GPD studies on EicC

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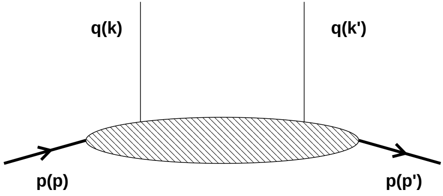
Overview

1. Generalized parton distributions
2. Electron-ion collider in China (EicC)
3. Simulation of DVCS on EicC
4. Simulation of DVMP on EicC
   - Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)
   - Simulation of DVMP: $ep \to en\pi^+$ (preliminary)
5. Summary and outlook

Generalized parton distributions

GPDs are the Lorentz covariant off-forward nonlocal matrix elements of the quark correlator in hadrons, which appear in many kinds of hard exclusive processes. [A. Radyushkin, Phys. Lett. B (1996); X. Ji, Phys. Rev. Lett. (1997)]

$$\frac{1}{2}\int \frac{e^{ixP^+z^-}}{2\pi} \left\langle P+\frac{\Delta}{2} \left| \bar{\psi}^q(-\frac{z}{2})\gamma^+\psi^q(\frac{z}{2}) \right| P-\frac{\Delta}{2} \right\rangle \Big|_{z^+=0, z_\perp=0}$$
$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{N}\gamma^+ N + E^q(x,\xi,t)\bar{N}\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}N \right]$$



$$P = \frac{p+p'}{2}$$

$$\Delta = p' - p$$

$$x = \frac{(k+k')n}{2Pn}$$

$$\xi = -\frac{\Delta n}{2Pn}$$

$$t = \Delta^2$$

Generalized parton distributions

Including chiral-odd GPDs, there are eight types of GPDs to describe the nucleon structure, which is illustrated in the table below. GPDs depend on three variables (x, ξ, and t), and they can be reduced to PDFs at the forward limit ($t = 0$).

$$H^q(x,0,0) = q(x);\ \tilde{H}^q(x,0,0) = \Delta q(x);\ H^q_T(x,0,0) = h^q_{1T}(x)$$

And there are model independent sum rules which relate GPDs to elastic form factors.

		Quark polarization		
		U	L	T
Nucleon polarization	U	H		$\bar{E}_T$
	L		$\tilde{H}$	
	T	E		H_T, $\tilde{H}_T$

$$\int_{-1}^{1} H^q(x,\xi,t)dx = F^q_1(t)$$

$$\int_{-1}^{1} E^q(x,\xi,t)dx = F^q_2(t)$$

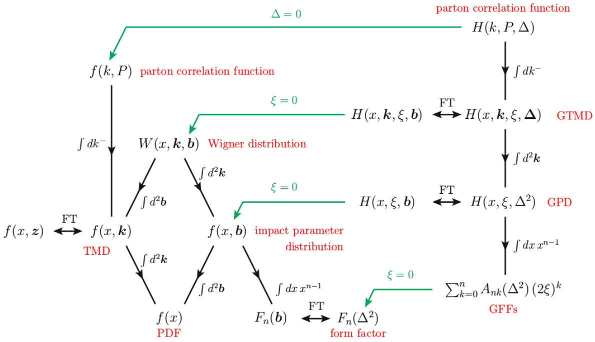
$$\int_{-1}^{1} \tilde{H}^q(x,\xi,t)dx = g^q_A(t)$$

$$\int_{-1}^{1} \tilde{E}^q(x,\xi,t)dx = h^q_A(t)$$

Generalized parton distributions

The figure shows the relations between GPD and GTMD, GPD and impact parameter distribution, GPD and gravitational form factors. The impact parameter distribution is just the Fourier transform of GPD H.

$$q(x, \vec{b}, Q^2) = \frac{1}{4\pi} \int_0^\infty d|t| J_0(\vec{b}\sqrt{|t|}) H(x, 0, t, Q^2)$$



[The left figure is from Markus Diehl, EPJA (2016).]

Extraction of GPD is actually measuring the tranverse spatial distribution of quarks. This is the 2D coordinate + 1D momentum imaging of partons inside hadrons.

Generalized parton distributions

Measuring GPDs is one way to access the gravitational form factors of nucleon. Therefore GPDs can give very usefull information of the nucleon, such as the nucleon spin and the mechanic pressure inside nucleon.

$$\int xH^q(x,\xi,t)dx = A^q(t) + \xi^2 C^q(t); \int xE^q(x,\xi,t)dx = B^q(t) - \xi^2 C^q(t)$$

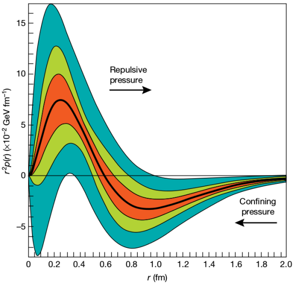
Ji's spin sum rule [X. Ji, PRL (1997)]:

$$\int x[H^q(x,\xi,0) + E^q(x,\xi,0)]dx$$

$$= A^q(0) + B^q(0) = 2J^q,$$

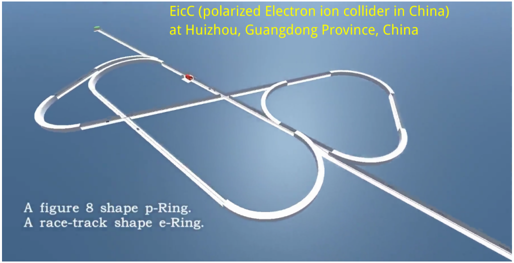
$$J^q + J^g = \frac{1}{2}$$

[The figure is from V. D. Burkert, L. Elouadrhiri, F. X. Girod, Nature (2018)]



Electron-ion collider in China (EicC)

The GPD framework is so beautiful! But how to probe them?

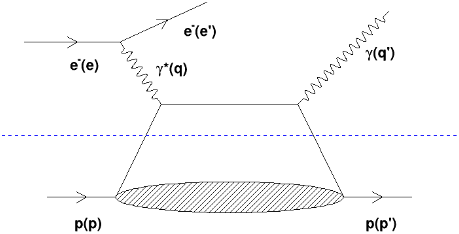


EicC opportunity:
3.5 GeV polarized electron * 20 GeV polarized proton,
Lumi.= 2-5$\times 10^{33}$cm^{-2}s^{-1}

- The recoil nucleon and the scattered electron go opposite directions
- The almost 4π acceptance is great for the exclusive measurement
- The high luminosity is quite important for the events of low cross-sections

Simulation of DVCS on EicC

DVCS is the simpliest and a very clean way to access GPDs. 1) There is no uncertainty of meson wave function; 2) Hard scale is guaranteed by the Q^2; 3) It is sensitive to both quark GPD and gluon GPD (using evolution).



$$Q^2 = -q^2, x_B = Q^2/(2pq),$$

$$t = (p - p')^2,$$

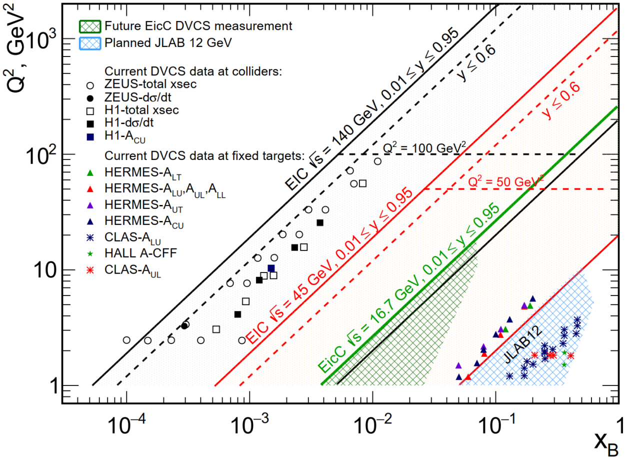
$$\xi = \frac{x_B(1 + t/2/Q^2)}{2 - x_B + x_B t/Q^2}$$

The measurement of GPD E would help us in understanding the orbital angular momentum of the quarks. In experiment, we can constrain the GPD E with the aysmmetry (A_{UT}) measurement of DVCS+BH process.

$$A_{UT} \propto \sqrt{\frac{-t}{4M^2}}[F_2(t)H(\xi,\xi,t) - F_1(t)E(\xi,\xi,t) + smaller\ quantities]$$

Pauli form factor F_2 is relatively small compared to Dirac form factor F_1.

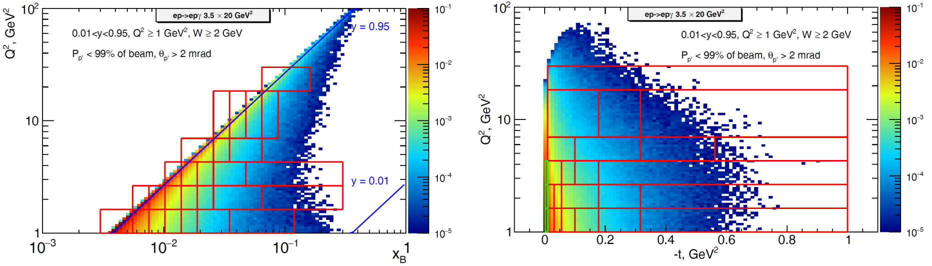
Simulation of DVCS on EicC



The plot shows the kinematic coverage of DVCS measurement on US-EIC and that on EicC. EicC would be a perfect machine to coverage the sea quark domain.

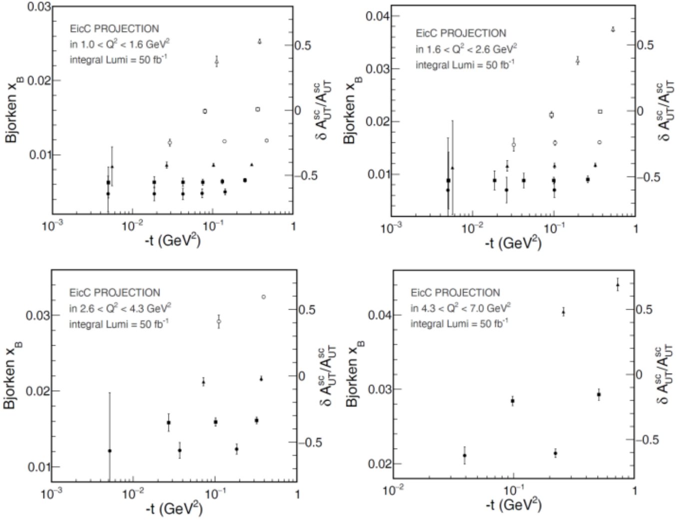
Simulation of DVCS on EicC

The invariant kinematical variable distribution of DVCS+BH on EicC. The binning strategy is shown in the figures below.



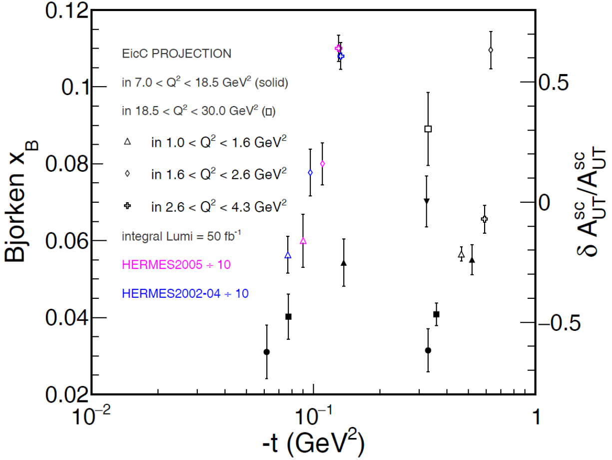
Simulation of DVCS on EicC

The projection of relative statistic uncertainties at different bins on EicC, with the integrated luminosity $= 50\ \mathrm{fb}^{-1}$.



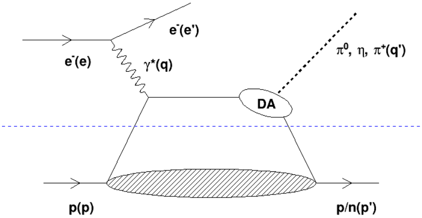
Simulation of DVCS on EicC

The projection of relative statistic uncertainties at different bins of high Q^2 on EicC, with the integrated luminosity $= 50\ \text{fb}^{-1}$. HERMES data are shown with the relative statistical errors divided by a factor of 10.



Simulation of DVMP on EicC

Similar to DVCS process, hard exclusive meson production (DVMP, deeply virtual meson production) is sensitive to GPDs of partons as well. DVMP can be used to check GPD university, and it is also important for the flavor-separation.



$$Q^2 = -q^2, x_B = Q^2/(2pq),$$

$$t = (p - p')^2$$

$$\xi = \frac{x_B}{2 - x_B}\left(1 + \frac{m_\pi^2}{Q^2}\right)$$

Simulation of DVMP on EicC

In the scaling region (high Q^2), pseudoscalar meson DVMP is sensitive to the polarized GPDs ($\tilde{H}, \tilde{E}$), vector meson DVMP is sensitive to the unpolarized GPDs (H, E), and heavy vector meson DVMP is sensitive to the gluon GPD. [Xiangdong Ji, J. Phys. G 1998; Vanderhaeghen, Guichon, Guidal, Phys. Rev. D 1999; Goeke, Polyakov, Vanderhaeghen, Prog. Part. Nucl. Phys. 2001; Belitsky, Radyushkin, Phys. Rep. 2005]

$$\tilde{H}_{\pi^0} \sim e^u \tilde{H}^u - e^d \tilde{H}^d$$

$$\tilde{H}_{\pi^+} \sim \tilde{H}^u - \tilde{H}^d$$

$$\tilde{H}_{\eta} \sim e^u \tilde{H}^u + e^d \tilde{H}^d - 2e^s \tilde{H}^s$$

$$H_{\rho_L^0} \sim e^u H^u - e^d H^d$$

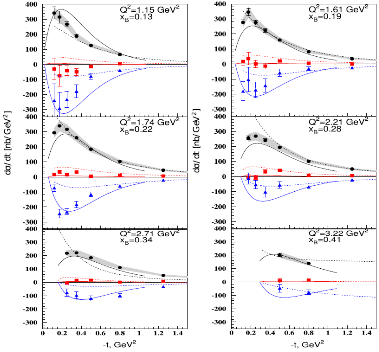
$$H_{\rho^+} \sim H^u - H^d$$

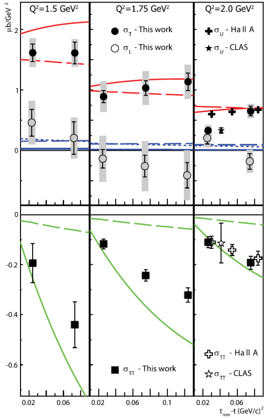
$$H_{\omega_L} \sim e^u H^u + e^d H^d$$

Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

Things become much complicated with nowadays experimental observation and theoretical development. The transversity GPDs is dominated for the pseudoscalar meson production in JLab kinematical region. (Transversity GPDs is actually the chiral-odd GPDs in which the quark helicity flipped.)

$\sigma_U > |\sigma_{TT}| > |\sigma_{LT}|$, and $\sigma_T > \sigma_L$ [CLAS, PRL 2012; JLab HallA, PRL, 2016]





Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

With the assumption that the handbag framework still works, the chiral-odd GPDs of the nucleon are coupled to a twist-3 distribution amplitude of the pion. There are four chiral-odd GPDs: H_T, E_T, $\tilde{H}_T$, and $\tilde{E}_T$ ($\bar{E}_T = 2\tilde{H}_T + E_T$). The chiral-odd GPDs are parameterized using either the double distribution representation or the reggeized diquark model (a connection between the chiral-even and chiral-odd reduced helicity amplitudes). [Ahmad, Goldstein, Liuti, PRD 2009; Goloskokov, Kroll, EPJC 2010; Goloskokov, Kroll, EPJA 2011; Goldstein, Hernandez, Liuti, PRD 2015]

- without pion-pole, it is convenient to extract the transversity GPDs, which is least known.
- the extraction of the tranversity GPDs may constrain the tensor charge and transverse anomalous moment.
  $\int_0^1 H_T^q(X,0,0)dX = \delta^q, \int_0^1 \bar{E}_T^q(X,0,0)dX = \kappa_T^q$
- π^0-DVMP is the background of the DVCS channel if one decay photon of π^0 is not detected

Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

Some formulas,

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, s)\frac{1}{2\pi}\left[\sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}cos(\phi_\pi)\sigma_{LT} + \epsilon cos(2\phi_\pi)\sigma_{TT}\right]$$

$$\sigma_T = \frac{4\pi\alpha_e}{2k(Q^2, x_B)}\frac{\mu_\pi^2}{Q^4}\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2\right]$$

$$\sigma_{TT} = \frac{4\pi\alpha_e}{2k(Q^2, x_B)}\frac{\mu_\pi^2}{Q^4}\frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2$$

$$t' = t - t_{\min}, \mu_\pi = m_\pi^2/(m_u + m_d)$$

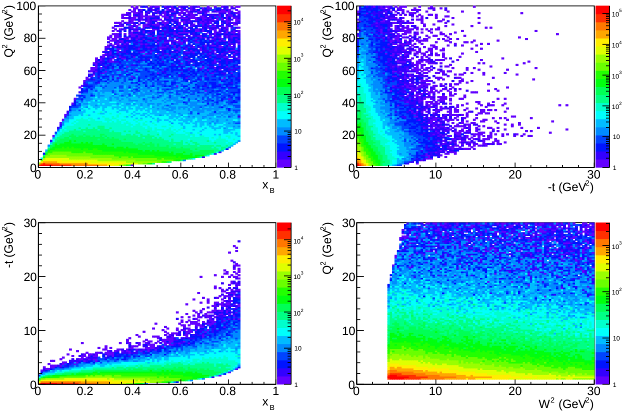
$$A_{LL} = \frac{\sigma^{+-} + \sigma^{-+} - \sigma^{++} - \sigma^{--}}{\sigma^{unpolarized}} = \frac{1}{P_e}\frac{1}{P_p}\frac{N^{+-} + N^{-+} - N^{++} - N^{--}}{N^{+-} + N^{-+} + N^{++} + N^{--}}$$

$$A_{LL}^{const}\sigma^{unpolarized} = \sqrt{1-\epsilon^2}\frac{4\pi\alpha}{\kappa}\frac{\mu_\pi^2}{Q^4}(1-\xi^2)|\langle H_T\rangle|^2$$

$\langle H_T\rangle$ and $\langle \bar{E}_T\rangle$ are the convolutions of the hard process with GPD H_T and $\bar{E}_T$ respectively.

Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

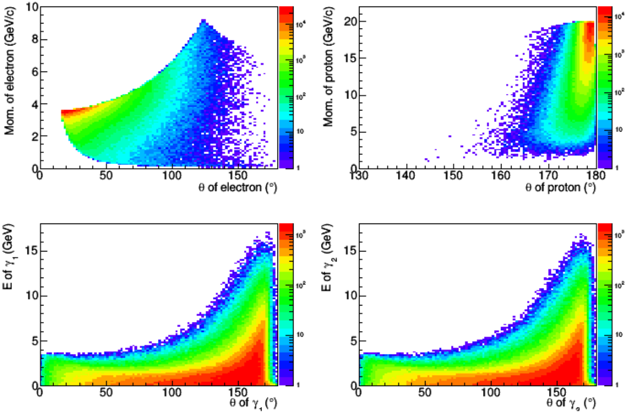
We have known that chiral-odd GPDs are important to the pion DVMP process. It's time to have more data to unveil chiral-odd GPDs.



The left graph shows the invariant kinematic coverage of EicC (smaller x_B and higher Q^2 compared to JLab experiments).

Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

The energy and θ angle distributions of the final particles.

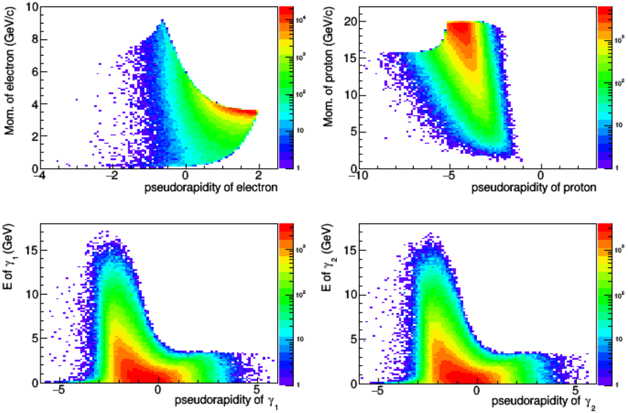


$x_B < 0.85$,
$1 < Q^2 < 100$ GeV^2,
$0.05 < |t| < 30$ GeV^2,
$W^2 > 4$ GeV^2

The electrons go forward. The γ's go backward. The protons go very backward.

Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

The energy and pseudorapidity distributions of the final particles.

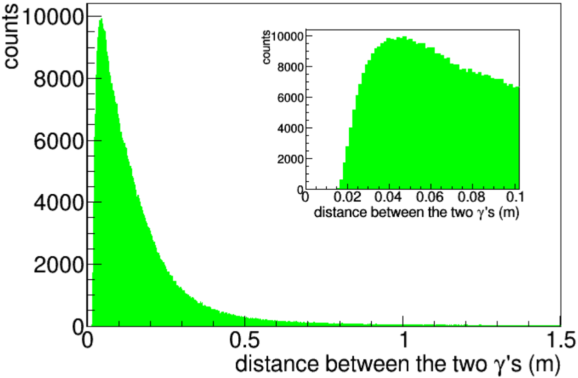


$x_B < 0.85$,
$1 < Q^2 < 100$ GeV^2,
$0.05 < |t| < 30$ GeV^2,
$W^2 > 4$ GeV^2

$|\eta|$ of electron is smaller than 2. $|\eta|$ of γ is smaller than 3. The proton has quite big pseudorapidity.

Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

The distance distribution between the two decay γ's, at one meter away from the interaction point. If we want 100% separation of photons, the spatial resolution should be better than 2 cm.



The Edep-averaged position resolution of the calorimeter is around 0.3 cm. Most of the photons go backward, and they are detected at longer distance ($\gg$ 1meter) from the vertex. So, the resolution of the calorimeter won't be an issue for backward photons.

Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

Let's look at the dynamic of π^0 production on EicC. Total cross-section from MC integral,

$$\sigma_{tot} = (Q^{2,high} - Q^{2,low})(x_B^{high} - x_B^{low})(t^{high} - t^{low})(\phi_\pi^{high} - \phi_\pi^{low})$$

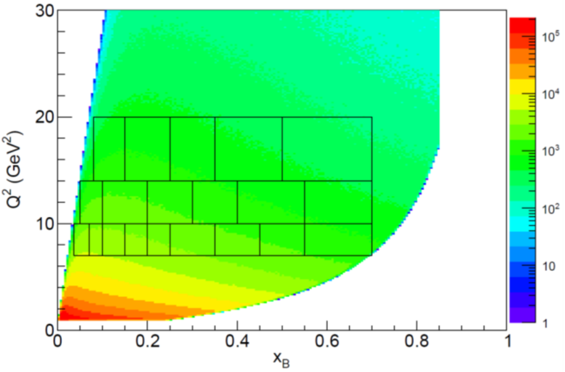
$$\times \frac{\sum_{i=1}^{N^{generated}} \frac{d_i^4\sigma}{dx_B dQ^2 dt d\phi_\pi}}{N^{generated}}$$

[if the sampling point outside of physical volume or mismatch the cuts $(W^2 > 4\ \text{GeV}^2,\ Q^2 > 1\ \text{GeV}^2)$, $\frac{d^4\sigma}{dx_B dQ^2 dt d\phi_\pi} = 0$]

Total cross-section = 1.689 nb.
Number of events = 1.689 nb $\times$ 50 fb^{-1} = 84.5 million.

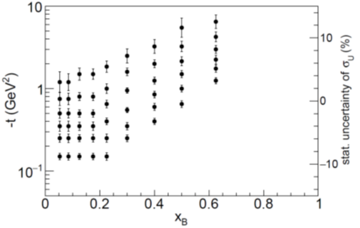
Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

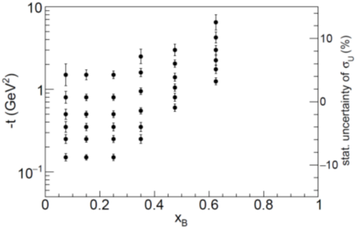
The x_B-Q^2 binning strategy is shown below.

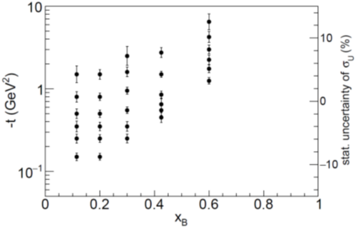


$x_B < 0.85$, $1 < Q^2 < 100$ GeV^2, $0.05 < |t| < 30$ GeV^2, $W^2 > 4$ GeV^2
θ-acceptance for electron or γ is $[2°, 178°]$.
θ-acceptance for proton is $[,179.5°]$. Energy cut for e or γ is > 100 MeV.
[Assuming 10 photoelectons per MeV (PWO4 crystal), the Poisson fluctuation= $\sqrt{10^3}/10^3 = 3.2\%$ for 100 MeV Edep.])

Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

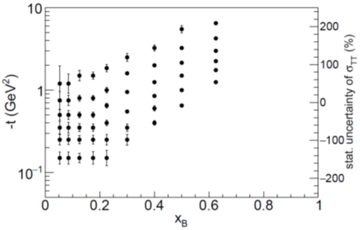


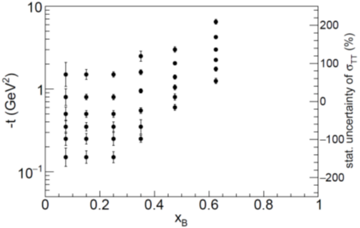


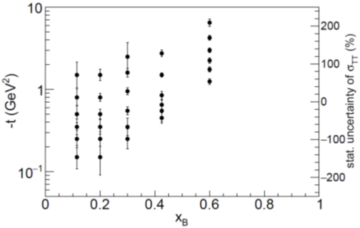


The relative statistic uncertainty of the un-separated cross-section σ_U. From top to bottom, and left to right, the Q^2 ranges are [7, 10], [10, 14], and [14, 20] GeV^2, respectively.

Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)



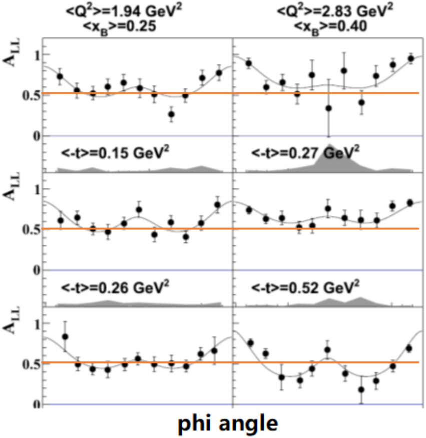


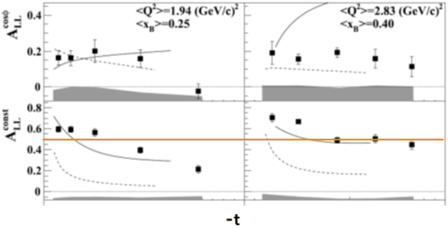


The relative statistic uncertainty of the cross-section σ_{TT}, which is sensitive to $\langle \bar{E}_T \rangle$. From top to bottom, and left to right, the Q^2 ranges are [7, 10], [10, 14], and [14, 20] GeV^2, respectively. The uncertainty is $\sim 20\%$ at small x_B; and $\sim 5\%$ at big x_B.

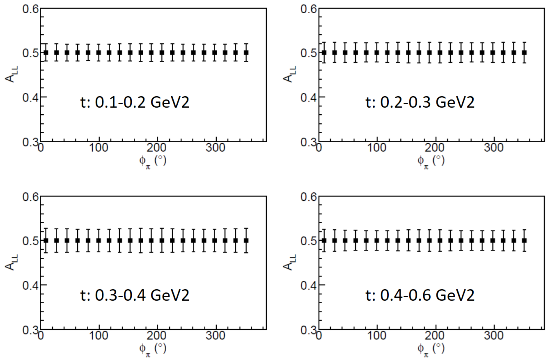
Simulation of DVMP: $ep \to ep\pi^0$ (preliminary)

A_{LL} data from clas, [CLAS, Phys. Lett. B, 2017].





A_{LL} of π^0-DVMP is huge, and the A_{LL}^{const} is dominated in the ϕ_π-modulation. $A_{LL} \sim 0.5$ roughly exists when $|t| < 1$ GeV^2.



Assuming $A_{LL} = 0.5$, we have estimated the statistical uncertainty of A_{LL} for the bin of $0.1 < x_B < 0.15$ and $7 < Q^2 < 10$ GeV^2. The uncertainty is calculated using the formulas shown below.

$$A_{LL} = \frac{\Delta N}{N},$$

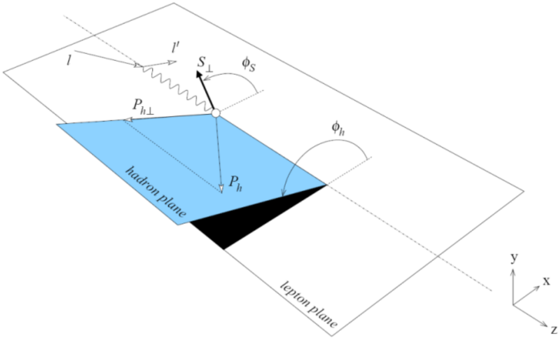
$$\delta(A) = \sqrt{\left(\frac{\delta(\Delta N)}{N}\right)^2 + \left(\frac{\Delta N}{N^2}\delta(N)\right)^2},$$

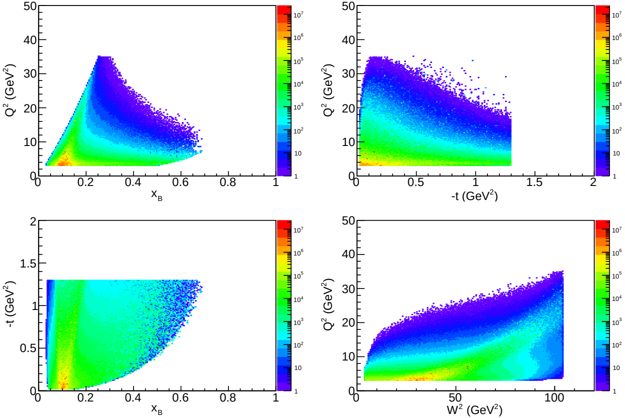
$$\frac{\delta(A)}{A} = \sqrt{\left(\frac{\delta(\Delta N)}{\Delta N}\right)^2 + \left(\frac{\delta(N)}{N}\right)^2}.$$

Simulation of DVMP: $ep \to en\pi^+$ (preliminary)

The $A_{UT}^{sin(\phi-\phi_S)}$ measurement of DVπ^+P is sensitive to constrain the polarized GPD $\tilde{E}$. This is a good opportunity to test the pion pole-dominated ansatz:

$$\tilde{E}^{u/d}(x,\xi,t) = F_\pi(t)\frac{\theta(\xi-|x|)}{2\xi}\phi_\pi(\frac{x+\xi}{2\xi})$$

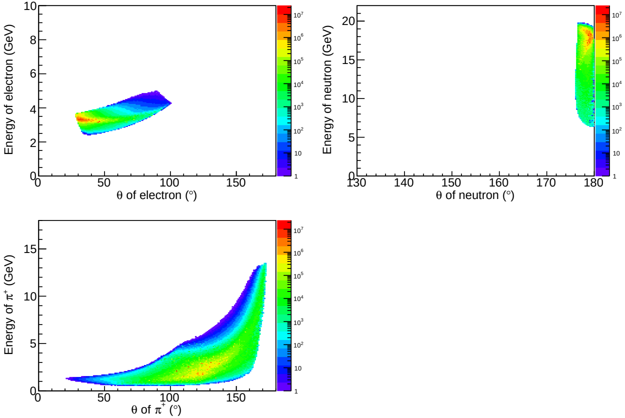




Kinematical requirements:
$0.02 < |t| < 1.3$ GeV^2,
$3 < Q^2 < 35$ GeV^2,
$4 < W^2 < 104$ GeV^2,
$E_e > 700$ MeV

Simulation of DVMP: $ep \to en\pi^+$ (preliminary)

The energy and θ angle distributions of the final particles.



$0.02 < |t| < 1.3$ GeV^2,
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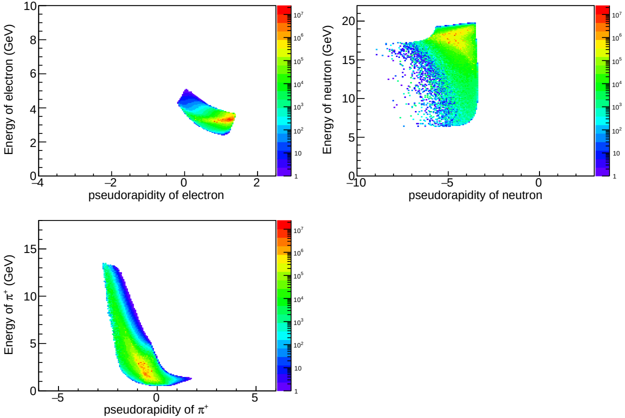
The electrons go forward. The π^+'s go backward. The protons go very backward.

Simulation of DVMP: $ep \to en\pi^+$ (preliminary)

The energy and pseudorapidity distributions of the final particles.



$0.02 < |t| < 1.3$ GeV^2,
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$E_e > 700$ MeV

$|\eta|$ of electron is smaller than 2. $|\eta|$ of π^+ is smaller than 3. The proton has quite big pseudorapidity.

Simulation of DVMP: $ep \to en\pi^+$ (preliminary)

Total cross-section of π^+ production on EicC from MC integral,

$$\sigma_{tot} = (E_e^{high} - E_e^{low})\Omega_e\Omega_{\pi^+} \times \frac{\sum_{i=1}^{N^{generated}} \frac{d_i^5\sigma}{dE_e d\Omega_e d\Omega_{\pi^+}}}{N^{generated}}$$

[if the sampling point outside of physical volume or mismatch the cuts ($0.02 < |t| < 1.3$ GeV^2, $4 < W^2 < 104$ GeV^2, $3 < Q^2 < 35$ GeV^2, $E_e > 700$ MeV), $\frac{d^5\sigma}{dE_e d\Omega_e d\Omega_{\pi^+}} = 0$]

Total cross-section = 3.95 nb.
Number of events = 3.95 nb $\times$ 50 fb^{-1} = 198 million.

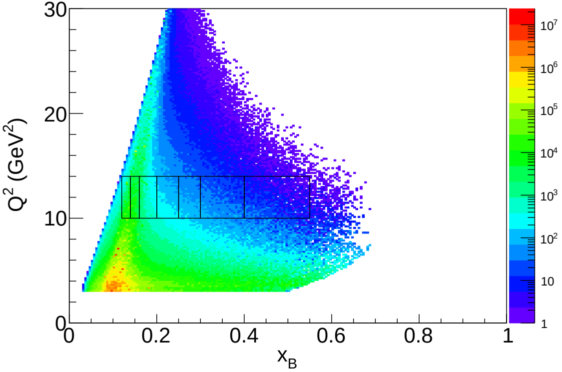
$$\frac{d^5\sigma_{UU}}{dE_e d\Omega_e d\Omega_{\pi^+}} = \Gamma_V \frac{d^2\sigma}{d\Omega_{\pi^+}}$$

$$\frac{d^2\sigma}{d\Omega_{\pi^+}} = J^{\Omega} \frac{d^2\sigma}{dt d\phi}$$

$$\frac{d^2\sigma}{dt d\phi} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)$$

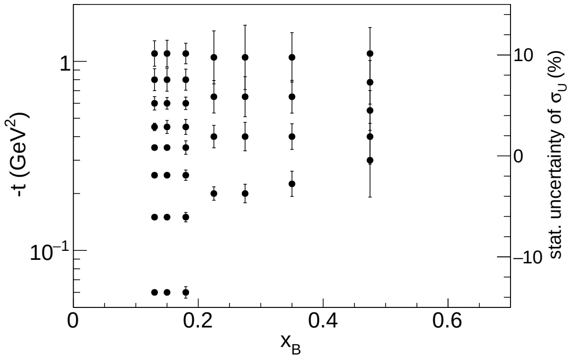
Simulation of DVMP: $ep \to en\pi^+$ (preliminary)

The x_B-Q^2 binning strategy is shown below.



Kinematical cuts:
$0.02 < |t| < 1.3$ GeV^2,
$3 < Q^2 < 35$ GeV^2,
$4 < W^2 < 104$ GeV^2,
$E_e > 700$ MeV

Simulation of DVMP: $ep \to en\pi^+$ (preliminary)



The relative statistic uncertainty of the un-separated cross-section σ_U for the Q^2 range between 10 GeV^2 and 14 GeV^2.

Summary and outlook

Summary:

- With $\sim$two years of accumulation of the data on EicC (50 fb^{-1}), we would have decent amounts of both DVCS and DVMP events;
- The statistical uncertainties of both the differential cross-section and the asymmetries are small, which would well constrain the GPD models and provide the possibilty of spatial imaging of nucleons.

Outlook:

- The extraction of GPDs using the fake data should be studied for the next step;
- The other type asymmetries should also be studied for the EicC domain;
- More studies on the detector capability should be considered.

The End,
thank you!