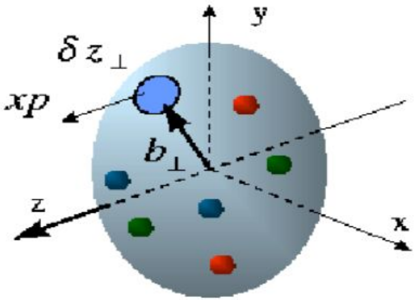
Overview of exclusive meson electroproduction program with CLAS12

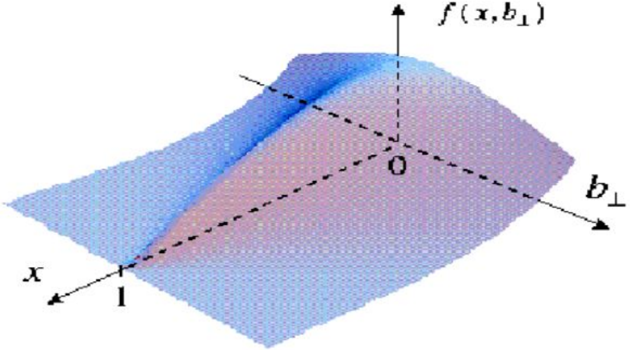
Towards improved hardron femtography with hard exclusive reactions
August 10th, 2023

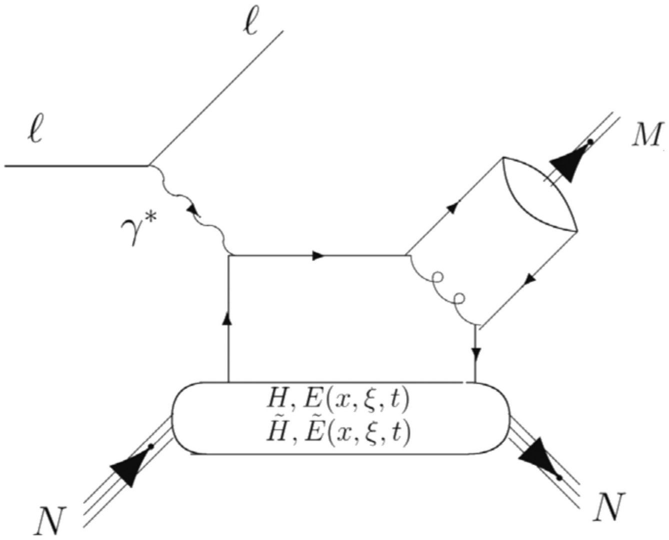
Andrey Kim
(University of Connecticut)

GPDs and exclusive meson electroproduction

- 4 chiral-even GPDs: H, E, H, E
- 4 chiral-odd GPDs: H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$

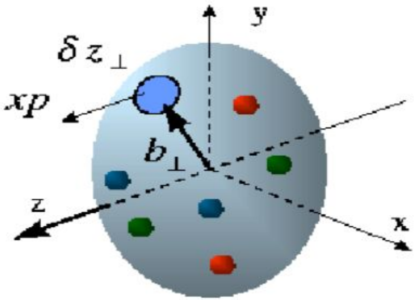


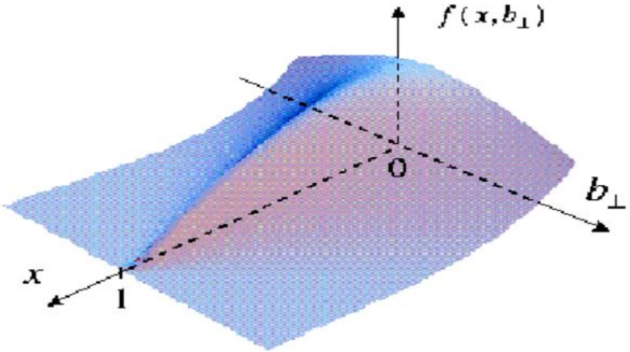




$$\langle F\rangle = \sum_{\lambda} \int_{-1}^{1} dx \mathcal{H}_{0\lambda,\mu\lambda}(x,\xi,Q^2,t) F(x,\xi,t)$$

GPDs and exclusive meson electroproduction





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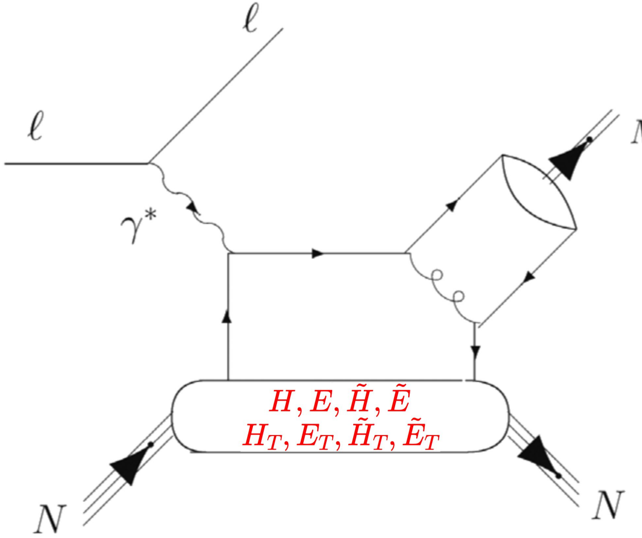
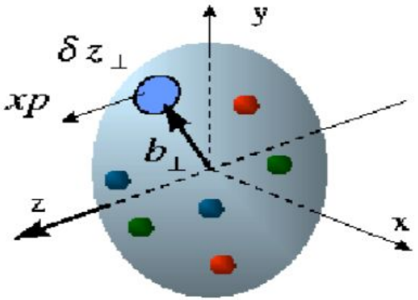
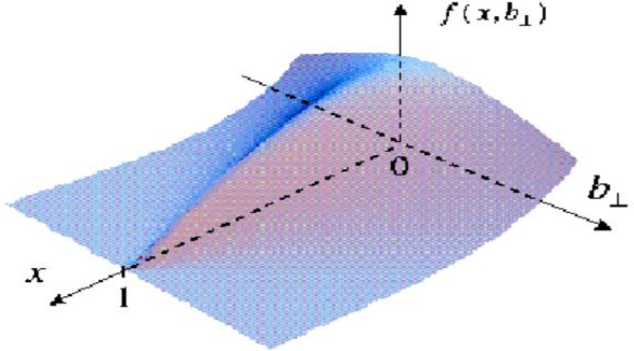


$$\langle F\rangle = \sum_{\lambda} \int_{-1}^{1} dx\, \mathcal{H}_{0\lambda,\mu\lambda}(x, \xi, Q^2, t)\, F(x, \xi, t)$$

GPDs and exclusive meson electroproduction





- 4 chiral-even GPDs: H, E, H, E
- 4 chiral-odd GPDs: H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$

	Meson	GPD flavor composition
$\tilde{H}$, $\tilde{E}$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
H_T, $\bar{E}_T$	η	$2\Delta u - \Delta d$
H, E	ρ^0	$2u + d$
	ρ^+	$u - d$
	ω	$2u - d$

Link GPDs to **PDF** and **Form Factors**

PDFs:

in the forward limit

$\xi = t = 0$:

$$H^q(x,0,0) = q(x)$$
$$\tilde{H}^q(x,0,0) = \Delta q(x)$$

Form Factors:

$$\int dx H^q(x,\xi,t) = F_1(t)$$
$$\int dx E^q(x,\xi,t) = F_2(t)$$
$$\int dx \tilde{H}^q(x,\xi,t) = G_A(t)$$
$$\int dx \tilde{E}^q(x,\xi,t) = G_P(t)$$

Link GPDs to **Tensor charge** and **Transversity**

PDFs: Form Factors:

- Proton tensor charge

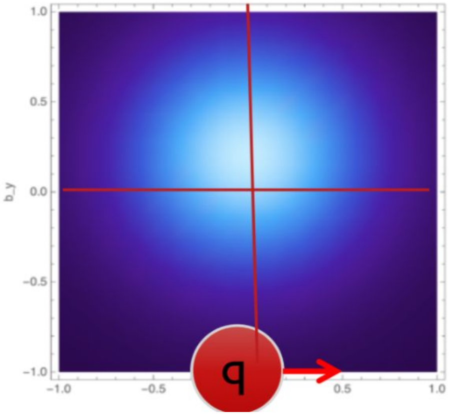
$$\delta_T^u = \int dx H_T^u(x,\xi,t=0)$$
$$\delta_T^d = \int dx H_T^d(x,\xi,t=0)$$

- Proton anomalous tensor magnetic moment

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

- Density of transversely polarized quarks in an unpolarized proton in the transverse plane

$$\delta(x,\vec{b}) = \frac{1}{2}[H(x,\vec{b}) - \frac{b_y}{m}\frac{\partial}{\partial b^2}\bar{E}_T(x,\vec{b})]$$

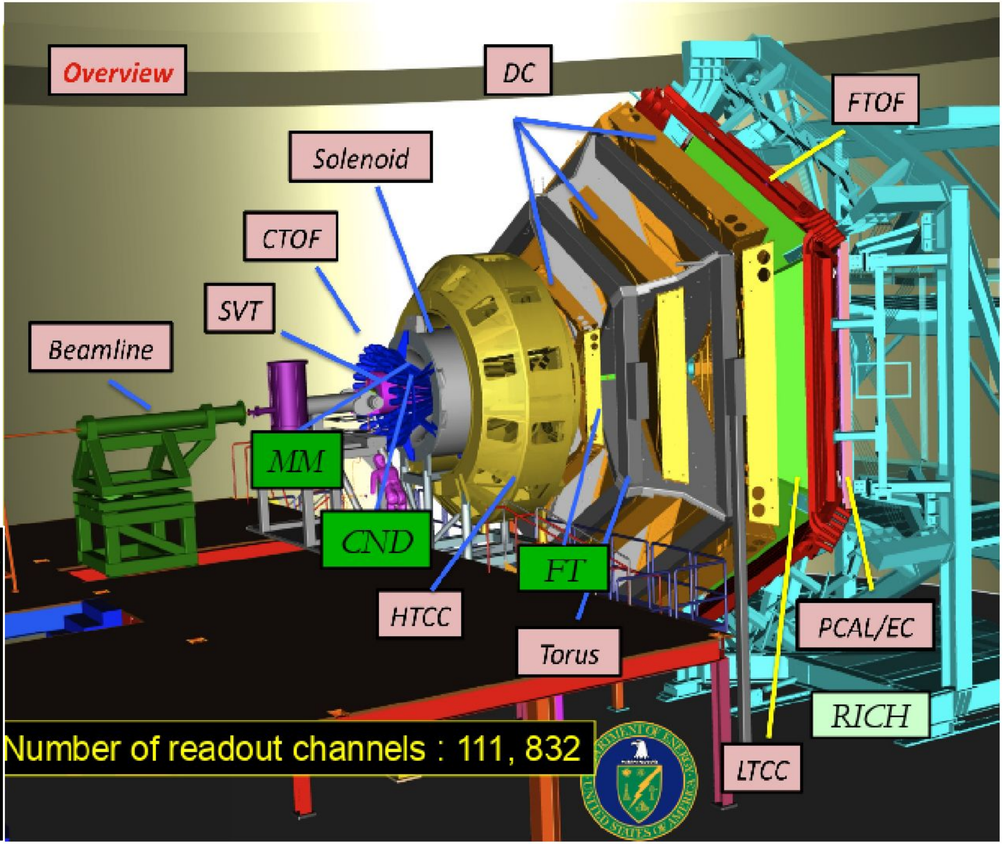


CLAS12 to map exclusive reactions in a wide kinematic space

- CEBAF Large Acceptance Spectrometer
- High luminosity frontier
- 86 % electron beam longitudinal polarization
- Unpolarized and polarized fixed targets
- Comprehensive detection system
- Access to the Q^2 up to 10 GeV^2

Central Detector (CD)
- Solenoid magnet
- Silicon Vertex Tracker
- Central Time-of-Flight
- Central Neutron Det.
- MicroMegas

Forward Detector (FD)
- TORUS magnet
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter
- Forward Tagger
- RICH detector

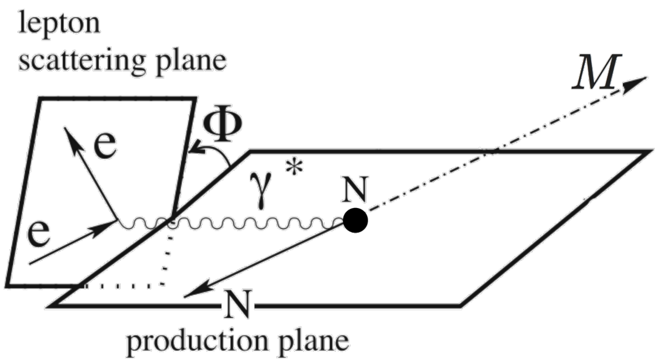


Experimental observables for exclusive meson electroproduction

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

$$\frac{1}{2\pi}\left\{\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\Phi) + \sqrt{\epsilon(2\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos(\Phi) + \lambda\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{LT'}}{dt}\sin(\Phi)\ \right\}$$

where λ is the helicity state of the incident electron beam



Access to GPDs

PHYSICAL REVIEW D 84, 034007 (2011)

Flexible parametrization of generalized parton distributions from deeply virtual Compton scattering observables

Gary R. Goldstein,[1,*] J. Osvaldo Gonzalez Hernandez,[2,†] and Simonetta Liuti[2,‡]
[1]Department of Physics and Astronomy, Tufts University, Medford, Massachusetts 02155, USA
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(Received 16 February 2011; published 5 August 2011)

Eur. Phys. J. A (2011) 47: 112
DOI 10.1140/epja/i2011-11112-6
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article – Theoretical Physics

Transversity in hard exclusive electroproduction of pseudoscalar mesons

S.V. Goloskokov[1,a] and P. Kroll[2,3,b]

Unpolarized beam and target — **within GK formalism**

$$\sigma_L \sim \left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2 \mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

$$\sigma_T \sim \left[(1-\xi^2)\,|\langle H_T\rangle|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

$$\sigma_{LT} \sim \xi\sqrt{1-\xi^2}\,\frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\sigma_{TT} \sim \frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

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THE EUROPEAN PHYSICAL JOURNAL A

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Unpolarized beam and target

within GK formalism

Longitudinally polarized beam and longitudinally polarized target

$$A_{LU}^{\sin(\phi)}\sigma_0 \sim -\sqrt{\epsilon(1-\epsilon)}\,\sqrt{-t'}\,\mathrm{Im}\Big[\langle \bar{E}_T\rangle^*\langle \widetilde{H}_{\mathrm{eff}}\rangle + \langle H_T\rangle^*\langle \tilde{E}\rangle\Big]$$

$$A_{LL}^{\mathrm{const}}\sigma_0 \sim \sqrt{1-\epsilon^2}\,|\,\langle H_T\rangle\,|^2$$

$$A_{LL}^{\cos(\phi)}\sigma_0 \sim -\sqrt{\epsilon(1-\epsilon)}\,\sqrt{-t'}\,\mathrm{Re}\Big[2\langle \bar{E}_T\rangle^*\langle \widetilde{H}_{\mathrm{eff}}\rangle + \langle H_T\rangle^*\langle \tilde{E}\rangle\Big]$$

within GK formalism

Measurements of exclusive meson production with CLAS

CLAS data:

Phys. Rev. C63: 065205, 2001 (φ)
Phys. Lett. B605: 256-264, 2005 (ρ^0)
Eur. Phys. J. A24: 445-458, 2005 (ω)
Phys. Rev. C78: 025210, 2008 (φ)
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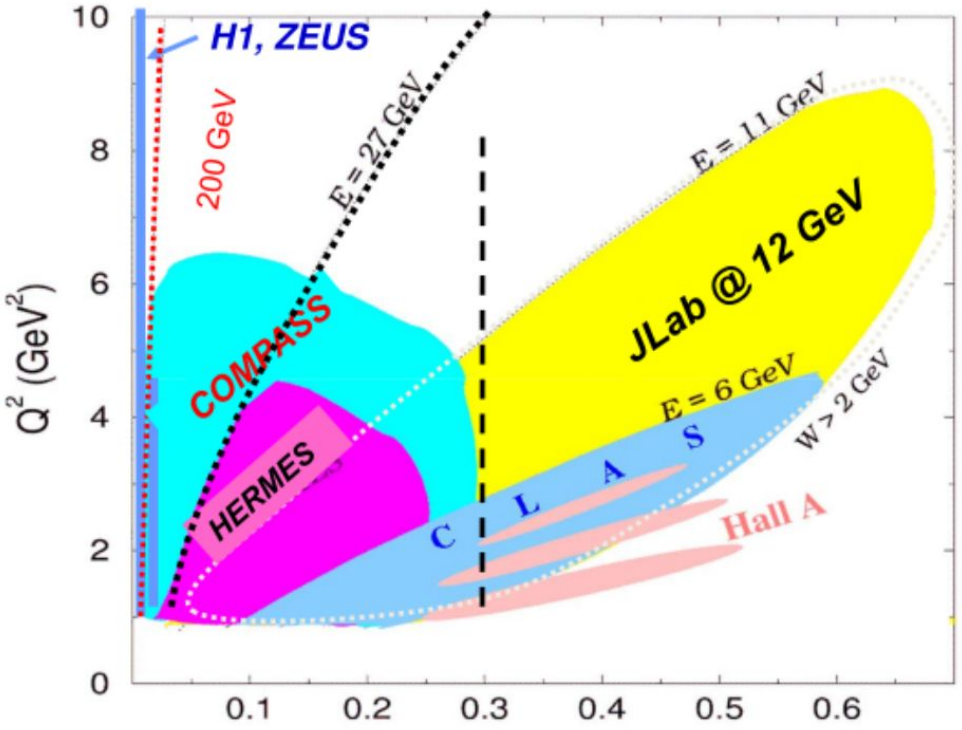
Phys. Lett. B 768, 168 (2017) (π^0)
Phys. Lett B. 789, 426 (2019) (η)



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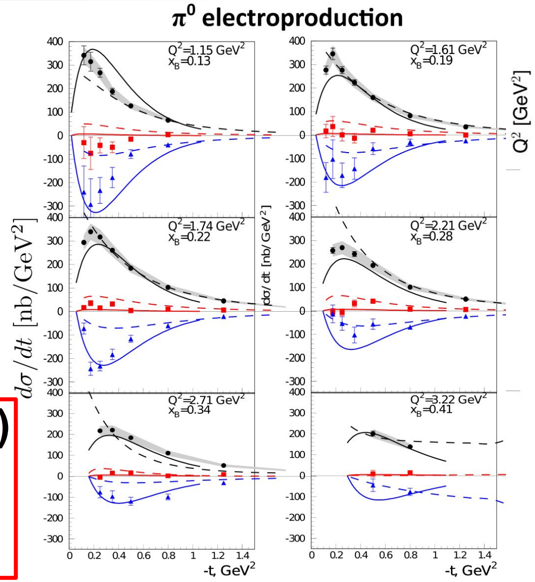

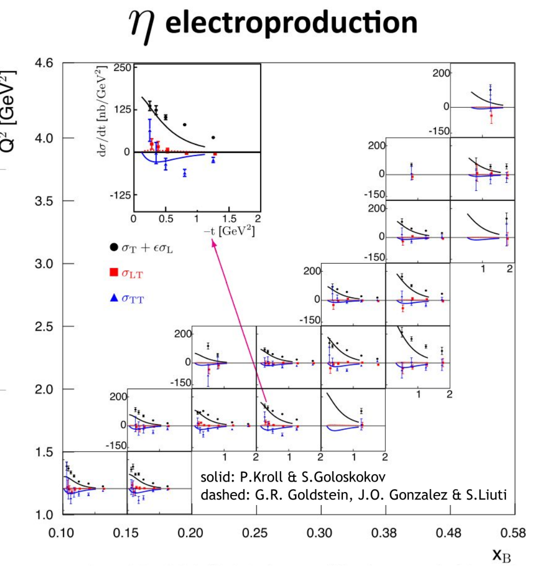

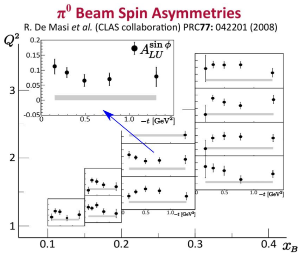

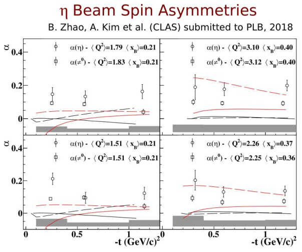

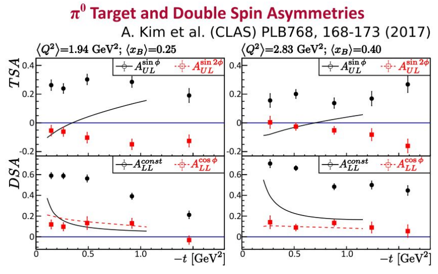

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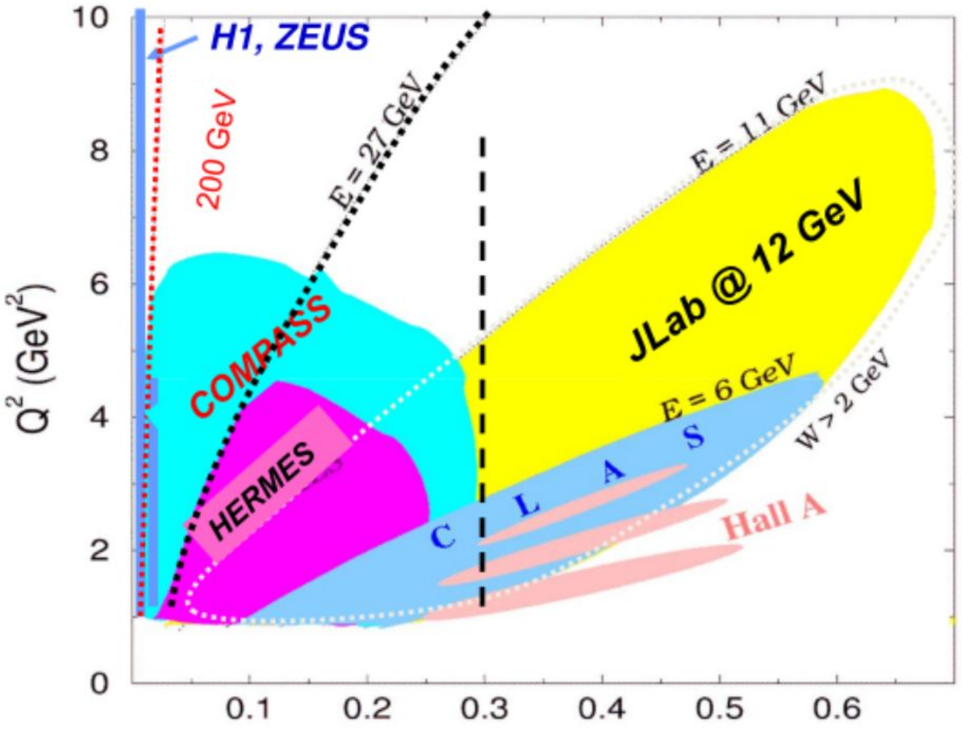
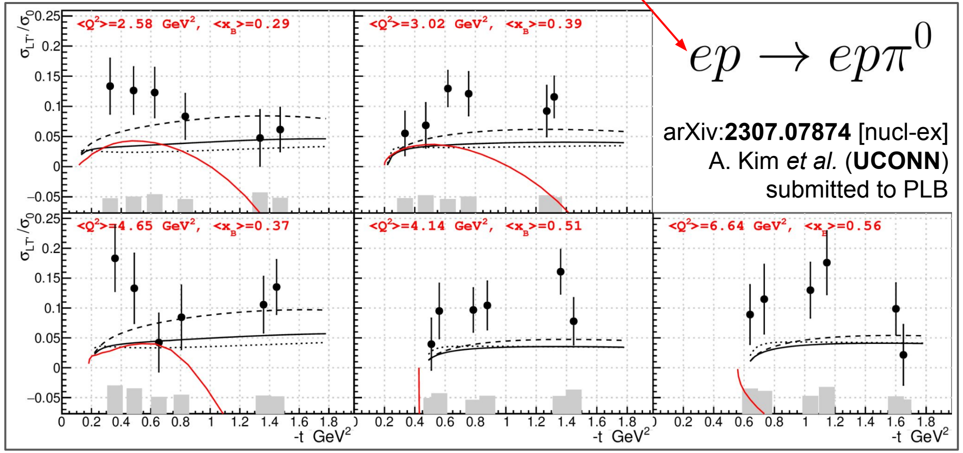
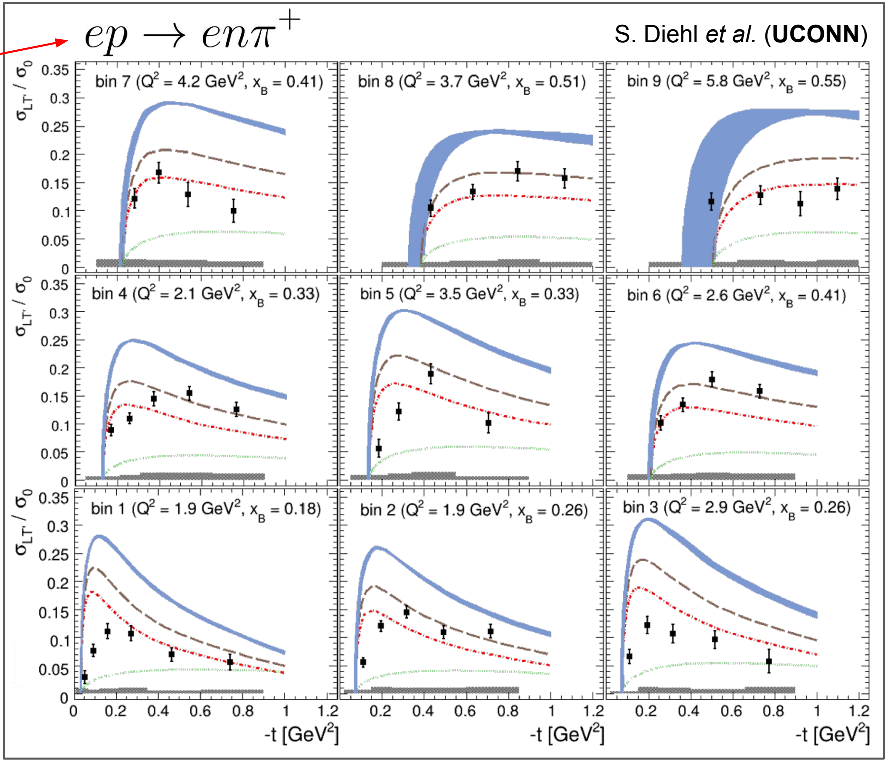


Pseudoscalar meson electroproduction with CLAS12

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



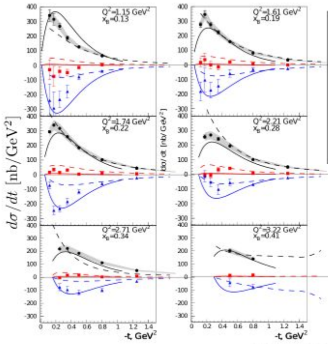


Phys. Rev. Lett. **125**, 182001 – Published 28 October 2020

- active work on cross-section extraction by **R. Johnston (MIT)**
- active work on η beam spin asymmetry and cross-section extraction **A. Kim (UCONN)**

GPD insight (in progress)

Unpolarized cross section



Inclusion of the Chiral-odd GPDs brings theoretical calculations into moderate agreement with the data.

$$\sigma_T \sim (1-\xi^2)|H_T|^2 - \frac{t'}{8m^2}|\bar{E}_T|^2$$

— $\sigma_0 = \sigma_T + \epsilon\sigma_L$
— σ_{TT}
— σ_{LT}

$$\sigma_{TT} \sim \frac{t'}{8m^2}|\bar{E}_T|^2$$

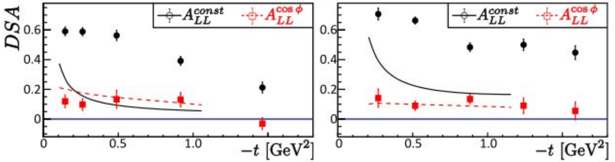
π^0 electroproduction is uniquely sensitive process to access **transversity GPDs.**

solid: P.Kroll & S.Goloskokov
dashed: G.R. Goldstein, J.O. Gonzalez & S.Liuti

PRL109:112001 (2012) I. Bedlinskiy et al. (CLAS collaboration)

Double Spin Asymmetry

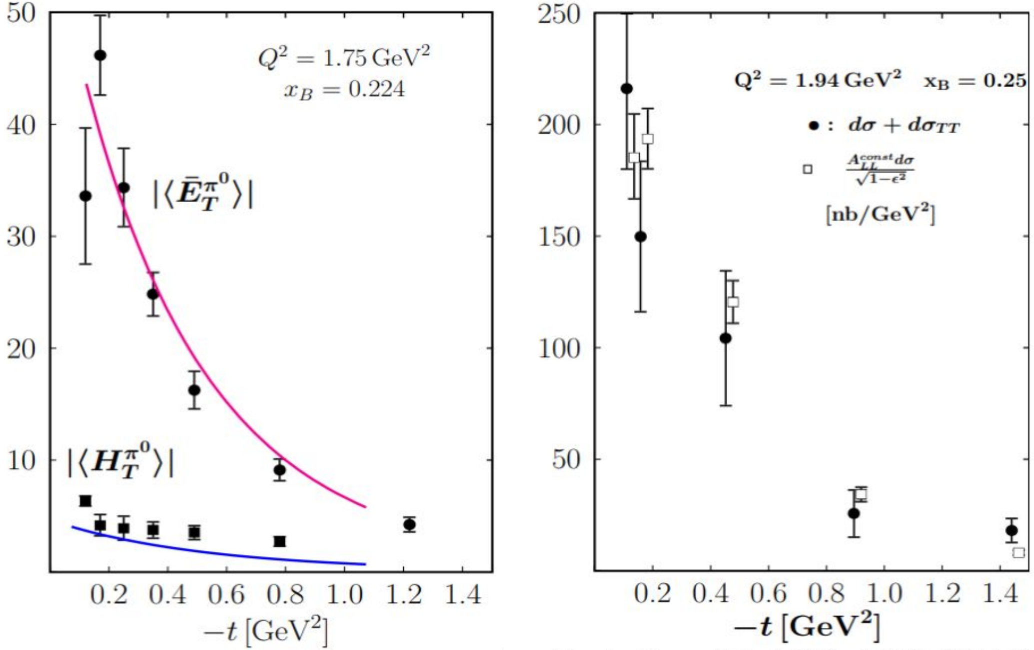
$$A_{LL}^{const} \sim |\langle H_T\rangle|^2$$



PLB768, 168-173 (2017)

H_T is underestimated in GK model

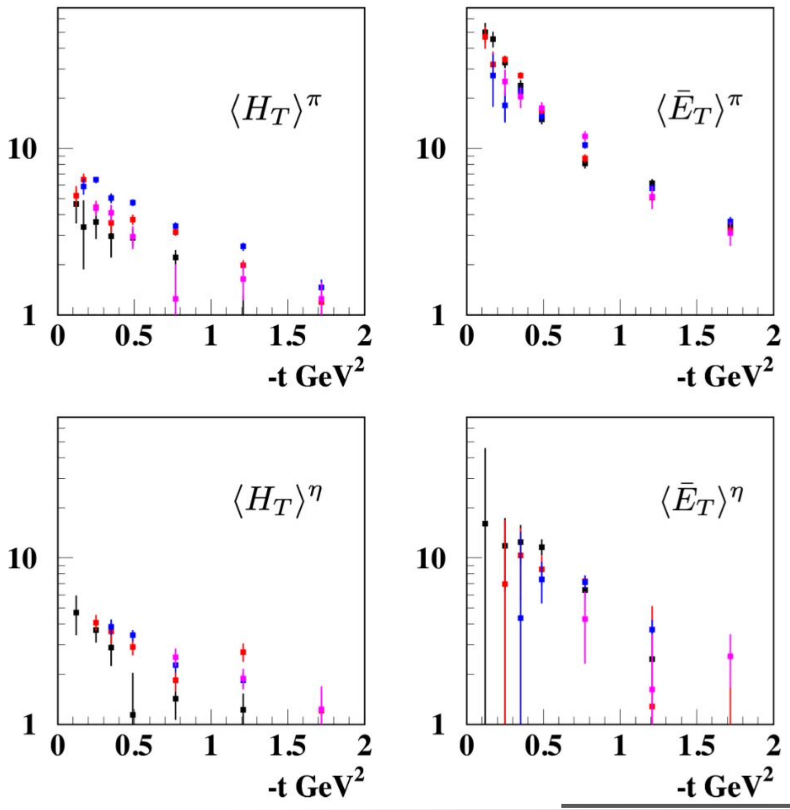
$$A_{LL}^{const} \sim |\langle H_T\rangle|^2$$



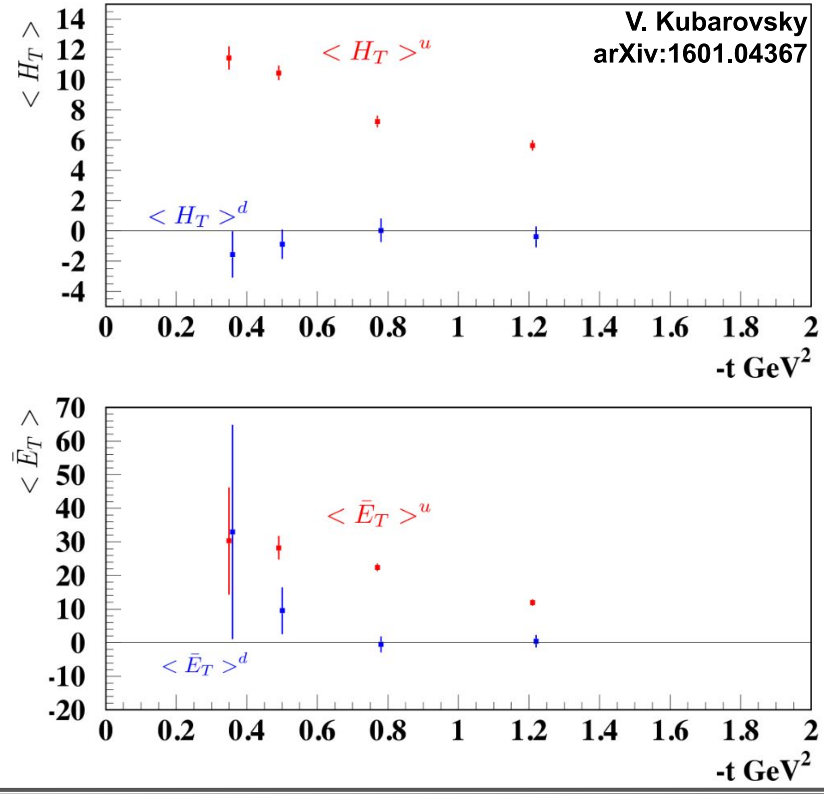
Few-Body Syst 57, 1041–1050 (2016)

GPD insight (in progress)

Generalized Form Factors

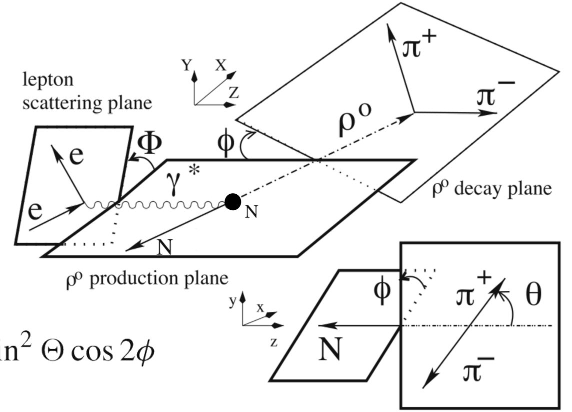


Quark flavor decomposition



Vector meson production to access Spin Density Matrix Elements (SDME)

$$\frac{d\sigma}{d\phi\, d\Phi\, d\Theta\, dQ^2\, dx_B\, dt} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left\{\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right\}\mathcal{W}^{U+L}(\Phi, \phi, \cos\Theta)$$



$$\mathcal{W}^{U+L}(\Phi, \phi, \cos\Theta) = \mathcal{W}^{U}(\Phi, \phi, \cos\Theta) + P_b\mathcal{W}^{L}(\Phi, \phi, \cos\Theta),$$

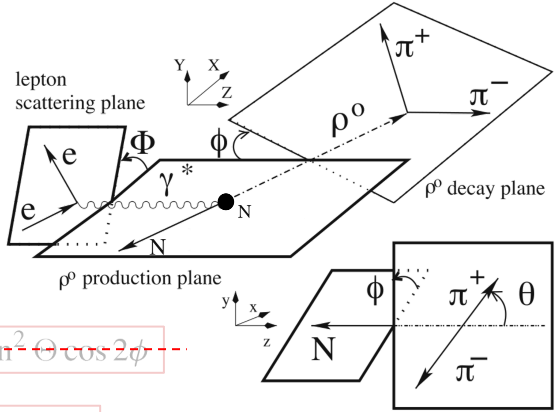
$$\begin{aligned}
\mathcal{W}^{U}(\Phi, \phi, \cos\Theta) = \frac{3}{8\pi^2}\Bigg[&\frac{1}{2}(1 - r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00} - 1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi \\
&-\epsilon\cos 2\Phi(r^1_{11}\sin^2\Theta + r^1_{00}\cos^2\Theta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

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

Vector meson production to access Spin Density Matrix Elements (SDME)

Terms that are cancelled after integration over decay plane ϕ

Terms that become constant after integration over decay plane Θ



$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta)=\mathcal{W}^{U}(\Phi,\phi,\cos\Theta)+P_b\mathcal{W}^{L}(\Phi,\phi,\cos\Theta),$$

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

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

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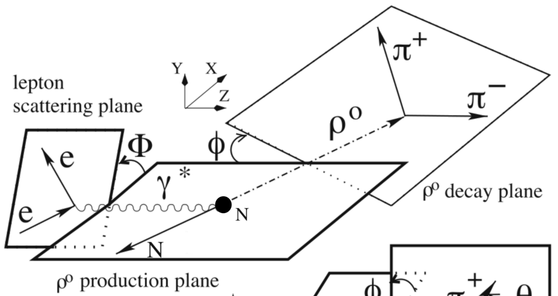
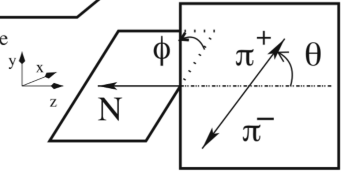




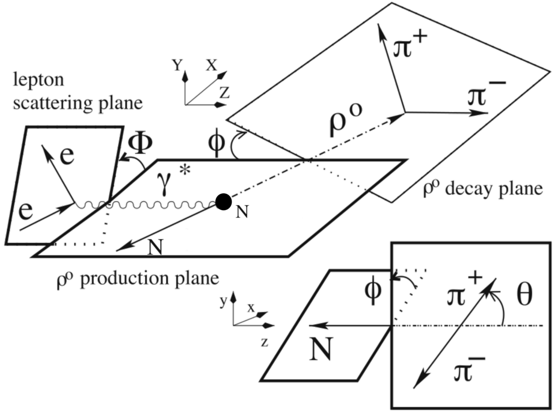
$$\mathcal{W}^{U+L}(\Phi, \phi, \cos\Theta) = \mathcal{W}^{U}(\Phi, \phi, \cos\Theta) + P_b\mathcal{W}^{L}(\Phi, \phi, \cos\Theta),$$

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

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

From SDME to GPDs

$$\frac{d\sigma}{d\phi\ d\Phi\ d\Theta\ dQ^2\ dx_B\ dt} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left\{\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right\}\mathcal{W}^{U+L}(\Phi, \phi, \cos\Theta)$$



After simplifications from Eur. Phys. J. C (2014):

$$r^1_{00}\sigma_0 \sim \left|\bar{E}_T\right|^2$$

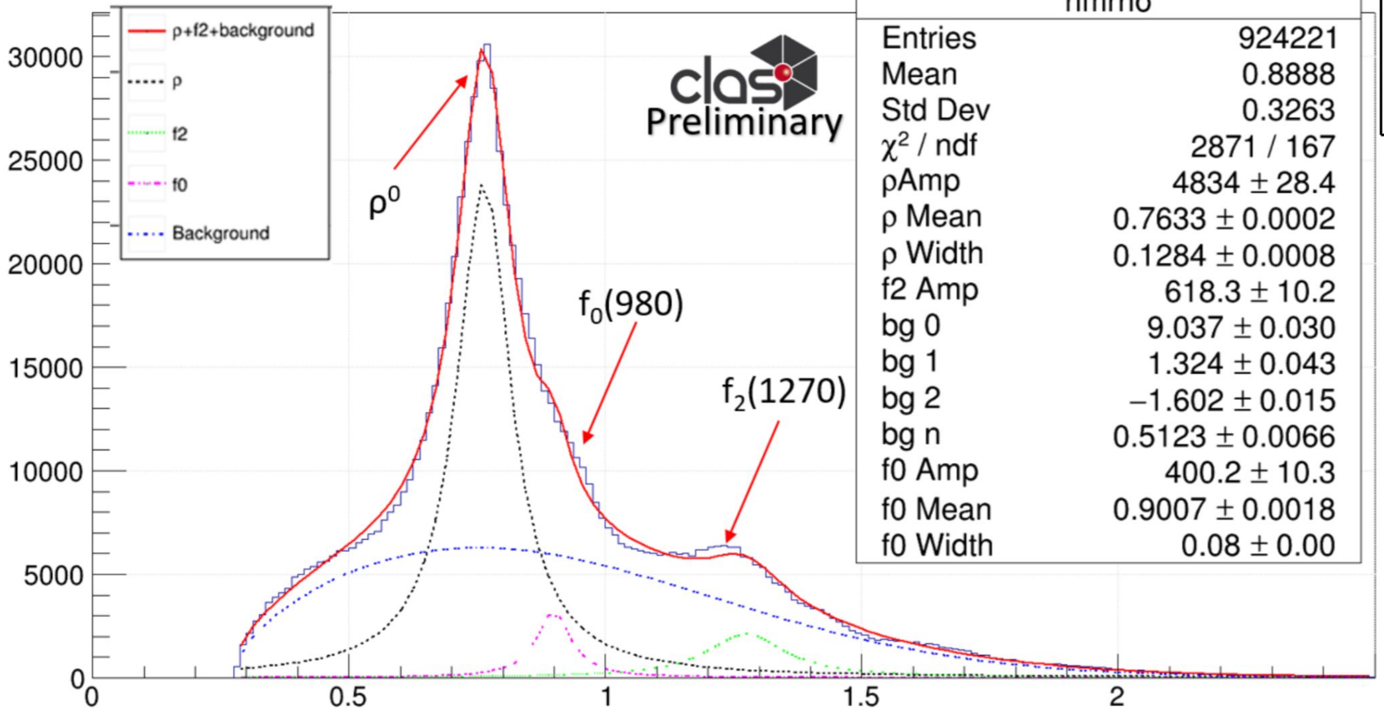
$$r^5_{00}\sigma_0 \sim \mathrm{Re}\left[\langle\bar{E}_T\rangle\langle H\rangle + \langle H_T\rangle\langle E\rangle\right]$$

$$r^8_{00}\sigma_0 \sim \mathrm{Im}\left[\langle\bar{E}_T\rangle\langle H\rangle + \langle H_T\rangle\langle E\rangle\right]$$

$$R = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}}$$

Vector meson electroproduction with CLAS12: $ep \to ep\rho^0 \to e\pi^+\pi^-(P)$

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



hmrho	
Entries	924221
Mean	0.8888
Std Dev	0.3263
χ^2 / ndf	2871 / 167
ρAmp	4834 ± 28.4
ρ Mean	0.7633 ± 0.0002
ρ Width	0.1284 ± 0.0008
f2 Amp	618.3 ± 10.2
bg 0	9.037 ± 0.030
bg 1	1.324 ± 0.043
bg 2	−1.602 ± 0.015
bg n	0.5123 ± 0.0066
f0 Amp	400.2 ± 10.3
f0 Mean	0.9007 ± 0.0018
f0 Width	0.08 ± 0.00

parameter	PDG value
ρ^0 mass M_ρ (MeV)	≈ 770
ρ^0 width Γ_ρ (MeV)	≈ 150
f_0 mass M_{f_0} (MeV)	≈ 980
f_0 width Γ_{f_0} (MeV)	40-100
f_2 mass M_{f_2} (MeV)	≈ 1275
f_2 width Γ_{f_2} (MeV)	≈ 185

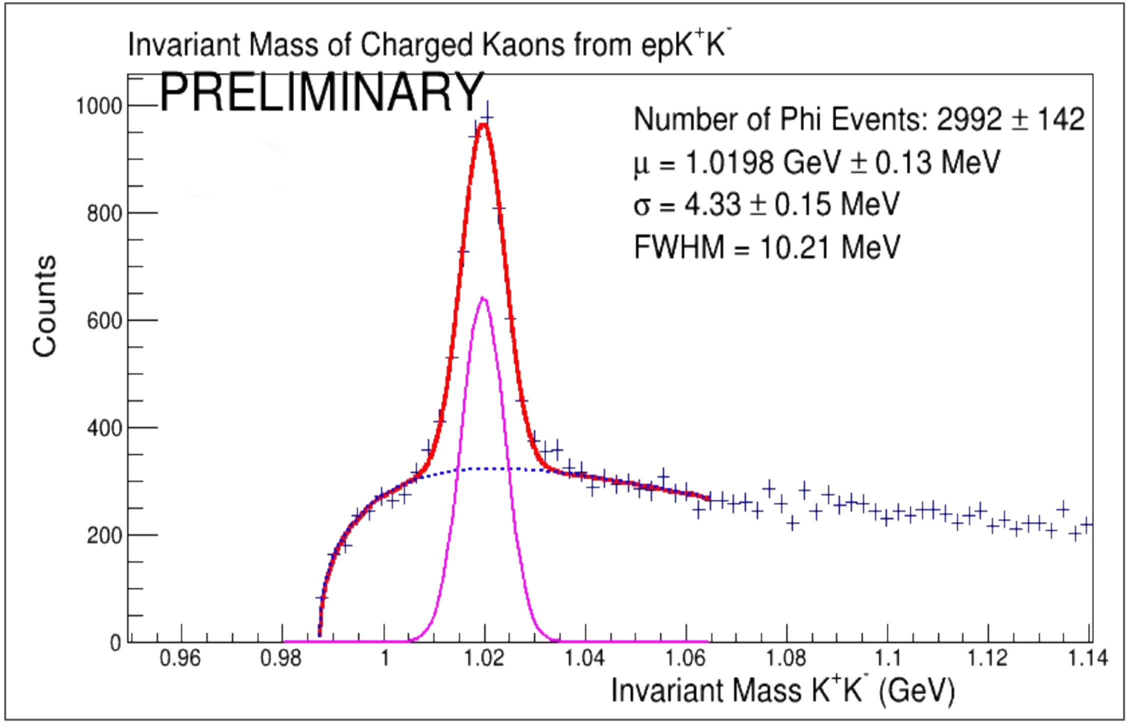
$$\frac{dN}{dM_{\pi\pi}} = BW_{\rho^0}(M_{\pi\pi}) + BW_{f_0}(M_{\pi\pi}) + BW_{f_2}(M_{\pi\pi}) + BG_{ARGUS}(M_{\pi\pi})$$

Vector meson electroproduction with CLAS12

$$ep \to ep\phi \to epK^+K^-$$

Access gluonic GPDs:

- ϕ $(s\bar{s})$ - low $|-t|$ measurements where GPDs are relevant
- J/ψ $(c\bar{c})$ - measure the t-dependence of the differential cross section of J/ψ photoproduction*



analysis by B. Clary (**UCONN**)

- active work on φ cross-section measurements by P. Moran (MIT)
- active work on J/ψ cross-section measurements by J. Newton (JLab)

- The exclusive meson electroproduction program at CLAS and CLAS12 has produced important measurements which are already improving our knowledge of Generalized Parton Distributions.

- Stay tuned for the new measurements of **pseudoscalar** and **vector** exclusive meson production channels from CLAS12 data.

THANK YOU