ECT* workshop: Opportunities with JLab Energy and Luminosity Upgrade

September 26 - 30 2022, Trento

Exploring the 3D structure of nucleon resonances based on transition GPD measurements at JLAB and JLAB20+

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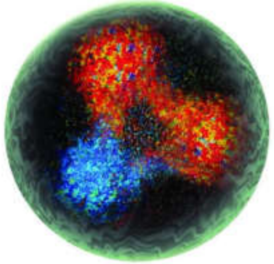
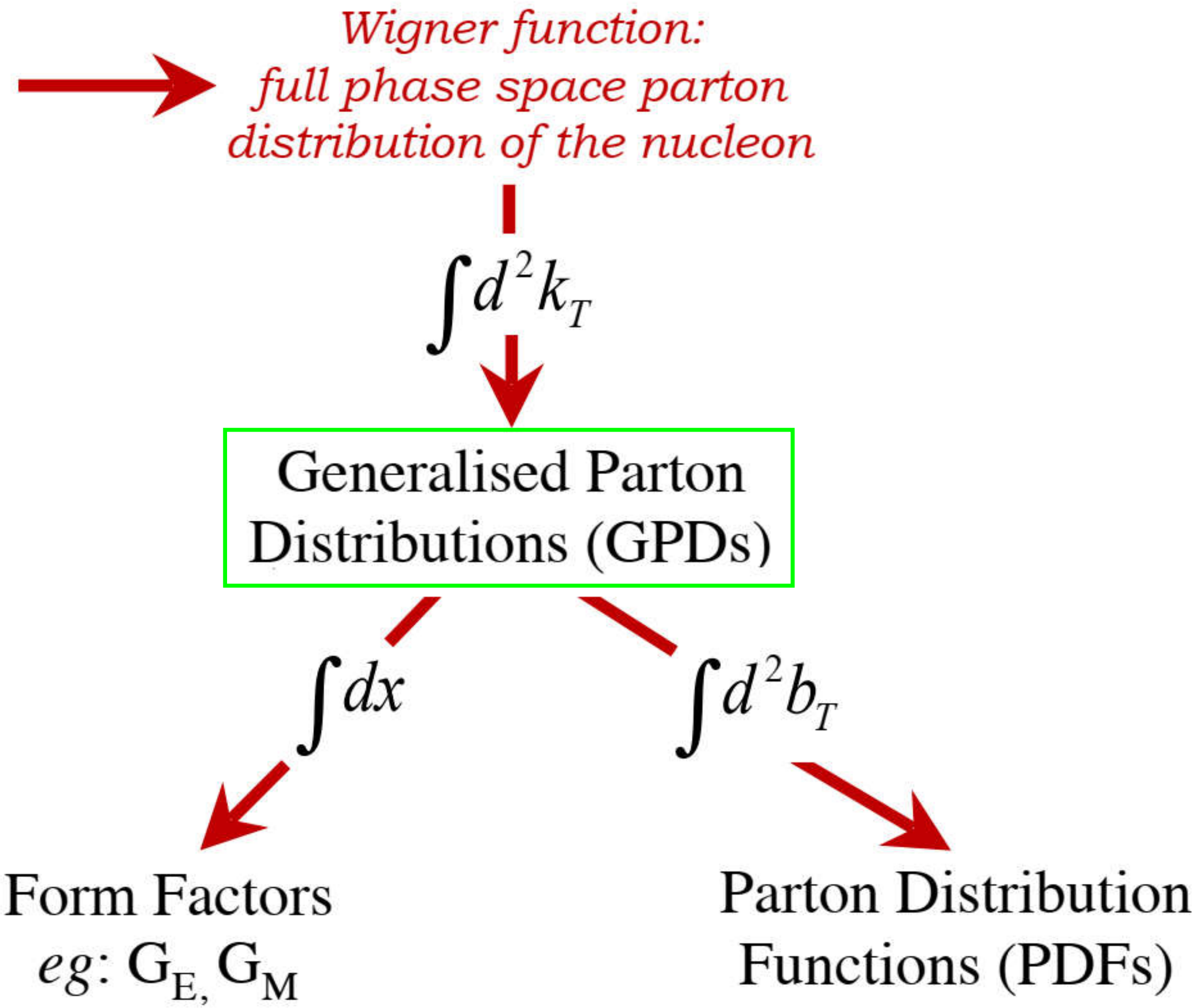
09/29/2022

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)

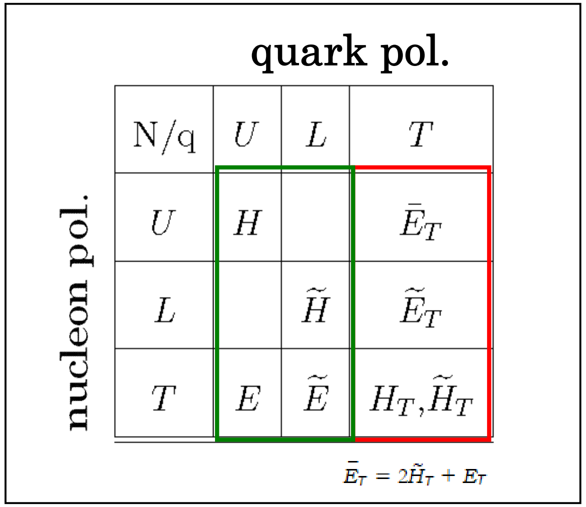
Generalized Parton Distributions (GPDs)

Generalized Parton Distributions (GPD)

↓

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

4 chiral even and 4 chiral odd GPDs



quark pol.

nucleon pol.

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

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

- Indirect access to mechanical properties of the nucleon

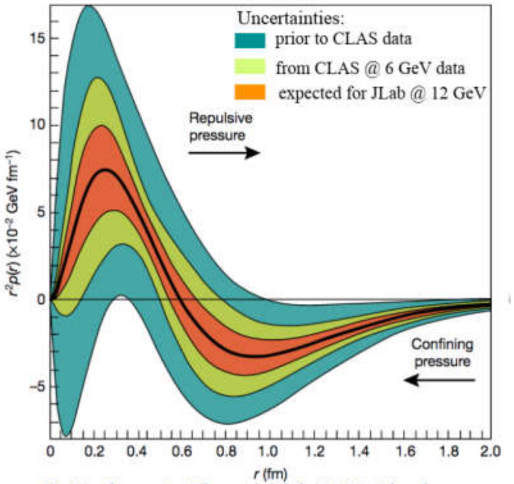
$$\int xH(x,\xi,t)\mathrm{d}x = \underset{\text{mass}}{M_2(t)} + \frac{4}{5}\xi^2 d_1(t) \leftarrow \text{pressure and shear forces}$$

- Additional physics content encoded in chiral odd GPDs

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

$\bar{E}_T$ is related to the protons anomalous tensor magnetic moment

H_T is related to the protons tensor charge

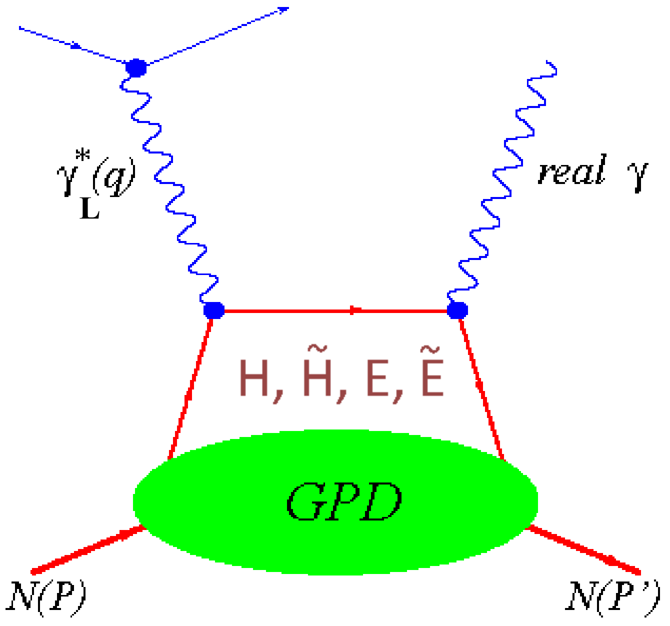


V. Burkert, L. Elouadrhiri, F.-X. Girod, Nature **557**, 396-399 (2018)

K. Kumerički, Nature **570**, E1-E2 (2019)

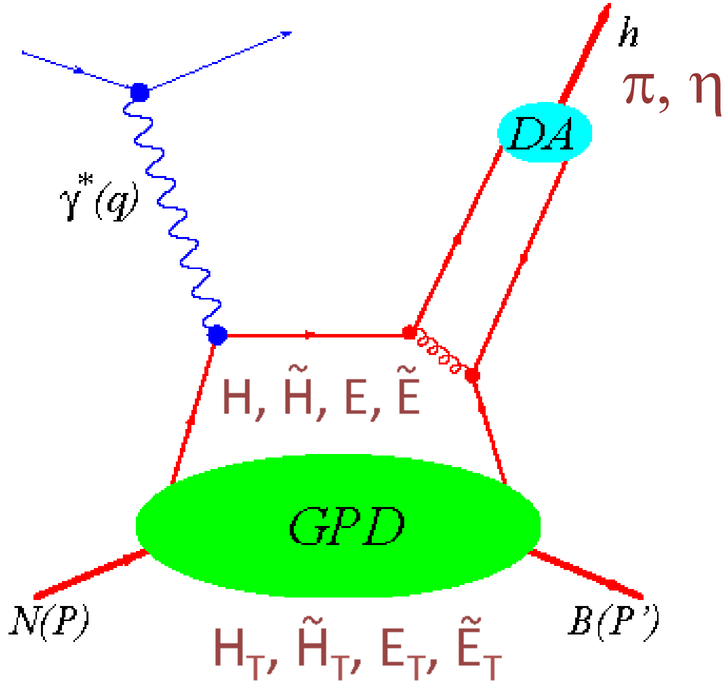
Study GPDs: Deeply Virtual Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



- + Clean process
- - Only sensitive to chiral even GPDs

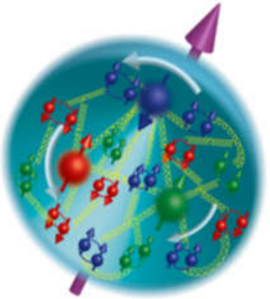
Deeply Virtual Meson Production (DVMP)

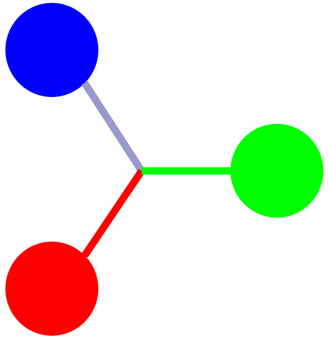


- + Enables Flavour decomposition of GPDs
- + Access to transversity degrees of freedom described by chiral-odd GPDs

From the ground state nucleon to resonances

Ground state nucleon:
(proton, neutron)

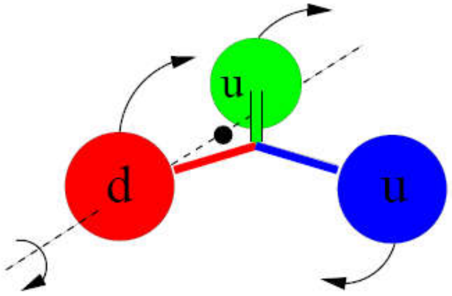


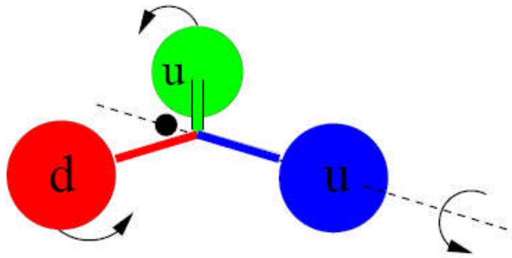


Nucleon resonances:

- Orbital excitations

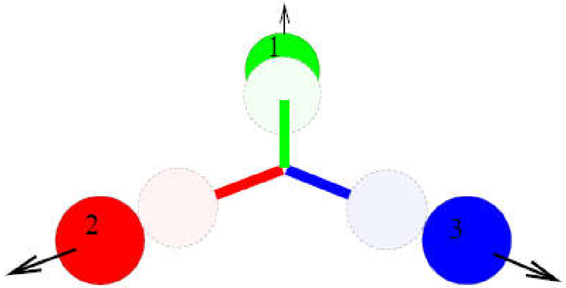
i.e N(1535)

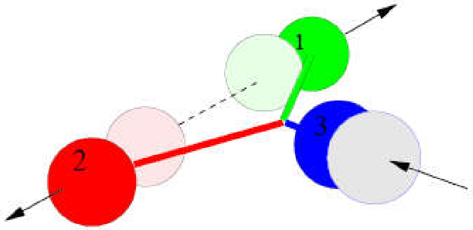




- Radial excitations

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

Simplest case: N→Δ transition ➔ **16 transition GPDs**

- **8 helicity non-flip transition GPDs (twist 2)**
- **8 helicity flip transition GPDs (twist 3)**

Transition GPDs in the twist-2 sector

N→Δ transition: 8 twist-2 helicity non-flip transition GPDs

unpolarized:

$$\int_{-1}^{1} dx H_M(x;\xi;t) = 2G_M^*(t)$$

$$\int_{-1}^{1} dx H_E(x;\xi;t) = 2G_E^*(t)$$

$$\int_{-1}^{1} dx H_C(x;\xi;t) = 2G_C^*(t)$$

$$\int_{-1}^{1} dx H_4(x;\xi;t) = 0$$

Jones-Scardon EM FF for the N → transition

polarized:

$$\int_{-1}^{1} dx C_1(x;\xi;t) = 2C_5^A(t)$$

$$\int_{-1}^{1} dx C_2(x;\xi;t) = 2C_6^A(t)$$

$$\int_{-1}^{1} dx C_3(x;\xi;t) = 2C_3^A(t)$$

$$\int_{-1}^{1} dx C_4(x;\xi;t) = 2C_4^A(t)$$

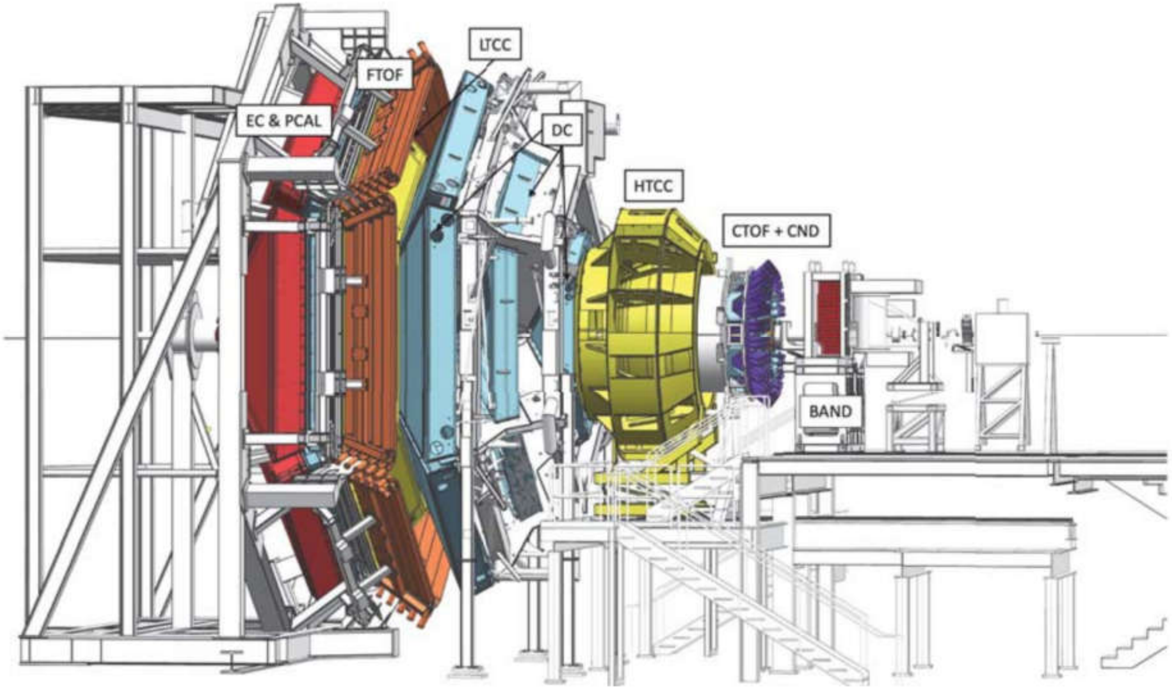
Adler form factors

→ 3 of them are dominating in the large N_C limit

→ Connection to proton-proton GPDs via symmetry considerations

→ Description of leading twist effects / longitudinal virtual photons

CLAS12 Experimental Setup in Hall B at JLAB



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

➔ Data of this talk was recorded with CLAS12 during fall 2018 and spring 2019

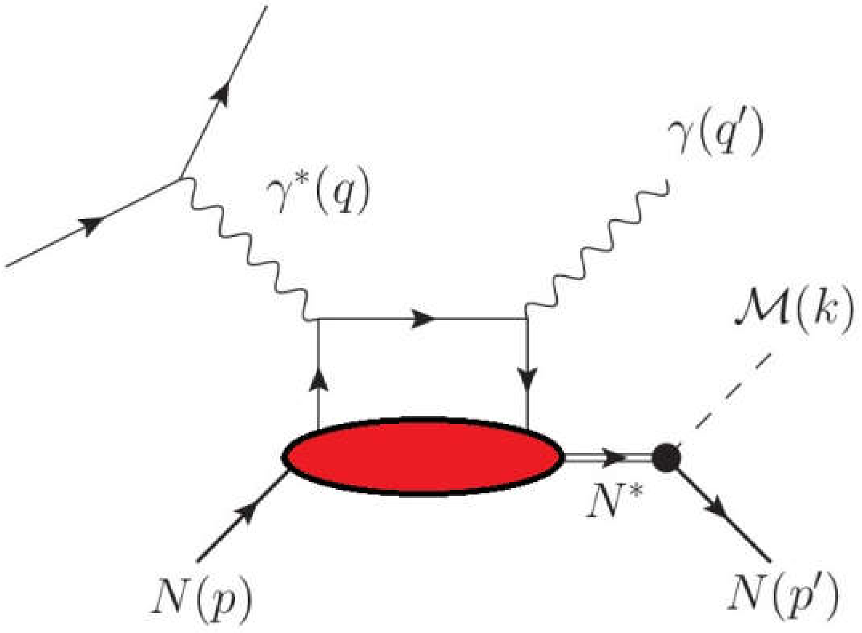
➔ 10.6 / 10.2 GeV e^- beam ➔ ~87 % average polarization ➔ liquid H_2 target

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

Experimental Access to Transition GPDs (twist 2)

Experimental access: Non diagonal DVCS process

$$\gamma * p \to N * \gamma \to N \ meson \ \gamma$$



factorisation for: $-t/Q^2$ small, x_B fixed

Two final states have been studied:

$$\gamma * p \to N^* \gamma \to p\pi^0\gamma \to p\gamma\gamma\gamma$$

$$\gamma * p \to N^* \gamma \to n\pi^+\gamma$$

➔ Exclusivity cuts were applied for event selection

➔ Kinematic cuts:

W > 2 GeV $Q^2 > 1$ GeV²   y < 0.8

-t < 2 GeV² $E_{\gamma\text{-DVCS}} > 2$ GeV

First Theoretical Description of the Δ Region

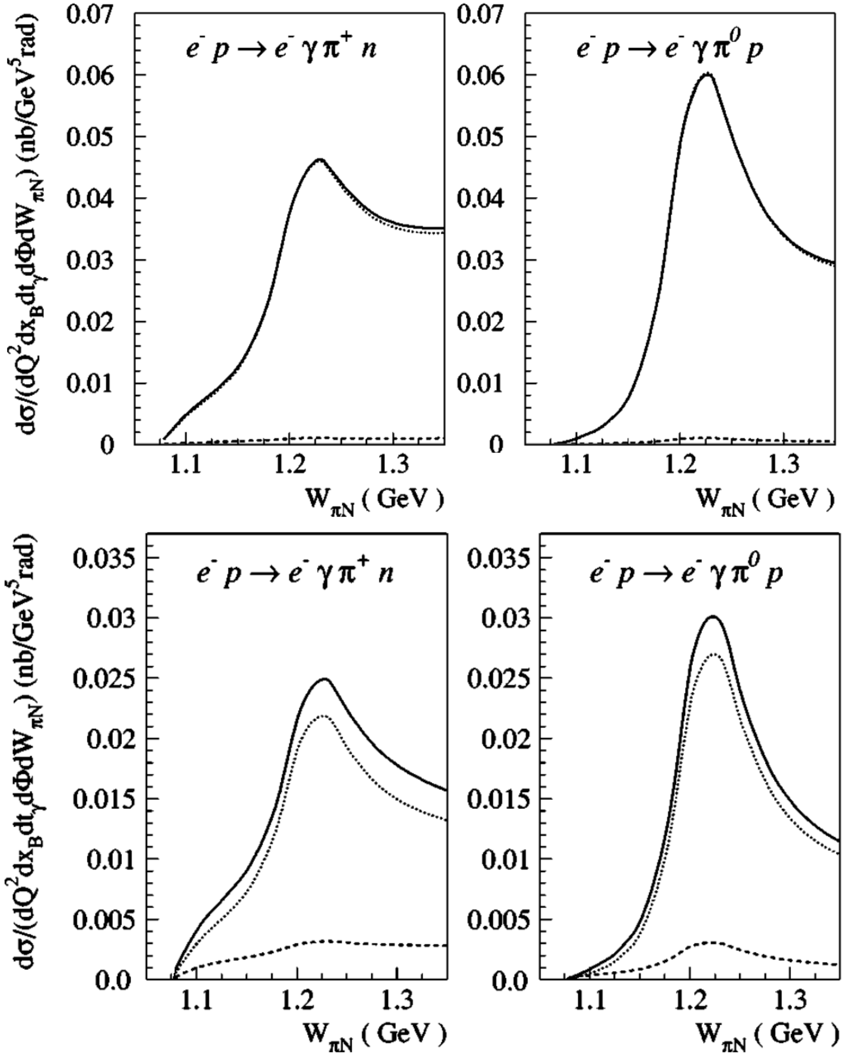
P. A. M Guichon, L. Mosse, M. Vanderhaeghen, Phys. Rev. D68 (2003) 034018

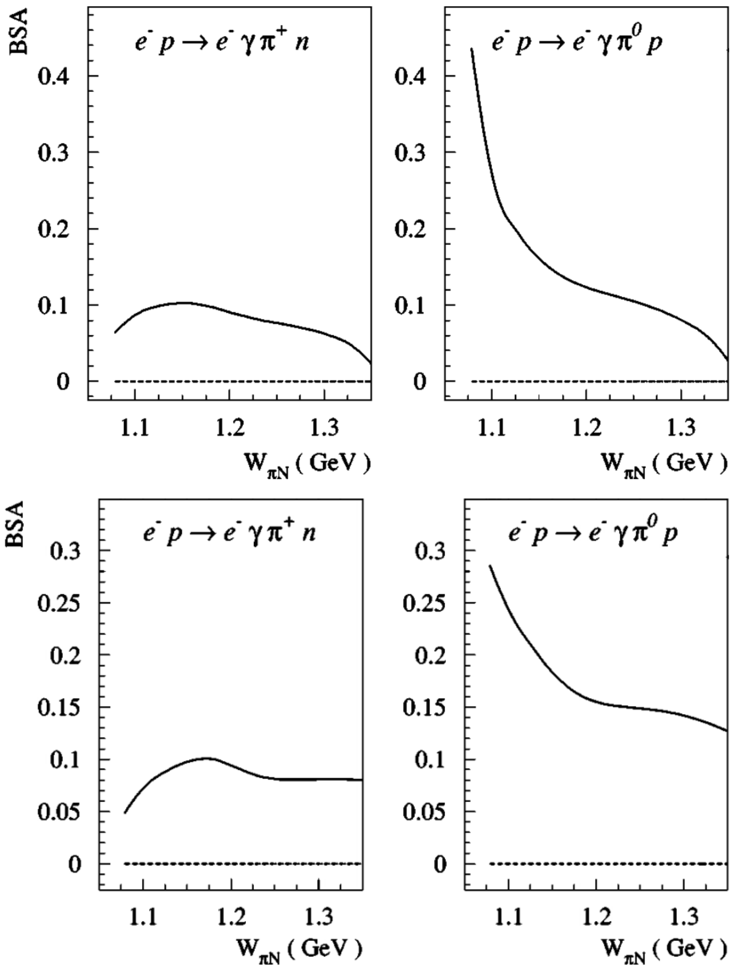
E_e = 6 GeV

Q^2 = 2.5 GeV
x_B = 0.3
t_γ = -0.5 GeV²

E_e = 27 GeV

Q^2 = 2.5 GeV
x_B = 0.15
t_γ = -0.25 GeV²





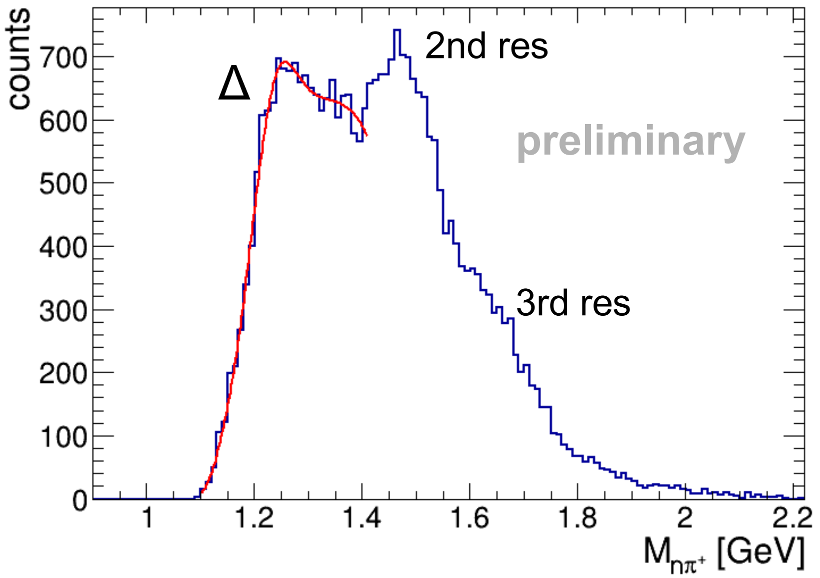
- - - Δ-DVCS .... BH

Resonance Mass Spectrum for $N^* \rightarrow n\pi^+$

$en\pi^+\gamma$

$\langle Q^2 \rangle$ = 2.3 GeV²

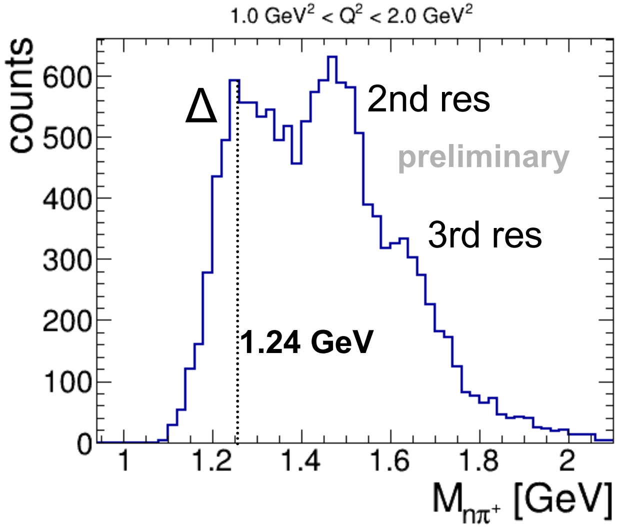
$\langle x_B \rangle$ = 0.25

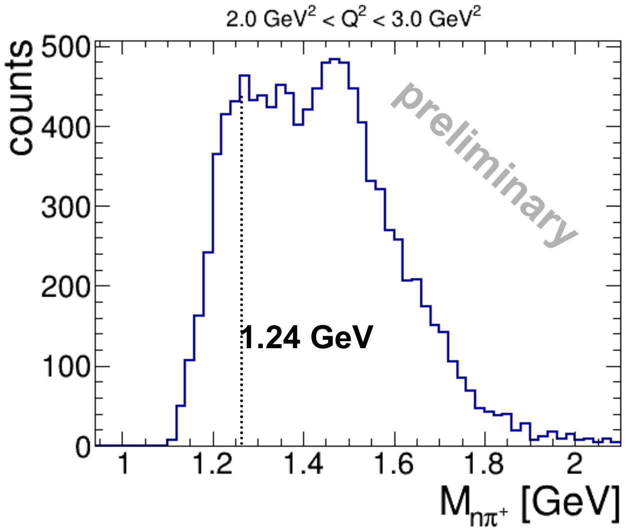


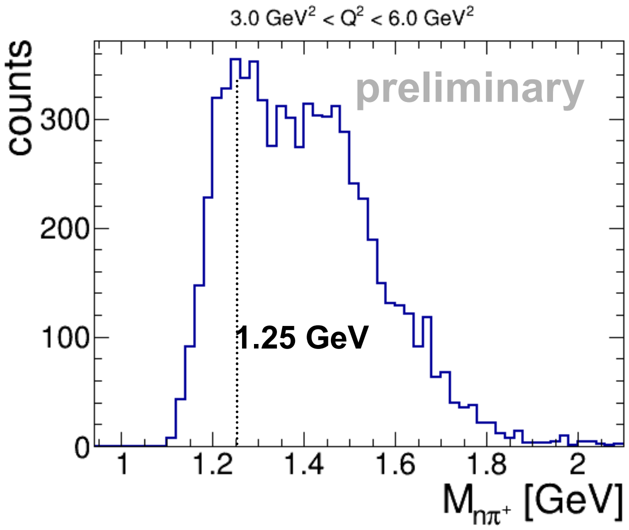
Δ-fit: Breit-Wigner
+ polyn. backgr.

μ = 1.235 GeV
Γ = 0.15 GeV

Q^2 dependence:



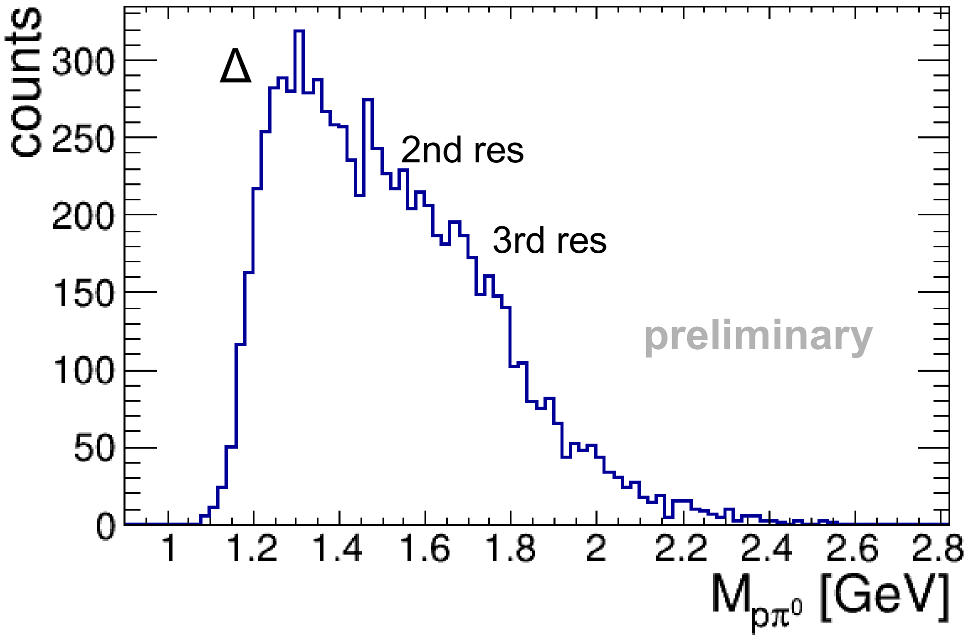




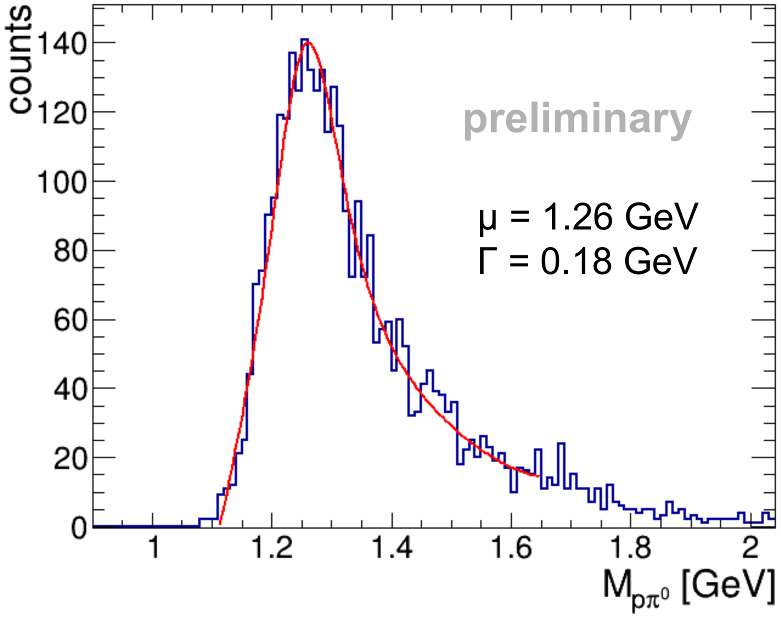
Resonance Mass Spectrum for $N^* \rightarrow p\pi^0$

$ep\pi^0\gamma$

full spectrum, no cuts



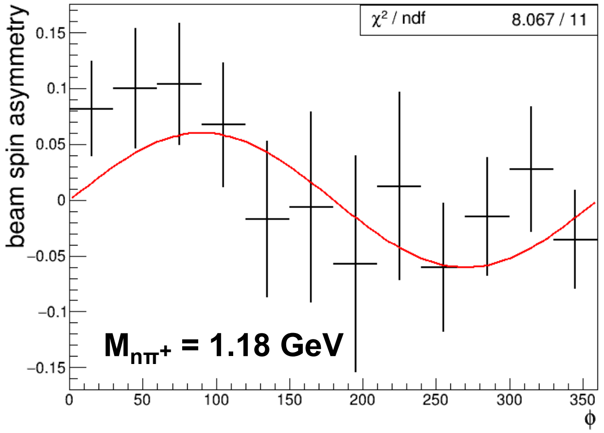
cut on the pion long. momentum fraction α



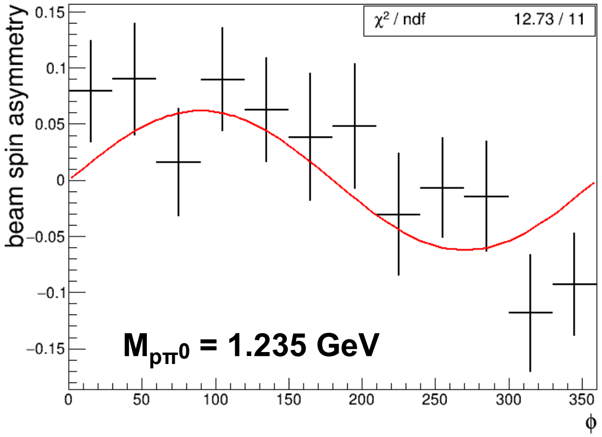
Raw Beam Spin Asymmetries

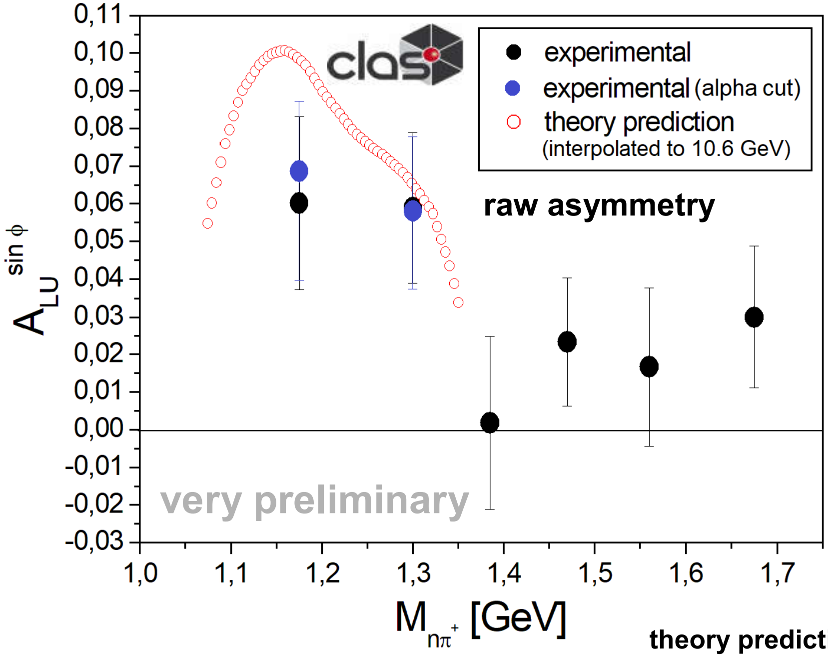
$$A = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-} \approx A_{LU}^{\sin\phi}\sin\phi$$

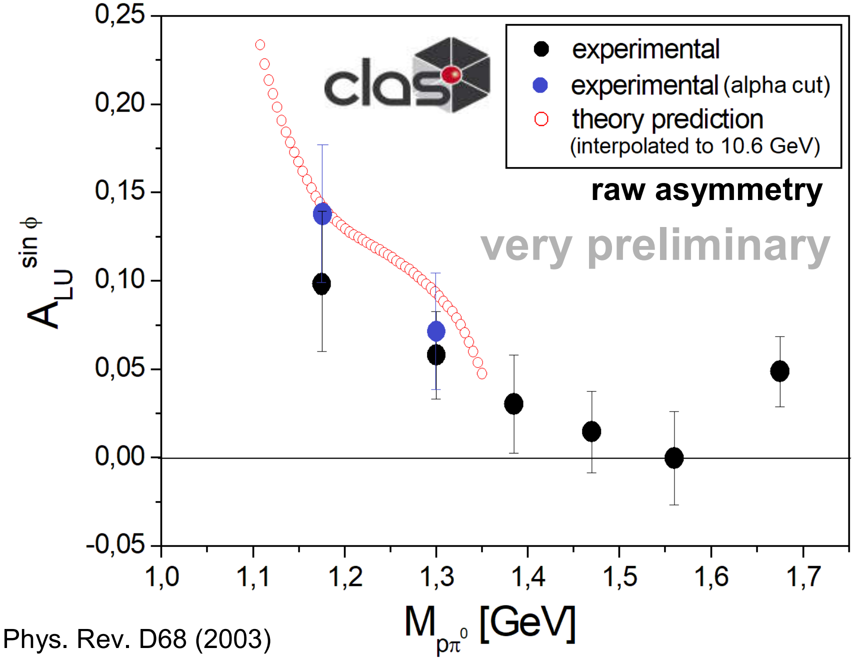
$en\pi^+\gamma$



$ep\pi^0\gamma$

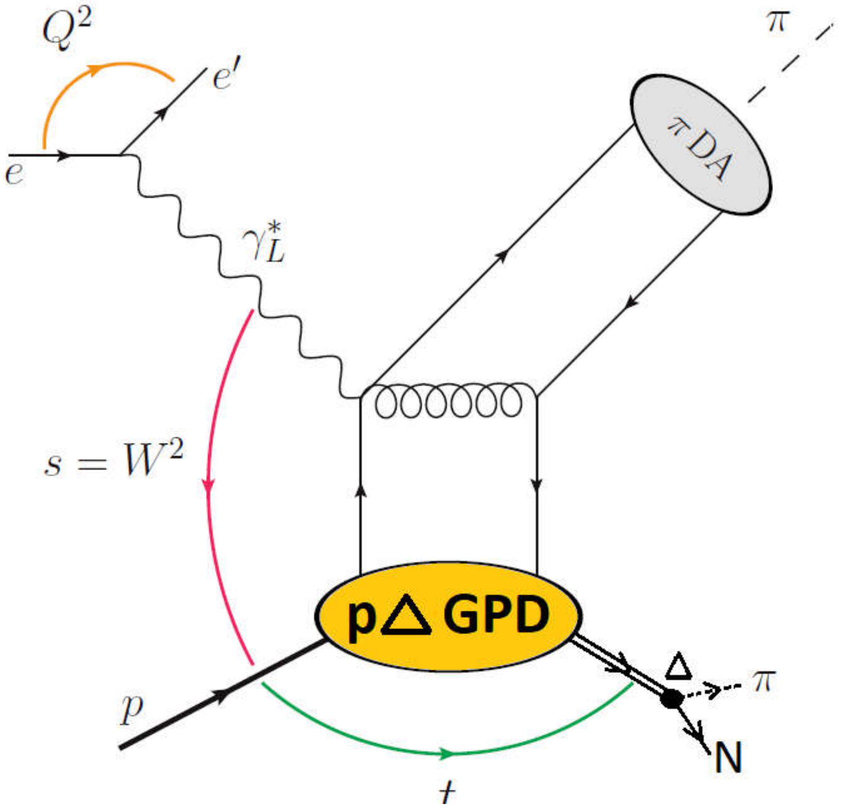






theory prediction: Phys. Rev. D68 (2003)

The non-diagonal DVMP processes



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

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

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

Factorisation expected for:

-t / Q² << 1 and $Q^2 > M_\Delta^2$, x_B fixed

8 helicity non-flip trans. GPDs

+

8 helicity flip trans. GPDs

→ Needed for twist-3 sector

→ No publications exist so far

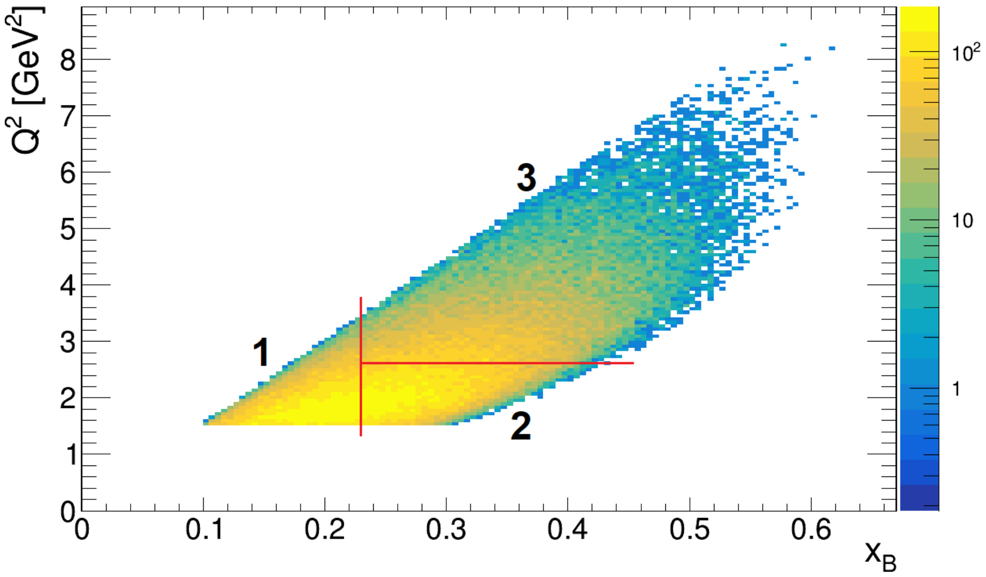
Hard exclusive $\pi^-\Delta^{++}$ production

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

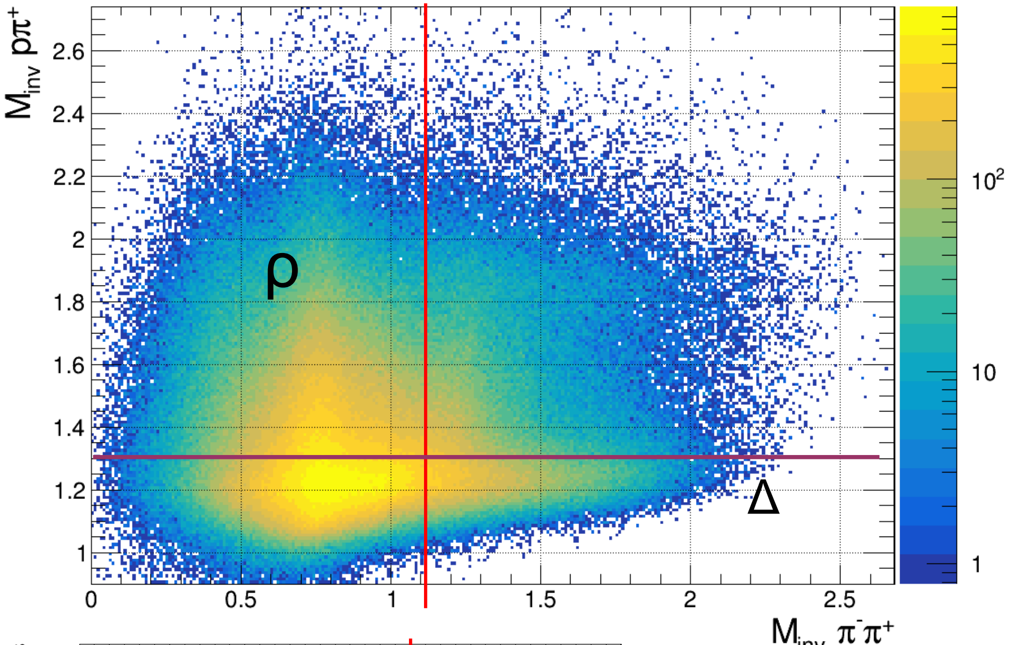
Kinematic cuts:

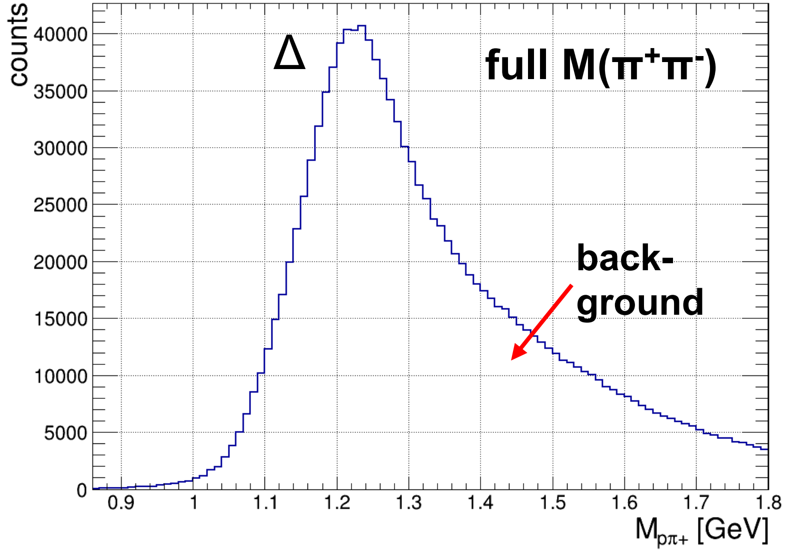
$Q^2 > 1.5$ GeV² W > 2 GeV $y < 0.75$

$-t < 1.5$ GeV² (forward region)

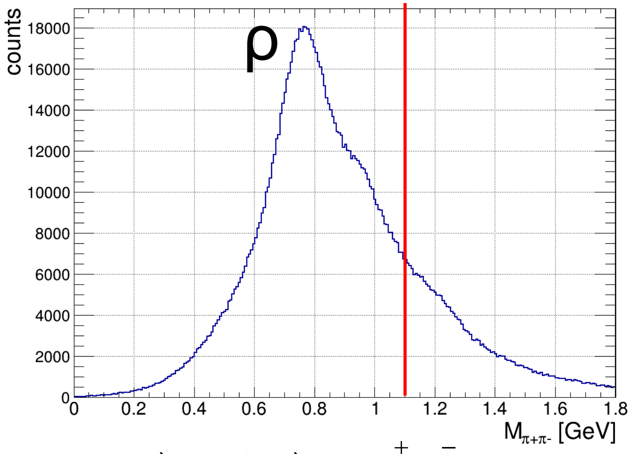


Event Selection and Background Rejection





full M($\pi^+\pi^-$)

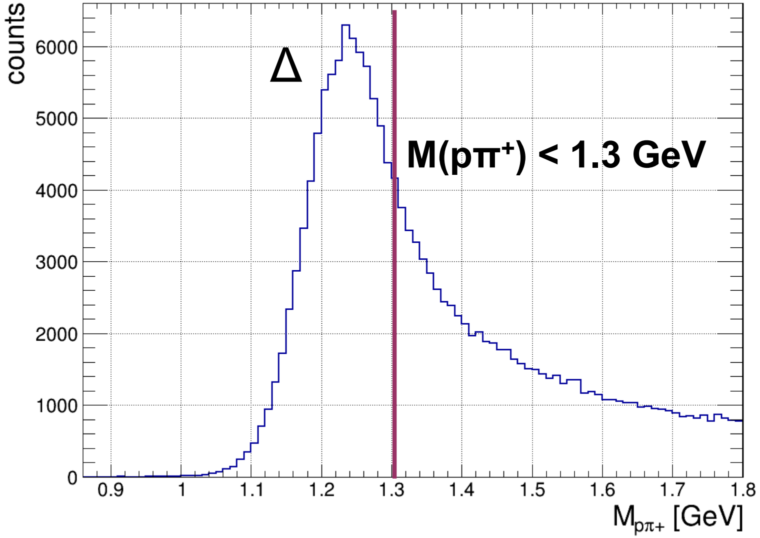


$ep \rightarrow ep\rho \rightarrow ep\pi^+\pi^-$

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

ρ contamination

< 0.8 %



M($p\pi^+$) < 1.3 GeV

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

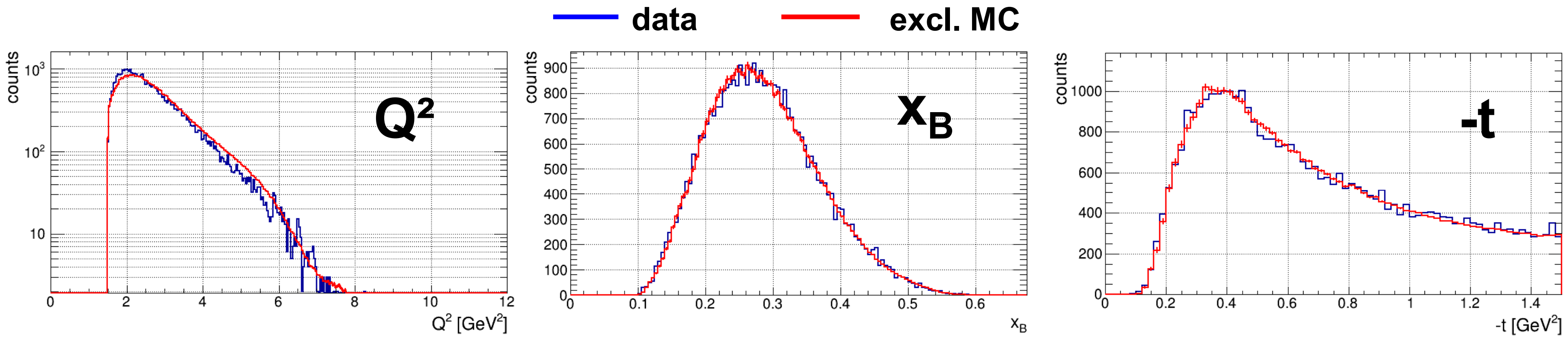
➔ Used to estimate background shape and contaminations

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

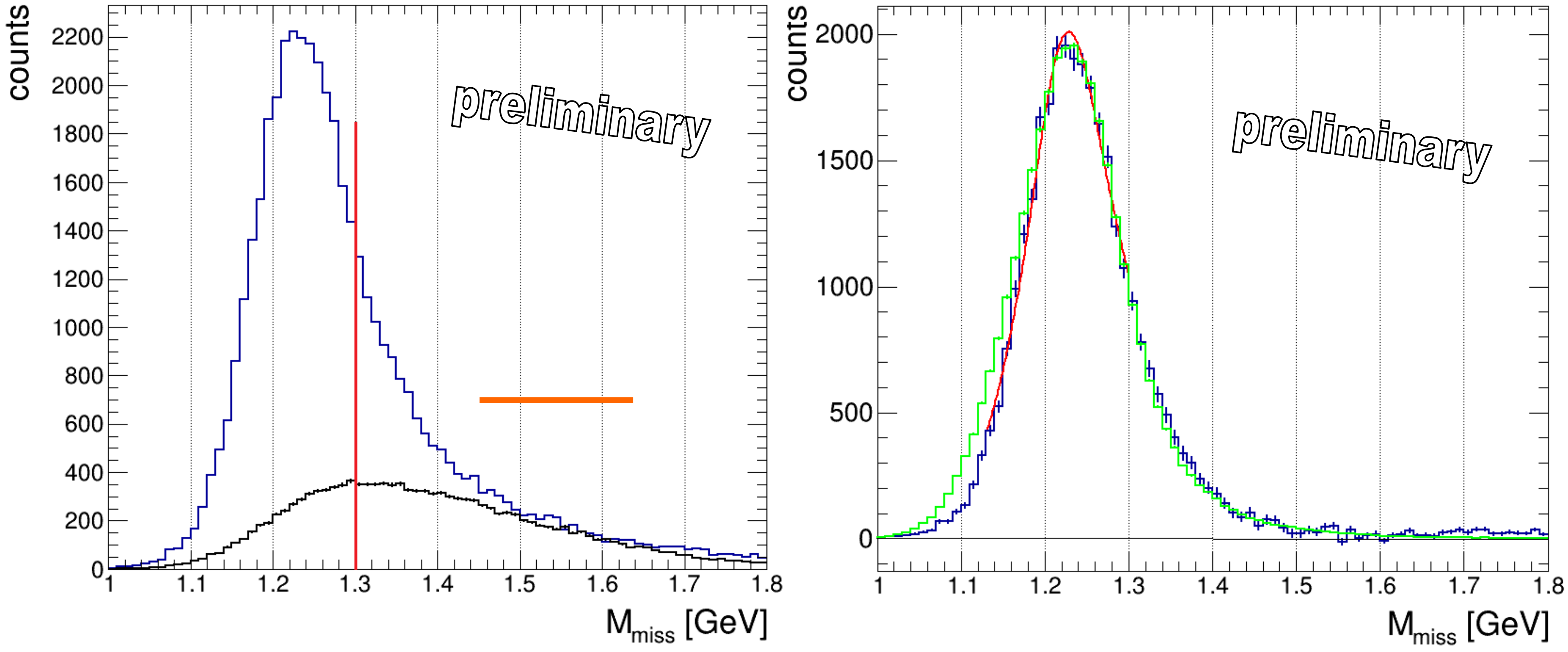
→ Phase space simulation with a weigth added to match experimental data

→ 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)

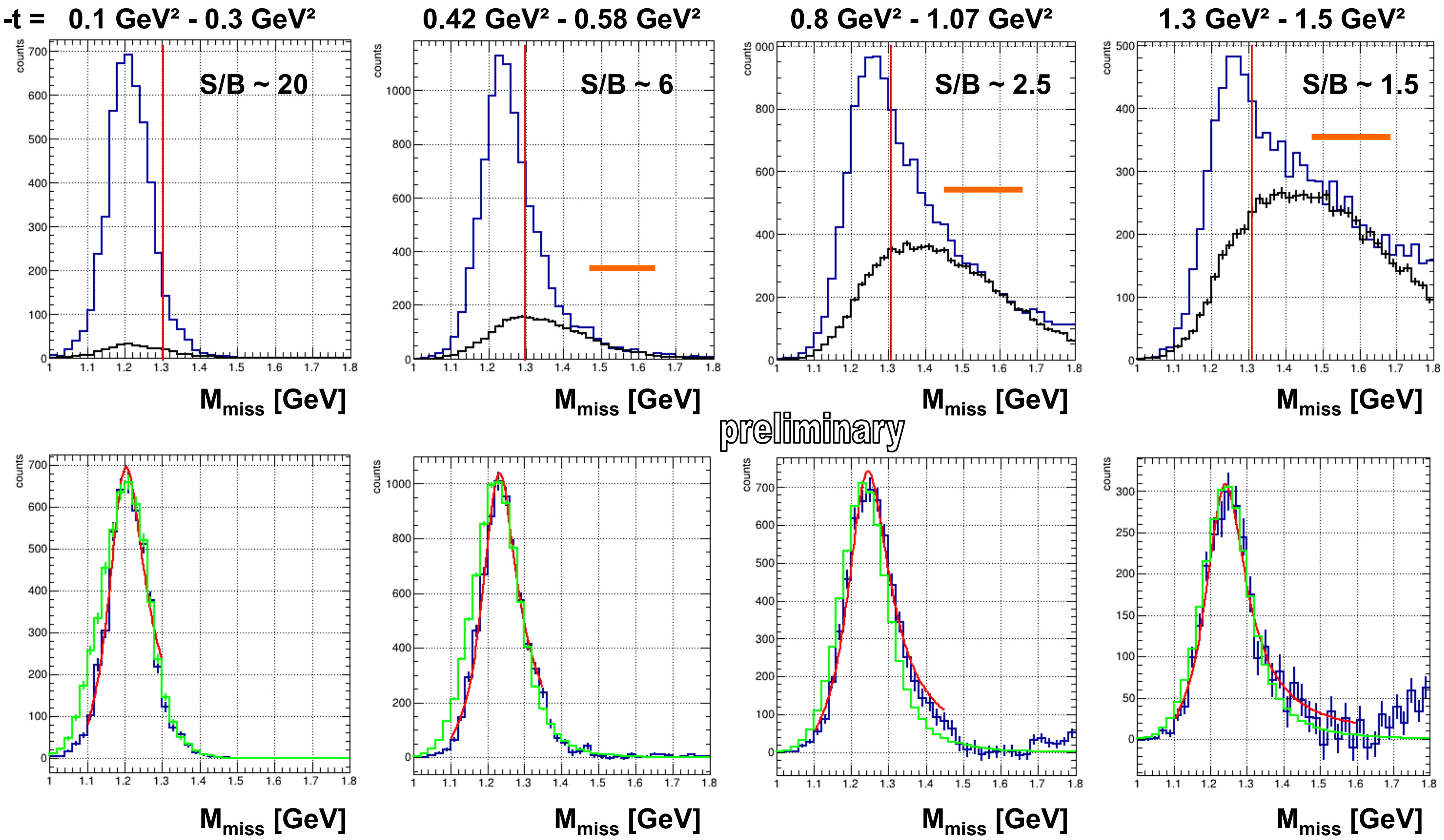
data after SIDIS MC subtraction

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

exclusive MC (for comparison)

Background: 98 – 99 % non-resonant events

Event Selection and Background Estimate



-t = 0.1 GeV² - 0.3 GeV²

0.42 GeV² - 0.58 GeV²

0.8 GeV² - 1.07 GeV²

1.3 GeV² - 1.5 GeV²

experimental data

SIDIS MC (same cuts)

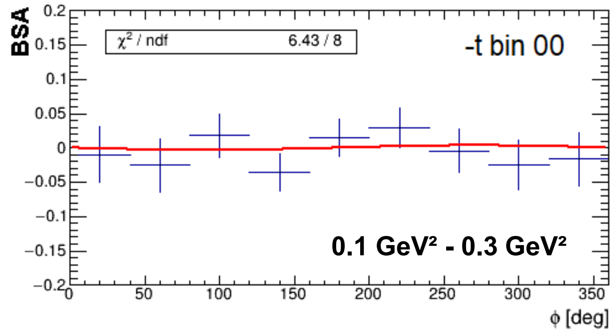
data after SIDIS MC subtraction

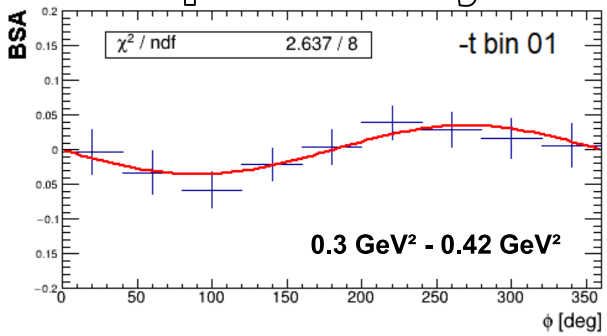
fit of a Sill function (BW with thr. effects)

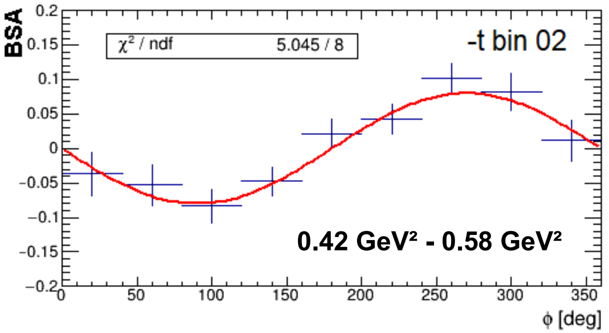
exclusive MC (for comparison)

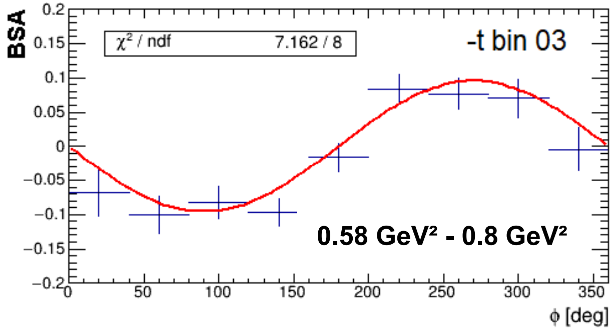
Resulting Beam Spin Asymmetries (Q²-x$_B$ integrated)

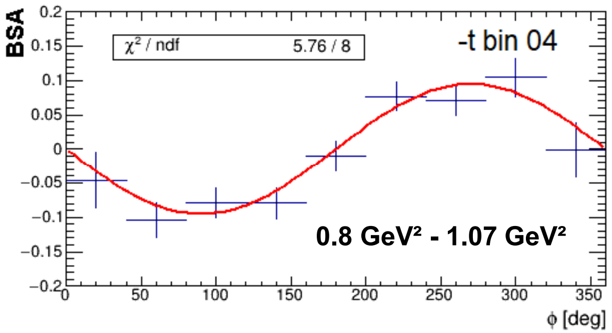
preliminary

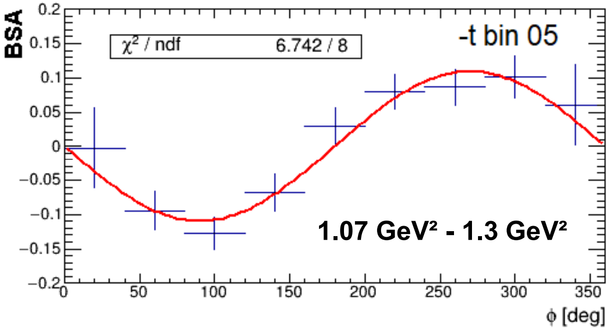


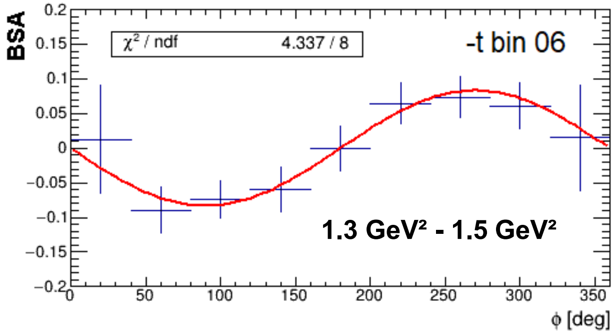








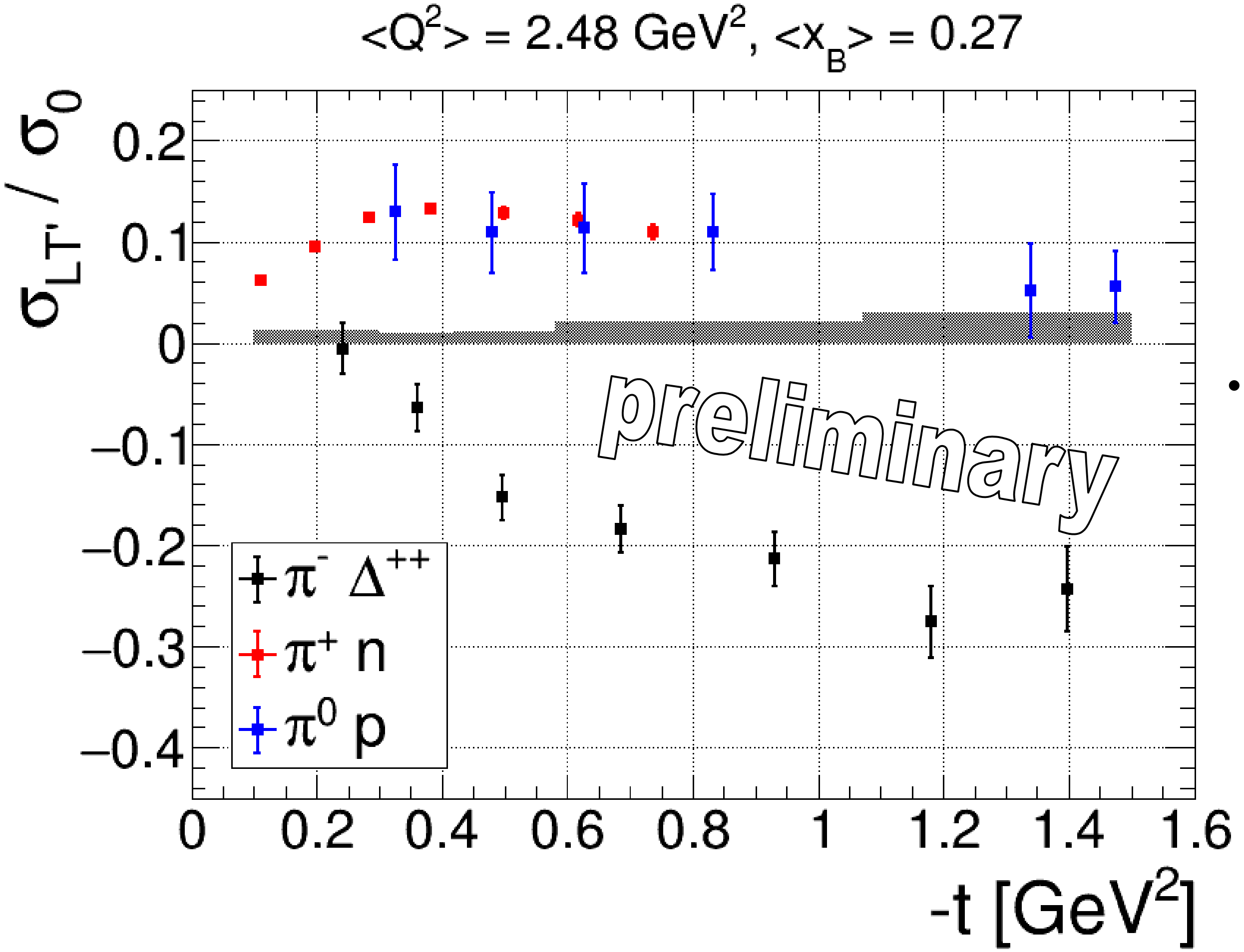




$$BSA(t,\phi,x_B,Q^2) \sim \sqrt{2\epsilon(1-\epsilon)}\boxed{\frac{\sigma_{LT'}}{\sigma_0}}\sin\phi$$

preliminary

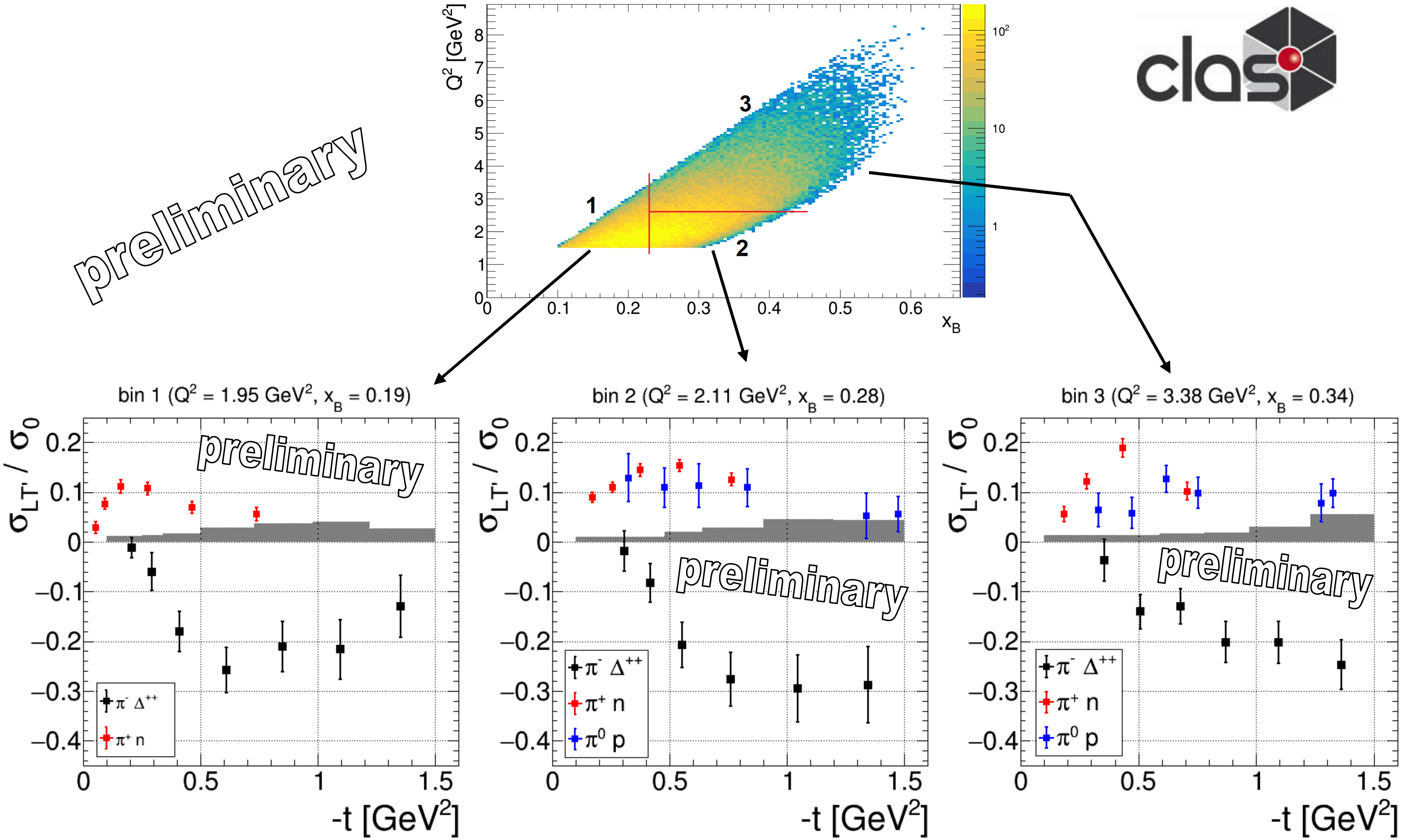
Q^2 - x_B Integrated Result



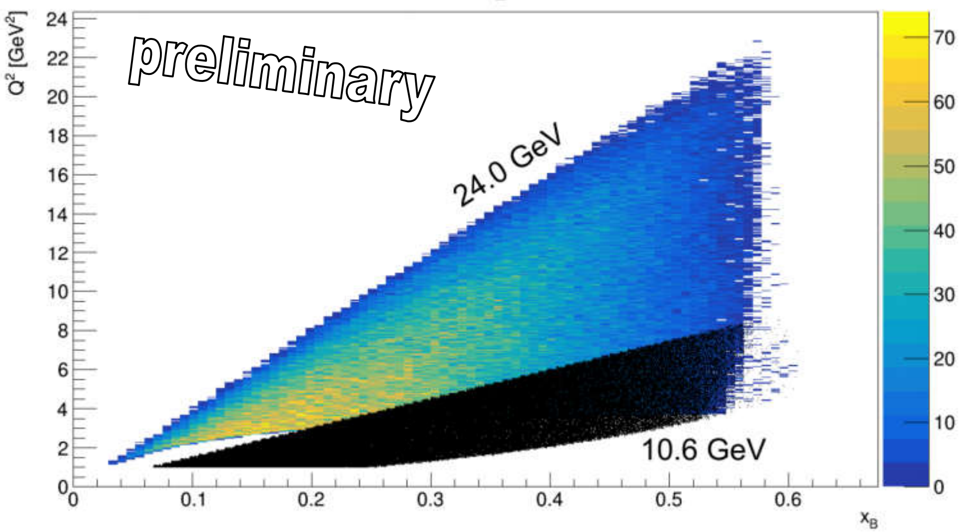
- The contribution of the non-resonant background has been subtracted

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 24 GeV JLAB upgrade



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

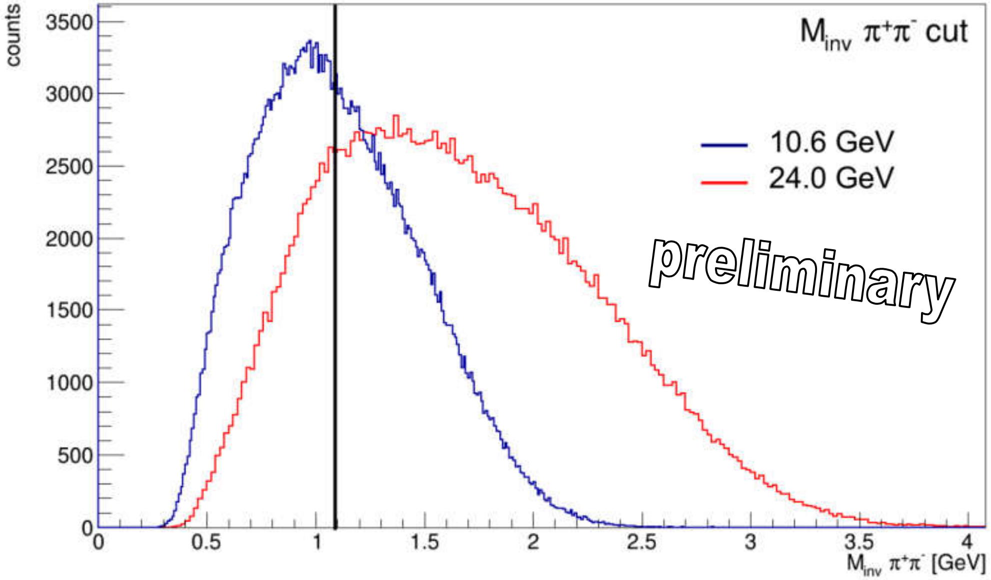
Extended Q² range

→ Advantage for factorisation

- Similar for non-diagonal DVCS

Better signal / background separation

➔ **Higher efficiency**



Conclusion and Outlook

- Transition GPDs can help us to better understand the 3D structure of resonances and the exitation process itself.
- Non-diagonal DVCS and hard exclusive $\pi^- \Delta^{++}$ production can be well measured with CLAS12
- The extracted $\pi^- \Delta^{++}$ BSA is a potential first „clean" observable sensitive to p-Δ transition GPDs
- Theory predictions are so far only available for twist-2 transition GPDs

  ➔ Extension of the framework to the twist-3 sector is in progress
- A JLAB energy and luminosity upgrade will help to significantly improve these measurements and the extraction of transition GPDs