From H-NS to EicC at HIAF

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Outline

- A brief introduction to HIAF
- EicC physics
- H-NS physics
- Summary

HIAF: High Intensity heavy-ion Accelerator Facility

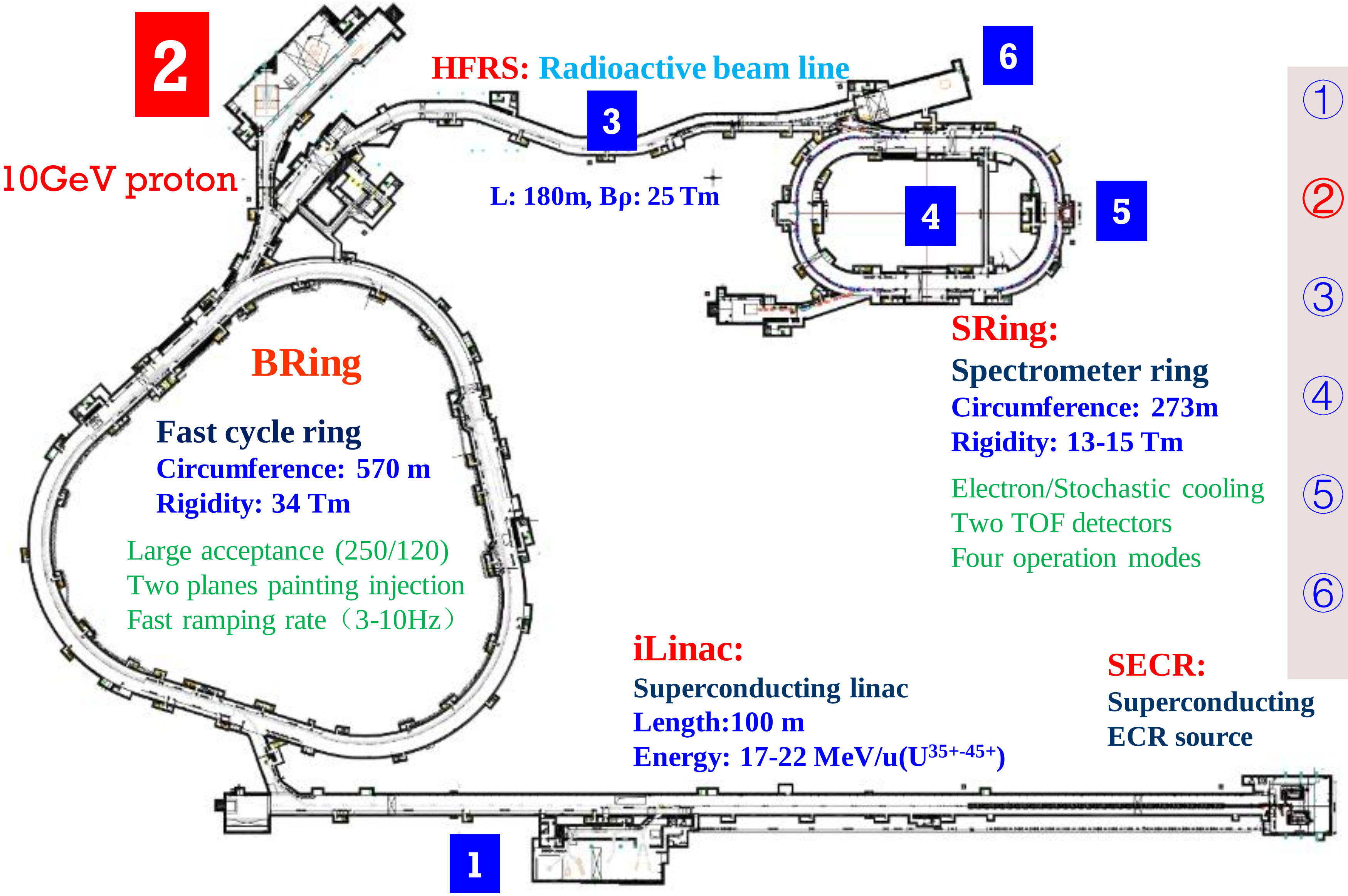
Budget ~3 billion CNY (including civil construction), start from Dec. 2018, installation finished in Sept. 2025, located in Huizhou.

December 2018

September 2025

First beam on Oct. 28th 2025 !

HIAF layout



① Low energy nuclear structure terminal
② **High energy experimental terminal**
③ High energy fragment separator HFRS
④ High precision spectrometer ring SRing
⑤ Electron ion recombination terminal
⑥ Radioactive ion beam physics terminal

HIAF beam parameters

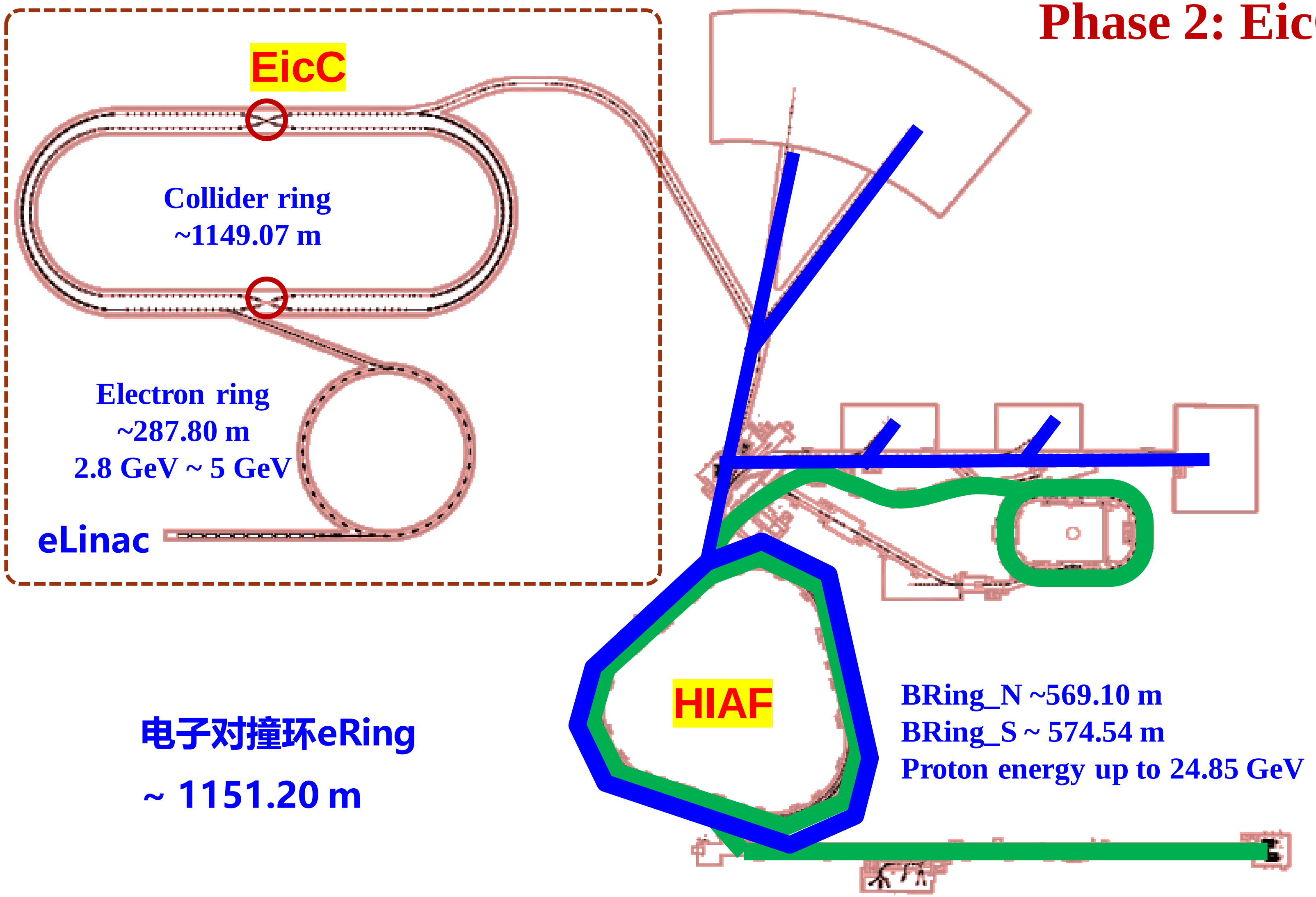
Ion species	Kinetic Energy (GeV/u)	Beam intensity (ppp)
p	9.3	6.0×10^{12}
$^{16}O^{8+}$	4.25	6.0×10^{11}
$^{18}O^{6+}$	2.6	6.0×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{35+}$	0.835	1.0×10^{11}
$^{238}U^{78+}$	2.6	1.0×10^{10}

HIAF upgrade

Phase 0-ongoing: HIAF for nuclear physics

Phase 1: HIAF upgrade for applied science

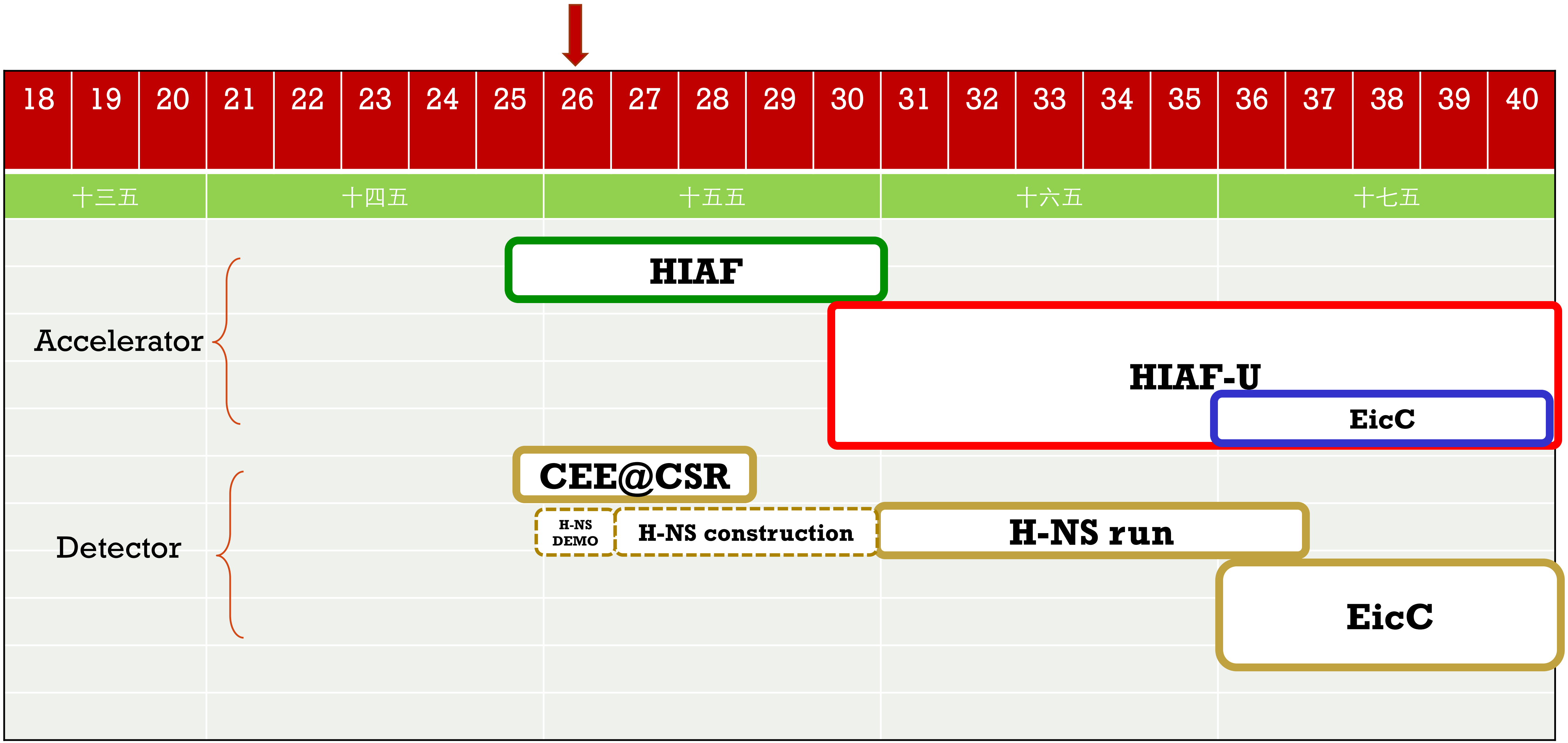
Phase 2: EicC



EicC beam parameters

Parameter	electron	proton
Circumference (m)	1151.20	1149.81
Kinetic energy (GeV)	3.5	19.08
CM energy (GeV)	**16.76**	
$f_{collision}$ (MHz)	100	
Polarization	80%	70%
Bunch intensity ($\times 10^{11}$)	1.7	1.05
$\varepsilon_x, \varepsilon_y$ (nm·rad, rms)	50/15	**100/50**
β_x^*/β_y^* (cm)	10/4	5/1.2
RMS divergence (mrad)	-	**1.4/2.0**
Bunch length (cm, rms)	0.75	8
Average current (A)	2.7	1.68
Crossing angle (mrad)	50	
Luminosity($cm^{-2}s^{-1}$)	**4.25×10^{33}**	

Timeline



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十三五
十四五
十五五
十六五
十七五
HIAF
Accelerator
HIAF-U
EicC
CEE@CSR
H-NS DEMO
H-NS construction
H-NS run
Detector
EicC

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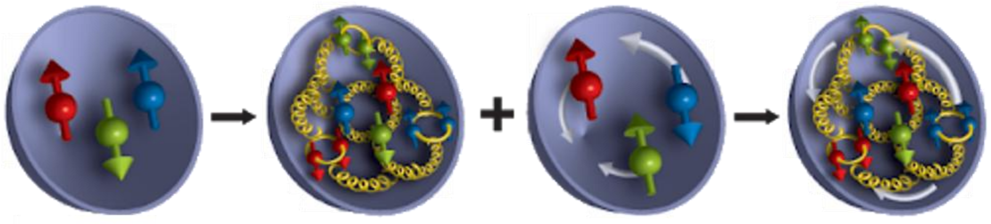
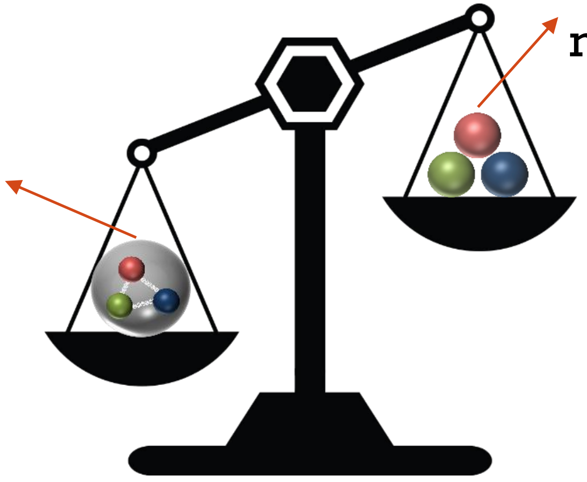
Physics of EicC:
Origin of nucleon spin and mass





Spin decomposition:

$$S_{tot} = \frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{Quark spin}} + \underbrace{\Delta G}_{\text{Gluon Spin}} + \underbrace{\mathcal{L}_q}_{\text{Quark OAM}} + \underbrace{\mathcal{L}_g}_{\text{Gluon OAM}}$$

Mass decomposition:

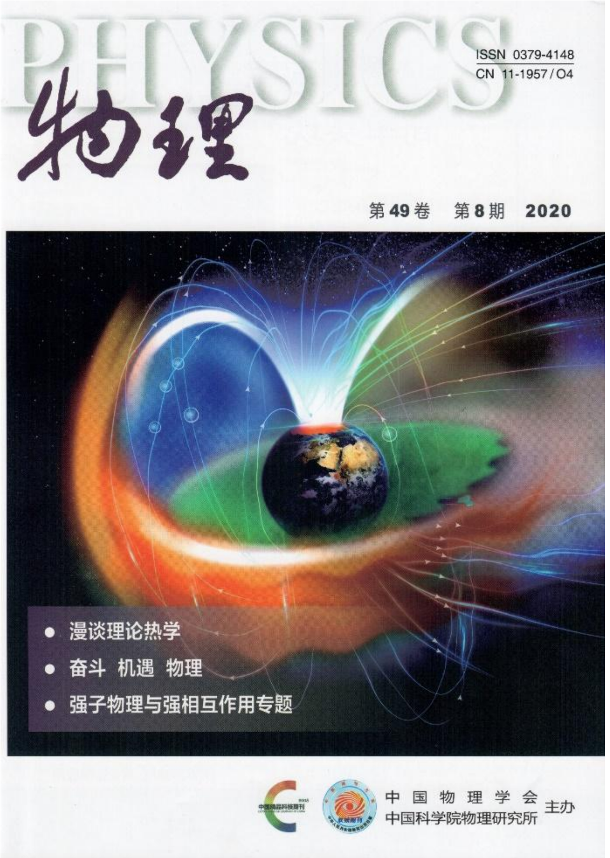
$$M = \underbrace{M_q}_{\text{Quark energy}} + \underbrace{M_m}_{\text{Quark mass}} + \underbrace{M_g}_{\text{Gluon energy}} + \underbrace{M_a}_{\text{Trace anomaly}}$$

we need to determine each of the above contributions

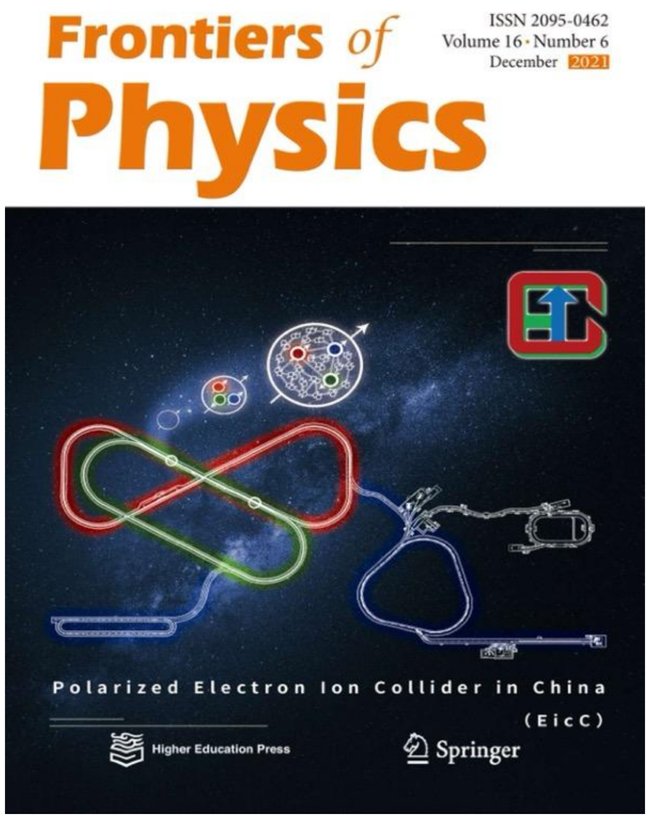
EicC milestones after the idea been proposed in 2012

EicC Chinese WP (2020)

Physics (2020)



EicC English WP (2021)



EicC CDR (2024)

EicC

Conceptual Design Report

Volume I: Accelerator

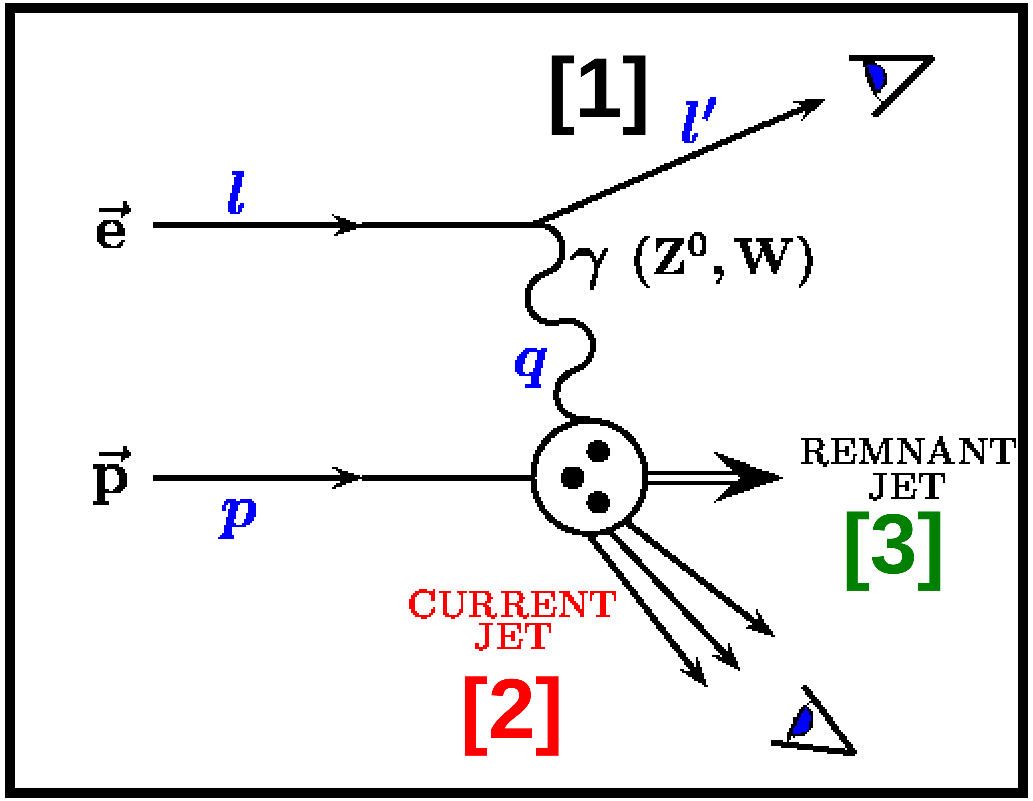
EicC

Conceptual Design Report

Volume II - Physics & Detector

Efforts of around 45 institutes and more than 200 physicists

Lepton-Nucleon Scatterings



QED tool to study QCD nature of the nucleon

$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p\cdot q}$$

$$y = \frac{p\cdot q}{p\cdot l}$$

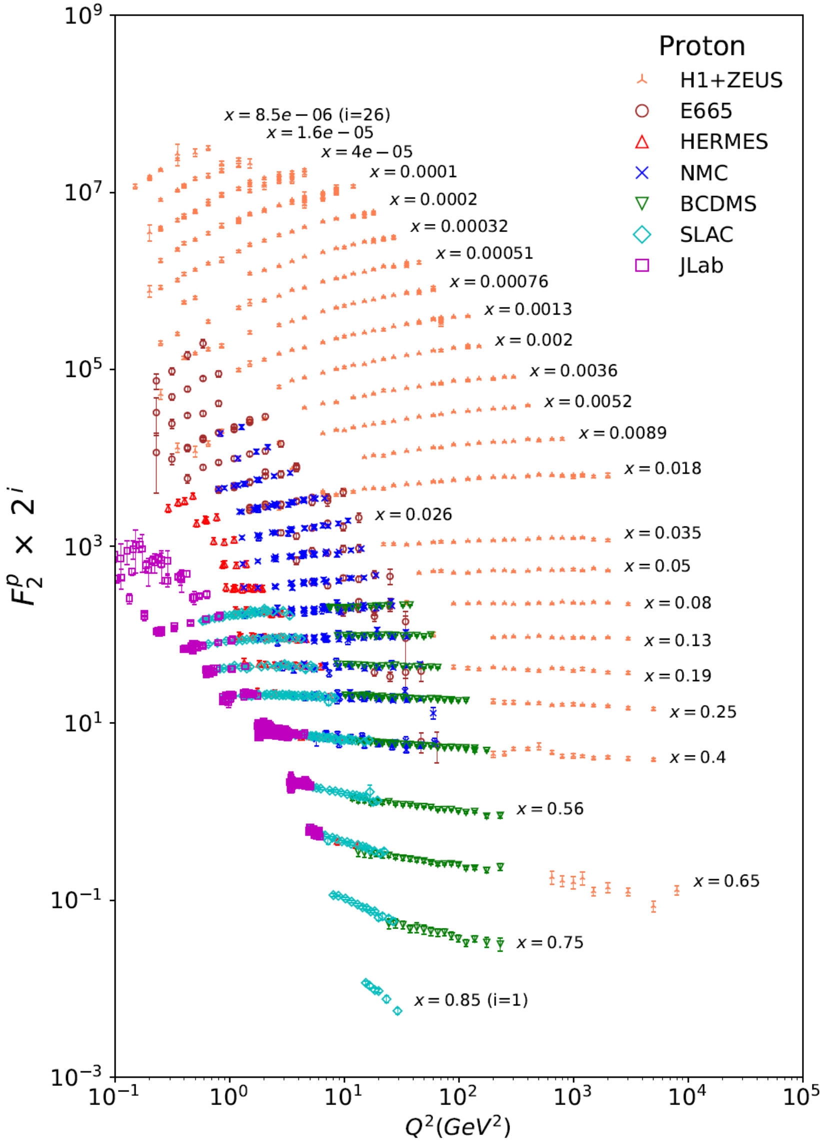
$$s = 4E_e E_p$$

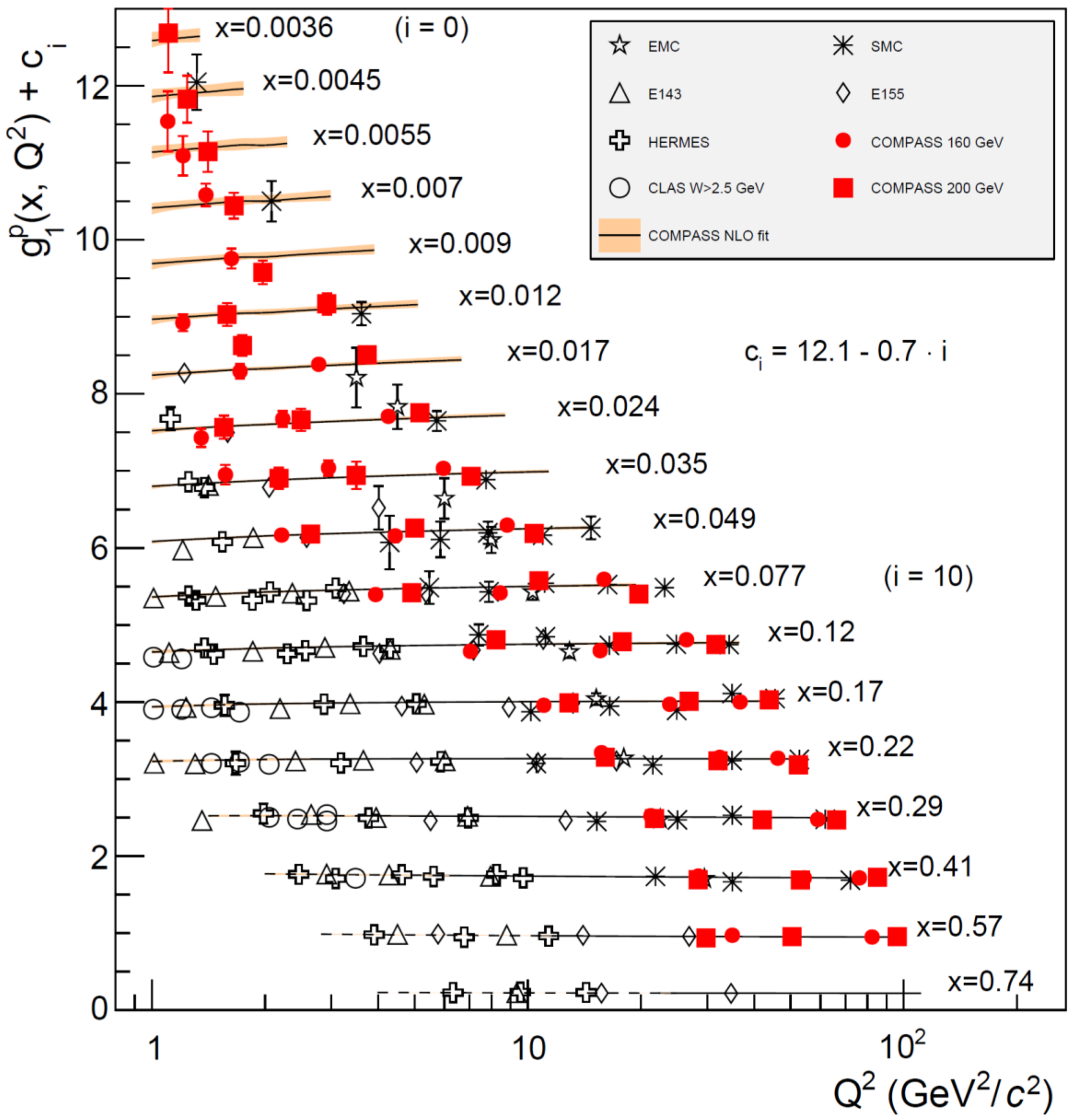
$$W = (q+p)^2$$

- QED probe is clean
- α_{EM} ~1/137 with broad Q coverage
- One-photon exchange approximation: ~1% accuracy
- Detection scale is determined by Q: 200MeV ~ nucleon size

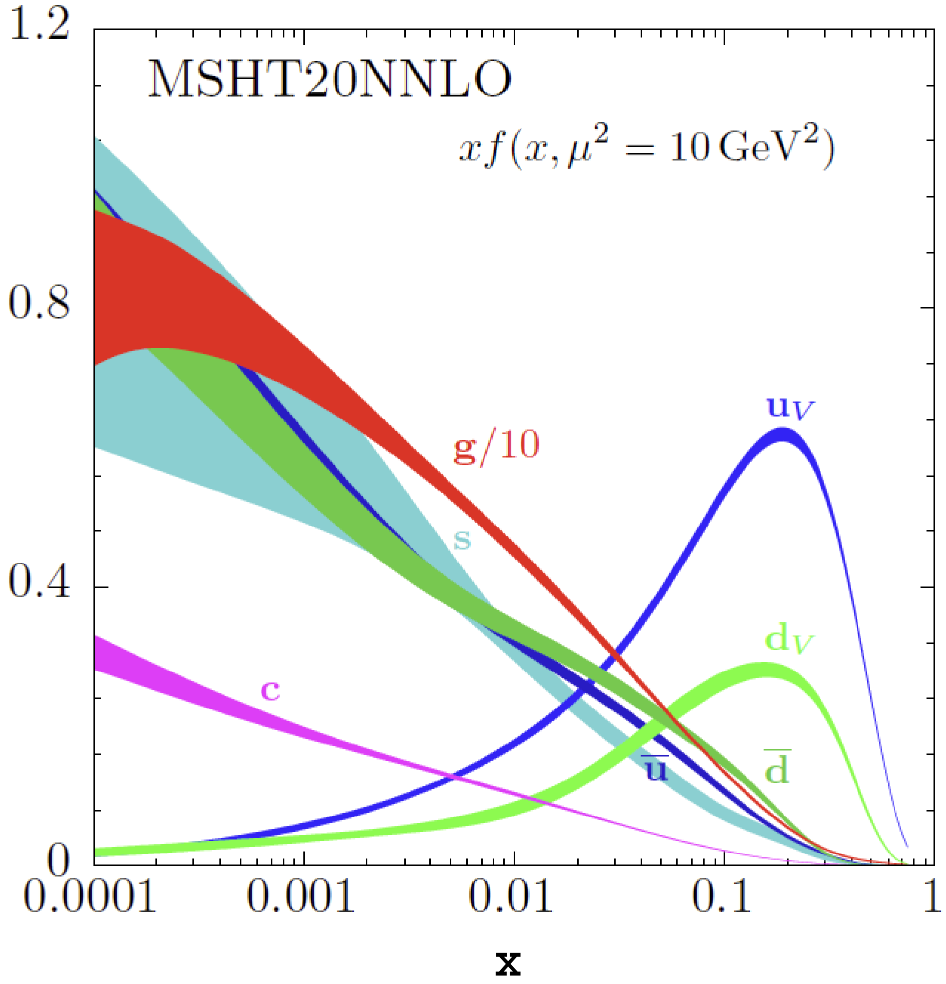
Observe scattered electron/muon	[1]	→ **inclusive**
Observe current jet/hadron	[1]+[2]	→ **semi-inclusive**
Observe remnant jet/hadron as well	[1]+[2]+[3]	→ **exclusive**

Inclusive process

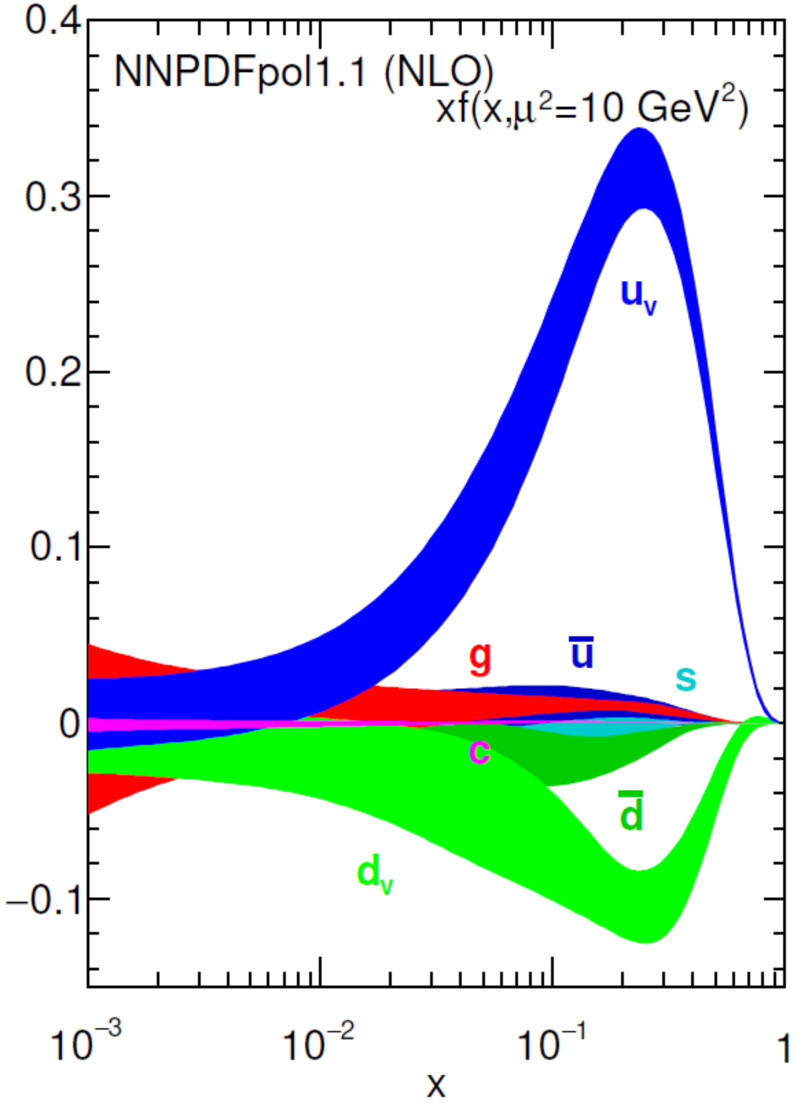




Inclusive process



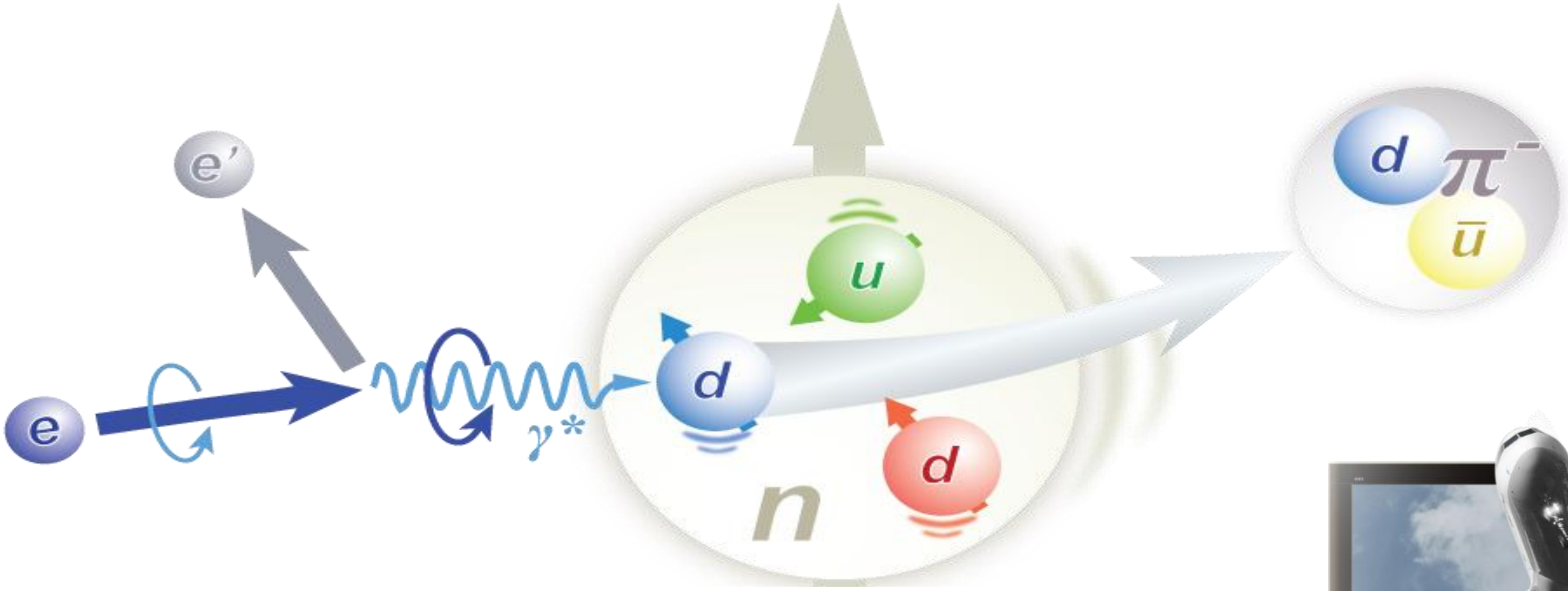
Unpolarized PDFs



Polarized PDFs: helicity distribution

Quark/gluon spin contribution to proton spin

Semi-inclusive process



From 1D to 3D for nucleon structure study

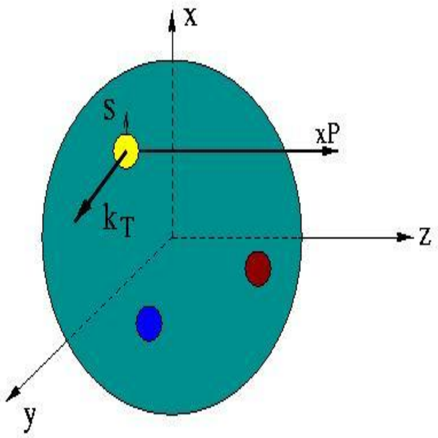
Need polarized target and polarized electron beam

Unified view of nucleon structure

$W_p^u(x,k_T,r)$ *Wigner distributions* **(X. Ji)**

6D Dist.

d^3r $\qquad$ $d^2k_T\, dr_z$



TMD PDFs

$f_1^u(x,k_T)$, ..

$h_1^u(x,k_T)$

GPDs/IPDs

3D imaging

Use it as an example to demonstrate the impact of EicC

d^2k_T $\qquad$ d^2r_T

dx & Fourier Transformation

PDFs

$f_1^u(x)$, $\Delta f_1^u(x)$, $h_1^u(x)$

1D

Form Factors

$G_E(Q^2)$,

$G_M(Q^2)$

Leading-Twist TMDs

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^{\perp} = \quad -$ Boer-Mulders
	L		$g_1 = \quad -$ Helicity	$h_{1L}^{\perp} = \quad -$ Worm Gear
	T	$f_{1T}^{\perp} = \quad -$ Sivers	$g_{1T} = \quad -$ Worm Gear	$h_1 = \quad -$ Transversity $h_{1T}^{\perp} = \quad -$ Pretzelosity

Nucleon Spin *Quark Spin*

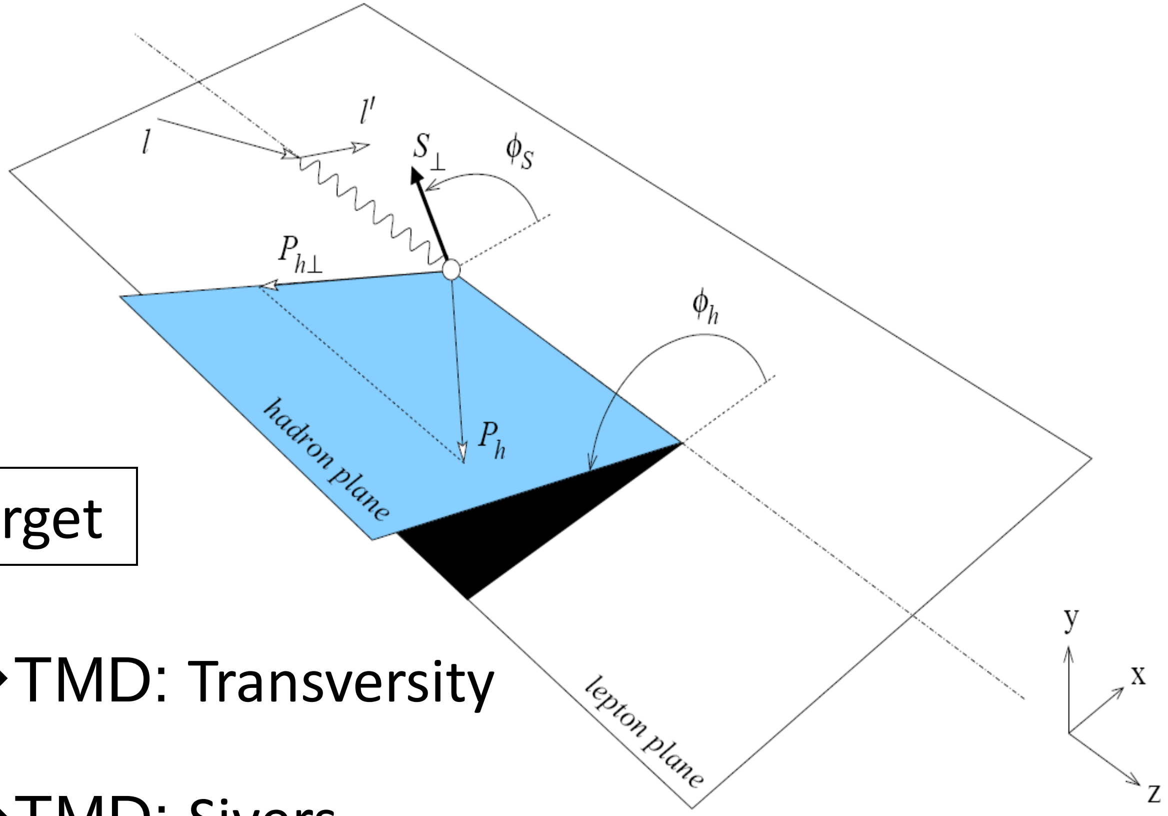
Survive the k_T integration, yield 1D pdfs

Separation of Collins, Sivers and Pretzelosity through azimuthal angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$



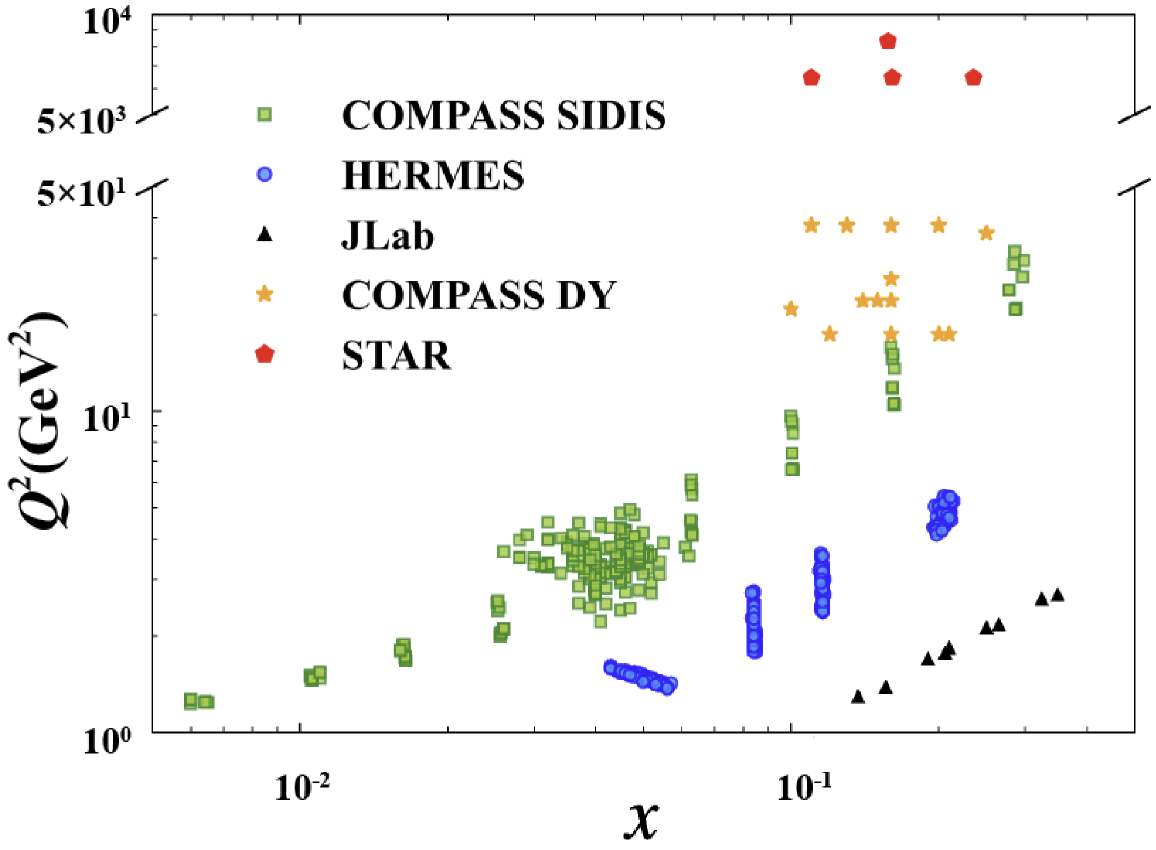
UT: **U**npolarized beam + **T**ransversely polarized target

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$ →TMD: Transversity

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$ →TMD: Sivers

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$ →TMD: Pretzelosity

World data



Data set	Target	Beam	Reaction
HERMES [39]	H_2	27.6 GeV $e^\pm$	$e^\pm p \to e^\pm \pi^\pm (K^\pm) X$
COMPASS [40]	^{6}LiD	160 GeV μ^+	$\mu^+ d \to \mu^+ \pi^\pm (K^\pm) X$
x bin			
z bin			
$P_{h\perp}$ bin			
COMPASS [41]	NH_3	160 GeV μ^+	$\mu^+ p \to \mu^+ \pi^\pm (K^\pm) X$
x bin			
z bin			
$P_{h\perp}$ bin			
COMPASS [45]	^{6}LiD	160 GeV μ^+	$\mu^+ d \to \mu^+ h^\pm X$
x bin			
z bin			
$P_{h\perp}$ bin			
JLab2011 [42]	^{3}He	5.9 GeV e^-	$e^- n \to e^- \pi^\pm X$
JLab2014 [43]	^{3}He	5.9 GeV e^-	$e^{-\,3}\mathrm{He} \to e^- K^\pm X$

Recent knowledge of TMDs via global data fit
- by Transverse Nucleon Tomography Collaboration

Sivers distribution functions:

Chunhua Zeng, Tianbo Liu, Peng Sun, Yuxiang Zhao, Phys. Rev. D 106 (2022) 094039.

Transversity distribution functions and Collins fragmentation functions:

Chunhua Zeng, Hongxin Dong, Tianbo Liu, Peng Sun, Yuxiang Zhao, Phys. Rev. D 109 (2024) 056002.

Trans-helicity worm-gear distribution functions:

Ke Yang, Tianbo Liu, Peng Sun, Yuxiang Zhao, Bo-Qiang Ma, Phys. Rev. D 110 (2024) 034036.

Transverse momentum dependent helicity distribution functions:

Ke Yang, Tianbo Liu, Peng Sun, Yuxiang Zhao, Bo-Qiang Ma, Phys. Rev. Lett. 134 (2025) 121902.

Sivers, transversity, and Collins functions including DY and new COMPASS data:

Chunhua Zeng, Hongxin Dong, Tianbo Liu, Peng Sun, Yuxiang Zhao, Phys. Lett. B (2025).

Helicity distributions and azimuthal modulations in longitudinal DSA:

Ke Yang, Tianbo Liu, Peng Sun, Yuxiang Zhao, Bo-Qiang Ma, in preparation.

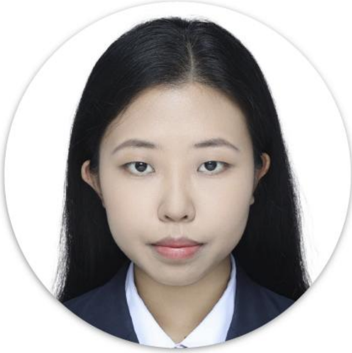
Transverse Nucleon Tomography Collaboration

Tianbo Liu
SDU

Bo-Qiang Ma
PKU/ZZU

Peng Sun
IMP

Yuxiang Zhao
IMP



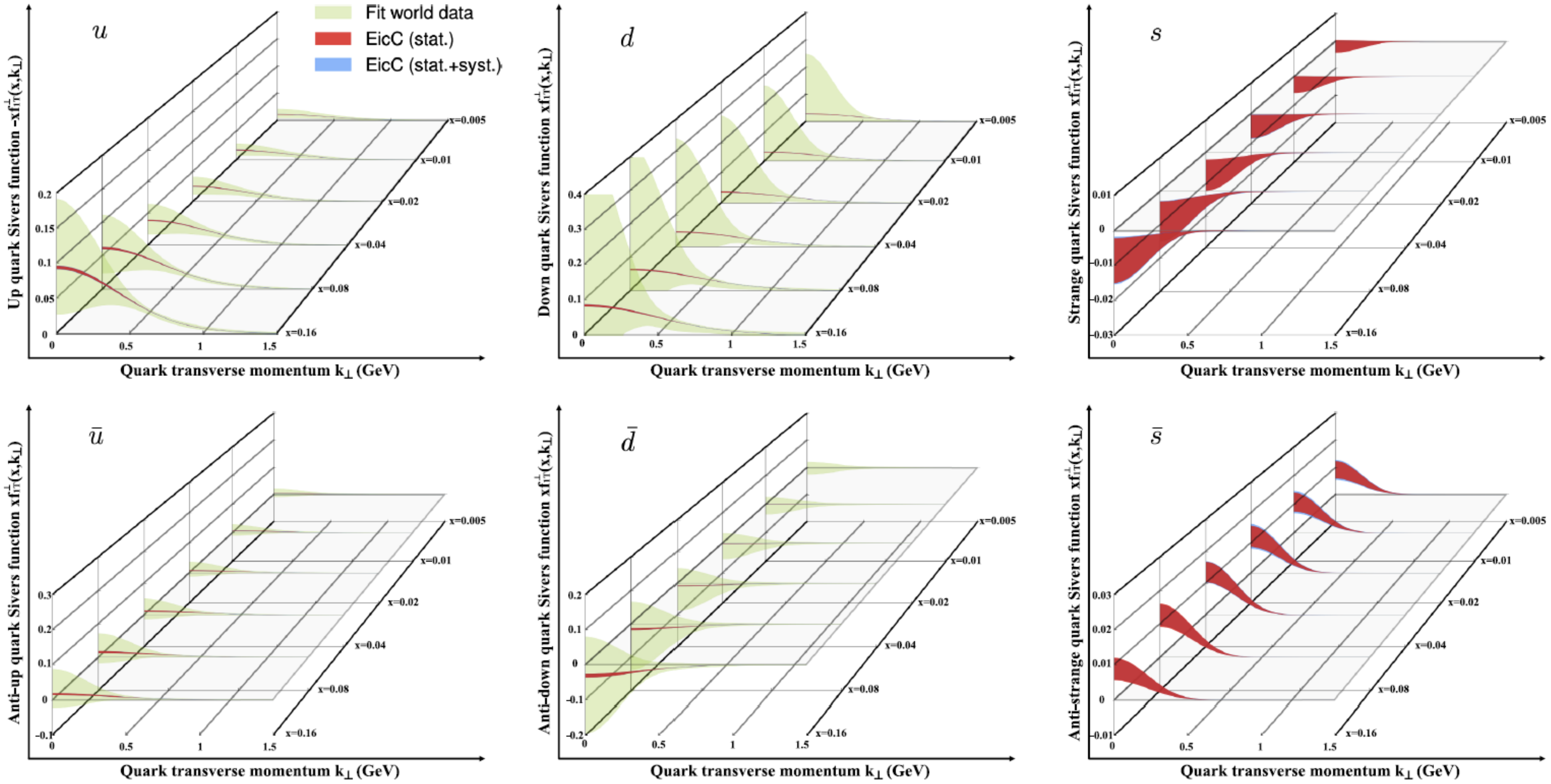
Weiwei Chen
SDU

Hongxin Dong
NJNU

Ke Yang
SDU

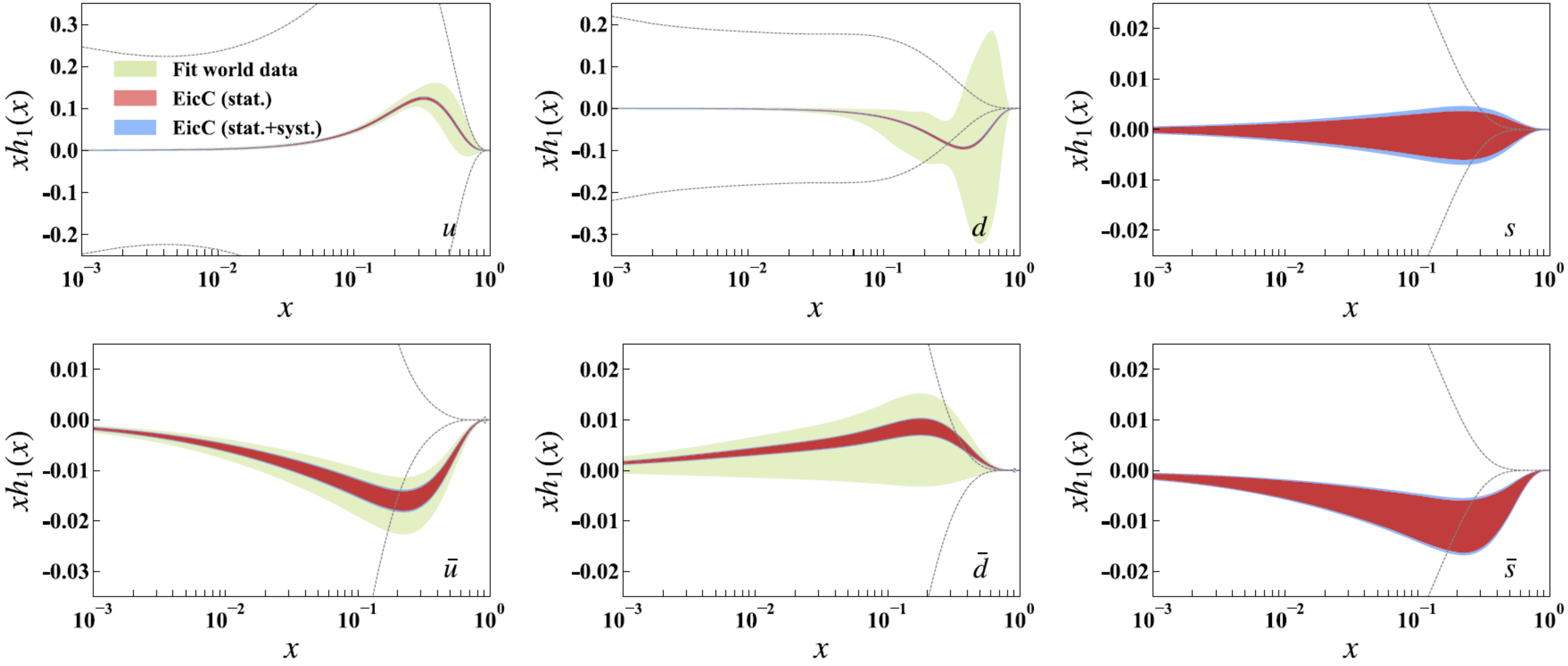
Chunhua Zeng
IMP

EicC impact on Sivers functions



C. Zeng, T. B. Liu, P. Sun, and Y. X. Zhao, Phys. Rev. D 106, 094039 (2022)

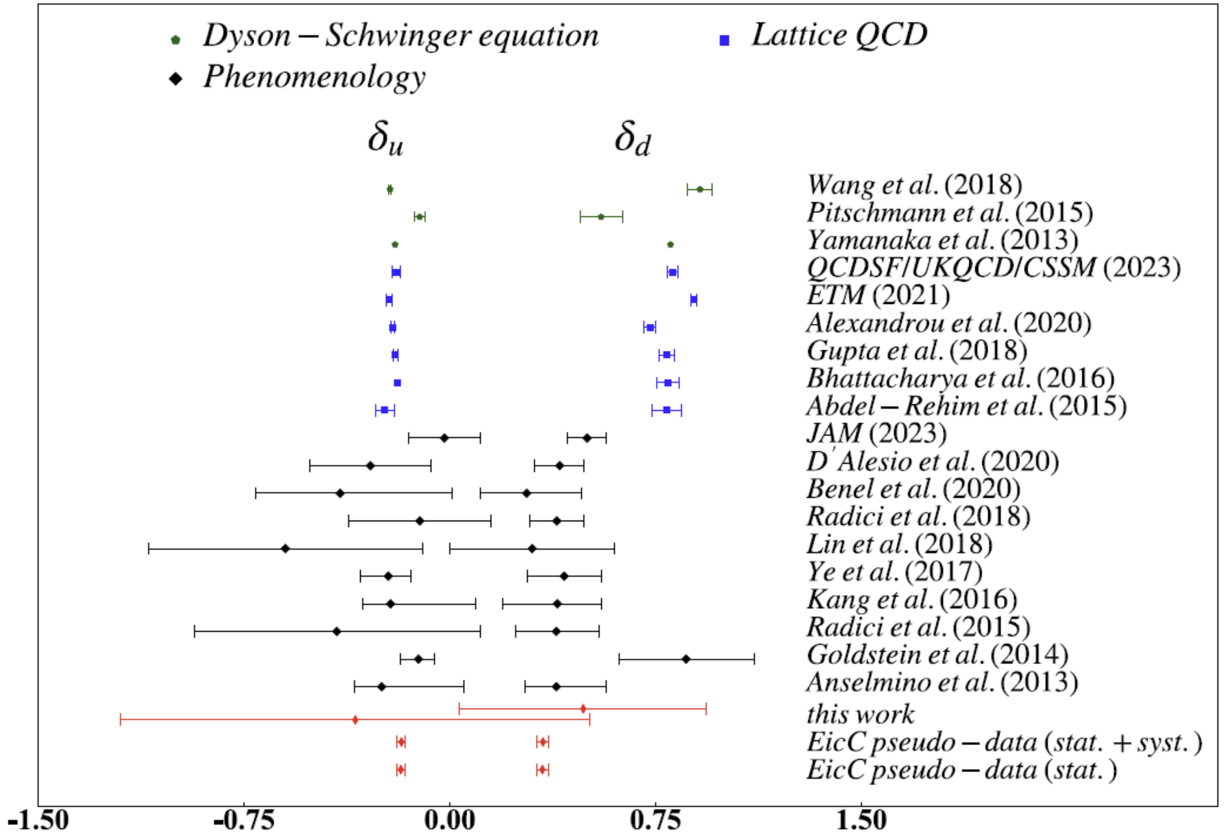
EicC impact on Transversity

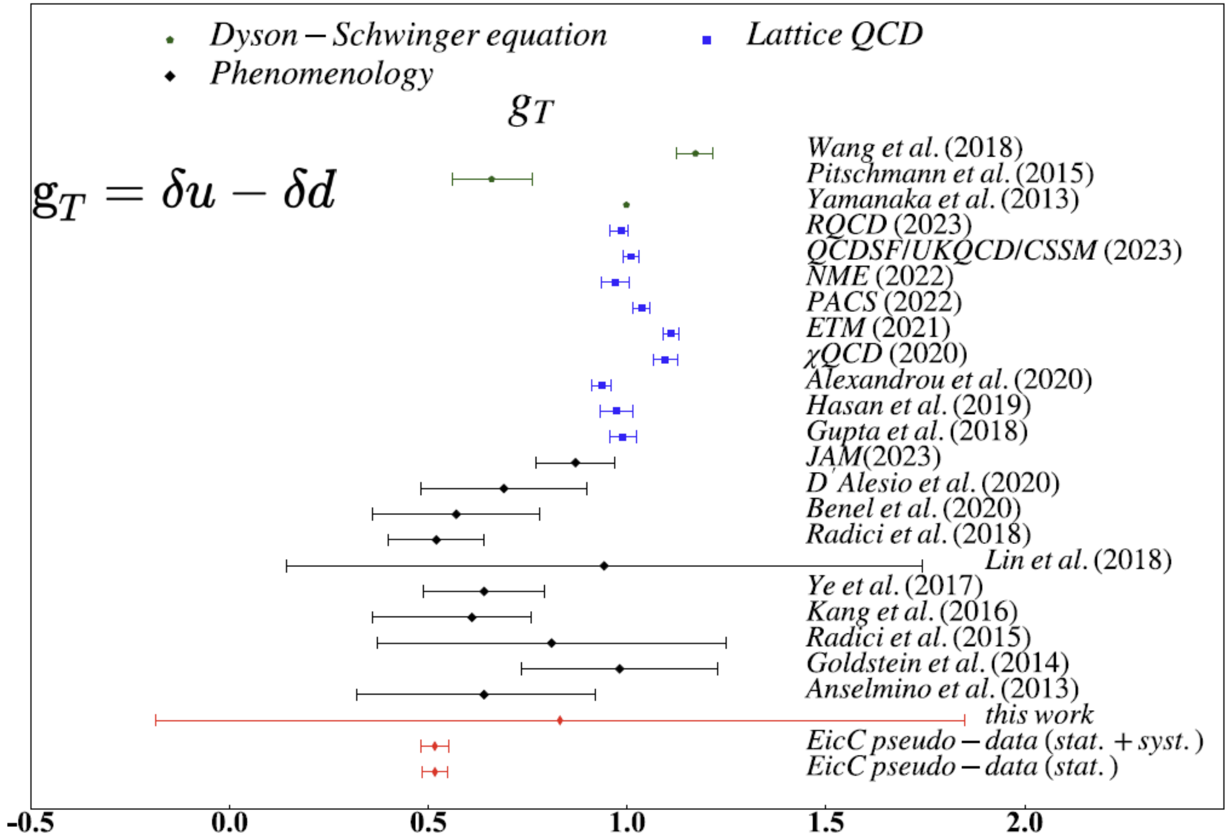


EicC can significantly improve the precision of transversity distributions, especially for sea quarks

C. Zeng, H. Dong, T. B. Liu, P. Sun, and Y. X. Zhao, Phys. Rev. D 109 (5), 056002 (2024)

EicC impact on Tensor Charge

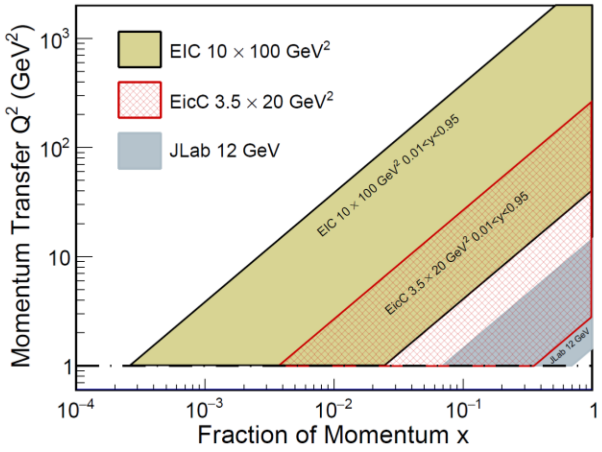




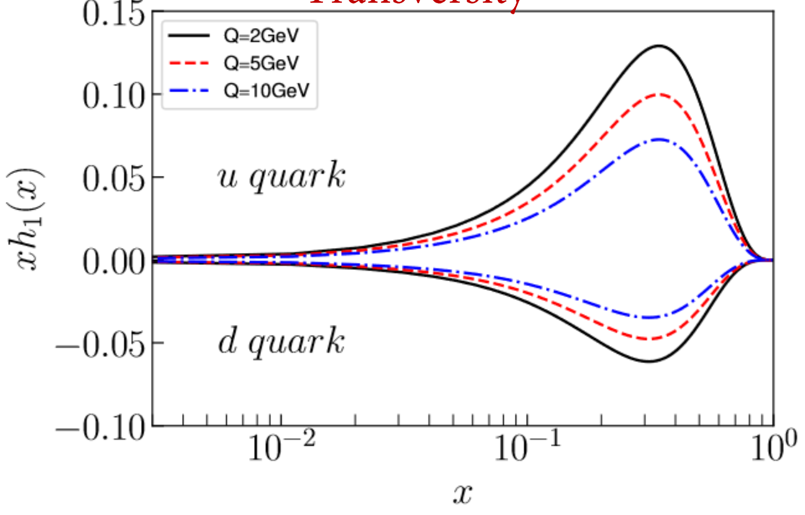
Larger uncertainties when including anti-quarks (less biased)
Compatible with lattice QCD calculations

C. Zeng, H. Dong, T. B. Liu, P. Sun, and Y. X. Zhao, Phys. Rev. D 109 (5), 056002 (2024)

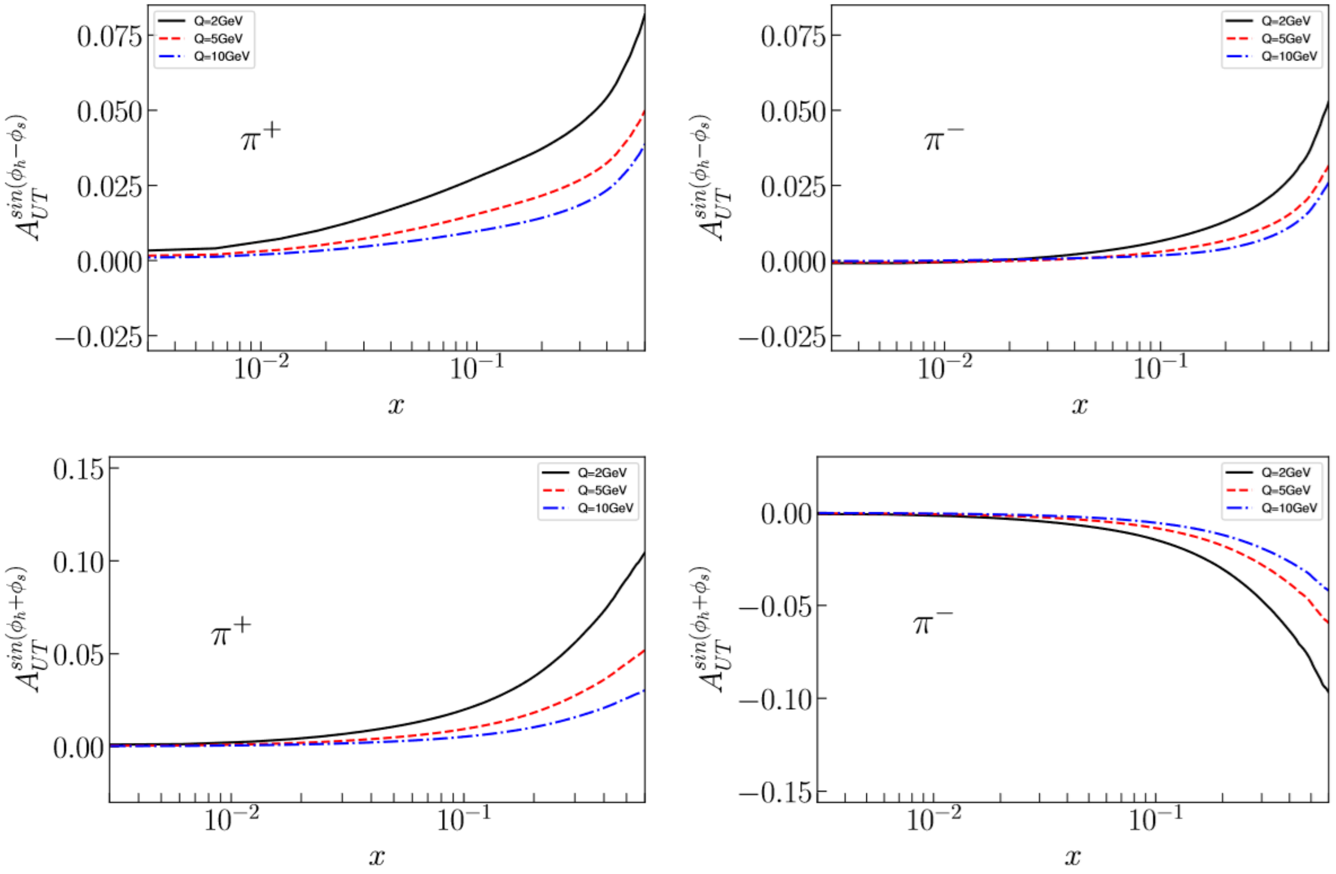
More words on TMDs study



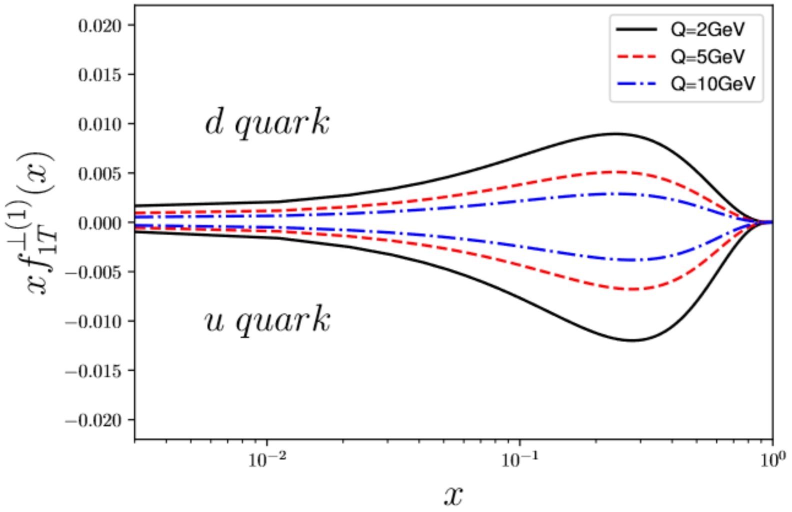
Transversity



Observables



Sivers



For TMDs study: We need a moderate-energy EIC but with high luminosity

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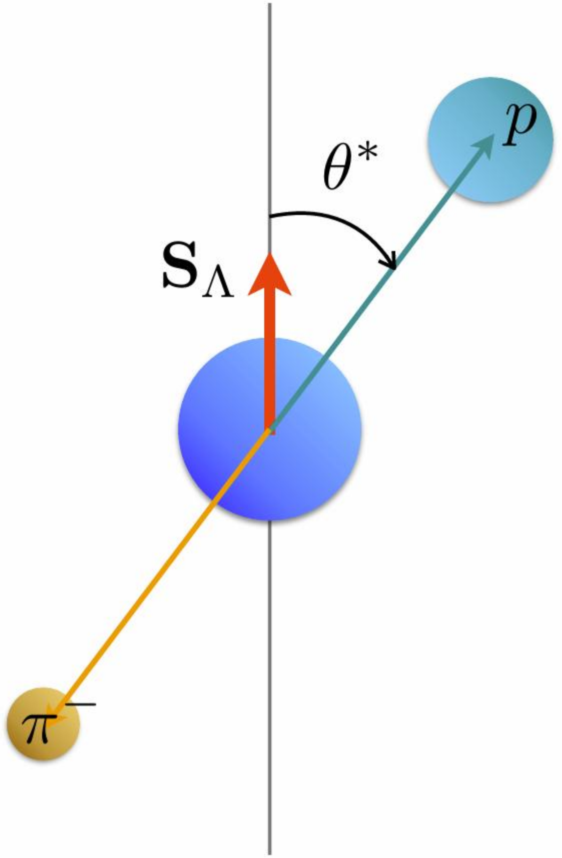
A new domain for spin physics: from nucleon to hyperon

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



Decay channel: $\Lambda \to p\pi^-$

branch ratio: $64.1 \pm 0.5\%$

parity violating weak decay

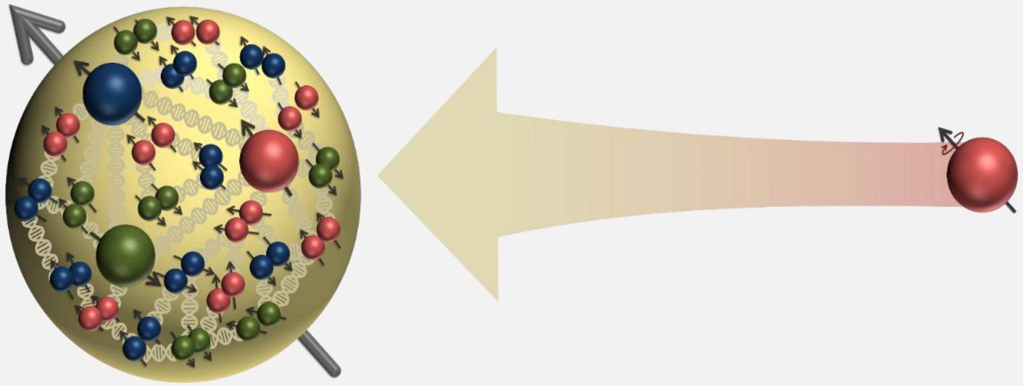
$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} \propto \mathcal{A}\left(1 + \alpha_\Lambda P_\Lambda \cos\theta^*\right)$$

decay parameter: $\alpha_\Lambda = 0.748 \pm 0.007$

[Current PDG value]

From Nucleon spin to hyperon polarization

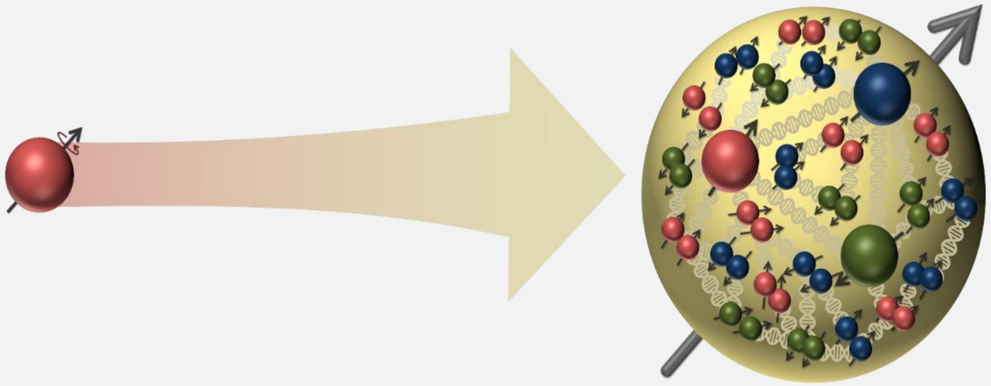
EIC: **Initial state** is polarized
-How do partons form up a polarized nucleon?



Initial state

Polarized by device

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

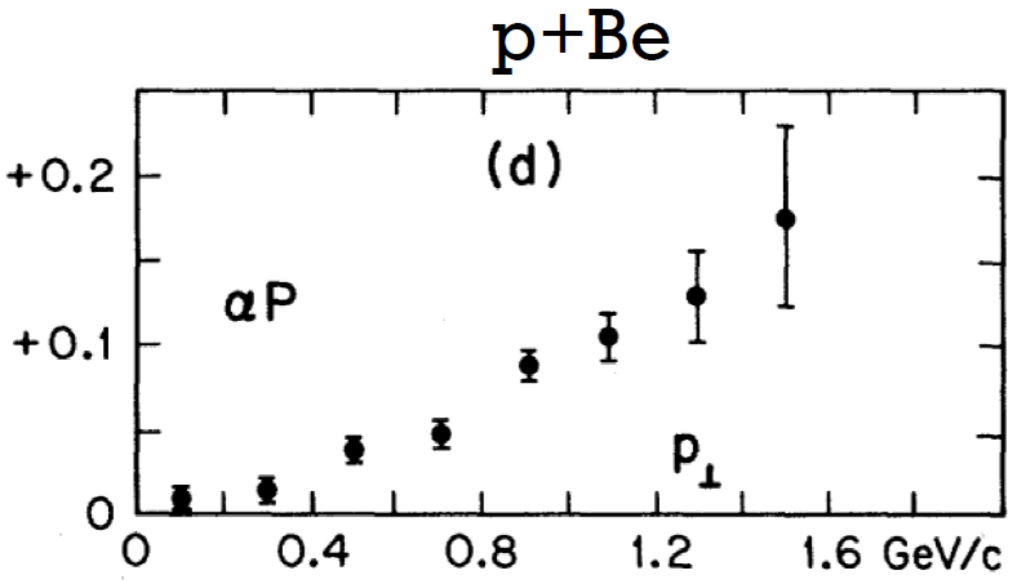


Final state

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

origin of nucleon spin VS origin of Λ polarization

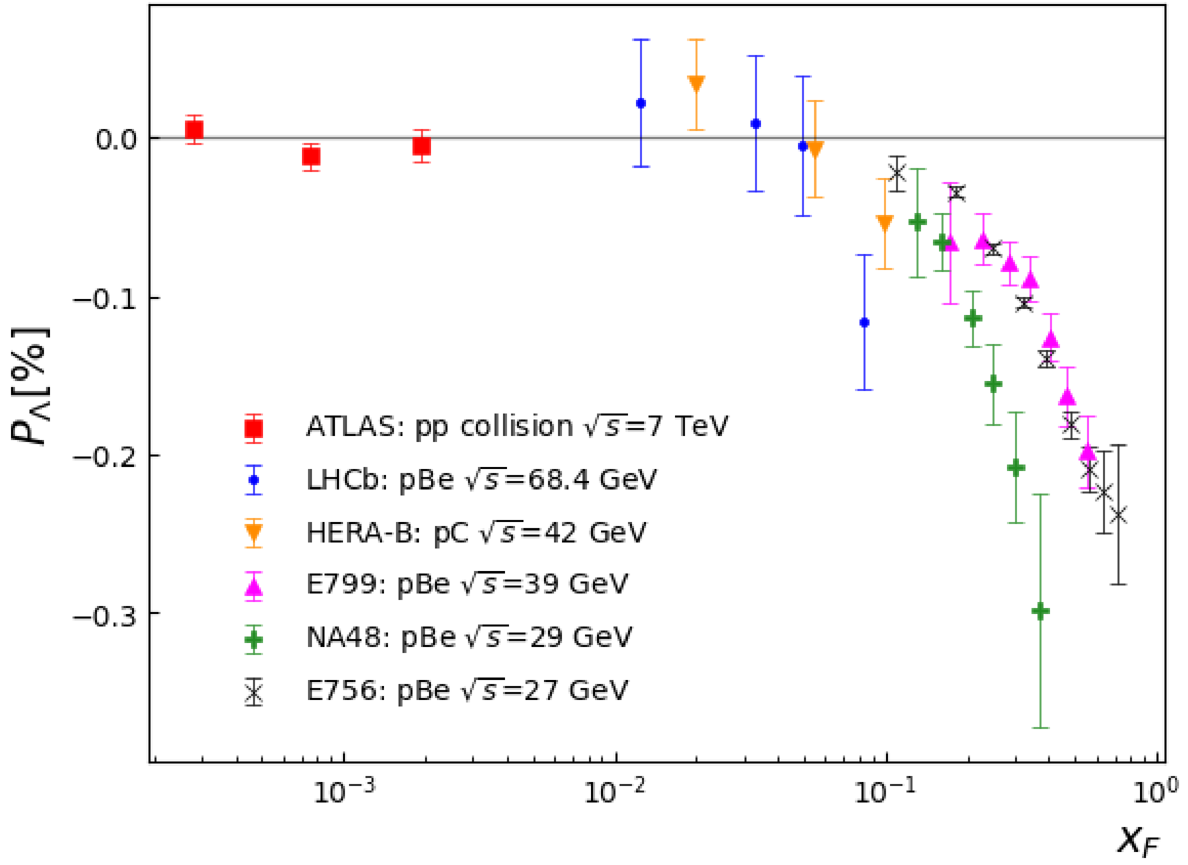
First observation of Λ^0 polarization in the 1970's

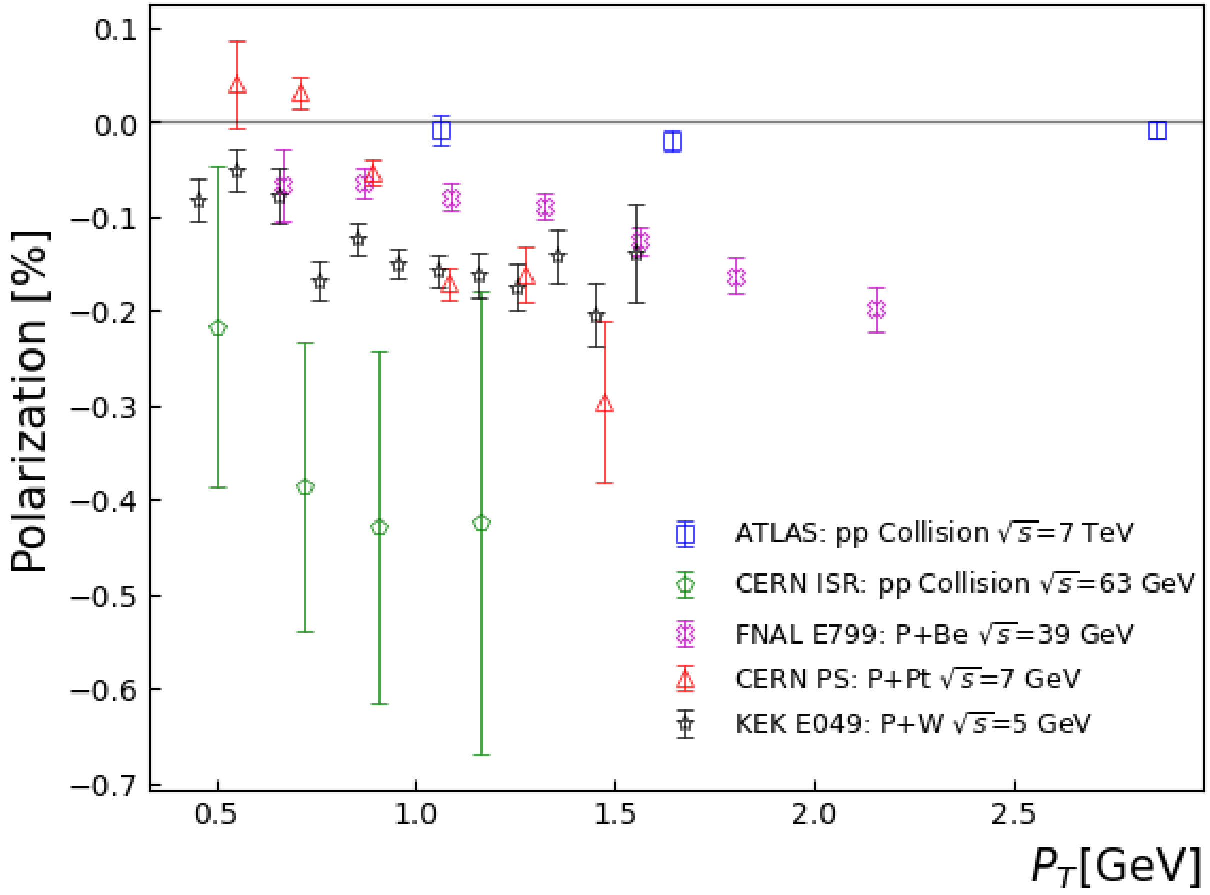


G.Bunce, *et al.*: Phys.Rev.Lett. 36, 1113-1116 (1976)

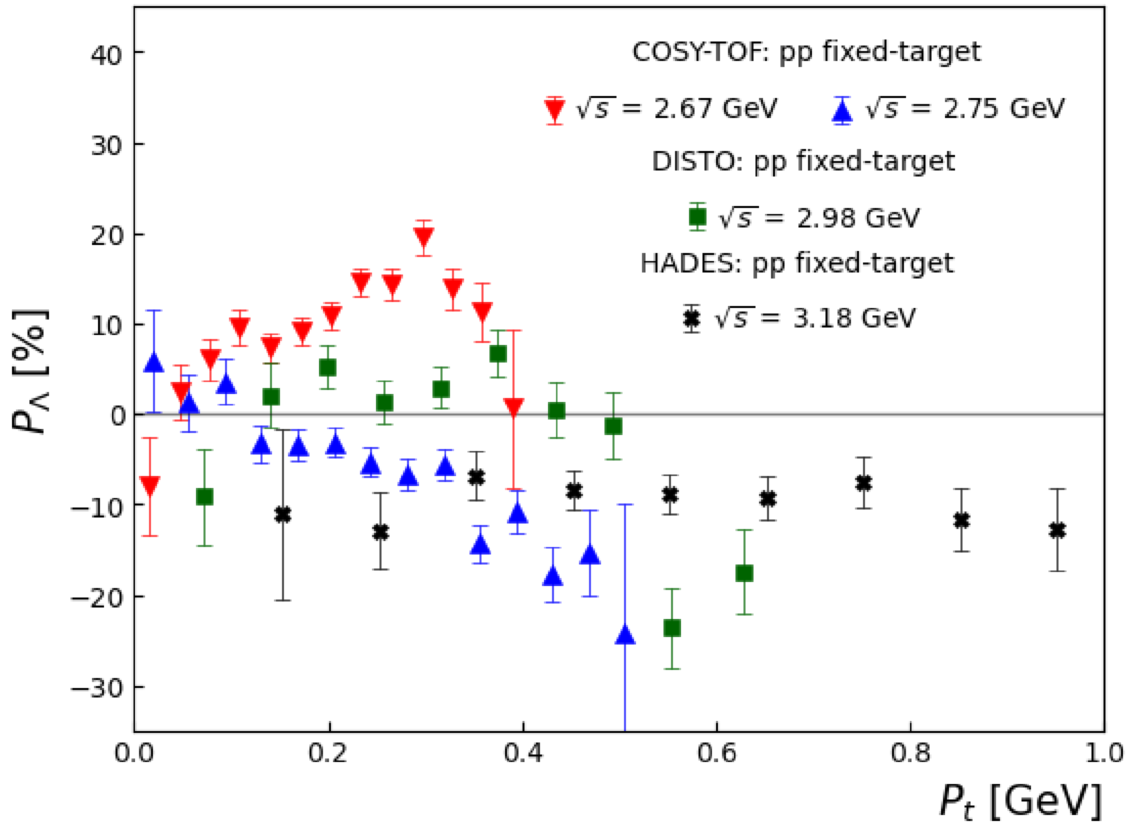
- Hyperons can be produced polarized in collisions of elementary particles
- Discovered at Fermilab in the 1970's in p + Be collisions: 400 GeV protons on Beryllium

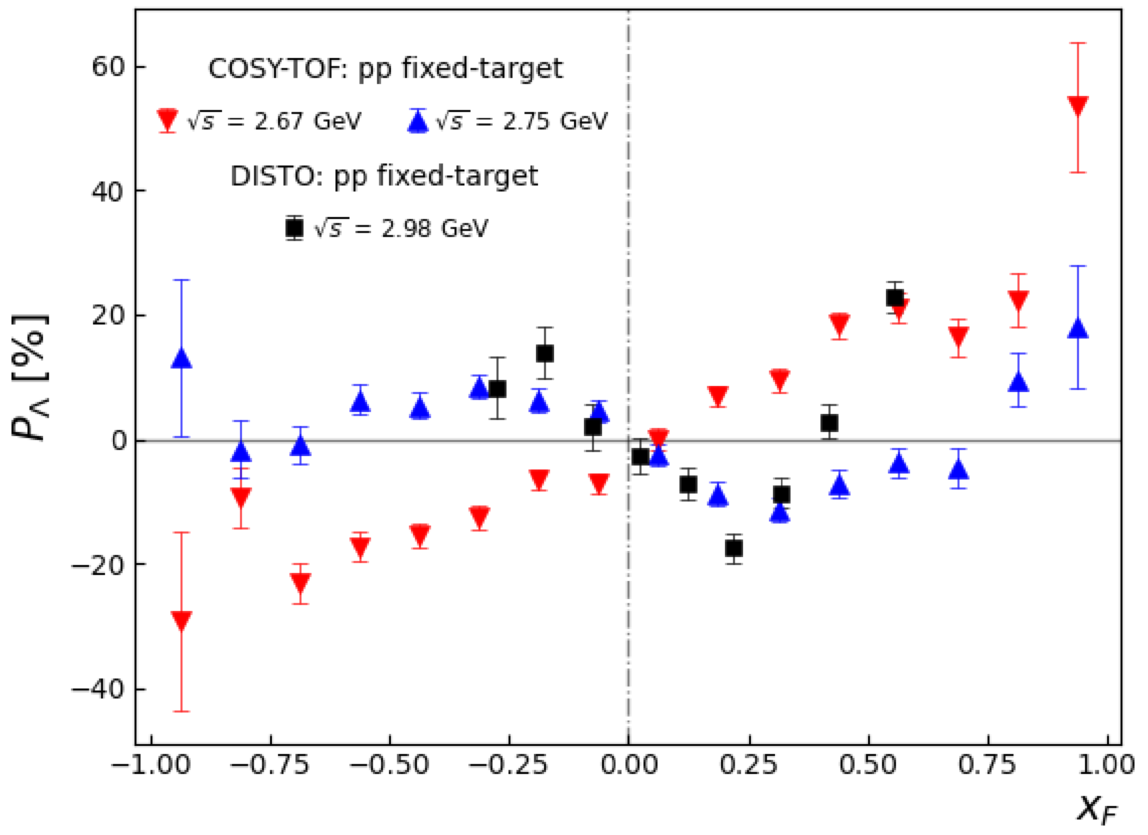
Λ^0 polarization measurements



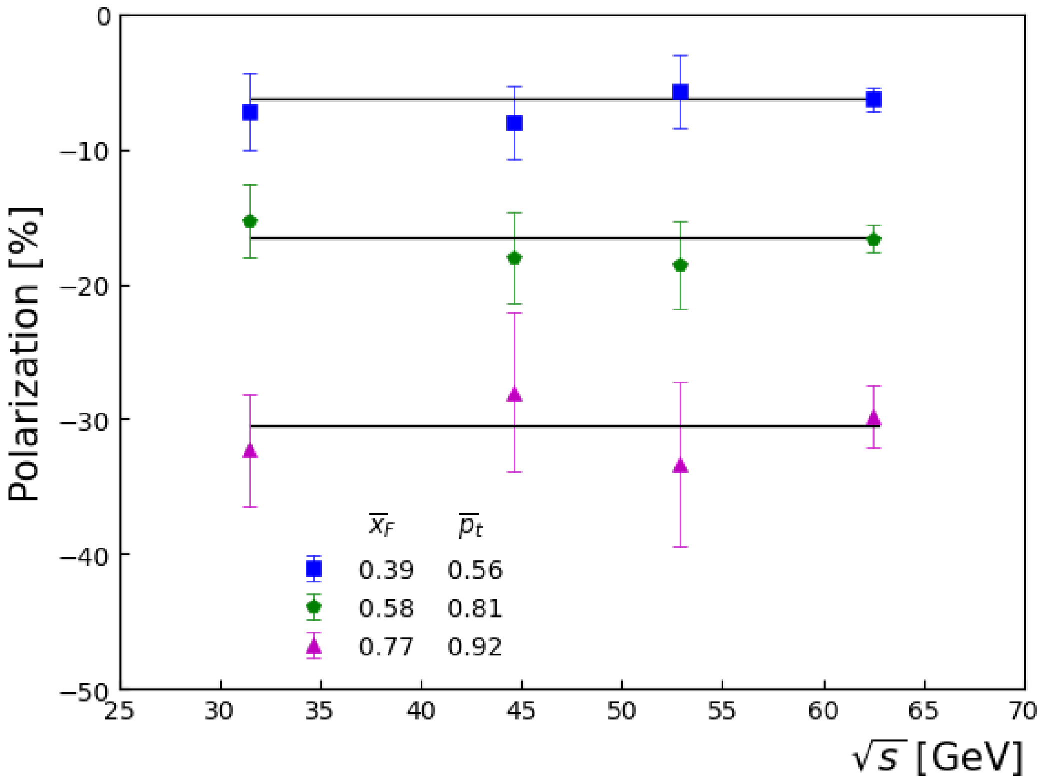


Puzzle in low energy collisions





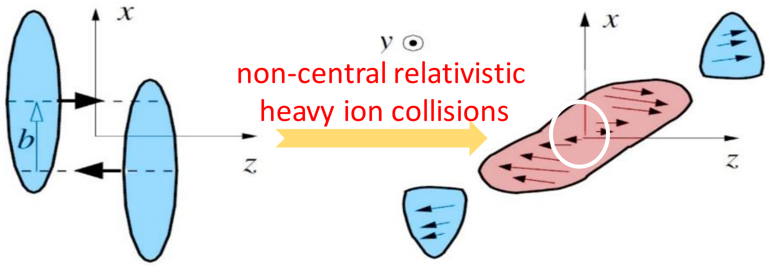
“Scaling” of Λ^0 polarization ?



R608: 10.1016/0370-2693(87)91556-5

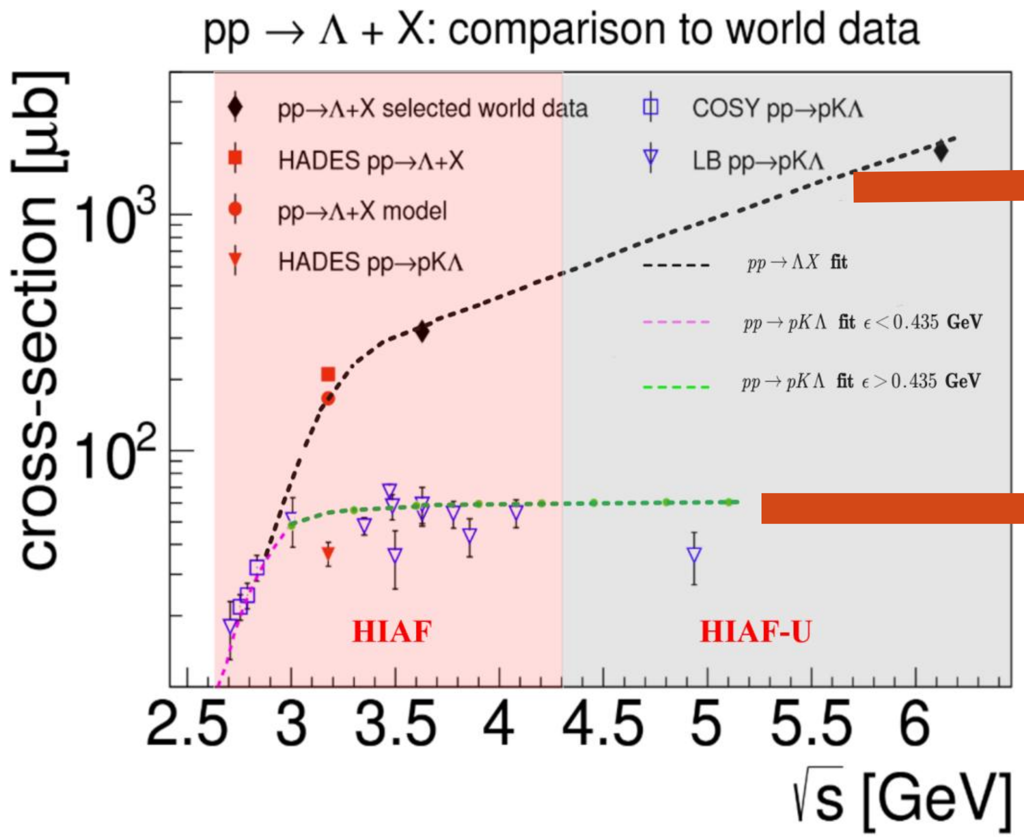
One has to take into account the production mechanism

- 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).

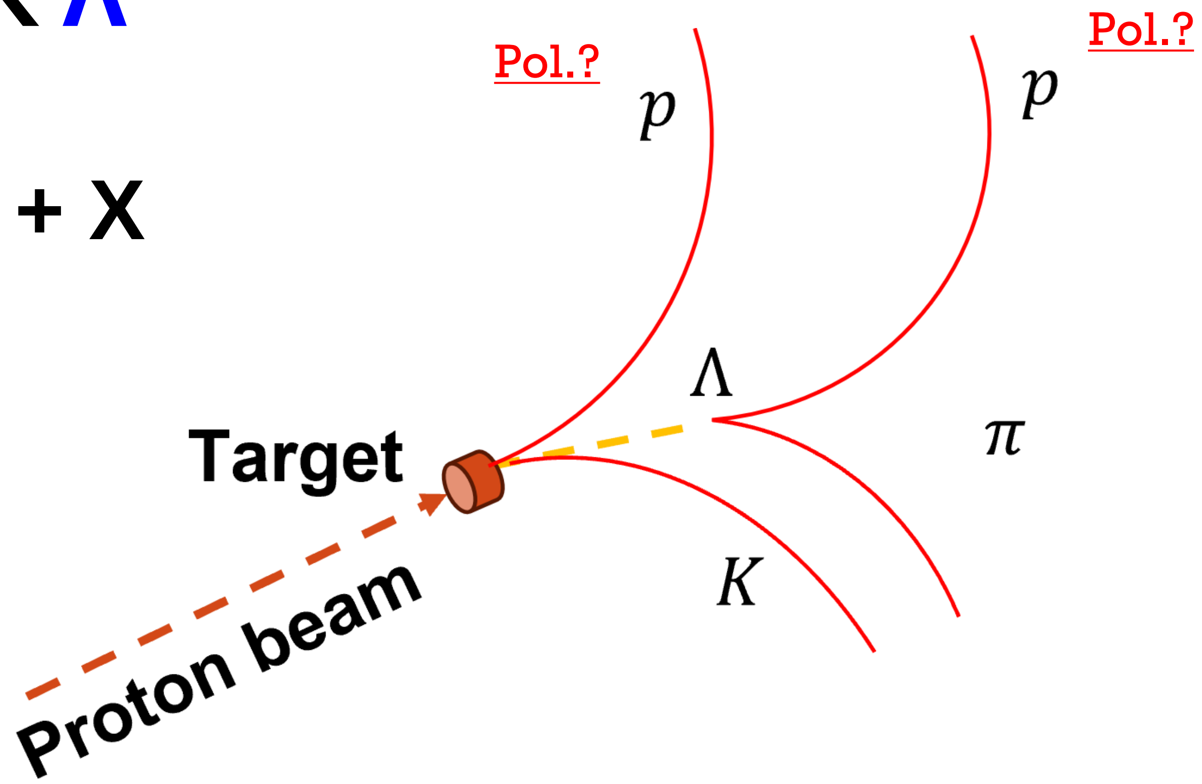
③ $pp \to pK\,\Lambda$ **Λ polarization through intermediate state**

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?

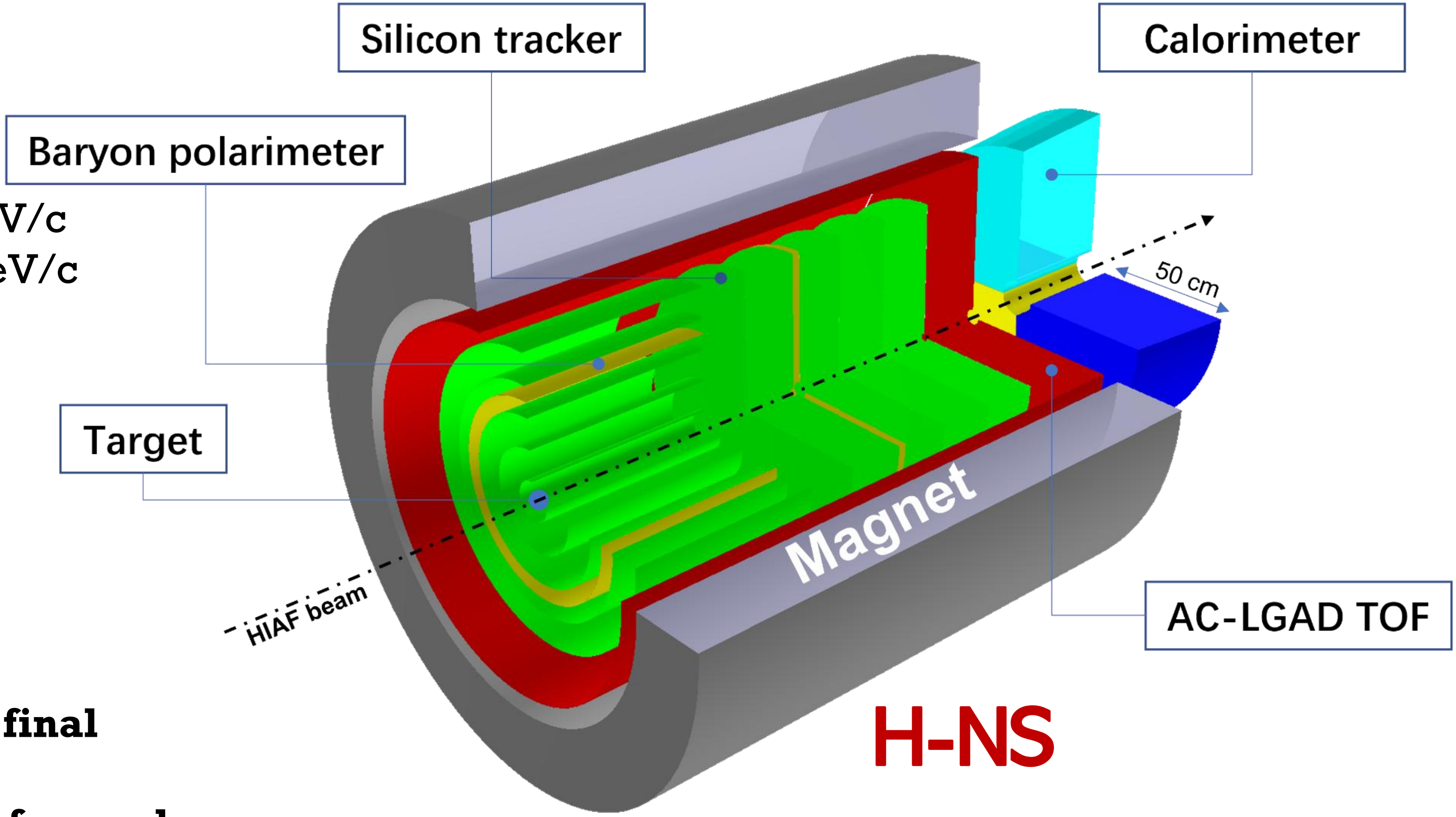
pp → p K Λ

pp → p/Λ + X

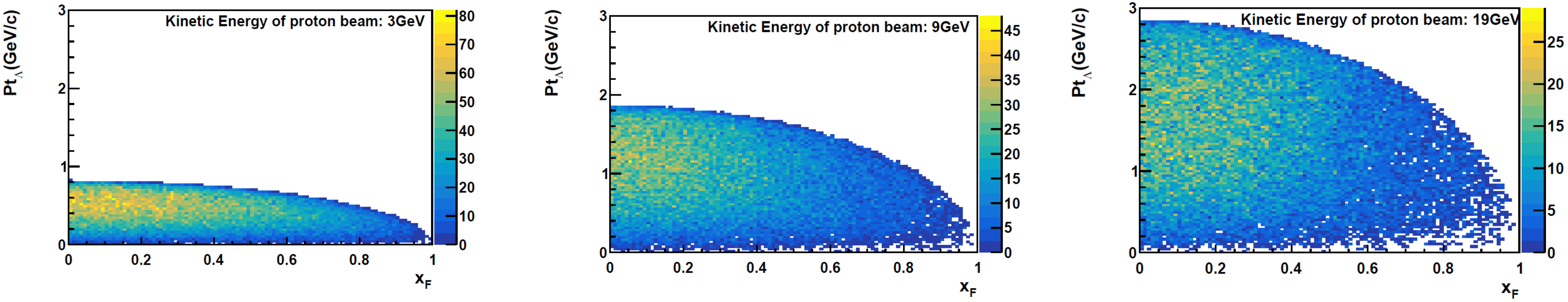


Hyperon-Nucleon Spectrometer

- **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**
  - 100kHz-1MHz
- **Baryon Polarimeter → determine final state proton's polarization**
- **Provide detector R&D platform in forward region**



H-NS kinematics coverage



3 GeV → 9 GeV → 20 GeV → 32 GeV (?)

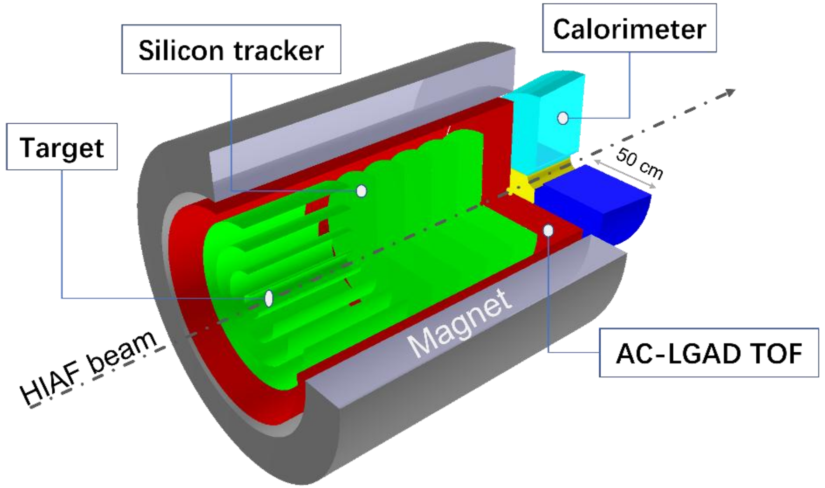
Allow for a multi-dimensional mapping of the Λ^0 polarization and production

- Beam energy scan
- p→p, p→A, A→A data taking

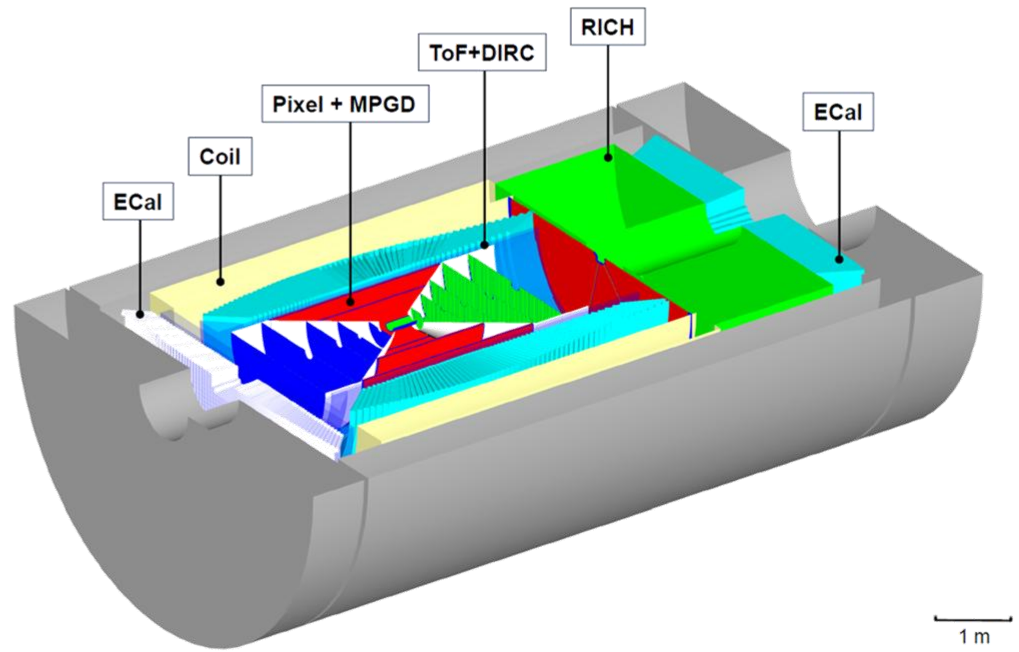
A smooth transition: H-NS detector to EicC detector

Large area Tracker: MPGD + dedicated electronics
PID: DIRC (up to 7 GeV) + RICH (up to 15 GeV)

Potential upgrade:
DIRC→ high momentum PID



Hyperon-Nucleon Spectrometer



EicC detector

Summary and outlook

➢ EicC physics study is NOT far away

1. Summarize world data: know where we are and guide us where to go
2. Take advantage of existing facilities (e.g. BESIII) for EIC/EicC physics

➢ HIAF is under commissioning

1. Hyperon-Nucleon Spectrometer at HIAF for Λ polarization study
2. H-NS to EicC: a smooth transition for both physics and detectors

EicC whitepaper: 2102.09222　　H-NS whitepaper: 2606.06553


Thank you !