

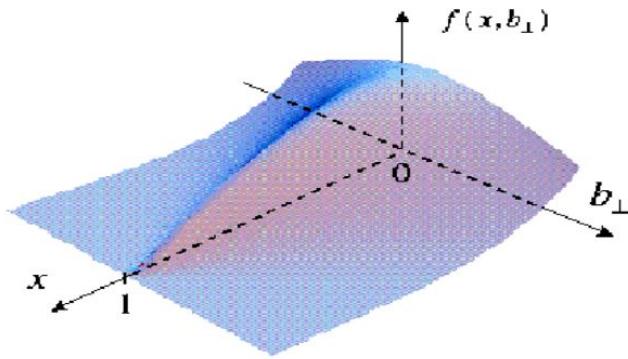
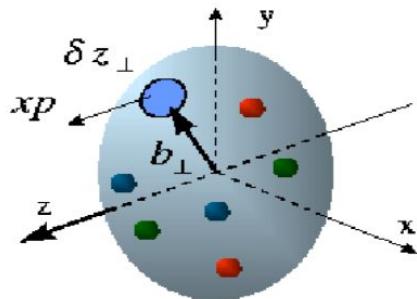
Exclusive meson production program with CLAS12 at 12 and 20+ GeV

APCTP Focus Program in Nuclear Physics 2022:
Hadron Physics Opportunities with JLab Energy and Luminosity Upgrade

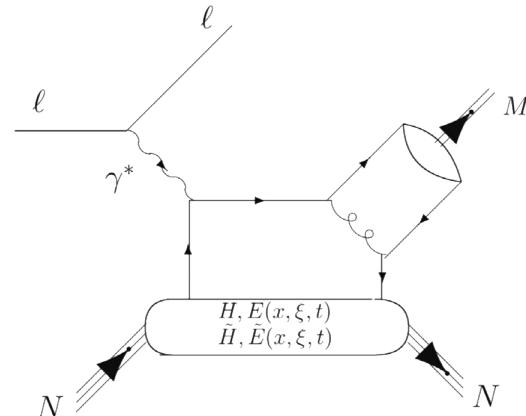
July 22, 2022

Andrey Kim
(University of Connecticut)

GPDs and exclusive meson electroproduction

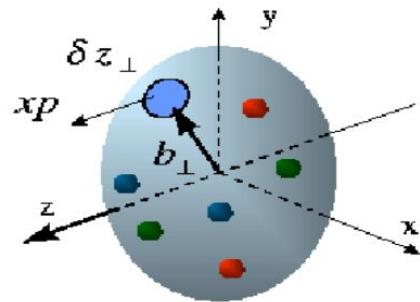


- 4 chiral-even GPDs: $H, E, \tilde{H}, \tilde{E}$
- 4 chiral-odd GPDs: $H_T, E_T, \tilde{H}_T, \tilde{E}_T$

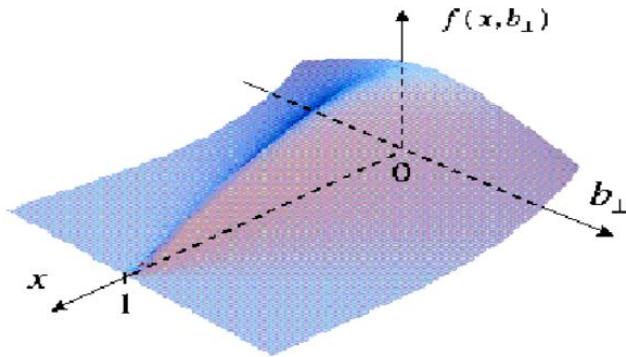


$$\langle F \rangle = \sum_{\lambda} \int_{-1}^1 dx \mathcal{H}_{0\lambda,\mu\lambda}(x, \xi, Q^2, t) F(x, \xi, t)$$

GPDs and exclusive meson electroproduction



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



\tilde{H}, \tilde{E}
 H_T, \bar{E}_T
 H, E

Meson	GPD flavor composition
π^+	$\Delta u - \Delta d$
π^0	$2\Delta u + \Delta d$
η	$2\Delta u - \Delta d$
<hr/>	<hr/>
ρ^0	$2u + d$
ρ^+	$u - d$
ω	$2u - d$

Link GPDs to PDF and Elastic 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:

$$\int dx H^q(x, \xi, t) = F_1(t)$$

$$\int dx E^q(x, \xi, t) = F_2(t)$$

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

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

X. Ji, Phys. Rev. Lett. 78, 610 (1997):

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

- Proton anomalous tensor magnetic moment

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

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

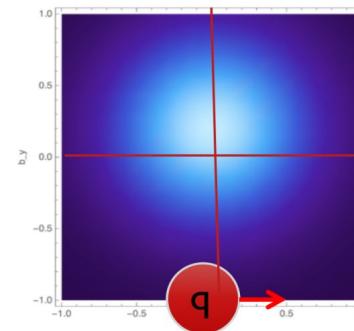
- Proton tensor charge

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

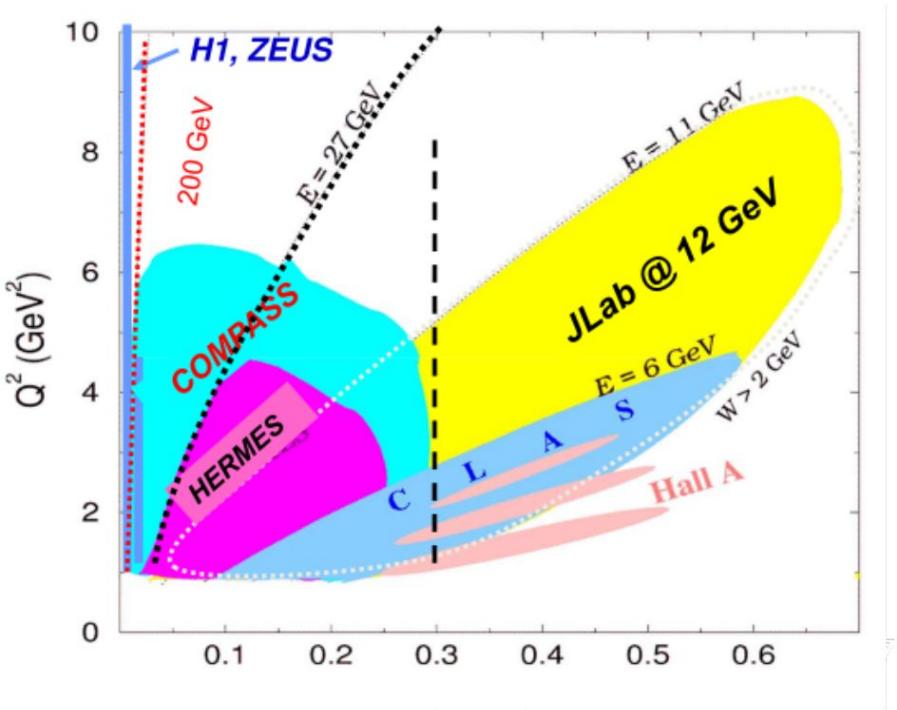
$$\delta_T^d = \int dx H_T^d(x, \xi, t=0)$$

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

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



Experimental observables for exclusive meson production

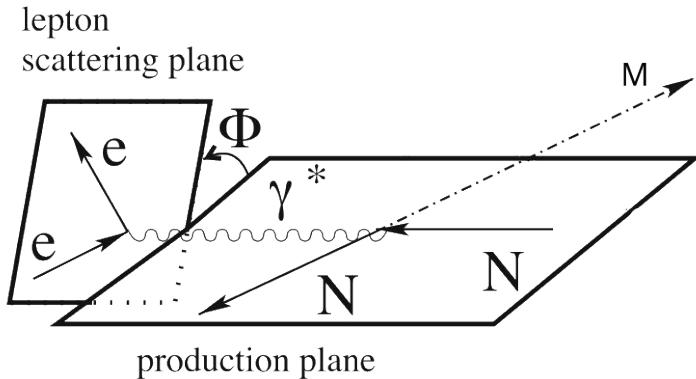


- Early results (2001) from non-dedicated experiment with CLAS (DVCS target spin asymmetry)
- First round of dedicated experiments in Halls A/B at JLab 2004/2005
- Second round of dedicated experiments 2008/2010
- Strong exclusive program at 12 GeV, CLAS12 first experiment data is under analysis

Experimental observables for exclusive meson production

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

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



where λ is the helicity state of the incident electron beam

Experimental observables for exclusive meson production

Unpolarized beam and target

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

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

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

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

Experimental observables for exclusive meson production

Unpolarized beam and target

Longitudinally polarized beam and longitudinally polarized target

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

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

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

Experimental observables for exclusive meson production

Unpolarized beam and target

Longitudinally polarized beam and longitudinally polarized target

Unpolarized beam and transversely polarized target

$$A_{UT}^{\sin(\phi - \phi_s)} \sigma_0 \sim -2\epsilon\sqrt{-t'} \operatorname{Im} \left[\langle \tilde{E} \rangle^* \langle \tilde{H}_{\text{eff}} \rangle \right] - \sqrt{-t'} \operatorname{Im} \left[\langle H_T \rangle^* \langle \bar{E}_T \rangle \right]$$

$$A_{UT}^{\sin(\phi_s)} \sigma_0 \sim -\sqrt{\epsilon(1 + \epsilon)} \operatorname{Im} \left[t' \langle \bar{E}_T \rangle^* \langle \tilde{E} \rangle + \langle H_T \rangle^* \langle \tilde{H}_{\text{eff}} \rangle \right]$$

$$A_{UT}^{\sin(2\phi - \phi_s)} \sigma_0 \sim -\sqrt{\epsilon(1 + \epsilon)} t' \operatorname{Im} \left[\langle \bar{E}_T \rangle^* \langle \tilde{E} \rangle \right]$$

$$A_{UT}^{\sin(\phi + \phi_s)} \sigma_0 \sim \epsilon \sqrt{-t'} \operatorname{Im} \left[\langle H_T \rangle^* \langle \bar{E}_T \rangle \right]$$

$$A_{LT}^{\cos(\phi_s)} \sigma_0 \sim \sqrt{\epsilon(1 - \epsilon)} \operatorname{Re} \left[t' \langle \bar{E}_T \rangle^* \langle \tilde{E} \rangle + \langle H_T \rangle^* \langle \tilde{H}_{\text{eff}} \rangle \right]$$

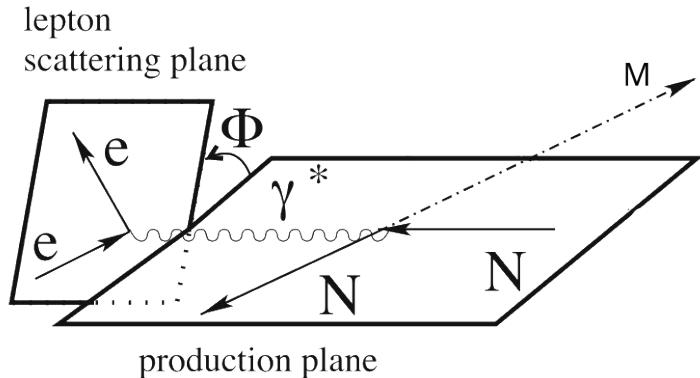
$$A_{LT}^{\cos(\phi - \phi_s)} \sigma_0 \sim \sqrt{1 - \epsilon^2} \sqrt{-t'} \operatorname{Re} \left[\langle H_T \rangle^* \langle \bar{E}_T \rangle \right]$$

$$A_{LT}^{\cos(2\phi - \phi_s)} \sigma_0 \sim \sqrt{\epsilon(1 - \epsilon)} t' \operatorname{Re} \left[\langle \bar{E}_T \rangle^* \langle \tilde{E} \rangle \right]$$

Experimental observables for exclusive meson production

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)
- Eur. Phys. J. A39: 5-31, 2009 (ρ^0)
- Phys. Rev. Lett. 109, 112001 (2012) (π^0)
- Phys. Rev. C 95, 035207 (2017) (η)
- Phys. Rev. C 95, 035206 (2017) (π^0)
- Phys. Rev. C 95, 035202 (2017) (π^+)
- Phys. Lett. B 768, 168 (2017) (π^0)
- Phys. Lett. B. 789, 426 (2019) (η)
- Phys. Rev. Lett. 125, 182001 (2020) (π^+)



Experimental observables for exclusive meson production

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Phys. Rev. C 95, 035207 (2017) (η)

Phys. Rev. C 95, 035206 (2017) (π^0)

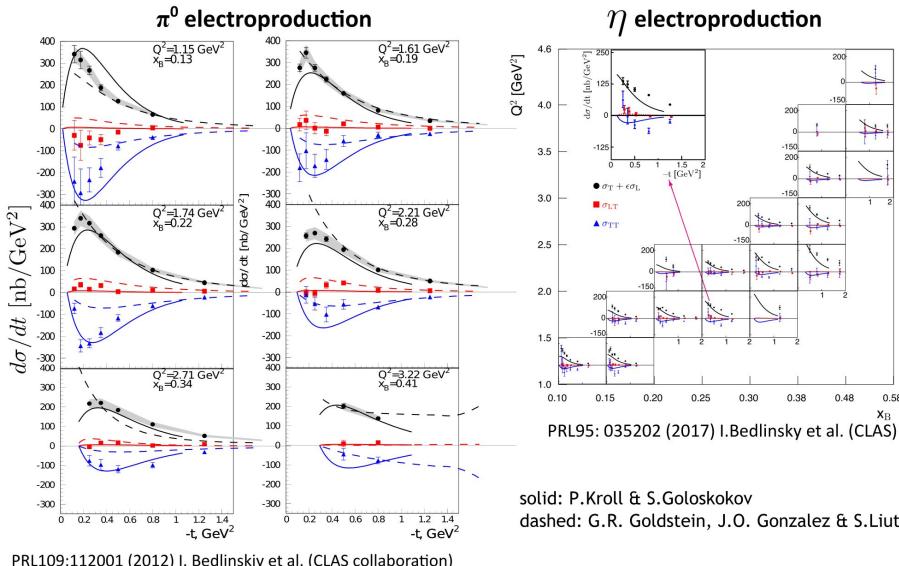
Phys Rev C 95 035202 (2017) (π^+)

Phys Lett B 768 168 (2017) (π^0)

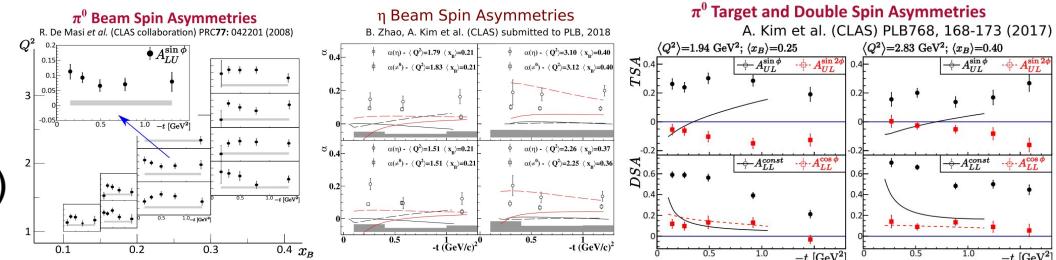
Phys Lett B 789 426 (2019) (n)

Phys. Rev. Lett. 125, 182001 (2020)

Phys. Rev. Lett. 125, 182001 (2020) (π^+)



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



Experimental observables for exclusive meson production

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Phys. Rev. C 95, 035202 (2017) (π^+)

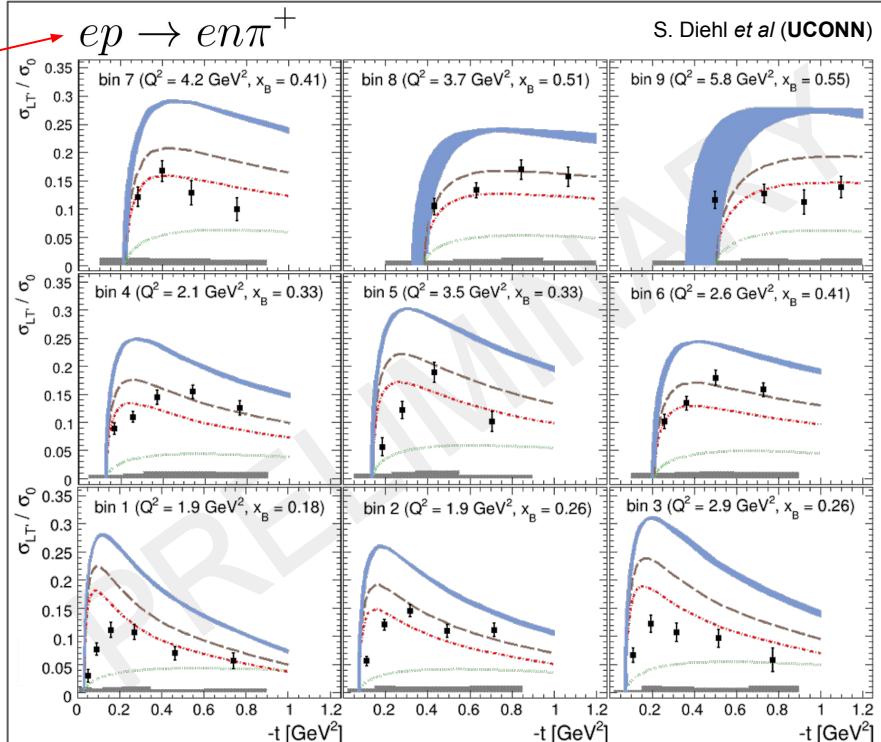
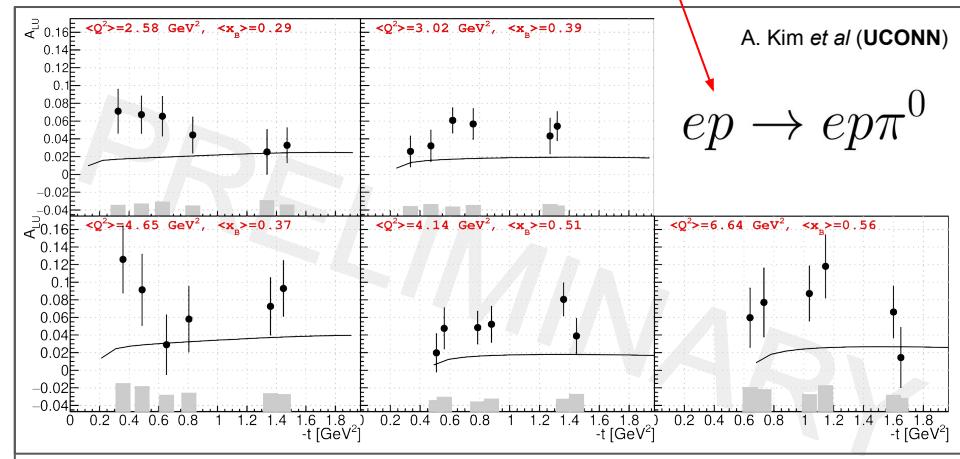
Phys. Lett. B 768, 168 (2017) (π^0)

Phys. Lett. B. 789, 426 (2019) (η)

Phys. Rev. Lett. 125, 182001 (2020) (π^+)

Pseudoscalar meson electroproduction with CLAS12

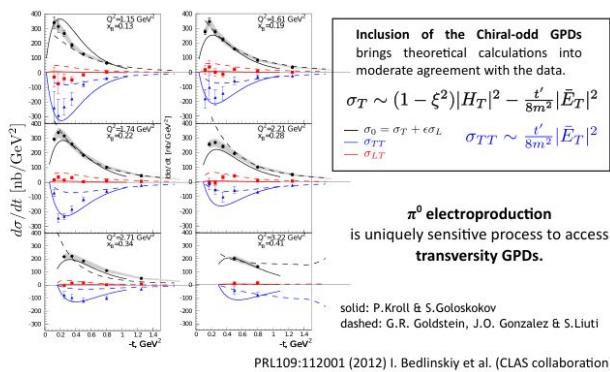
$$\sigma_{LT'} = \xi \sqrt{1 - \xi^2} \frac{\sqrt{-t'}}{2m} \times \\ \times \text{Im} [\langle H_T \rangle^* \langle \tilde{E} \rangle + \langle \bar{E}_T \rangle^* \langle \tilde{H} \rangle]$$



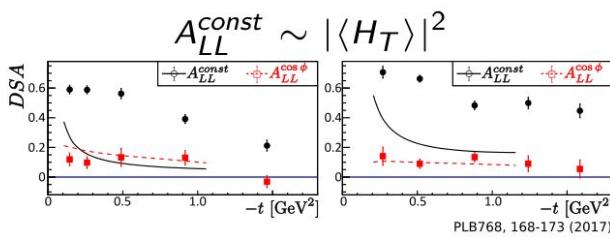
Additionally active work on η beam spin asymmetry and cross-section extraction

GPD insight (in progress)

Unpolarized cross section

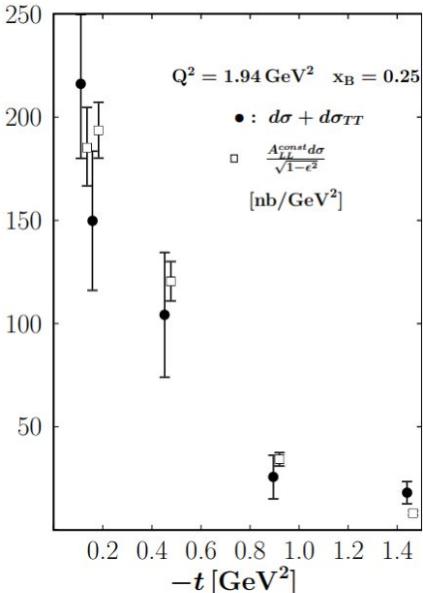
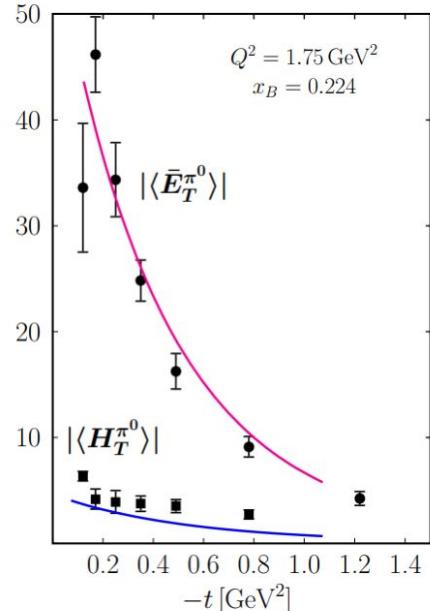


Double Spin Asymmetry



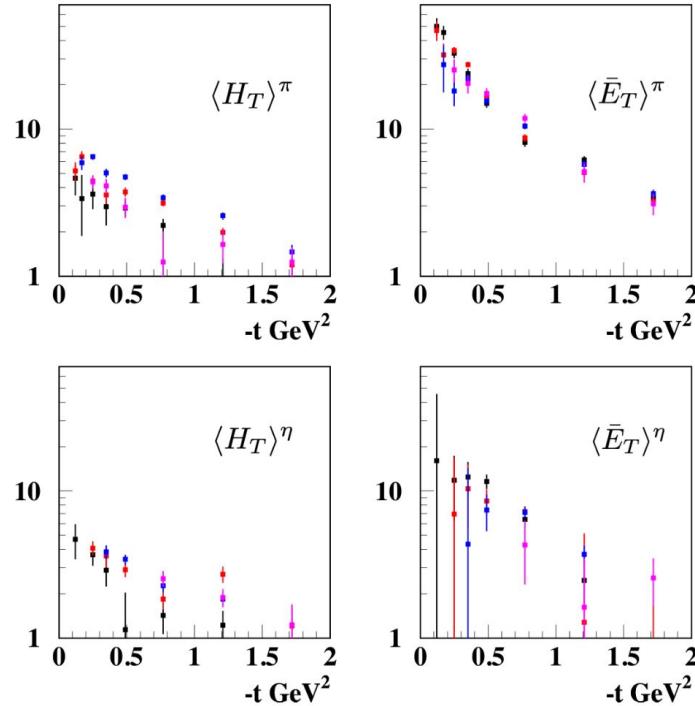
H_T is underestimated in GK model

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

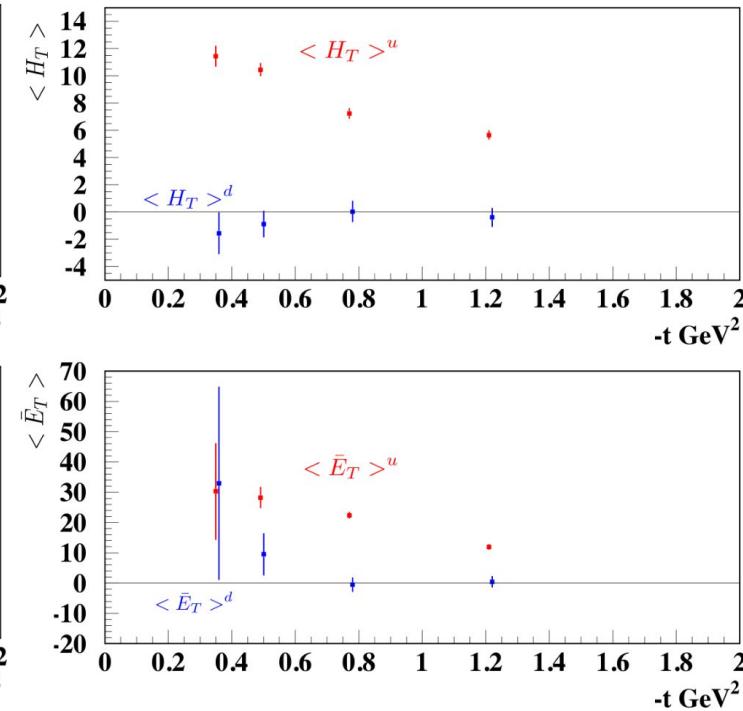


Few-Body Syst 57, 1041–1050 (2016)

Generalized Form Factors



Quark flavor decomposition



Valery Kubarovsky, arXiv:1601.04367

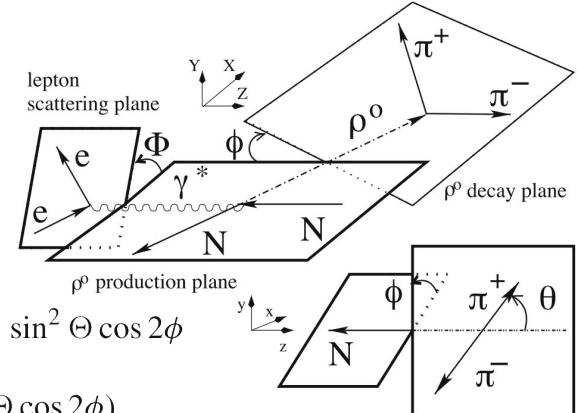
Vector meson production: Spin Density Matrix Elements (SDME)

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

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

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

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



Vector meson production: Spin Density Matrix Elements (SDME)

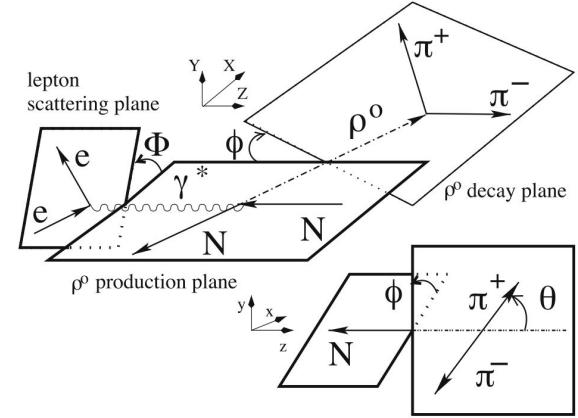
$$\frac{d\sigma}{d\phi \, d\Phi \, d\Theta \, dQ^2 \, dx_B \, dt} = \Gamma(Q^2, x_B, E) \frac{1}{2\pi} \left\{ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right\} \mathcal{W}^{U+L}(\Phi, \phi, \cos \Theta)$$

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

$$r_{00}^1 \sigma_0 \sim |\bar{E}_T|^2$$

$$r_{00}^5 \sigma_0 \sim \text{Re} [\langle \bar{E}_T \rangle \langle H \rangle + \langle H_T \rangle \langle E \rangle]$$

$$r_{00}^8 \sigma_0 \sim \text{Im} [\langle \bar{E}_T \rangle \langle H \rangle + \langle H_T \rangle \langle E \rangle]$$

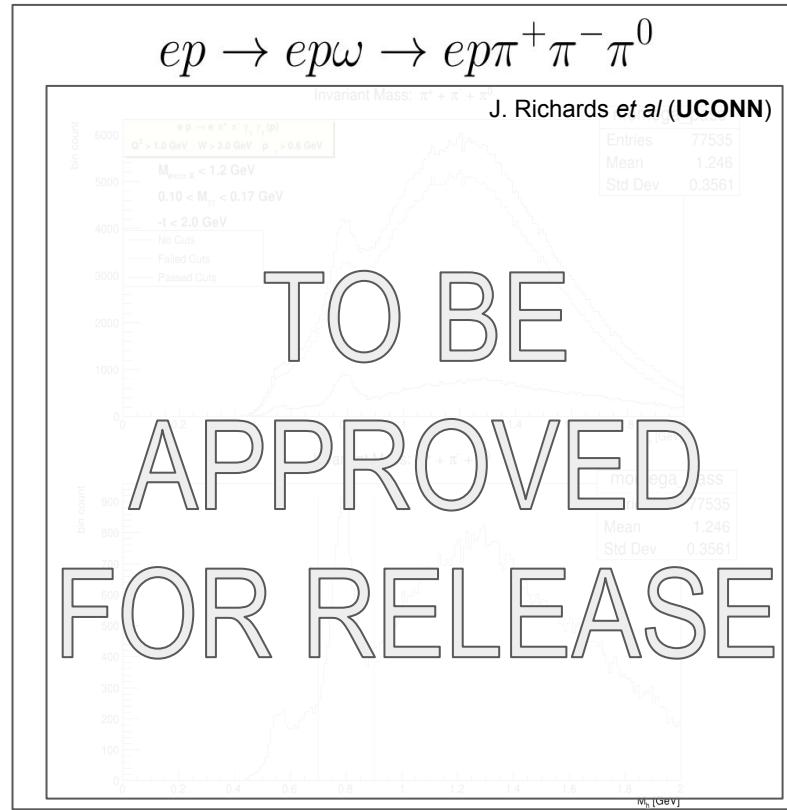
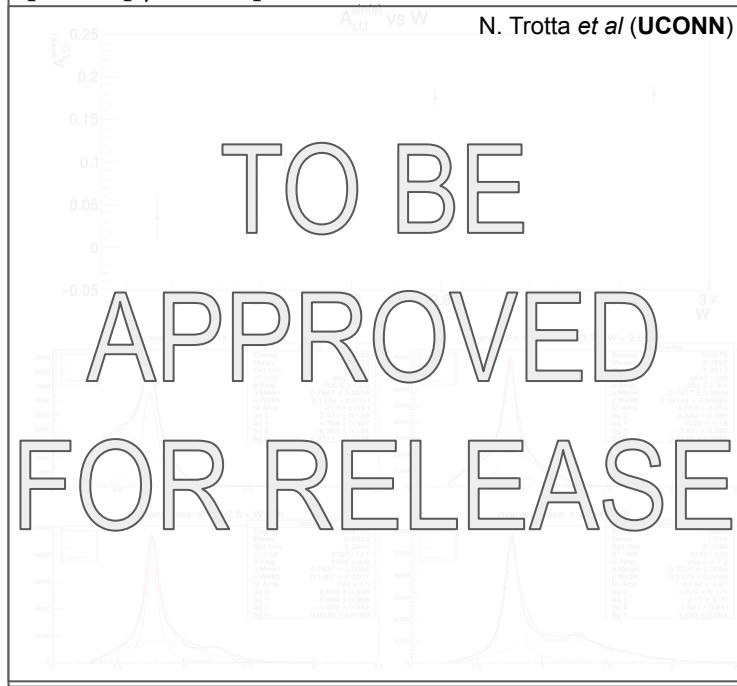


$$R = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

Vector meson electroproduction with CLAS12: ρ and ω

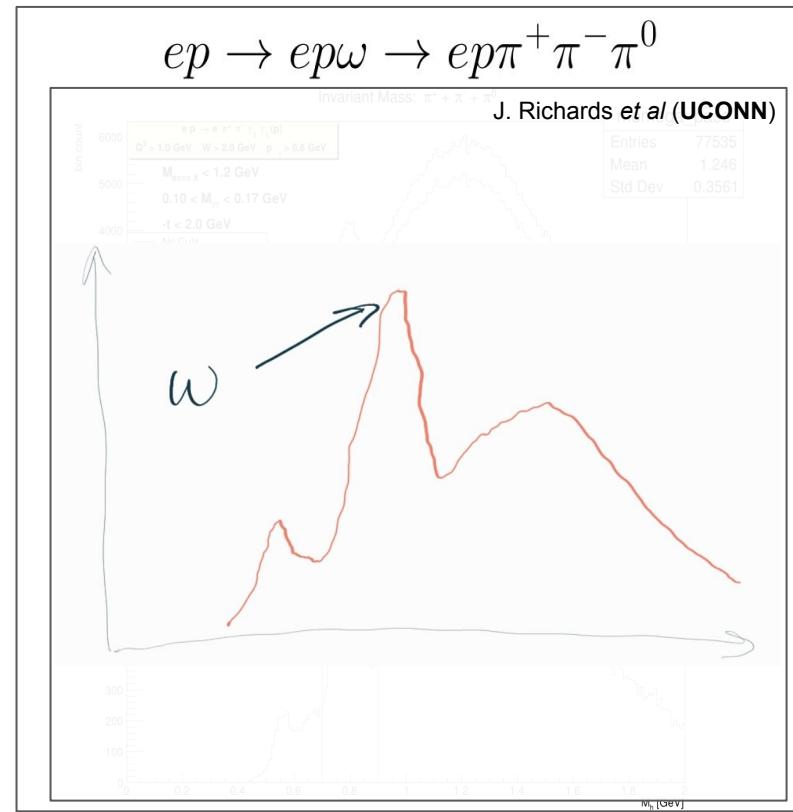
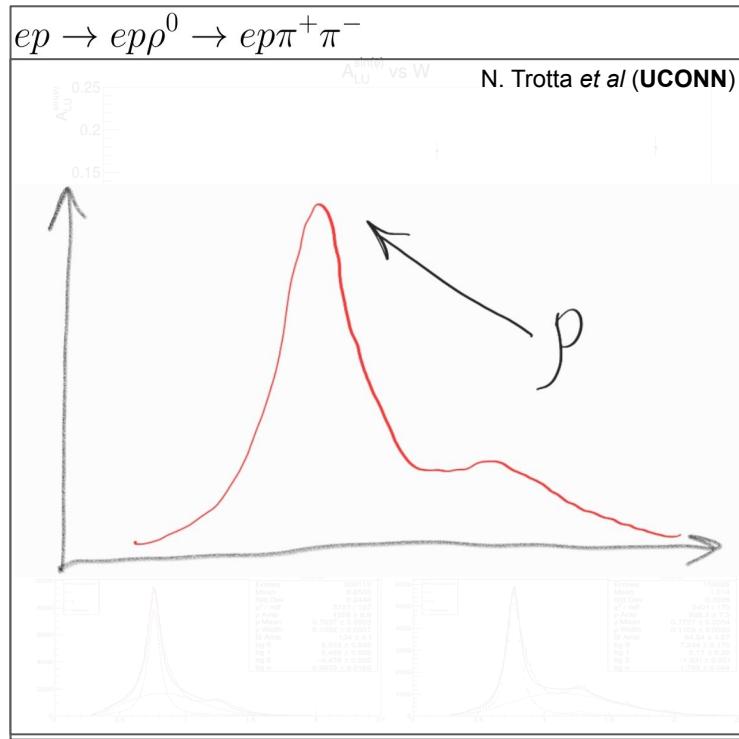
$$\sigma_{LT'} \sim r_{00}^8 \sim \text{Im} [\langle H_T \rangle^* \langle E \rangle + \langle \bar{E}_T \rangle^* \langle H \rangle]$$

$$ep \rightarrow ep\rho^0 \rightarrow ep\pi^+\pi^-$$



Vector meson electroproduction with CLAS12: ϱ and ω

$$\sigma_{LT'} \sim r_{00}^8 \sim \text{Im} [\langle H_T \rangle^* \langle E \rangle + \langle \bar{E}_T \rangle^* \langle H \rangle]$$



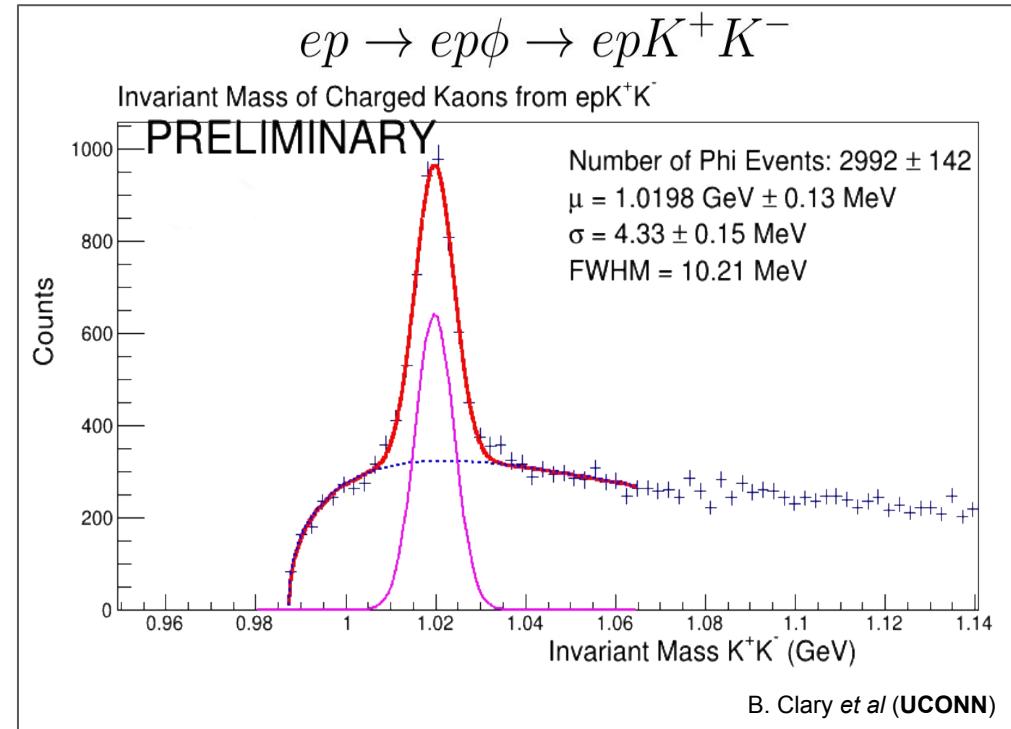
Vector meson electroproduction with CLAS12: φ

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*

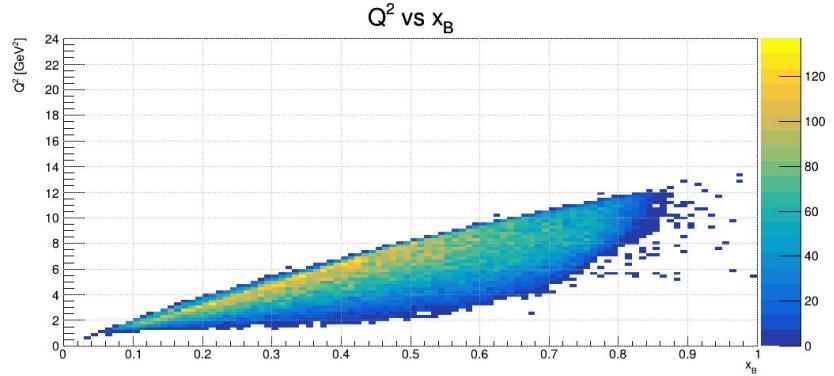
* active work on φ cross-section measurements by P. Moran (MIT)

* active work on J/ψ cross-section measurements by J. Newton (JLab)

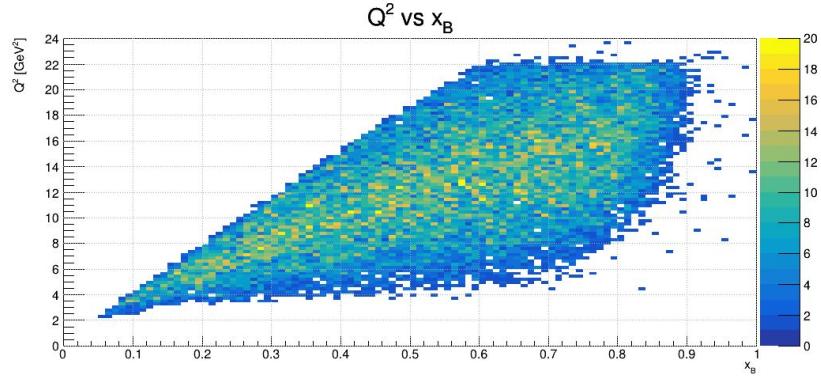


Kinematic coverage for ρ electroproduction: MC

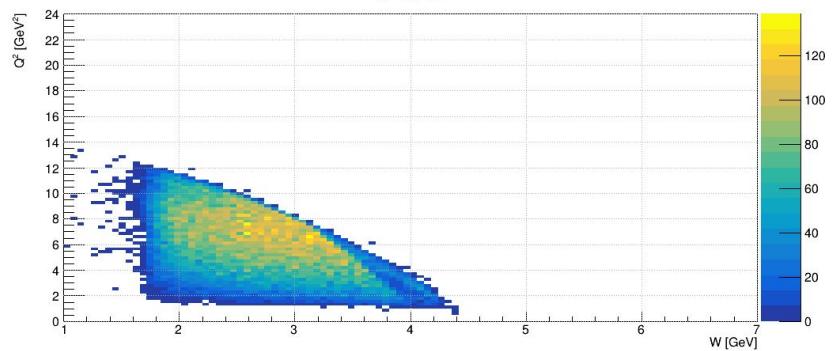
@ 10.6 GeV beam energy



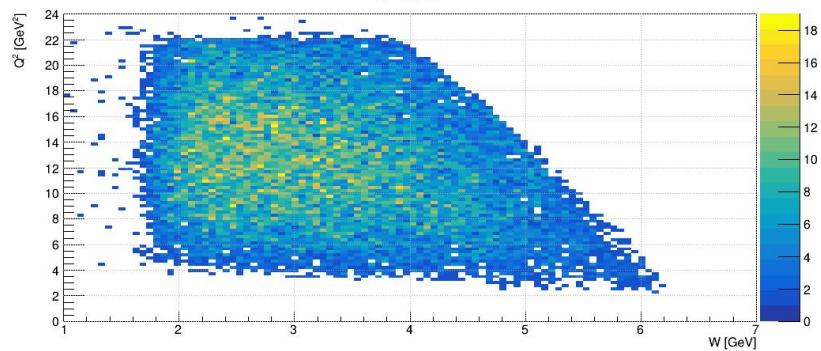
@ 22 GeV beam energy



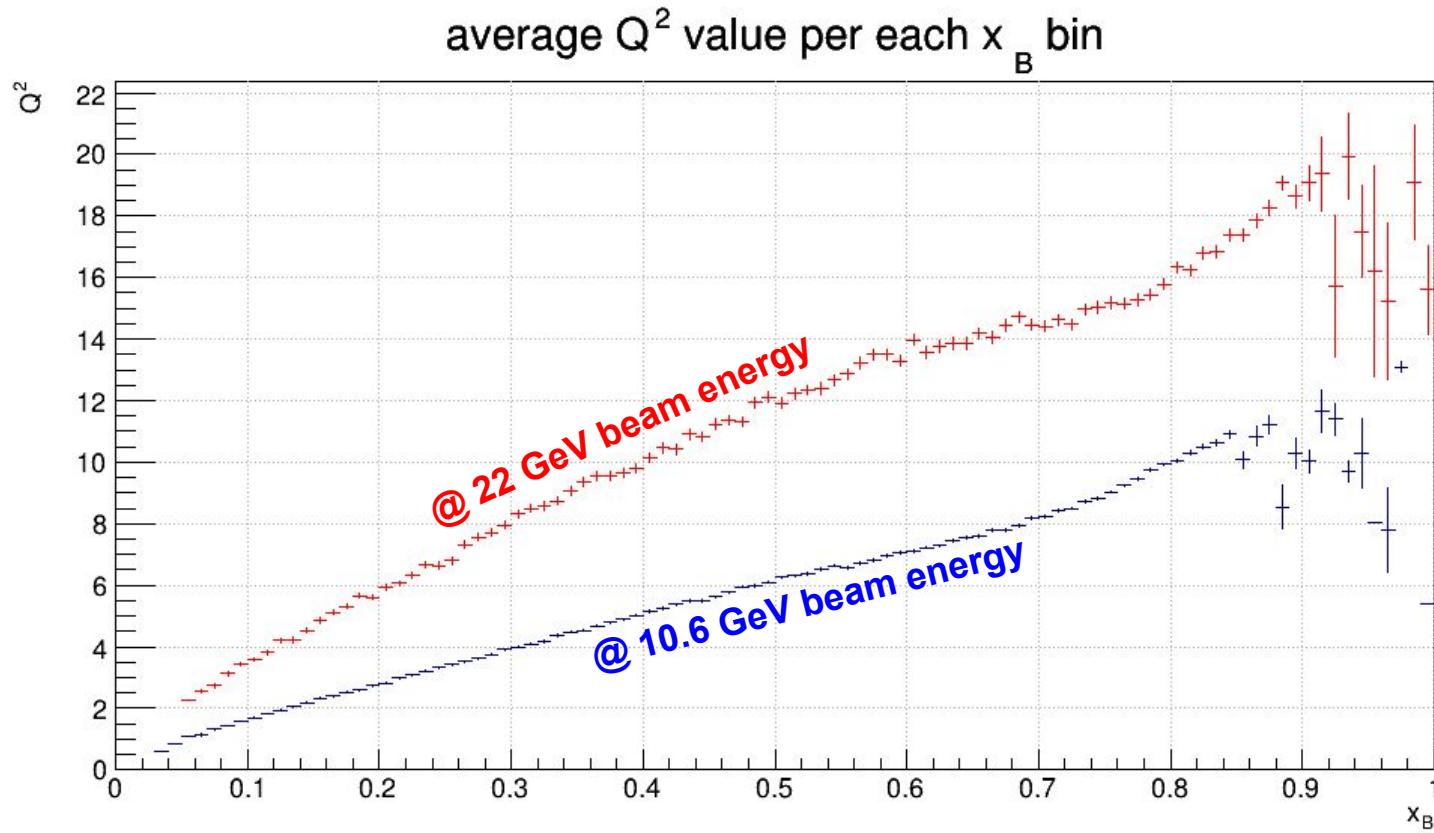
Q² vs W



Q² vs W

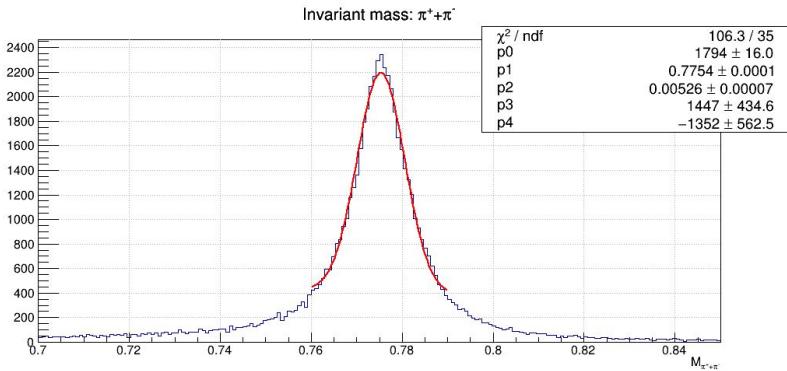


Kinematic coverage for ρ electroproduction: MC

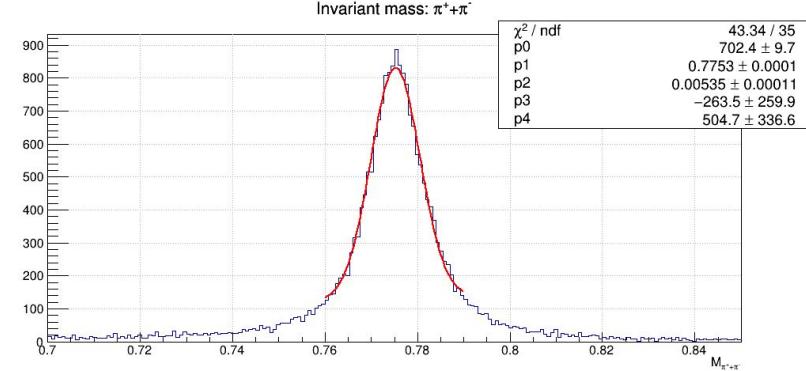


Invariant and missing masses for ϱ electroproduction: MC

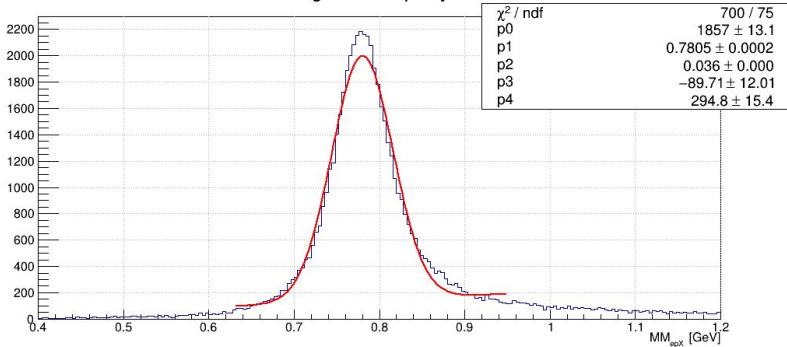
@ 10.6 GeV beam energy



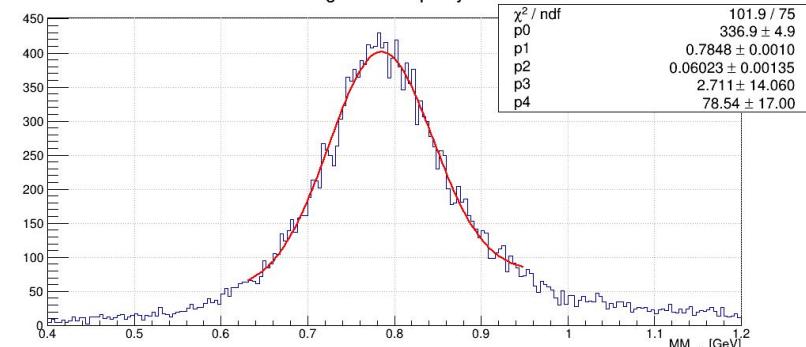
@ 22 GeV beam energy



Missing mass of epX system



Missing mass of epX system



Conclusions

- CLAS spectrometer combined with 20+ GeV beam upgrade will extend ongoing 12 GeV measurements of deeply virtual meson production channels
- The variety of reactions provide opportunity for selective access to different GPDs, as well as access to valence quark and gluonic GPDs
- High luminosity and wide kinematic coverage of CLAS spectrometer provide opportunity for multi-dimensional analysis in a wide kinematic region and allow the extraction of structure functions and spin density matrix elements from the azimuthal distributions

THANK YOU