New concept of general-purpose spectrometer with polarimeter function

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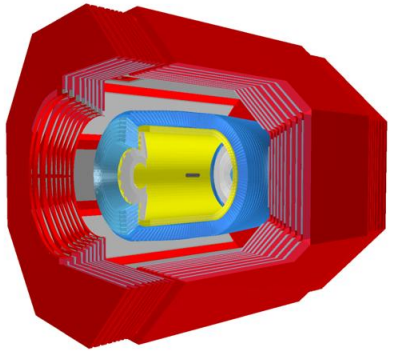
Spin 2025 Qingdao

Outline

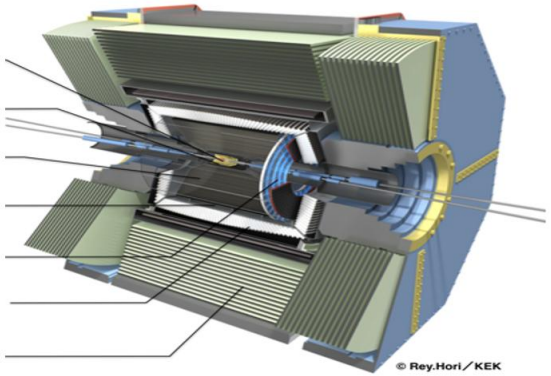
- Introduction
- New concept with polarimeter function
- Performance study with H-NS at HIAF
- Physics potentials with the new concept
- Summary

General-purpose spectrometer

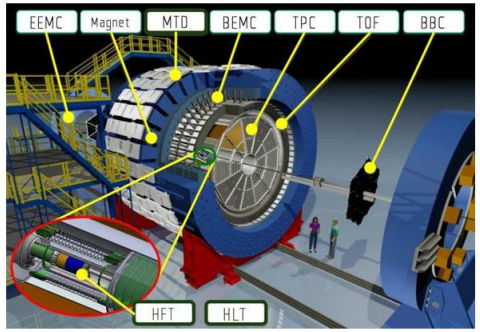
BESIII



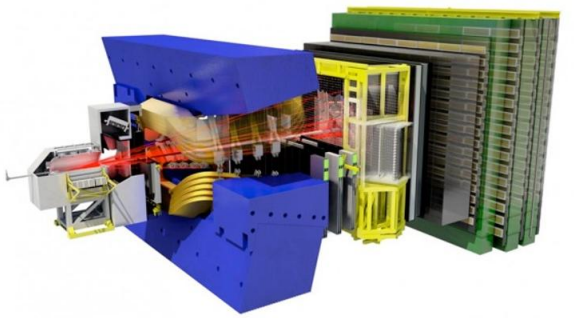
BELLE-II



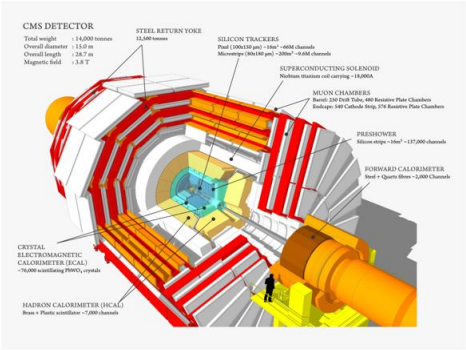
STAR



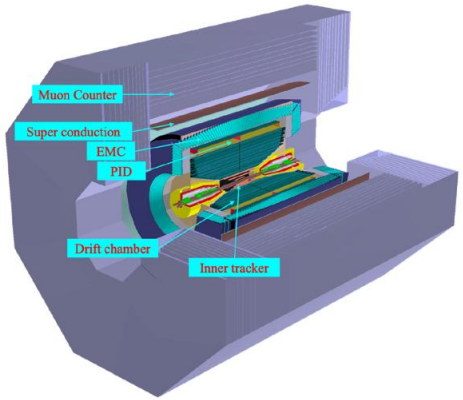
LHCb



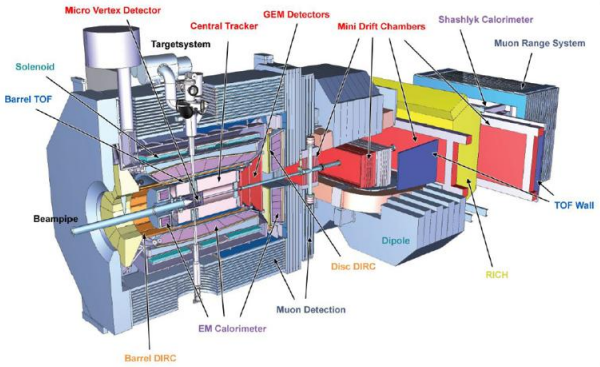
CMS



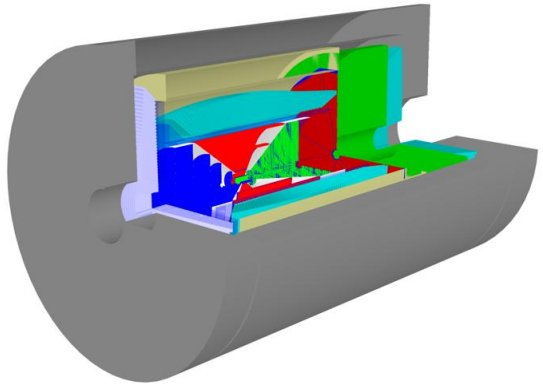
STCF



PANDA

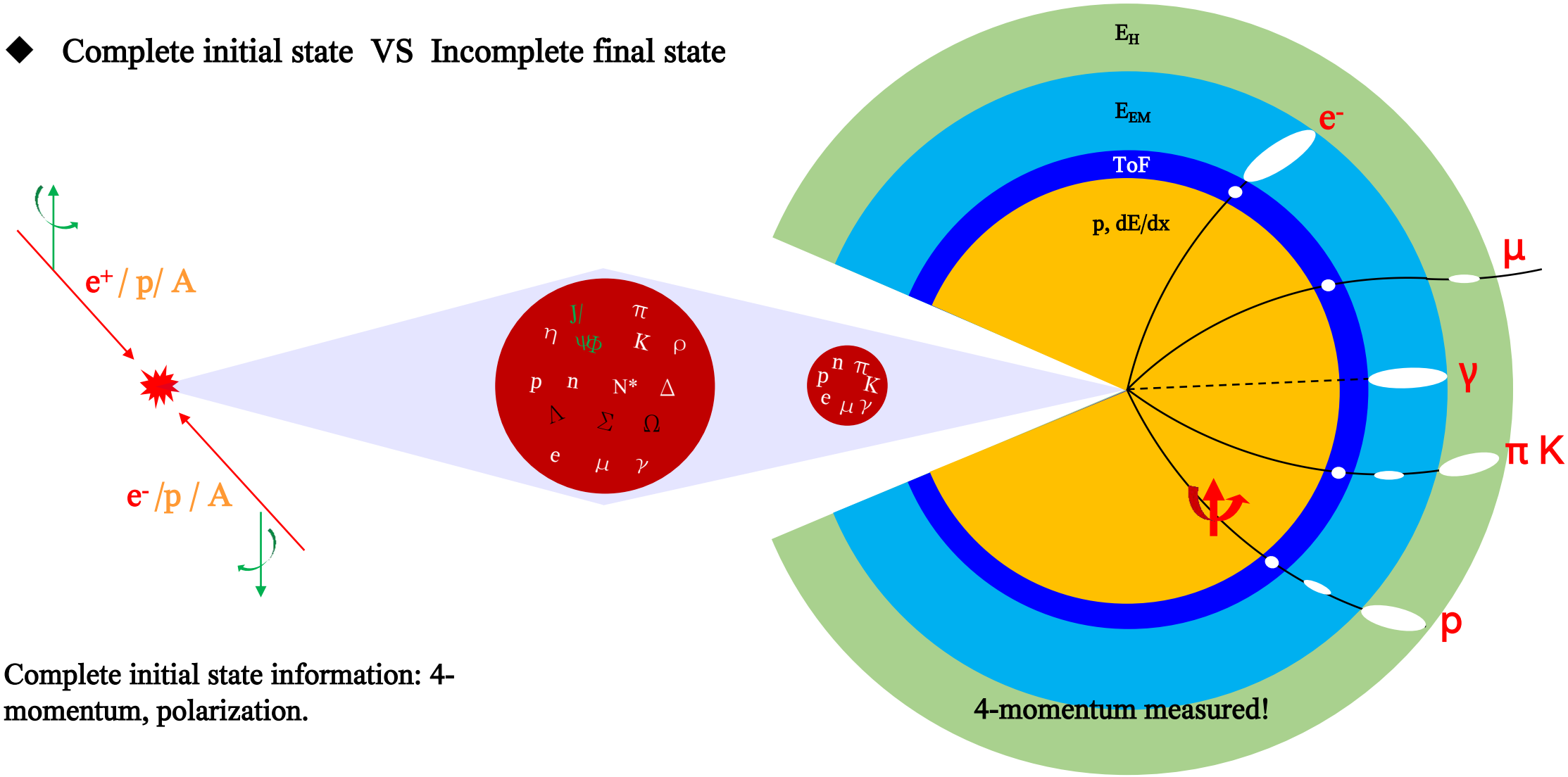


EicC



General-purpose spectrometer

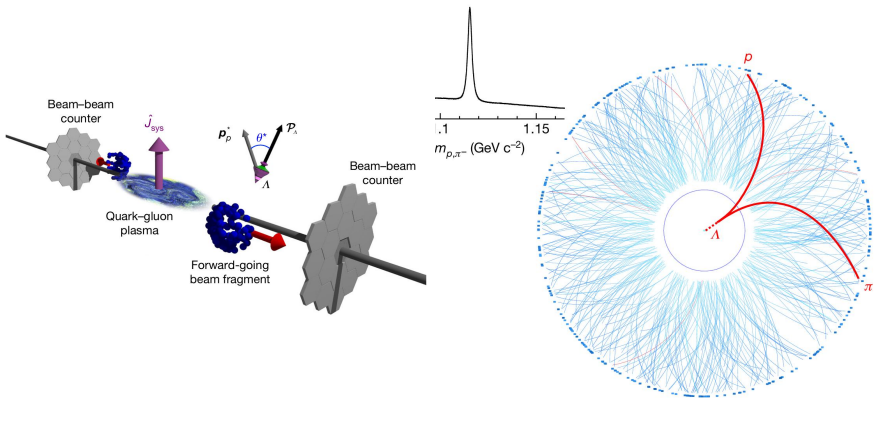
- Complete initial state VS Incomplete final state

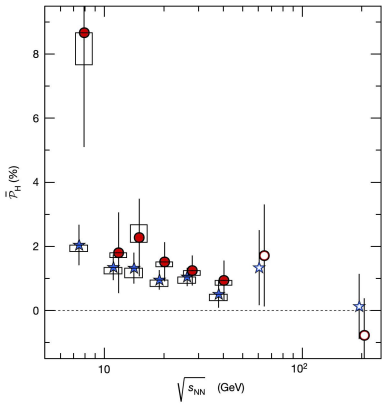


Complete initial state information: 4-momentum, polarization.

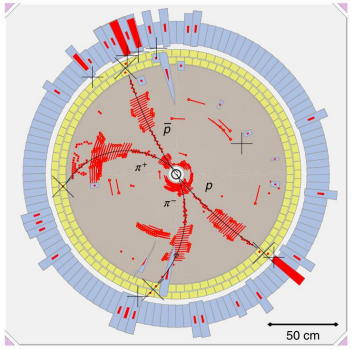
- Spin polarization of final state contains valuable information

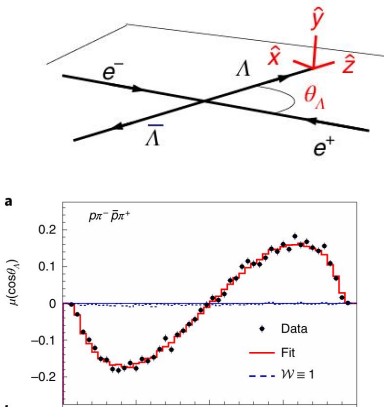
Spin with valuable information



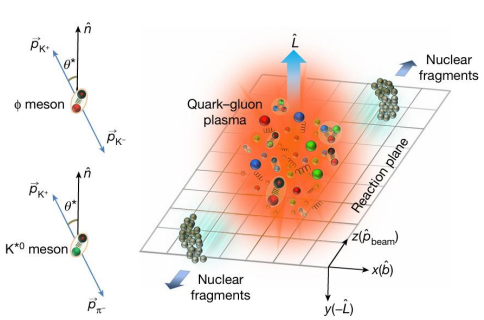


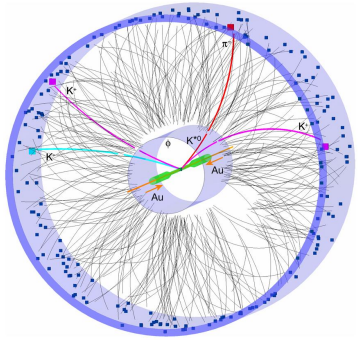
STAR, Nature 548, 62 (2017)

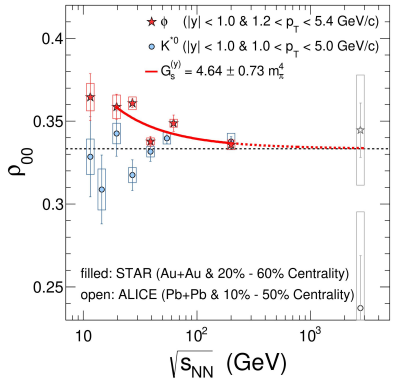




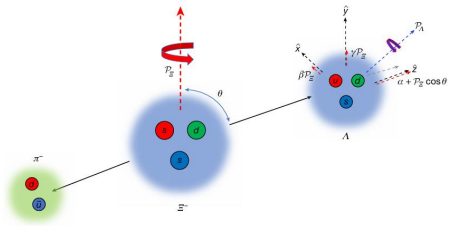
BESIII, Nature Physics, 15, 631 (2019)

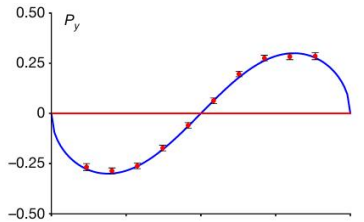






STAR, Nature 614, 244 (2023)





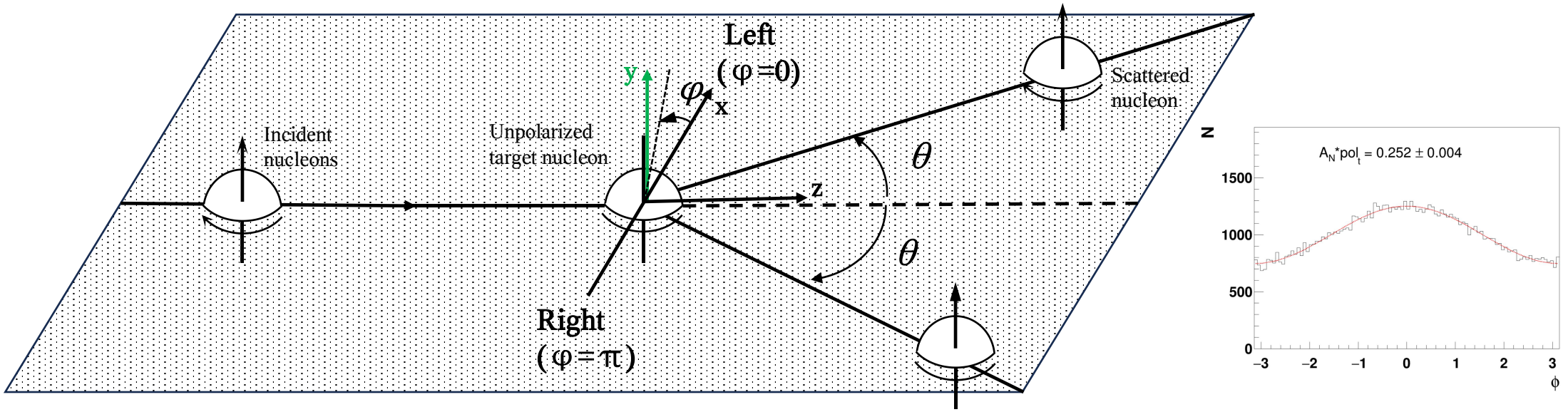
BESIII, Nature, 606, 64 (2022)

New detector concept with polarimetry function

Principle of proton polarimeter

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

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



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

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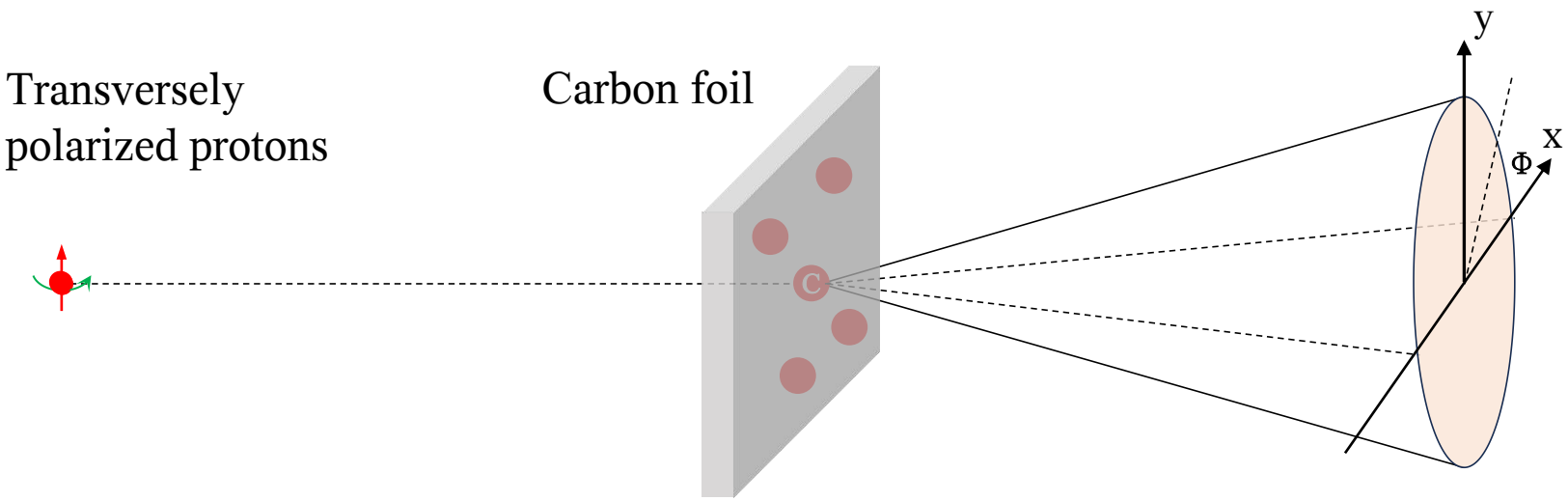
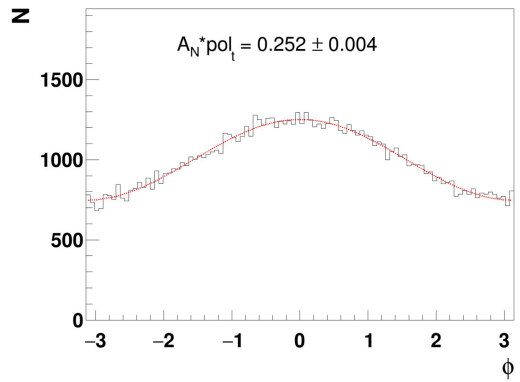
Transversely polarized protons

Carbon foil

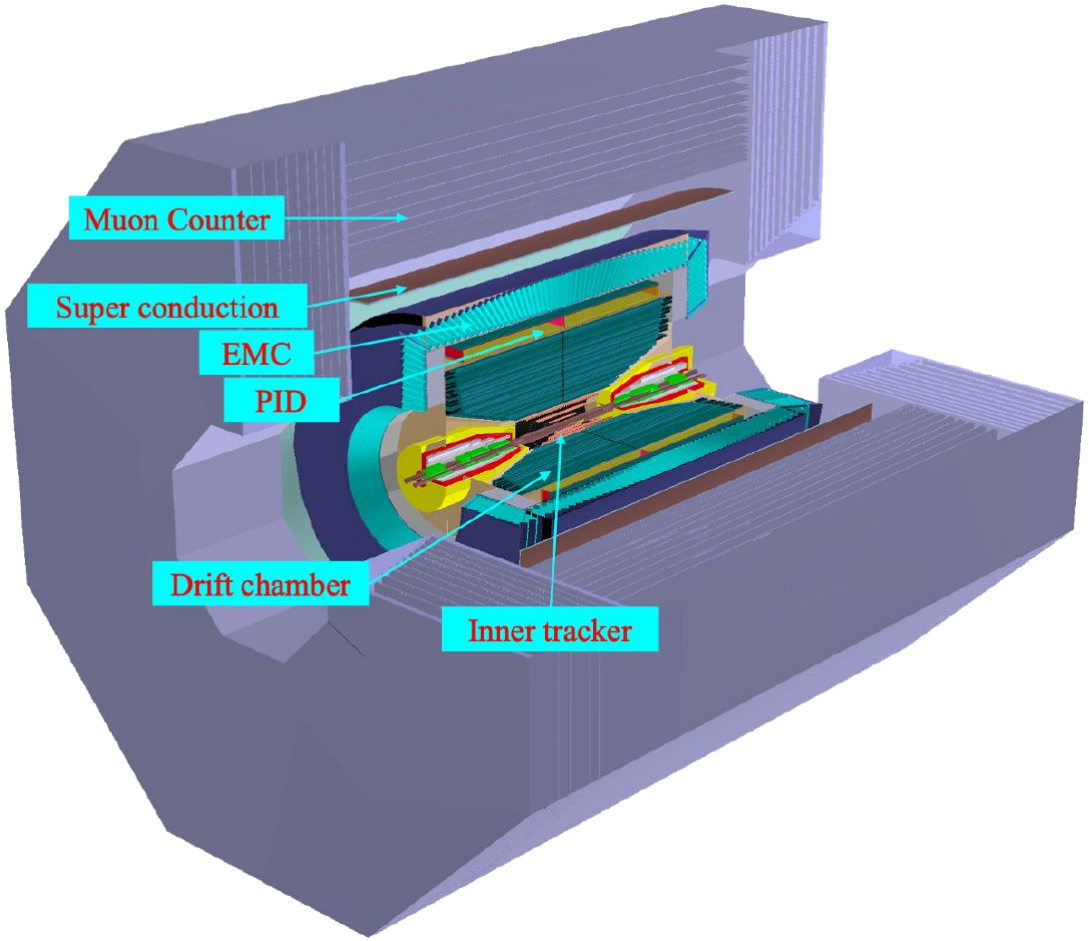




More protons to the left:
Left-right asymmetry

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

Add polarimeter function in general-purpose detector ?



- General-use detector requirements:

  $e^{\pm}$ $\mu^{\pm}$ $\pi^{\pm}$ $K^{\pm}$ $p^{\pm}$ γ

  1) Good tracking efficiency
  2) Good momentum resolution
  3) Good energy resolution

- Secondary interaction

tracking || target || tracking

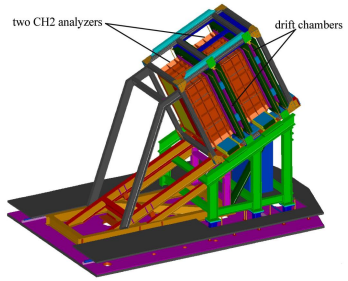


Figure 5: The FPP in the HMS in Hall C as currently designed.

target || tracking

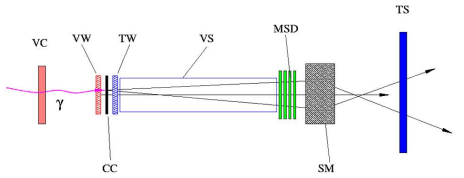
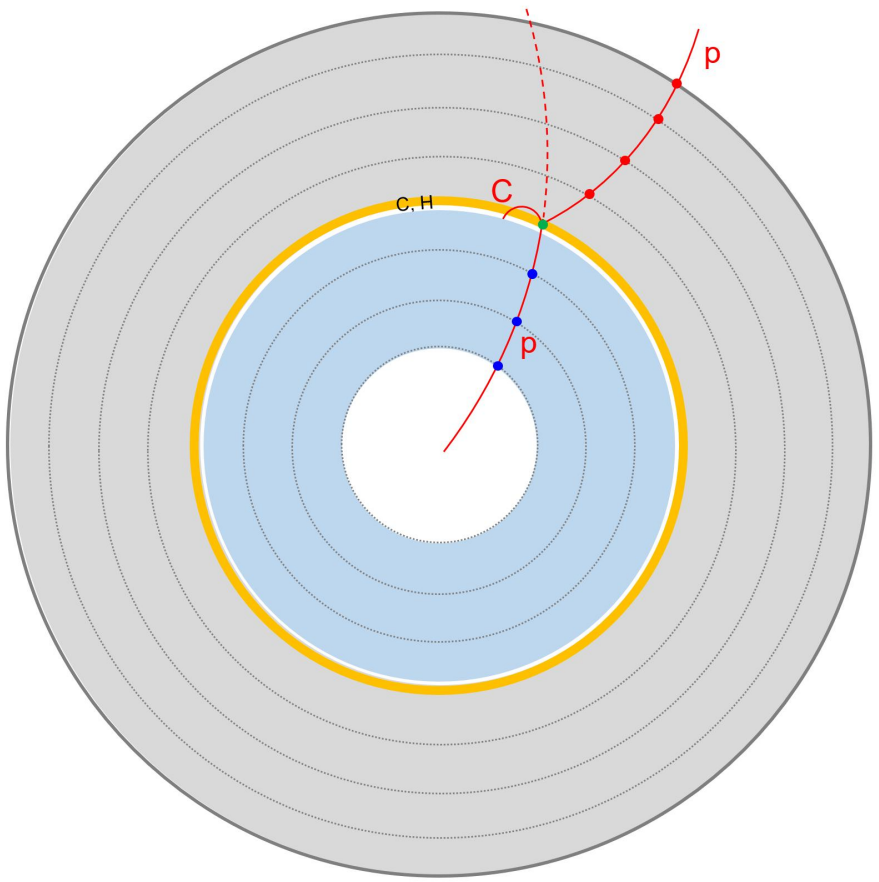


Fig. 3. The layout of the photon polarimeter. The photon arrives from the left. The veto detector is marked as VC, the veto wire chamber as VW, the converter as CC, the trigger wire chamber as TW, the vacuum straight section as VS, the set of micro-strip detectors as MSD, the separation magnet as SM, and the trigger scintillator counter as TS

- **High luminosity machine?**

An extra carbon layer



- Carbon layer
  - ~1 mm thickness
  - Material budget: <1% X/X_0
  - Probability: pC (4E-4)
  - Tiny influence to the conventional performance
- Position : in-between the tracking devices
  - Appliable in all reactions: ee/ep/pp/pA/AA
  - Appliable in high energy machines

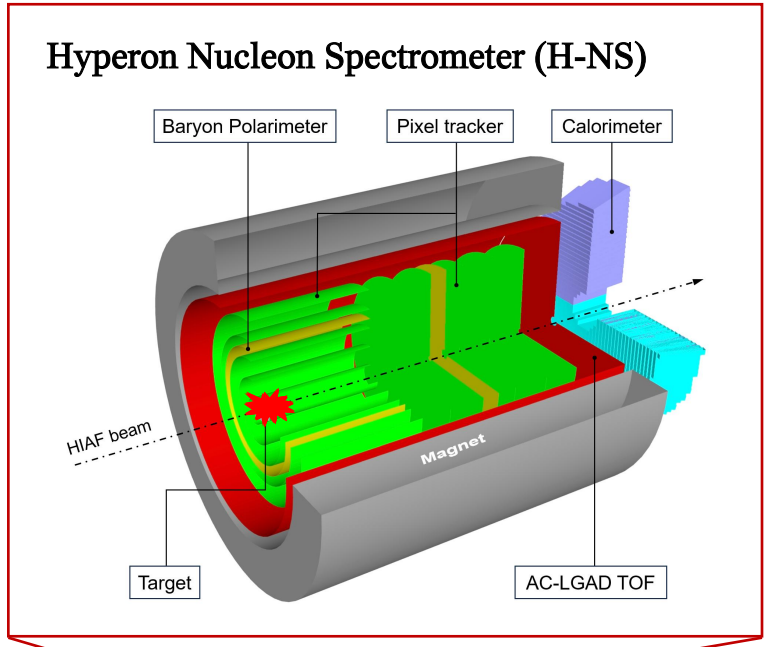
Phys. Rev. D 112, L031502

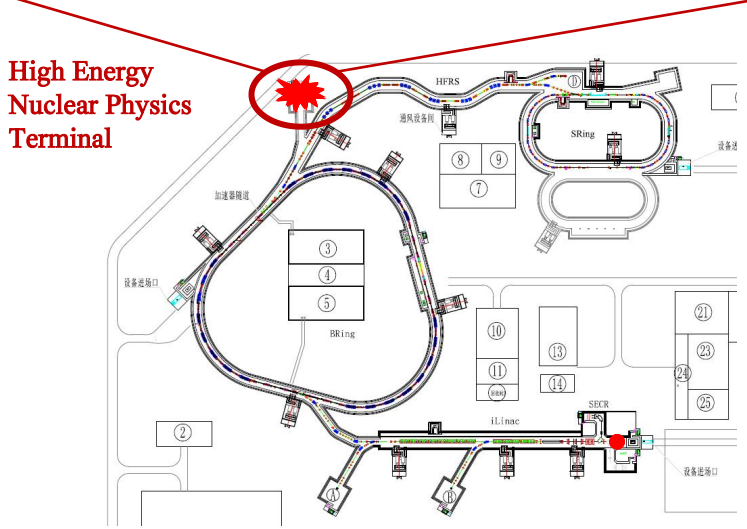
Performance study with an example experiment H-NS

Hyperon Nucleon Spectrometer (H-NS)

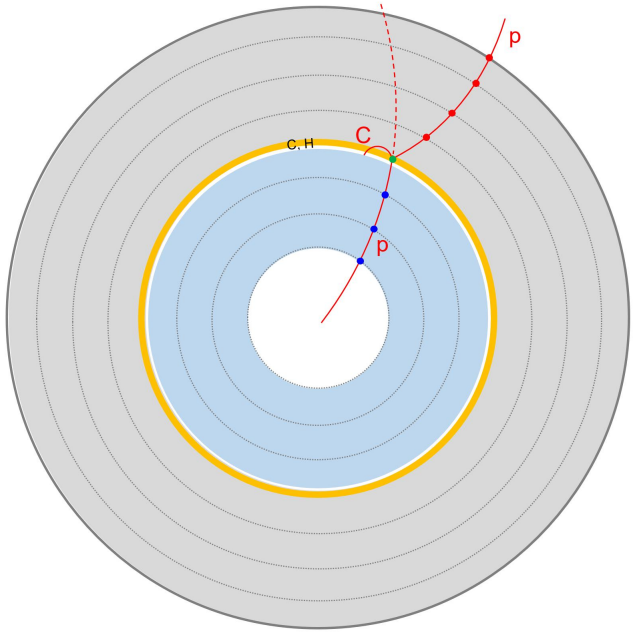
Talk of Yuxiang Zhao at Wednesday 10:50

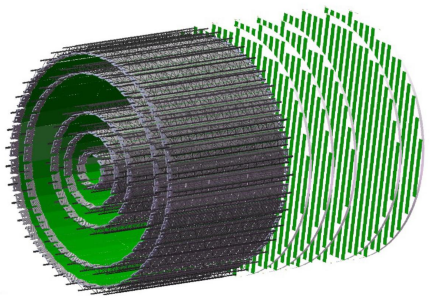
- **Momentum resolution:**
  - ~2%@1GeV when η<2.5
- **PID:**
  - K, π separation (~3σ) up to 2 GeV/c
  - K, p separation (~3σ) up to 5 GeV/c
- **Vertex resolution:**
  - Excellent vertex resolution for background suppression
  - Material budget (<10%)
- **Acceptance:**
  - 5 to 100 degree
- **High event rate**
  - 1MHz
- **Baryon Polarimeter → determine final state proton's polarization**
- **Provide detector R&D platform in forward region**

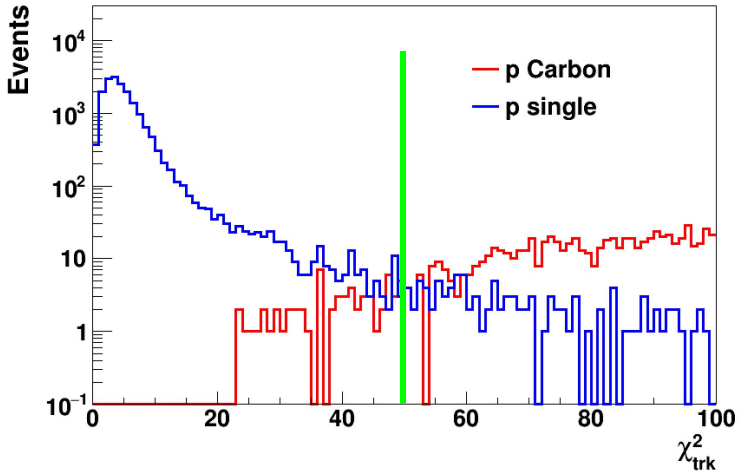


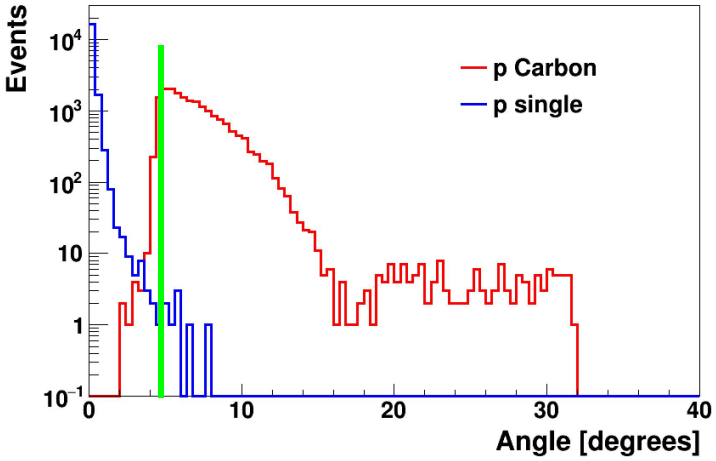


Signature of pC scattering tracks

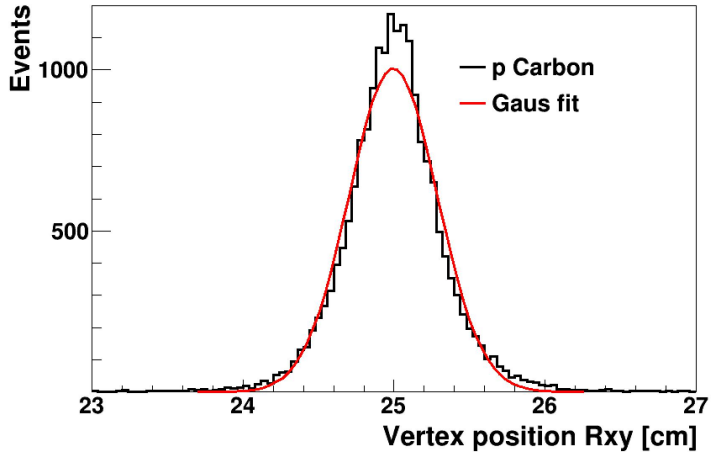






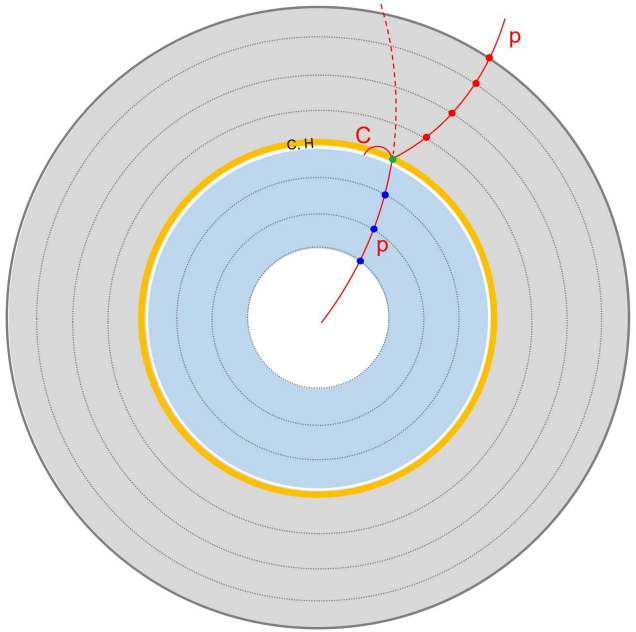


$\sigma = 0.29$ cm

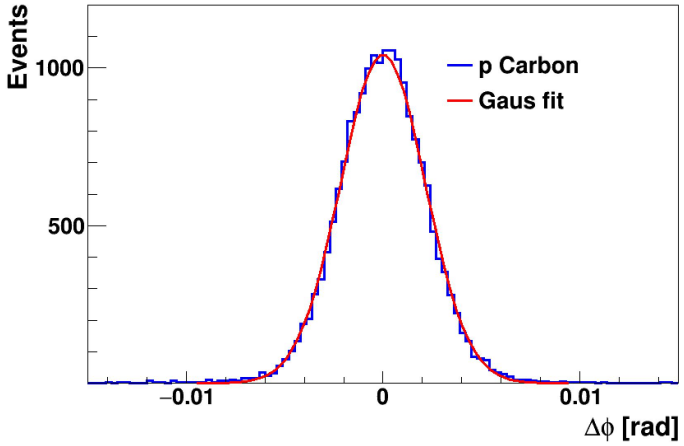


- ✓ Scattering track: > 70%
- ✓ Non-scattering track: ~ 4E-6
- ➢ Low background contamination!

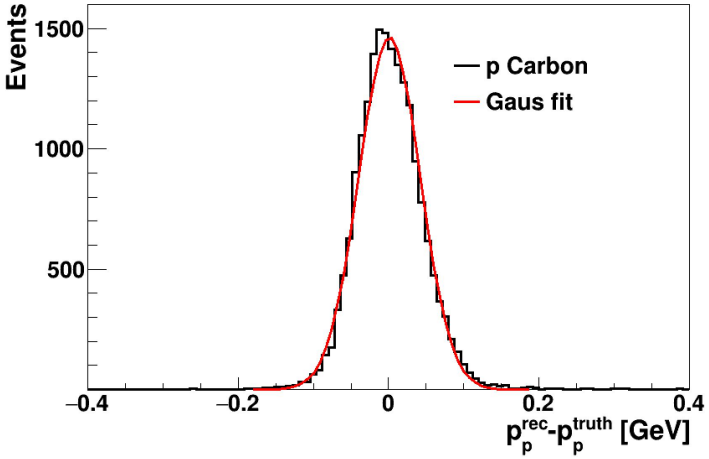
Precision measurement of proton polarization



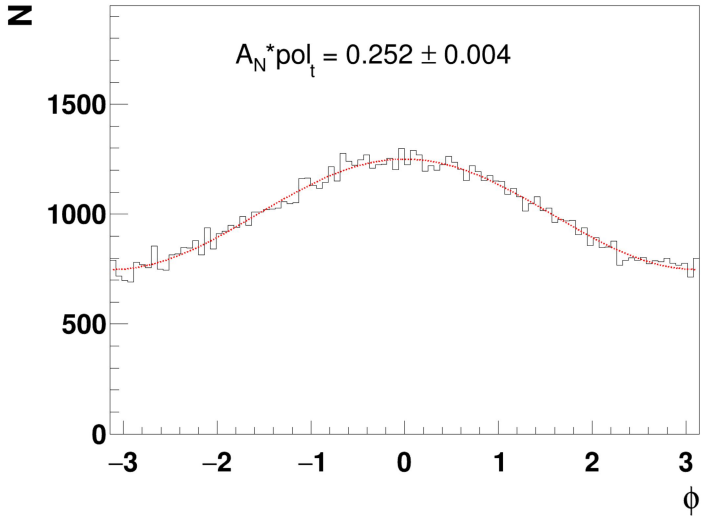
$\sigma = 2.16$ mrad



$\sigma = 0.041$ GeV

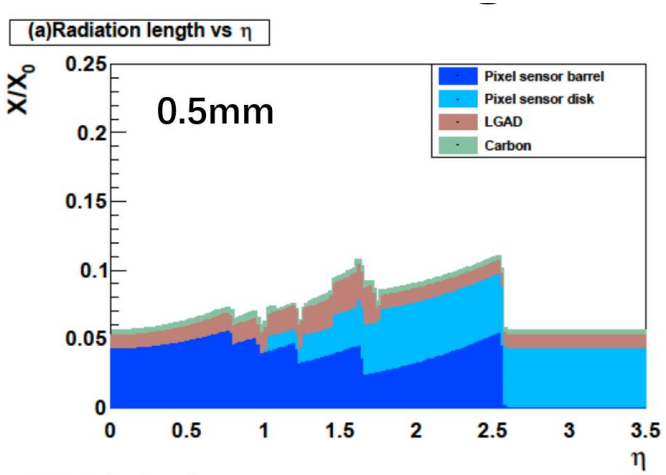


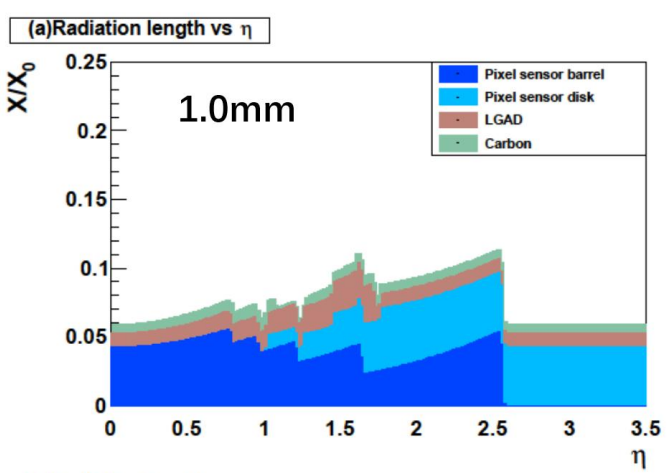
Input: 0.250

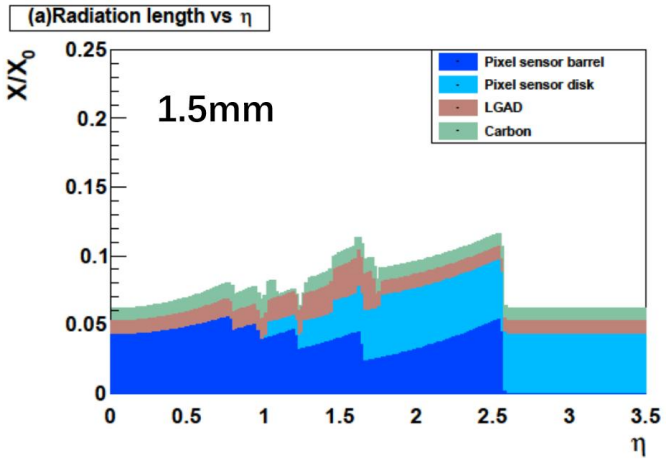


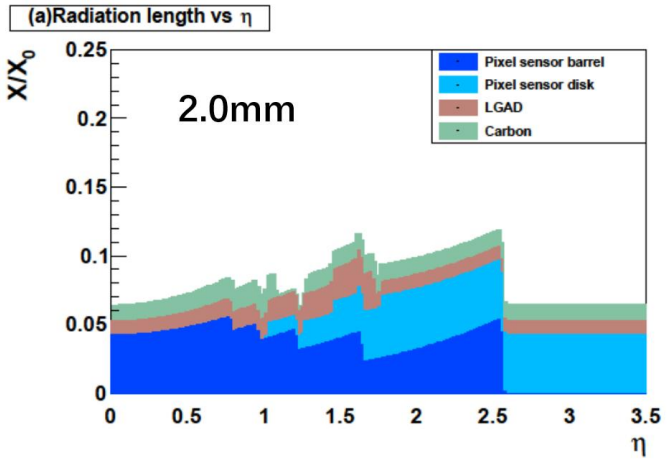
- ✓ Scattering track: > 70%
- ✓ Non-scattering track: ~ 4E-6
- ➢ Low background contamination!
- ➢ High precision measurement!

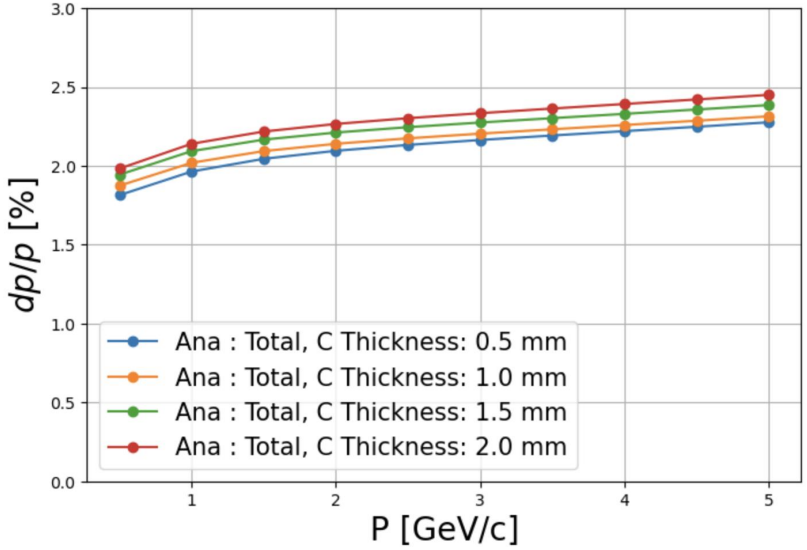
Material budget of carbon layer







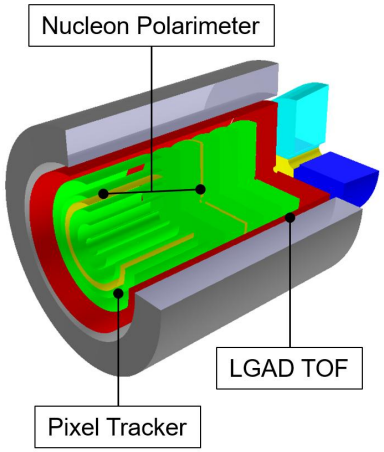




Physics potentials

Physics potentials at H-NS

➢ Spin structure of baryon?



H-NS

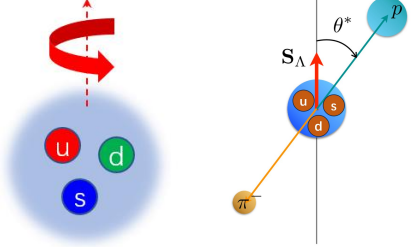
Reaction: p+p

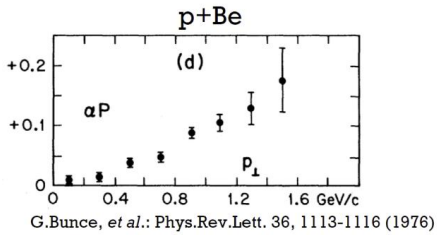
Event rate:1MHz

Time: 3 months

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

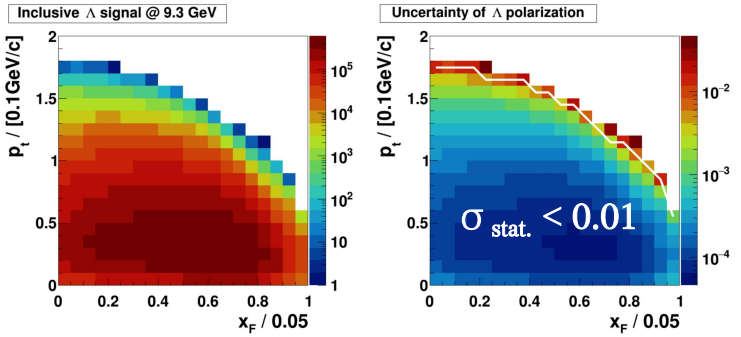
p p → Λ + X $\sigma_{stat.} < 0.01$ 2D:400 bins





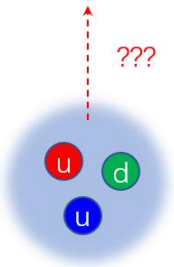
G.Bunce, *et al.*: Phys.Rev.Lett. 36, 1113-1116 (1976)

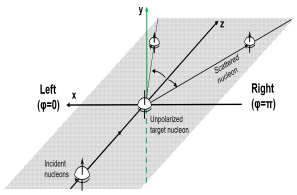
Λ polarization

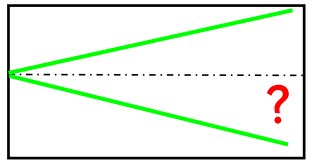


p p → p + X $\sigma_{stat.} < 0.02$ 2D:400 bins

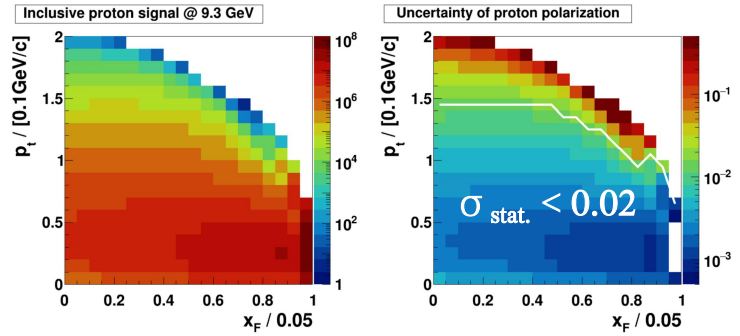
pC scattering ~ 10^{13} * $4*10^{-4}$ = $4*10^{9}$





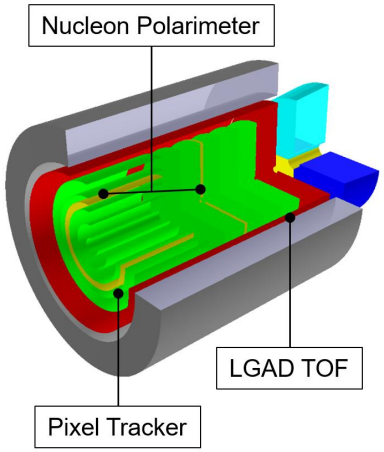


proton polarization



Physics potentials at H-NS

- Spin structure of baryon?



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- pp → Λ+X N ~ 10^{11}
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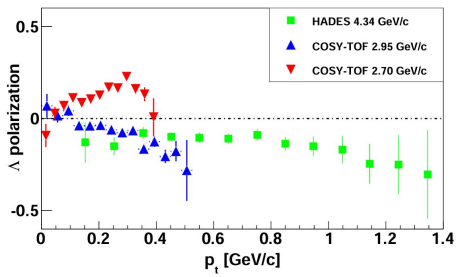
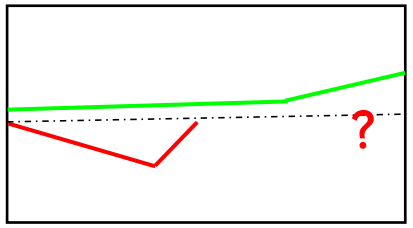
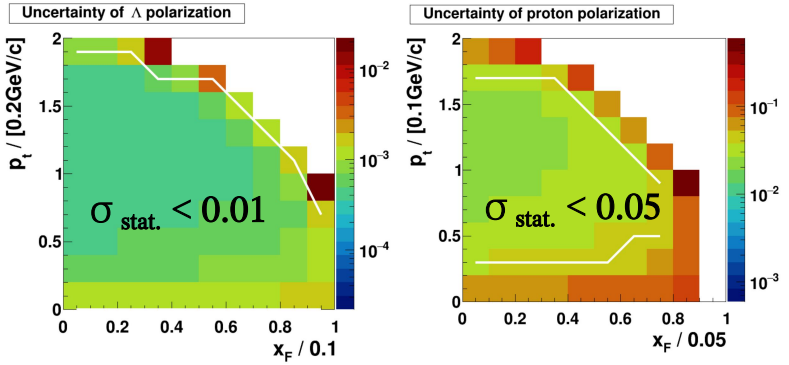
p p → p K Λ $\sigma_{stat.}$ < 0.01 for Λ; < 0.05 for p



Λ polarization



proton polarization



p p → p K Λ → p K p π $\sigma_{stat.}$ < 0.005

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

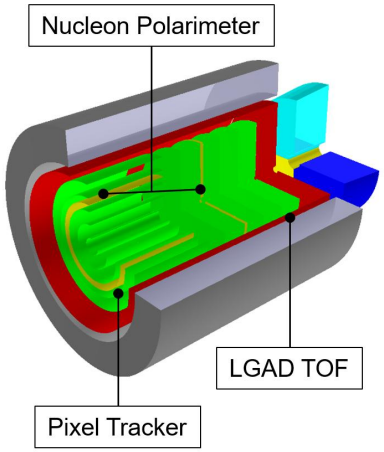
$$\alpha = 2\,\mathrm{Re}sp^*/(|s|^2 + |p|^2).$$

$$\beta = 2\,\mathrm{Im}sp^*/(|s|^2 + |p|^2).$$

$$\gamma = (|s|^2 - |p|^2)/(|s|^2 + |p|^2)$$

Physics potentials at H-NS

- **Heavy ion physics?**



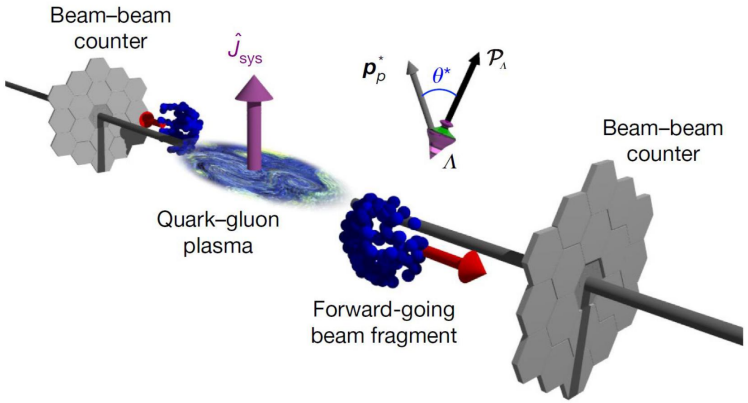
H-NS

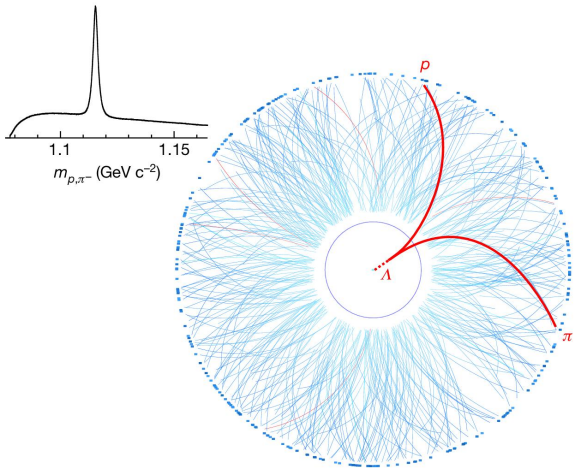
Reaction: A+A

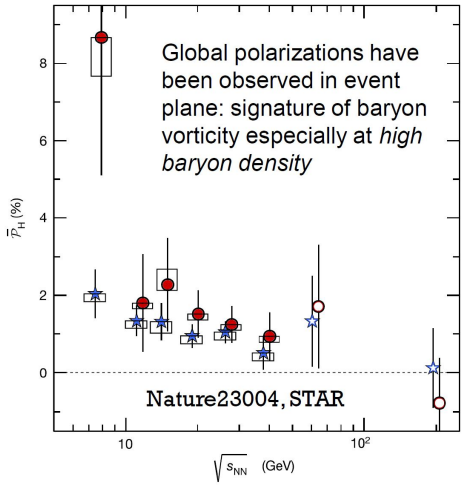
Event rate:

Time:

- AA → Λ+X
- AA → p+X
-

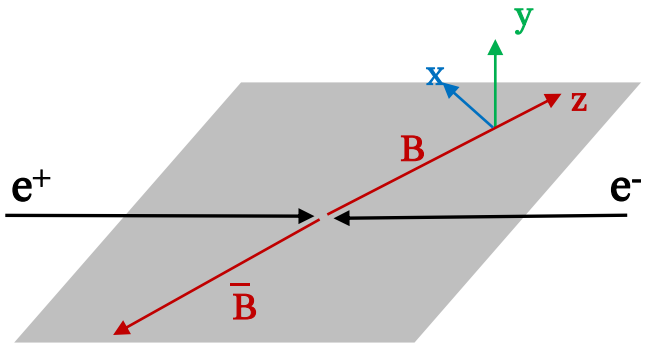




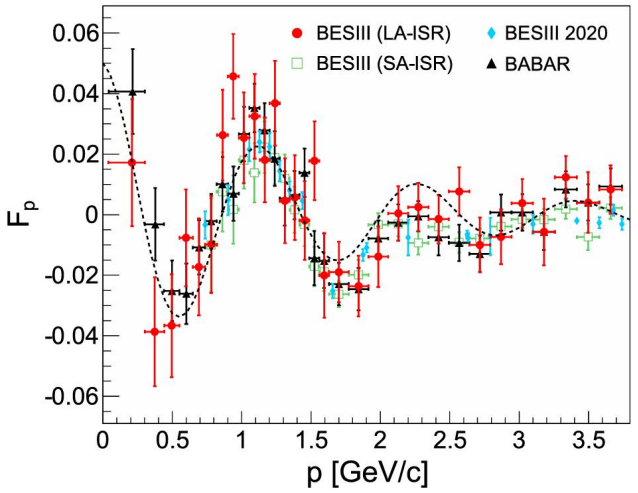


- A new probe with proton polarization?
- Difficult at STAR, but possible at H-NS
  - Global polarization of proton?

In e^+e^- colliders -- BESIII



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



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 nucleons: $P_x P_y$

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

✓ **At BESIII,** 10^{10} J/ψ

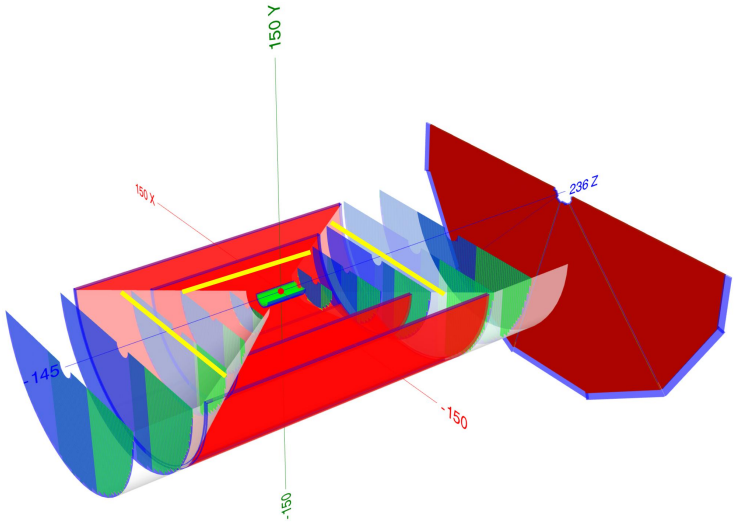
Br(J/ψ → p pbar) ~ 2E-3

Prob. pp scattering 1E-4

For $\Delta\Phi$, $\sigma_{stat.} \sim 0.35$

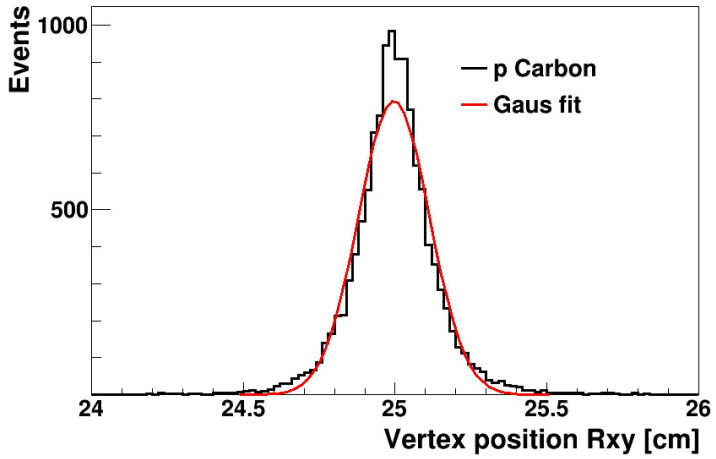
✓ **At STCF**, assuming a 100x luminosity: $\sigma_{stat.} \sim 0.03$

In electron ion colliders -- EicC

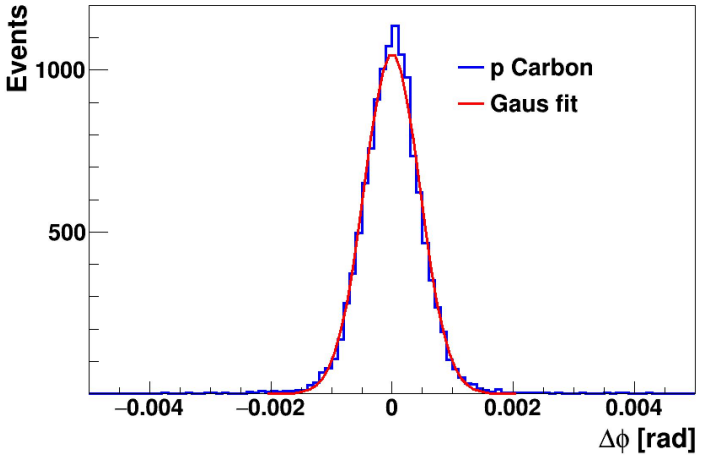


What can we get with the final state proton polarization in the EICs?

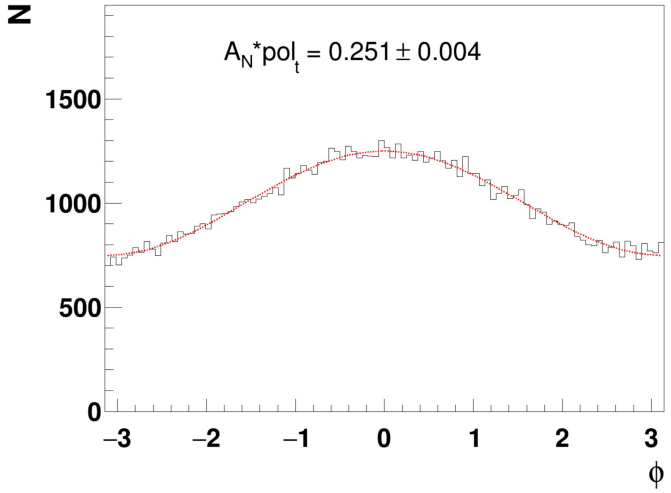
$\sigma = 0.11$ cm



$\sigma = 0.46$ mrad



Input: 0.250



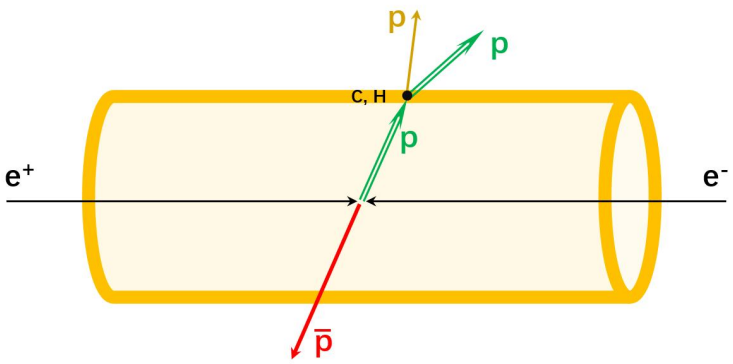
- ✓ Scattering track: > 70%
- ✓ Non-scattering track: < 1E-6
- ➢ Low background contamination!
- ➢ High precision measurement!

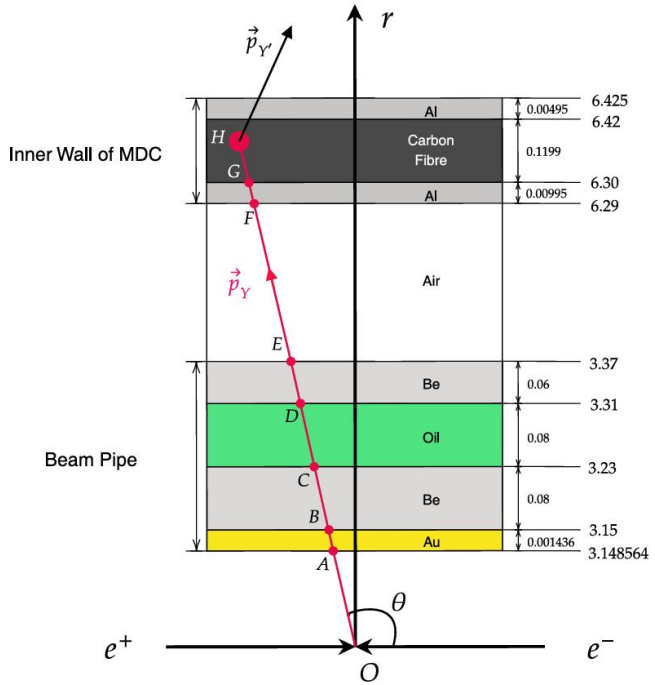
Summary

- ✓ **Method to measure final state proton polarization at collider experiments proposed.**
  - new concept of general-purpose spectrometer
- ✓ **Optimization and performance study based on H-NS detector performed.**
  - obtain the spin polarization of final state proton
  - applicable at all reactions (ee, ep, pp, AA) and in a wide energy range
  - almost no impact on the conventional performance
  - almost negligible expense
- ✓ **Potentials of the new general-purpose spectrometer discussed.**
  - a reference measurement compare to the previous Λ polarization
  - relative phase of EMFF, etc.

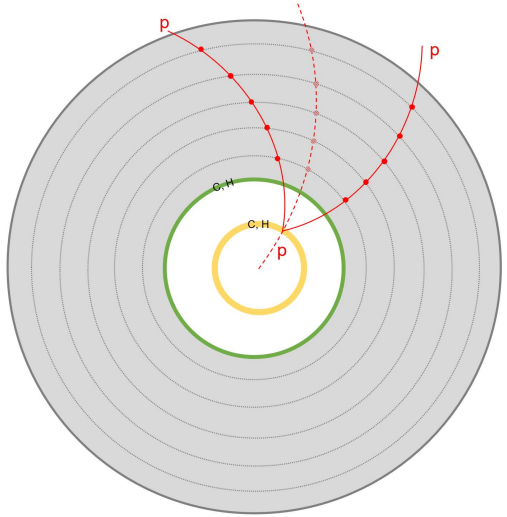
Thank You

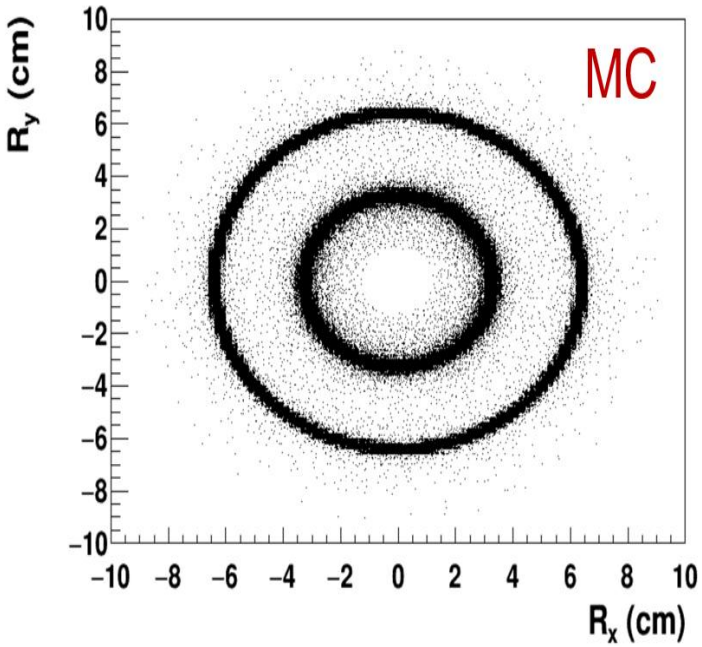
In e^+e^- colliders -- BESIII

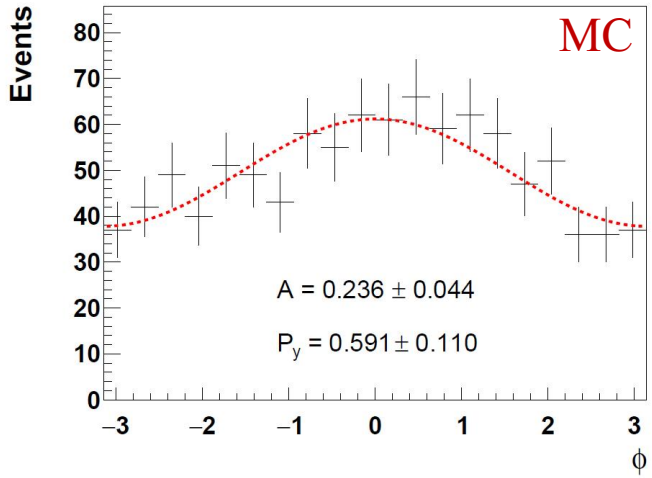




Chin. Phys. C 48, 073003 (2024)







With good tracking and vertexing, the BESIII detector is ideal to:

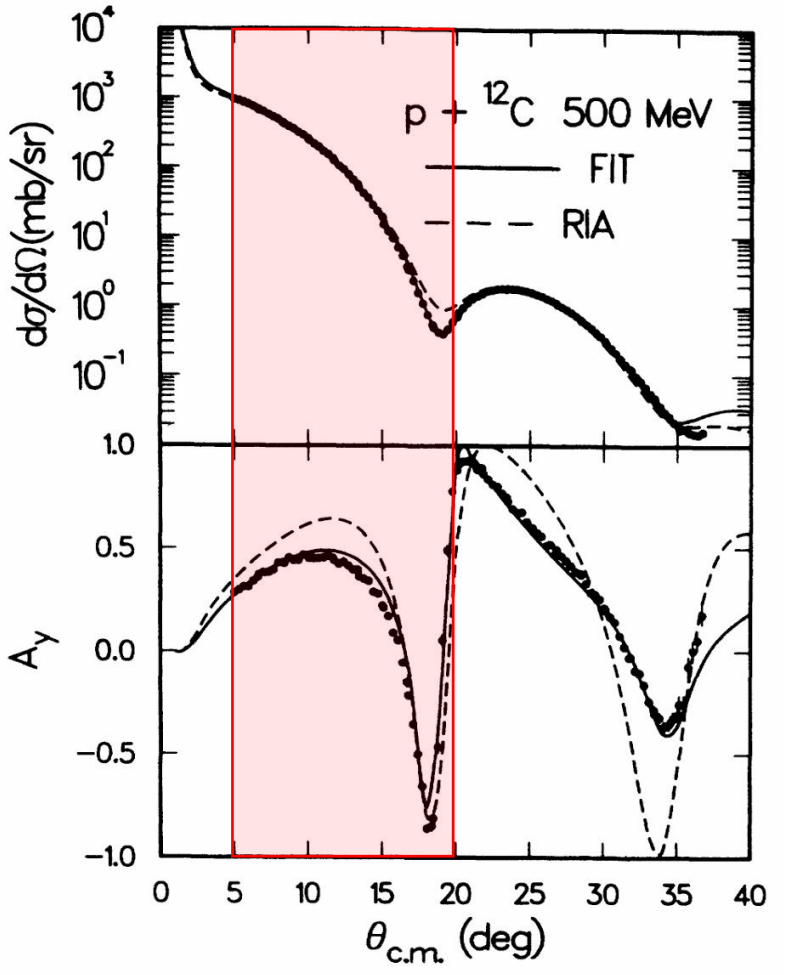
1) select the pp scattering signal.

2) measure the polarization precisely.

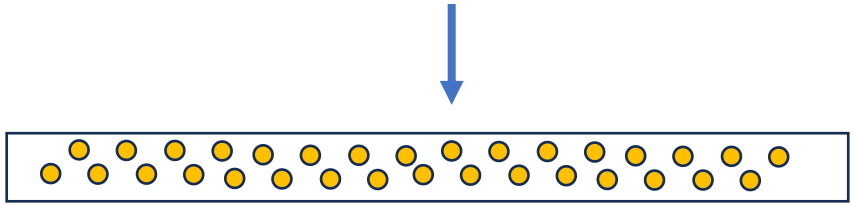
But statistics is limited!

Probability of pC scattering

σ ~ 54.5 mb



PRC.41 1651



Number of C nucleus per unit area (cm^{-2}), in CarbonFiber layer
= d * ρ * N_C/Molar_mass * A
= 0.1 cm * 1.57 g/cm^3 * 1/12 mol/g * $6.022*10^{23}$ /mol
= $7.9 * 10^{21}$ $/cm^2$

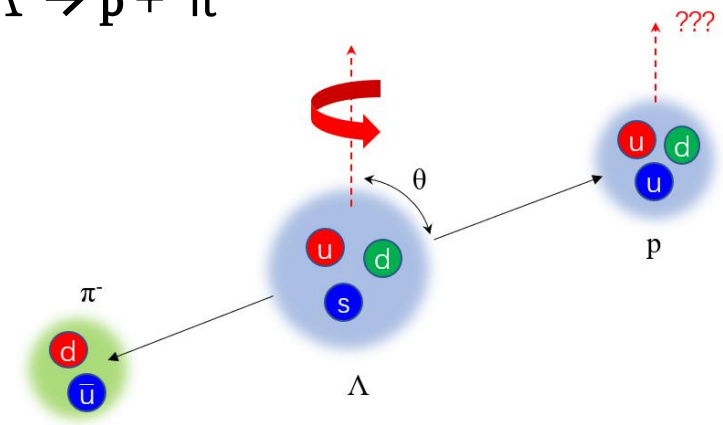
Cross section of p scattering off Carbon with scattering angle > 5°:
54.5 mb = $54.5* 10^{-27}$ cm^2

The probability of pC elastic scattering in Carbon layer of 1 mm:
Prob = $7.9 * 10^{21}$ $/cm^2$ * $54.5 * 10^{-27}$ cm^2
= $4.3 *10^{-4}$

Spin with valuable information

A reaction is described by the cross section and the polarization.

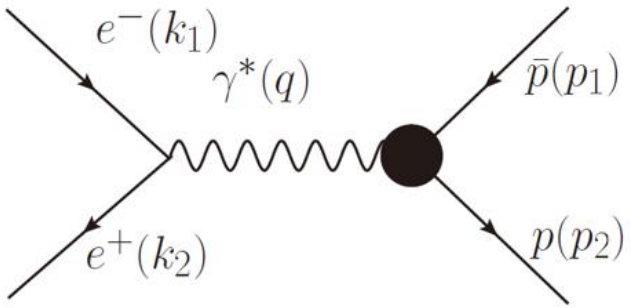
- $\Lambda \rightarrow p + \pi$



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

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

- $e^+e^- \rightarrow p\ \bar{p}$



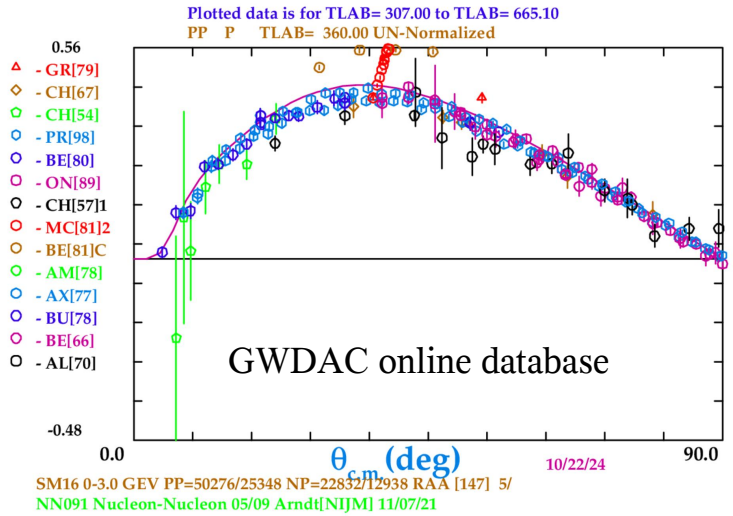
$$\frac{d\sigma_{p\bar{p}}(s)}{d\Omega} = \frac{\alpha^2\beta C}{4s}\left[|G_M(s)|^2(1+\cos^2\theta) + \frac{4m_p^2}{s}|G_E(s)|^2\sin^2\theta\right]$$ Cross section

$$\mathcal{P}_y = \frac{\sin 2\theta_p\,\Im\left[G_E G_M^*\right]}{\sqrt{\tau}\mathcal{D}}, \quad \mathcal{P}_x = \mathcal{P}_e\frac{\sin\theta_p\,\Re\left[G_E G_M^*\right]}{\sqrt{\tau}\mathcal{D}}, \quad \mathcal{P}_z = \mathcal{P}_e\frac{2\cos\theta_p|G_M|^2}{\mathcal{D}},$$ Polarization

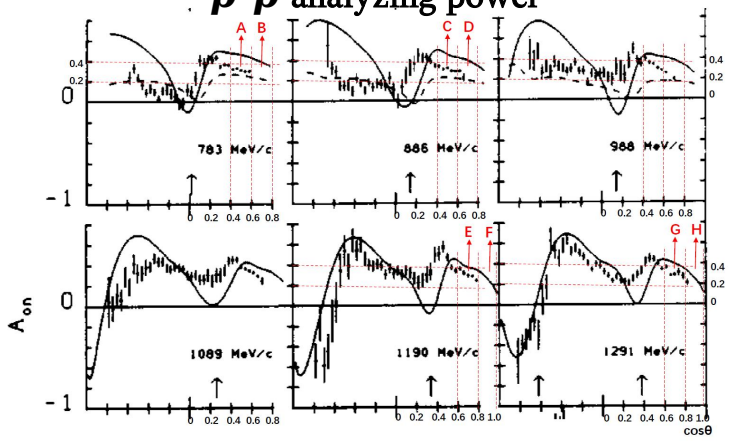
➢ The polarization contains valuable information.

Analyzing power well measured

$\vec{p}\ p$ analyzing power

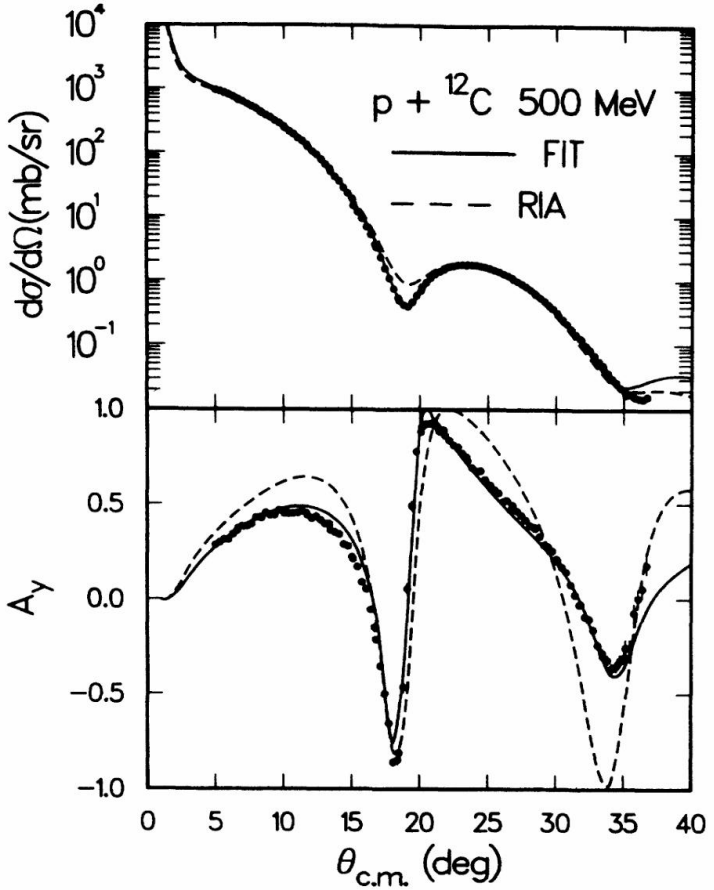


$\vec{\vec{p}}\ p$ analyzing power



Phys. Lett. B 206, 3, 1988

$\vec{p}$C analyzing power



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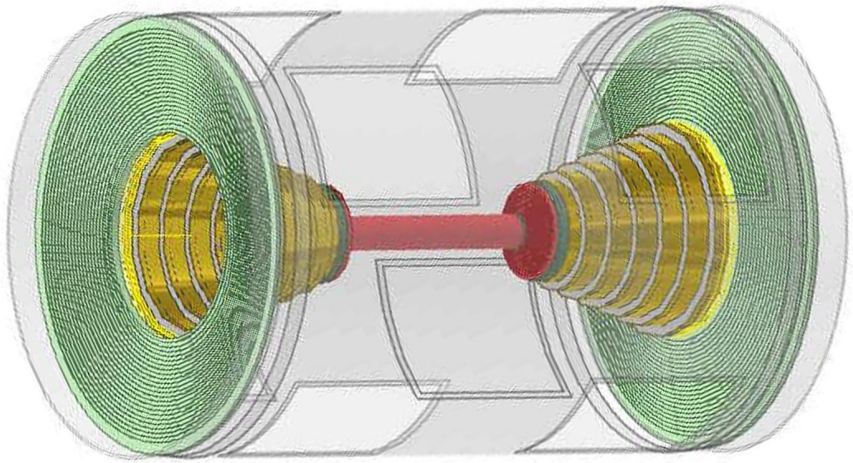
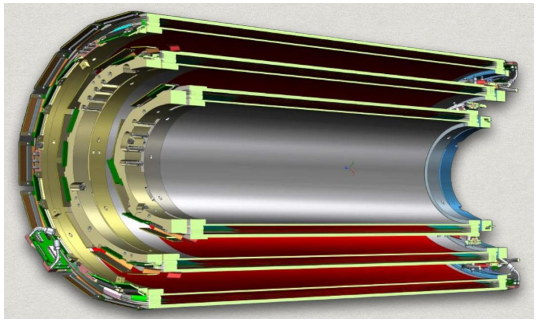
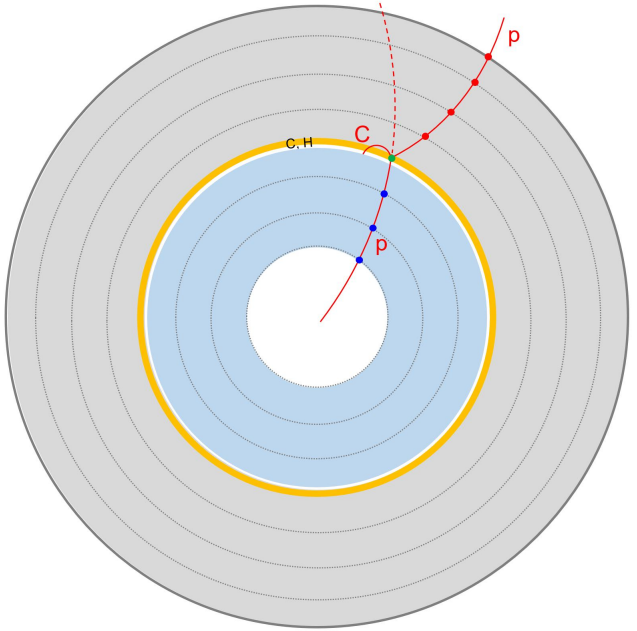
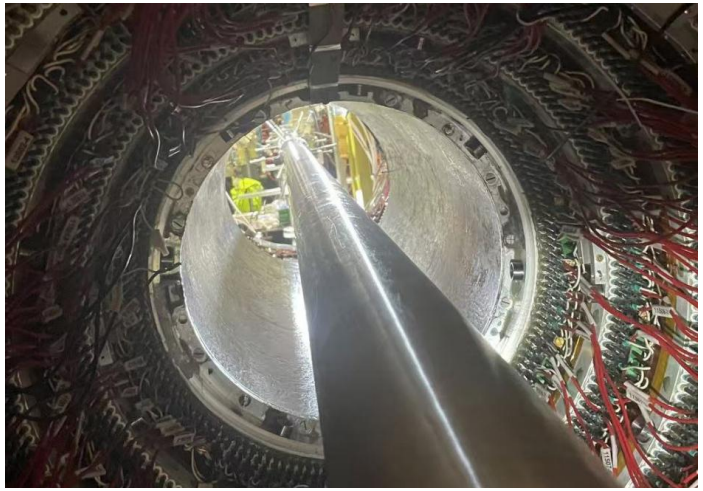
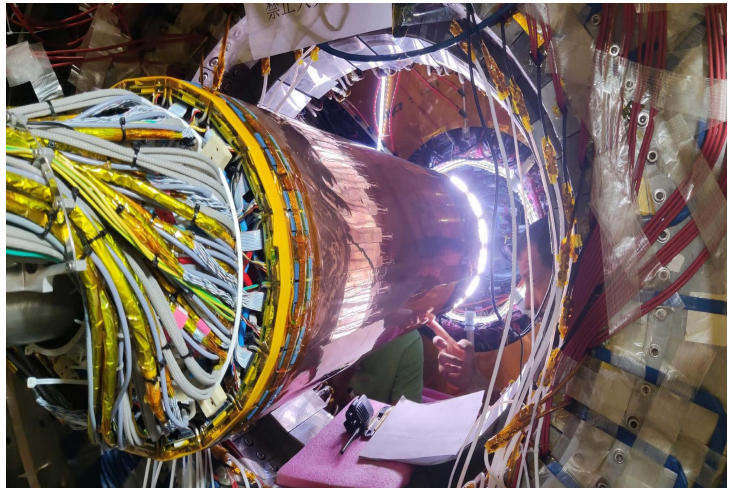
Physics potentials in e^+e^- machine -- BESIII











Dedicated proton polarimeter

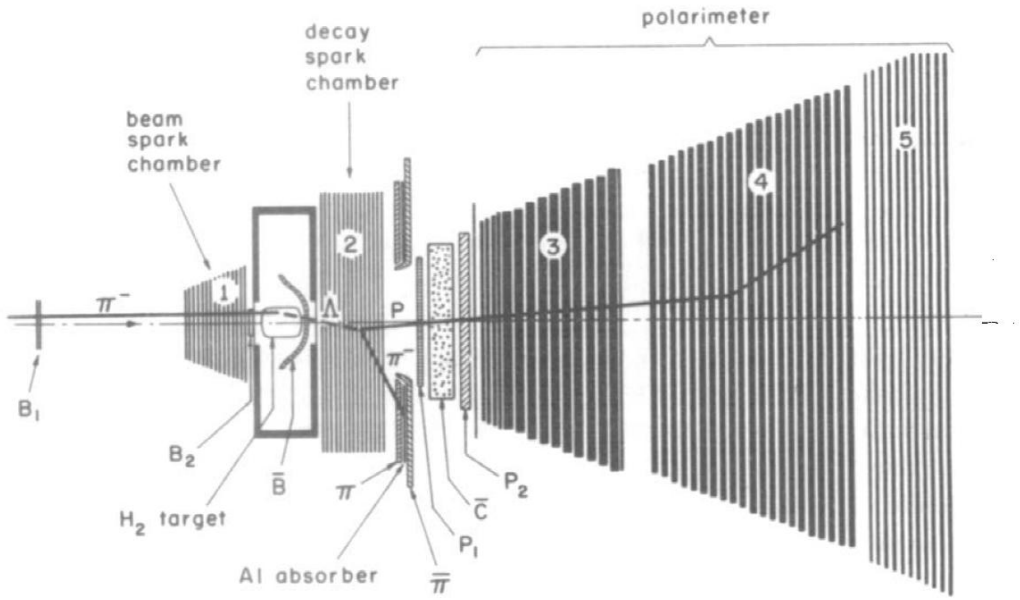


Fig. 3. Apparatus used to measure the polarization of protons from Λ^0 decay through proton-carbon scattering. The Λ^0 are produced in hydrogen. The counters π and $\bar{\pi}$ select low-energy decay pions, while P_1 P_2 $\bar{C}$ select decay protons. All counters are made of plastic scintillator except for $\bar{C}$, which is a water Čerenkov counter. The polarimeter consists of carbon plate spark chambers. The tracks are photographically recorded with 90° stereo.

[1] Nuclear Physics B40 (1972) 221-254.

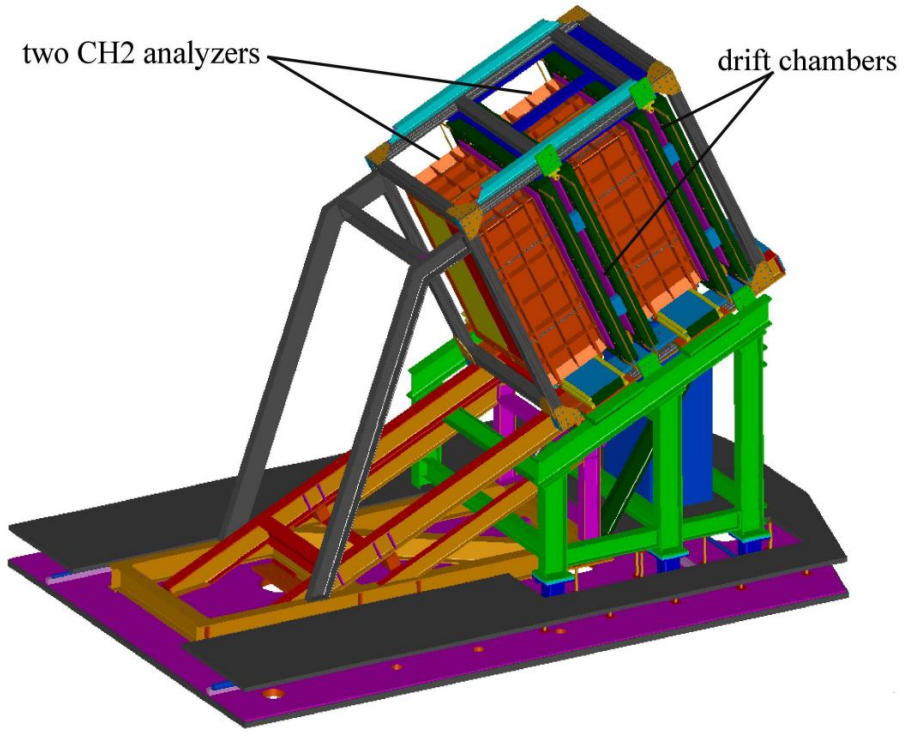


Figure 5: The FPP in the HMS in Hall C as currently designed.

[2] AIP Conf. Proc. 412, 342 – 348 (1997)

- **Difficult to integrate to the multi-purpose detector concept**