High Energy Nuclear Physics at HIAF

-- from H-NS to EicC

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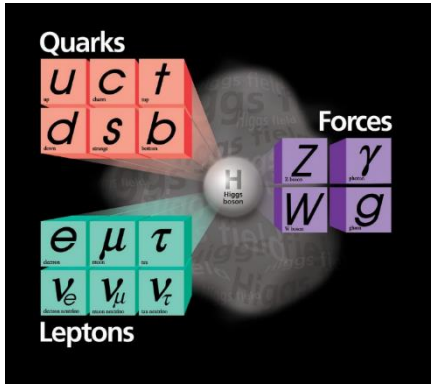
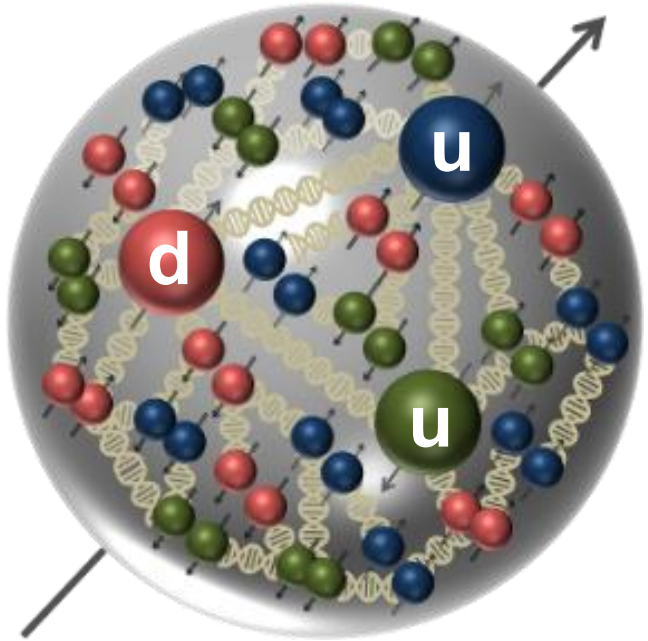
31.03-03.04 2026
PBT 2026 Huizhou

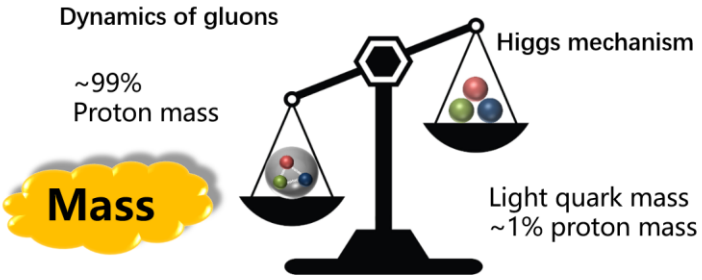
Outline

- Introduction
- Electron ion collider in China - EicC
- Hyperon-Nucleon Spectrometer - H-NS
- From H-NS to EicC
- Summary

Nucleon structure

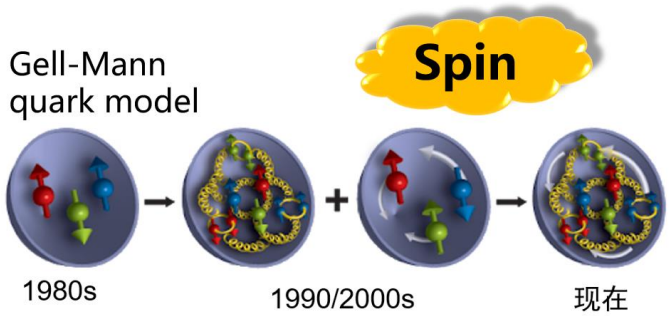


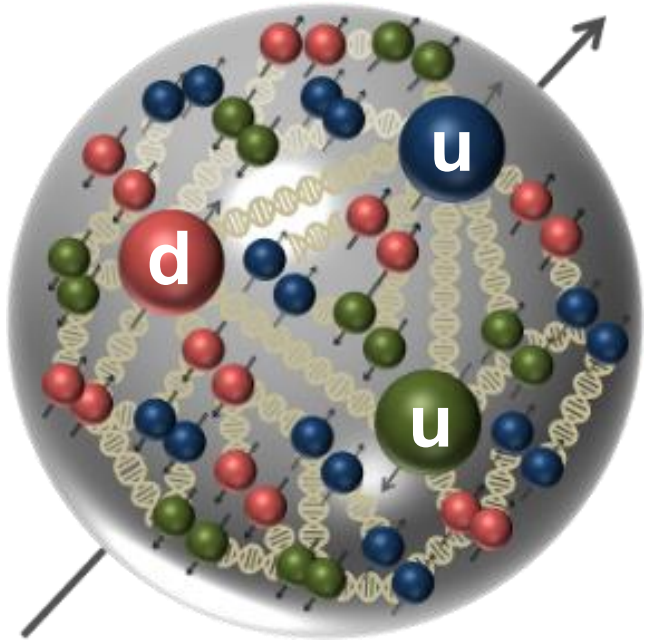




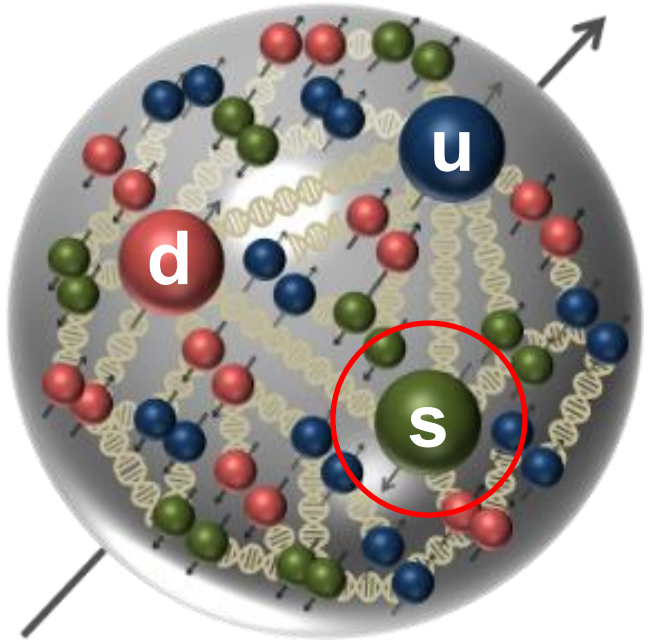
Proton spin structure?

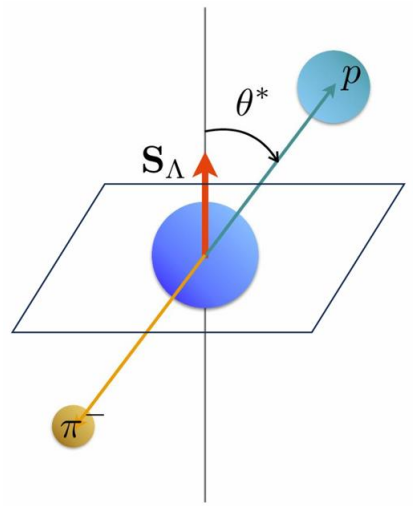
Origin of proton mass?





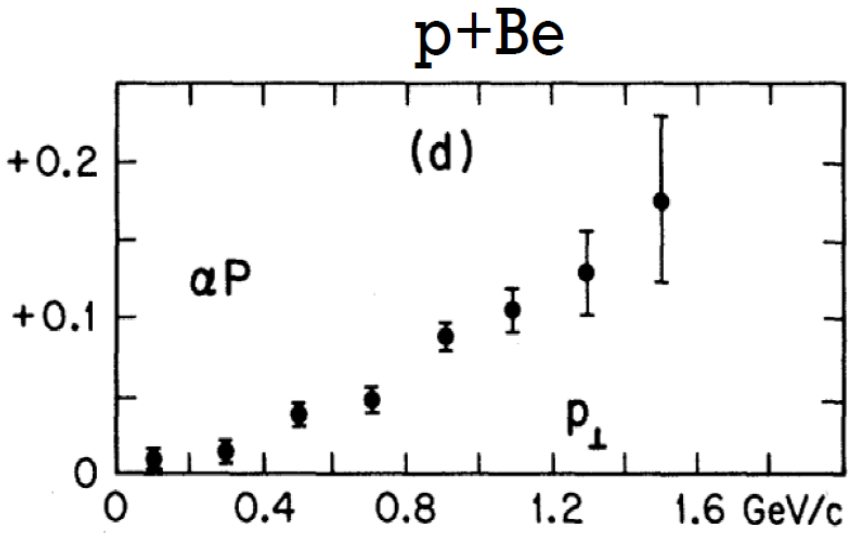
Spin → Polarization



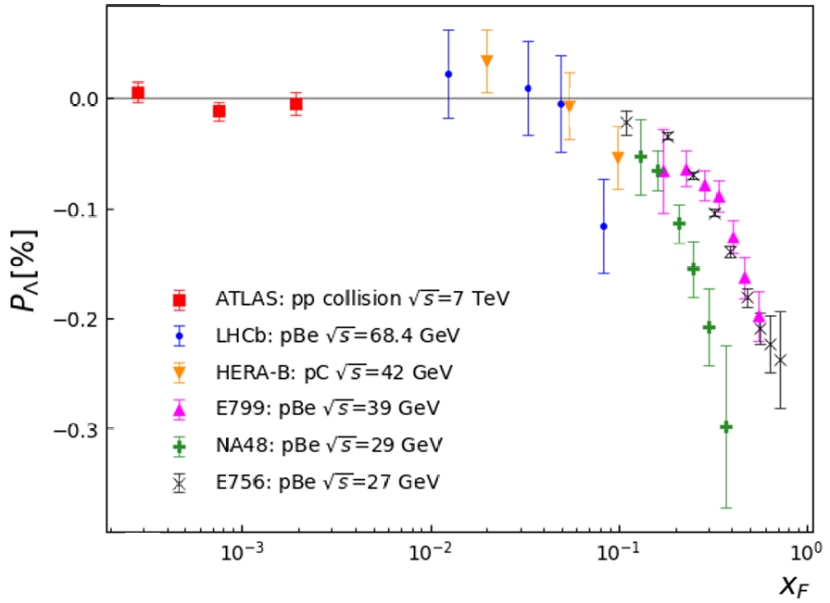


Hyperon is special

First observation of Λ polarization in the 1970's

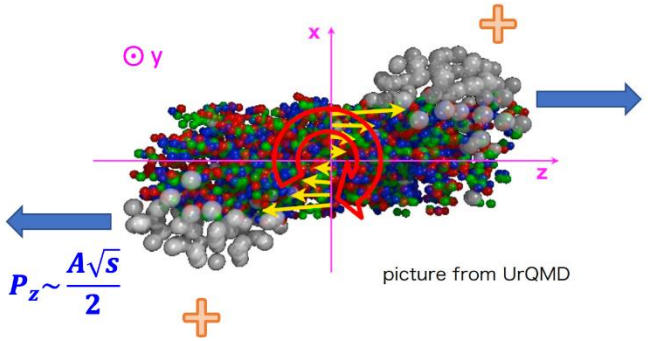


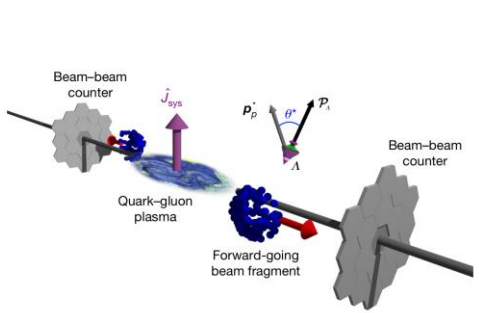
G.Bunce, *et al.*: Phys.Rev.Lett. 36, 1113-1116 (1976)

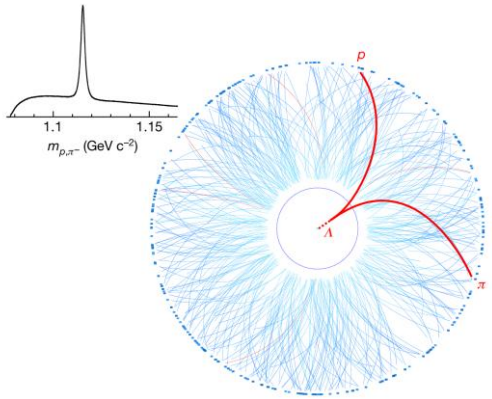


First observation:
In 1976 at Fermi-Lab, Hyperons were produced polarized in p + Be collisions: 300 GeV protons on Beryllium target

Λ polarization in heavy ion collision







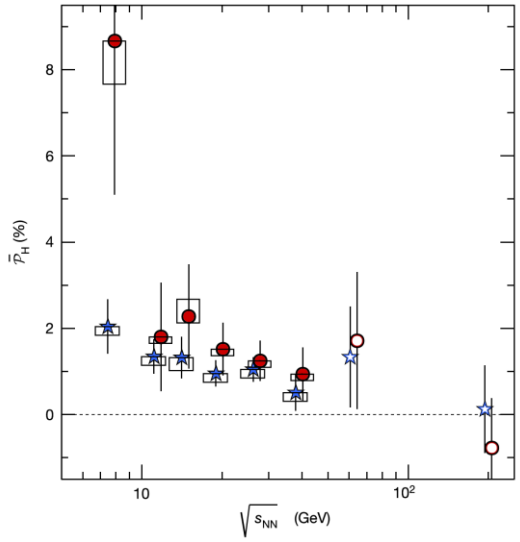
$$J_0 \sim \frac{Ab\sqrt{s}}{2} \sim 10^6 \hbar$$

Global angular momentum

$$eB \sim \gamma \alpha_{\mathrm{EM}} \frac{Z}{b^2} \sim 10^{18}\ \mathrm{G}$$

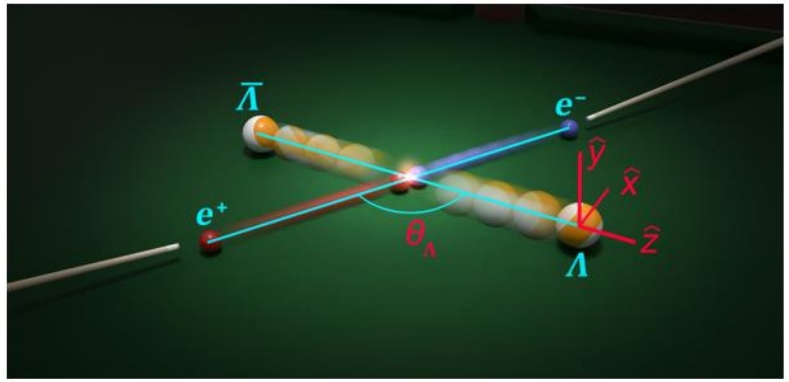
Strong magnetic field

- Λ polarization studied in heavy ion collision.
- This effect can be attributed to the vorticity of the QGP, strong magnetic fields, and quantum anomalies.
  - Clear centrality dependent
  - Expect vanished at $\sqrt{s_{NN}} \sim 2m_N$

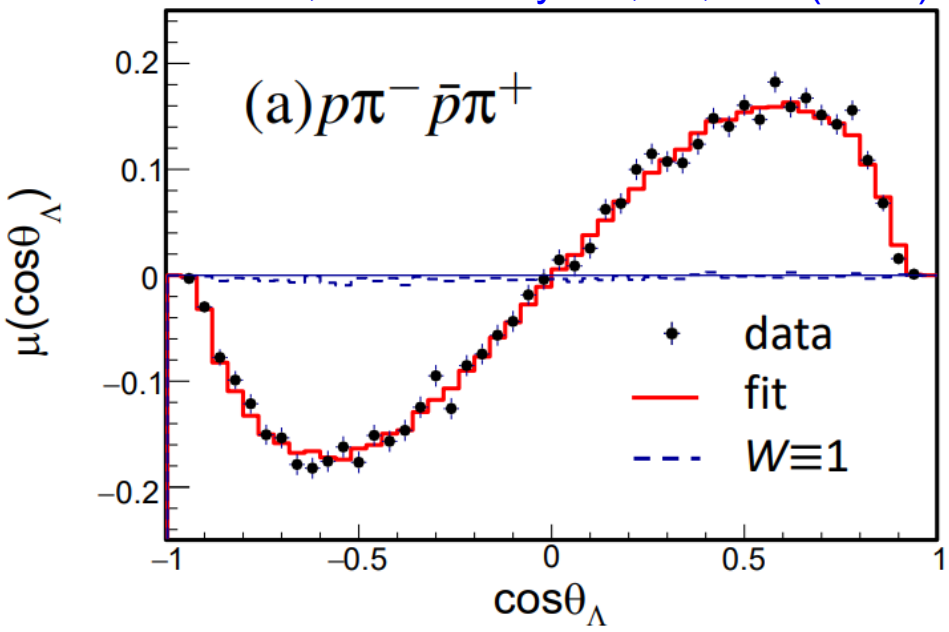


STAR, Nature 548, 62 (2017)

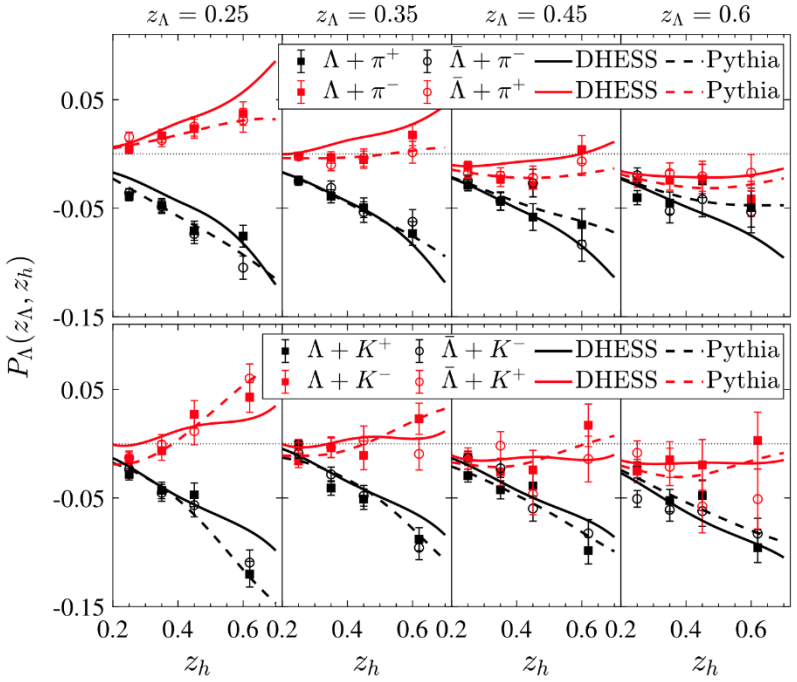
Λ polarization in e^+e^- machine



BESIII, Nature Physics, 15, 631 (2019)



Relative phase of G_E/G_M



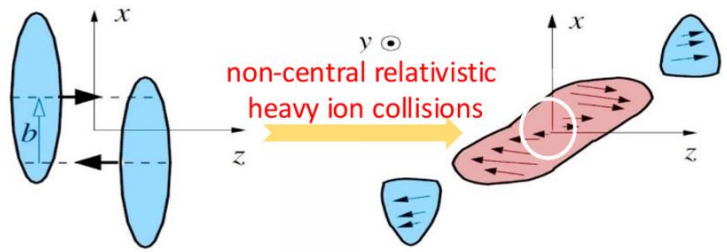
Y. Guan *et al.* (Belle Collaboration), Phys. Rev. Lett. 122, 042001 (2019).

U. D'Alesio *et al.*, Phys. Rev. D 102, 054001 (2020);
D. Callos *et al.*, Phys. Rev. D 102, 096007 (2020);
K.b. Chen *et al.*, Phys. Lett. B 816, 136217 (2021).

- First observation of the spontaneous polarization of Λ hyperons in e^+e^- annihilation
- Clear environment to study the polarization due to fragmentation of the partons, free of initial state effect
- Extract the polarized fragmentation function

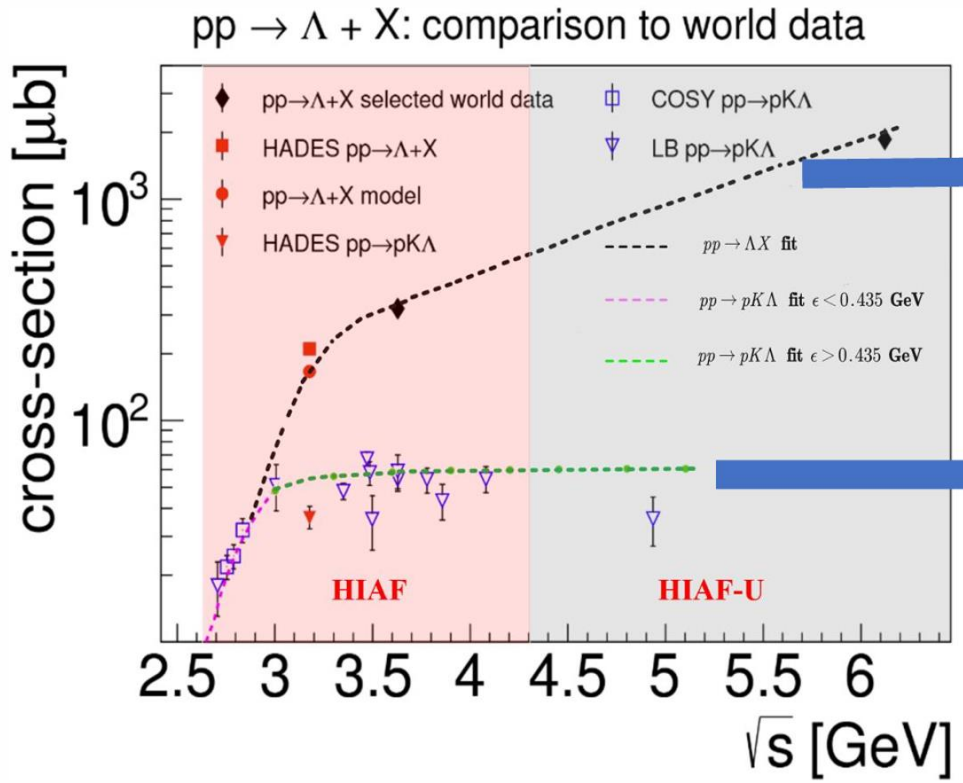
One has to take into account the production mechanism

across energy region and collision system



① $AA \to \Lambda X$ **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).



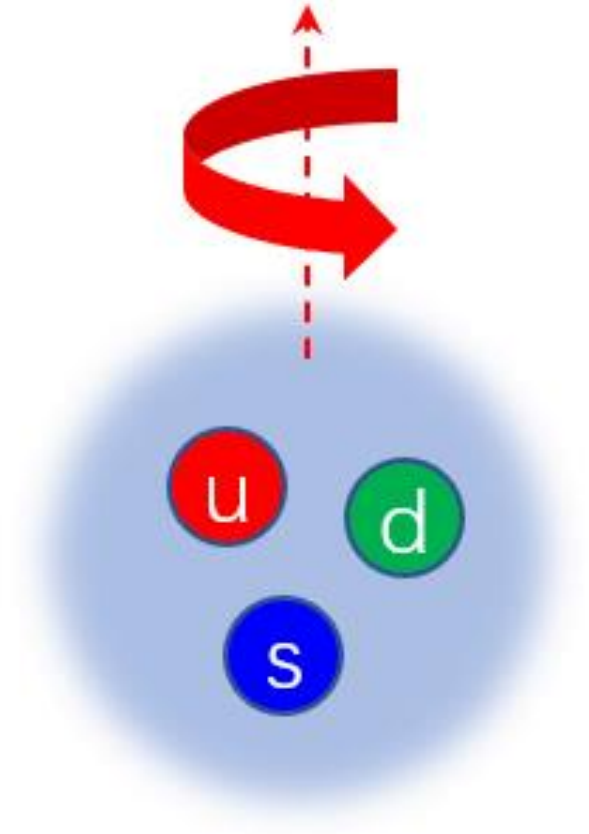
② $pp\,(A) \to \Lambda X$ **polarization through hadronization**

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).

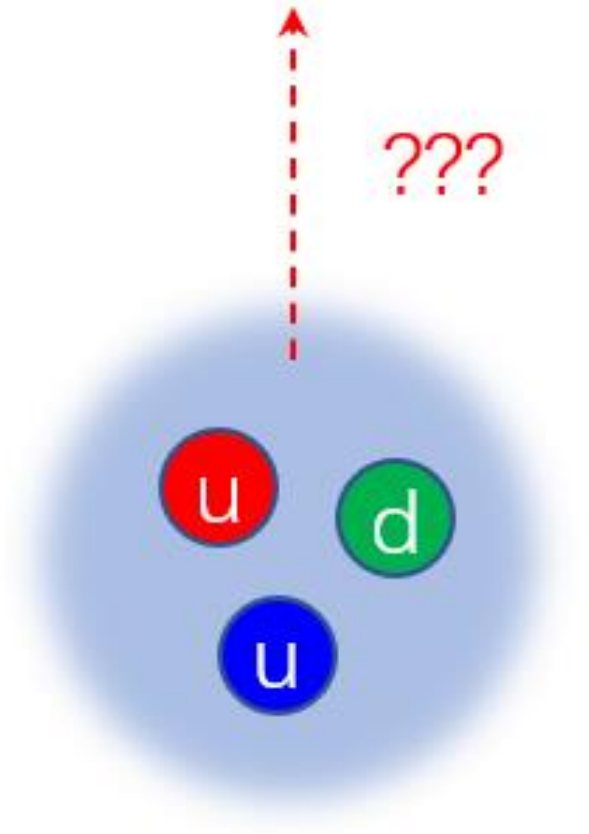
③ $pp \to pK\Lambda$ **Λ polarization in exclusive processes**

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

An interesting question: Is proton polarized as well?



pp/ee/ep → Λ + X



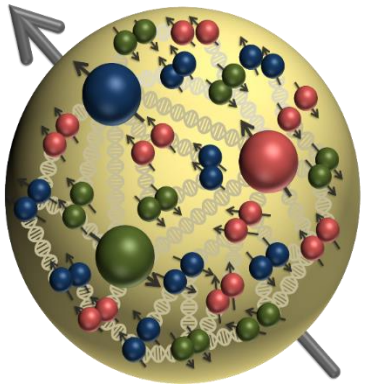
pp/ee/ep → p + X

Electron ion collider in China (EicC)

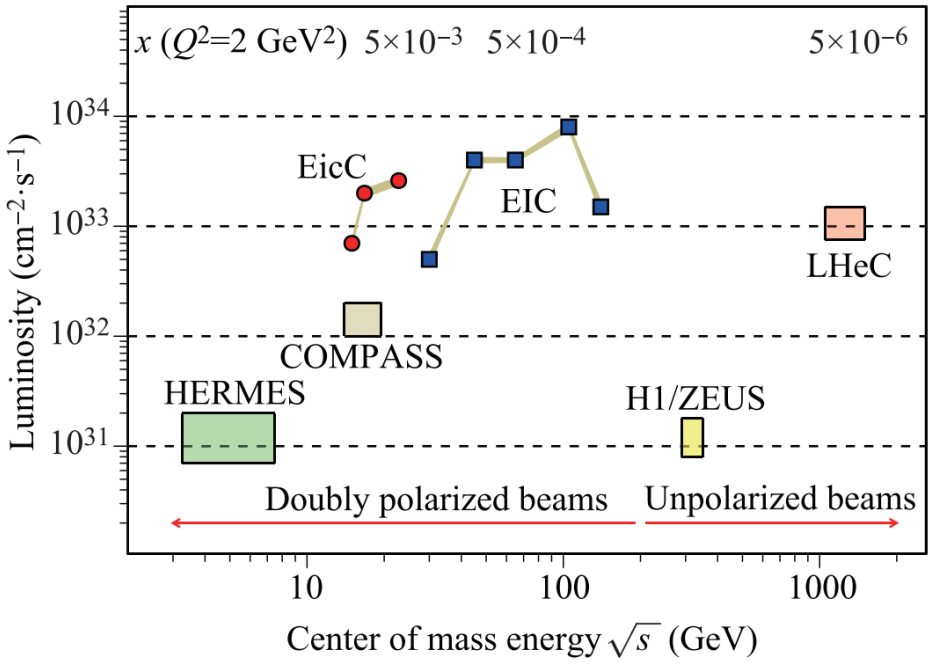
EicC accelerator complex overview

- 20 GeV p + 3.5 GeV e
- $\sqrt{S}$: 16.7GeV
- High Lumi.:

  2-4 x10^{33} $cm^{-2}s^{-1}$
- Polarized beams



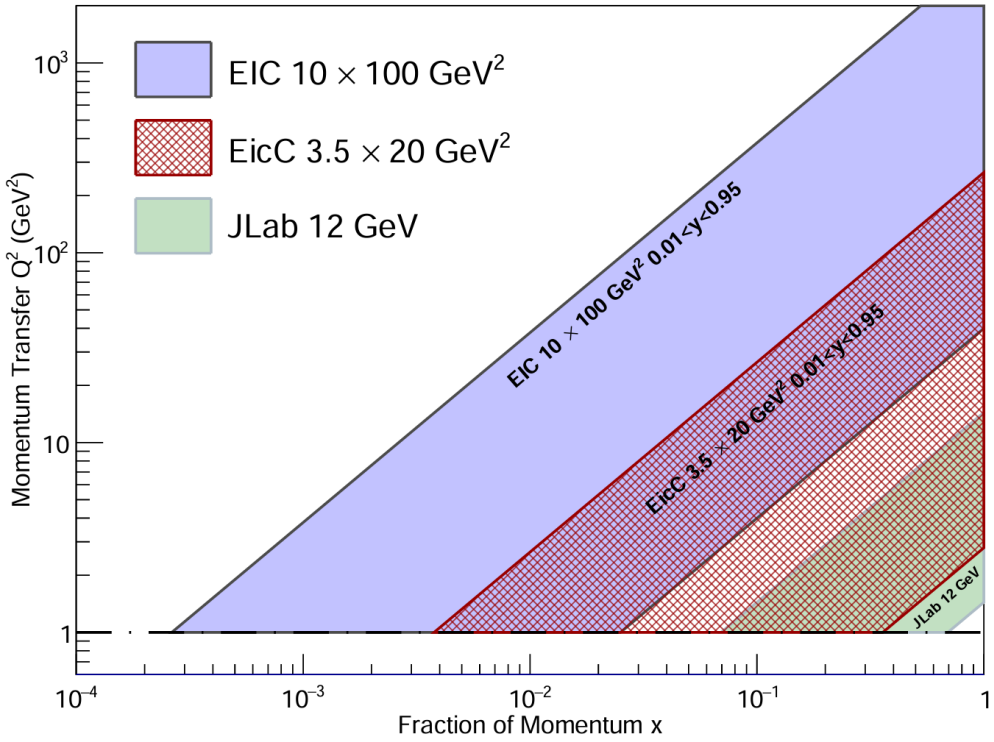
Machine Kinematics



Facilities	Main goals
JLab 12 GeV	Valence quark
EicC	Valence and Sea
US and Europe EIC	gluon

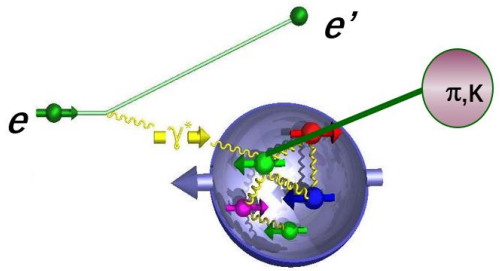
EicC, √s : 15 ~ 20 GeV

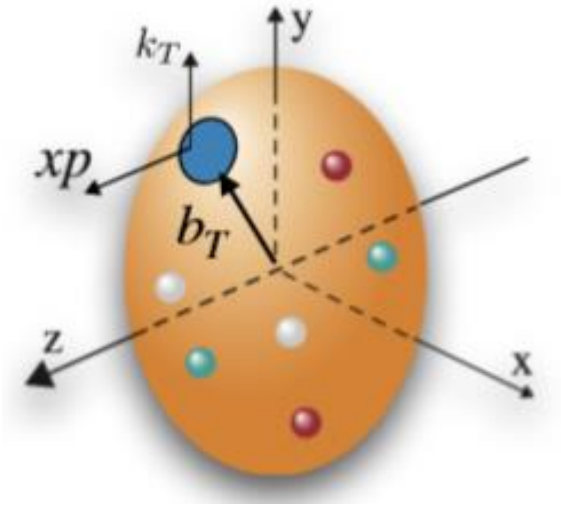
1) The energy is in the sea quark region, closer to nuclear physics
2) Nearer to the threshold for the production of heavy quarkonium

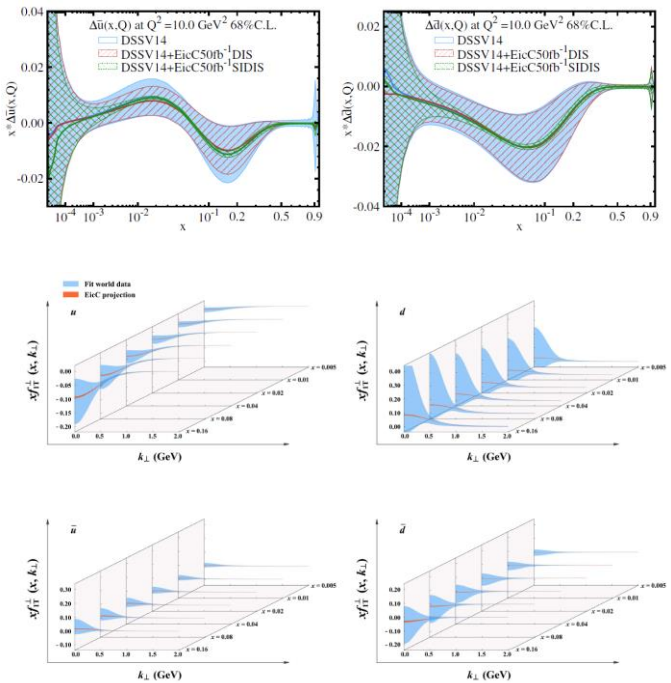


EicC Physics

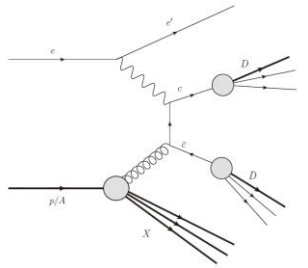
(Semi)-Inclusive DIS

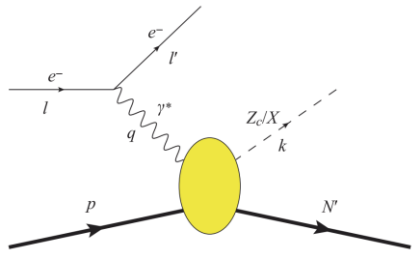


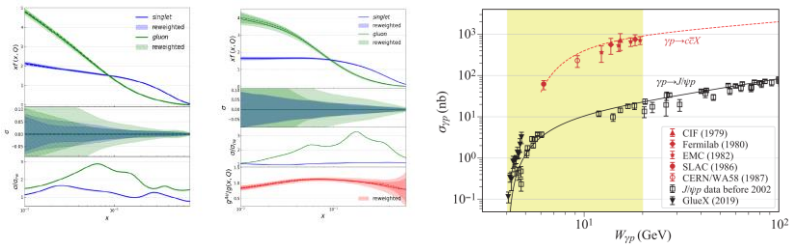




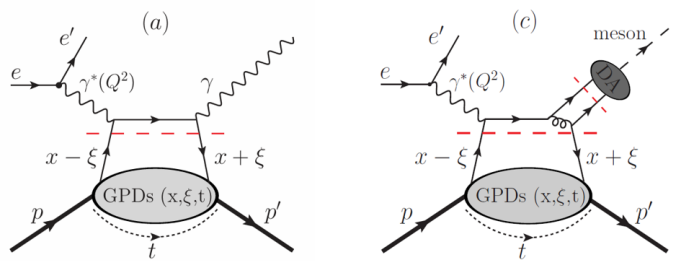
Heavy flavor

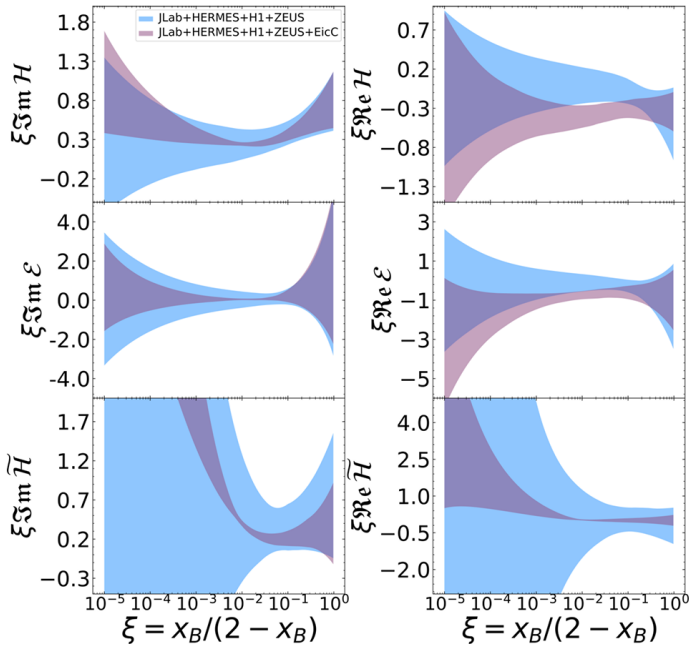




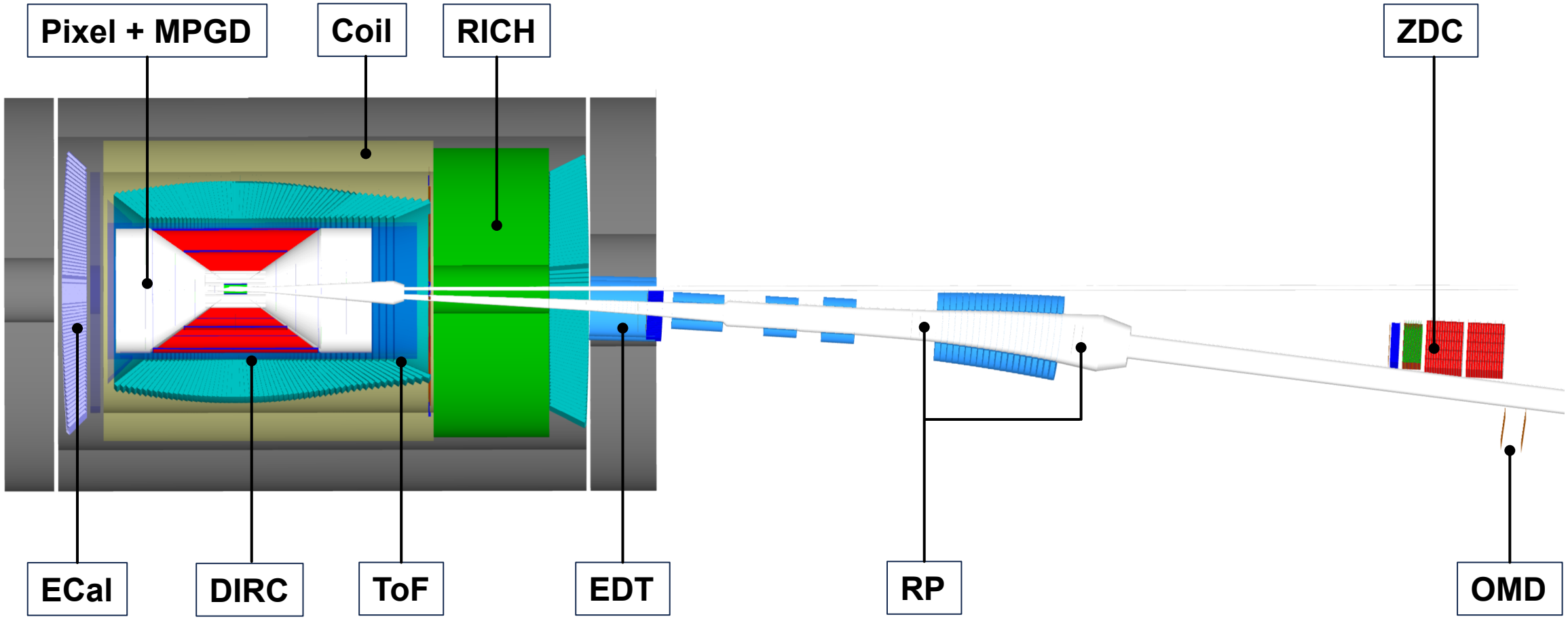


Exclusive process





EicC Detector (central + ion far-forward)



Development in EicC

EicC

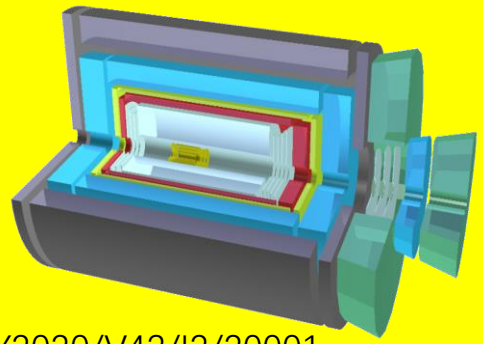
2012:Discussion in community

2020.2,2021.6:white paper(CN,EN)

2021-2025:CDR

(213 authors from 69 institutes)

As part of the long-term planning project for major scientific and technological infrastructure in particle physics and nuclear physics, the project has undergone two international expert reviews and one domestic expert review.



http://www.j.sinap.ac.cn/hjs/CN/Y2020/V43/I2/20001

https://journal.hep.com.cn/fop/EN/10.1007/s11467-021-1062-0

EicC's advantages (to EIC-US):

1) The energy is in the sea quark region, closer to nuclear physics
2) Nearer to the threshold for the production of heavy quarkonium

HIAF:

Completed by the end of 2025, it will provide the world's highest-intensity pulsed heavy ion beams, creating unique conditions for the construction of the EicC

Hyperon-Nucleon Spectrometer (H-NS)

Hyperon-Nucleon Spectrometer (H-NS)

Mag. Field: 1.5 Tesla

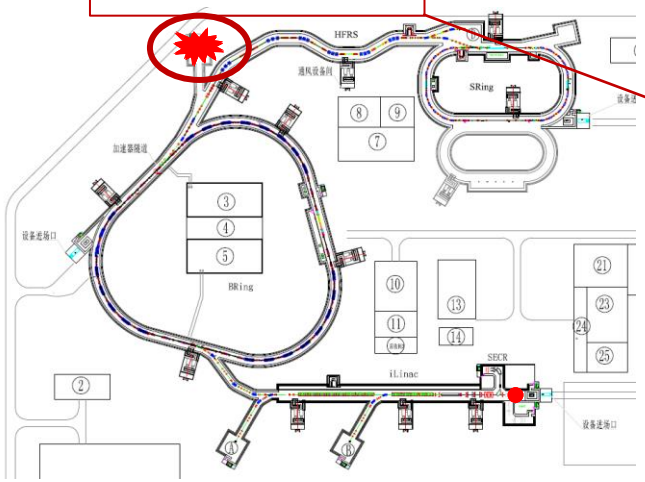
Tracker: MIC6, 30X30 μm^2, 0.35%X/X_0

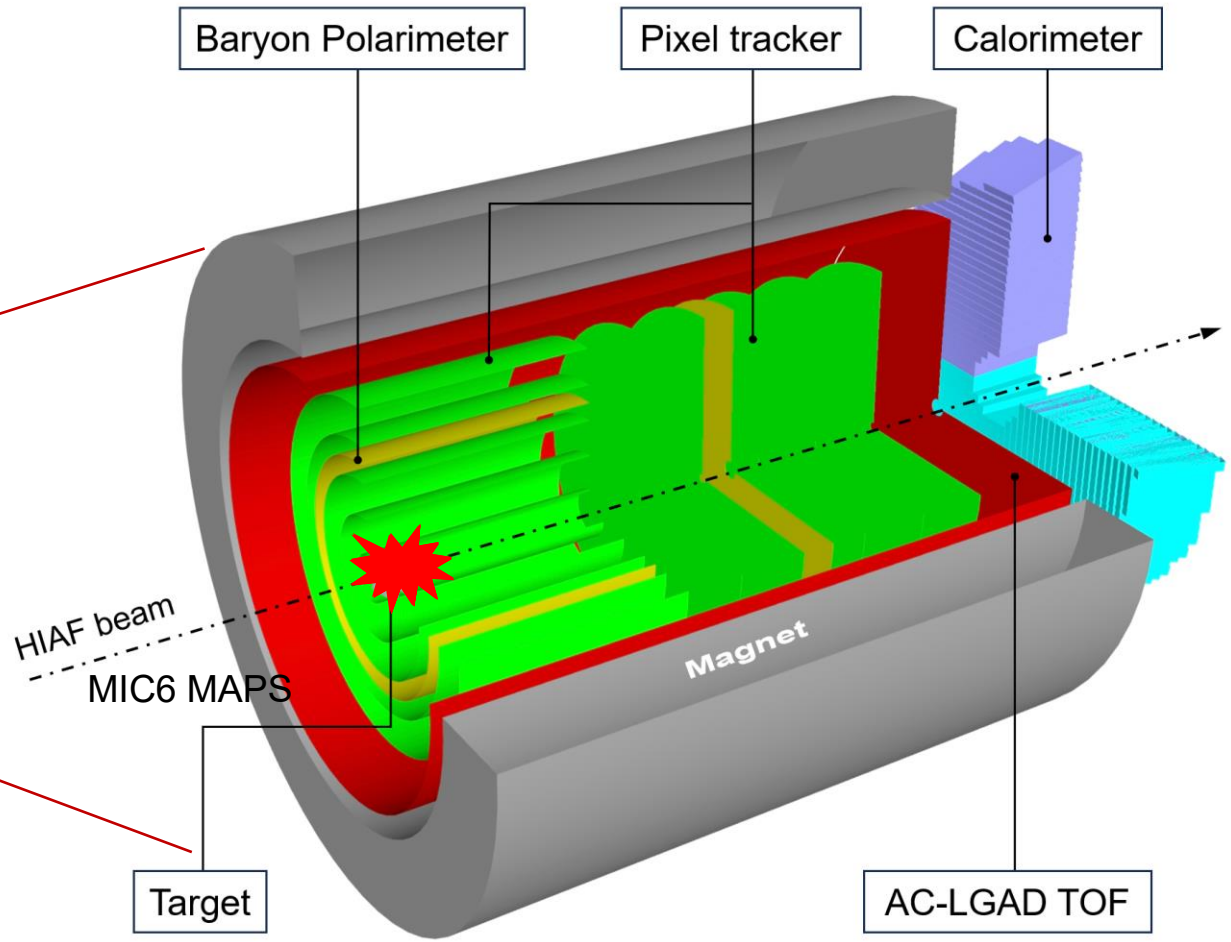
LGAD: σ_t ~ 30 ps , 300X300 μm^2

Calorimeter: σ_E ~ 3% @ 1GeV

Polarimeter: nucleon and photon polarization

High Energy Nuclear Physics Terminal





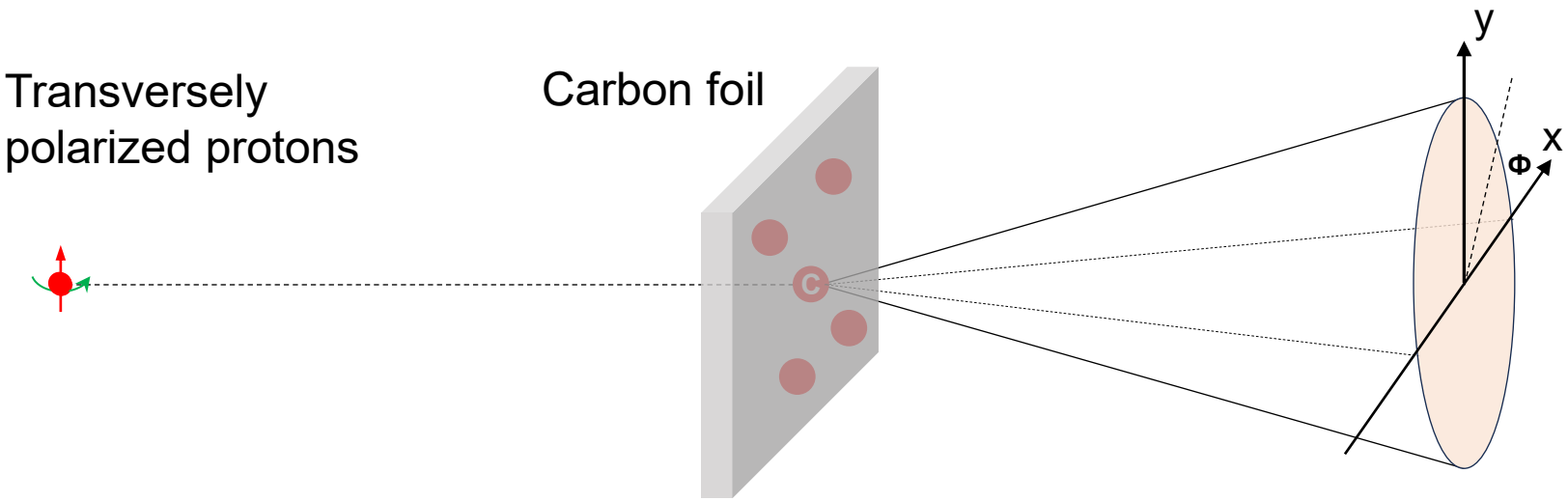
Principle of proton polarimeter

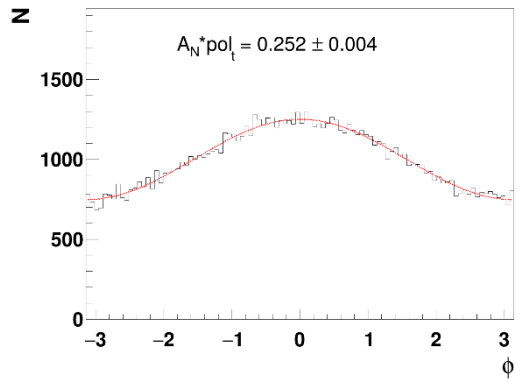
Relation between the **spin-dependent cross-section** of p + p/C scattering and the **asymmetries**

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

Transversely polarized protons

Carbon foil

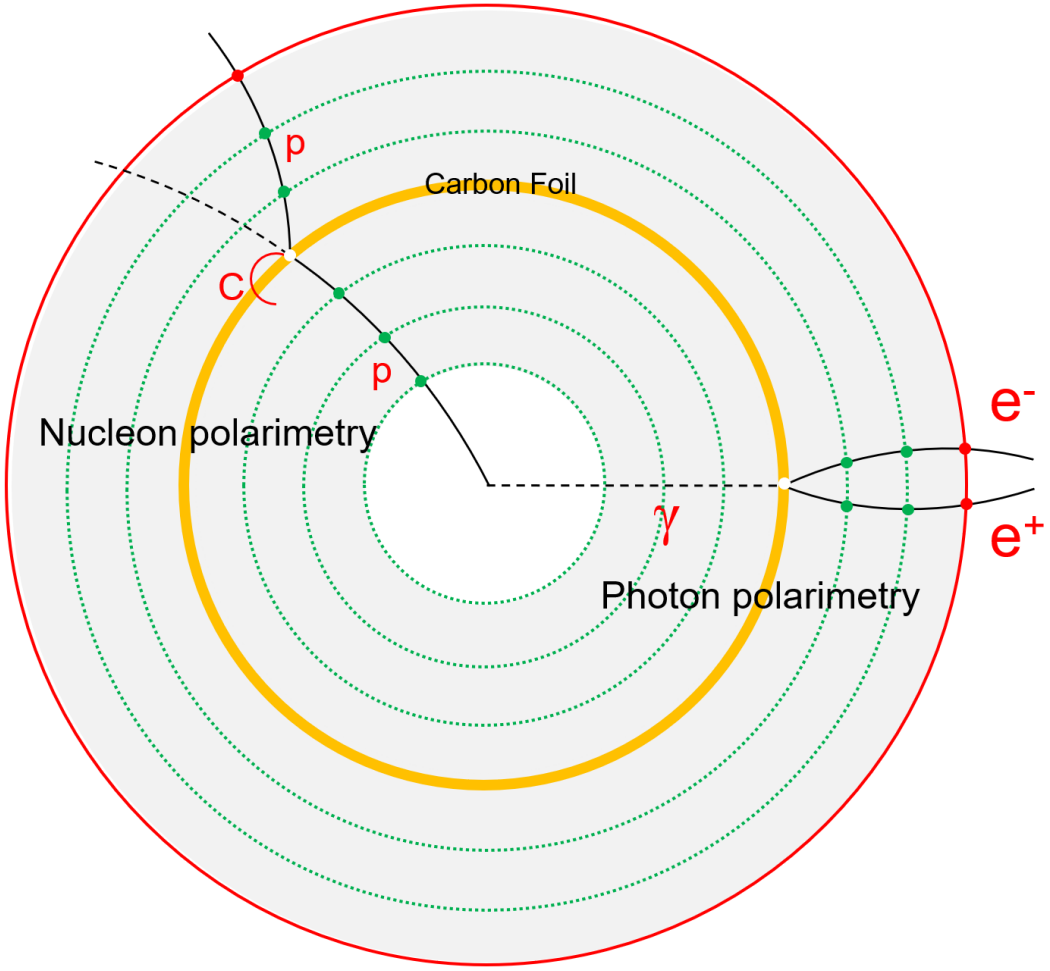




More protons to the left:
Left-right asymmetry

Widely used as polarimetric reaction to measure proton beam polarization (PSI, TRIMUF, LAMPF, COSY, SATURNE, ZGS, KEK-PS, AGS, RHIC …)

An extra scattering layer serve as polarimeter



- **Carbon foil**
  - **0.5-1 mm thickness (<1% X/X_0)**
  - **R: 20-30 cm**
  - **Probability: pC / pp , γ-conversion(1E-3)**
  - **Tiny influence to conventional performance**
- **Position : in-between the tracking devices**
  - **Appliable in all reactions: ee/ep/pp/pA/AA**
  - **Appliable in high energy machines**

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

NST in press, arXiv: 2512.02804

Uncertainty projection of the polarization measurement

pp → p/Λ + X

H-NS

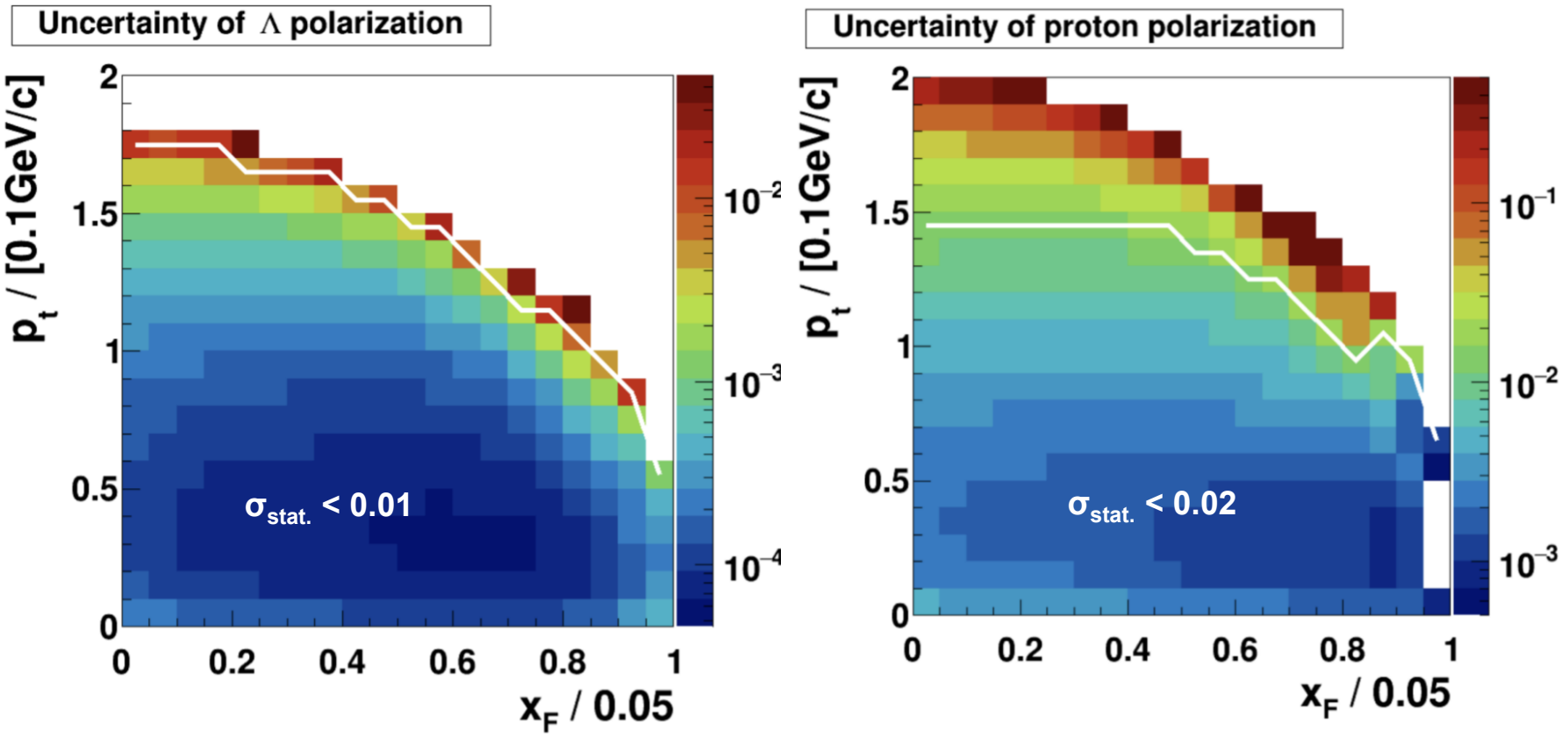
Reaction: p+p

Event rate:1MHz

Time: 3 months

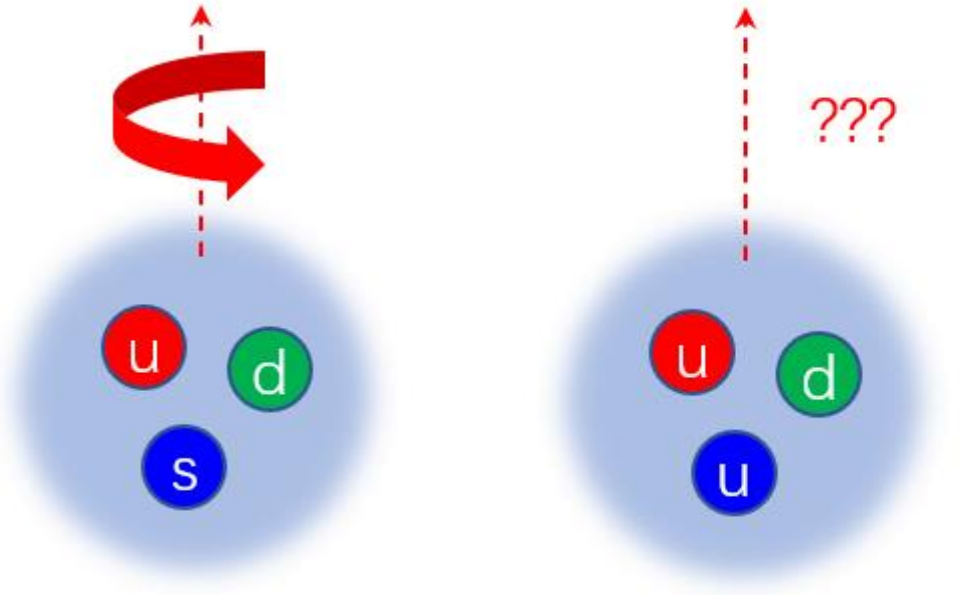
- pp →Λ+X N ~ 10^{11}
- pp → p+X N ~ 10^{13}
- pp → pKΛ N ~ 10^{10}

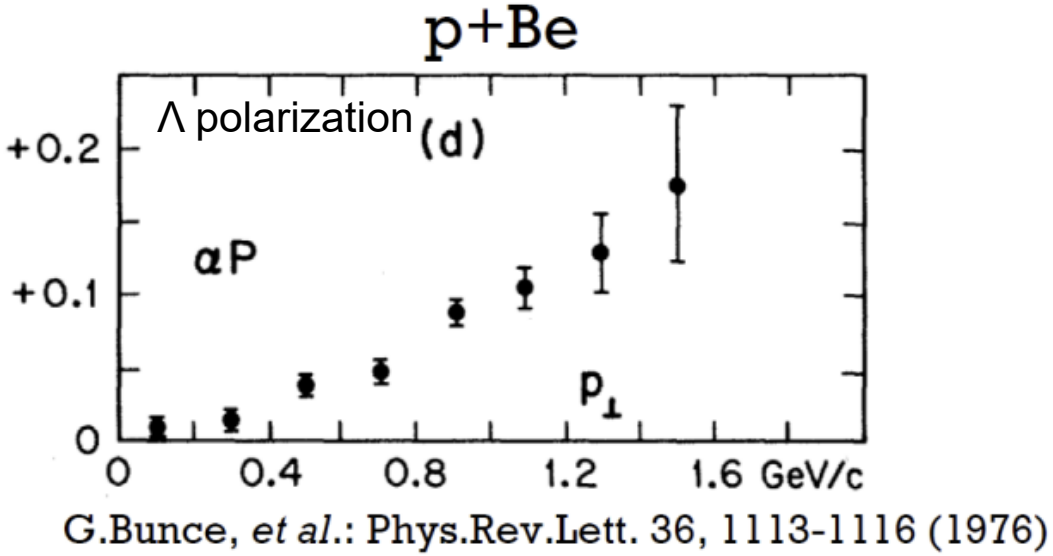
$\sigma_{stat.}$ < 0.01 for Λ 400 bins $\sigma_{stat.}$ < 0.02 for p 400 bins



Baryon spin structure -- inclusive production of p/Λ

pp → p/Λ + X





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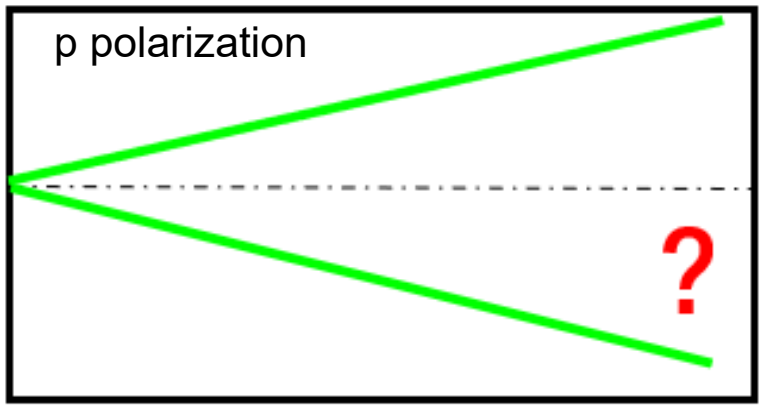


Physics potentials at H-NS -- Hadron structure

✓ Λ*, Σ*, Ξ*, Ω*, resonance need ECal.

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

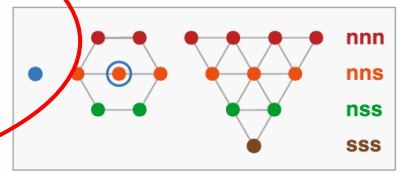
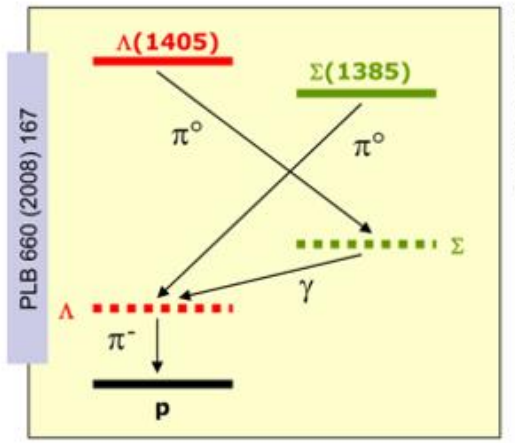
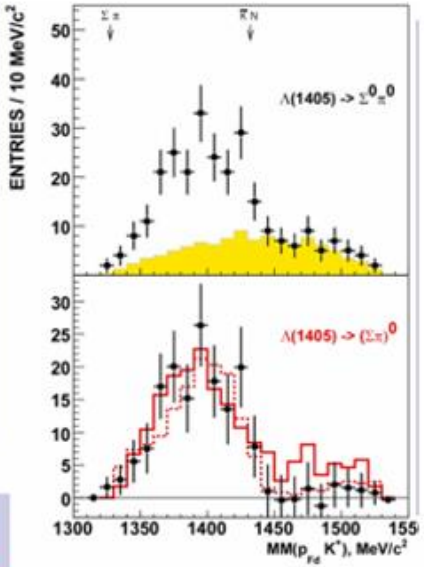


Fig. 1 Light and strange baryon spectrum from the PDG [1] up to $J^P = 11/2^+$. The columns correspond to different J^P and the colors to isospin and hypercharge. The different font weights represent four-, three- and two-star resonances

■ Reaction (p_{beam}=3.65 GeV/c):

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





Thomas 73, $\pi^-p \rightarrow K^0(\Sigma\pi)^0$

Hemmingway 84, $K^-p \rightarrow \pi^+\pi^-(\Sigma^+\pi^-)$

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

Physics potentials at H-NS -- Heavy ion physics

H-NS

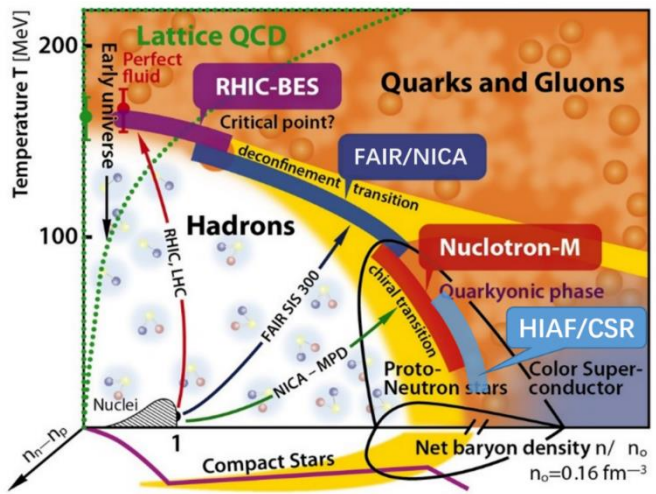
Reaction: A+A

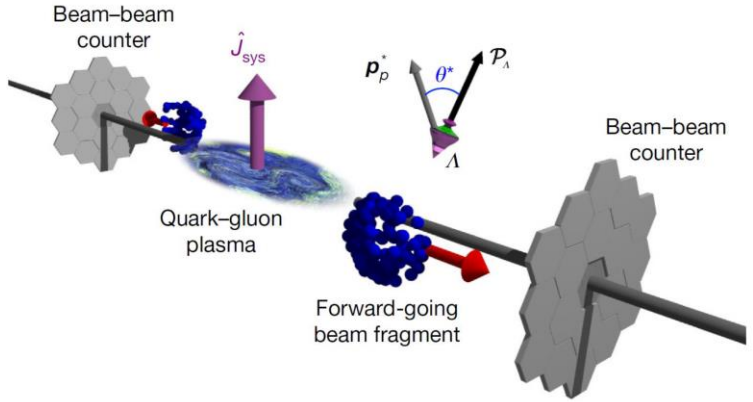
Event rate:?

Time:

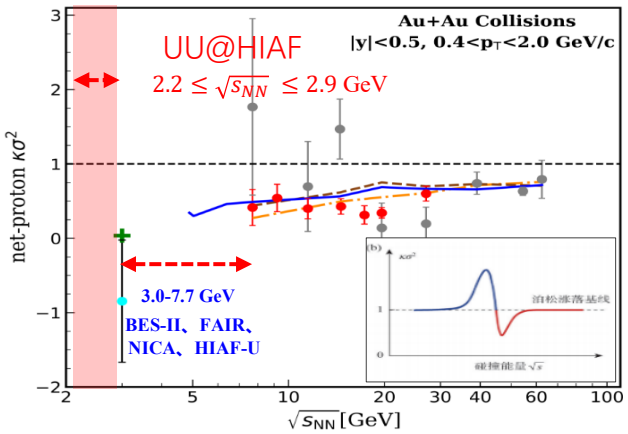
- AA →Λ+X
- AA → p+X

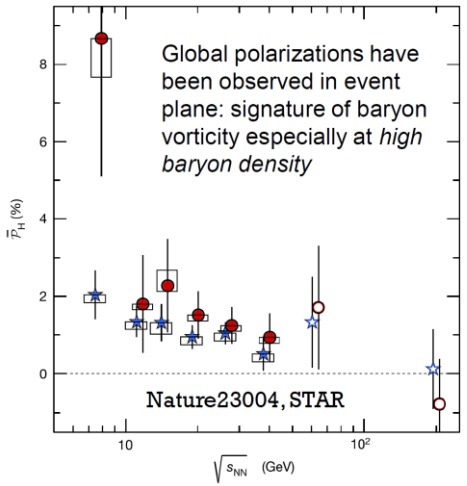
HICs@HIAF (T<100 MeV, ρ≤3 ρ_0)





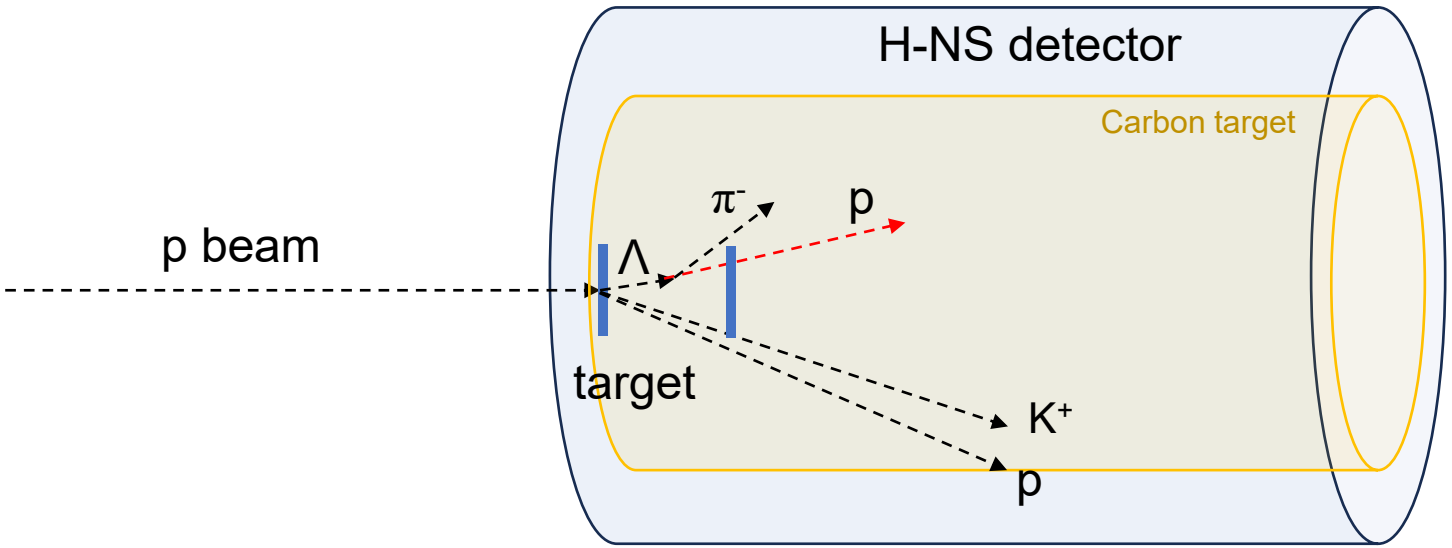
QCD Phase Structure

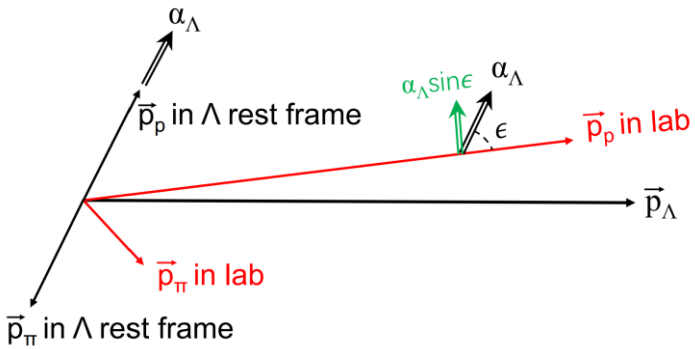


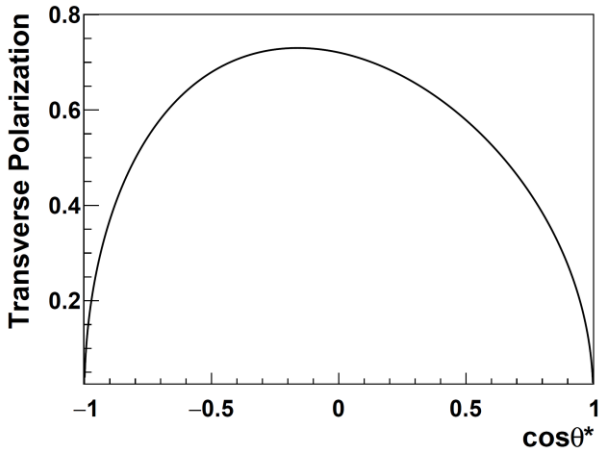


- A new probe with proton polarization?
- Global polarization of proton?

Polarized experiments at H-NS



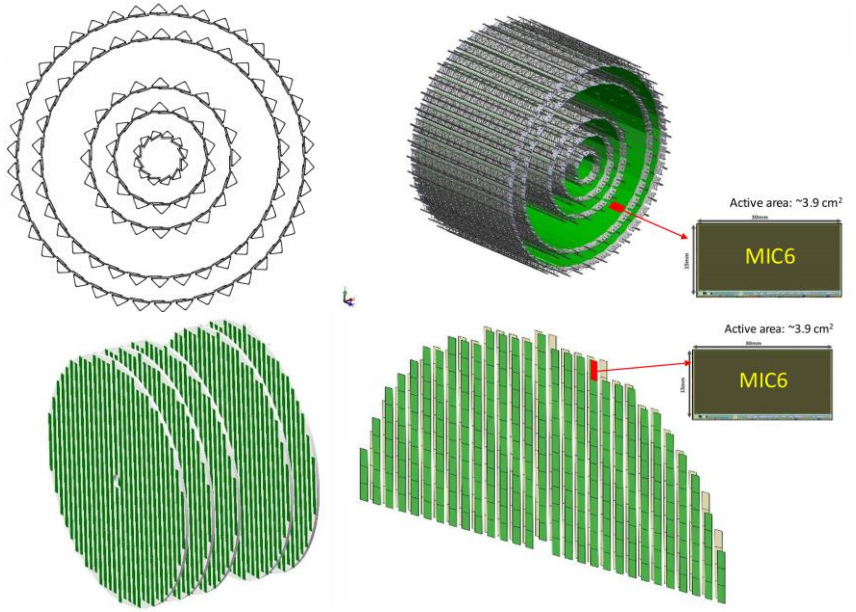




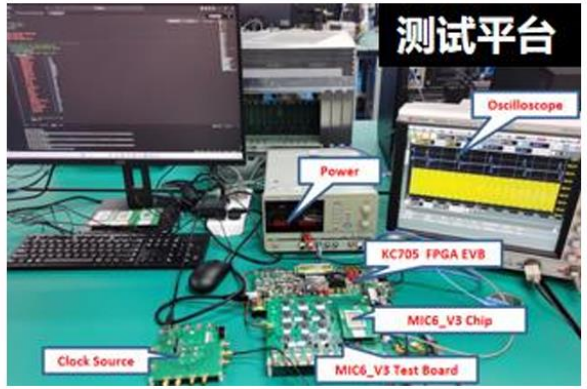
- **For Λ at ~ 1 GeV: average polarization is 0.57**
- **Event-by-event analysis to define polarization axis, effective polarized beam with 57% polarization**

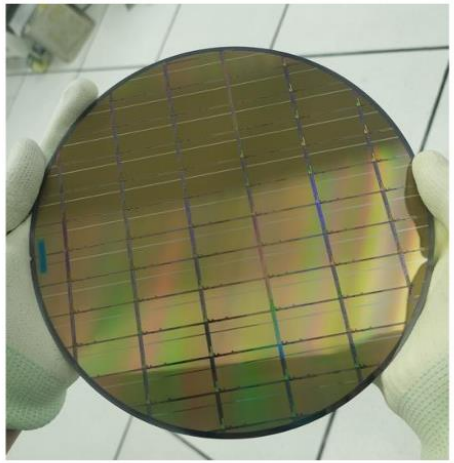
Yutie Liang, et. al., Phys. Rev. D 112, L031502

Silicon tracker at H-NS



MIC6 development at CCNU



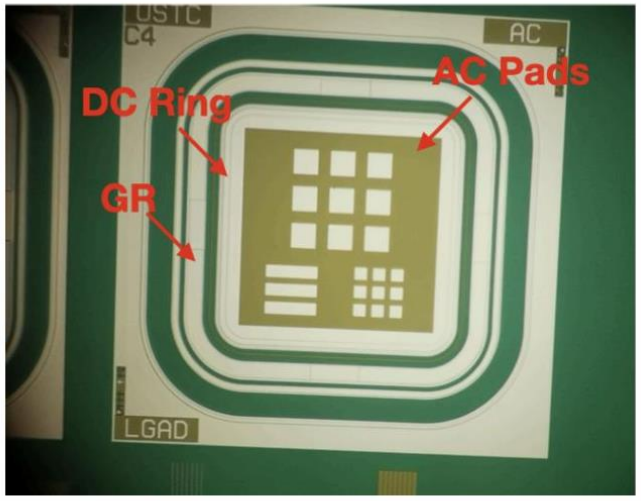


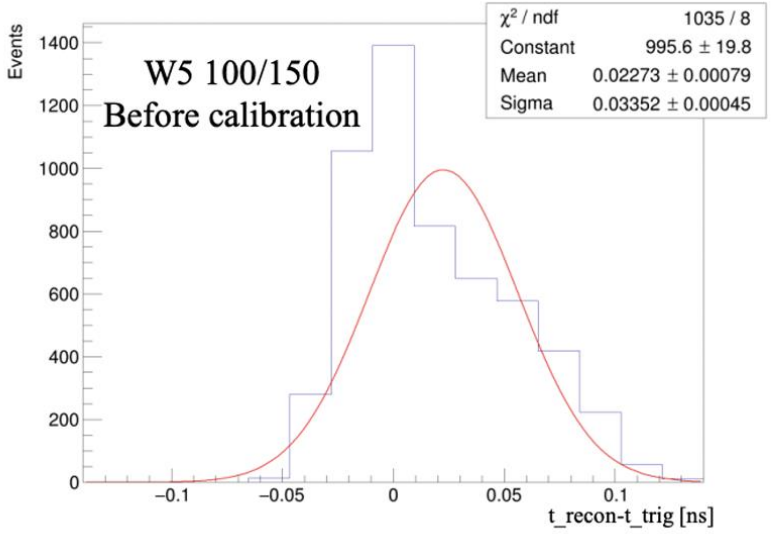
- **MIC6 MAPS pixel chip:** development and manufacture with the domestic process
- **Readout electronics** (ITS2 based design) **and DAQ** (ALICE CRU/FELIX protocol, GBTx, …)
- **Detector assembly and integration:**
  - **Vertex detector:** Stave module design (spatial resolution: ~ 5 μm with pixel size 30 μm, total material < 0.35%X/X_0 per layer)
  - **Forward tracker:** Ladder module aligned to disc super-module (spatial resolution: ~ 5 μm with pixel size 30 μm, total material < 0.45%X/X_0 per layer)

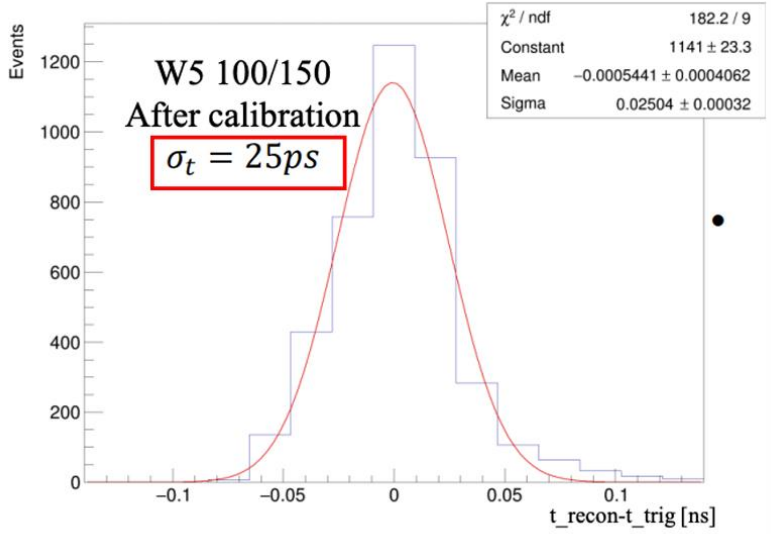
AC-LGAD at H-NS

Recent development at USTC:

- Two wafers with different n+ dose: W5 high n+ dose and W6 low n+ dose.
- Sensor size : 1300×1300×50 μm.
- Sensor with different pad-pitch size: Large pad size/pitch: 100/150 μm, Small pad (Strip) size/pitch: 50/75 μm.

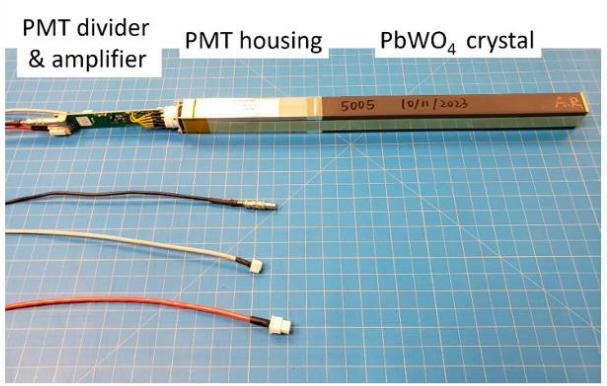




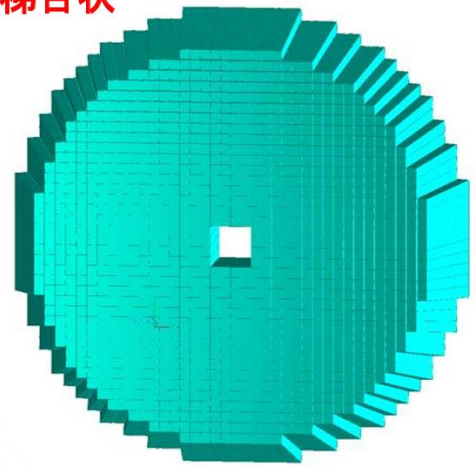


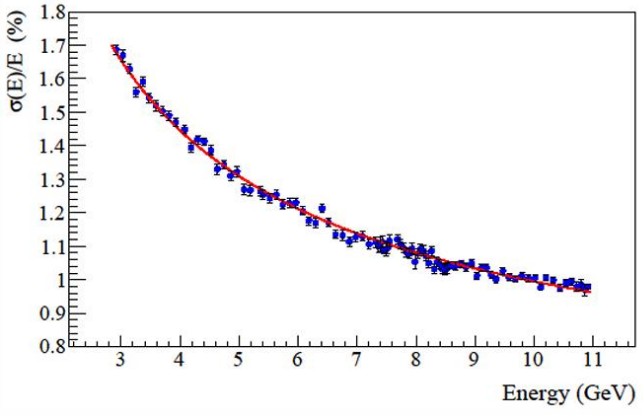
Endcap EMCal design

- **PbWO4 crystal**: compact size, good energy resolution

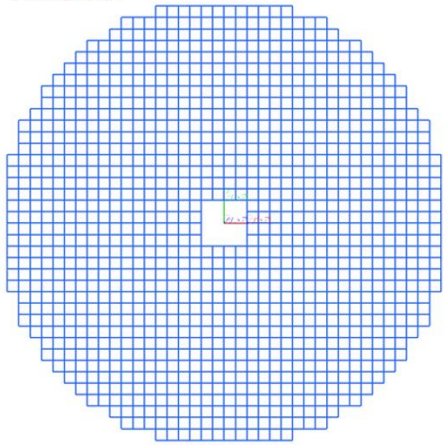


梯台状

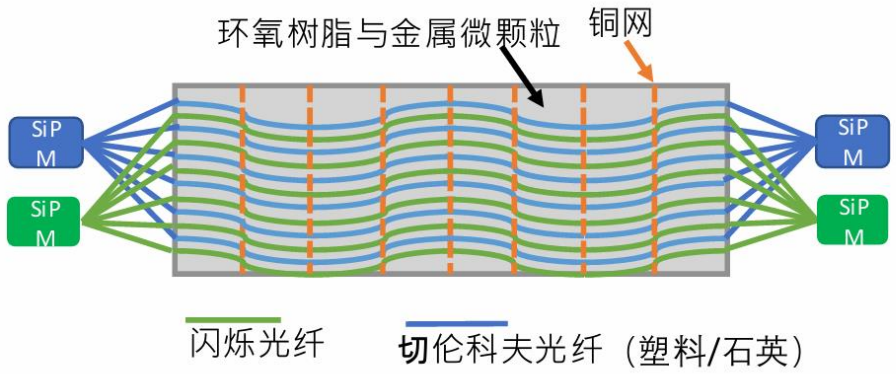


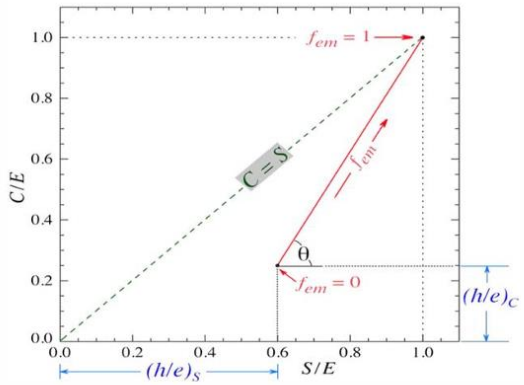


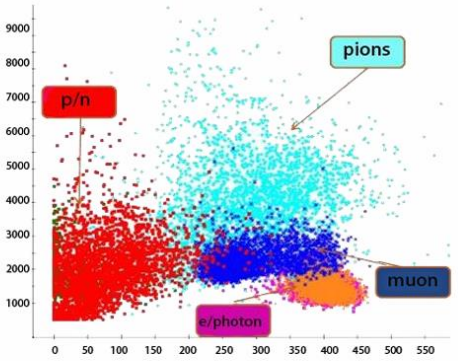
长方体



- **Dual-Read out**: better hadron shower resolution, PID capability

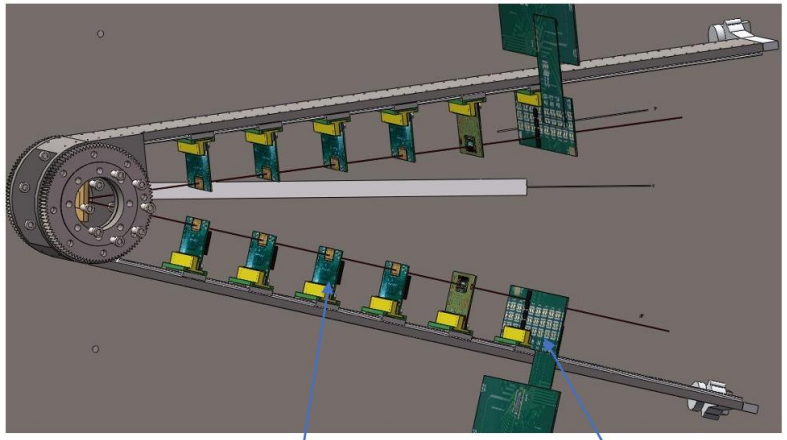


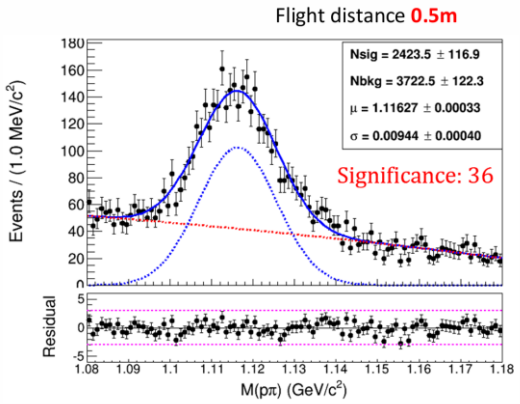




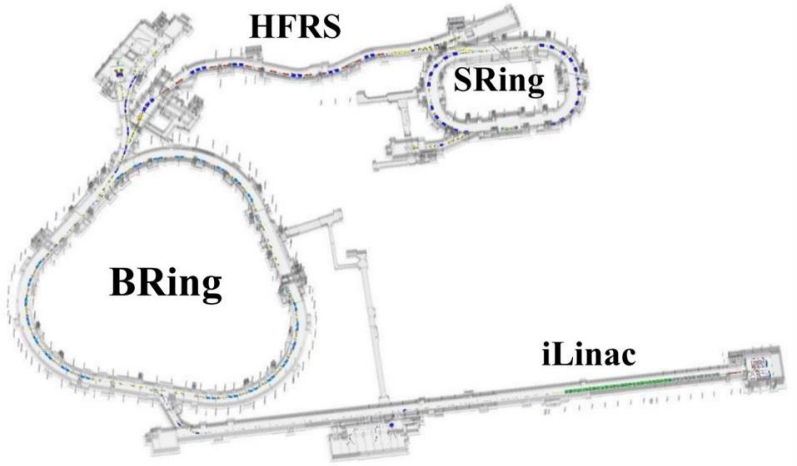
H-NS0 prototype

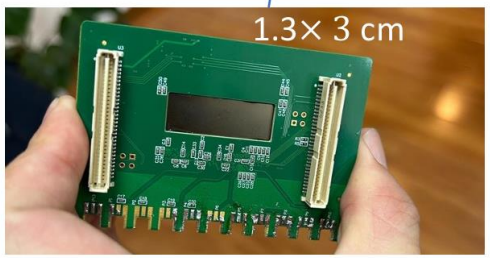
The mechanical design of ***HNSØ***





➢ 10000 Lambda in few weeks





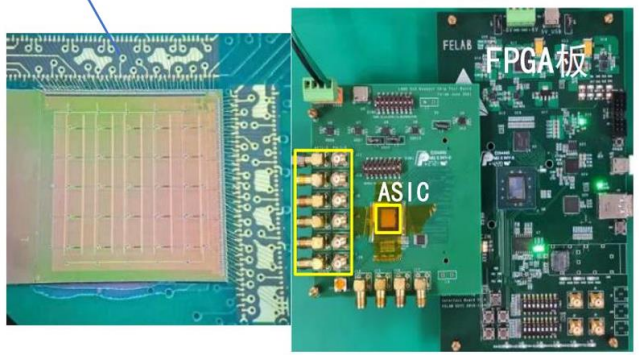
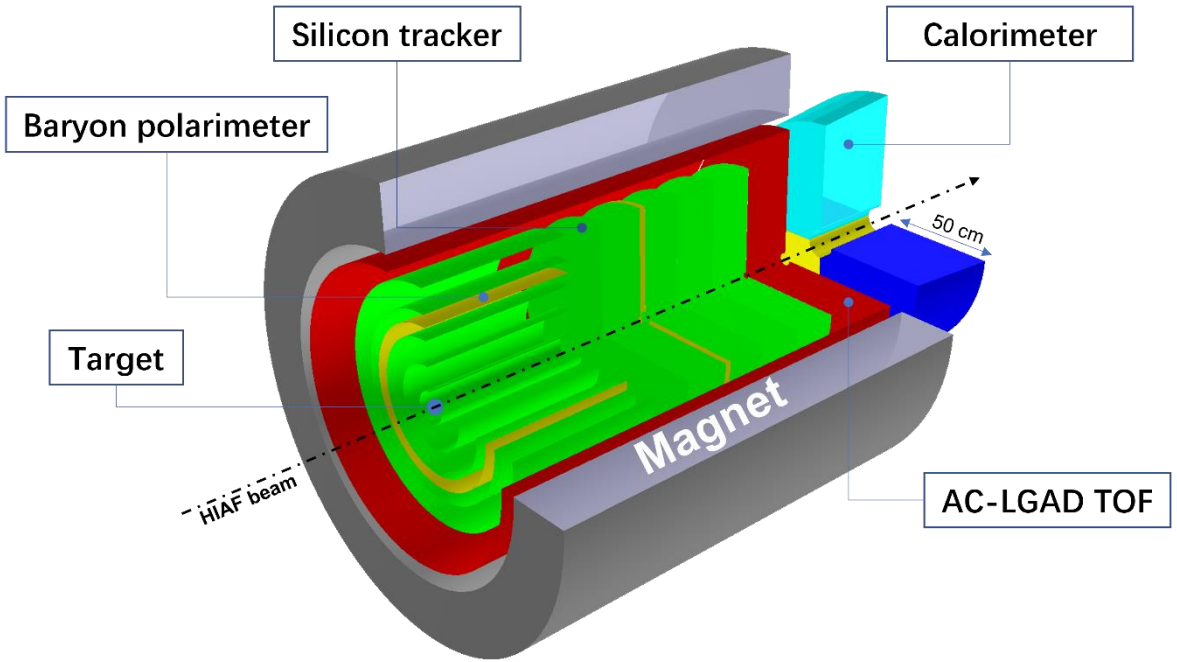


表 1-3 HIAF 验收束流指标

离子		最高能量(GeV/u)	脉冲流强(ppp)
非金属 $^{18}O^{6+}$或 $^{78}Kr^{19+}$任选一	$^{18}O^{6+}$	2.6	1.0×10^{10}
	$^{78}Kr^{19+}$	1.7	7.5×10^{9}
金属 $^{209}Bi^{31+}$或 $^{238}U^{35+}$任选一	$^{209}Bi^{31+}$	0.85	3.0×10^{9}
	$^{238}U^{35+}$	0.8	3.0×10^{9}

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)

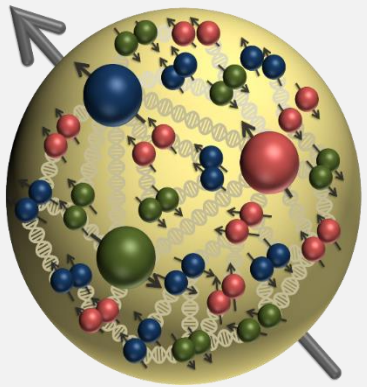
From H-NS to EicC

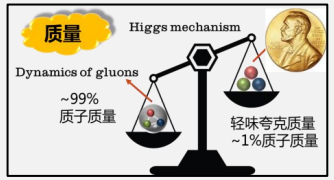
A new domain: from nucleon to hyperon

- What is the origin of Λ/p polarization
- What is the link between Λ/p spin structure and polarization

Electron ion collider in China (EicC)

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



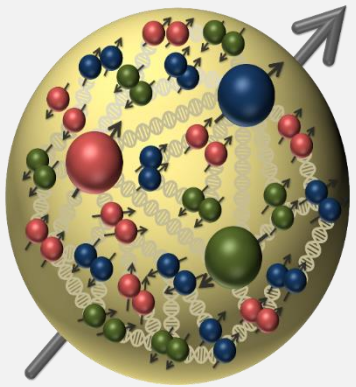


Initial state

Polarized by device

Hyperon-Nucleon Spectrometer (H-NS)

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

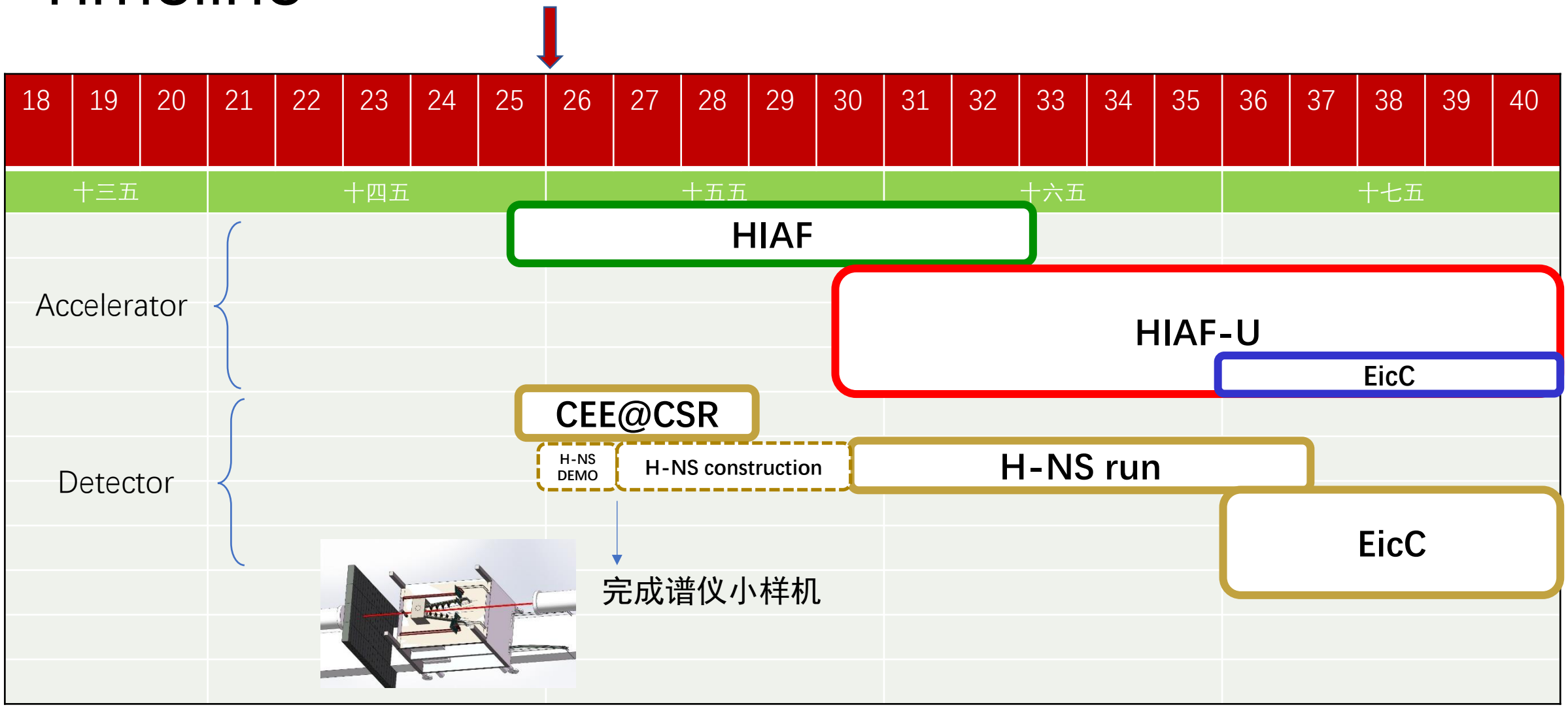


Final state

Λ polarization: self-analyzing; p polarization: new concept detector

Baryon spin structure: origin of nucleon spin VS origin of Λ/p polarization

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
Detector
HIAF
HIAF-U
EicC
CEE@CSR
H-NS DEMO
H-NS construction
H-NS run
EicC
完成谱仪小样机

Summary

- ✓ **Long range plan of high energy nuclear physics at HIAF: from H-NS to EicC**
- ✓ **Focus on the spin structure of baryon (H-NS & EicC)**
- ✓ **H-NS as ½ of EicC in many aspects, and way ahead of EicC**
- ✓ **H-NS supports both communities of hadron physics and heavy ion physics.**

Thank You