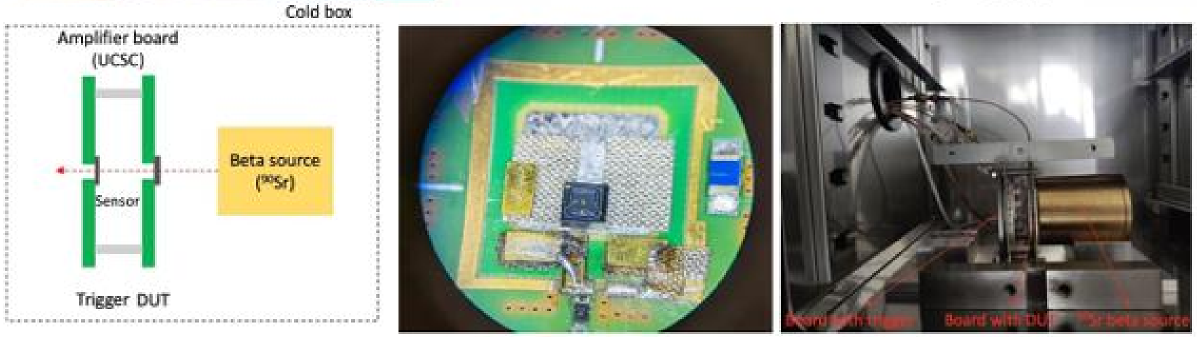
华中师范大学 + 中科大 + 近物所 + 西工大

H-NS 粒子鉴别系统



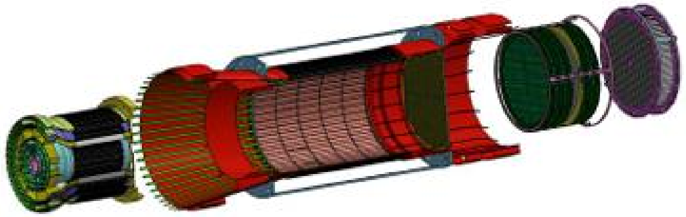






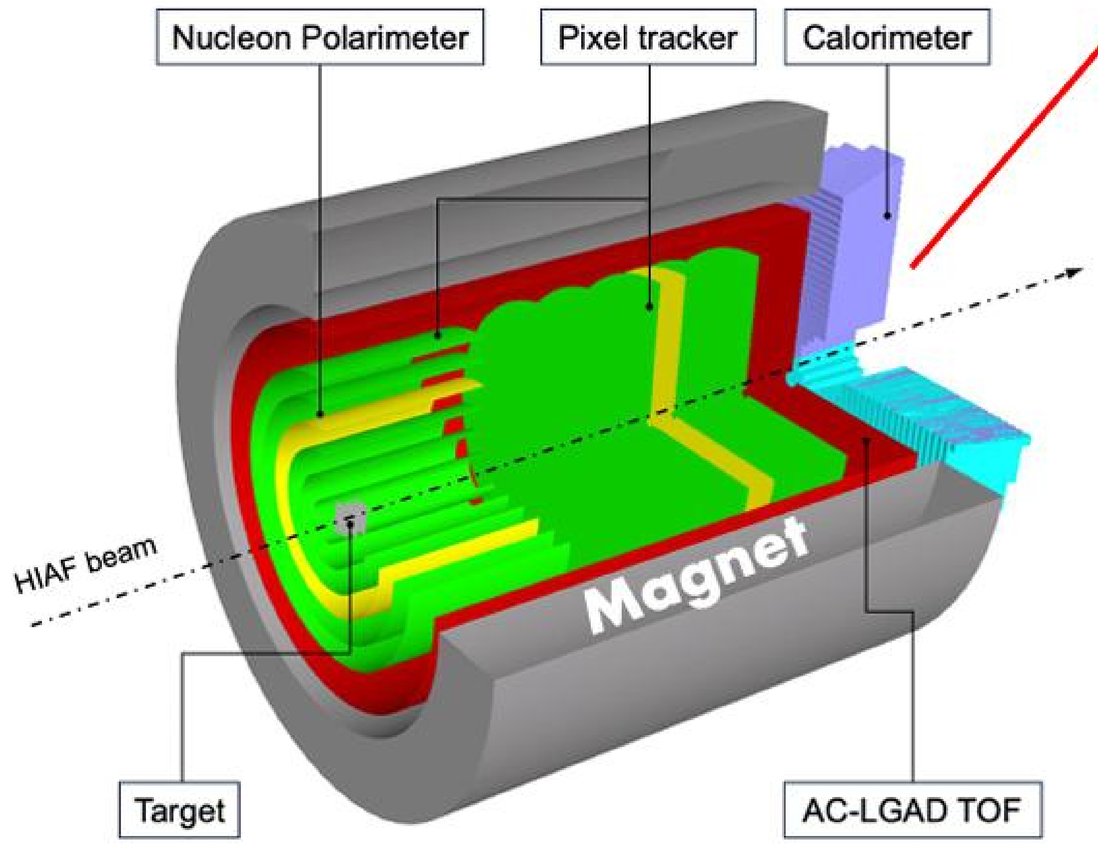
(a) (b) (c)

➢ AC-LGAD
- 结构紧凑
- 时间分辨率: ~30 ps
- 空间分辨率: ~100μm



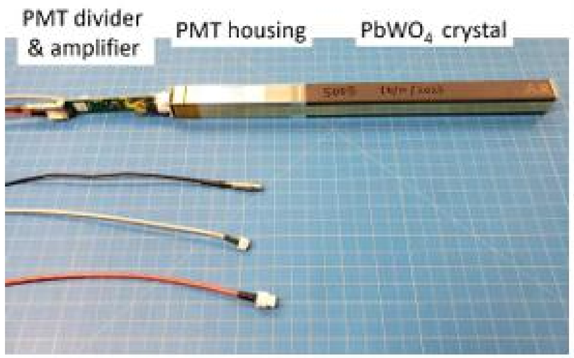
中科大 + 山东大学 + 清华大学 + 近物所

H-NS 量能器系统

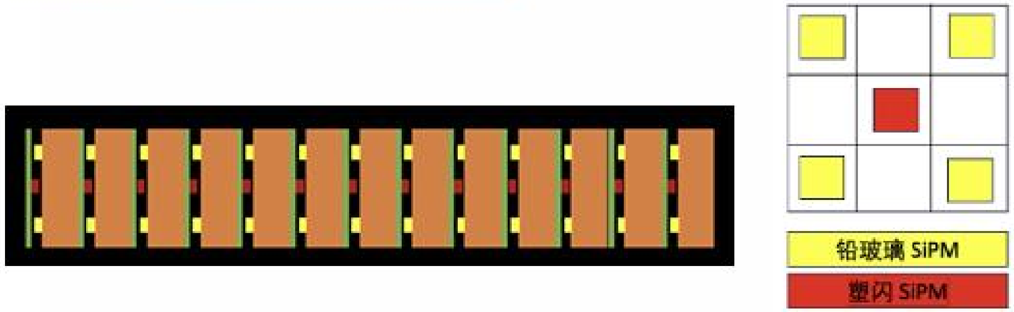


量能器系统双重功能：

1. 重建中性粒子γ, π^0 等，服务物理研究
2. 高性能量能器R&D 平台，支撑未来实验



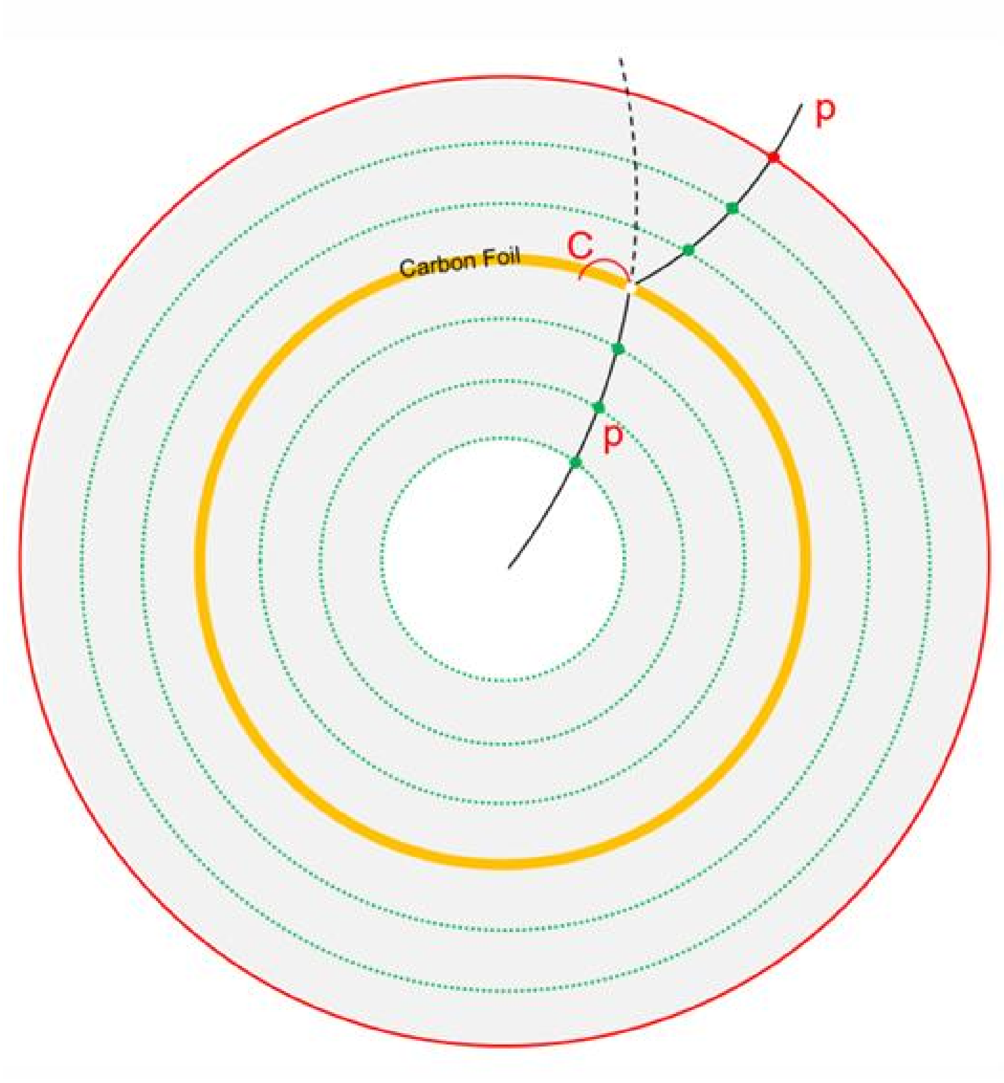
- PbW04晶体：体积紧凑，能量分辨率良好
  - 能量分辨：$3\%/\sqrt{E}$
  - 空间分辨：～3mm



切伦科夫光和闪烁光双读出量能器预研

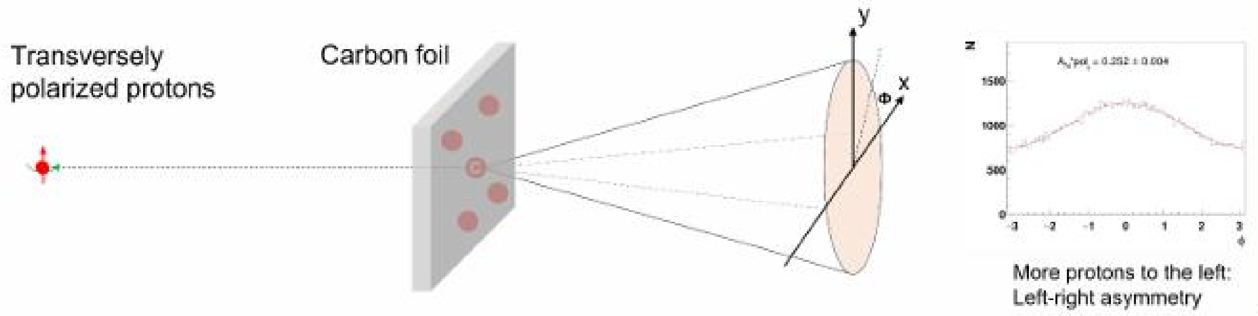
清华大学 + 复旦大学 + 近物所

H-NS 核子极化测量仪



通过弹性散射确定质子极化

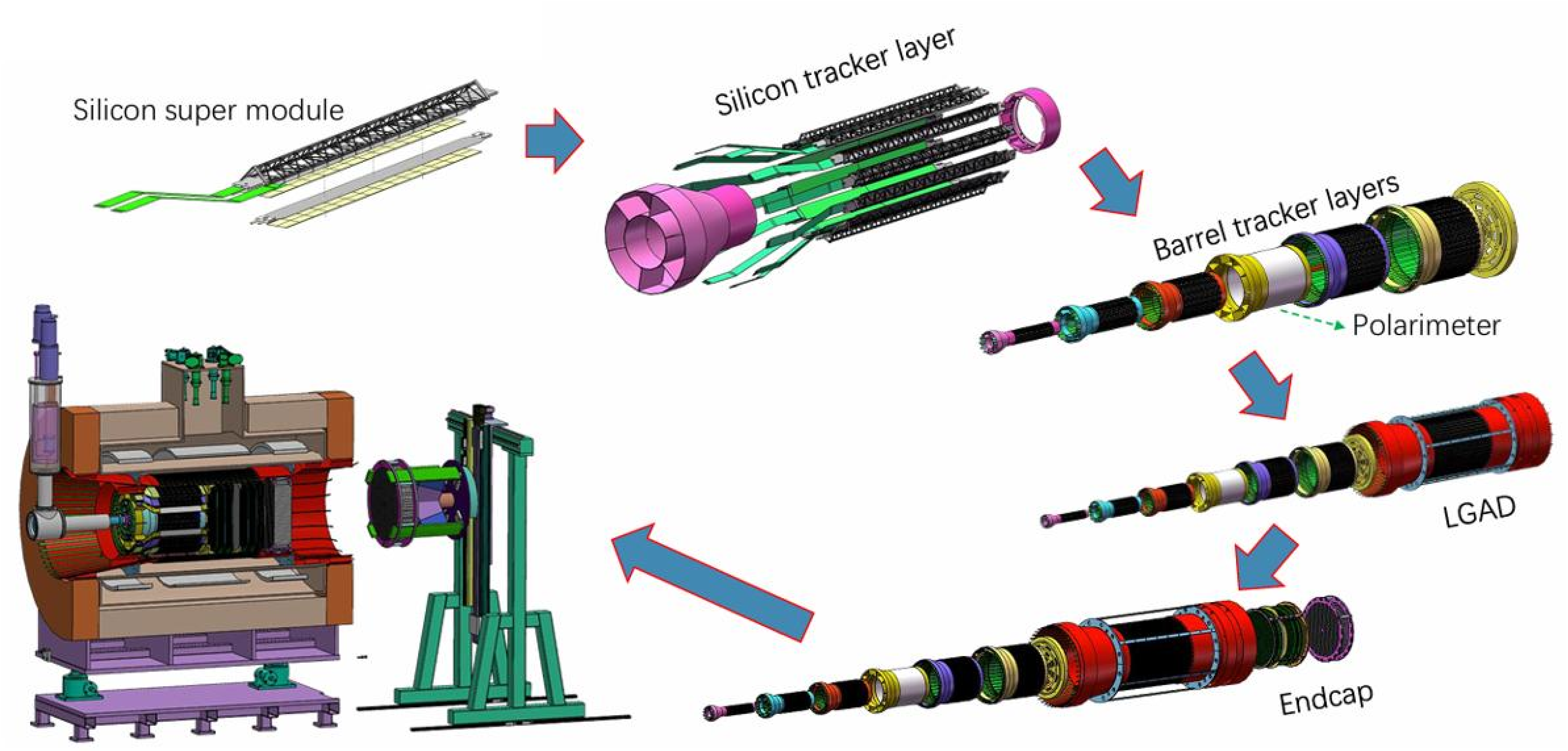
$$\frac{d\sigma}{d\phi d\cos\theta} = \frac{1}{2\pi}\frac{d\sigma_0}{d\cos\theta}\left[1 + \underline{P_y A_N(\theta)} \cos\phi\right]$$



- **碳靶层**
  - **~1 mm thickness**
  - **物质量: <1% X/X_0**
  - **反应几率: pC (1E-3)**
- **位置：径迹探测器中间**

Y. T. Liang et. al. Phys. Rev. D 112, L031502 (2025)

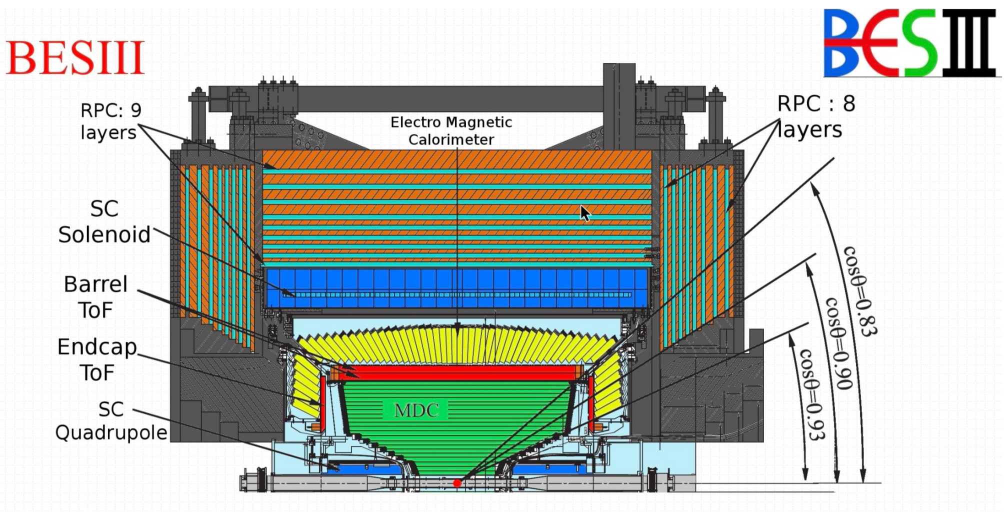
H-NS 探测器集成

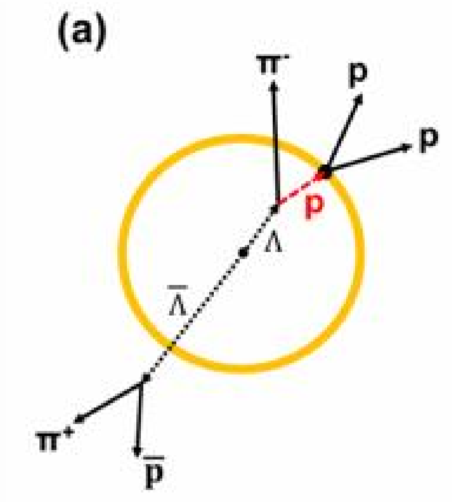


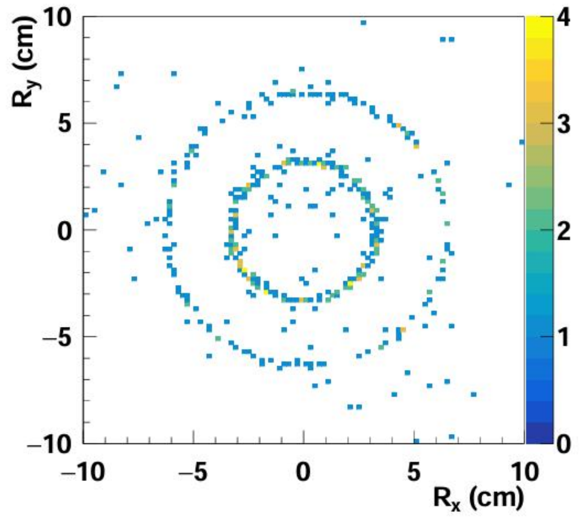
Silicon super module
Silicon tracker layer
Barrel tracker layers
Polarimeter
LGAD
Endcap

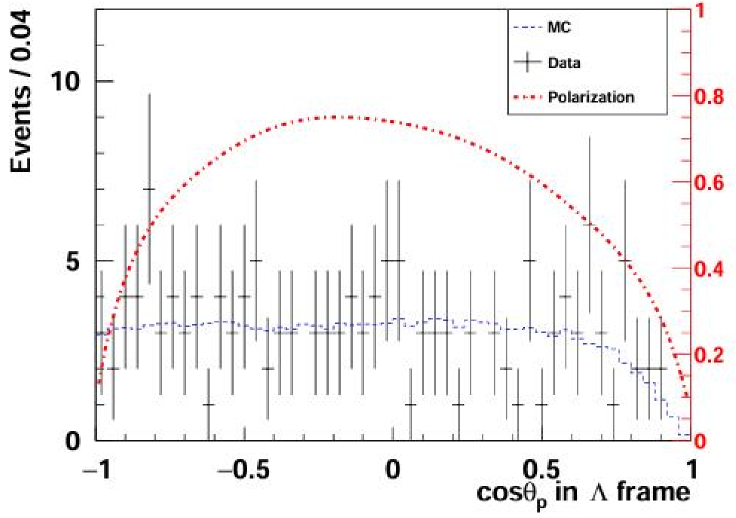
性能预期与物理潜力

核子极化测量功能验证--BESIII



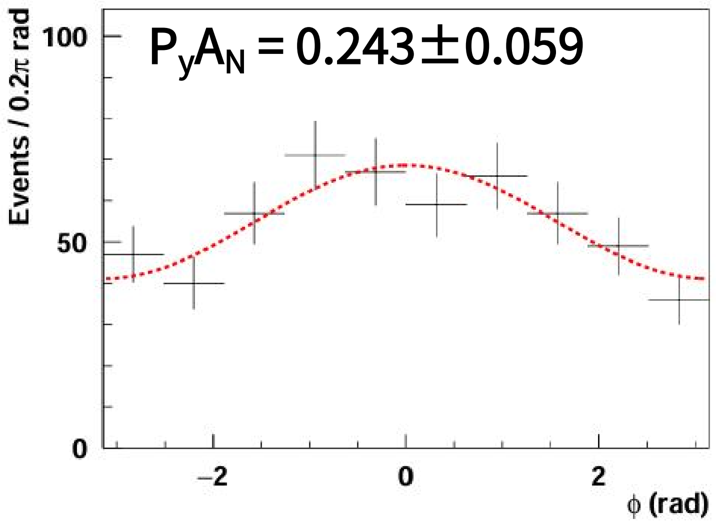






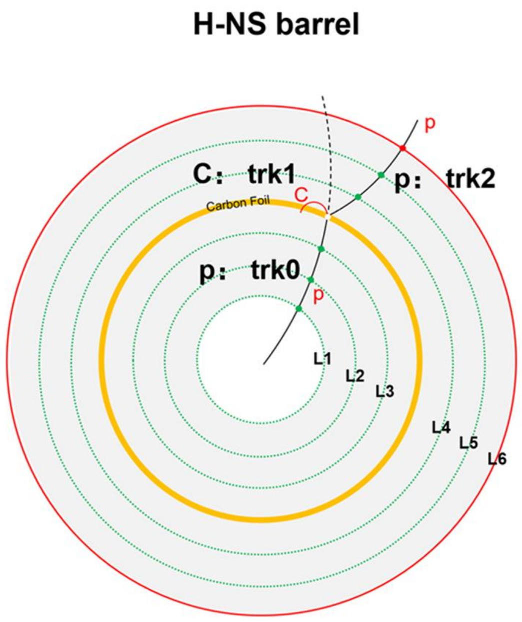
→ expected
$P_yA_N = 0.22 \pm 0.01$

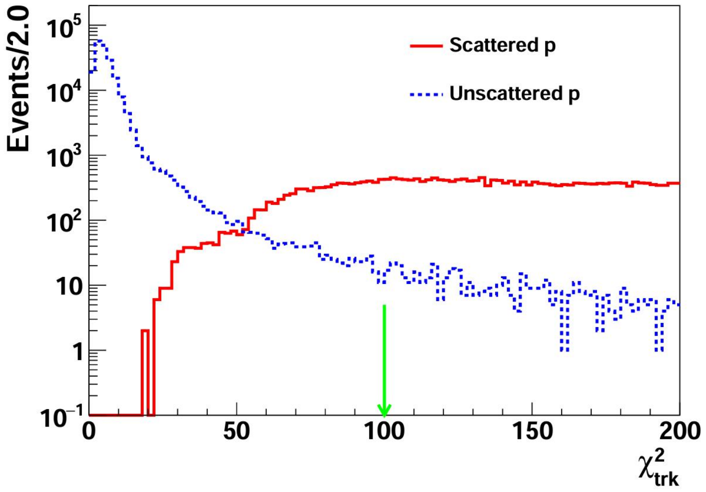
→ measured
$P_yA_N = 0.243 \pm 0.059$

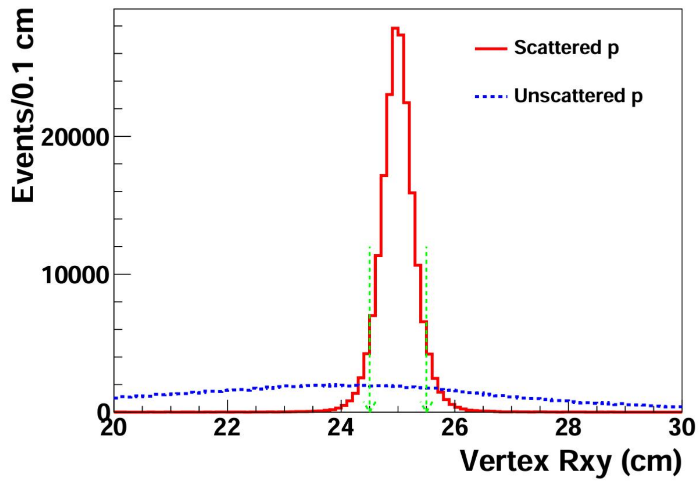


arXiv: 2607.19927

质子极化测量性能

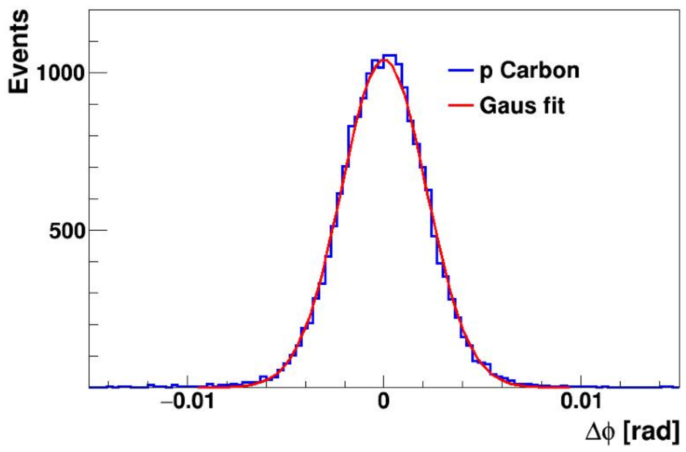




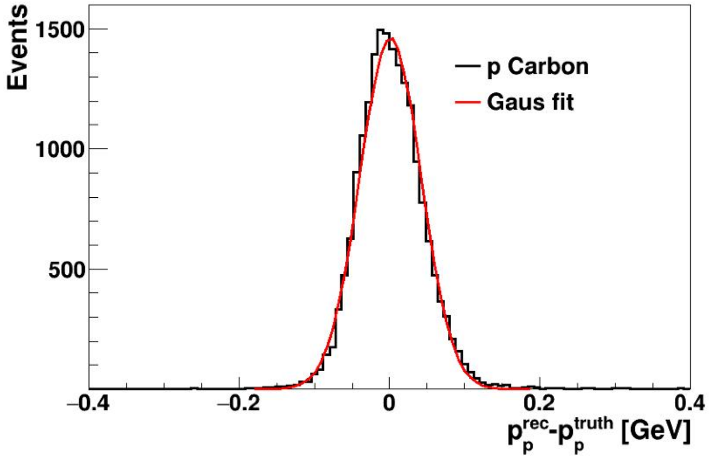


信号/本底特征区分明显

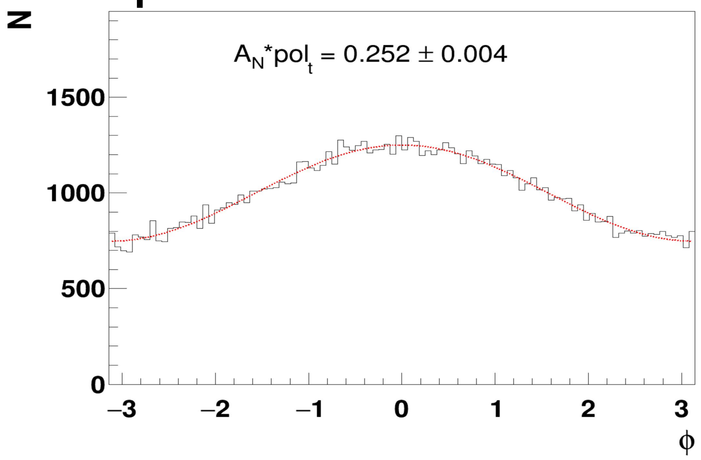
$\boldsymbol{\sigma = 2.16\ \mathrm{mrad}}$



$\boldsymbol{\sigma = 0.041\ \mathrm{GeV}}$



Input: 0.250



入射、散射径迹测量准确

极化率提取准确

极化测量的统计误差

$pp \rightarrow p/\Lambda + X$

H-NS

Reaction: p+p

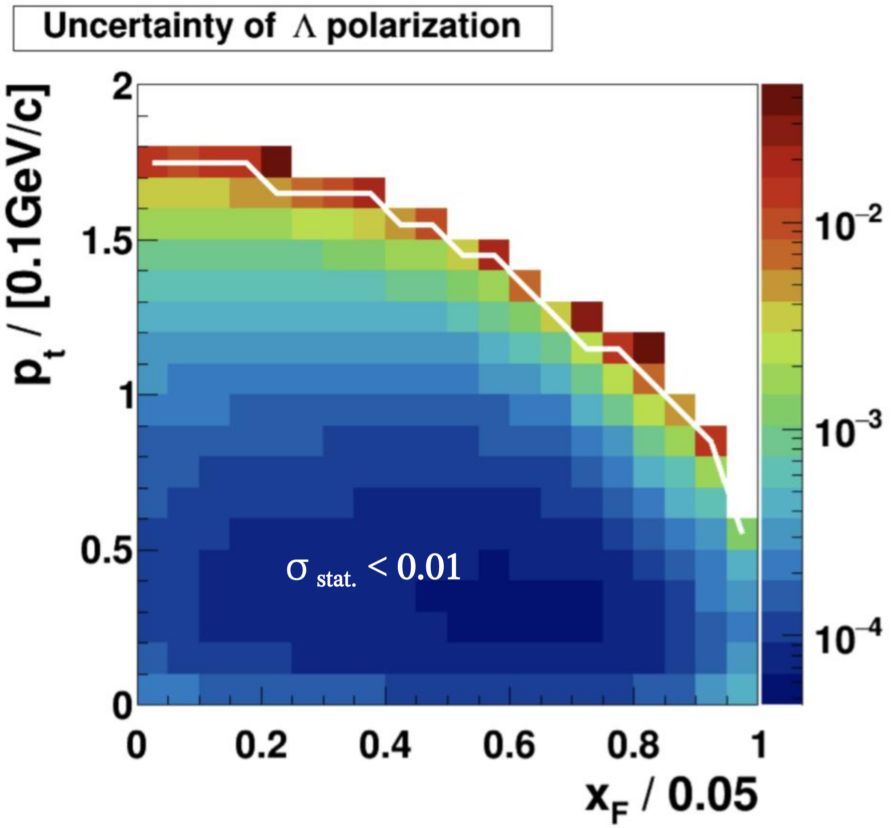
Event rate:1MHz

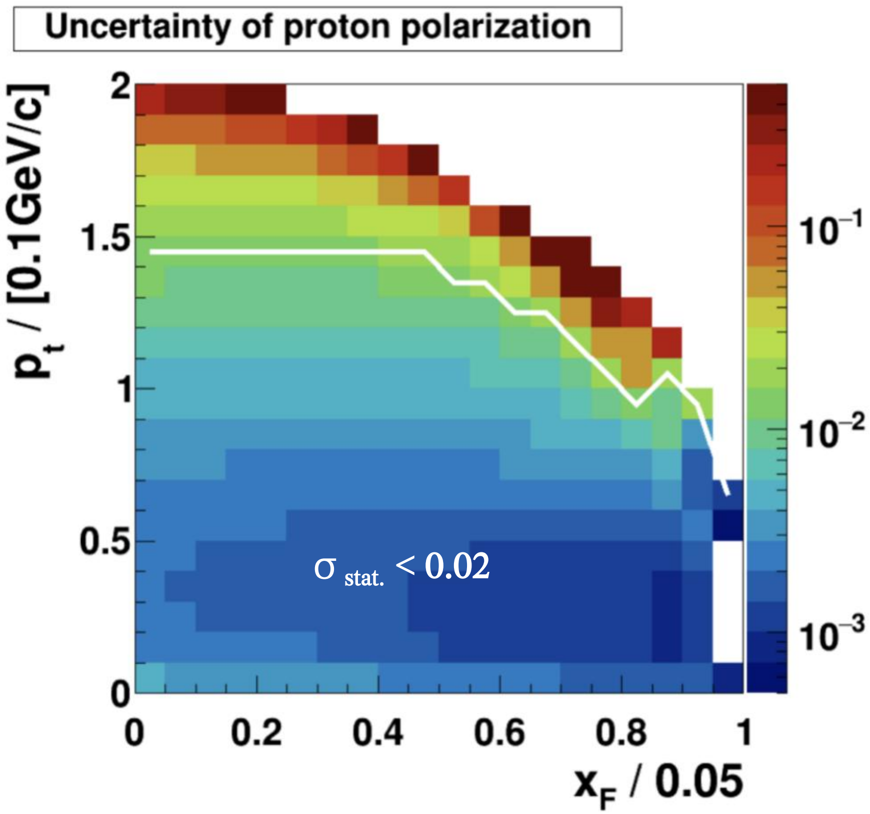
Time: 3 months

- $pp \rightarrow \Lambda + X \quad N \sim 10^{11}$
- $pp \rightarrow p + X \quad N \sim 10^{13}$
- $pp \rightarrow pK\Lambda \quad N \sim 10^{10}$

$\sigma_{\text{stat.}} < 0.01$ for Λ 400 bins

$\sigma_{\text{stat.}} < 0.02$ for p 400 bins

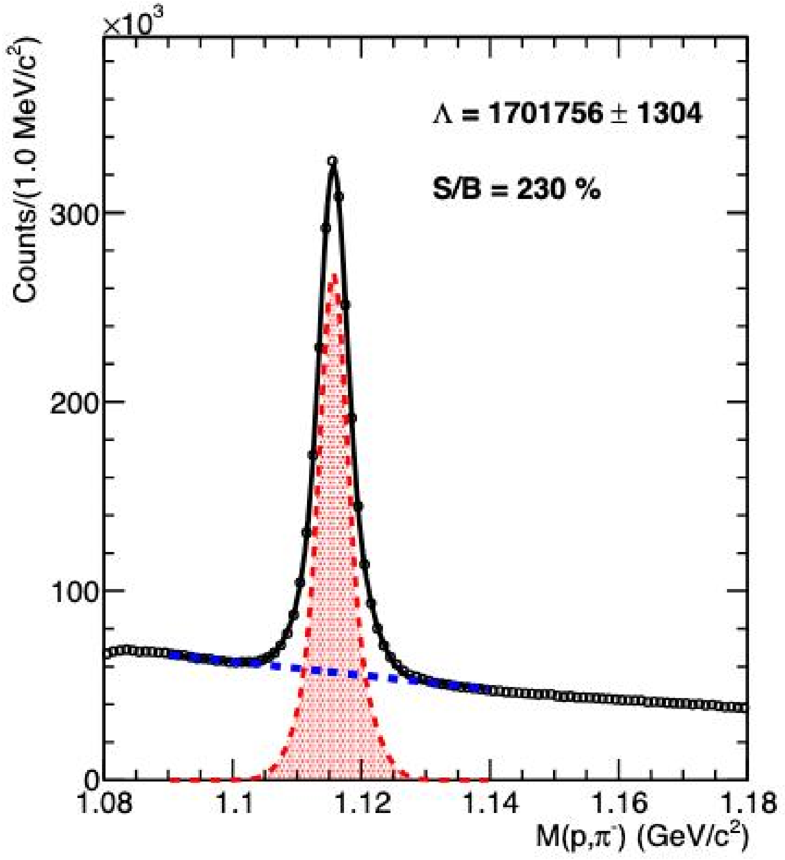


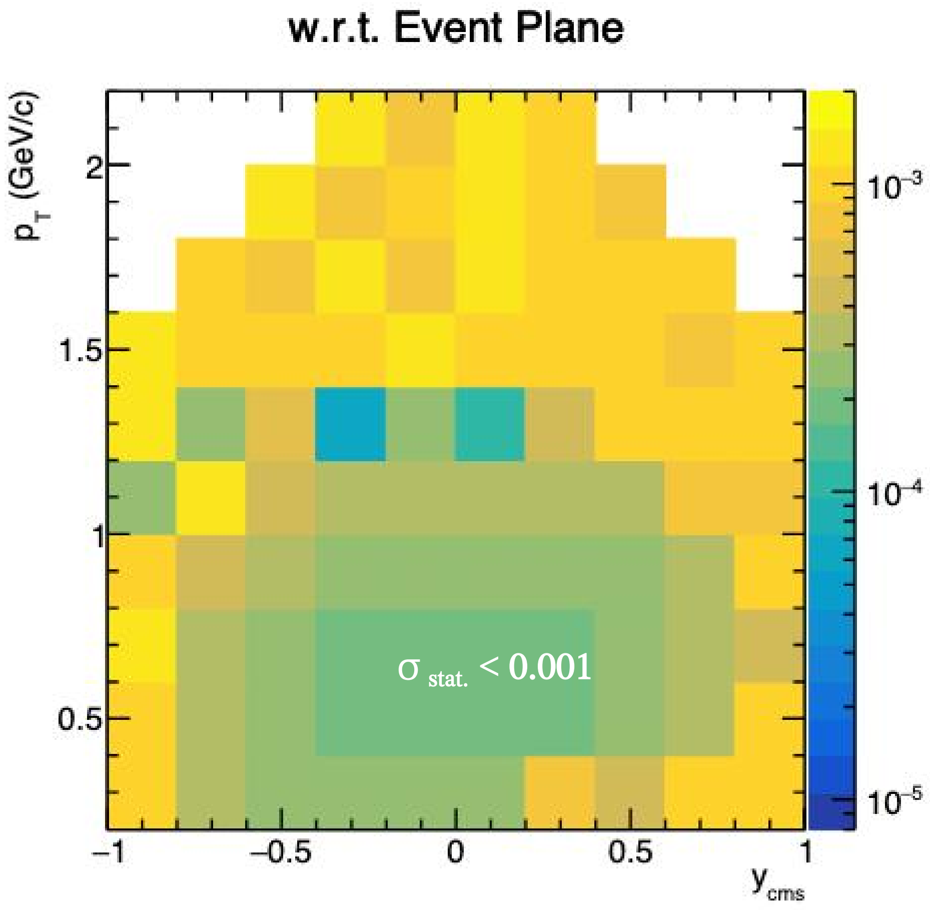


极化测量的统计误差

Au+Au → Λ + X

beam kinetic energy of 2.8 GeV/u





2D uncertainty of Λ polarization using 10^{11} Au+Au events, few weeks data taking

H-NS极化实验

General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

T. D. LEE* AND C. N. YANG
Institute for Advanced Study, Princeton, New Jersey

(Received October 22, 1957)

Phys. Rev. 108, 1645 (1957)

The amplitude of spin ½ baryon B_i decay to a spin ½ baryon B_f and π:

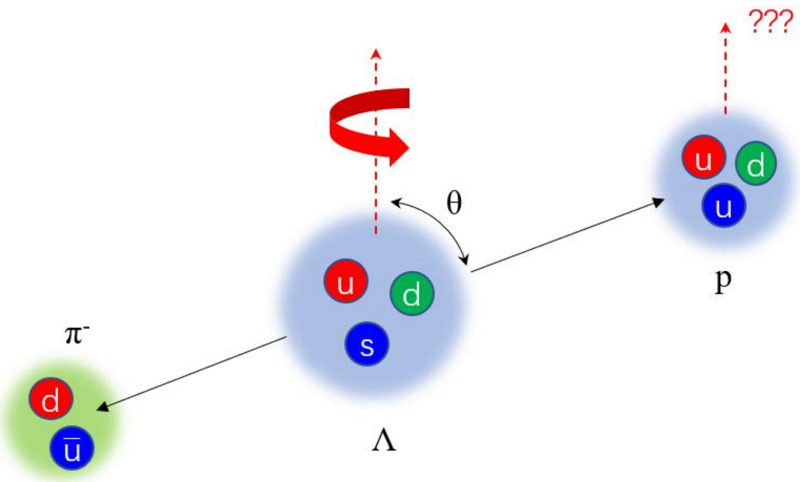
$$\mathcal{A} \sim S\sigma_0 + P\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}$$

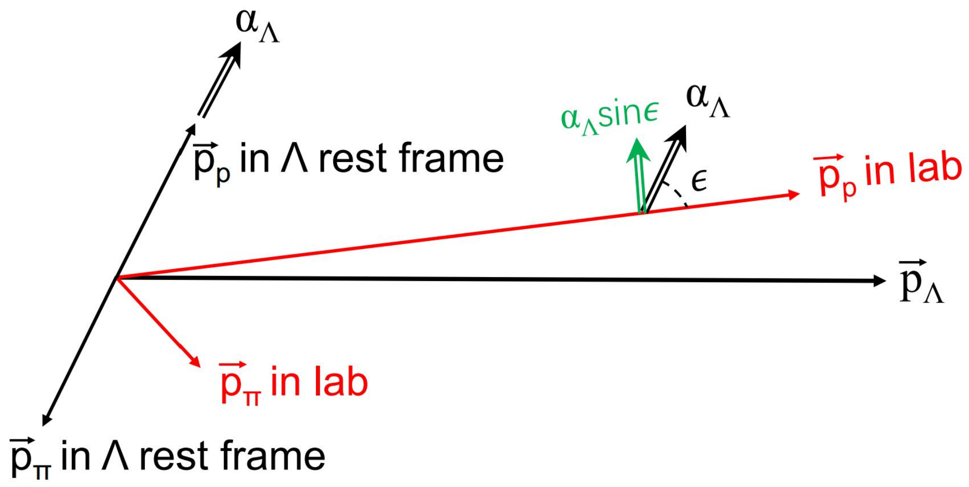
The decay parameters are defined as:

$$\alpha = \frac{2\mathrm{Re}(S^*\cdot P)}{|S|^2+|P|^2} \qquad \beta = \frac{2\mathrm{Im}(S^*\cdot P)}{|S|^2+|P|^2} \qquad \gamma = \frac{|S|^2-|P|^2}{|S|^2+|P|^2} \qquad \alpha^2+\beta^2+\gamma^2=1$$

$$dw(\theta) = \frac{1}{4\pi}(1+\alpha P_\Lambda\cdot\hat{q})d\Omega$$

$$P_p = \frac{(\alpha+P_\Lambda\cdot\hat{q})\hat{q}+\beta(P_\Lambda\times\hat{q})+\gamma(\hat{q}\times[P_\Lambda\times\hat{q}])}{1+\alpha P_\Lambda\cdot\hat{q}}$$

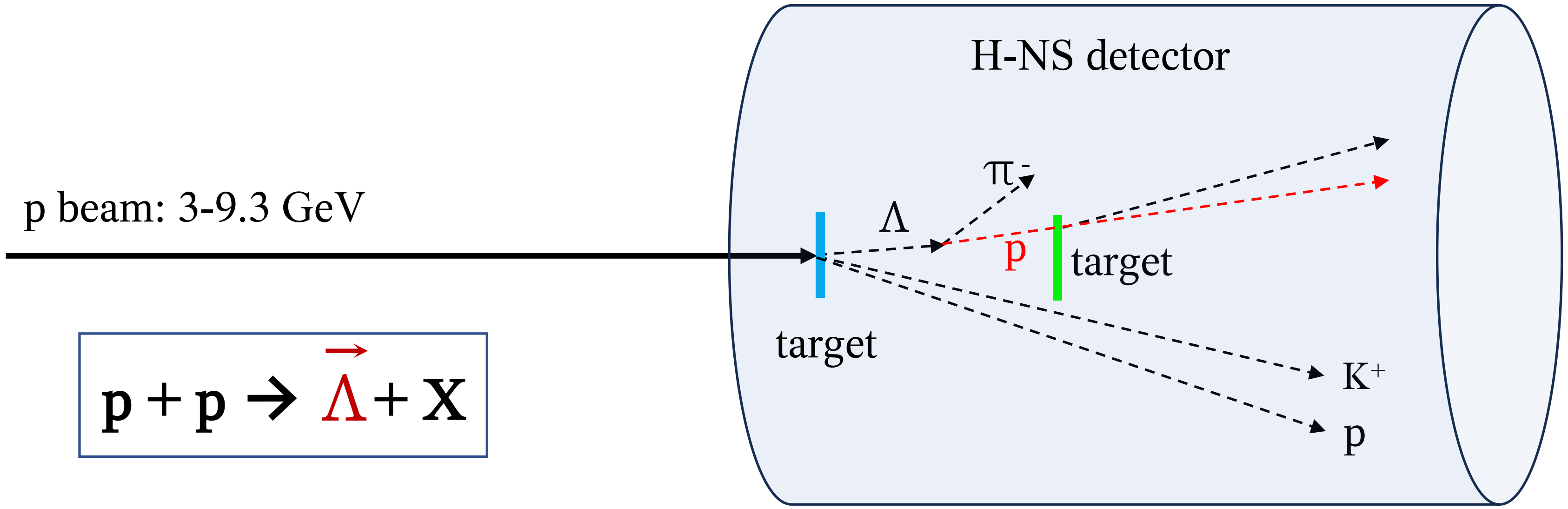




T. D. Lee, C. N. Yang Phys. Rev. 108,1645 (1957)

H-NS极化实验

➢ **Potential at H-NS**

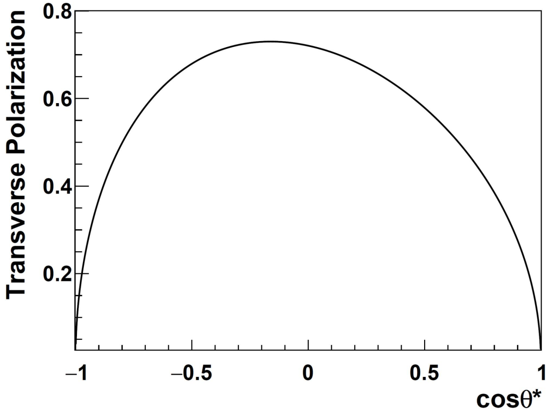


$$p + p \rightarrow \vec{\Lambda} + X$$

$$\vec{p} + p \rightarrow \vec{\Lambda} + X$$

Polarized proton experiment: polarization transfer from beam?

- **Average transverse polarization of proton, pol = 0.57**
- **Polarized proton beam intensity: 1 KHz**
- **Calibrate the pC analyzing power**



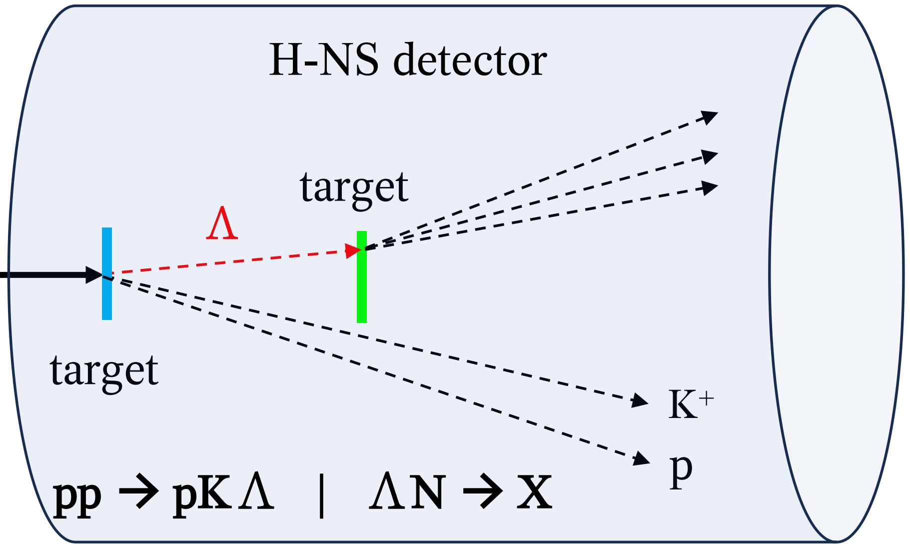
Yutie Liang, et. al., Phys. Rev. D 112, L031502

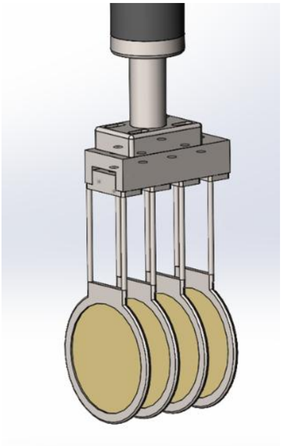
H-NS研究超子-核子相互作用

➢ **Potential at H-NS**

p beam: 3-9.3 GeV

$I\_max = 5*10^{12}$ ppp
$I = 10^{8}$ ppp, 1% target
Event rate : 1 MHz





参考CEE 4层靶设计

- **Event rate : 1 MHz → Λ beam from pKΛ : 1 KHz**
- **Λ N interaction (0.1% target): 1 Hz**
- **$N \sim 10^7$ signals in 3 months; $N\_obs \sim 10^6$ (assuming efficiency of 10%)**
- **Statistics can be improved by implementing a hyperon trigger**

强子物理

✓ Λ^*, Σ^*, Ξ^*, Ω^*, resonance

$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$	$\frac{5}{2}^+$	$\frac{5}{2}^-$	$\frac{7}{2}^+$	$\frac{7}{2}^-$	$\frac{9}{2}^+$	$\frac{9}{2}^-$	$\frac{11}{2}^+$
N(939) N(1440) N(1710) N(1880) N(2100) N(2300)	N(1535) N(1650) N(1895)	N(1720) N(1900)	N(1520) N(1700) N(1875) N(2120)	N(1680) N(1860) N(2000)	N(1675) N(2060) N(2570)	N(1990)	N(2190)	N(2220)	N(2250)	
Δ(1910)	Δ(1620) Δ(1900)	Δ(1232) Δ(1600) Δ(1920)	Δ(1700) Δ(1940)	Δ(1905) Δ(2000)	Δ(1930)	Δ(1950)	Δ(2200)	Δ(2300)	Δ(2400)	Δ(2420)
Λ(1116) Λ(1600) Λ(1810)	Λ(1380) Λ(1405) Λ(1670) Λ(1800)	Λ(1890)	Λ(1520) Λ(1690)	Λ(1820) Λ(2110)	Λ(1830)	Λ(2085)	Λ(2100)	Λ(2350)		
Σ(1189) Σ(1660) Σ(1880)	Σ(1750) Σ(1900)	Σ(1385)	Σ(1670) Σ(1910)	Σ(1915)	Σ(1775)	Σ(2030)				
Ξ(1315)		Ξ(1530)	Ξ(1820)							
		Ω(1672)								

m < 3.1 GeV/c²

m < 3.1 GeV/c²

m < 2.6 GeV/c²

m < 2.1 GeV/c²

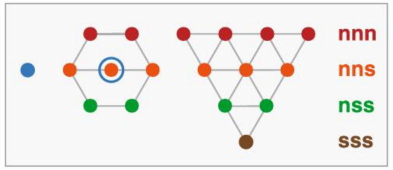
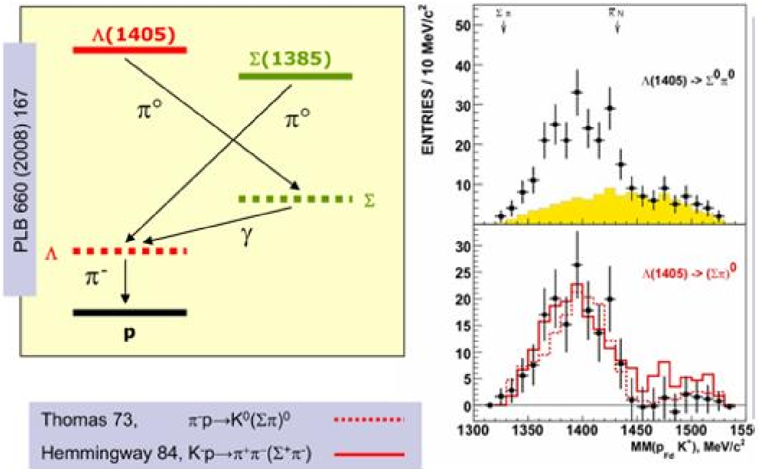


Fig. 1 Light and strange baryon spectrum from the PDG [1] up to $J^P = 11/2^+$. The columns correspond to different J^P and the colors to isospin and hypercharge. The different font weights represent four-, three- and two-star resonances

https://doi.org/10.1007/s00601-022-01756-y

■ Reaction (p_{beam}=3.65 GeV/c):

$$pp \to pK^+\Sigma^0(1385) \to pK^+(p\pi^-)\pi^0$$
$$pp \to pK^+\Lambda(1405) \to pK^+(\Sigma^0\pi^0) \to pK^+(p\pi^-)\gamma\pi^0$$



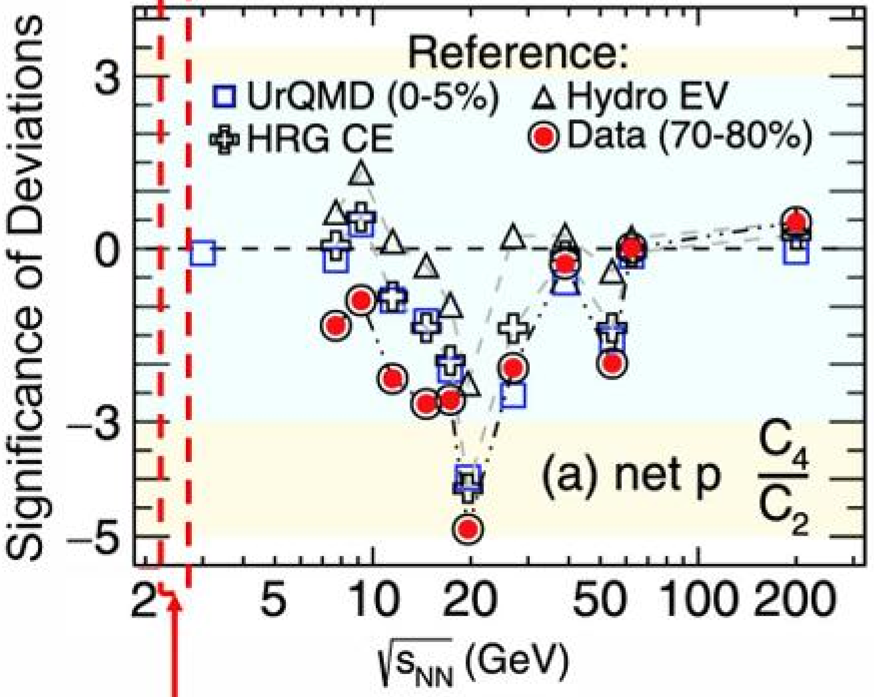
- $\sqrt{s}$ = 4.6 GeV @ E_{beam} = 9.3 GeV
- $\sqrt{s}$ = 7.1 GeV @ E_{beam} = 25 GeV

□ s-sbar 系统，与BESIII等实验的c-cbar 相互补充

重离子物理

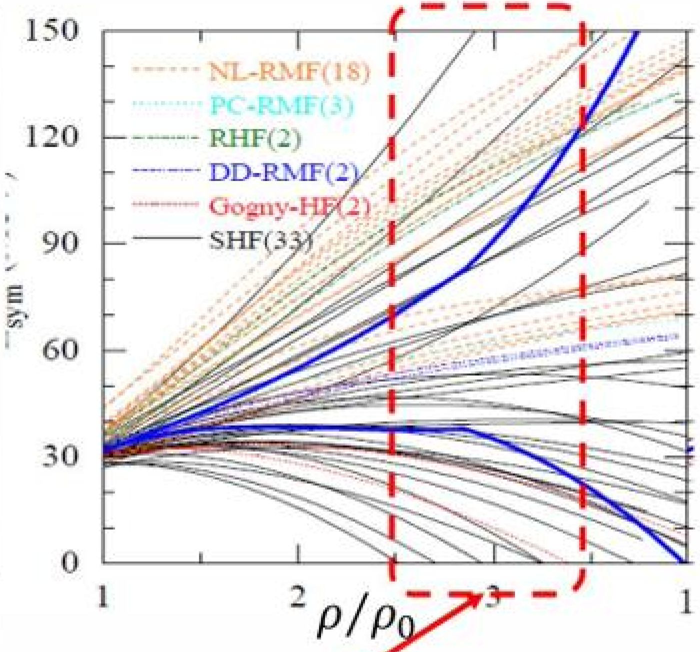
QCD Critical Point

PRL 135, 142301 (2025)



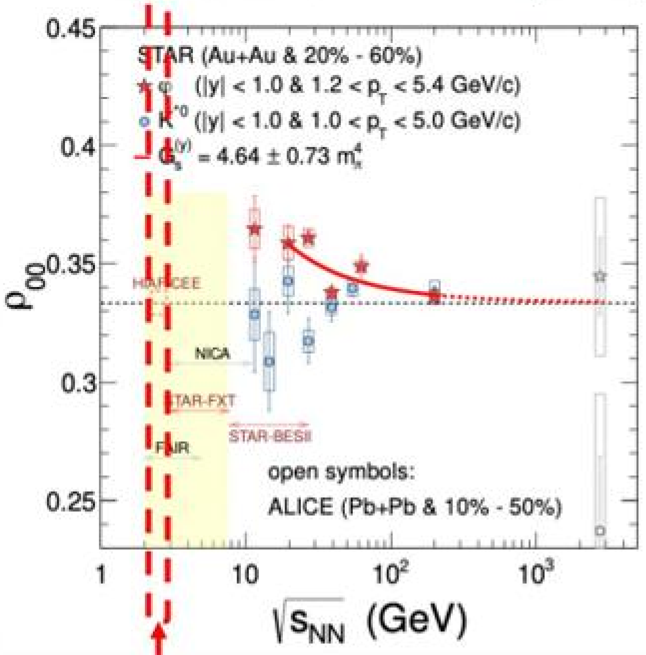
Equation of State

Universe 7, 182 (2021)



Global Spin Alignment

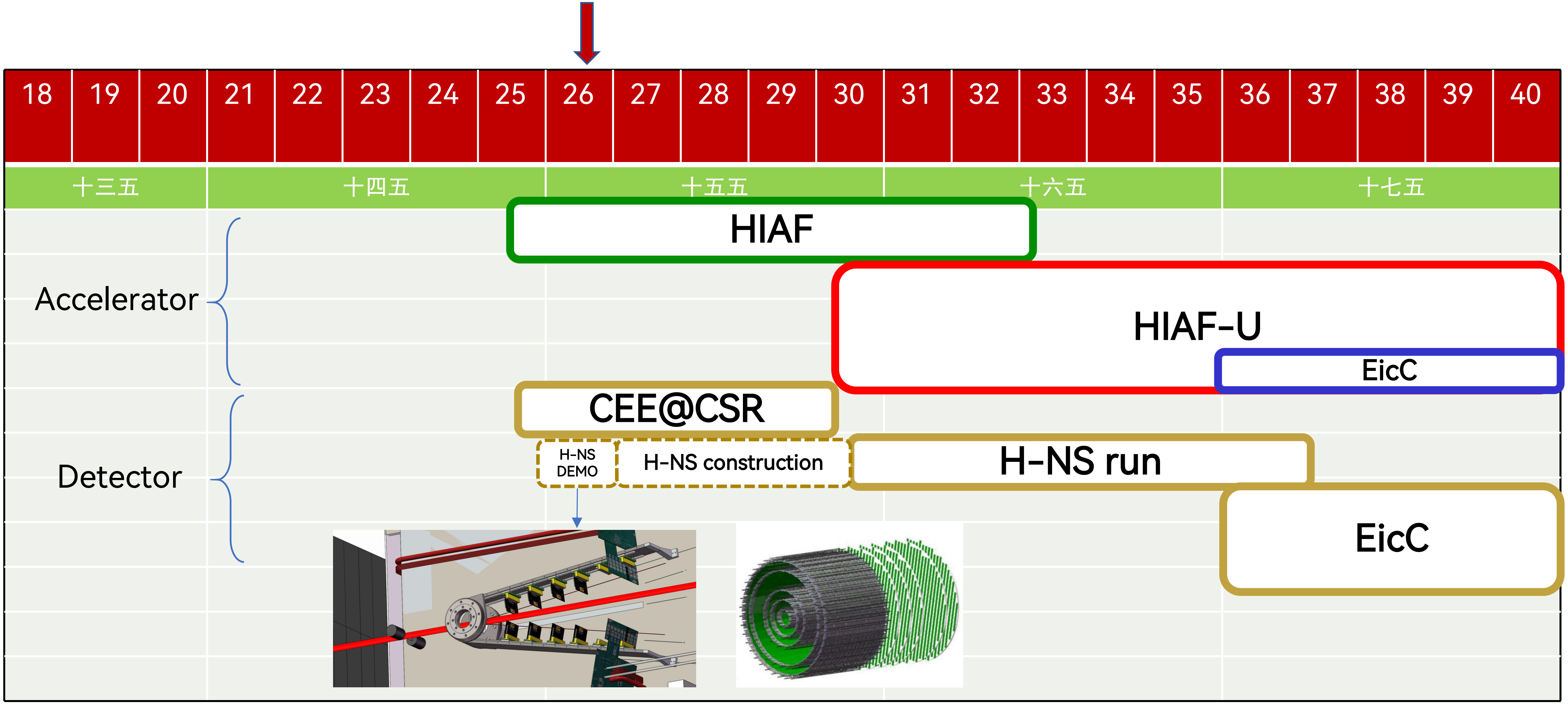
Nature 614, 244-248 (2023)



H-NS @ HIAF

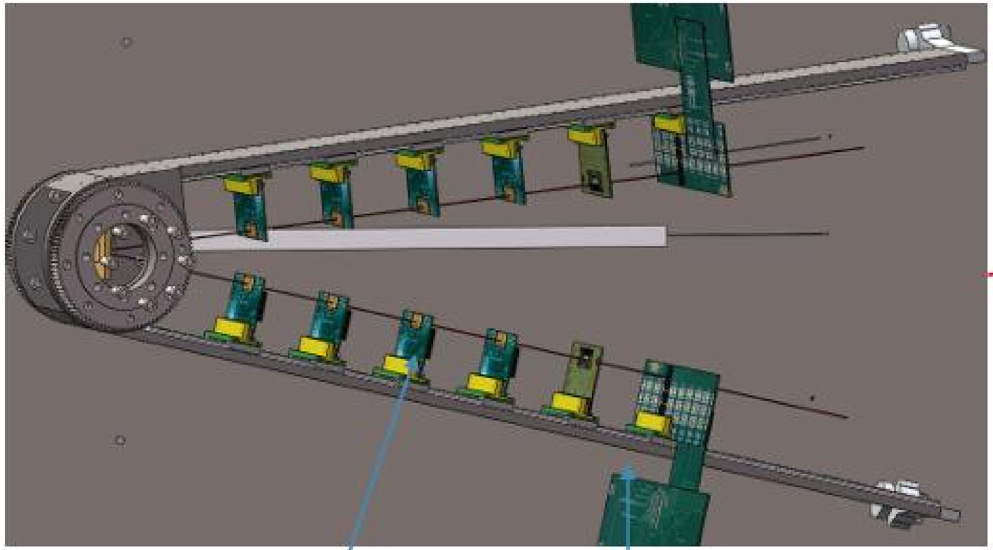
H-NS发展规划

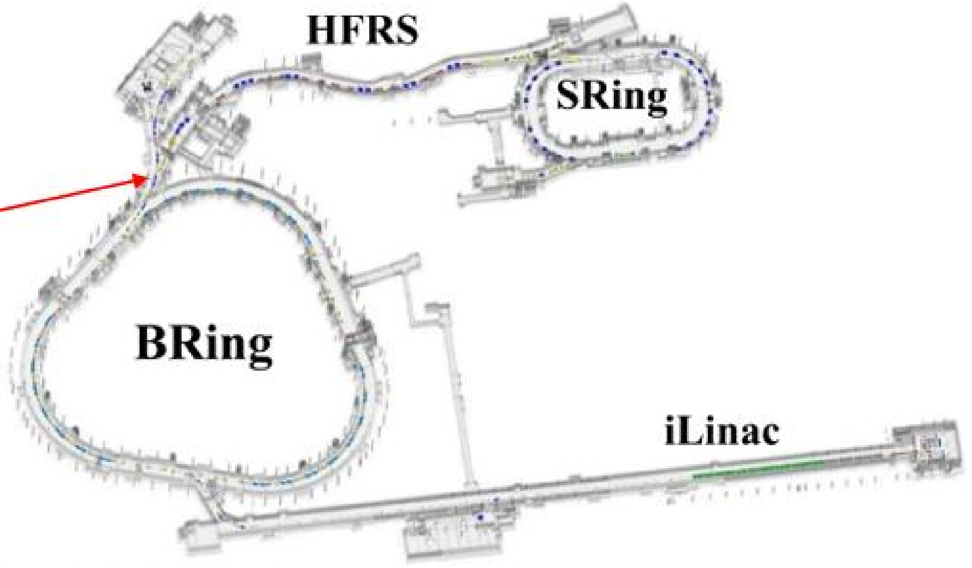
Timeline



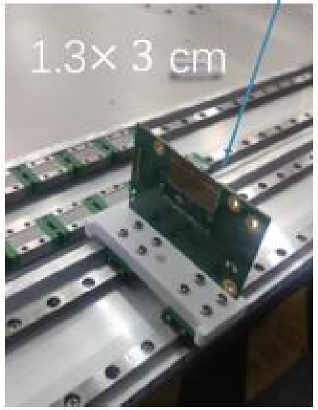
18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
十三五
十四五
十五五
十六五
十七五
Accelerator
HIAF
HIAF-U
EicC
Detector
CEE@CSR
H-NS DEMO
H-NS construction
H-NS run
EicC

H-NS0样机

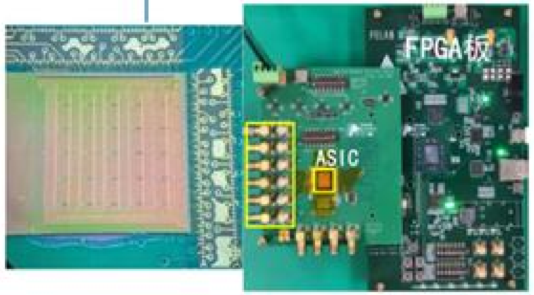




目前正在惠州整体集成，2026年完成!



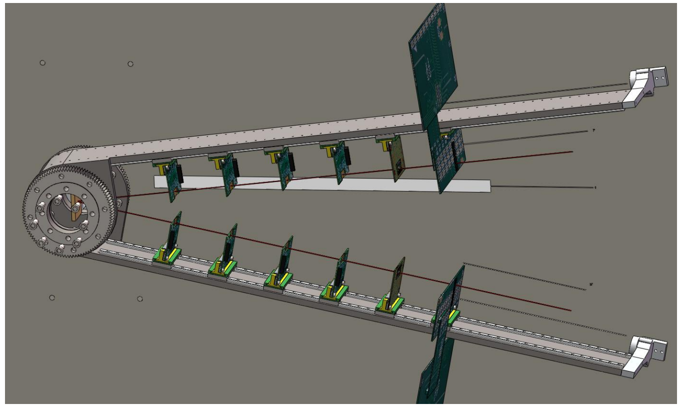
MAPS



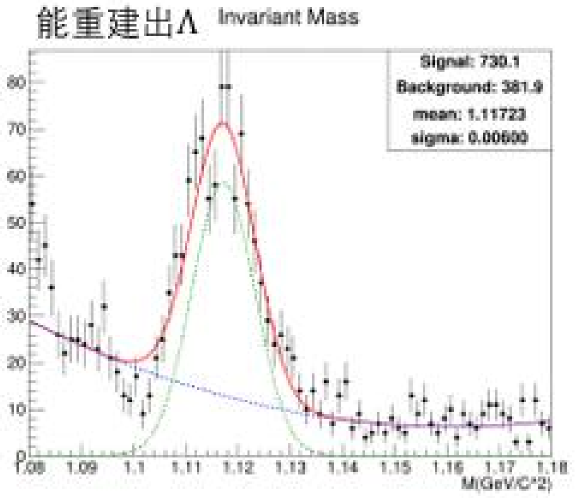
LGAD

H-NS0: DEMO 验证关键技术
detector + electronics + DAQ + control system

H-NS 阶段规划

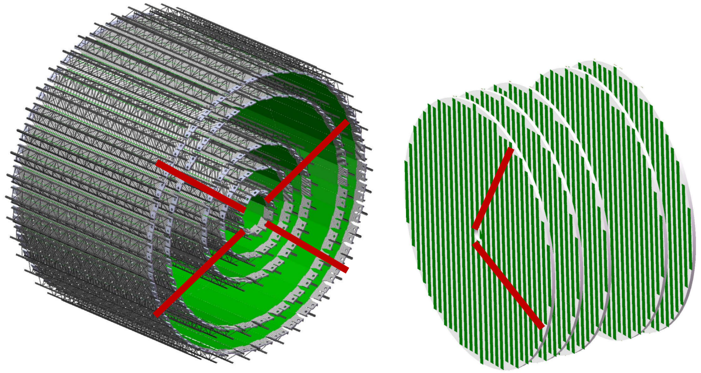


能重建出Λ



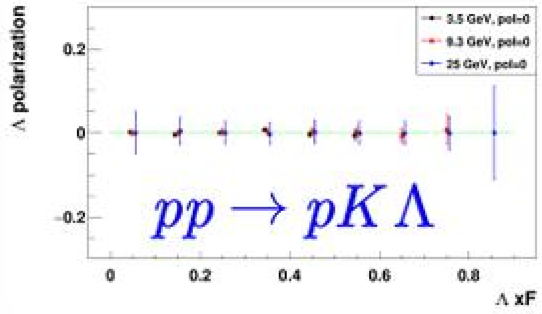
MIC6/LGAD芯片验证

2026



TOF，ECal 未显示

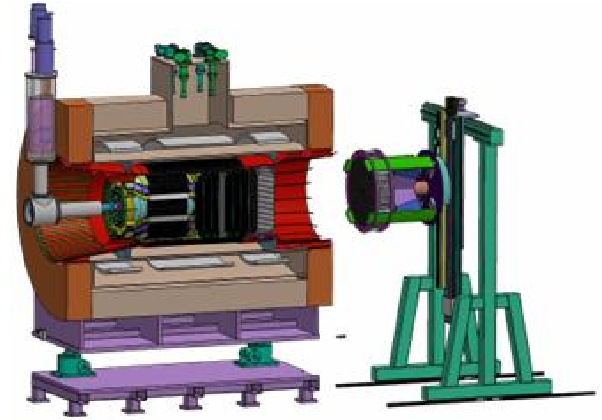
部分探测器，可扩展性



全尺寸磁铁，部分立体角覆盖探测器；可运行，用于物理产出

部分经费支持

2026-2030



全尺寸探测器

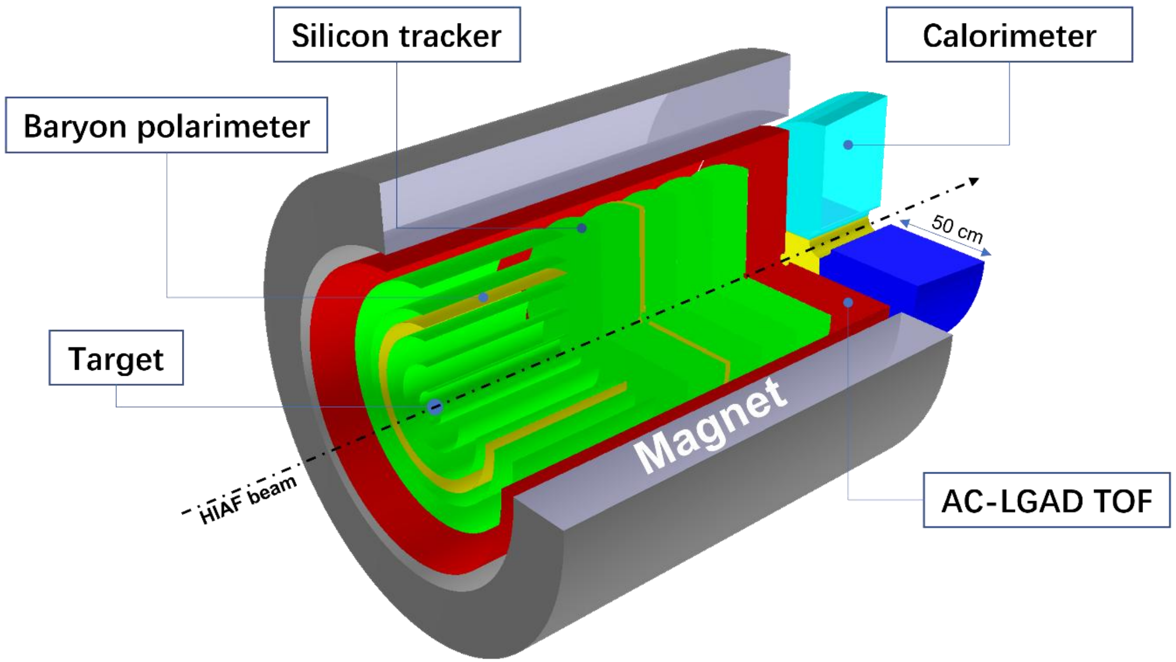
丰富的物理：

- 高精度、多维度超子极化测量
- 轻强子物理、奇特强子态…
- 核介质效应
- 超核物理
- 核物质相结构
- …

全额支持

2030-

Hyperon-Nucleon Spectrometer



Participating Institute： 近代物理研究所、高能物理研究所、清华大学、山东大学、北京航空航天大学、复旦大学、国科大、华中师范大学、华南师范大学、北京师范大学、香港中文大学(深圳)、中科大、中国原子能研究院、中山大学、湖州师范学院、…

Subsystems： Silicon tracker, AC-LGAD, Target, Baryon polarimeter, Calorimeter, Electronics, DAQ, Magnet, Beamline, Mechanics + Engineering

I. Physics：

- Λ production and polarization (p+p)
  - Medium effect (p+A)
  - Global polarization of Λ hyperon (A+A)
- Hadron physics via p+p

II. Community：

- Supports both communities of hadron structure and heavy-ion physics
- International participations are expected

III. Detector R&D

- Many parts are similar for CEPC, H-NS, EicC, and STCF. Save resources!
- H-NS: a detector R&D platform for EicC(½ EicC)

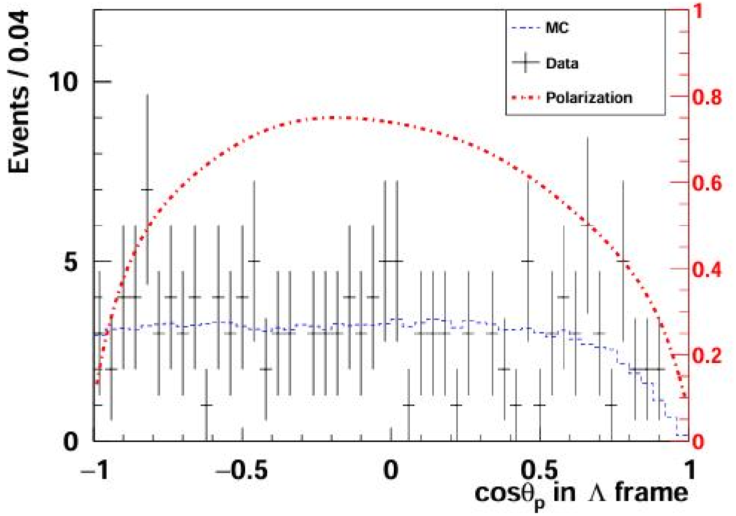
总结

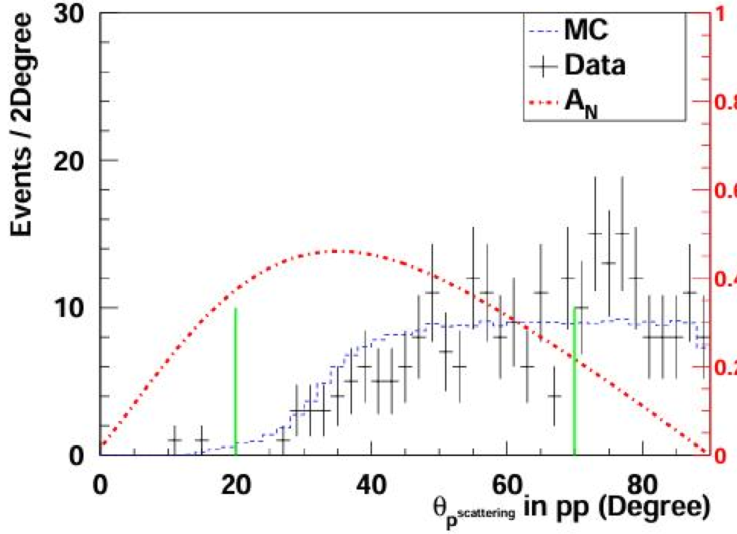
- **物理：重子自旋结构**
  - 基于HIAF优质束流、利用p-p，p-A, A-A过程研究重子（包括超子**和质子**）极化现象，以自旋为抓手探索物质深层次结构，连接未来国际高能核物理大方向电子离子对撞物理
  - 在HIAF能区开展能量扫描，研究高重子密度区核物质相图并寻找液-气相变临界点

- **探测器技术：自主研发，突破瓶颈**
  - 采用国产工艺的硅像素探测器+LGAD飞行时间探测器，将成为首个基于全硅径迹探测器的通用谱仪，领先世界
  - 首次提出**具备末态质子极化测量功能**的新型探测器谱仪概念，并应用于H-NS，可以**同时确定质子与超子极化**

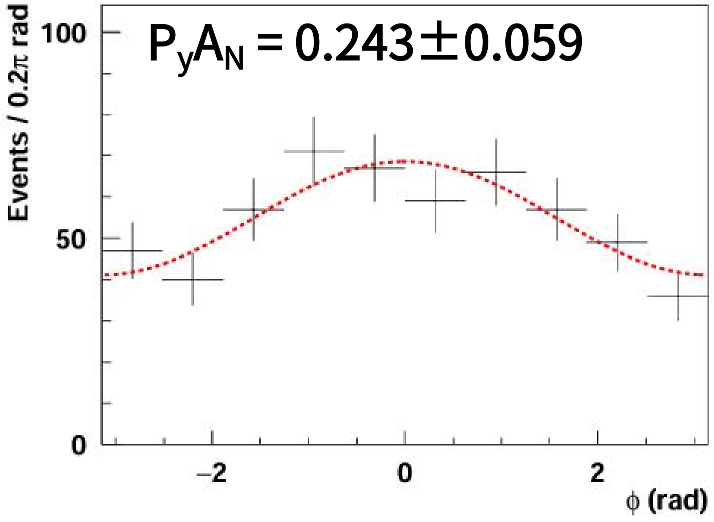
- **加速器技术：**
  - 非极化束流已世界领先
  - 极化束流研发已展开，不仅为H-NS极化实验，更为将来的EicC实验打下坚实基础

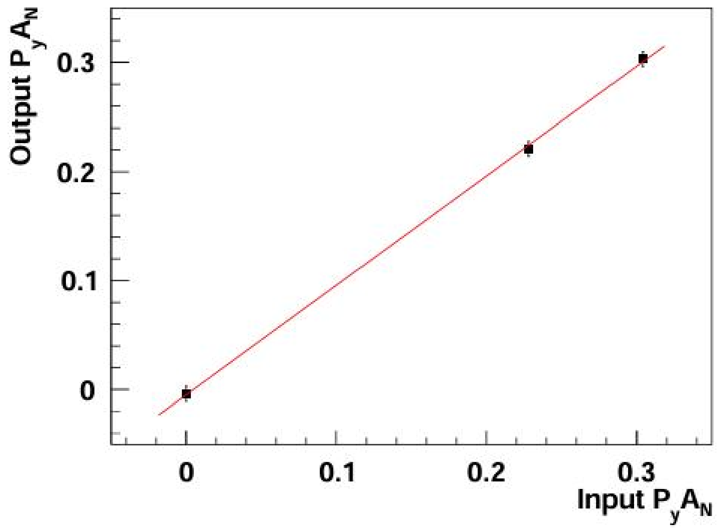
H-NS 核子极化测量仪--BESIII验证





→ expected
$P_yA_N = 0.22 \pm 0.01$

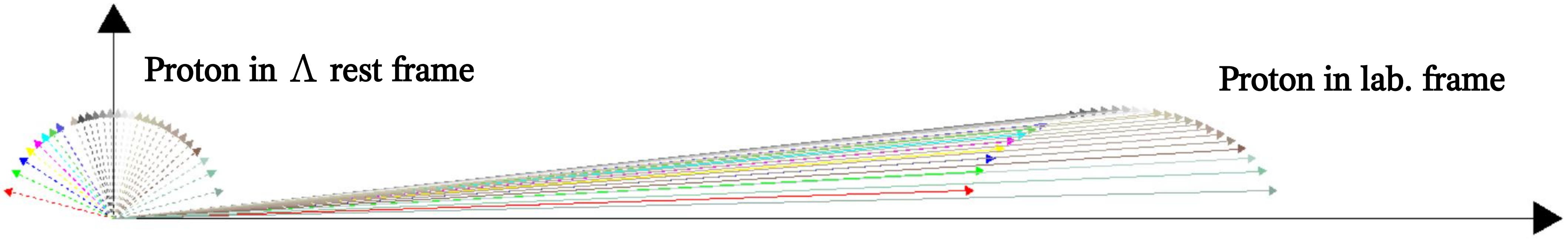


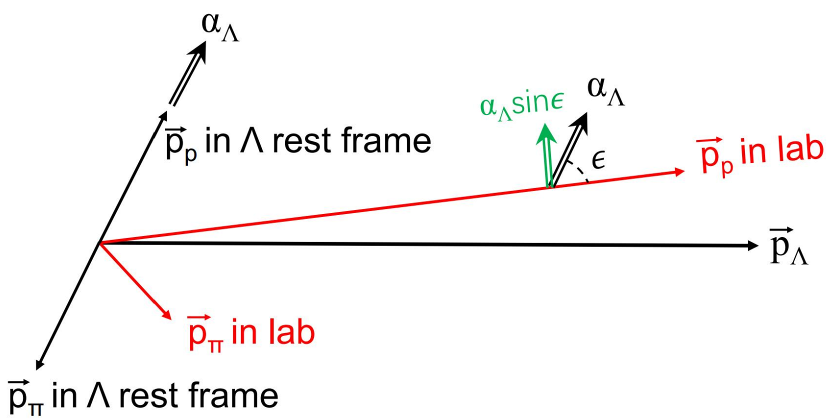


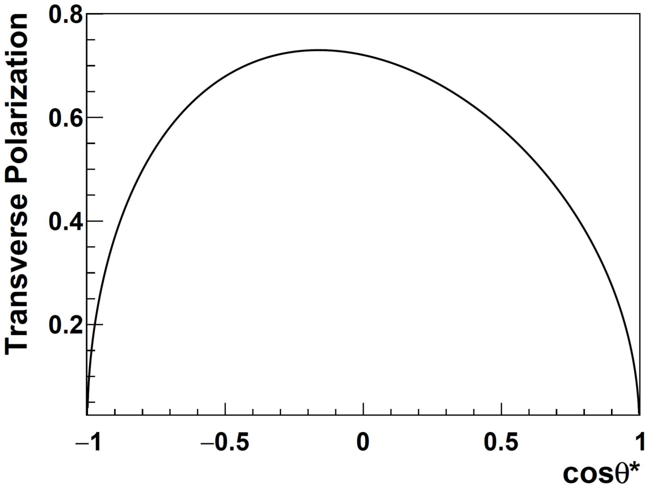
→ measured
$P_yA_N = 0.243 \pm 0.059$

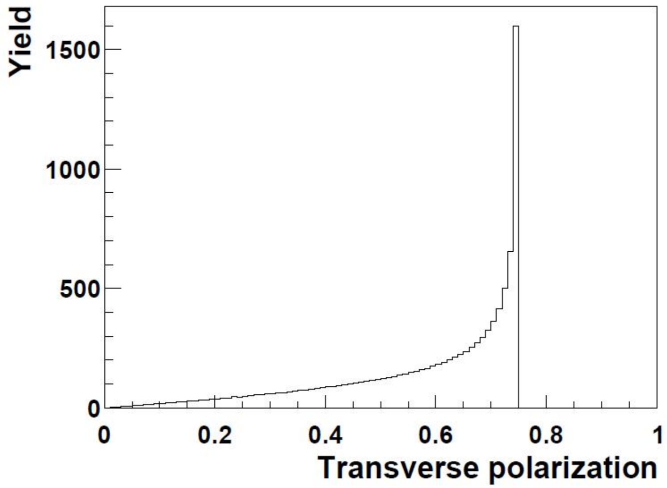
arXiv: 2607.19927

H-NS极化实验

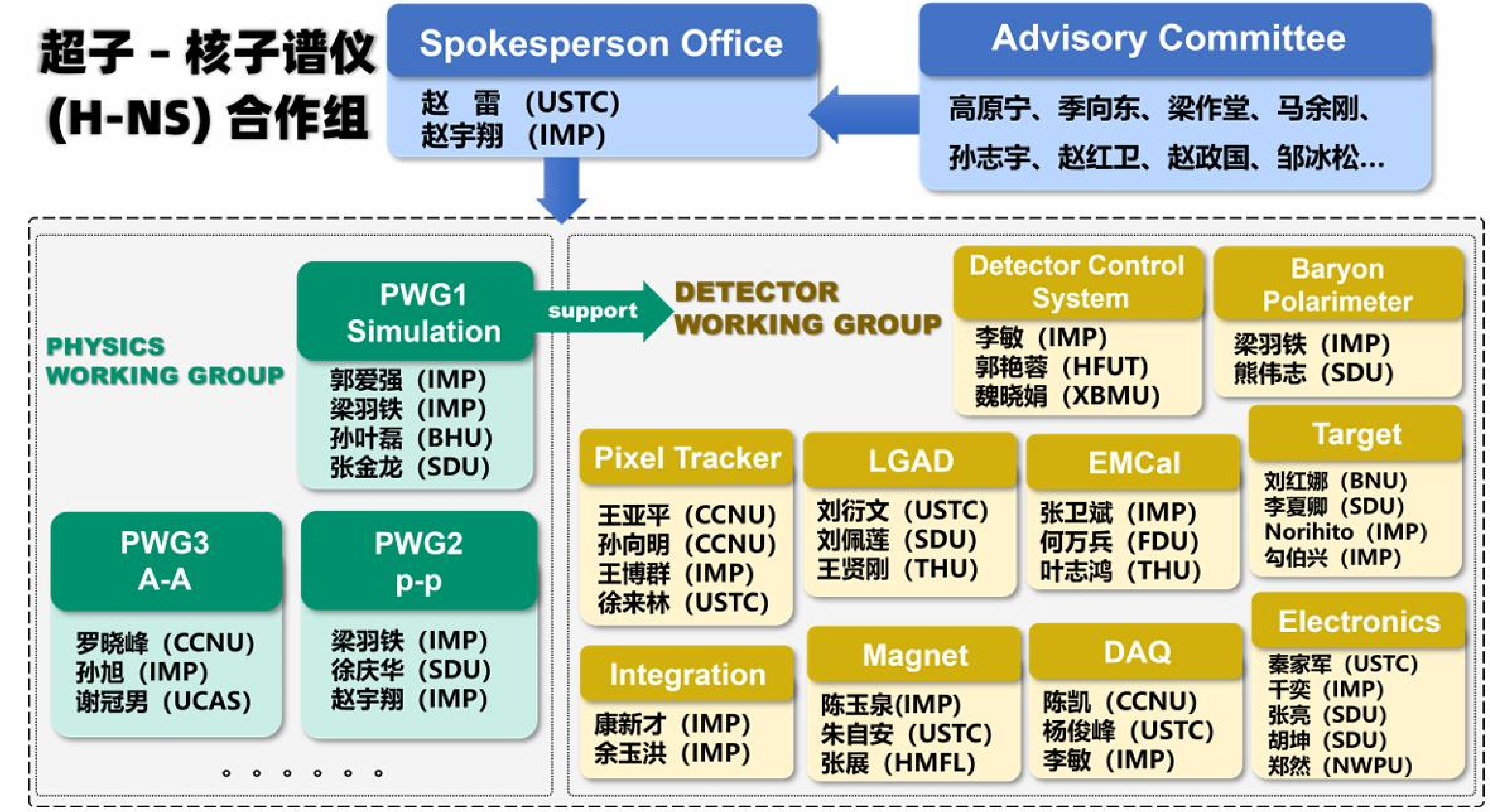








- Transverse polarization of proton from Λ decay: $\mathrm{Pol}_t \sim 0.59$
  - Λ unpolarized
  - relativistic effect taken into account



超子－核子谱仪
(H-NS) 合作组
Spokesperson Office
赵 雷 （USTC）
赵宇翔 （IMP）
Advisory Committee
高原宁、季向东、梁作堂、马余刚、
孙志宇、赵红卫、赵政国、邹冰松…
PHYSICS WORKING GROUP
PWG1 Simulation
郭爱强（IMP）
梁羽铁（IMP）
孙叶磊（BHU）
张金龙（SDU）
support
PWG3 A-A
罗晓峰（CCNU）
孙旭（IMP）
谢冠男（UCAS）
PWG2 p-p
梁羽铁（IMP）
徐庆华（SDU）
赵宇翔（IMP）
。。。。。。
DETECTOR WORKING GROUP
Detector Control System
李敏（IMP）
郭艳蓉（HFUT）
魏晓娟（XBMU）
Baryon Polarimeter
梁羽铁（IMP）
熊伟志（SDU）
Pixel Tracker
王亚平（CCNU）
孙向明（CCNU）
王博群（IMP）
徐来林（USTC）
LGAD
刘衍文（USTC）
刘佩莲（SDU）
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EMCal
张卫斌（IMP）
何万兵（FDU）
叶志鸿（THU）
Target
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李夏卿（SDU）
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李敏（IMP）
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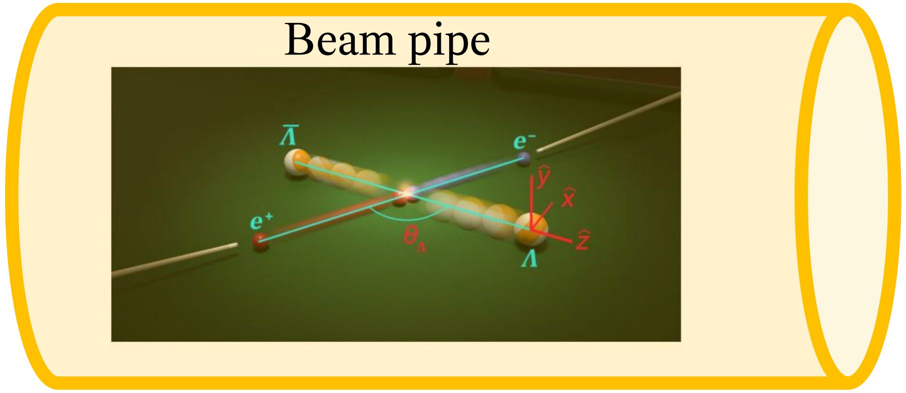
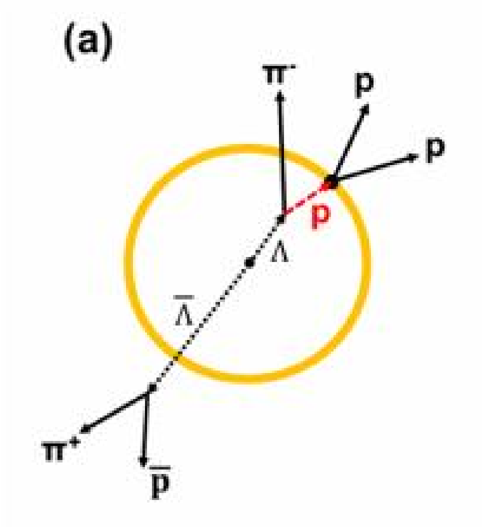
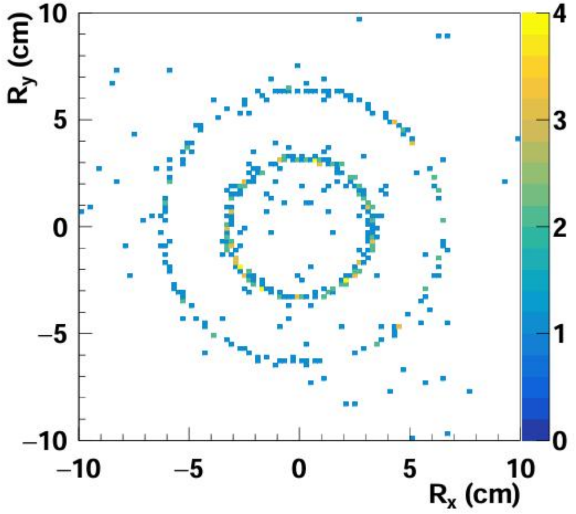
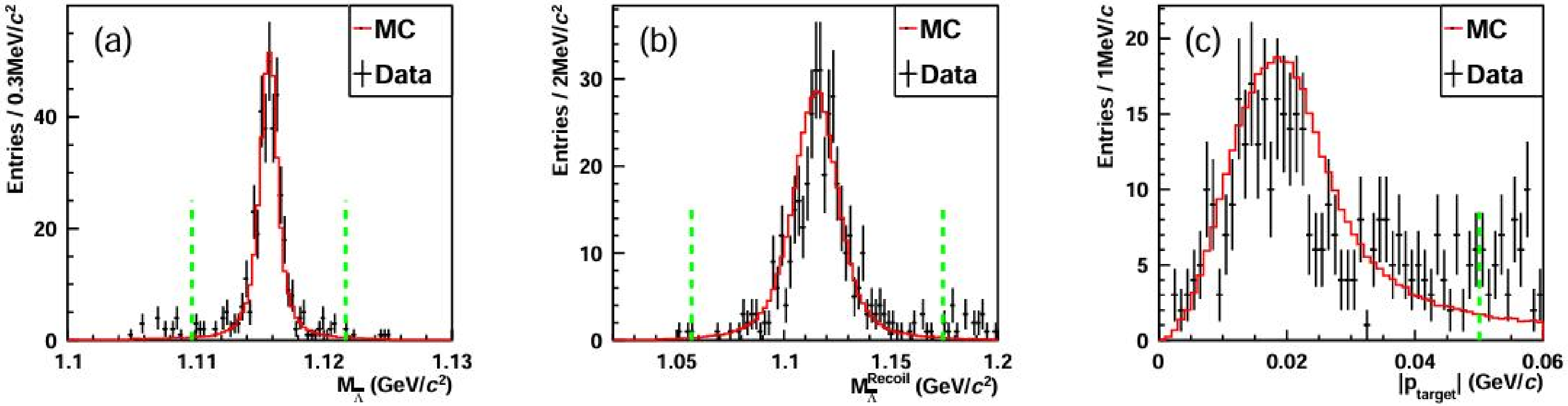
千奕（IMP）
张亮（SDU）
胡坤（SDU）
郑然（NWPU）

H-NS 核子极化测量仪--BESIII验证



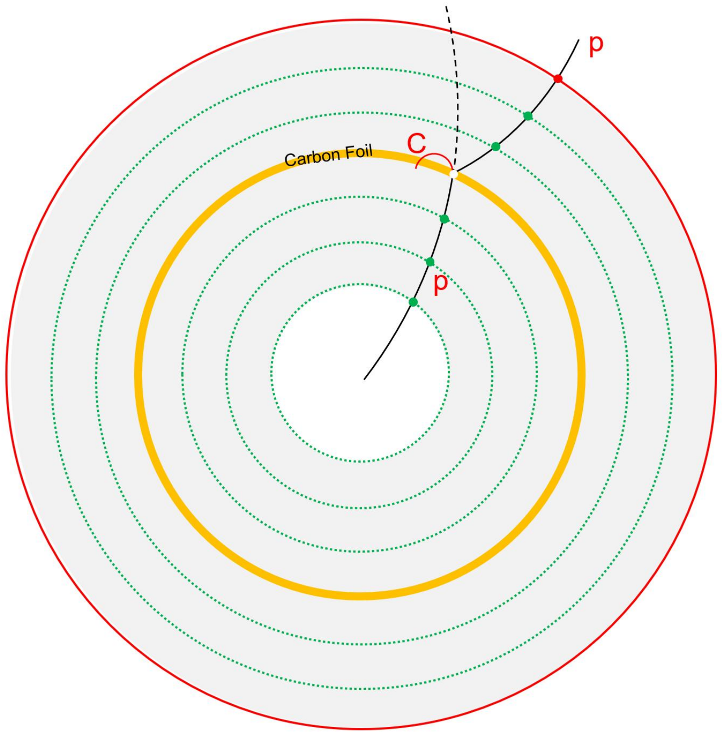




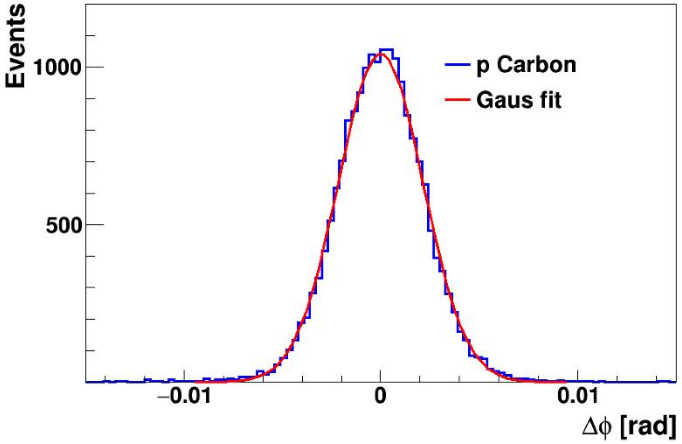


arXiv: 2607.19927

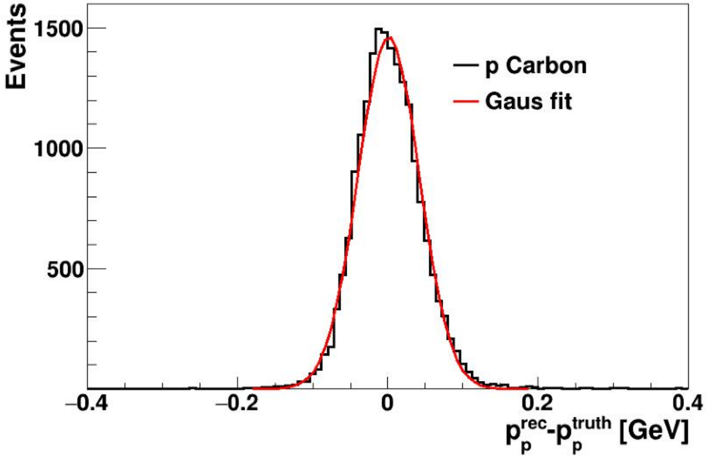
Precision measurement of proton polarization



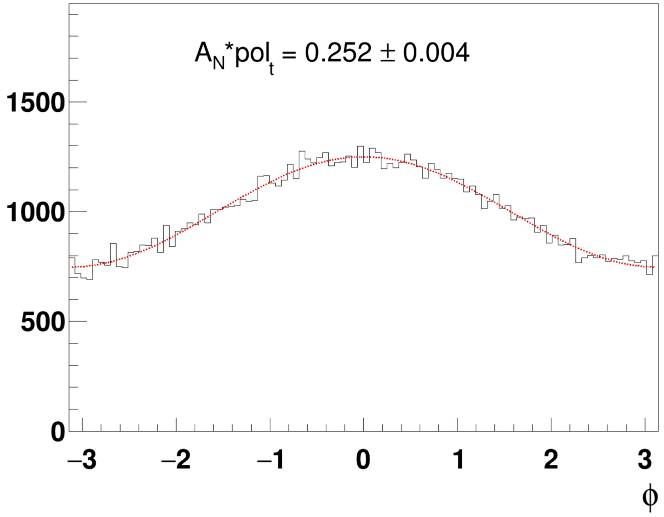
$\sigma = 2.16$ mrad



$\sigma = 0.041$ GeV



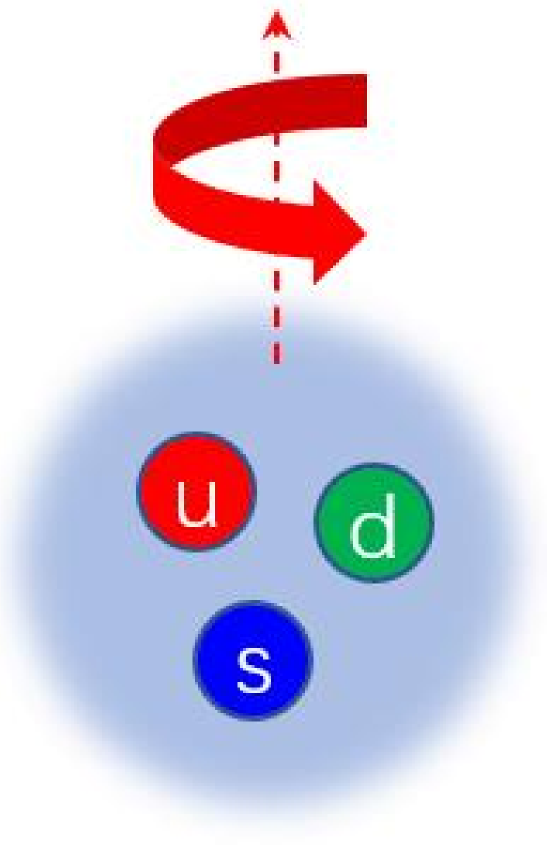
Input: 0.250



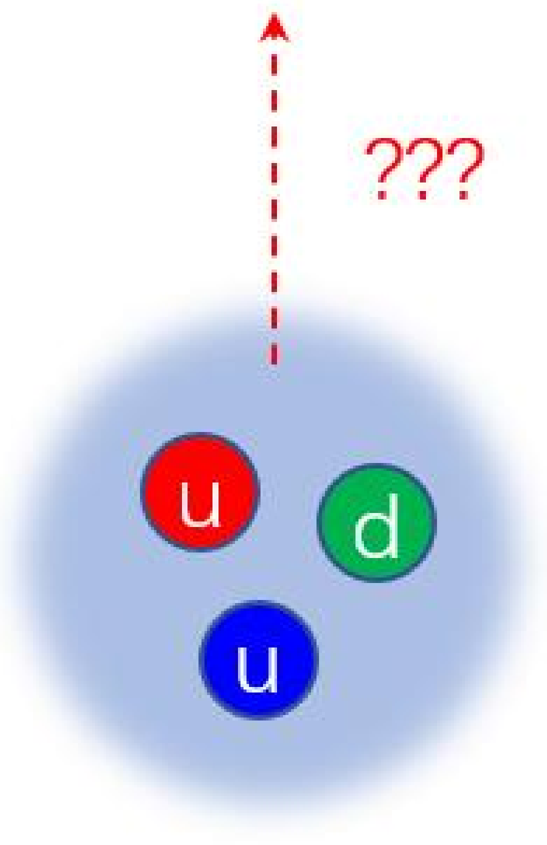
- ✓ Reconstruction effi: > 70%
- ➢ Low background contamination!
- ➢ High precision measurement!

NST in press, arXiv: 2512.02804

An interesting question: Is proton polarized as well?

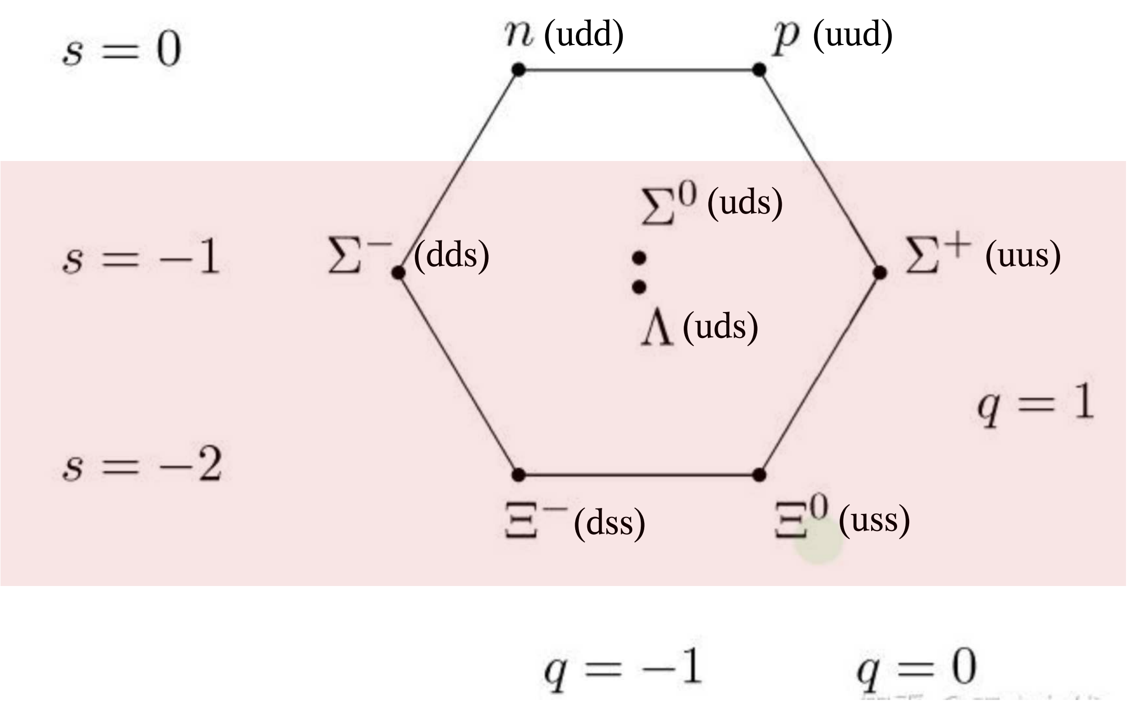


pp/ee/ep → Λ + X



pp/ee/ep → p + X

Various baryons at H-NS



Beam energy @ 9.3 GeV

- Number of hyperons relative to Λ

Σ^- ~ 0.05 Σ^0 ~ 0.15 Σ^+ ~ 0.25 2D √

Ξ^- ~ 1E-2 Ξ^0 ~ 1E-2 1D √

- Number of anti-hyperons relative to Λ

$\overline{\Lambda}$ ~ 5E-4

$\overline{\Sigma}^+$ $\overline{\Sigma}^0$ $\overline{\Sigma}^-$ ~ 1E-4 1D √

$\overline{\Xi}^+$ ~ 1E-6

- Number of anti-proton relative to p

$\overline{p}$ ~ 1E-4 1D √