General-purpose spectrometer with polarimeter function

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HENPIC
2026.08.27

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 BESIII
arXiv: 2607.19948 BESIII

Outline

- Introduction
- Polarization measurement of stable particles
- Validation and application at BESIII
- Application and potentials at H-NS
- Summary

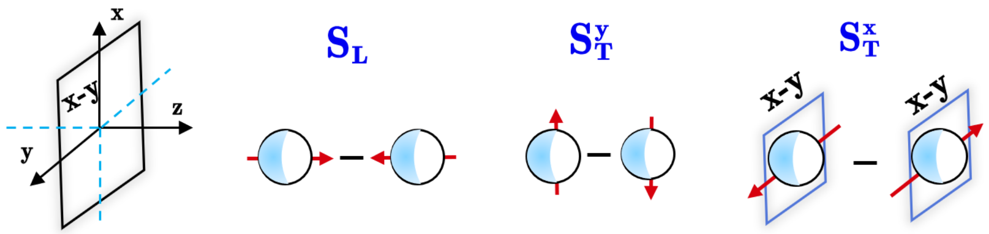
Spin and Polarization

Spin ½ : e p Λ …

$$\rho_{1/2} = \frac{1}{2} I + S^i \Sigma^i$$

$$\Sigma^x = \frac{1}{2}\sigma^x, \quad \Sigma^y = \frac{1}{2}\sigma^y, \quad \Sigma^z = \frac{1}{2}\sigma^z$$

$$S^i = (S_T^x, S_T^y, S_L)$$

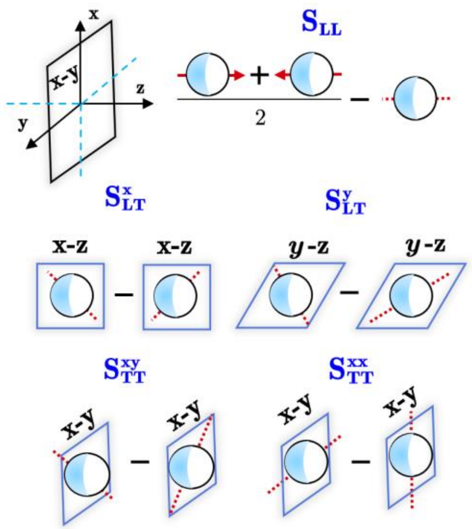


Vector polarization

Spin 1 : Φ J/Ψ …

$$\boldsymbol{\rho} = \frac{1}{3}\left(1 + \frac{3}{2} S^i \boldsymbol{\Sigma}^i + 3T^{ij}\boldsymbol{\Sigma}^{ij}\right)$$

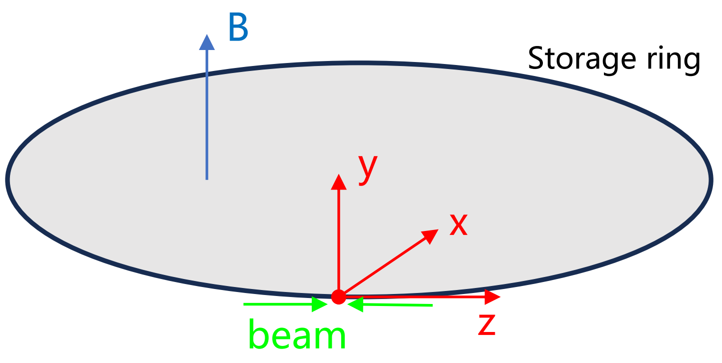
$$\boldsymbol{\Sigma}^{ij} = \frac{1}{2}(\boldsymbol{\Sigma}^i\boldsymbol{\Sigma}^j + \boldsymbol{\Sigma}^j\boldsymbol{\Sigma}^i) - \frac{2}{3} 1 \delta^{ij}$$

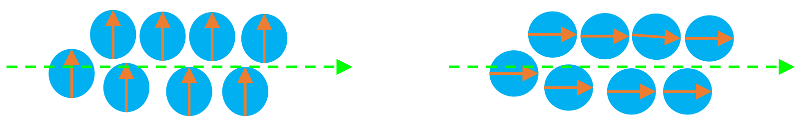


Vector + Tensor polarization

Reference frame

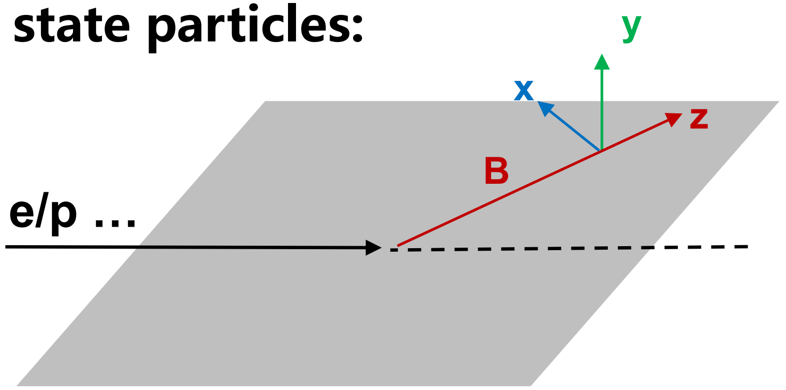
Initial beam:



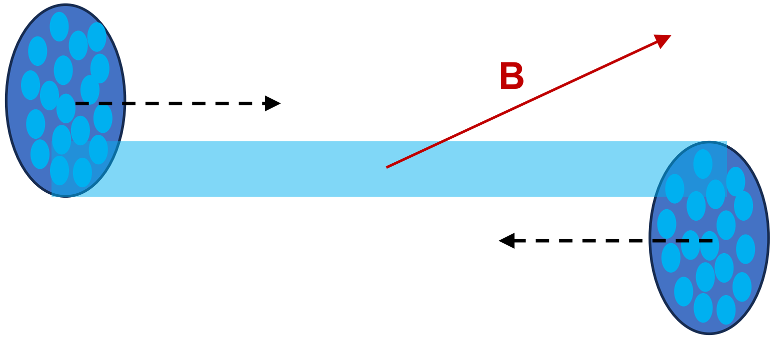


Global: polarized beam with a global reference frame

Final state particles:

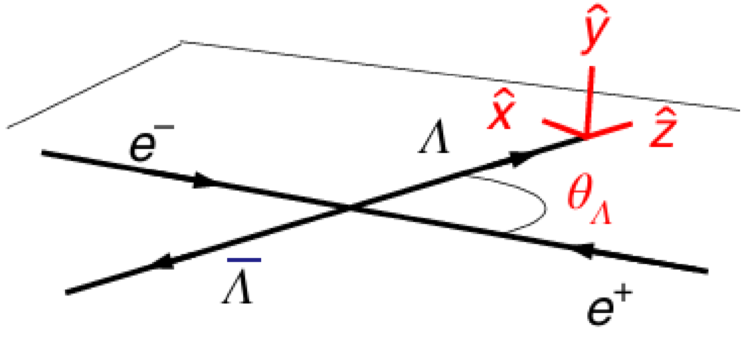


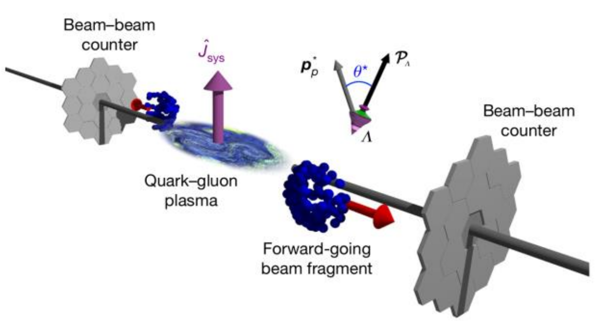
Local: reference on the production plane of the dedicated particle at study

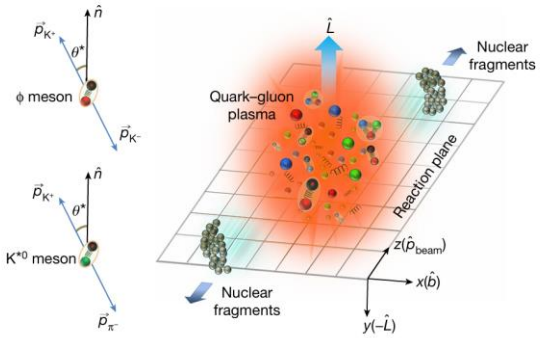


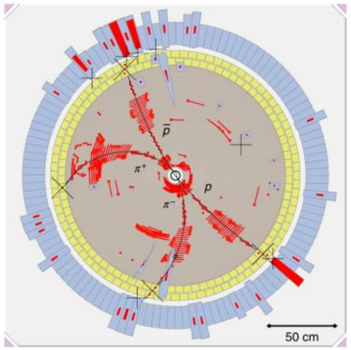
Global: relative to a global reaction plan

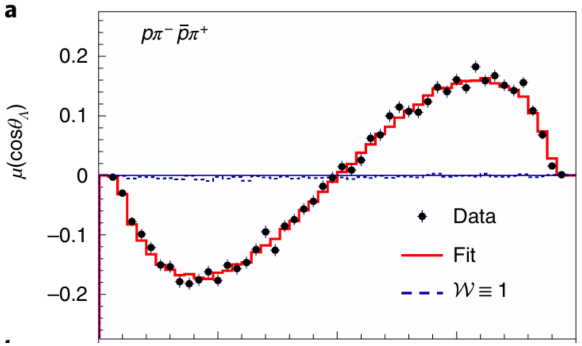
Polarization measurements

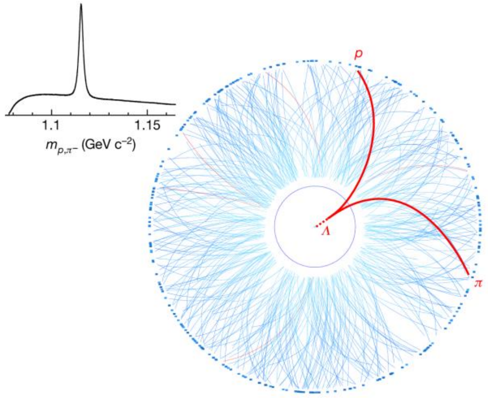


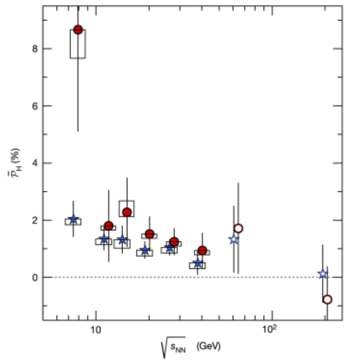


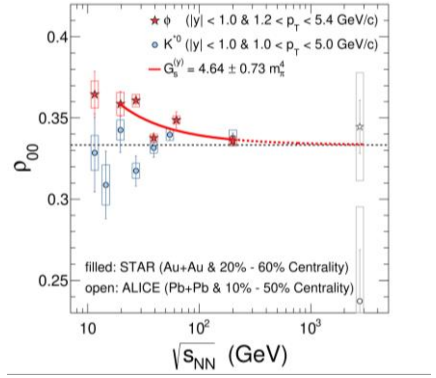












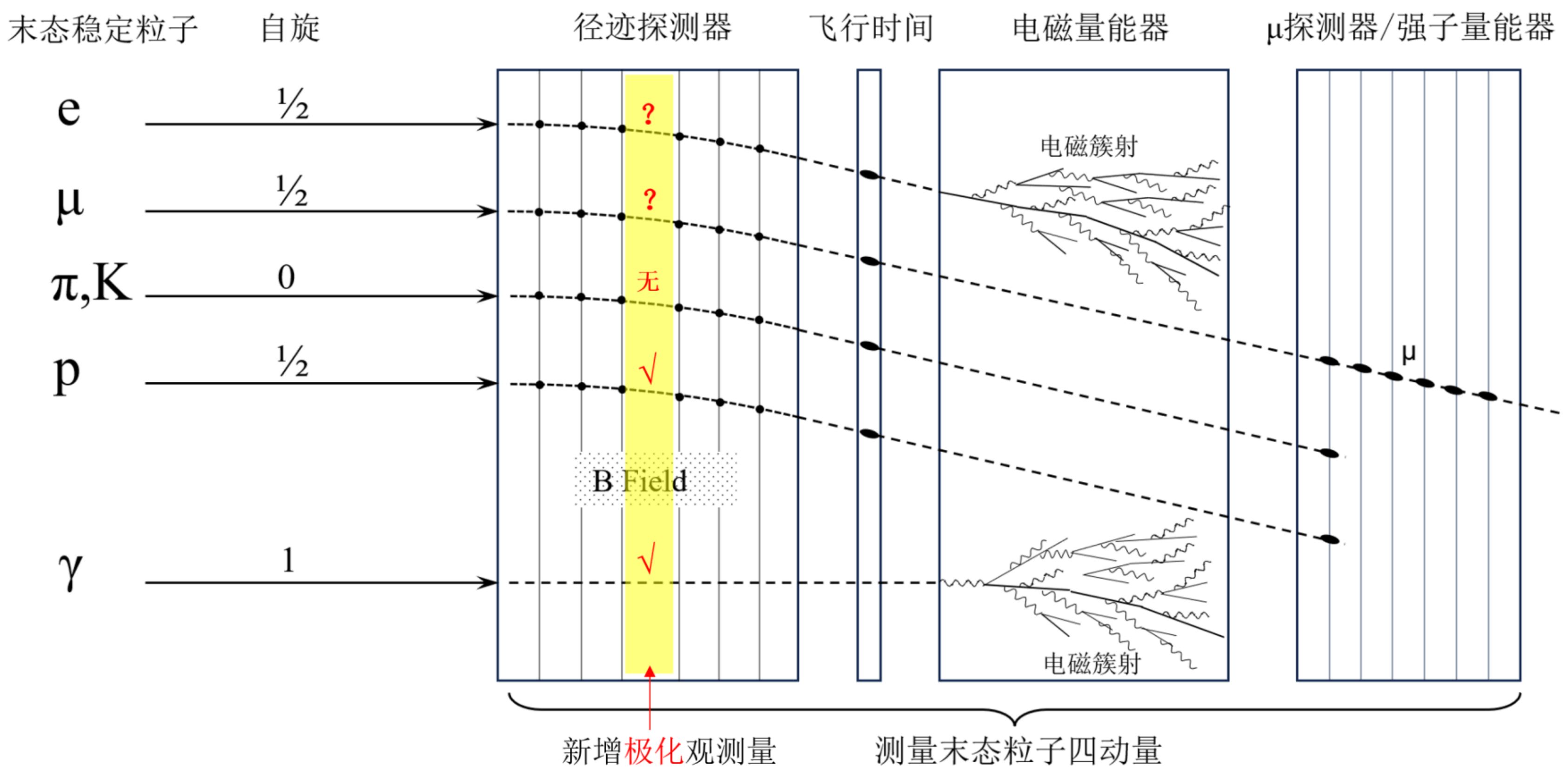
BESIII, Nature Physics, 15, 631 (2019)

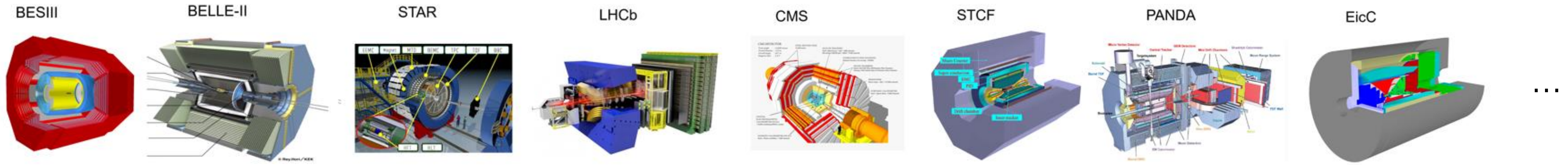
BESIII, Nature, 606, 64 (2022)

STAR, Nature 548, 62 (2017)

STAR, Nature 614, 244 (2023)

General-use spectrometer + polarimeter?

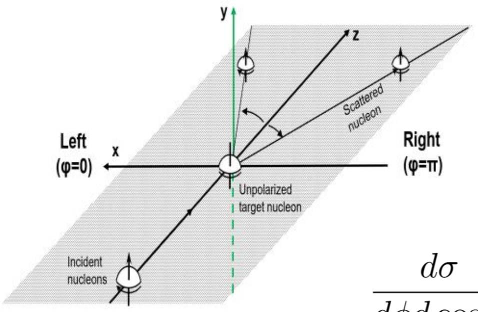




Stable particles -- Spin dependent processes

Proton: elastic scattering on proton or carbon

$\vec{p}\,p \rightarrow pp$ or $\vec{p}\,C \rightarrow pC$

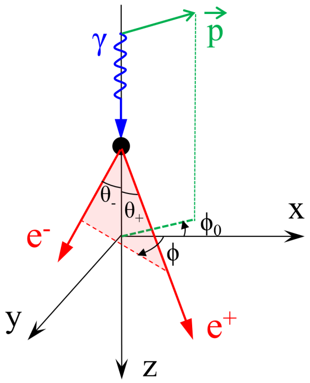


A_N ~ few 10%

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

Photon: gamma conversion

$\gamma Z \rightarrow e^+ e^- Z$

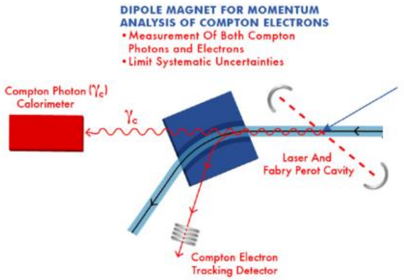


A_N ~ 10%

$$\frac{d\sigma}{d\phi} \propto 1 + \mathcal{A}P\cos[2(\phi - \phi_0)]$$

Electron (GeV): Compton or Møller scattering

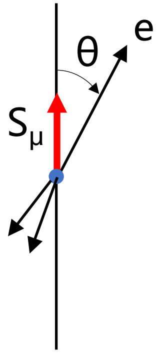
$\vec{e}\vec{\gamma} \rightarrow e\gamma$ or $\vec{e}\vec{e} \rightarrow ee$



A_N ~ few %

$$\frac{d\sigma}{dY}(Y) = (\frac{d\sigma}{dY})_{unp}(Y)[1 - S_3 P_y A_y(Y)]$$

Muon: $\mu \rightarrow e\nu_\mu\bar{\nu}_e$



A_N ~ few 10%

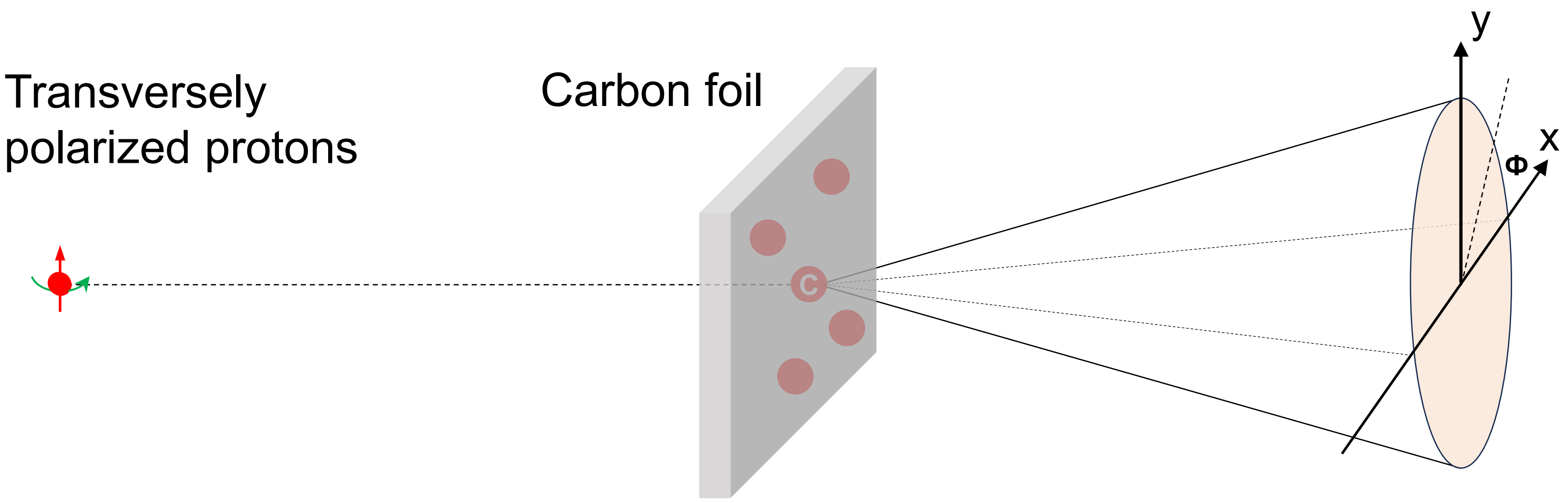
$$\frac{dN}{d\cos\theta} \propto 1 + a\,P_\mu\cos\theta$$

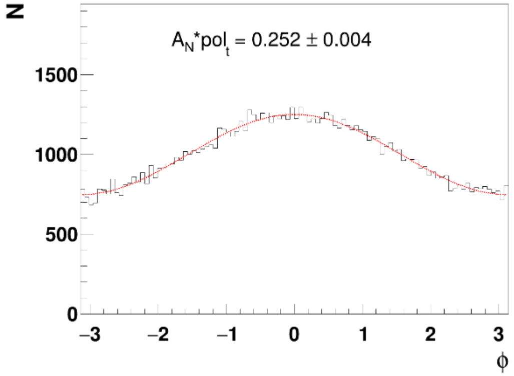
Spin polarization measurement of p and γ

Principle of proton polarimeter

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

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



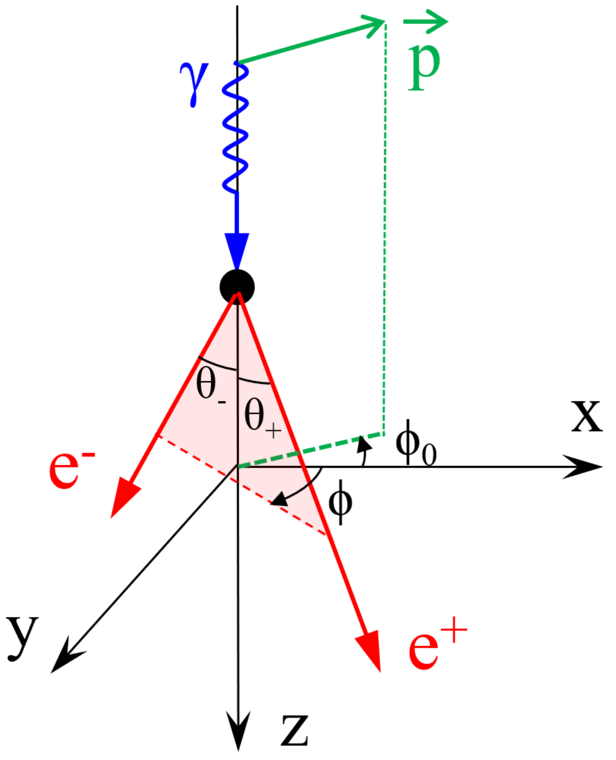


More protons to the left:
Left-right asymmetry

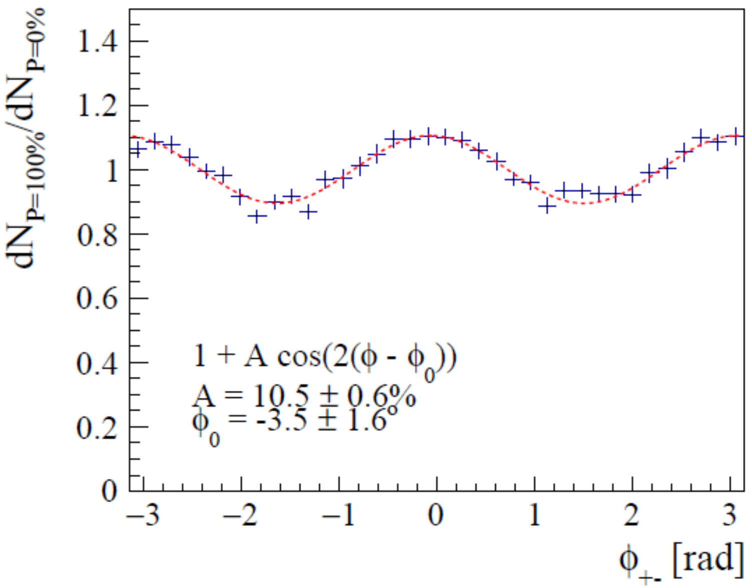
Widely used as polarimetric reaction to measure proton beam polarization (PSI, TRIMUF, LAMPF, COSY, SATURNE, ZGS, KEK-PS, AGS, RHIC …)

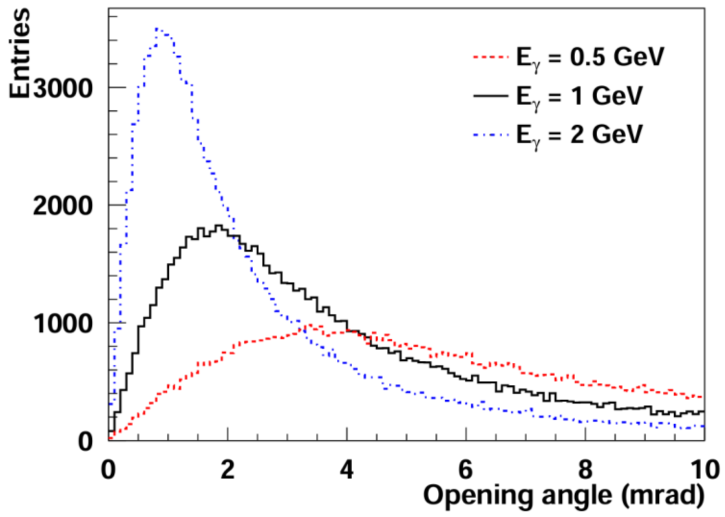
Principle of photon polarimeter

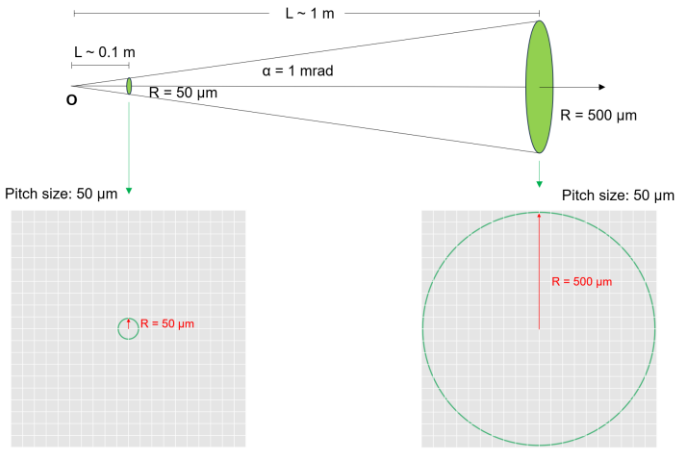
Relation between the **spin-dependent cross-section** of gamma conversion and the **asymmetries**



$$\frac{d\sigma}{d\phi} \propto 1 + \mathcal{A}P\cos[2(\phi - \phi_0)]$$

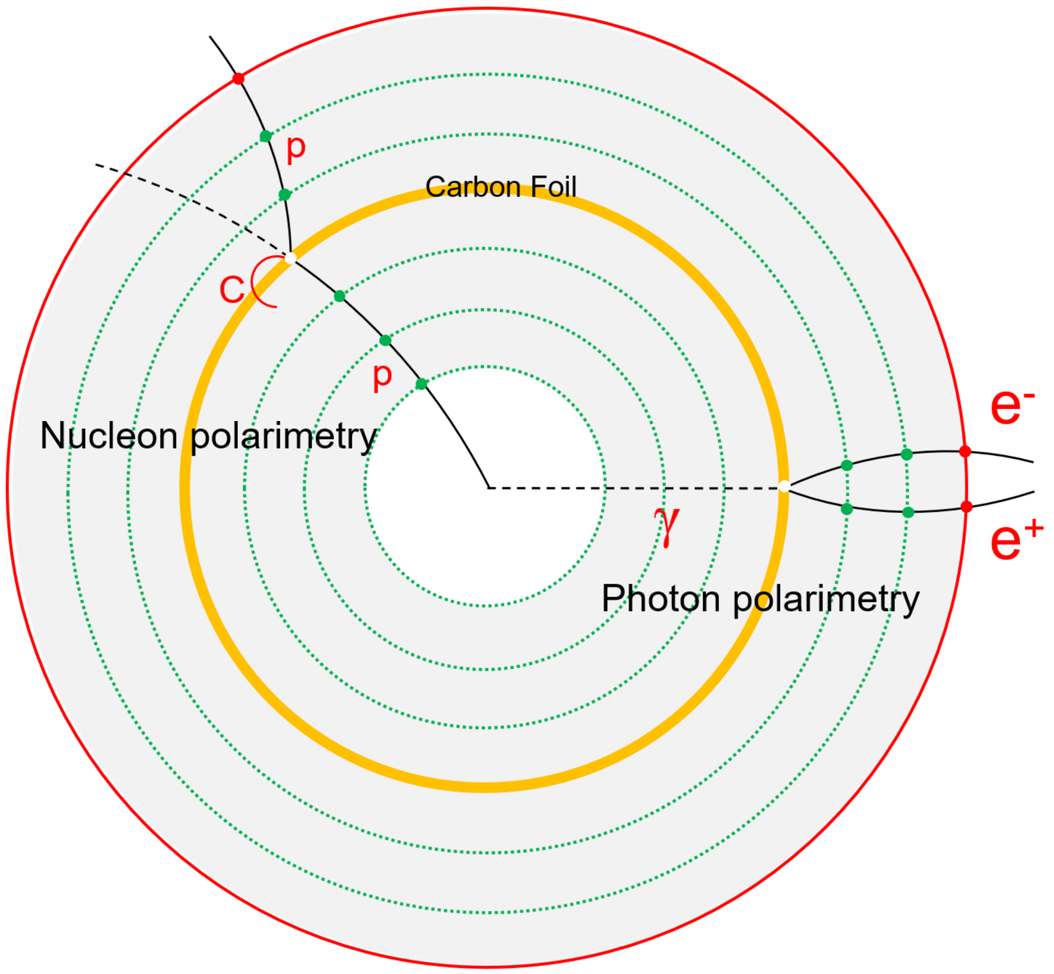






- $\gamma Z \to e^+ e^- Z$ ("nuclear" conversion);
- $\gamma e^- \to e^+ e^- e^-$ ("triplet" conversion).

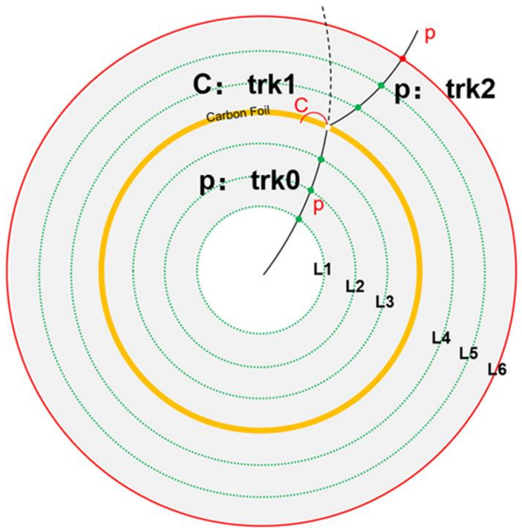
An extra scattering layer serve as polarimeter



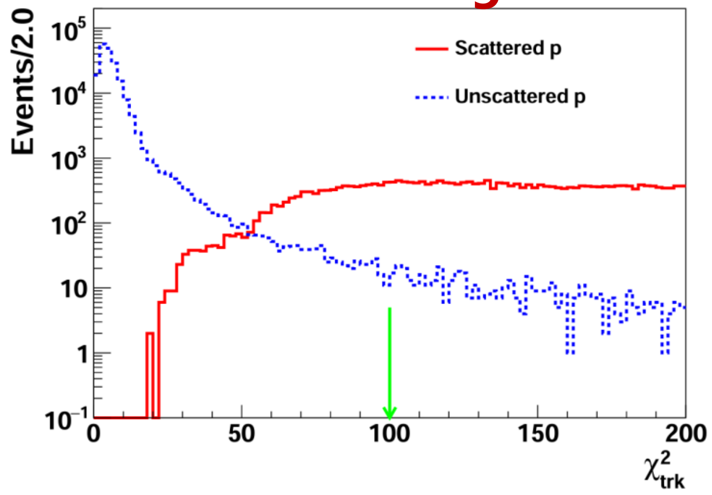
- **Carbon foil**
  - **0.5-1 mm thickness (<1% X/X_0)**
  - **R: 20-30 cm**
  - **Probability: pC / pp , γ-conversion(1E-3)**
  - **Tiny influence to conventional performance**
- **Position : in-between the tracking devices**
  - **Appliable in all reactions: ee/ep/pp/pA/AA**
  - **Appliable in high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

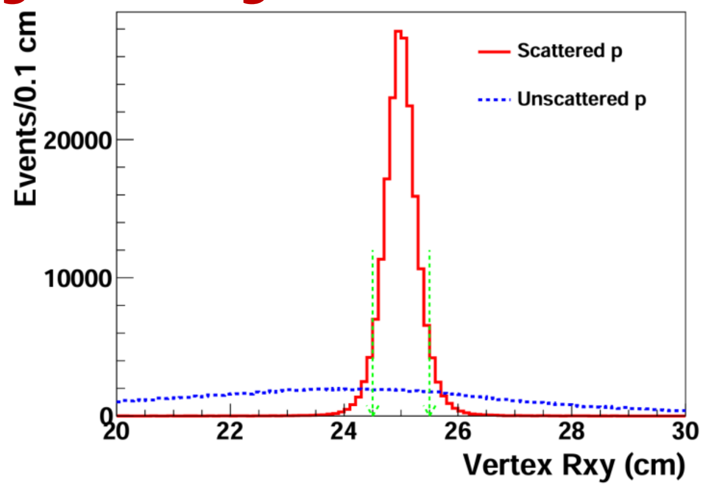
Yutie Liang, et. al., Phys. Rev. D 112, L031502
NST in press, arXiv: 2512.02804
NST in press, arXiv: 2601.21325

Precision measurement of proton polarization

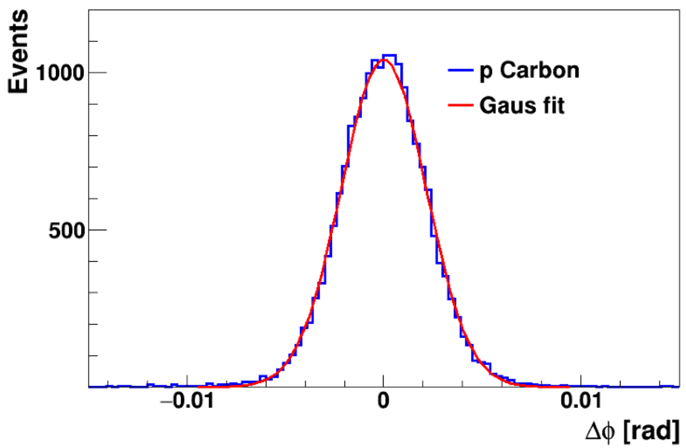


Signature of signal/background

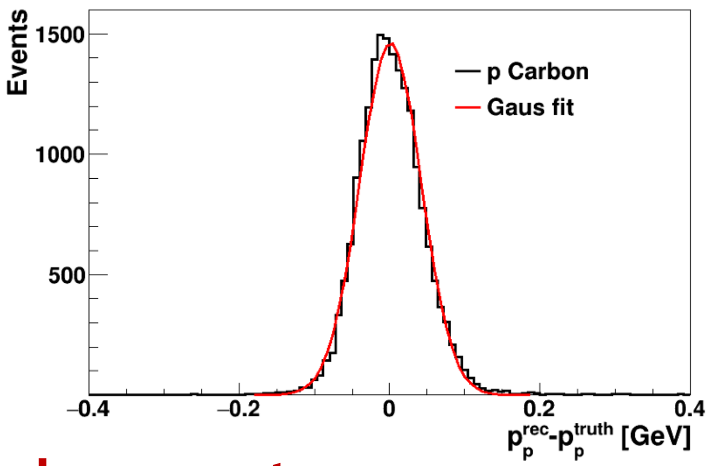




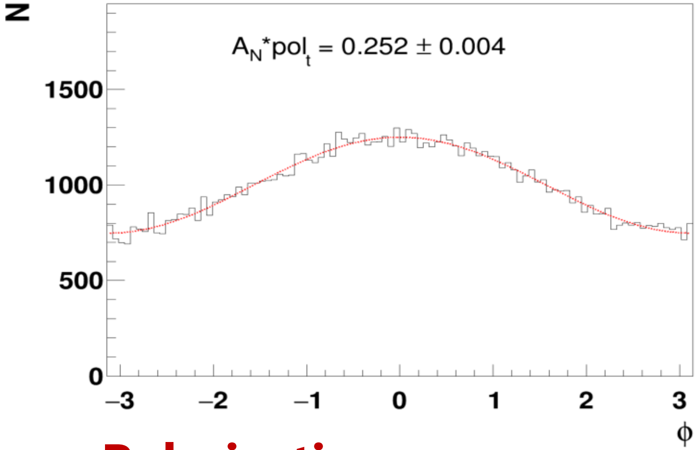
$\sigma = 2.16$ mrad



$\sigma = 0.041$ GeV



Input: 0.250

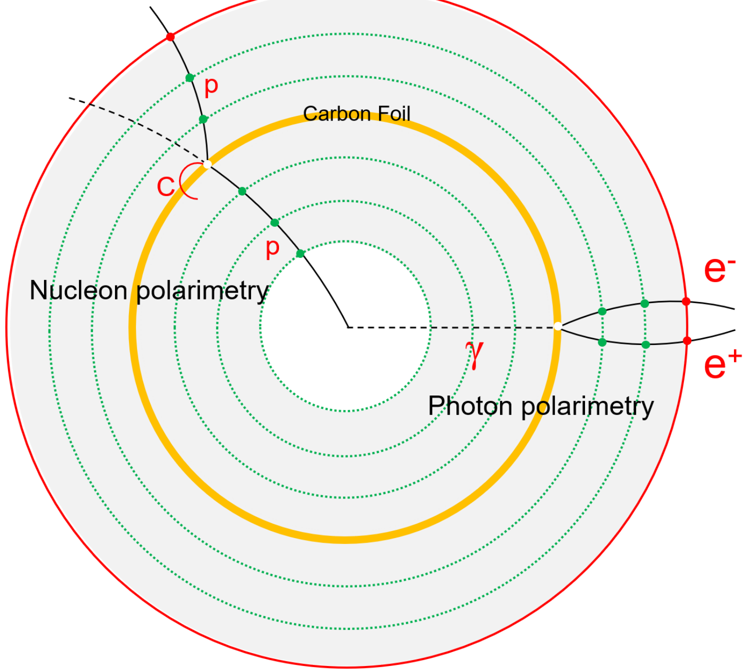


Measuring track segments

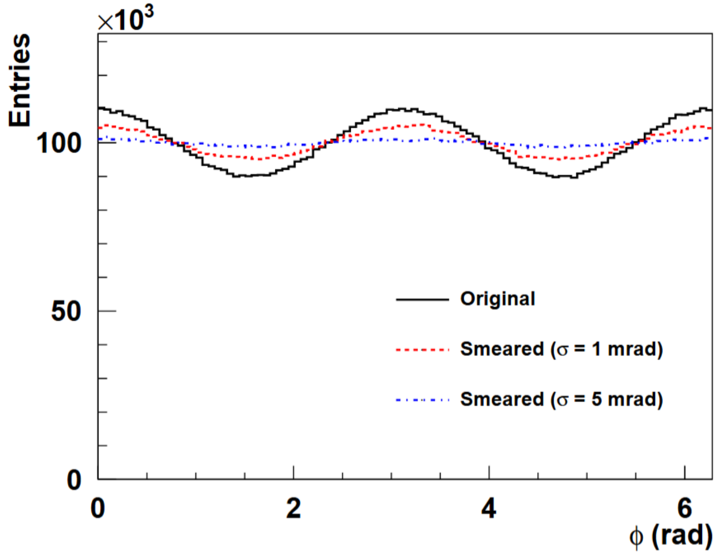
Polarization measurement

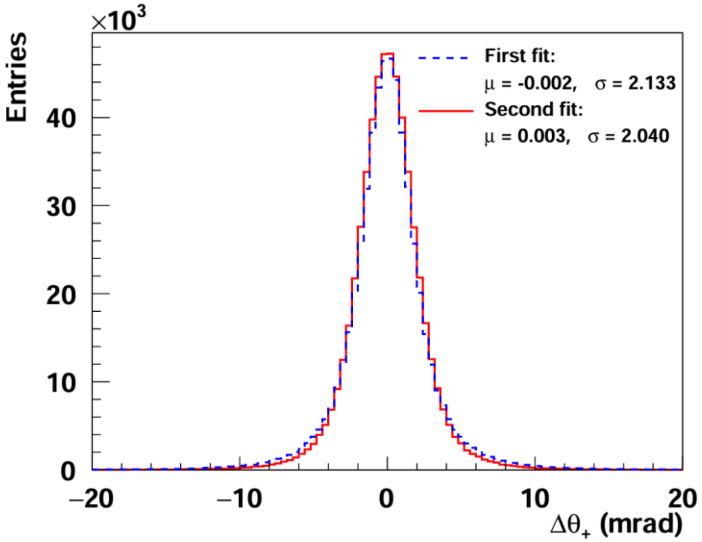
NST in press, arXiv: 2512.02804

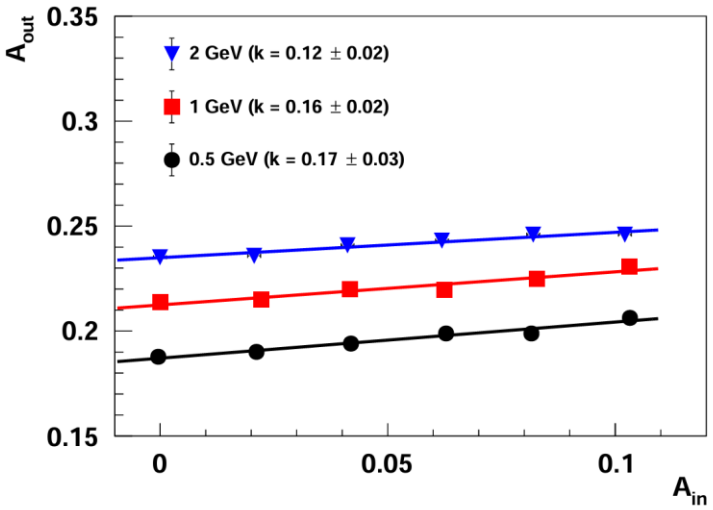
Measurement of photon polarization



$A\_out = \mathbf{f(E_\gamma, \theta_\gamma, \ldots)}\ A\_in$







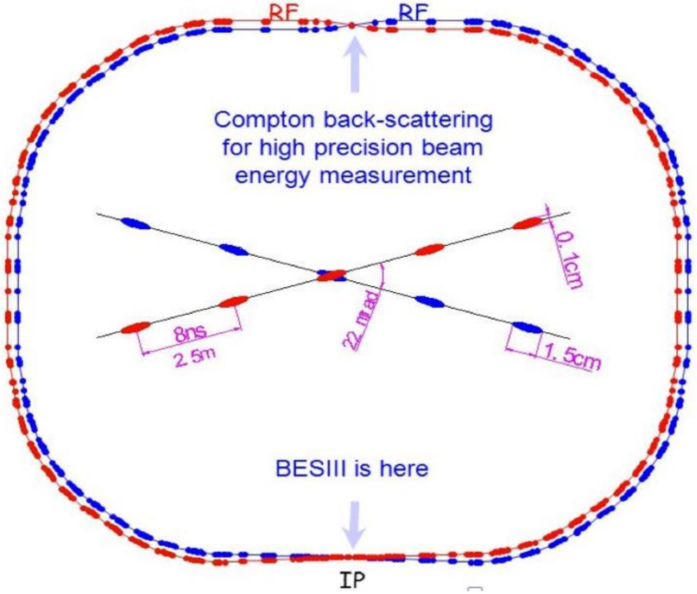
- ✓ A_out differs from A_in
- ✓ A dilution table can be compiled
- ✓ The slope amplifies uncertainty

arXiv: 2601.21325, NST in press

Validation and application at BESIII

- **Polarized proton at BESIII**
- Validation of the concept
- Application at BESIII

BEPCII storage rings: a tau-charm factory



e^+e^- collider, First collisions July 2008

Beam energy : 0.92 - 2.475 GeV

Crossing angle: 11 mrad

Beam energy measurement: $\Delta E/E \sim 5*10^{-5}$

Design Luminosity: $1*10^{33}$ $cm^{-2}s^{-1}$

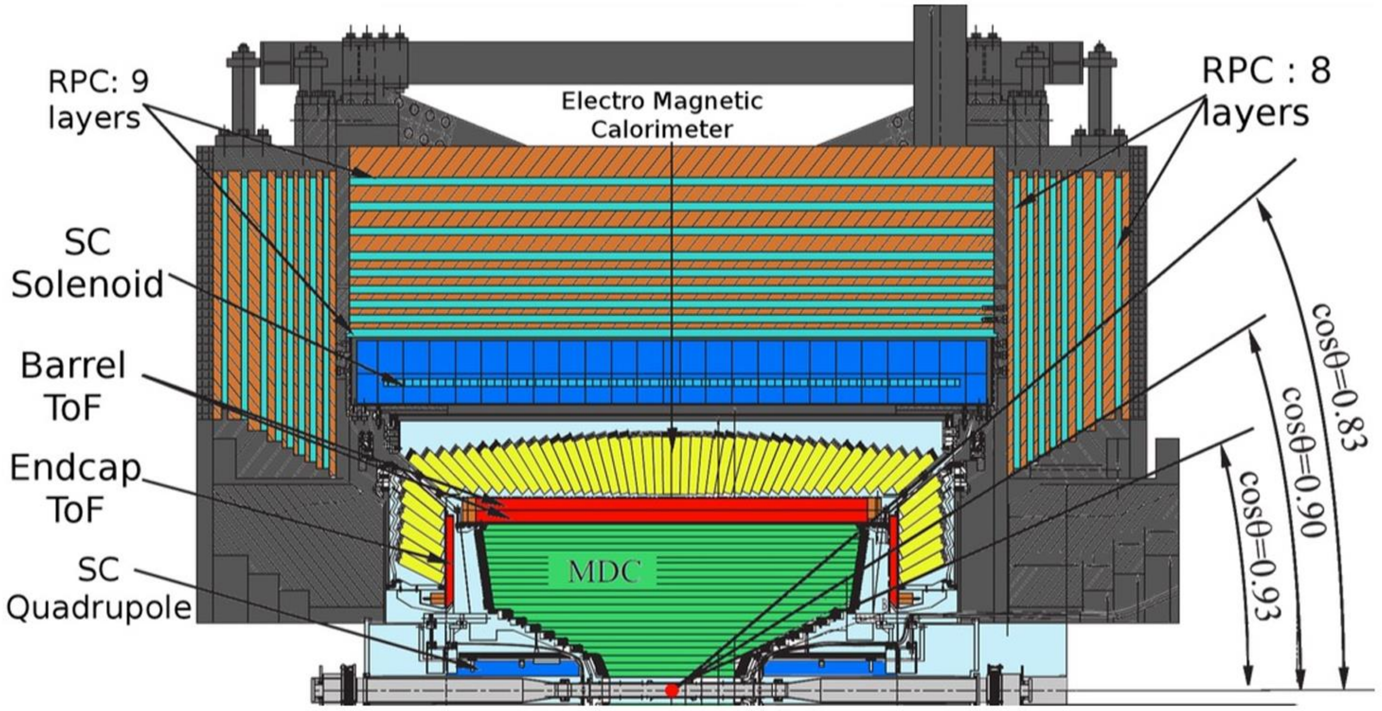
Achieved: $1.1*10^{33}$ $cm^{-2}s^{-1}$

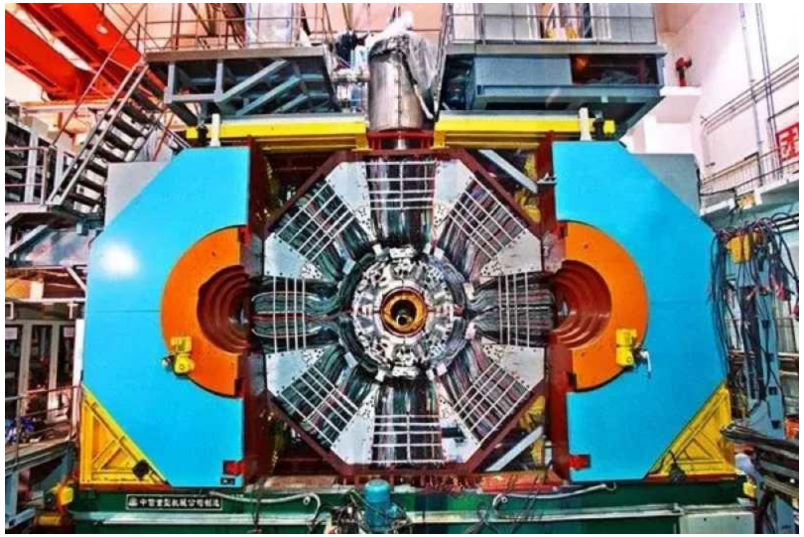
Original unpolarized e^+ e^- beam

~10-20% (average) transverse polarization

due to self-polarization

BESIII detector





- Main Drift Chamber (MDC)
  - $\sigma(p)/p = 0.5\%$
  - $\sigma_{dE/dX} = 5.0\%$
- Time-of-flight (TOF)
  - $\sigma(t) = 68ps$ (barrel)
  - $\sigma(t) = 65ps$ (endcap)
- Electro Magnetic Calorimeter (EMC)
  - $\sigma(E)/E = 2.5\%$
  - $\sigma_{z,\phi}(E) = 0.5 – 0.7$ cm
- RPC MUON Detector
  - $\sigma(xy) < 2$ cm

Polarized proton from hyperon decay

General Partial Wave Analysis of the Decay of a Hyperon of Spin ½

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:

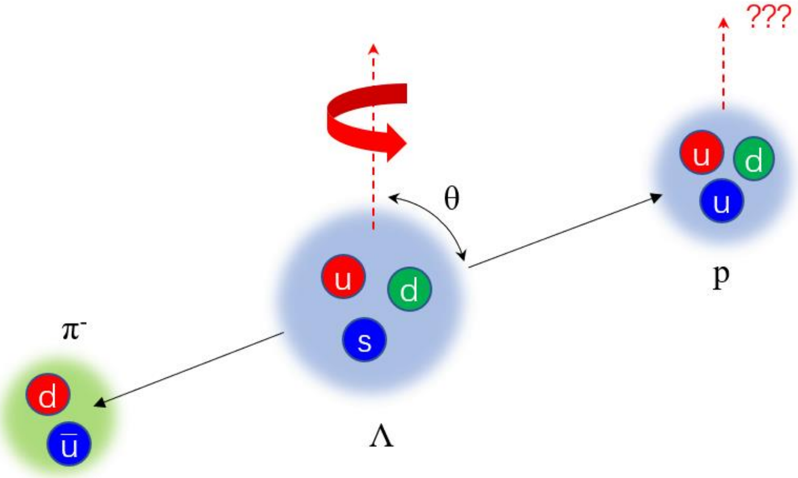
$$\mathcal{A} \sim S\sigma_0 + P\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}$$

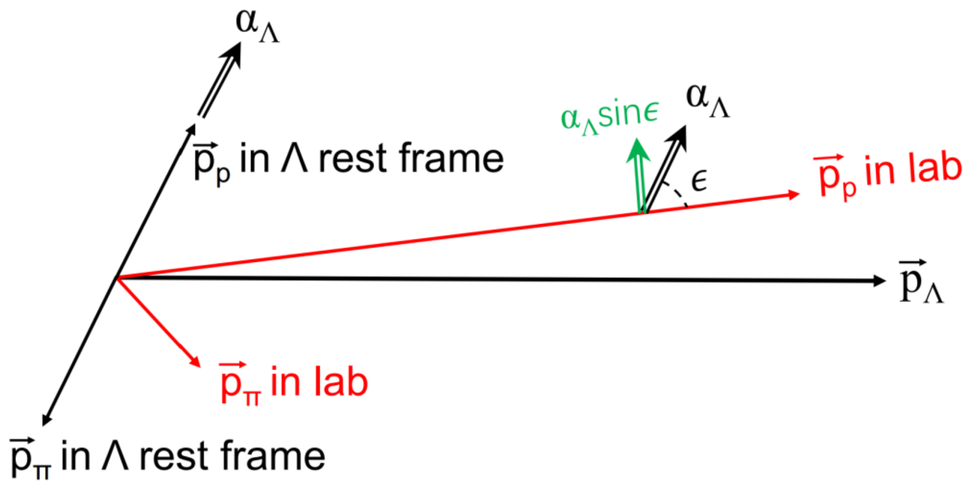
The decay parameters are defined as:

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

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

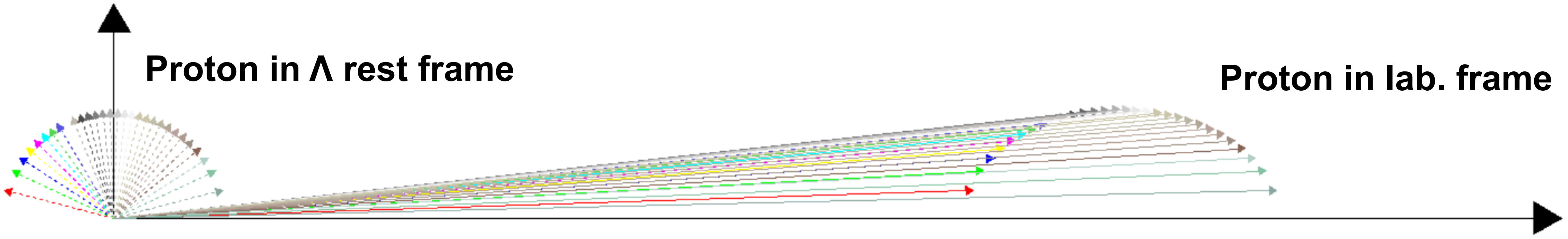
$$\boldsymbol{P}_p = \frac{(\alpha+\boldsymbol{P}_\Lambda\cdot\hat{\boldsymbol{q}})\hat{\boldsymbol{q}} + \beta(\boldsymbol{P}_\Lambda\times\hat{\boldsymbol{q}}) + \gamma(\hat{\boldsymbol{q}}\times[\boldsymbol{P}_\Lambda\times\hat{\boldsymbol{q}}])}{1+\alpha\boldsymbol{P}_\Lambda\cdot\hat{\boldsymbol{q}}}$$

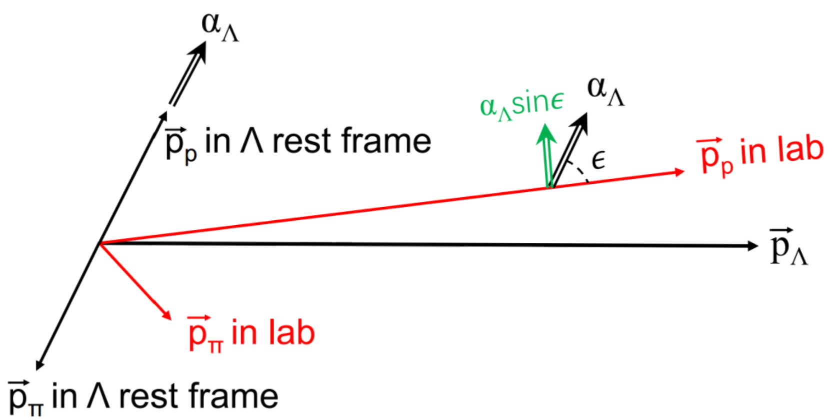


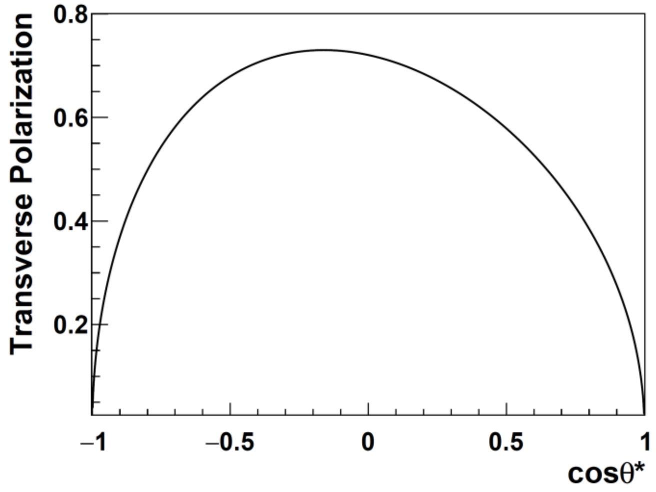


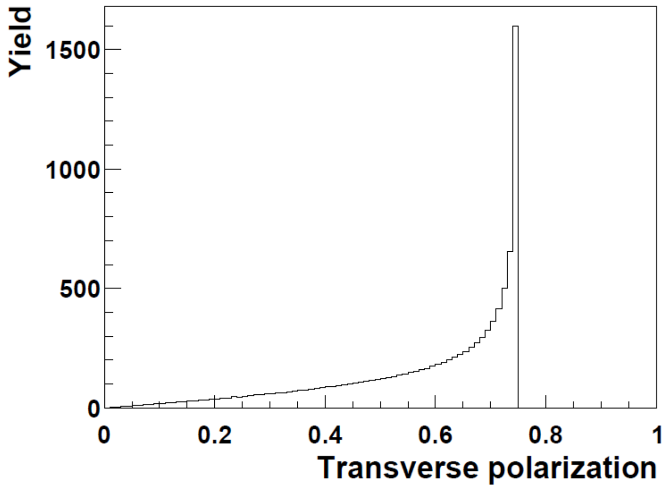
T. D. Lee, C. N. Yang Phys. Rev. 108,1645 (1957)

Polarized proton from hyperon decay









- Transverse polarization of proton from Λ decay: Pol_t ~ 0.59
  - Λ unpolarized
  - relativistic effect taken into account

Polarized proton from Λ decay

The Fermilab Polarized Beam Facility*

D. P. Grosnick†
High Energy Physics Division
Argonne National Laboratory
Argonne, IL 60439

ANL-HEP-CP--90-103
DE91 006556

Abstract

A description[1] of the Fermilab 200-GeV/c polarized beam is presented, including the production, transport, and spin rotation of the polarized protons and antiprotons. The momentum and polarization of each beam particle is measured by a beam-tagging system. Verification of the beam polarization and of the beam-tagging method is given by two polarimeters. A brief summary of the E-704 experimental program using the polarized beam is also presented.

A. The Polarized Beam

The polarized proton beam is produced from the parity-nonconserving decay, $\Lambda^0 \to p + \pi^-$. As viewed in the Λ rest frame, the proton spin is aligned in the same direction as the proton's momentum. For unpolarized Λ particles, the polarization of the proton has been measured[2] to be ~~64~~%. This value comes from the interference of S and P-wave amplitudes.
75%

As shown in Fig. 1, an 800-GeV incident proton beam from the Tevatron hits a beryllium target and produces many particles in the collision, including both Λ and $\bar{\Lambda}$ hyperons. The unpolarized Λ particles then decay some distance downstream from the target. In the laboratory frame, the proton trajectory from this decay can be traced back to the plane of the target. The protons then appear to originate from a virtual source at the target. A correlation exists between the transverse distance from the target and the proton trajectory, which in turn is correlated to the proton spin direction. The correlation between the horizontal transverse distance from the target and the proton polarization is shown in Fig. 2. Protons with the same transverse spin component appear to originate

1

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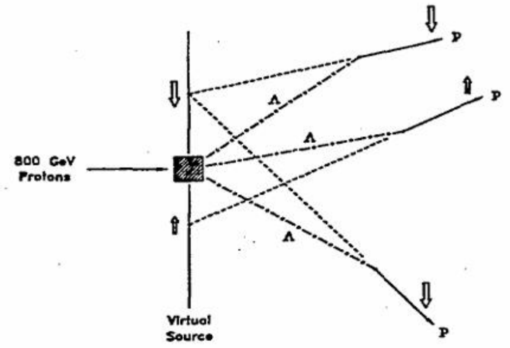


Figure 1: Diagram of the production target and Λ decays, showing the virtual source of polarized protons.

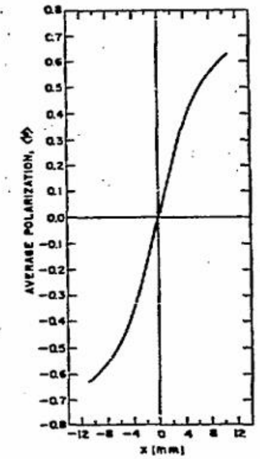


Figure 2: Correlation between the average particle polarization and the horizontal position.

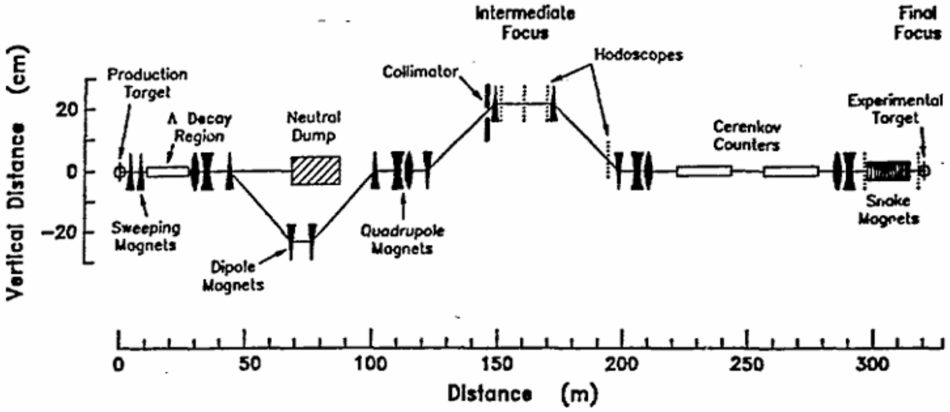
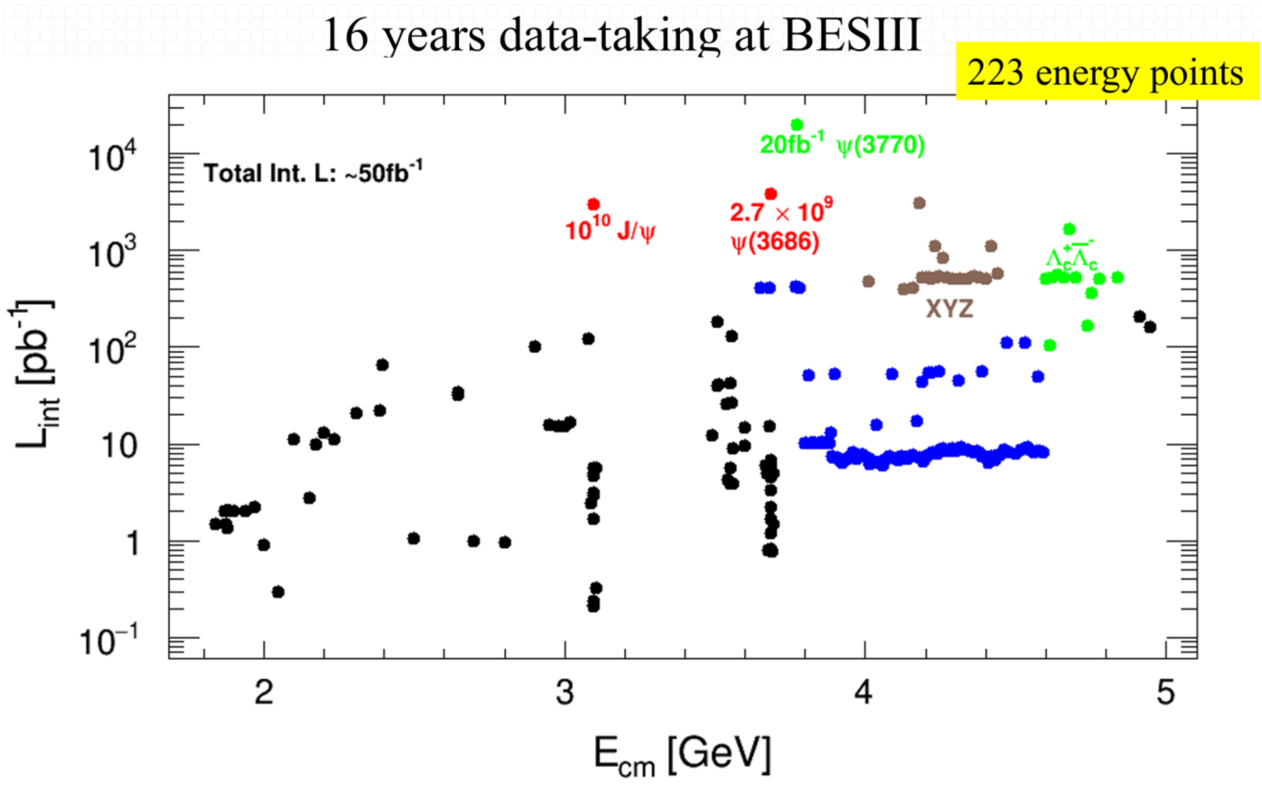


Figure 4: Side view of the Fermilab polarized beam line.

Hyperon pairs at BESIII



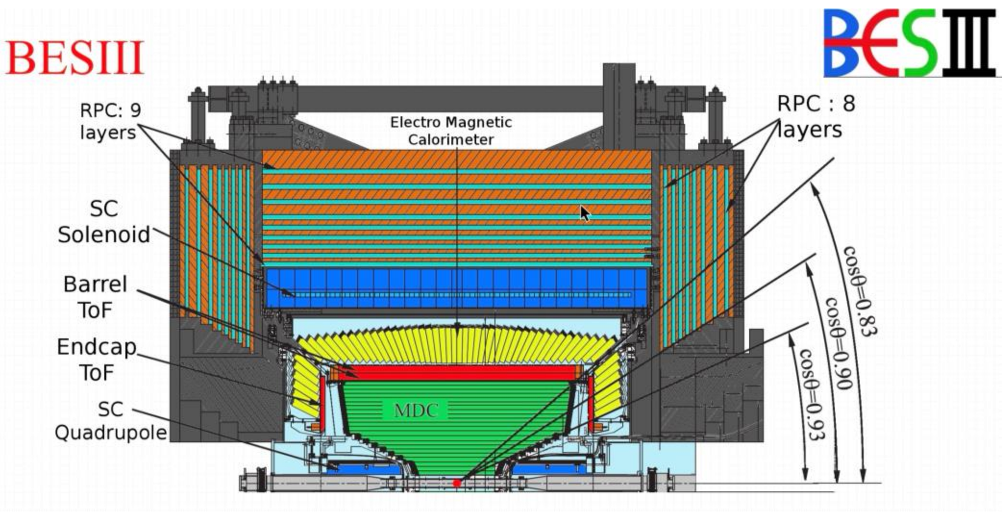
Hyperon pairs at BESIII

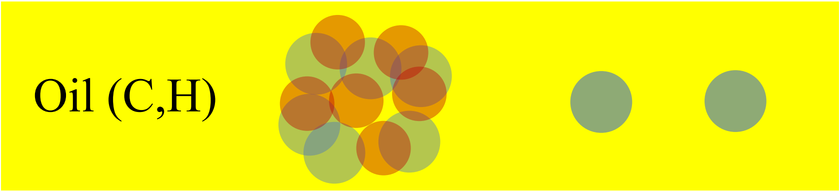
Decay	$\mathcal{B}$ (10^{-5})	Events at BESIII
$J/\psi \to \Lambda\bar{\Lambda}$	189 ± 9	18.9×10^6
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	150 ± 24	15.0×10^6
$J/\psi \to \Xi\bar{\Xi}$	97 ± 8	9.7×10^6
$\psi(2S) \to \Sigma\bar{\Sigma}$	23.2 ± 1.2	116×10^3
$\psi(2S) \to \Omega\bar{\Omega}$	5.66 ± 0.30	28×10^3

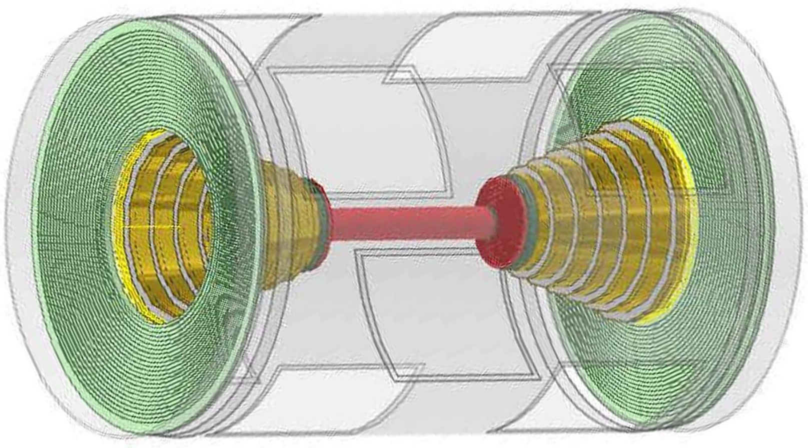
Validation and application at BESIII

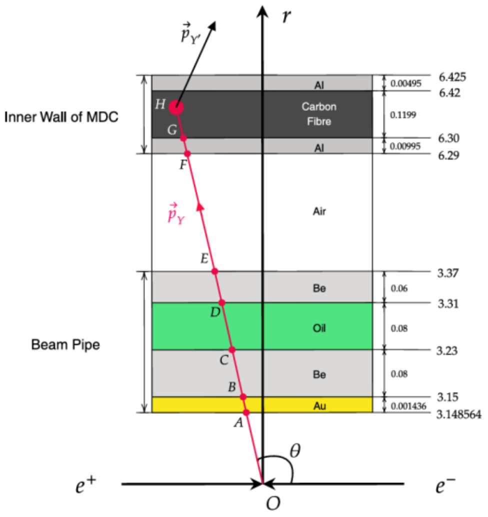
- Polarized proton at BESIII
- **Validation of the concept**
- Application at BESIII

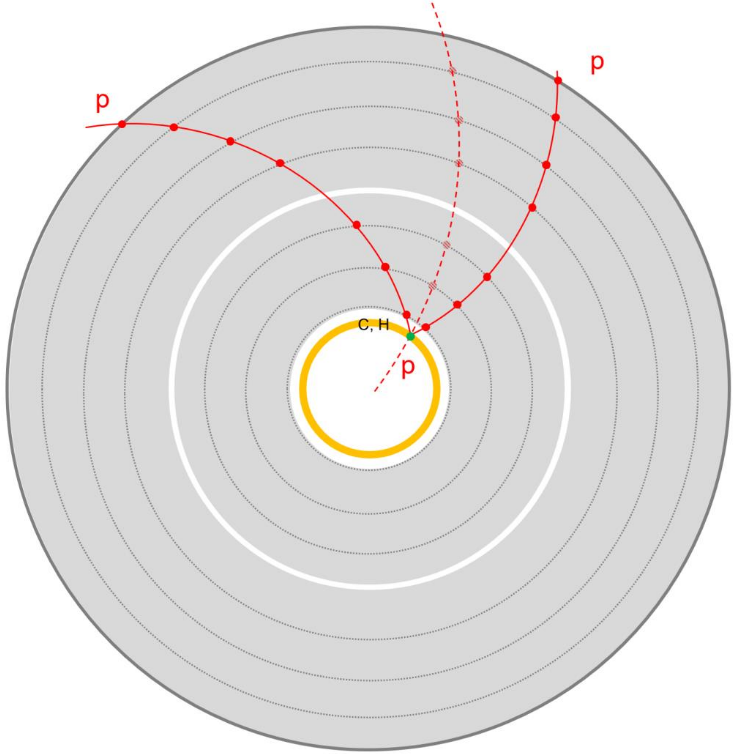
Validation of proton polarimetry at BESIII



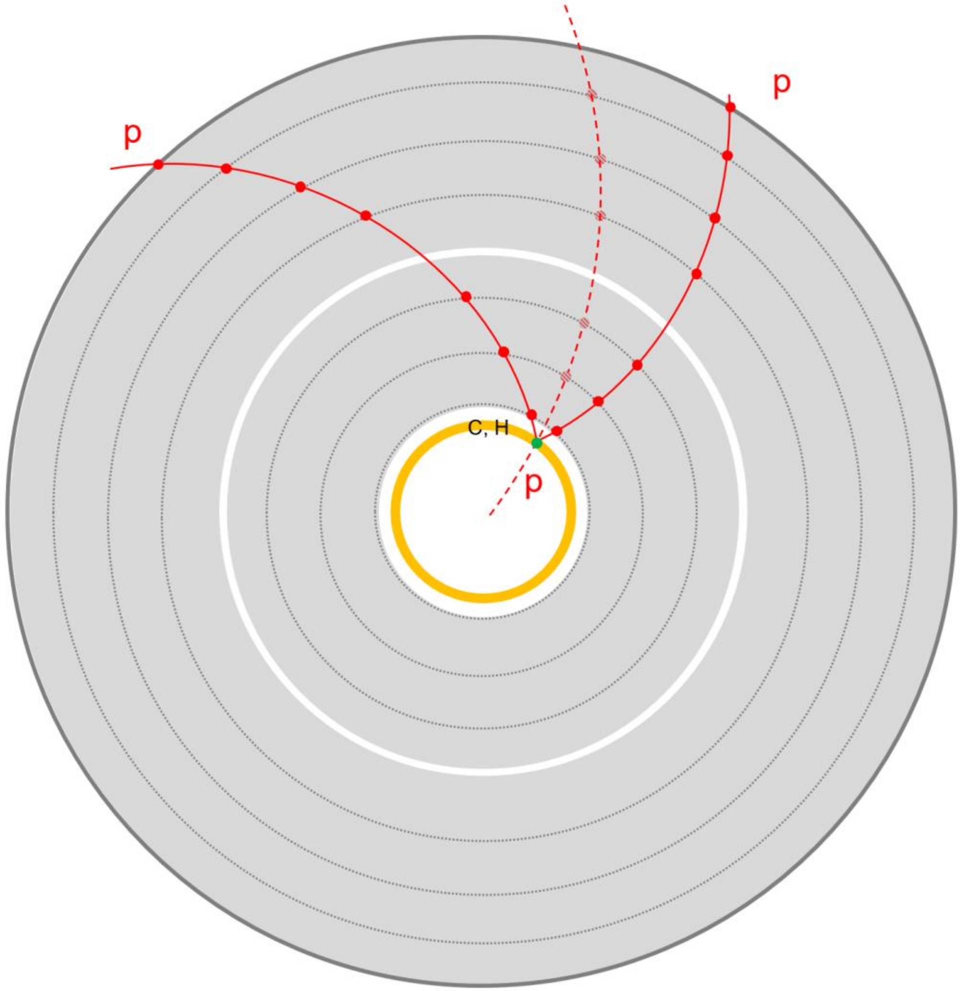




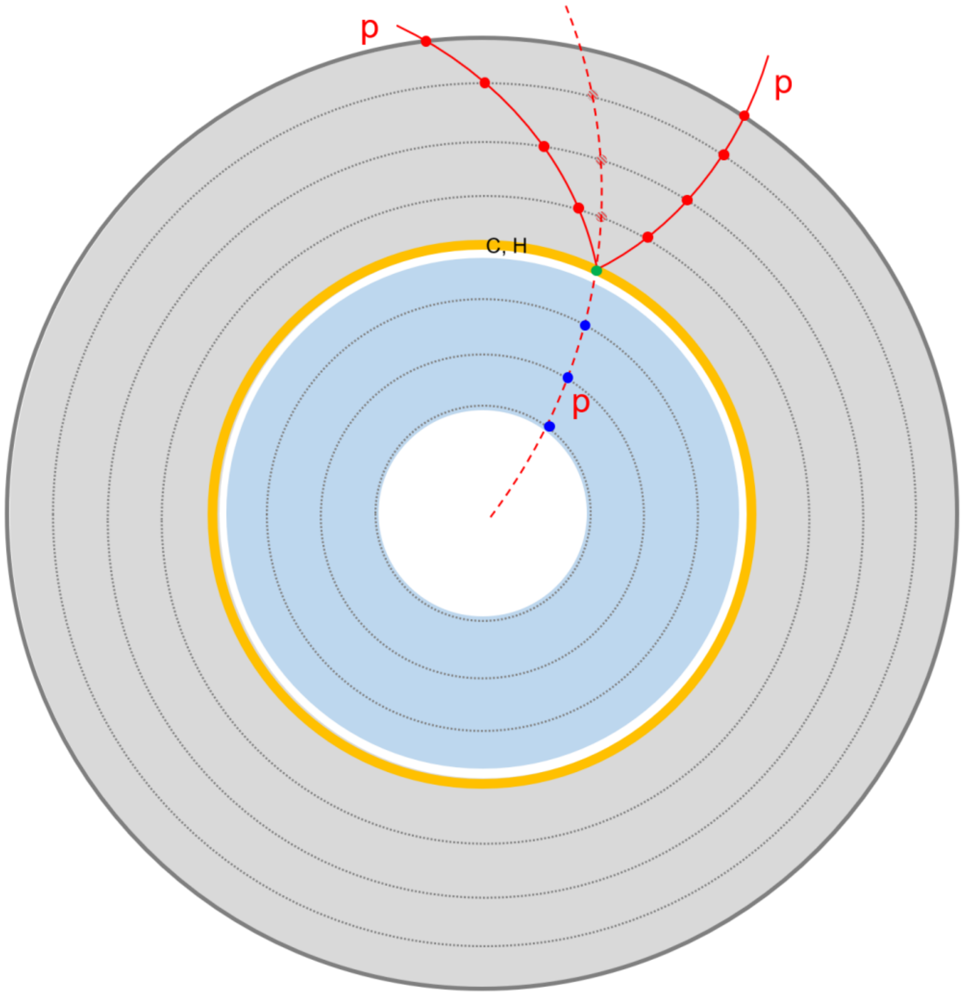




Comparison of two configurations

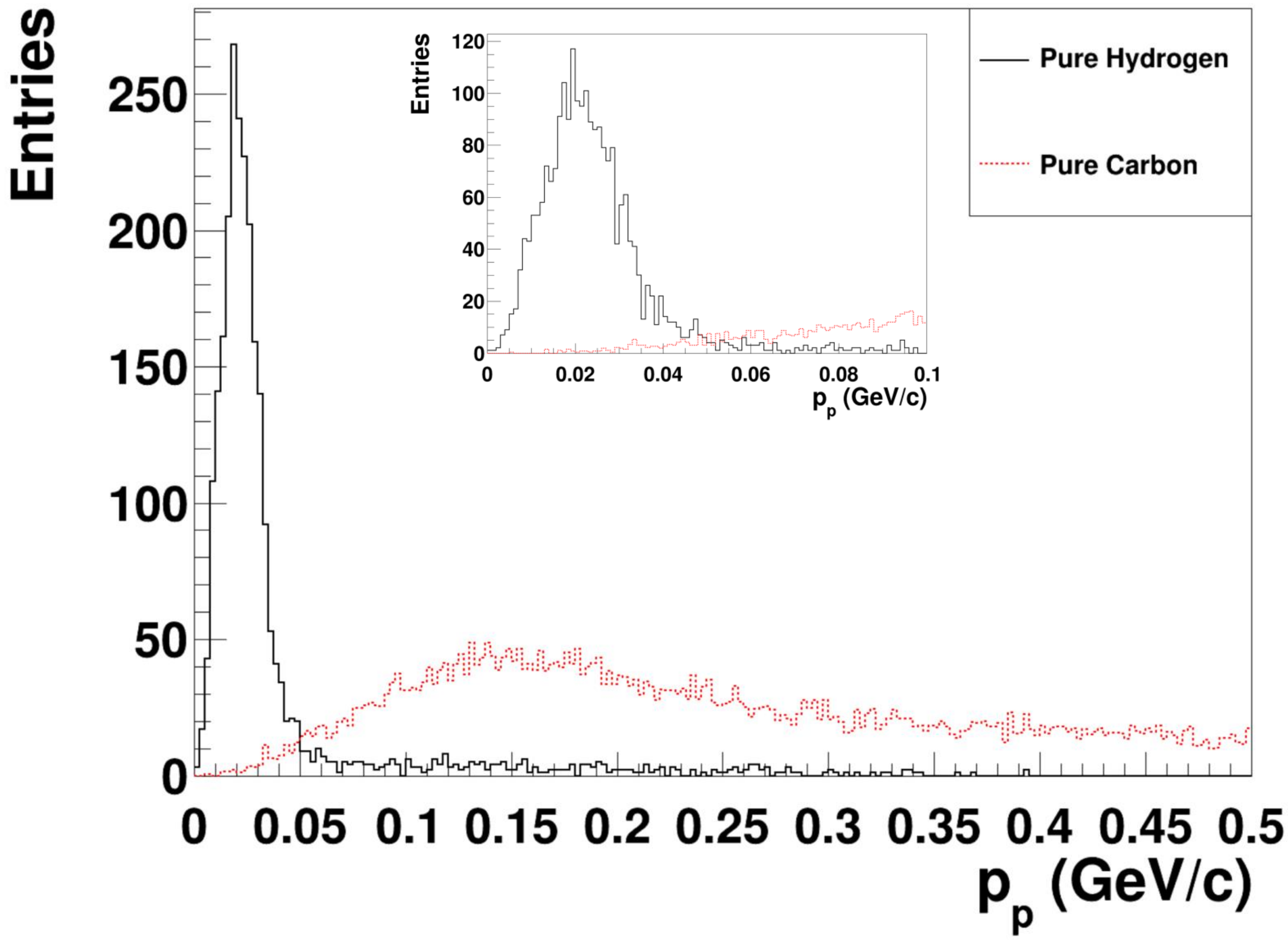


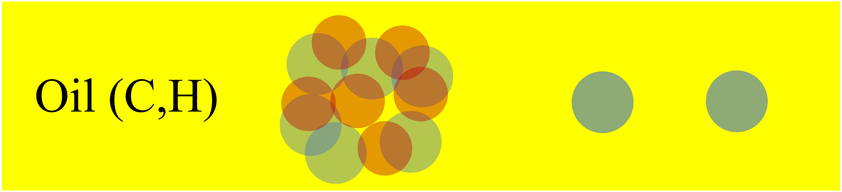
Only pp elastic scattering, only exclusive processes.



pC scattering possible, inclusive possible

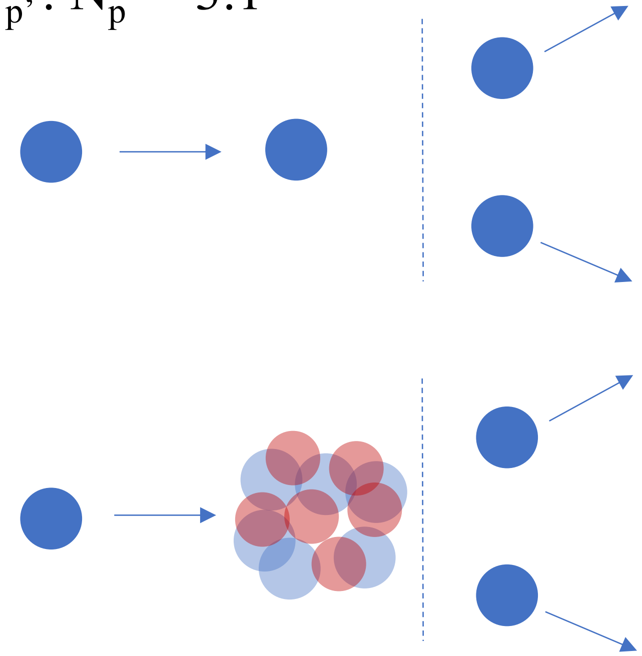
Signature of proton in Oil



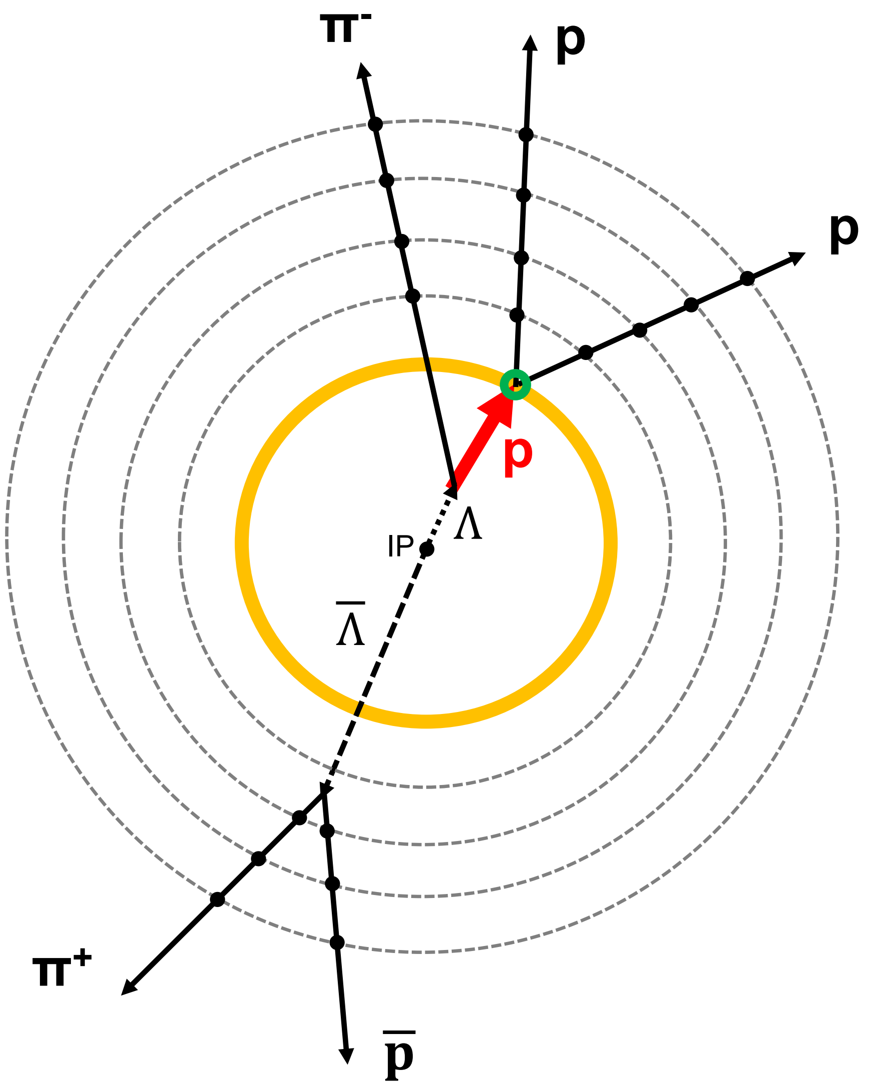


$N_C : N_H \sim 1:2$

$N_{p'} : N_p \sim 3:1$



Validation of proton polarimetry at BESIII



- **Polarized proton from Λ decay:**
  $\mathrm{J}/\psi \rightarrow \Lambda\bar{\Lambda} \rightarrow \pi^-\, p\;\; \pi^+\, \bar{p}$

- **Polarized proton scattering off a proton:**
  pp → pp indicated by the red arrow,
  with transverse polarization of 59%, scattered before entering tracking detector.

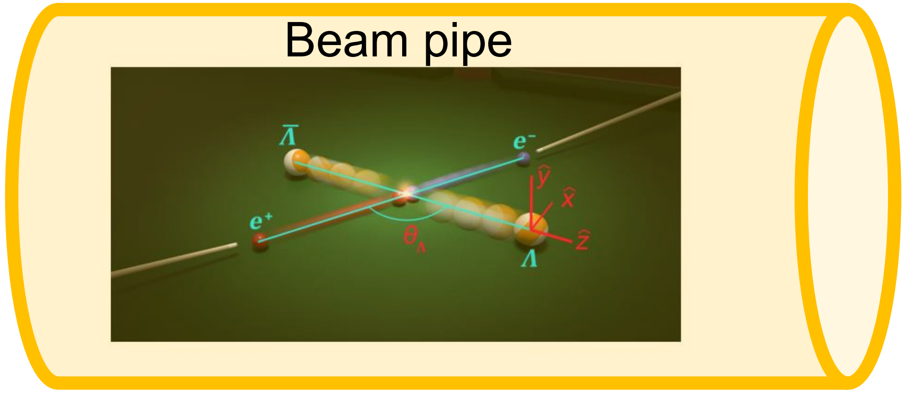
- **Five final state particles: π^+ $\bar{p}$ π^- p p** are measured by the detector.

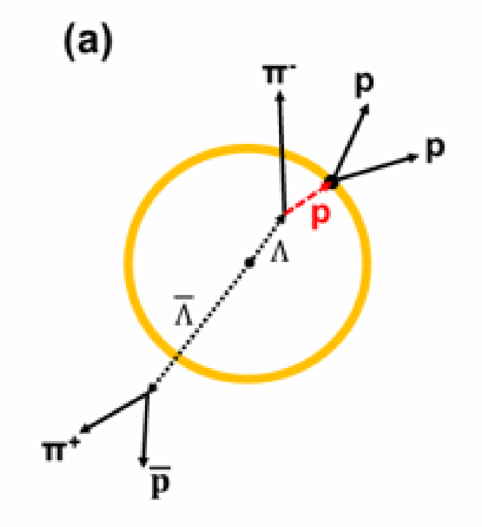
- The unmeasured proton: its four momentum $\vec{p}$ is deduced by the four-momentum constraint:

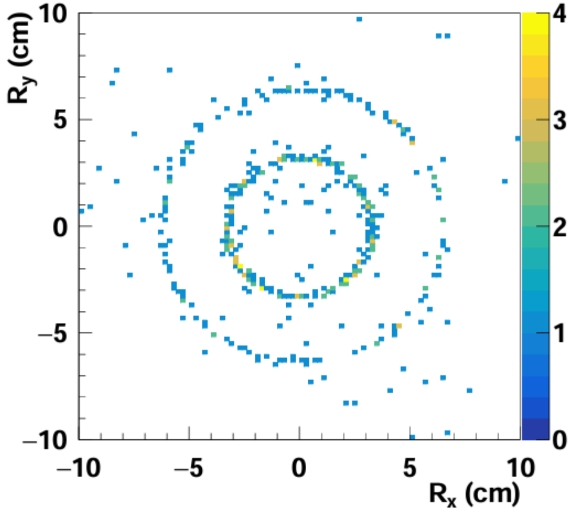
  $$\vec{p} = \overrightarrow{e^+} + \overrightarrow{e^-} - \overrightarrow{\pi^+} - \vec{\bar{p}} - \overrightarrow{\pi^-}$$

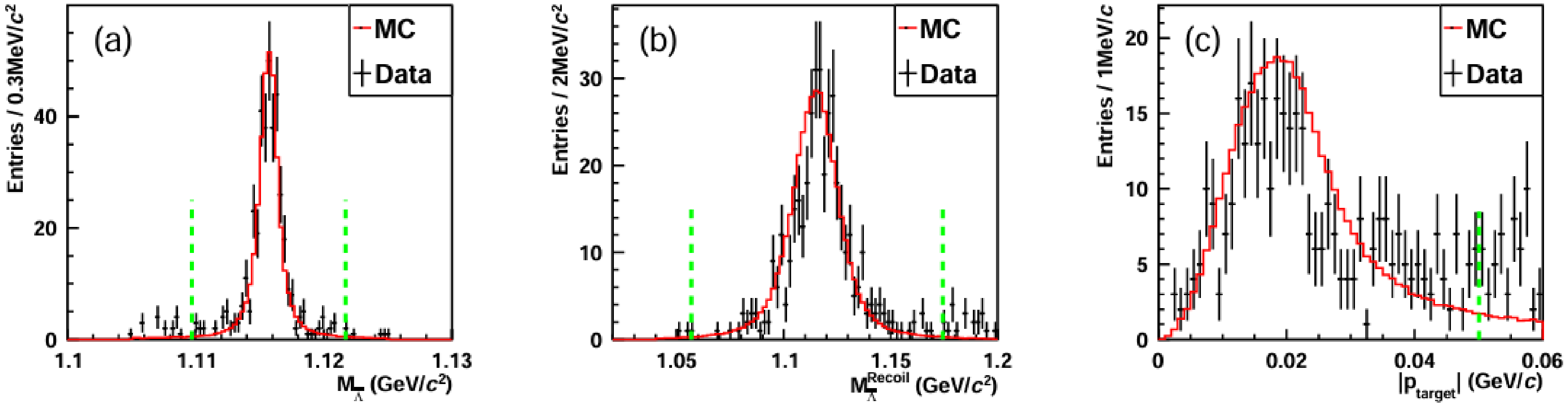
- pp scattering vertex, indicated by green circle, is calculated by VertexFit.

Validation of proton polarimetry at BESIII





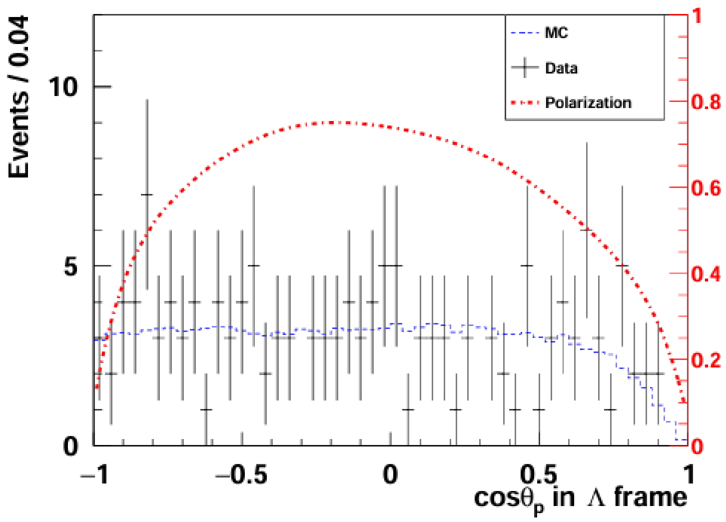


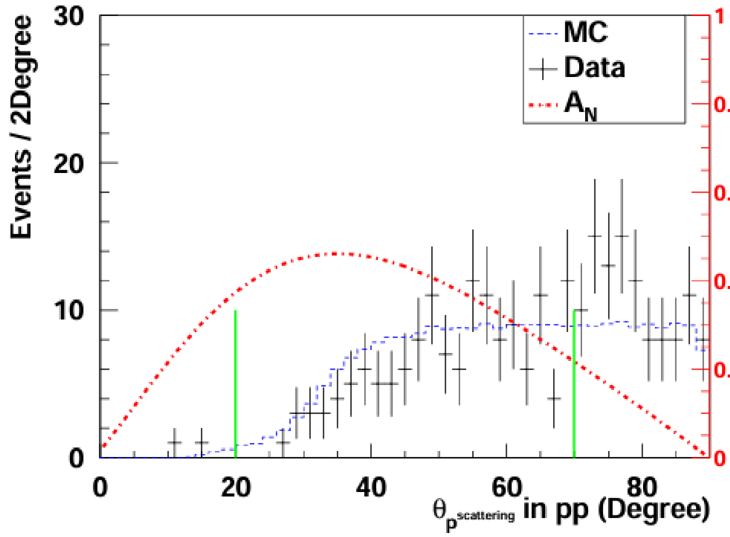


arXiv: 2607.19927

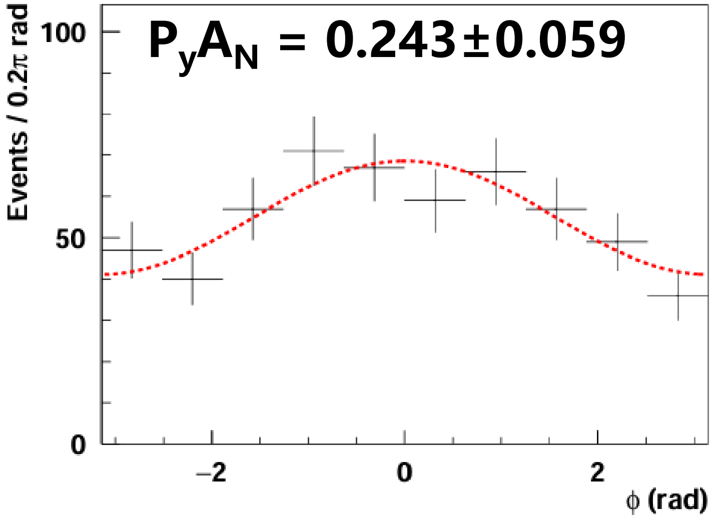
Validation of proton polarimetry at BESIII

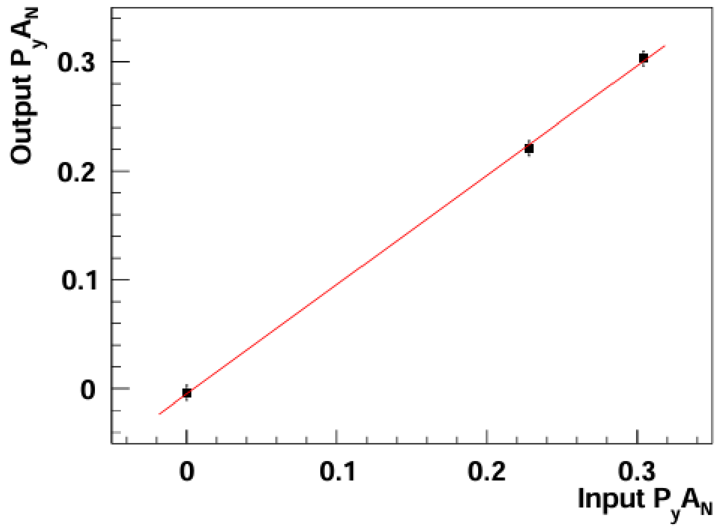
arXiv: 2607.19927 BESIII





→ expected
P_yA_N = 0.22±0.01



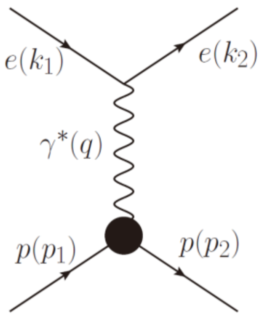


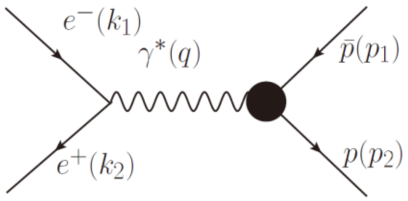
→ measured
P_yA_N = 0.243±0.059

Validation and application at BESIII

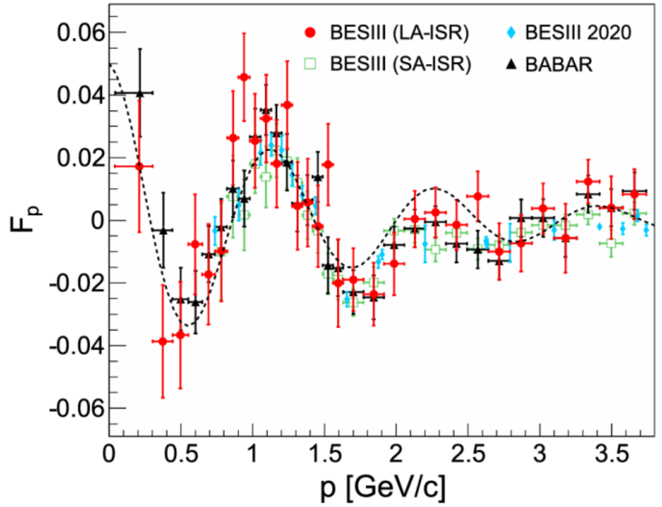
- Polarized proton at BESIII
- Validation of the concept
- **Application at BESIII**

Time-like EMFF of baryon





$$\frac{d\sigma_{p\bar{p}}(s)}{d\Omega} = \frac{\alpha^2 \beta C}{4s}\left[|G_M(s)|^2(1+\cos^2\theta) + \frac{4m_p^2}{s}|G_E(s)|^2\sin^2\theta\right]$$



BESIII, Phys. Rev. Lett. **124**, 042001(2020)
BESIII, Nature Physics, **17**, 1200–1204 (2021)
…

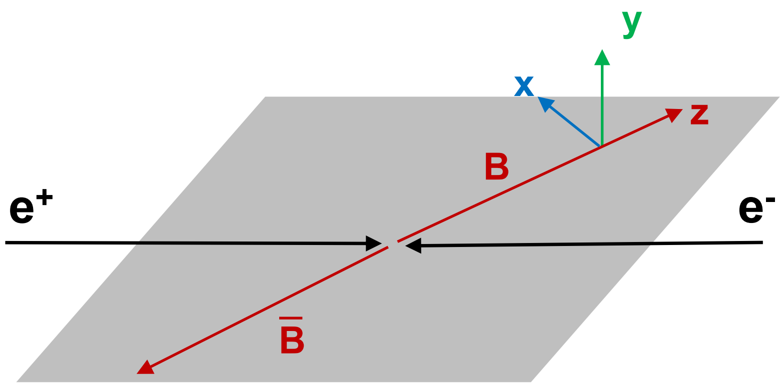
✓ **Nucleon time-like form factors G_E/G_M**

- Absolute value of G_E,G_M can be obtained from the cross-section measurement
- Relative phase **$\Delta\Phi$ = $\Phi_M - \Phi_E$**, is linked to the polarization of final state baryon: P_x P_y

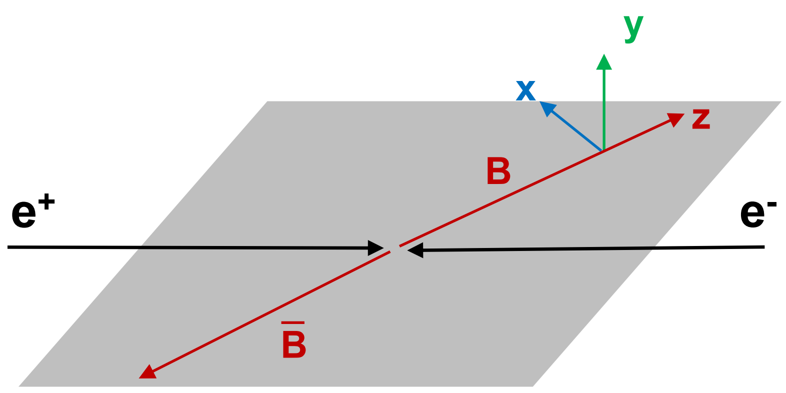
$$\mathcal{P}_y = \frac{\sin 2\theta_p \Im\left[G_E G_M^*\right]}{\sqrt{\tau}\mathcal{D}},$$

$$\mathcal{P}_x = \mathcal{P}_e \frac{\sin\theta_p \Re\left[G_E G_M^*\right]}{\sqrt{\tau}\mathcal{D}},$$

$$\mathcal{P}_z = \mathcal{P}_e \frac{2\cos\theta_p |G_M|^2}{\mathcal{D}},$$



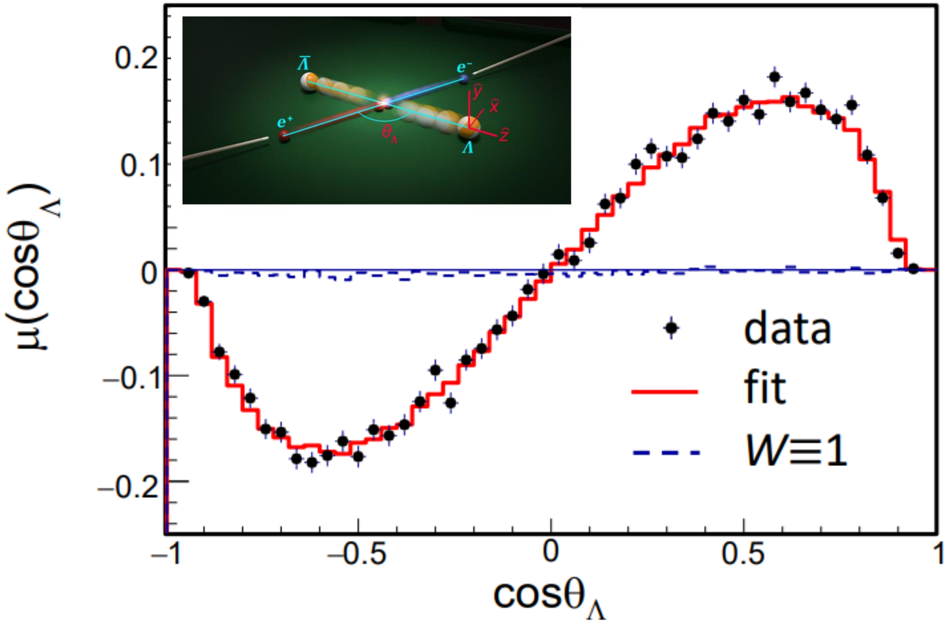
Time-like EMFF of baryon



$e^+e^- \rightarrow B\bar{B}$ pair includes helicity conserving and helicity flip amplitudes. The helicity phase of the time-like form factors **G_E/G_M**, **$\Delta\Phi = \Phi_M - \Phi_E$** is directly linked to the polarization of final state baryons P_y

If $\Delta\Phi$ is not 0, the baryon pair will be **polarized in the direction perpendicular to the production plane**.

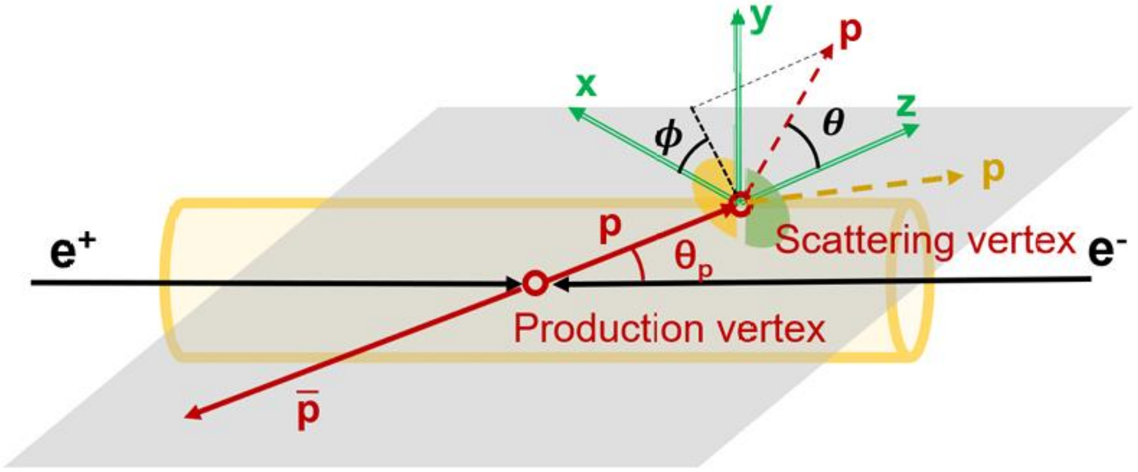
$$\mathcal{P}_y = \frac{\sin 2\theta \,\mathrm{Im}\, G_E^* G_M}{D\sqrt{\tau}}$$

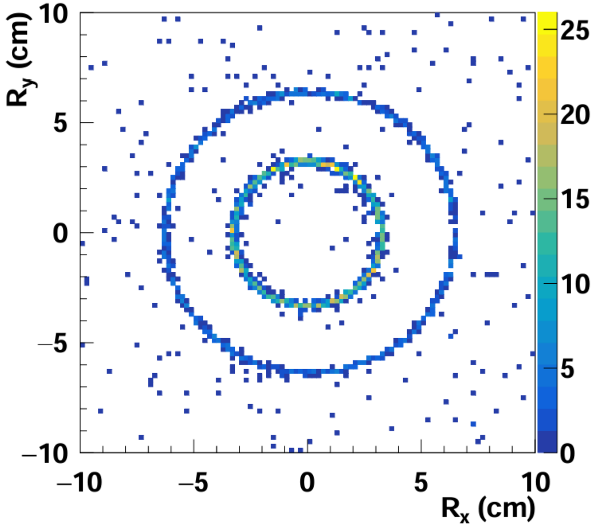


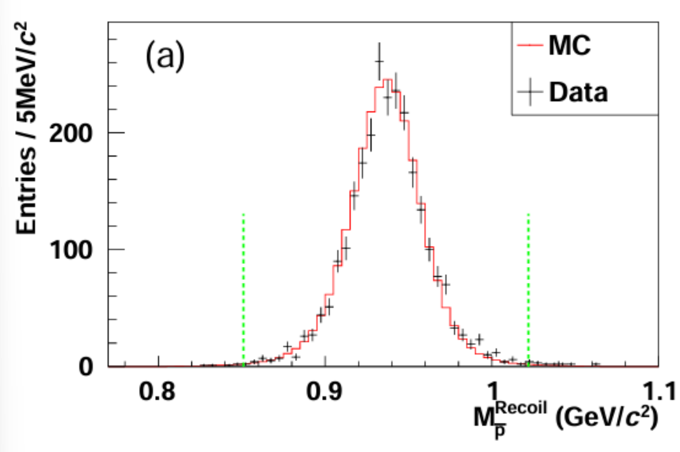
By measuring the polarization of the outgoing baryons, we obtain valuable information on the baryon structure.

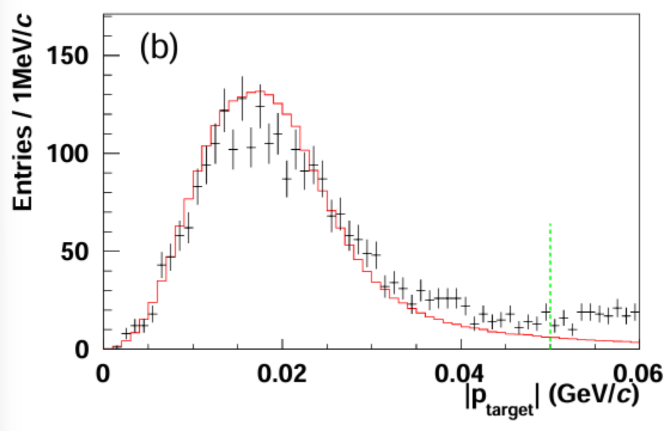
- Hyperons, are easy to measure the polarization with their self-analyzing power.
- For the other baryons, we need a polarimeter to measure the polarization of outgoing baryon.

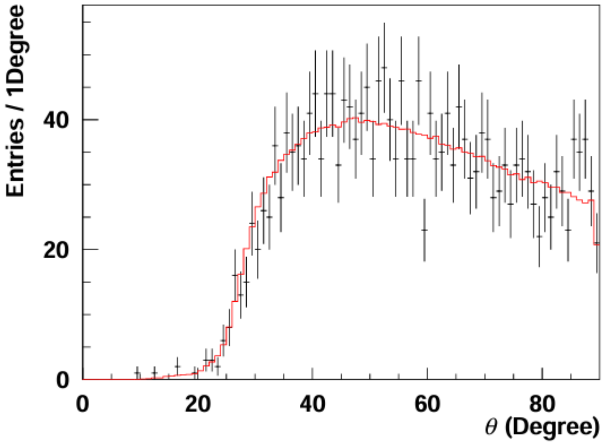
Relative phase between proton Psionic Form Factors





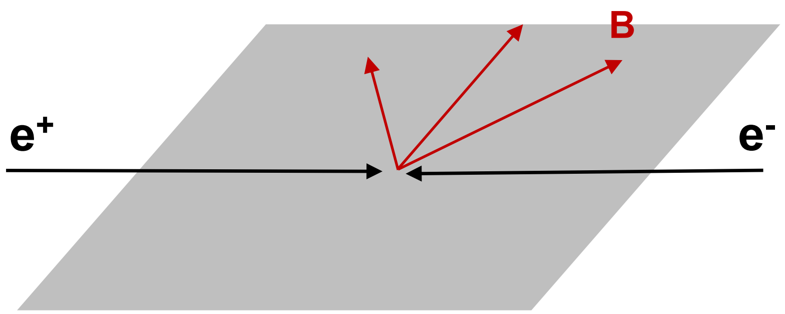


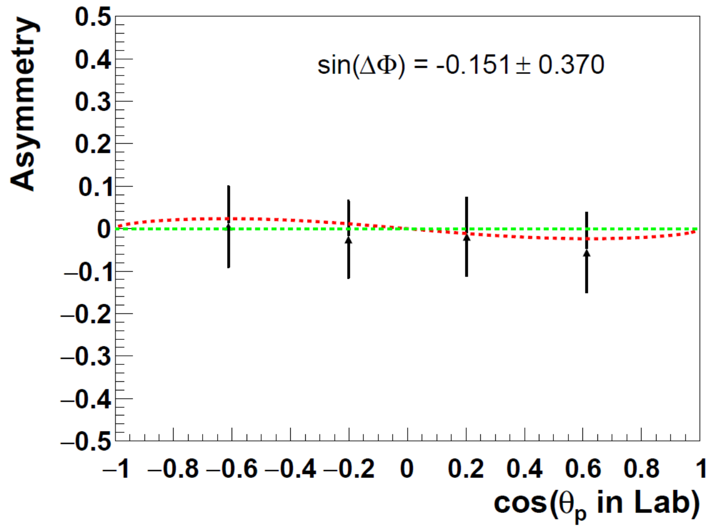


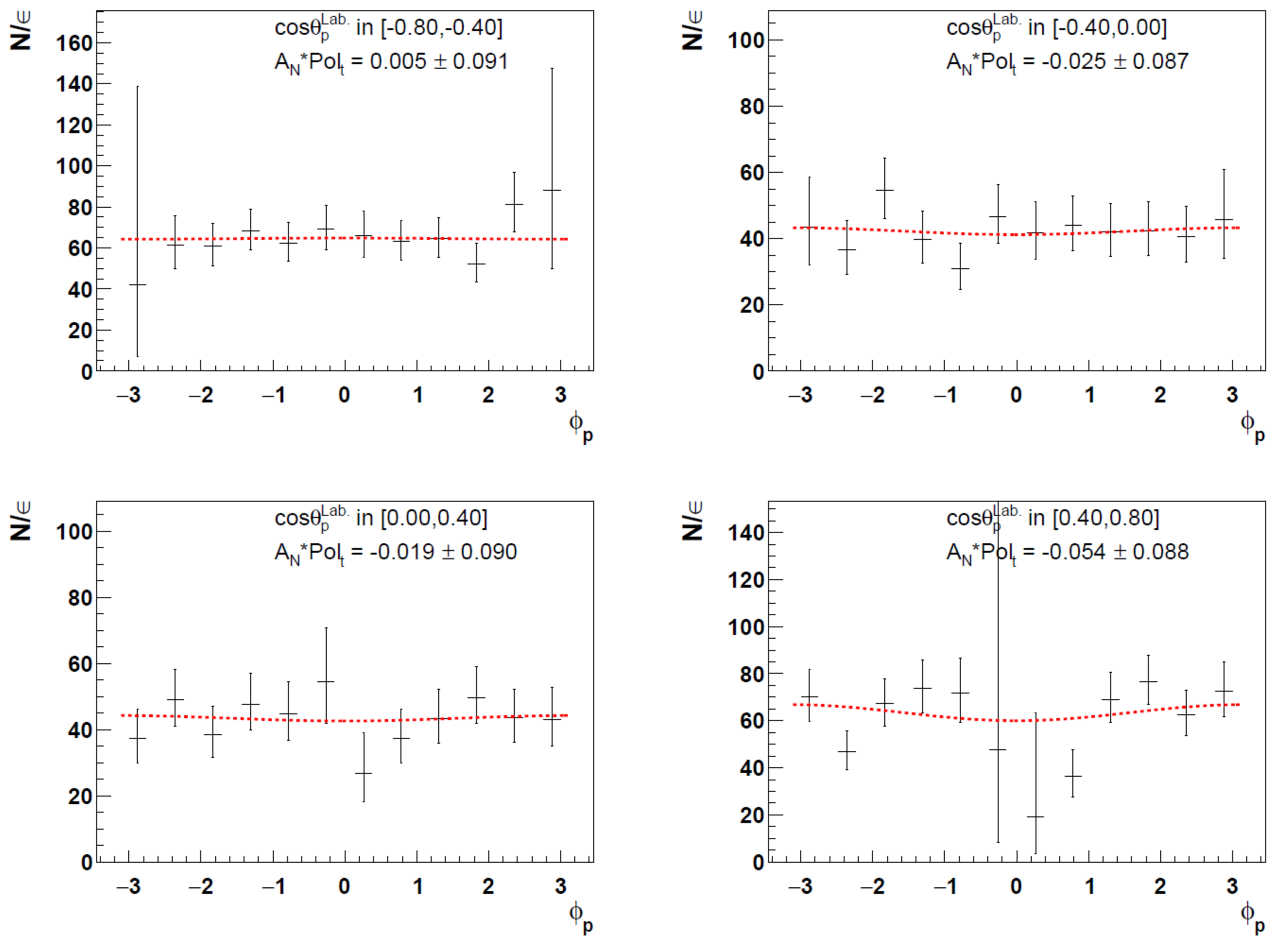


Relative phase between proton Psionic Form Factors

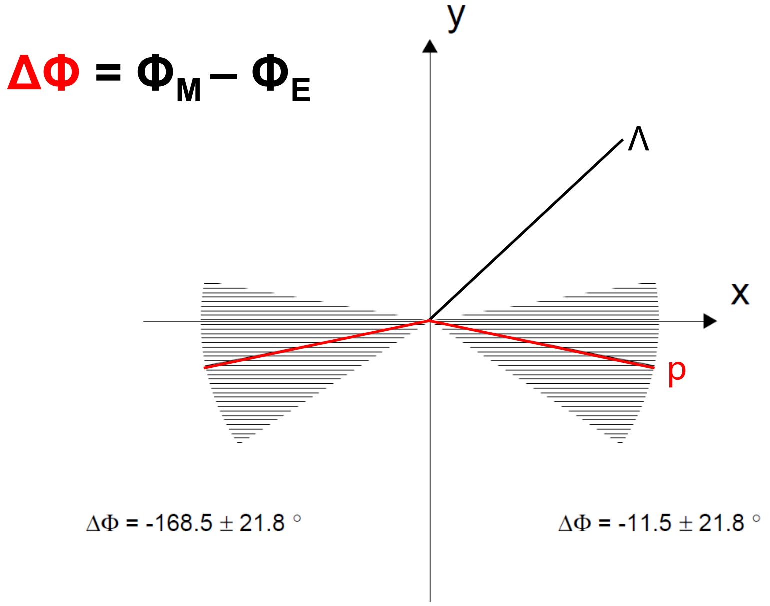
$$\mathcal{P}_y = \frac{\sin 2\theta \,\mathrm{Im}\, G_E^* G_M}{D\sqrt{\tau}}$$

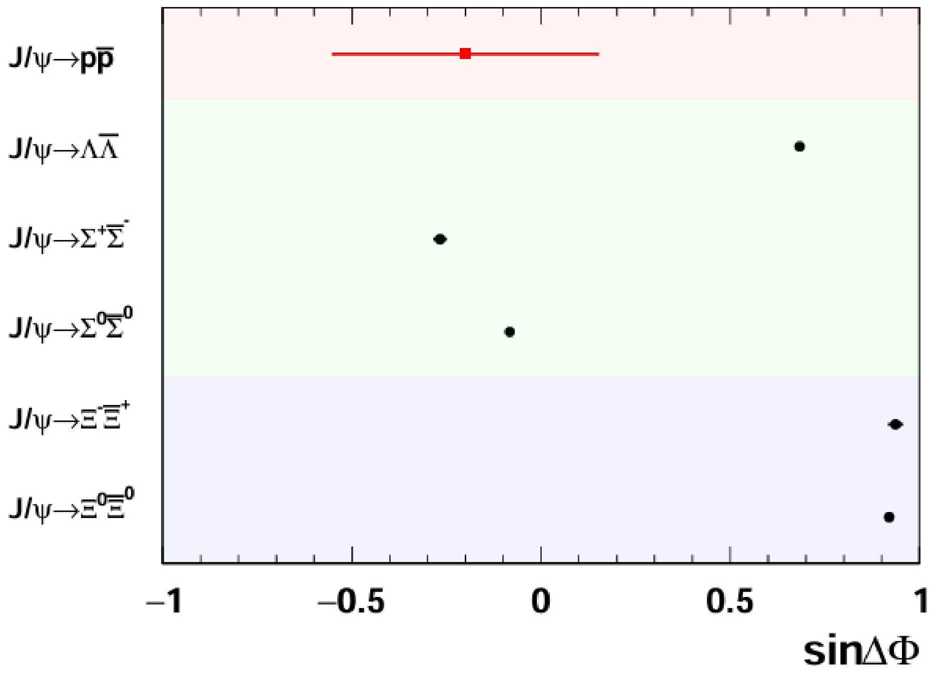






Relative phase between proton Psionic Form Factors





- ➢ Two solutions of $\Delta\Phi$ with $\sin(\Delta\Phi)$
- ➢ Measure $\cos(\Delta\Phi)$, possible at future STCF
- Longitudinal polarized electron, measure $\cos(\Delta\Phi)$
- Measure polarization of p and $\bar{p}$， spin correlation

$$\mathcal{P}_x = \mathcal{P}_e \frac{\sin\theta_p \Re\left[G_E G_M^*\right]}{\sqrt{\tau}\mathcal{D}},$$

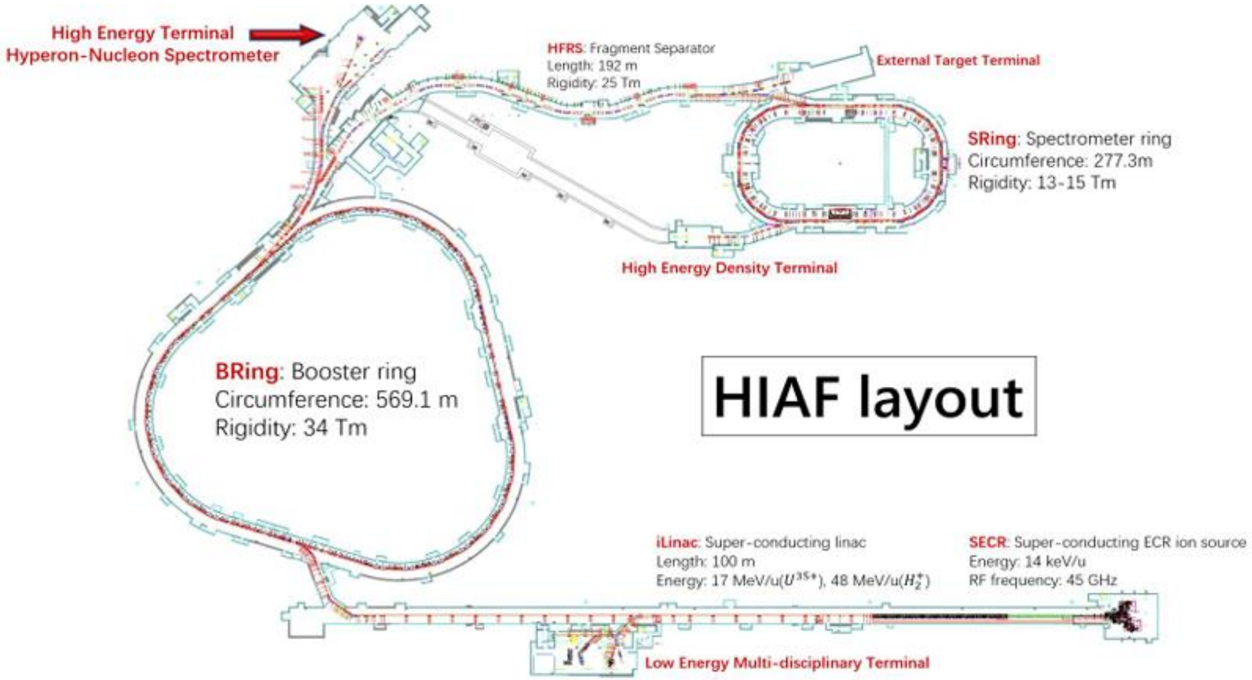
$$\mathcal{P}_y = \frac{\sin 2\theta_p \Im\left[G_E G_M^*\right]}{\sqrt{\tau}\mathcal{D}},$$

$$\mathcal{P}_z = \mathcal{P}_e \frac{2\cos\theta_p |G_M|^2}{\mathcal{D}},$$

Application and potentials at H-NS

High-Intensity Heavy Ion Accelerator Facility - HIAF

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**

近期规划：利用HIAF束流开展高能核物理研究

长期规划：HIAF → HIAF-U → EicC

Hyperon-Nucleon Spectrometer (H-NS)

Mag. Field: 1.5 Tesla

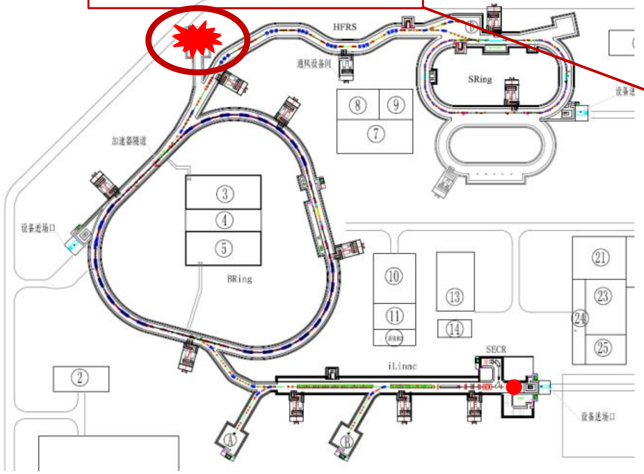
Tracker: MIC6, 30X30 μm^2, 0.35%X/X_0

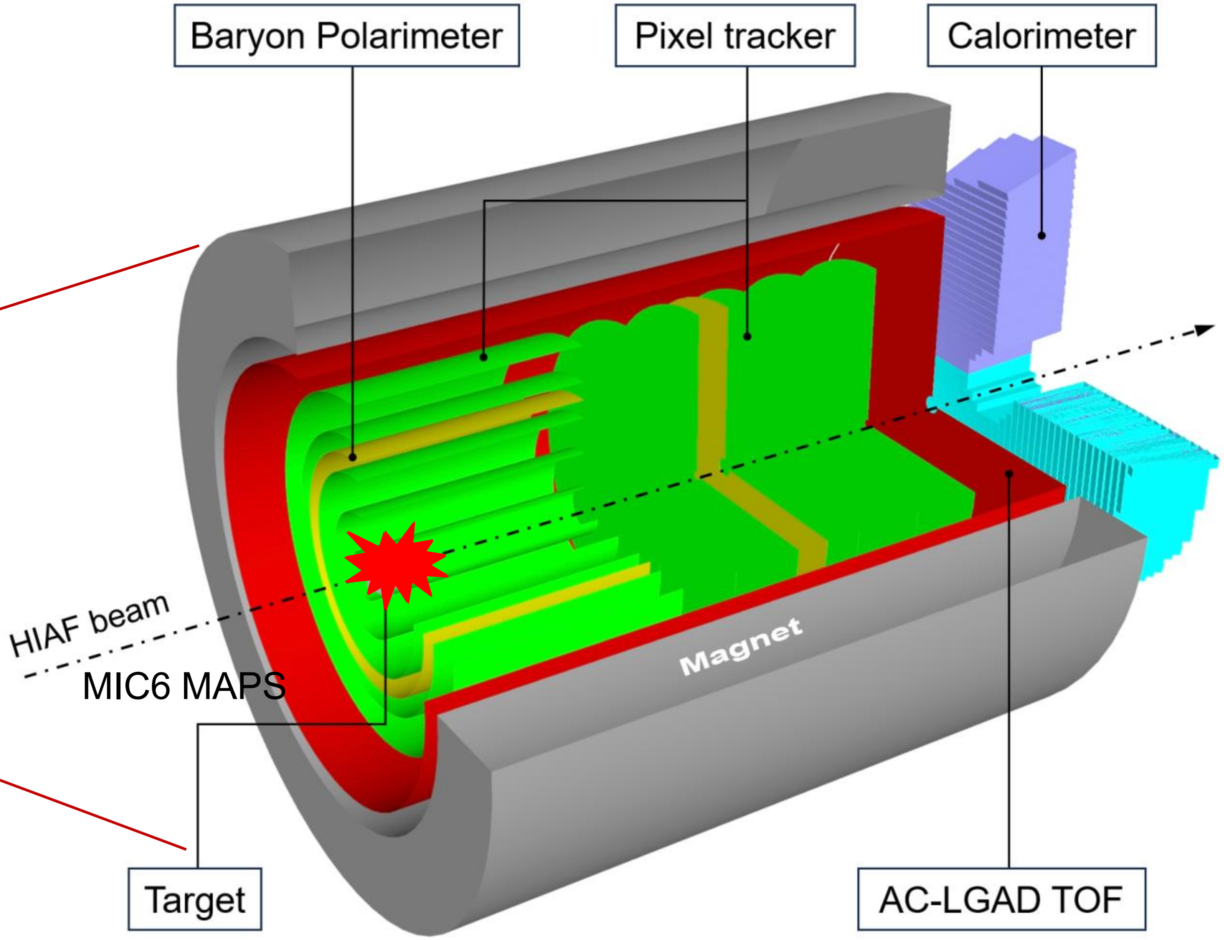
LGAD: σ_t ~ 30 ps , 300X300 μm^2

Calorimeter: σ_E ~ 3% @ 1GeV

Polarimeter: nucleon and photon polarization

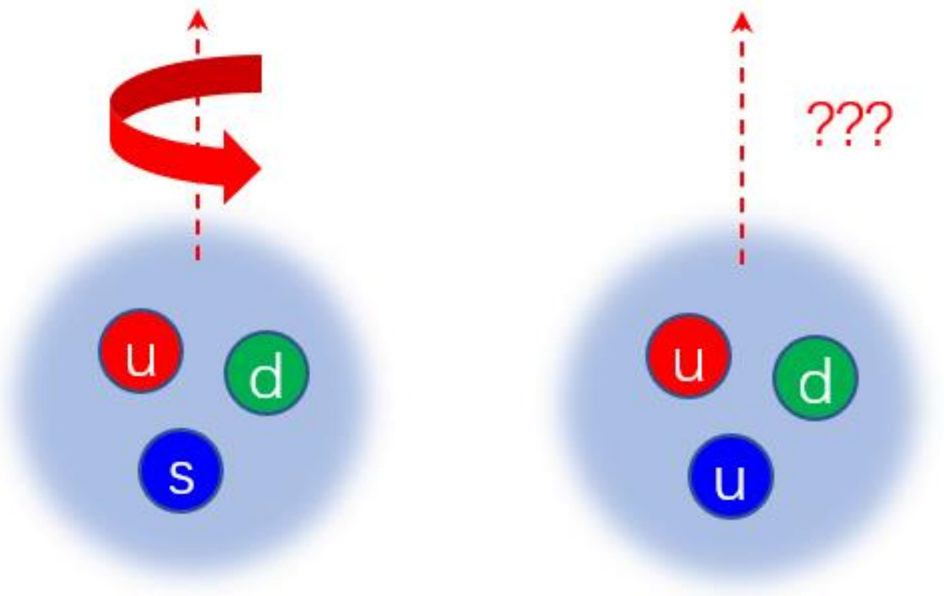
High Energy Nuclear Physics Terminal

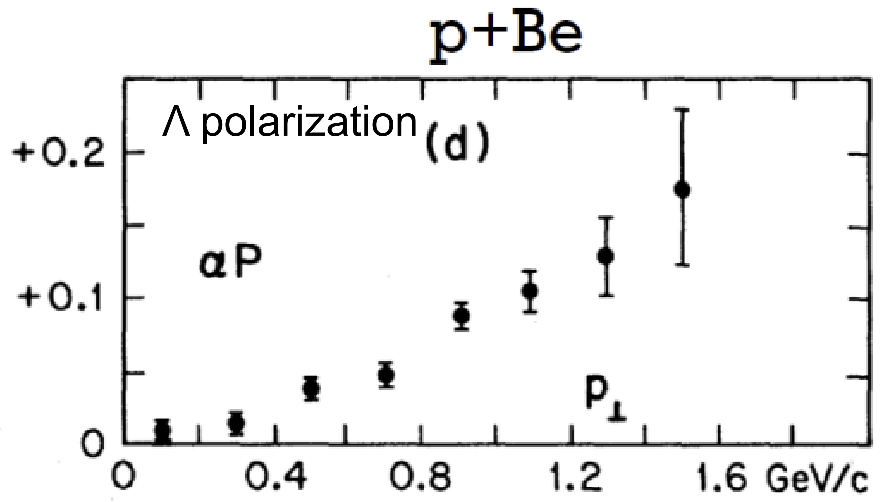




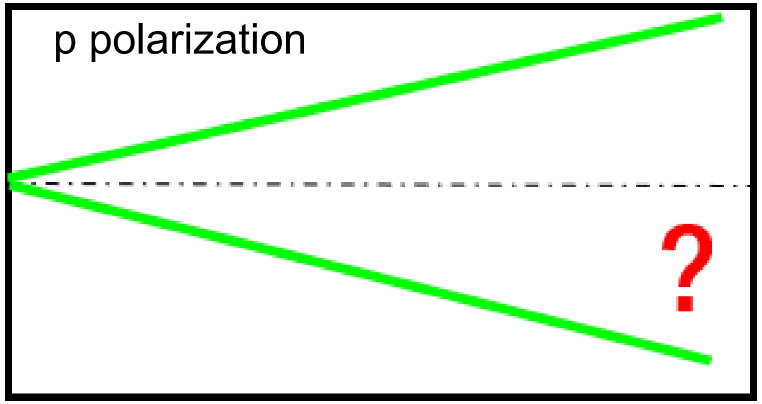
Baryon spin structure – polarization of p/Λ

pp → p/Λ + X



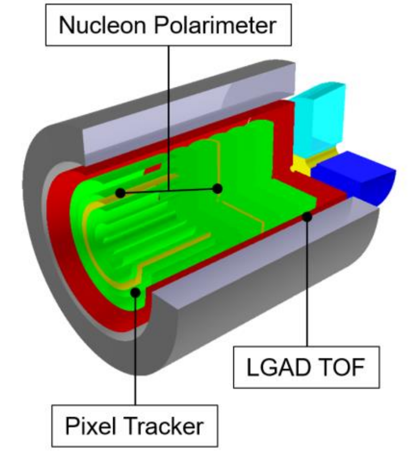


G.Bunce, *et al.*: Phys.Rev.Lett. 36, 1113-1116 (1976)



Physics potentials at H-NS

➢ Spin structure of baryon?



H-NS

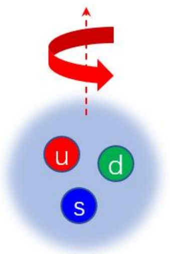
Reaction: p+p

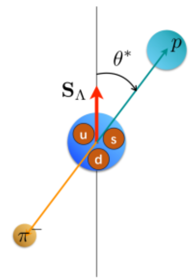
Event rate:1MHz

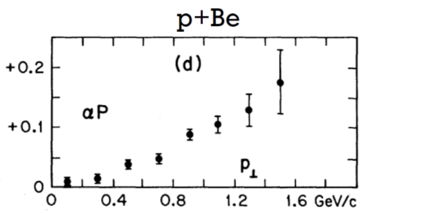
Time: 3 months

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

p p → Λ + X $\sigma_{stat.} < 0.01$ 2D:400 bins

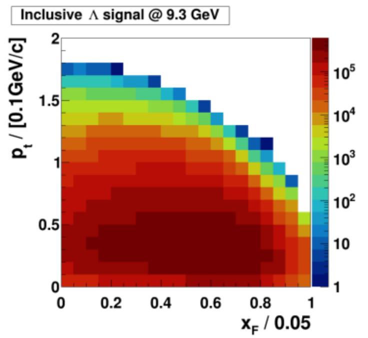


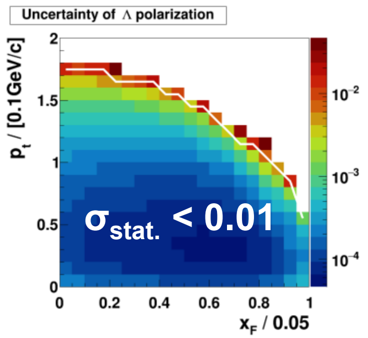




G.Bunce, *et al.*: Phys.Rev.Lett. 36, 1113-1116 (1976)

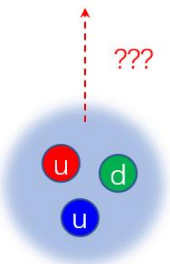
Λ polarization

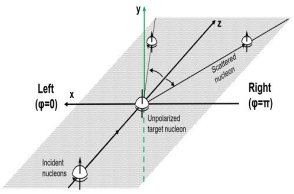


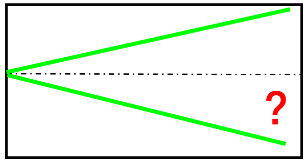


p p → p + X $\sigma_{stat.} < 0.02$ 2D:400 bins

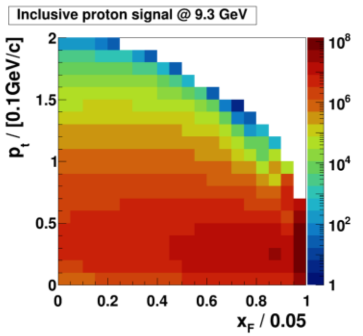
pC scattering ~ 10^{13} * $4*10^{-4}$ = $4*10^{9}$

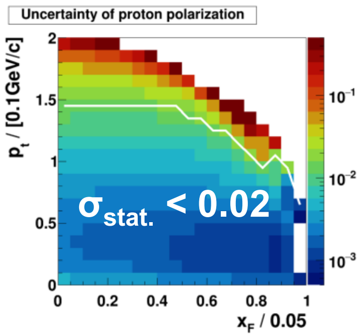






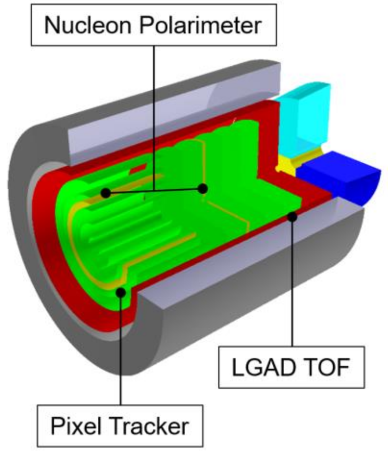
proton polarization





Physics potentials at H-NS

➢ **Heavy ion physics?**



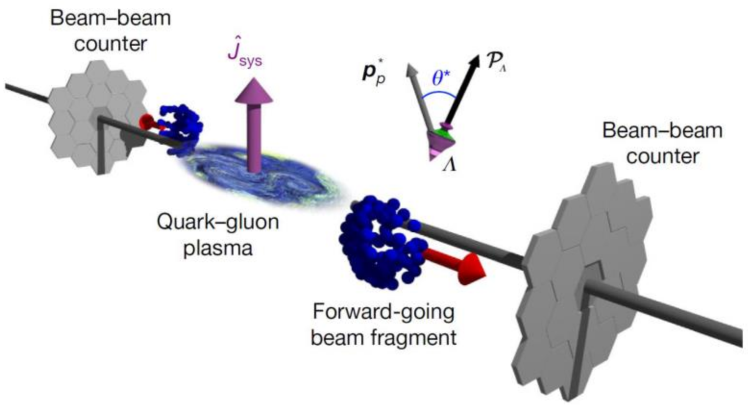
H-NS

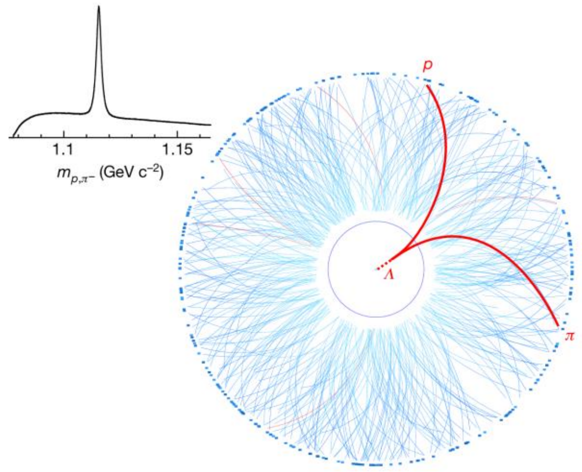
Reaction: A+A

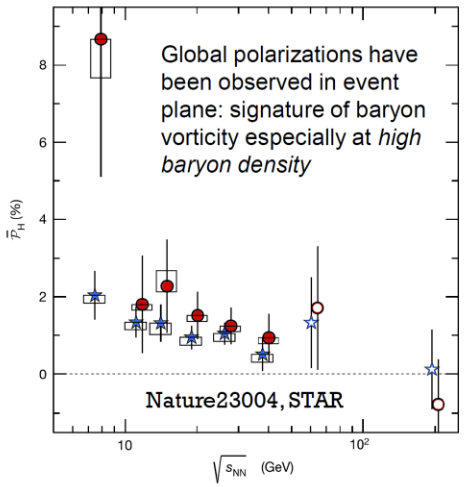
Event rate:

Time:

- AA → Λ+X
- AA → p+X
-







➢ A new probe with proton polarization?

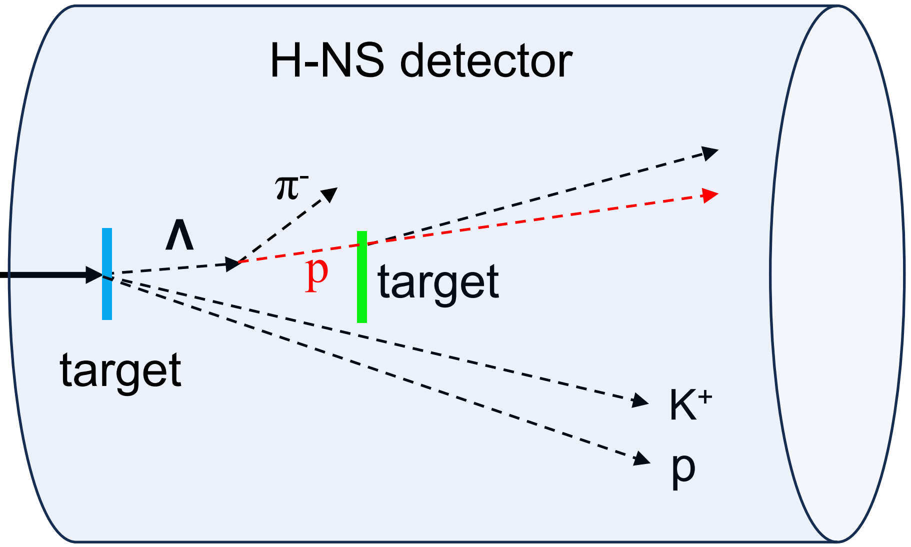
➢ Difficult at STAR, but possible at H-NS

- Global polarization of proton?

Polarized experiments at H-NS

- **Potential at H-NS**

p beam: 3-9.3 GeV

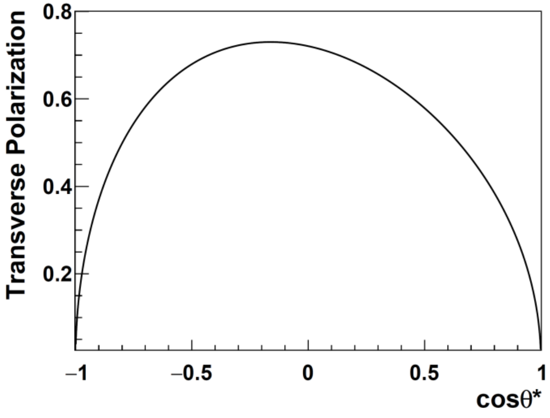


$\mathbf{p + p \rightarrow \vec{\Lambda} + X}$

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

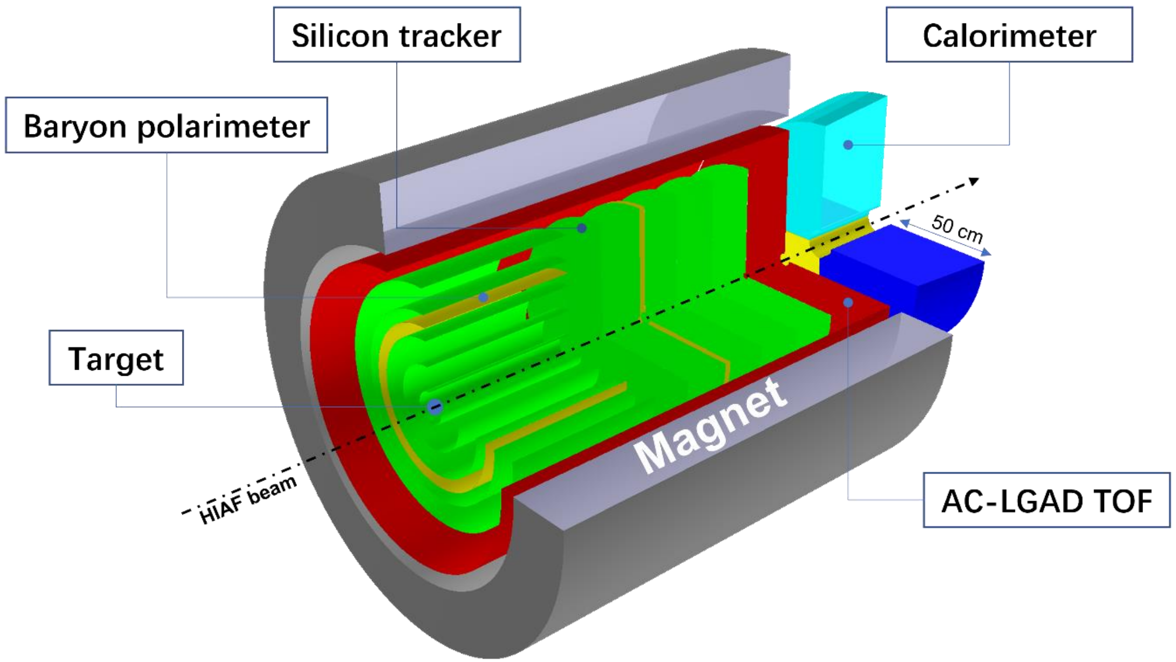
Polarized proton experiment: polarization transfer from beam?

- **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

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*

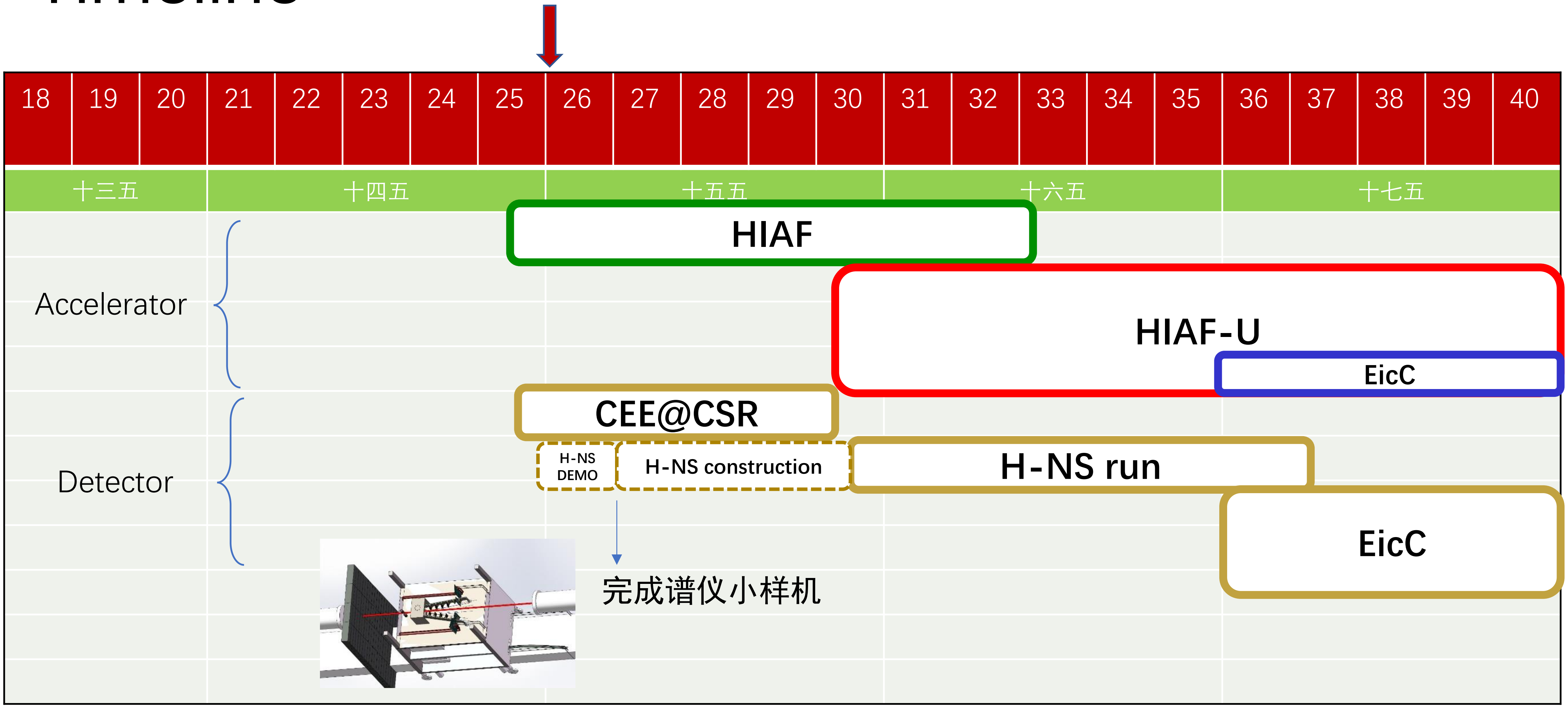
II. Community：

- 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)

Timeline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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
完成谱仪小样机

Summary

- ✓ **New concept of general-use spectrometer with polarimeter function**
  - applicable at all reactions (ee, ep, pp, AA) and in a wide energy range
  - almost no impact on the conventional performance, almost negligible expense
- ✓ **Validation and application at BESIII**
  - Validation performed with polarized proton at BESIII
  - First measurement for relative phase of proton EMFF
- ✓ **Potentials of the concept at HIAF**
  - H-NS with polarimetry function
  - Rich spin physics, bridging the future EicC physics

Thank You