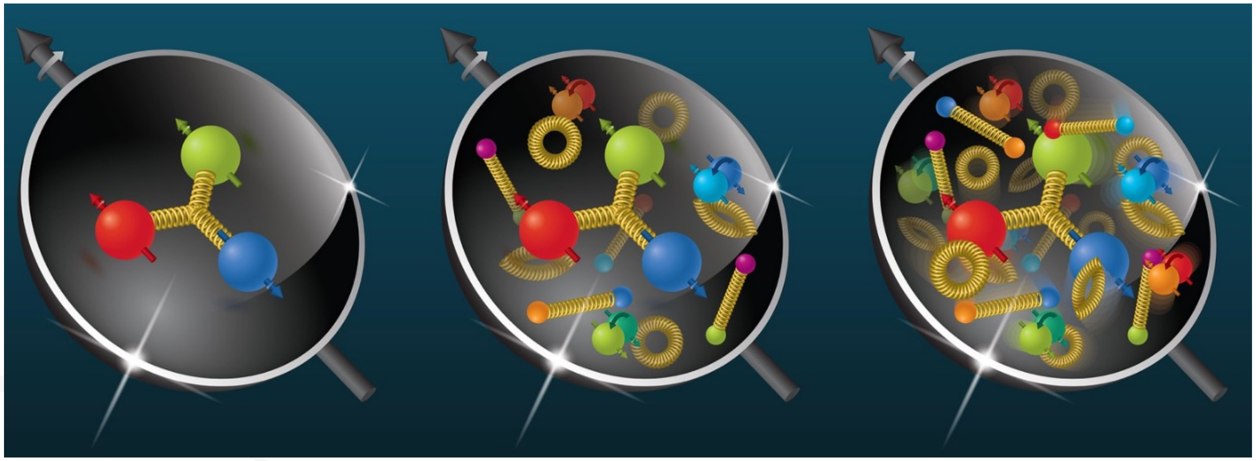
Deeply Virtual Exclusive Processes



Workshop on parton distribution functions in the EIC era

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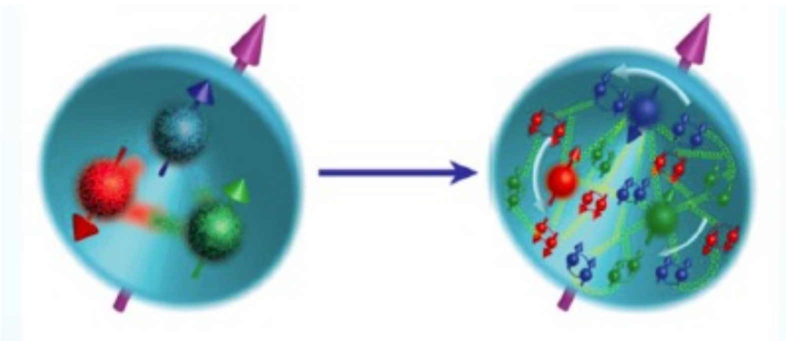
University of Connecticut

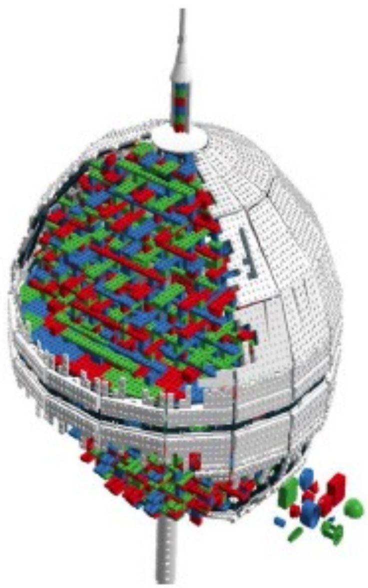
(For the CLAS Collaboration)

UCONN | UNIVERSITY OF CONNECTICUT

June 17, 2025

QCD Science Questions



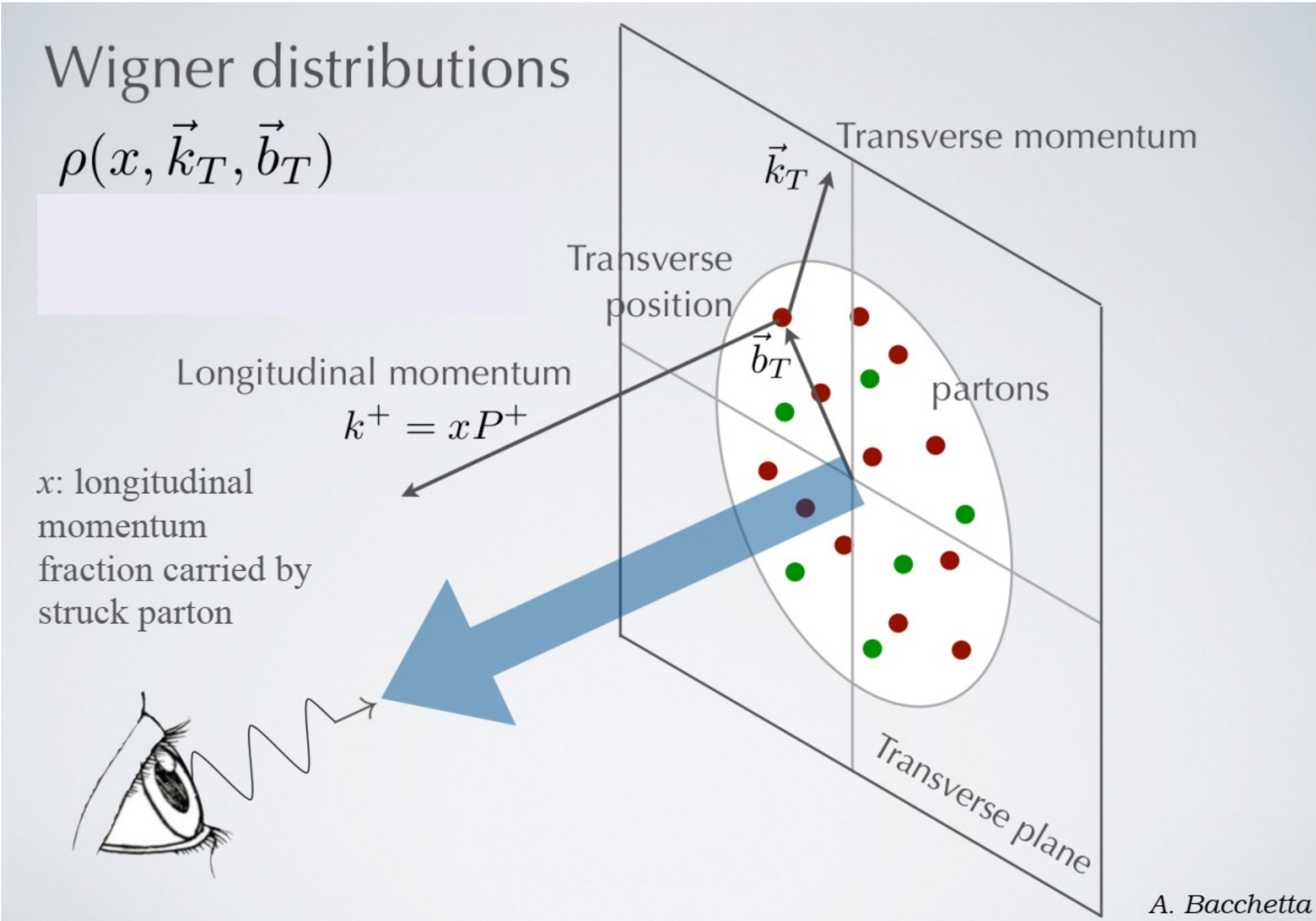


How can we recover the well-known characterics of the nucleon from the properties of its **colored building blocks**?

Mass?
Spin?
Charge?
...

What are the relevant **effective degrees of freedom** and **effective interaction** at large distance?

3-Dimensional Imaging of Quarks and Gluons



Generalized Parton Distributions (GPDs)

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle$$

S. Liuti et al., Phys. Rev. D 84, 034007 (2011) (GGL)

P. Kroll et al., Eur. Phys. J. A 47, 112 (2011) (GK)

Integrate over transverse ***momentum*** space

Generalized Parton Distributions (GPD)

3-D nucleon images in the transverse coordinate and longitudinal momentum space

quark pol.

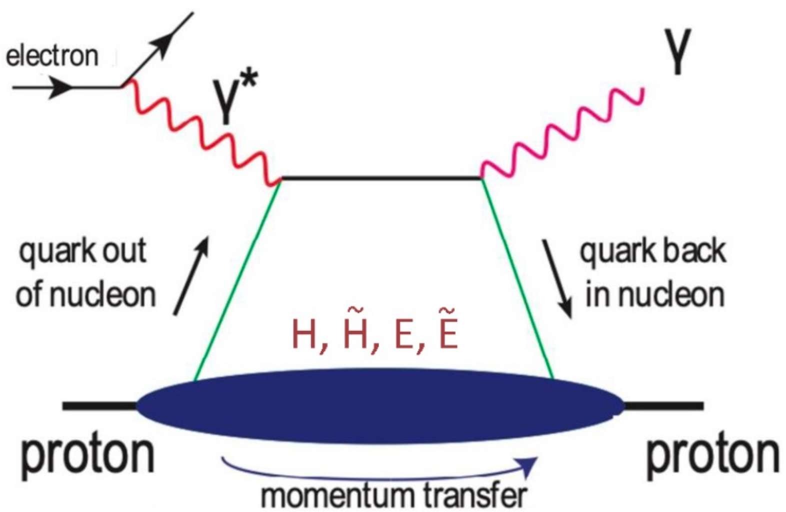
nucleon pol.

N/q	U	L	T
U	H		$\bar{E}_T$
L		$\widetilde{H}$	$\widetilde{E}_T$
T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

$$\bar{E}_T = 2\widetilde{H}_T + E_T$$

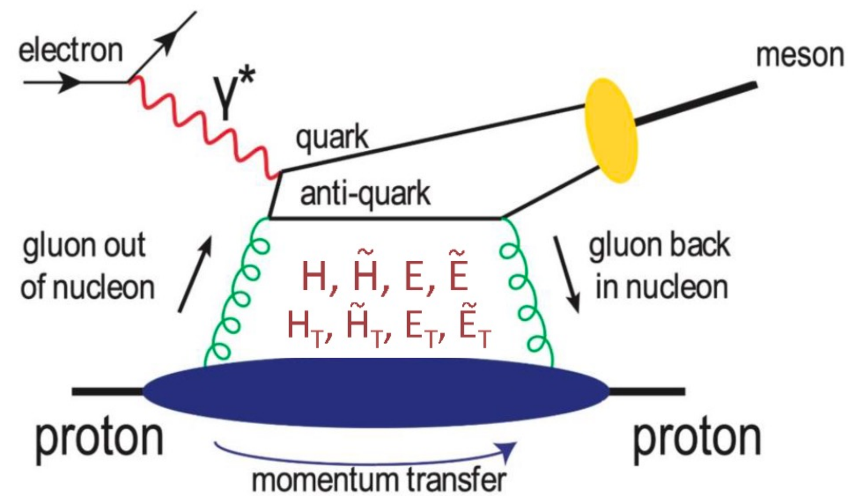
Study GPDs: Deeply Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



Deeply Virtual Compton scattering:
real photon is produced

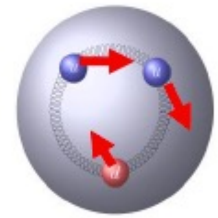
Deeply Virtual Meson Production (DVMP)



Deeply Virtual Meson production:
quark-antiquark bound state is produced

➔ **Access to Generalized Parton Distributions (GPDs)**

Physics Content of GPDs: From GPDs and CFFs to the D-term



- GPDs can not be directly measured with the DVCS and DVMP processes

DVCS Process: Observables are the Compton-FFs (CFF)

→ Complex integrals over the *x*-dependence of the GPDs

$$\underbrace{\mathrm{Re}\mathcal{H}(\xi,t)}_{\textbf{CFF}}+i\,\underbrace{\mathrm{Im}\mathcal{H}(\xi,t)}_{\textbf{CFF}}=\sum_q e_q^2\int \mathrm{d}x\left[\frac{1}{\xi-x-i\epsilon}-\frac{1}{\xi+x-i\epsilon}\right]\underbrace{H^q(x,\xi,t)}_{\textbf{GPD}}$$

GPD, Compton-FFs and the pressure within the nucleon:

- GPDs provide indirect access to mechanical properties of the nucleon ➔ gravitational form factors

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t)+\frac{4}{5}\xi^2 d_1(t)$$

X. D. Ji, PR**D 55**, 7114-7125 (1997)
M. Polyakov, PL**B 555**, 57-62 (2016)

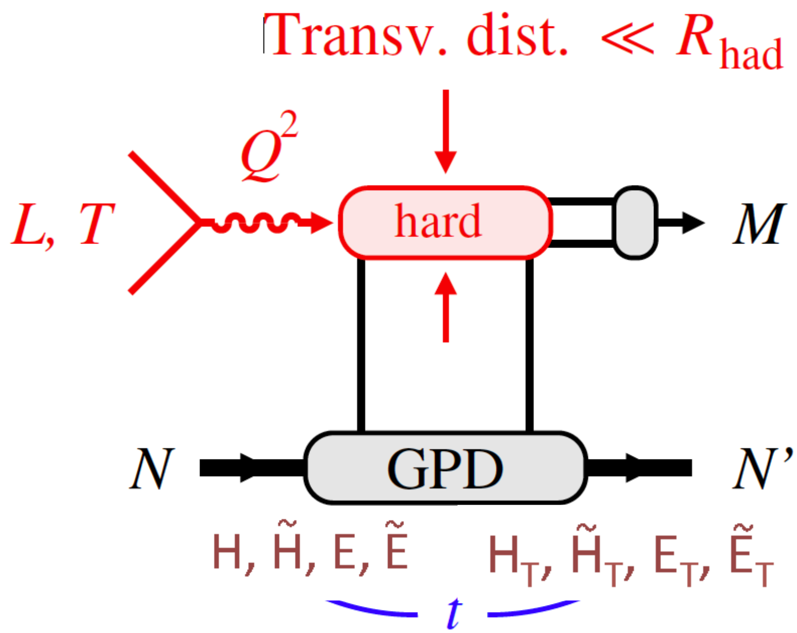
- Real- and imaginary part of the Compton-FF $\mathcal{H}$ follow the dispersion relation:

$$\boxed{\mathrm{Re}\mathcal{H}(\xi,t)} \propto \boxed{D(t)}+\frac{2}{\pi}\mathcal{P}\int \mathrm{d}x\,\frac{x\,\boxed{\mathrm{Im}\mathcal{H}(x,t)}}{\xi^2-x^2}$$

M. Diehl, D. Y. Ivanov, Eur. Phys. J. C 2007, 52, 919

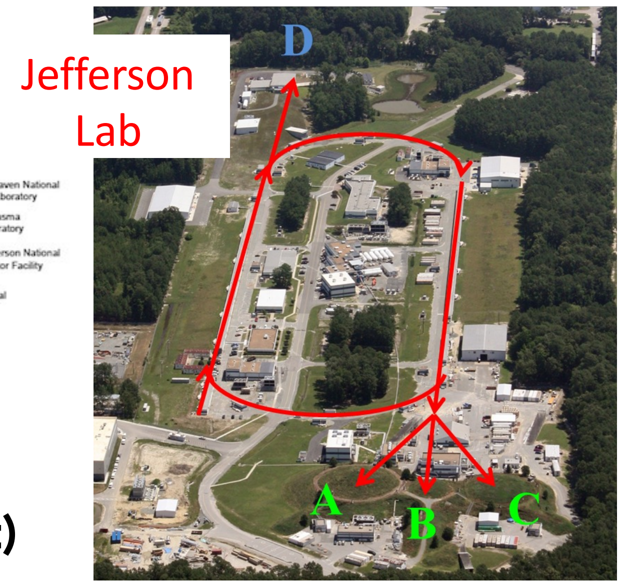
Deeply Virtual Meson Production in the GPD regime

	Meson	Flavor
$\bar{\mathcal{H}}_T, \bar{\mathcal{E}}_T$ $\tilde{\mathcal{H}}, \tilde{\mathcal{E}}$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}, \mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	g



- DVMP enables Flavour decomposition of GPDs.
- The small-size regime: the production of q-qbar pair with sizes << hadronic size dominates.
  - ❖ QCD factorization and GPD extraction assume that this regime is attained.

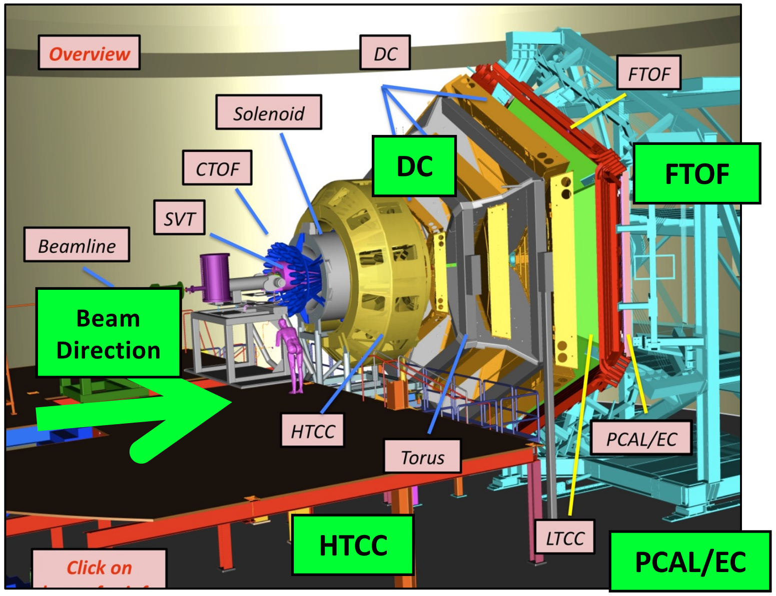
Thomas Jefferson National Accelerator Facility (Jefferson Lab)

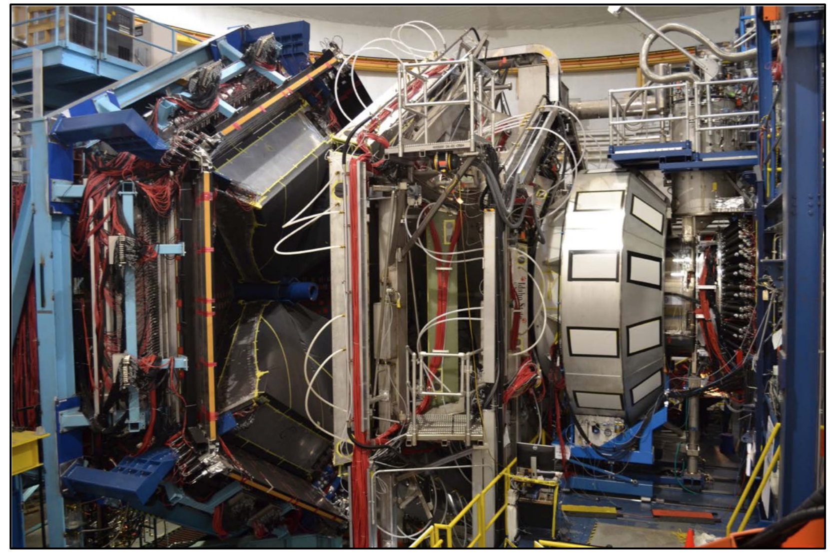


- **Newport News, Virginia (US east coast)**
- **1995 - 2012 6 GeV electron beam**
- **2018 - today 11 / 12 GeV electron beam / photon beam**

CEBAF Large Acceptance Spectrometer (CLAS12) in Hall B

https://www.jlab.org/Hall-B/clas12-web/





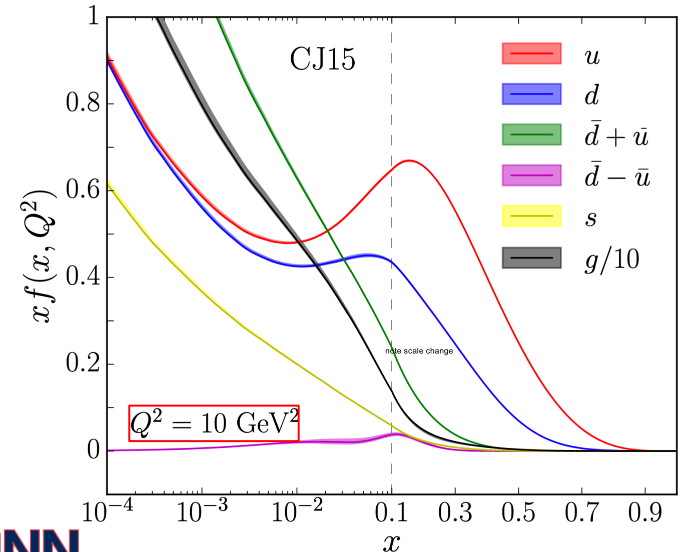
V. Burkert et al., Nucl. Instrum. Meth. A 959 (2020) 163419

- CLAS12: 10^{35} $cm^{-2}sec^{-1}$ luminosity, nearly 4π acceptance, $0.05\ GeV^2 < Q^2 < 10.0\ GeV^2$ coverage over photon virtuality.
- Began data taking in Spring 2018 – many “run periods” now available
- Data from Fall 2018 - 10.6 GeV electron beam, longitudinally polarized beam, liquid H_2 target.

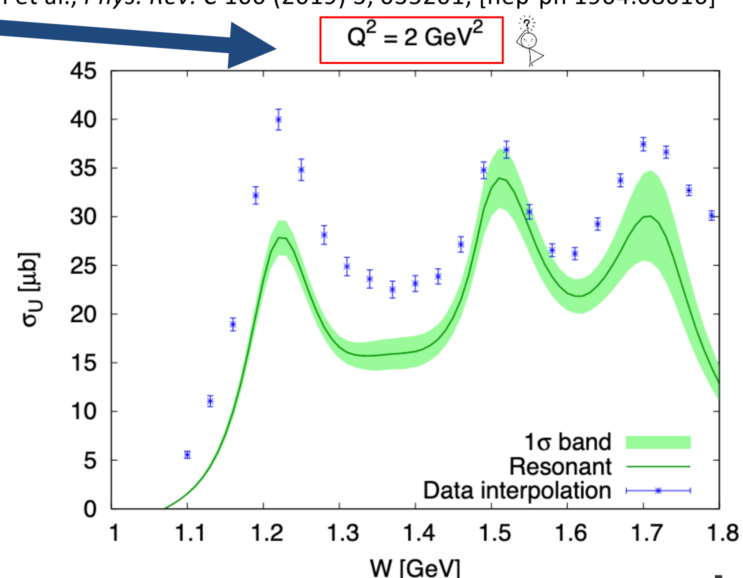
Extending Knowledge of the Nucleon PDF in the Resonance Region

- Global QCD analyses have provided detailed information on the nucleon PDFs in a wide range of parton fractional longitudinal momentum, x, from 10^{-4} to 0.9.
- At large x, in the nucleon resonance region W < 2.5 GeV, the PDFs are significantly less explored.
- Extractions in this region require accounting for higher twist effects, target-mass corrections and evaluation from the nucleon resonance electroexcitations.

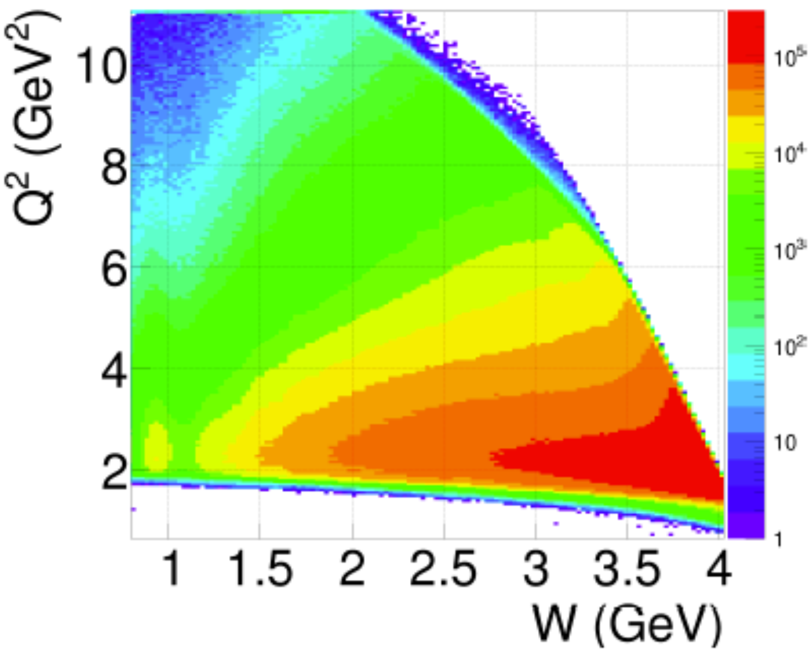
A. Accardi et al., *Phys. Rev. D.* 11, 114017 (2016), [hep-ph 1602.03154]

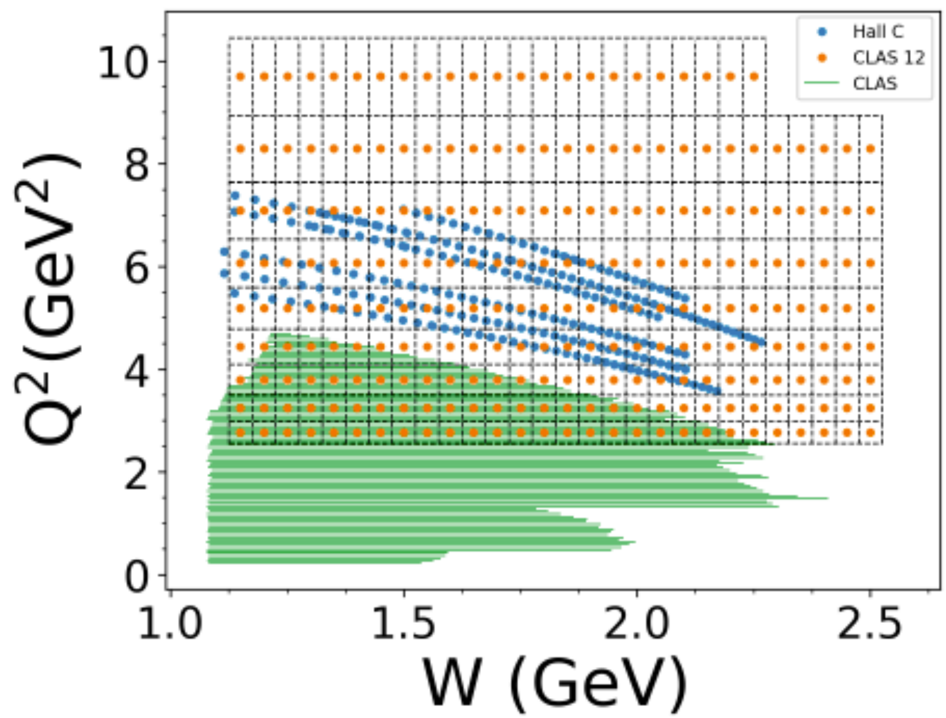


A. N. Hiller Blin et al., *Phys. Rev. C* 100 (2019) 3, 035201, [hep-ph 1904.08016]



Inclusive Electron Scattering Kinematic Coverage with CLAS12
ep->e'X





Orange: CLAS12
Green: CLAS6
Blue: Hall C

Cross Section Calculation

$$\frac{d\sigma}{dQ^2dW} = \frac{1}{\Delta Q^2 \Delta W} \cdot \frac{N}{\eta \cdot R \cdot B \cdot N_0} \cdot \frac{1}{N_A \rho t / A_\omega}$$

- Q^2 - four-momentum transfer squared
- W - invariant mass of the final hadron system
- R - radiative correction factor
- B - bin size correction
- N - bin event yield
- η - is the product of geometrical acceptance and electron detection efficiency
- N_0 - live-time corrected incident electron flux summed over all data runs
- N_A - Avogadro's number
- ρ - target density
- t - target length
- A_ω - atomic weight of the target

Matrix Deconvolution

- **Acceptance Matrix:** $A_{(i,j)}$ describes both acceptance (geometrical acceptance and detector efficiency) and bin migration:

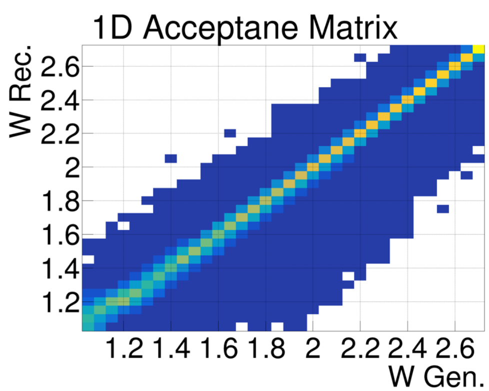
$$A_{(i,j)} = \frac{\#\, Events\ Generated\ in\ bin\ j\ but\ Reconstructed\ in\ bin\ i}{Total\ number\ of\ Events\ Generated\ in\ the\ jth\ bin}$$

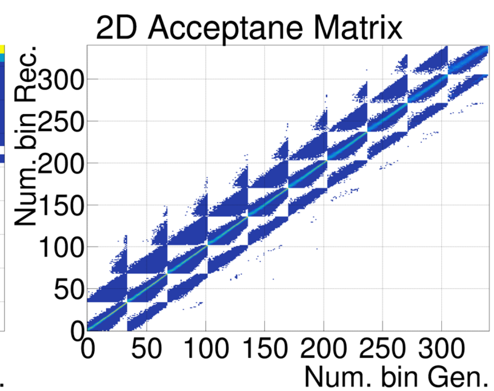
CERN RooUnfold package was used:
https://gitlab.cern.ch/RooUnfold/RooUnfold

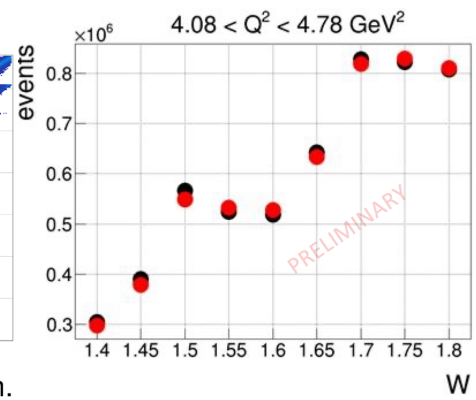
Acceptance unfolding: $Y_i = A_{(i,j)} X_j \Rightarrow X_j = A^{-1}_{(i,j)} Y_i$ where Y_i number of measured events in i-th bin, X_j is number of acceptance corrected events in j-th bin

We used:

1. Bin-by-bin
2. SVD
3. Bayesian Matrix 2D







Red - 2D Bayesian method
Black - Bin-by-bin method

2024 JLUO ANNUAL MEETING, June 10, 2024 to June 12, 2024

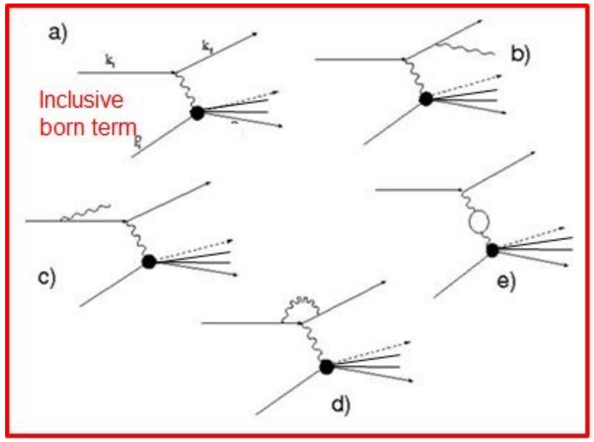
Radiative Corrections

Each (Q^2,W) bin was divided into 21x11 sub bins. Cross Sections with rad. effects on and off were calculated in every sub bin.

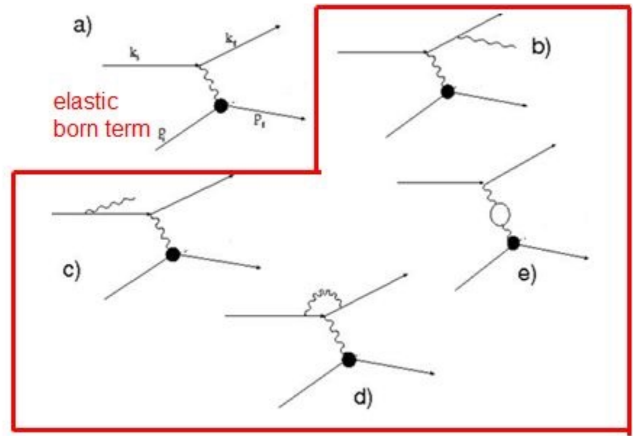
Radiative Correction factor:

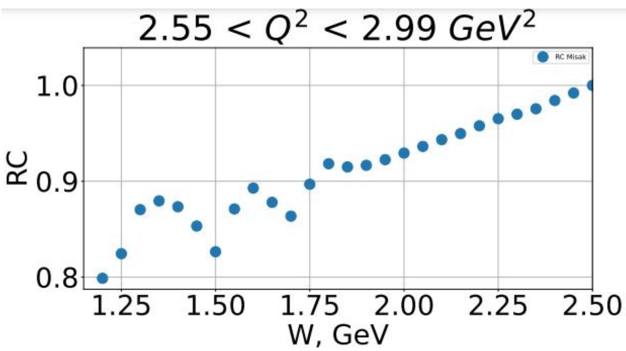
$$\frac{Mean\ Cross\ Section\ (Rad)}{Mean\ Cross\ Section\ (No\ Rad)}$$

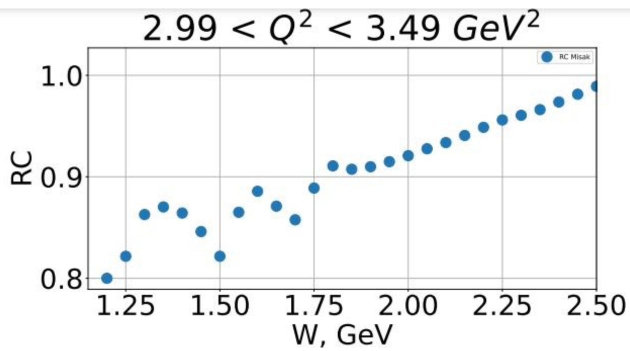
Inclusive with radiative effects

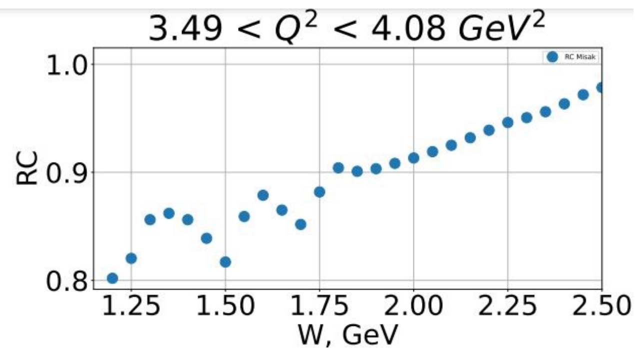


Elastic with radiative effects



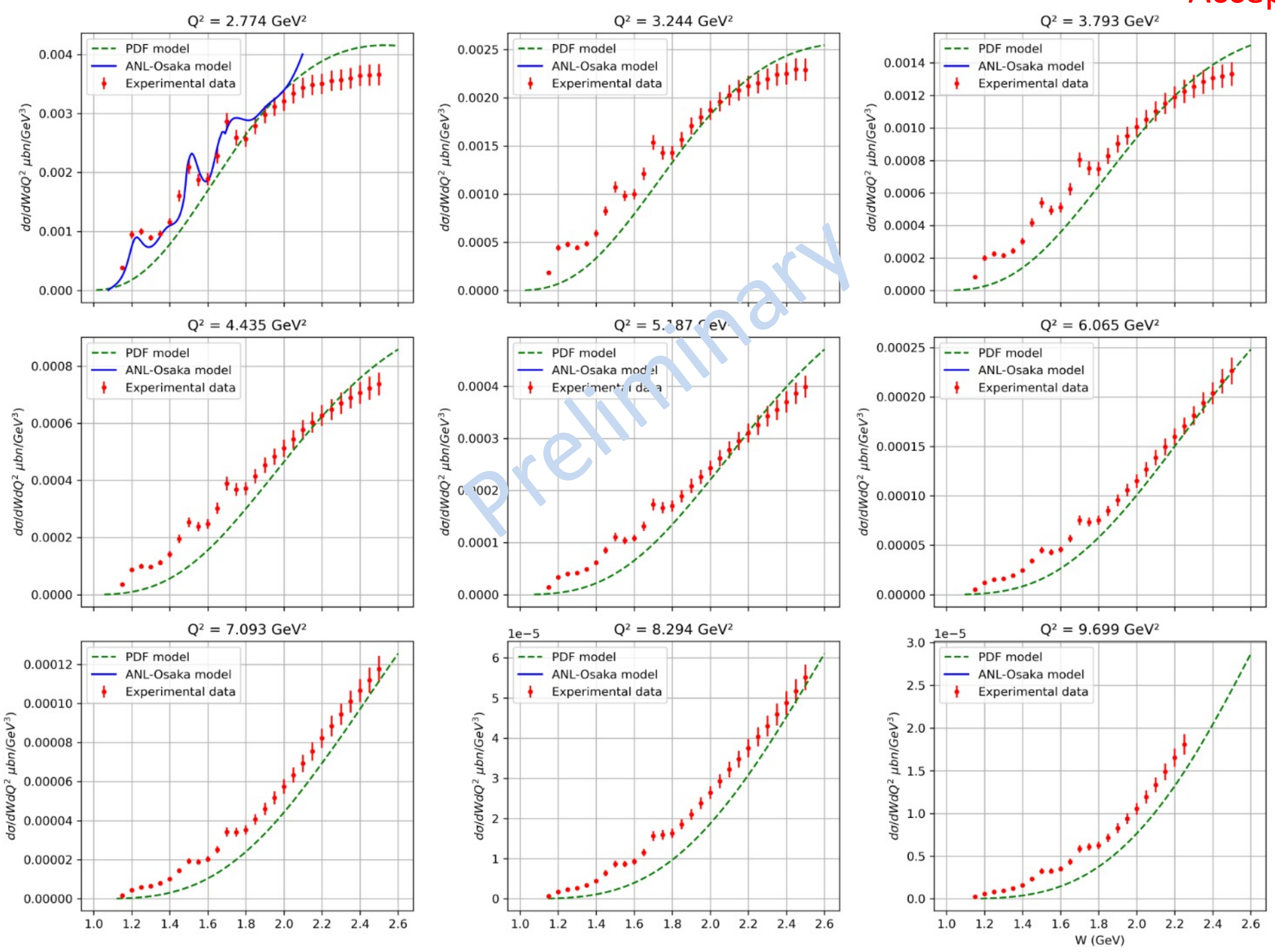






Preliminary Cross Sections vs. W (GeV)

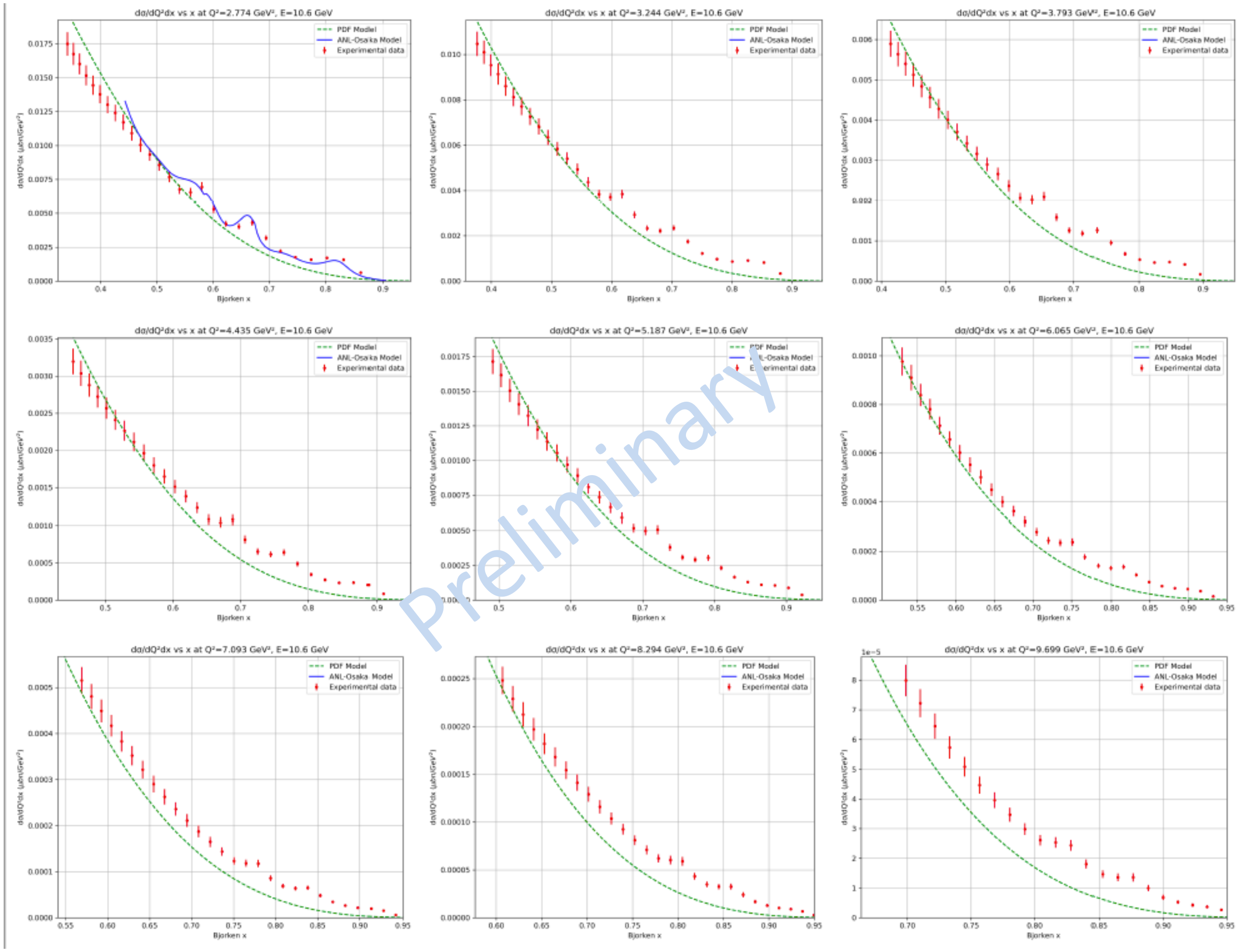
Accepted in PRC for publication



Red: CLAS12
Blue: ANL-Osaka Model
Green: CTEQ-6 PDFs

W (GeV)

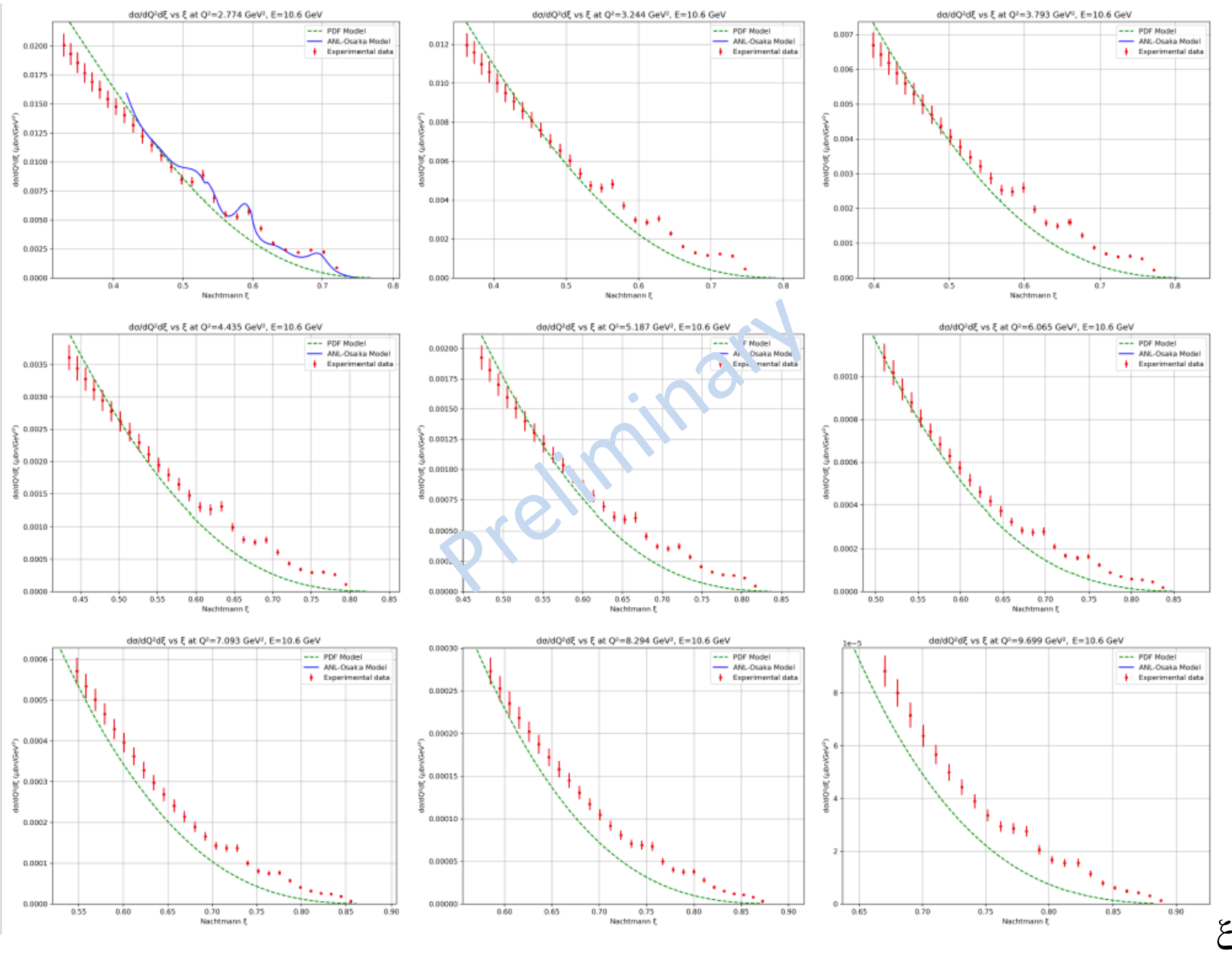
Preliminary Cross Sections vs. x_B



Red: CLAS12
Blue: ANL-Osaka Model
Green: CTEQ-6 PDFs

x_B

Preliminary Cross Sections vs. ξ

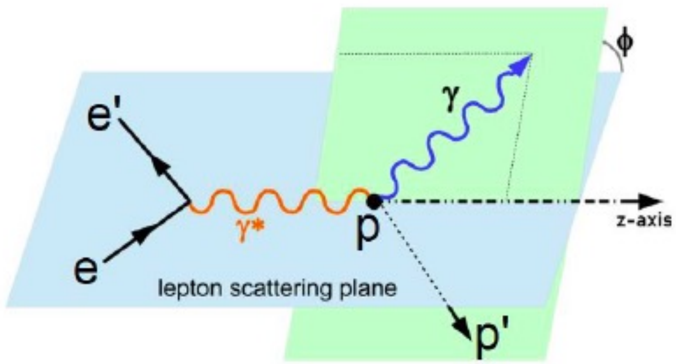


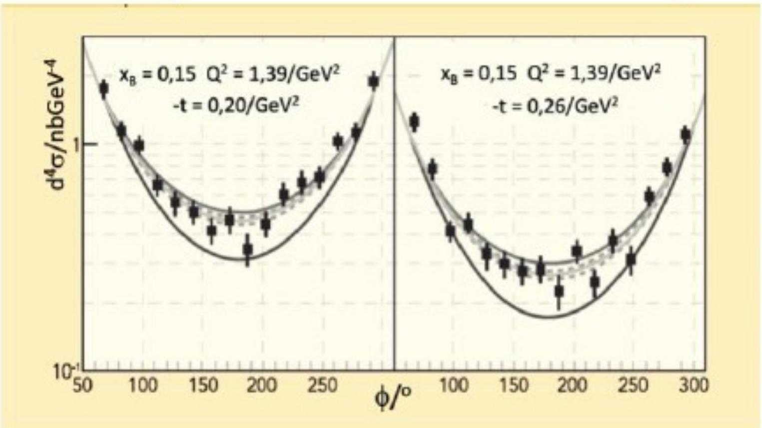
Red: CLAS12
Blue: ANL-Osaka Model
Green: CTEQ-6 PDFs

Observables of the DVCS process

How can we measure the CFFs in the DVCS process?

1. Cross-section $\sigma^{ep\gamma}(x,Q^2,t,\phi) \propto \boxed{Re\{\mathcal{H}\}}$

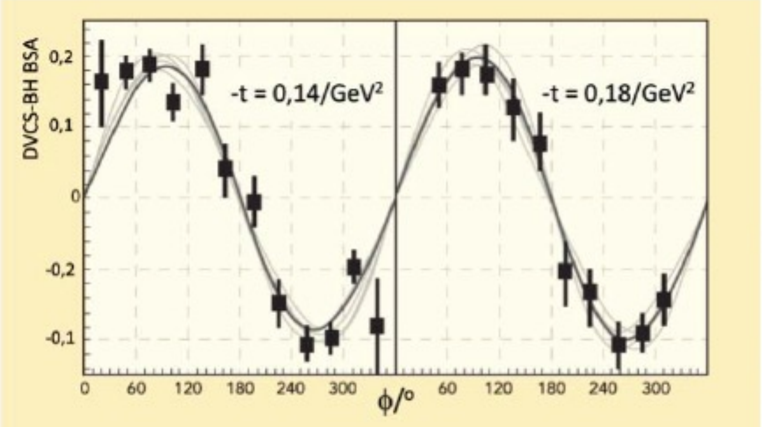




2. Beam-Spin Asymmetry

$$\mathrm{BSA}(x,Q^2,t,\phi) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

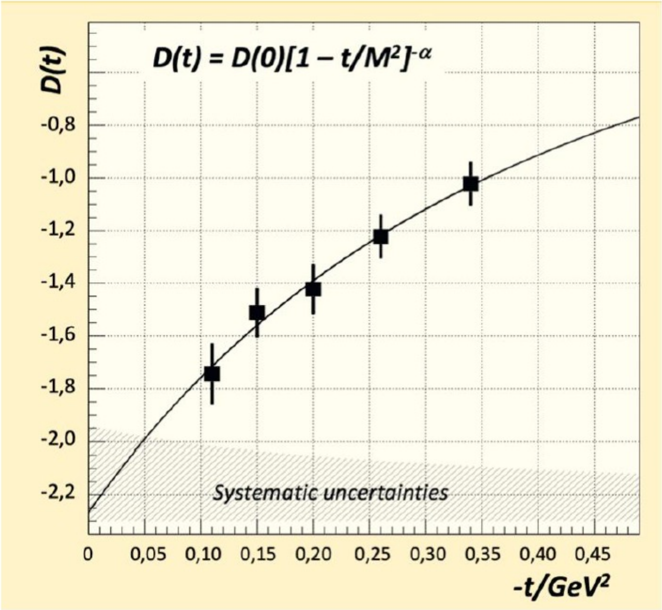
$$\propto \boxed{Im\{\mathcal{H}\}} \sin\phi$$



V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396 (2018)

From the D-term to the pressure distribution

$$\boxed{\mathrm{Re}\mathcal{H}(\xi,t)} \propto \boxed{D(t)} + \frac{2}{\pi}\mathcal{P}\int dx \frac{x\,\boxed{\mathrm{Im}\mathcal{H}(x,t)}}{\xi^2 - x^2}$$



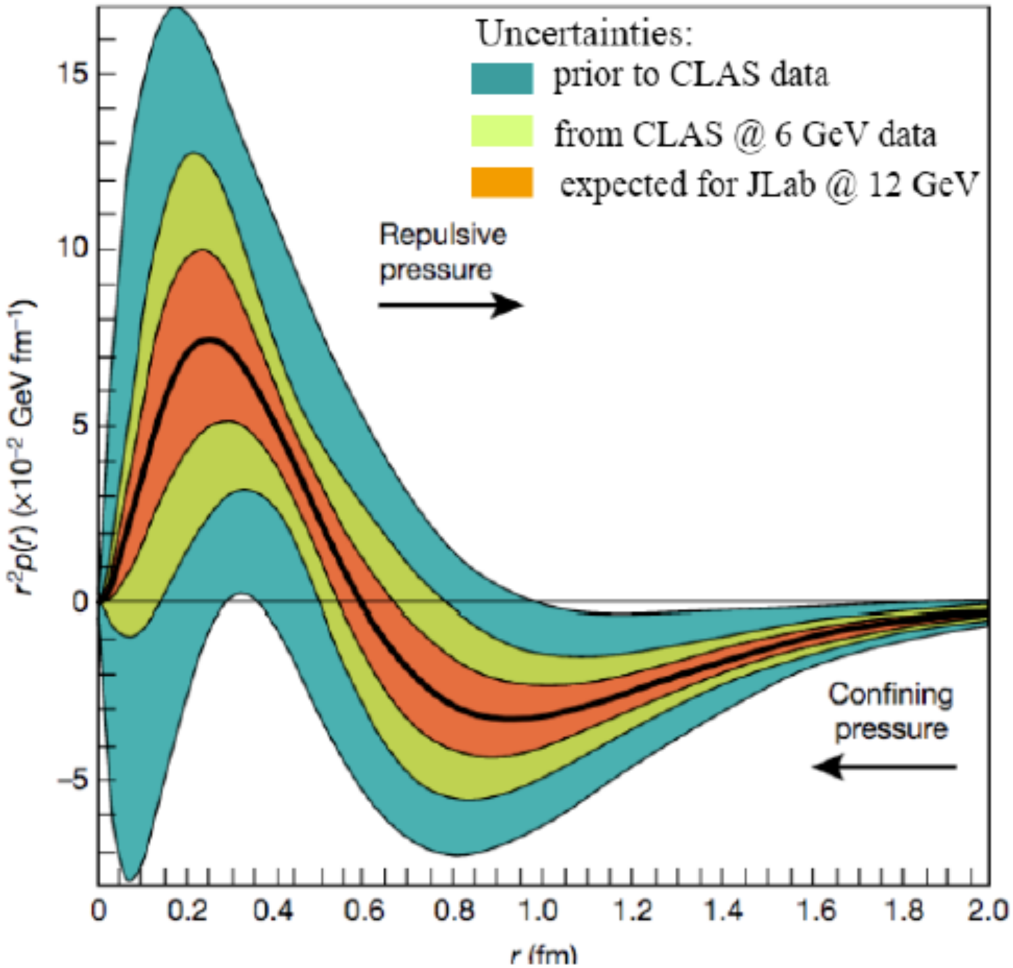
V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396 (2018)

The pressure distribution: $$p(r) = \frac{1}{6m_p}\int \frac{d^3\Delta}{(2\pi)^3}\, t\,\boxed{D(t)}\, e^{-i\Delta r}$$

with $t = -\Delta^2$

K. Goeke et al., Phys. Rev. D 75, 094021 (2007)

Pressure inside the proton



V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396 (2018)

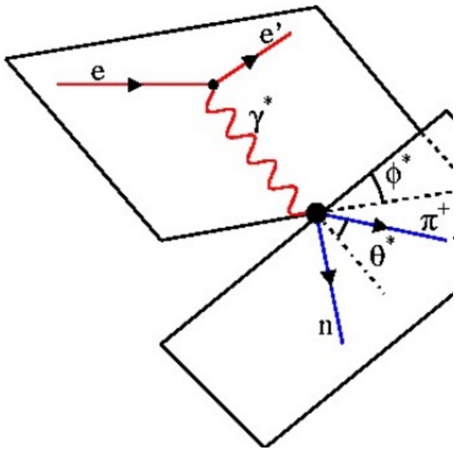
- Positive maximal pressure of 10^{35} Pa in the center at r = 0 fm
  - ➔ Highest known pressure in the universe
  - ➔ Resulting forces away from the center avoid a collaps of the quark matter
- Negative pressure in the outer areas of the proton, for r > 0,6 fm
  - ➔ Forces towards the center stabilize the proton

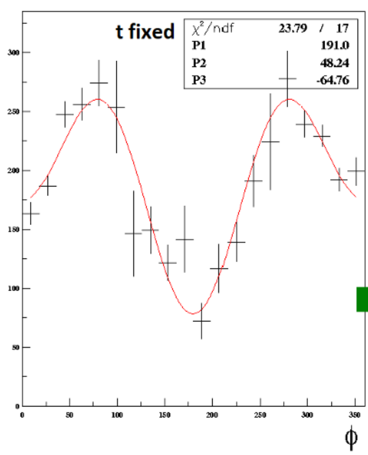
Interplay of the two regions leads to the stability of the proton

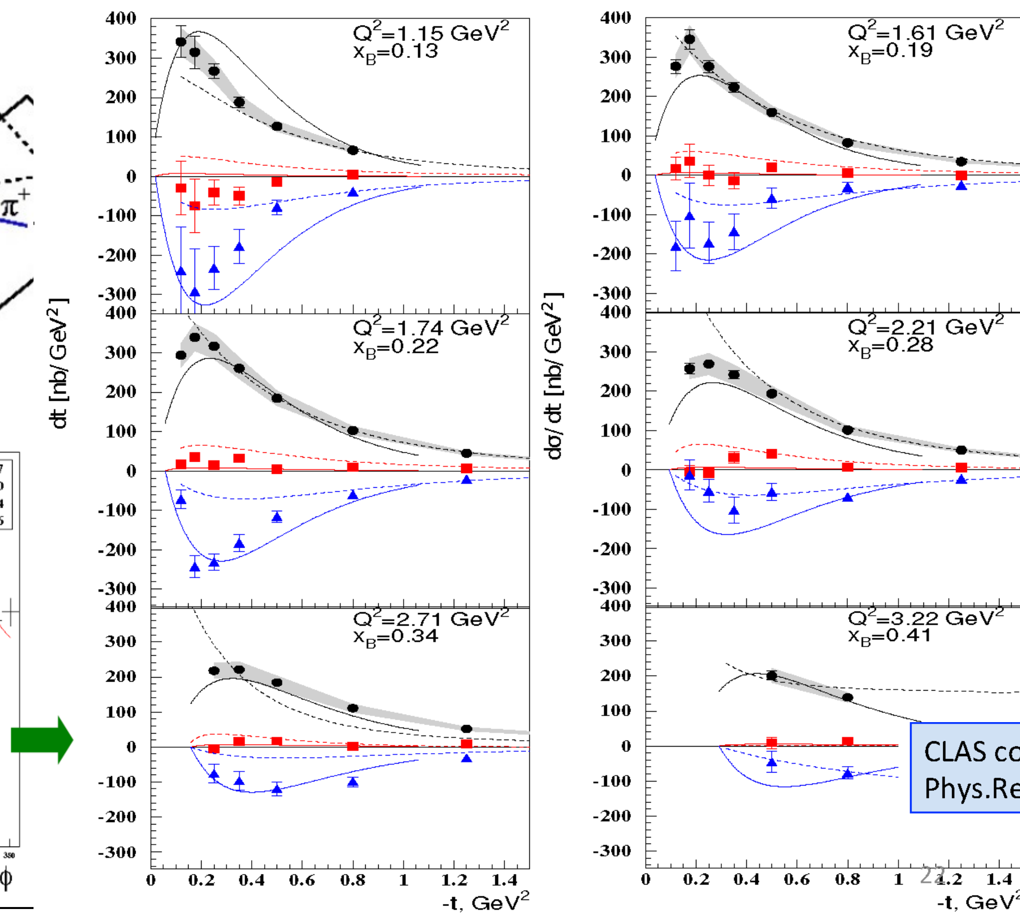
$$p(r) = p(0) \times (1 - \frac{r}{r_0}) \times e^{-ar}$$

DVMP (π^0) Differential Cross Section

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







CLAS in Hall B
E=6 GeV

- σ_0
- σ_{TT} → cos(2φ)
- σ_{LT} → cos(φ)

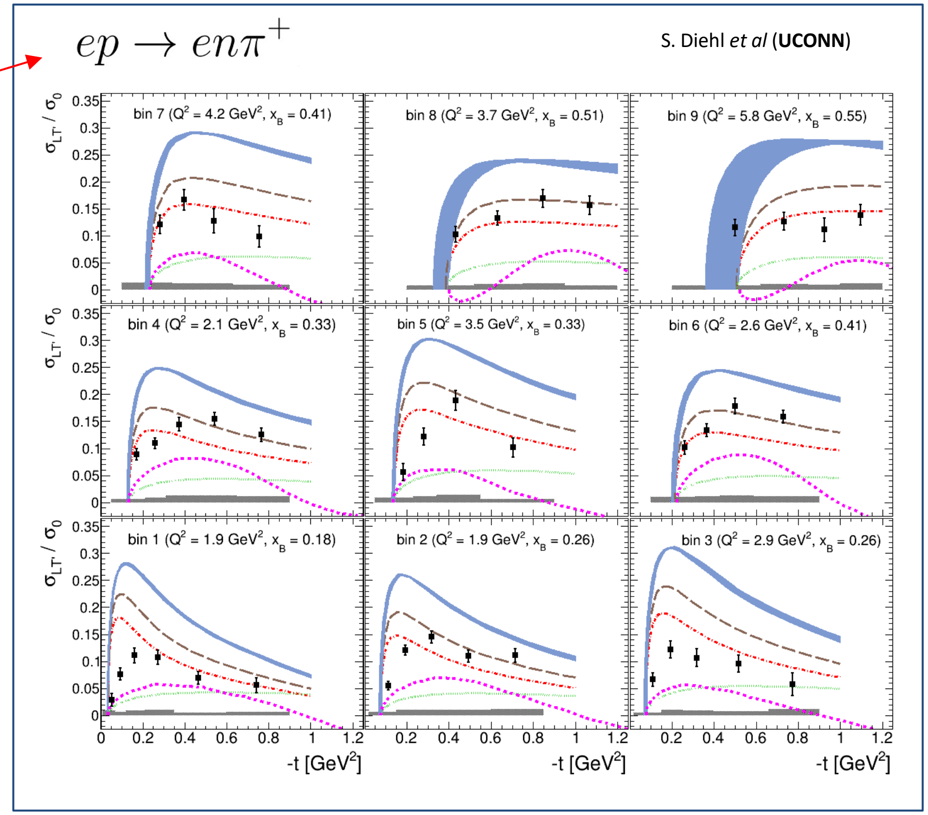
— GK
--- GGL

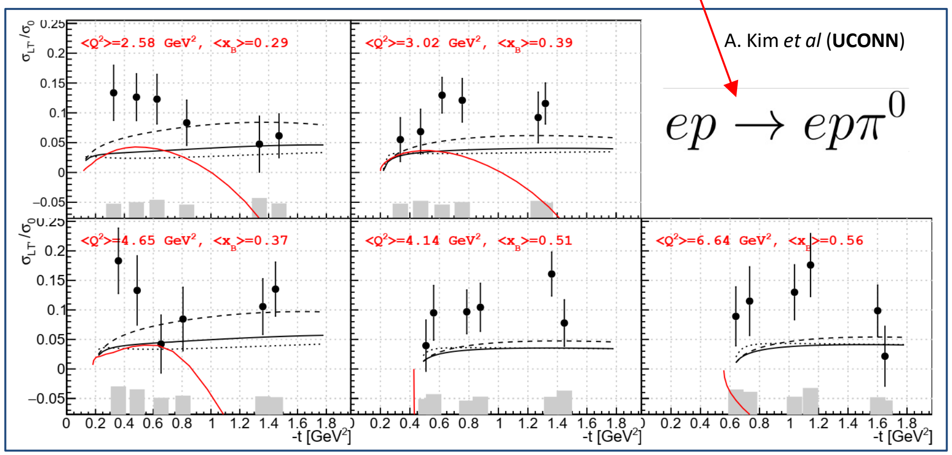
CLAS collaboration. I Bedlinskiy et al. Phys.Rev.Lett. 109 (2012) 112001

Pseudoscalar meson electroproduction with CLAS12

E=10.6 GeV

$$\sigma_{LT'} = \xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\times$$
$$\times \ \mathrm{Im}\left[\boxed{\langle H_T\rangle^*\langle\tilde{E}\rangle} + \boxed{\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle}\right]$$





GK model

JML model

$\bar{E}_T$ is related to the proton's anomalous tensor magnetic moment.

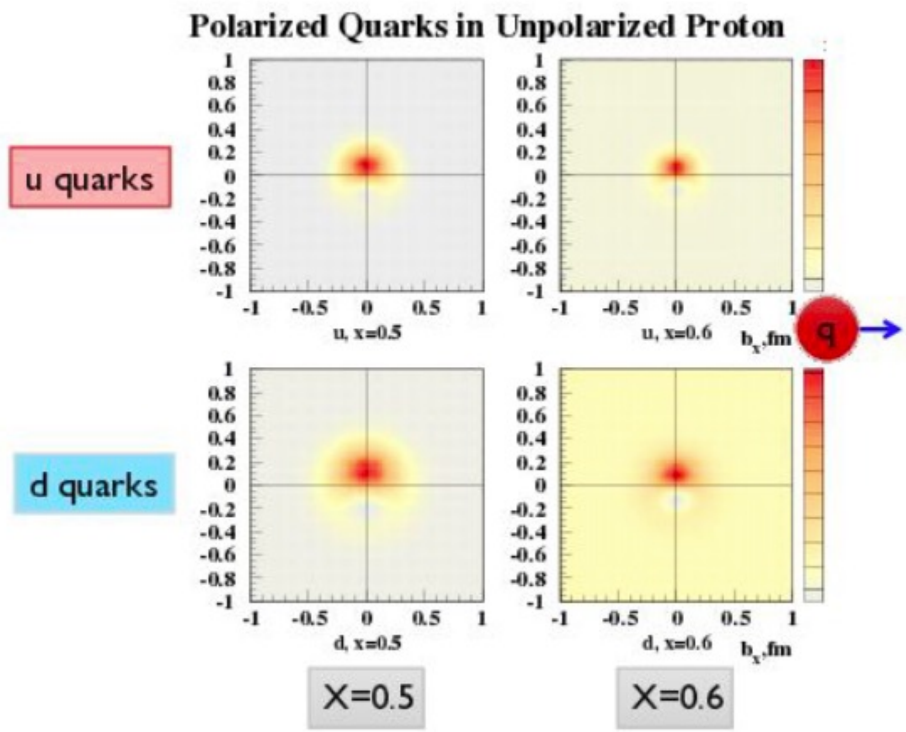
H_T is related to the proton's tensor charge.

$$\kappa_T^u = \int dx \bar{E}_T^u(x,\xi,t=0) \qquad \delta_T^u = \int dx H_T^u(x,\xi,t=0)$$

$$\kappa_T^d = \int dx \bar{E}_T^d(x,\xi,t=0) \qquad \delta_T^d = \int dx H_T^d(x,\xi,t=0)$$

Transverse densities for u and d quarks in the proton (after global fit of π^0 and η data)

- $\bar{E}_T$ is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon



V. Kubarovsky et al.

$\bar{E}_T$ is similar to Boer Mulders TMD function in SIDIS.

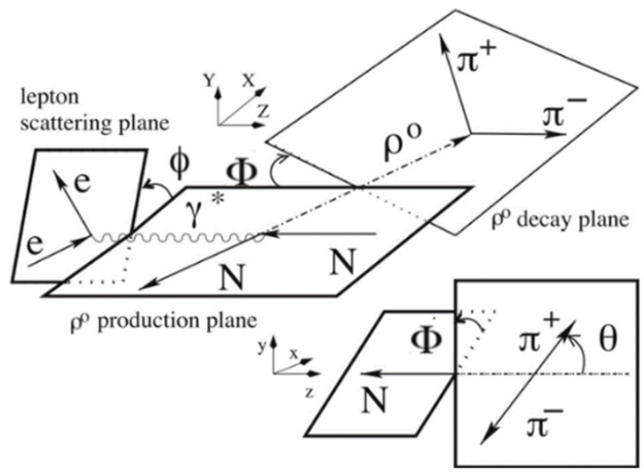
The fit results agree with the large-N_c limit analysis by P. Schweitzer and C. Weiss *Phys.Rev.C* 94 (2016) 4, 045202

GPD parameterization used in GK model can be improved through global fits using existing Hall A and Hall B data

Exclusive vector meson ρ^0 production with CLAS12

Exclusive vector meson ρ^0 production is sensitive to

$$\mathcal{H}, \mathcal{E}$$



$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\Phi} = \Gamma(Q^2, x_B, E)$$

$$\frac{1}{2\pi}\Big\{\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}$$

$$+\,\epsilon\frac{d\sigma_{TT}}{dt}\cos(2\Phi) + \sqrt{2\,(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos(\Phi)$$

$$+\,\lambda\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{LT'}}{dt}\sin(\Phi)\ \Big\}$$

where λ is the helicity state of the incident electron beam

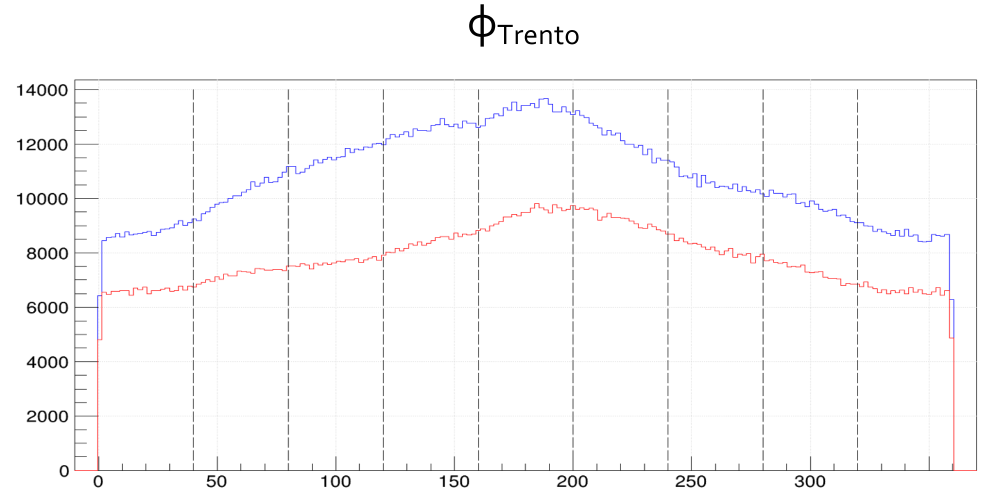
$$BSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \sim \sigma_{LT'} \sim r^8_{00} \sim \ \mathrm{Im}\left[\langle H_T\rangle^*\langle E\rangle + \langle \bar{E}_T\rangle^*\langle H\rangle\right]$$

1D Bins in -t

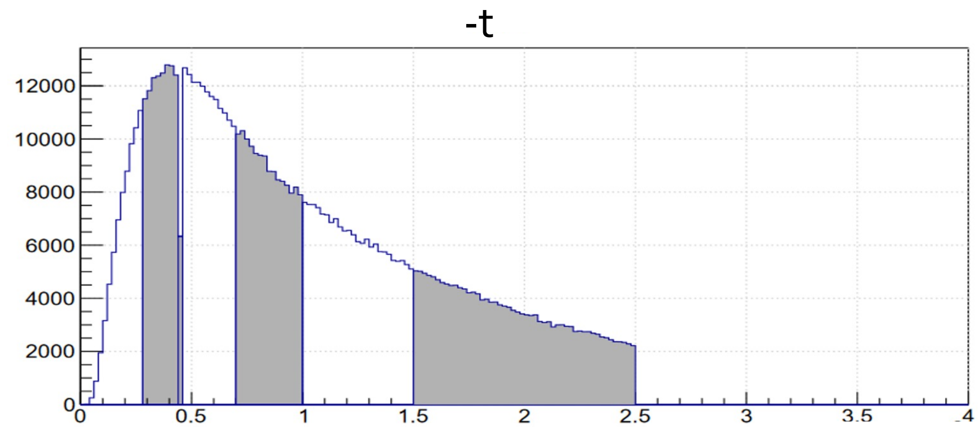
- 6 bins in -t
- 9 equidistance bins in ϕ
- Events were divided into either positive or negative helicity
- 108 invariant mass were fitted
- This was done independently for both inbending and outbending
- $N^{+}_{\rho o}$ and $N^{-}_{\rho o}$ are the amplitude of ρ^{o} fits in positive and negative helicity bins

$$BSA = \frac{1}{P_b} \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

P_b is the average beam polarization



Negative helicity in red and positive helicity in blue ϕ



-t [GeV²]

Fitting ρ^0 example

Breit Wigner Distribution (Mesons)

$$F_x^{bw} = \frac{1}{\pi}\frac{N_x \frac{1}{2}\Gamma}{x^2 + (\frac{1}{2}\Gamma)^2}$$

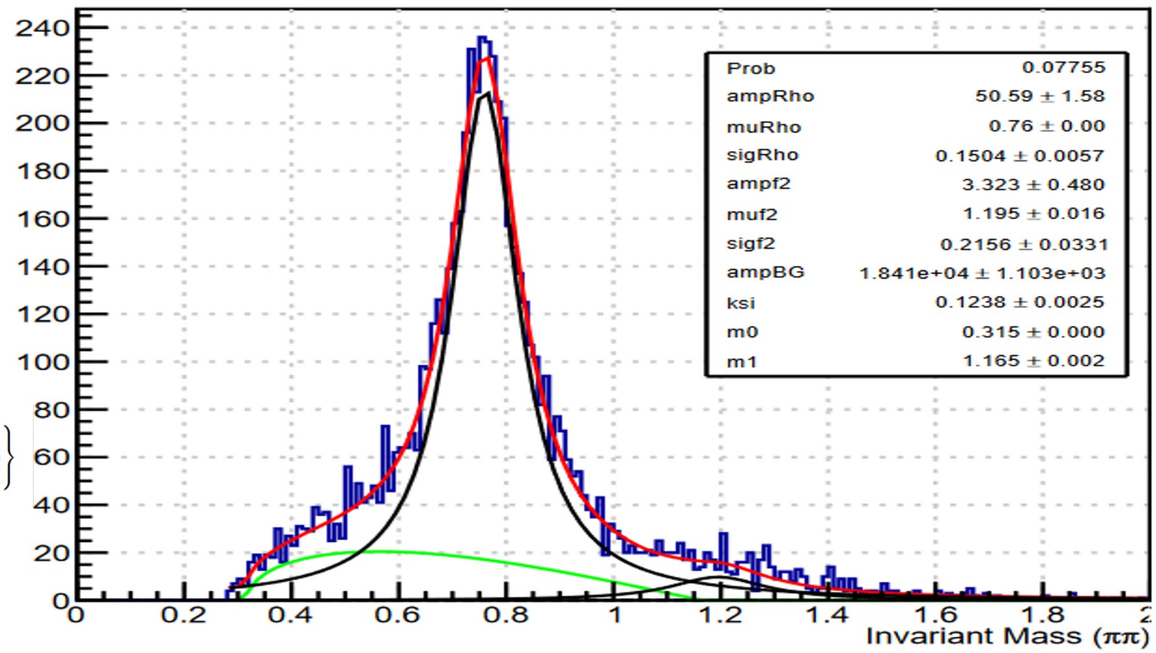
ARGUS inspired Distribution (Background)

$$F_{bg}(x) = N_{bg}\xi^3 \frac{m_1 - x}{(m_1 - m_0)^2}\sqrt{1 - \frac{(m_1 - x)^2}{(m_1 - m_0)^2}}\exp\left\{-\frac{1}{2}\xi^2(1 - \frac{(m_1 - x)^2}{(m_1 - m_0)^2})\right\}$$

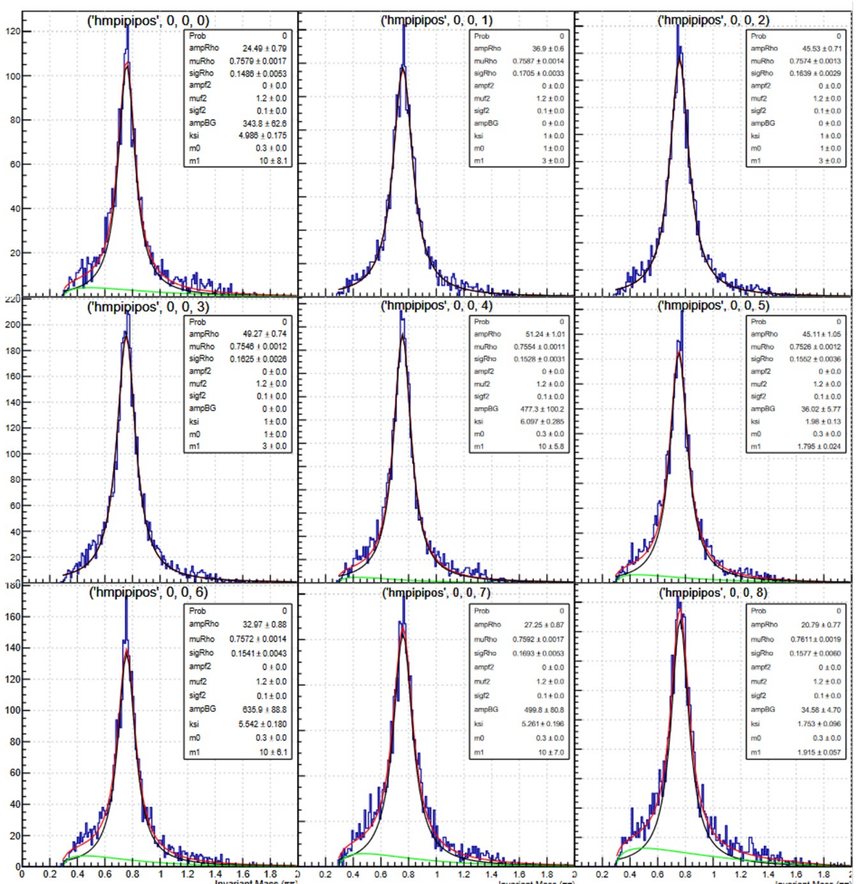
Total Distribution

$$F(M_{\pi\pi}) = N_\rho F_\rho^{bw} + N_{f2}F_{f2}^{bw} + N_{bg}F_{bg}$$

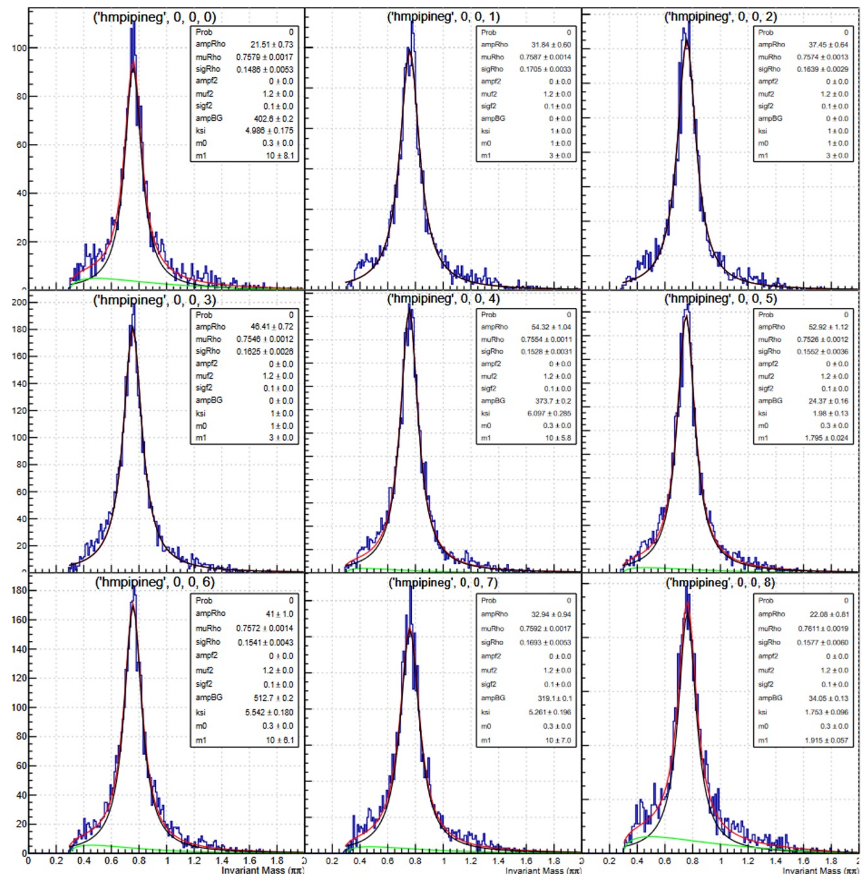
Invariant Mass of π+π-



1D ϕ Bins in -t: Invariant Mass Fits (-t bin 1)



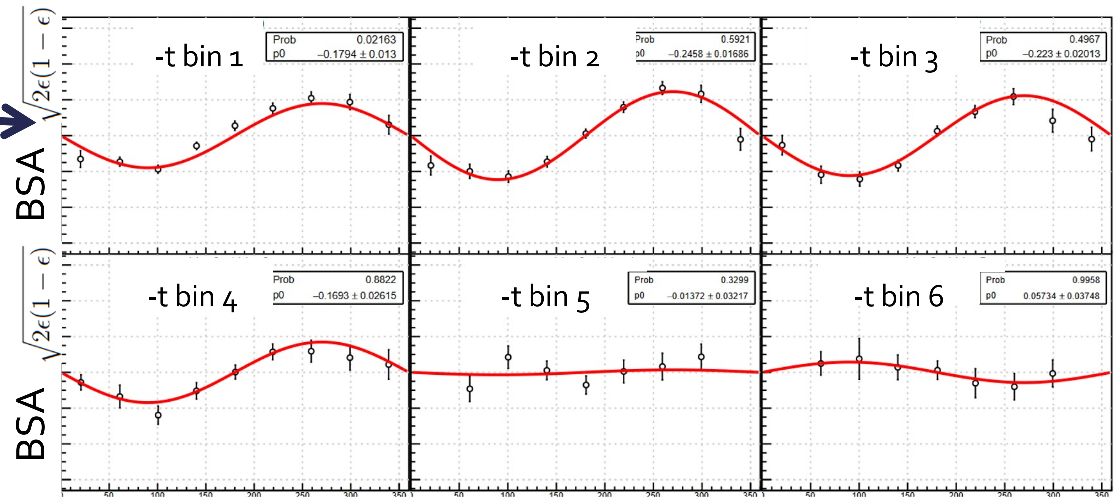
Positive Helicity



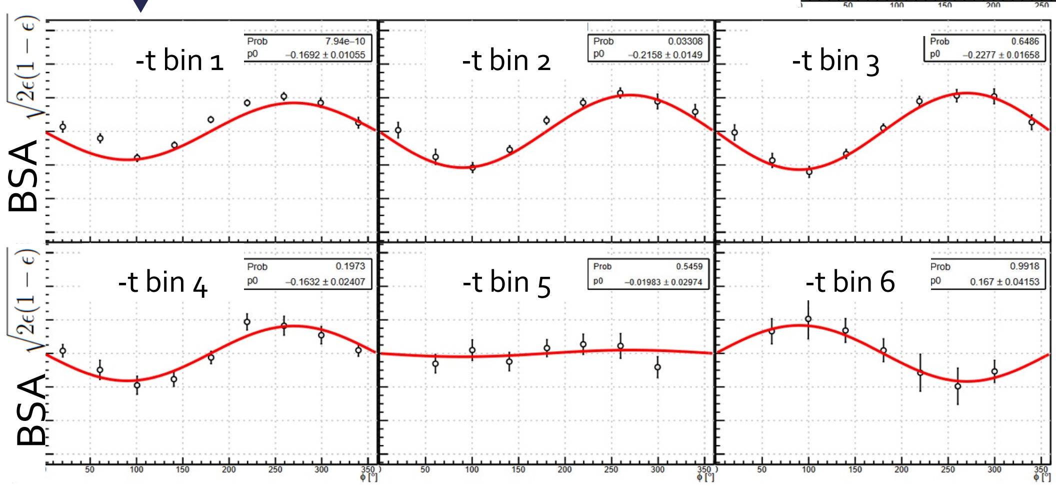
Negative Helicity

1D Bins in -t: BSA

Inbending



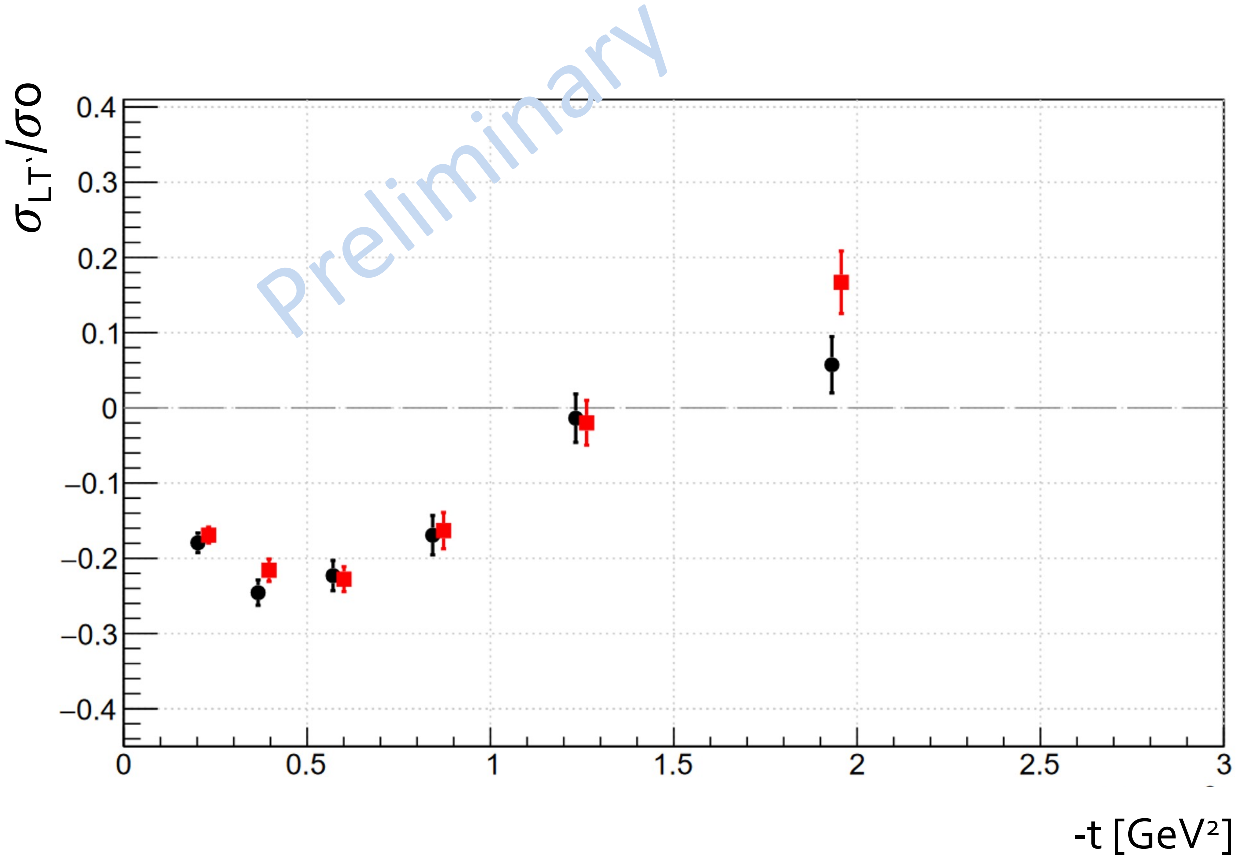
Outbending



$$BSA = \frac{1}{P_b}\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

$$BSA = A_{LU}\sin\phi$$

1D Bins in -t: $\sigma_{LT`}/\sigma_0$ for both inbending and outbending



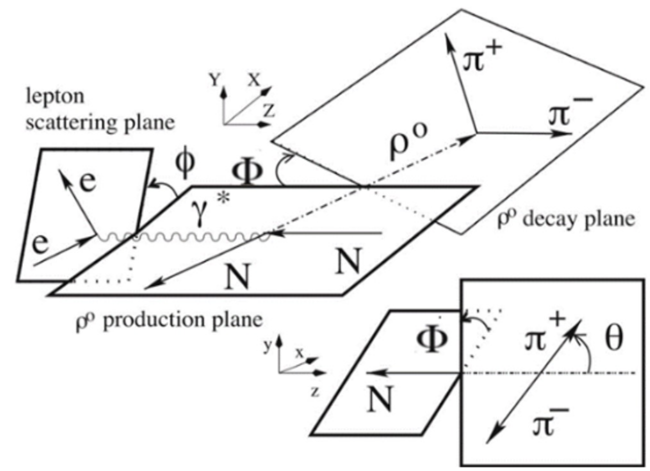
$$BSA = A_{LU} \sin\phi$$

$$A_{LU}^{\sin\phi} = \sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}^{\sin\phi}}{\sigma_0}$$

SDMEs from Exclusive ρ production with CLAS12

- 23 SDME elements are extract using the MLM:

$$-\ln L(\mathcal{R}) = -\sum_{i=1}^{N} \ln \frac{\mathcal{W}^{U+L}(\mathcal{R};\Phi_i,\phi_i,\cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R})}$$



15 unpolarized SDMEs

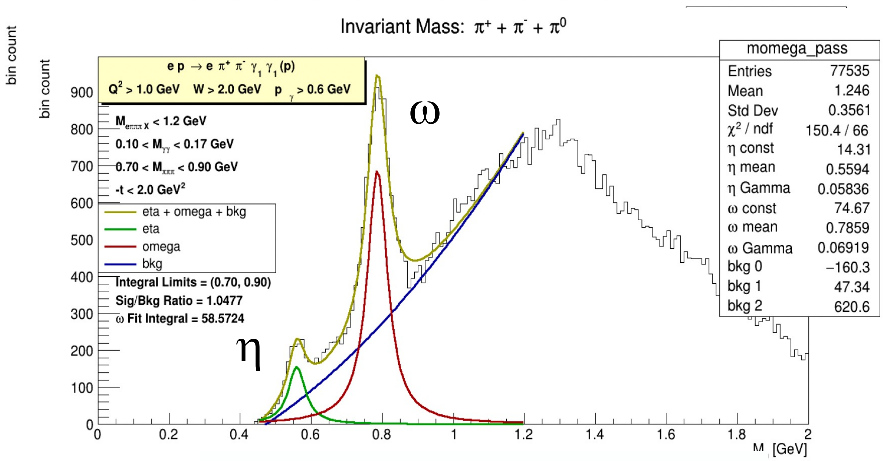
$$
\begin{aligned}
W^U(\Phi,\phi,cos(\Theta)) = {} & \frac{3}{8\pi^2}\Big(\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2(\Theta) \\
& -\sqrt{2}Re r^{04}_{10}\sin(2\Theta)\cos(\phi) - r^{04}_{1-1}\sin^2(\Theta)\cos(2\phi) \\
& -\epsilon\cos(2\Phi)[r^1_{11}\sin^2(\Theta) + r^1_{00}\cos^2(\Theta) \\
& -2Re\{r^1_{10}\}\sin(2\Theta)\cos(\phi) - r^1_{1-1}\sin^2(\Theta)\cos(2\phi)] \\
& -\epsilon sin(2\Phi)[\sqrt{2}Im\{r^2_{10}\}sin(2\Theta)sin(\phi) \\
& +Im\{r^2_{1-1}\}\sin^2(\Theta)\sin(2\phi)] \\
& \sqrt{2\epsilon(1+\epsilon)}\cos(\Phi)[r^5_{11}\sin^2(\Theta) + r^5_{00}\cos^2(\Theta) \\
& -\sqrt{2}Re\{r^5_{10}\}\sin(2\Theta)\cos(\phi) - r^5_{1-1}\sin^2(\Theta)\cos(2\phi)] \\
& +\sqrt{2\epsilon(1+\epsilon)}\sin(\Phi)[\sqrt{2}Im\{r^6_{10}\}\sin(2\Theta)\sin(\phi) \\
& +Im\{r^6_{1-1}\}\sin^2(\Theta)\sin(2\phi)]\Big)
\end{aligned}
$$

8 polarized SDMEs

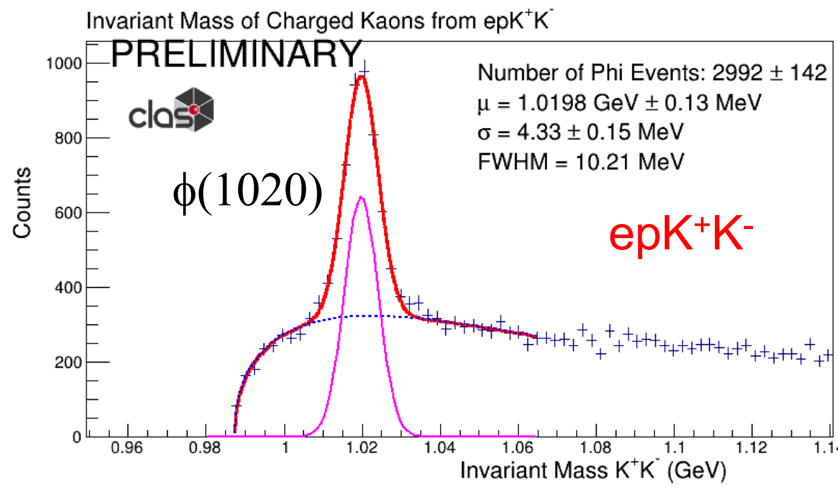
$$
\begin{aligned}
W^L(\Phi,\phi,cos(\Theta)) = {} & \frac{3}{8\pi^2}\Big(\sqrt{1-\epsilon^2}[\sqrt{2}Im\{r^3_{10}\}\sin(2\Theta)\sin(\phi) \\
& +Im\{r^3_{1-1}\}\sin^2(\Theta)\sin(2\phi)] \\
& +\sqrt{2\epsilon(1+\epsilon)}\cos(\Phi)[\sqrt{2}Im\{r^7_{10}\sin(2\Theta)\sin(\phi) \\
& +Im\{r^7_{1-1}\}\sin^2(\Theta)\sin(2\phi)] \\
& +\sqrt{2\epsilon(1+\epsilon)}\sin(\Phi)[r^8_{11}\sin^2(\Theta) + r^8_{00}\cos^2(\Theta) \\
& -\sqrt{2}Re\{r^8_{10}\}\sin(2\Theta)\cos(\phi) + r^8_{1-1}\sin^2(\Theta)\cos(2\phi)]\Big)
\end{aligned}
$$

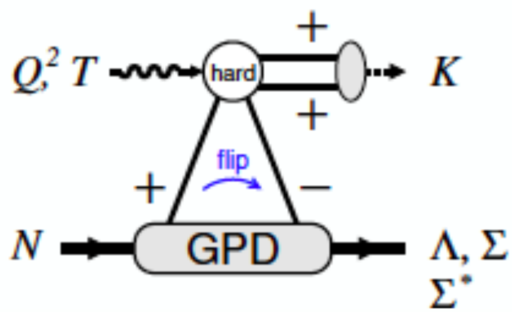
Exclusive ω, ϕ productions and $K\Lambda(1520)$ with CLAS12

Invariant Mass: $\pi^+ + \pi^- + \pi^0$



Invariant Mass: K^+K^-



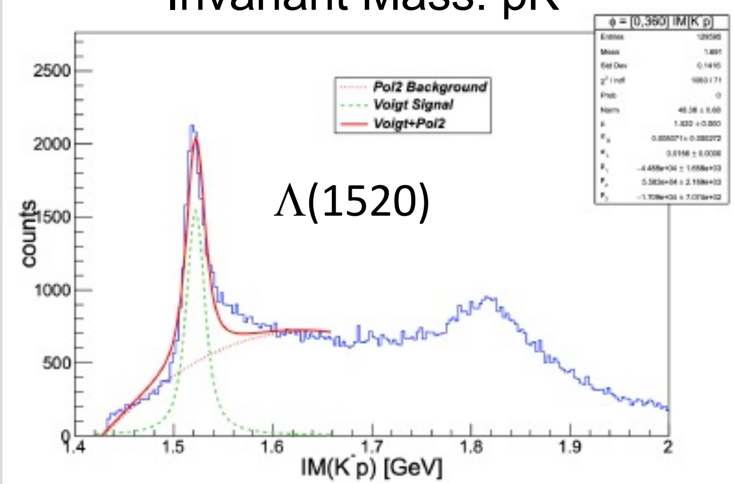


Symmetry relations for strange chiral-odd GPDs

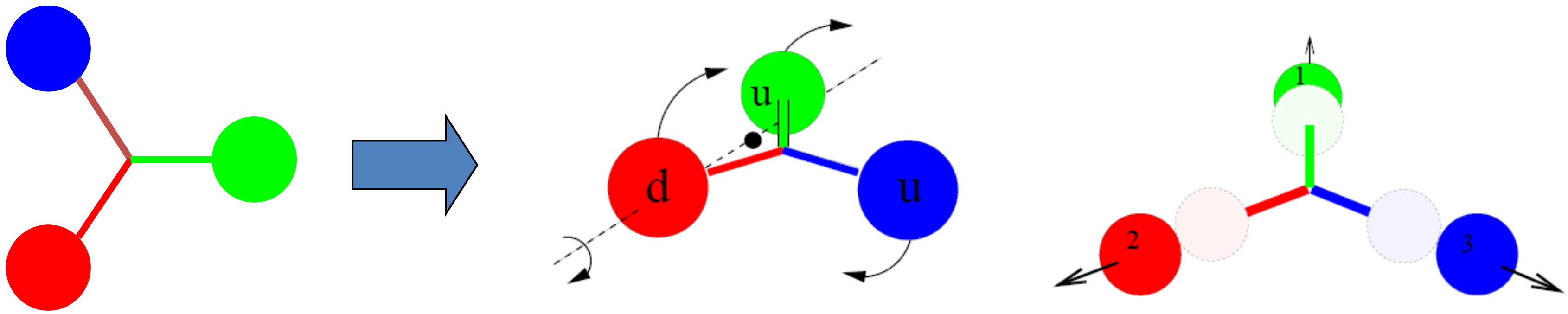
$N \to \Lambda, \Sigma$ related to $N \to N$
by conventional SU(3) flavor symmetry

$N \to \Sigma^*$ related to $N \to N, \Lambda, \Sigma$
by SU(6) spin-flavor symmetry in large-N_c limit

Invariant Mass: pK^-



From the ground state nucleon to resonances



How does the exitation affect the 3D structure of the Nucleon?

→ Pressure distributions, tensor charge, … of resonances?

Traditional way: Study of transition form factors (**2D picture** of transv. position)

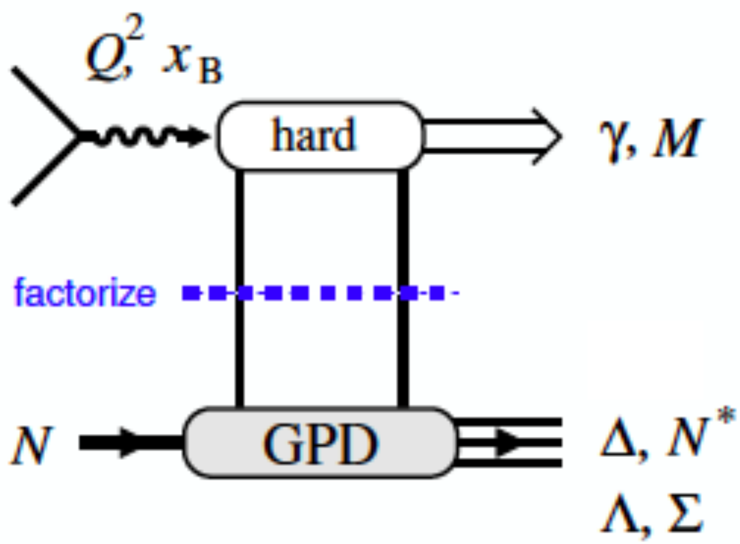
3D picture of the exitation process: Encoded in **transition GPDs**

Simplest case: N→Δ transition ➔ **16 transition GPDs**

P. Kroll and K. Passek-Kumericki, Phys. Rev. D 107, 054009 (2023).
K. Semenov, M. Vanderhaeghen, arXiv:2303.00119 (2023).

- **8 helicity non-flip transition GPDs (twist 2)**
  - Related to the Jones-Scardon and Adler EM FF for the N → Δ transition
- **8 helicity flip transition GPDs (transversity)**

Exploring Transition GPDs with CLAS12



Transition GPDs

Factorization of hard exclusive processes

GPDs for resonance final states

Theoretical methods: Chiral dynamics, $1/N_c$ expansion of QCD

Processes

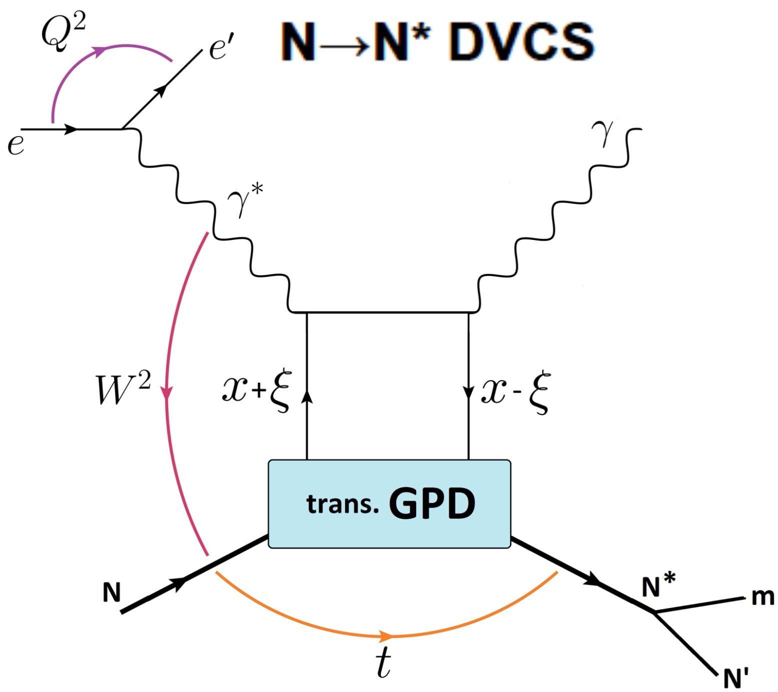
$N \rightarrow \Delta$ in DVCS

$N \rightarrow \Delta, N^*$ in π, η production

$N \rightarrow \Lambda, \Sigma$ in K, K^* production

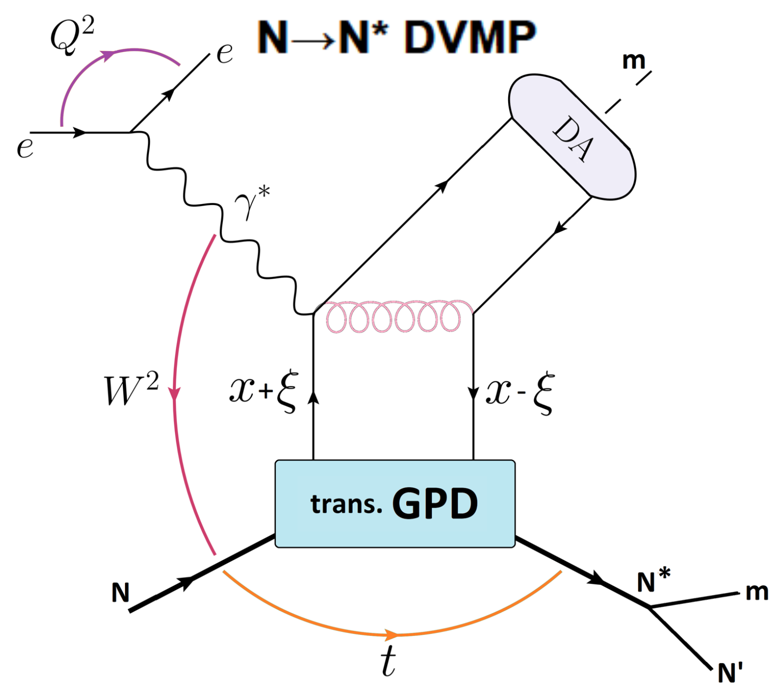
Non-diagonal DVCS / DVMP

non-diagonal DVCS



Access to the helicity non-flip transition GPDs

non-diagonal DVMP

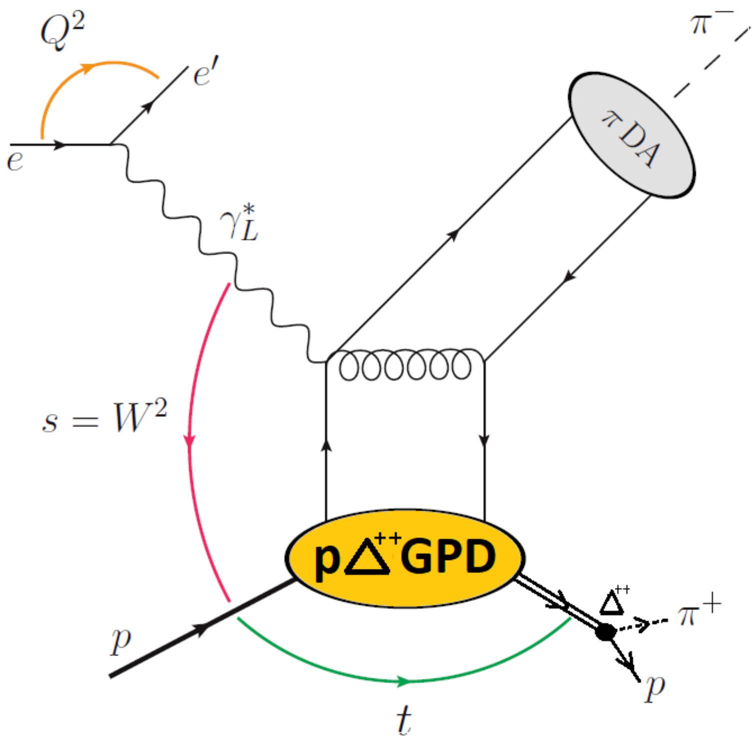


+ Access to the helicity flip transition GPDs

W > 2 GeV

Factorisation expected for: $-t / Q^2 \ll 1$, x_B fixed and $Q^2 > M^2_{N^*}$

$ep \to e\Delta^{++}\pi^{-} \to ep\pi^{+}\pi^{-}$



Factorization expected for:

$-t / Q^2 << 1$, x_B fixed, and $Q^2 > M_\Delta{}^2$

- Provides access to p-Δ transition GPDs

$$ep \to e\Delta^{++}\pi^{-} \to ep\pi^{+}\pi^{-}$$

I_z = +3/2

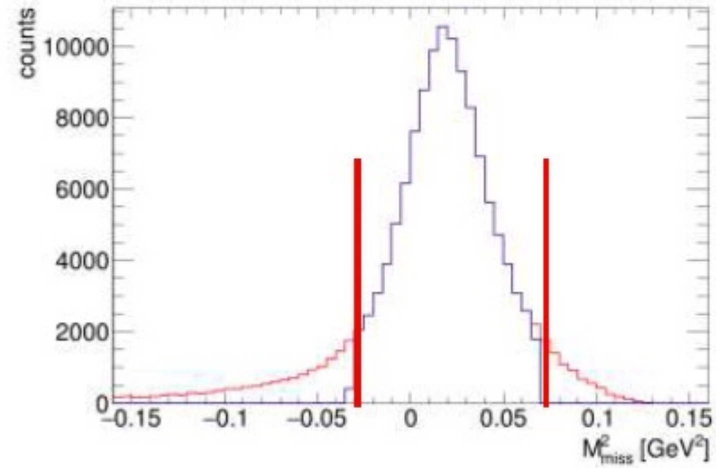
- The $p\pi^+$ final state can **only** be populated by **Δ-resonances ->** Large gap between Δ(1232) and higher resonances

Event Selection and Kinematic Cuts

Event selection: $ep \rightarrow ep\pi^- X$

$$X = \pi^+$$

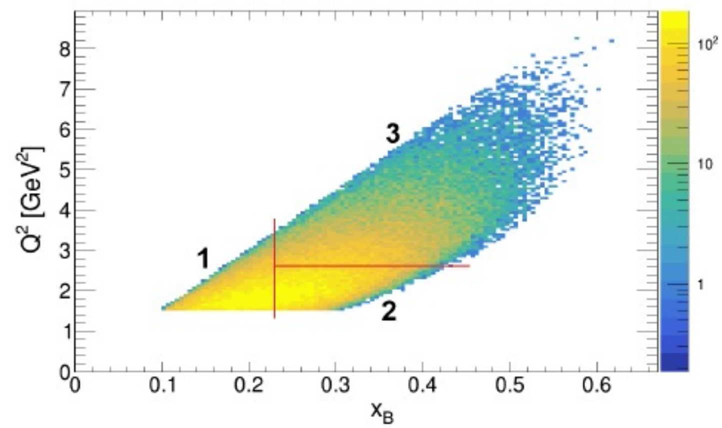
➔ 2 sigma cut around the missing π^+



Kinematic cuts:

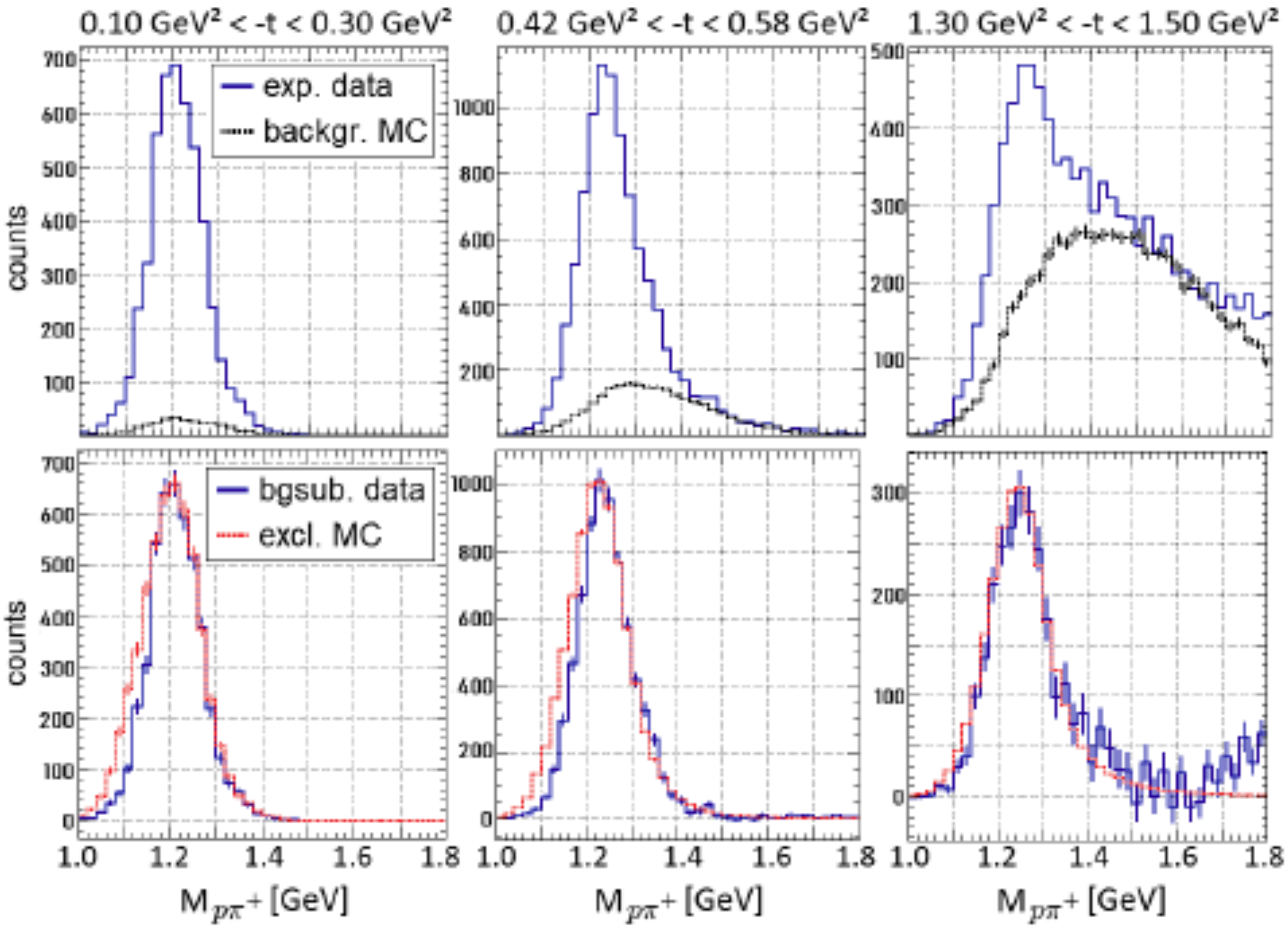
$Q^2 > 1.5$ GeV^2 $\quad$ $W > 2$ GeV

$y < 0.75$ $\quad$ $-t < 1.5$ GeV^2

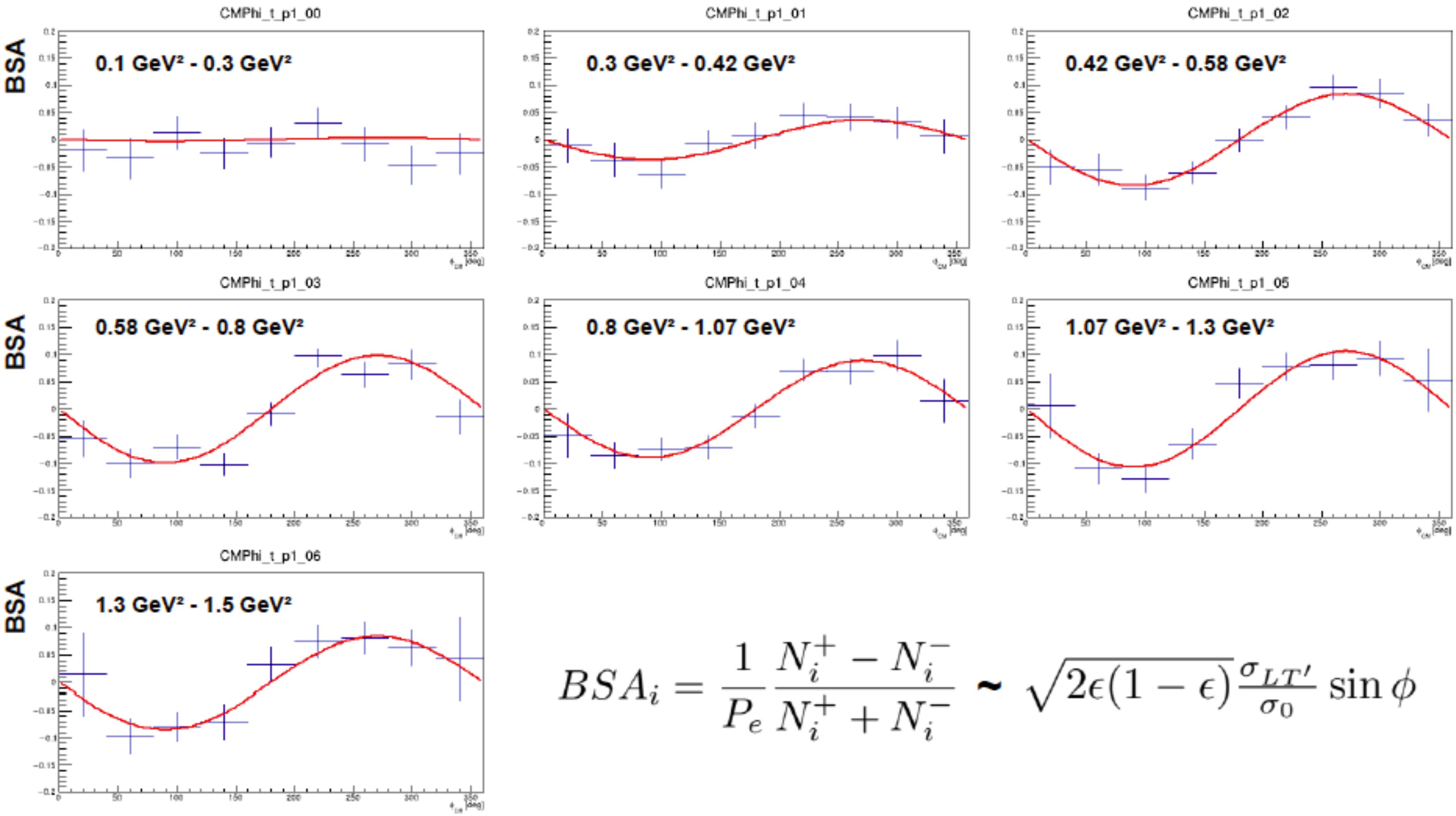


Signal and Background Separation

$$ep \to e\Delta^{++}\pi^{-} \to ep\pi^{+}\pi^{-}$$



Resulting Beam Spin Asymmetries (Q^2-x_B integrated)



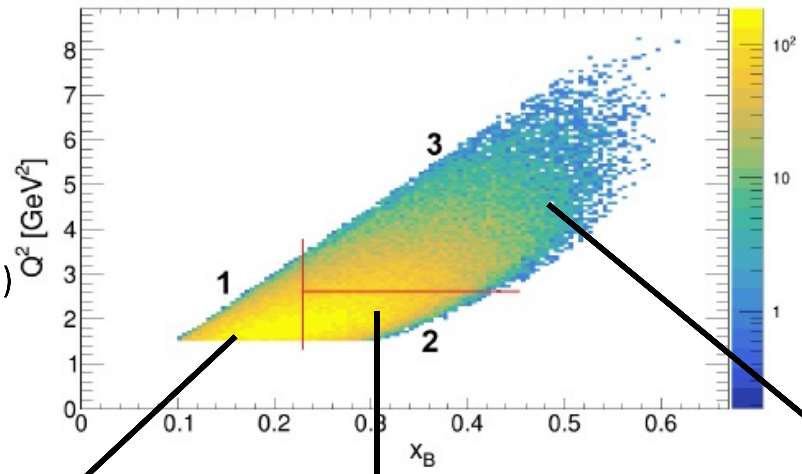
$$BSA_i = \frac{1}{P_e}\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-} \sim \sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi$$

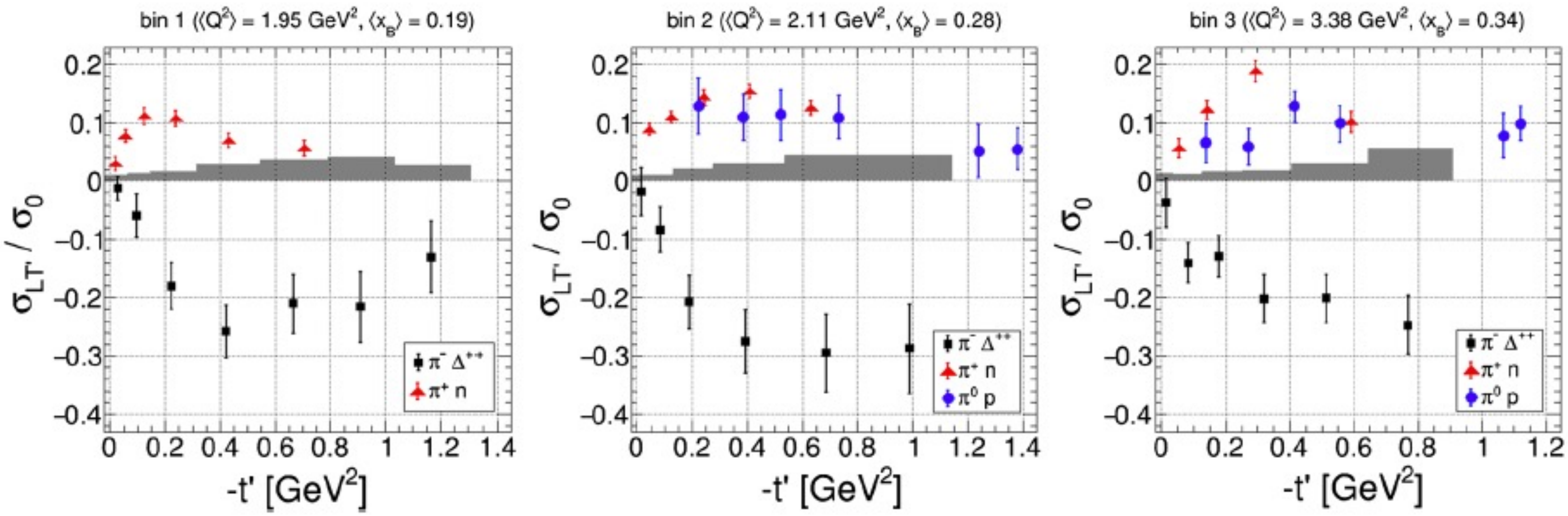
Results

$$ep \to e\Delta^{++}\pi^{-}$$
$$\to ep\pi^{+}\pi^{-}$$

S. Diehl et al. (CLAS collab.),
Phys. Rev. Lett. 131, 021901 (2023)

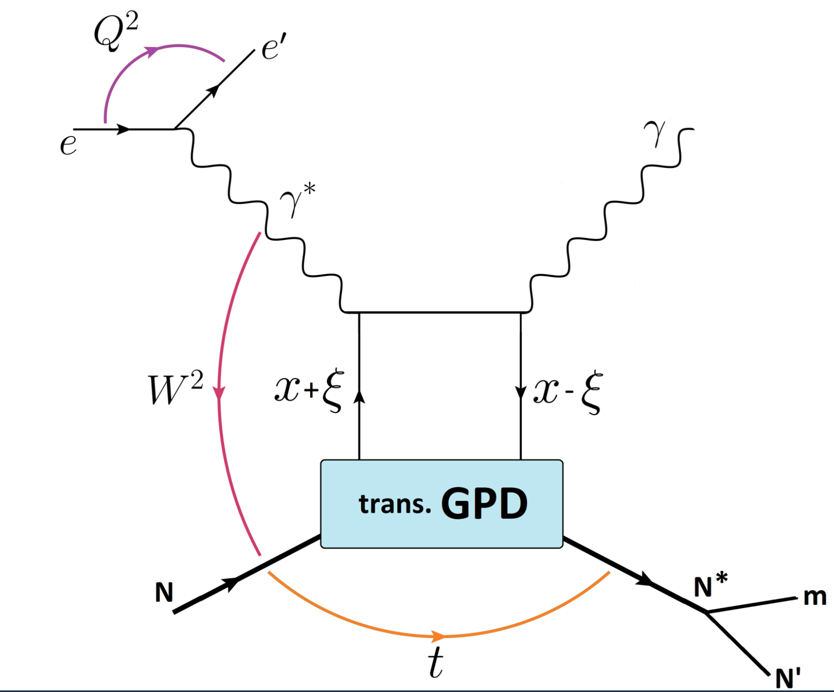
S. Diehl et al. (CLAS collab.)
Phys. Lett. B 839, 137761 (2023)
A. Kim et al. (CLAS collab.)
Phys. Lett. B 849, 138459 (2024)



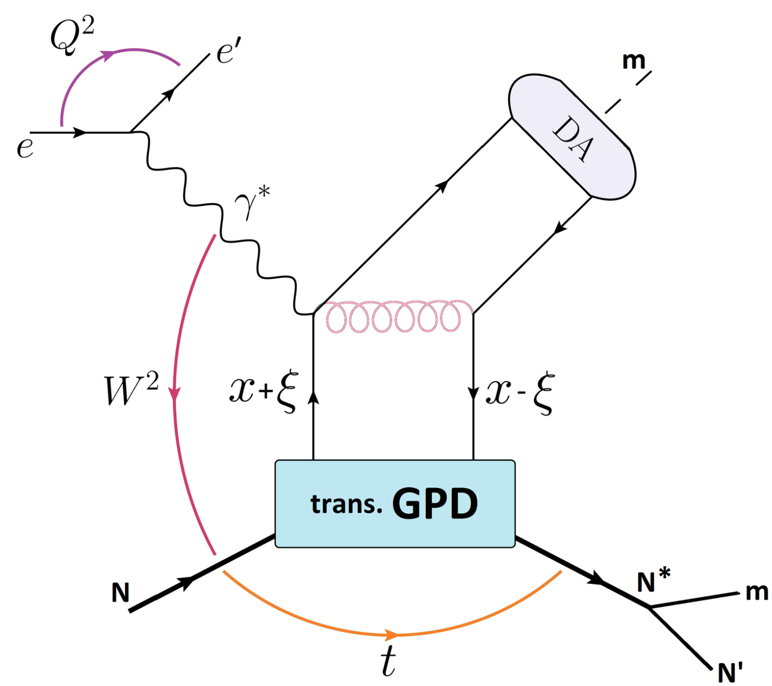


Non-diagonal DVCS / DVMP

non-diagonal DVCS



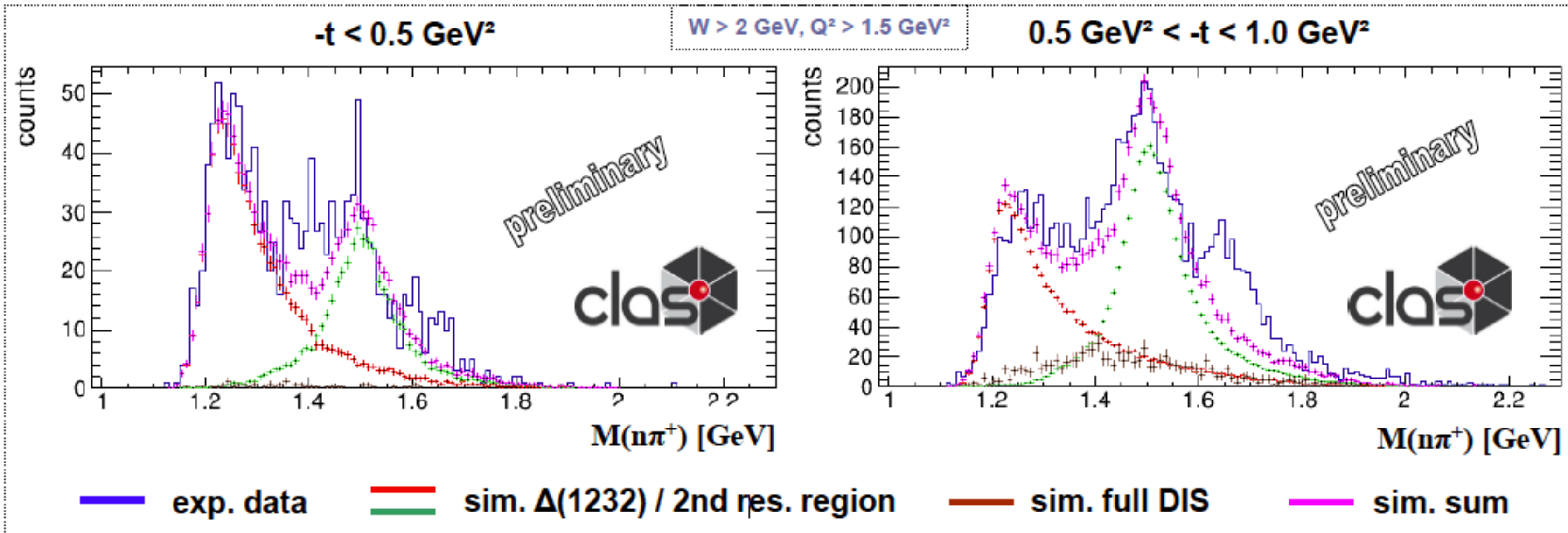
non-diagonal DVMP



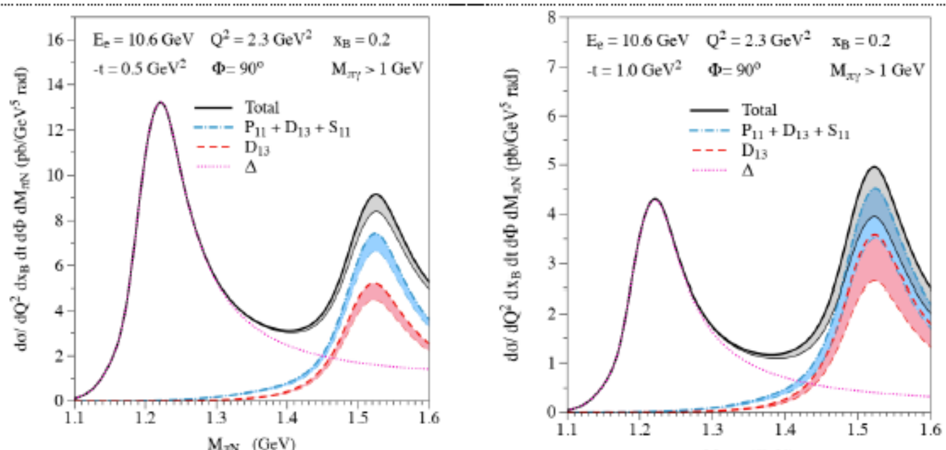
factorization expected for: $-t/Q^2$ small, $Q^2 > M^2_{N^*}$ x_B fixed

N->$\Delta(1232)$ transition GPDs: 8 twist-2 GPDs: 4 unpolarized, 4 polarized. K. Semenov, M. Vanderhaeghen, arXiv:2303.00119 (2023)

N–>N* DVCS Processes: ep->e′N*γ->e′nπ⁺γ



Experiment: S. Diehl
(JLU Gießen + UConn)

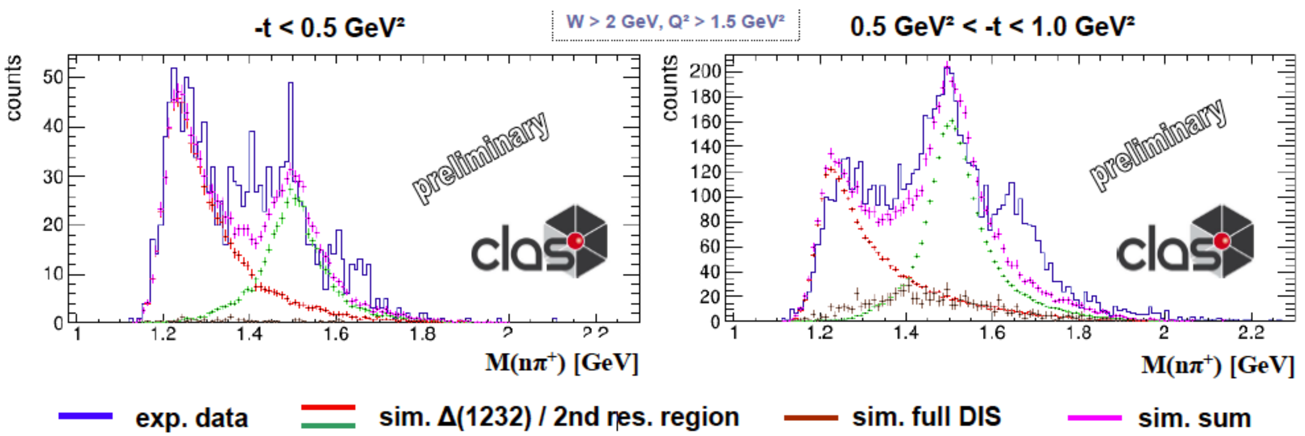


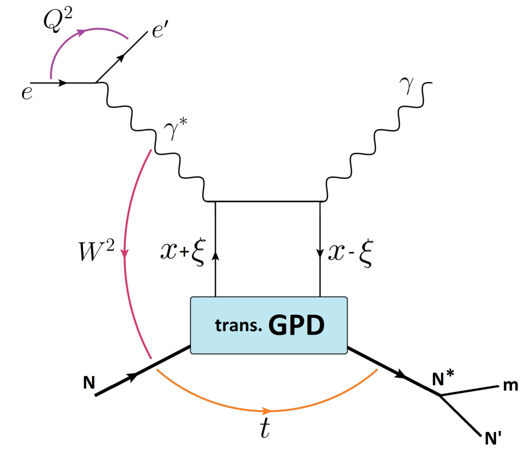
M($n\pi^+$) (GeV) M($n\pi^+$) (GeV)

Theroy:
K. Semenov-Tian-Shansky,
M. Vanderhaeghen,
Phys. Rev. D 108,
034021 (2023)

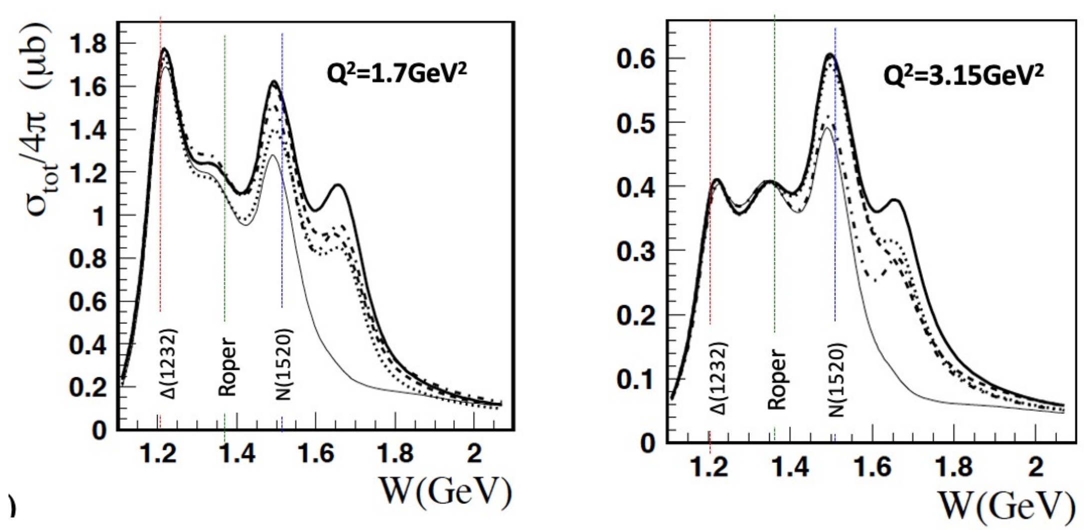
N–>N* DVCS Processes: ep->e´N*γ->e´nπ⁺γ

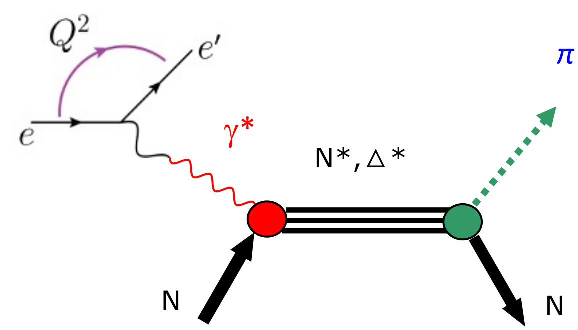
ep->e´nπ⁺γ





ep->e´nπ⁺





Electron Scattering Binning Scheme

	Resonance Region	DIS Region
Inclusive Scattering	Q^2, W	Q^2, x_B
Exclusive Process (γ, π)	Q^2, W, $\cos\theta_h$, ϕ_h	Q^2, x_B, $-t$, ϕ_h
Exclusive Process (ρ, ϕ, ..)	Q^2, W, $\cos\theta_h$, ϕ_h, θ, ϕ	Q^2, x_B, $-t$, ϕ_h , θ, ϕ

Off-diagonal DVCS or DVMP Q^2, x_B, $-t$, ϕ_h, $M_{\pi N}$, $\cos\theta$, ϕ

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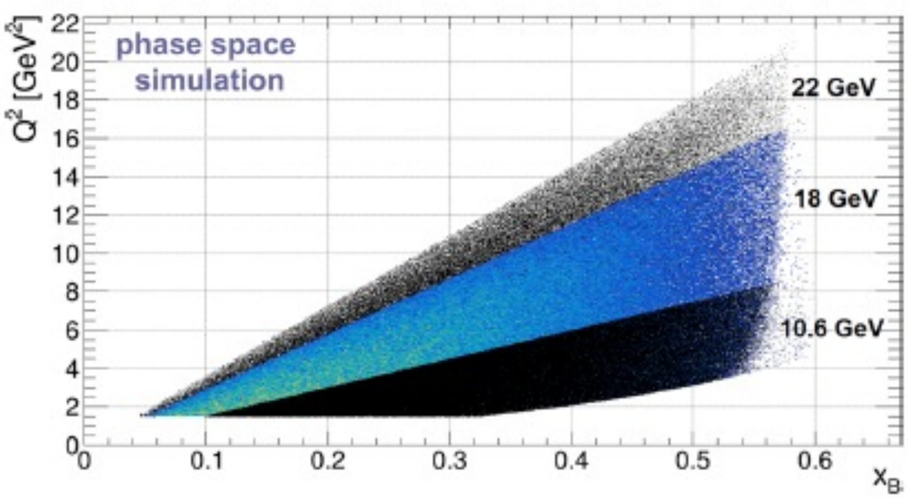
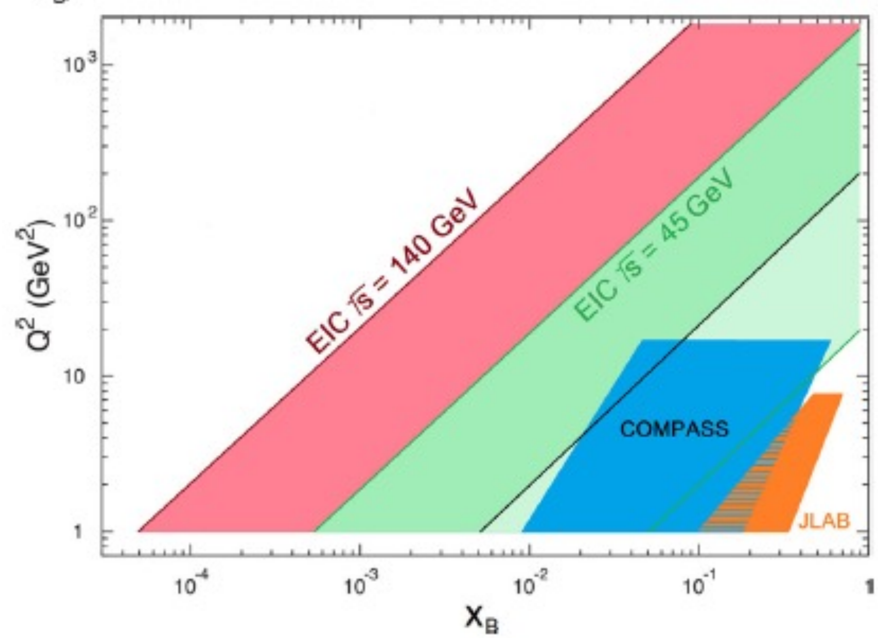
Jefferson Lab

From JLab 11 GeV to JLab 22 GeV to COMPASS to EIC



JLab 12+22 : low-x regime, valence quark.

EIC: Extending the kinematic regime to the sea-quark and gluon sector.



Conclusion and Outlook

1. Deeply virtual exclusive processes (DVEP) will help us to map the spatial distributions of quarks and gluons in the nucleon and potentially also in baryon resonances.

2. JLab CLAS12 has a comprehensive program in deeply virtual exclusive processes.

3. One essential point concerns the approach to the small-size regime, where the production of q q-qbar pair with sizes << hadronic size dominates. QCD factorization and GPD extraction assume that this regime is attained (!).

4. At present 12 GeV kinematics, whether we attain this regime is under investigation.

5. EIC science program will profoundly impact our understanding of the most fundamental inner structure of the matter that builds us all.

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