Exploring GPDs with deeply virtual π^0 and ρ^0 electroproduction at CLAS12

ECT*-APCTP Joint Workshop:
Exploring resonance structure with transition GPDs

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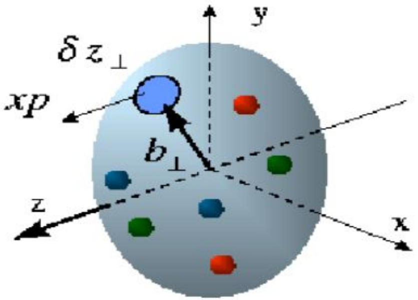
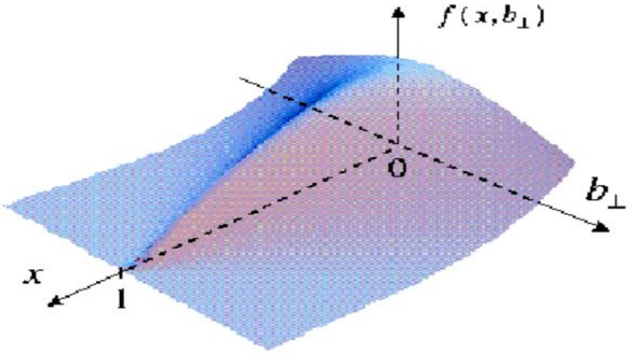
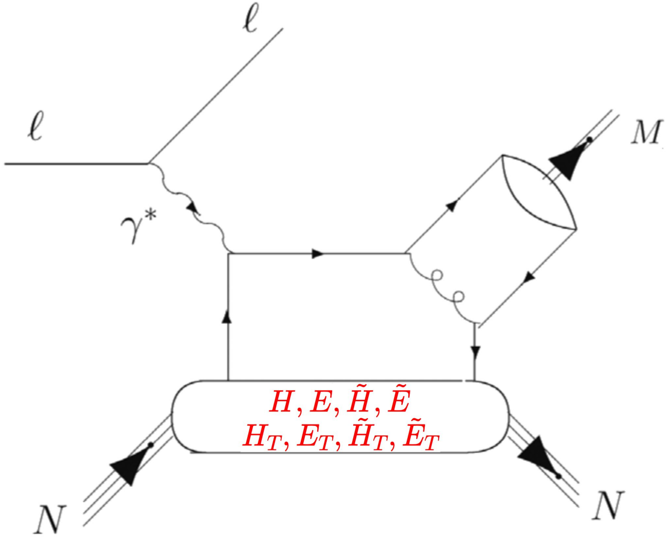
GPDs and exclusive meson electroproduction

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

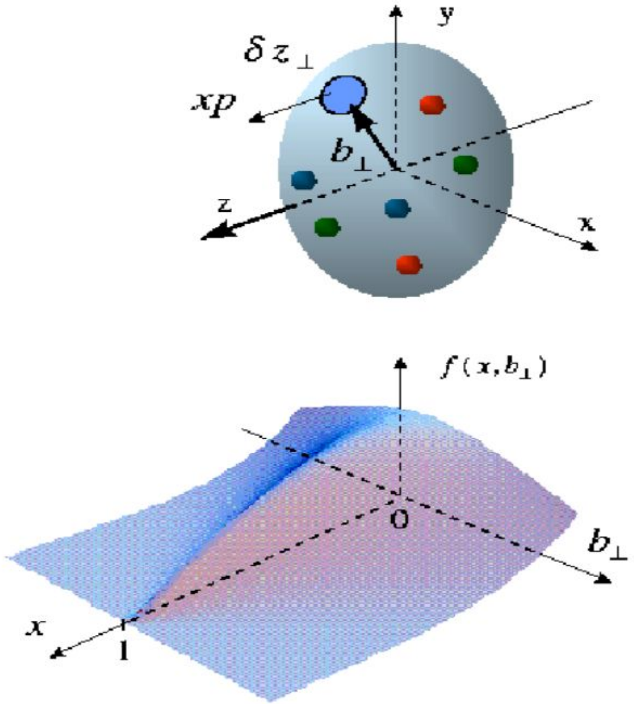






$$\langle F \rangle = \sum_{\lambda} \int_{-1}^{1} dx \mathcal{H}_{0\lambda,\mu\lambda}(x, \xi, Q^2, t) F(x, \xi, t)$$

GPDs and exclusive meson electroproduction



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

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

in the

- Proton tensor charge

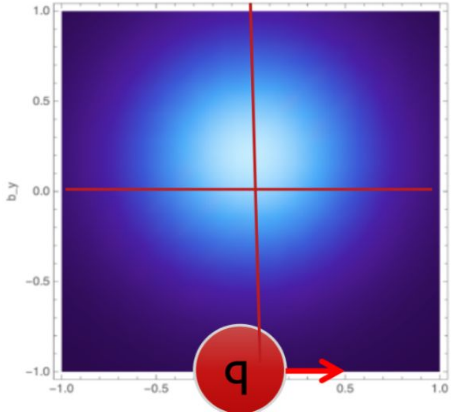
$$\delta_T^u = \int dx H_T^u(x,\xi,t=0)$$
$$\delta_T^d = \int dx H_T^d(x,\xi,t=0)$$

- 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

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



Experimental observables for exclusive meson electroproduction

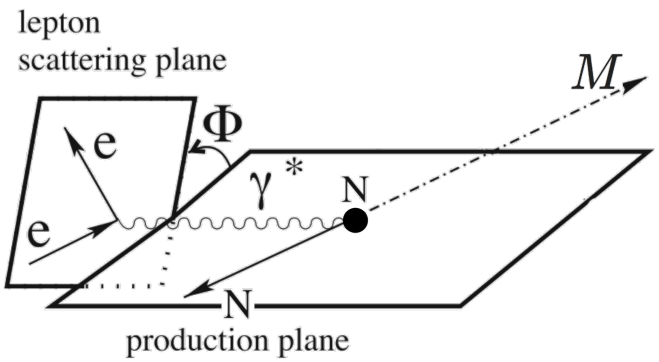
$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\Phi} = \Gamma(Q^2, x_B, E)$$

$$\frac{1}{2\pi}\left\{\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right.$$

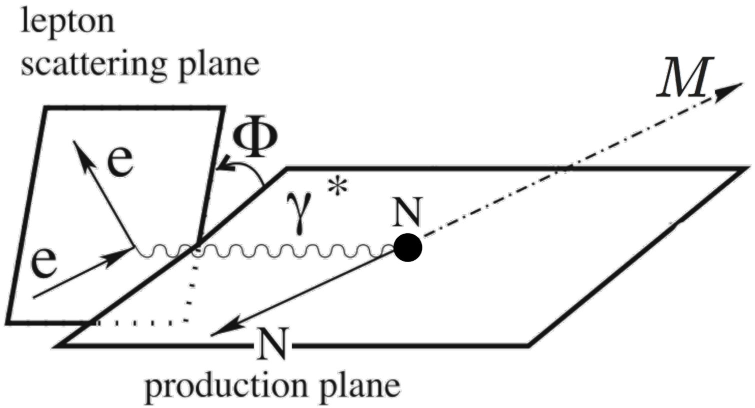
$$+\,\epsilon\frac{d\sigma_{TT}}{dt}\cos(2\Phi) + \sqrt{\epsilon(2\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos(\Phi)$$

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

where λ is the helicity state of the incident electron beam



Experimental observables for exclusive meson production



$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\Phi} = \Gamma(Q^2, x_B, E)\,\frac{1}{2\pi}\left\{\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right.$$

$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto A_{LU}^{\sin\phi}\sin\phi$$

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

Access to GPDs

PHYSICAL REVIEW D 84, 034007 (2011)

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

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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**

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

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

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

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

Access to GPDs

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Unpolarized beam and target

within GK formalism

Longitudinally polarized beam and longitudinally polarized target

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

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

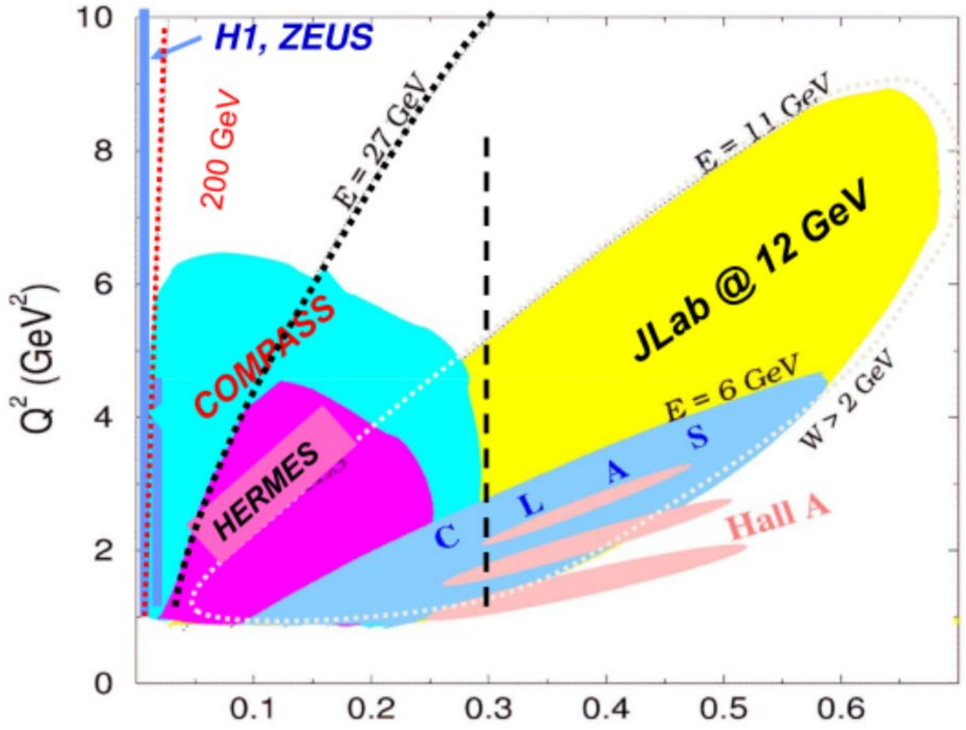
$$A_{LL}^{\cos(\phi)}\sigma_0 \sim -\sqrt{\epsilon(1-\epsilon)}\sqrt{-t'}\,\mathrm{Re}\Big[2\langle \bar{E}_T\rangle^* \langle \widetilde{H}_{\mathrm{eff}}\rangle + \langle H_T\rangle^* \langle \tilde{E}\rangle\Big]$$

within GK formalism

Measurements of exclusive meson production with CLAS

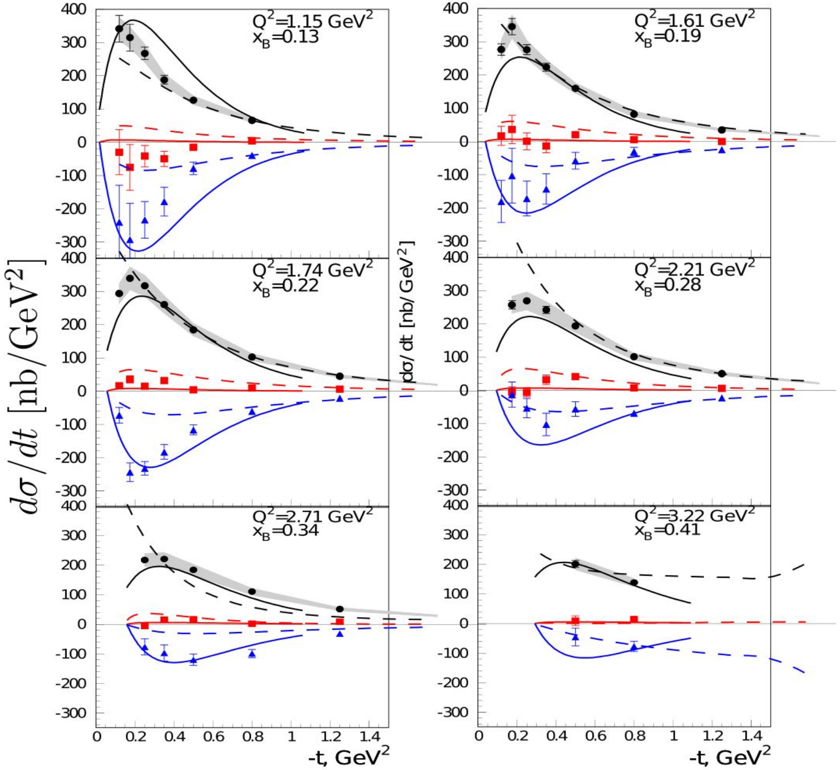
CLAS data:

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)
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)



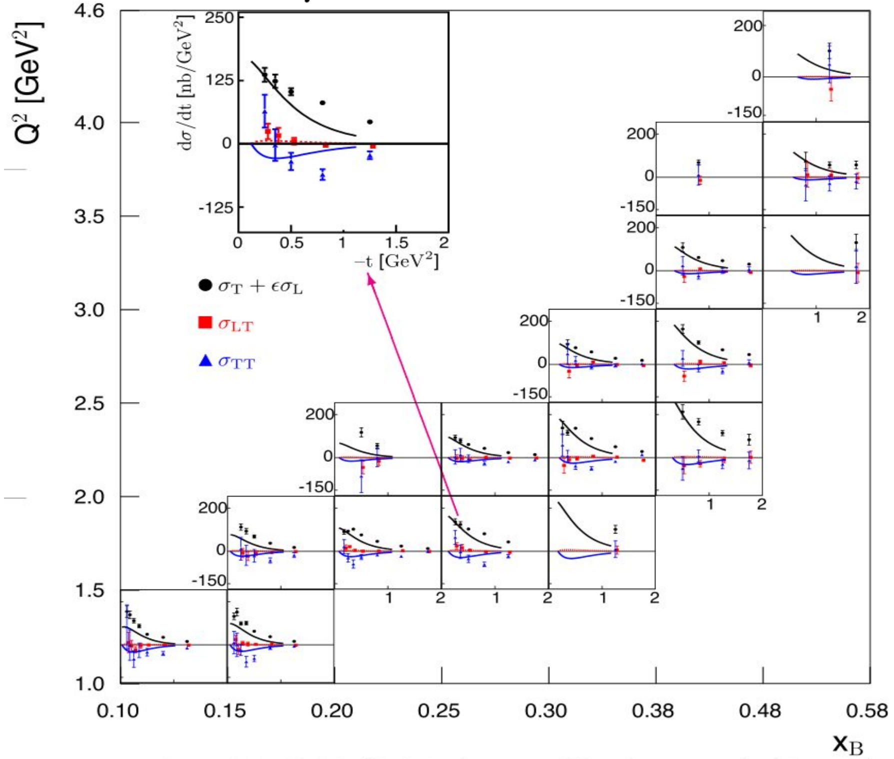
Experimental observables for exclusive meson production

π^0 electroproduction



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

η electroproduction

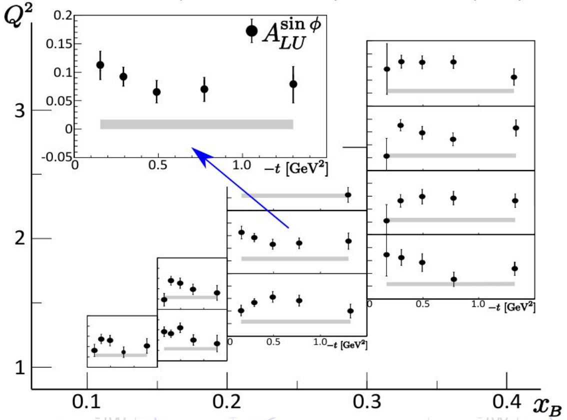


PRL95: 035202 (2017) I.Bedlinsky et al. (CLAS)

Experimental observables for exclusive meson production

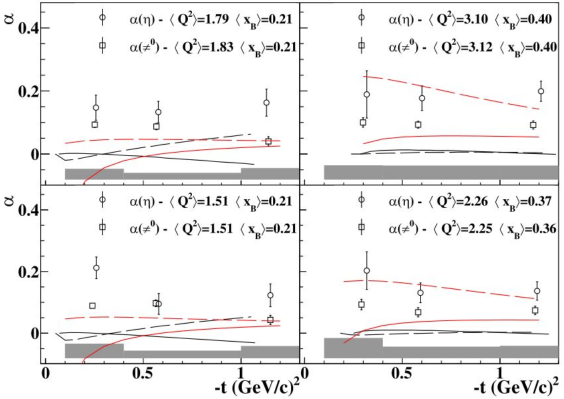
π^0 Beam Spin Asymmetries

R. De Masi *et al.* (CLAS collaboration) PRC**77:** 042201 (2008)



η Beam Spin Asymmetries

B. Zhao, A. Kim et al. (CLAS) submitted to PLB, 2018

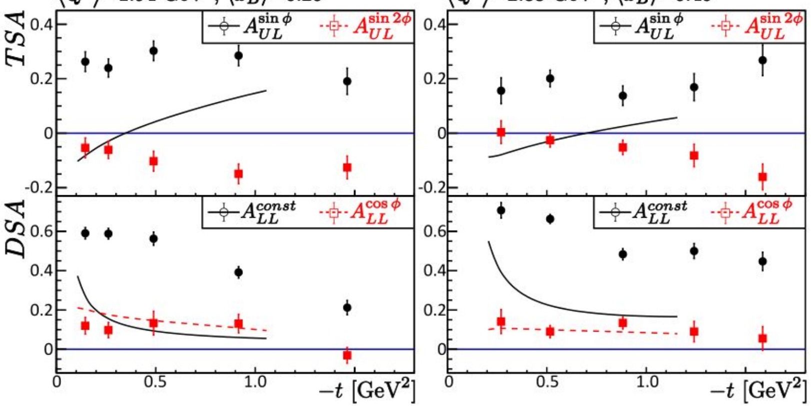


η electroproduction

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

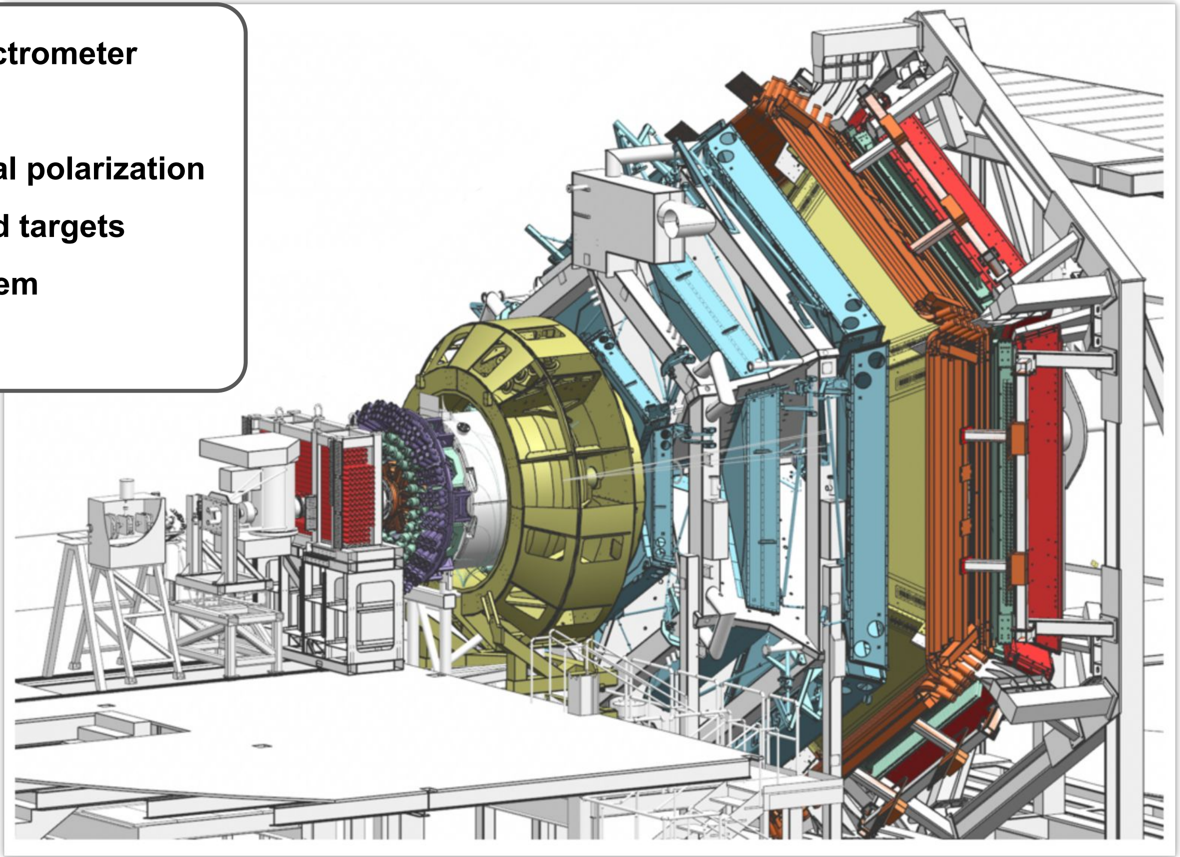
π^0 Target and Double Spin Asymmetries

A. Kim et al. (CLAS) PLB768, 168-173 (2017)



CLAS12 to map exclusive reactions in a wide kinematic space

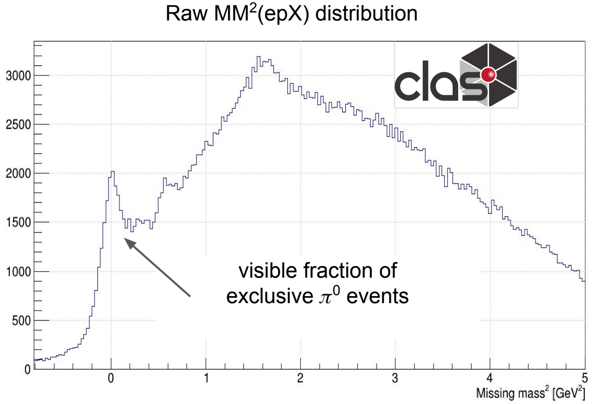
- CEBAF Large Acceptance Spectrometer
- High luminosity frontier
- 86 % electron beam longitudinal polarization
- Unpolarized and polarized fixed targets
- Comprehensive detection system
- Access to the Q^2 up to 10 GeV^2



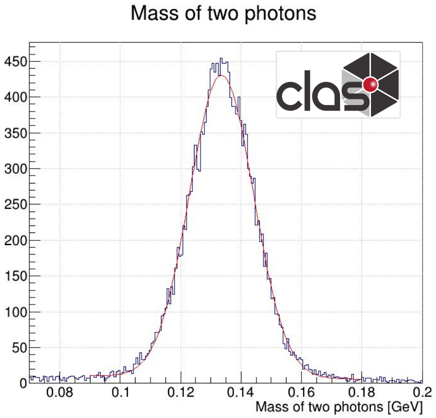
$$ep \to ep\pi^0 \to ep\gamma\gamma$$

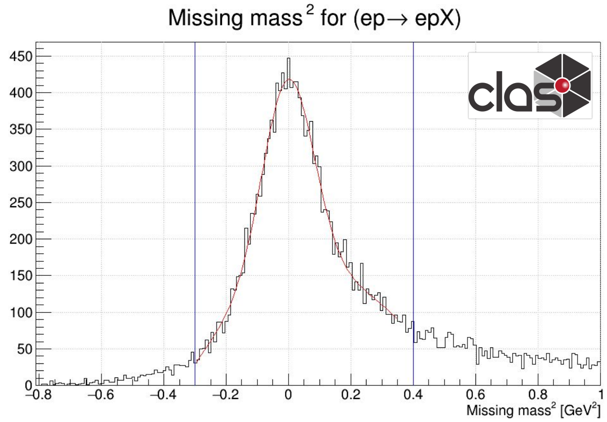
from CLAS12 first experiment

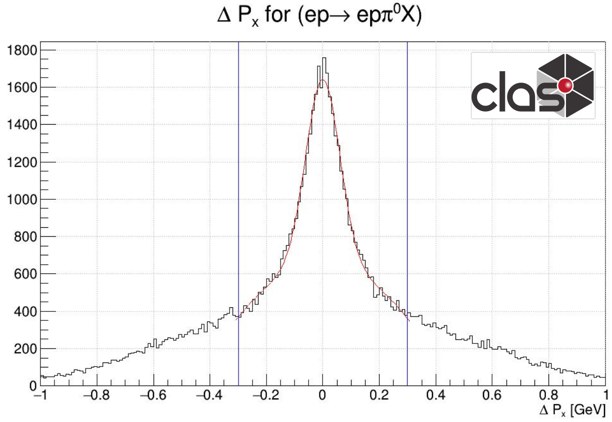
Exclusive π^0 selection

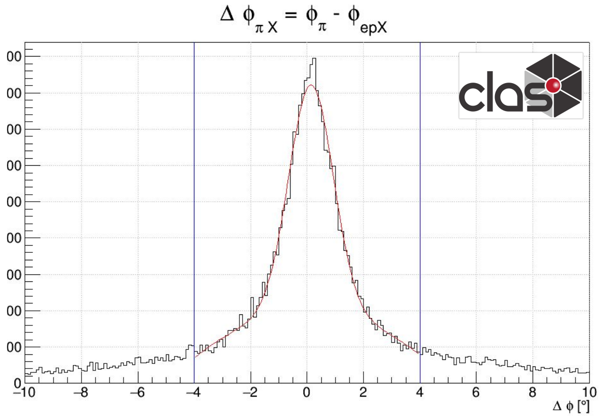


- All final state particle detected: electron, proton, two photons
- Reconstructed mass of two photons is used to identify π^0 candidates
- The momentum and energy conservation laws provide powerful constraints to suppress background: the plots show clear exclusive sample after application of exclusivity cuts







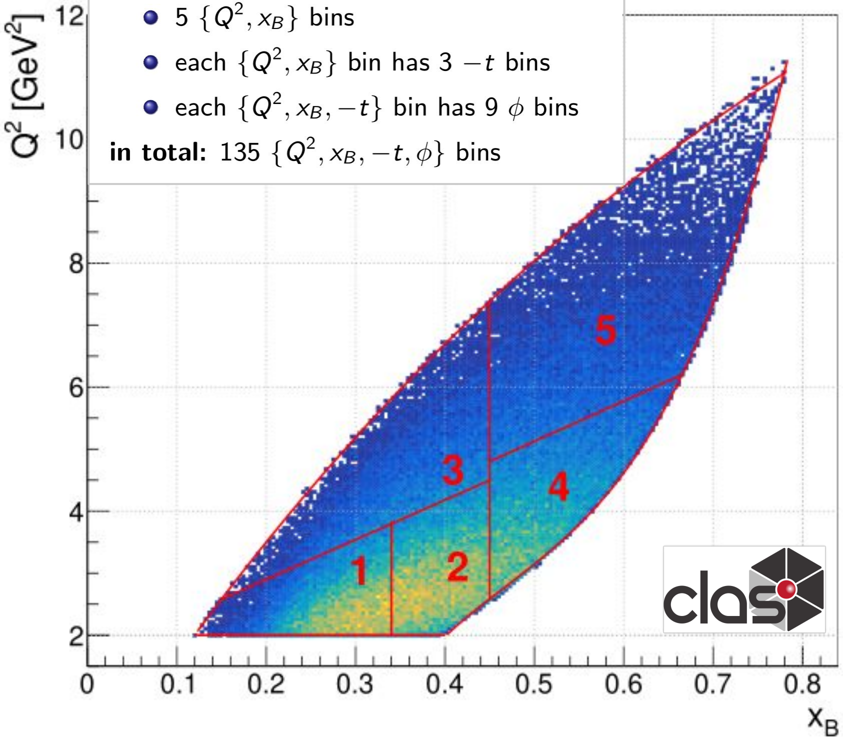


Exclusive π^0 kinematic coverage

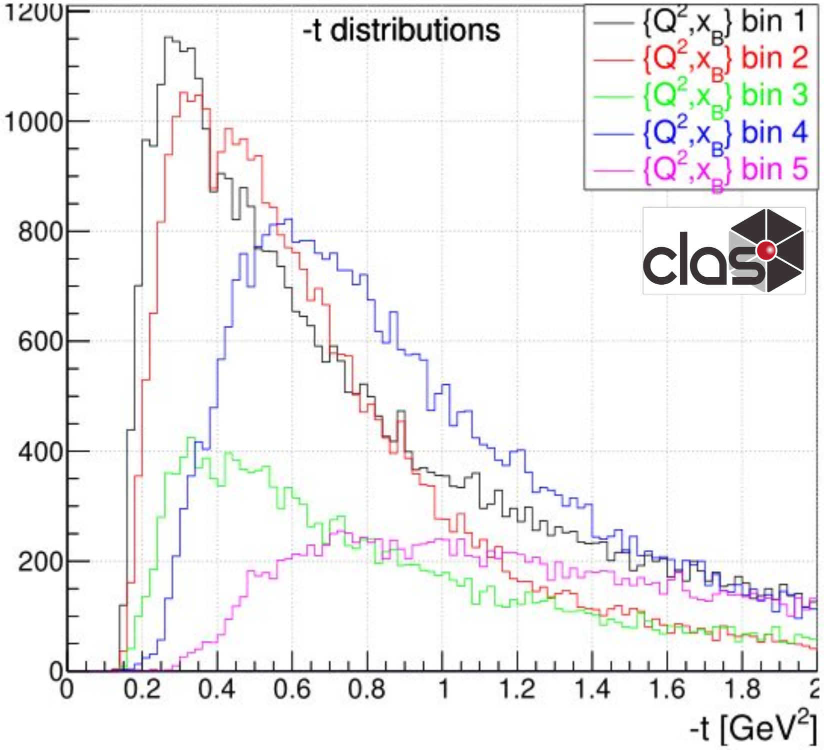
DIS cuts: $Q^2 > 2$ GeV^2 and $W > 2$ GeV

- 5 $\{Q^2, x_B\}$ bins
- each $\{Q^2, x_B\}$ bin has 3 $-t$ bins
- each $\{Q^2, x_B, -t\}$ bin has 9 ϕ bins

in total: 135 $\{Q^2, x_B, -t, \phi\}$ bins

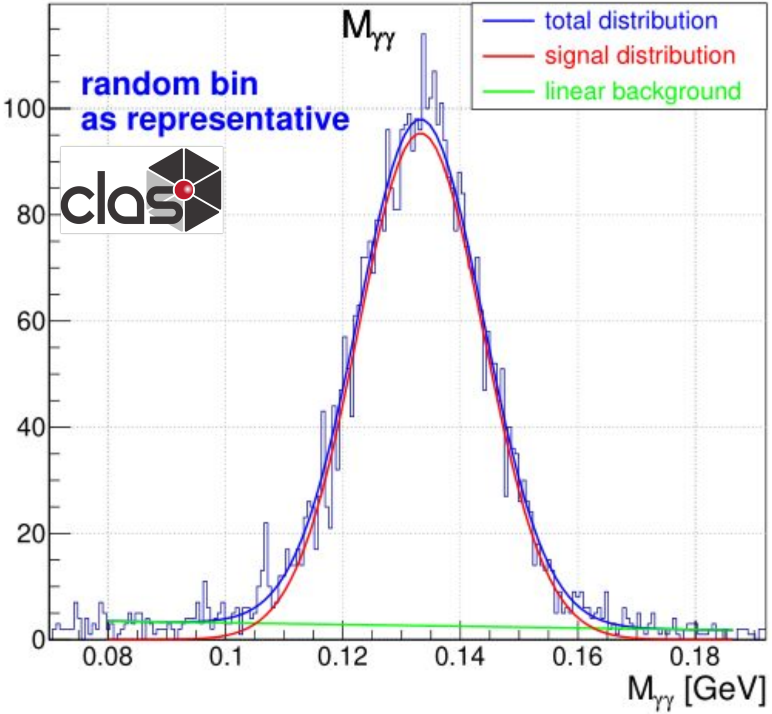


(a) Q^2 vs x_B coverage



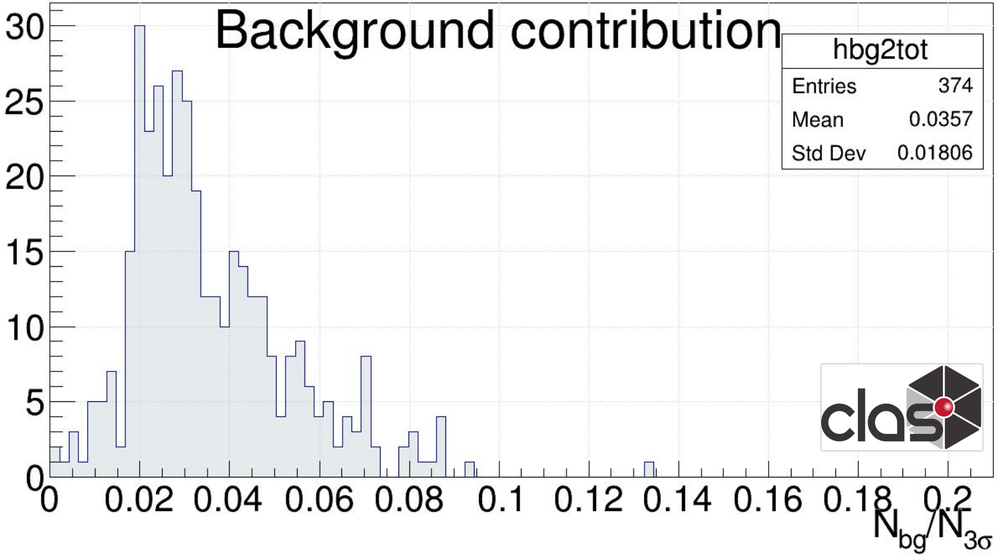
(b) $-t$ distributions for each $\{Q^2, x_B\}$ bin

Invariant mass of two photons



Sideband background subtraction:

$$N_{signal} = N_{3\sigma} - N_{bg}$$



Exclusive π^0 Beam Spin Asymmetry

$$\text{BSA} = \frac{1}{P_b}\frac{n^+ - n^-}{n^+ + n^-},$$

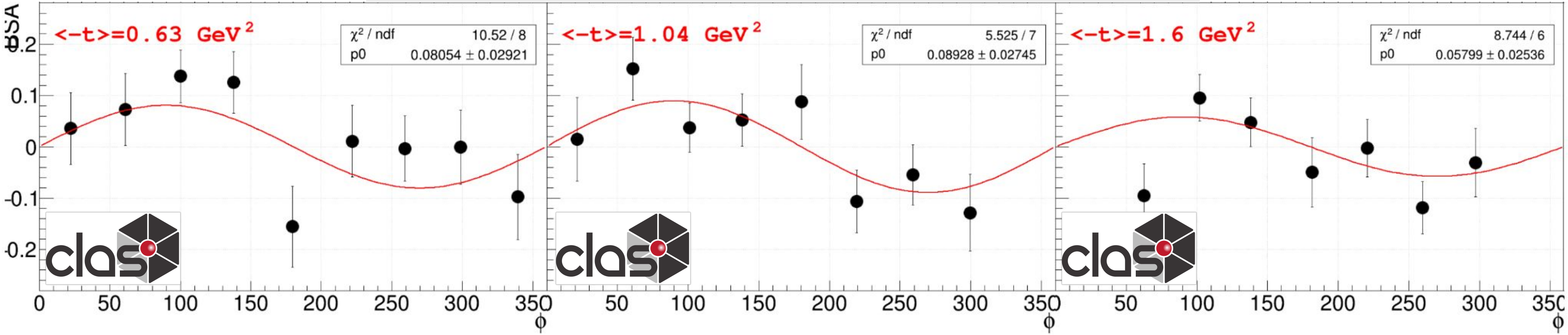
where P_b is an average electron beam polarization

$$\sigma = \sigma_0 + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}^{\cos\phi}\cos\phi + \epsilon\sigma_{TT}^{\cos 2\phi}\cos 2\phi + \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}^{\sin\phi}\sin\phi$$

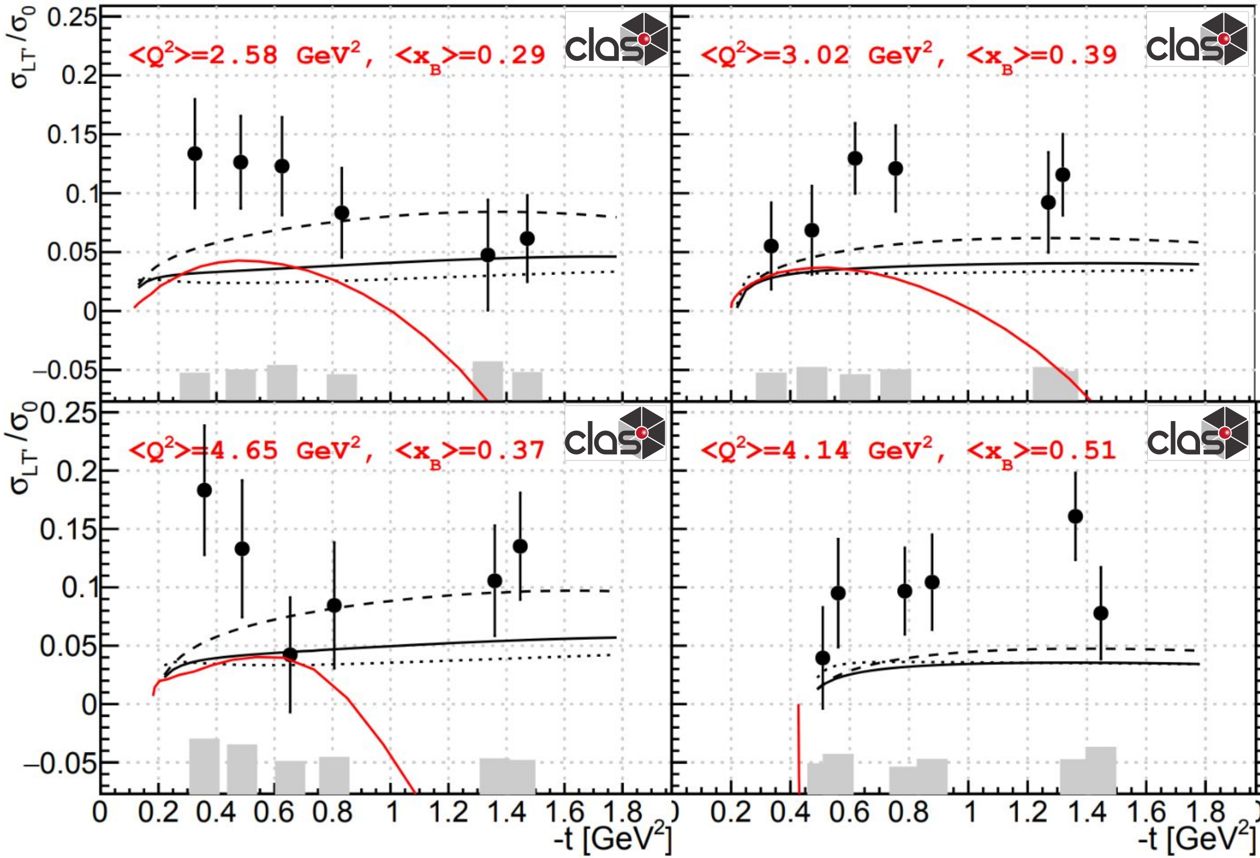
$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto A_{LU}^{\sin\phi}\sin\phi$$

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

Beam spin asymmetries for 3 <-t> bins in the 5th <Q^2,x_B> bin



Exclusive π^0 Beam Spin Asymmetry



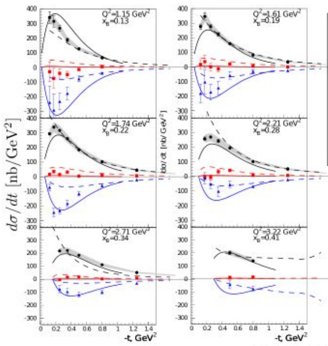
$$A_{LU}^{\sin\phi} = \sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}^{\sin\phi}}{\sigma_0}$$

within Goloskokov-Kroll model:

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

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}

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

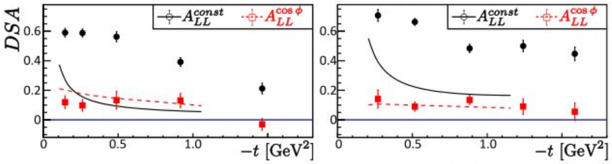
π^0 electroproduction is uniquely sensitive process to access **transversity GPDs.**

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

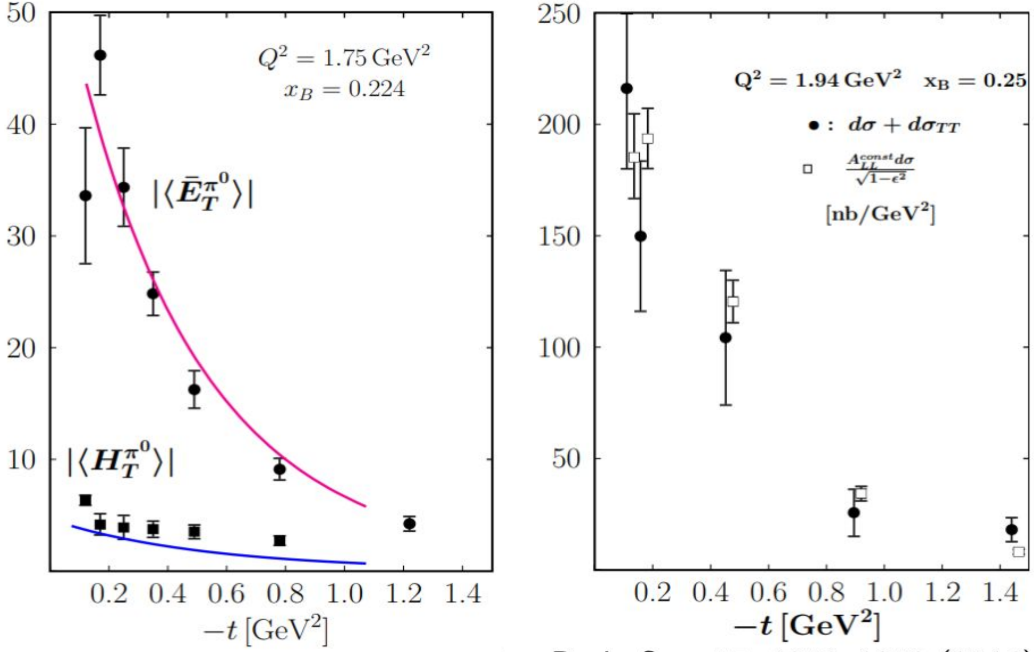
$$A_{LL}^{const} \sim |\langle H_T \rangle|^2$$



PLB768, 168-173 (2017)

H_T is underestimated in GK model

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



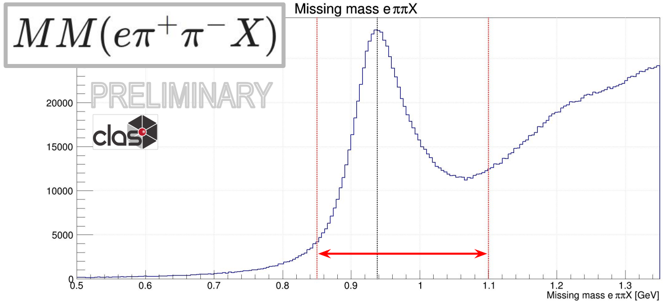
Few-Body Syst 57, 1041–1050 (2016)

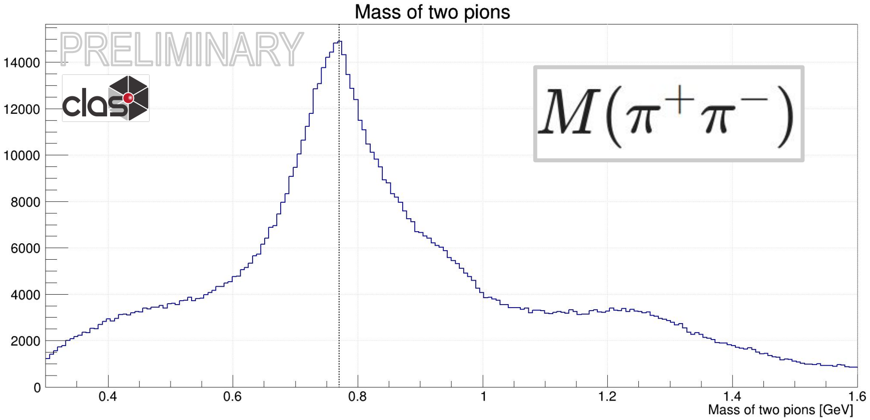
$$ep \to ep\rho^0 \to e\pi^+\pi^-(P)$$

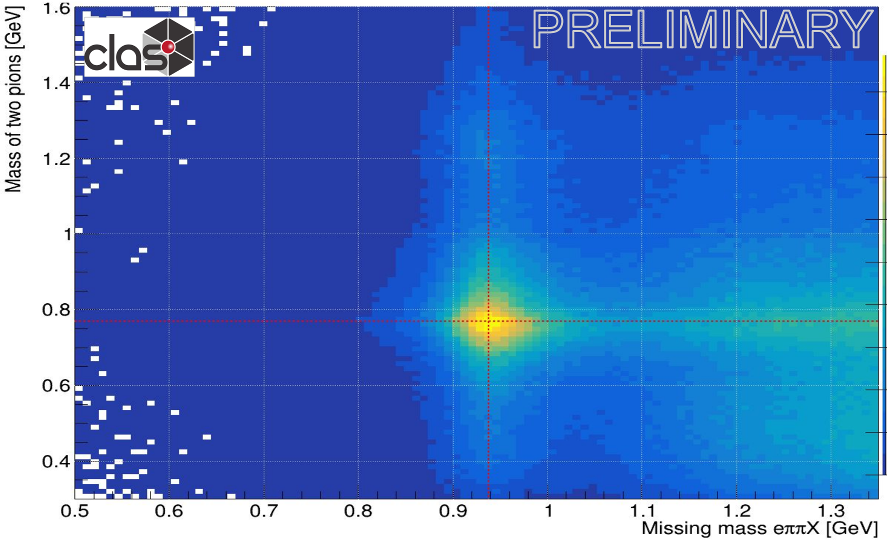
from CLAS12 first experiment

Exclusive event selection: $ep \to ep\rho^0 \to e\pi^+\pi^-(P)$

- 3 final state particles detected: **electron and both pions**
- Enhanced PID procedures
- **Invariant mass** of two pions is used to identify **ρ meson** and estimate **signal to background** ratio
- The **missing mass cut** is used to suppress background and select exclusive event candidates





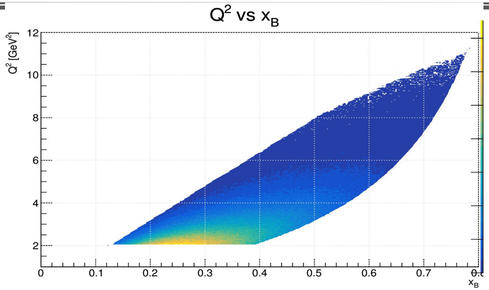


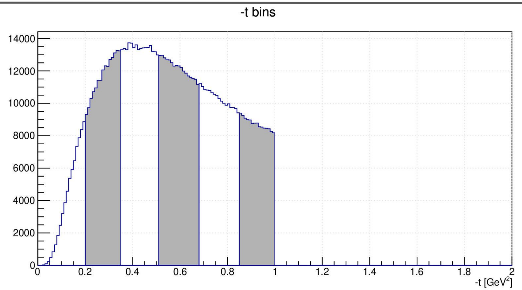
-*t* binning for exclusive ρ^0 electroproduction

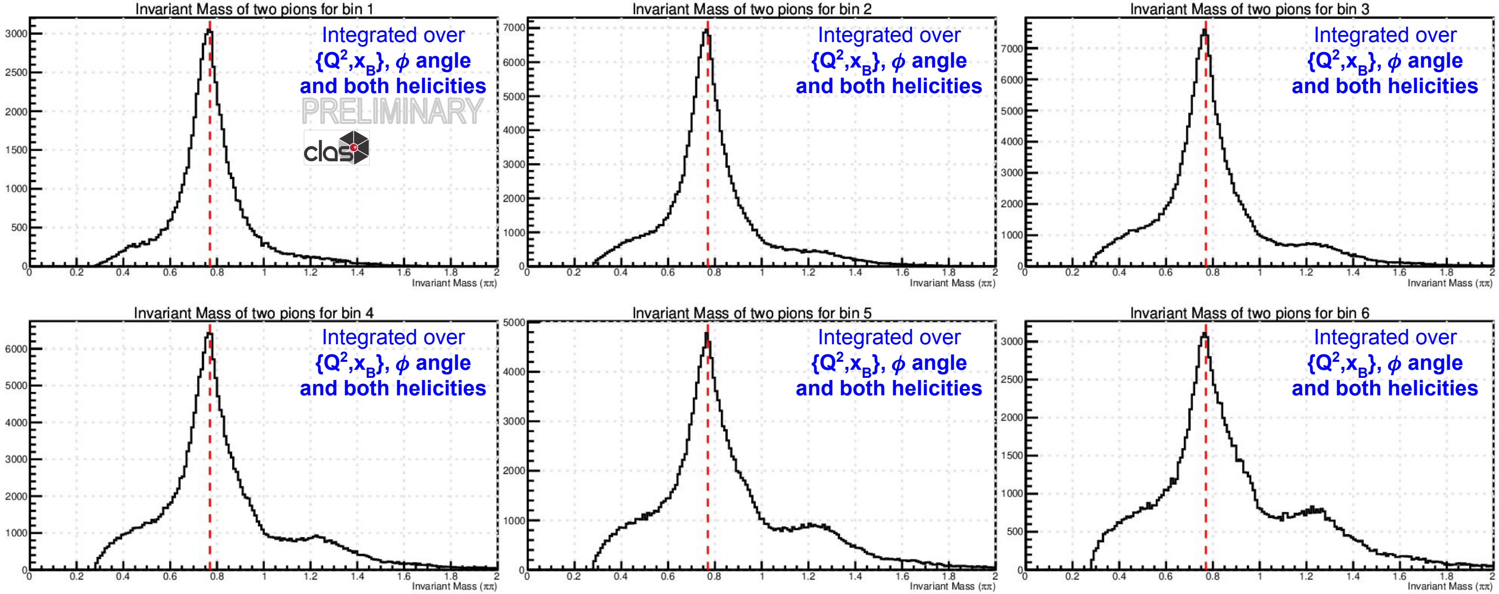
DIS cuts: $Q^2 > 2$ GeV^2 and $W > 2$ GeV

- 6 $\{-t\}$ bins
- 9 $\{\phi\}$ bins for each $\{-t\}$ bin

In total: 54 $\{-t, \phi\}$ bins

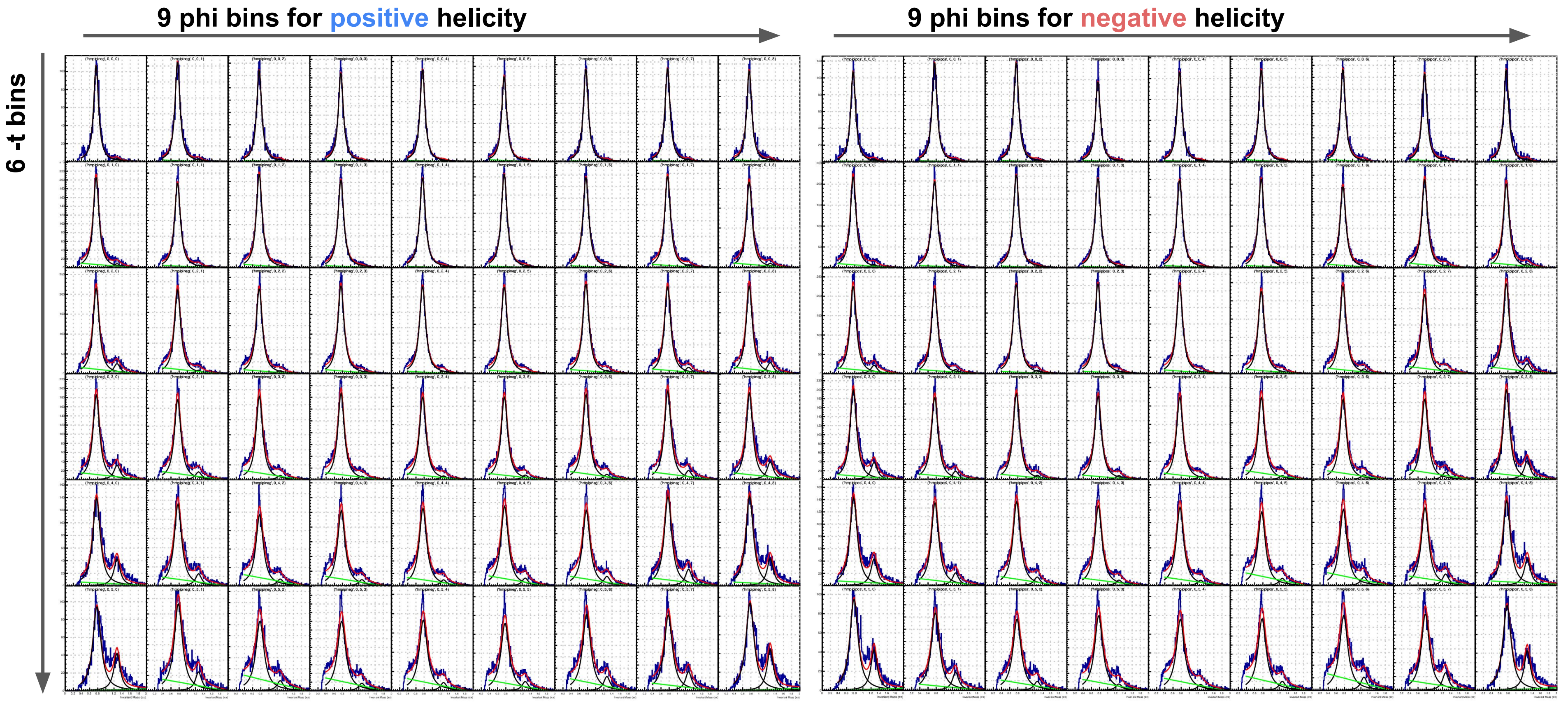






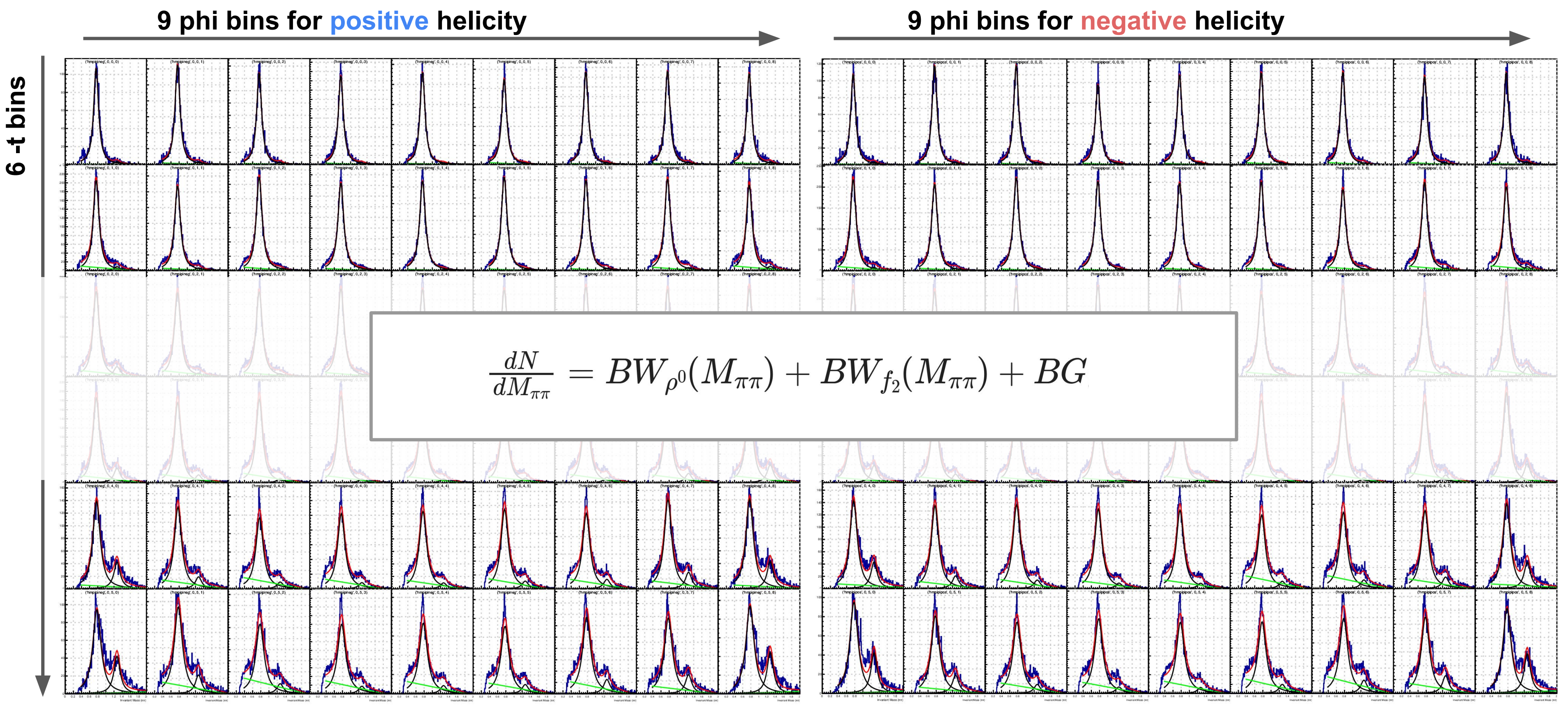
Exclusive events: Invariant mass of two pions

CLAS PRELIMINARY



Exclusive events: Invariant mass of two pions

PRELIMINARY

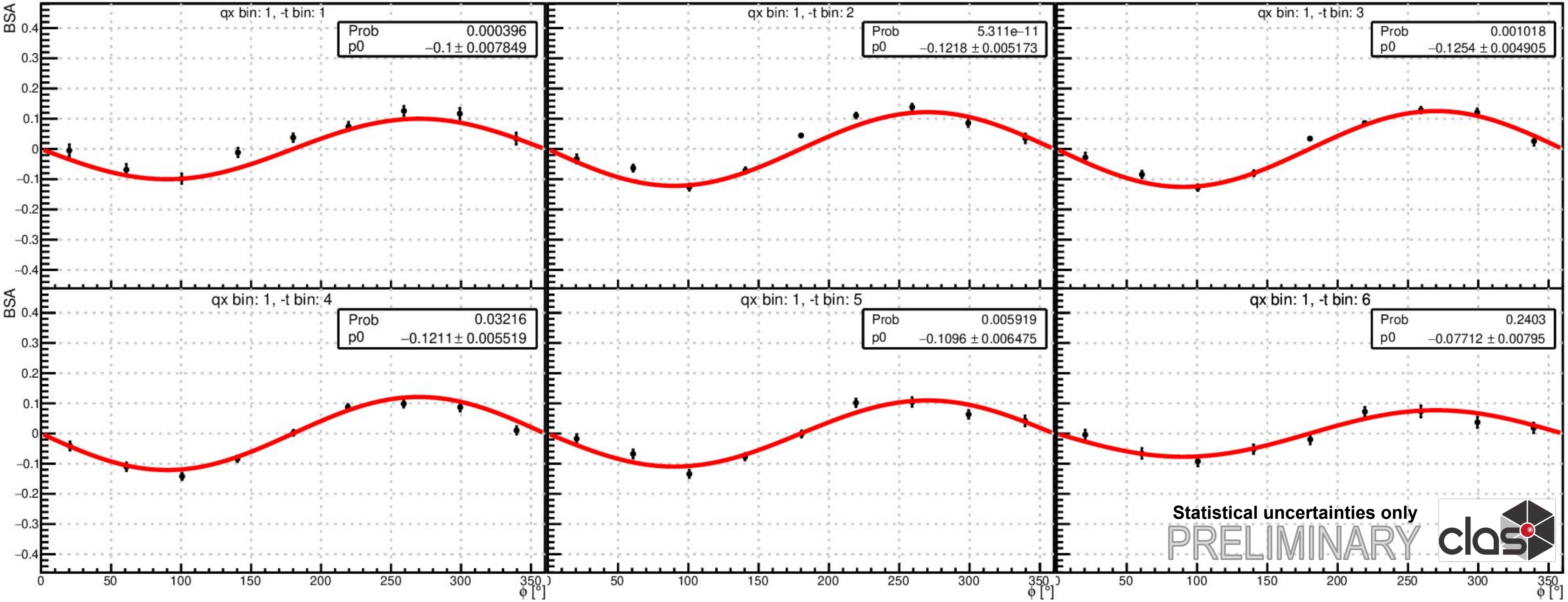


$$\frac{dN}{dM_{\pi\pi}} = BW_{\rho^0}(M_{\pi\pi}) + BW_{f_2}(M_{\pi\pi}) + BG$$

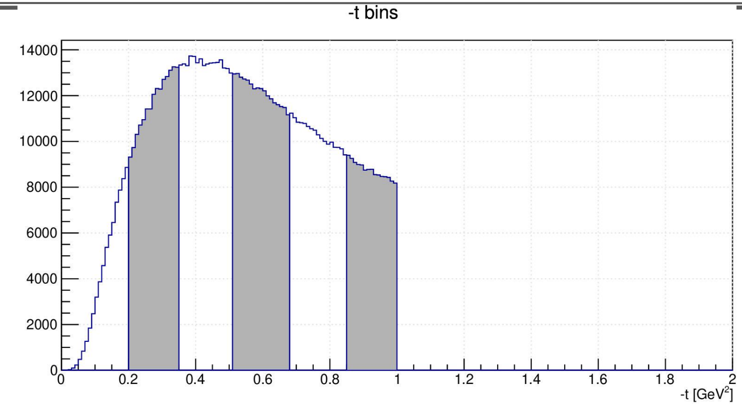
Beam Spin Asymmetry measurements

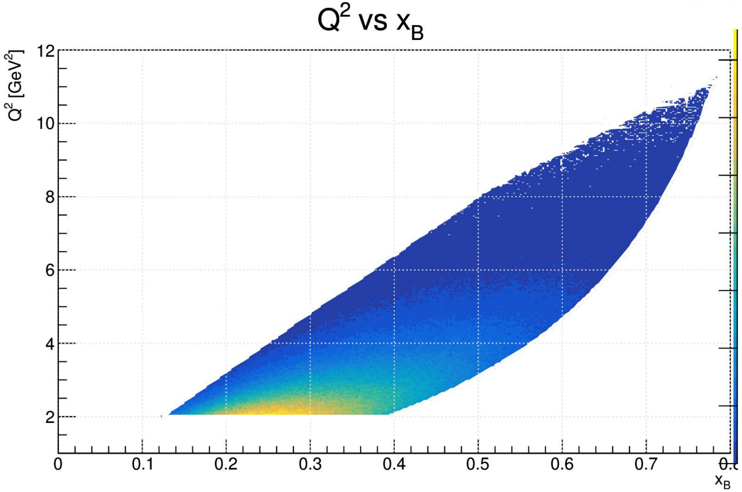
$$BSA = \frac{1}{P_b}\frac{n^+ - n^-}{n^+ + n^-},$$ where P_b is an average electron beam polarization

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



-t binning for exclusive ρ^0 electroproduction





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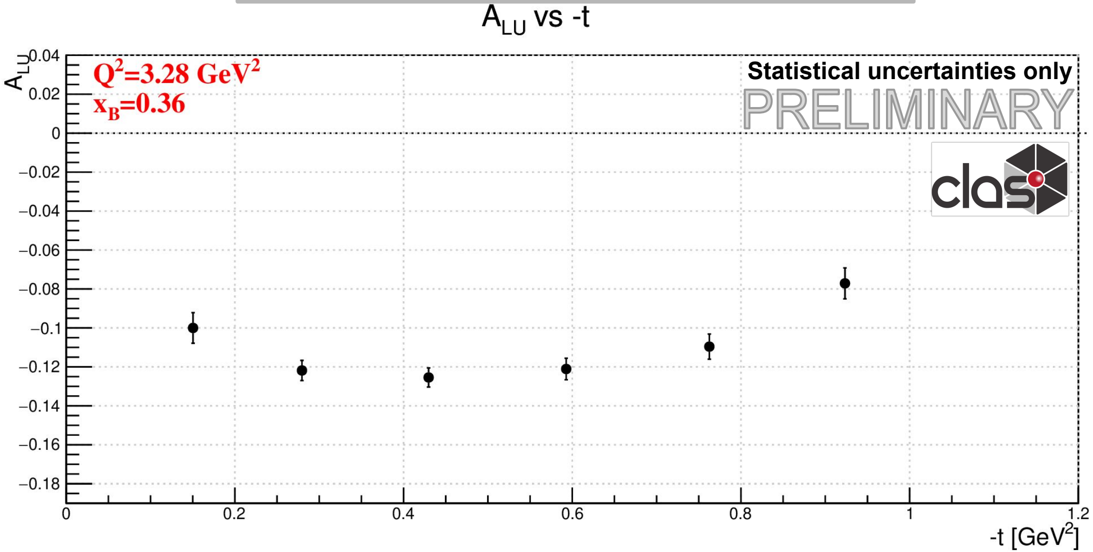
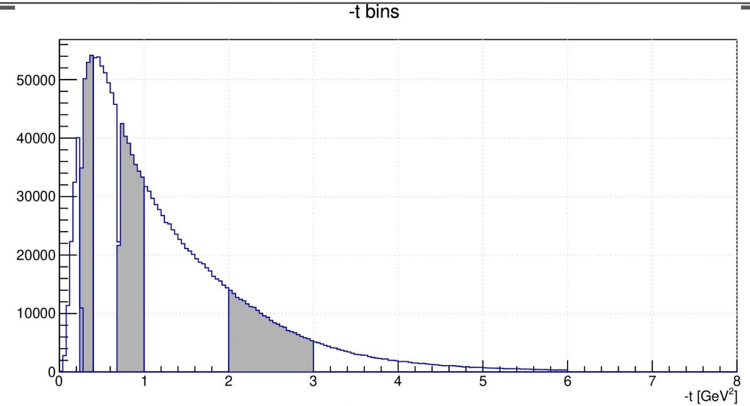


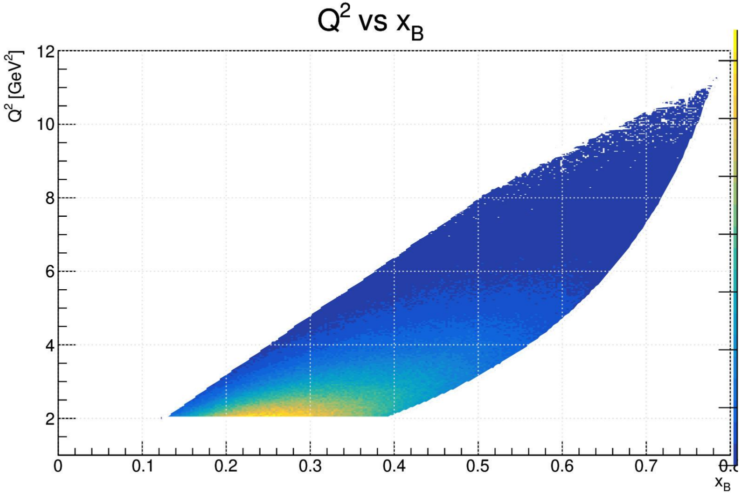
Full *-t* range binning for exclusive ρ^0 electroproduction

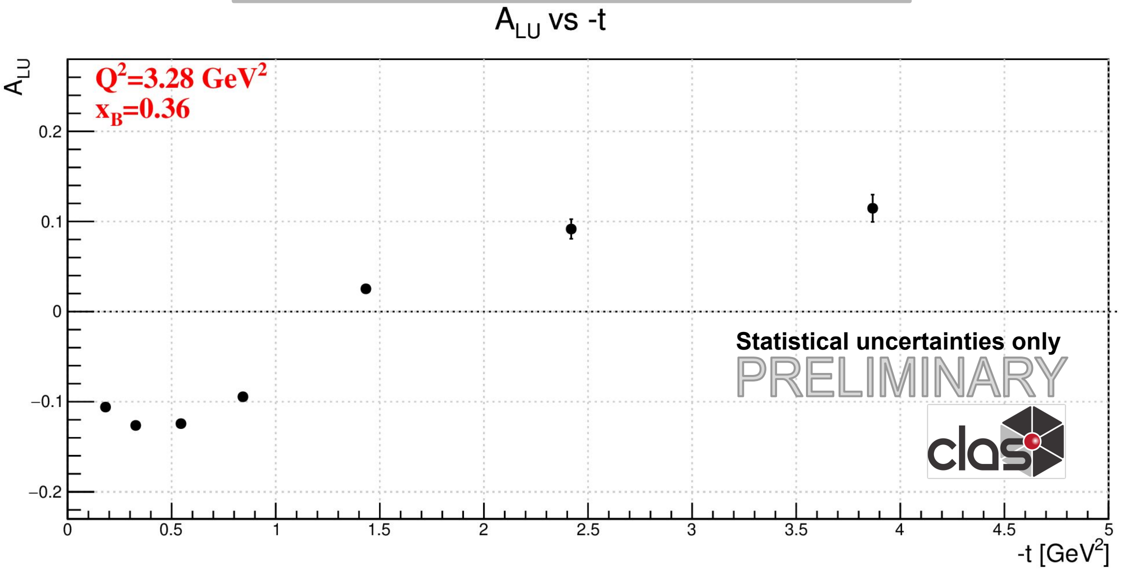


DIS cuts: $Q^2 > 2$ GeV^2 and $W > 2$ GeV

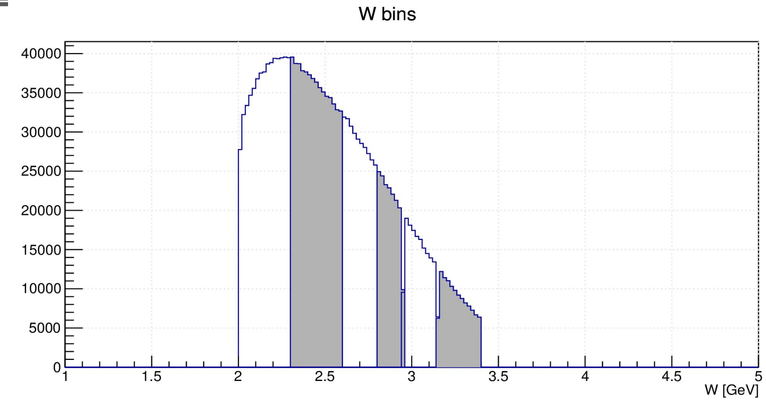
- 7 $\{-t\}$ bins in full range
- 9 $\{\phi\}$ bins for each $\{-t\}$ bin

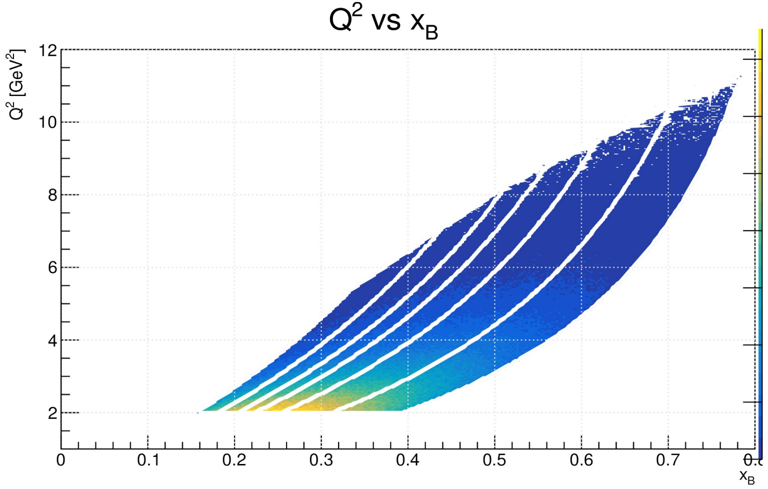
In total: 63 $\{-t, \phi\}$ bins





W binning for exclusive ρ^0 electroproduction

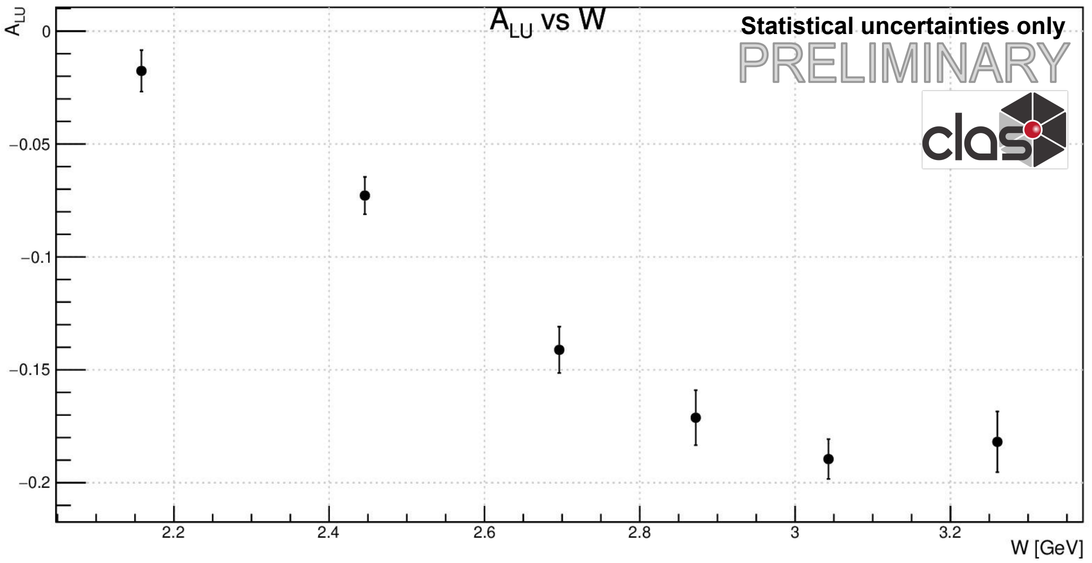




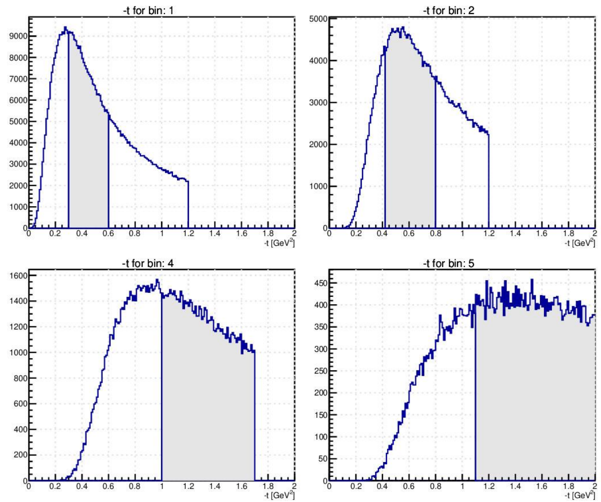
DIS cuts: $Q^2 > 2$ GeV^2, $W > 2$ GeV, and $-t < 1$ GeV^2

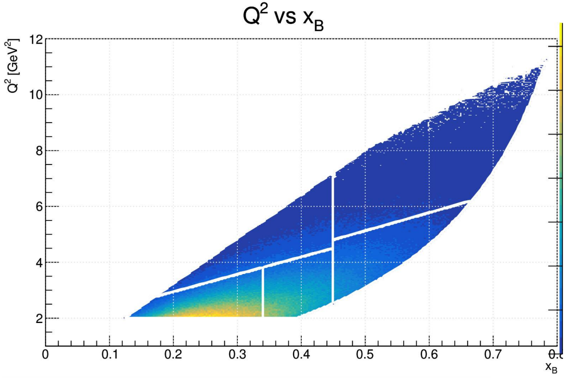
- 6 bins in W
- 9 $\{\phi\}$ bins for each W bin

In total: 54 $\{W, \phi\}$ bins



3D binning for exclusive ρ^0 electroproduction

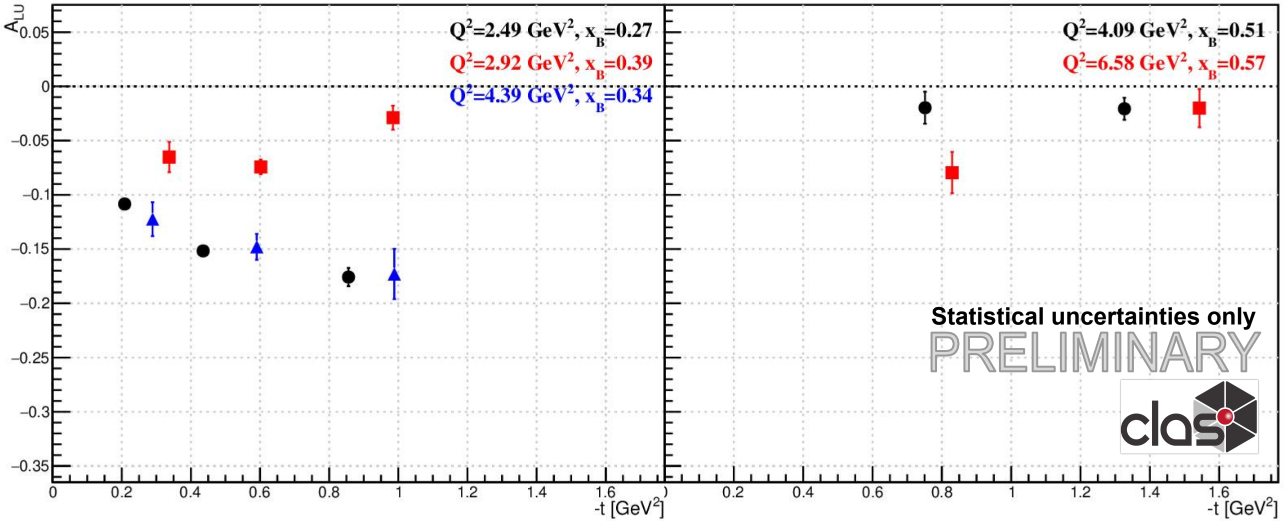




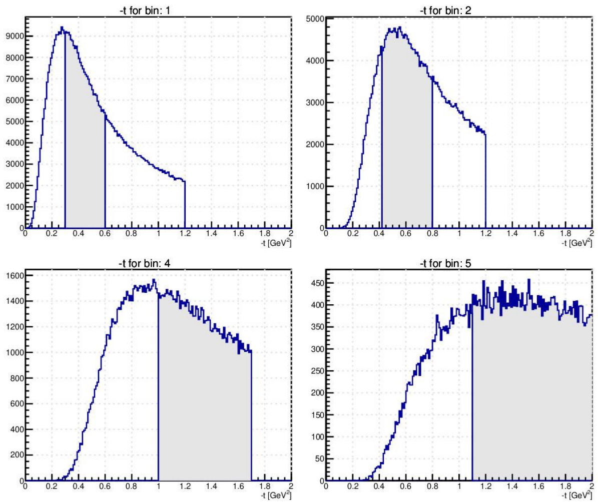
DIS cuts: $Q^2 > 2$ GeV^2 and $W > 2$ GeV

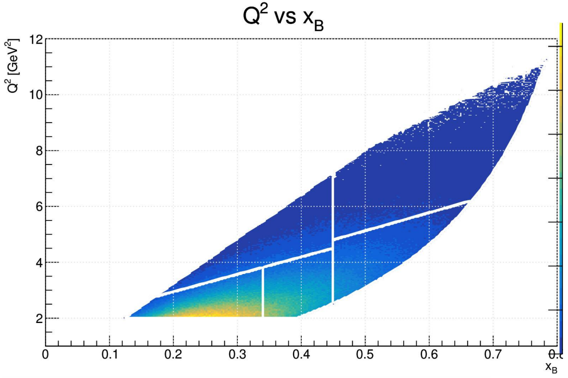
- 2-3 $\{-t\}$ bins for each of 5 $\{Q^2, x_B\}$ bin
- 9 $\{\phi\}$ bins for each $\{Q^2, x_B, -t\}$ bin

In total: 117 $\{Q^2, x_B, -t, \phi\}$ bins



Comparison with π^0 and π^+ electroproduction measurements

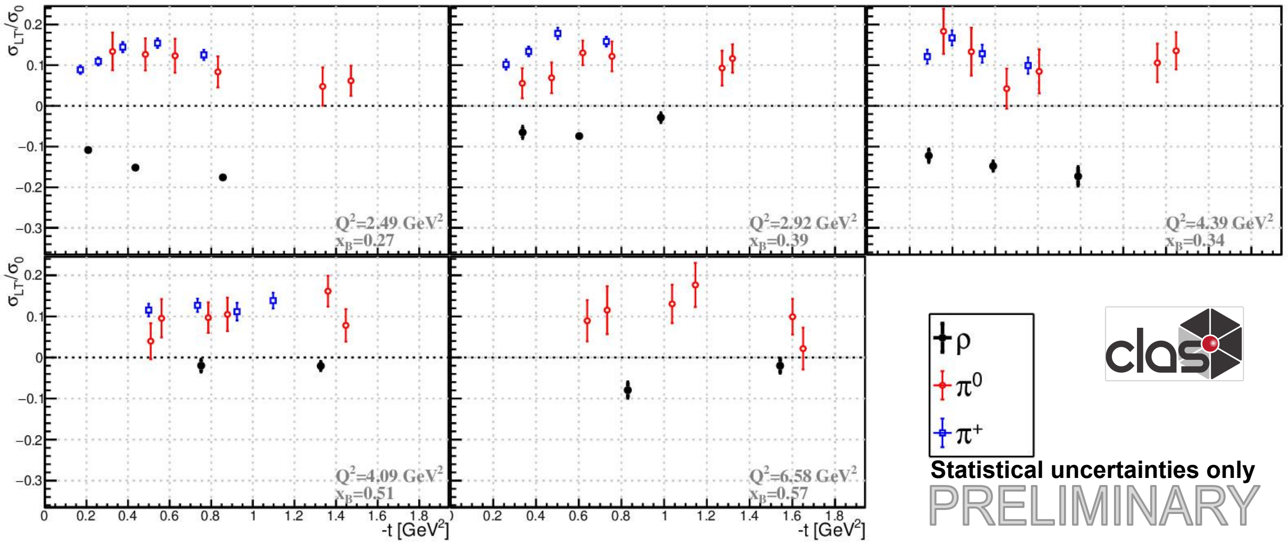




DIS cuts: $Q^2 > 2$ GeV^2 and $W > 2$ GeV

- 2-3 $\{-t\}$ bins for each of 5 $\{Q^2, x_B\}$ bin
- 9 $\{\phi\}$ bins for each $\{Q^2, x_B, -t\}$ bin

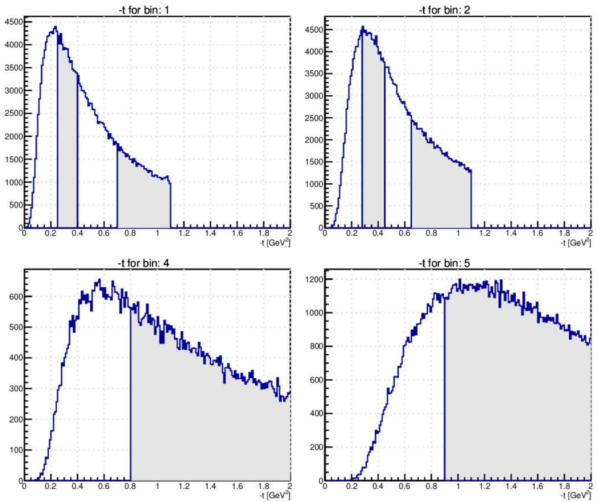
In total: 117 $\{Q^2, x_B, -t, \phi\}$ bins



Statistical uncertainties only

PRELIMINARY

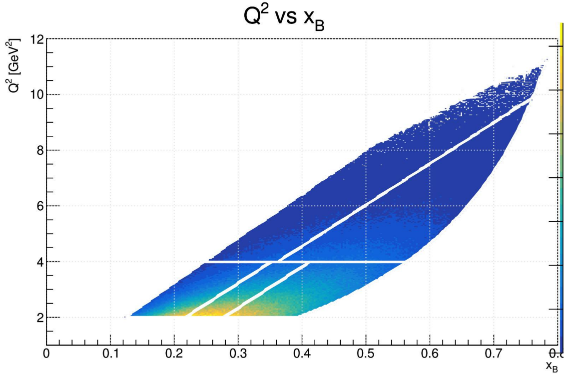
Another 3D binning for exclusive ρ^0 electroproduction

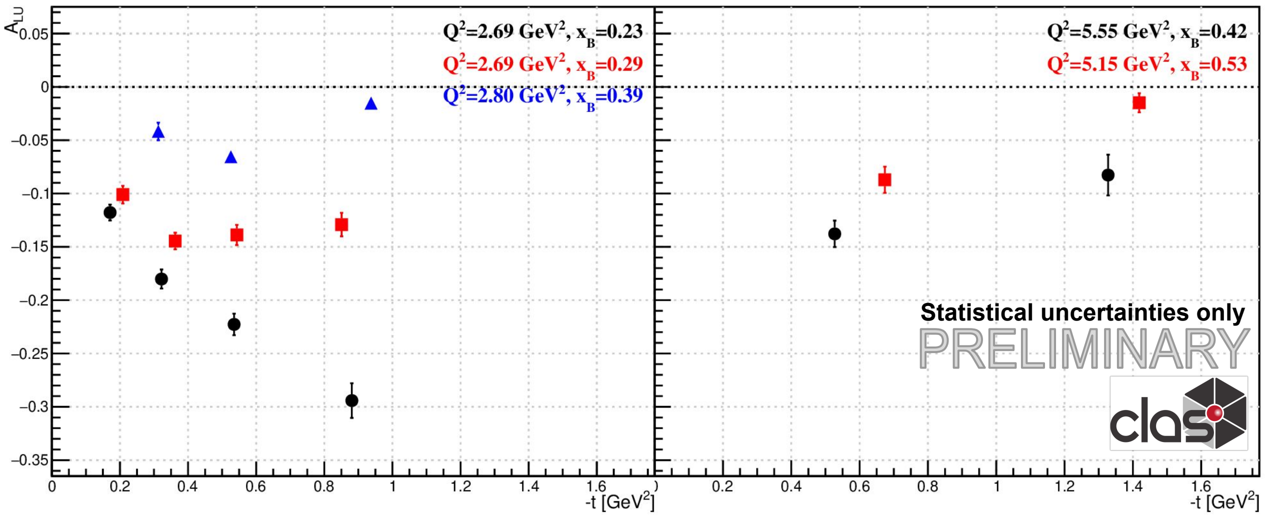


DIS cuts: $Q^2 > 2$ GeV^2 and $W > 2$ GeV

- 2-4 $\{-t\}$ bins for each of 5 $\{Q^2, x_B\}$ bin
- 9 $\{\phi\}$ bins for each $\{Q^2, x_B, -t\}$ bin

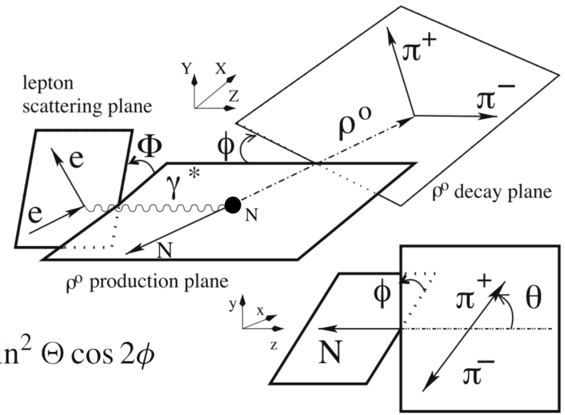
In total: 135 $\{Q^2, x_B, -t, \phi\}$ bins





Future access: Spin Density Matrix Elements (SDME)

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



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

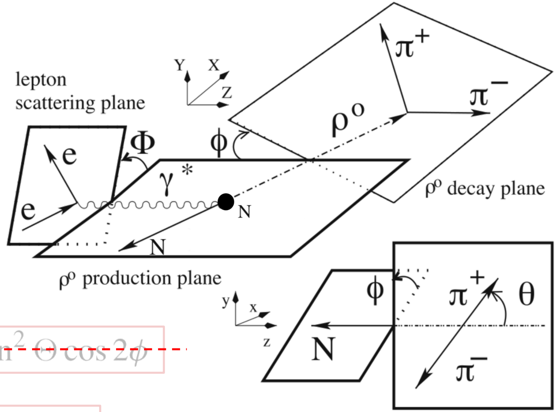
$$\begin{aligned}
\mathcal{W}^{U}(\Phi, \phi, \cos\Theta) = \frac{3}{8\pi^2}\Bigg[&\frac{1}{2}(1 - r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00} - 1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi \\
&-\epsilon\cos 2\Phi(r^{1}_{11}\sin^2\Theta + r^{1}_{00}\cos^2\Theta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

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

Future 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

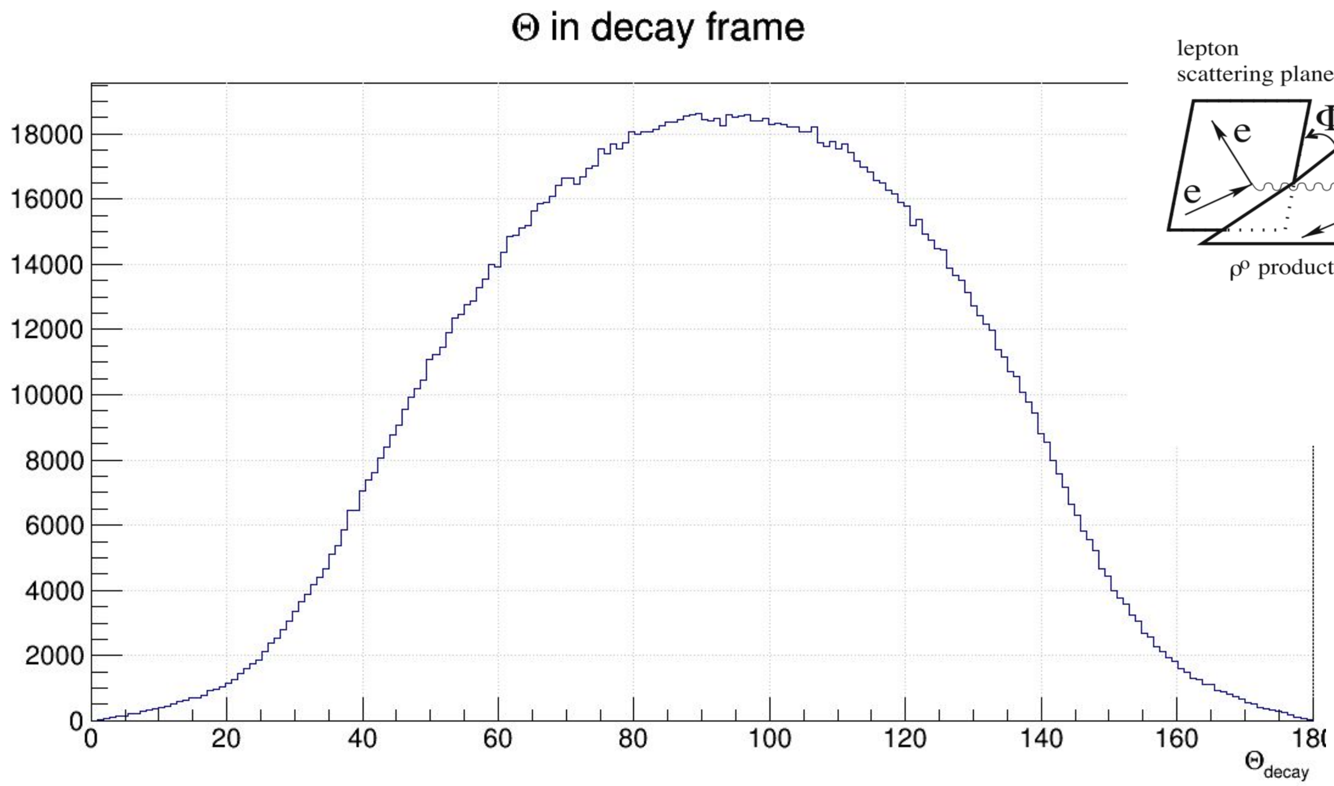


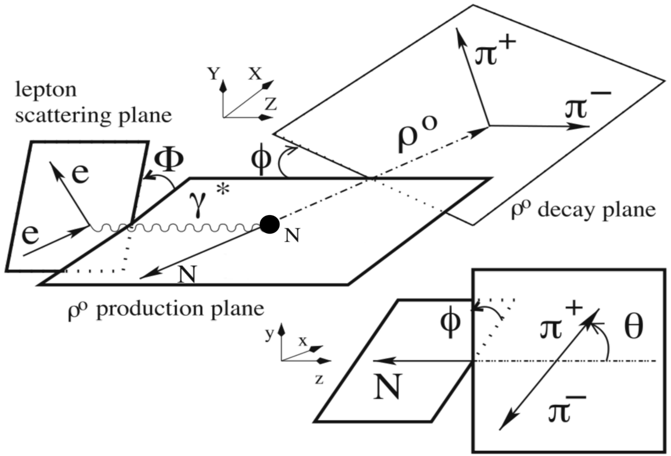
$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta) = \mathcal{W}^{U}(\Phi,\phi,\cos\Theta) + P_b\mathcal{W}^{L}(\Phi,\phi,\cos\Theta),$$

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

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

Future access: Spin Density Matrix Elements (SDME)





Conclusions

- CLAS12 with longitudinally polarized electron beam at high luminosity frontier provides measurements of deeply virtual exclusive meson production channels in a wide multi-dimensional kinematic space with a reach up to 10 GeV^2
- Extracted sizable BSA moments may indicate significant contributions from chiral-odd GPDs
- Future access to SDME provides more experimental constraints for GPDs-based models
- Stay tuned for the new measurements of pseudoscalar and vector exclusive meson production channels from CLAS12 data

THANK YOU