Exclusive Processes and GPDs with CLAS/CLAS12

Kyungseon Joo

University of Connecticut

For the CLAS Collaboration

August 31, 2022

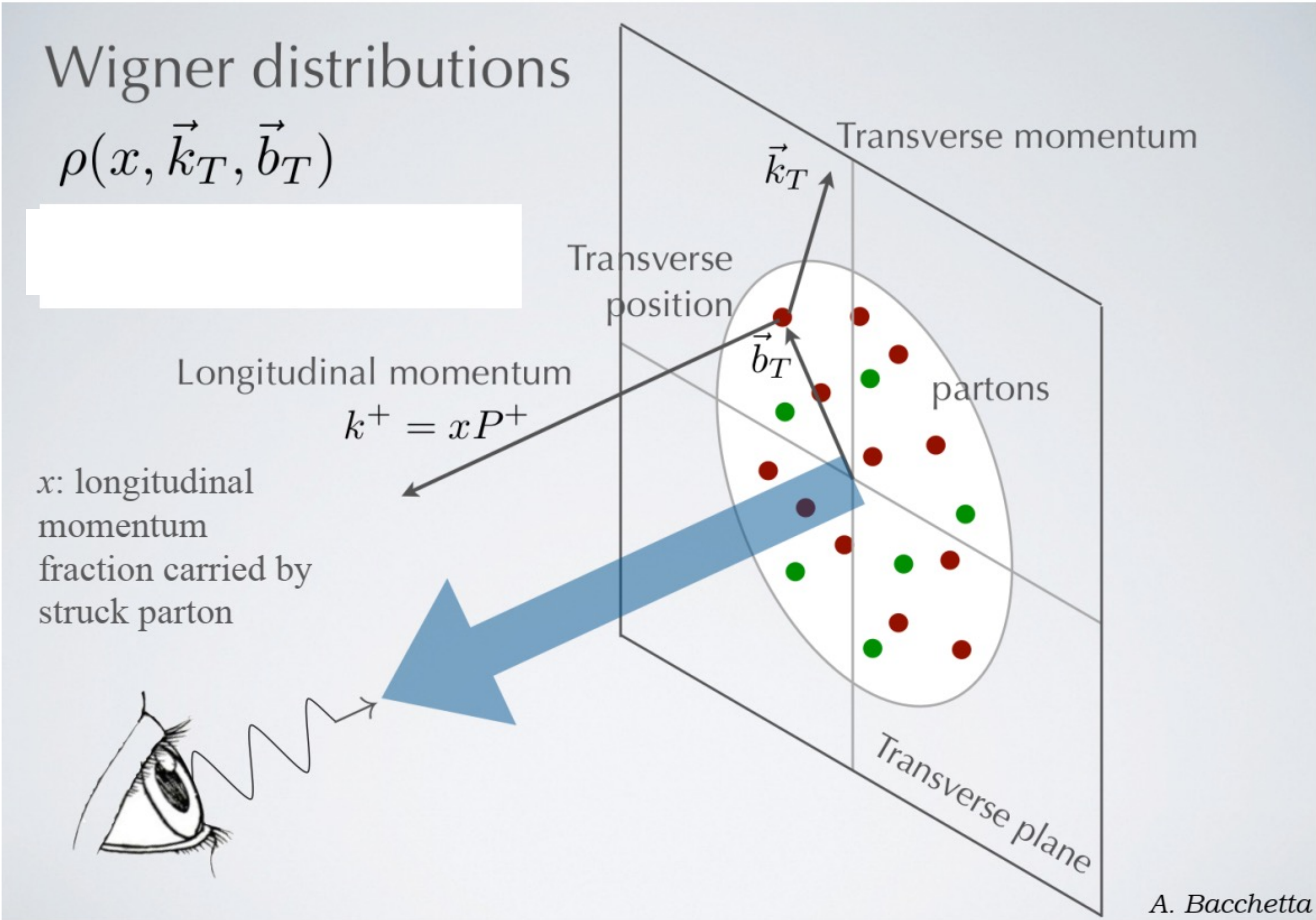
UCONN | UNIVERSITY OF CONNECTICUT

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

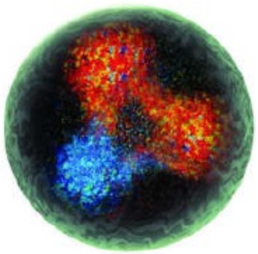
Jefferson Lab

clas

3-Dimensional Imaging of Quarks and Gluons



3-Dimensional Imaging of Quarks and Gluons



→ *Wigner function: full phase space parton distribution of the nucleon*

$\int d^2 k_T$ ↓

Generalised Parton Distributions (GPDs)

$\int dx$ ↙ ↘ $\int d^2 b_T$

Form Factors
eg: $G_{E,}$ G_M

Parton Distribution Functions (PDFs)

Generalized Parton Distributions (GPDs)

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

↓

Integrate over transverse ***momentum*** space

↓

Generalized Parton Distributions (GPD)

↓

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

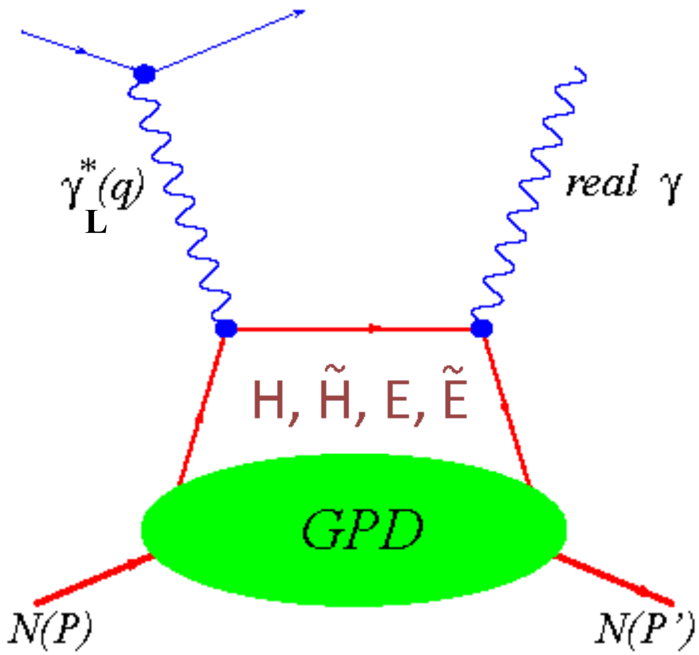
quark pol. / nucleon pol.

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

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

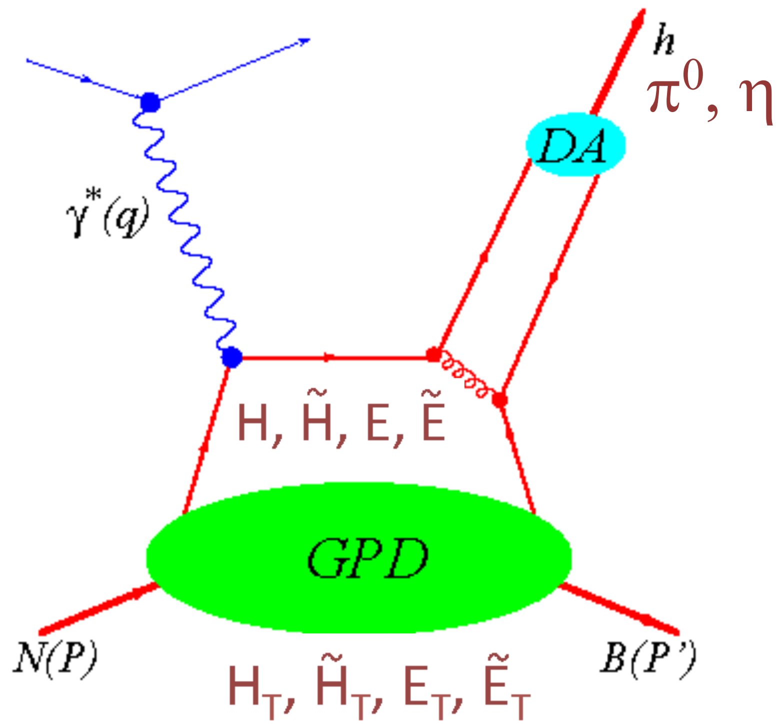
Study GPDs: Deeply Virtual Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



+ Clean process
- Only sensitive to chiral even GPDs

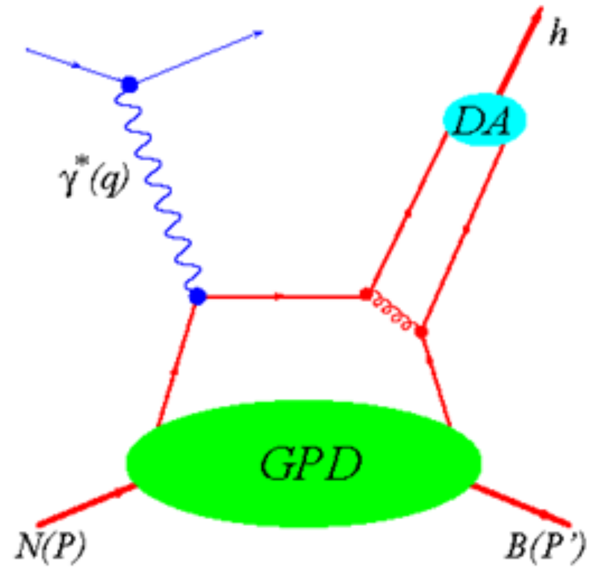
Deeply Virtual Meson Production (DVMP)



+ Enables Flavour decomposition of GPDs
+ 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 in the GPD regime

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



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

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

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

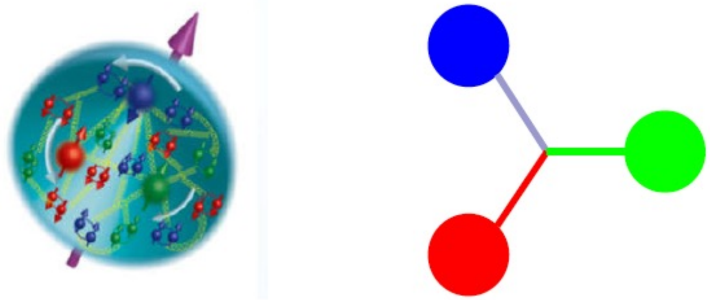
$$\delta_T^d = \int dx H_T^d(x, \xi, t = 0)$$

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

H_T is related to the proton's tensor charge
➔ Absolute magnitude of transversly polarized valence quarks inside a transv. polarized nucleon

From the ground state nucleon to resonances

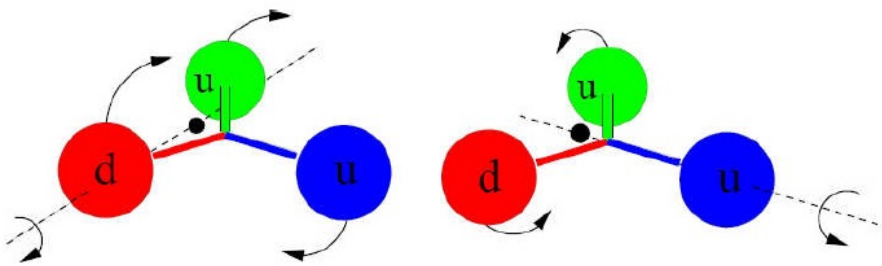
Ground state nucleon:
(proton, neutron)



Nucleon resonances:

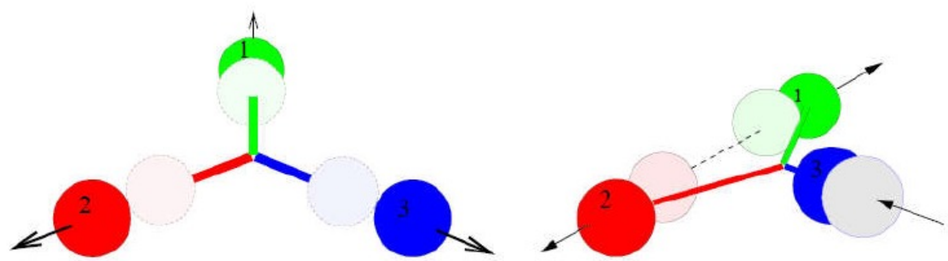
- Orbital excitations

i.e N(1535)



- Radial excitations

i.e N(1440)



From classical GPD to transition GPDs

Past: Extensive studies of transition form factors (**2D picture** of transv. position)

But: How does the exitation affect the **3D structure** of the Nucleon?

→ Pressure distributions, tensor charge, … of resonances?

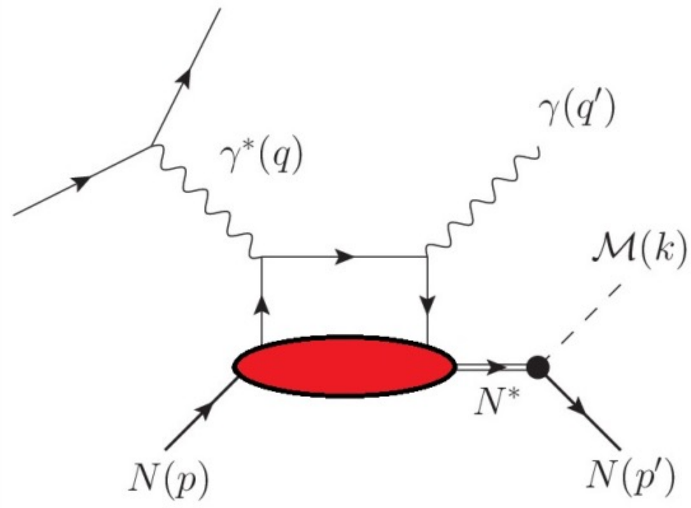
➔ Information encoded in **transition GPDs**

→ More difficult theoretical description due to additional degrees of freedom

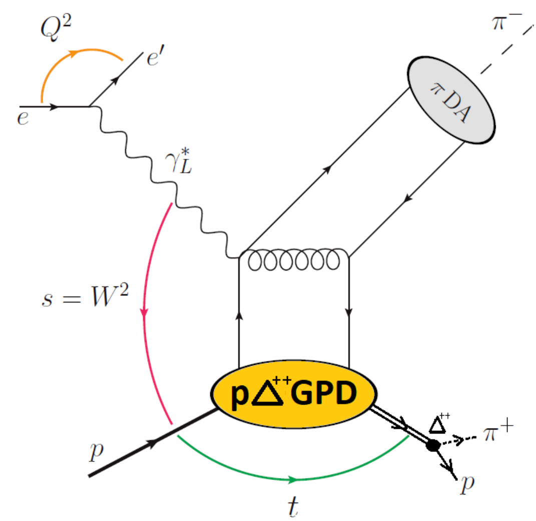
<u>**Simplest case**: N→Δ transition</u> ➔ **16 transition GPDs**

- **8 helicity non-flip transition GPDs (twist 2)**
- **8 helicity flip transition GPDs**

Studies of Transition GPDs



non-diag. DVCS



non-diag. DVMP

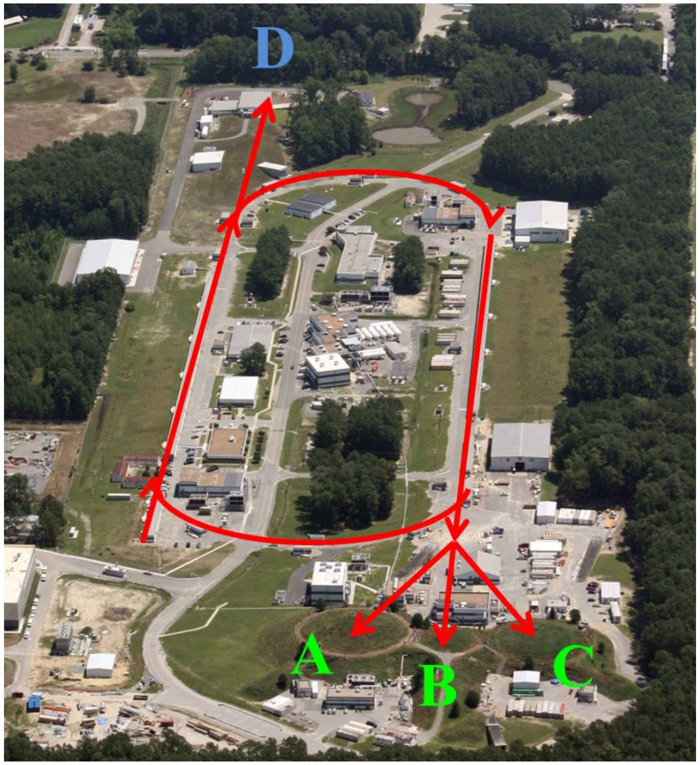
- **8 helicity non-flip trans. GPDs (twist 2)**

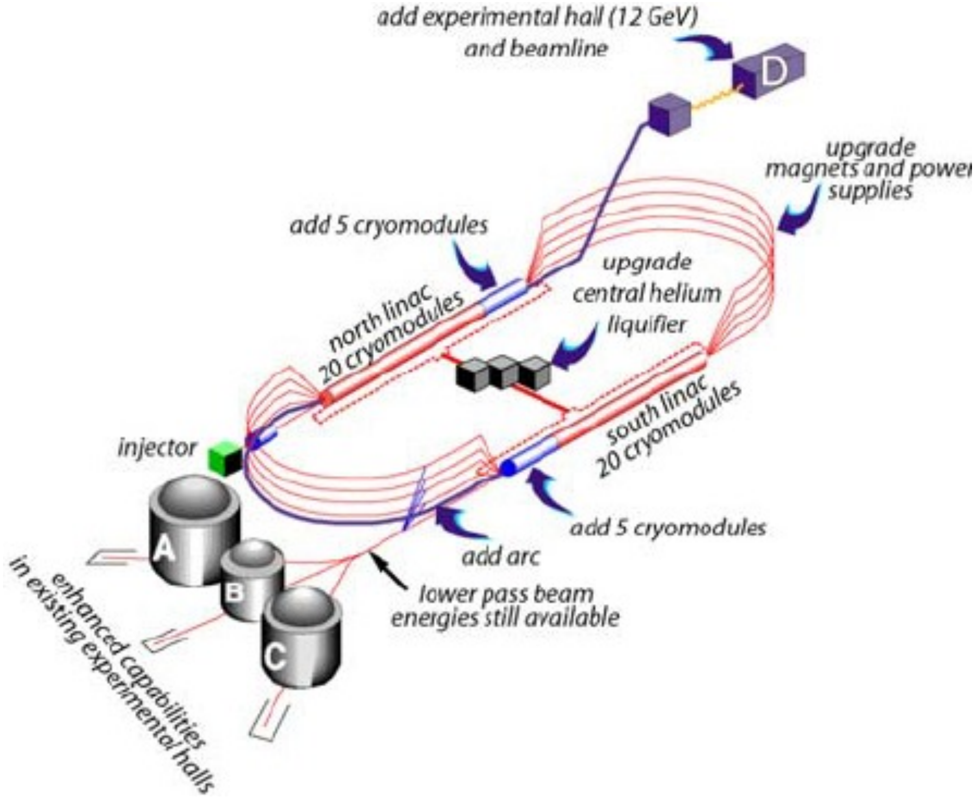
→ 3 are dominating in the large N_C limit
→ Connection to proton-proton GPDs via symmetry considerations
➔ Description of leading twist effects / longitudinal photons → σ_L
→ First theoretical works available

- **8 helicity flip trans. GPDs**

→ Needed for twist-3 sector (non-diag DVMP)
→ Theory in progress (no publ. so far)

Thomas Jefferson National Accelerator Facility (Jefferson Lab)





➡ **CEBAF Upgrade completed in September 2017**

→ electron beam

→ E_{max} = 12 GeV

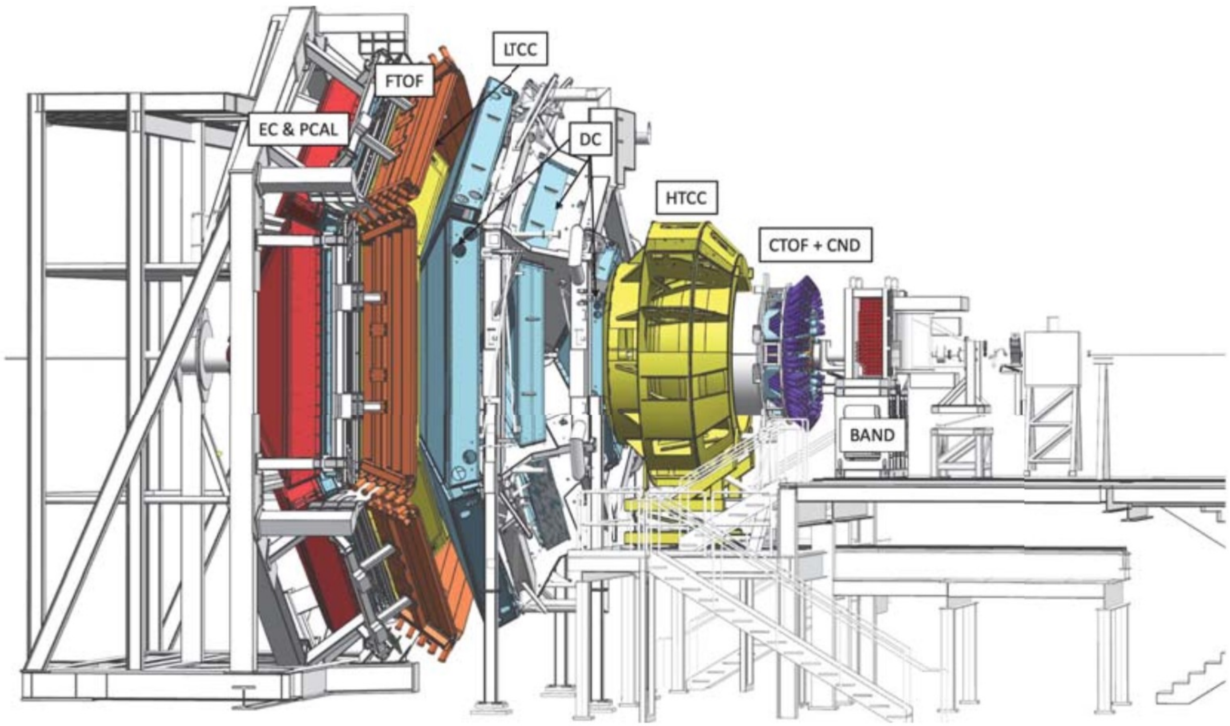
→ I_{max} = 90 μA

→ Pol_{max} ~ 90%

Physics Operation

- 4 halls running simultaneously since January 2018

CLAS12 Experimental Setup in Hall B at JLAB



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

- Data recorded with CLAS12 during fall 2018 and spring 2019

- 10.6 / 10.2 GeV e^- beam
- ~87 % average polarization
- liquid H_2 target

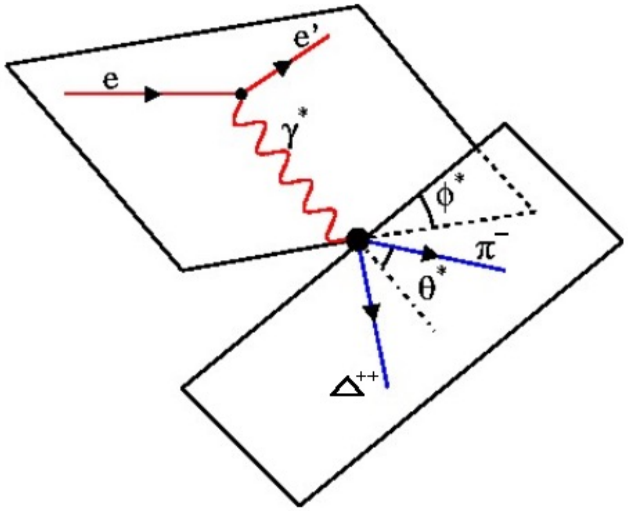
1. **Hard exclusive pseudoscalar / vector meson Electroproductions (GPDs)**

2. $ep \to e\Delta^{++}\pi^{-} \to ep\pi^{+}\pi^{-}$ **(N->Δ transition GPDs)**

Hard Exclusive Meson Electroproduction and Beam Spin Asymmetries (BSA)

Cross section (longitudinally pol. beam and unpol. target):

$$2\pi\frac{d^2\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cdot cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cdot cos(\phi)\frac{d\sigma_{LT}}{dt} + h\cdot\sqrt{2\epsilon(1-\epsilon)}\cdot sin(\phi)\frac{d\sigma_{LT'}}{dt}$$



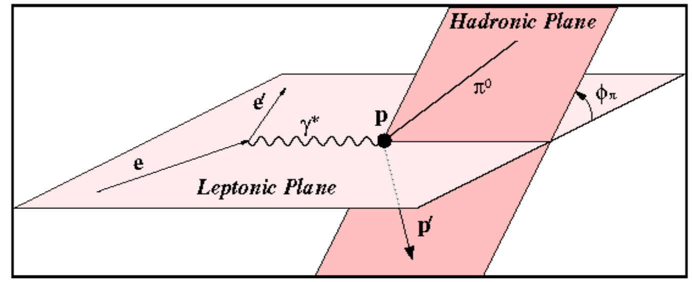
Beam Spin Asymmetry:

$$BSA(t,\phi,x_B,Q^2) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi + \epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$

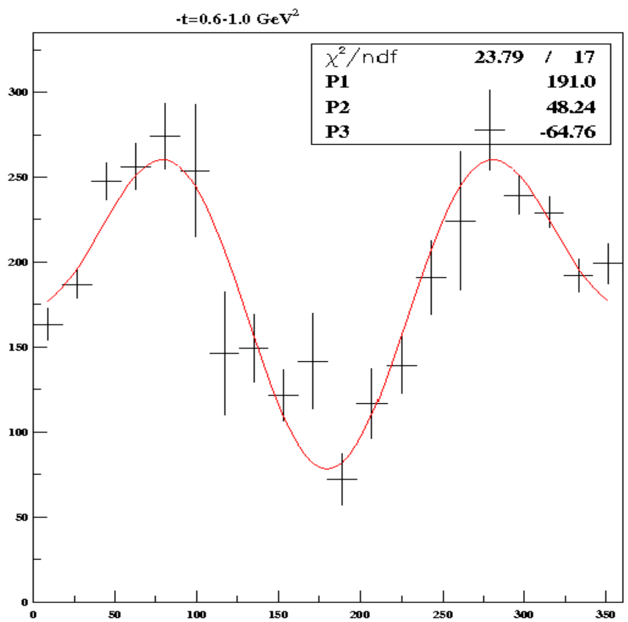
Differential Cross Sections for $ep \rightarrow ep\pi^0$

Structure Functions

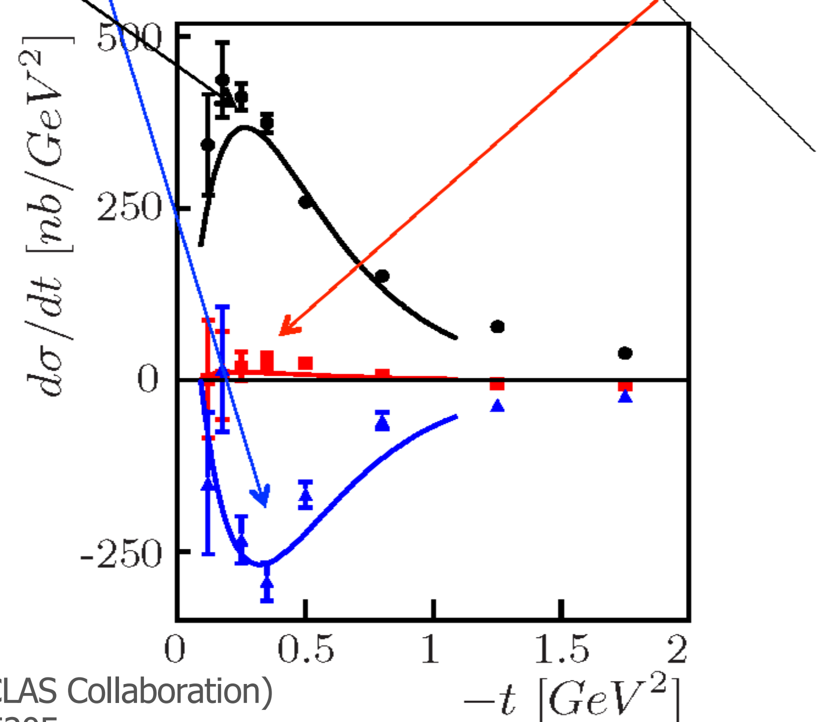
$\sigma_U = \sigma_T + \varepsilon\sigma_L \quad \sigma_{TT} \quad \sigma_{LT}$



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



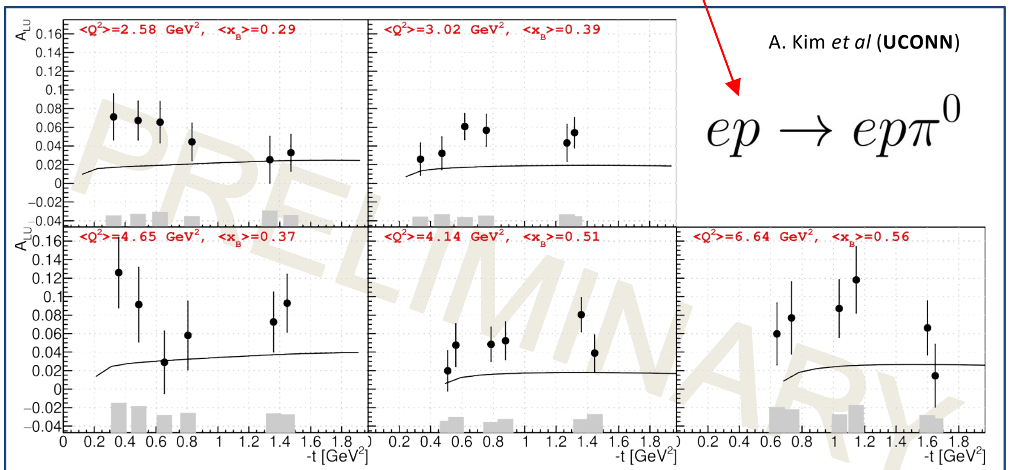
φ distribution



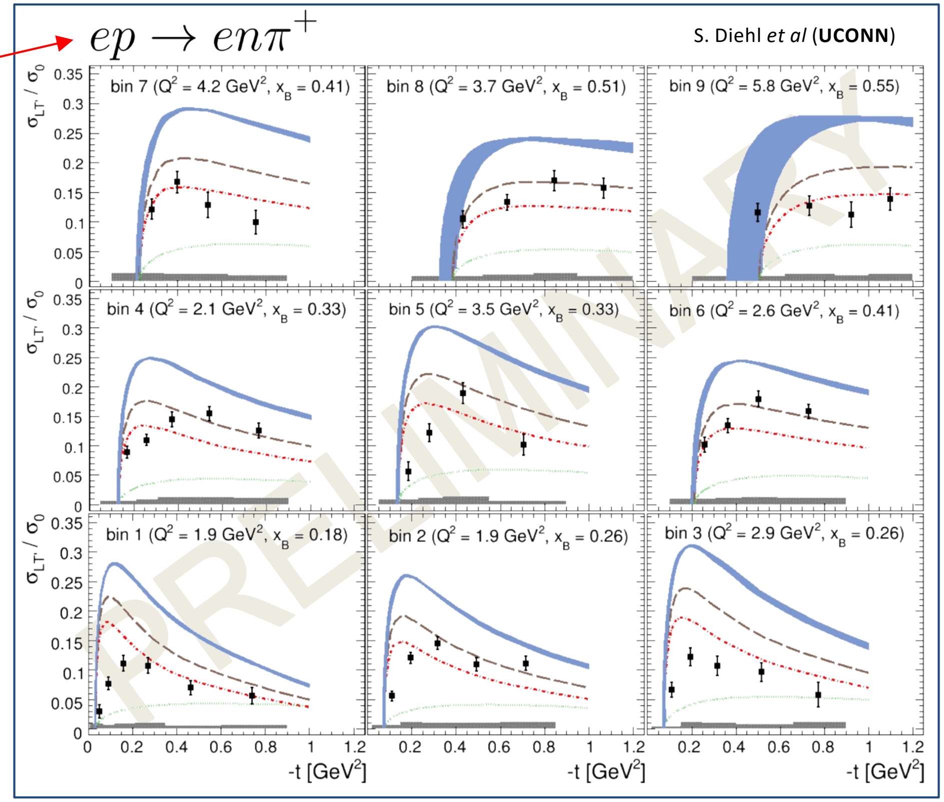
I. Bedlinskiy *et al.* (CLAS Collaboration)
Phys. Rev. C **90**, 025205

Pseudoscalar meson electroproduction with CLAS12

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



- active work on cross-section extraction by R. Johnston (MIT)



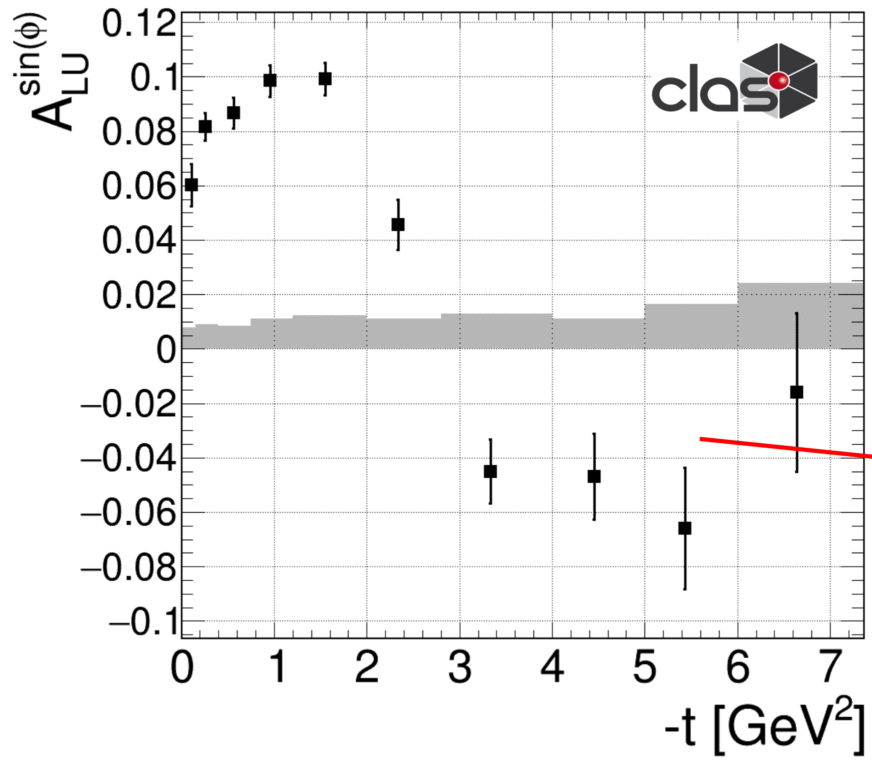
GK model

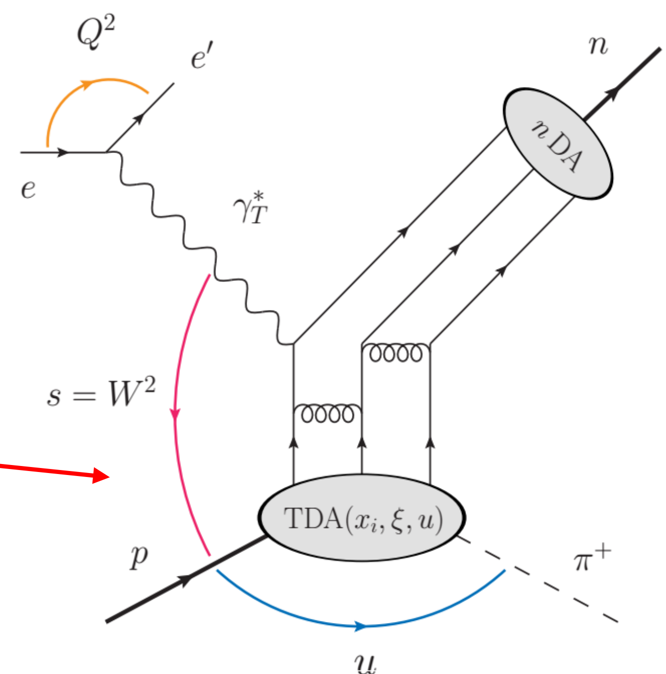
Additionally active work on η beam spin asymmetry and cross-section extraction

Beam spin asymmetry for $ep \to en\pi^+$

$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

$$BSA = \frac{A_{LU}^{\sin\phi} \sin\phi}{1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos(2\phi)} \cos(2\phi)}$$

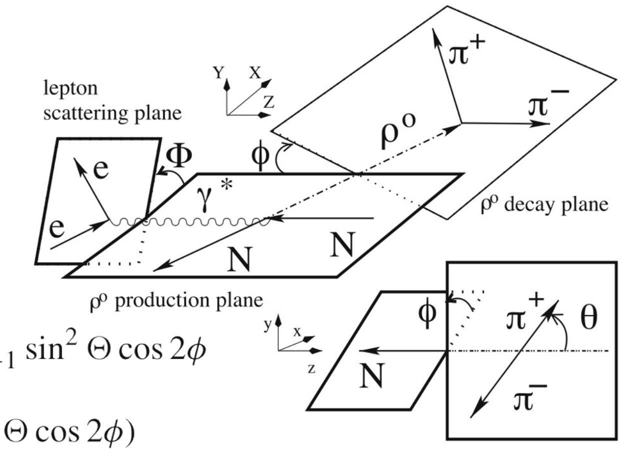




S. Diehl et al. (CLAS collaboration),
Phys. Rev. Lett. 125, 182001 (2020)

Vector meson production: Spin Density Matrix Elements (SDME)

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



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

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

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

Vector meson production: Spin Density Matrix Elements (SDME)

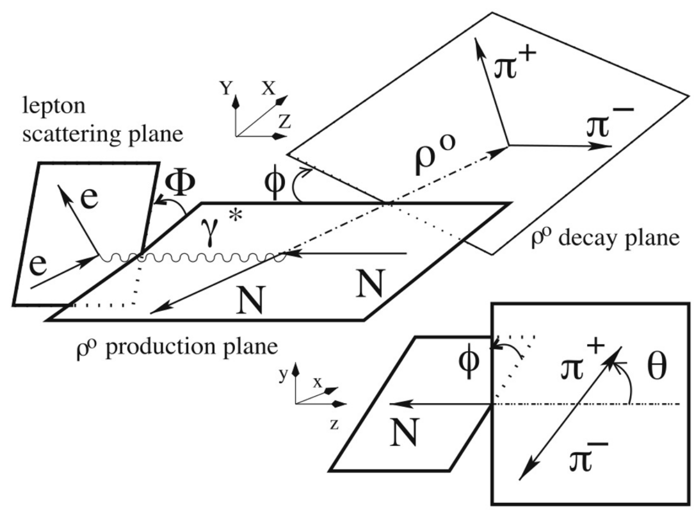
$$\frac{d\sigma}{d\phi\; d\Phi\; d\Theta\; dQ^2\; dx_B\; dt} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left\{\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right\}\mathcal{W}^{U+L}(\Phi, \phi, \cos\Theta)$$

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

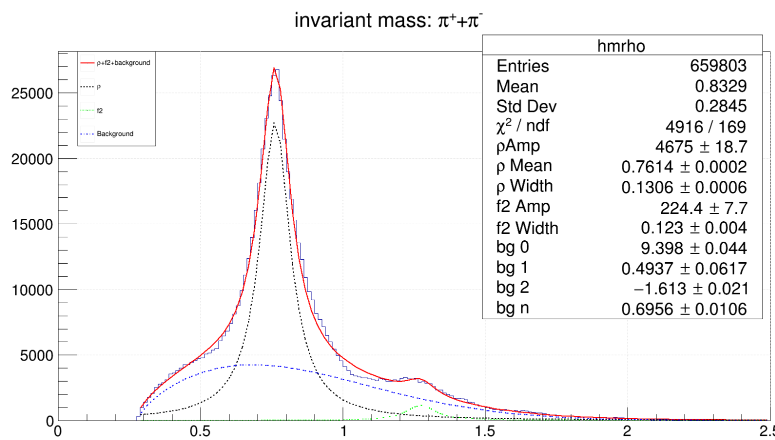
$$r^1_{00}\sigma_0 \sim \left|\bar{E}_T\right|^2$$

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

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



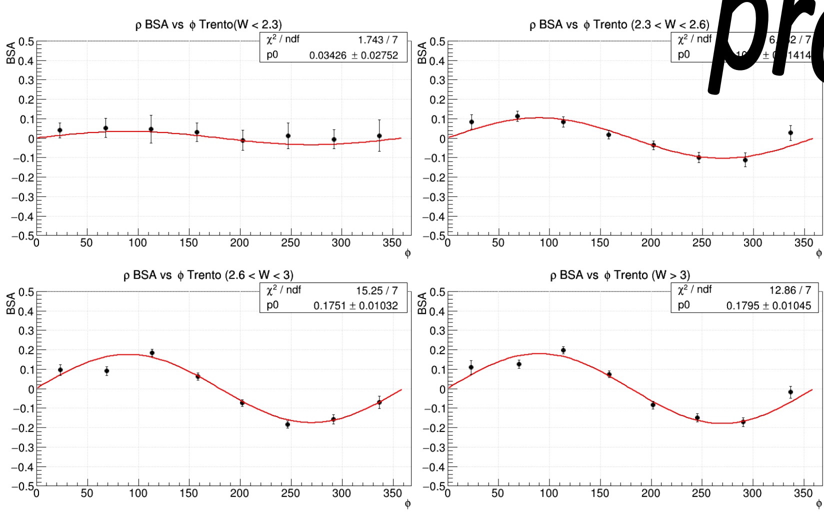
Exclusive ρ production with CLAS12

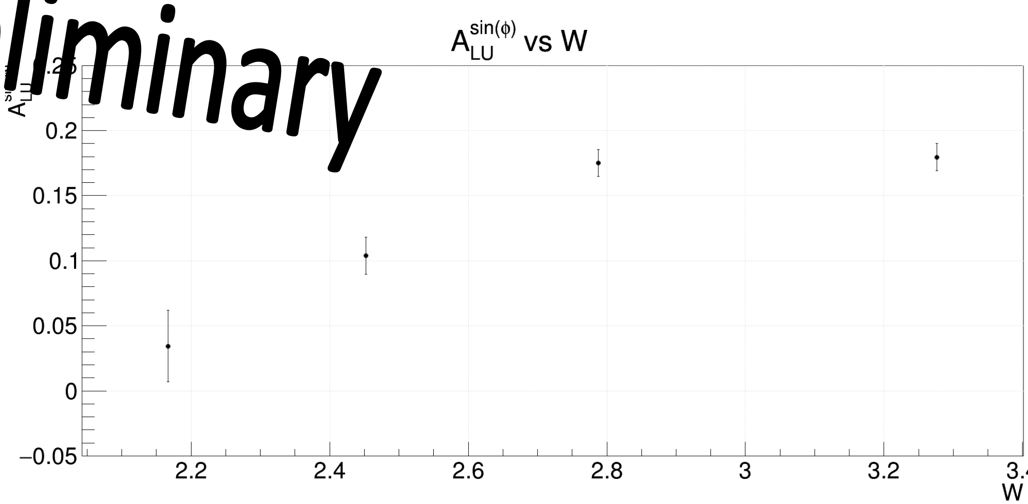


$$\sigma_{LT'} \sim r^8_{00} \sim \ \mathrm{Im}\left[\langle H_T\rangle^*\langle E\rangle + \langle \bar{E}_T\rangle^*\langle H\rangle\right]$$

$$BSA = \frac{A_{LU}^{\sin\phi}\sin\phi}{1 + A_{UU}^{\cos\phi}\cos\phi + A_{UU}^{\cos(2\phi)}\cos(2\phi)}$$

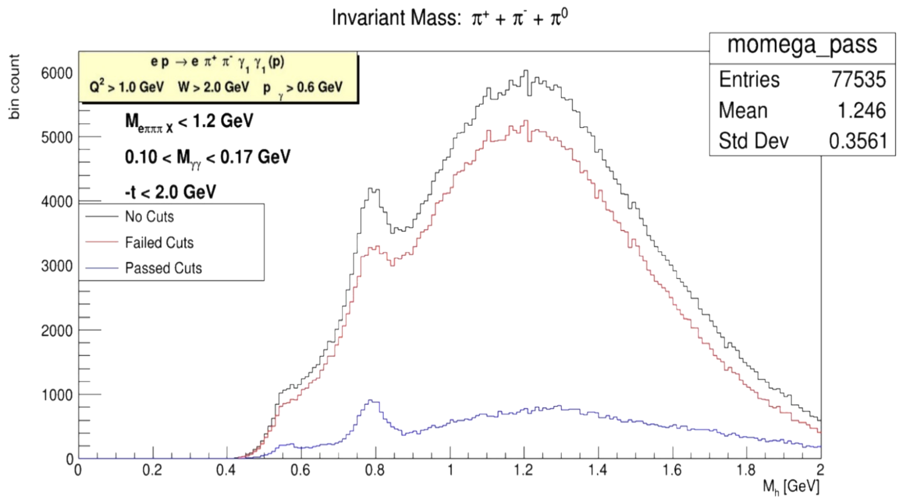
preliminary

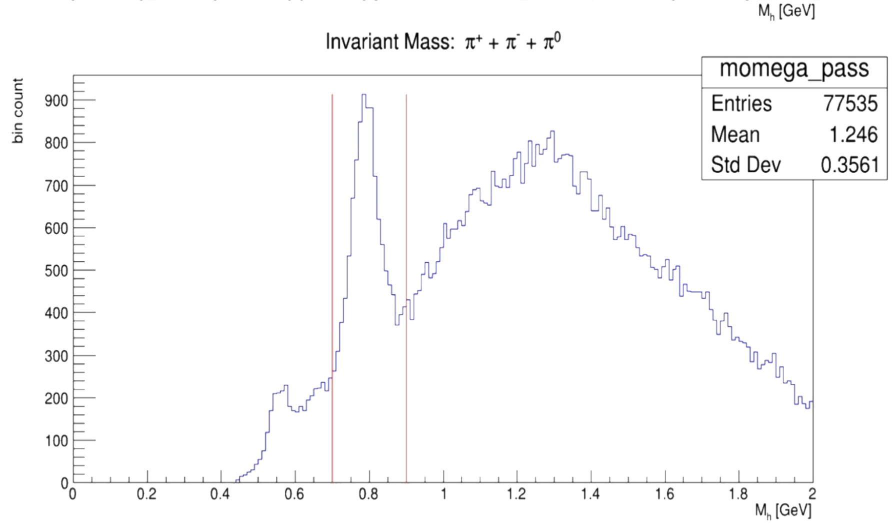


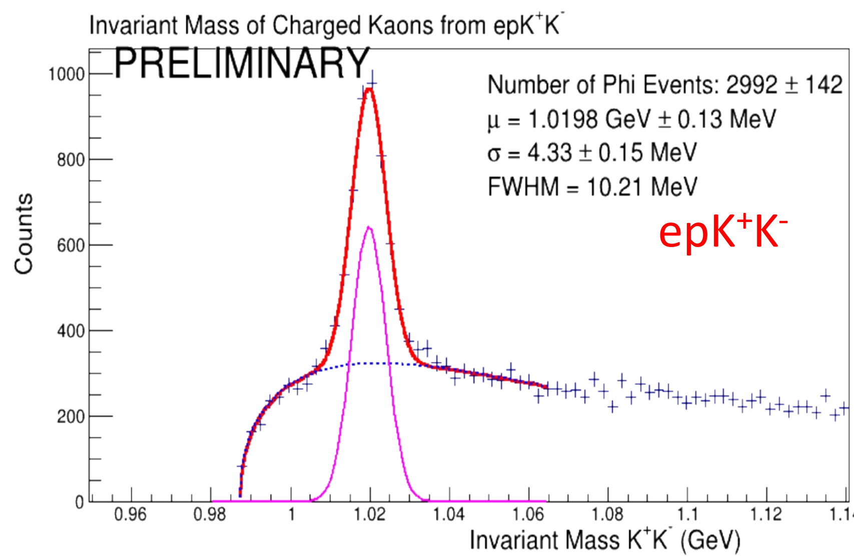


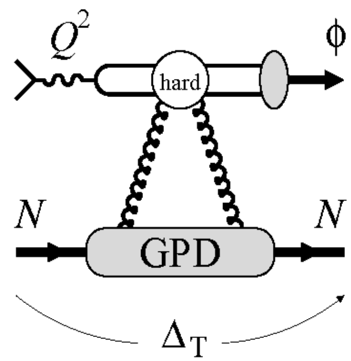
$$BSA_i = \frac{1}{P_e}\cdot\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

Exclusive ω, ϕ production with CLAS12









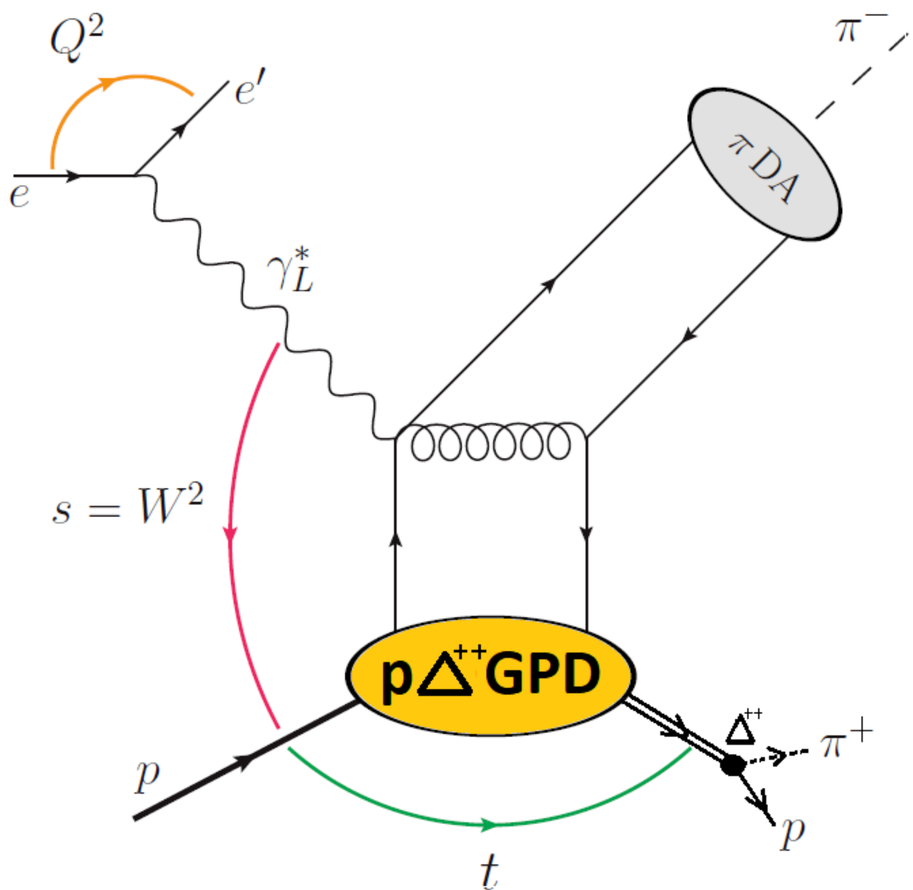
Exclusive Φ production probes gluon GPDs

Transverse spatial distribution of gluons

$x < 0.01$ measured at HERA, FNAL

$x > 0.1$ practically unknown

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



Factorization expected for:

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

x_B fixed

➔ Provides access to p-Δ transition GPDs

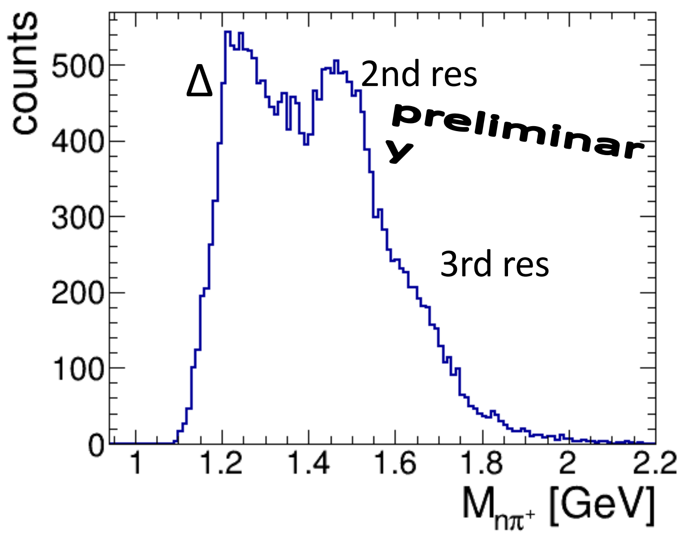
➔ 3D structure of the Δ resonance and of the excitation process

- $\pi^{\pm}$ is expected to be especially sensitive to the tensor charge of the resonance

Why is $\pi^- \Delta^{++}$ special?

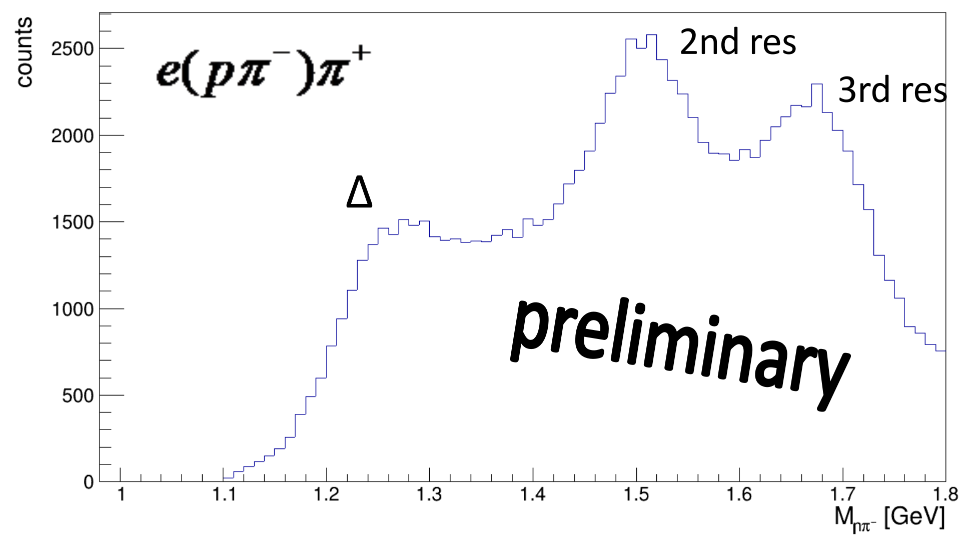
non-diagonal DVCS

$$\gamma^* p \rightarrow N^* \gamma \rightarrow p \ meson \ \gamma$$



other non-diagonal DVMP channels

$$ep \rightarrow e\Delta^0 \pi^+ \rightarrow e(p\pi^-)\pi^+$$



$$ep \rightarrow e\Delta^{++}\pi^- \rightarrow \underbrace{ep\pi^+}_{I_z = +3/2}\pi^-$$

➔ The $p\pi^+$ final state can **only** be populated by **Δ-resonances**

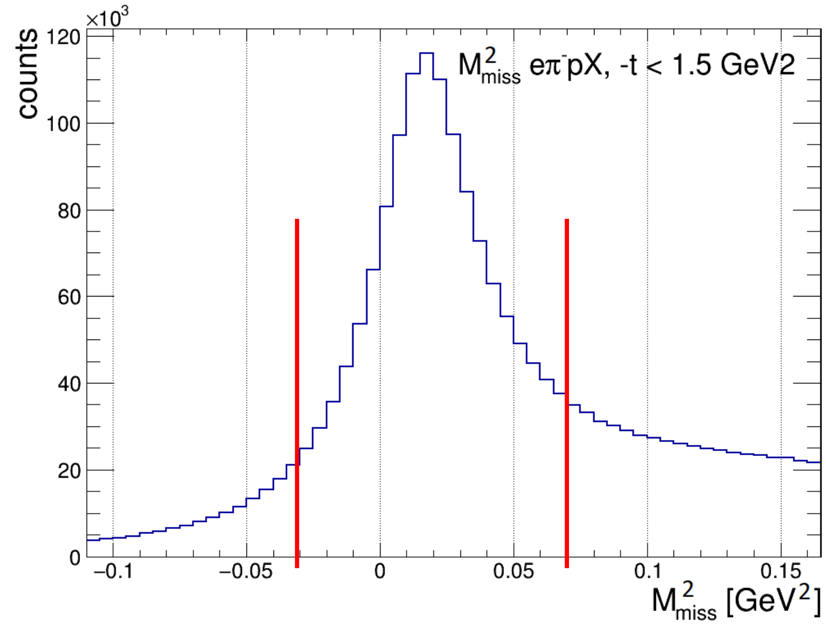
- Large gap between Δ(1232) and higher resonances

Event Selection and Kinematic Cuts

$$ep \rightarrow e\Delta^{++}\pi^{-} \rightarrow ep\pi^{-}X$$

$$X = \pi^{+}$$

- 2 σ cut around the missing π^+

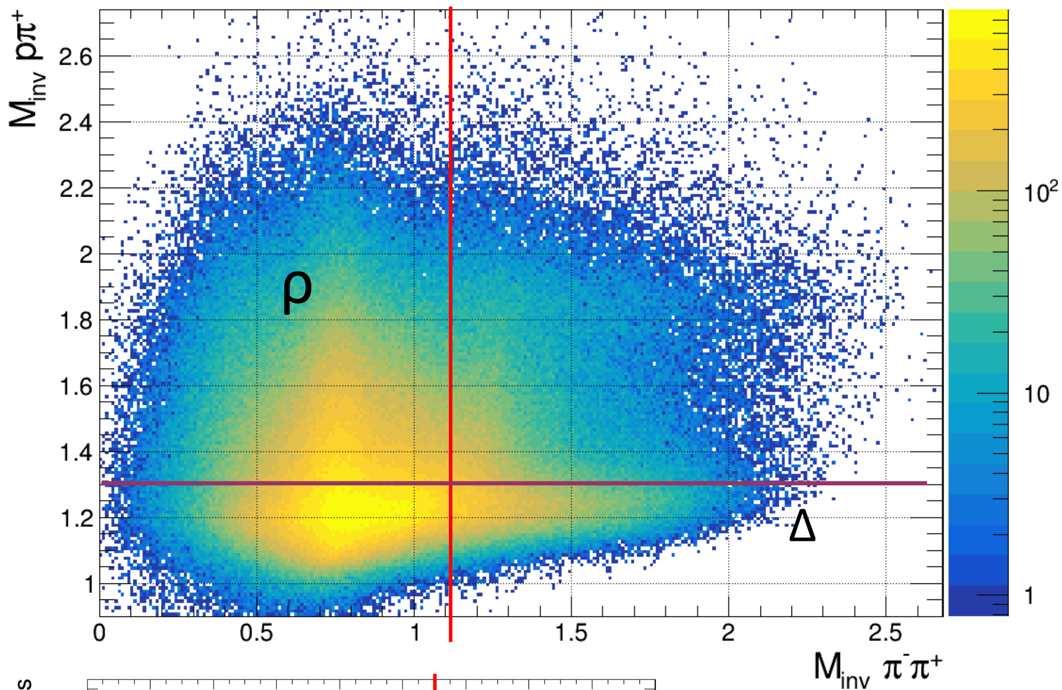


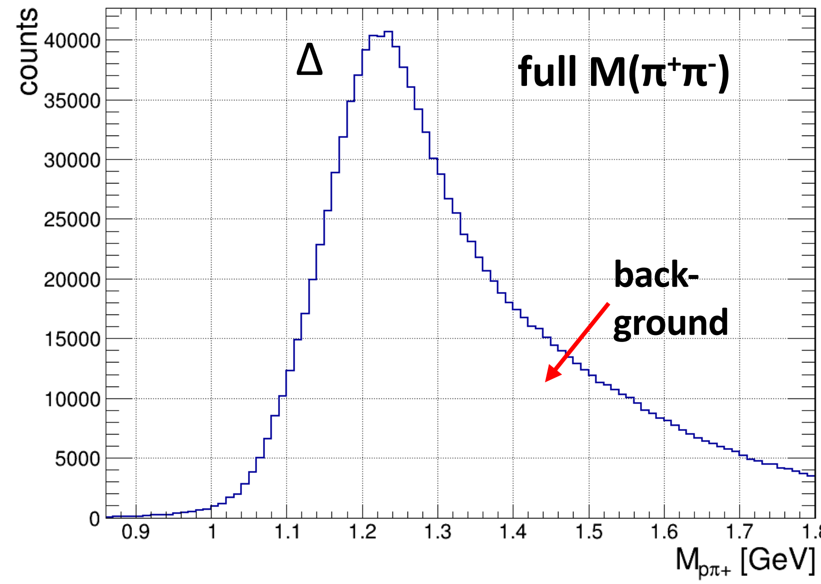
Kinematic cuts:

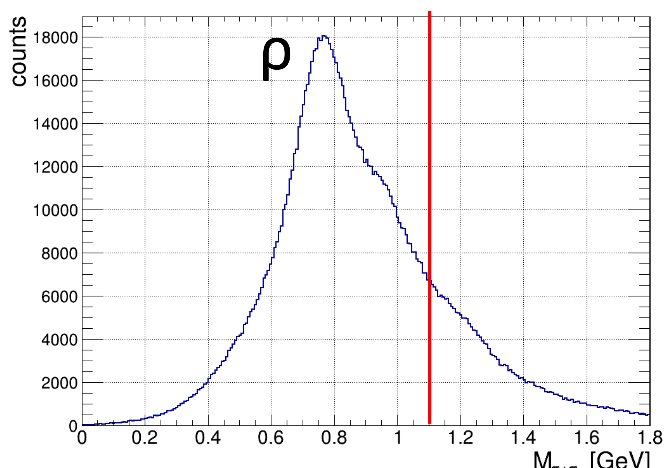
$Q^2 > 1.5$ GeV² W > 2 GeV y < 0.75

-t < 1.5 GeV² (only the forward region)

Event Selection and Background Rejection





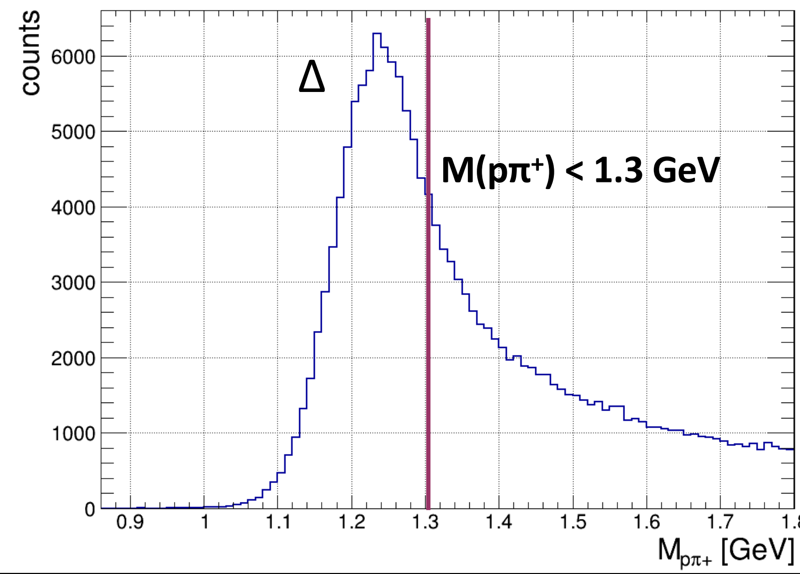


$ep \rightarrow ep\rho \rightarrow ep\pi^+\pi^-$

$M(\pi^+\pi^-) > 1.1$ GeV

ρ contamination

< 0.8 %



Monte Carlo Simulations

2 MC samples have been used:

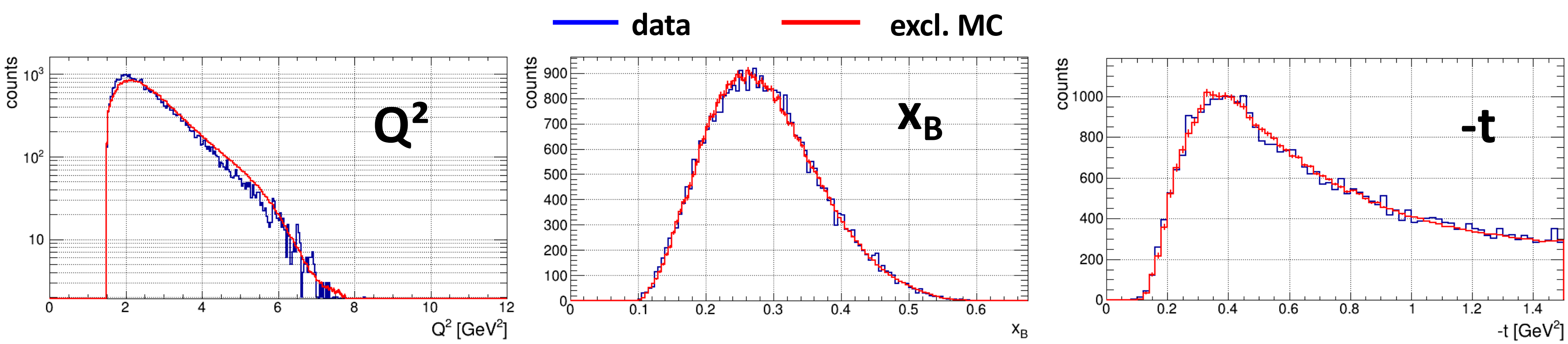
a) Semi-inclusive DIS MC

- Does not contain the $\pi^- \Delta^{++}$ production in „forward“ kinematics
- Contains nonres. background as well as ρ production and other potential BG channels
- Used to estimate background shape and contaminations

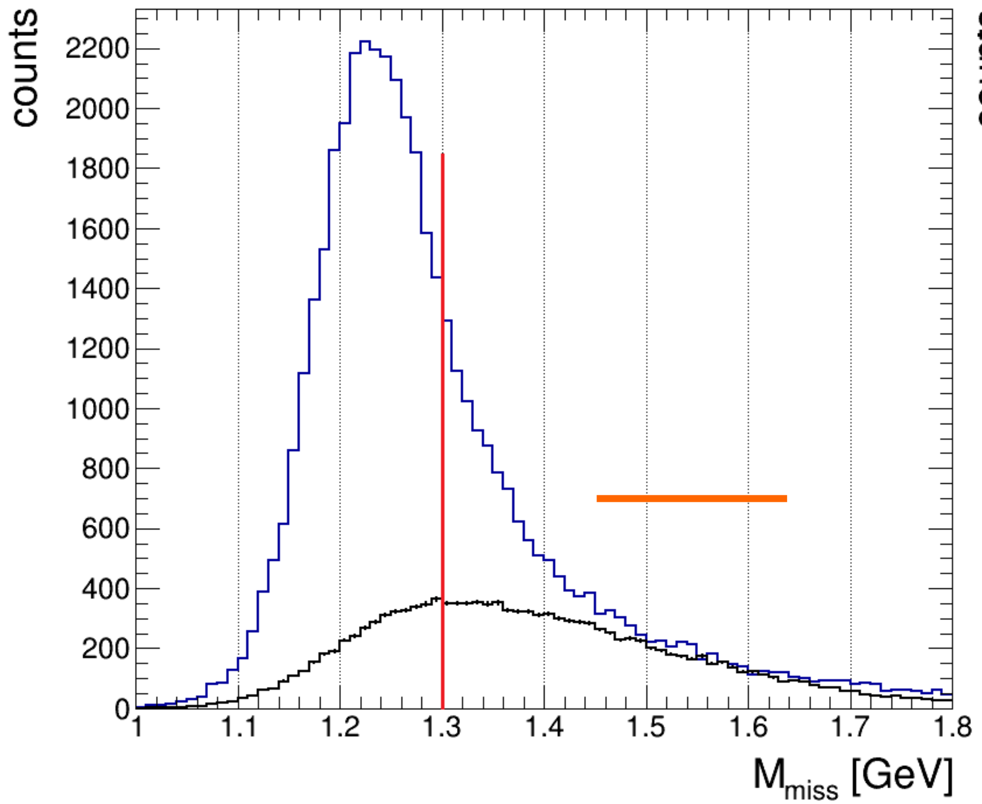
b) Exclusive $\pi^- \Delta^{++}$ MC

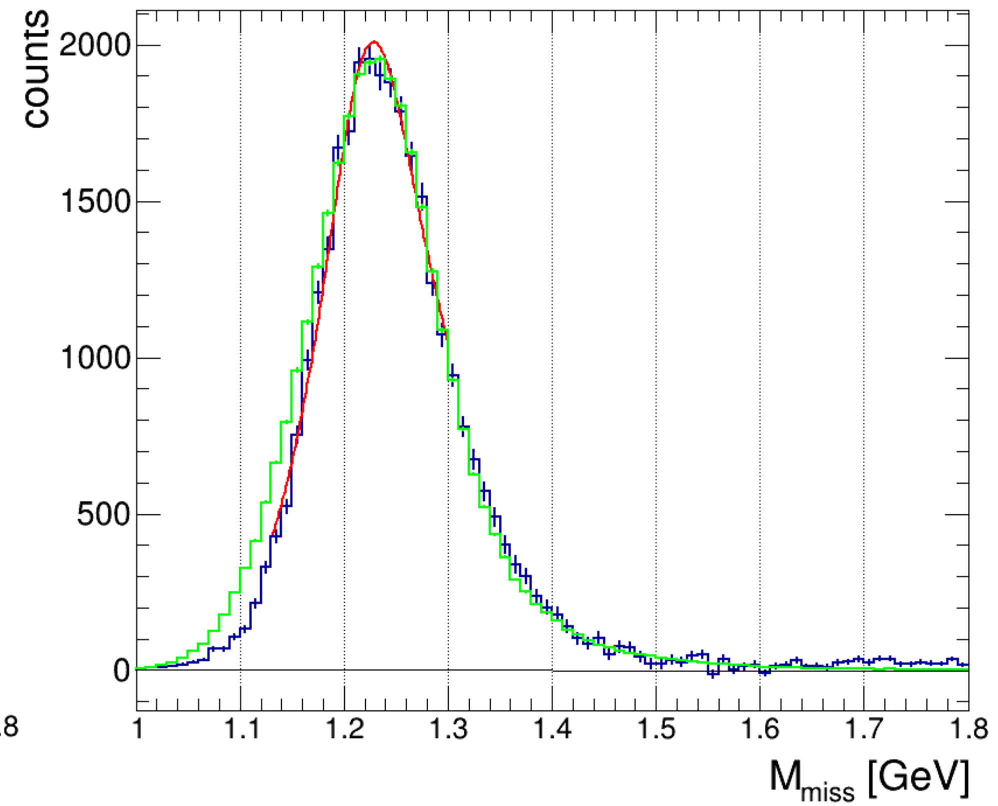
- Phase space simulation with a weigth added to match experimental data
- Δ peak with PDG mass and FWHM

➔ Both MCs are processed through the full simulation and reconstruction chain



Event Selection and Background Estimate





experimental data

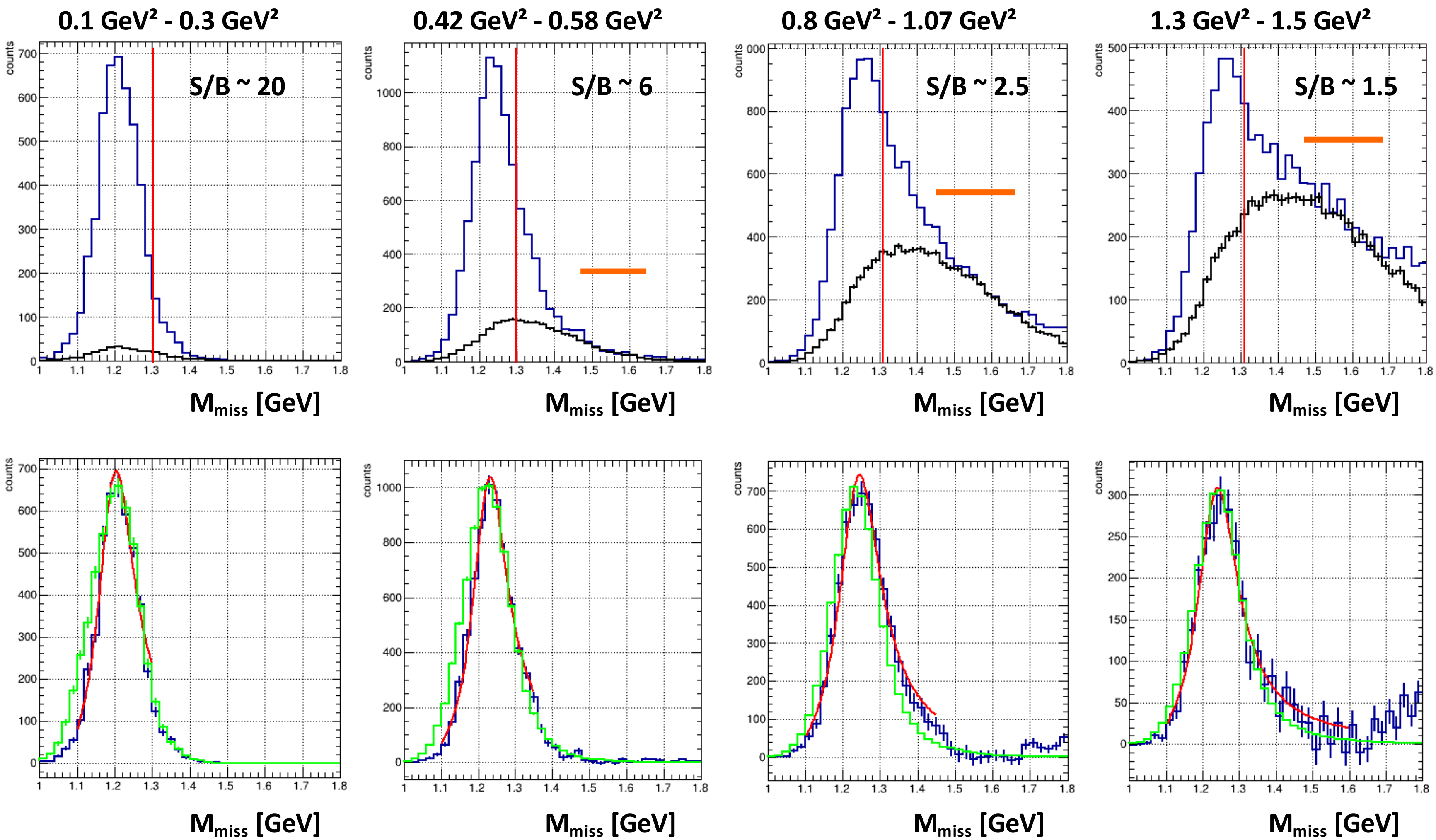
SIDIS MC (same cuts)

data after SIDIS MC subtraction

fit of a Sill function (BW with thr. effects)

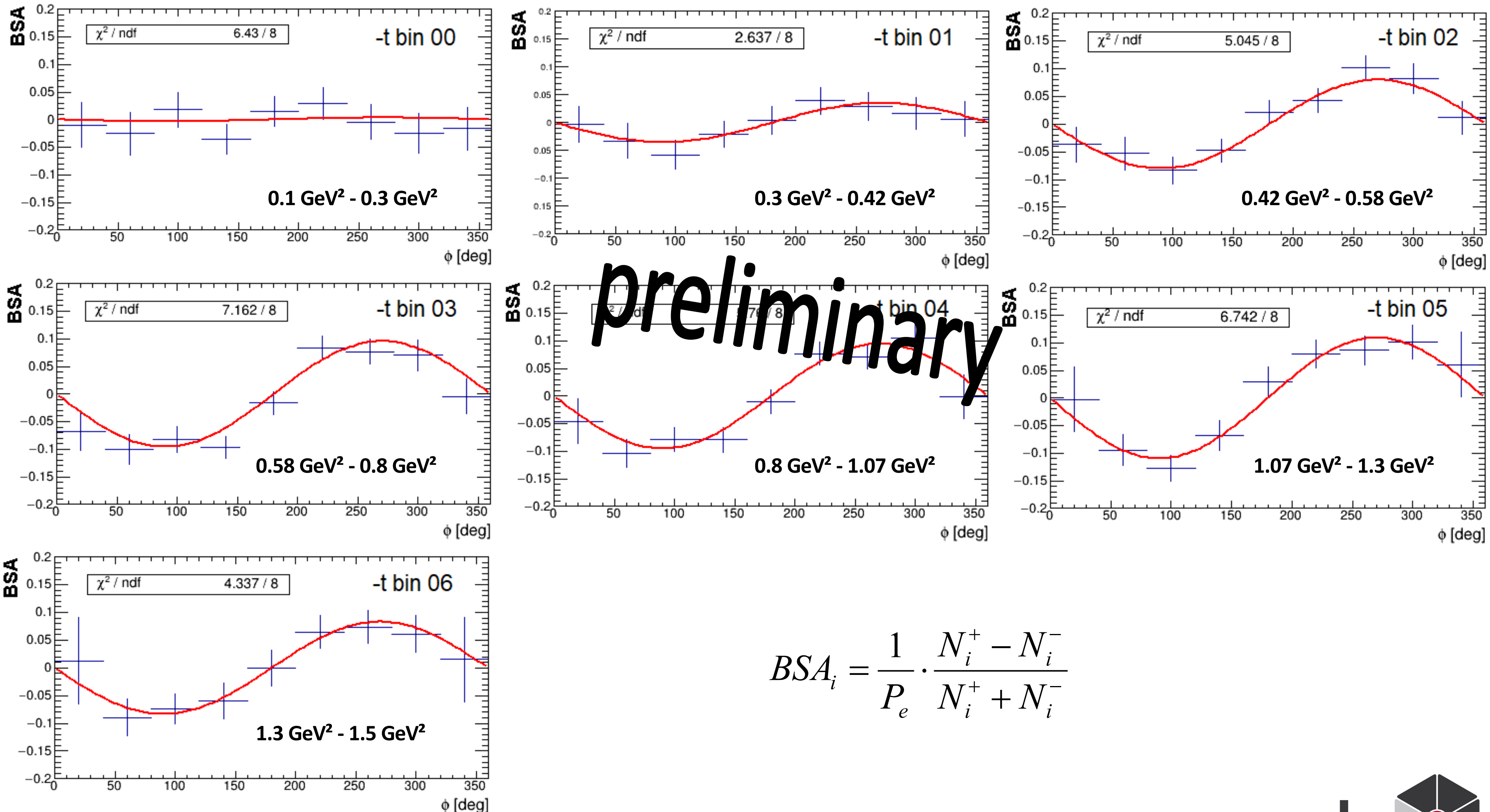
exclusive MC (for comparison)

Event Selection and Background Estimate



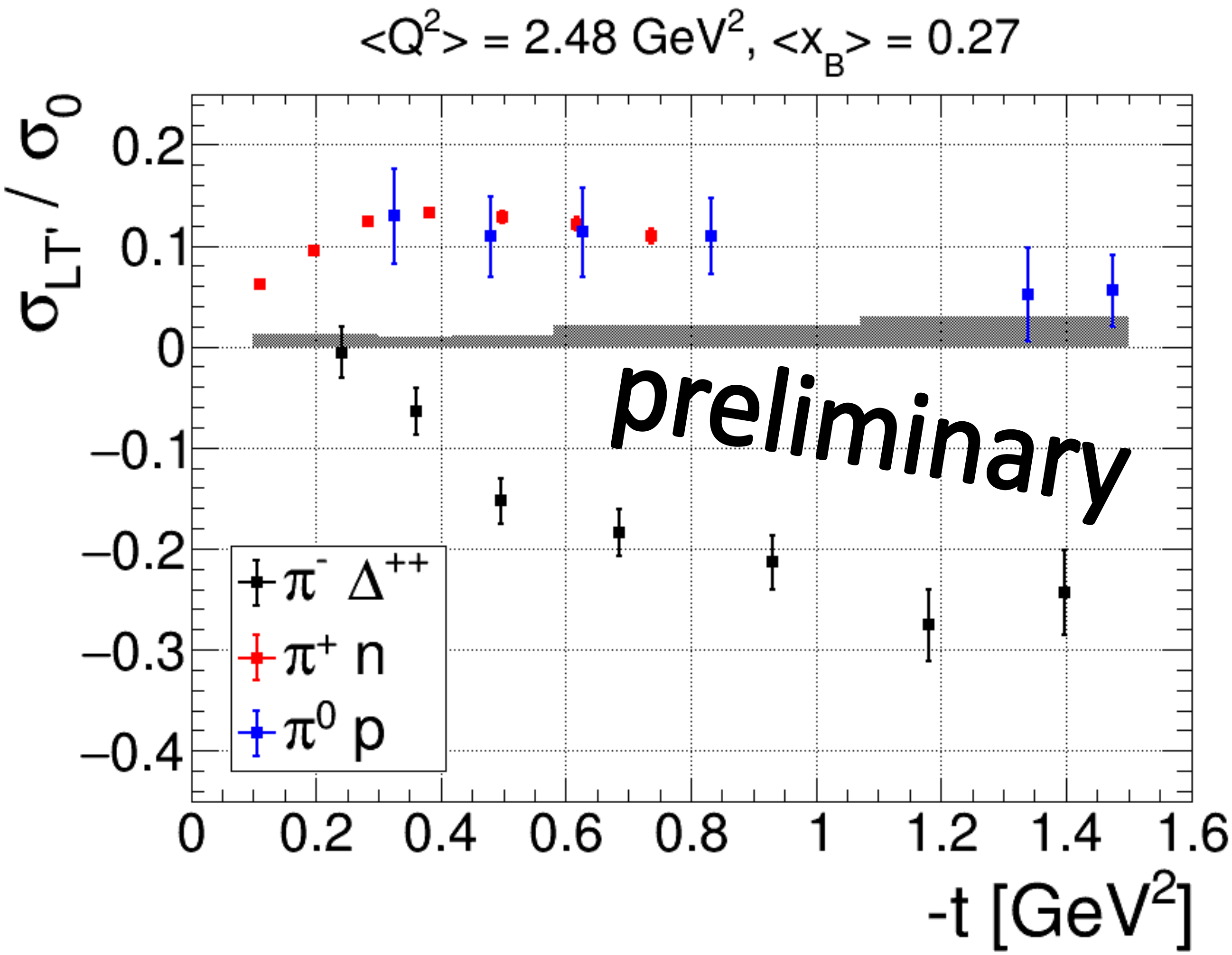
- experimental data
- SIDIS MC (same cuts)
- data after SIDIS MC subtraction
- fit of a Sill function (BW with thr. effects)
- exclusive MC (for comparison)

Resulting Beam Spin Asymmtries (Q²-x$_B$ integrated)



$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

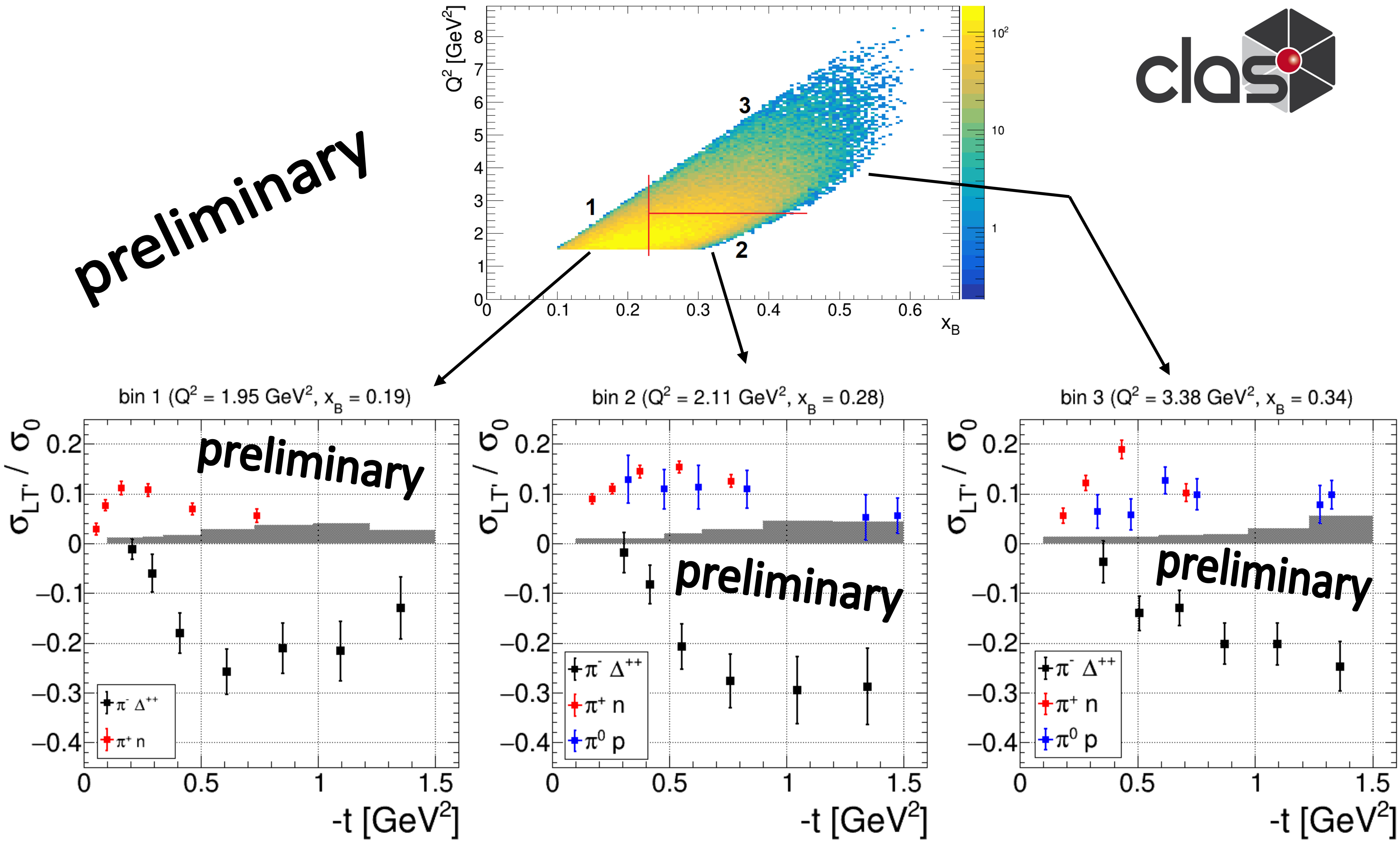
Q^2 - x_B Integrated Result



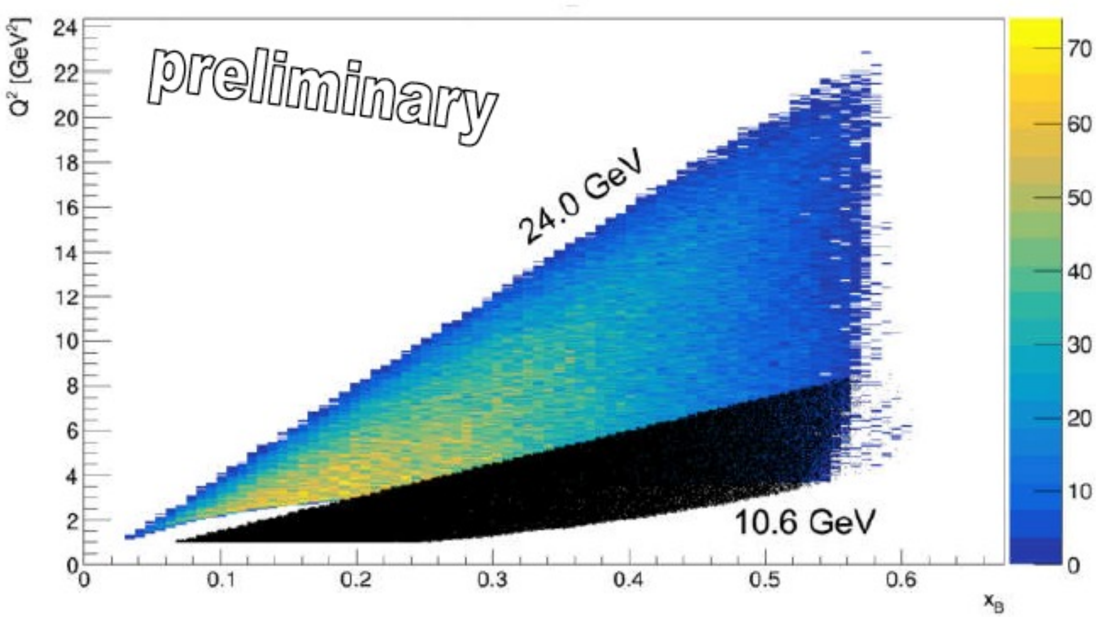
Different sources of systematic uncertainty have been studied:

beam polarisation, background subtraction, fiducial volume, extraction method, acceptance, bin migration, radiative effects

Multidimensional Results



Perspectives for a 20+ GeV JLAB upgrade



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

Extended Q^2 range

→ Advantage for factorisation

- Similar for non-diagonal DVCS

Conclusion and Outlook

- CLAS12 has a comprehensive program in measuring hard exclusive pseudoscalar and vector meson productions to access GPDs.

- Hard exclusive $\pi^-\Delta^{++}$ production can be well measured with CLAS12 to study transition GPDs.

- The obtained BSA from $\pi^-\Delta^{++}$ production is clearly negative and ~ 2 times larger than for the hard exclusive π^+ / π^0 production.

- The extracted BSA is a potential first "clean“ observable sensitive to p-Δ transition GPDs

- More comprehensive theoretical framework for the exclusive meson productions would be needed.

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

UCONN | UNIVERSITY OF CONNECTICUT

clas