3D nucleon structure with CLAS12 at Jefferson Lab

2024
JAN
29-31
EIC Asia Workshop

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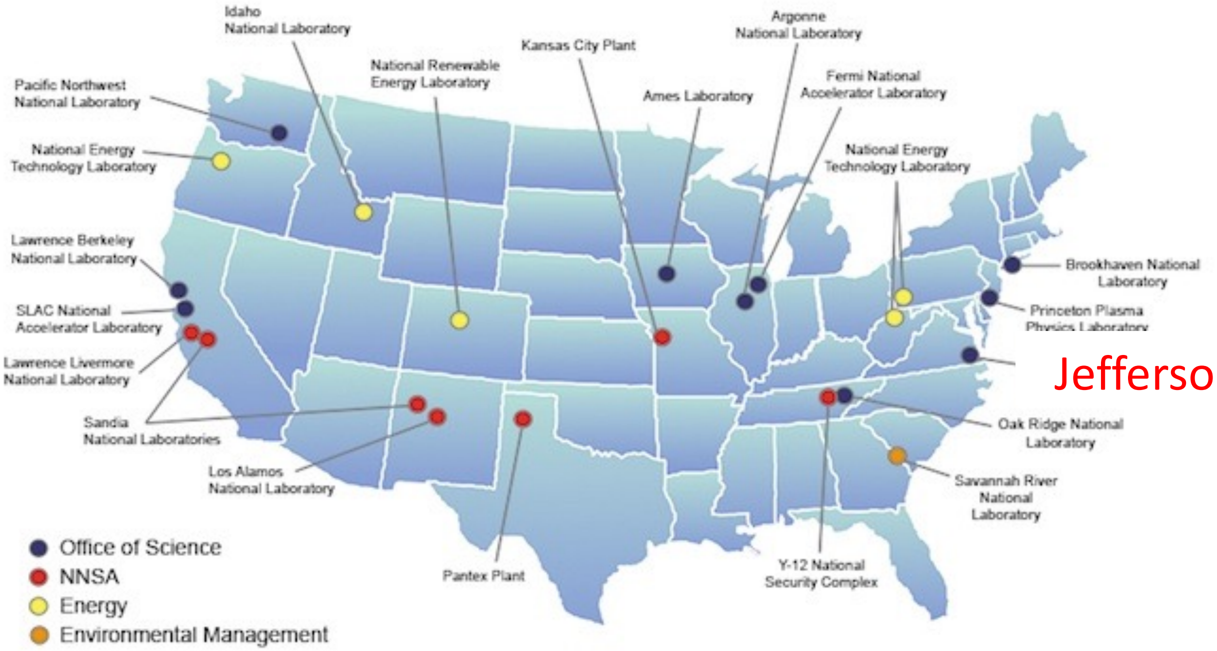
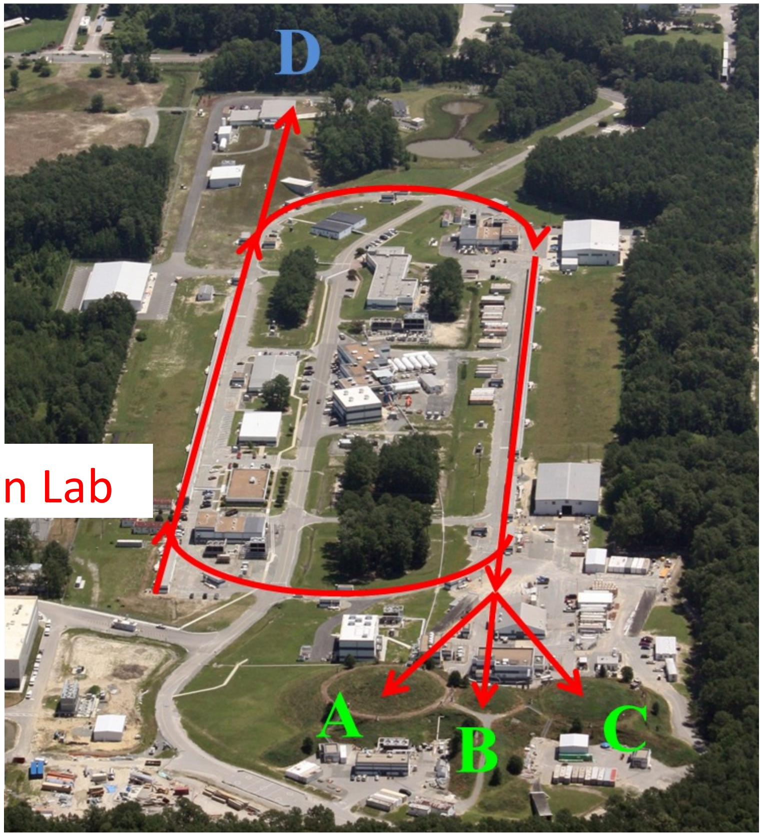
January 29, 2024

Thomas Jefferson National Accelerator Facility (Jefferson Lab)



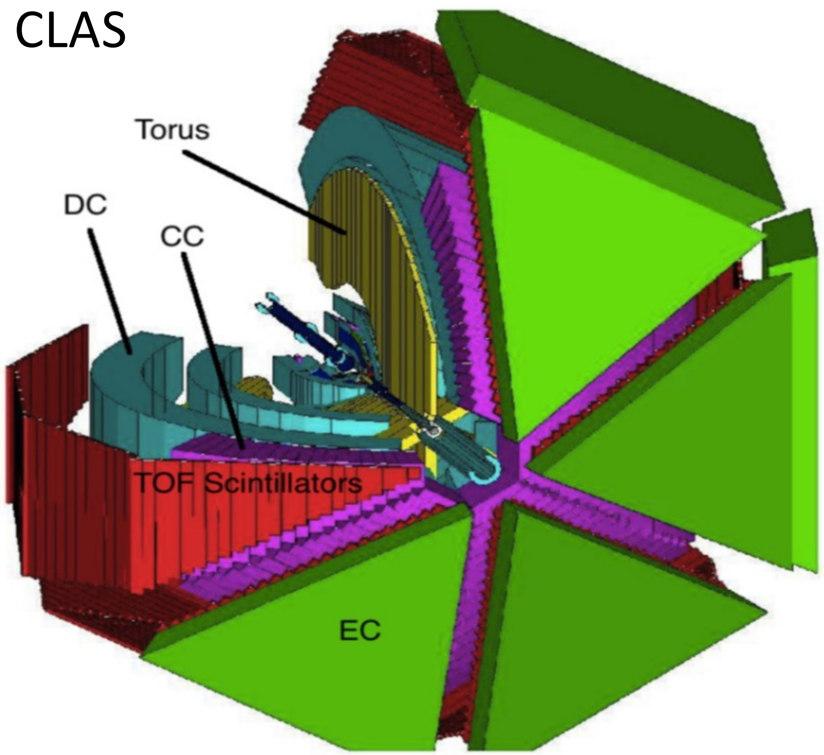
Jefferson Lab

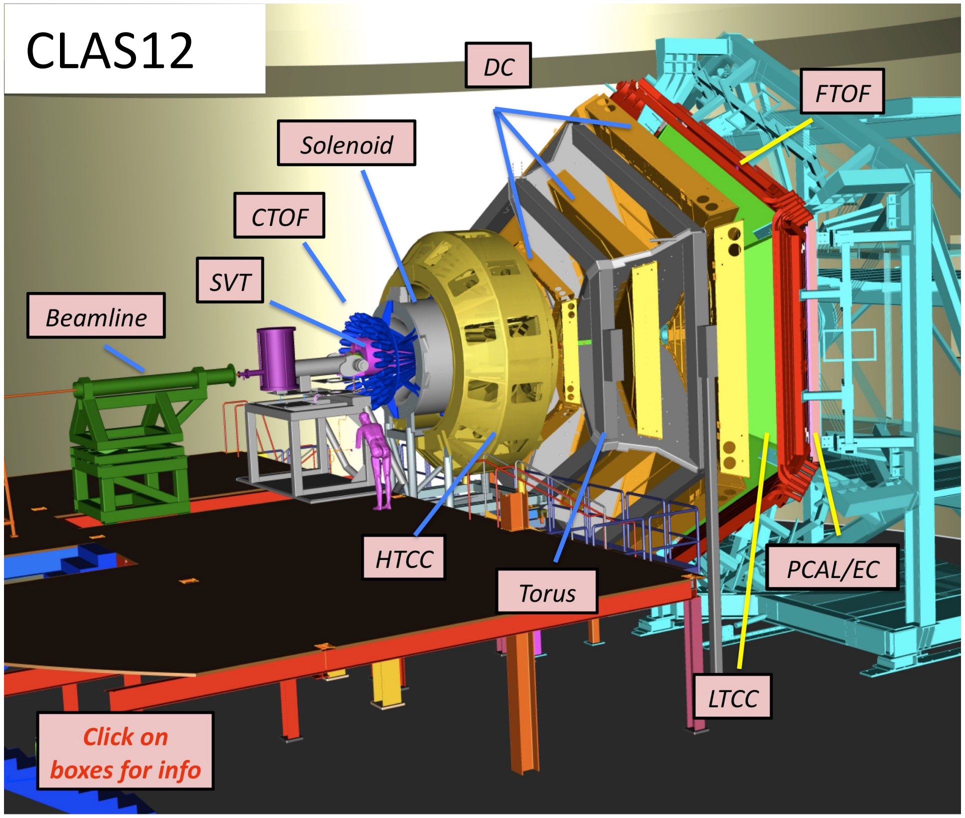


- **Newport News, Virginia (US east coast)**
- **1995 - 2012 6 GeV electron beam**
- **2018 - today 11 / 12 GeV electron beam / photon beam**

CLAS / CLAS12 in Hall B at Jefferson Lab

- **1995 – 2012, 6 GeV electron beam**
- **2018 – today, 11 GeV electron beam**

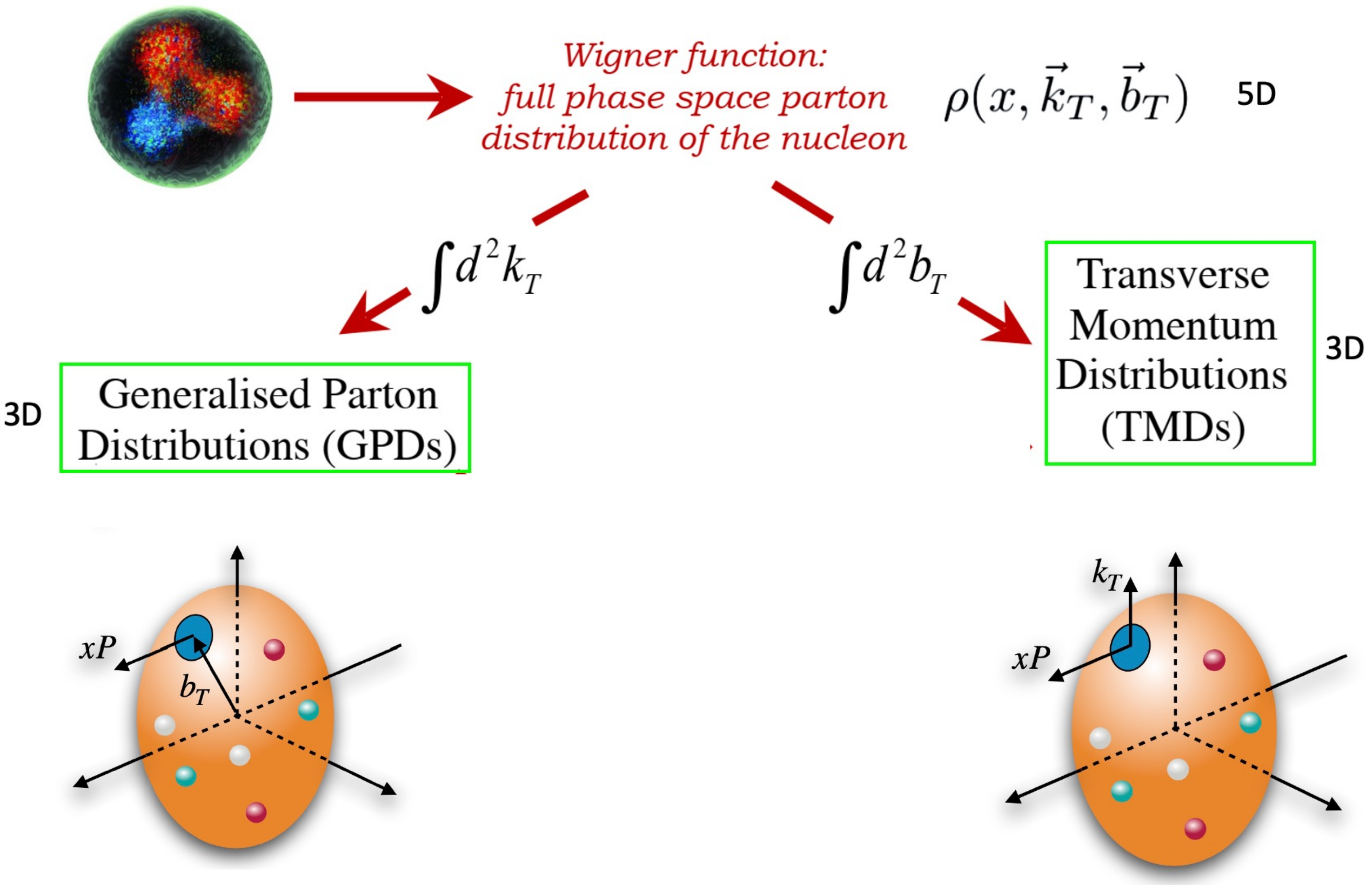




- $\mathcal{L} = 1 \times 10^{35}$ cm^{-2}s^{-1}
- Inclusive electron trigger (all reactions will be analyzed in parallel)

→ $I_{max} = 90\ \mu A$, $Pol_{max} \sim 90\%$

3-Dimensional Imaging of Quarks and Gluons



Wigner function: full phase space parton distribution of the nucleon

$\rho(x,\vec{k}_T,\vec{b}_T)$ 5D

$\int d^2k_T$

$\int d^2b_T$

3D Generalised Parton Distributions (GPDs)

Transverse Momentum Distributions (TMDs) 3D

Generalized Parton Distributions (GPDs)

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

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

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

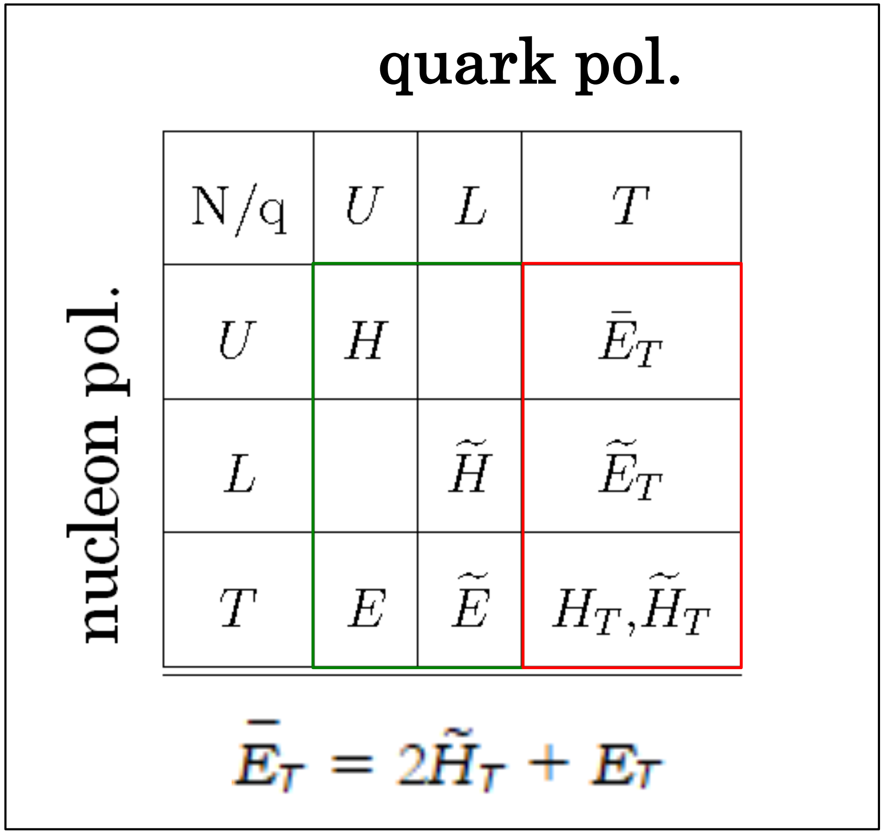
Integrate over transverse ***momentum*** space

↓

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	$\widetilde{E}$	$H_T, \widetilde{H}_T$

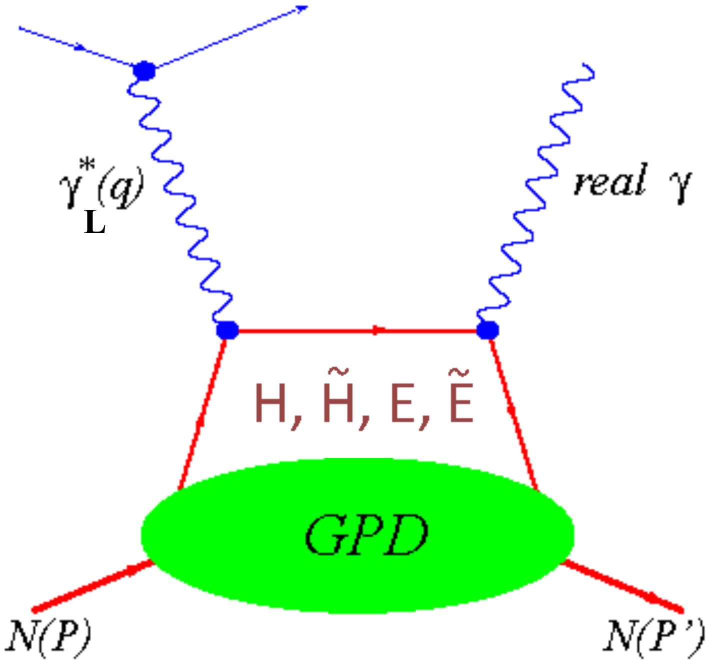
$$\bar{E}_T = 2\widetilde{H}_T + E_T$$

Key Information from GPDs

- Multi-dimensional picture of the proton in (1+2)D
- Access to form factors of energy momentum tensor
  - Mechanical properties of the nucleon
  - Quark and gluon contribution to mass of the nucleon
- Sum rule for angular momentum

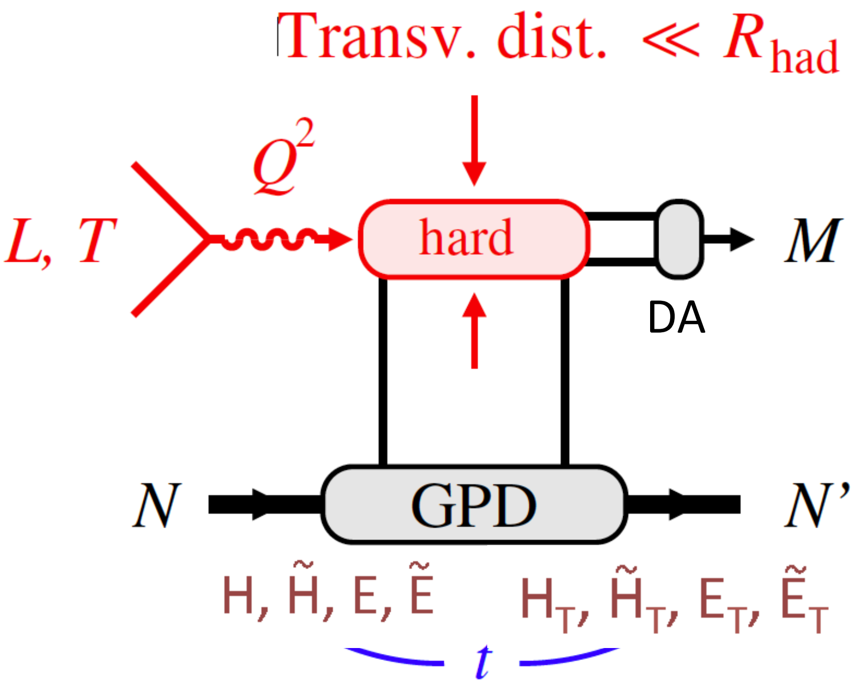
Study GPDs: Deeply Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



- + Clean process
- - Only sensitive to chiral even GPDs

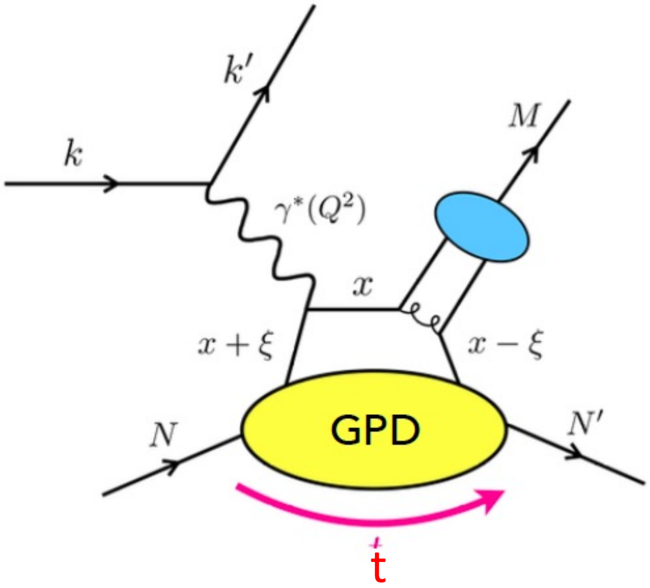
Deeply Virtual Meson Production (DVMP)



- + Access to transversity degrees of freedom described by chiral-odd GPDs
- - Distribution Amplitude (DA) is involved as additional soft non pert. quantity

Deeply Virtual Meson Production

	Meson	Flavor
$\mathcal{H}_T, \bar{\mathcal{E}}_T$	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



H_T is related to the protons tensor charge

$$\delta_T^{u,d} = \int dx H_T^{u,d}(x, \xi = 0, t = 0)$$

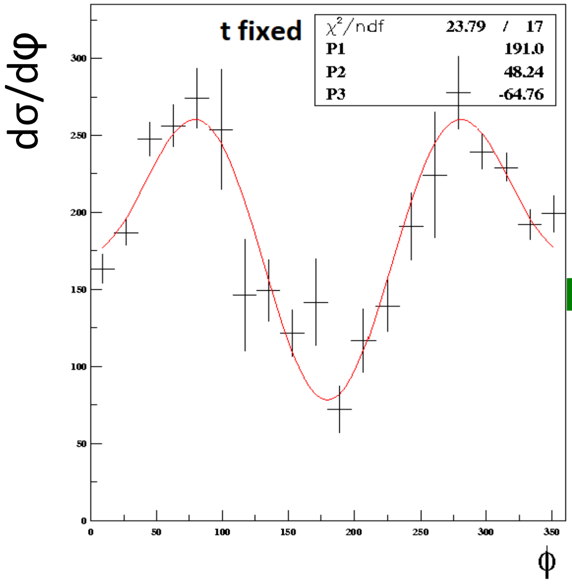
➔ Absolute magnitude of transversly polarized valence quarks inside a transv. polarized nucleon

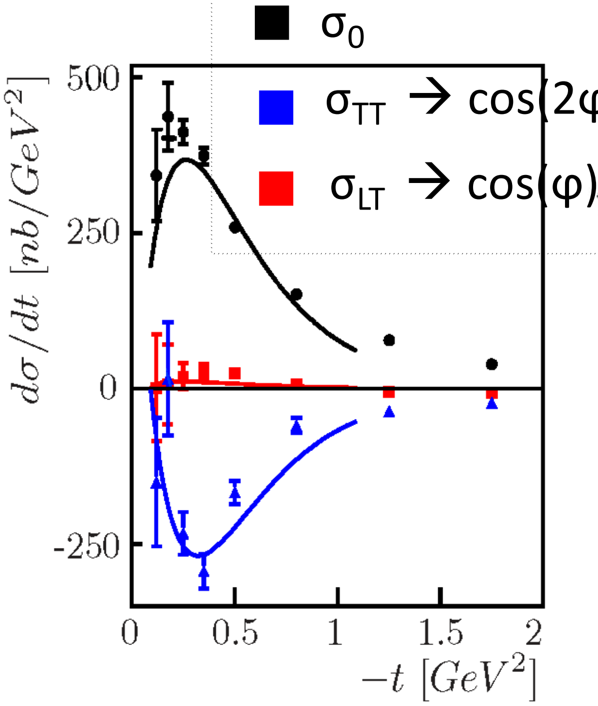
$\bar{E}_T$ is related to the protons anomalous tensor magnetic moment

$$k_T^{u,d} = \int dx \bar{E}_T^{u,d}(x, \xi = 0, t = 0)$$

Differential Cross Section of DVMP (π^0)

$$\frac{d^4\sigma}{dQ^2 dx_B d\phi dt} \propto \boxed{\sigma_T + \epsilon\sigma_L} + \epsilon\boxed{\sigma_{TT}} \cdot \cos(2\phi) + \sqrt{2\epsilon(1+\epsilon)} \cdot \boxed{\sigma_{LT}} \cdot \cos(\phi)$$

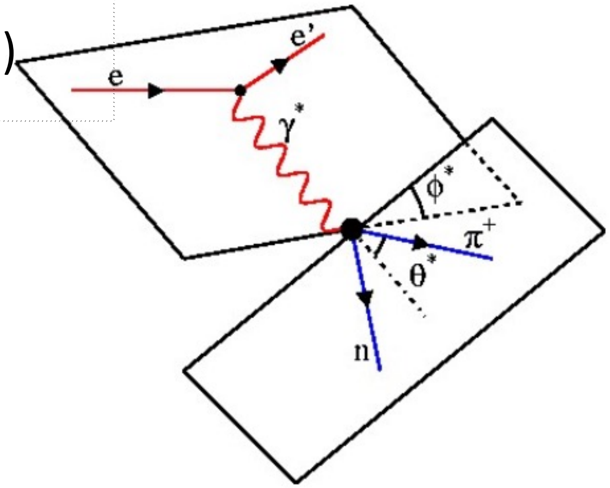




■ σ_0

🟦 σ_{TT} → cos(2φ)

🟥 σ_{LT} → cos(φ)



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

$$\sigma_{TT} \propto \frac{t'}{Q^4}\left|\bar{E}_T\right|^2 \qquad \sigma_{LT} \propto \frac{\sqrt{-t'}}{Q^4}\,\xi\,\sqrt{1-\xi^2}\;Re\left[\langle H_T\rangle^* \left\langle \widetilde{E} \right\rangle\right]$$

Pseudoscalar meson electroproduction with CLAS12

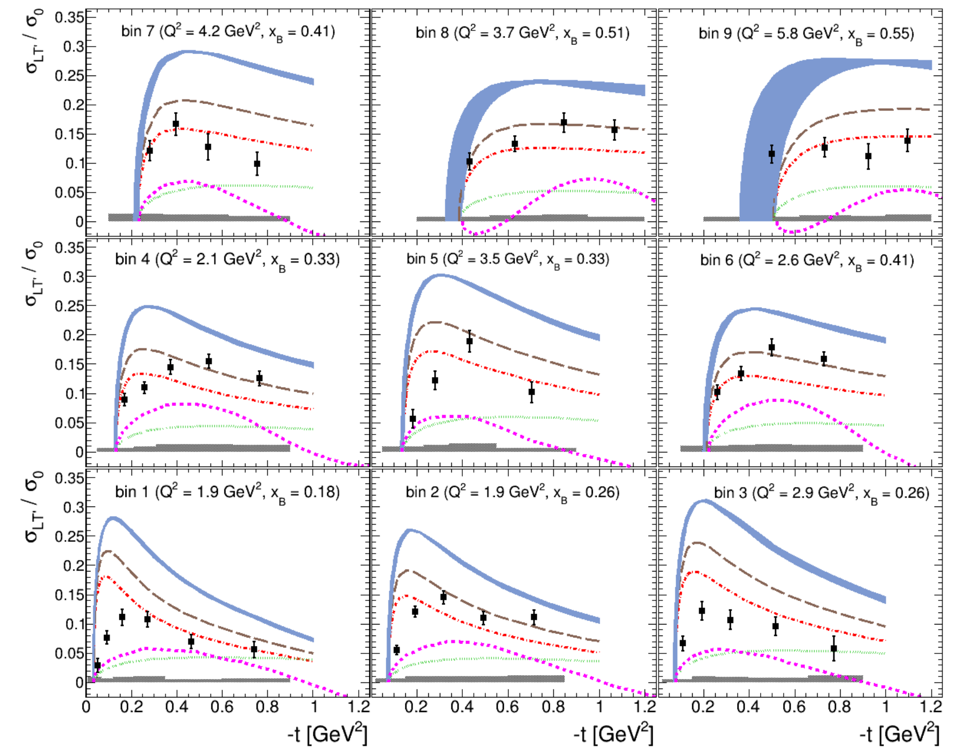
$$\frac{d^4\sigma}{dQ^2dx_Bd\phi dt} \propto \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cdot\cos(2\phi) + \sqrt{2\epsilon(1+\epsilon)}\cdot\sigma_{LT}\cdot\cos(\phi) + P_b\cdot\boxed{\sqrt{2\epsilon(1-\epsilon)}\cdot\sigma_{LT'}\cdot\sin(\phi)}$$

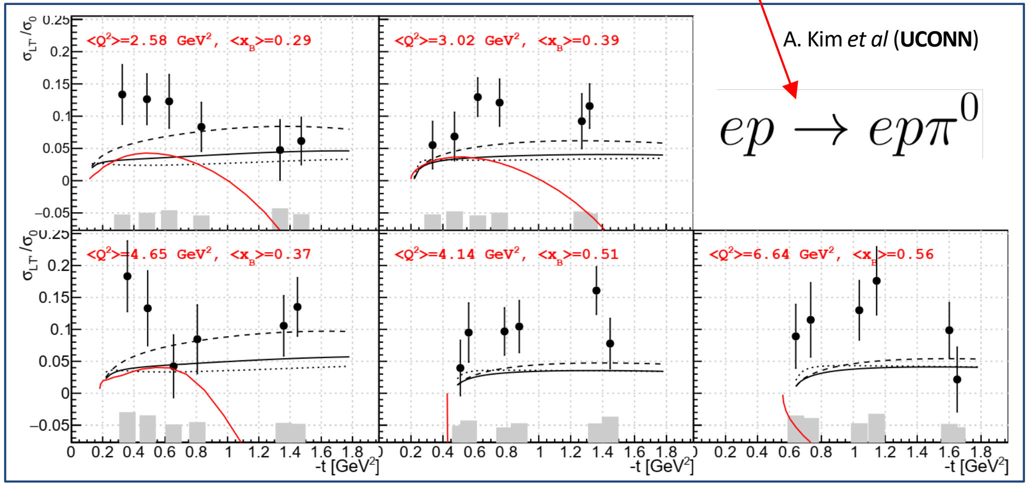
$$\sigma_{LT'} = \xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\times$$
$$\times\ \mathrm{Im}\left[\boxed{\langle H_T\rangle^*\langle\tilde{E}\rangle} + \boxed{\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle}\right]$$

E=10.6 GeV

$ep \rightarrow en\pi^+$

S. Diehl et al. (UConn & Giessen)
Phys. Lett. B 839, 137761 (2023)





A. Kim *et al* (**UCONN**)

$ep \rightarrow ep\pi^0$

A. Kim *et al* (UCONN)
Submitted to Phys. Lett. B

▬ 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.

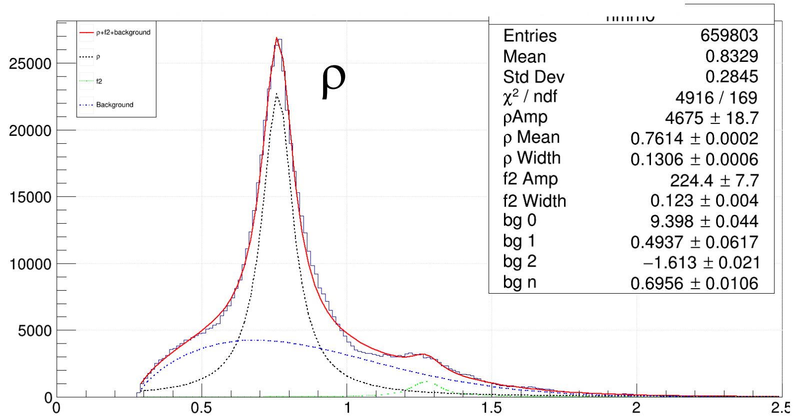
$$\kappa_T^u = \int dx\bar{E}_T^u(x,\xi,t=0) \qquad \delta_T^u = \int dx H_T^u(x,\xi,t=0)$$

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

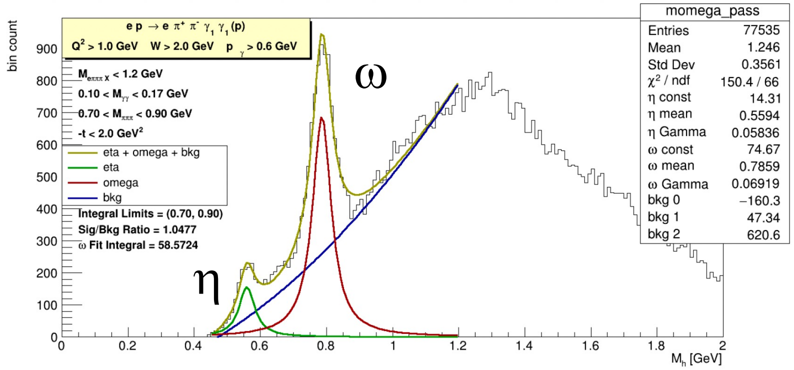
Exclusive ρ/ω production with CLAS12, ep-> ep (ρ/ω)

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

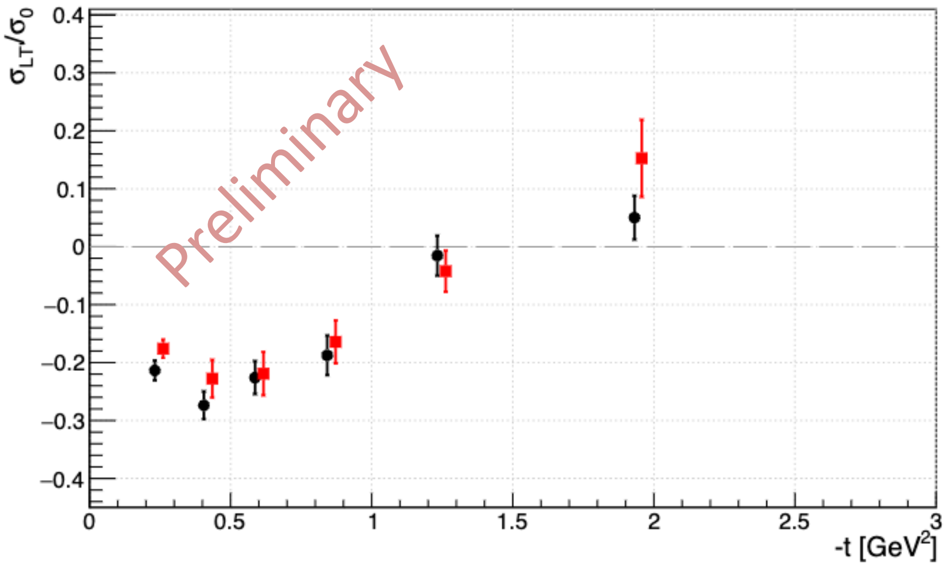
Invariant Mass: $\pi^+ + \pi^-$



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

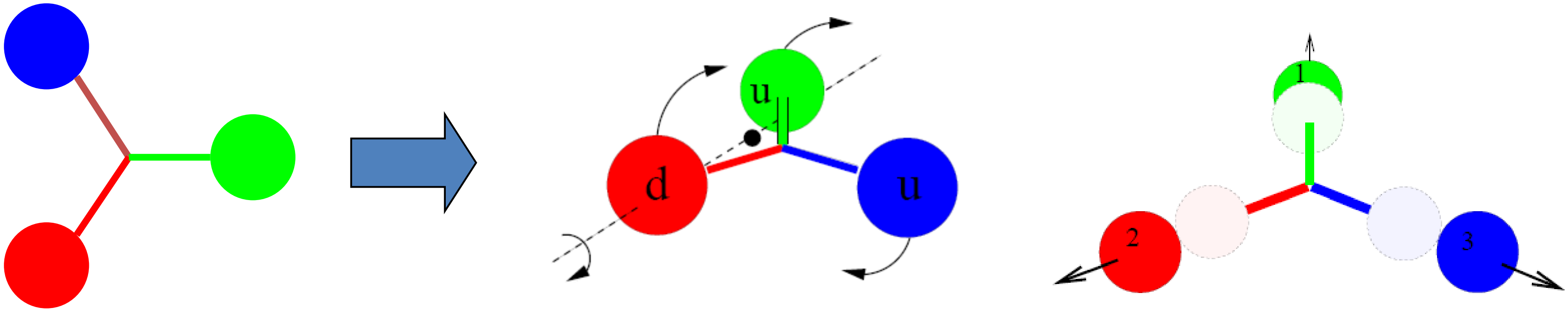


$$ep \rightarrow ep\rho$$



N. Trotta *et al* (UCONN)

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**

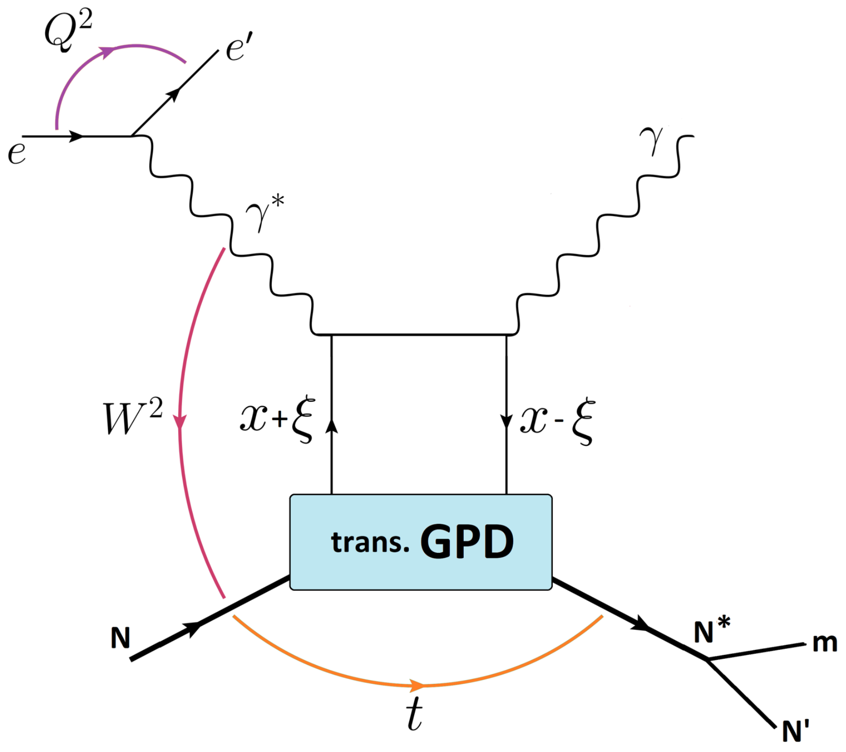
Simplest case: N→Δ transition → **16 transition GPDs**

- **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)**

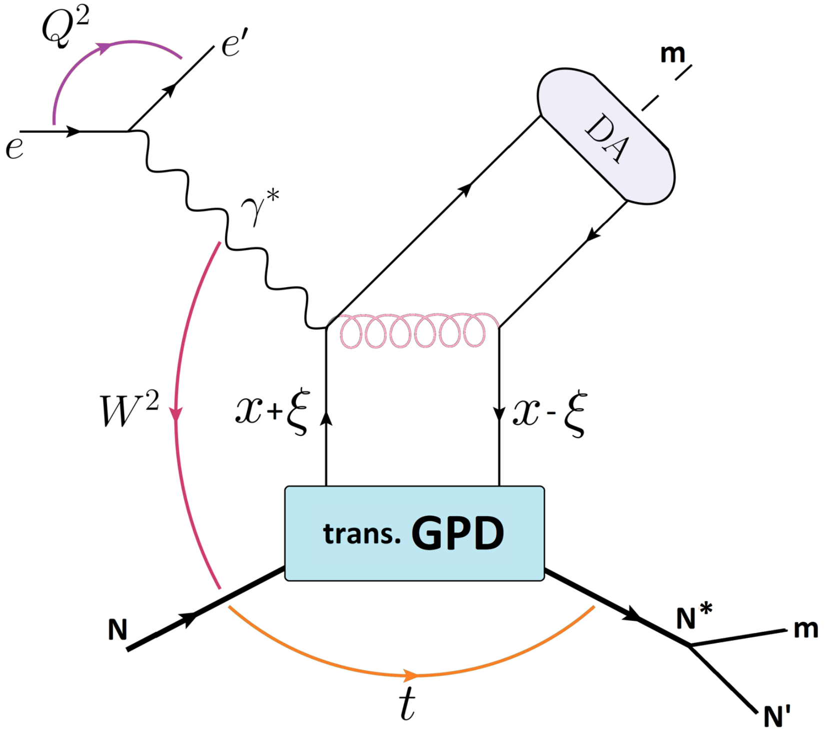
P. Kroll and K. Passek-Kumericki, Phys. Rev. D 107, 054009 (2023).
K. Semenov, M. Vanderhaeghen, arXiv:2303.00119 (2023).

Transition GPDs

non-diagonal DVCS



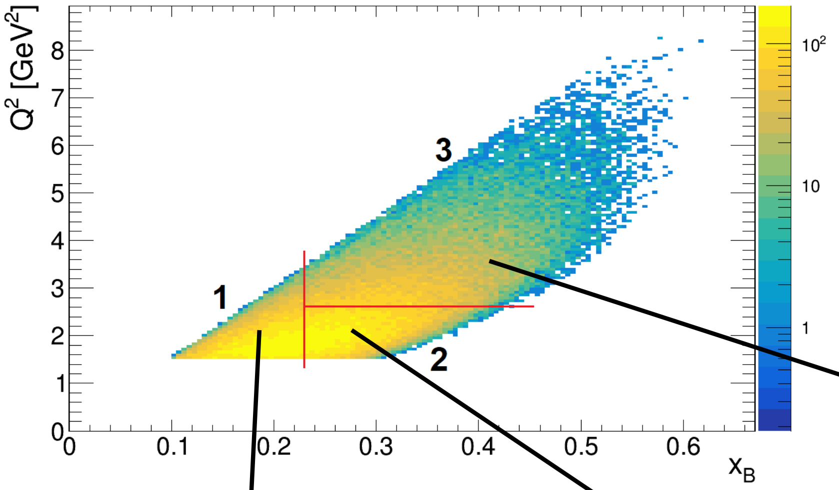
non-diagonal DVMP



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

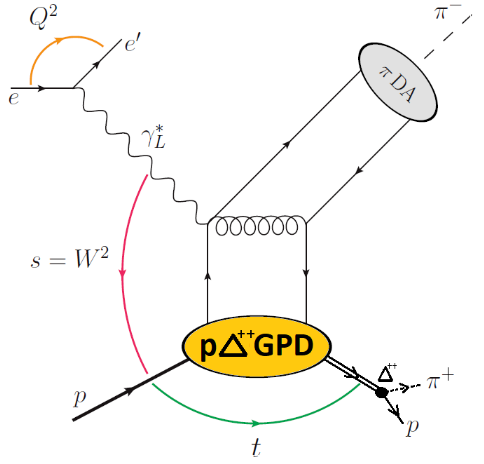
N->$\Delta(1232)$ transition GPDs: 8 twist-2 GPDs: 4 unpolarized, 4 polarized. K. Semenov, M. Vanderhaeghen, arXiv:2303.00119 (2023)

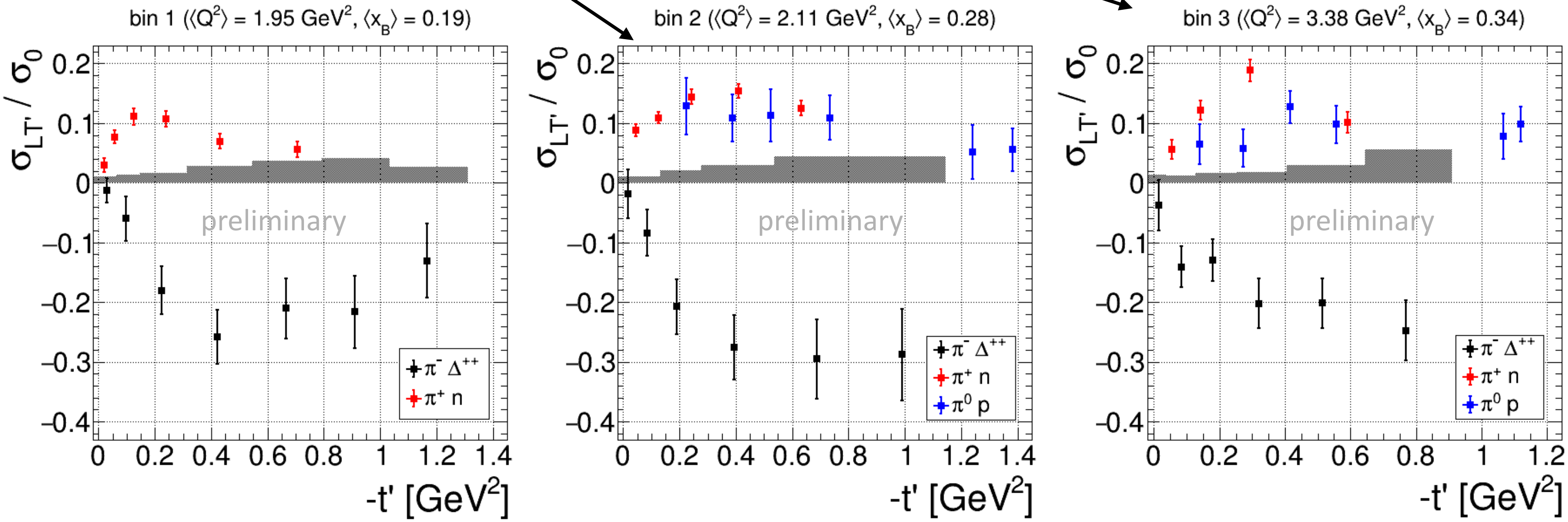
N → Δ^{++} GPDs $ep \to e\Delta^{++}\pi^- \to ep\pi^+\pi^-$



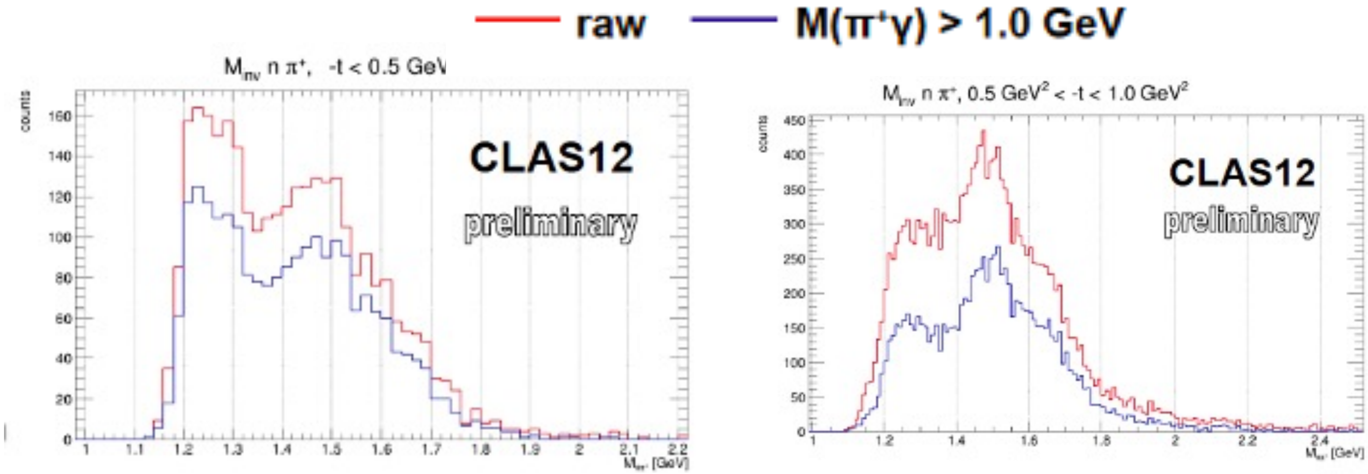
S. Diehl et al. (UConn & Giessen)
Phys. Rev. Lett. 131, 021901 (2023)

Provides access to
p-Δ transition GPDs

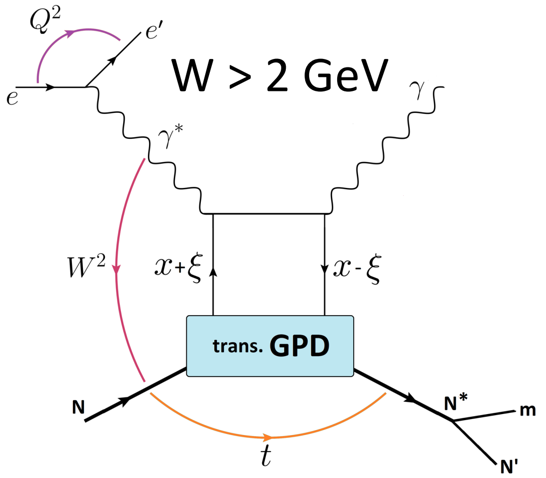




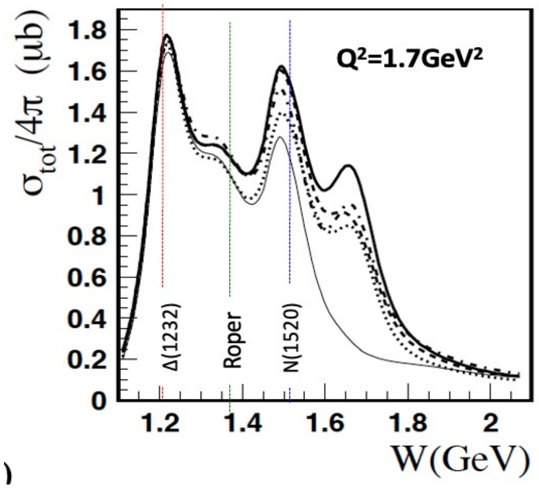
Non Diagonal DVCS $ep\text{->}en\pi^+\gamma$

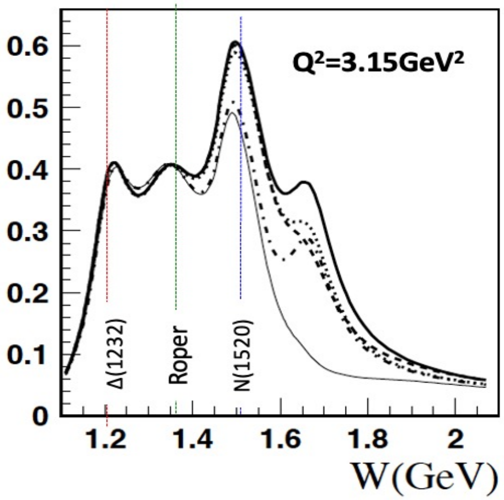


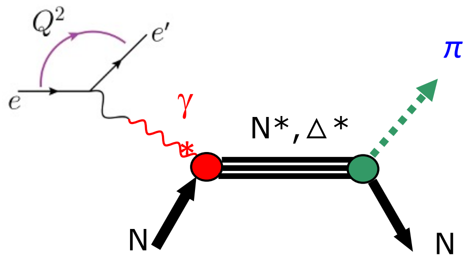
$M(n\pi^+)$ $M(n\pi^+)$



$ep\text{->}e\gamma n\pi^+$

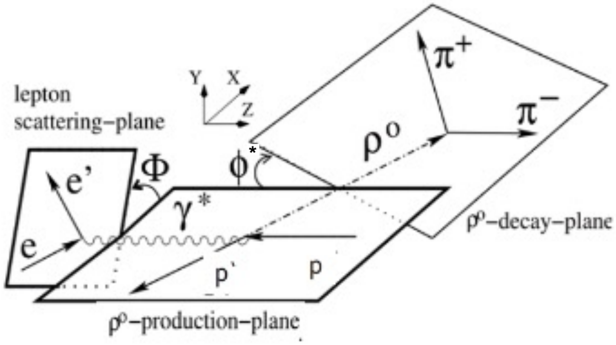






$ep\text{->}en\pi^+$

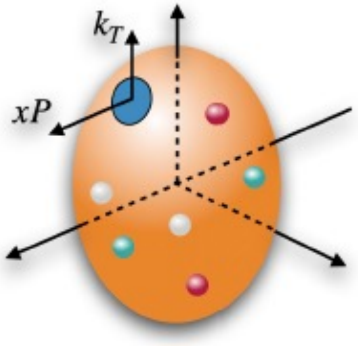
Electron Scattering Binning Scheme



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

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

Key Information from TMDs



- Complete momentum spectrum of single particle
- Transverse momentum size as function of x (3D map) at different Q^2
- Spin-Spin and Spin-Orbit Correlations of partons
- Information on parton orbital angular momentum (no direct model-independent relation)

8 Leading TMDs

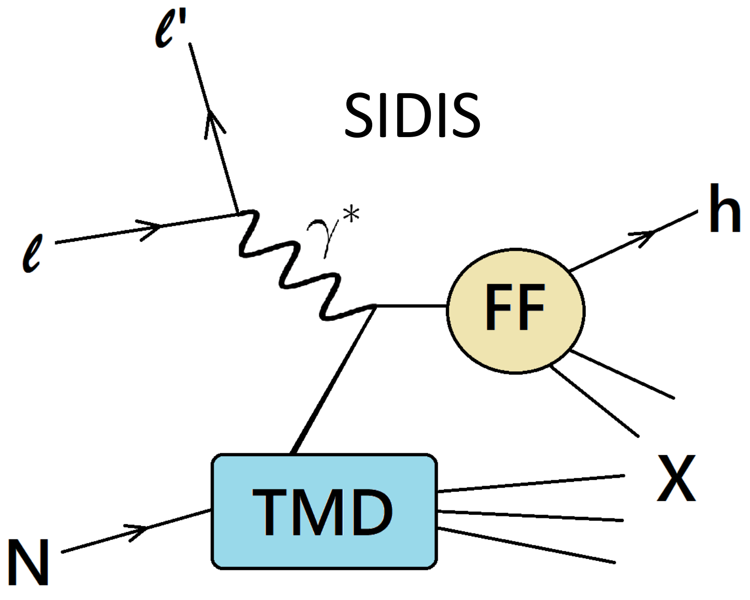
quark pol.

nucleon pol.

	U	L	T
U	f_1		$h^{\perp}_{1}$
L		g_1	$h^{\perp}_{1L}$
T	$f^{\perp}_{T}$	g_{1T}	h_1, $h^{\perp}_{1T}$

Boer-Mulder

Sivers



TMDs in **black** survive integration over transverse momentum and reduce to the PDFs

TMDs in **blue** and **red** vanish if there is no quark orbital angular momentum

TMDs in **red** are time-reversal odd

SIDIS with a Longitudinally Polarized Beam and an Unpolarized Target

$$\frac{d\sigma}{dx\,dQ^2\,dz\,dP_{h\perp}^2\,d\phi_h} \sim F_{UU,T} + \epsilon\, F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h} + \epsilon\,\cos 2\phi_h\, F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\epsilon(1-\epsilon)}\,\sin\phi_h\, F_{LU}^{\sin\phi_h}$$

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M}f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z}\right)\right)$$

twist-3 pdf

Collins FF

unpolarized dist.
function

twist-3 FF

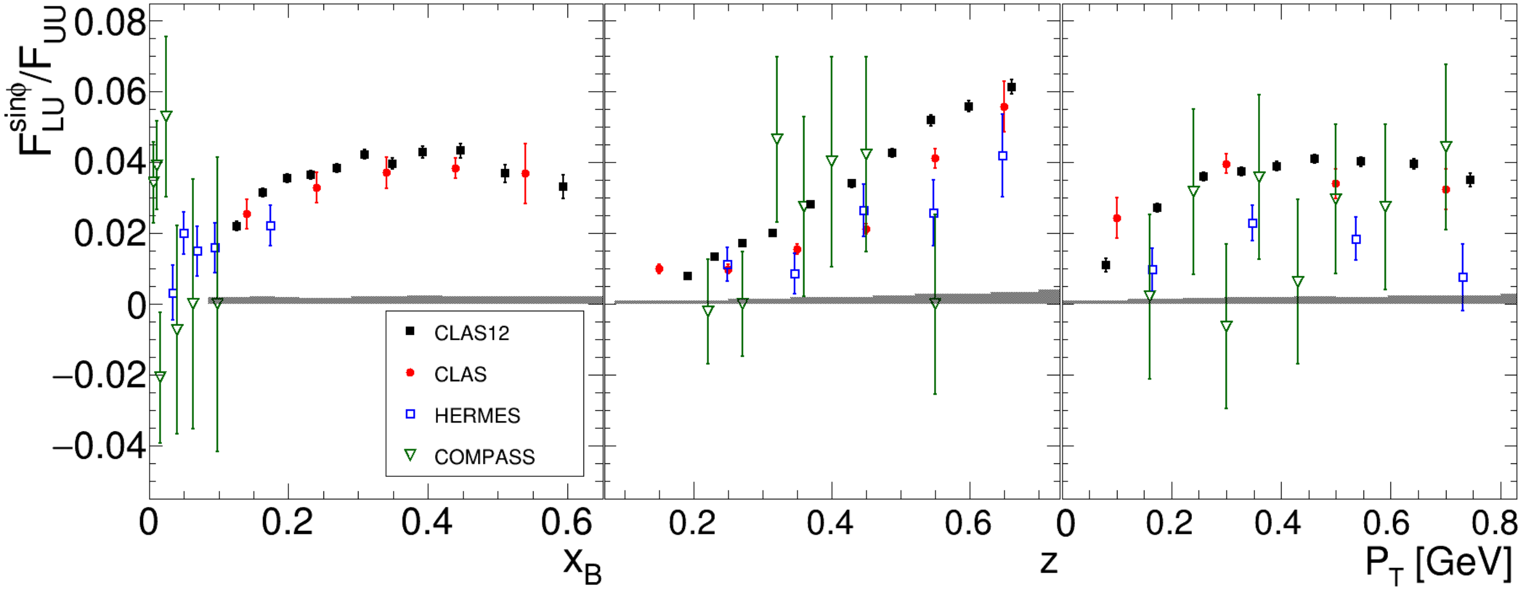
twist-3 t-odd
dist. funcion

Boer-Mulders

twist-3 FF

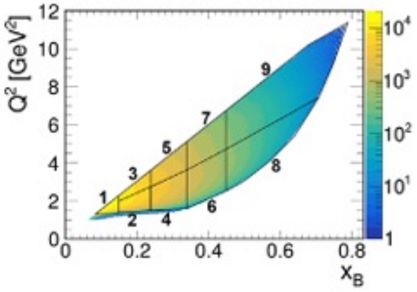
➔ TMDs and
Fragmentation
functions

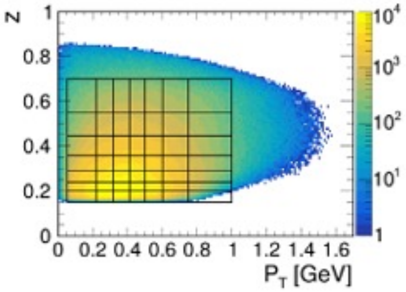
eπ$^+$X



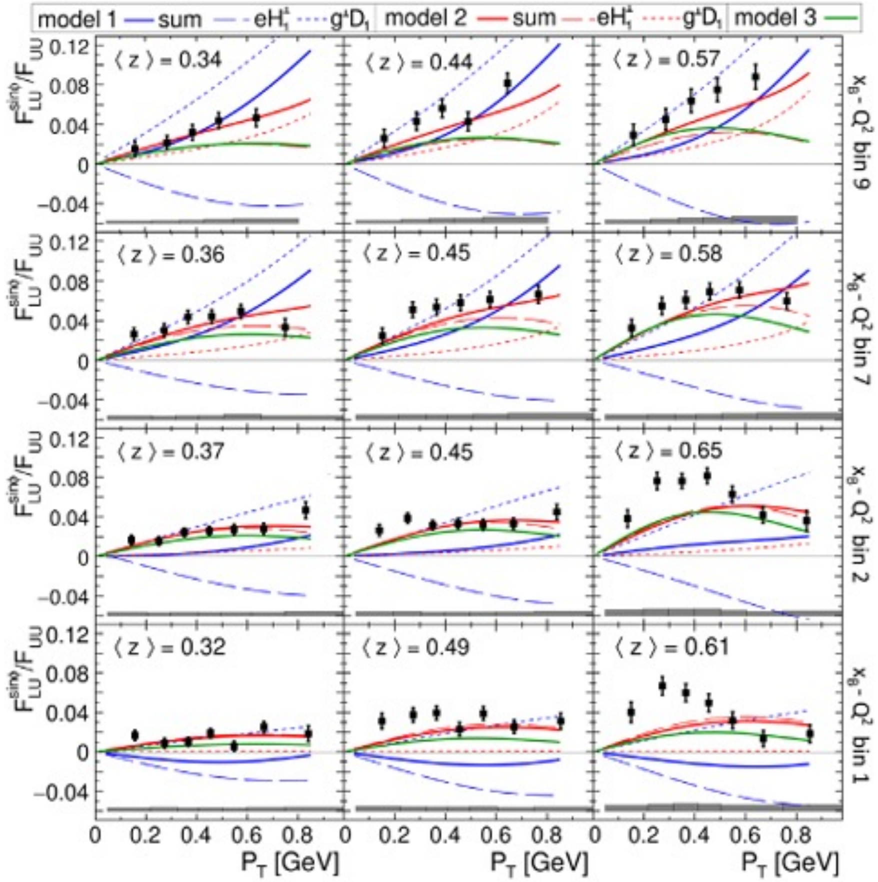
S. Diehl et. al (UConn)
Phys. Rev. Lett. 128,
062005 (2022)

SIDIS with a Longitudinally Polarized Beam and an Unpolarized Target

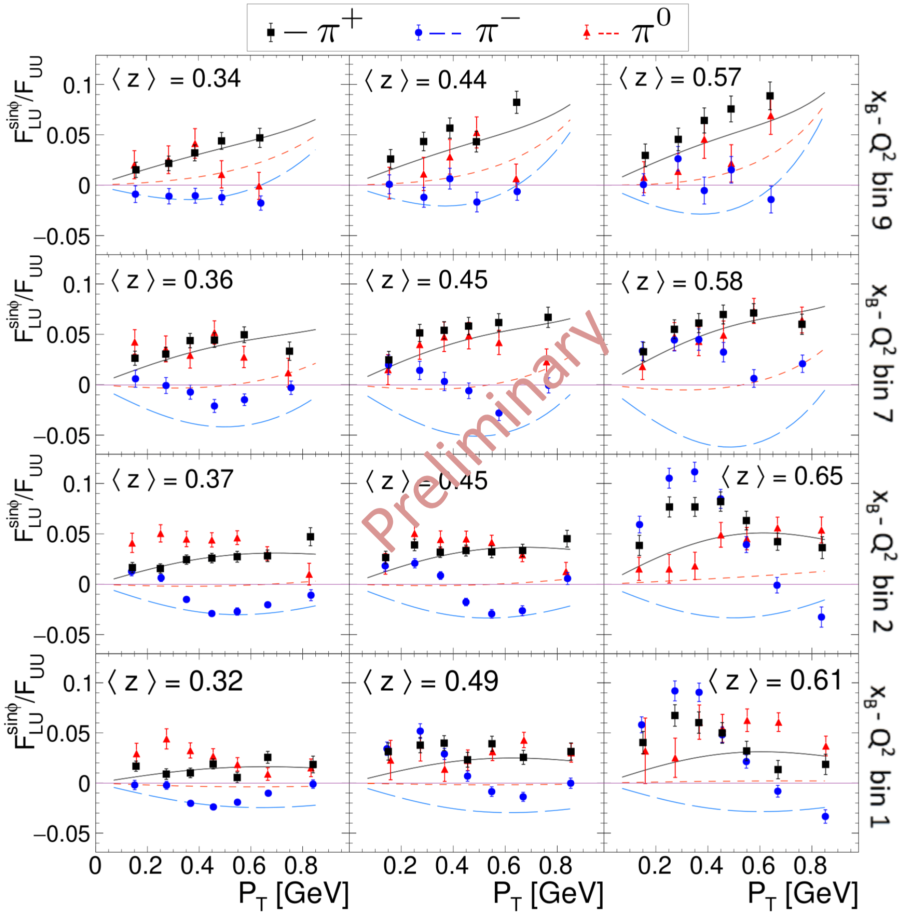




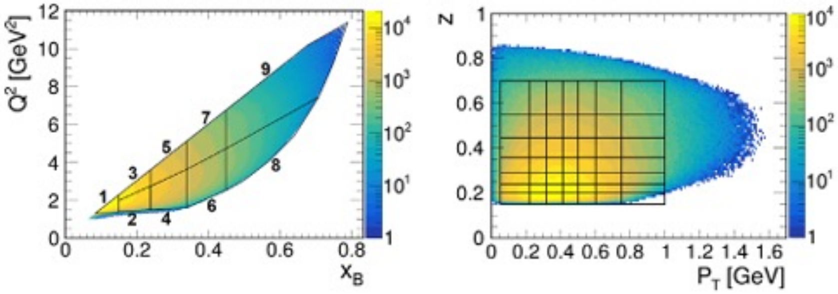
$e\pi^+X$



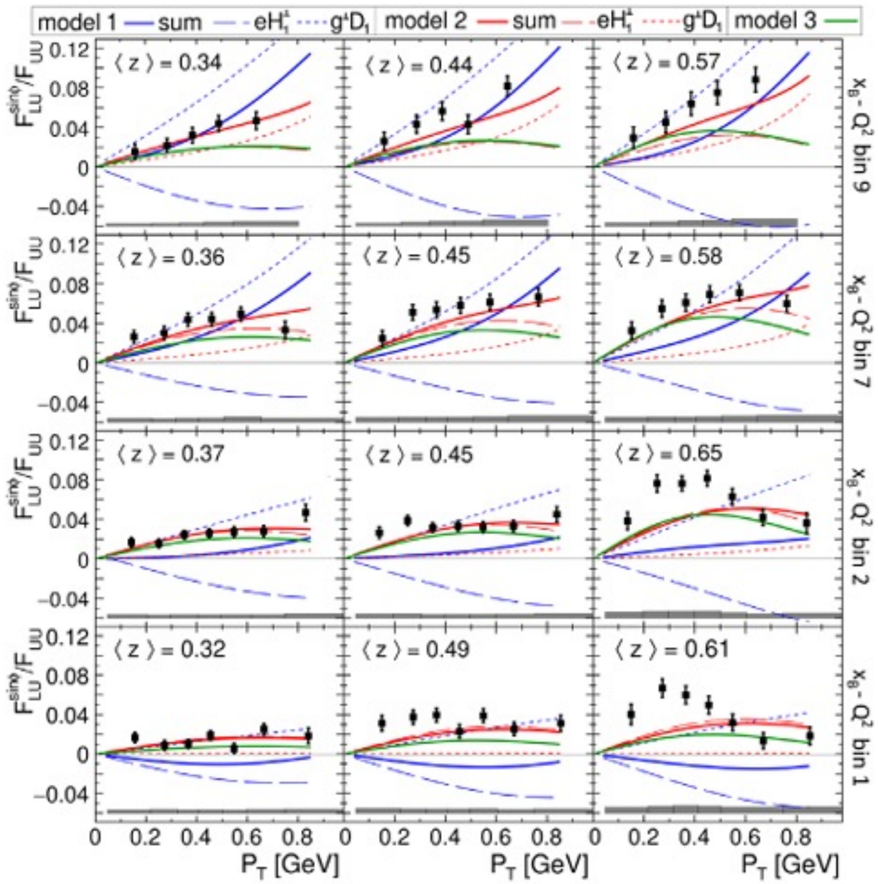
S. Diehl et. al (UConn) Phys. Rev. Lett. 128, 062005 (2022)



SIDIS with a Longitudinally Polarized Beam and an Unpolarized Target

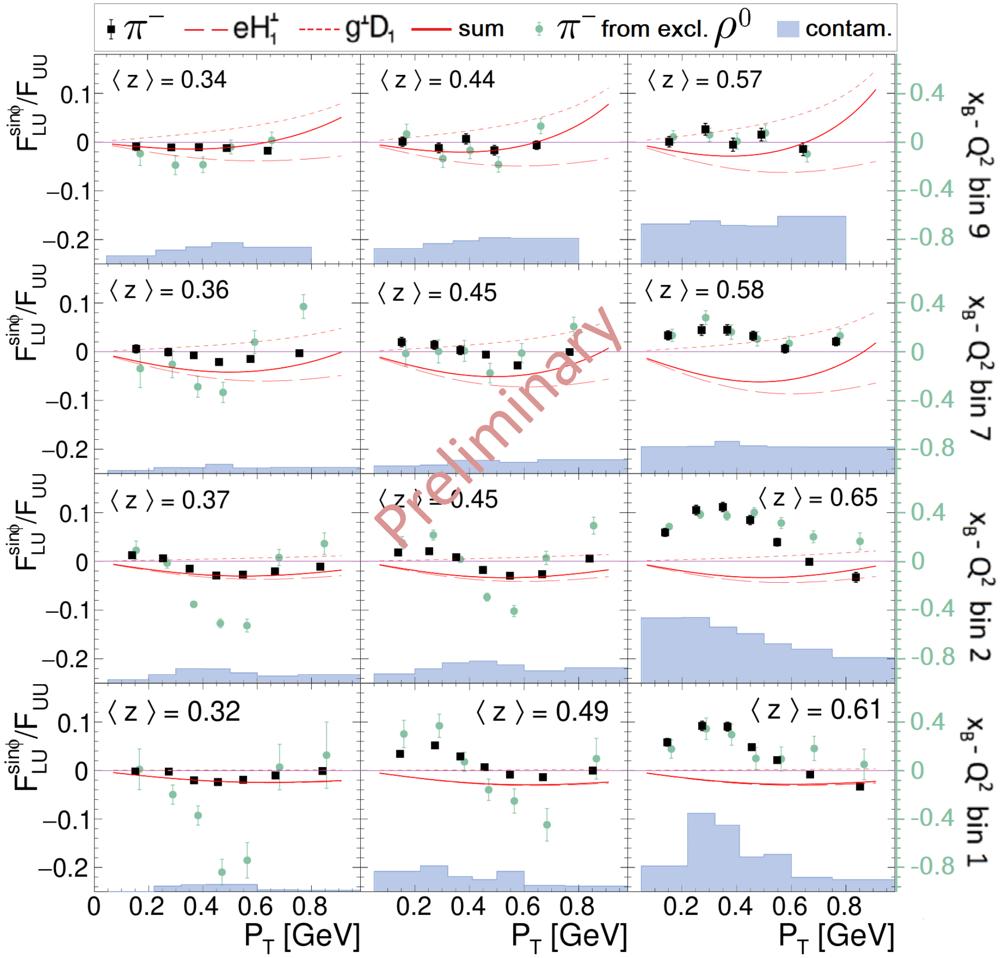


eπ⁺X



S. Diehl et. al (UConn) Phys. Rev. Lett. 128, 062005 (2022)

eπ⁻X



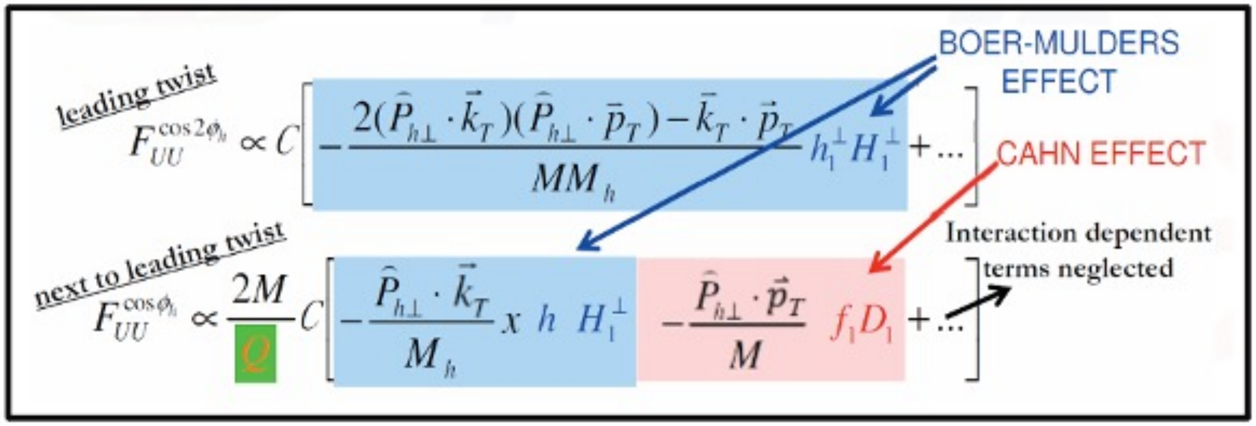
SIDIS Cross-Section and Boer-Mulders

The lepton-hadron Unpolarized SIDIS Cross-Section:

$$\frac{d^5\sigma}{dx\, dQ^2\, dz\, d\phi_h\, dP_{h\perp}^2} =$$

$$\underbrace{\frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)(F_{UU,T}+\epsilon F_{UU,L})}_{A_0}\left\{1+\underbrace{\frac{\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos\phi_h}}\cos\phi_h+\underbrace{\frac{\epsilon F_{UU}^{\cos 2\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\right\}$$

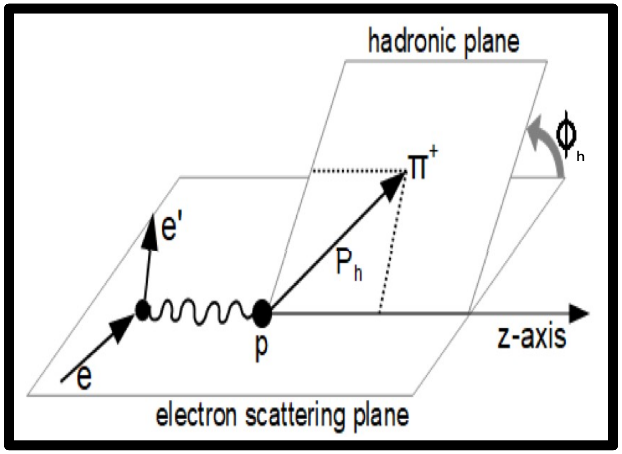
The Boer-Mulders and Cahn effects are present in the Structure Functions:



$$F_{UU}^{\cos 2\phi_h} \propto C\left[-\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{MM_h}h_1^{\perp}H_1^{\perp}+\ldots\right]$$

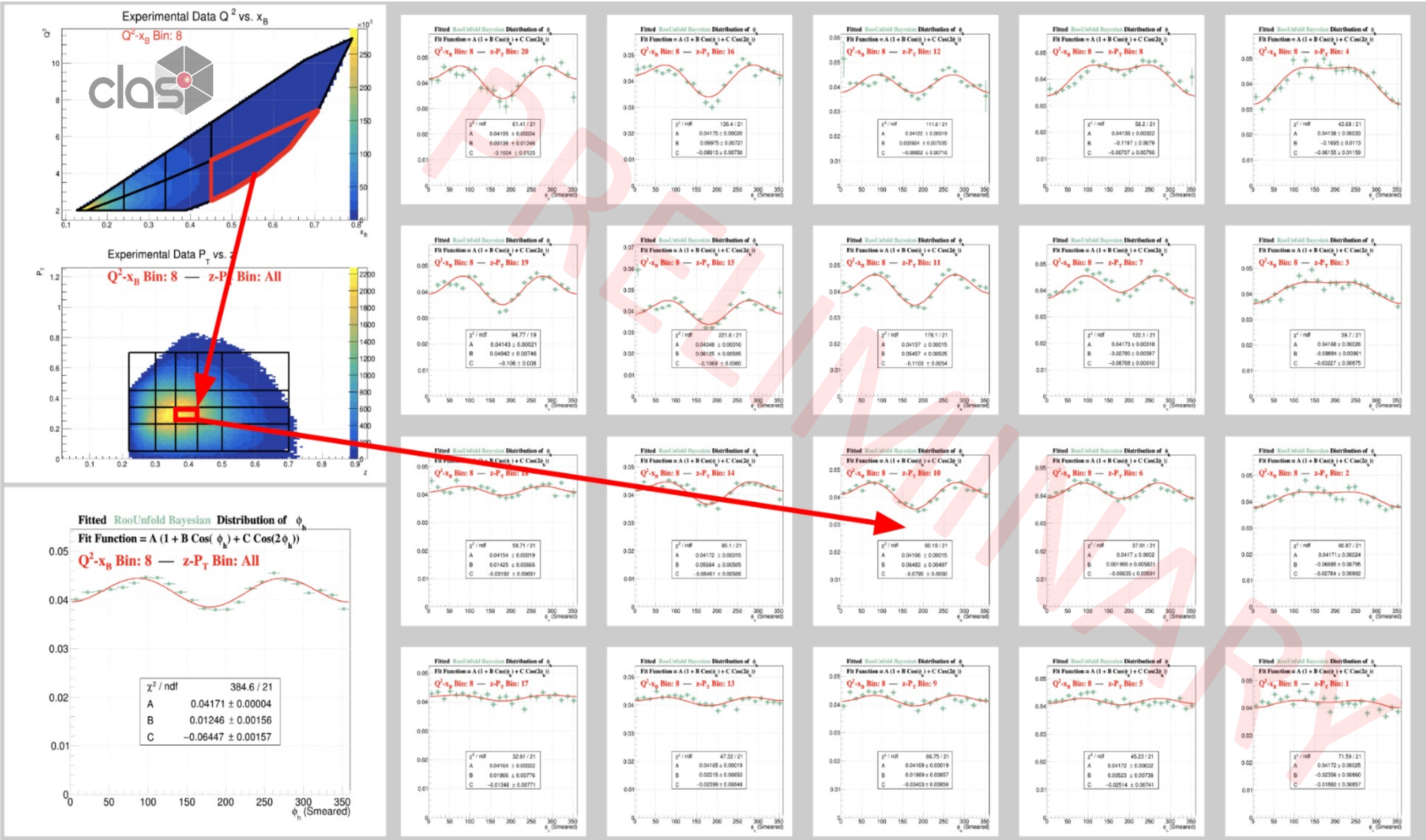
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M_h}x\ h\ H_1^{\perp}-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M}f_1D_1+\ldots\right]$$

Interaction dependent terms neglected

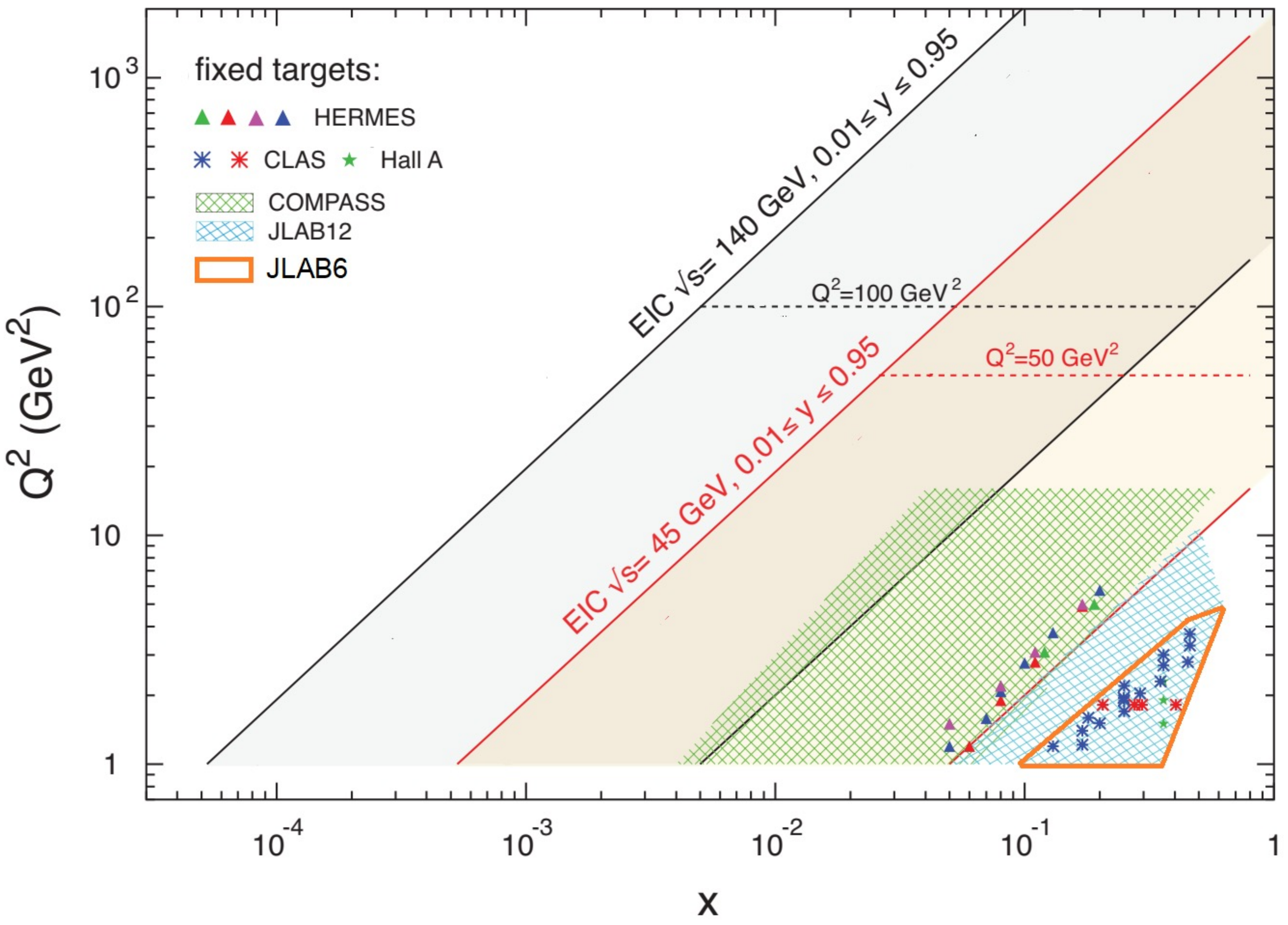


Example of Unfolding Procedure (5-fold)

R. Capobianco (UConn)

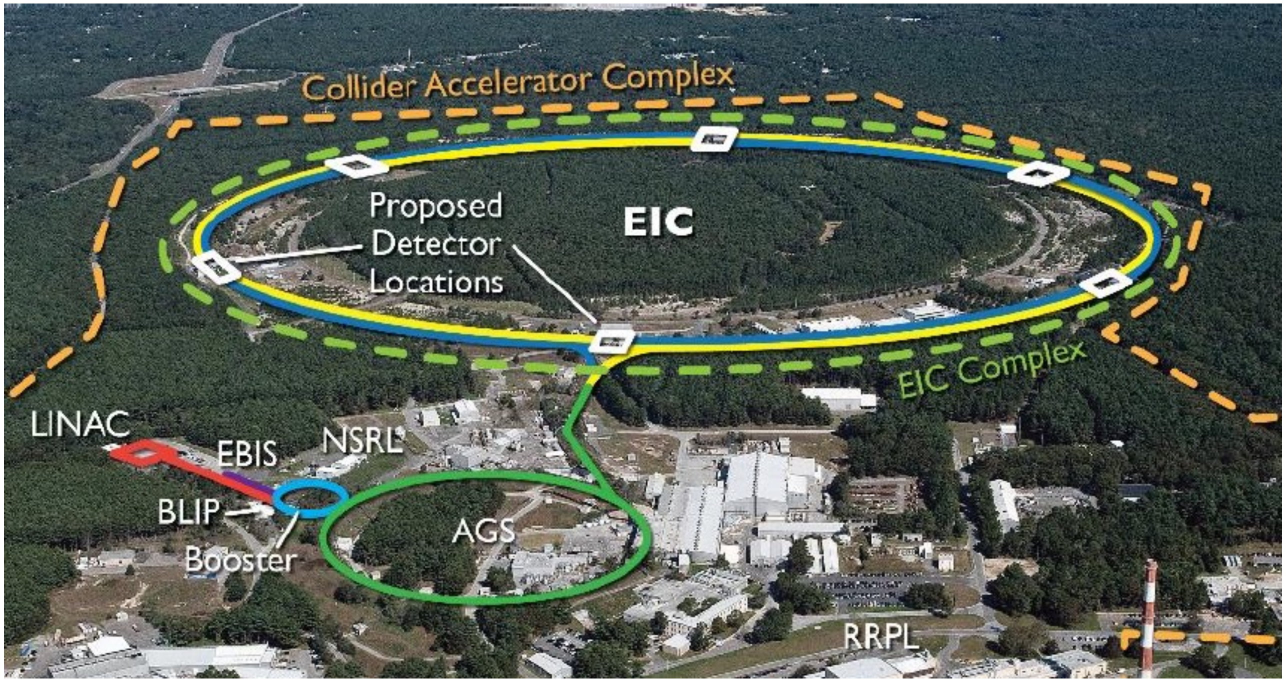


From CLAS to JLAB to COMPASS to EIC



➔DVMP/SIDIS at JLab 12 GeV / COMPASS and EIC

Electron Ion Collider at BNL



For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Conclusion and Outlook

- GPDs and TMDs provide a unifying framework to study the 3-D quark and gluon structure of the nucleon
- 3-D imaging of nucleons uncovers the rich dynamics of QCD.
- CLAS12 allows high precision measurements of TMDs and GPDs with large kinematic coverages in the valence quark regime!
- The COMPASS, J-PARC, PANDA, EIC and other experiments will allow us a full picture of the 3D structure of the nucleon.

Joo’s Group

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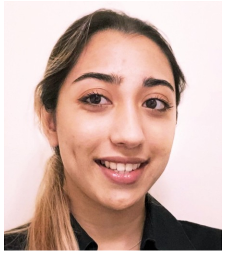
G. Kainth

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