Overview of physics at the EicC

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Understanding the universe out of nothing

Out of QCD vacuum, (anti-)quarks are born;
Out of (anti-)quarks, hadrons;
Out of hadrons, mass;
Out of mass, the created universe
--- modified from Tao Te Ching

3D·Imaging@EicC

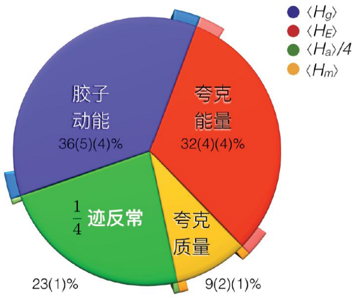
Institute of Modern Physics, Chinese Academy of Sciences

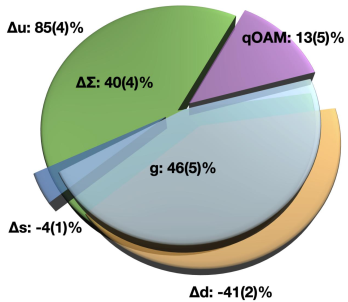
Introduction

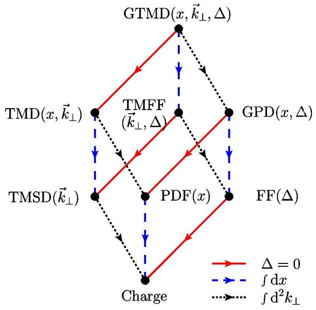
- **From 1D to 3D picture of hadron & nuclei**
- **TMD: Transverse Momentum Distributions (k⊥ & longi. Momentum):**
- How is proton's spin correlated with the motion of the quarks/gluons?
- …… probed by the semi-inclusive process

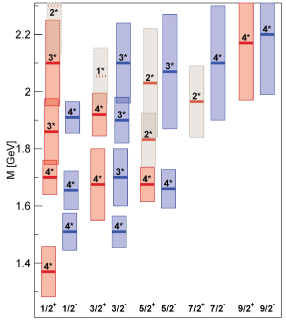
- **GPD: General Parton Distributions (trans. spatial position b⊥ & longi. Momentum)**
- **TDA: Transition Distribution Amplitudes (nucleon-to-Δ & nucleon-to-meson)**
- How does proton's spin influence the spatial distribution of partons?
- …… probed by the exclusive process

- **Origin of the Proton/Meson mass & spin: from hadron tomography to spectrum**









Introduction

- **The Electron-ion collider (EIC) at BNL (~ 2030-2034)**
- **Energy:**

Eur. Phys. J. A 52, 268 (2016)

Nucl. Phys. A 1026, 122447 (2022)

electron: 5 ~ 18 GeV
proton: 41 ~ 275 GeV, also ^{3}He, d, Pb, Au *(RHIC exists!)*

- **Luminosity:**

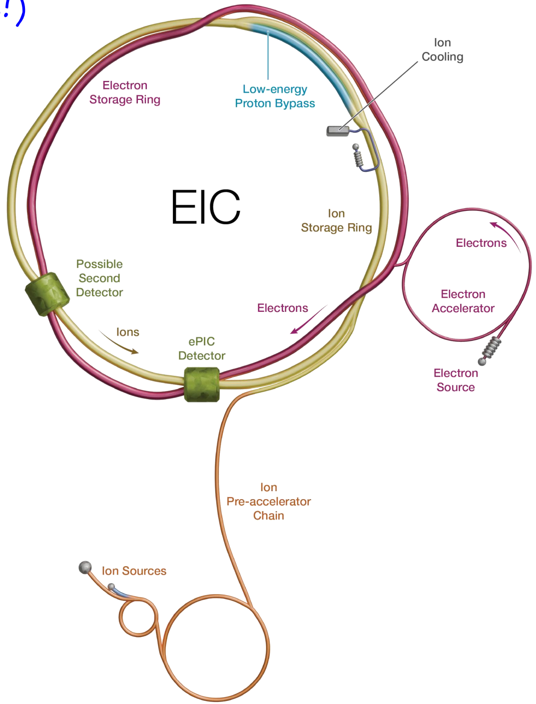
Instantaneous Lumi: $10^{33} \sim 10^{34}$ cm^{-2} s^{-1}
Integrated Lumi for simulation = 10 or 100 fb^{-1}

- **Polarization:**

electron: 70% L
proton&^{3}He: 70% L&T

- **Phase space coverage**

$\sqrt{s}$ ~ 20 – 140 GeV
$10^{-4} < x <\sim 0.01$



Introduction

- **The Large Hadron-Electron Collider (LHeC) at CERN**
- **Energy:**

  electron: 50 or 60 GeV

  proton: 7 or 14 TeV *(CERN exists!)*

  Pb: 0.574 PeV *(CERN exists!)*

J.Phys.G 39 (2012) 075001

J.Phys.G 48 (2021) 110501

- **Luminosity:**

  Instantaneous Lumi: $10^{33} \rightarrow 10^{34}$ cm^{-2} s^{-1}

  Integrated Lumi for simulation = 1 ab^{-1}

- **Polarization:**

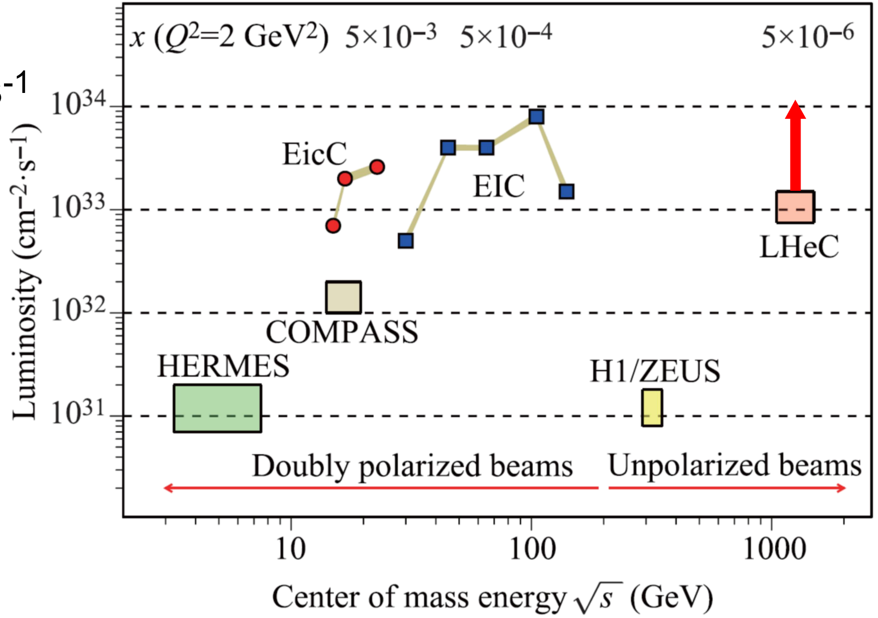
  electron: 80% L

  proton&ion: unpolarization

- **Phase space coverage**

  $\sqrt{s}$ <~ 1.7 TeV (→3.5 TeV if FCC)

  $10^{-5} < x <\sim 0.01$



Introduction

- **The Polarized Electron-ion collider in China (EicC)**
- **Energy:**

  electron + proton: 3.5 GeV × 20 GeV

  electron + ^{3}He: 3.5 GeV × 40 GeV (nucleus energy)

中国科学: 物理学力学天文学, 50: 112005 (2020)

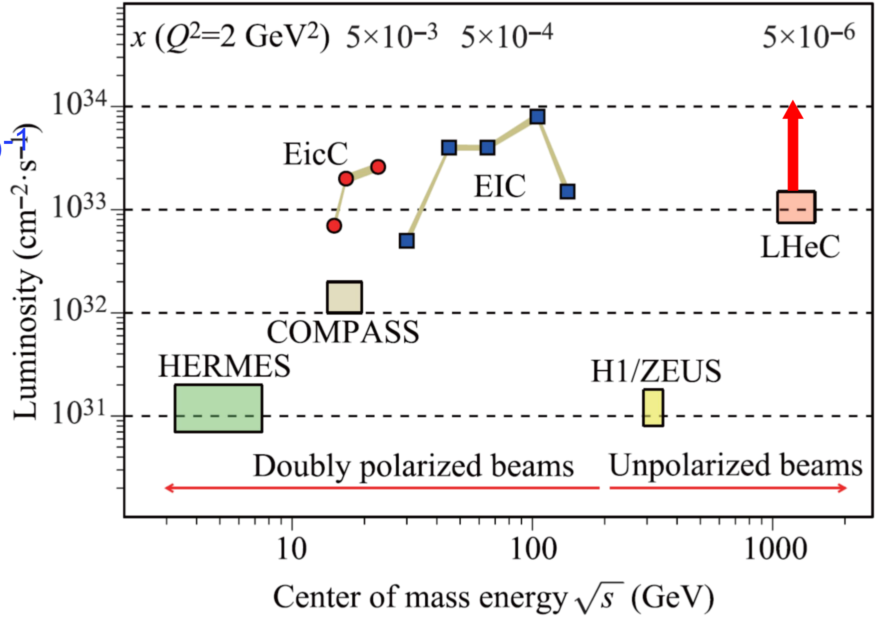
核技术, 43(2): 020001 (2020)

Front. Phys. 16, 64701 (2021)

- **Luminosity:**

  Instantaneous Lumi: 2 x 10^{33} cm^{-2} s^{-1}

  Integrated Lumi for sim. = 50 or 100 fb^{-1}



- **Polarization:**

  electron: 80% L

  proton& ^{3}He: 70% L&T

- **Phase space coverage**

  $\sqrt{s}$ ~ 16.7 (15 ~ 20)GeV

  $4\times10^{-3} < x < \sim 0.1$

Introduction

- **The Polarized Electron-ion collider in China (EicC)**
- **Energy:**

  electron + proton: 3.5 GeV × 20 GeV

  electron + ^{3}He: 3.5 GeV × 40 GeV (nucleus energy)

中国科学: 物理学力学天文学, 50: 112005 (2020)

核技术, 43(2): 020001 (2020)

Front. Phys. 16, 64701 (2021)

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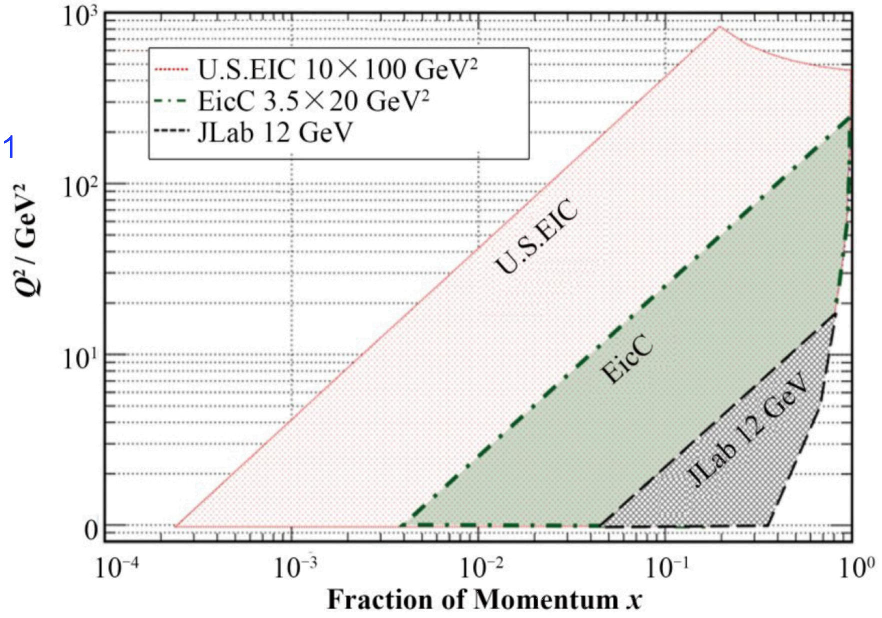
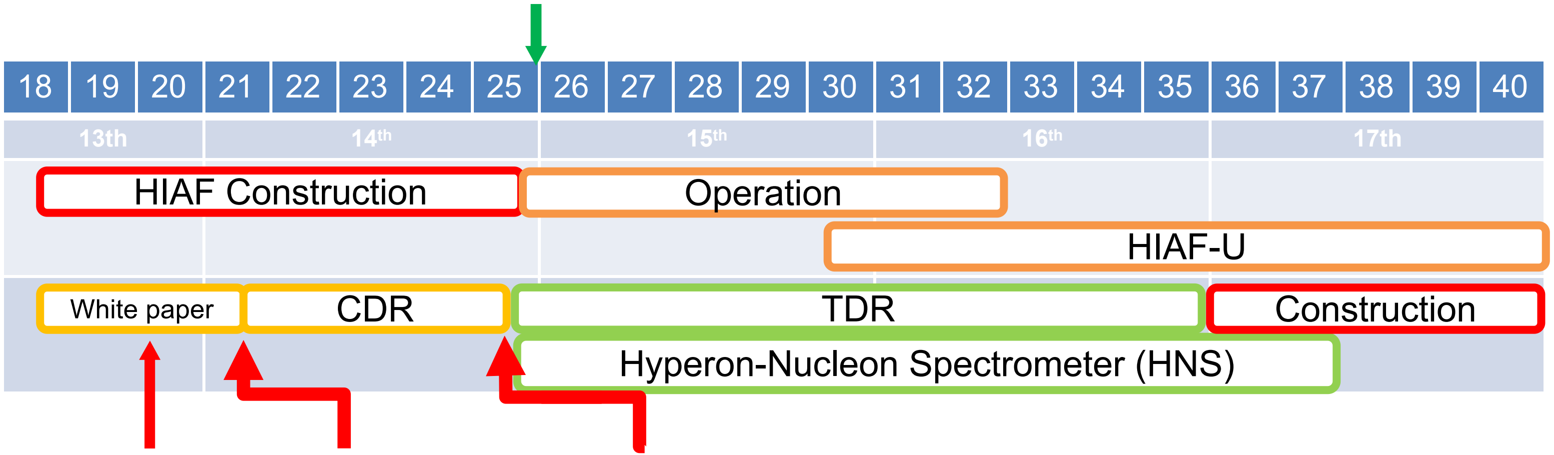


High Intensity heavy-ion Accelerator Facility at Huizhou, Guangdong

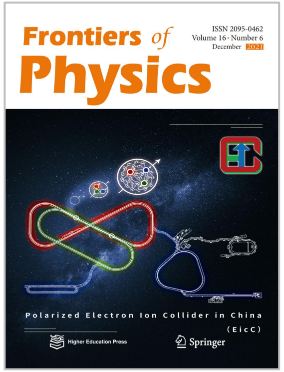
Status&Agenda of EicC

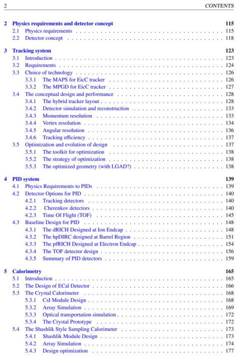


2020.02

2021.06

2025.12 CDR





2 CONTENTS

Upgrade of HIAF (HIAF-U): 9.3 GeV to 25 GeV

Fundings for detector and accelerator R&D:

Forward detectors: ZDC, OMD, EDT

proton polarimetry

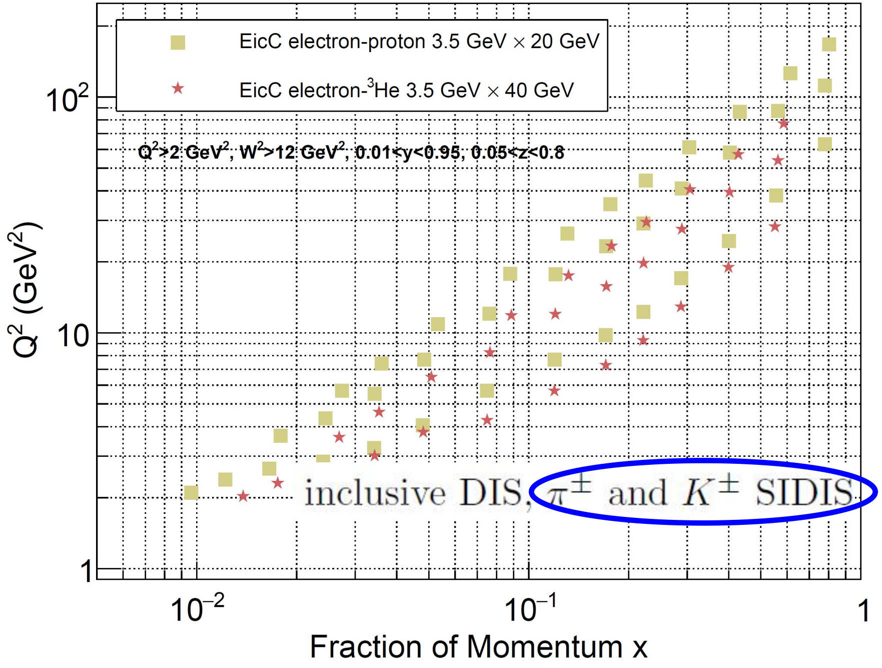
Polarized proton beam

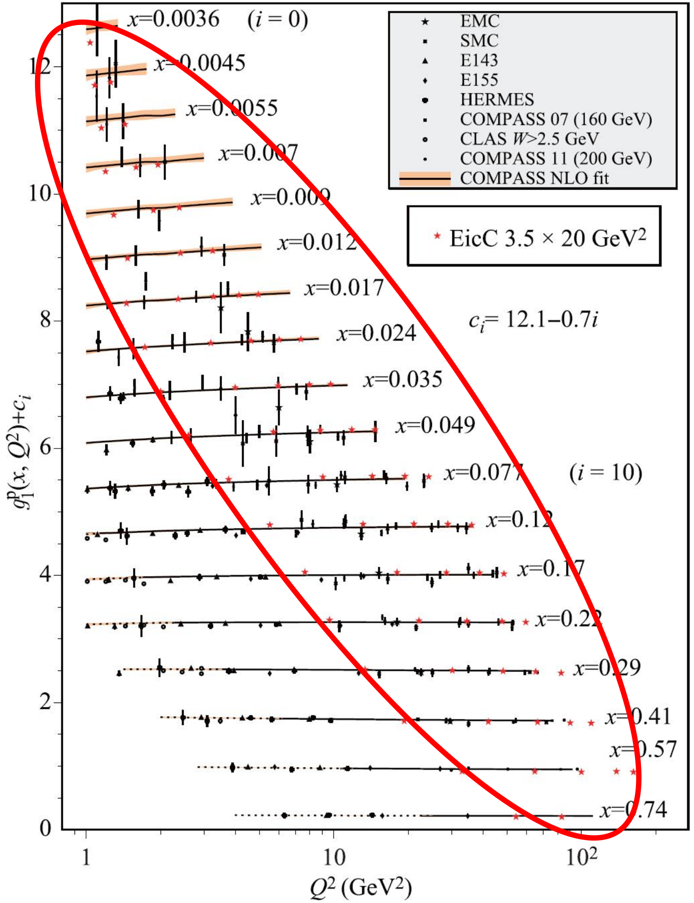
(Semi-)Inclusive Process

- Double-Spin-Asymmetry $A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} \propto \frac{g_1}{F_1}$

$$F_1^h(x,Q^2,z) = \frac{1}{2}\sum_q e_q^2[q(x,Q^2)D^{q\to h}(Q^2,z) + \Delta\bar{q}(x,Q^2)D^{\bar{q}\to h}(Q^2,z)]$$

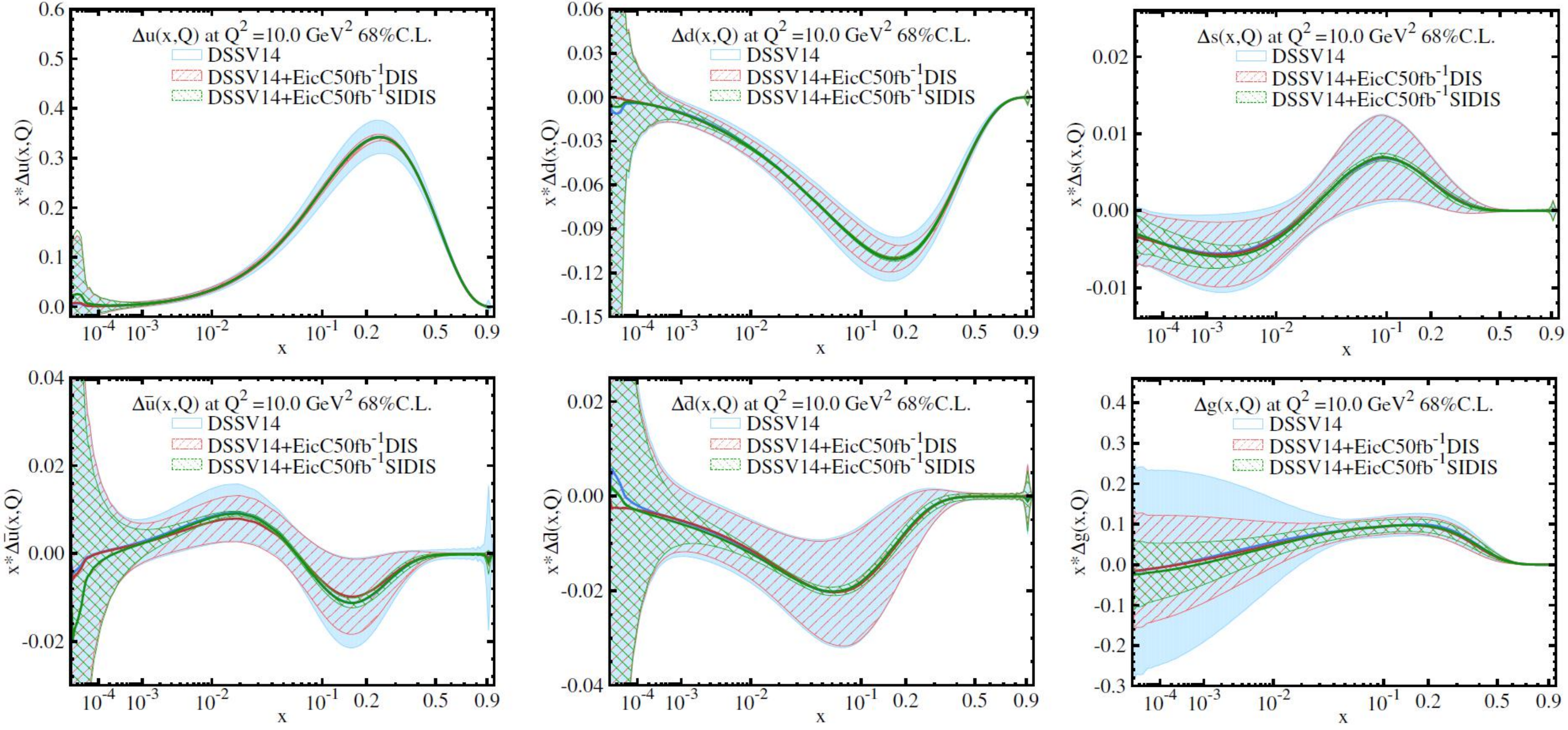
$$g_1^h(x,Q^2,z) = \frac{1}{2}\sum_q e_q^2[\Delta q(x,Q^2)D^{q\to h}(Q^2,z) + \Delta\bar{q}(x,Q^2)D^{\bar{q}\to h}(Q^2,z)]$$





(Semi-)Inclusive Process

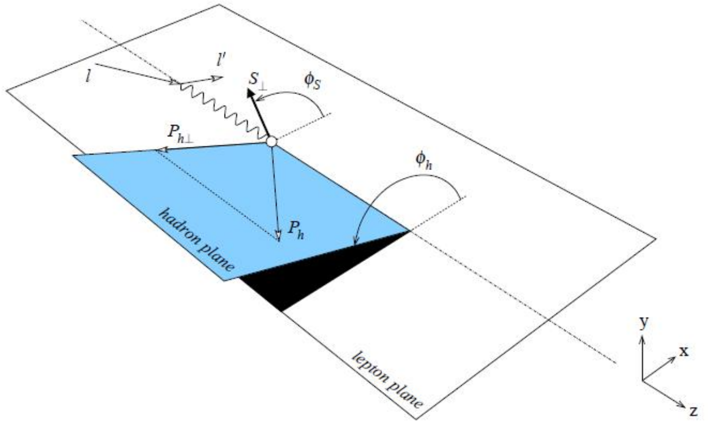
- **Flavored Helicity PDF@EicC: reweighting Hessian PDF sets by ePump**
- D. P. Anderle, Tie-Jiun Hou, Hongxi Xing, Mengshi Yan, C.-P. Yuan, Yuxiang Zhao, JHEP08(2021)034



Semi-Inclusive Process

- **TMD: Transverse Momentum Distributions (k ⊥ & longi. Momentum)**
- **Sivers function: the correlation between quark transverse momentum and the transverse spin of the nucleon**

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ & F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
& +\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
& +S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
& +S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
& +|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
& \quad+\varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \quad+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
& +|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
& \quad+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$



A. Bacchetta, M. Diehl, *et al.*, JHEP 0702:093(2007)
A. Bacchetta, U. D'Alesio, Phys.Rev.D 70 (2004) 117504

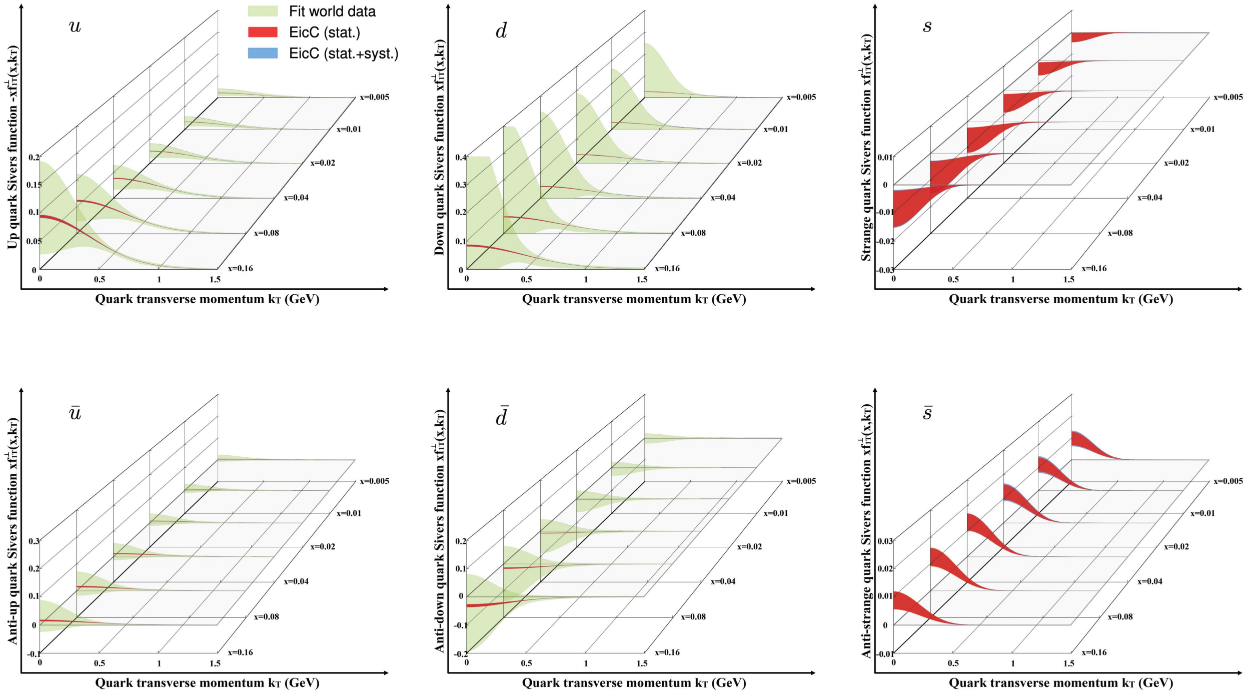
$$\delta \equiv |P_{h\perp}|/(zQ)$$

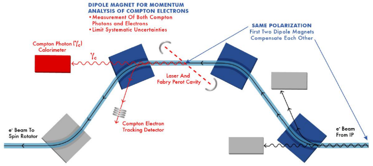
Semi-Inclusive Process

- **TMD: Transverse Momentum Distributions (k ⊥ & longi. Momentum)**
- **Sivers function: the correlation between quark transverse momentum and the transverse spin of the nucleon**
- Chunhua Zeng, Tianbo Liu, Peng Sun, Yuxiang Zhao, PhysRevD.106.094039 (2022)

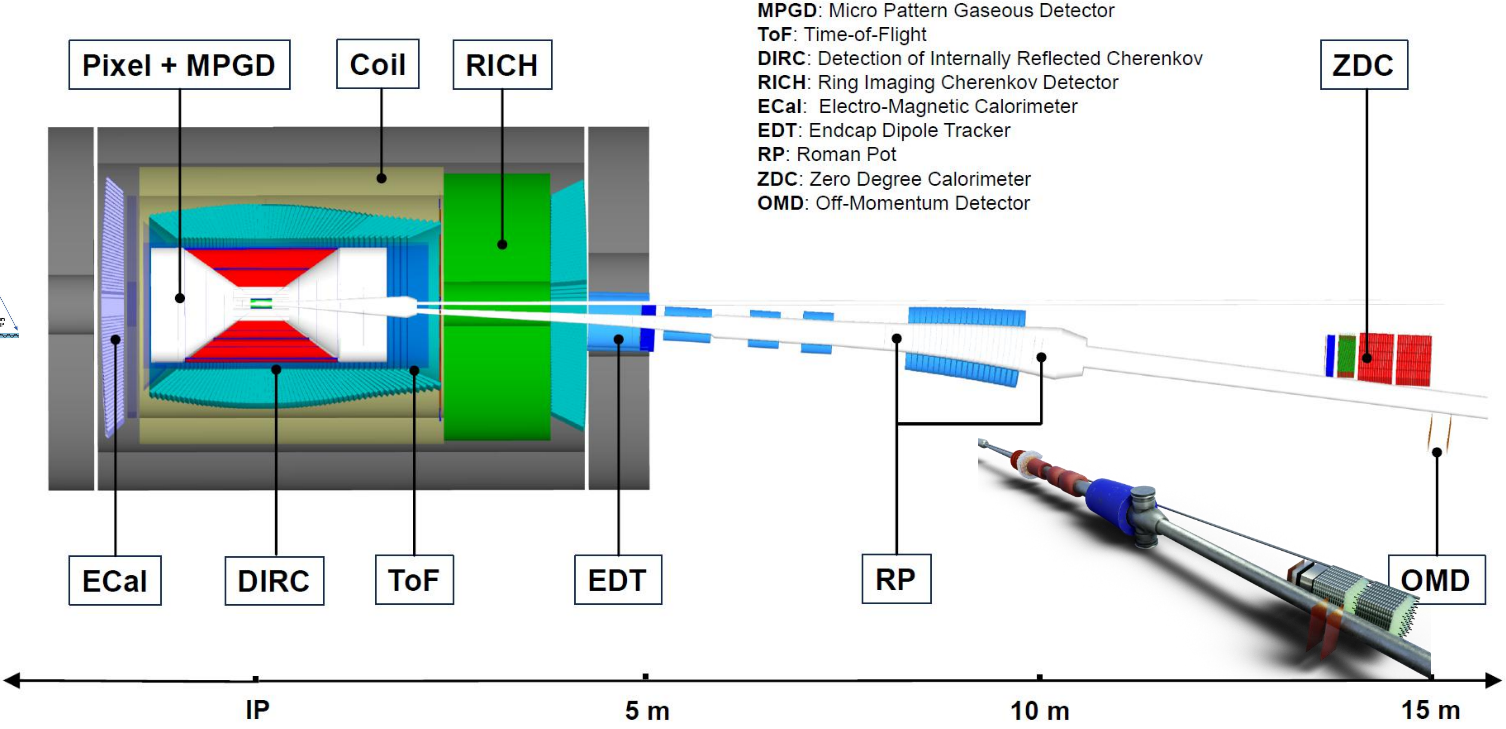
Evolution Included. Constrained by COMPASS, HERMES Jlab data & EicC

T





electron far-forward detectors



Ion far-forward detectors

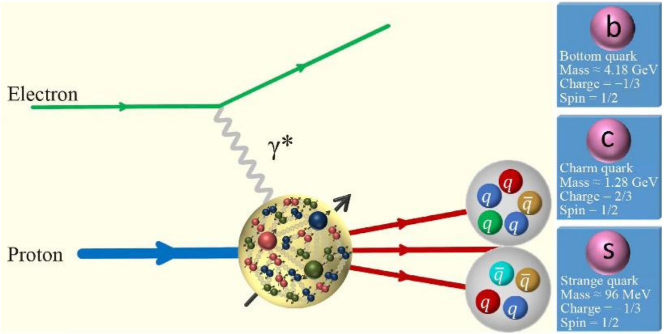
- effort from: 山东大学，中国科学技术大学，华中师范大学, 清华大学 .....

Exclusive Process I

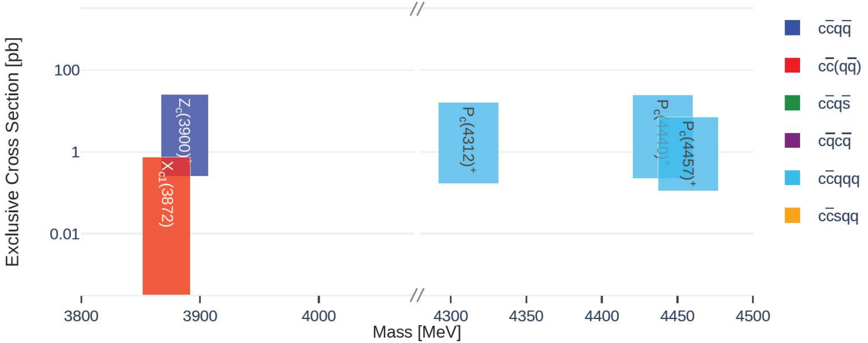
- **From conventional to exotic spectrum of Hadrons:**

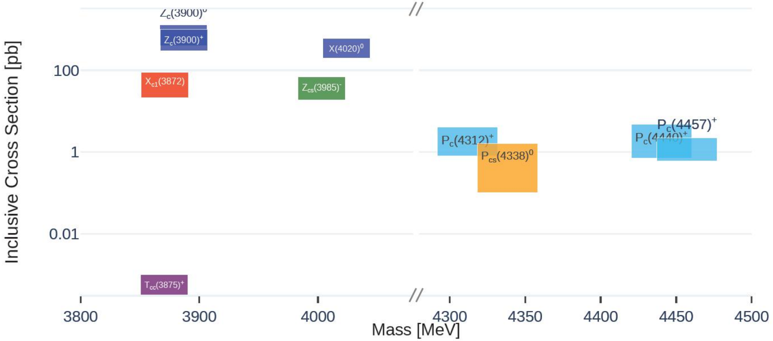
X.C, Front. Phys. 18 (2023) 44600

- Heavy Charmonium Production ≲ 1 nb
- From quasi-real to deep virtual photon
- Exotic States Production < 10pb



- Semi-inclusive electroproduction gives another upper limit of exclusive production

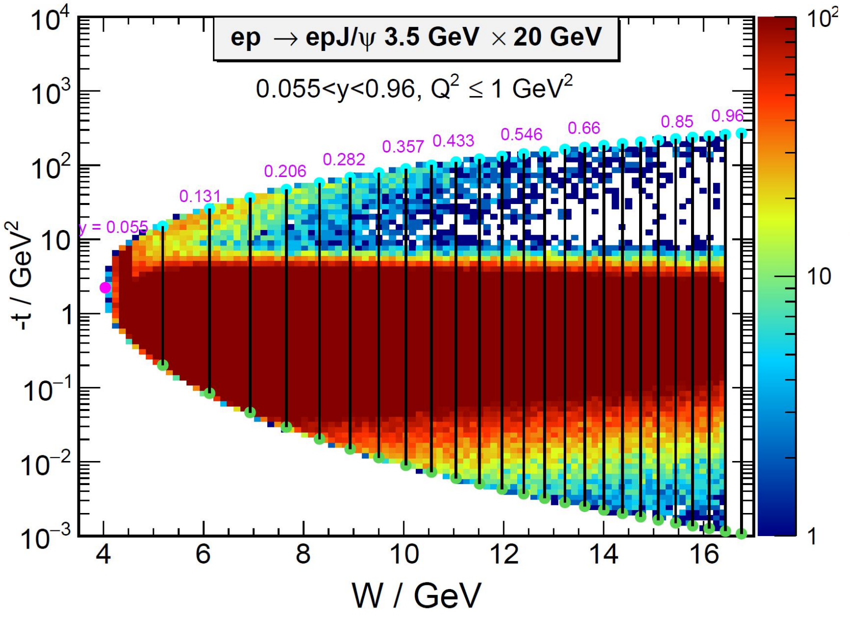


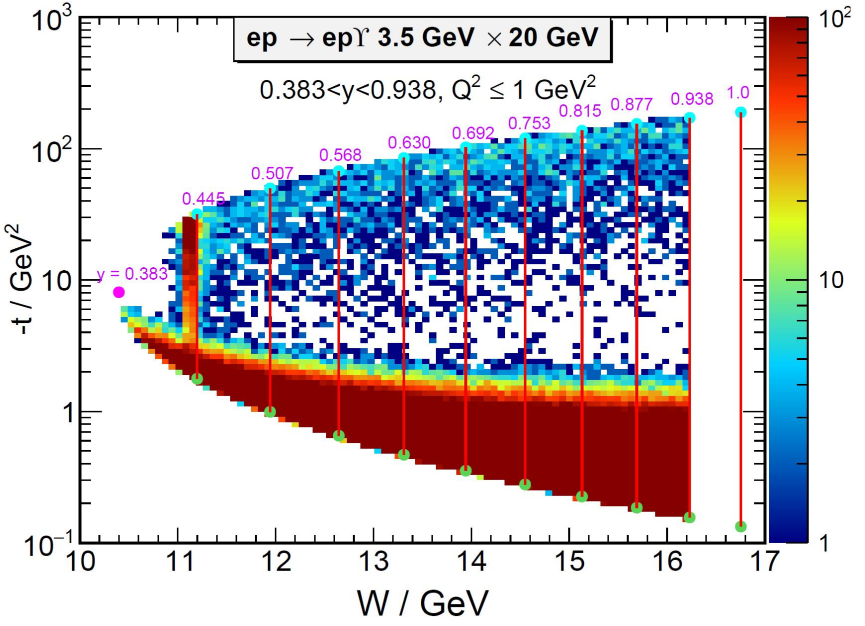


courtesy : Panpan Shi & Fengkun Guo

Exclusive Heavy Flavor

- **From light quarks to charm and up to bottom: Photo- and electro-production of narrow exotic states**
- Generated by lAger and eSTARlight: X.C, Front. Phys. 18 (2023) 44600, see also PhysRevD.101.074010



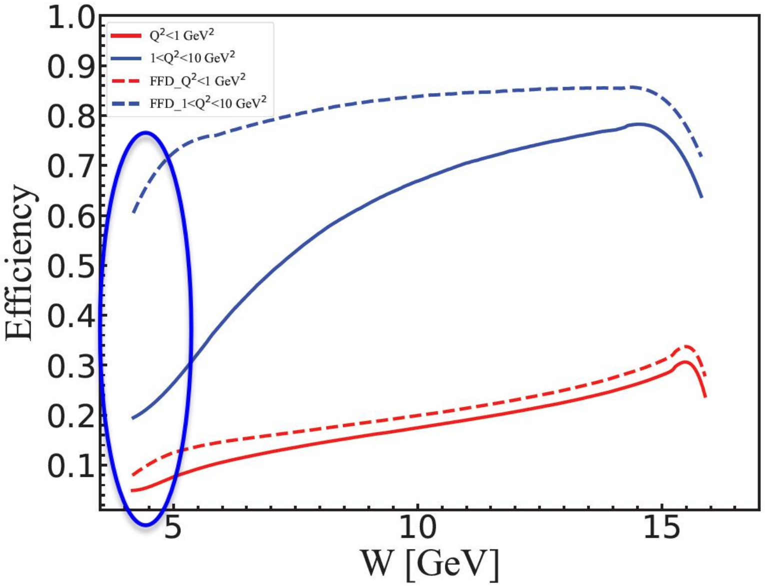


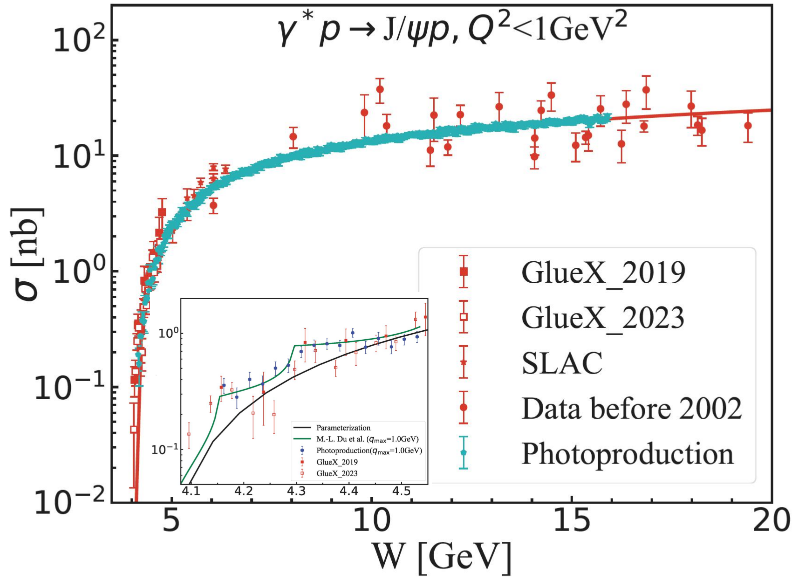
Exclusive Heavy Flavor

- **Exclusive Heavy Quarkonium Production** probes several interesting topics
- e.g. pentaquarks, cusps, Charmonium-nucleon interaction, Gravitational Form Factors …

X. Wang, X. C *et al.*, 2311.07008, EPJC (2024)

ΔW = 25 MeV, 480 bins

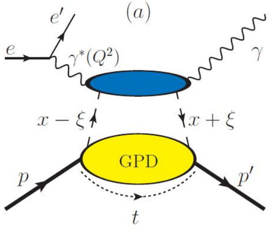




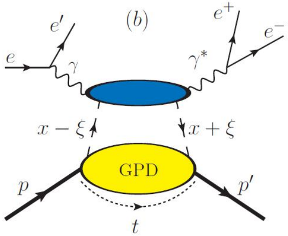
- Optimization the efficiency and resolution of detector will helpful for approaching close to the threshold region W<5.0 GeV

Exclusive Process II

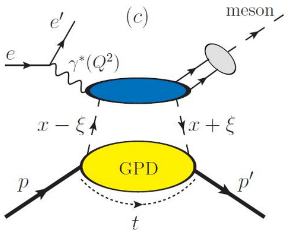
- **From 1D to 3D structure of proton & nuclei:**
  - GPD: DVCS, TCS, DVMP, DDVCS
  - TDA: backward (u-channel) meson production



- Deeply Virtual Compton Scattering $\xi = x_B/(2 - x_B)$



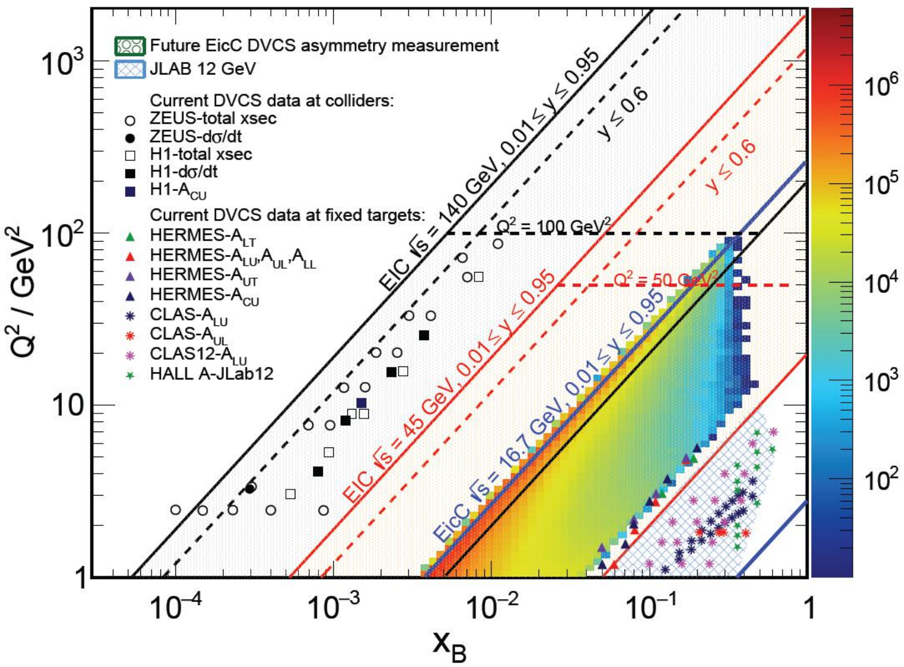
- Timelike Compton Scattering
- **share the same final states with nucleon-to-photon TDA**
- **but with backward u-channel** $\xi = \tau/(2 - \tau)$

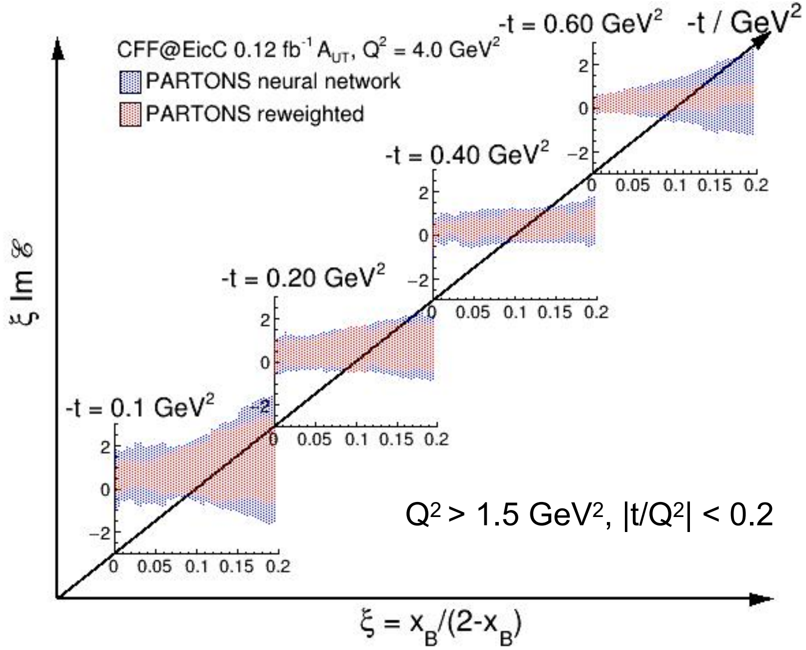


- Deeply Virtual Meson Production
- **share the same light meson with nucleon-to-meson TDA & hadron physics**
- **heavy quarkonium: gravitation form factors or proton mass?**
- **fully construction of all particles & kinematics**

Proton DVCS

- Worldwide data *VS.* pseudodata @ EicC detector generated by MILOU
- … statistical precision 1.0 ~ 1.5 %, ~ 1day running surpasses old data of A_{UT}
- reweighting the replicas from PARTONS(EPJC79:614), see X. C, Jinlong Zhang, EPJC 83 (2023) 505

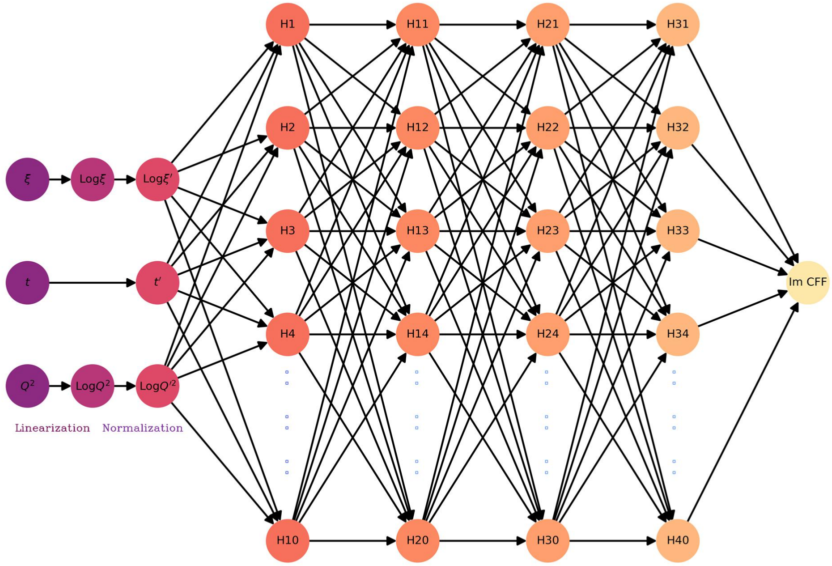


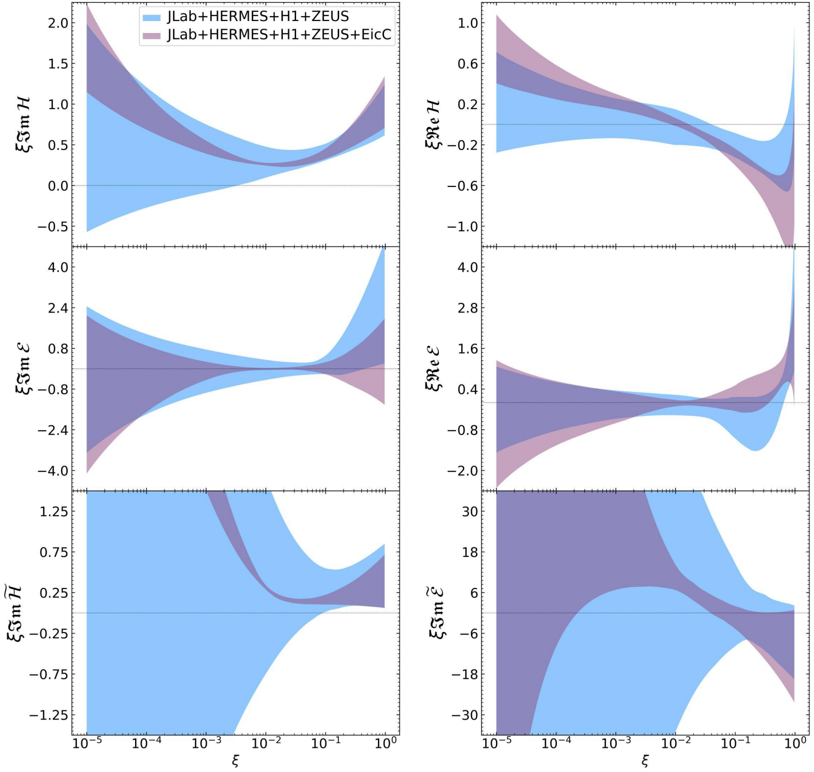


- A_{UT} in 69 (Q^2 , x_B) bins: $[1.0, 1.6]$, $[1.6, 2.6]$, $[2.6, 4.3]$, $[4.3, 7.0]$, $[7.0, 18.5]$, $[18.5, 30.0]$, $[30.0, 80.0]\ \mathrm{GeV}^2$

Proton DVCS

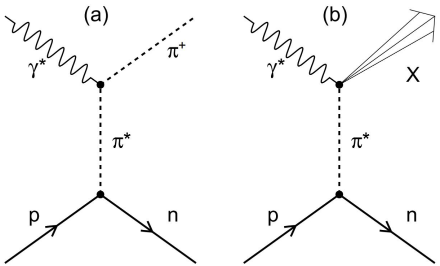
- Impact of the pseudodata of all asymmetries at EicC (Gepard + PyTorch)



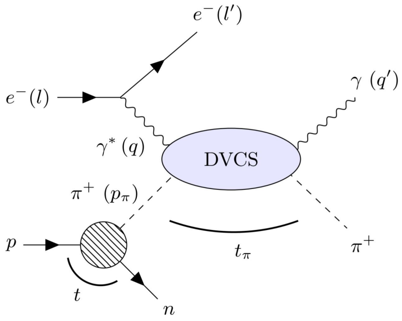


Yuanyuan Huang, XC, Taifu Feng, K. Kumericki, Yu Lu, Neural network extraction of CFFs + LQCD data, to appear

- **From 1D to 3D structure of pions & kaons:**
- Pions/Kaons as the approximate Nambu–Goldstone bosons of spontaneously broken chiral symmetries associated with the (near) masslessness of quarks
- Probed by Drell-Yan process and Sullivan process
- Detection of leading neutron/Lambda?

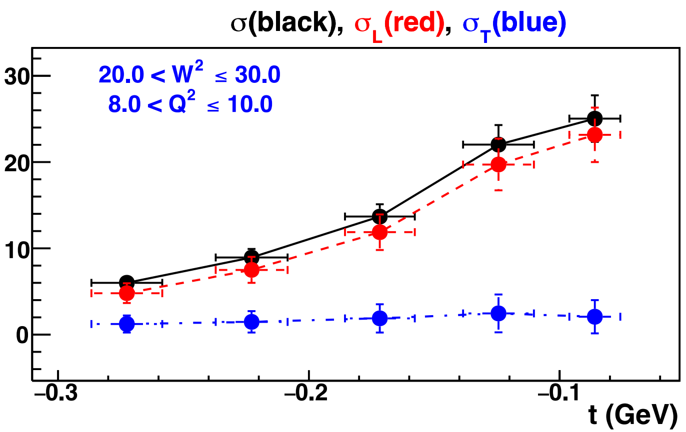


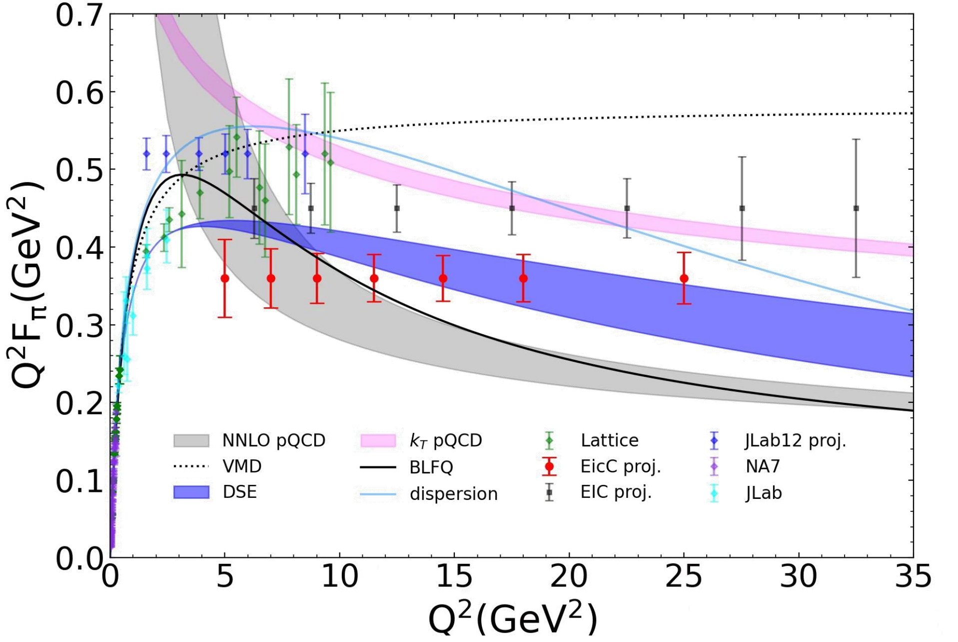
- Structure function
- **Sensitivity to elastic form factor and Parton Distribution Functions**



- π^+-DVCS
- **quarks and gluons interfere destructively**
- see J. M. Morgado Chávez *et al.*, Phys.Rev.Lett. 128 (2022) 202501
- Y. Hatta, J. Schoenleber, Phys.Rev.Lett. 134 (2025) 251901

Meson Form Factor



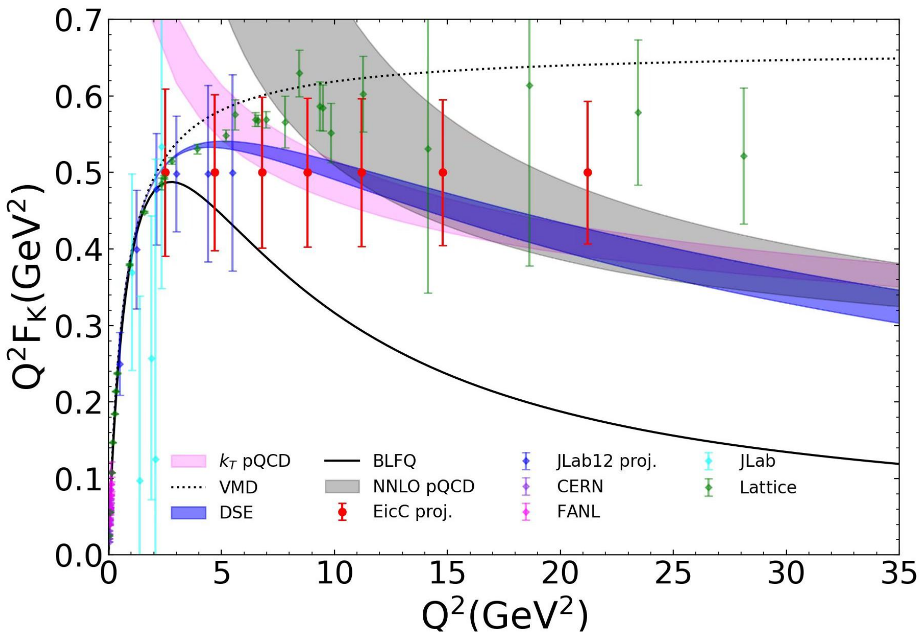


- In hard scattering regime, QCD scaling predicts $\sigma_L \propto Q^{-6}$, $\sigma_T \propto Q^{-8}$
- 100% uncertainty in R = σ_T / σ_L from model subtraction
- 2.5% point-to-point syst. uncertainty 12% scaling syst. uncertainty

Significant contribution from theory and lattice:
Hengtong Ding, Shan Cheng, Longbin Chen, Yuming Wang, Jiangshan Lan, XIngbo Zhao

Meson Form Factor

- energy setting: 3.5 GeV e x 20 GeV p
- Integrated luminosity: 50 fb^{-1}
- Include full detector acceptance
- 100% uncertainty in $R = \sigma_T / \sigma_L$ from model subtraction
- 2.5% point-to-point syst. uncertainty
  12% scaling syst. uncertainty

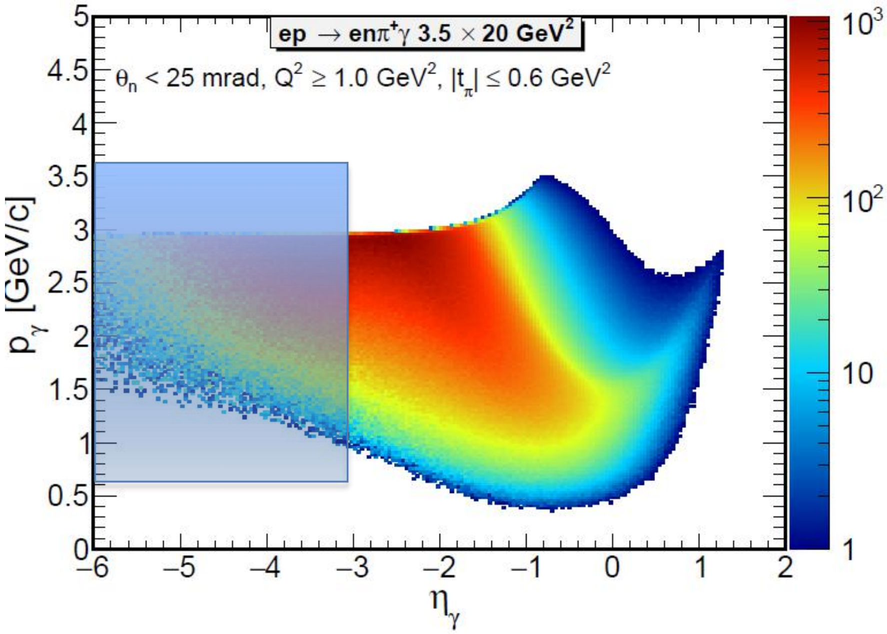


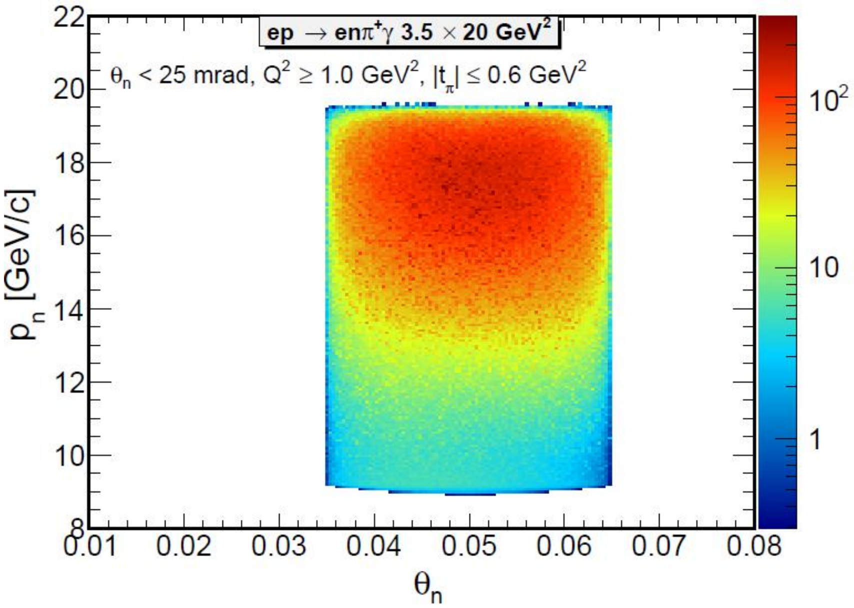
Significant contribution from theory and lattice:
Hengtong Ding, Shan Cheng, Longbin Chen, Yuming Wang, Jiangshan Lan, XIngbo Zhao

pion DVCS

- π^+-DVCS through Sullivan process: detecter coverage of EicC

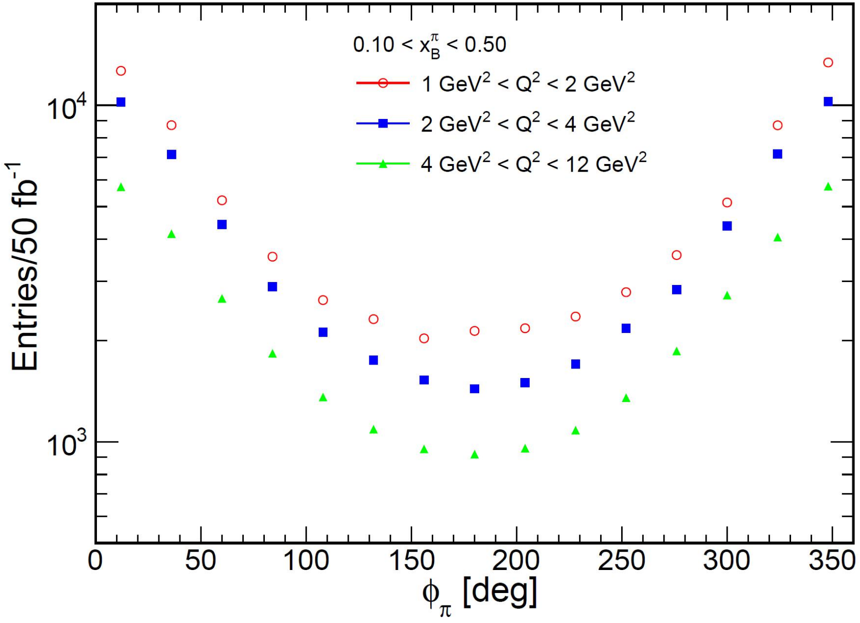
  in collaboration with M. Defurne, C. Mezrag, J. M. Morgado Chávez

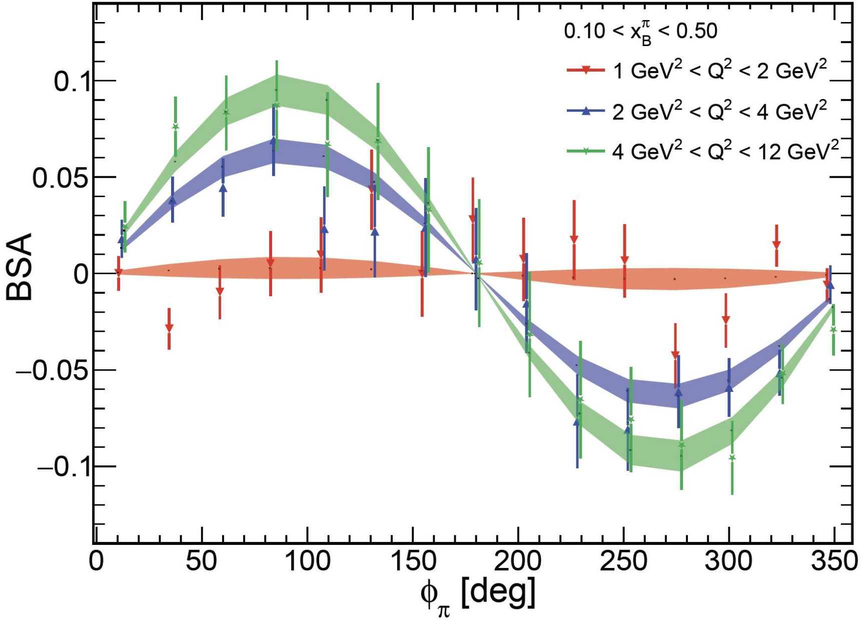




pion DVCS

- π^+-DVCS through Sullivan process (filtered by detector at EicC)
- Over eff. ~ 35.0%   Asy. 0.003±0.006
  ~ 36.0%   0.064±0.006
  ~ 33.9%   0.095±0.008





Challenge

- **What Q^2 is deep enough for DVMP?**

- **From CFFs to GPDs, for example, in the case of DVCS:**

1. Determination of form factors, more or less directly, from experimental observables
2. Determination of GPDs from the corresponding form factors.

$$\mathcal{H}(x_B, t, Q^2) = \sum_{a=u,d,\dots,g} \int_{-1}^{1} \frac{dx}{2\xi} T^a_{\mathrm{DVCS}}(x, \xi, Q^2)\, H^a(x, \xi, t, Q^2)\,,$$

- **inverse problem!**

- **Deep Neural Network?**

Summary

- **Fruitful measurements are expected at the EicC.**
  Selected topics are present:
- SIDIS: PDF and TMD
- Proton/Pion DVCS: GPD
- Exclusive Heavy Flavor: quarkonium production

- **Not cover here:**
- Exotic hadron states
- charm physics
- DVMP, TCS, DDVCS
- Nuclear medium effects

- **Common interests in the field:**
- Detector design&technology
- polarized electron/positron beam
- Fragmentation functions

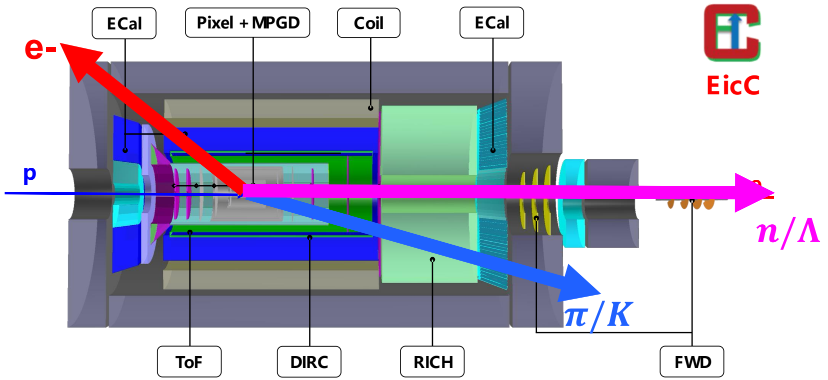
- **Many efforts from detector group: CDR ~250 authors, ~70 affiliations**

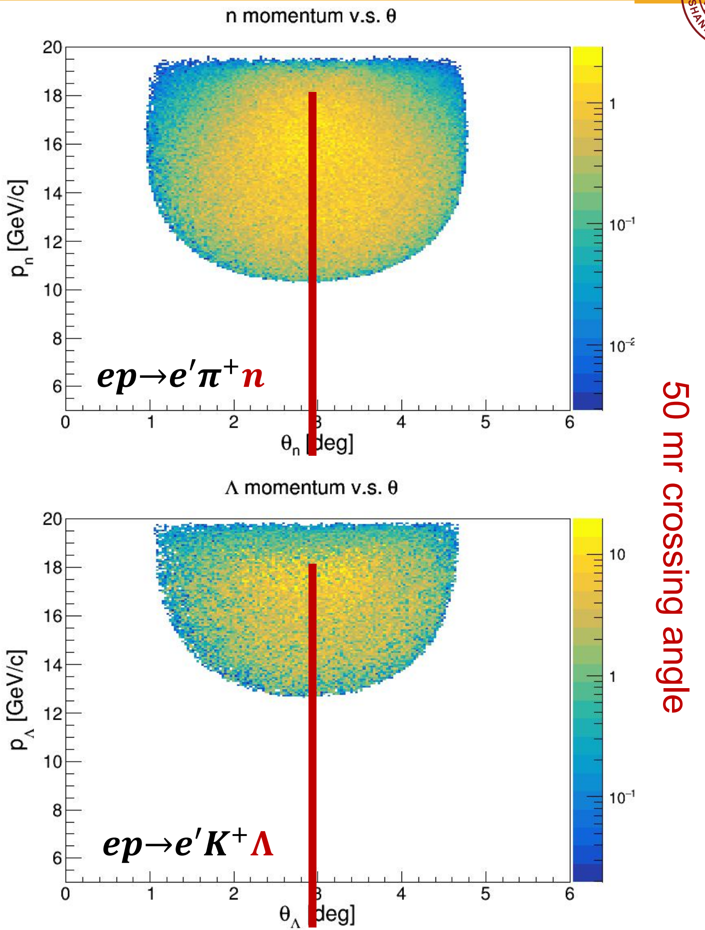
Thanks to EicC Working Group

Meson Structure

- Scattered electron and meson very well covered by central detector: Eff. > 95%
- “Spectator” neutron and **Λ** move very close to the initial p-beam: far-forward detectors

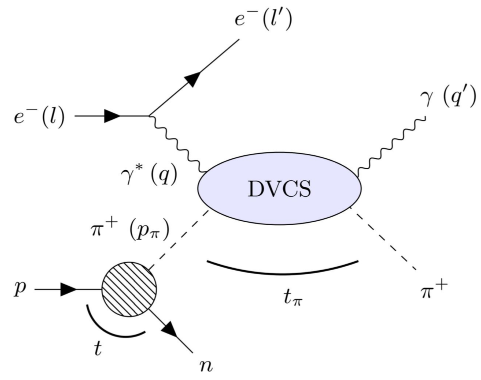
- Pion FF and SF require ZDC for neutron detection
- Kaon FF and SF need all detectors in far-forward region for **Λ** neutral & charged decay

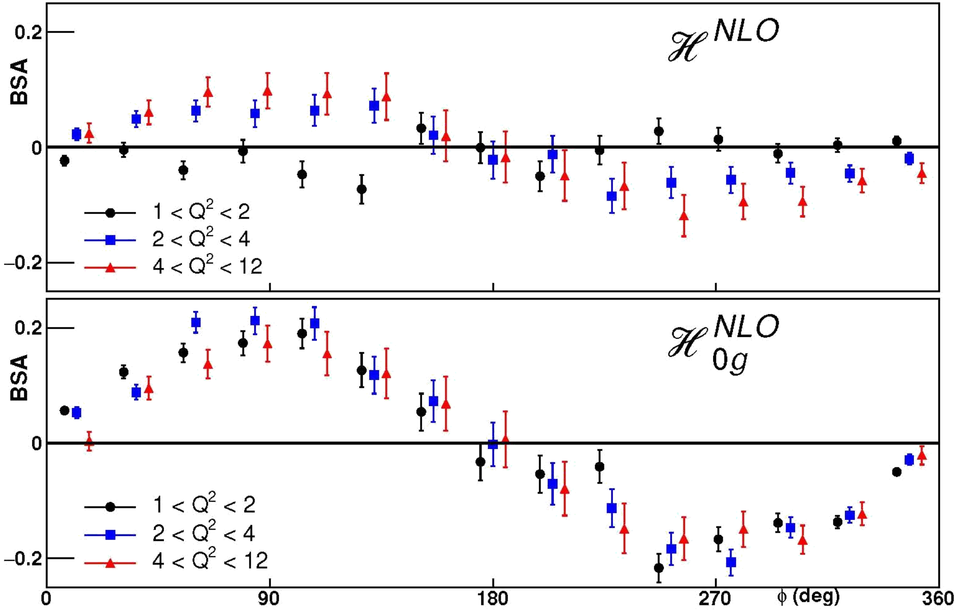


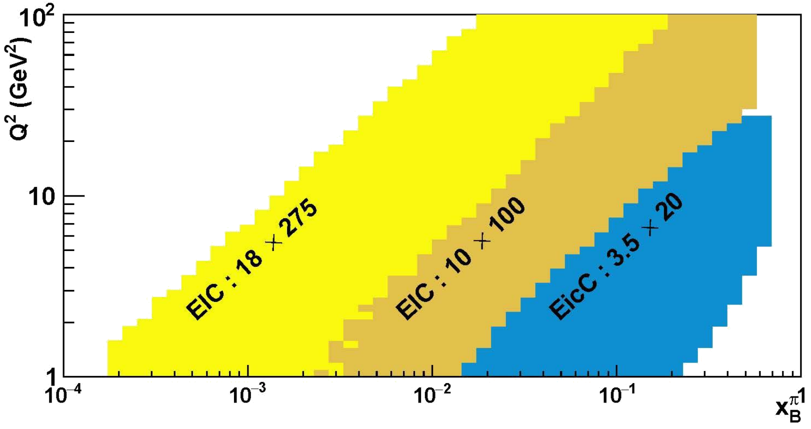


Meson Structure

- π^+-DVCS through Sullivan process
- (J. M. Morgado Chávez et al., Phys.Rev.Lett. 128 (2022) 202501)







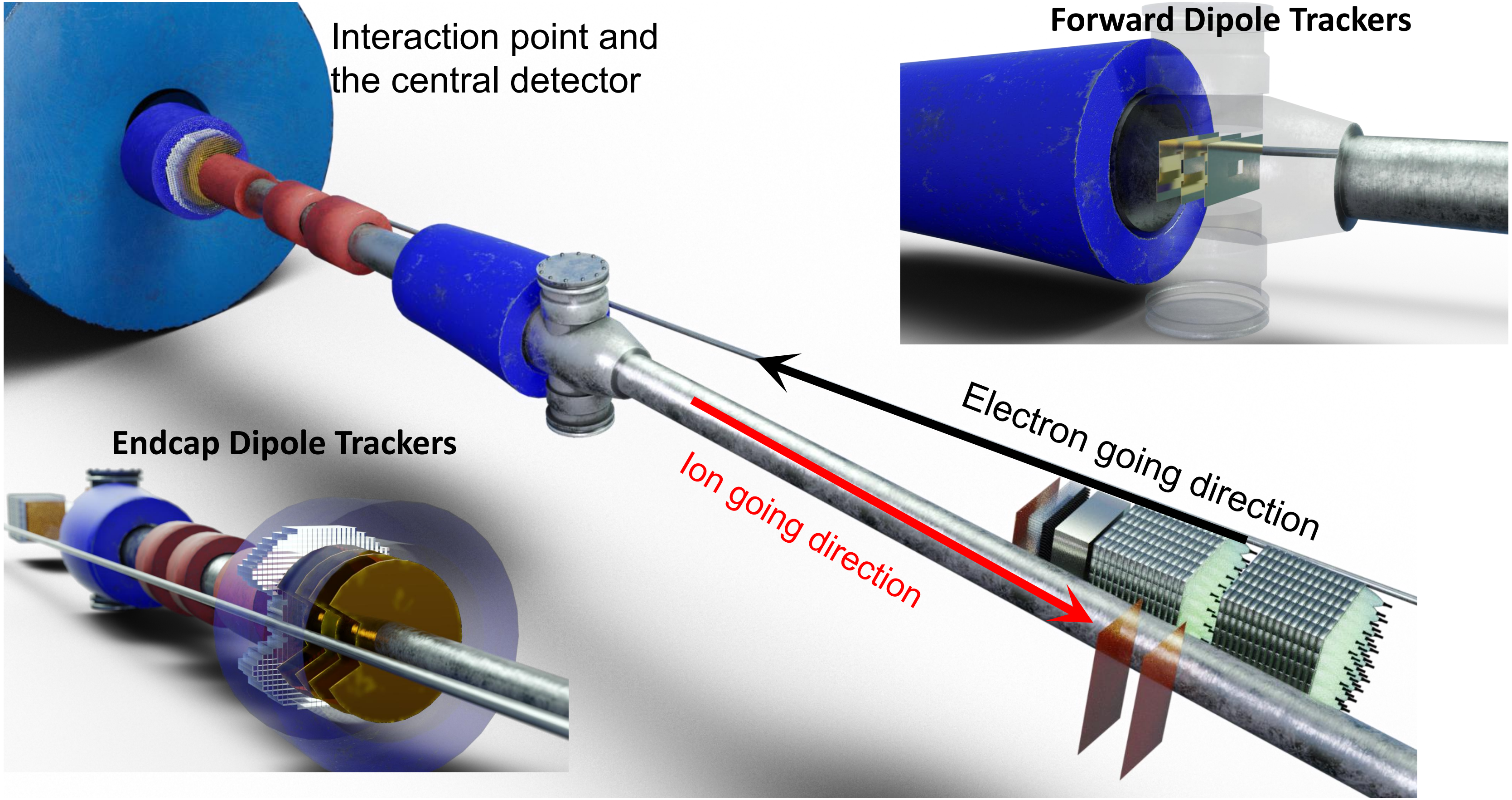
Status&Agenda of EicC

- e+p, e+d, e+^{3}He ……
- Effective tool for flavor separation

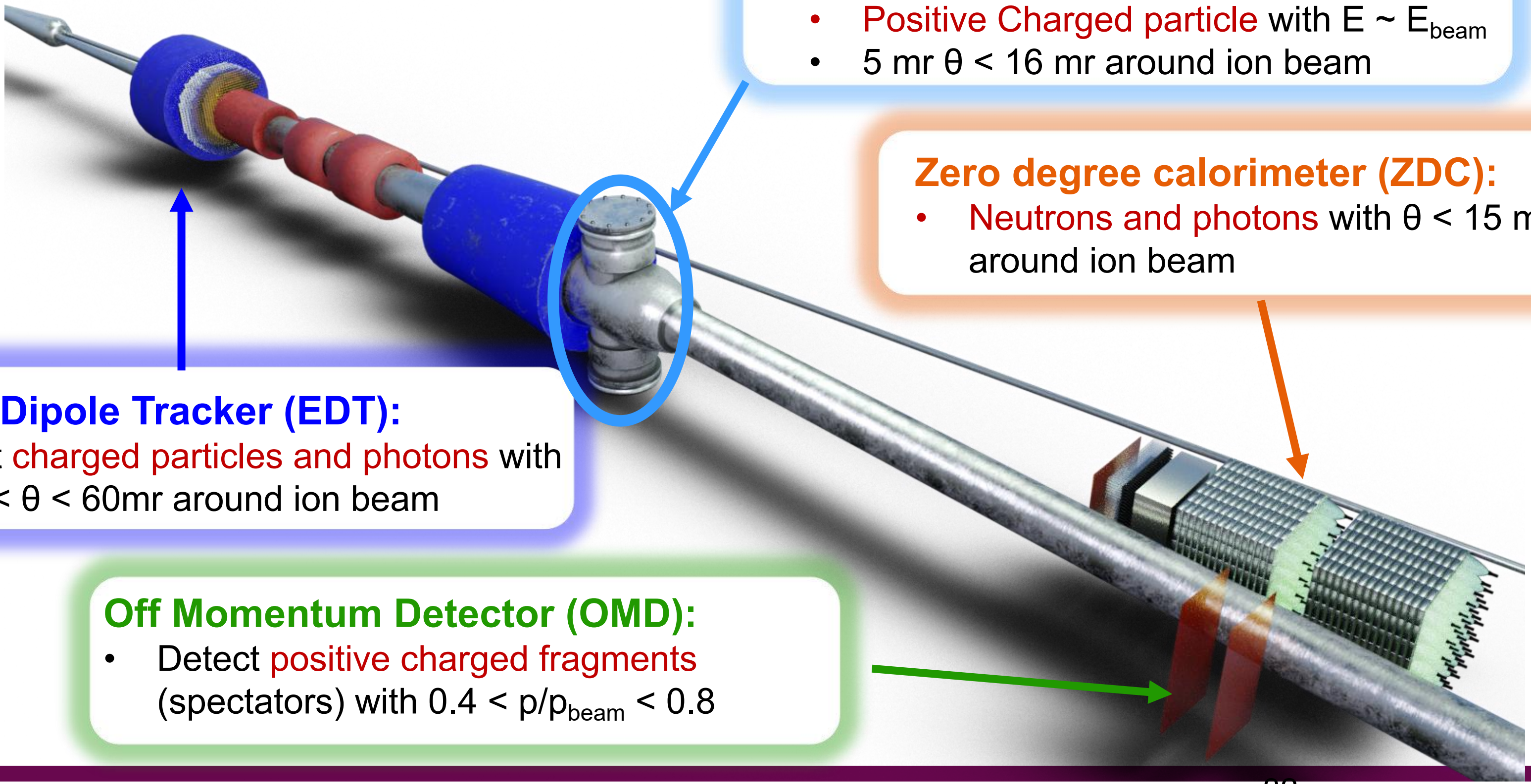
Particle	e	d	$^3He^{++}$	$^7Li^{3+}$	$^{12}C^{6+}$	$^{40}Ca^{20+}$	$^{197}Au^{79+}$	$^{208}Pb^{82+}$	$^{238}U^{92+}$
Kinetic energy (GeV/u)	3.5	12.00	16.30	10.16	12.00	12.00	9.46	9.28	9.09
Momentum (GeV/c/u)	3.5	12.90	17.21	11.05	12.90	12.90	10.35	10.17	9.98
Total energy (GeV/u)	3.5	12.93	17.23	11.09	12.93	12.93	10.39	10.21	10.02
CM energy (GeV/u)	–	13.48	15.55	12.48	13.48	13.48	12.09	11.98	11.87
$f_{collision}$ (MHz)	–	499.25	499.82	498.79	499.25	499.25	498.54	498.47	498.39
Polarization	80%	Yes	Yes	No	No	No	No	No	No
$B\rho$ (T·m)	11.67	86.00	86.00	86.00	86.00	86.00	86.00	86.00	86.00
Particles per bunch ($\times 10^9$)	40	6.1	3.0	2.04	1.00	0.30	0.07	0.065	0.055
$\varepsilon_x/\varepsilon_y$ (nm·rad, rms)	20	100/60	100/60	100/60	100/60	100/60	100/60	100/60	100/60
β_x^*/β_y^* (m)	0.2/0.06	0.04/0.02	0.04/0.02	0.04/0.02	0.04/0.02	0.04/0.02	0.04/0.02	0.04/0.02	0.04/0.02
Bunch length (m, rms)	0.01	0.015	0.015	0.02	0.015	0.015	0.02	0.02	0.02
Beam–beam parameter ξ_x/ξ_y	0.007	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Laslett tune shift	–	0.07	0.06	0.04	0.06	0.06	0.06	0.06	0.06
Current (A)	3.3	0.49	0.48	0.49	0.48	0.48	0.44	0.43	0.40
Crossing angle (mrad)					50				
Hourglass	–	0.94	0.94	0.92	0.94	0.94	0.92	0.92	0.92
Luminosity at nucleon level ($cm^{-2}\cdot s^{-1}$)	–	8.48×10^{32}	6.29×10^{32}	9.75×10^{32}	8.35×10^{32}	8.35×10^{32}	9.37×10^{32}	9.22×10^{32}	8.92×10^{32}

- The Luminosity is under optimization
- lever arm Q^2 > 30 GeV^2

Current Design for EicC Far-Forward (FF) Region



Current Design for EicC Far-Forward (FF) Region



Roman Pot Station:
- Located inside the ion beam pipe
- Positive Charged particle with $E \sim E_{beam}$
- 5 mr θ < 16 mr around ion beam

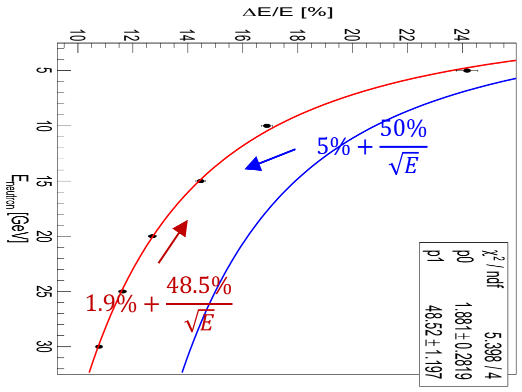
Zero degree calorimeter (ZDC):
- Neutrons and photons with θ < 15 mr around ion beam

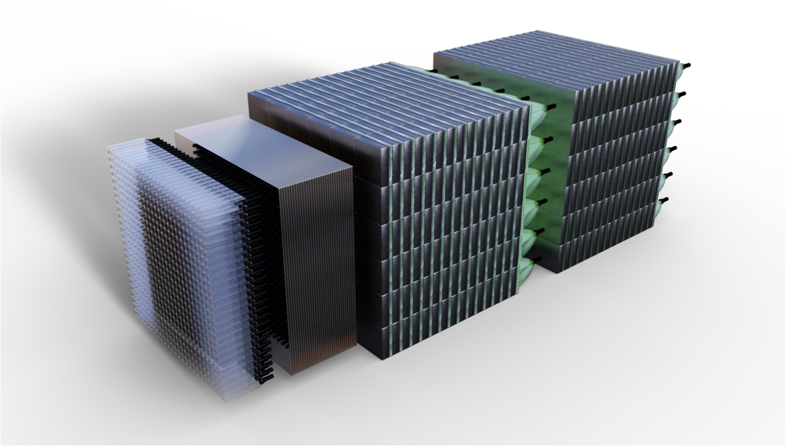
Endcap Dipole Tracker (EDT):
- Detect charged particles and photons with 15mr < θ < 60mr around ion beam

Off Momentum Detector (OMD):
- Detect positive charged fragments (spectators) with $0.4 < p/p_{beam} < 0.8$

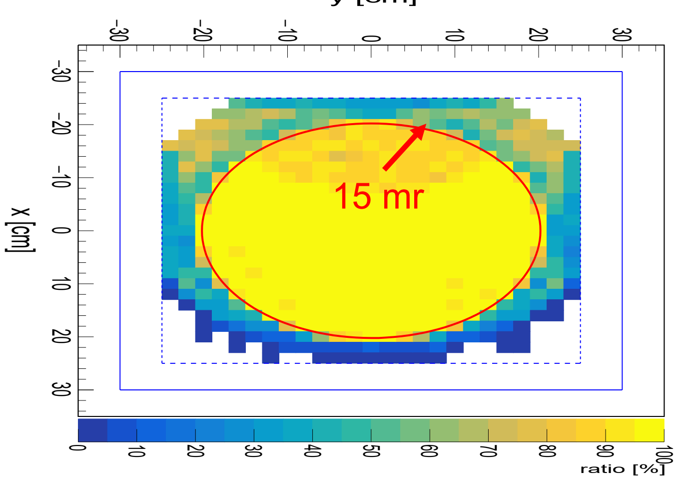
Neutron Detection for Pion FF and SF

- Main detector for neutron is ZDC:
  - 15 mrad acceptance around the ion beam
  - Nearly 100% accept rate for neutrons of interest
  - Energy resolution : 1.9% + 48.5%/sqrt(E [GeV])
  - Position resolution : 2.4 mr /sqrt(E [GeV])



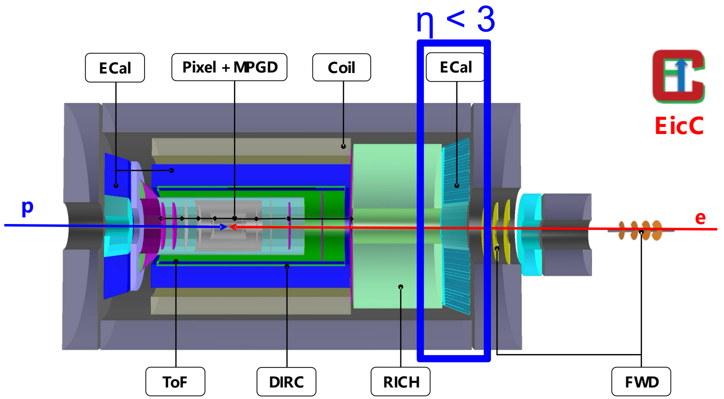


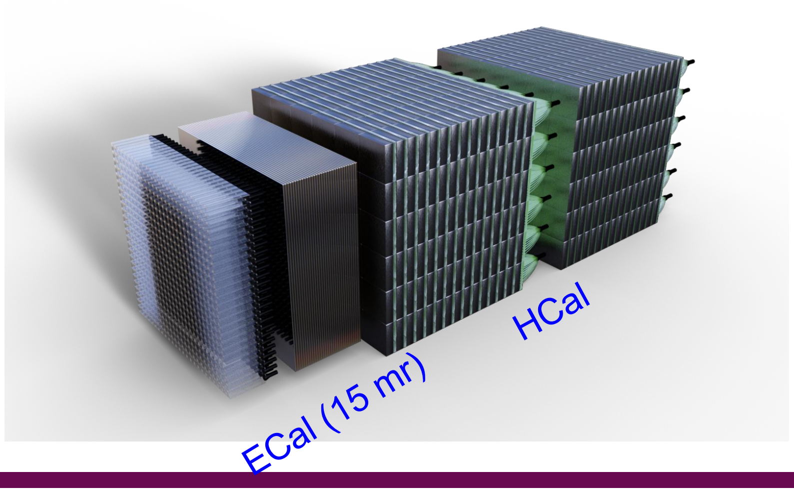
Accept/Throw Ratio for 15 GeV neutron

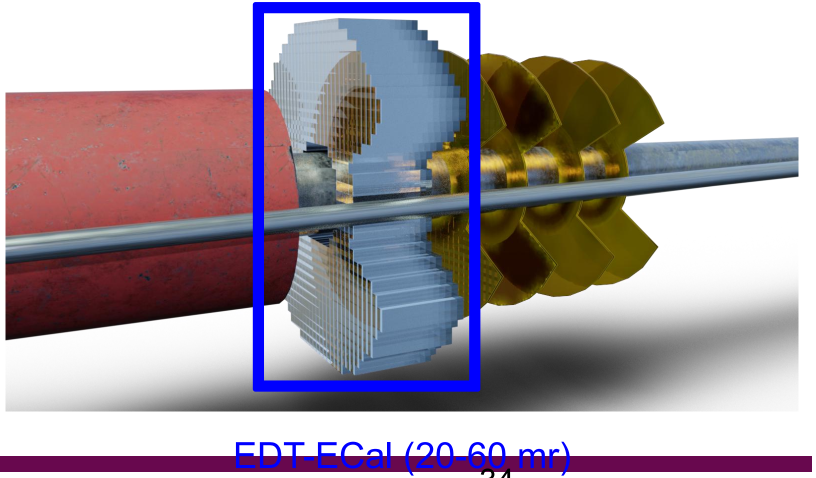


Λ Detection for Kion FF and SF (Neutral Channel)

- $\Lambda \to \pi^0 n$ with 36% branching ratio
- Neutrons only detected by ZDC (15 mr acceptance)
- Photons can be detected by ZDC, EDT-ECal and EMCal on central detector ion endcap



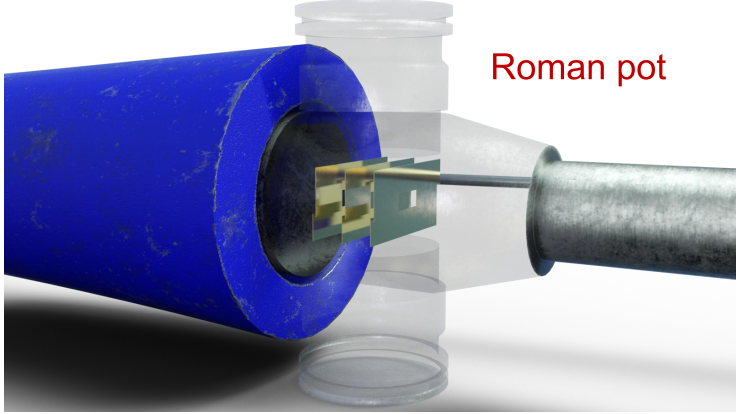


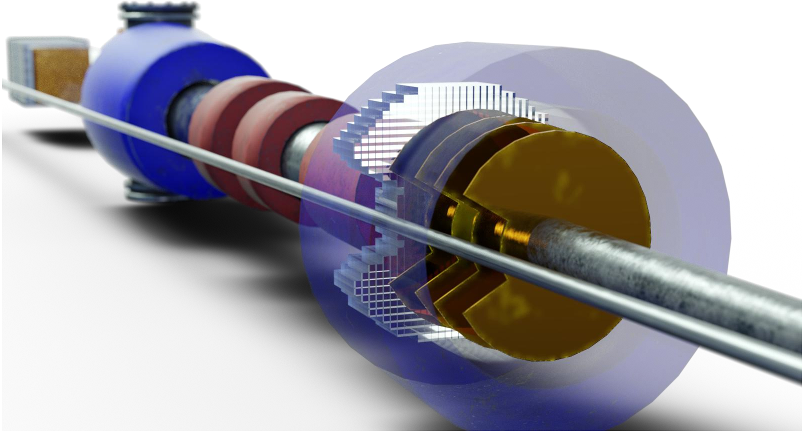


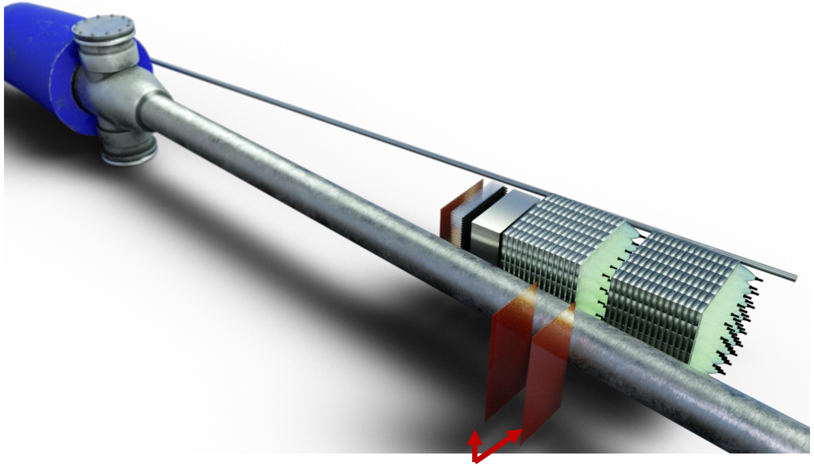
Λ Detection for Kion FF and SF (Charged Channel)

- $\boldsymbol{\Lambda \rightarrow \pi^- p}$ with 64% branching ratio
- π^- can only be detected by EDT (16 – 60 mr)
- Proton will be detected by EDT, Roman pots (~5-16mrad) as well as OMD

- EDT resolution: ~0.6% for p, 0.2mr for θ
- RP resolution: ~6.0% for p, 1.2mr for θ



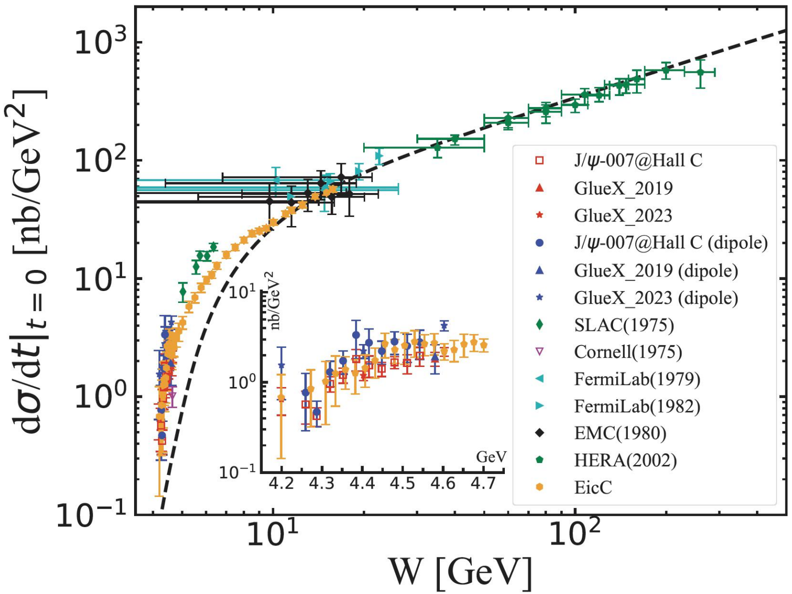




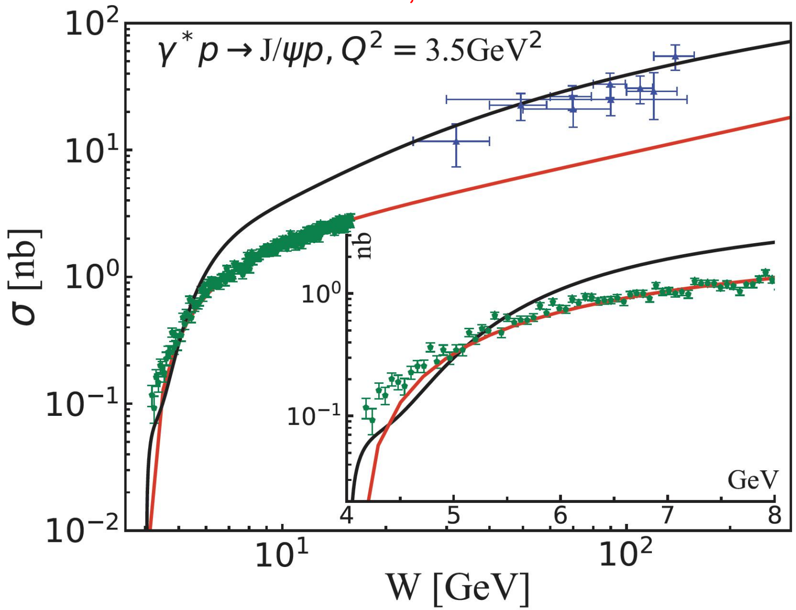
Exclusive Heavy Flavor

- **Exclusive Heavy Quarkonium Production** probes several interesting topics
- e.g. pentaquarks, cusps, Charmonium-nucleon interaction, Gravitational Form Factors …

X. Wang, X. C *et al.*, 2311.07008, EPJC (2024)



ΔW = 60 MeV, 195 bins



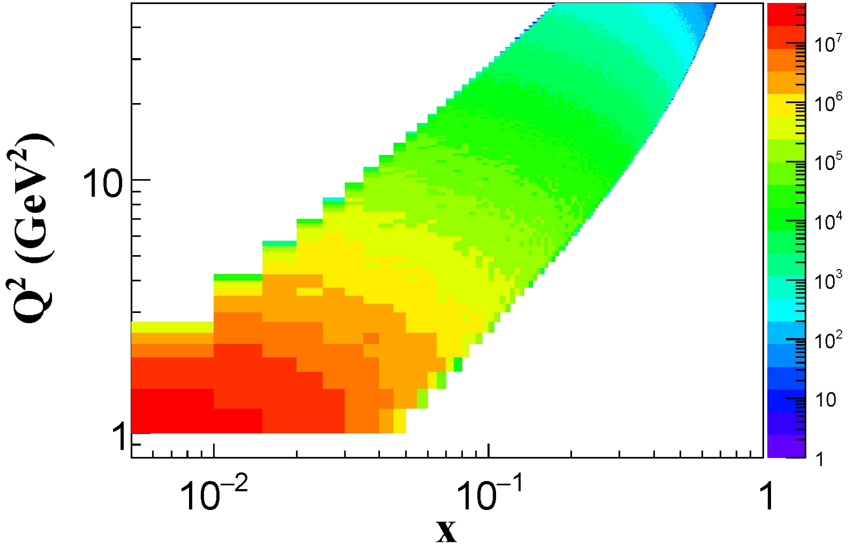
- Optimization the efficiency and resolution of detector will helpful for approaching close to the threshold region W<5.0 GeV

Inclusive Process

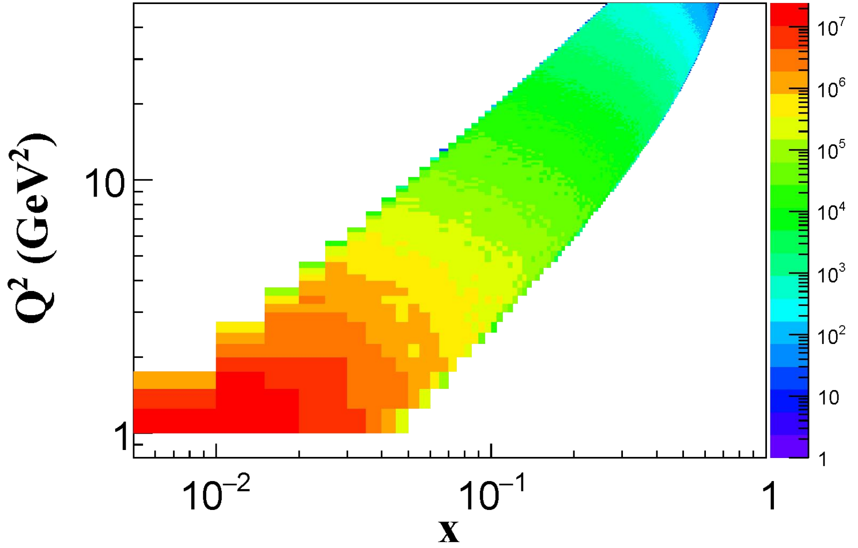
arXiv:2102.09222 SIDIS and TMD@EicC

$$Q^2 > 1\,\mathrm{GeV}^2,\ W > 5\,\mathrm{GeV},\ W' > 2\,\mathrm{GeV},\ 0.3 < z < 0.7$$

π^+ production from the proton



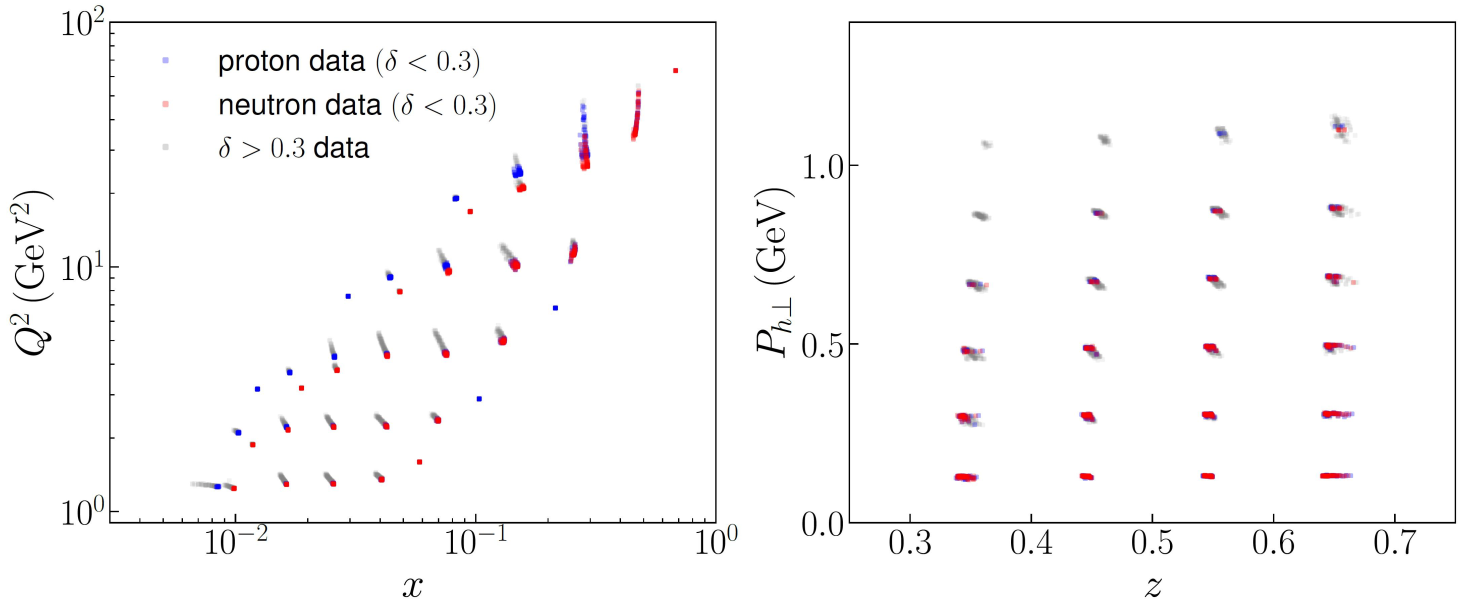
K^+ production from the ^{3}He beam.



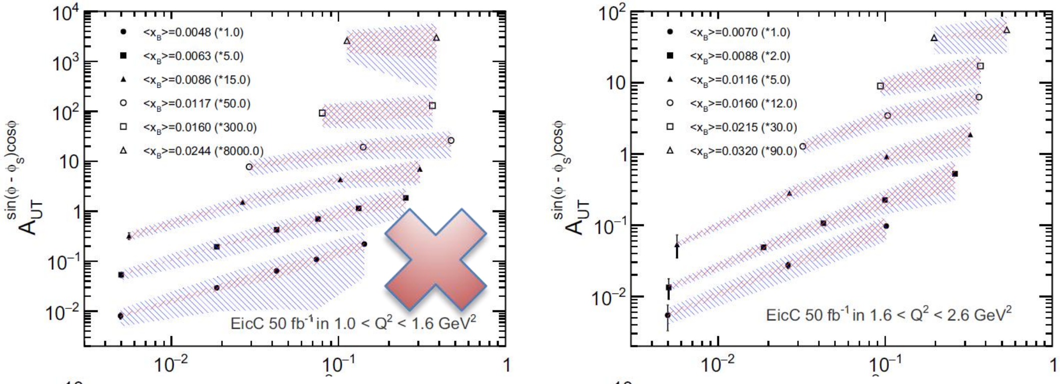
arXiv:2208.14620 SIDIS and TMD@EicC

$$Q^2 > 1\,\mathrm{GeV}^2,\ W > 5\,\mathrm{GeV},\ \ W' > 2\,\mathrm{GeV},\ 0.3 < z < 0.7$$

$$A_{UT}^{\sin(\phi_h-\phi_S)} \qquad \delta \equiv |P_{h\perp}|/(zQ)$$

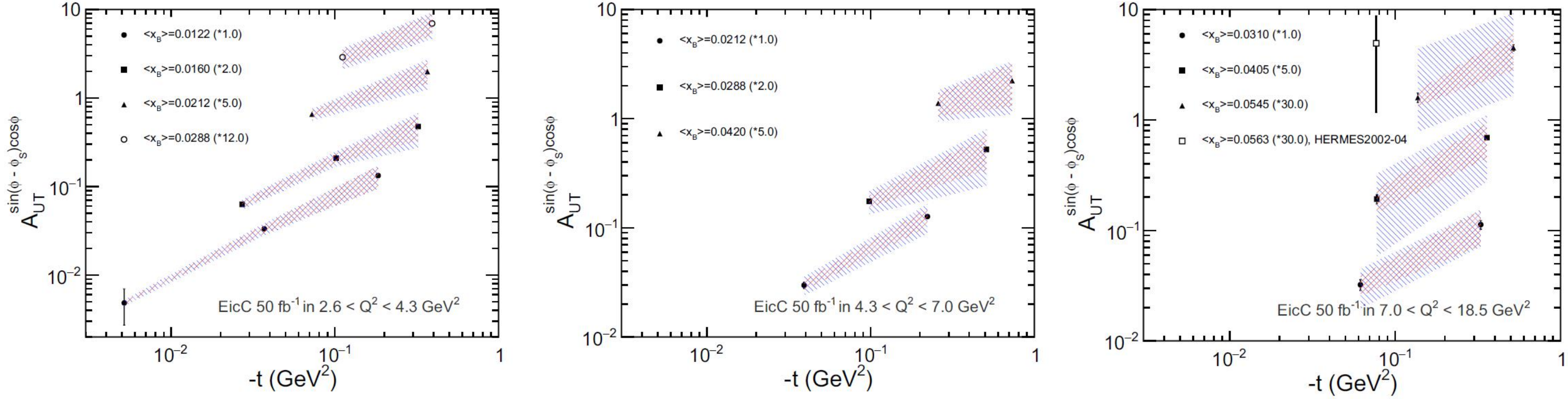


Proton DVCS



- 69 (Q^2 , x_B) bins in total

$$A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi} \propto \mathrm{Im}\Big[-\frac{t}{4M^2}(F_2\mathcal{H}-F_1\mathcal{E})+\xi^2\big(F_1+\frac{t}{4M^2}F_2\big)(\mathcal{H}+\mathcal{E}) -\xi^2(F_1+F_2)\big(\widetilde{\mathcal{H}}+\frac{t}{4M^2}\widetilde{\mathcal{E}}\big)\Big],$$

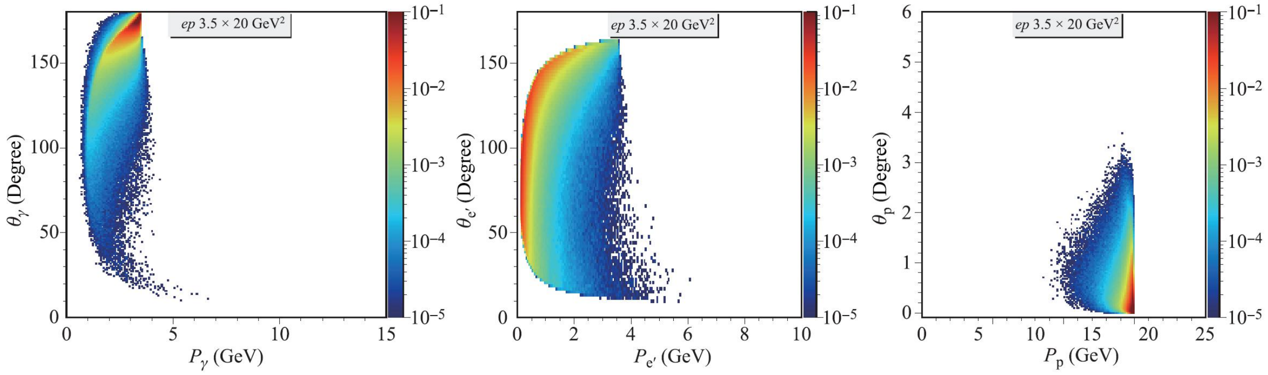


- A_{UT} in all $1.0 < Q^2 < 80.0$ GeV^2 and x_B & -t bins. Cut: $Q^2 > 1.5$ GeV^2, $|t/Q^2| < 0.2$

Proton DVCS

- Pseudo-rapidity, azimuthal angle coverage and pt coverage?
- Any requirement on far-forward detector?

- large rapidity coverage, good high momentum resolution
- DVCS&DVMP Electron ($Q^2 > 1.0$ GeV^2, $\eta > 2.0$); TCS & hadron ($Q^2 < 1.0$ GeV^2) need e-far-forward
- Proton: good far-forward detector; Photon: several to 15 GeV, 4π coverage

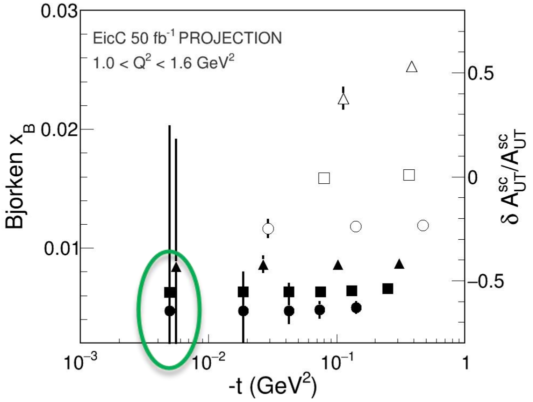


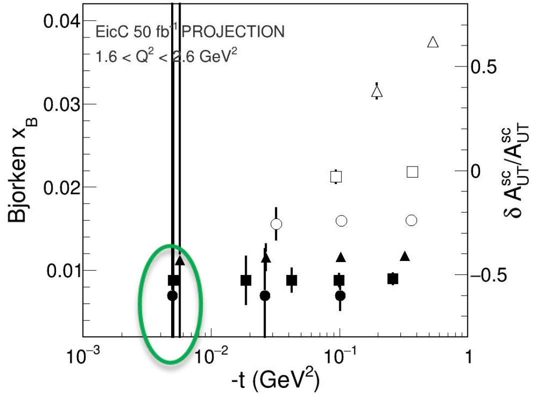
- >5mrad (previously

- π / K / η / η' / ω / φ separation: $\eta/\pi^0 \to \gamma\ \gamma$ required by DVMP and TDA physics

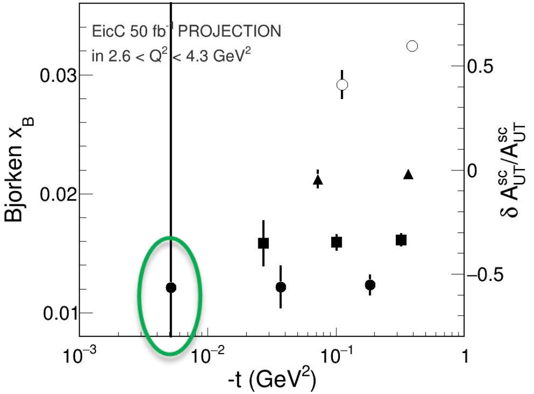
Proton DVCS

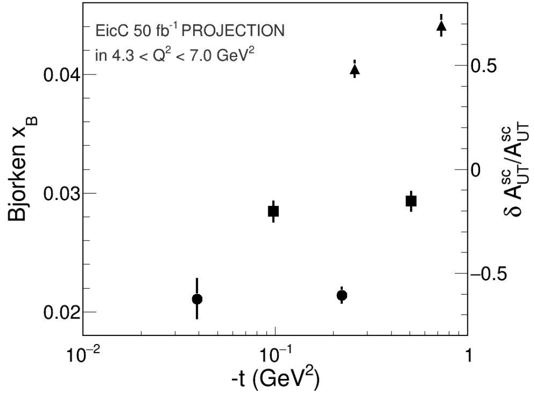
- Moderate Asymmetry precision < 1.0 ~ 1.5 % in all kinematic region

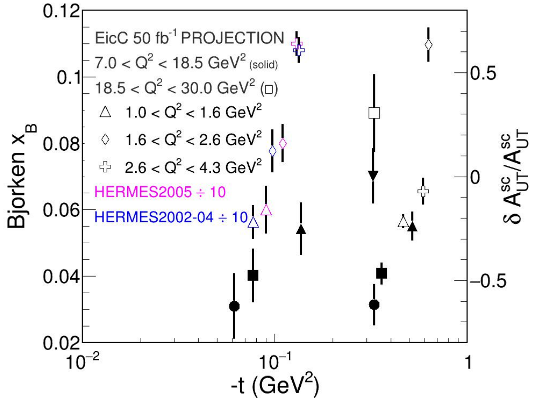




Tiny asymmetry
in –t < 0.01 GeV^2
predicted by GK model
with large uncertainties

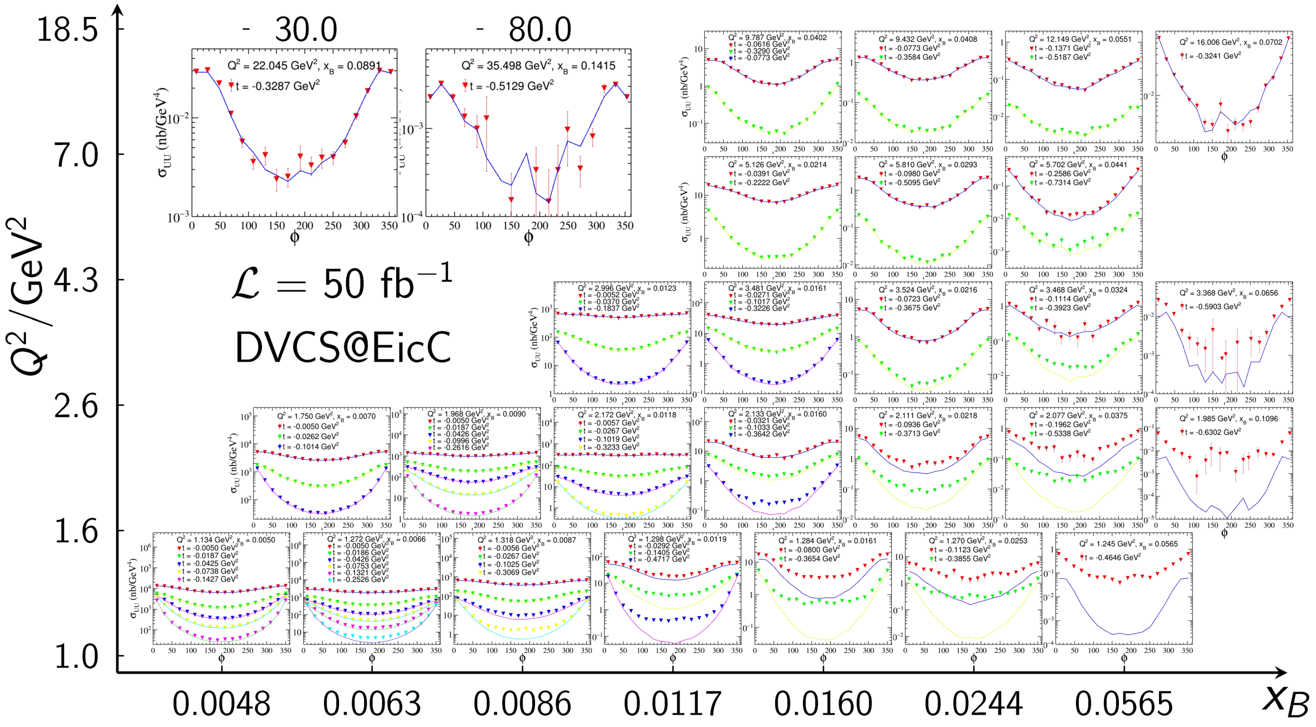






Proton DVCS

- Accessing Compton Form Factors / GPD? by all pseudo-data at the EicC



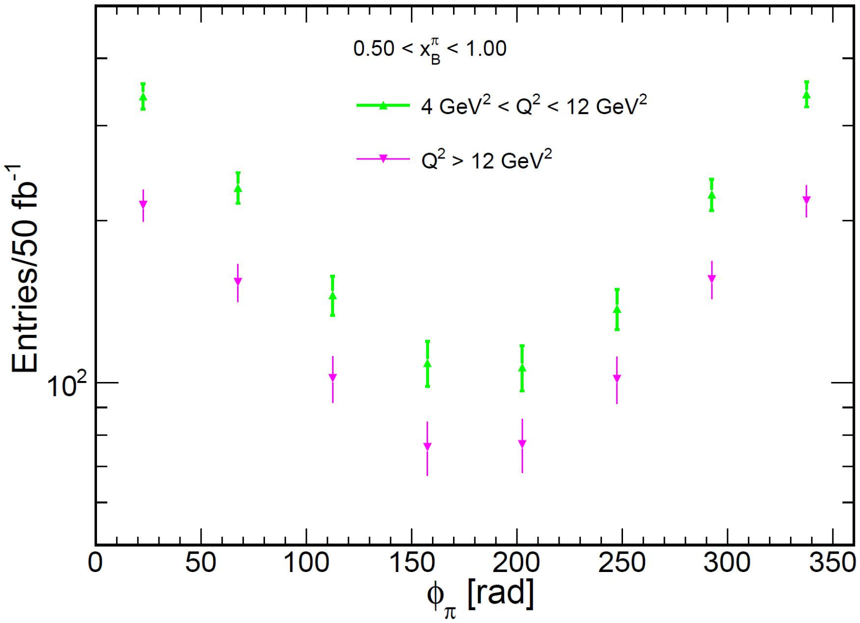
- Re-training (less-biased) within Gepard framework in collaboration with K. Kumericki

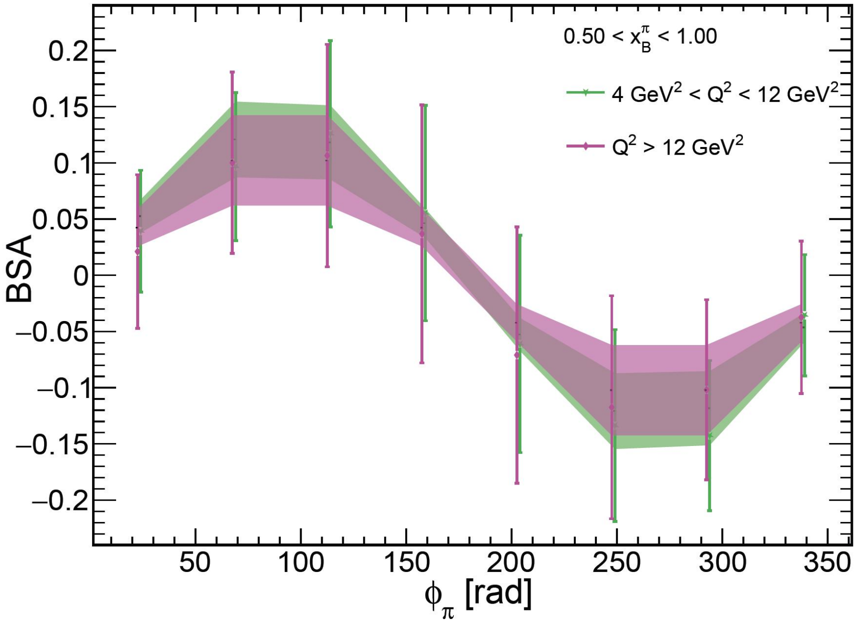
Meson GPD

- π^+-DVCS through Sullivan process (filtered by detector at EicC)
- Over eff. ~ 45.9% ~ 42.6%

0.13±0.04
0.11±0.04

$$\mathcal{A}(\varphi_{\text{Trento}}) = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto \text{Im}(\mathcal{H}_{\pi}) \sin(\varphi_{\text{Trento}}),$$



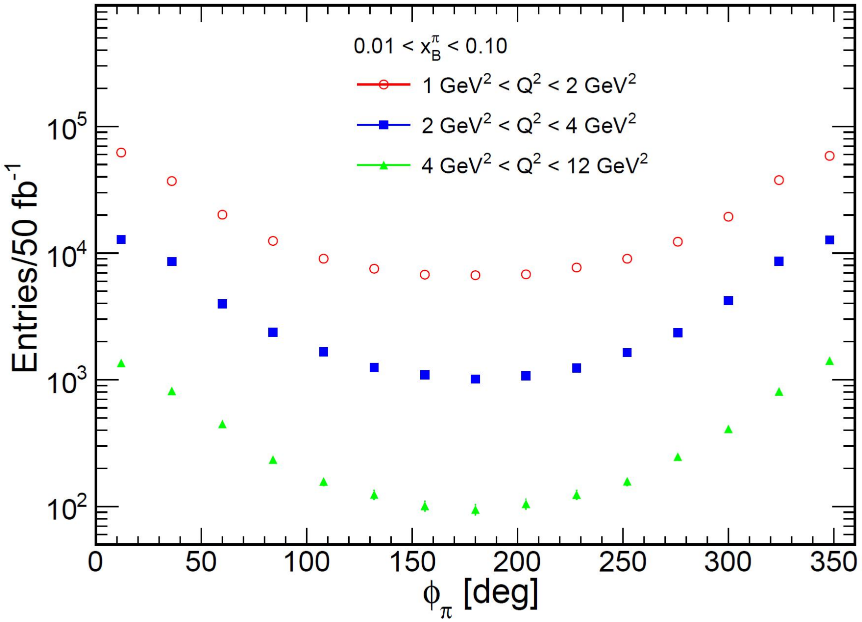


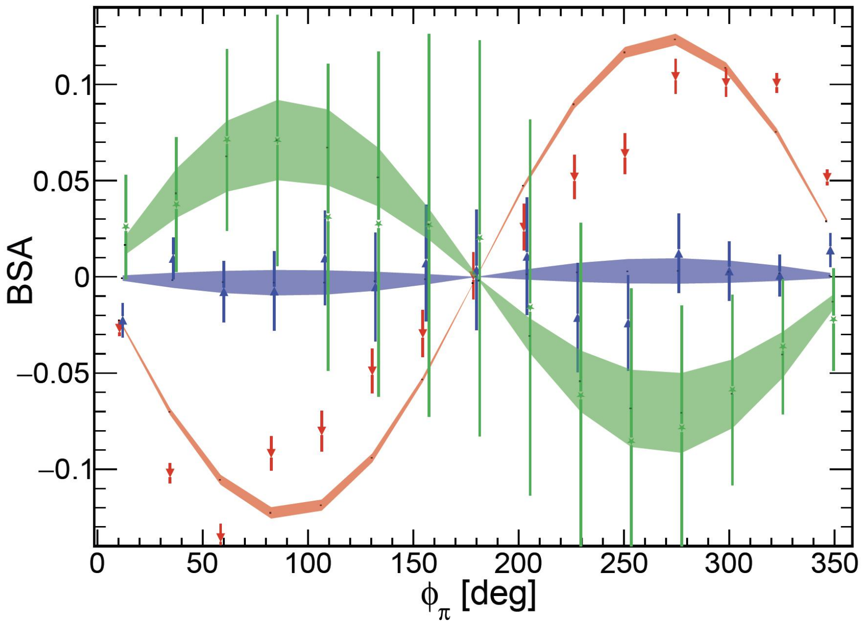
Meson GPD

- π^+-DVCS through Sullivan process (filtered by detector at EicC)
- Over eff. ~ 17.8% Asy. -0.124±0.003

  ~ 19.9% -0.003±0.007

  ~ 20.6% 0.07 ± 0.02





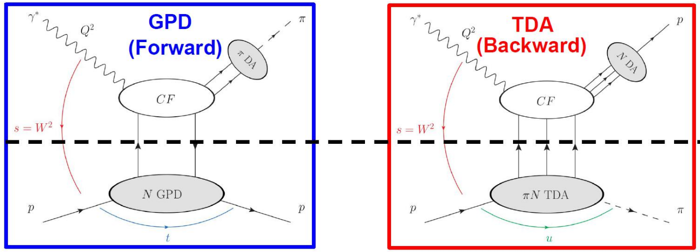
Exclusive Process

- **3D structure of nucleon (TDA)**
- *u*-channel meson production (borrowed from Bill Wenliang@WM&JLab)

Hard structure

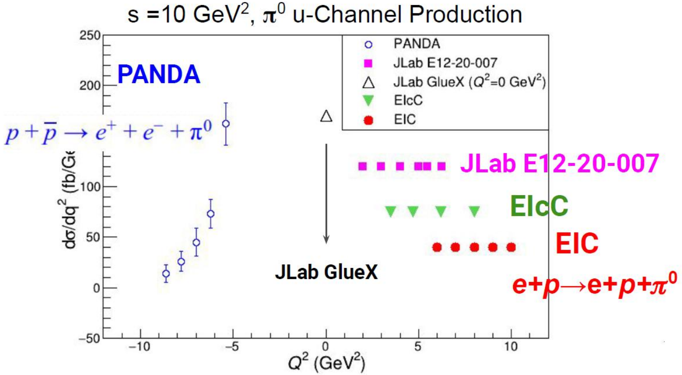
Soft structure

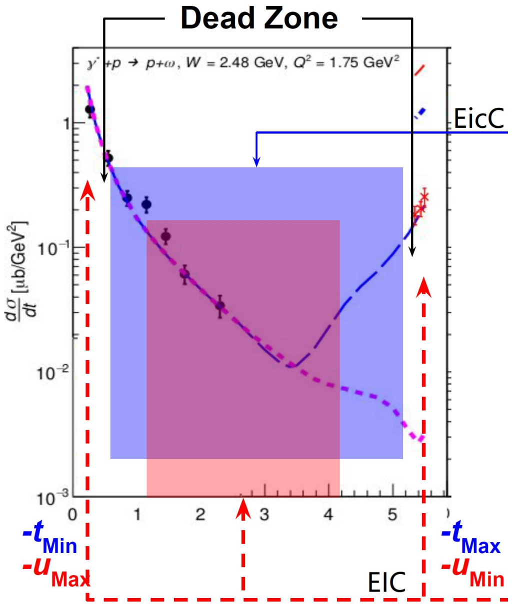
By **X. Ji et al.** in 1997



Collinear factorization

Developed by **B. Pire, L. Szymanowski** and **K Semenov-Tian-Shansky** in 2000



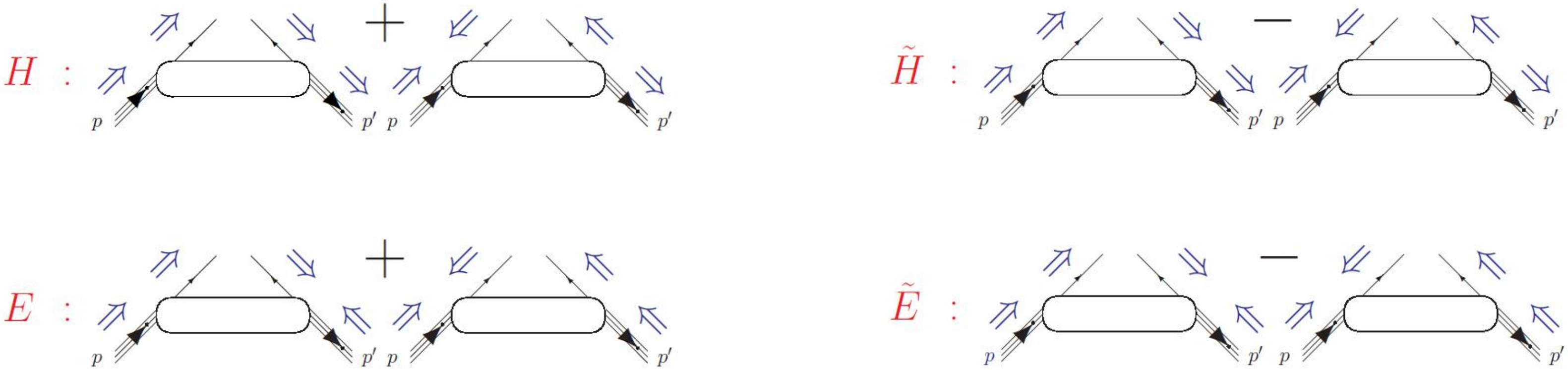


Lumi. is OK, but
15 (VS. 4.5)mRad acceptance for 2γ from π^0
other mesons: reduce the dead zone near the beamline

Deeply Virtual Compton Scattering (DVCS)

- **From 1D to 3D structure of proton & atom, and vice versa:**
- GPD: General Parton Distribution
- DVCS: Deeply Virtual Compton Scattering

averages over the quark helicity



➢Rept. Prog. Phys. 76 (2013) 066202

Reweighting replicas @ PARTONS NN

- Given an PARTONS NN ensemble one can evaluate any quantity or experimental observable O[f] depending on the CFFs by computing O[f] for each of the replicas, and averaging the results:

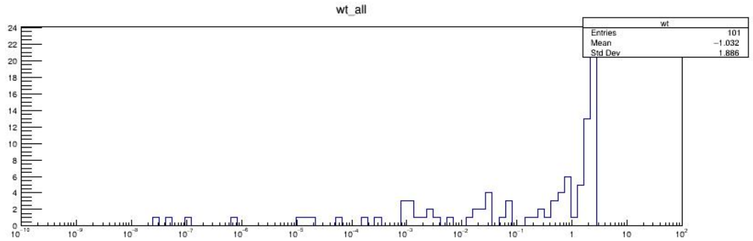
NNPDF: Nucl.Phys.B849:112,2011 (arxiv: 1012.0836)

$$\langle \mathcal{O} \rangle = \int \mathcal{O}[f]\, \mathcal{P}(f)\, Df = \frac{1}{N} \sum_{k=1}^{N} \mathcal{O}[f_k] \,.$$

(Pseudo-)data n：

$$\chi^2(y,f) = \sum_{i,j=1}^{n} (y_i - y_i[f]) \sigma_{ij}^{-1} (y_j - y_j[f]).$$

$$w_k = \frac{(\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2}}{\frac{1}{N}\sum_{k=1}^{N} (\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2}}.$$



$$\langle \mathcal{O} \rangle_{\rm new} = \int \mathcal{O}[f]\, \mathcal{P}_{\rm new}(f)\, Df = \frac{1}{N} \sum_{k=1}^{N} w_k \mathcal{O}[f_k] \,.$$

Reweighting replicas @ PARTONS NN

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$$\langle \mathcal{O} \rangle_{\rm new} = \int \mathcal{O}[f]\, \mathcal{P}_{\rm new}(f)\, Df = \frac{1}{N}\sum_{k=1}^{N} w_k \mathcal{O}[f_k]\,.$$

- We can quantify this loss of efficiency by using the Shannon entropy to compute the effective number of replicas left after reweighting:

$$N_{\rm eff} \equiv \exp\left\{\frac{1}{N}\sum_{k=1}^{N} w_k \ln(N/w_k)\right\}.$$

- If $N_{\rm eff}$ becomes too low, the reweighting procedure will no longer be reliable,

1. either because the new data contain a lot of information on the PDFs, necessitating a full refitting with more replicas. (pseudo-data：integrated luminosity)
2. or because the new data are inconsistent with the old. (pseudo-data：smeared)

Ultimate Goal: impact of EicC on GPD of proton

- Flavor seperation? CFF H, E, $\widetilde{H}$, $\widetilde{E}$ & H, E, $\widetilde{H}$, $\widetilde{E}$

$$A_{LU,I}^{\sin\phi} \propto \mathrm{Im}\left[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4m^2}F_2\mathcal{E}\right],$$

$$A_{UL,I}^{\sin\phi} \propto \mathrm{Im}\left[\xi(F_1+F_2)(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}) + F_1\widetilde{\mathcal{H}} - \xi(\frac{\xi}{1+\xi}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}\right]$$

$$A_{LL,I}^{\cos\phi} \propto \mathrm{Re}\left[\xi(F_1+F_2)(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}) + F_1\widetilde{\mathcal{H}} - \xi(\frac{\xi}{1+\xi}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}\right]$$

$$A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi} \propto \mathrm{Im}\Big[-\frac{t}{4M^2}(F_2\mathcal{H} - F_1\mathcal{E}) + \xi^2(F_1 + \frac{t}{4M^2}F_2)(\mathcal{H}+\mathcal{E}) -\xi^2(F_1+F_2)(\widetilde{\mathcal{H}} + \frac{t}{4M^2}\widetilde{\mathcal{E}})\Big],$$

$$A_{UT,I}^{\cos(\phi-\phi_s)\sin\phi} \propto \mathrm{Im}\left(F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}\right),$$

$$A_{LT,I}^{\sin(\phi-\phi_s)\sin\phi} \propto \mathrm{Re}\left(F_2\mathcal{H} - F_1\mathcal{E}\right),$$

$$A_{LT,I}^{\cos(\phi-\phi_s)\cos\phi} \propto \mathrm{Re}\left(F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}\right).$$

Ultimate Goal: impact of EicC on GPD of neutron

- Error propagation? CFF $H, E, \widetilde{H}, \widetilde{E}$ → GPD H, E, $\widetilde{\text{H}}$, $\widetilde{\text{E}}$

$$A_{LU,I}^{\sin\phi} \propto \mathrm{Im}\left[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4m^2}F_2\mathcal{E}\right],$$

$$A_{UL,I}^{\sin\phi} \propto \mathrm{Im}\left[\xi(F_1+F_2)(\mathcal{H}+\frac{\xi}{1+\xi}\mathcal{E}) + F_1\widetilde{\mathcal{H}} - \xi(\frac{\xi}{1+\xi}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}\right]$$

$$A_{LL,I}^{\cos\phi} \propto \mathrm{Re}\left[\xi(F_1+F_2)(\mathcal{H}+\frac{\xi}{1+\xi}\mathcal{E}) + F_1\widetilde{\mathcal{H}} - \xi(\frac{\xi}{1+\xi}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}\right]$$

$$A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi} \propto \mathrm{Im}\Big[-\frac{t}{4M^2}(F_2\mathcal{H} - F_1\mathcal{E}) + \xi^2(F_1 + \frac{t}{4M^2}F_2)(\mathcal{H}+\mathcal{E}) - \xi^2(F_1+F_2)(\widetilde{\mathcal{H}} + \frac{t}{4M^2}\widetilde{\mathcal{E}})\Big],$$

$$A_{UT,I}^{\cos(\phi-\phi_s)\sin\phi} \propto \mathrm{Im}\left(F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}\right),$$

$$A_{LT,I}^{\sin(\phi-\phi_s)\sin\phi} \propto \mathrm{Re}\left(F_2\mathcal{H} - F_1\mathcal{E}\right),$$

$$A_{LT,I}^{\cos(\phi-\phi_s)\cos\phi} \propto \mathrm{Re}\left(F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}\right).$$

Deeply Virtual Compton Scattering (DVCS)

➢Proejction Bins of DVCS@EicC: Assume |t|>0.01， Δt>0.02

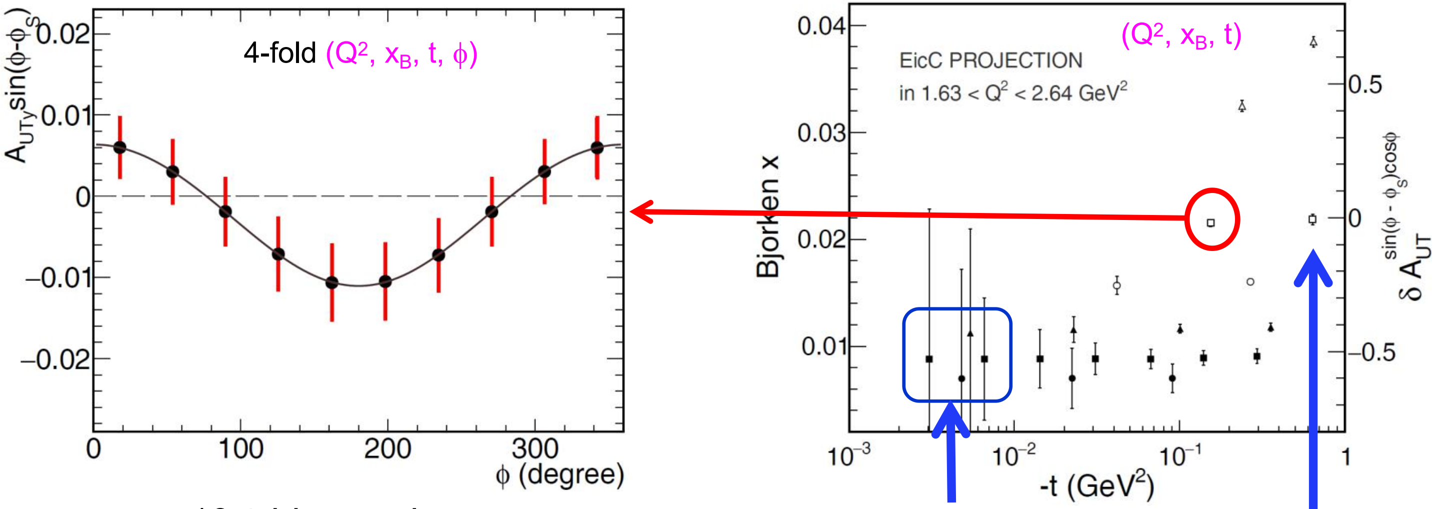
- 1. Only several projection points with |t|<0.01

- 2. Magnitude of asymmetry is tiny with |t|<0.01, so the relative errors are usually above 50% there

- 3. A big challenge for the detector design for |t|~0.002 & Δt~0.002: detector simulation?

the first t-bin in $1.63 < Q^2 < 2.64$ GeV^2

absolute asymmetry: GK model for illustration only



10 ϕ bins each

|t|<0.01 GeV^2

|t| ~ 1 GeV^2

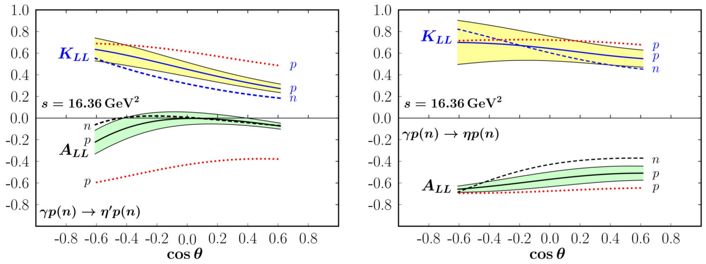
Exclusive Process

- **3D structure of nucleon (TDA)**
- *u*-channel meson production (Bill Wenliang@WM&JLab)

- Pseudo-rapidity, azimuthal angle coverage and pt coverage?
- outgoing scattered e': $0 < \eta < 3$; recoiled proton: $1.5 < \eta < 4$; π^0 : $0 < \eta < 3.69$;
- Note: $\eta = 3.69$ is the far-forward region

- Momentum/Energy resolution?
- Energy resolution ($\sigma(\Delta E / E)$) in the far forward region and forward endcap: $0.02 + 0.077\sqrt{E}$ for photon. minimum requirement $0.35*\sqrt{0.35}$

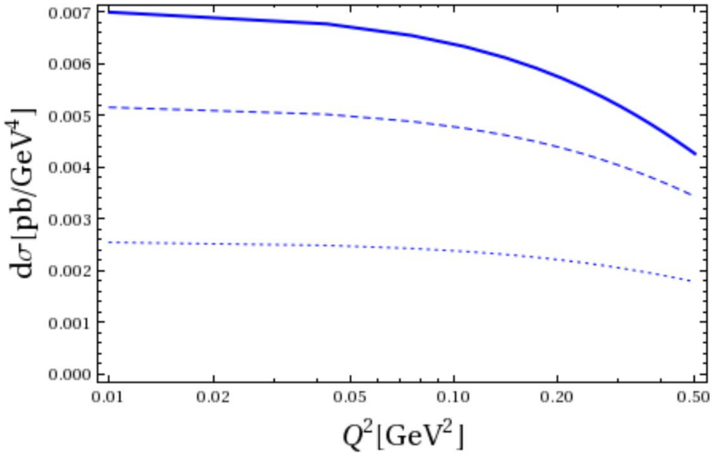
- PID requirements? Note (η' for glue, see 2111.08965):
- Any requirement on far-forward detector?
- Excellent forward γ/neutron separation
- Reconstruct photon energy.
- The forward acceptance: ±7mrad, >±5 mrad

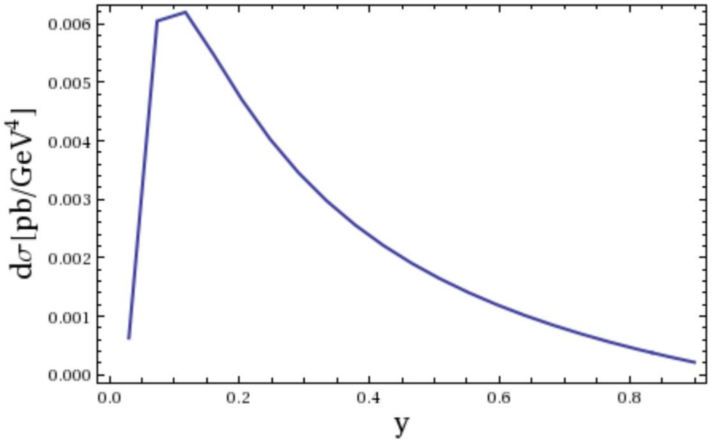


GPD physics

- 3D structure of nucleon (GPDs) @ EicC
- *Charged current electroproduction of a charmed meson* (PRD104, 094002)
- Courtesy: B. Pire, L. Szymanowski, J. Wagner

- The rates are quite small
- missing mass technique: the neutrino at final states.
- Ds reconstruction: difficult





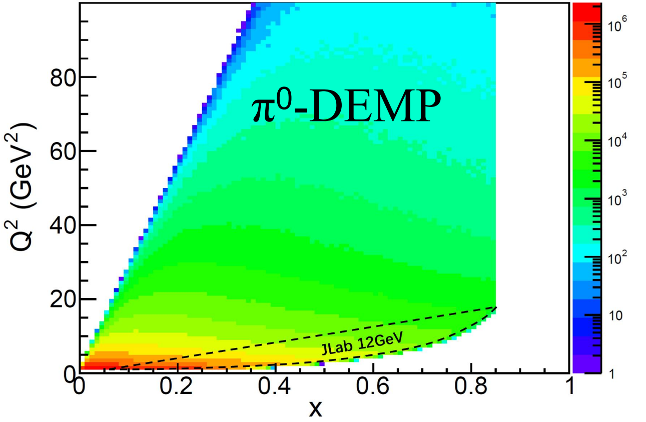
Conclusion & Perspective

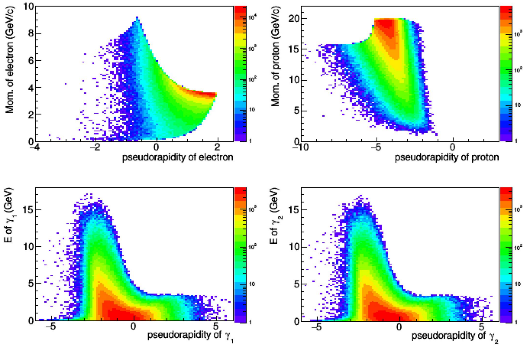
- The exclusives of EicC (DVCS, DEMP…):

- Impact of A_{UT} is noticeable to imaginary CFF-E (KK);
- Present data constraining power in sea CFF-E :
  ~ 0.01 fb^{-1} (PARTONS-NN);

- Future:
- Local extracting of CFF
- Feed the numerical framework and models

- … GPD impact study of electron-ion collider





Introduction

- **From 1D to 3D picture of hadron & atom:**
- TMD: Transverse Momentum Distribution (k ⊥ & longi. Momentum)
- How is proton's spin correlated with the motion of the quarks/gluons?
- GPD: General Parton Distribution (trans. spatial position b⊥ & longi. Momentum)
- How does proton's spin influence the spatial distribution of partons?
- TDA: nucleon-to-photon & nucleon-to-meson Transition Distribution Amplitudes

- **Origin of the Proton spin**

$$J_{q,g} = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\,[H_{q,g}(x,\xi,t=0) + E_{q,g}(x,\xi,t=0)]$$

- **Quark OAM?**

$$\mathcal{F}(\xi,t,Q^2) = \sum_{q=u,d,s,\cdots} e_q^2 \int_{-1}^{1} \mathrm{d}x \left[\frac{1}{\xi - x - i\epsilon} \mp \frac{1}{\xi + x - i\epsilon}\right] F^q(x,\xi,t)$$