3D hadron imaging at the EicC

Xu CAO

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Institute of Modern Physics, Chinese Academy of Sciences

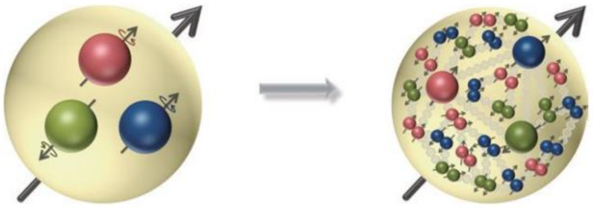
The REVESTRUCTURE workshop
Zagreb, 10-12 Jul. 2023

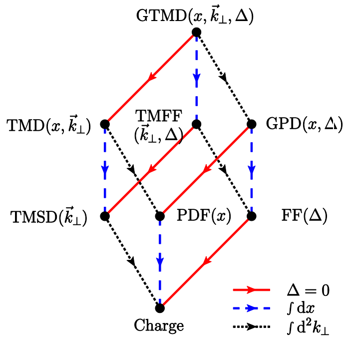
Introduction

- **TMD: Transverse Momentum Distributions ($k_\perp$ & longi. Momentum):**
- How is proton's spin correlated with the motion of the quarks/gluons?
- …… probed by the inclusive process

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

- **From 1D to 3D picture of hadron & nuclei**
- **Origin of the Proton mass & spin**





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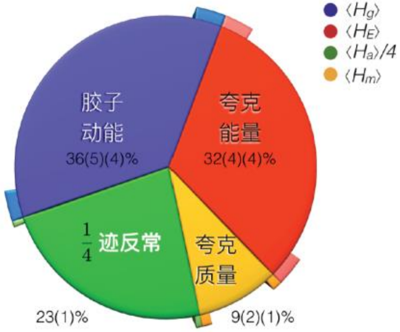
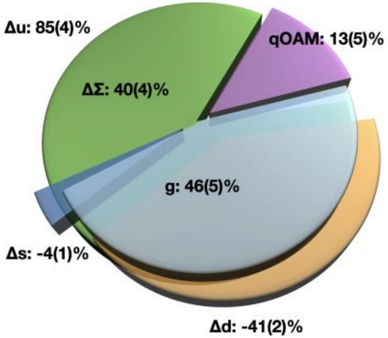




Introduction

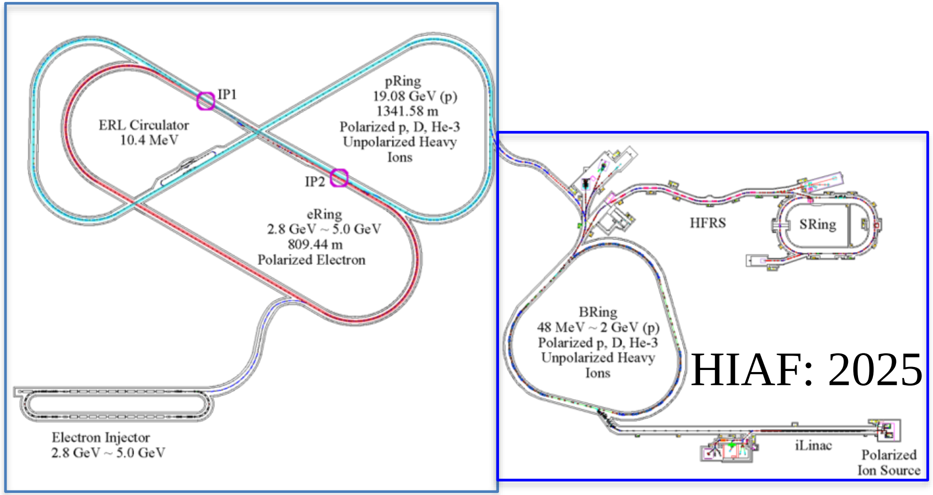
- **Energy:**
  electron + proton: 3.5 GeV × 20 GeV
  electron + ^{3}He: 3.5 GeV × 40 GeV (nucleus energy)

arXiv:2102.09222,
Front. Phys. 16, 64701 (2021)

- **Luminosity:**
  Instantaneous Lumi: 2 x 10^{33} cm^{-2} s^{-1}
  Integrated Lumi for simulation = 50 fb^{-1} for ep & e^{3}He

- **Polarization:**
  electron: 80% L
  proton: 70% L&T
  ^{3}He: 70% L&T

- **Phase space coverage**
  $\sqrt{s}$ ~ 16.7 (15 ~ 20)GeV
  4×10^{-3} < x < ~ 0.1



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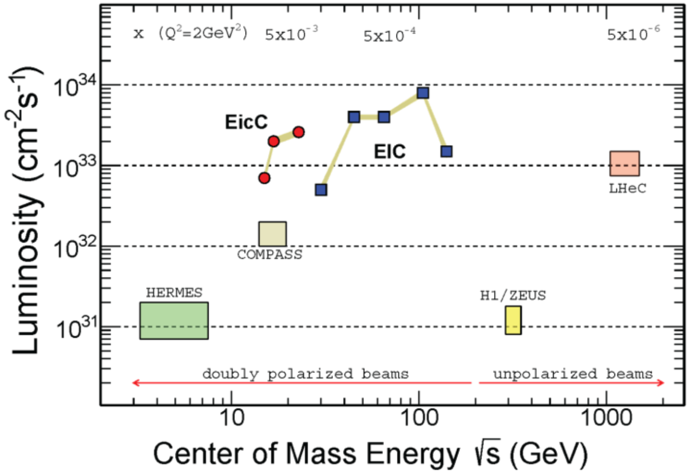


Introduction

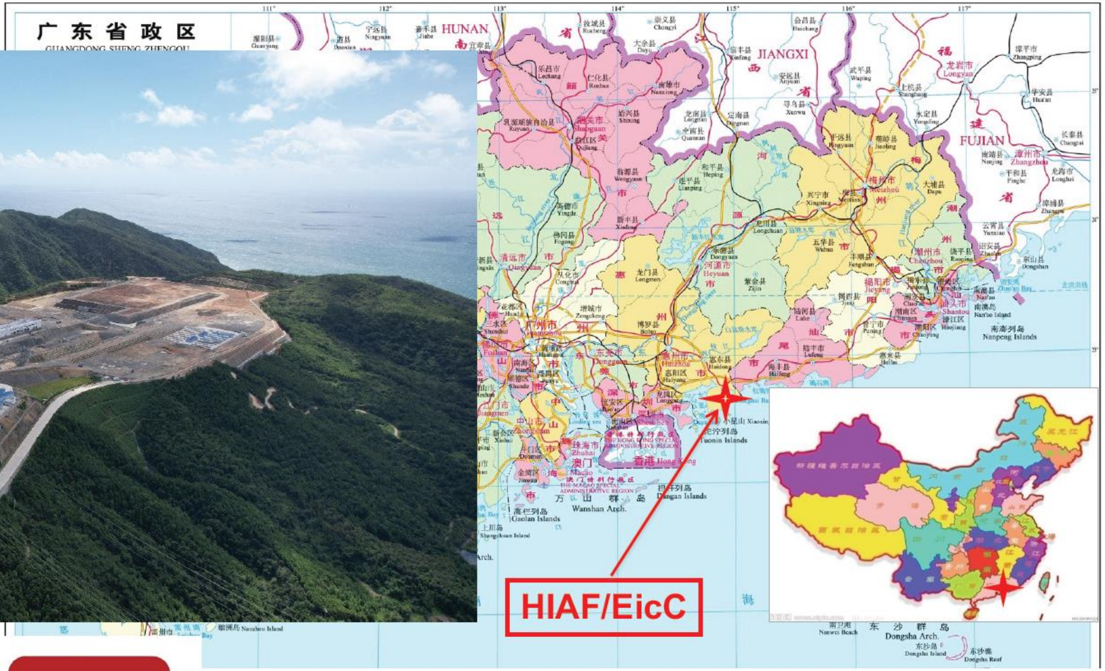
- e+p, e+d, e+^{3}He ……
- Effective tool for flavor separation

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

Introduction

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



HIAF under construction

EIC in China

Electron Ion Collider in China, EicC

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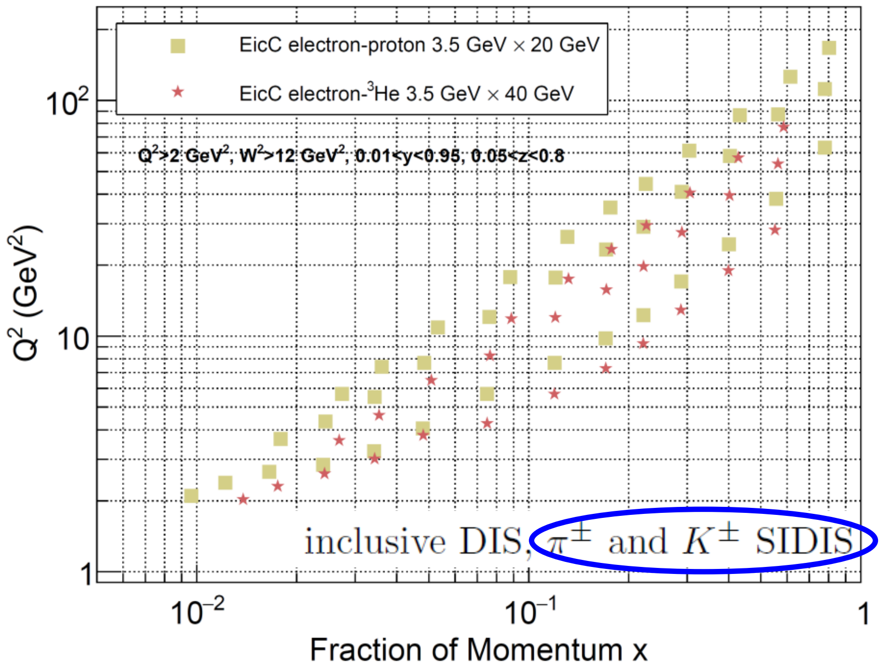
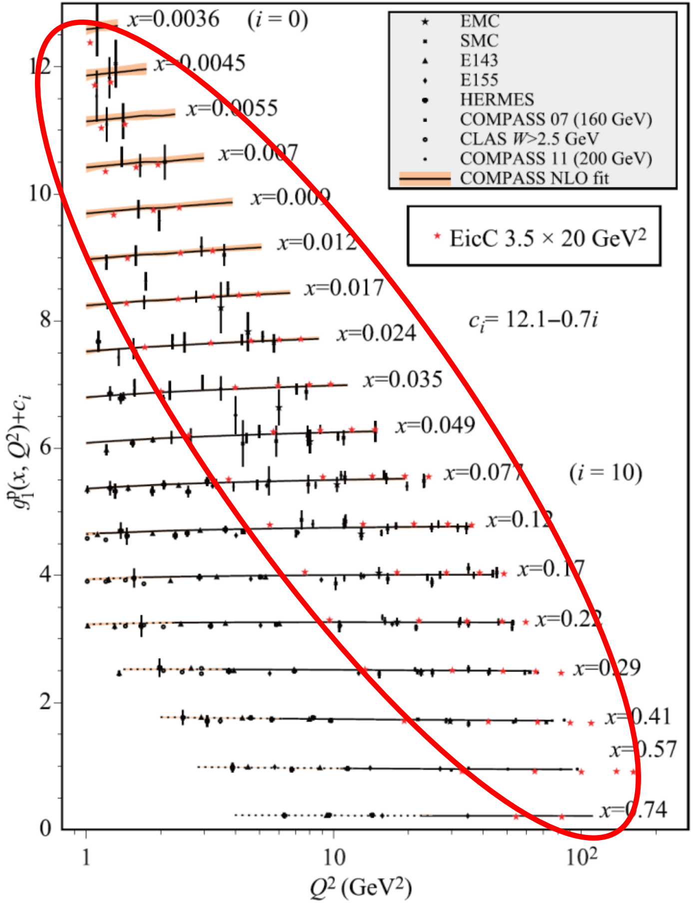
Inclusive Process

arXiv:2102.09222

Double-Spin-Asymmetry (DSA) $A_{LL} \propto \frac{g_1}{F_1}$

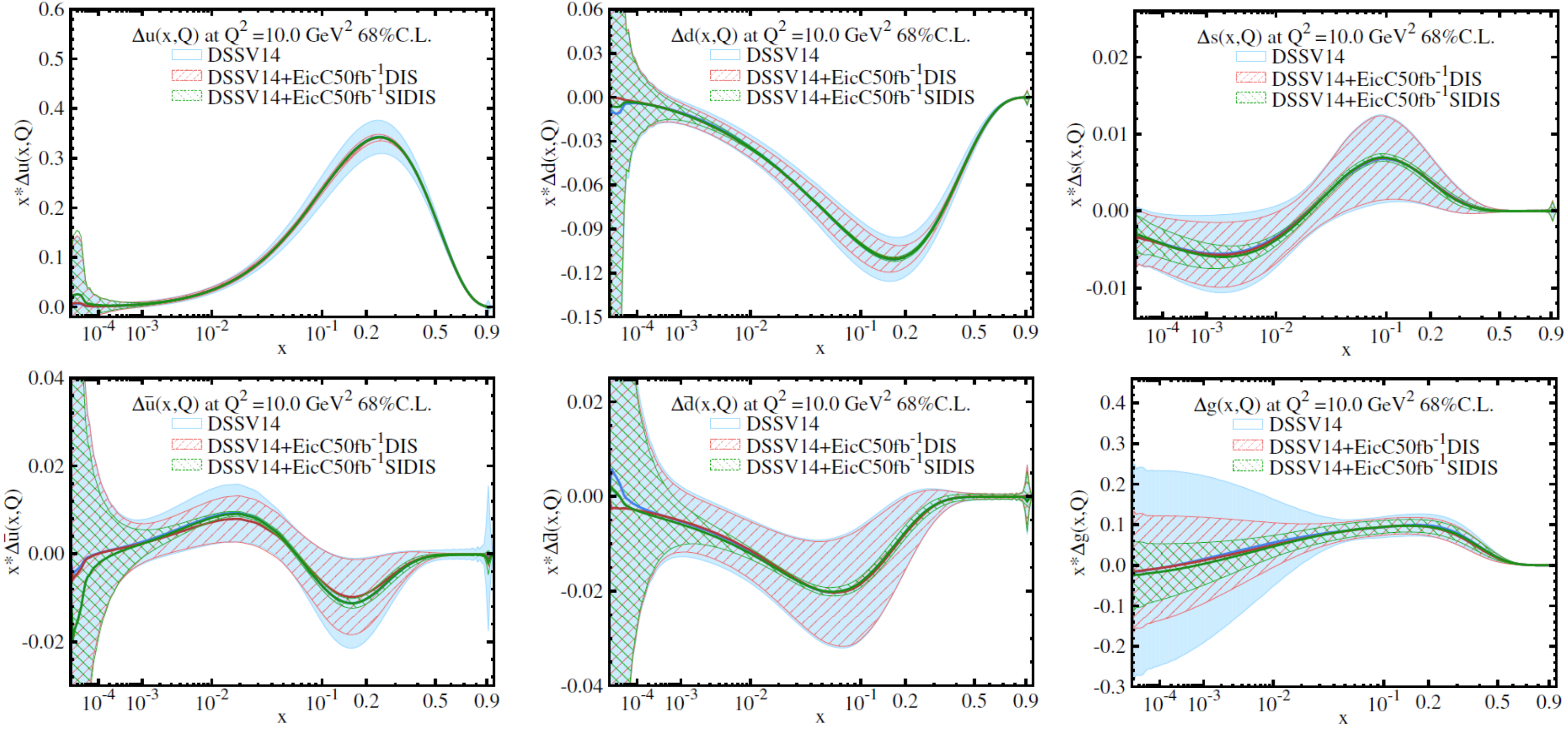




Inclusive Process

arXiv:2103.10276

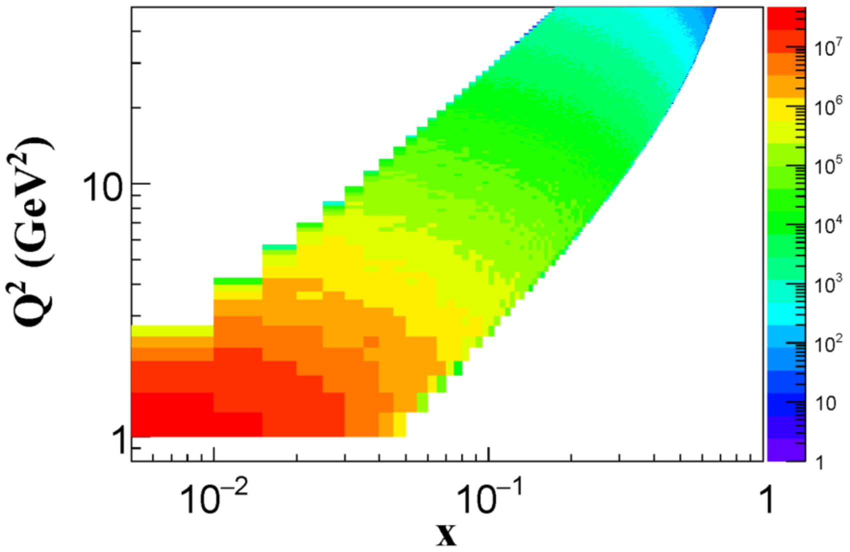
Flavored Helicity PDF@EicC:
reweighting Hessian PDF sets by ePump



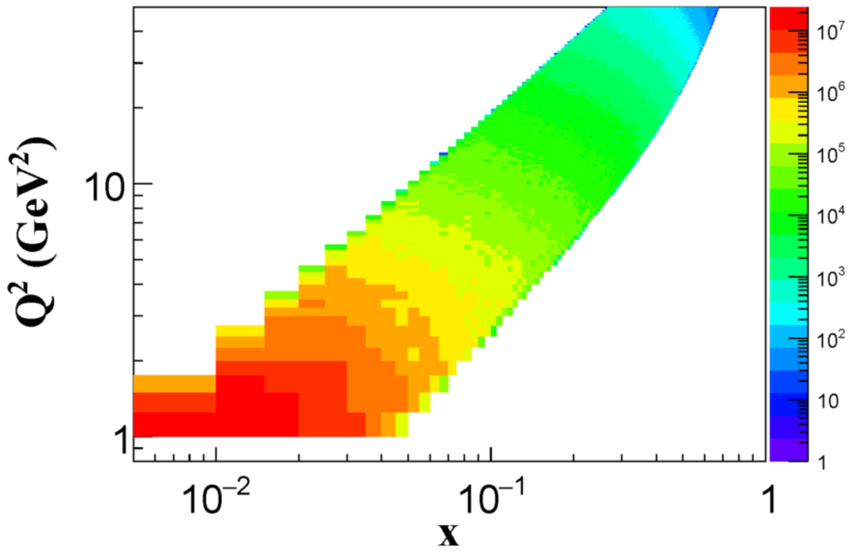
arXiv:2102.09222 SIDIS and TMD@EicC

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

π^+ production from the proton



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

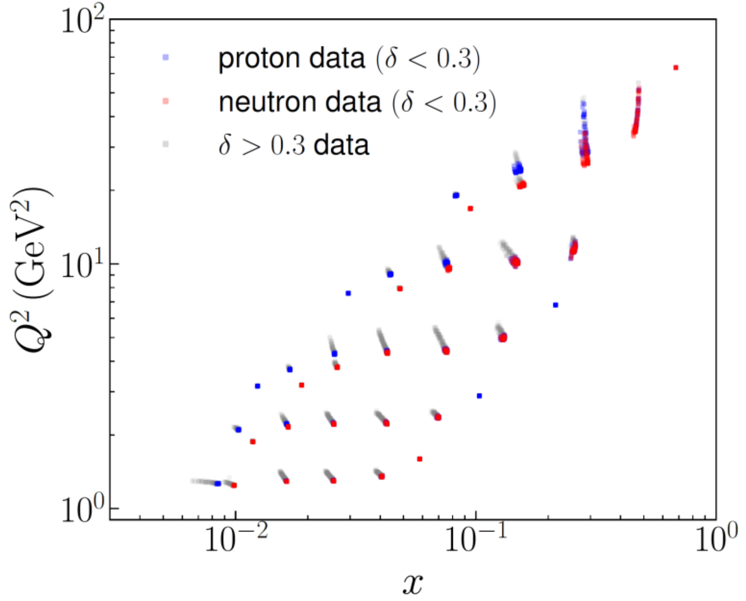


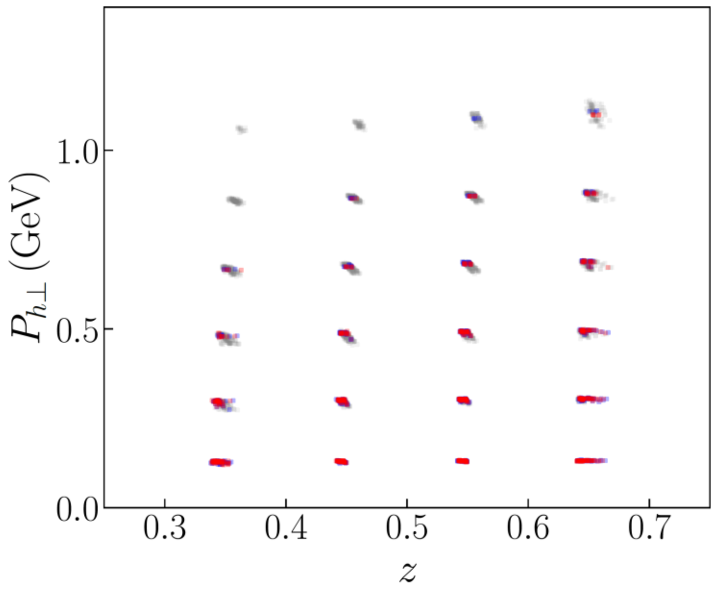
Inclusive Process

arXiv:2208.14620 SIDIS and TMD@EicC

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

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

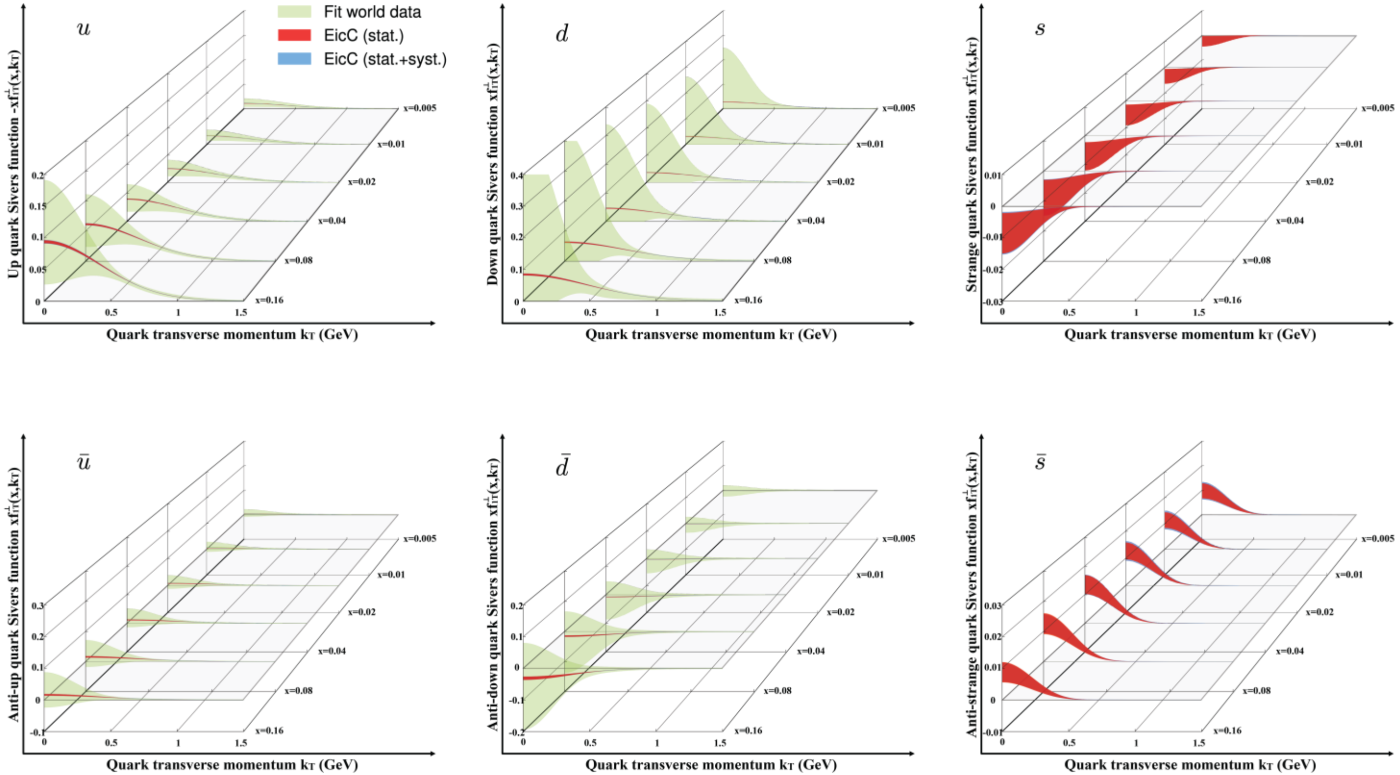




Inclusive Process

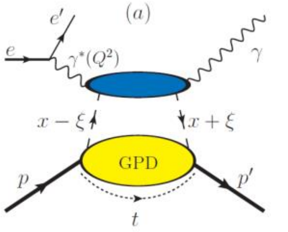
arXiv:2208.14620 The precision of extractions of Sivers functions @ EicC

Evolution Included. Constrained by COMPASS, HERMES & Jlab data



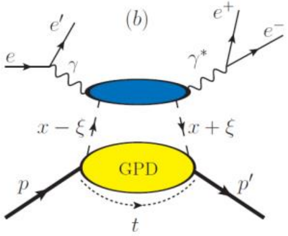
Exclusive Process

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



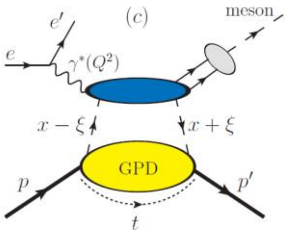
- Deeply Virtual Compton Scattering

$\xi = x_B/(2 - x_B)$



- 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**

Exclusive Process

- 3D structure of nucleon (GPDs)
- What is the flagship physics at EicC and the golden observables?
- Beam polarization requirement?

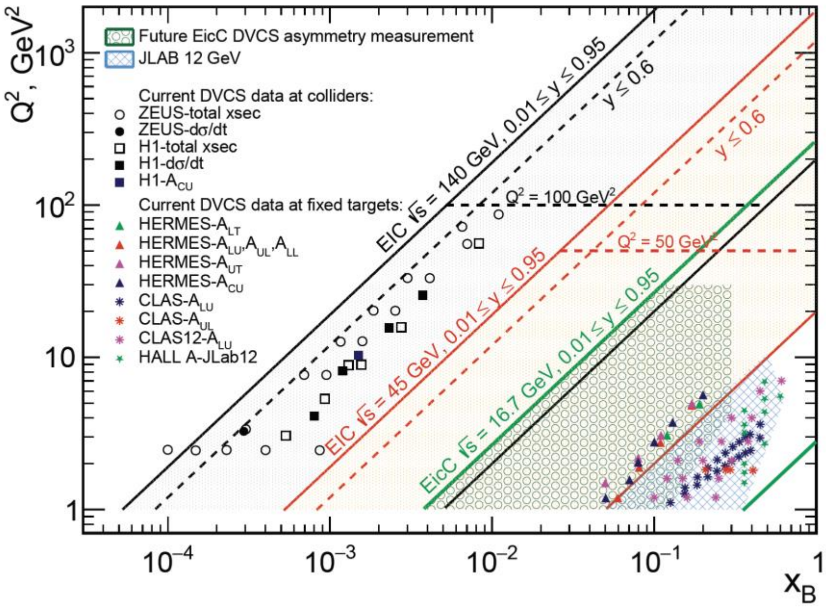
DVCS observables for Compton form factors (Leading Twist GPDs)

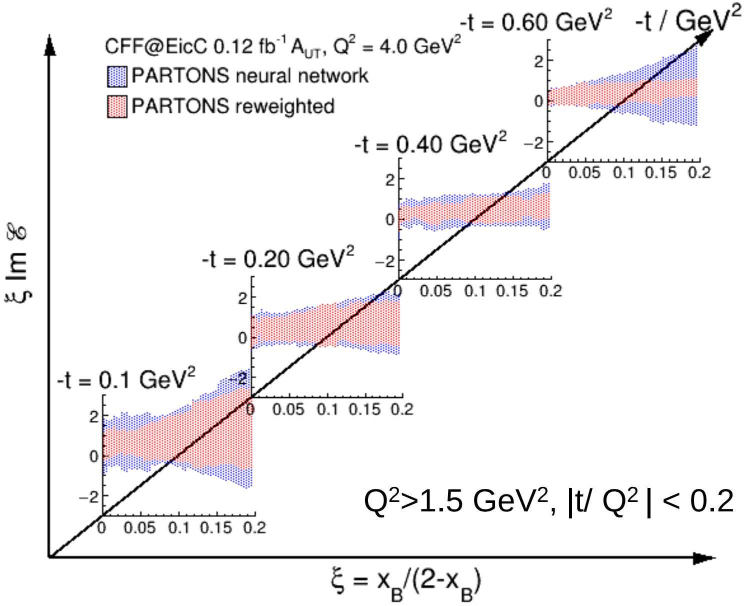
Lepton Beam Polarization	Nucleon Polarization: Un-Polarized (U)	Nucleon Polarization: Longitudinal Polarized (L)	Nucleon Polarization: Transversely Polarized (T)
U	Separates h.t. contributions to DVCS $\Re e\mathcal{T}^{DVCS}$	$\Delta\sigma_{UL} \sim \sin\phi$ $\mathrm{Im}\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+x_B/2\,\mathcal{E})+\ldots\}$ p $\Im m\tilde{\mathcal{H}}(x=\xi,\xi)$ n $\Im m\mathcal{H}(x=\xi,\xi)$	$\Delta\sigma_{UTy} \sim \cos\phi\, \sin(\phi_s-\phi)\{k[(2-x_B)F_1\mathcal{E} - 4(1-x_B)/(2-x_B)F_2\mathcal{H})]+\ldots\}$ p $\Im m\mathcal{E}(x=\xi,\xi)$ n $\Im m\mathcal{H}(x=\xi,\xi)$
L	$\Delta\sigma_{LU} \sim \sin\phi$ $\mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}}+kF_2\mathcal{E}+\ldots\}$ p $\Im m\mathcal{H}(x=\xi,\xi)$ n $\Im m\mathcal{E}(x=\xi,\xi)$	$\Delta\sigma_{LL} \sim (A+B\cos\phi)$ $\mathrm{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H}+x_B/2\,\mathcal{E}) - \xi(x_B/2\,F_1+kF_2)\tilde{\mathcal{E}}\}$ p $\Re e\tilde{\mathcal{H}}(x,\xi)$ n $\Re e\mathcal{H}(x,\xi)$	$\Delta\sigma_{LTx} \sim (A+B\cos\phi)$ $\mathrm{Re}\{k(F_2\mathcal{H} + F_1\mathcal{E})\}$ p $\Re e\mathcal{E}(x,\xi)$ n $\Re e\mathcal{H}(x,\xi)$

Exclusive Process

- 3D structure of nucleon (GPDs) @ EicC
- Accessing Compton Form Factors: An (Unbiased) Impact study on Im$\mathcal{E}$

see Xu Cao, Jinlong Zhang, arXiv:2301.06940, EPJC





- reweighting the replicas from PARTONS by $\sin(\phi-\phi_s)\cos(\phi)$ module of A_{UT}

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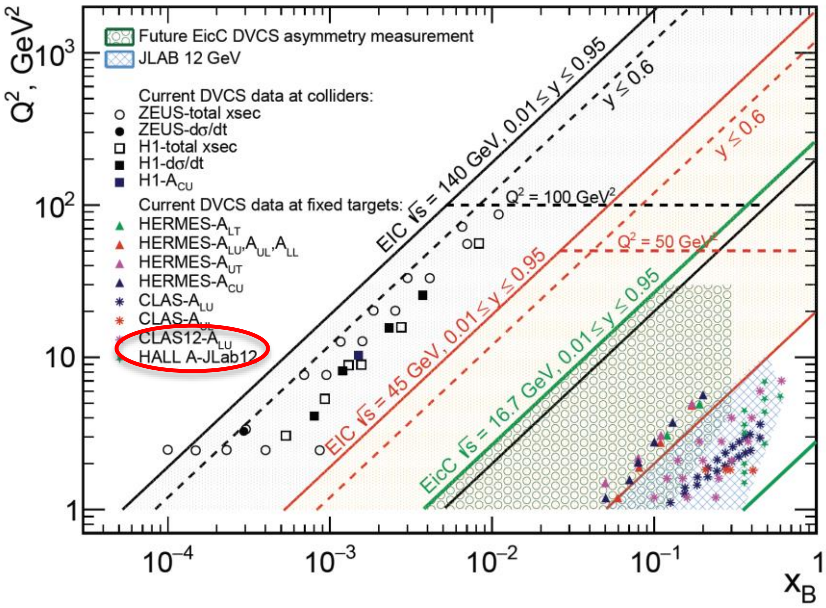
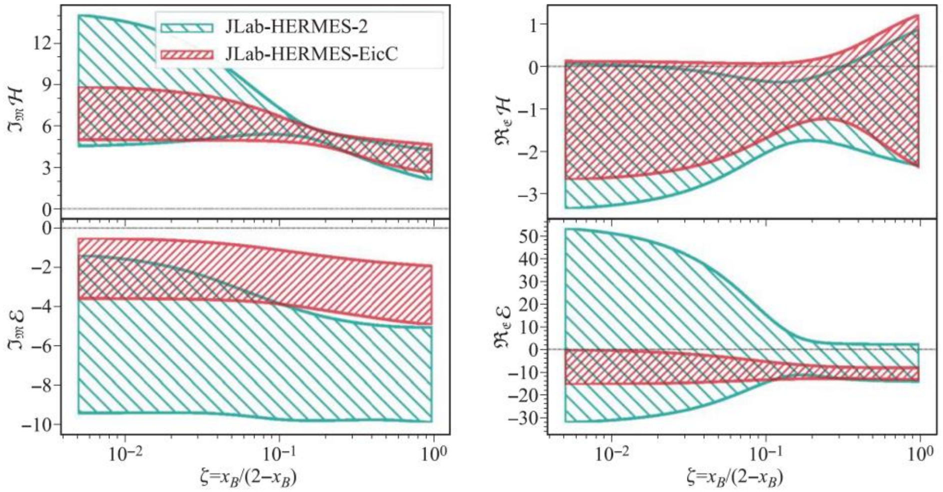


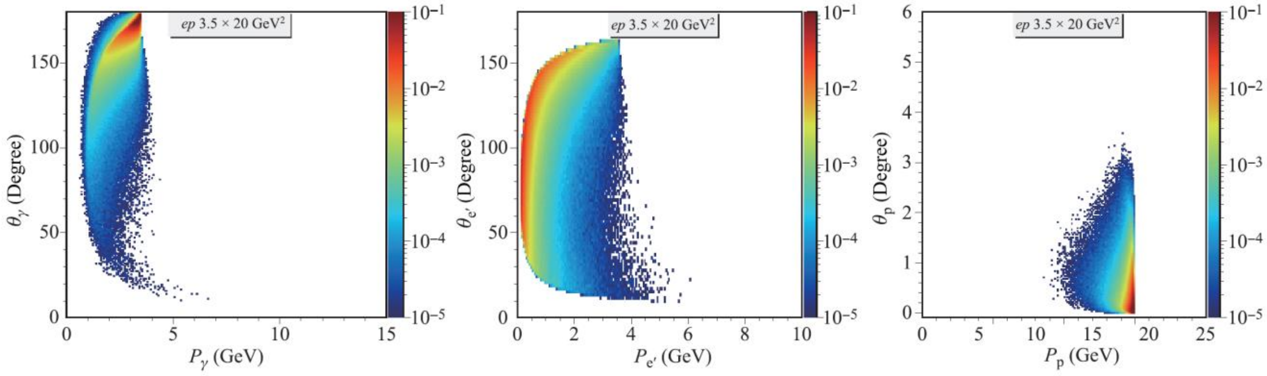


- re-trained within Gepard by $\sin(\phi-\phi_s)\cos(\phi)$ module of A_{UT}

Exclusive Process

- 3D structure of nucleon (GPDs) @ EicC
- 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

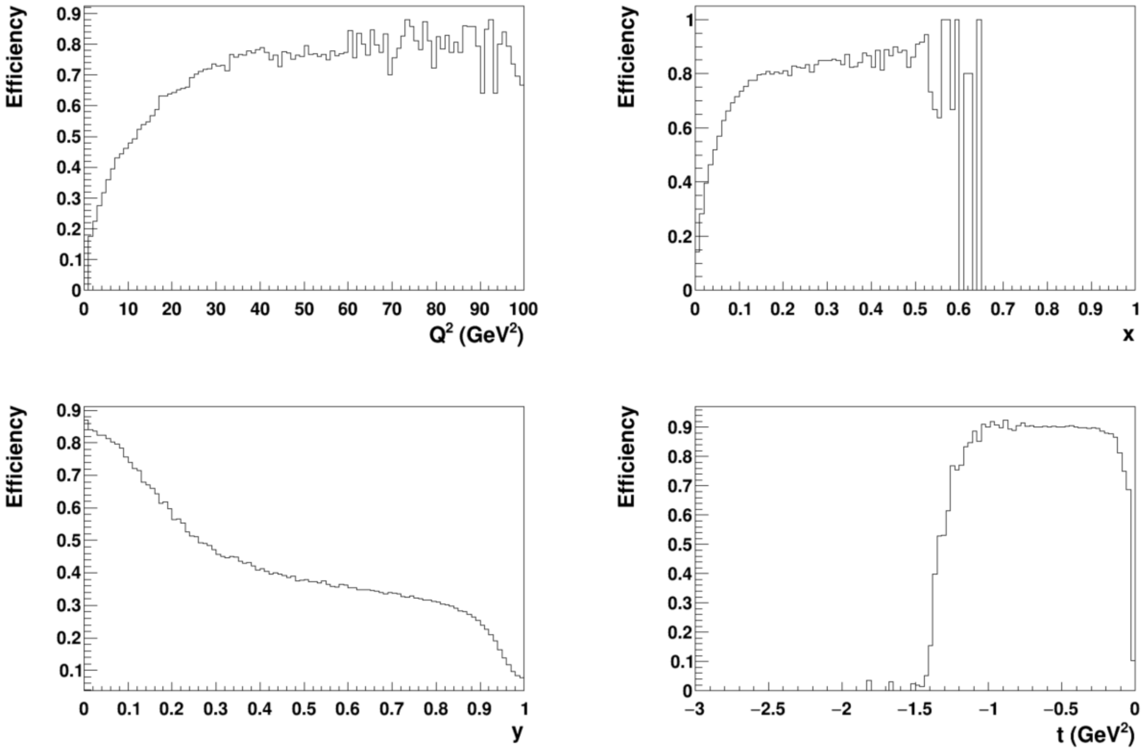


- >5mrad (previously 2mrad)

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

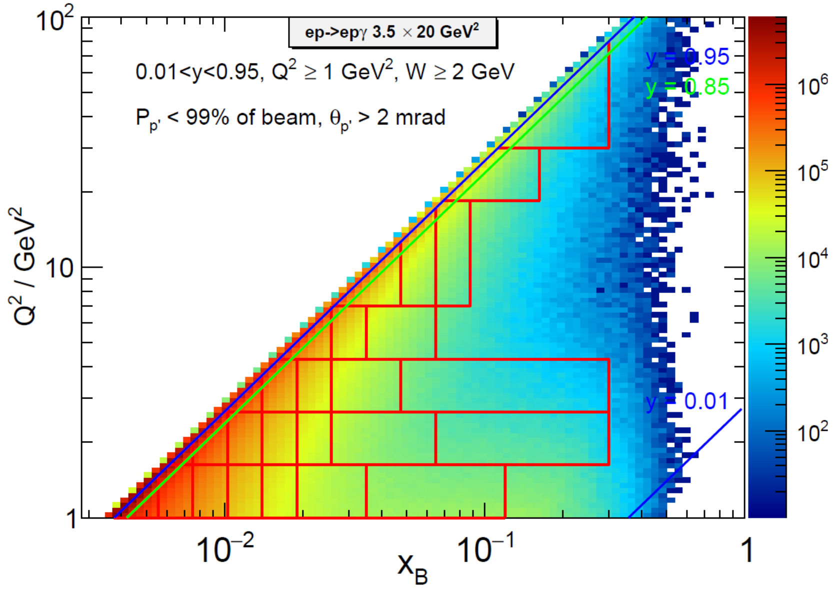
Exclusive Process

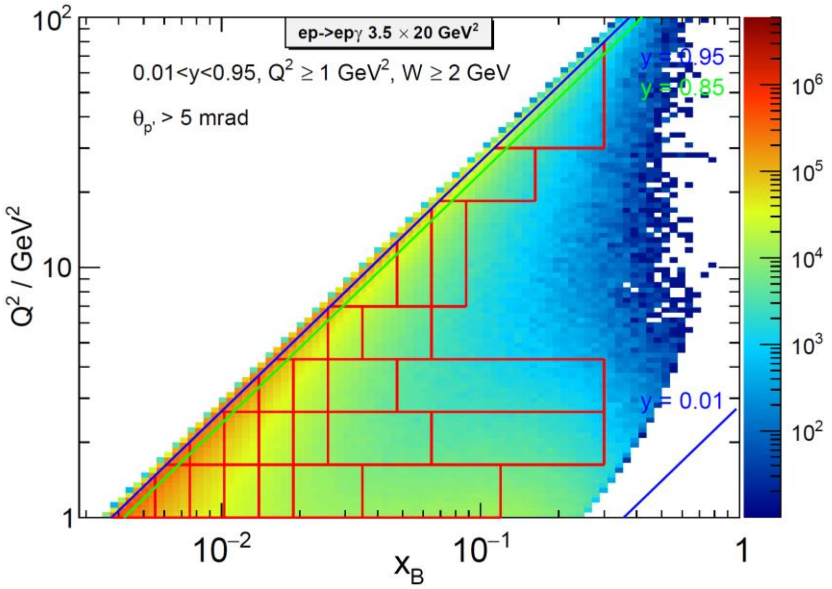
- **Detector efficiency**
- coutercy of detector group

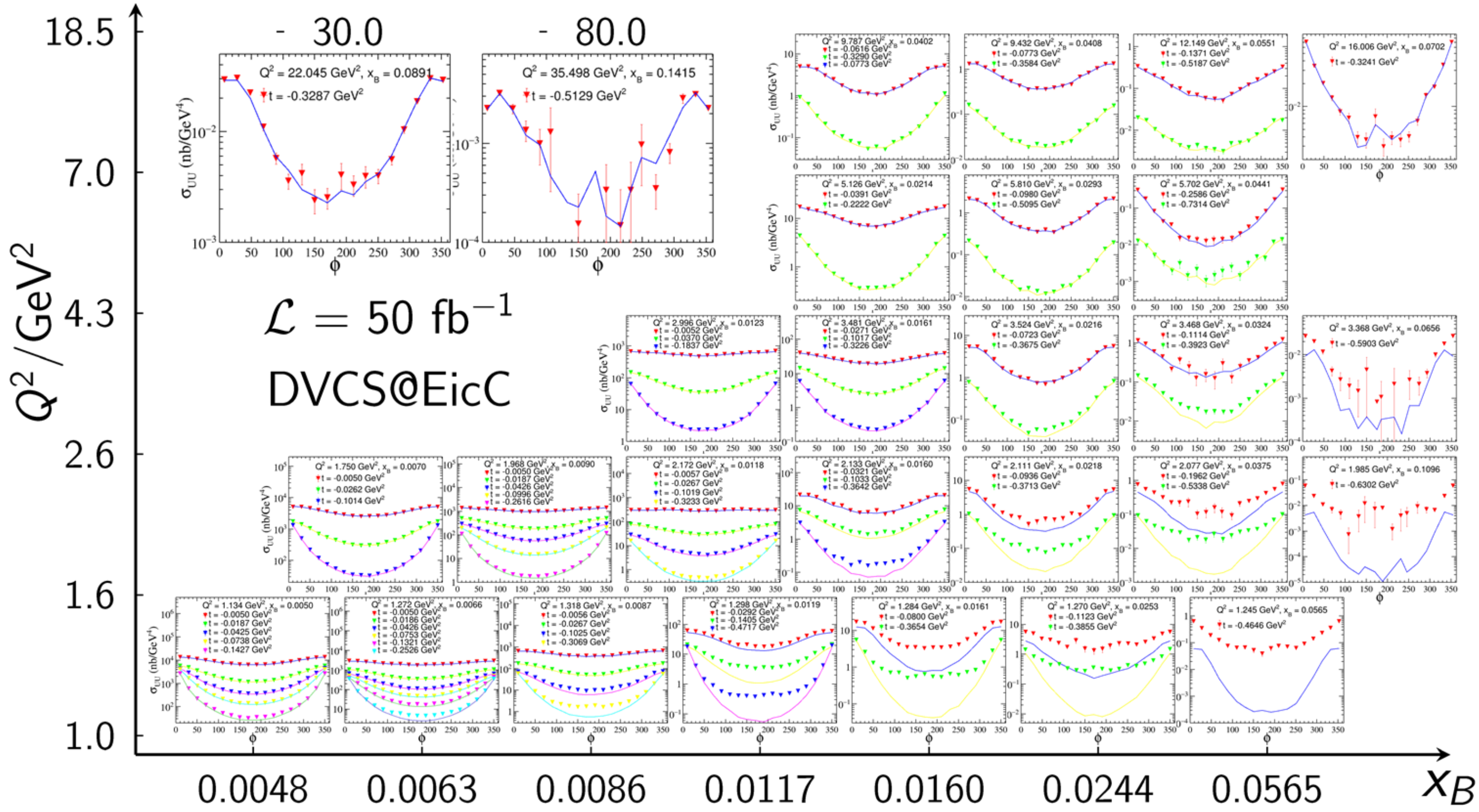


- **Detector efficiency**

- before — after



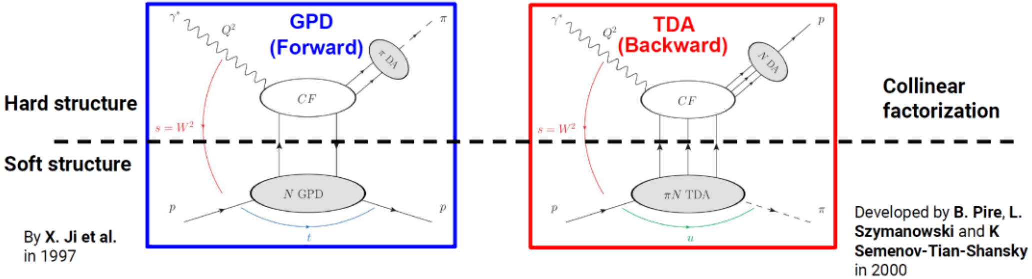


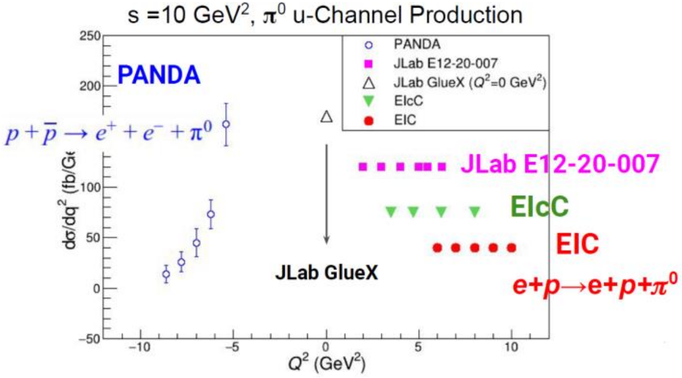


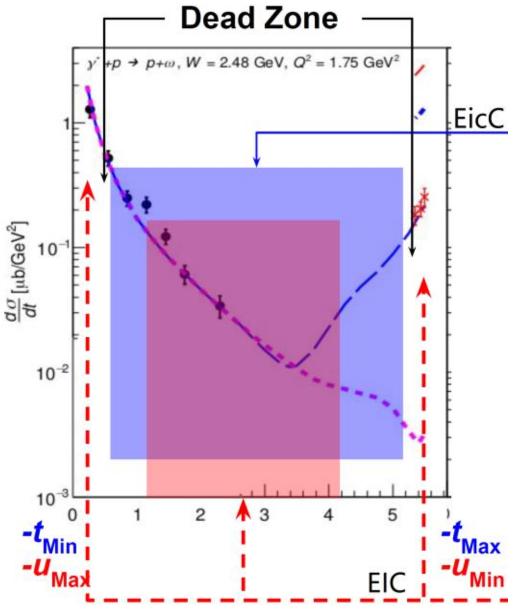
18.5
7.0
4.3
2.6
1.6
1.0
Q^2/GeV^2
- 30.0
- 80.0
$\mathcal{L} = 50\ fb^{-1}$
DVCS@EicC
0.0048
0.0063
0.0086
0.0117
0.0160
0.0244
0.0565
x_B

Exclusive Process

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



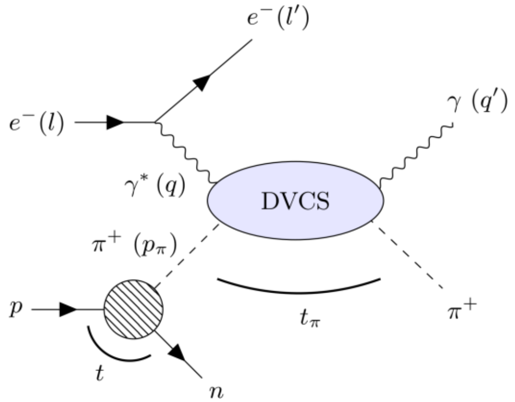


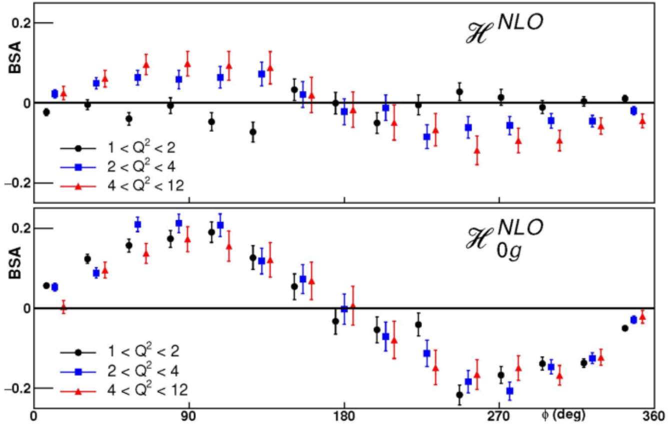


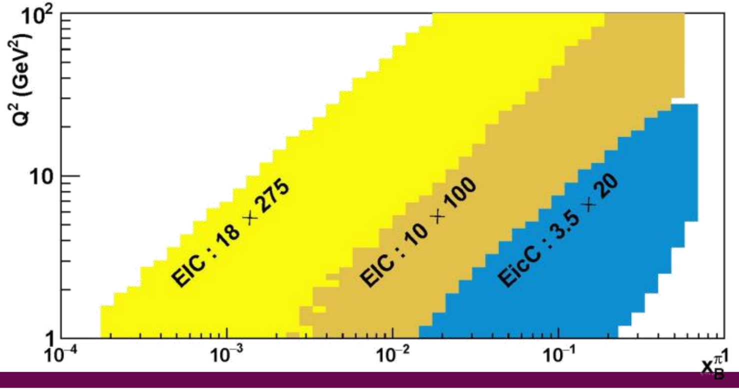
Lumi. is OK, but
15 (VS. 4.5)mRad acceptance for 2γ from π^0
other mesons: reduce the dead zone near the beamline

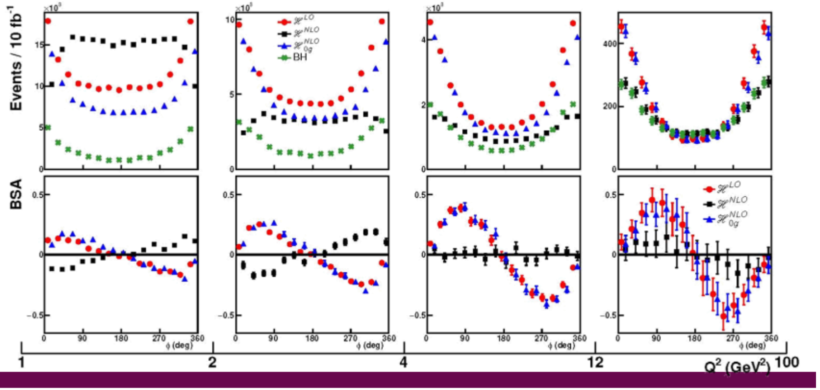
Exclusive Process

- 3D structure of pion (GPDs)
- π^+-DVCS through Sullivan process (2110.09462)



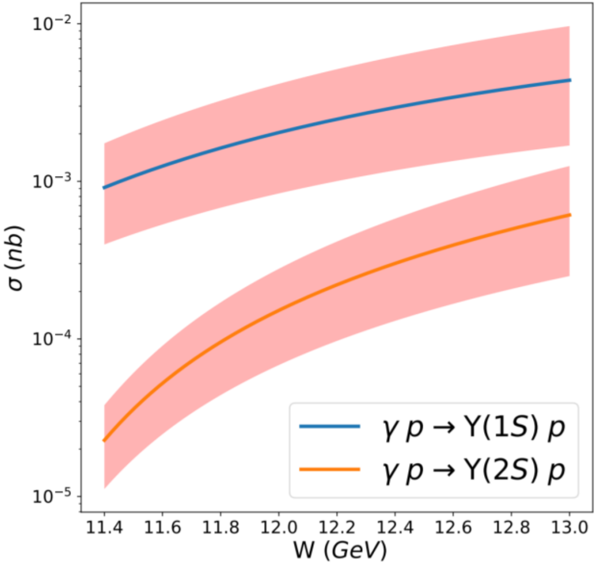


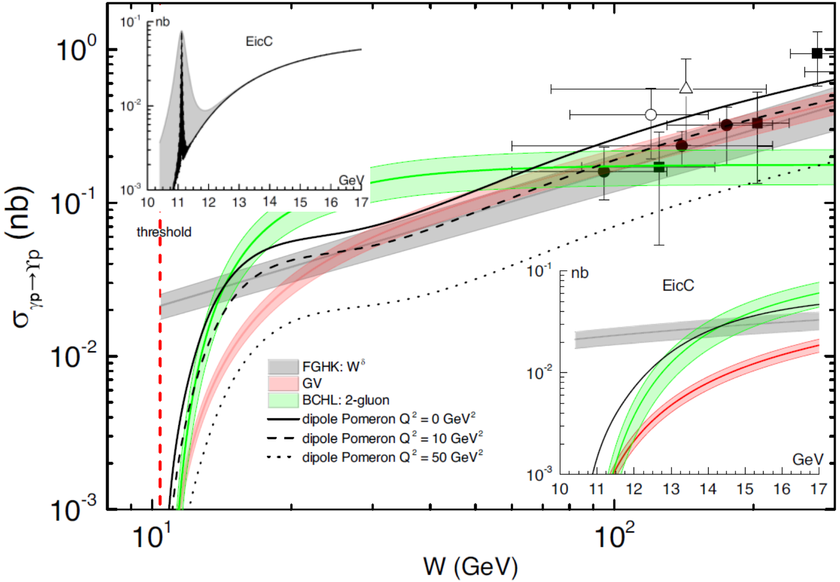




Exclusive Process

- **3D structure of nucleon (gravitation form factors & internal excitation)**
- Require heavy flavor reconstruction: detect Positron & Electron from heavy quarkonium decay; approaching near-threshold: slow Upsilon need more luminosity.





P. Sun, X-B Tong, F. Yuan, 2111.07034, 2103.12047;
see also 2101.02395, 1808.02163

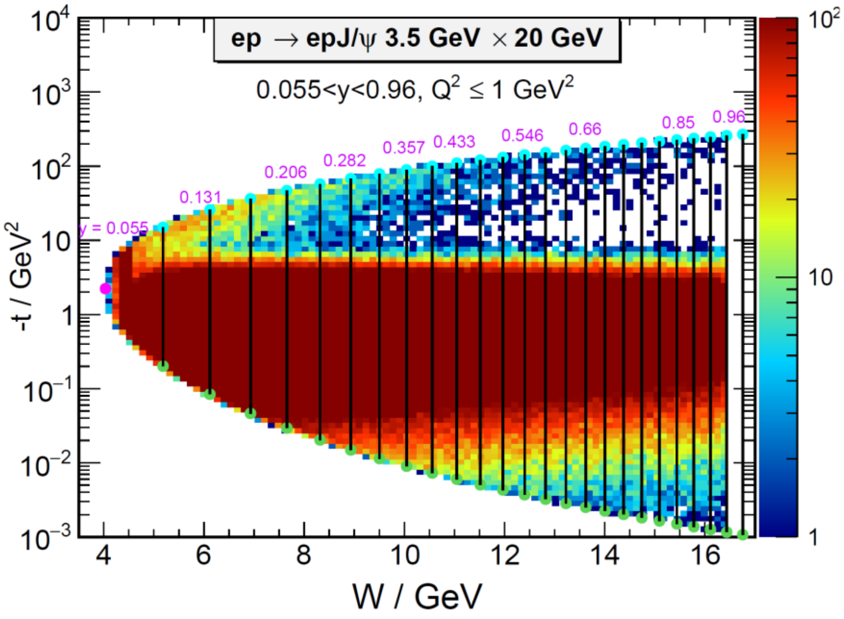
PhysRevD.101.074010
Front. Phys. 18(4), 44600 (2023)

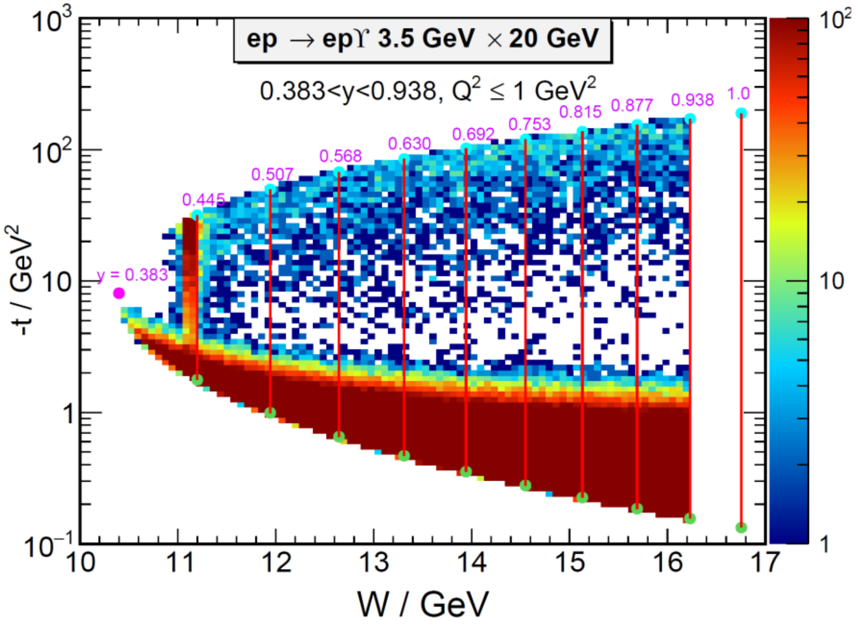
- Theorists usually ask for very low W or large-|*t*| or high-Q^2

Exclusive Process

- **From 1D to 3D structure of proton & atom:** GPD, TMD, TDA

- **From light quarks to charm and up to bottom:**
- **Photo- and electro-production of narrow exotic states**
- Generated by lAger and eSTARlight



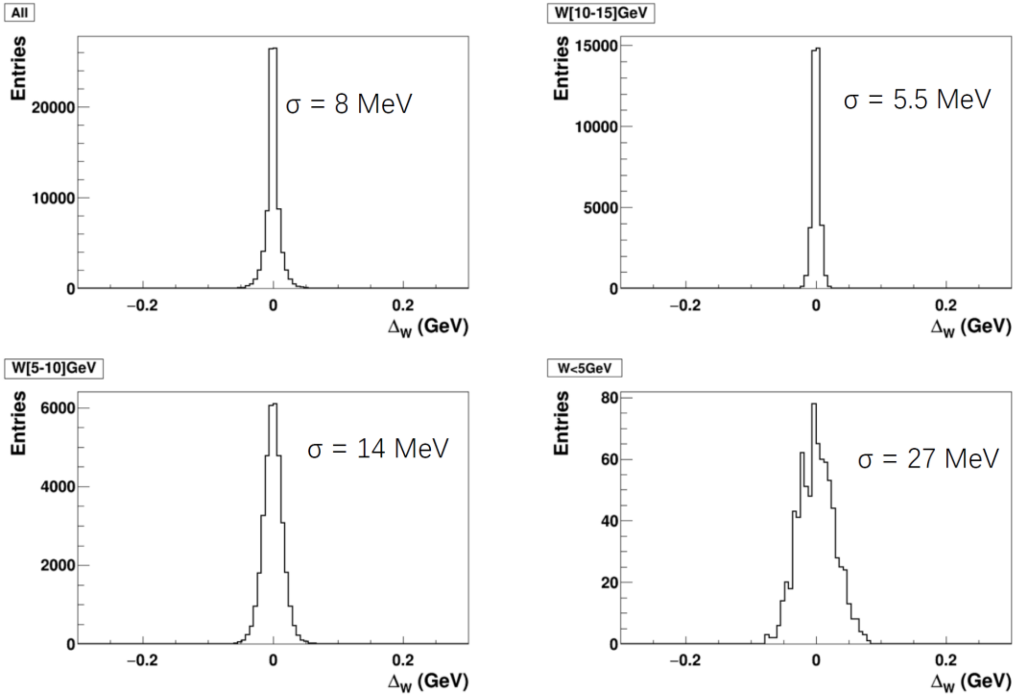


Exclusive Process

- **From light quarks to charm and up to bottom:**
- **Photo- and electro-production of narrow exotic states**
- Resolution generated by detector group

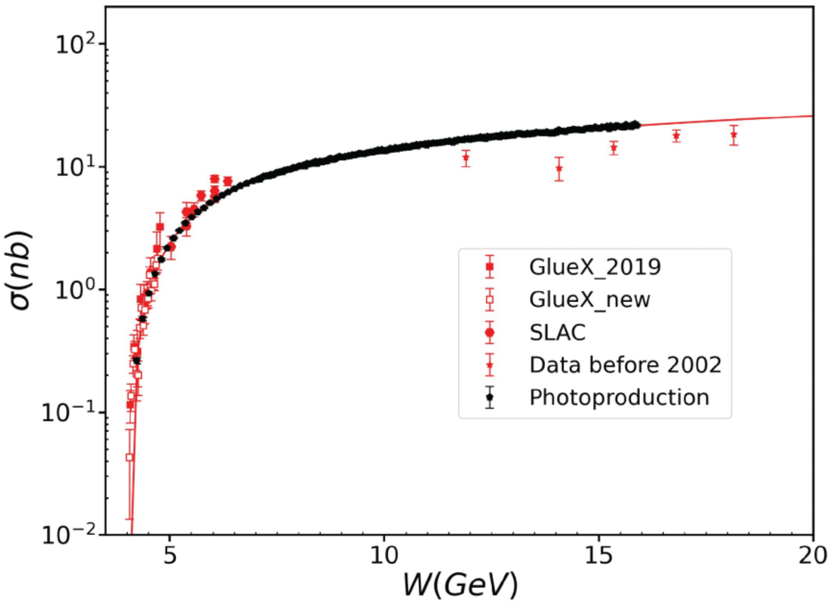
Mom. Res. = 0.1%

Recoil of scattered electron

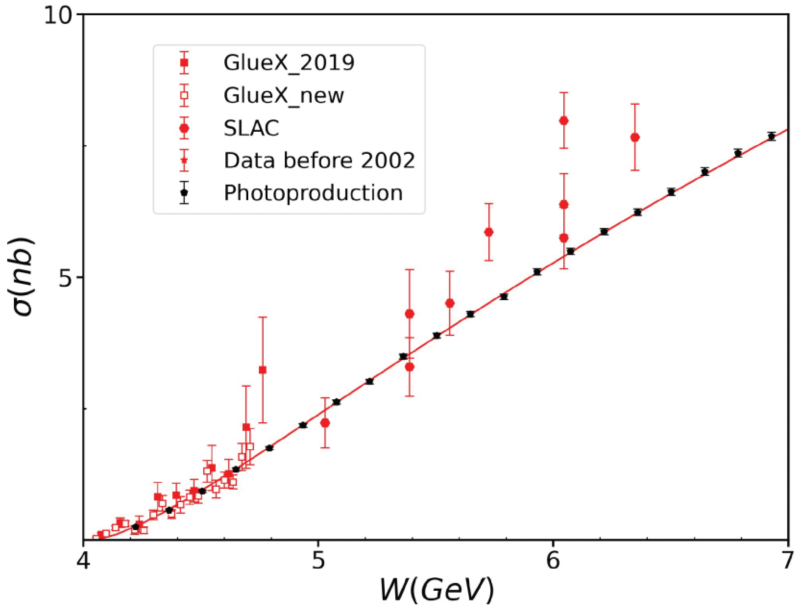


Exclusive Process

- **From light quarks to charm and up to bottom:**
- **Photo- and electro-production of narrow exotic states**
- Preminінary pseudo-data

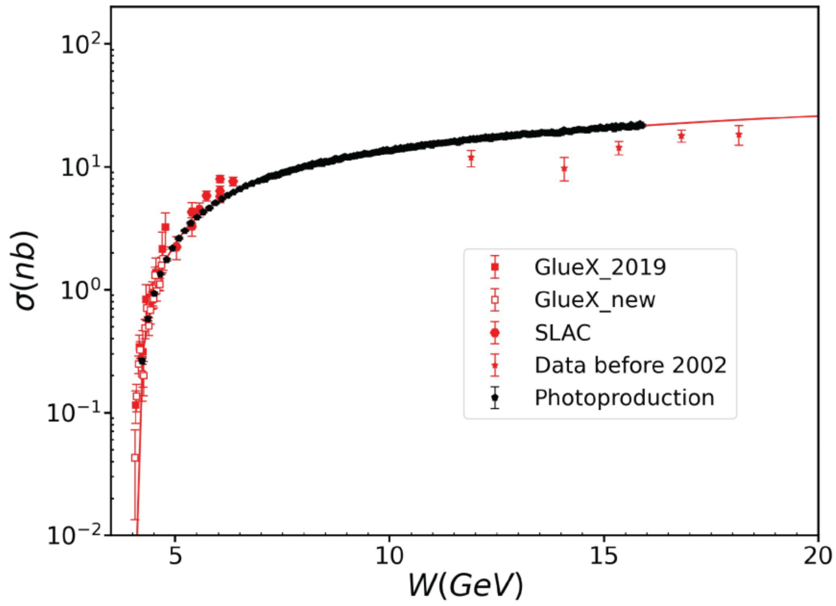


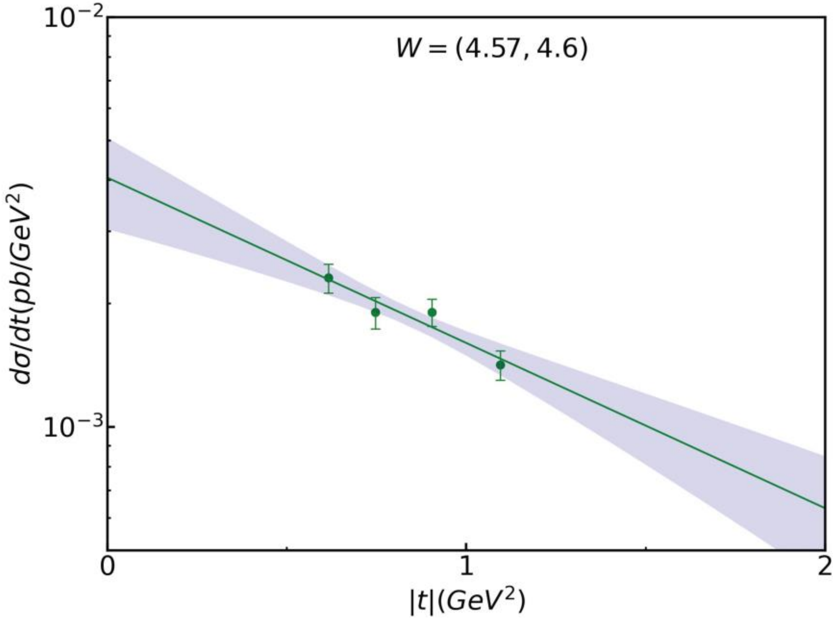
Rescaled to recent Jlab data



Exclusive Process

- **From light quarks to charm and up to bottom:**
- **Photo- and electro-production of narrow exotic states**
- Preminінary pseudo-data





Rescaled to recent Jlab data

Summary

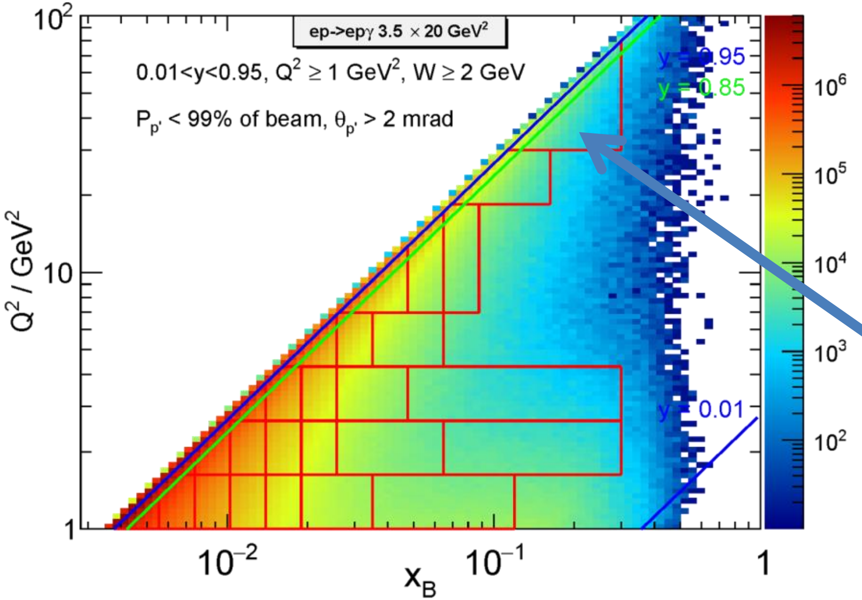
- Fruitful inclusive & exclusive measurements are expected at the EicC. Selected topics are present:
- TMD
- GPD & TDA
- Heavy flavor

- **A lot of efforts from detector group**
- Coverage, reconstruction efficiency and resolution of detector

Not cover here:
- DVMP
- TCS, DDVCS
- Light nuclei: medium effect

Special Thanks to PARTONS, Gepard ......

Projection Bins of DVCS@EicC



- $1.0 < Q^2 < 30.0$ GeV²
- |t|>0.01, Δt>0.02 GeV²

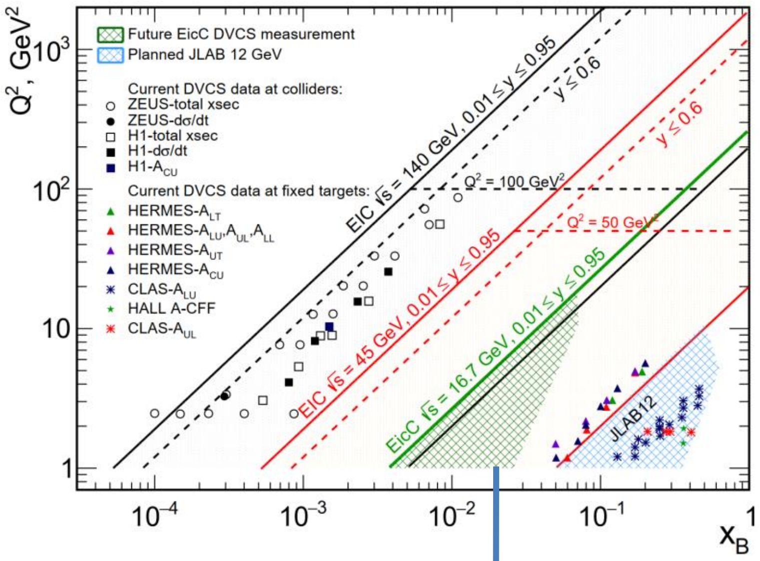
VS. |t|>0.03, Δt>0.03@US-EIC

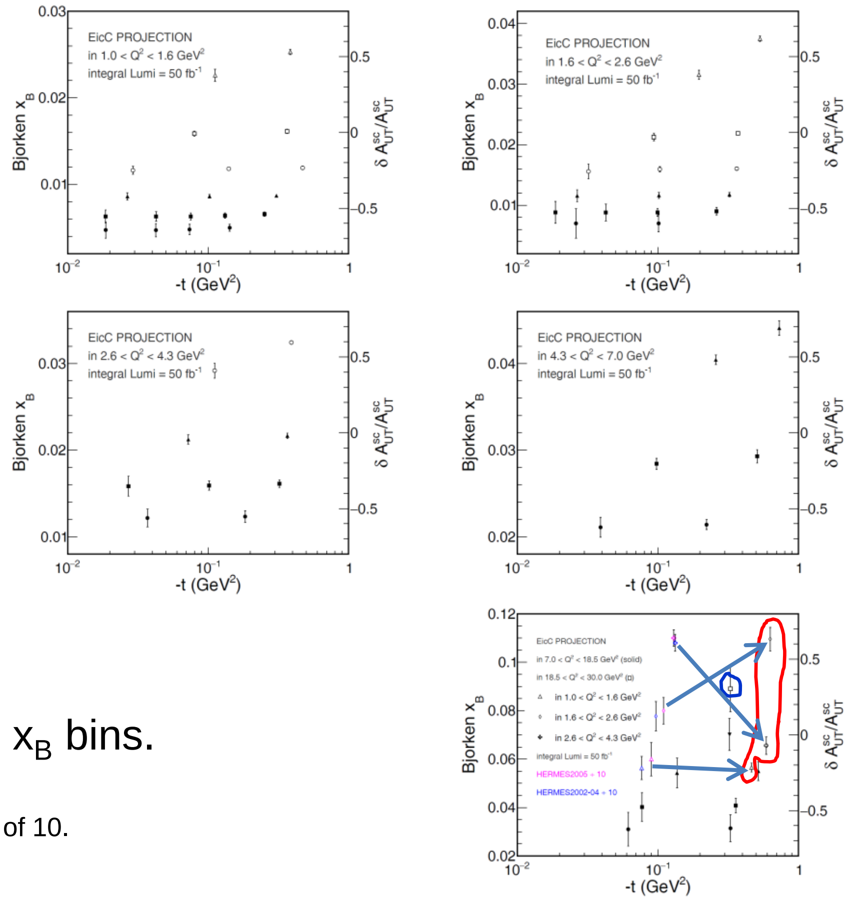
- Tips: Coverage extension to $30.0 < Q^2 < 80.0$ GeV²

several bins with relative big errors

- Magnitude of asymmetry is tiny with |t|<0.01, so the relative errors are usually above 50% there
- A big challenge for the detector design for |t|~0.002 & Δt~0.002: detector simulation?
- Also true for TCS and DVMP

Projection Bins of DVCS@EicC





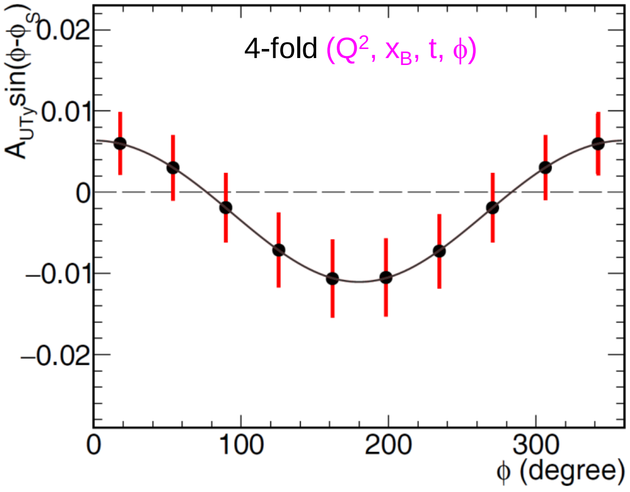
- A_{UT} with -t in all 1.0 < Q^2 < 30.0 GeV^2 and x_B bins.
- HERMES data with the relative statistical errors divided by a factor of 10.

Deeply Virtual Compton Scattering (DVCS)

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

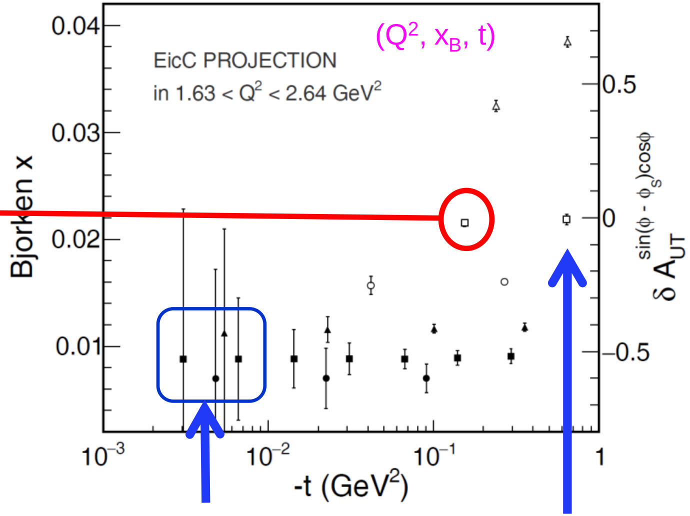
- 1. Only several projection points with |t|<0.01
- 2. Magnitude of asymmetry is tiny with |t|<0.01, so the relative errors are usually above 50% there
- 3. A big challenge for the detector design for |t|~0.002 & Δt~0.002: detector simulation?

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



10 ϕ bins each

absolute asymmetry: GK model for illustration only



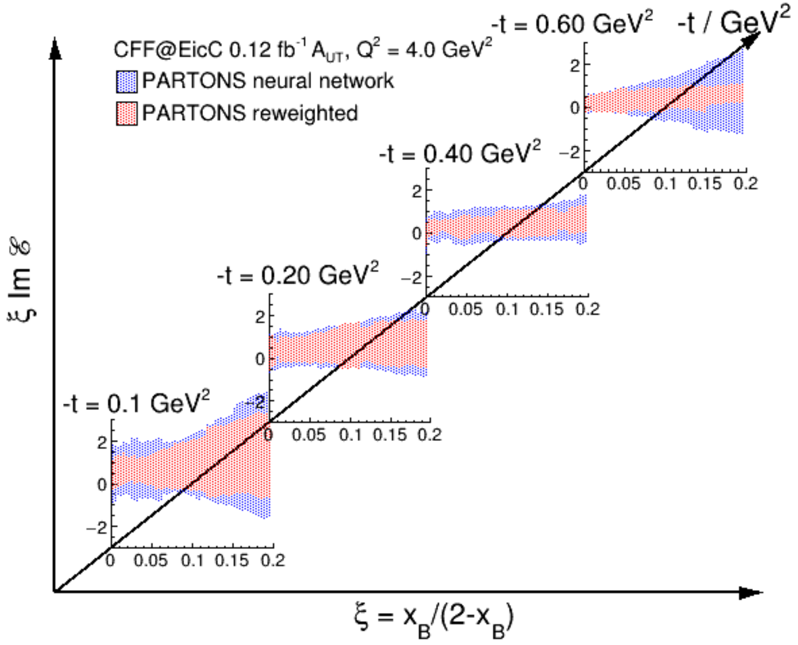
|t|<0.01 GeV^2 |t| ~ 1 GeV^2

Accessing CFF Im$\mathcal{E}$@EicC

H. Moutarde, P. Sznajder, J. Wagner, Eur. Phys. J. C (2019) 79:614

The CFF impact study of EicC with reweighting replicas under PARTONS neural network (NN)

Stastical uncertainties only – 7 hours running



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

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

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:

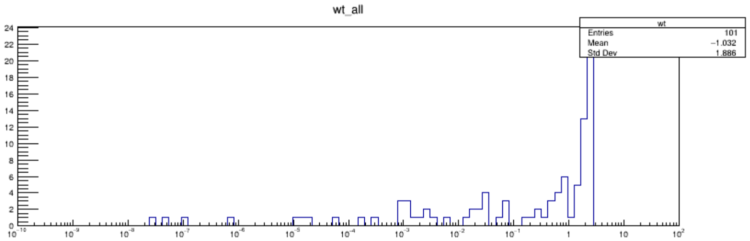
NNPDF: Nucl.Phys.B849:112,2011 (arxiv: 1012.0836)

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

(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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- 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)

Schematic Design of EicC

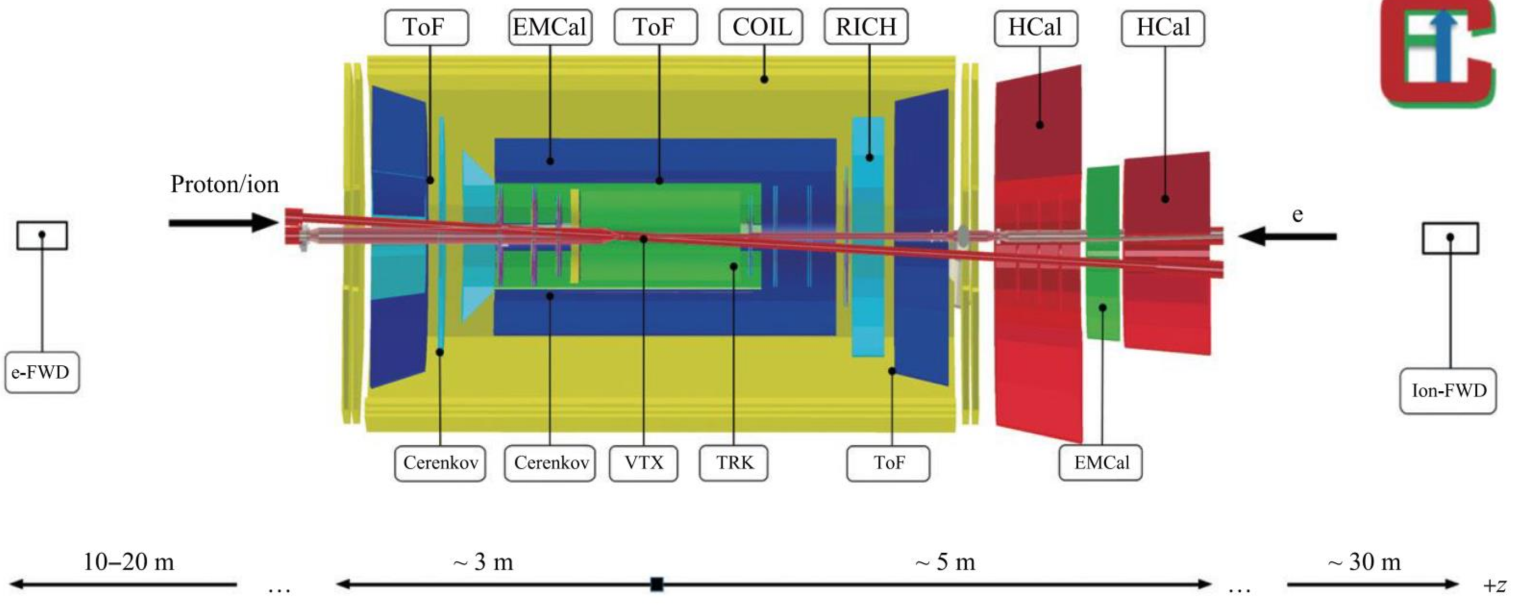
- **Energy:**

  electron + proton: 3.5 GeV × 20 GeV

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

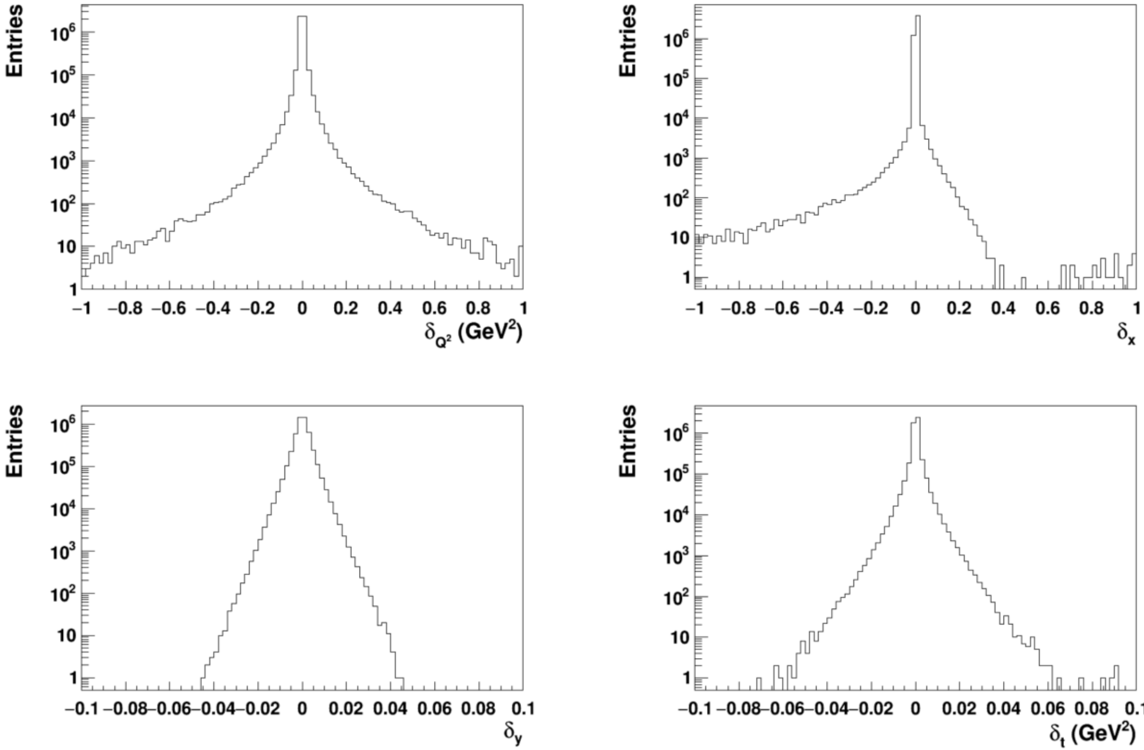
Front.Phys.(Beijing)16(2021)64701

- **arXiv:2102.09222**



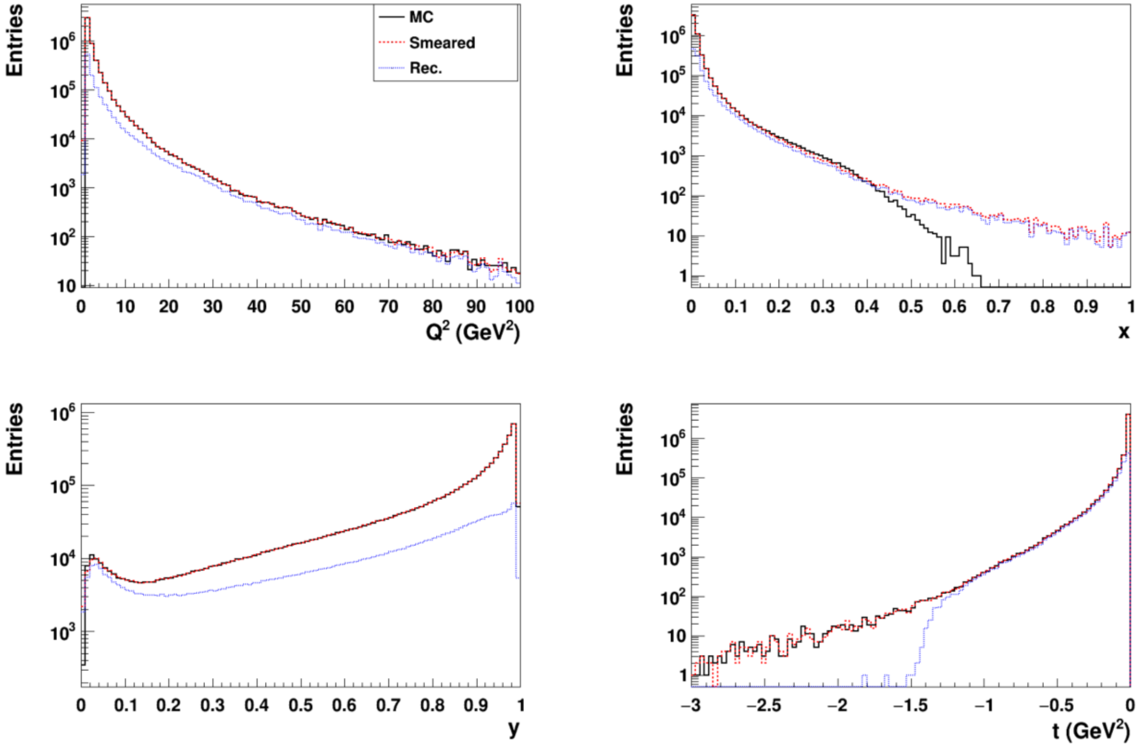
Exclusive Process

- **Detector resolution**
- coutercy of detector group



Exclusive Process

- **Detector efficiency**
- coutercy of detector group



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< η <3; recoiled proton: 1.5 < η < 4; π^0 : 0 < η < 3.69;
- Note: η = 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