TMDs study at the EicC

Yuxiang Zhao (Institute of Modern Physics, Chinese Academy of Sciences)

The talk is based on:

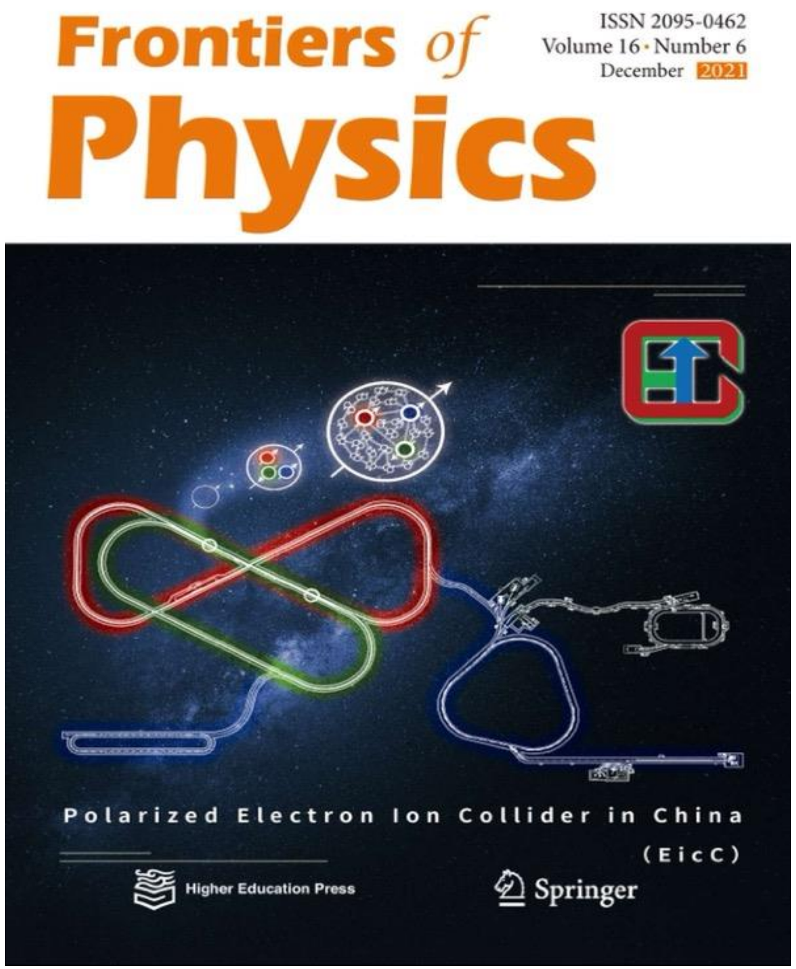
Frontiers of Physics 16 (6), 64701 (2021), Phys. Rev. D 106, 094039 (2022), Phys. Rev. D 109, 056002 (2024), and arXiv: 2403.12795 (2024)

Outline

- Introduction of EicC
- TMDs Physics at EicC
- Summary

EicC white paper (arXiv: 2102.09222)

Published in the *Frontiers of Physics* (2021)



https://link.springer.com/article/10.1007/s11467-021-1062-0

- Spin structure of the nucleon: 1D, 3D
  - ➢ polarized electron + polarized proton/light nuclei
- Partonic structure of nuclei and the Parton interaction with the cold nuclear environment
  - ➢ unpolarized electron + unpolarized various nuclei
- Quarkonium with c/cbar, b/bbar
- Origin of the proton mass study via J/Psi and Upsilon near-threshold production

Detector + Accelerator preliminary design

45 institutes and >100 physicists

Electron Ion Collider in China…Huizhou(惠州) in Guangdong province

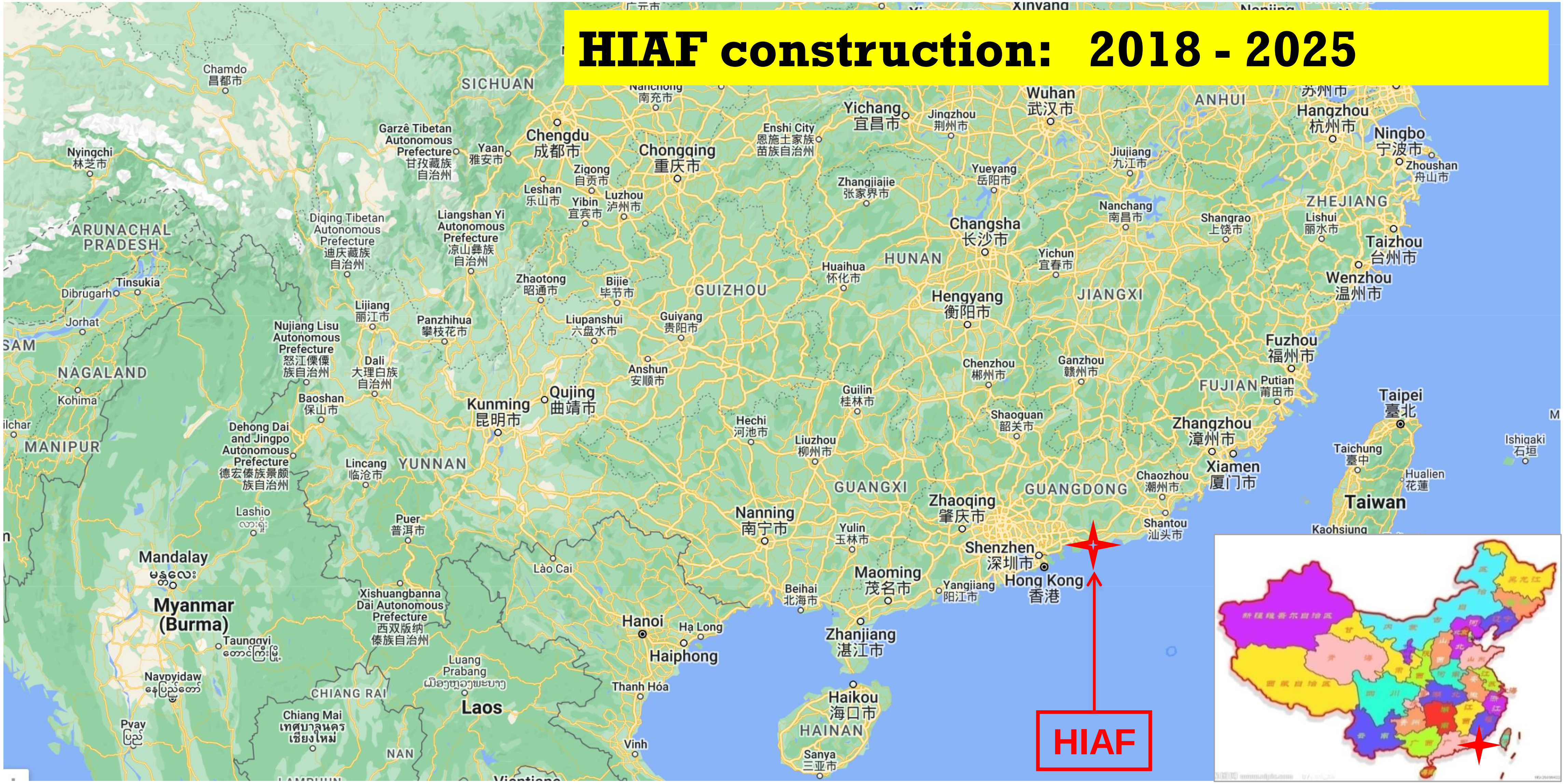
HIAF under construction

EIC in China

Electron Ion Collider in China, EicC

Location: Huizhou, Guangdong

HIAF construction: 2018 - 2025

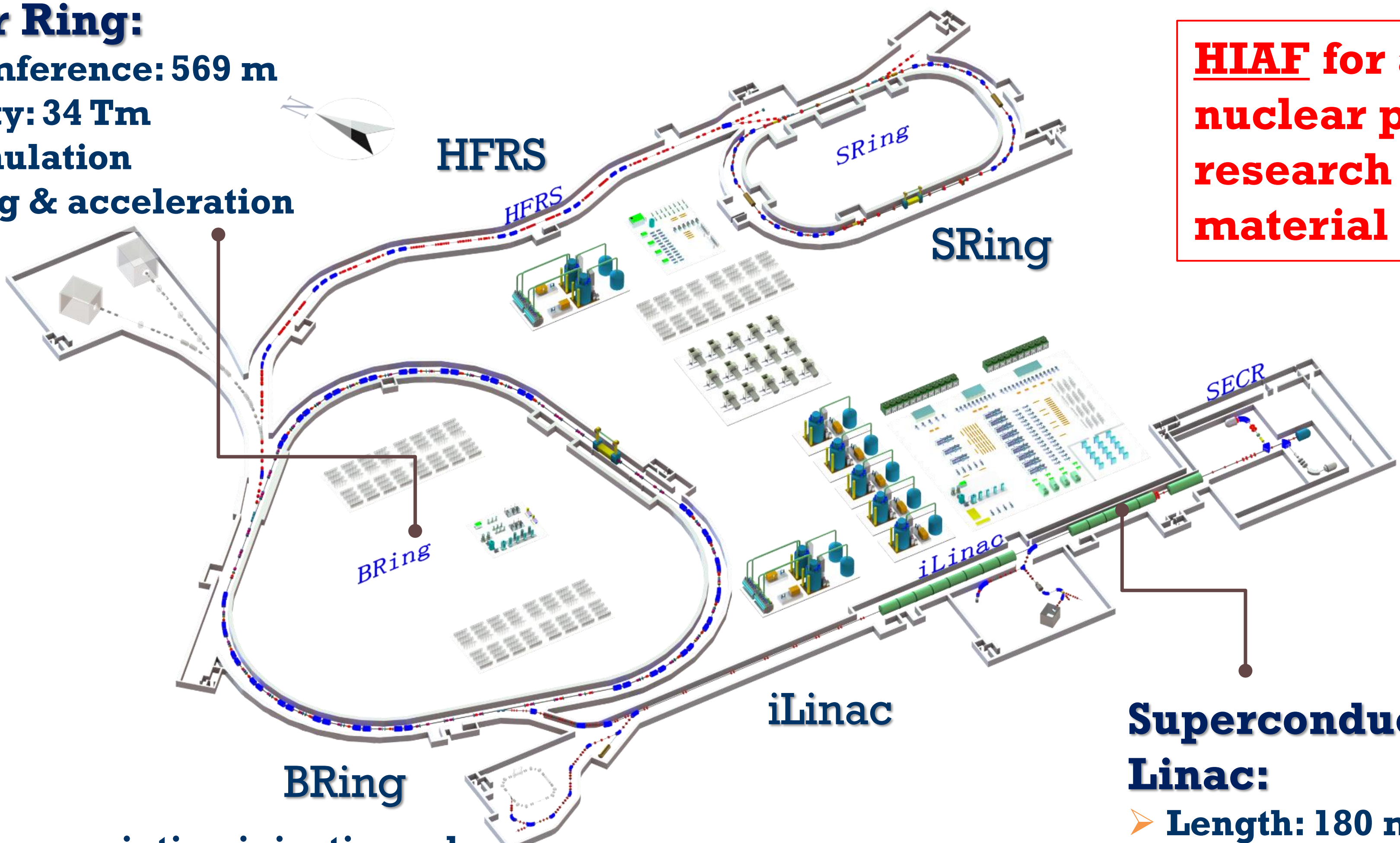


High Intensity heavy-ion Accelerator Facility (HIAF)

HIAF total investment: 2.5 billion RMB (Funded)

Booster Ring:

- Circumference: 569 m
- Rigidity: 34 Tm
- Accumulation
- Cooling & acceleration



HIAF for atomic physics, nuclear physics, applied research in biology and material science etc.

- Two-plane painting injection scheme
- Fast ramping rate operation

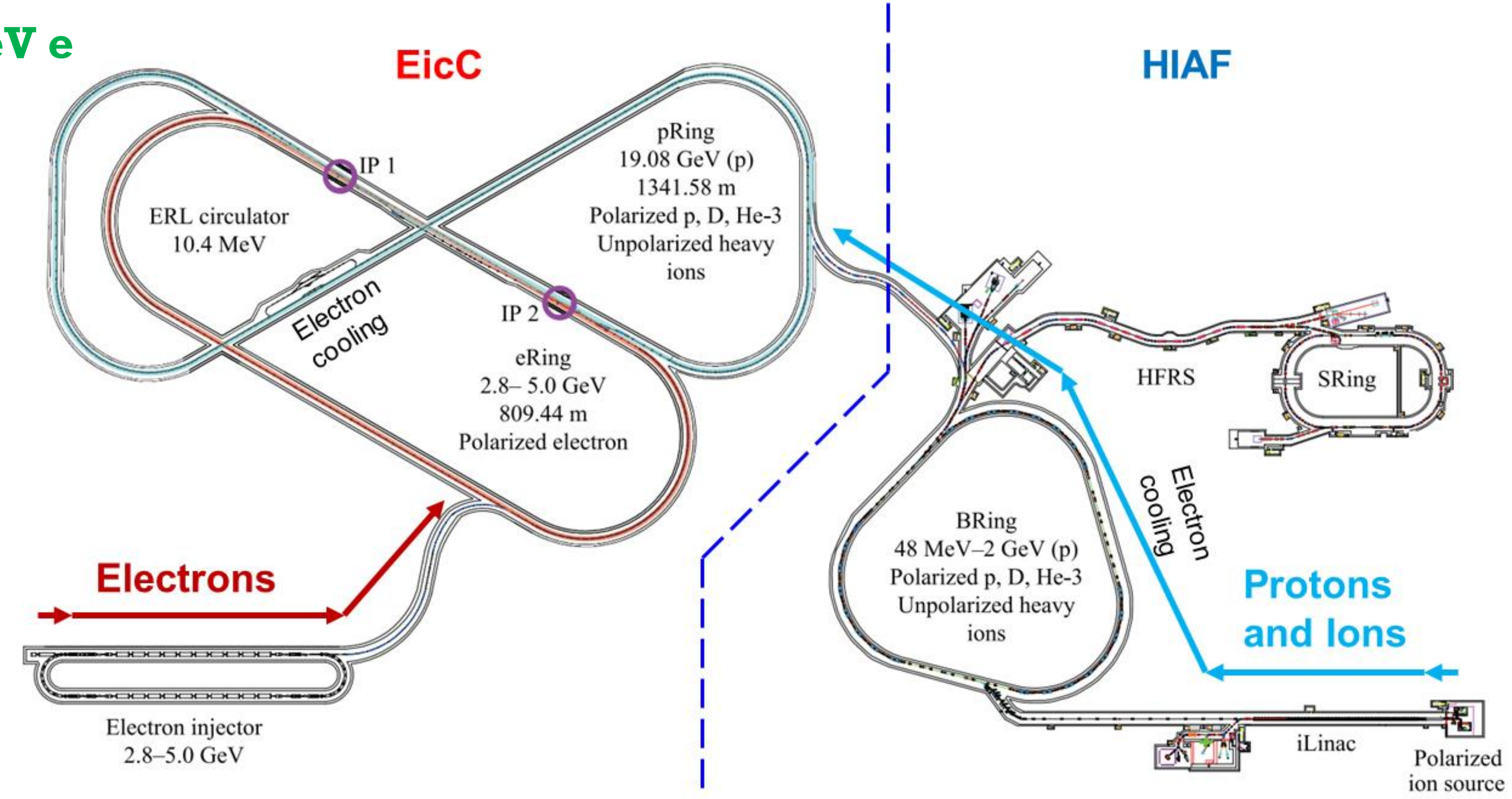
Superconducting Ion Linac:

- Length: 180 m
- Energy: 17 MeV/u (U^{34+})
- CW and pulse modes

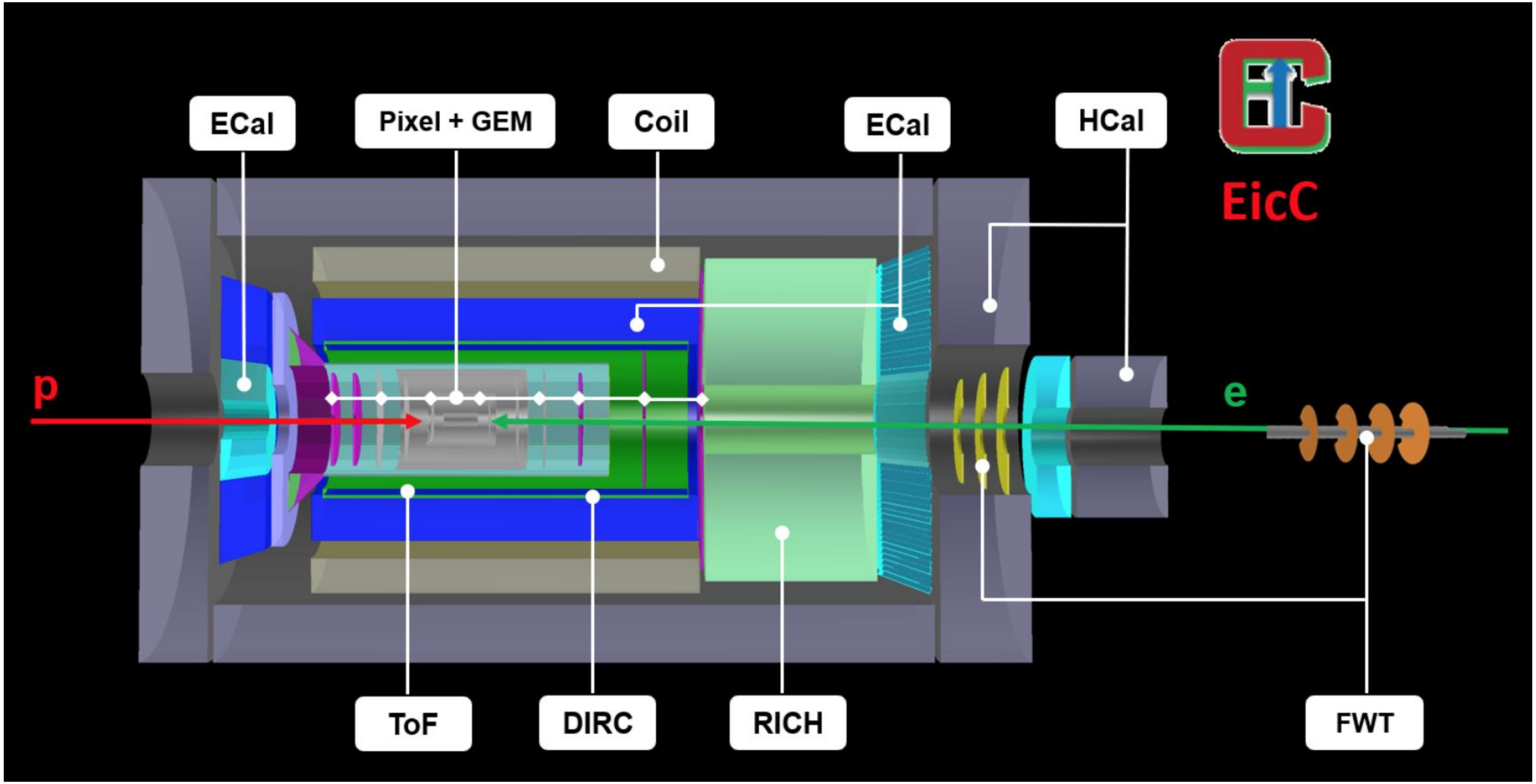
EicC Accelerator complex layout

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

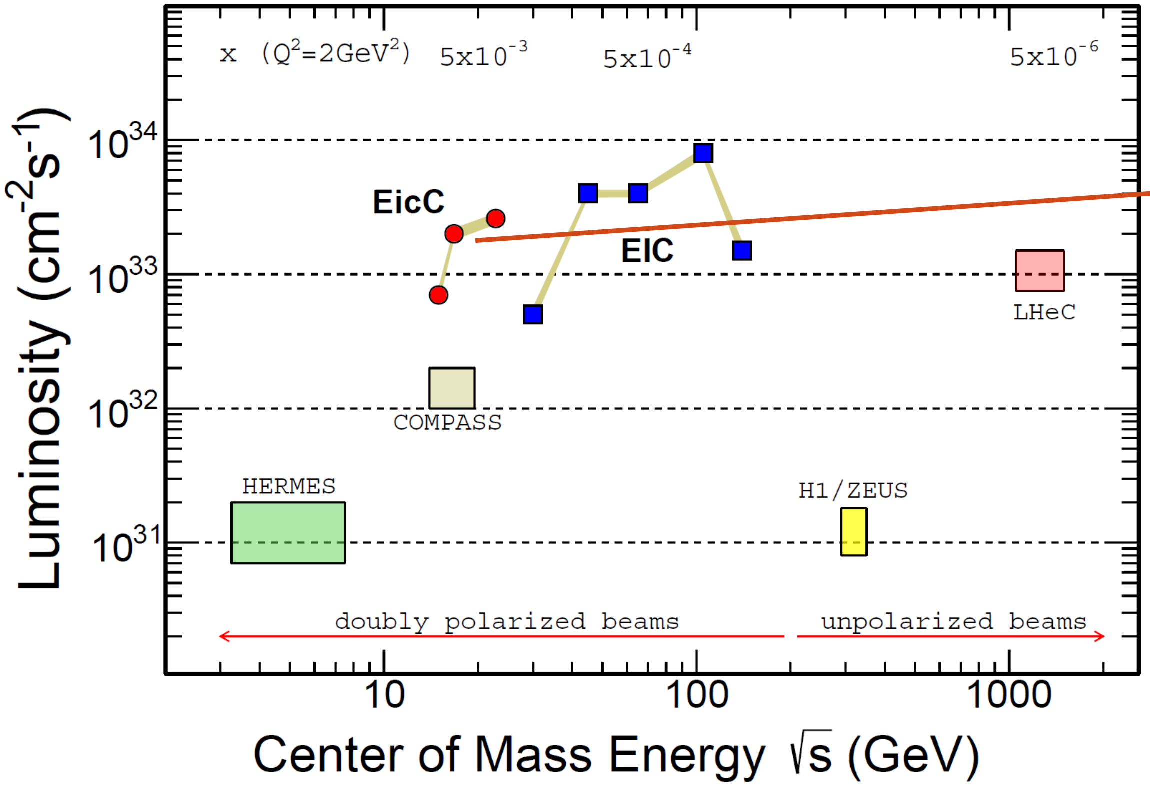
  2-4 x10^{33} $cm^{-2}s^{-1}$
- Polarized beams

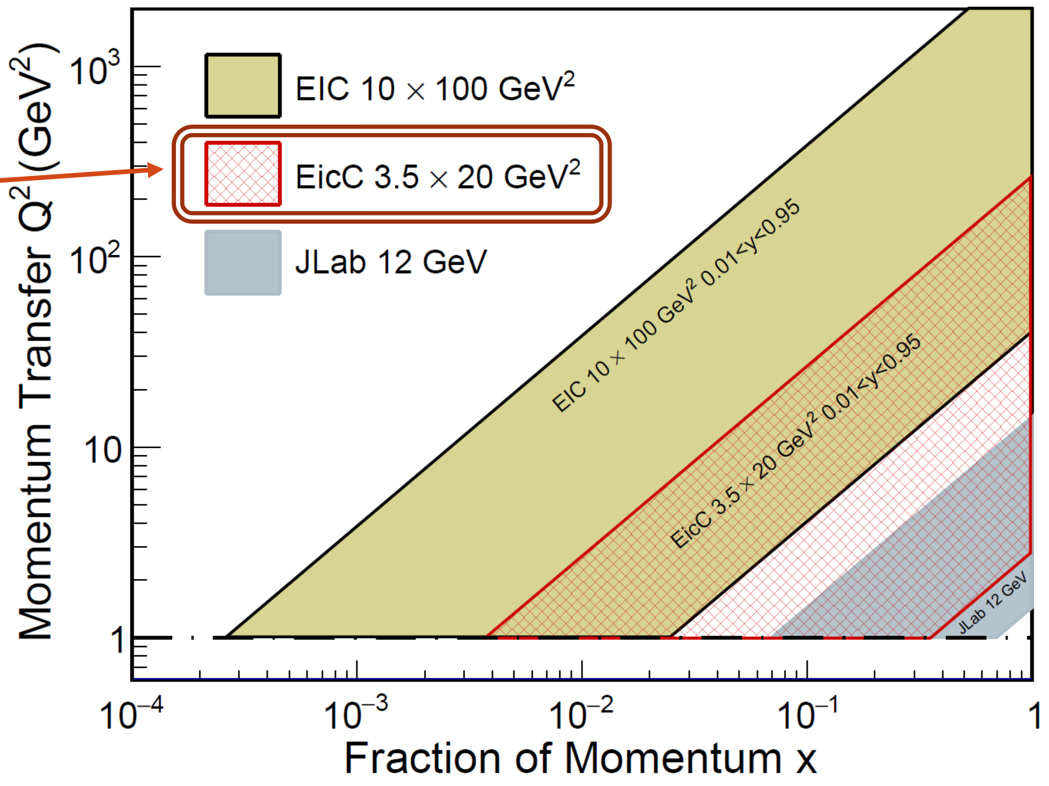


EicC detector design



EicC parameters

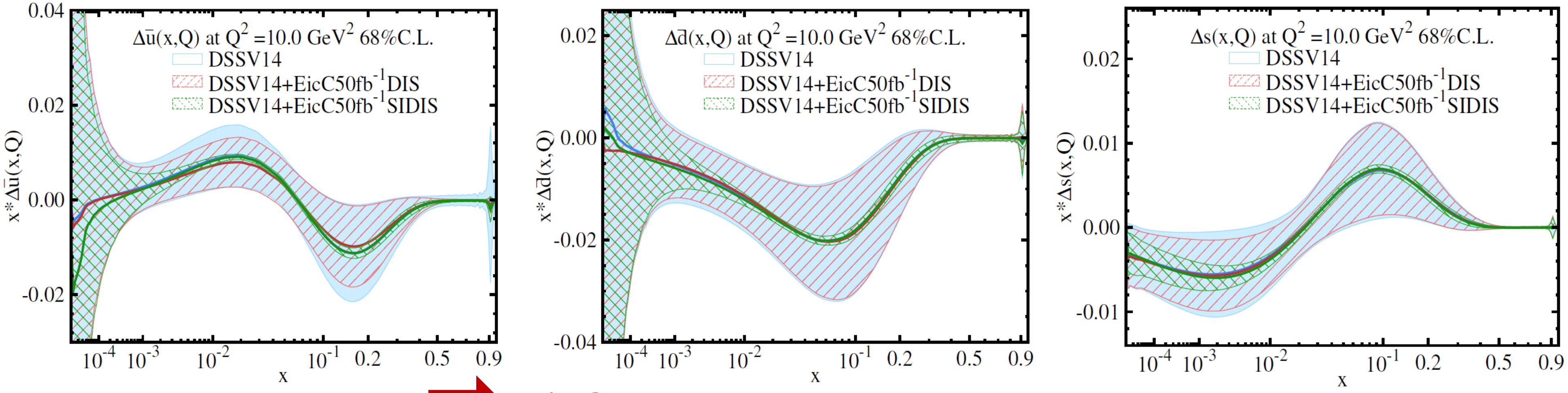




- EicC covers the kinematic region between JLab experiments and EIC@BNL
- EicC complements the ongoing scientific programs at JLab and future EIC project
- EicC focuses on moderate x and sea-quark region

EicC and EIC-helicity distribution via SIDIS (1D spin)

D. Anderle, T. Hou, H. Xing, M. Yan, C. -P. Yuan, Y. X. Zhao, JHEP08, 034 (2021)



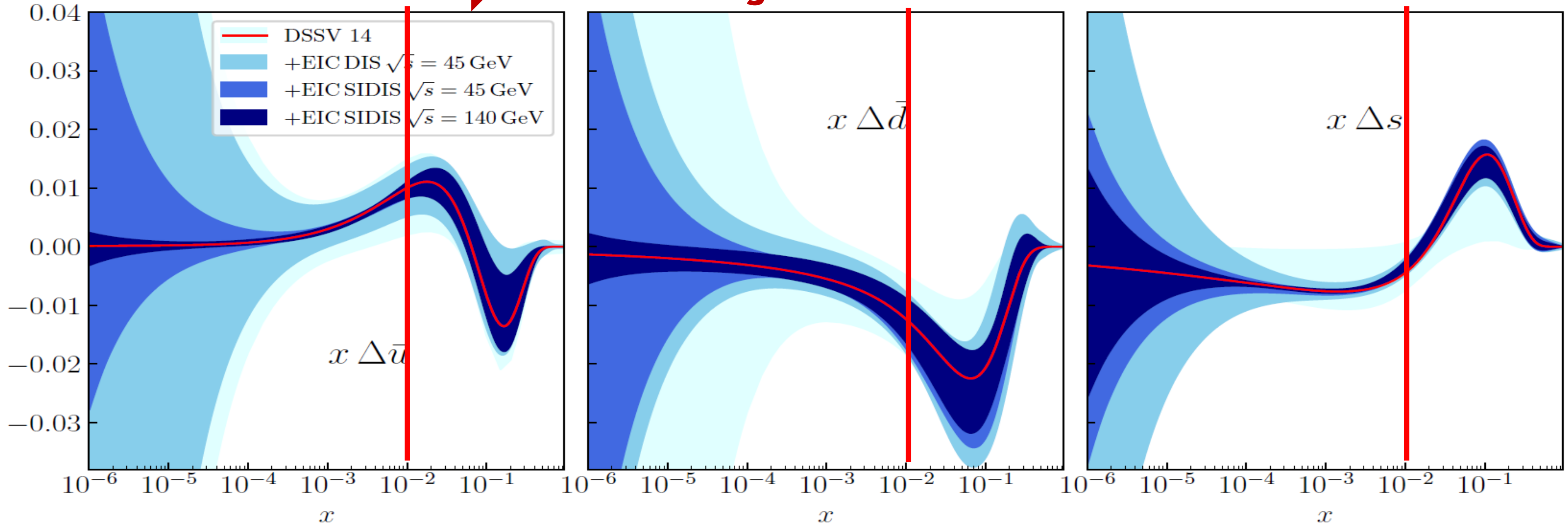
An NLO study

EicC white paper

complementary

EIC Yellow Report

EicC coverage



Outline

- Introduction of EicC
- TMDs Physics at EicC
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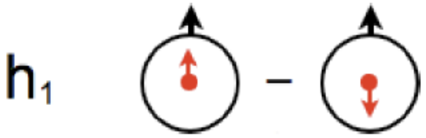
Leading-Twist TMDs

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

Nucleon Spin *Quark Spin*

Transversity distribution

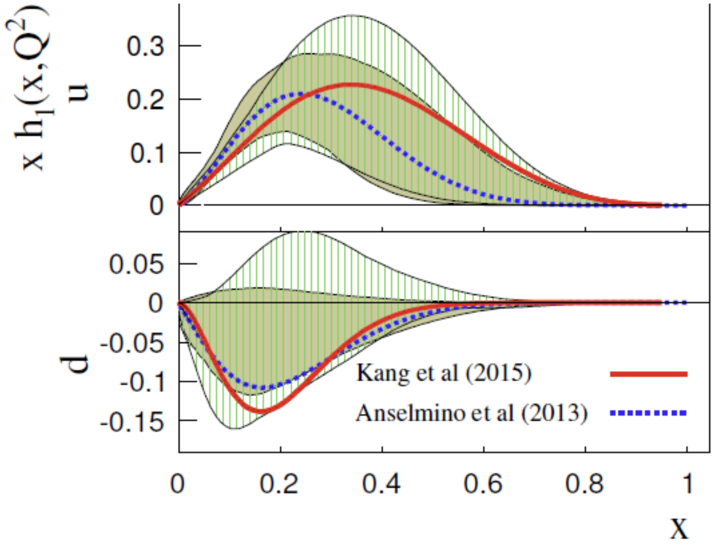


(Collinear & TMD)

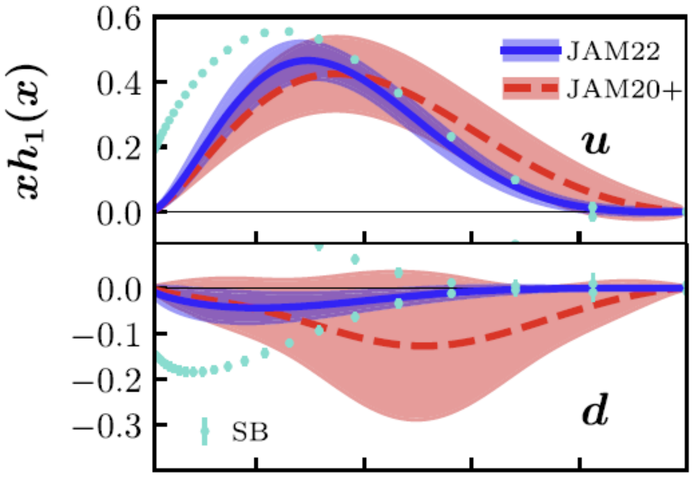
A transverse counter part to the longitudinal spin structure: helicity g_{1L}, but NOT the same.

- Chiral-odd:
  No mixing with gluons
  Valence dominant
  Couple to another chiral-odd function.

  e.g. $h_1(x, \mathbf{k}_\perp^2) \bigotimes H_1^\perp(z, \mathbf{p}_\perp^2)$



Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, PRD 93, 014009 (2016).



JAM Collaboration, PRD 104, 034014 (2022).

Question: Is the assumption of vanishing sea quark transversity justified?

Our phenomenological analysis

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

Theoretical framework

- SIDIS and SIA at low P_T
- TMD factorization, include TMD evolution (ζ-prescription)
- No assumption of vanishing anti-quark transversity distributions

TABLE II. The precision of the factors in powers of α_s in this work.

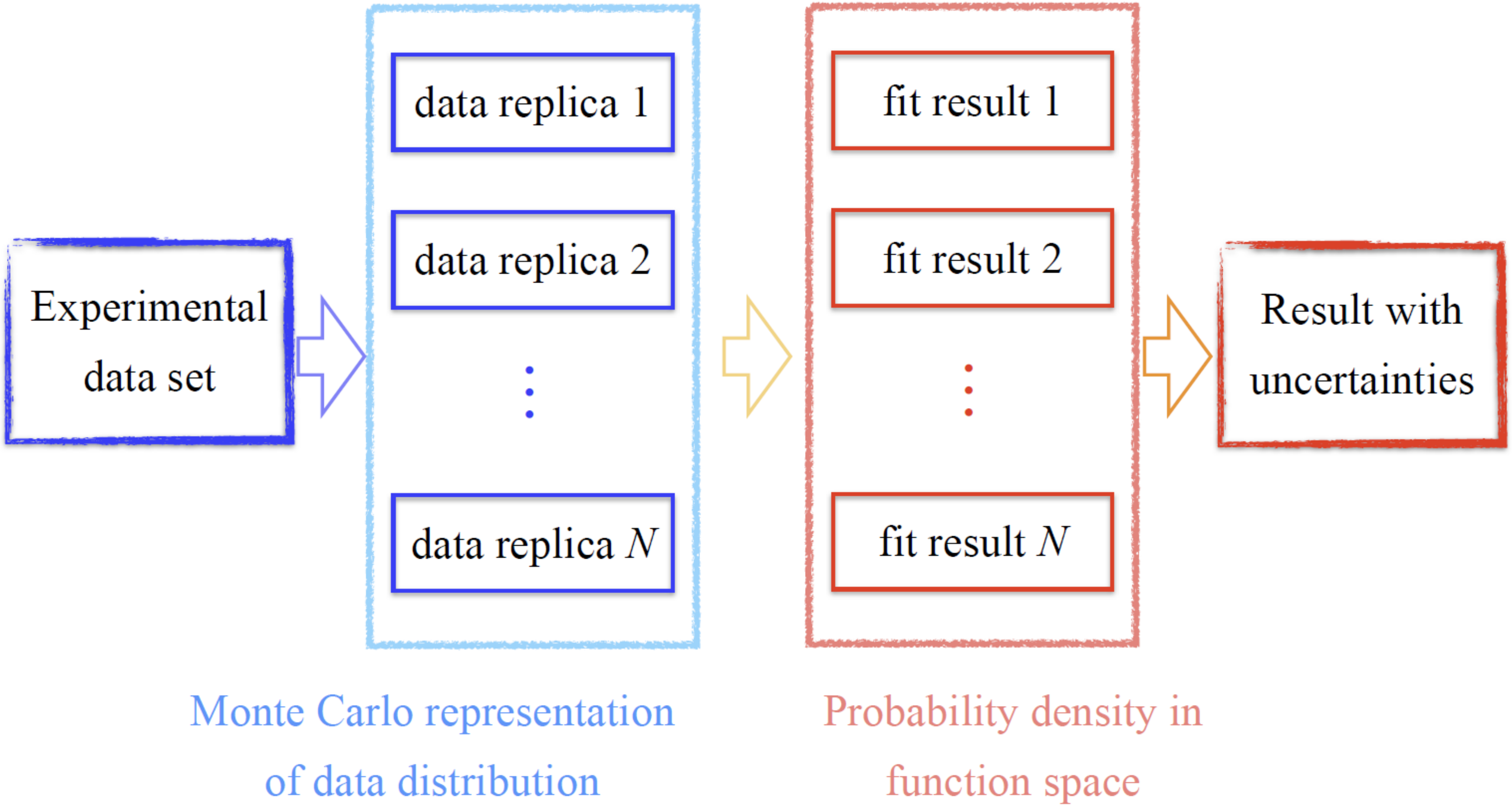
	Γ_{cusp}	γ_V	$\mathcal{D}_{\text{resum}}$	ζ_μ^{pert}	ζ_μ^{exact}	$C(\mathbb{C})$
F_{UU}	α_s^3	α_s^2	α_s^2	α_s^1	α_s^1	α_s^1
F_{UT}	α_s^3	α_s^2	α_s^2	α_s^1	α_s^1	α_s^0

Data sets

SIDIS	Target	Lepton beam	Hadron	# data
COMPASS	^6LiD	160 GeV	$\pi^\pm$, $K^\pm$	92
COMPASS	NH_3	160 GeV	$\pi^\pm$, $K^\pm$	92
HERMES	H_2	27.6 GeV	$\pi^\pm$, $K^\pm$	80
JLab	^3He	5.9 GeV	$\pi^\pm$, $K^\pm$	13

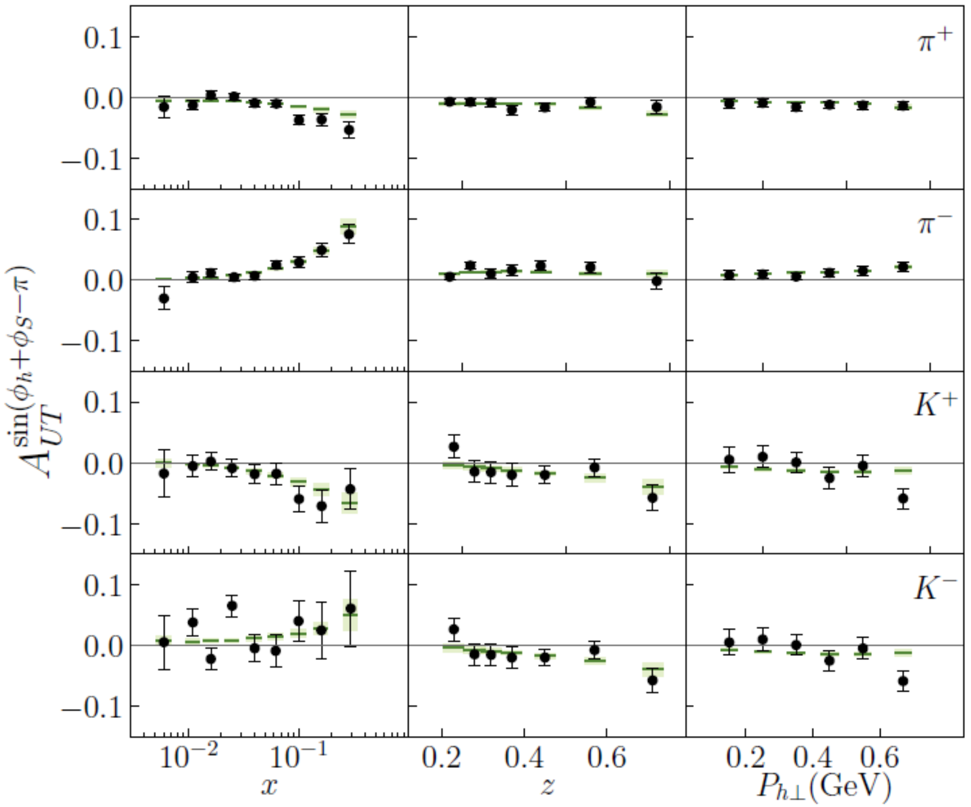
SIA	Energy	Hadron pair	# data
Belle	10.58 GeV	ππ	16
BaBar	10.6 GeV	ππ	45
BaBar	10.6 GeV	ππ, πK, KK	48
BESIII	3.68 GeV	ππ	11

Fit methodology

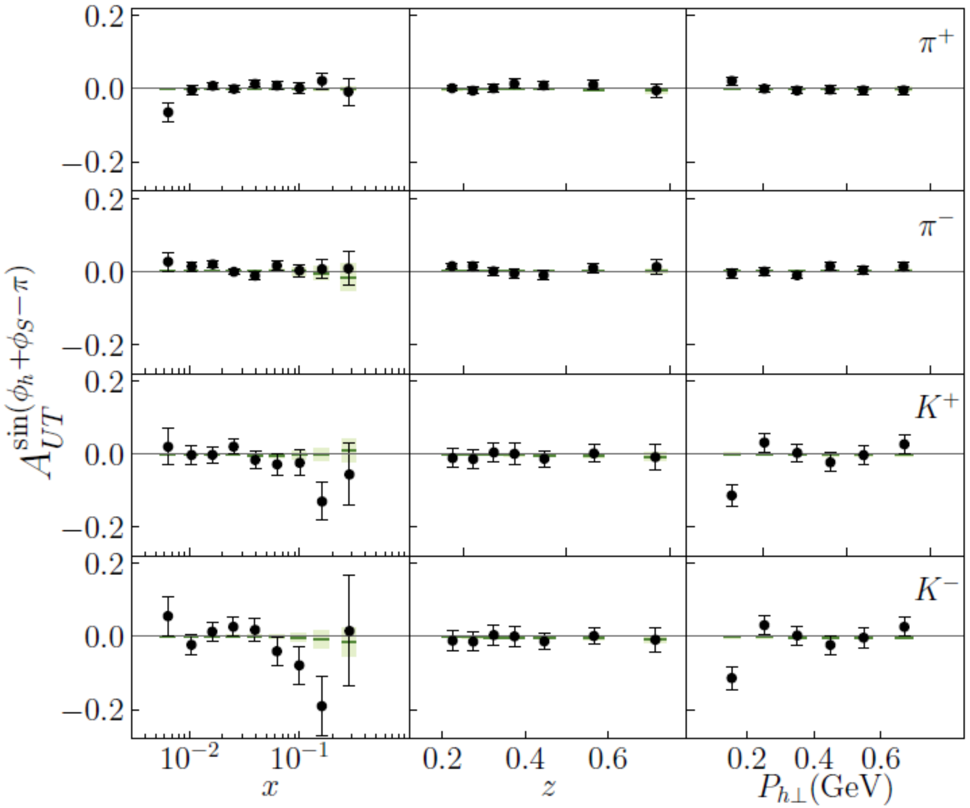


Comparison with data

COMPASS (proton)

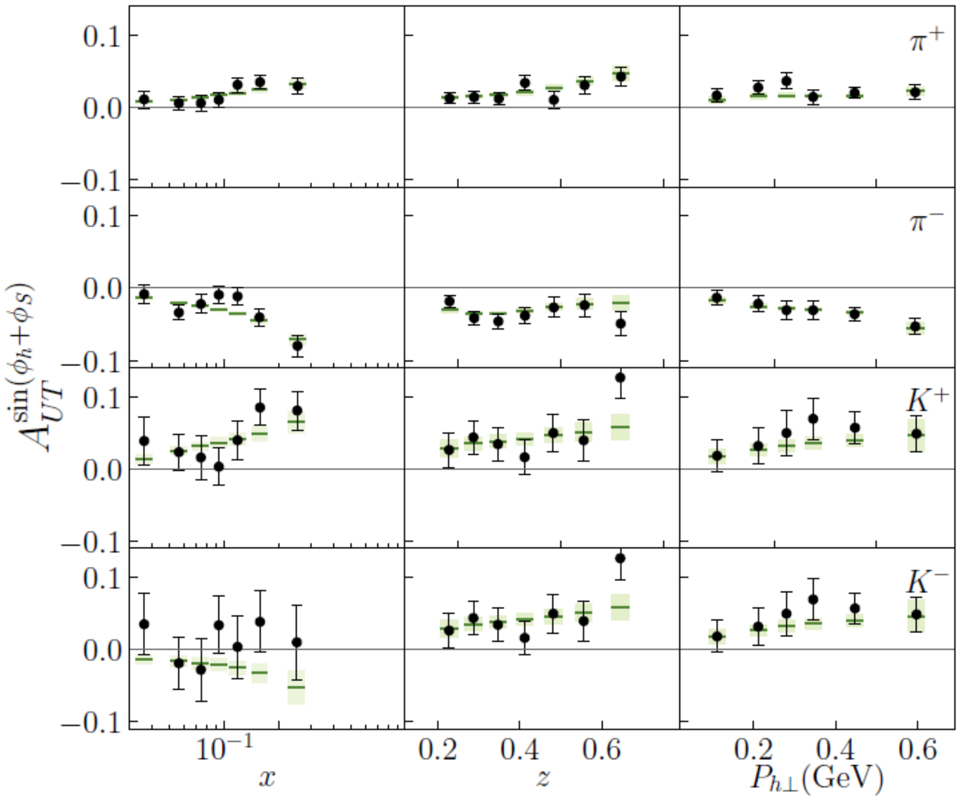


COMPASS (deuteron)

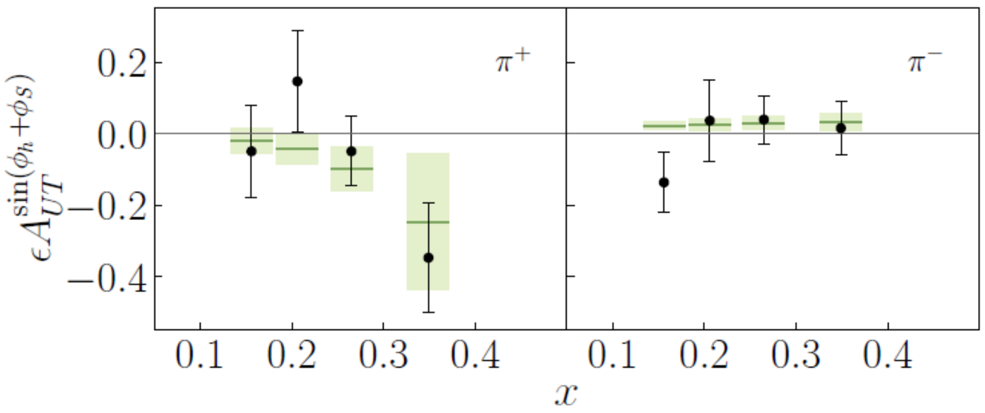


Comparison with data

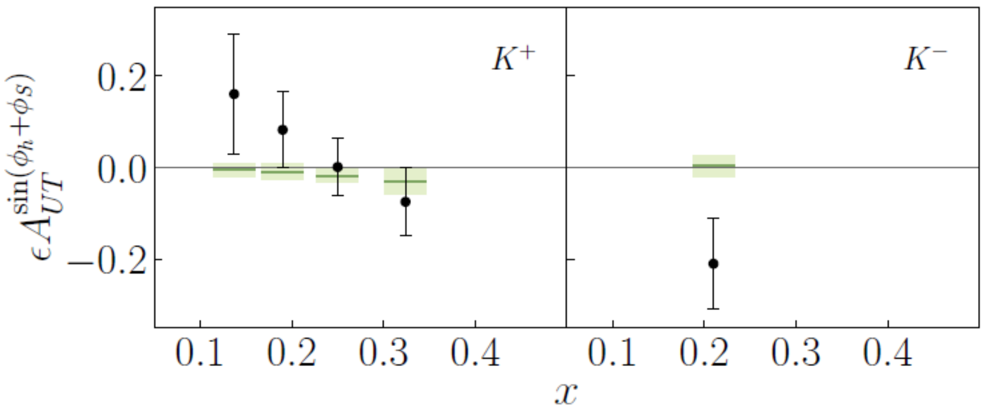
HERMES (proton)



JLab (neutron)

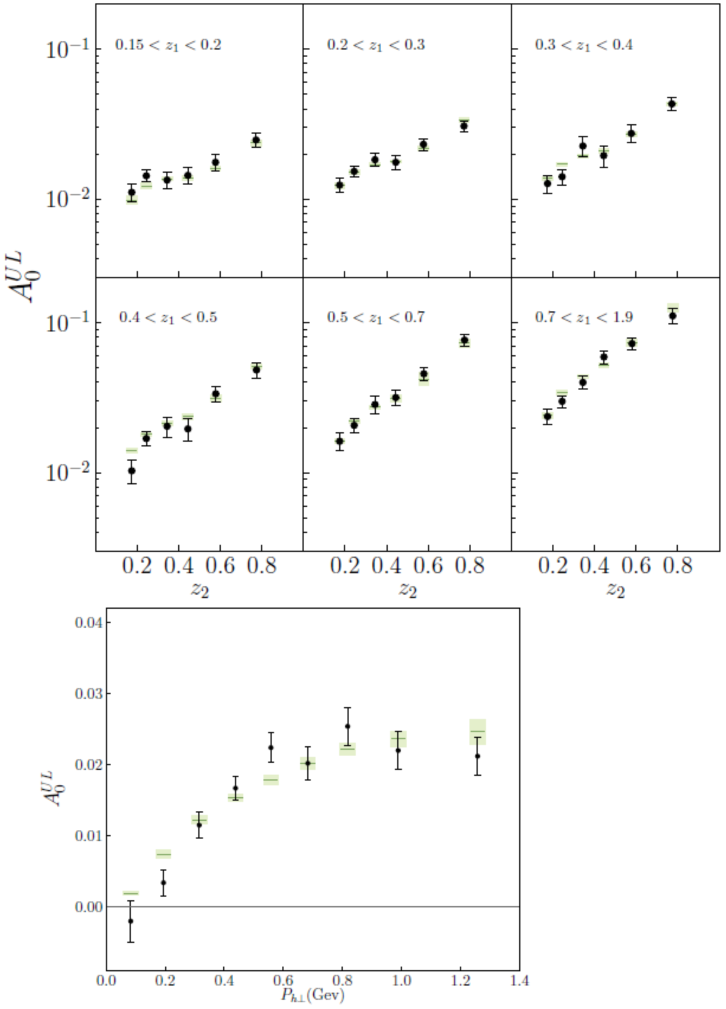


JLab (helium-3)

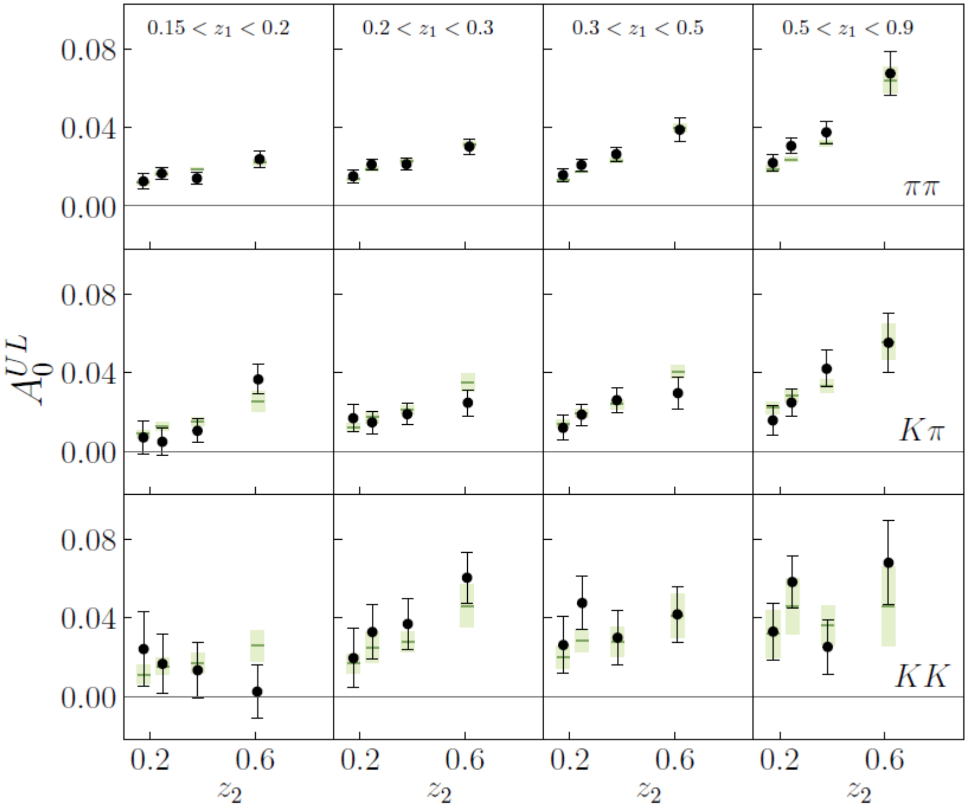


Comparison with data

BaBar (2014)

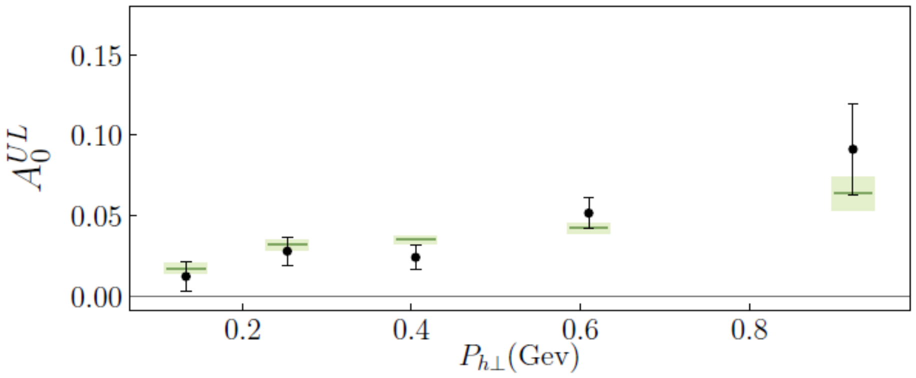


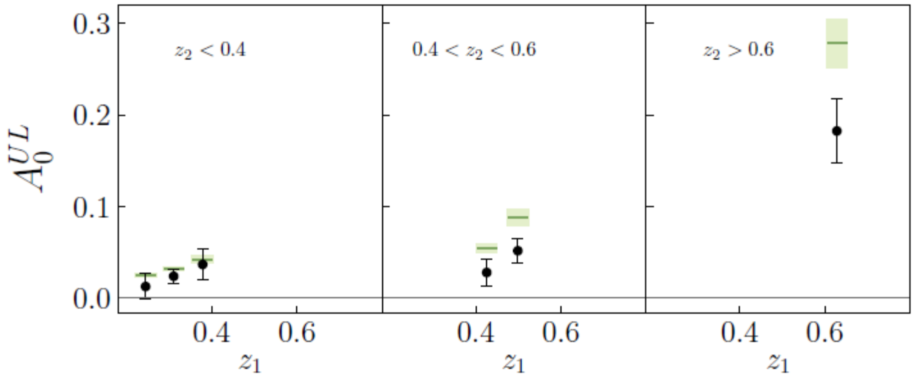
BaBar (2016)



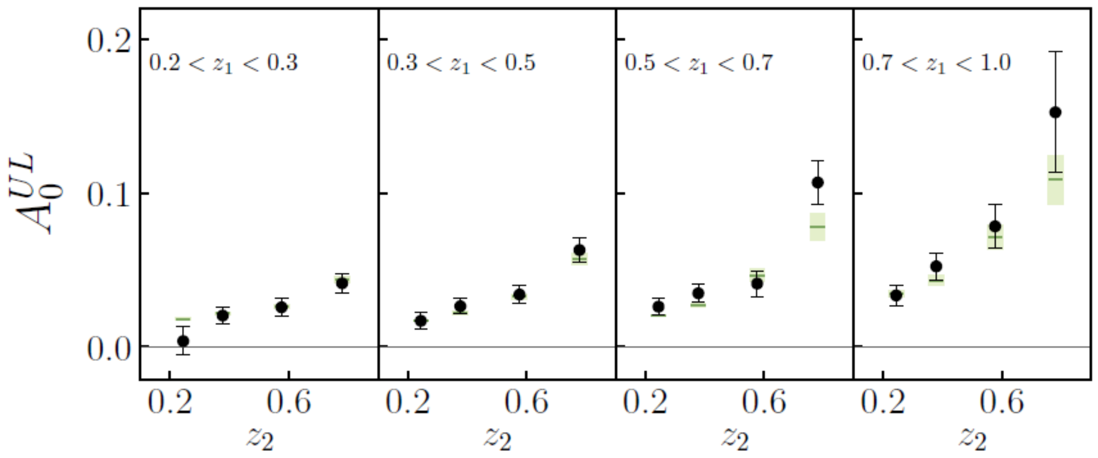
Comparison with data

BESIII

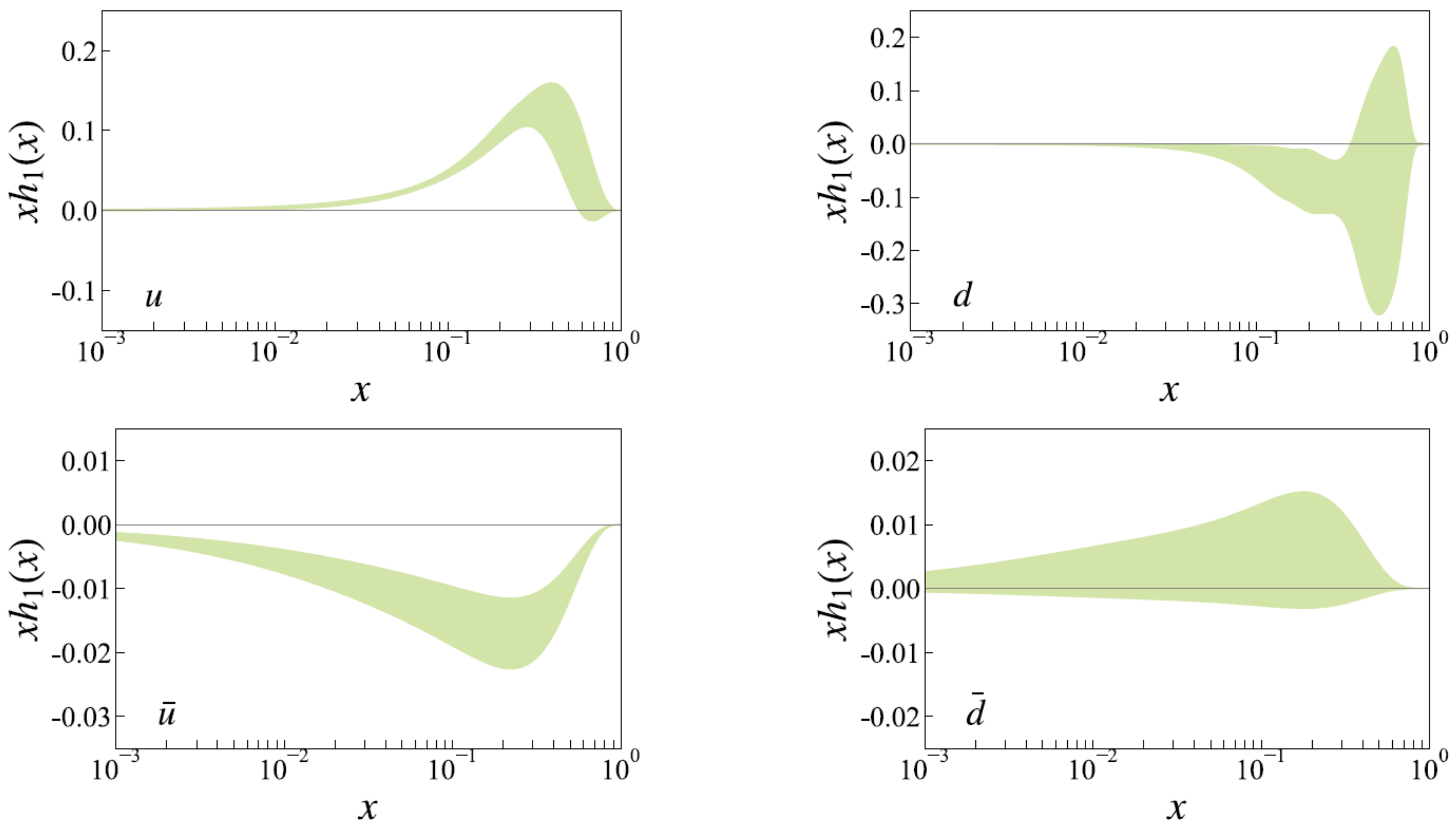




Belle



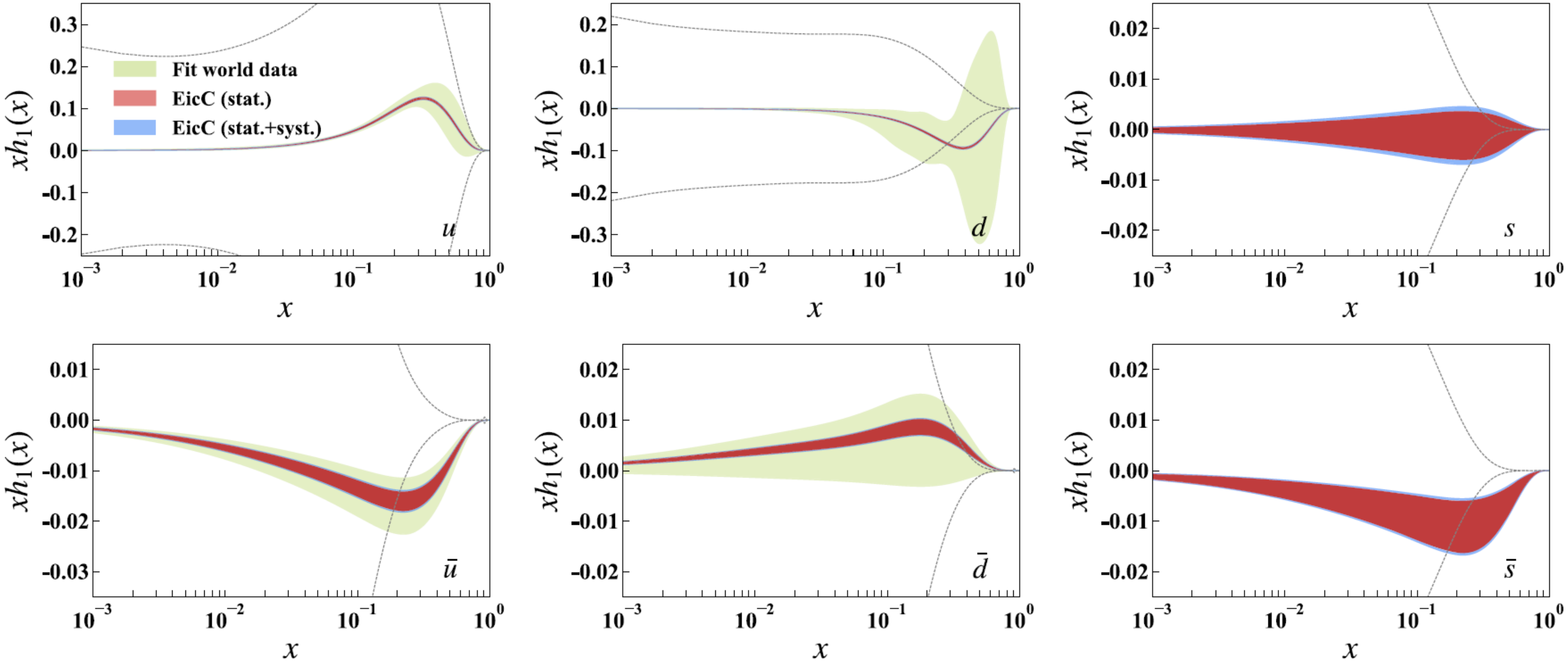
Extracted Transversity distribution



- $\bar{u}$ quark favors negative distribution ?
- $\bar{d}$ quark hints a positive distribution ?

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

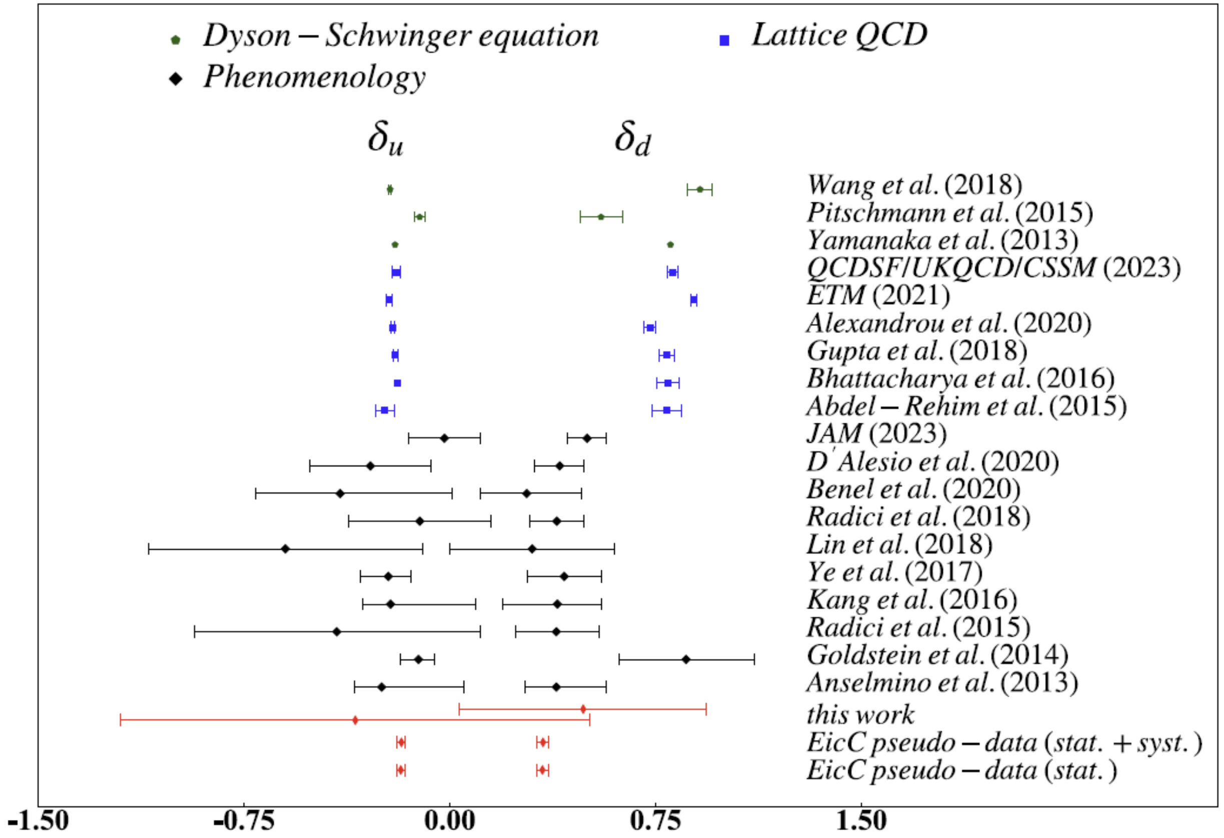
EicC impact on Transversity

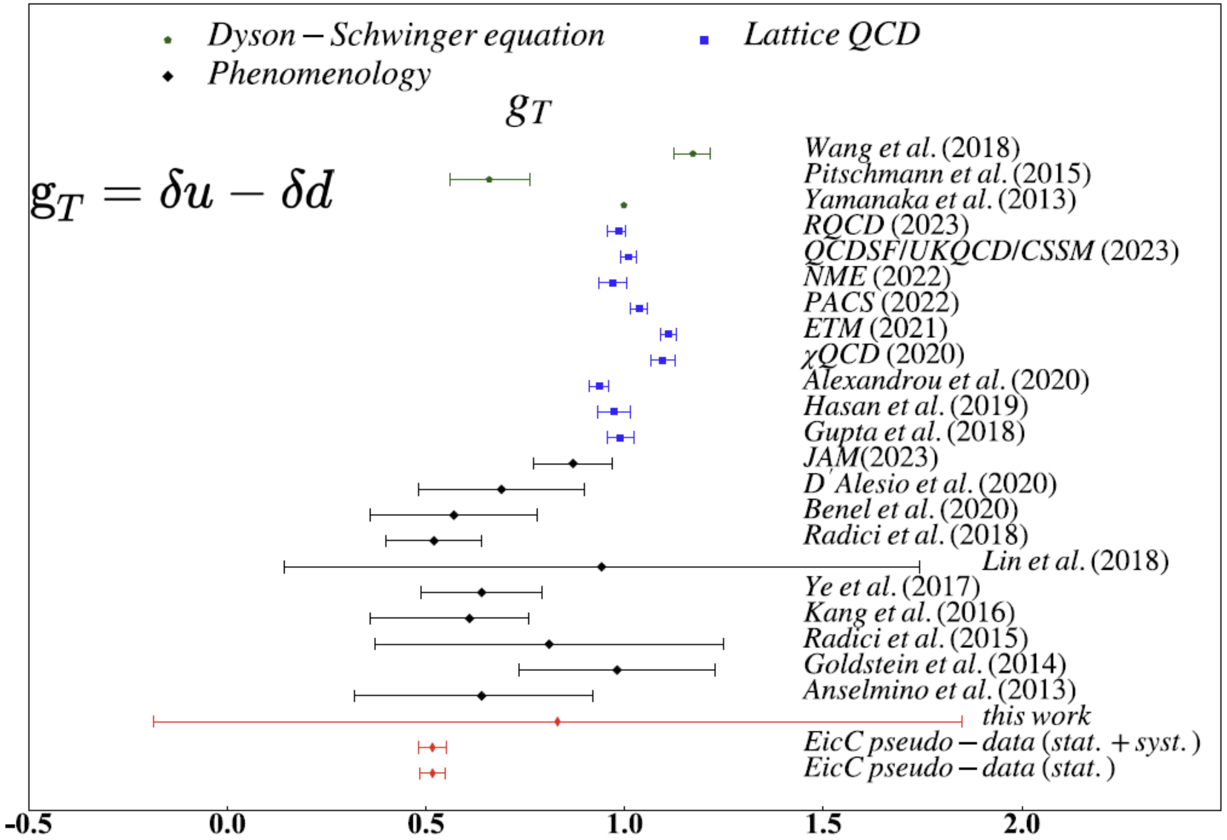


EicC can significantly improve the precision of transversity distributions, especially for sea quarks

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

Results 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)

Something more

COMPASS 2022 data, arXiv: 2401.00309

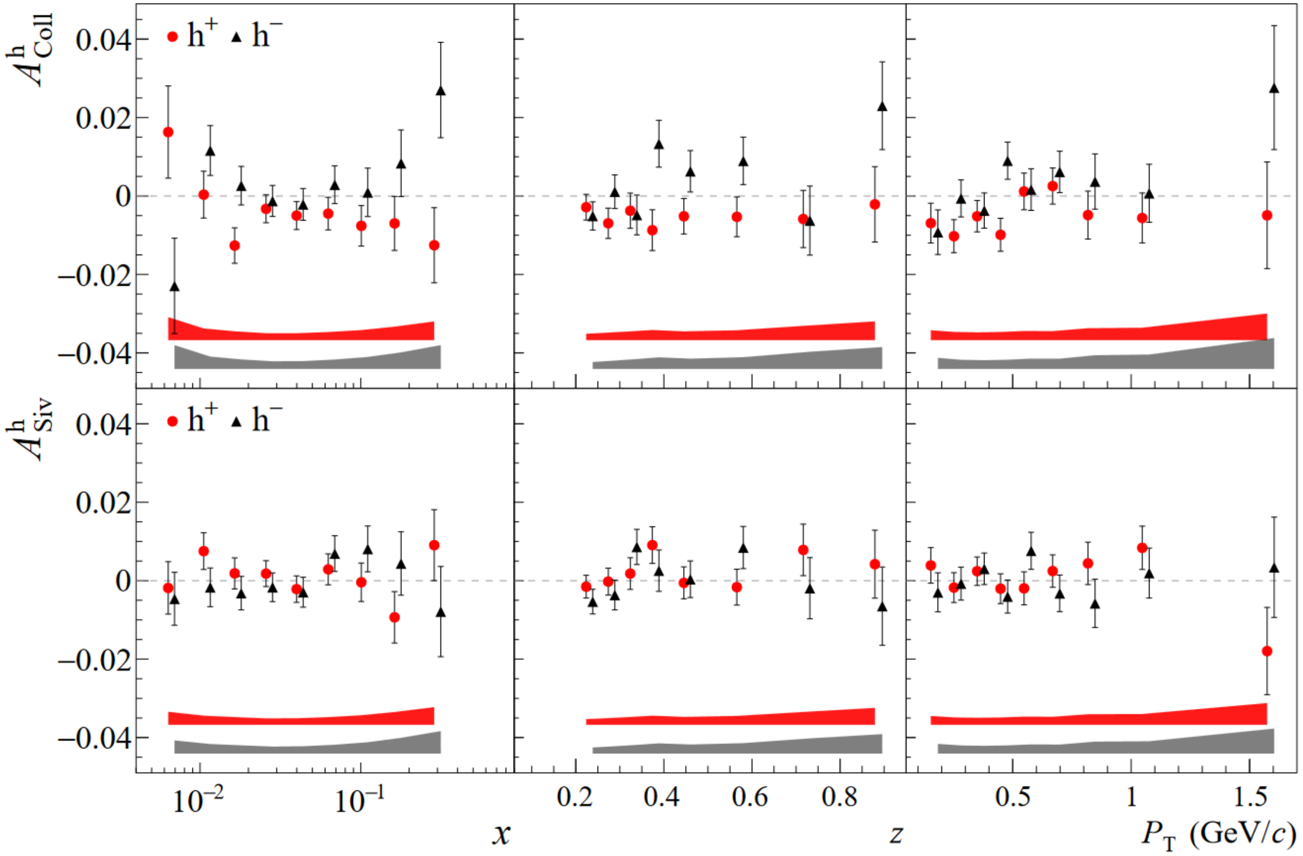
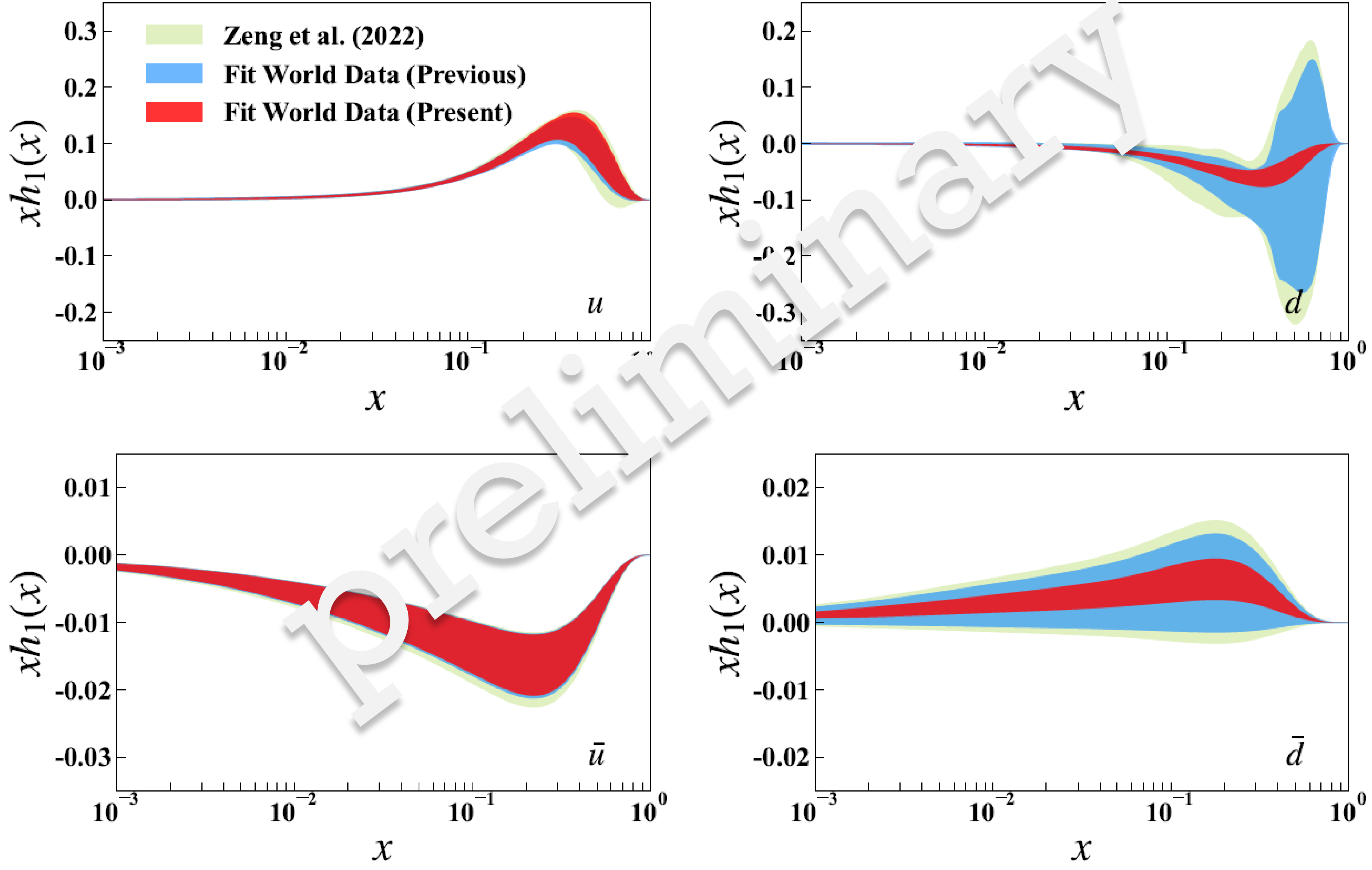
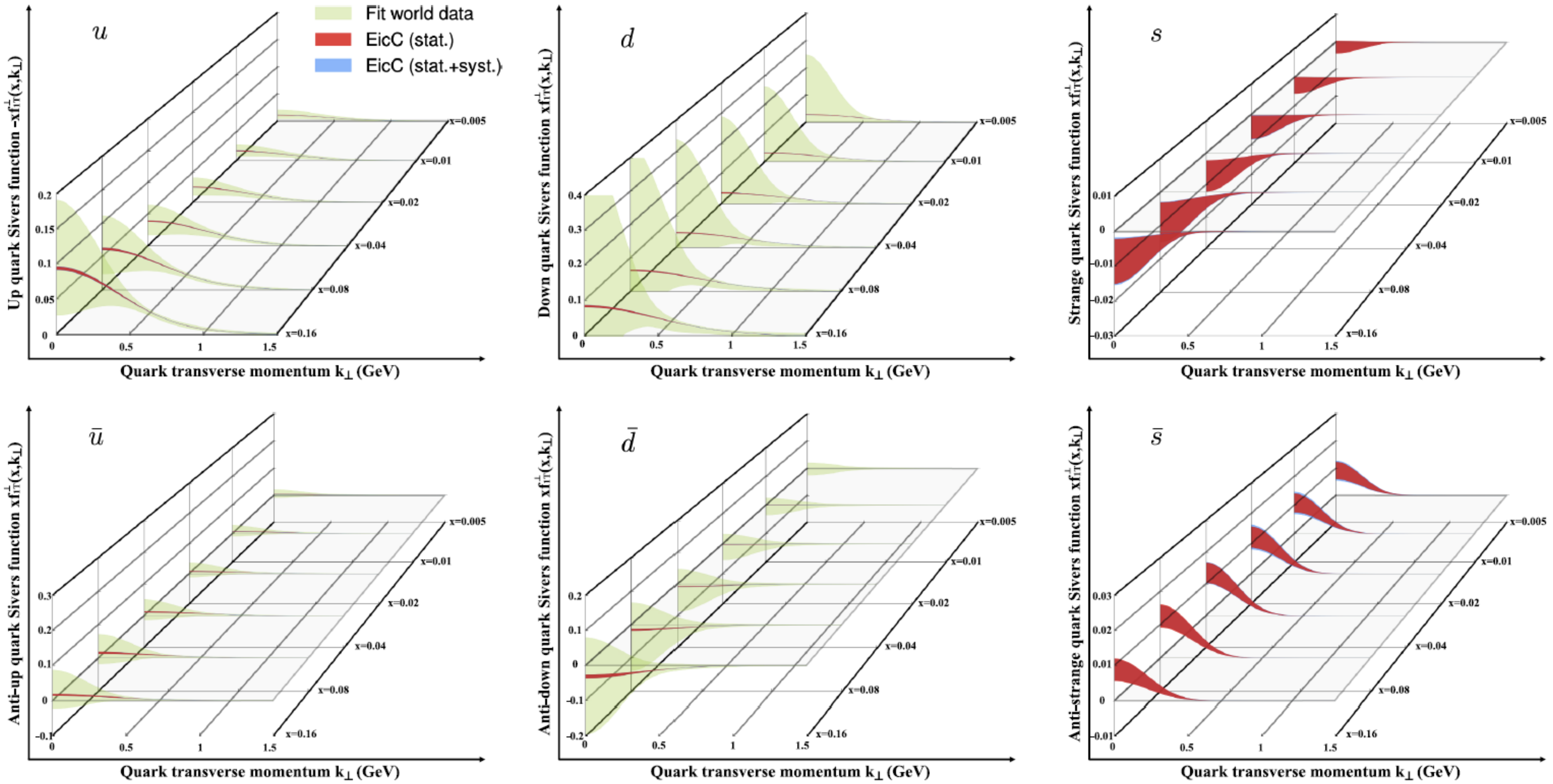


Fig. 2: Results for the Collins (top) and Sivers (bottom) asymmetries for deuterons from 2022 data as a function of x, z and P_T for positive (red circles) and negative (black triangles) hadrons. The error bars are statistical only. The bands show the systematic point-to-point uncertainties.

Something more

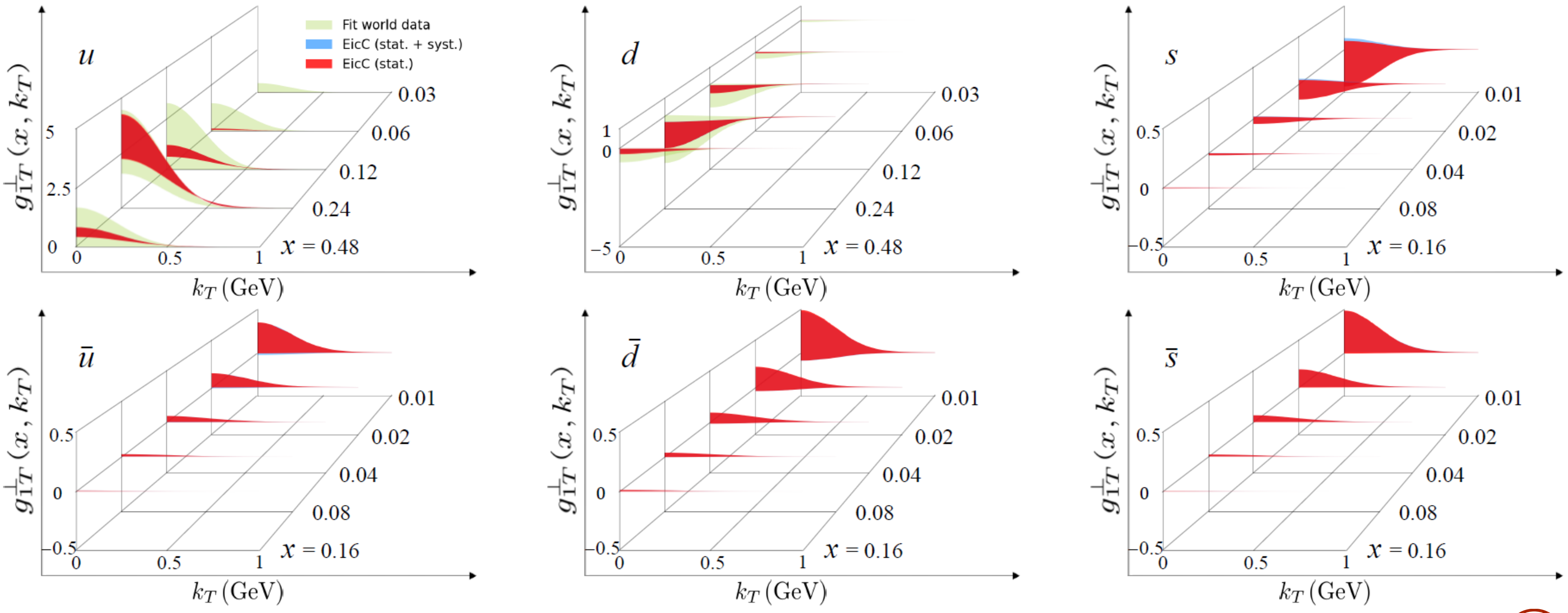


EicC impact on Sivers functions



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

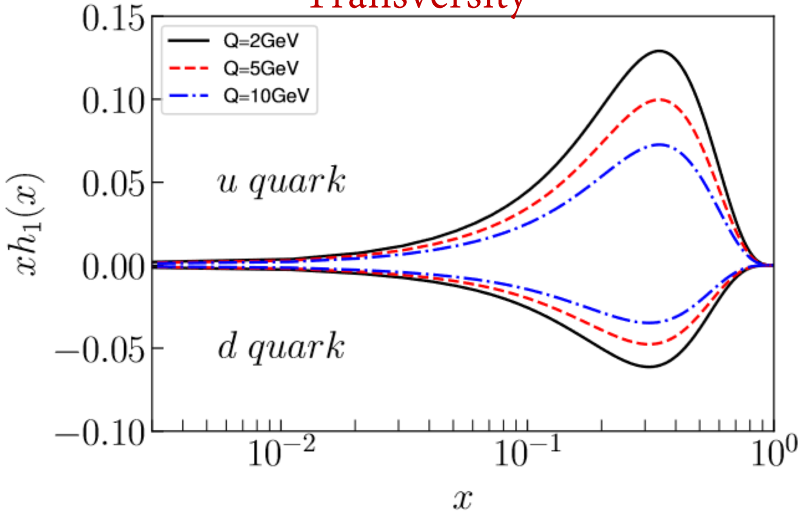
EicC impact on Worm-Gear functions



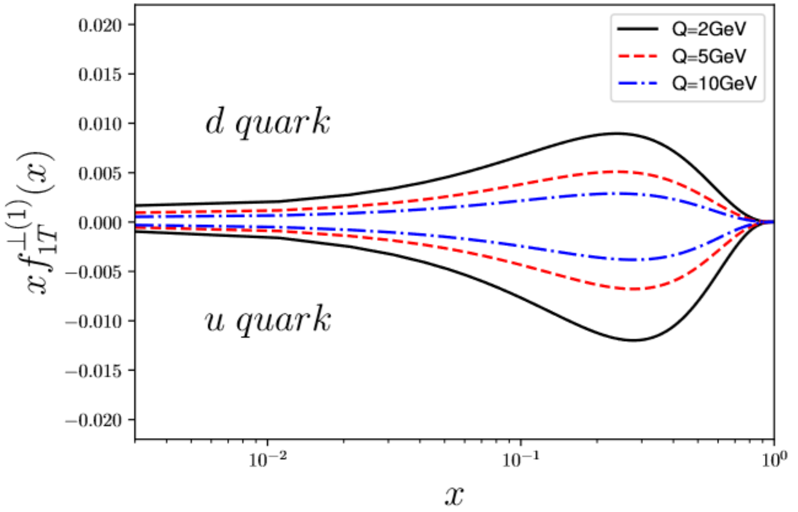
K. Yang, T. B. Liu, P. Sun, Y. X. Zhao, and B.-Q. Ma, arXiv: 2403.12795 (2024)

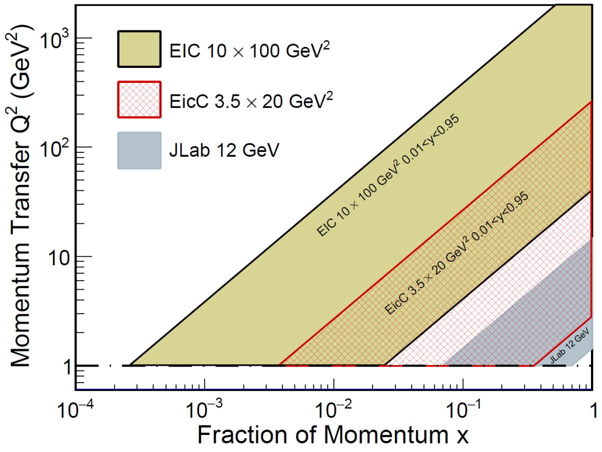
More words on TMDs study

Transversity

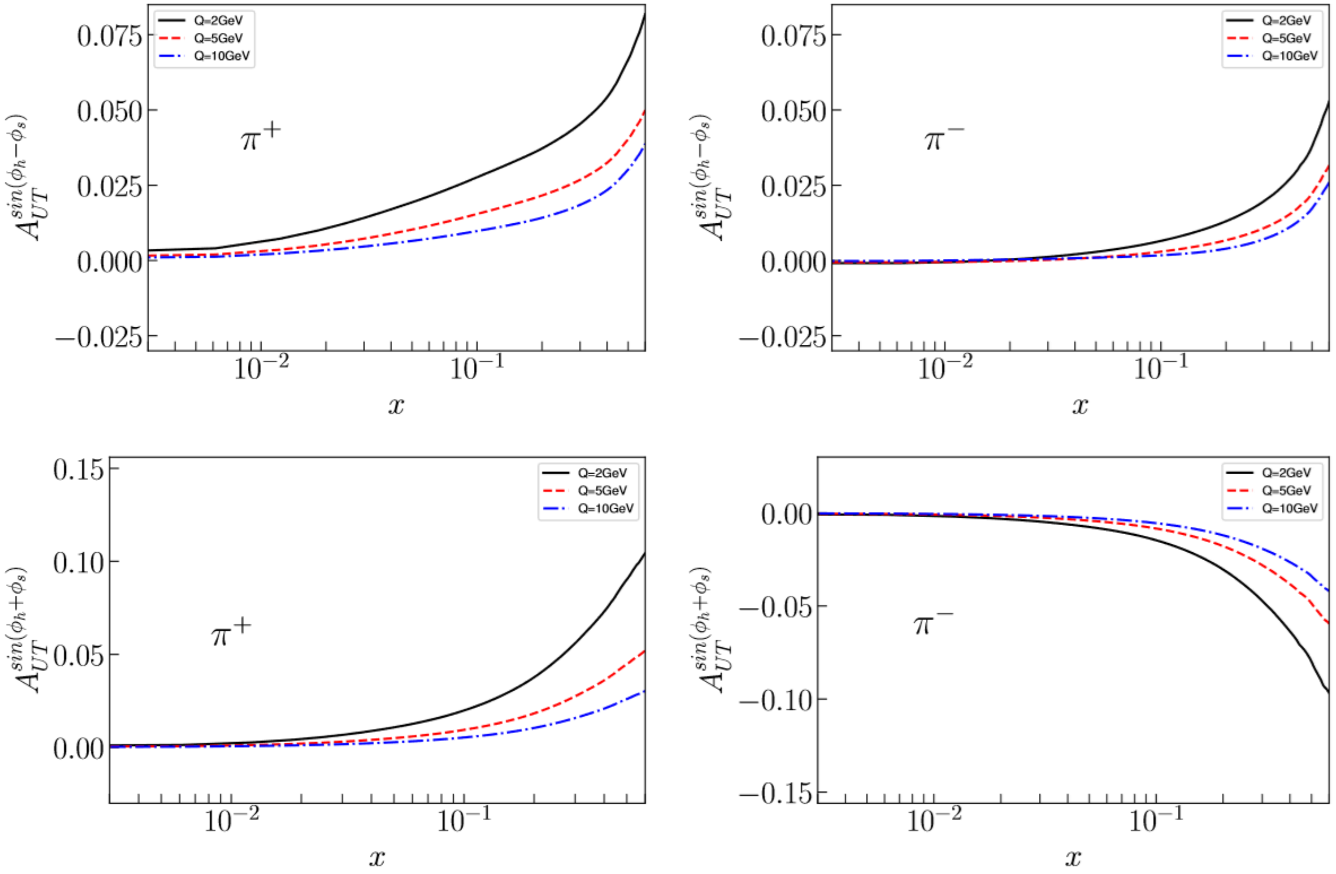


Sivers





Observables



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

Summary

- A new global analysis framework is set up for TMDs study
- EicC can significantly enhance our knowledge of TMDs, especially for sea quarks
- For TMDs study, a moderate-energy EIC with high luminosity is preferable

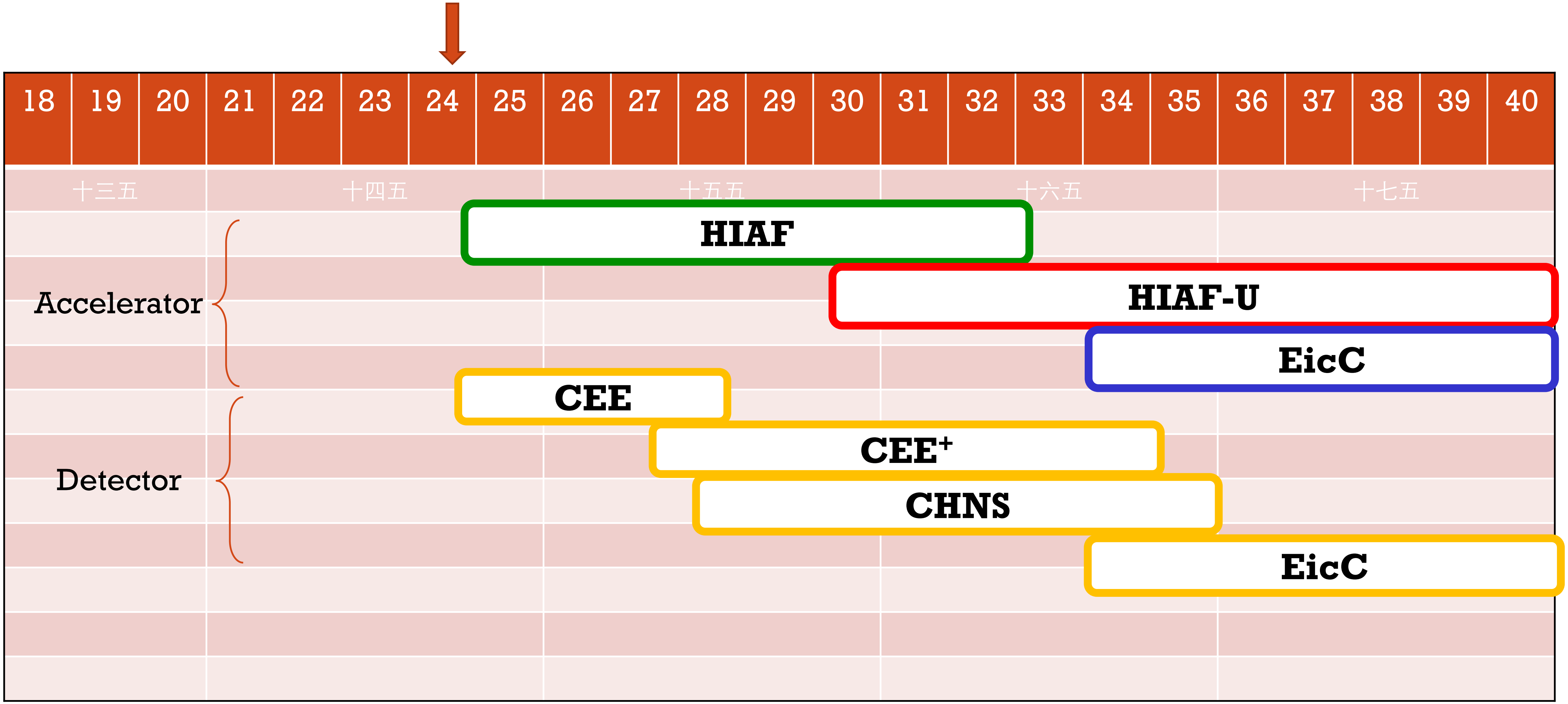
Please refer to the following papers for more details:

Frontiers of Physics 16 (6), 64701 (2021), Phys. Rev. D 106, 094039 (2022), Phys. Rev. D 109, 056002 (2024), and arXiv: 2403.12795 (2024)

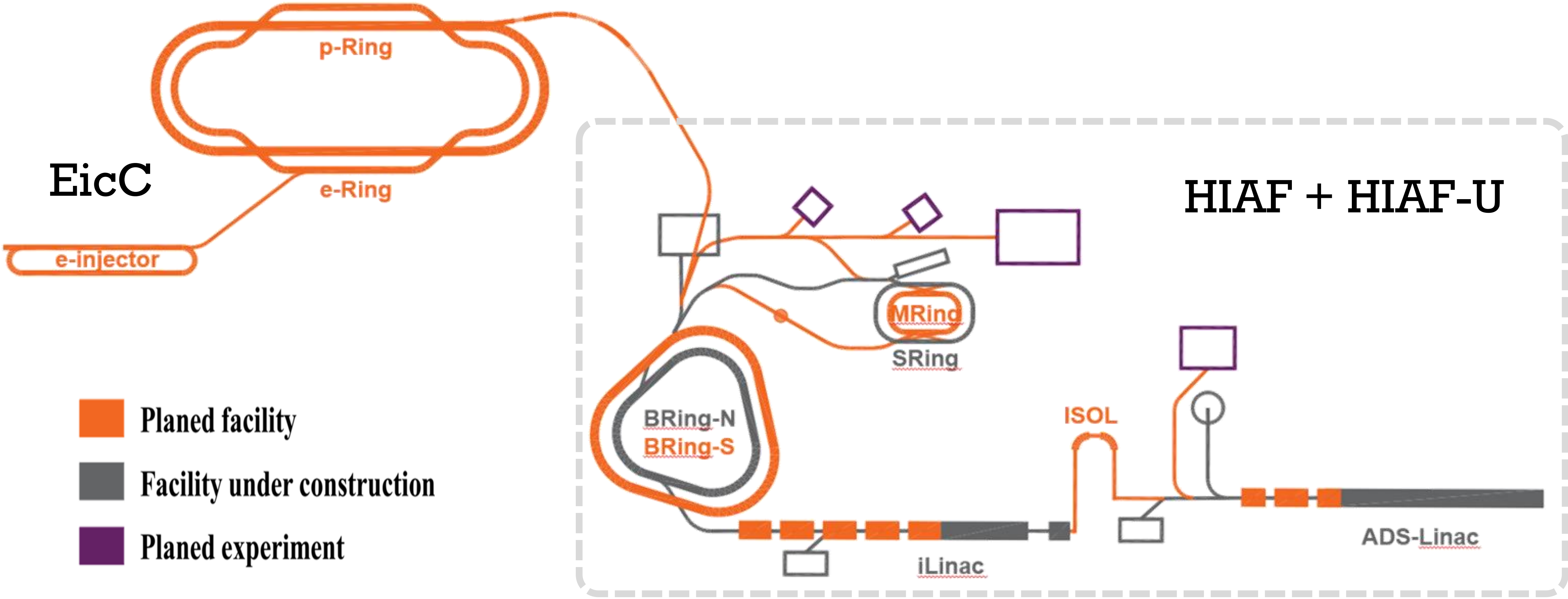
Special thanks to Hongxin Dong, Tianbo Liu, Boqiang Ma, Peng Sun, Ke Yang, Chunhua Zeng, and the EicC Team

Backups

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
HIAF
Accelerator
HIAF-U
EicC
CEE
CEE+
Detector
CHNS
EicC

EicC Accelerator complex layout



Parametrization

Transversity distributions

$$h_{1,q\leftarrow p}(x,b) = h_{1,q\leftarrow p}(x,\mu_0)h_{\rm NP}(x,b) \qquad \mu_0 = 2\,\text{GeV}$$

$$h_{1,q\leftarrow p}(x,\mu_0) = N_q \frac{(1-x)^{\alpha_q}x^{\beta_q}(1+\epsilon_q x)}{n(\beta_q,\epsilon_q,\alpha_q)} f_{1,q\leftarrow p}(x,\mu_0), \qquad h_{\rm NP}(x,b) = \exp(-r_q b^2)$$

Collins fragmentation functions

$$H^{\perp}_{1,q\to h}(z,b) = \frac{1}{z^2}\hat{H}^{(3)}_{1,q\to h}(z,\mu_0)H_{\rm NP}(z,b)$$

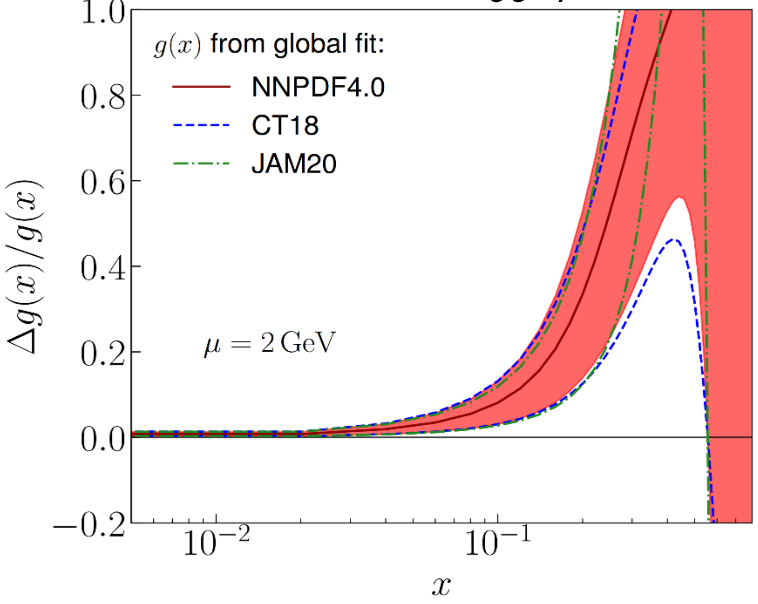
$$\hat{H}^{(3)}_{1,q\to h}(z,\mu_0) = N_q^h \frac{(1-z)^{\alpha_q^h}z^{\beta_q^h}(1+\epsilon_q^h z)}{n(\beta_q^h,\epsilon_q^h,\alpha_q^h)}, \qquad D_{\rm NP}(z,b) = \exp\left[-\frac{\eta_1 z+\eta_1(1-z)}{\sqrt{1+\eta_3(b/z)^2}}\frac{b^2}{z^2}\right]\left(1+\eta_4\frac{b^2}{z^2}\right)$$

Transversity	r	β	ϵ	α	N
u	r_u	β_u	ϵ_u	α_u	N_u
d	r_d	β_d	ϵ_d	α_d	N_d
$\bar{u}$	$r_{\rm sea}$	0	0	0	$N_{\bar{u}}$
$\bar{d}$	$r_{\rm sea}$	0	0	0	$N_{\bar{d}}$

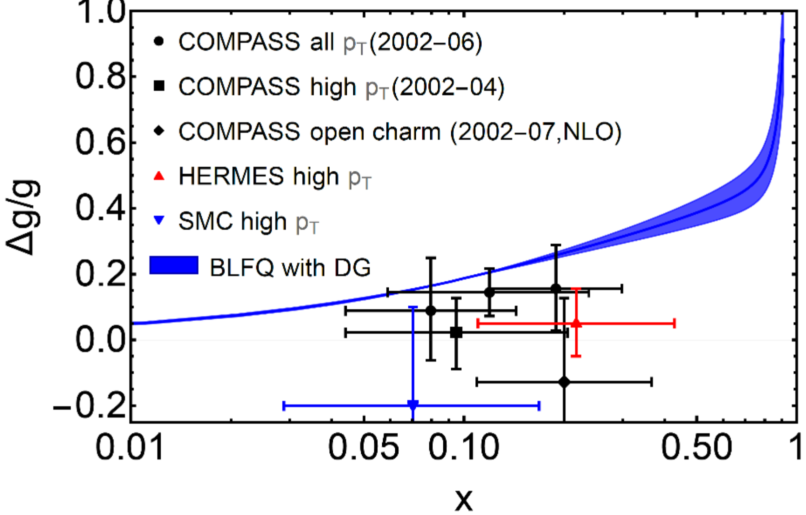
Collins	η_1	η_3	η_4	β	ϵ	α	N
π_{fav}	η_{1f}^{π}	η_{3f}^{π}	η_{4f}^{π}	β_f^{π}	0	α_f^{π}	N_f^{π}
π_{unf}	η_{1u}^{π}	η_{3u}^{π}	η_{4u}^{π}	β_u^{π}	0	α_u^{π}	N_u^{π}
K_{fav}	η_{1f}^{K}	0	η_{4f}^{K}	β_f^{K}	0	α_f^{K}	N_f^{K}
K_{unf}	η_{1u}^{K}	0	η_{4u}^{K}	β_u^{K}	0	α_u^{K}	N_u^{K}

EicC and EIC-gluon polarization (at large x)

ArXiv:2211.15587



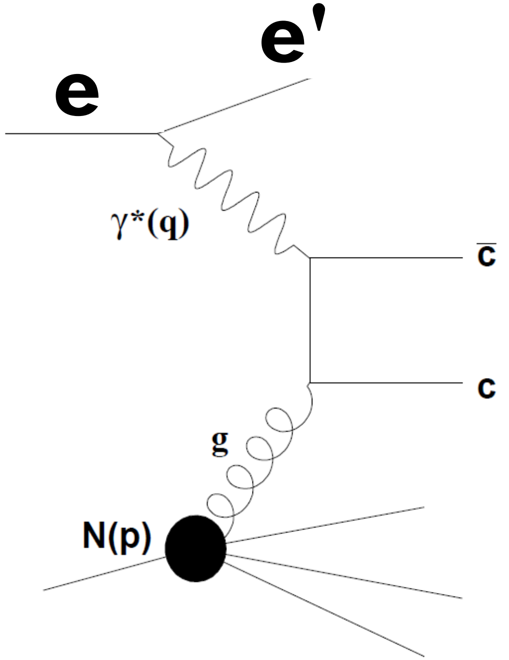
ArXiv:2209.08584

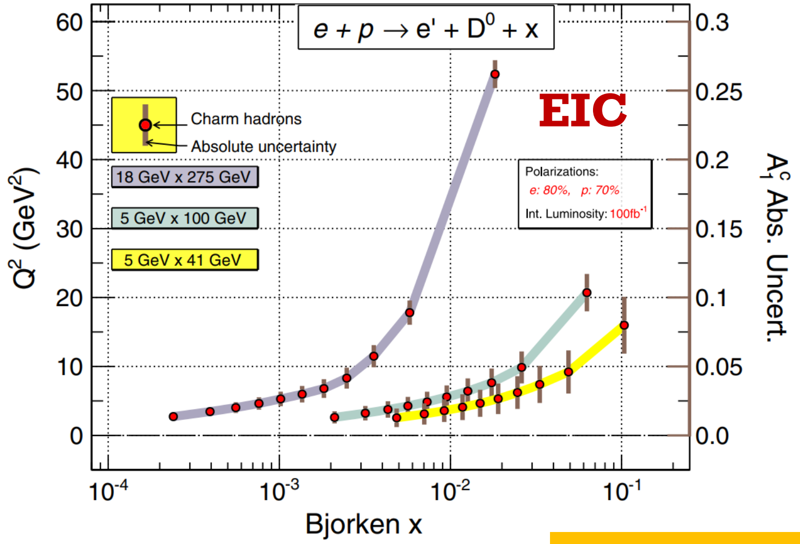


D. Anderle , X. Dong, …, E. Sichtermann, …, F. Yuan, **Y. X. Zhao**# Phys. Rev. D104, 114039 (2021)

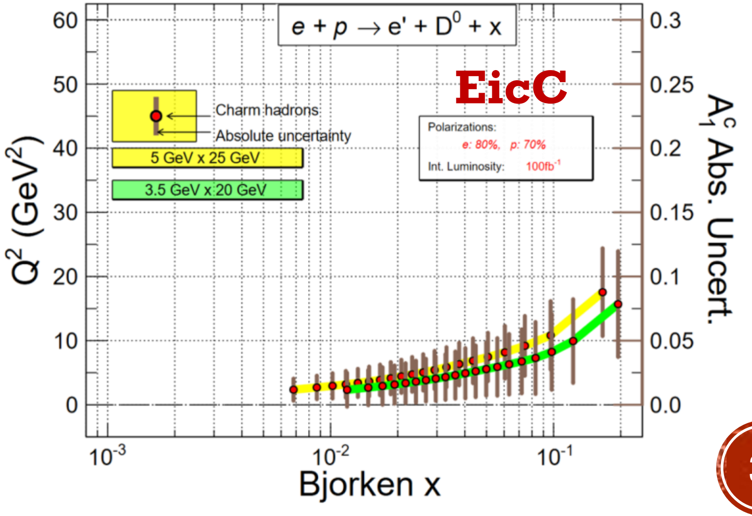
$$A_{LL}^{\vec{e}+\vec{p}\to e'+D^0+X} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

$$= \frac{1}{P_e P_p} \frac{N^{++} - N^{+-}}{N^{++} + N^{+-}}$$



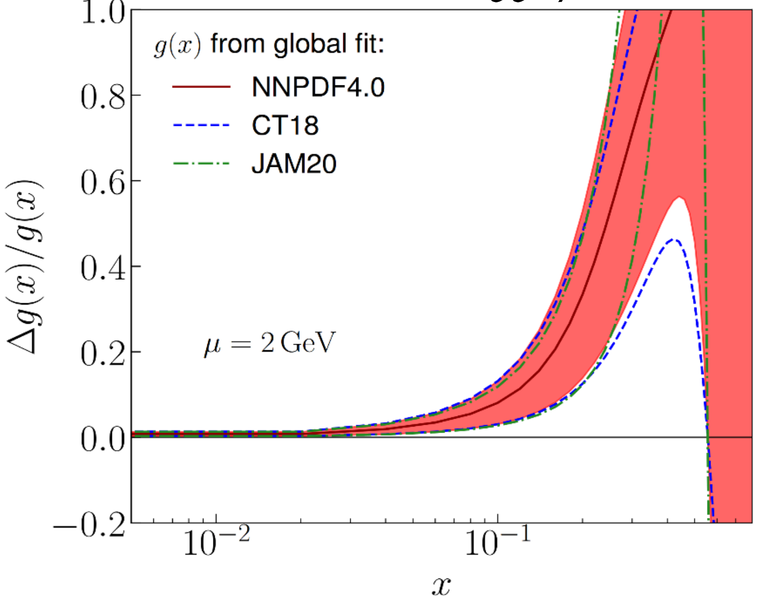


complementary

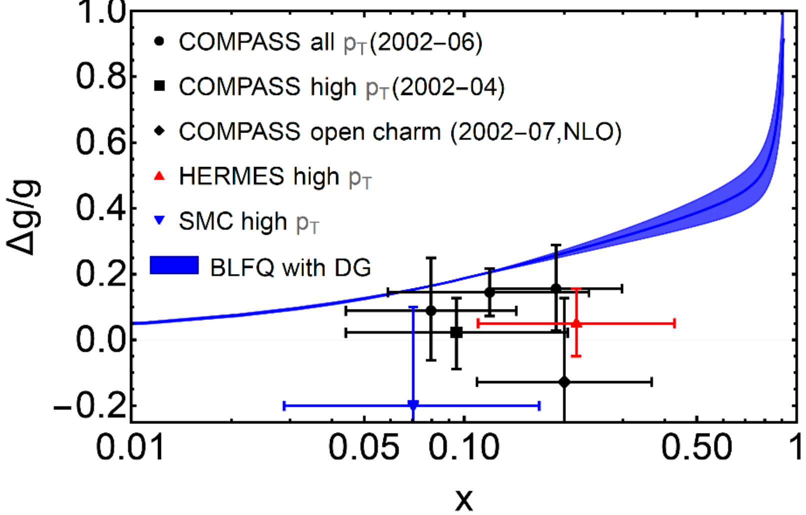


EicC and EIC-gluon polarization (at large x)

ArXiv:2211.15587

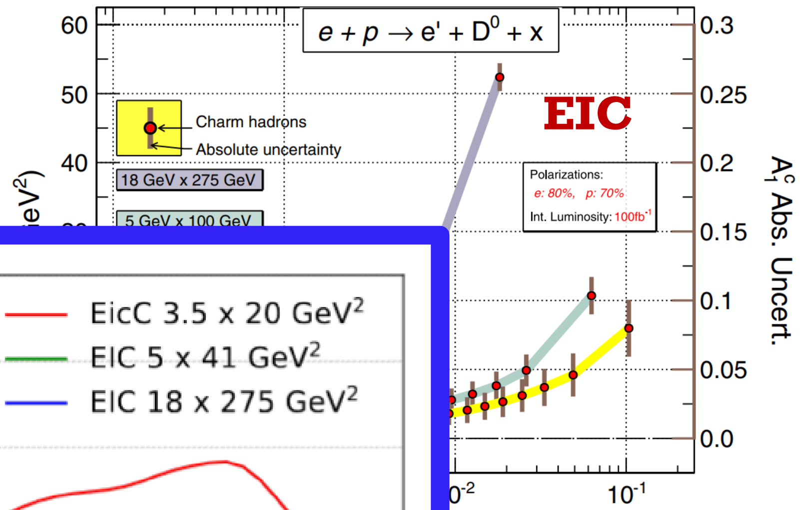


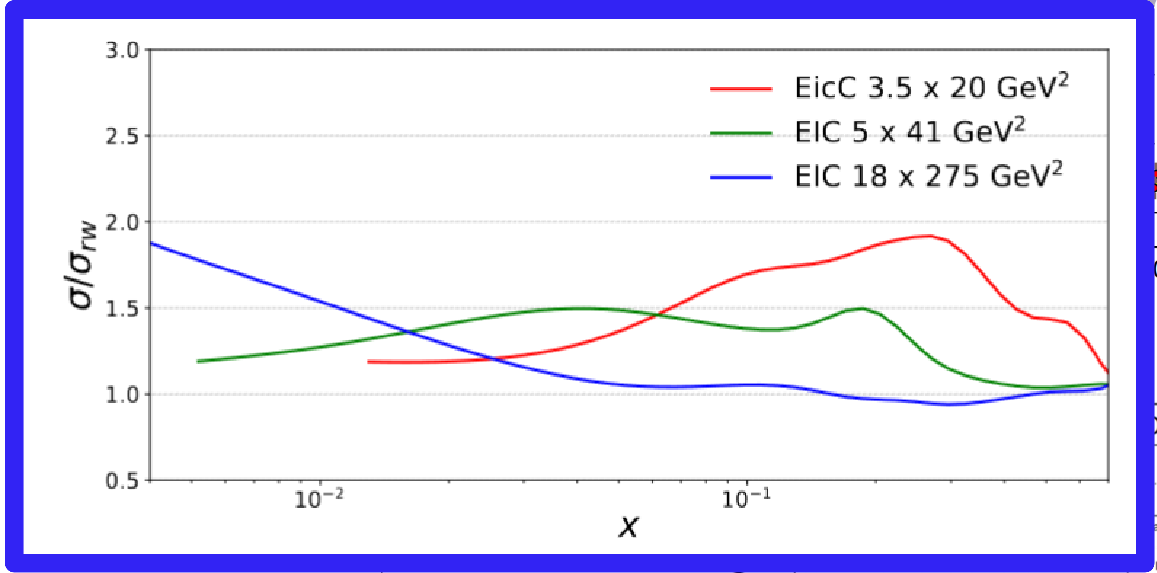
ArXiv:2209.08584



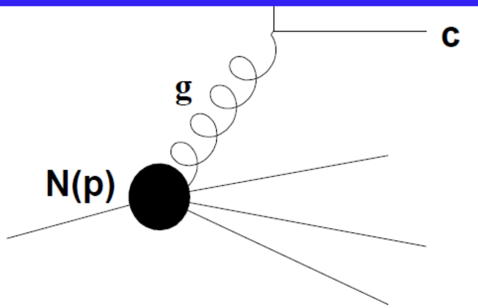
D. Anderle , X. Dong, …, E. Sichtermann, …, F. Yuan, **Y. X. Zhao#** Phys. Rev. D104, 114039 (2021)

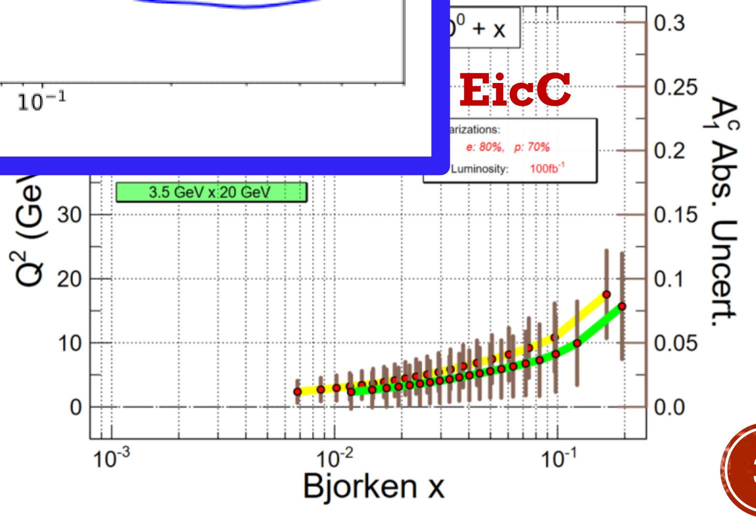
$$A_{LL}^{\vec{e}+\vec{p}\to e'+D^0+X} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$



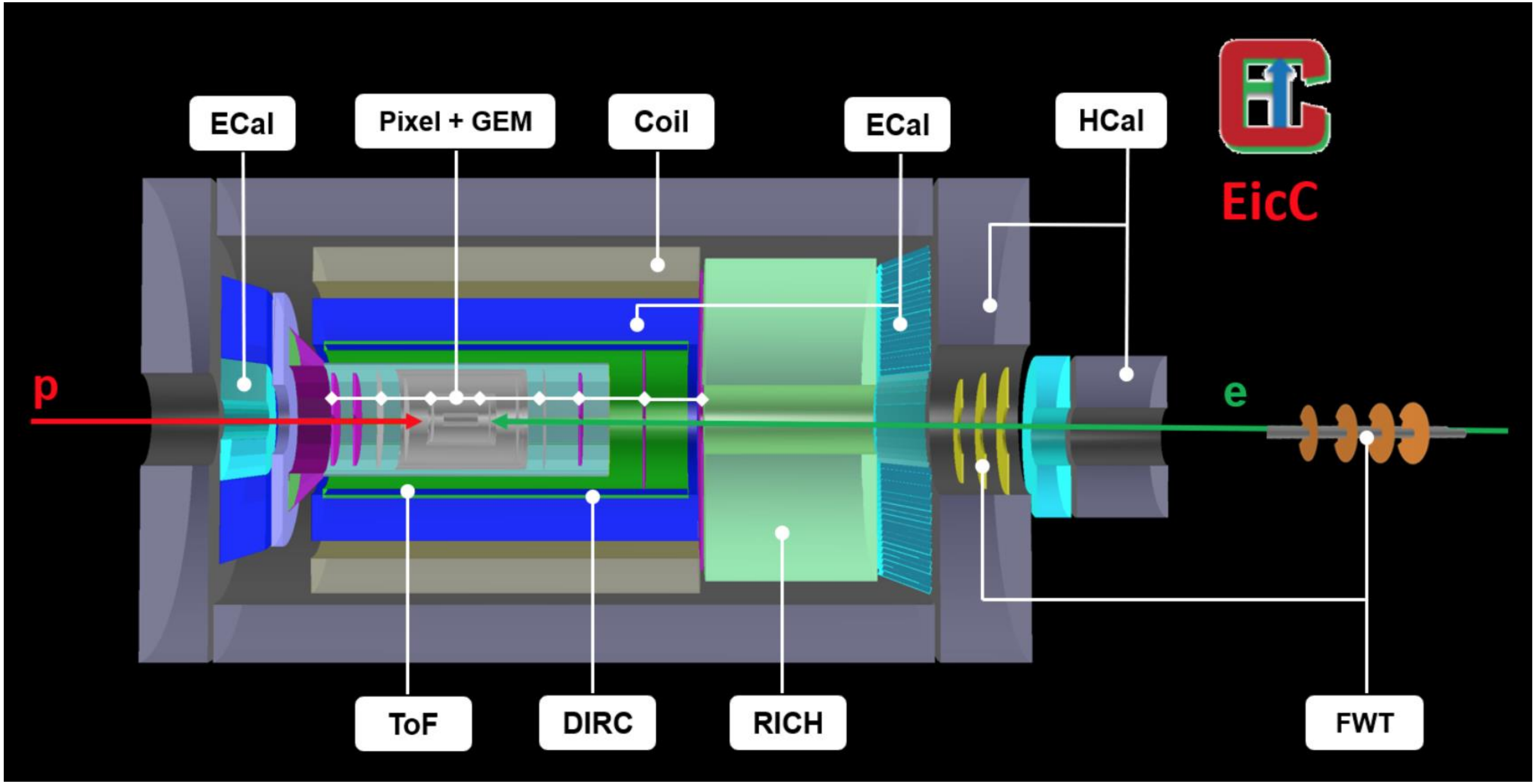


complementary





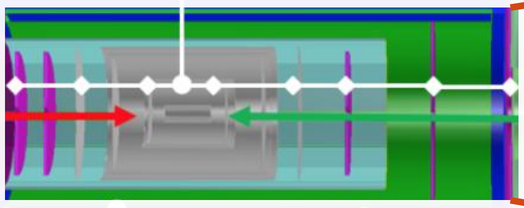
EicC detector design



EicC detector design

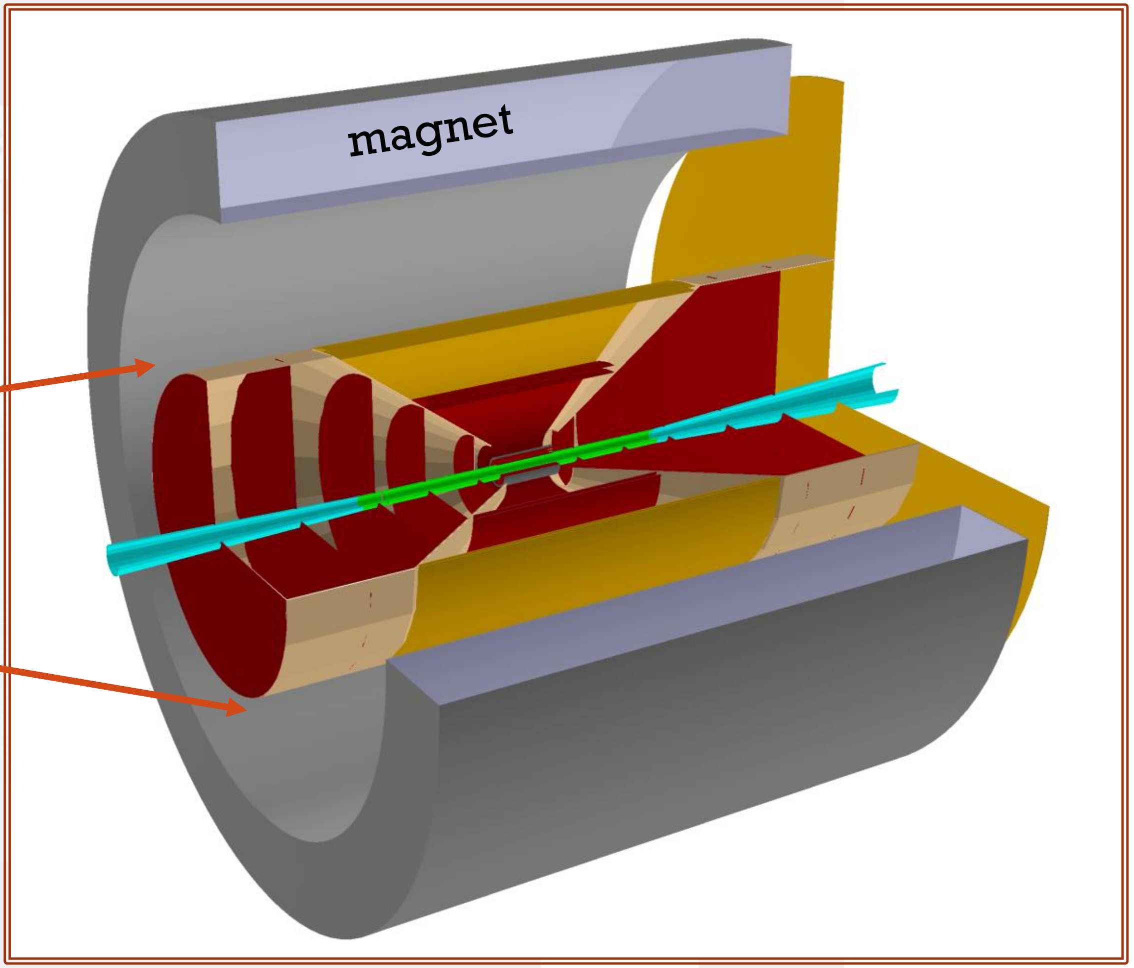
Tracking: Silicon + MPGD

R(cm)	Length(cm)	Pixel Pitch(μm)	Material Budget (X/X0 %)	Tech
3.30	28.0	20	0.05	MIC7
4.35	28.0	20	0.05	MIC7
5.40	28.0	20	0.05	MIC7
34.85	90.61	25	0.85	MIC6
38.15	90.61	25	0.85	MIC6
65.50	174.88	150(rϕ)x150(z)	0.40	MPGD
67.50	174.88	150(rϕ)x150(z)	0.40	MPGD



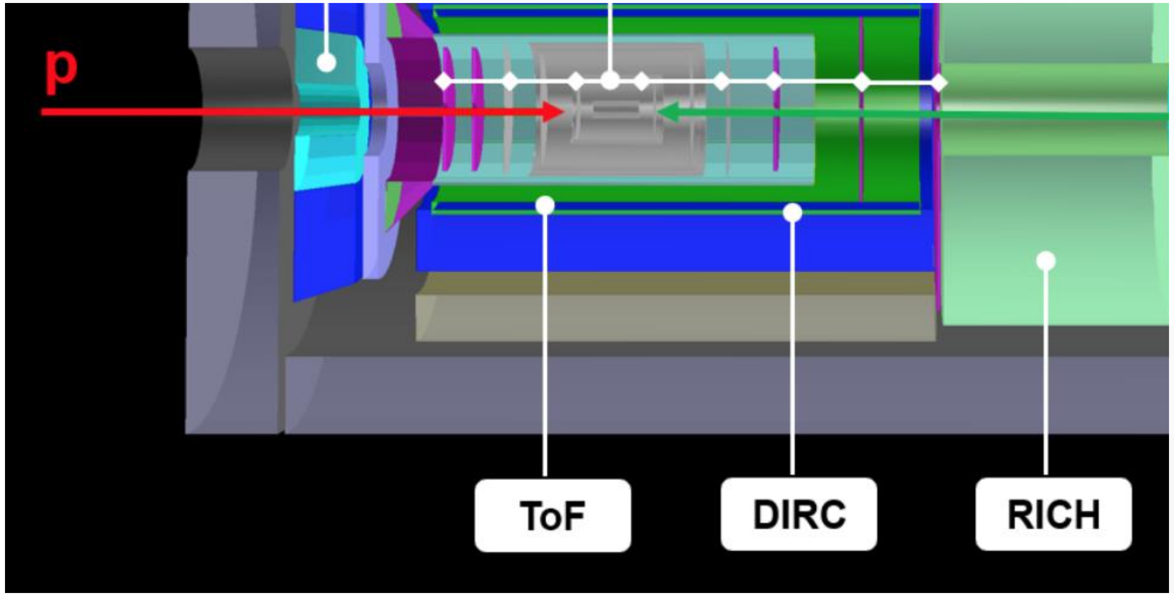
In R(cm)	Out R(cm)	Z(cm)	Pixel Pitch(μm)	Material Budget (X/X0 %)	Tech
3.18	18.62	25	25	0.42	MIC6
3.18	36.50	49	25	0.42	MIC6
3.47	55.00	73	25	0.42	MIC6
5.08	67.50	103.65	25	0.42	MIC6
6.58	67.50	134.33	25	0.42	MIC6
8.16	150.00	165.00	50(rϕ)x250(r)	0.26	MPGD

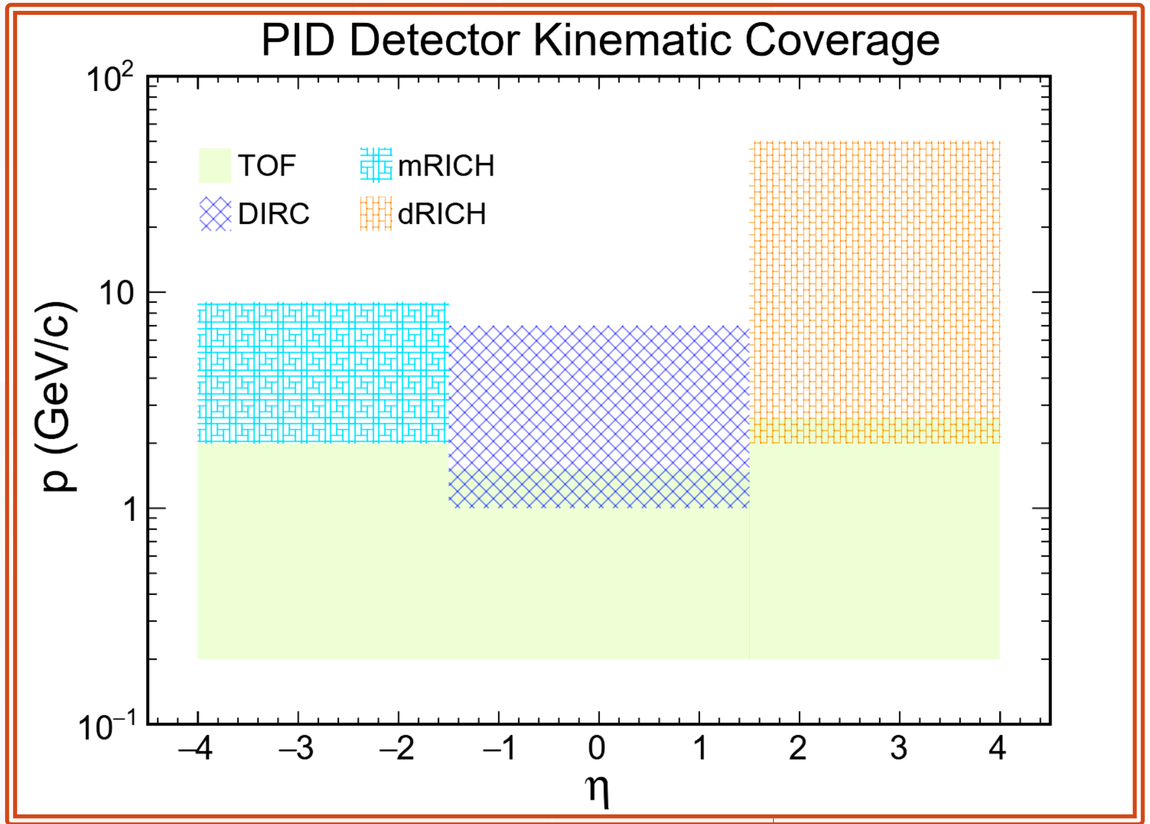
In R(cm)	Out R(cm)	Z(cm)	Pixel Pitch(μm)	Material Budget (X/X0 %)	Tech
3.18	18.62	-25	25	0.42	MIC6
3.18	36.50	-49	25	0.42	MIC6
3.18	55.00	-73	25	0.42	MIC6
3.95	67.50	-109.0	25	0.42	MIC6
5.26	67.50	-145.0	25	0.42	MIC6



EicC detector design

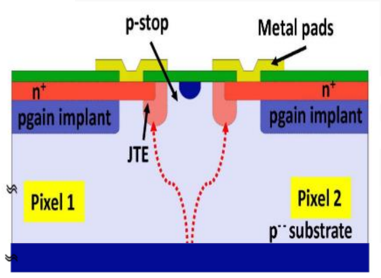
PID: ToF + (DIRC + RICH)



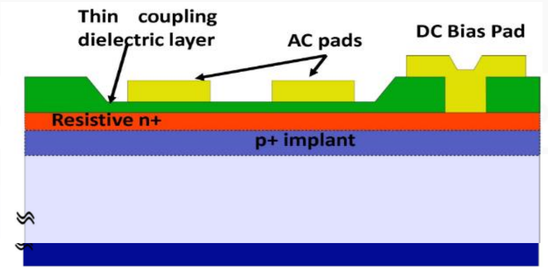


EicC detector design

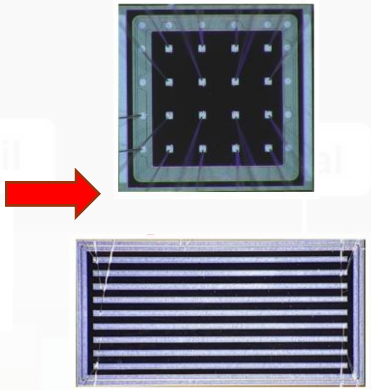
PID: ToF + (DIRC + RICH)

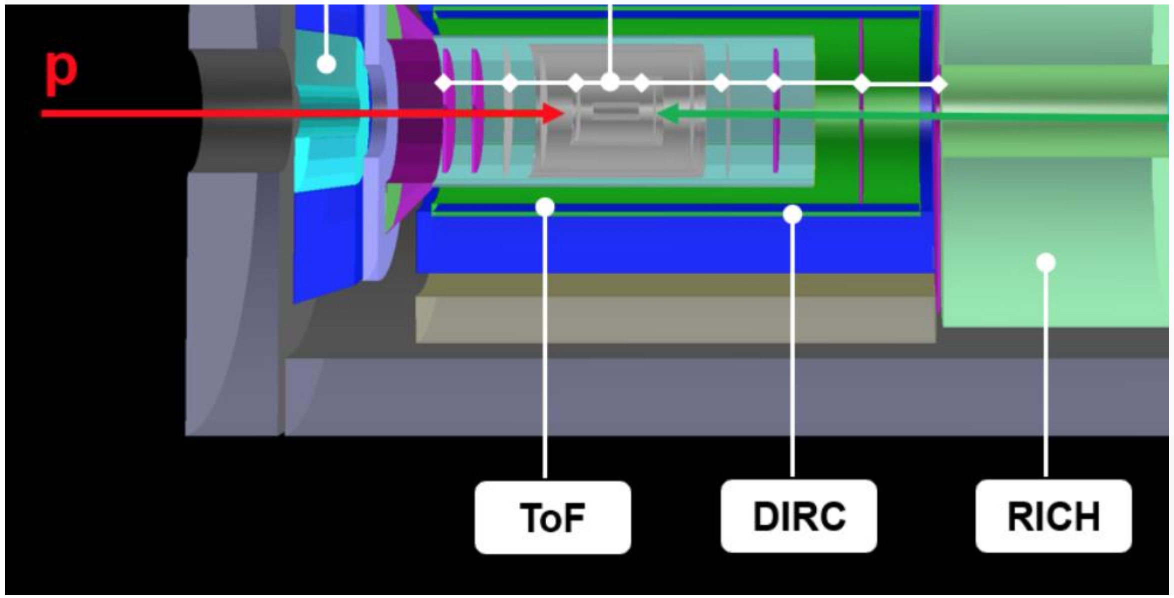


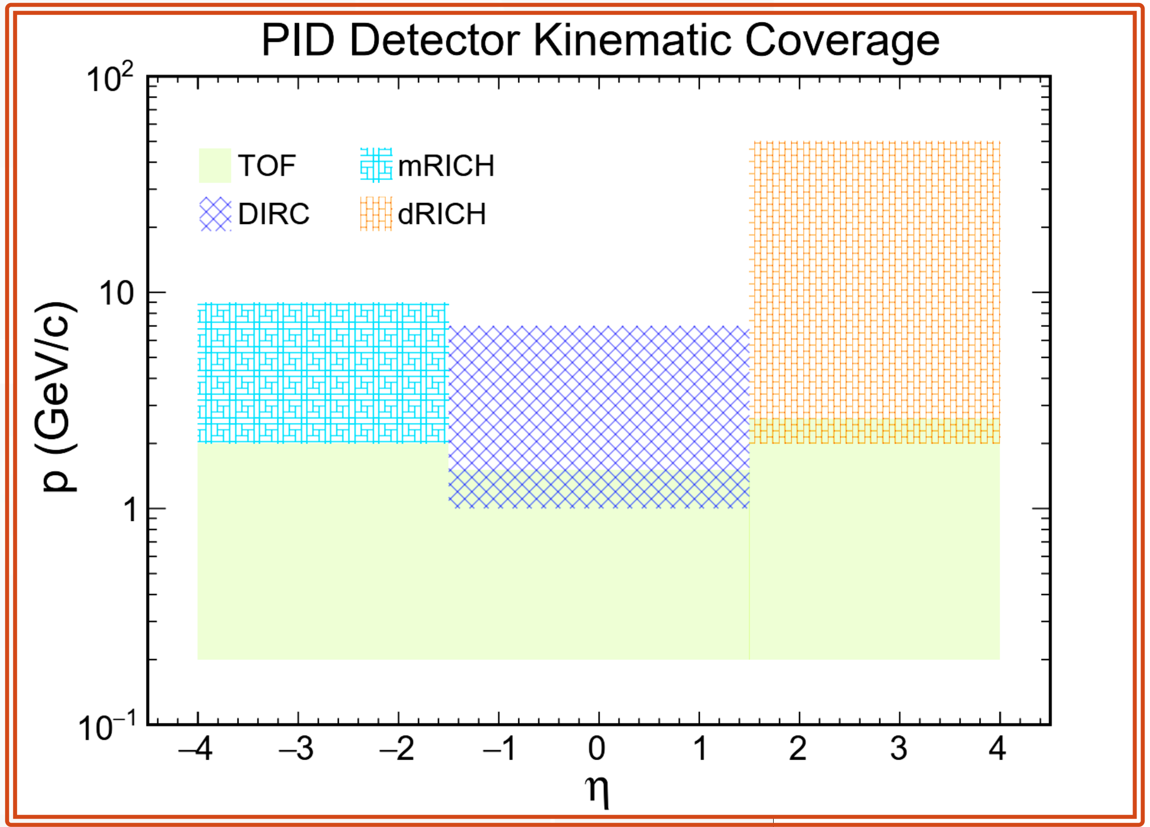
DC-LGAD



AC-LGAD

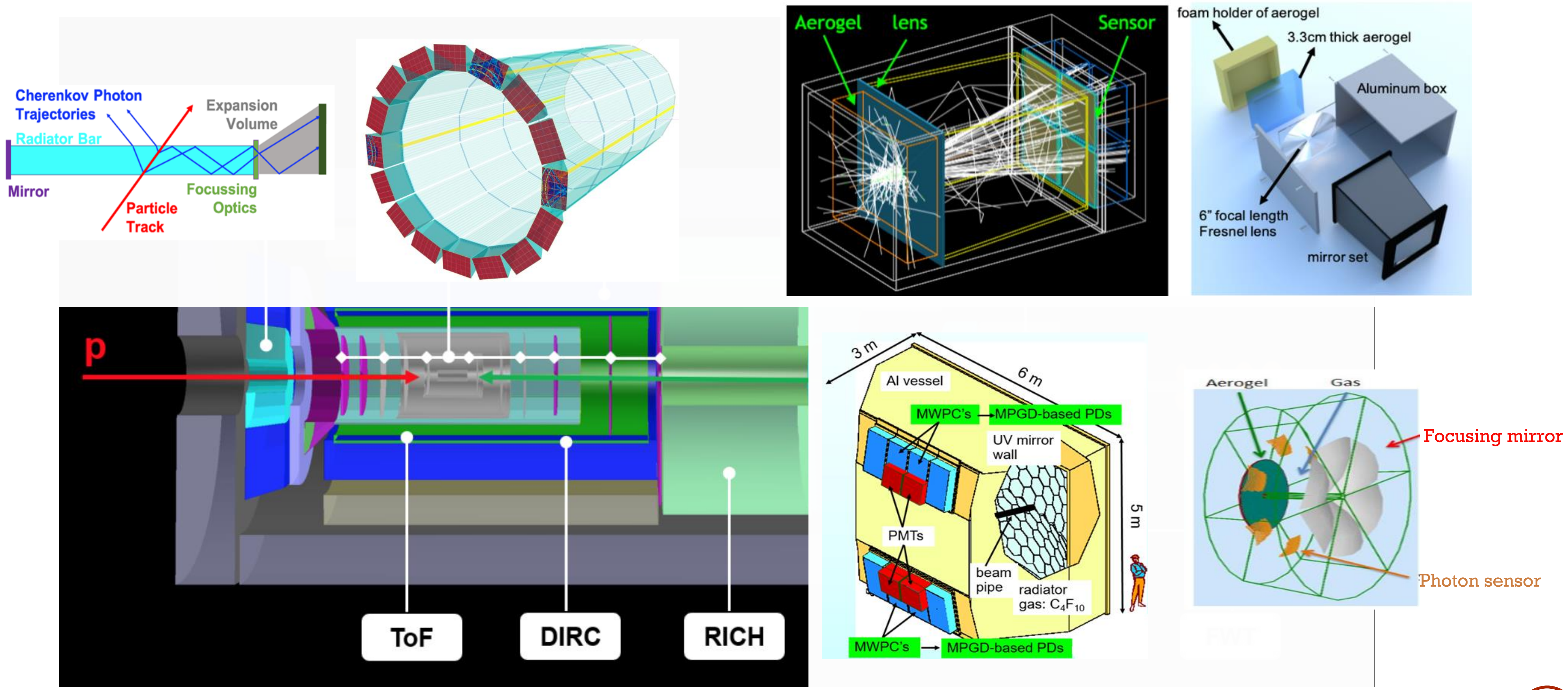






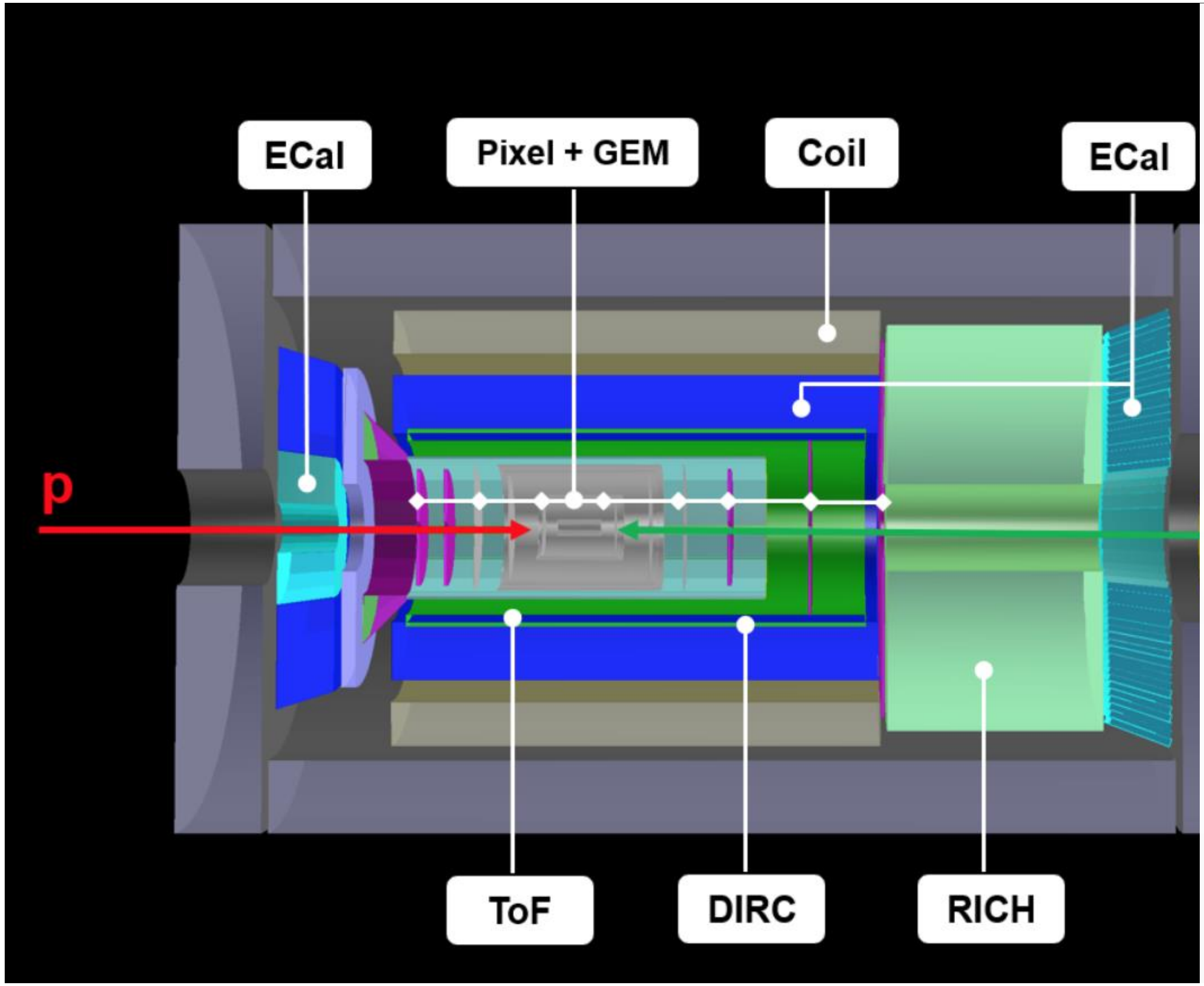
EicC detector design

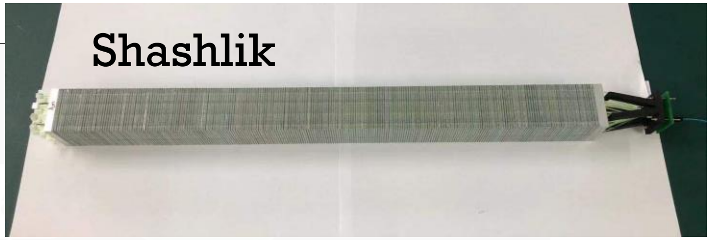
PID: ToF + (DIRC + RICH)

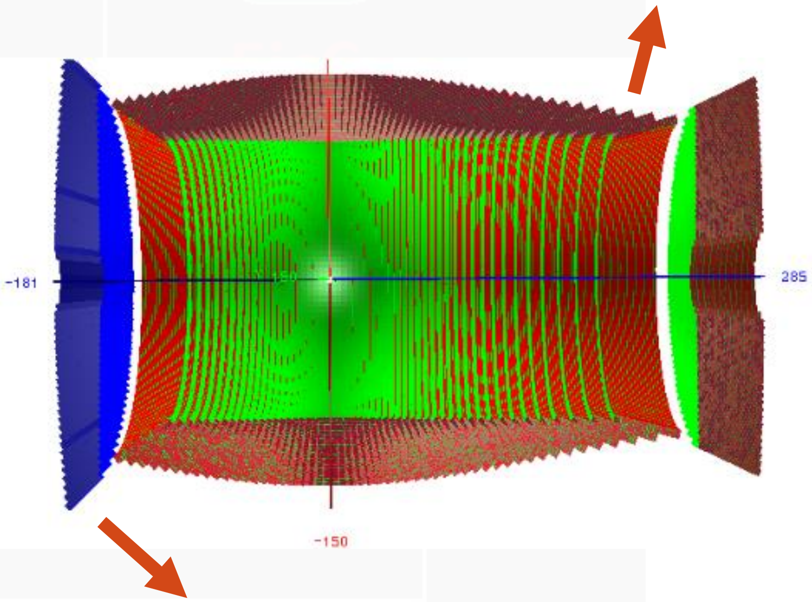


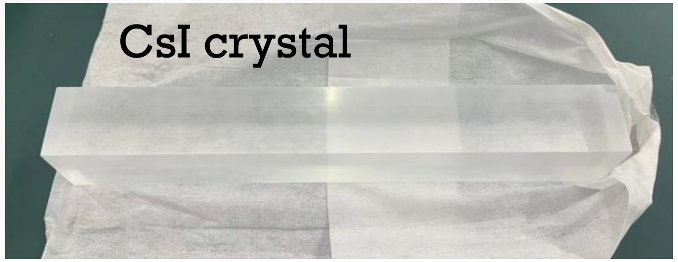
EicC detector design

Ecal: Shashlik + CsI crystal



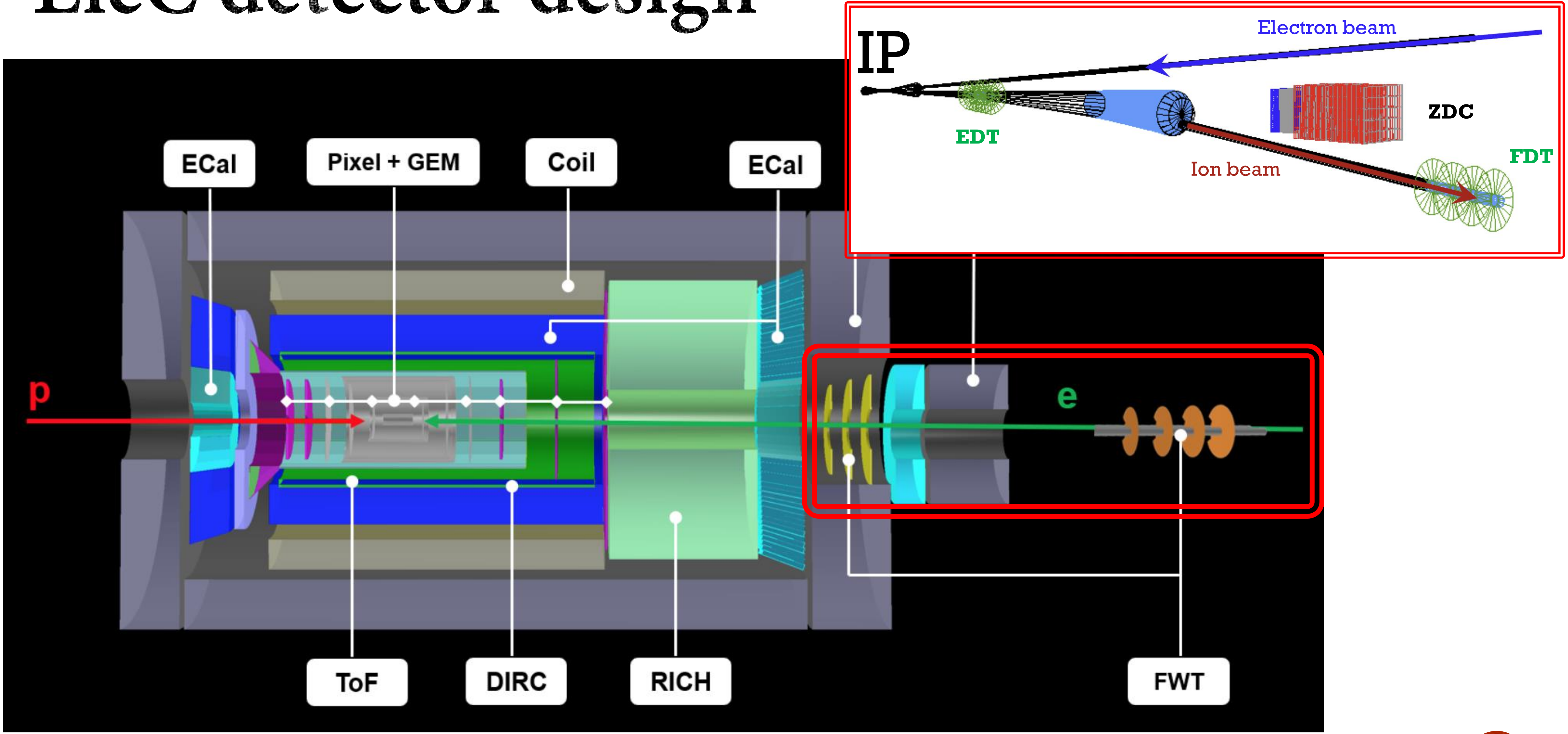






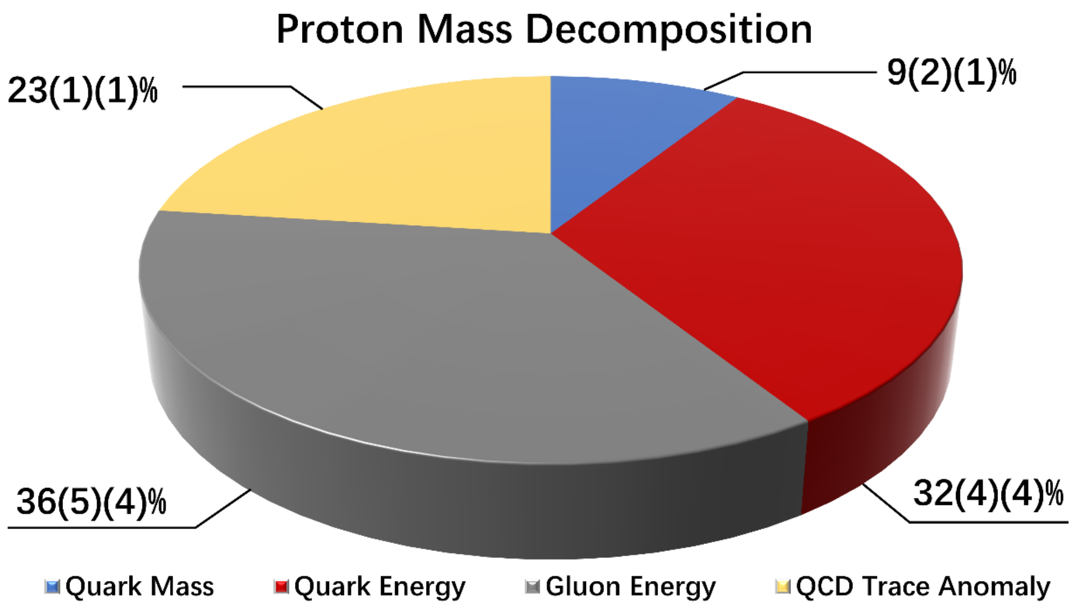
EicC detector design

Far-Forward detector



Proton mass study

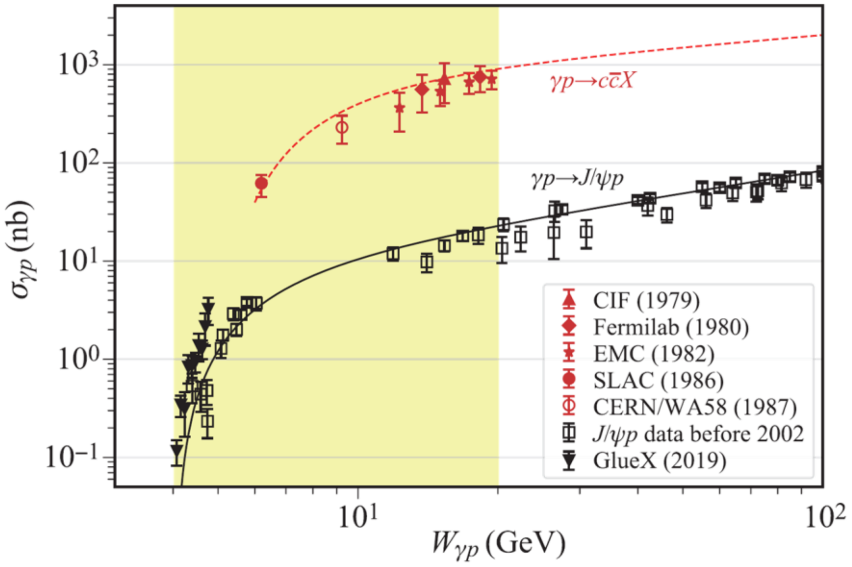
Lattice QCD calculation
Phys. Rev. Lett. 121 (2018) 21, 212001



- **Quark energy** and **gluon energy** constrained by PDFs
- **Quark mass** via πN low energy scattering
- **Trace anomaly** via threshold production of J/Psi and Upsilon ?

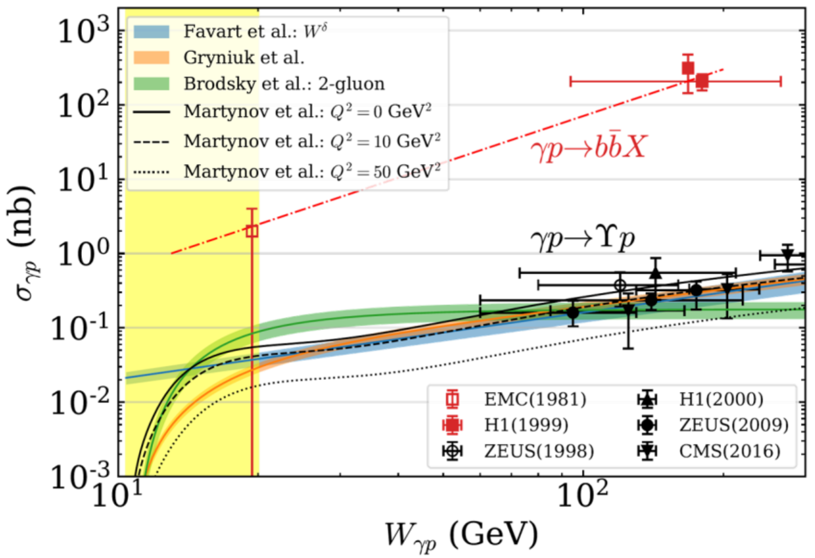
One of the hot topics under discussions

Near threshold J/Psi production



JLab & EicC & EIC

Near threshold Upsilon production



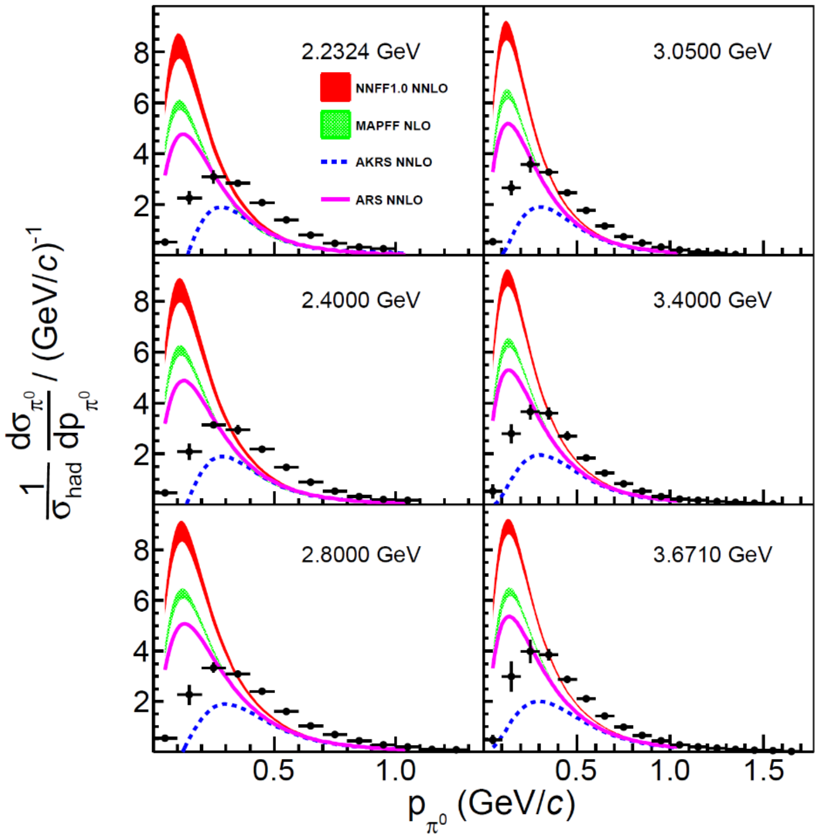
EicC & EIC

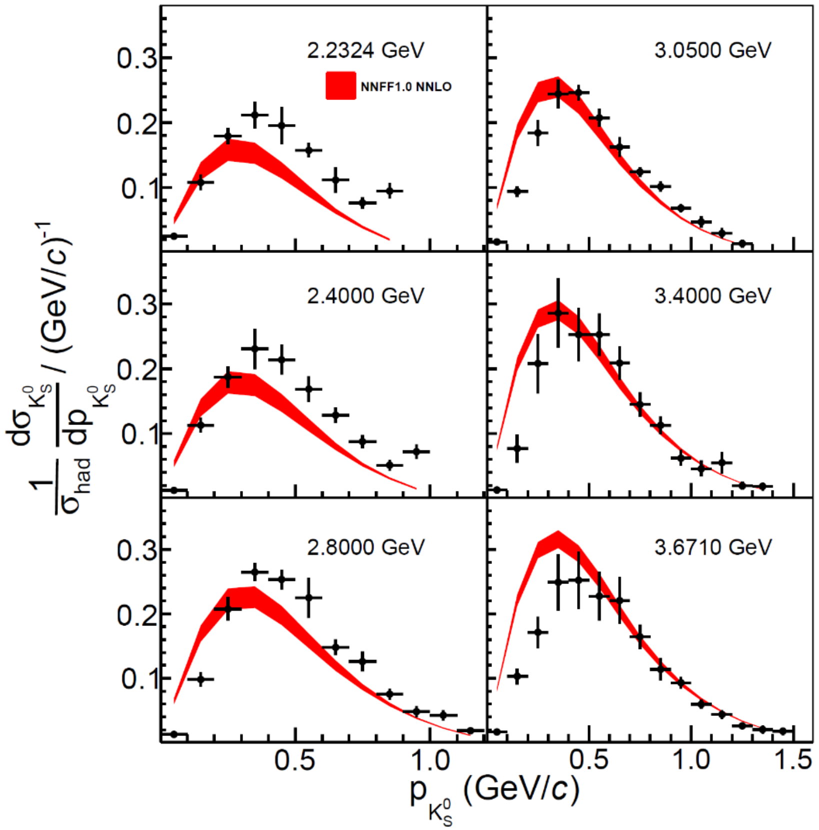
Multiplicity measurements at BESIII

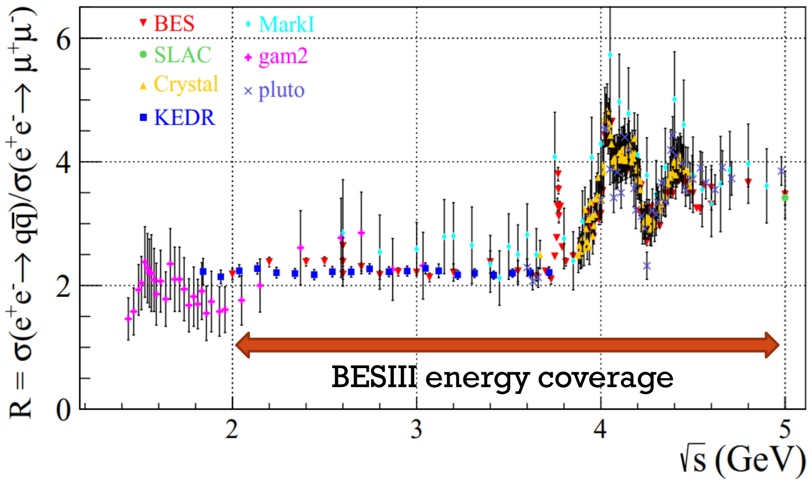
Multiplicity: $$\frac{1}{\sigma_{tot}(e^+e^- \rightarrow \ hadrons)} \frac{d\sigma(e^+ e^- \rightarrow h \ + \ X)}{d\ P_h} \sim \ \sum_q e_q^2 D_1^{h/q}(z) \quad \text{at LO}$$

h is a particular type of hadron such as π^0, $\pi^{+/-}$, $K^{+/-}$ …

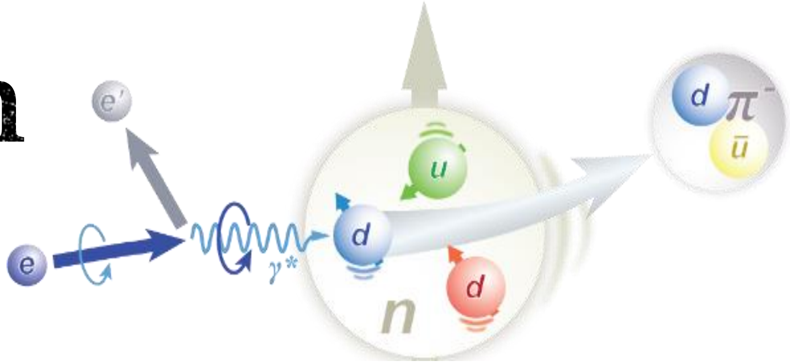
- First precision measurements at BESIII: Phys. Rev. Lett. 130, 231901 (2023)
- Analyses of many other final states are ongoing → provide inputs for future EIC







TMDs in SIDIS Cross Section



$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\varepsilon)}\cdot$$

$$\{F_{UU,T} + \dots$$
$$+\,\varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \dots$$

Unpolarized

$$+\,S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \dots]$$
$$+\,S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+\sin(\phi_h-\phi_S)\cdot(F_{UT}^{\sin(\phi_h-\phi_S)} + \dots)$$
$$+\,\varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \dots]$$

Polarized Target

$$+\,S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \dots]$$
$$+\,S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \dots]\}$$

Polarized Beam and Target

f_1 =

Boer-Mulder $h_1^\perp$ =

$h_{1L}^\perp$ =

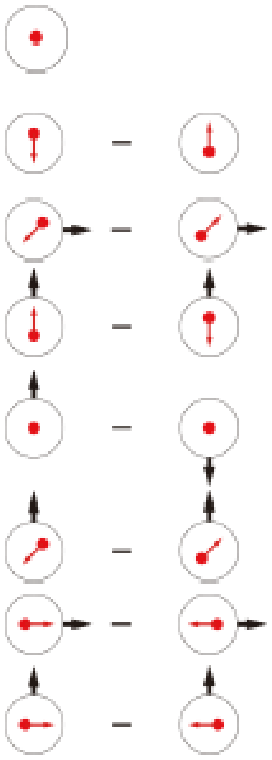
Transversity h_{1T} =

Sivers $f_{1T}^\perp$ =

Pretzelosity $h_{1T}^\perp$ =

g_1 =

$g_{1T}^\perp$ =



S_L, S_T: Target Polarization; λ_e: Beam Polarization

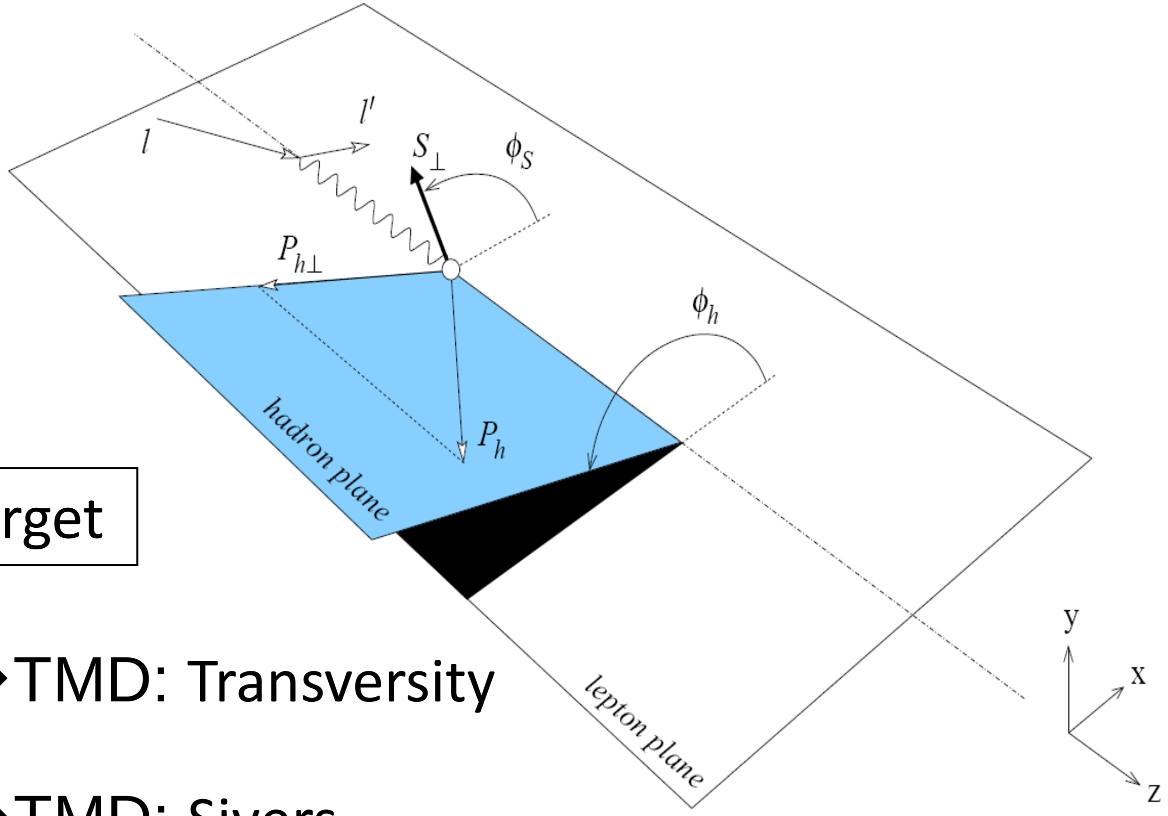
Target SSA, beam-target DSA measurements

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

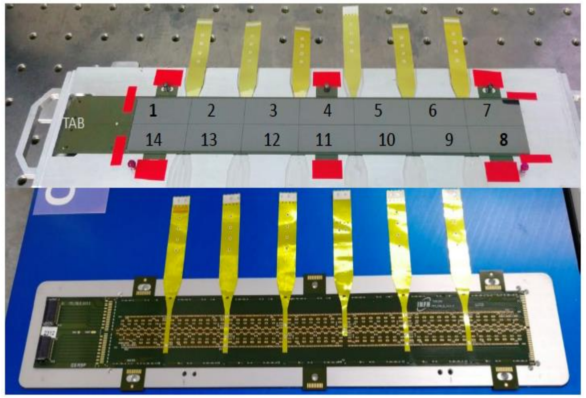
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$ →TMD: Sivers

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

Detector R&Ds

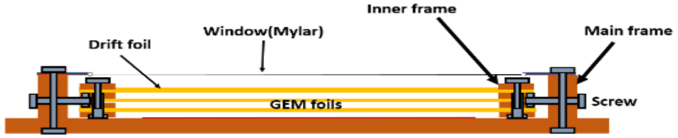
Clean rooms of ISO6 and ISO7 (in total of 200 m²) for detector assembling

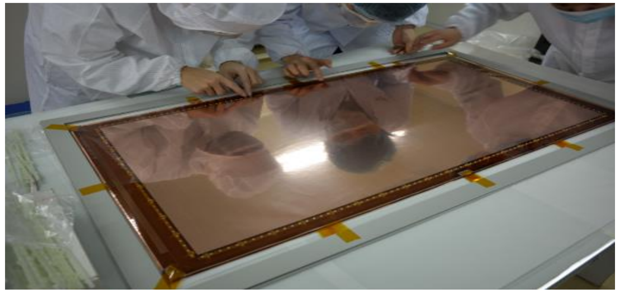
ALICE style ITS2 MAPS pixel detector



- 25cm x 25 cm Micromegas mass production
- R&D on 0.4m x 0.4m

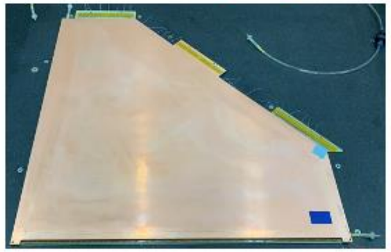
1m x 0.5 m GEM (self-stretching)



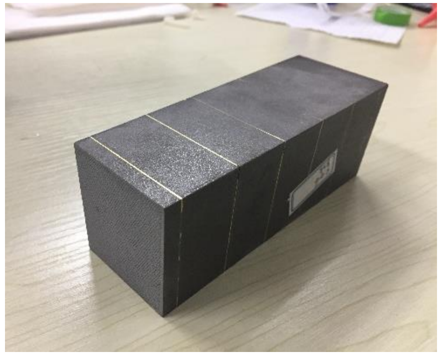


sTGC detector

~55cm * 55cm pentagon



Shashlyk and W-powder+ScFi EMCal



DIRC prototype