N->Δ Transition GPDs with CLAS12

APCTP Workshop on Nuclear Physics 2022: Physics of Excited Hadrons in the Present and Future Facilities

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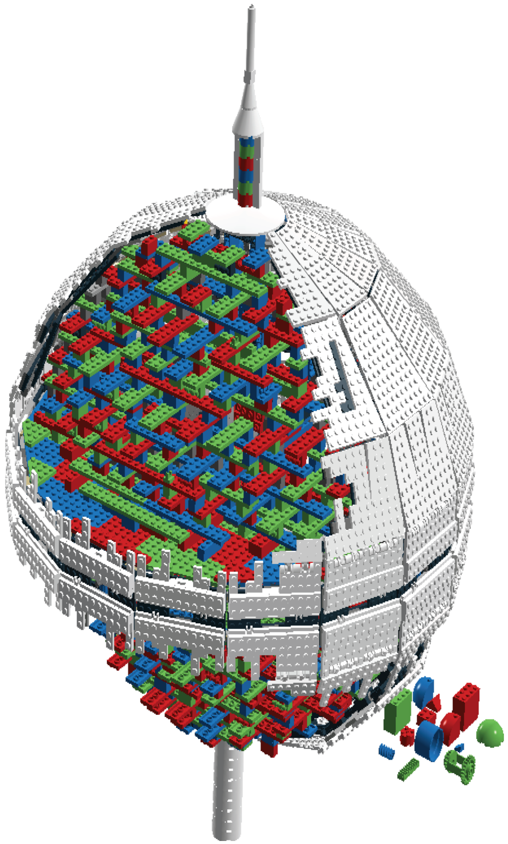
QCD Science Questions

How are the quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon?

How can we recover the well-known characterics of the nucleon from the properties of its **colored building blocks**?

Mass?
Spin?
Charge?
...

What are the relevant **effective degrees of freedom** and **effective interaction** at large distance?

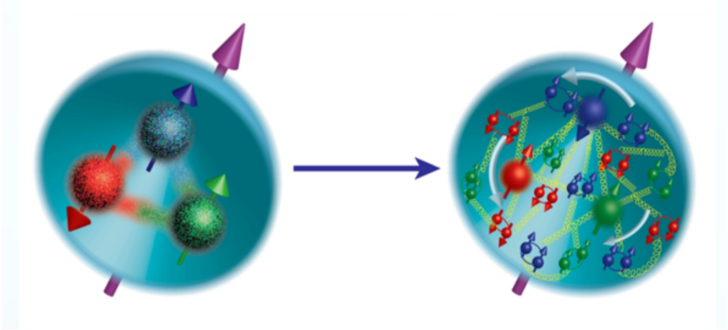


What is the role of orbital angular motion?

The Incomplete Nucleon Spin: Spin Puzzle

- Proton has spin-1/2

- Proton is a composite system consisting of spin-1/2 quarks and spin-1 gluons



$$J_N = \frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

 Sum of angular momentum of quarks and gluons together must be 1/2

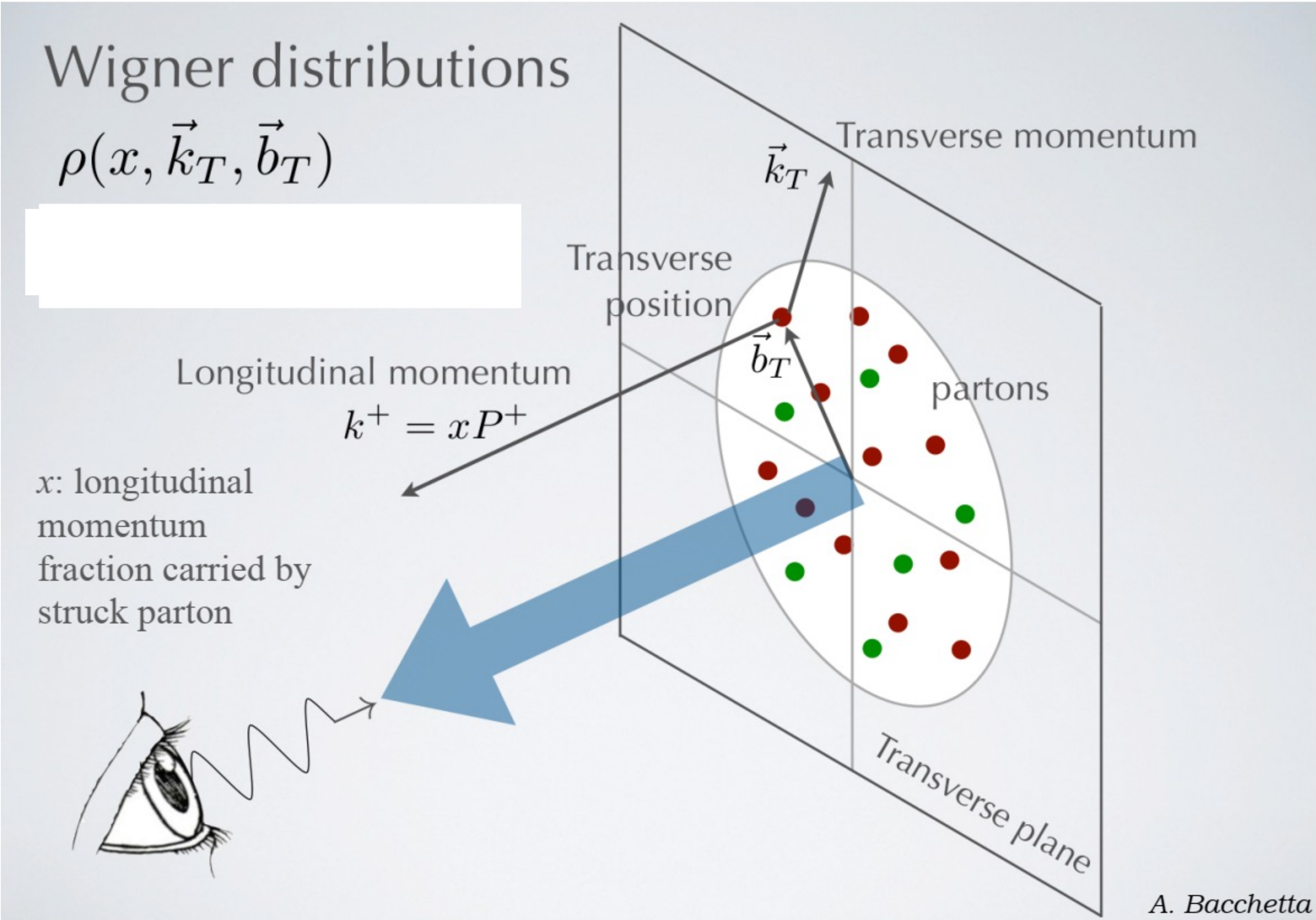
Possible contributions Quark spin, Quark orbital momentum
Gluon spin, Gluon orbital momentum

Classical: L ~ **r** x **p**

Needs a cross-product or something three-dimensional!

We need to investigate the 3D nucleon structure!

3-Dimensional Imaging of Quarks and Gluons



Generalized Parton Distributions (GPDs)

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

↓

Integrate over transverse ***momentum*** space

↓

Generalized Parton Distributions (GPD)

↓

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

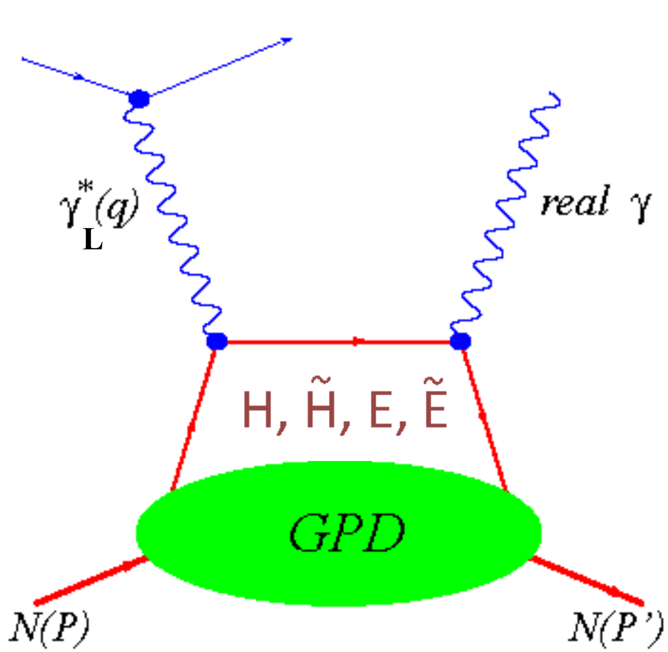
quark pol. (columns) / **nucleon pol.** (rows)

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

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

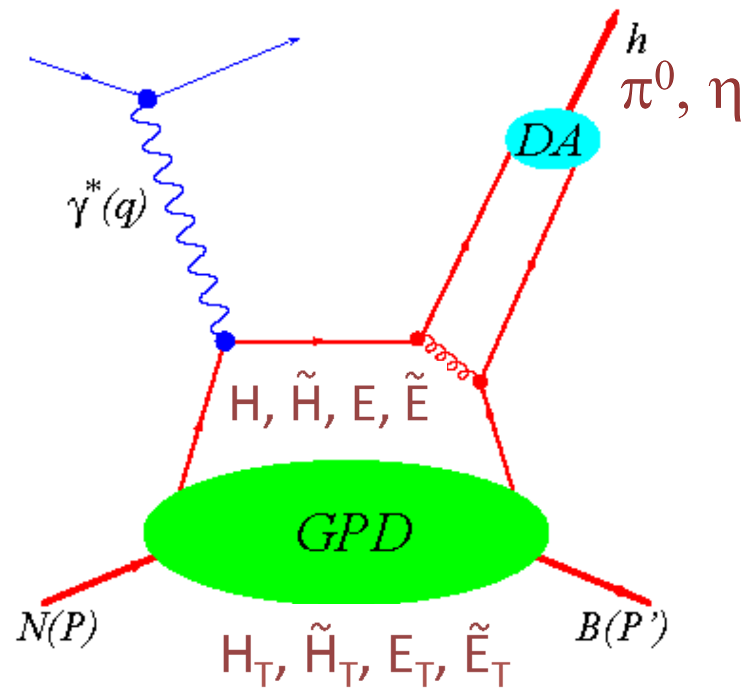
Study GPDs: Deeply Virtual Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



+ Clean process
- Only sensitive to chiral even GPDs

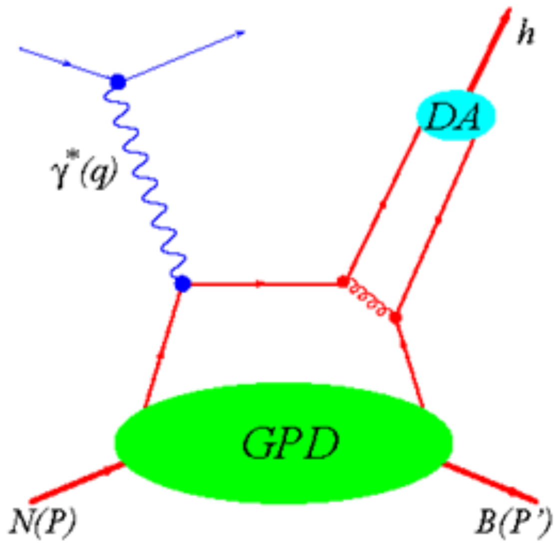
Deeply Virtual Meson Production (DVMP)



+ 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
$\mathcal{H}_T, \mathcal{E}_T$	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



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

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

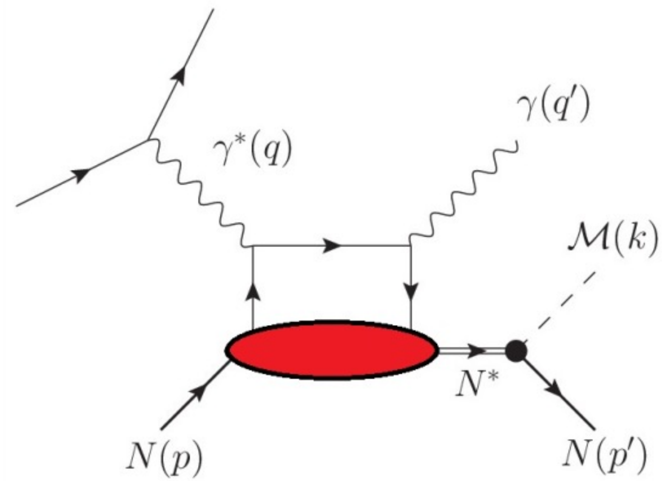
$$\delta_T^u = \int dx H_T^u(x, \xi, t = 0)$$

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

$\bar{E}_T$ 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

Studies of Transition GPDs



non-diag. DVCS

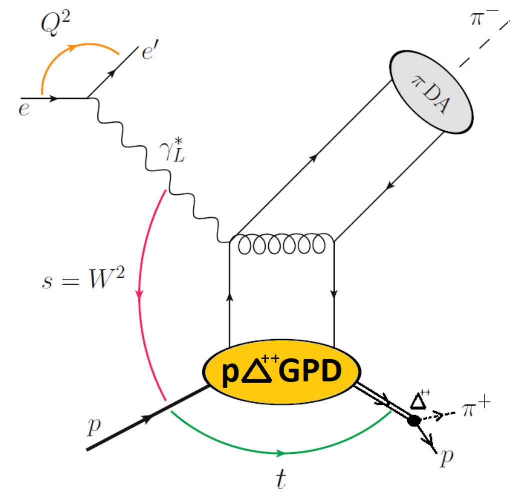
- **8 helicity non-flip trans. GPDs (twist 2)**

→ 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



non-diag. DVMP

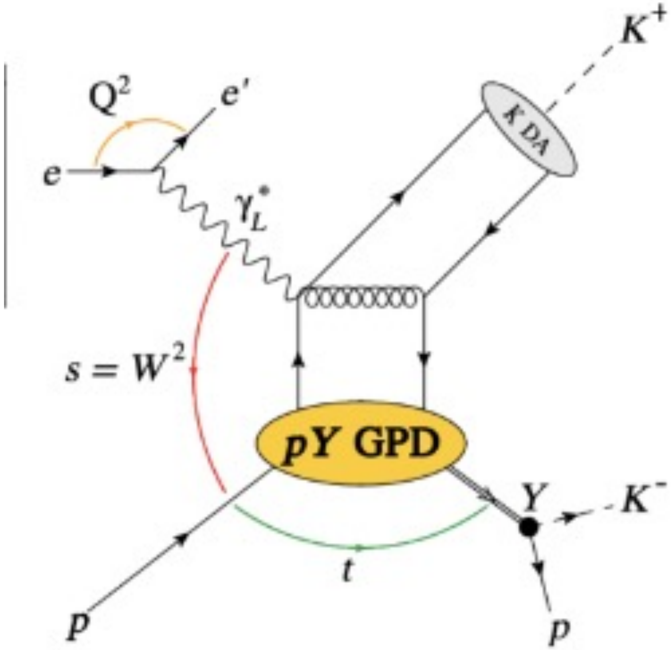
- **8 helicity flip trans. GPDs**

→ Needed for twist-3 sector (non-diag DVMP)

→ Theory in progress (no publ. so far)

Studies of Transition GPDs

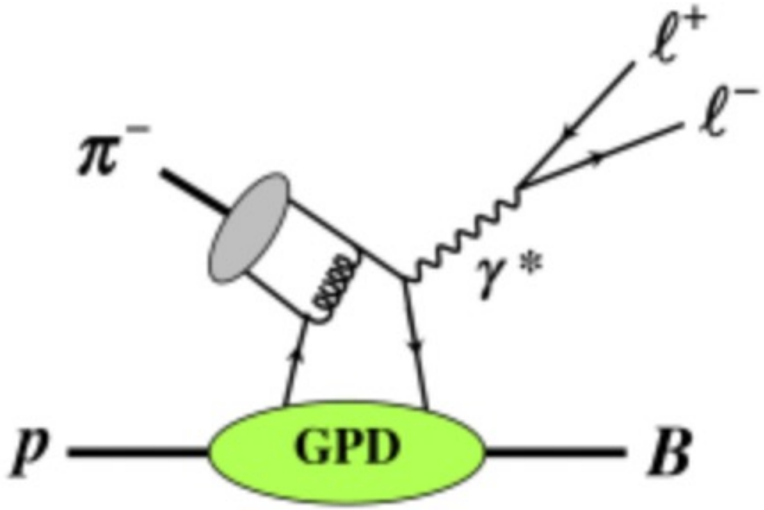
Jefferson Lab



Exclusive KY Production

p->Y Transition GPDs

J-PARC

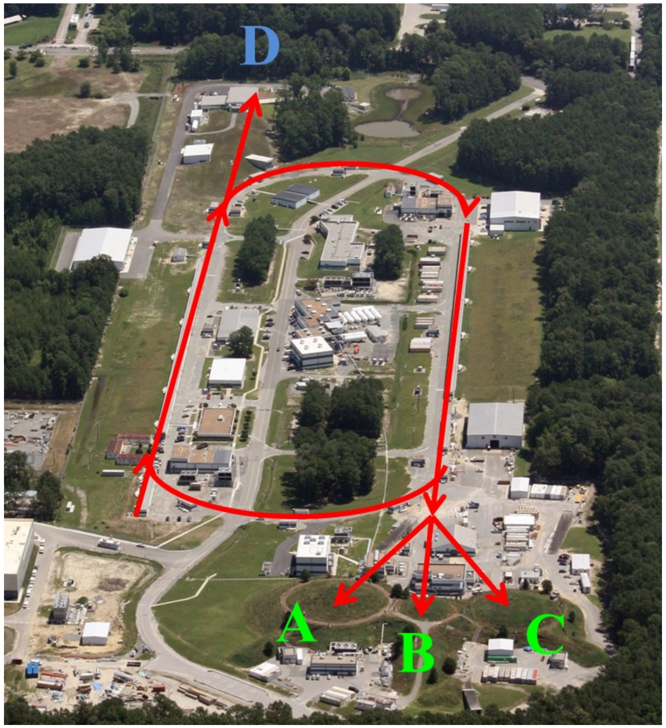


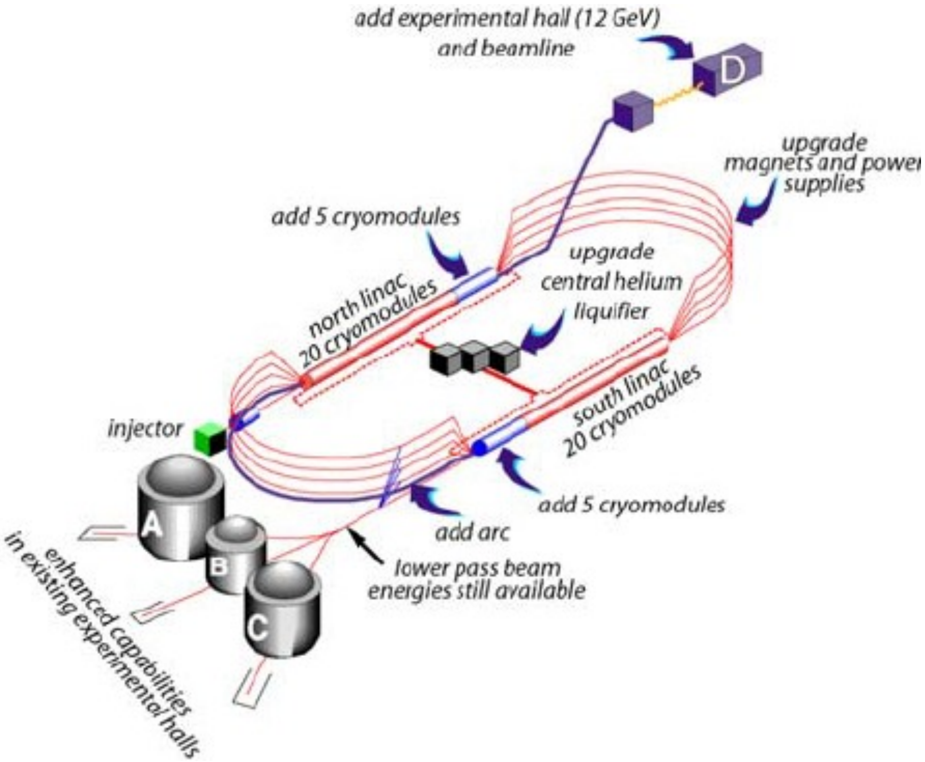
Exclusive Drell-Yan Process

If B = Y, p->Y Transition GPDs

J-PARC Letter of Intent

Thomas Jefferson National Accelerator Facility (Jefferson Lab)



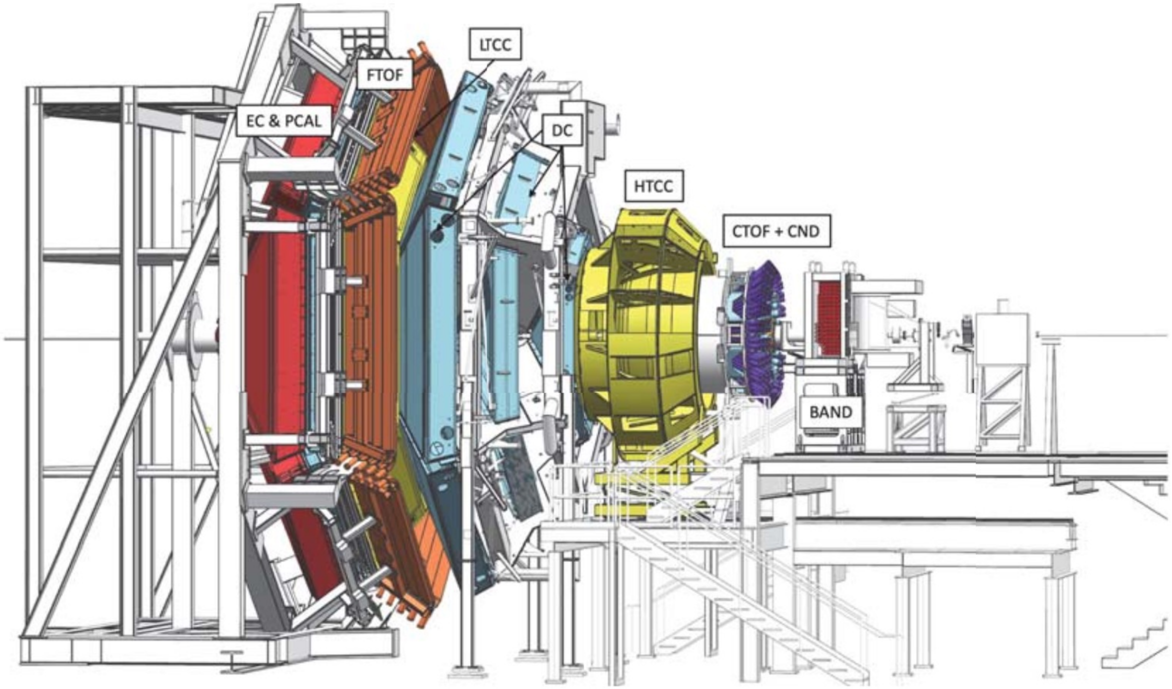


- **CEBAF Upgrade completed in September 2017**
  - → electron beam
  - → E_{max} = 12 GeV
  - → I_{max} = 90 μA
  - → Pol_{max} ~ 90%

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
- Analysed data ~ 35 % of the approved RG-A beam time

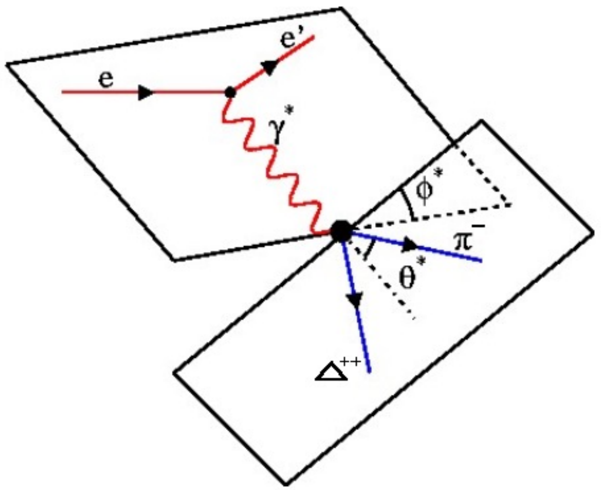
1. **Hard exclusive pseudoscalar / vector meson Electroproductions (GPDs)**

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

Hard Exclusive Meson Electroproduction and Beam Spin Asymmetries (BSA)

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

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

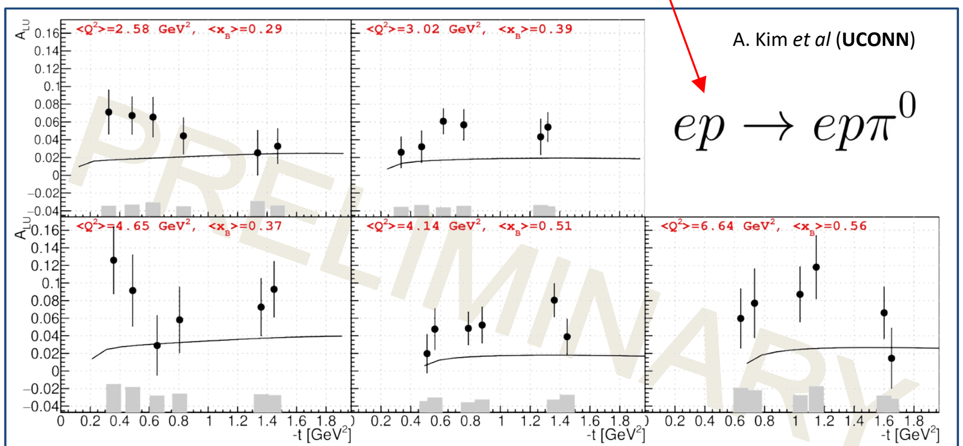


Beam Spin Asymmetry:

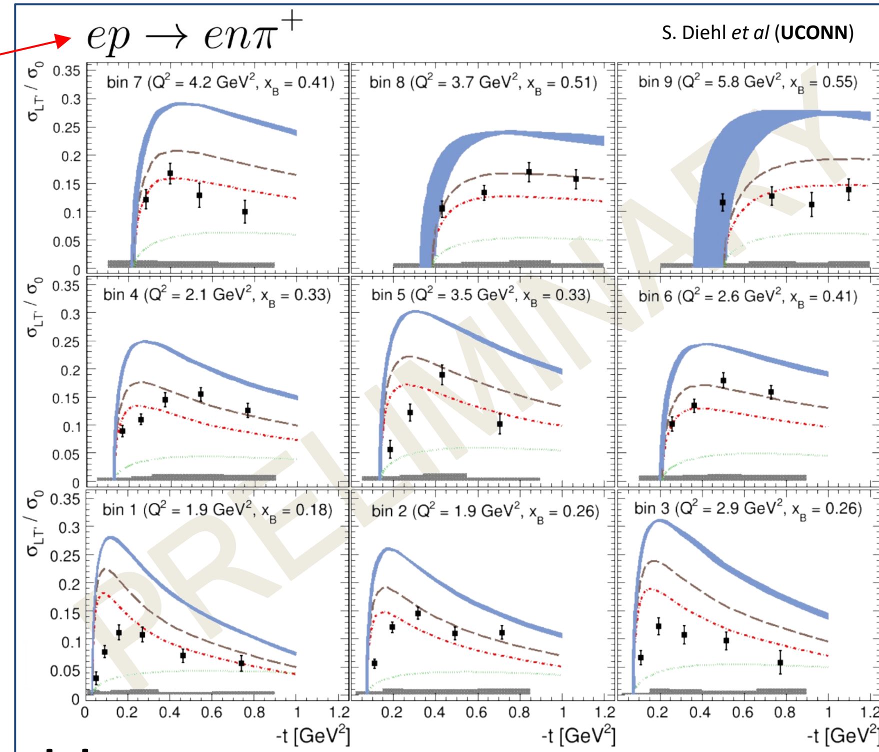
$$BSA(t,\phi,x_B,Q^2) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi + \epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$

Pseudoscalar meson electroproduction with CLAS12

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



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



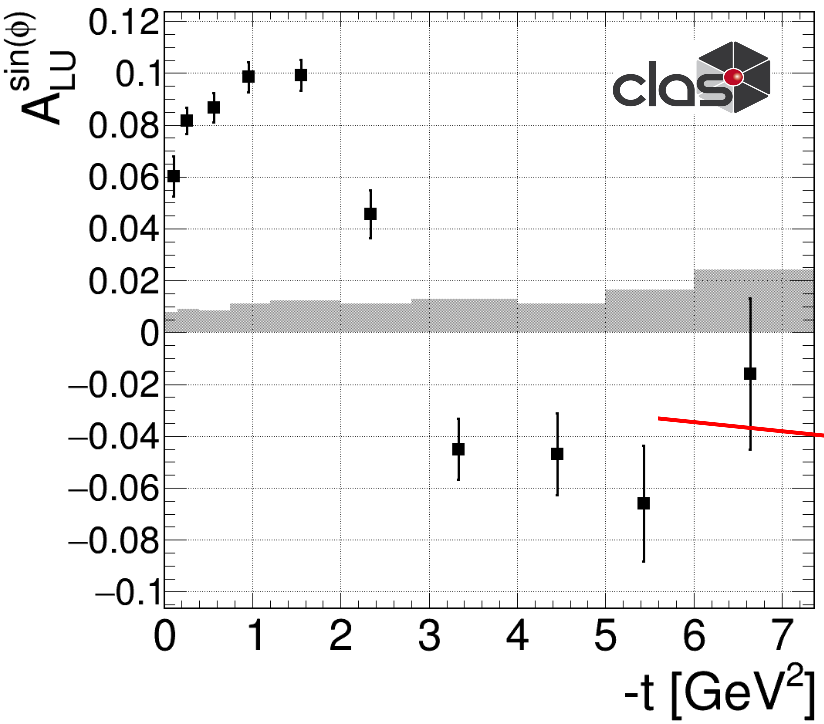
GK model

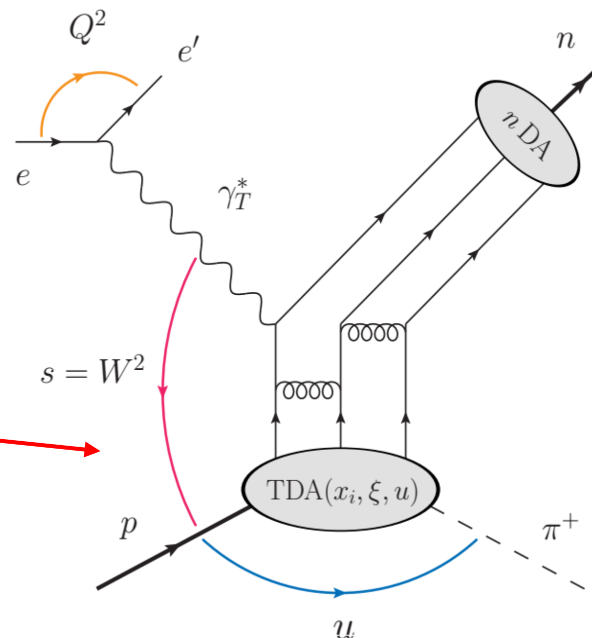
Additionally active work on η beam spin asymmetry and cross-section extraction

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

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

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

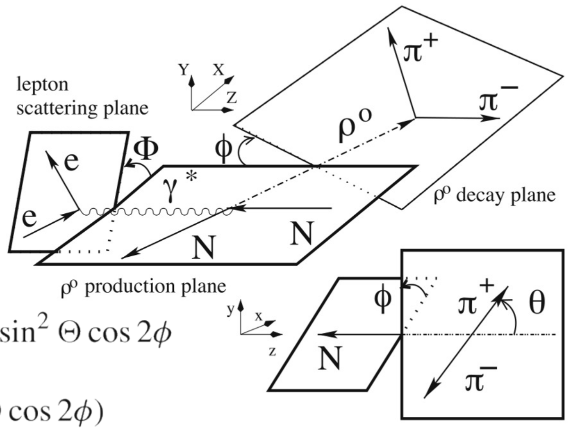




S. Diehl et al. (CLAS collaboration),
Phys. Rev. Lett. 125, 182001 (2020)

Vector meson production: Spin Density Matrix Elements (SDME)

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



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

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

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

Vector meson production: Spin Density Matrix Elements (SDME)

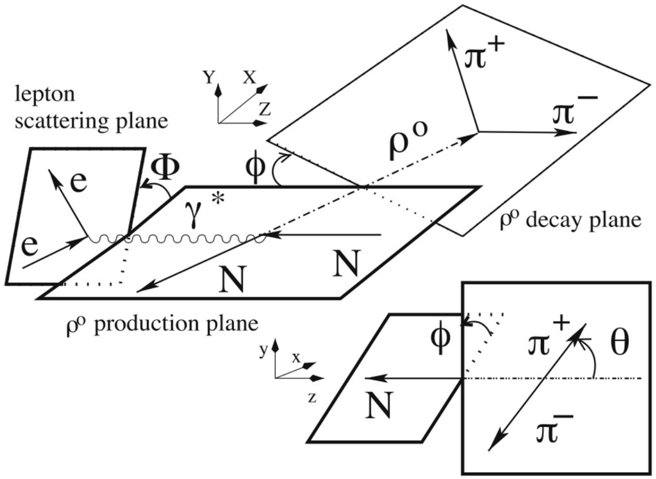
$$\frac{d\sigma}{d\phi\ d\Phi\ d\Theta\ dQ^2\ dx_B\ dt} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left\{\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right\}\mathcal{W}^{U+L}(\Phi, \phi, \cos\Theta)$$

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

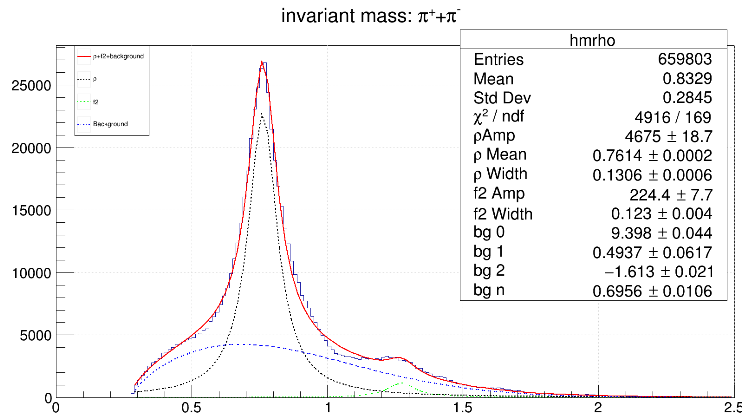
$$r^1_{00}\sigma_0 \sim \left|\bar{E}_T\right|^2$$

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

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

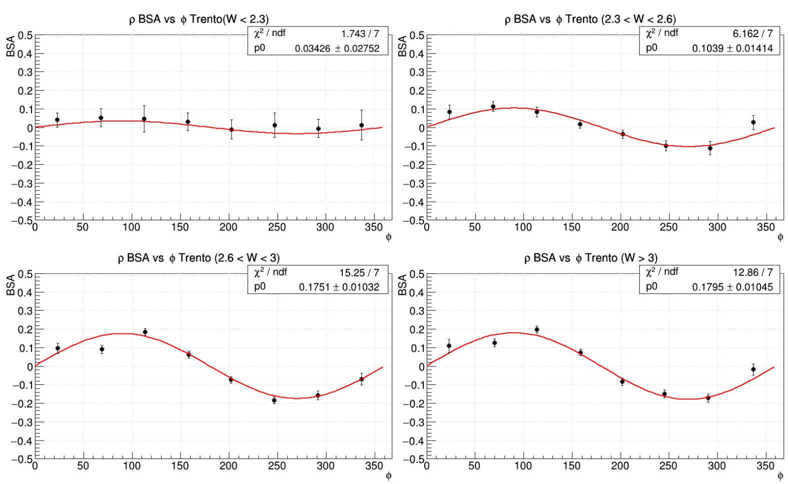


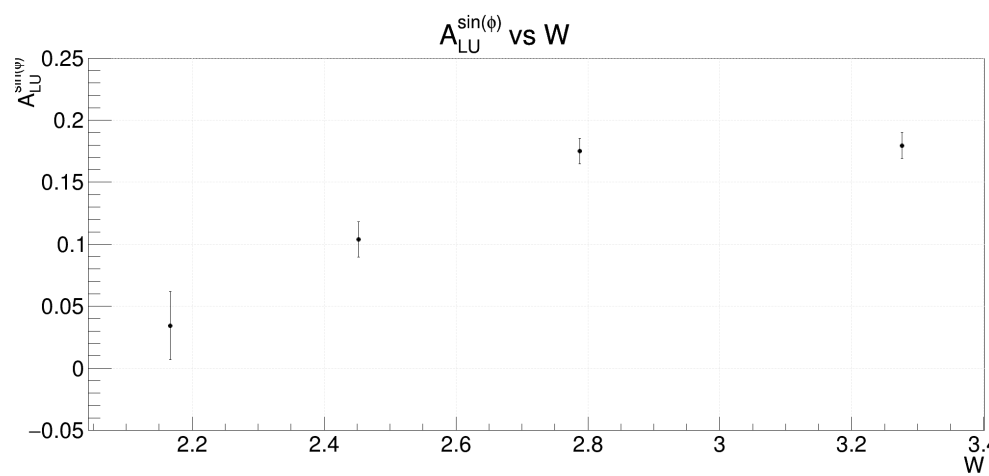
Exclusive ρ production with CLAS12



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

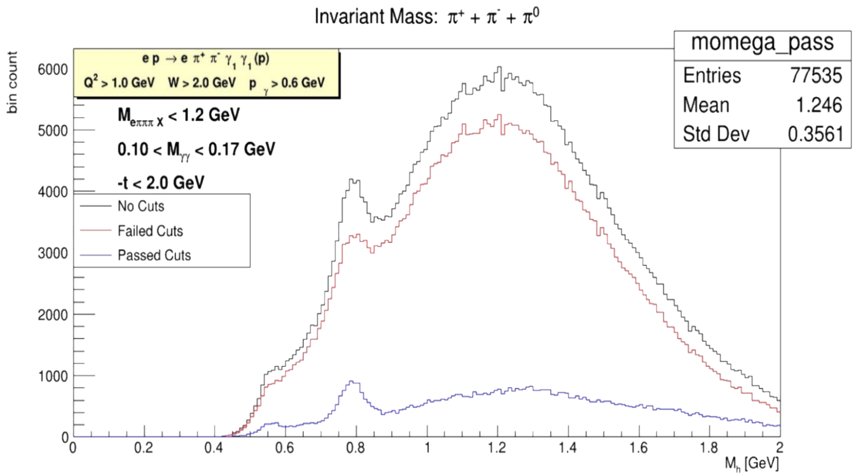
$$BSA = \frac{A_{LU}^{\sin\phi}\sin\phi}{1 + A_{UU}^{\cos\phi}\cos\phi + A_{UU}^{\cos(2\phi)}\cos(2\phi)}$$

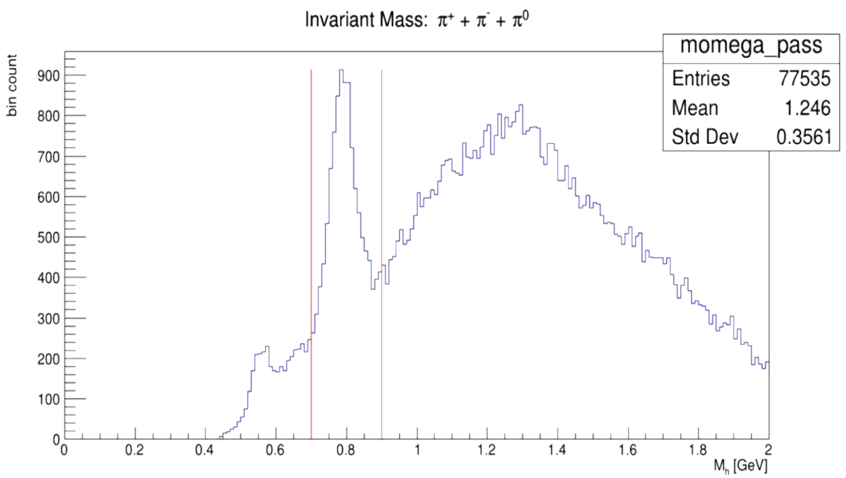


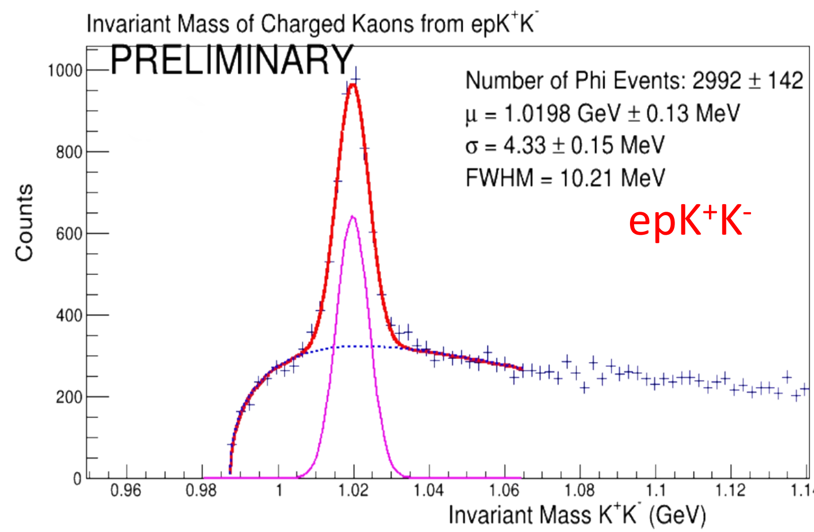


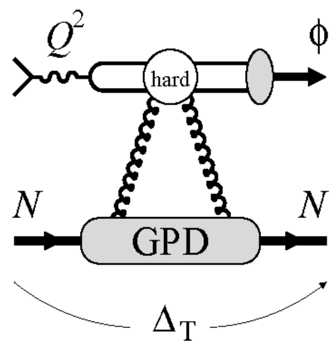
$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

Exclusive ω, ϕ production with CLAS12









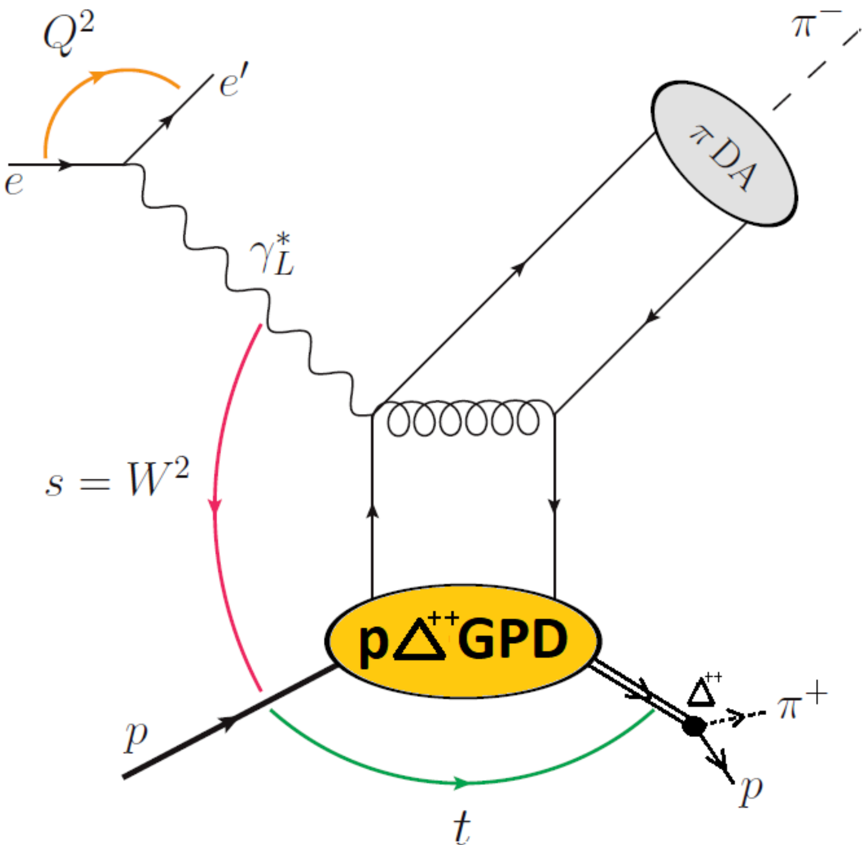
Exclusive Φ production probes gluon GPDs

Transverse spatial distribution of gluons

x < 0.01 measured at HERA, FNAL

x > 0.1 practically unknown

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



Factorization expected for:

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

x_B fixed

➔ Provides access to p-Δ transition GPDs

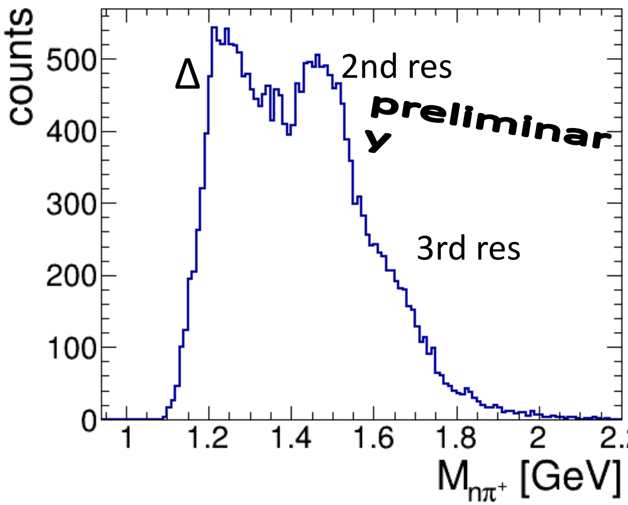
➔ 3D structure of the Δ resonance and of the excitation process

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

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

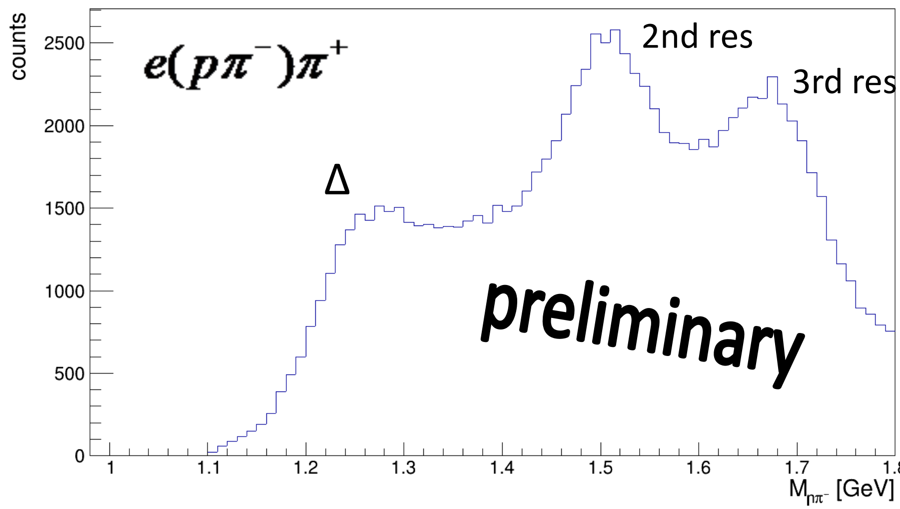
non-diagonal DVCS

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



other non-diagonal DVMP channels

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



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

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

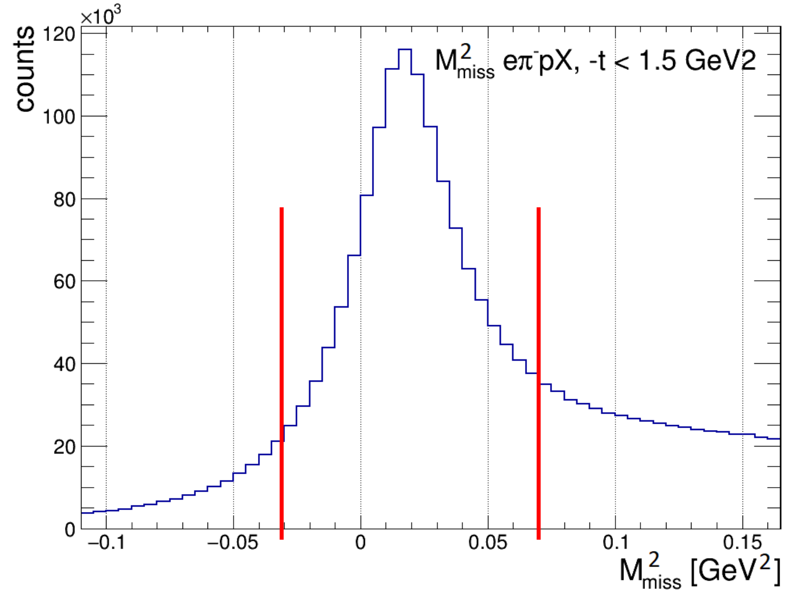
- Large gap between Δ(1232) and higher resonances

Event Selection and Kinematic Cuts

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

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

- 2 σ cut around the missing π^+

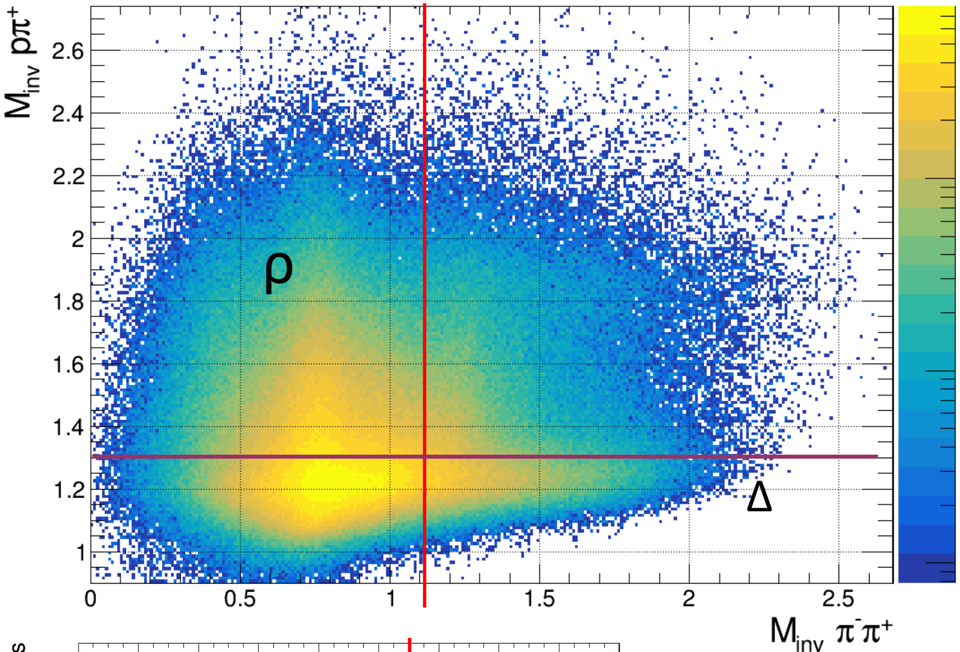


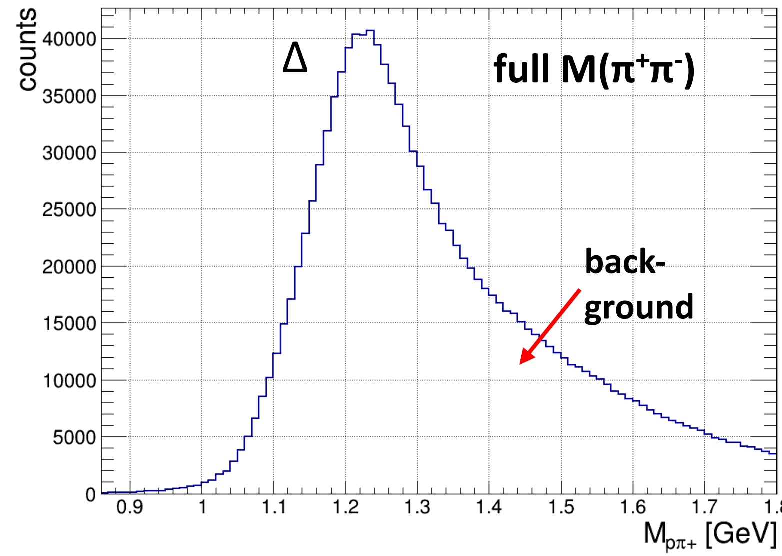
Kinematic cuts:

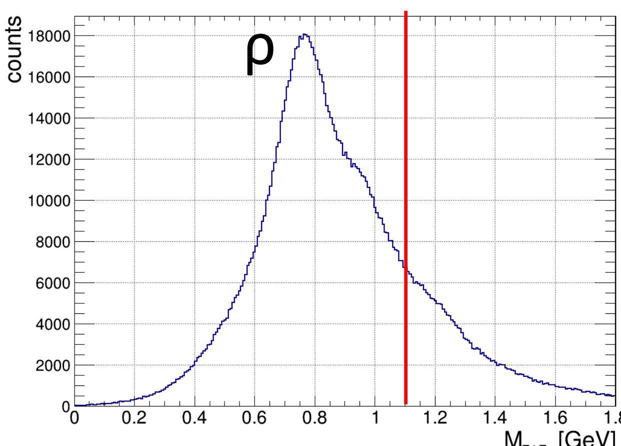
$Q^2 > 1.5$ GeV^2 W > 2 GeV y < 0.75

-t < 1.5 GeV^2 (only the forward region)

Event Selection and Background Rejection





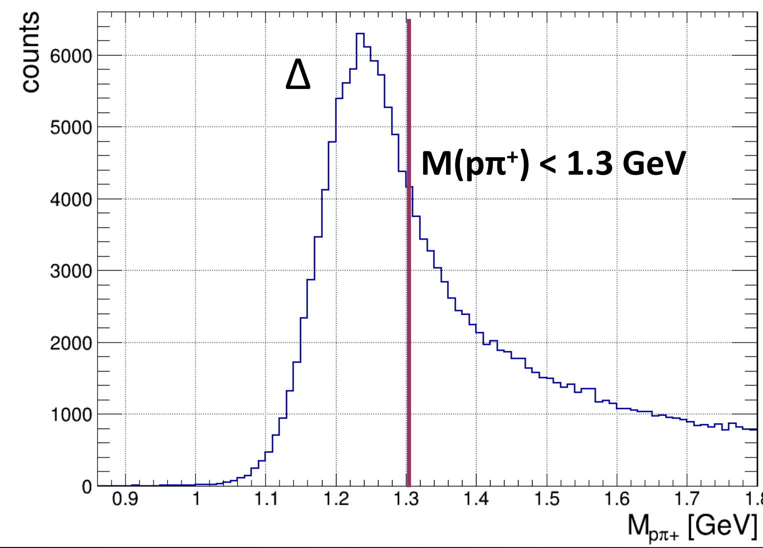


$$ep \to ep\rho \to ep\pi^+\pi^-$$

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

ρ contamination

< 0.8 %



Monte Carlo Simulations

2 MC samples have been used:

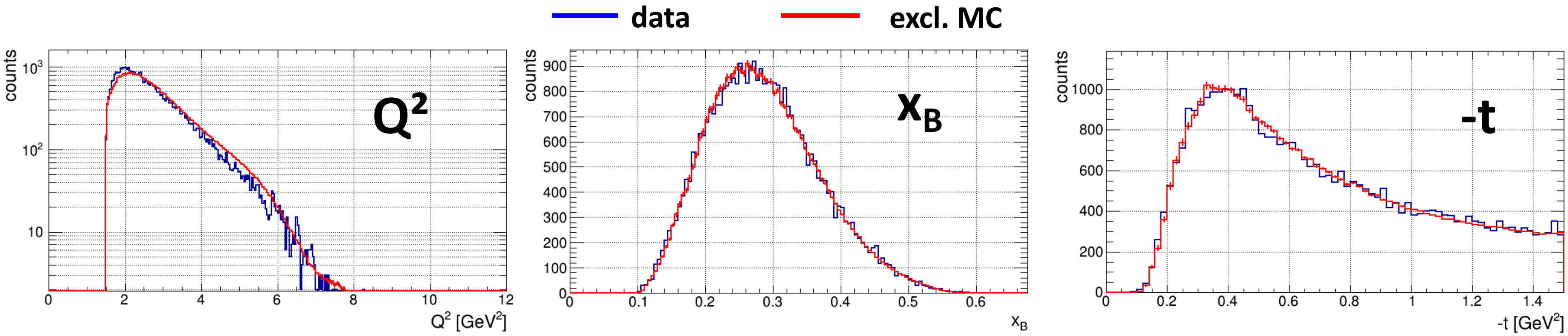
a) Semi-inclusive DIS MC

- 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

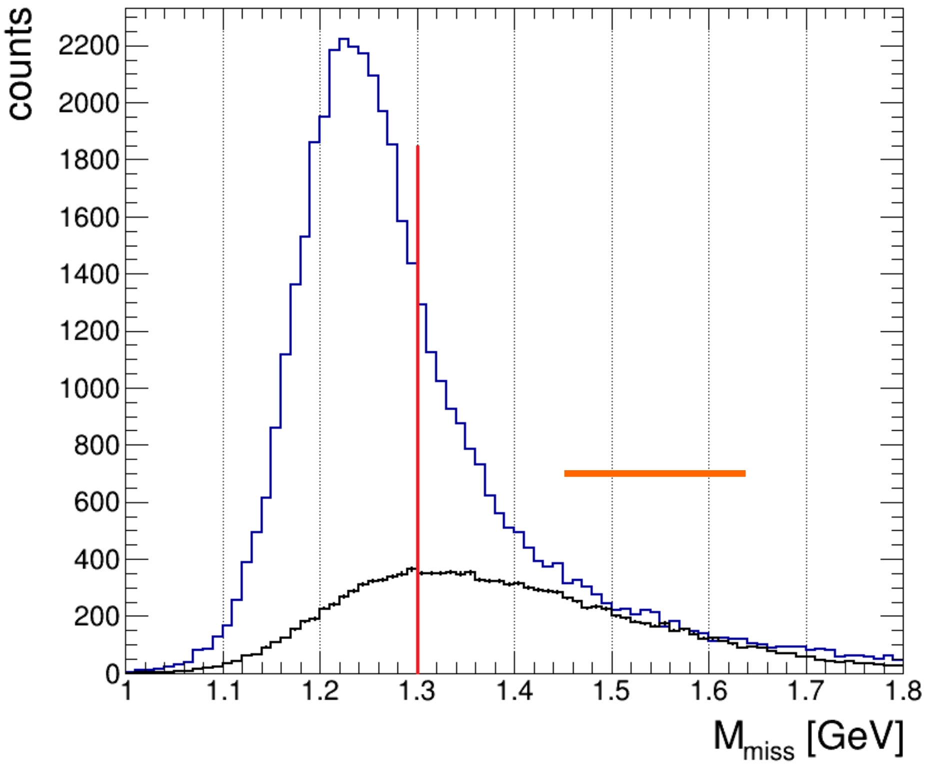
b) Exclusive $\pi^{-}\Delta^{++}$ MC

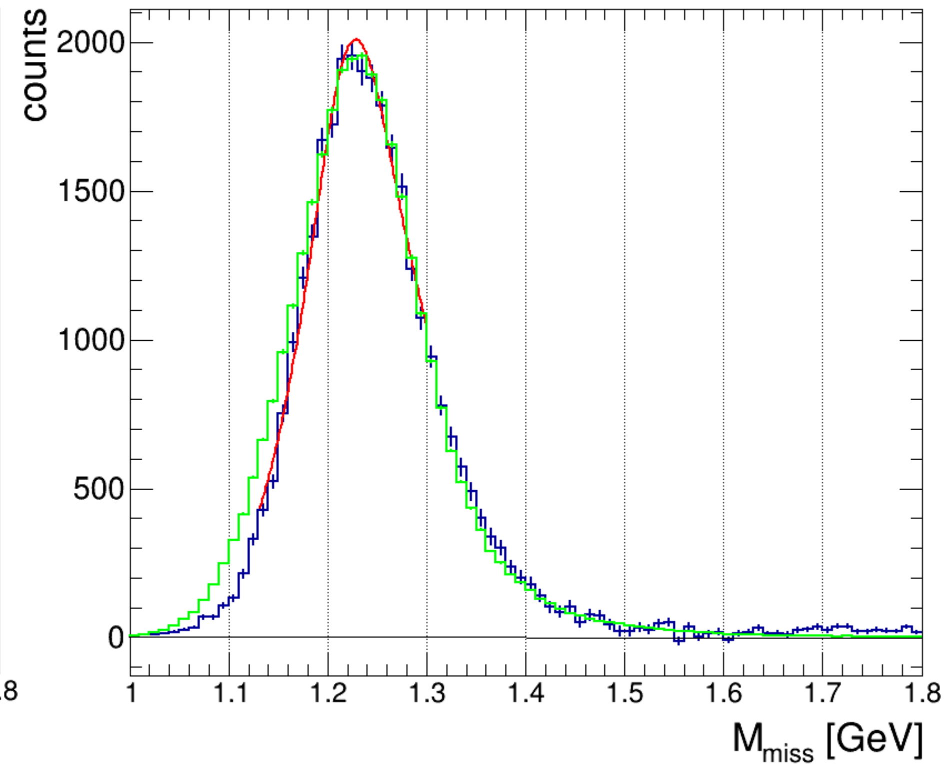
- Phase space simulation with a weigth added to match experimental data
- Δ peak with PDG mass and FWHM

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



Event Selection and Background Estimate





experimental data

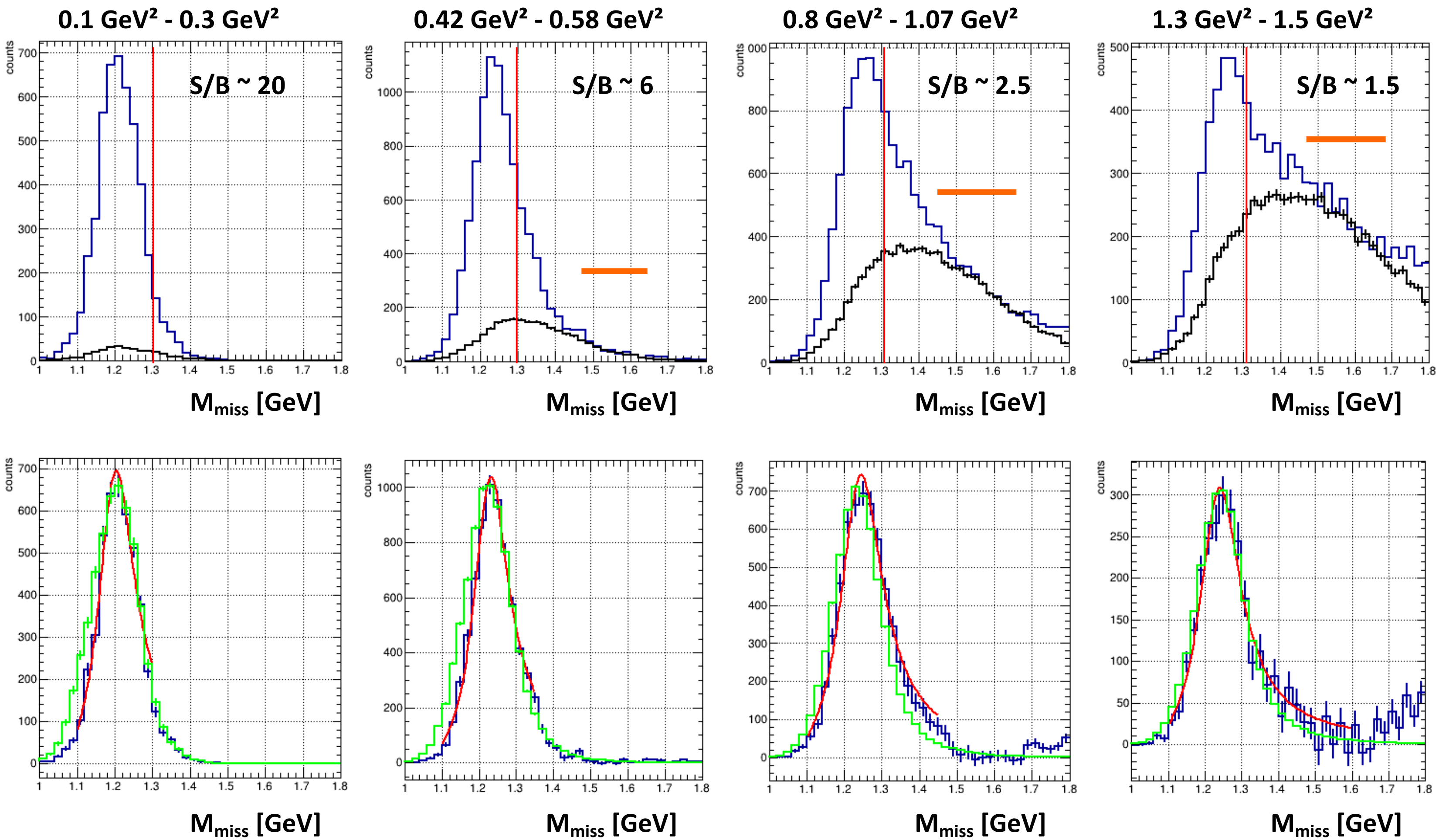
SIDIS MC (same cuts)

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

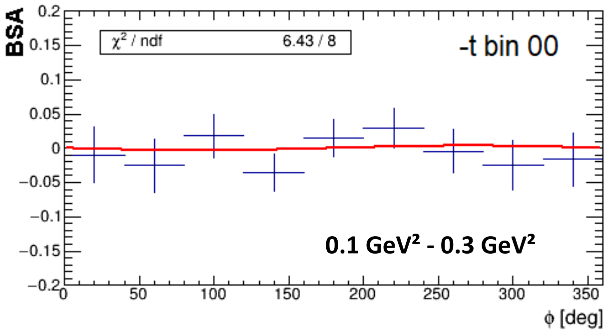
SIDIS MC (same cuts)

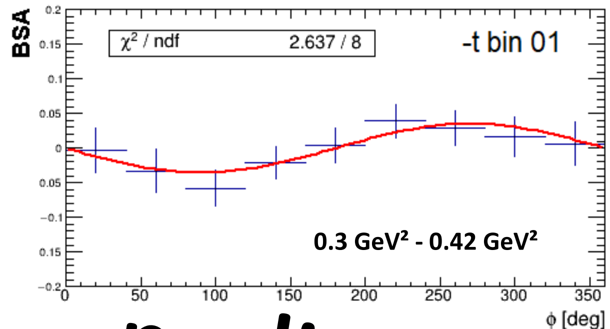
data after SIDIS MC subtraction

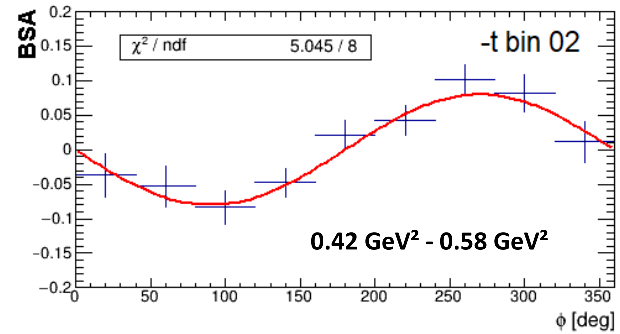
fit of a Sill function (BW with thr. effects)

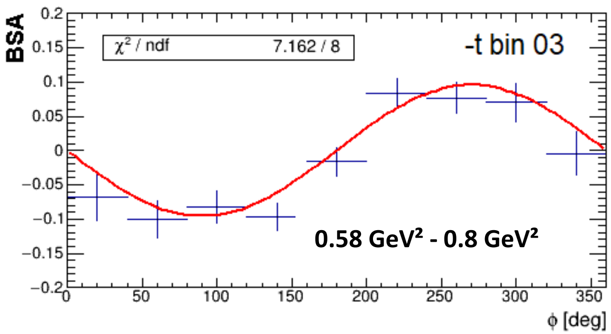
exclusive MC (for comparison)

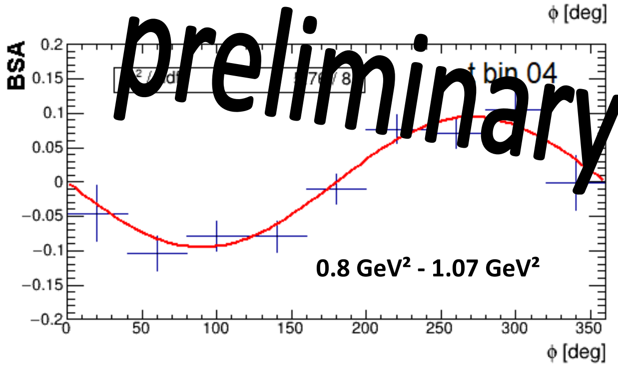
Resulting Beam Spin Asymmtries (Q^2-x_B integrated)

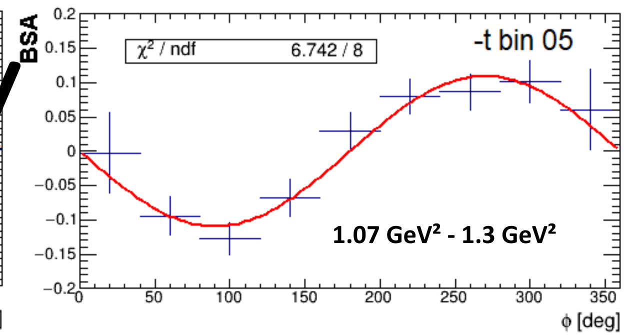


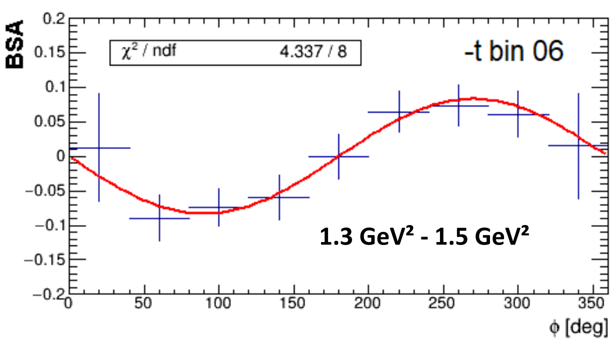












$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

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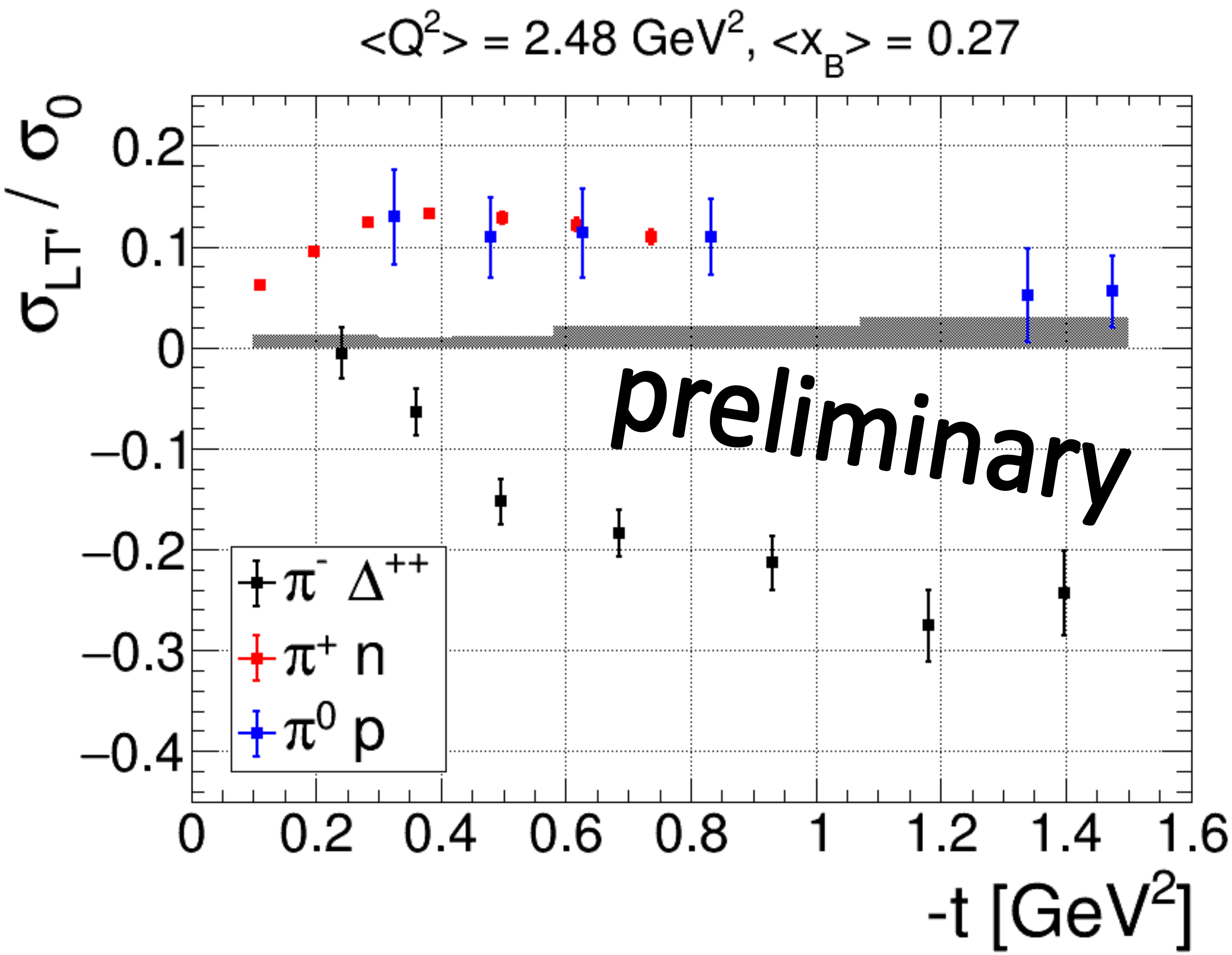
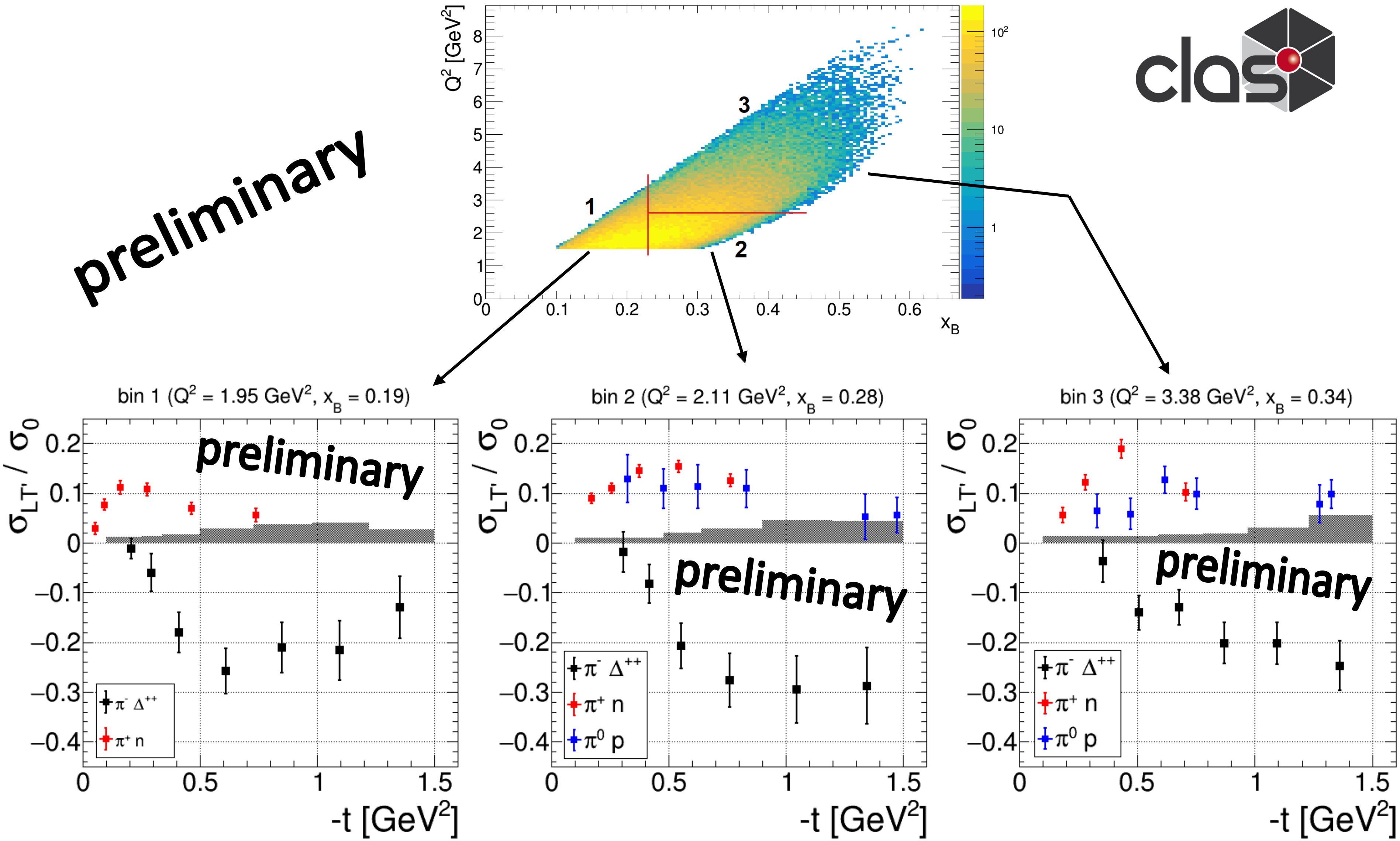
Q^2 - x_B Integrated Result



Different sources of systematic uncertainty have been studied:
beam polarisation, background subtraction, fiducial volume, extraction method, acceptance, bin migration, radiative effects

Multidimensional Results



Conclusion and Outlook

• CLAS12 has a comprehensive program in measuring hadr exclusive meson productions to access nucleon and transition GPDs.

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

• The obtained BSA is clearly negative and ~ 2 times larger than for the hard exclusive π^+ 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.

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Wish Kai Brinkmann a full and speedy recovery.

Background Subtraction

- Based on the obtained S/B ratio and based on the asymmetry of the sideband, the contribution of the non-resonant background has been subtracted.

- As a crosscheck, a bin-by-bin background subtraction has been performed with a fit of the signal and background function in each phi bin and for each helicity state.

 A good agreement of the two methods has been found.