KNU PHYSICS SEMINAR

August 29 2022

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

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

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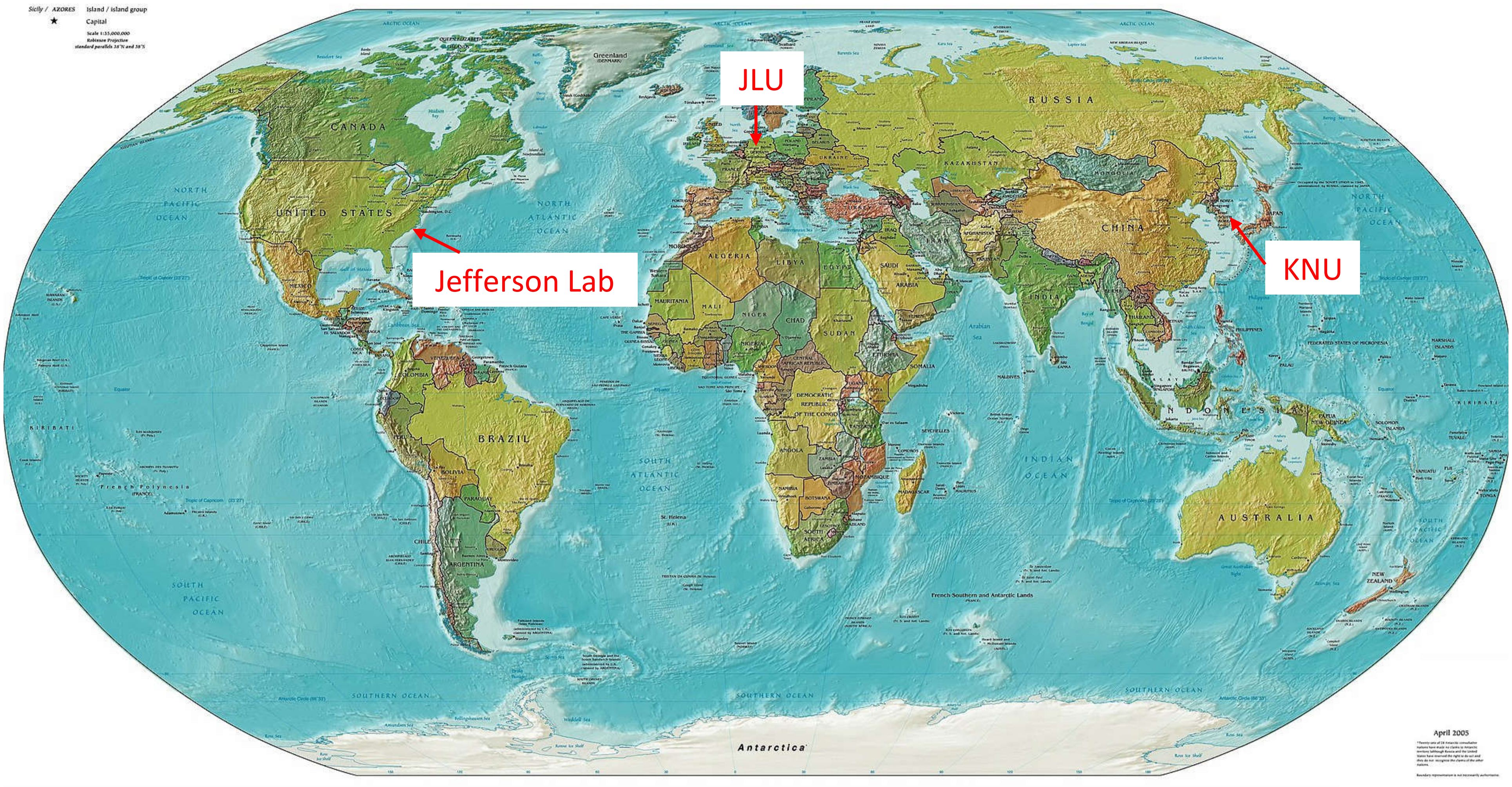
08/29/2022

Thomas Jefferson National Accelerator Facility (JLAB)

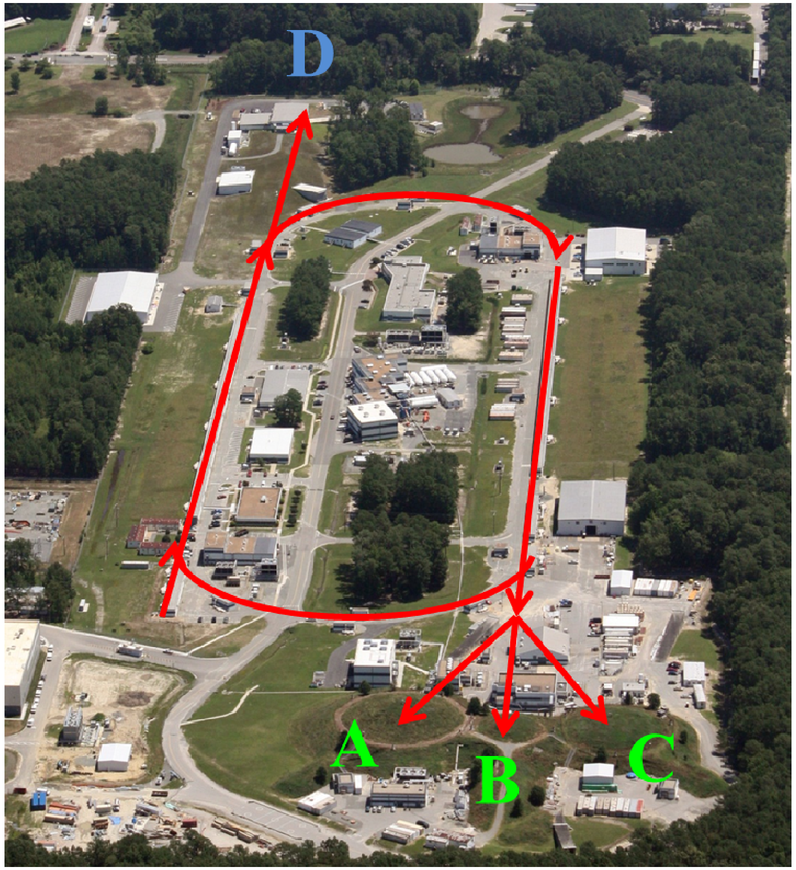


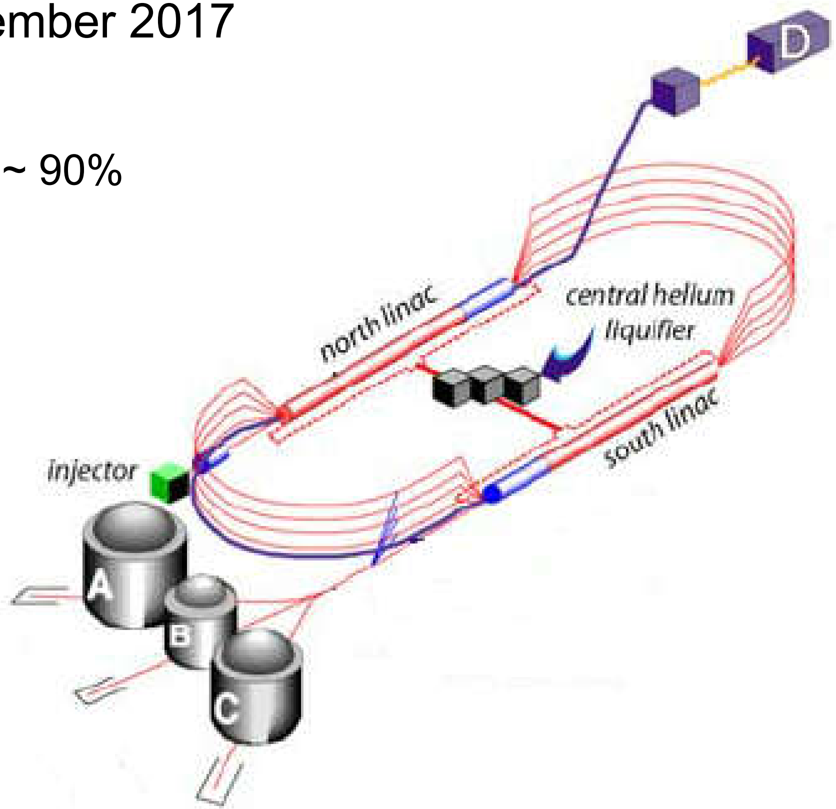
Thomas Jefferson National Accelerator Facility (JLAB)

- CEBAF Upgrade completed in September 2017

  $\longrightarrow$ electron beam

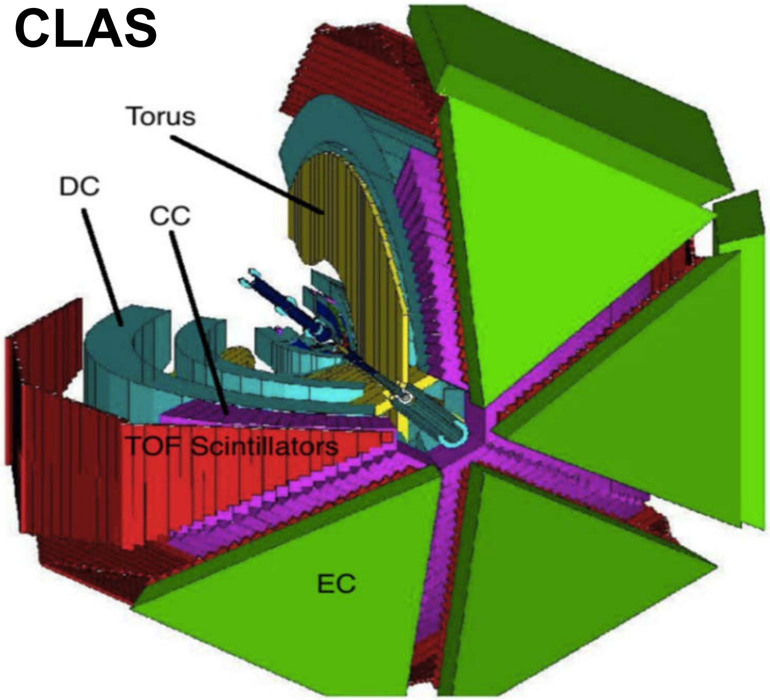
  $\longrightarrow E_{max} = 12$ GeV, $I_{max} = 90\ \mu A$, $Pol_{max} \sim 90\%$

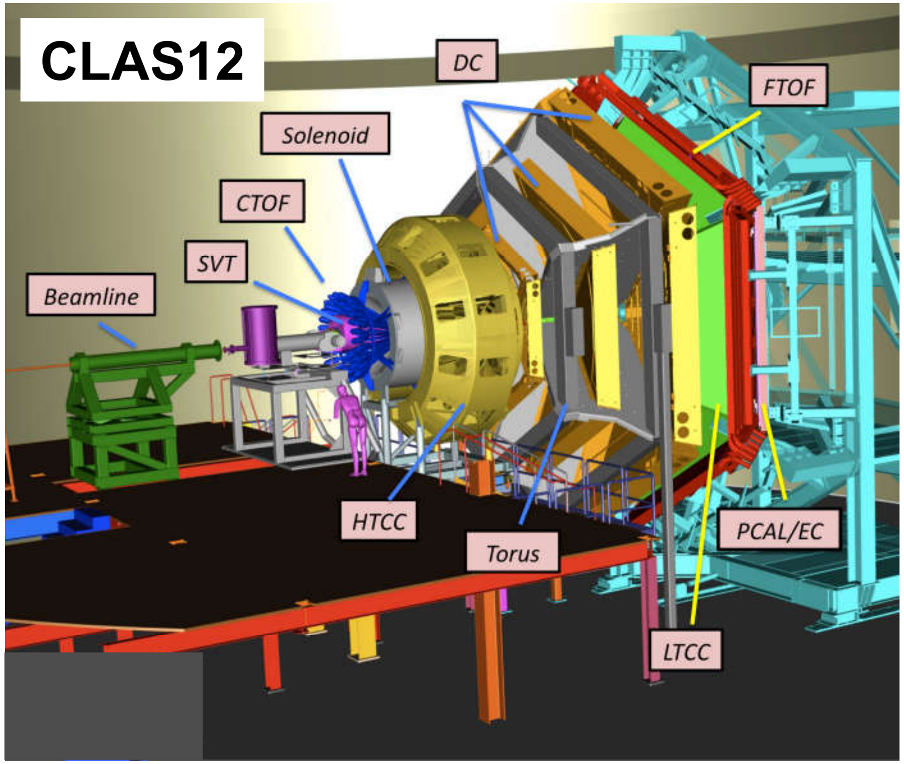




- 4 halls running simultaneously since January 2018

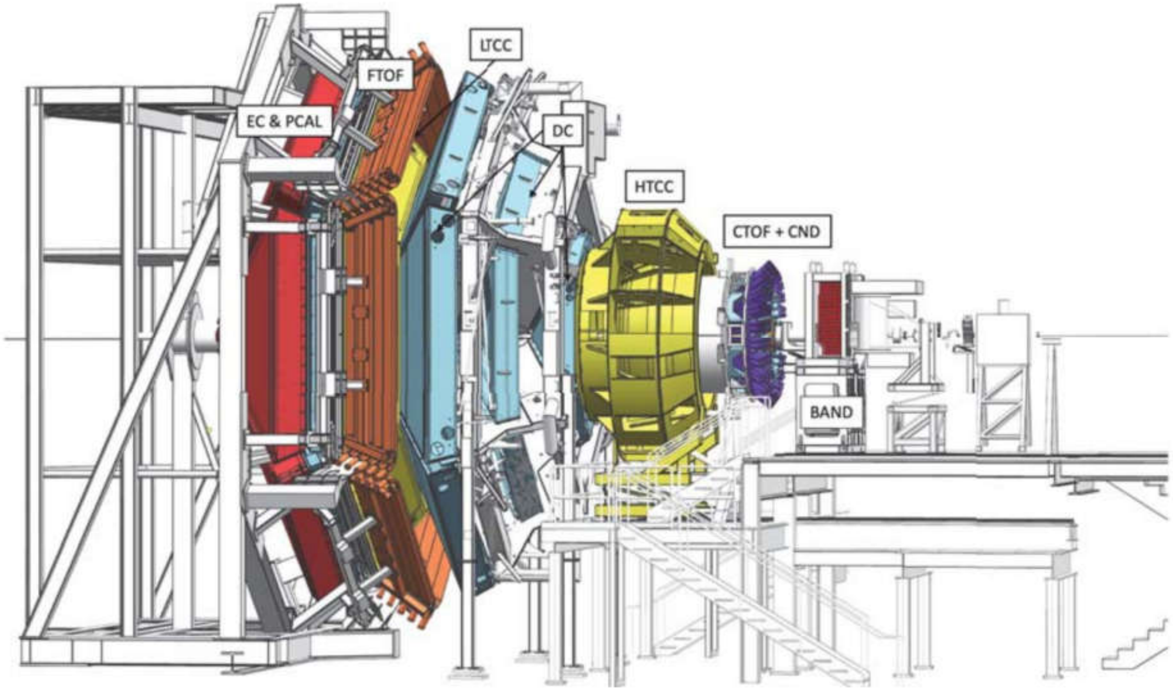
CLAS / CLAS12 in Hall B at JLAB





- $\mathcal{L} = 1 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Inclusive electron trigger (all reactions will be analyzed in parallel)

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

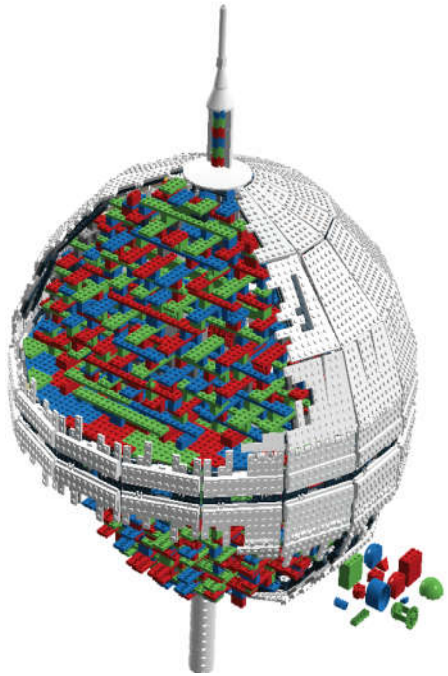
QCD Science Questions

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

How can we recover the well-known characteristics 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?



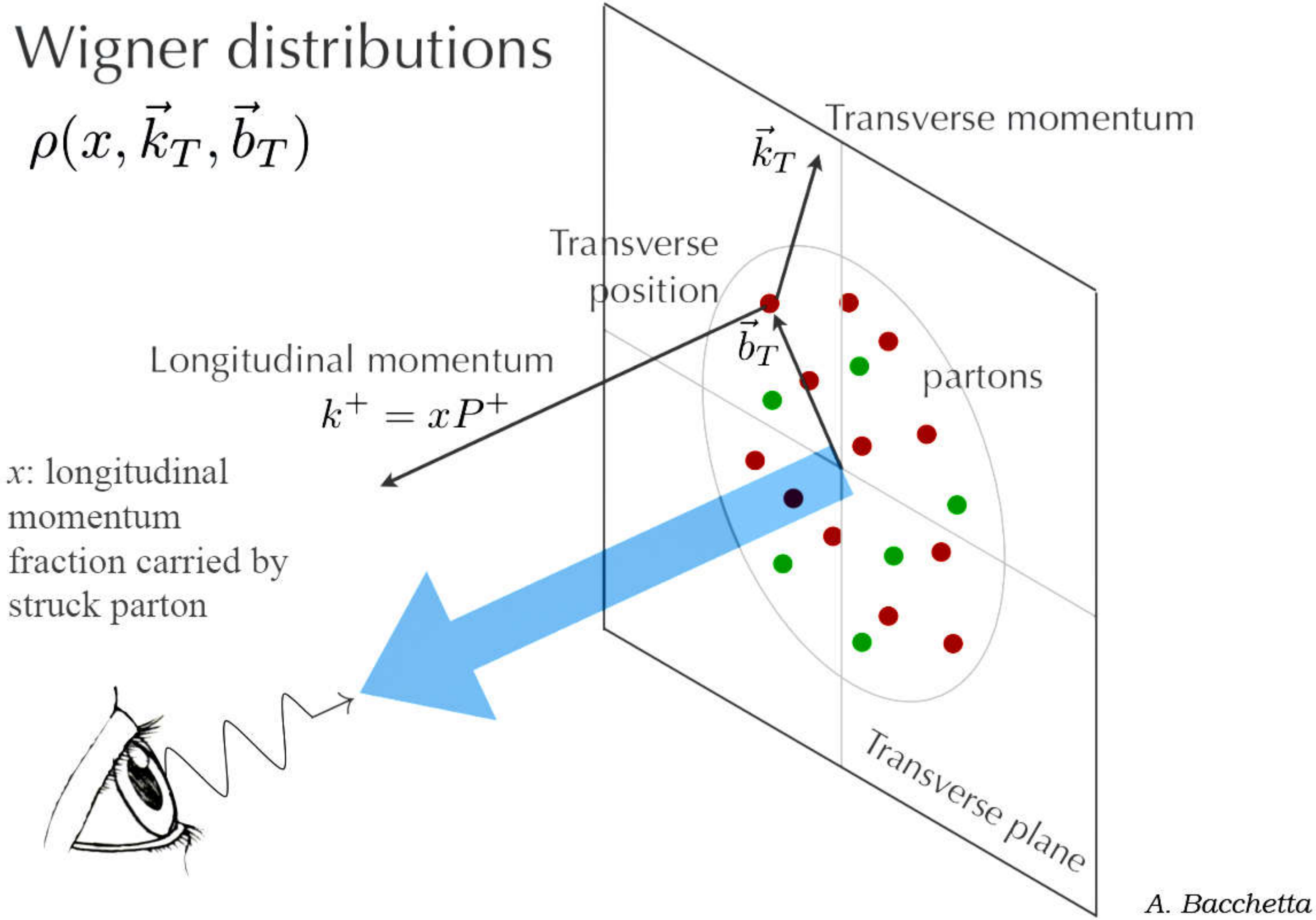
What is the role of orbital angular motion?

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

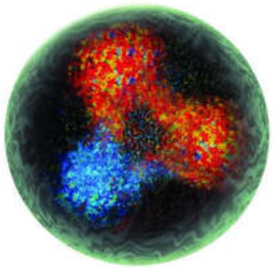
We need something three-dimensional!

We need to investigate the 3D nucleon structure!

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)

$$\int dx \qquad\qquad \int d^2 b_T$$

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

quark pol.

nucleon pol.

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

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

4 chiral even GPDs

4 chiral odd GPDs

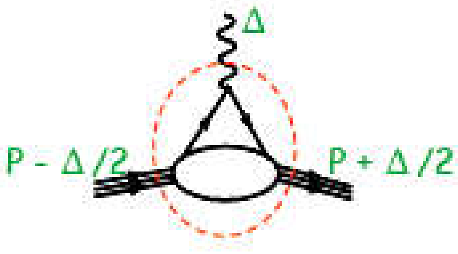
Interpretation of GPDs in the kinematic limits

$\xi \sim x_B/(2-x_B)$

- in forward kinematics (ξ=0, t = 0) : **PDF limit**

$$\boxed{H^q(x, \xi = 0, t = 0) = q(x)}$$

- first moments of GPDs : **elastic form factor limit**



$t = \Delta^2$

$$\int_{-1}^{+1} dx H^q(x, \xi, t) = F_1^q(t) \rightarrow \text{Dirac FF}$$

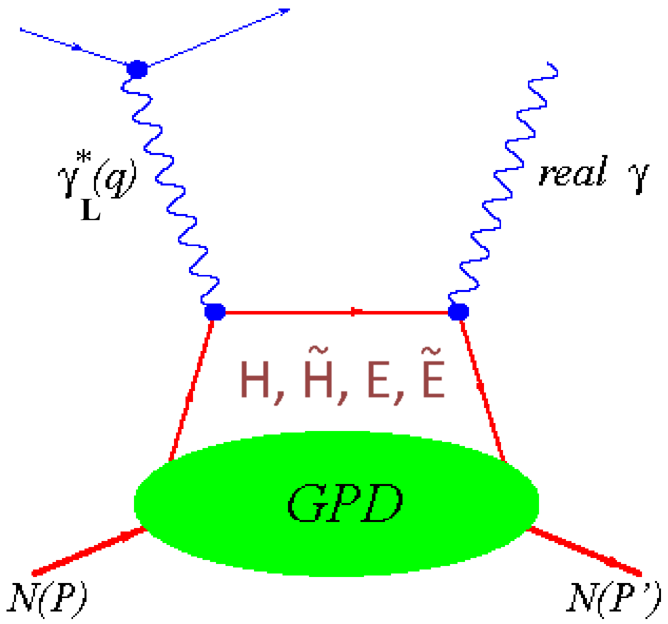
$$\int_{-1}^{+1} dx E^q(x, \xi, t) = F_2^q(t) \rightarrow \text{Pauli FF}$$

$$\int_{-1}^{+1} dx \tilde{H}^q(x, \xi, t) = G_A^q(t) \rightarrow \text{axial FF}$$

$$\int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) = G_P^q(t) \rightarrow \text{pseudoscalar FF}$$

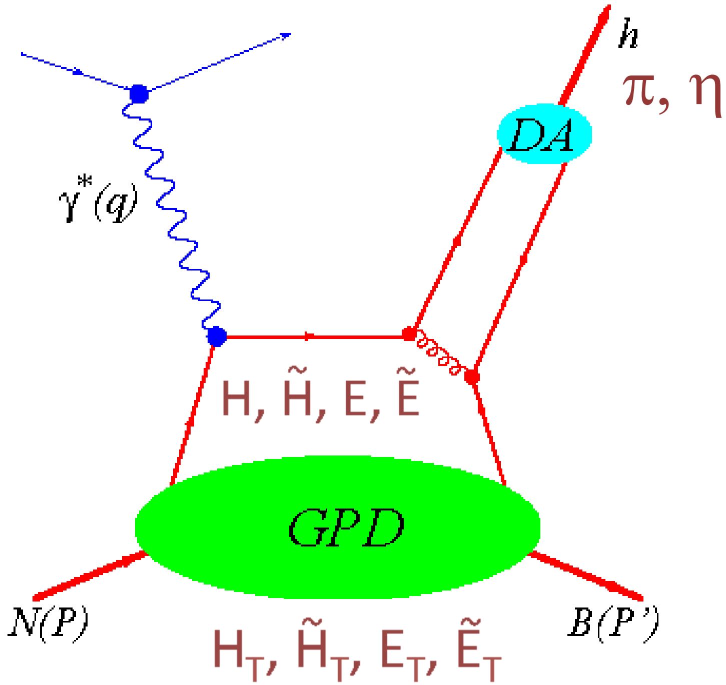
Study GPDs: Deeply Virtual Exclusive Processes

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

Physics content of GPDs

- GPDs provide indirect access to mechanical properties of the nucleon (encoded in gravitational form factors of the energy-momentum tensor)

X. D. Ji, PRD **55**, 7114-7125 (1997) M. Polyakov, PLB **555**, 57-62 (2016)

<u>GFFs are related to GPDs via sum rules</u>:

angular momentum

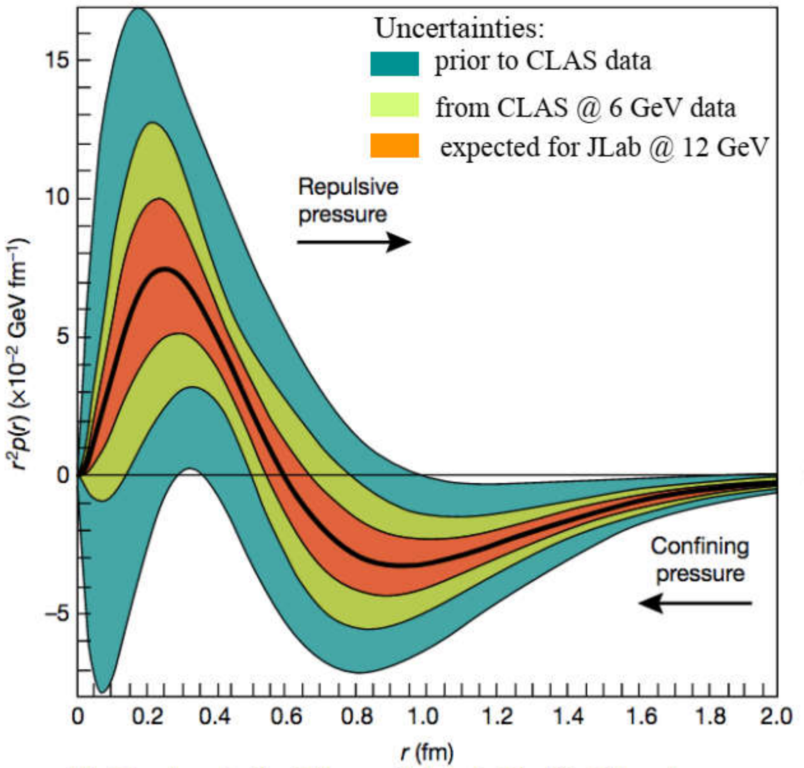
$$\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,\mathrm{d}x = 2J(t)$$

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

mass

pressure and shear forces

➔ Posibility to extract pressure distributions

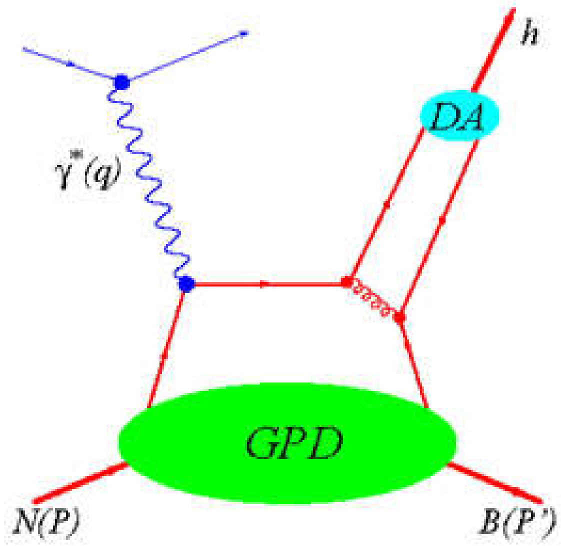


V. Burkert, L. Elouadrhiri, F.-X. Girod, Nature **557**, 396-399 (2018)

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

Physics content of DVMP results

	Meson	Flavor
$\mathcal{H}_T, \overline{\mathcal{E}}_T$	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



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

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

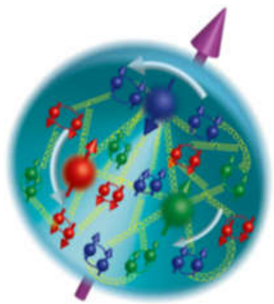
$\bar{E}_T$ is related to the protons anomalous tensor magnetic moment

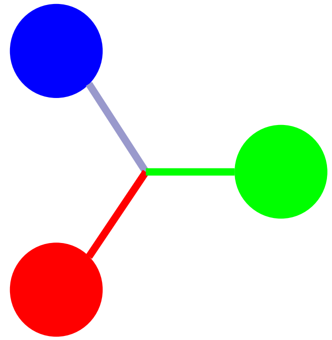
H_T is related to the protons tensor charge

➔ Absolute magnitude of transversly polarized valence quarks inside a transv. polarized nucleon

From the ground state nucleon to resonances

Ground state nucleon:
(proton, neutron)

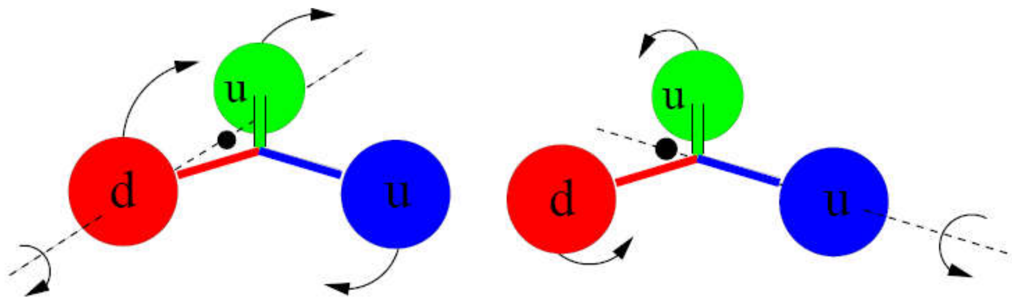




Nucleon resonances:

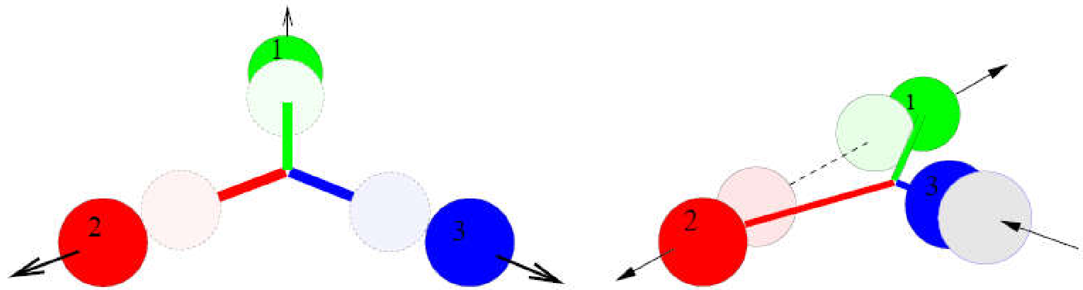
- Orbital excitations

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

Simplest case: N→Δ transition

➔ **16 transition GPDs**

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

Transition GPDs in the twist-2 sector

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

unpolarized:

$$\left.\begin{aligned}\int_{-1}^{1} dx H_M(x;\xi;t) &= 2G_M^*(t)\\ \int_{-1}^{1} dx H_E(x;\xi;t) &= 2G_E^*(t)\\ \int_{-1}^{1} dx H_C(x;\xi;t) &= 2G_C^*(t)\\ \int_{-1}^{1} dx H_4(x;\xi;t) &= 0\end{aligned}\right\}$$

Jones-Scardon EM FF for the N → transition

polarized:

$$\left.\begin{aligned}\int_{-1}^{1} dx C_1(x;\xi;t) &= 2C_5^A(t)\\ \int_{-1}^{1} dx C_2(x;\xi;t) &= 2C_6^A(t)\\ \int_{-1}^{1} dx C_3(x;\xi;t) &= 2C_3^A(t)\\ \int_{-1}^{1} dx C_4(x;\xi;t) &= 2C_4^A(t)\end{aligned}\right\}$$

Adler form factors

→ 3 of them are dominating in the large N_C limit

→ Connection to proton-proton GPDs via symmetry considerations

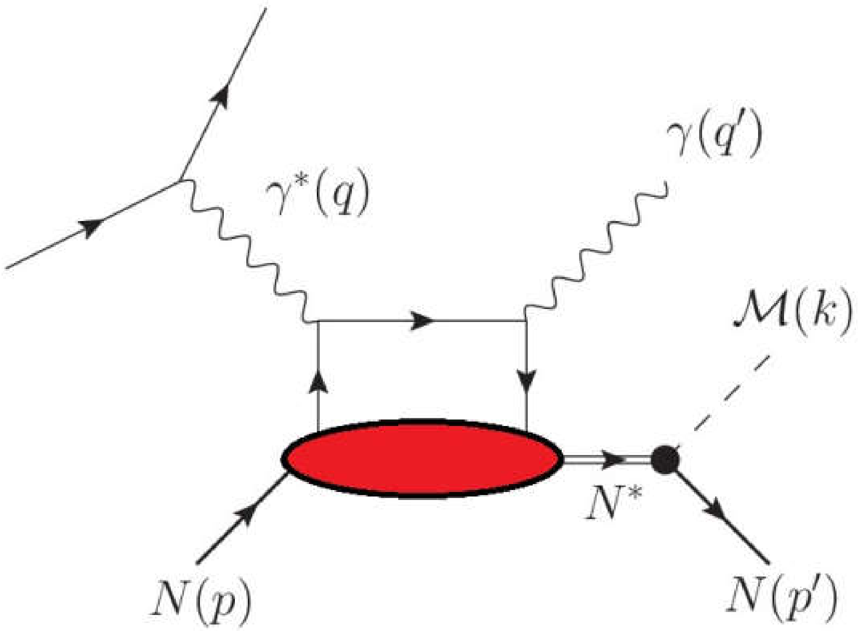
➔ Description of leading twist effects / longitudinal virtual photons (σ_L)

→ First theoretical works available

Experimental Access to Transition GPDs (twist 2)

Experimental access: Non diagonal DVCS process

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



Two final states have been studied:

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

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

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

First Theoretical Description of the Δ Region

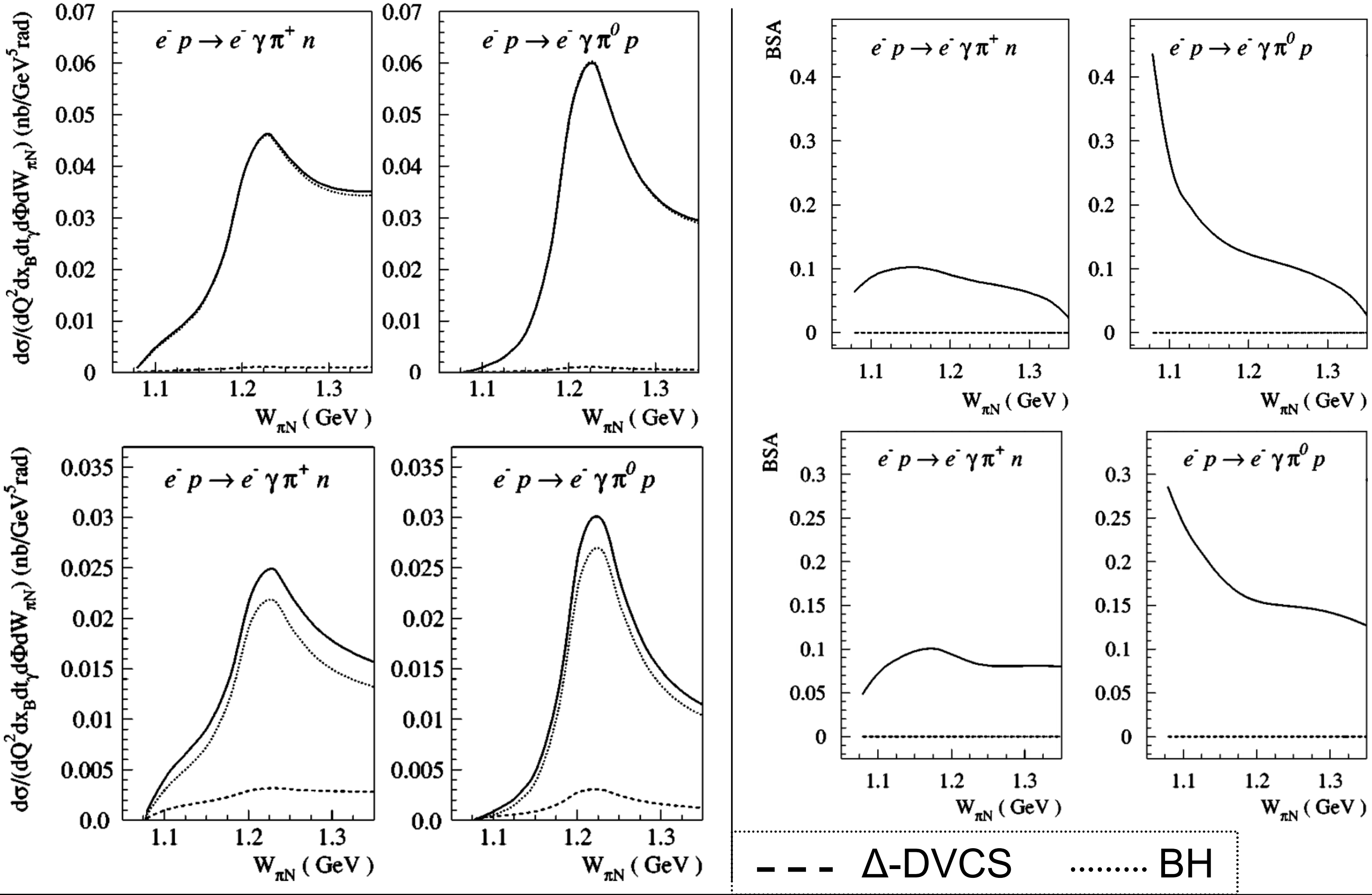
P.A.M Guichon, L. Mosse, M. Vanderhaeghen, Phys. Rev. D68 (2003) 034018

E_e = 6 GeV

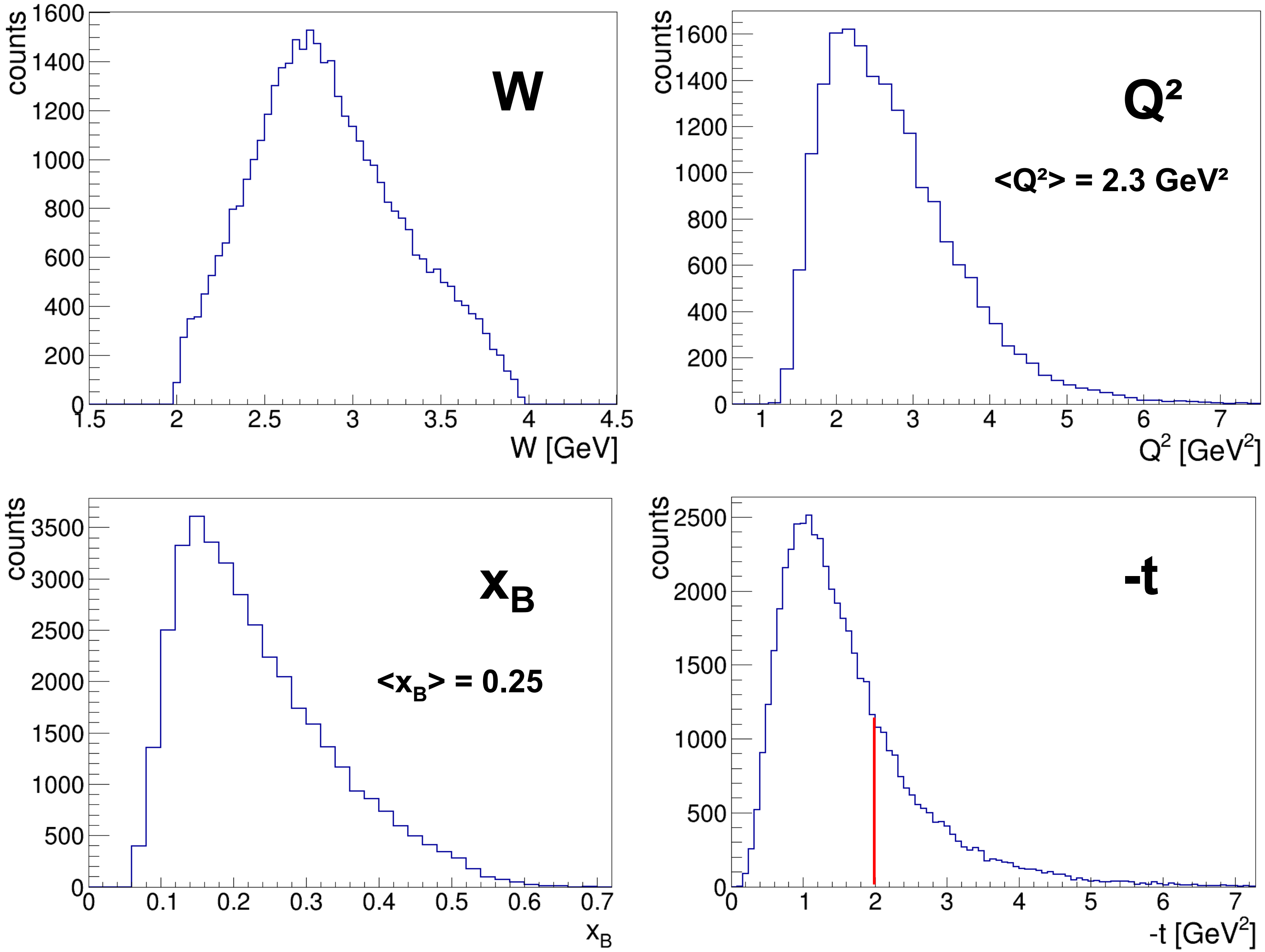
Q^2 = 2.5 GeV
x_B = 0.3
t_γ = -0.5 GeV²

E_e = 27 GeV

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



Accessible Kinematic Region with CLAS12 (10.6 GeV)



exclusivity cuts were applied for event selection

Kinematic cuts:

$W > 2$ GeV

$Q^2 > 1$ GeV²

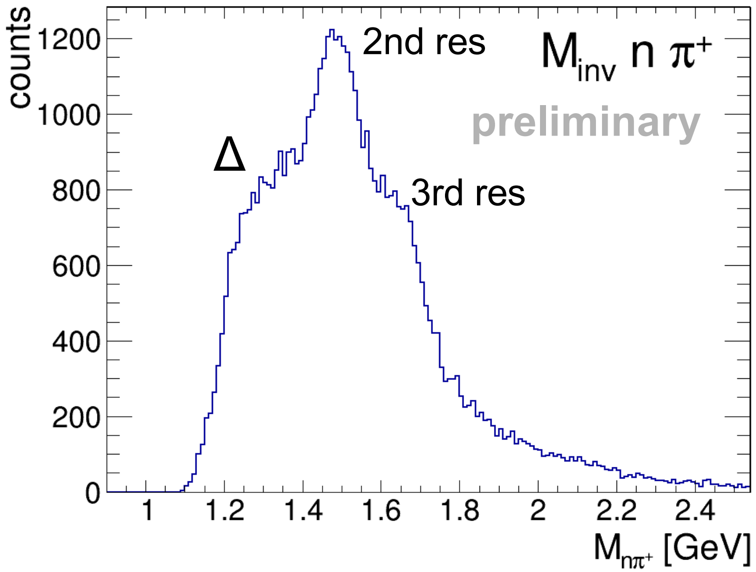
$y < 0.8$

$-t < 2$ GeV²

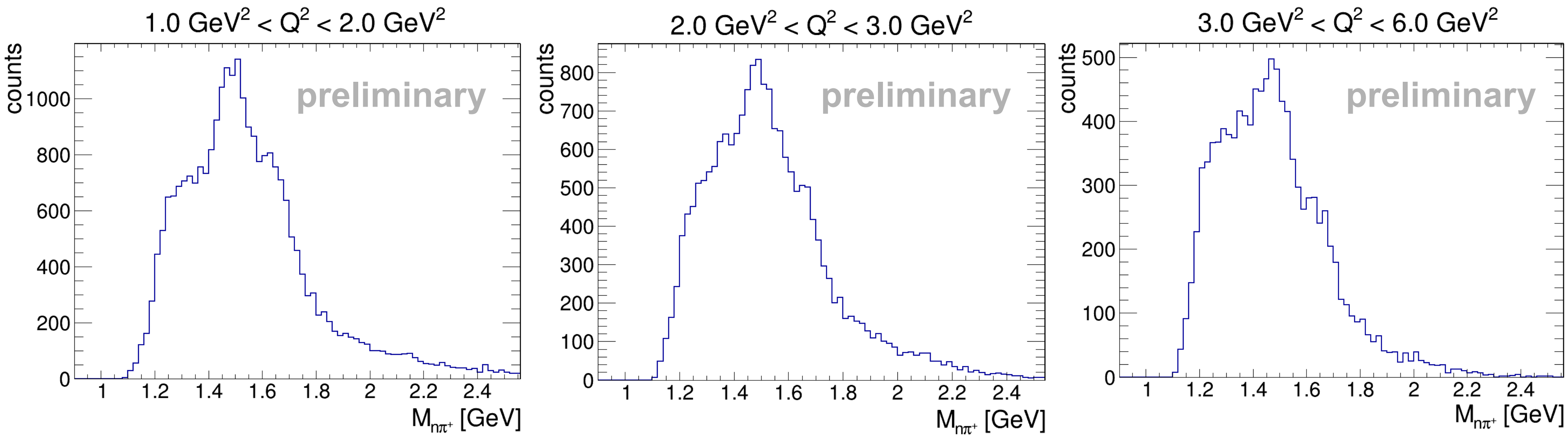
$E_{DVCS} > 2$ GeV

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

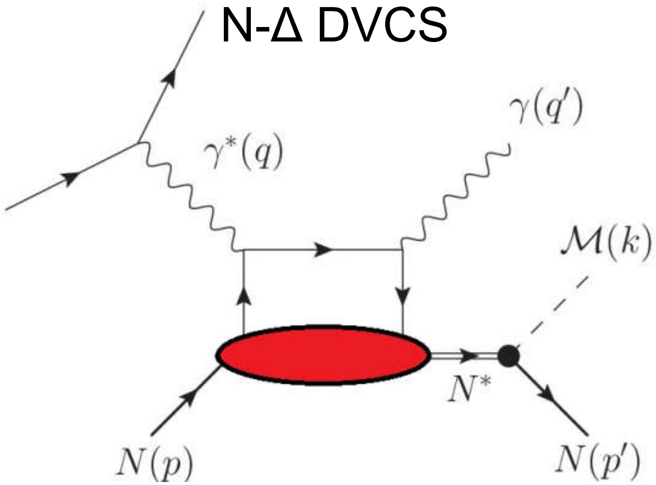
$en\pi^+\gamma$



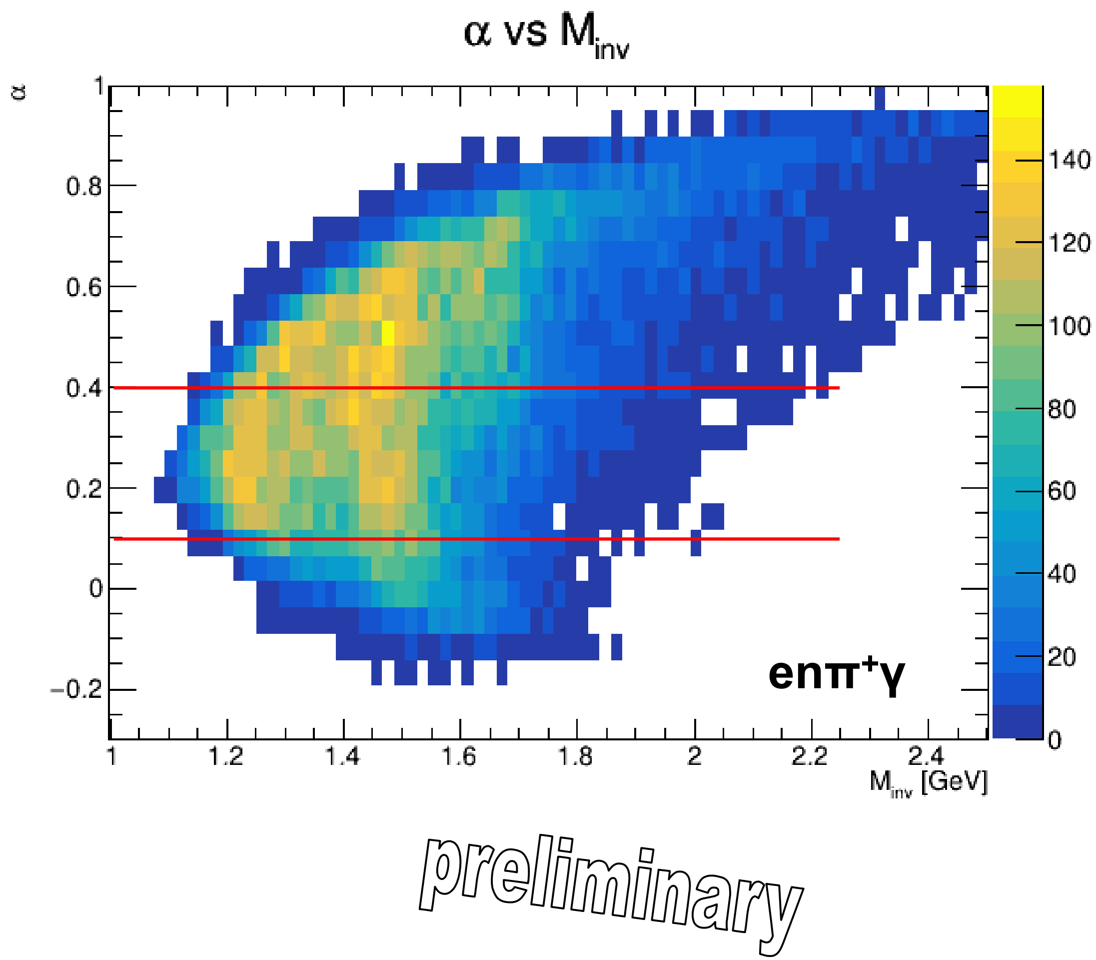
preliminary



The Pion Longitudinal Momentum Fraction

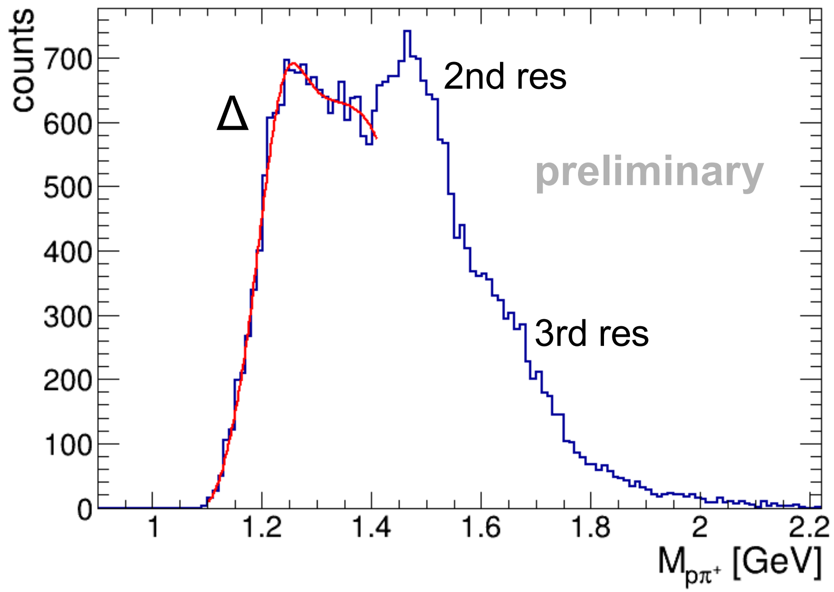


$$\alpha = \frac{(p'+k)\cdot k}{(p'+k)^2}$$



Resonance Mass Spectrum for 0.1 < α < 0.4

$en\pi^+\gamma$

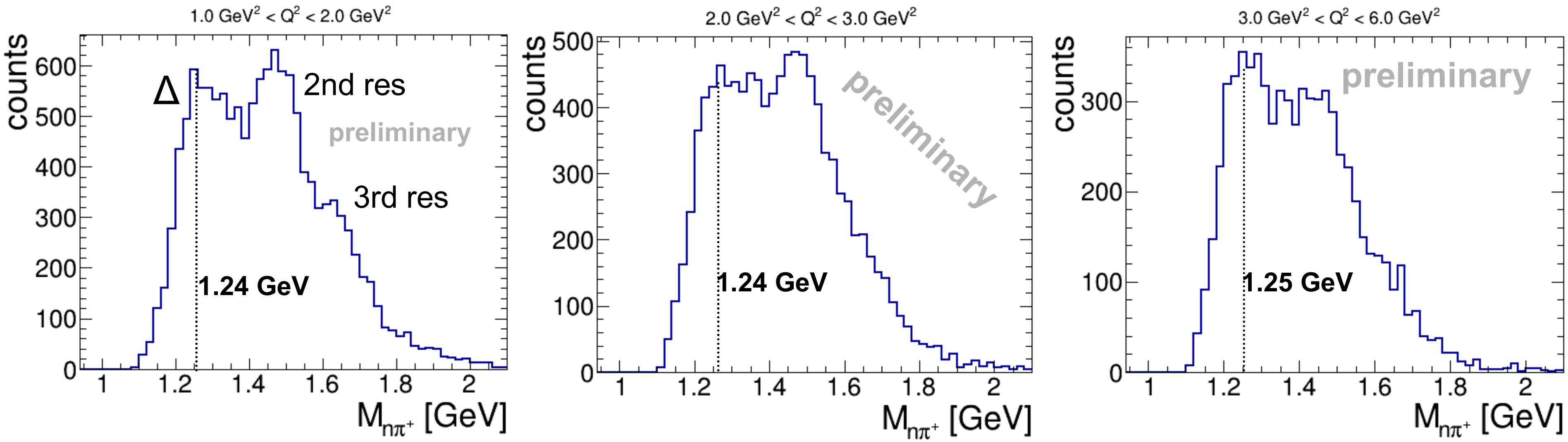


preliminary

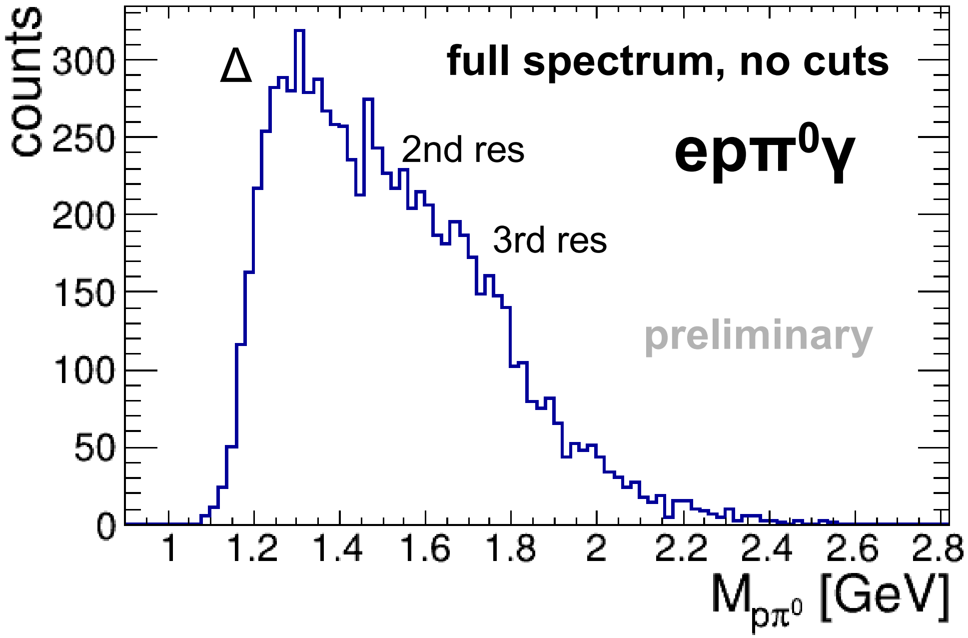
Δ-fit: Breit-Wigner
+ polyn. backgr.

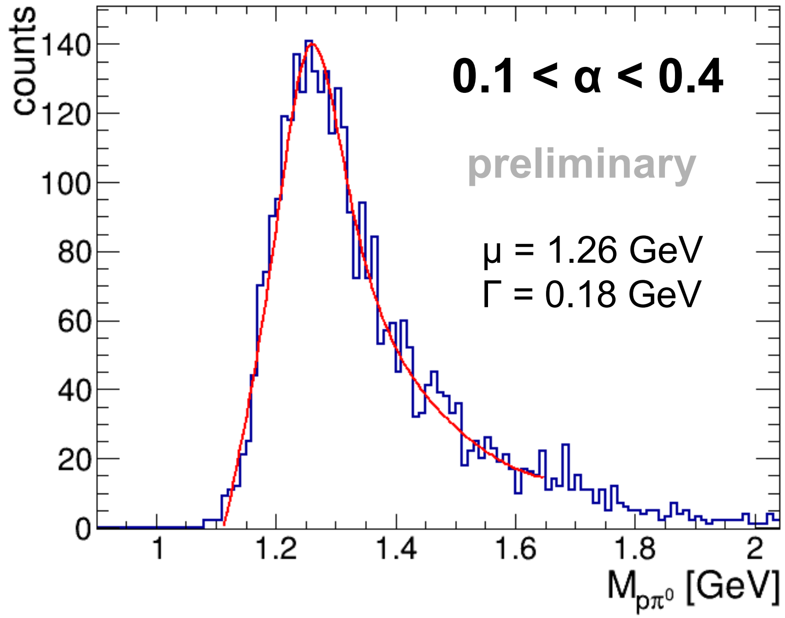
μ = 1.235 GeV
Γ = 0.15 GeV

Q² dependence:

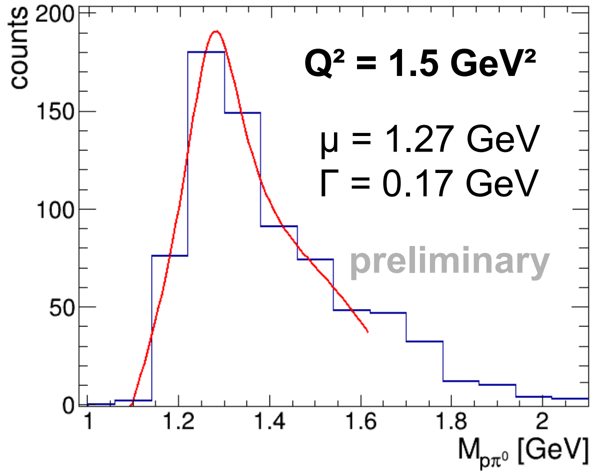


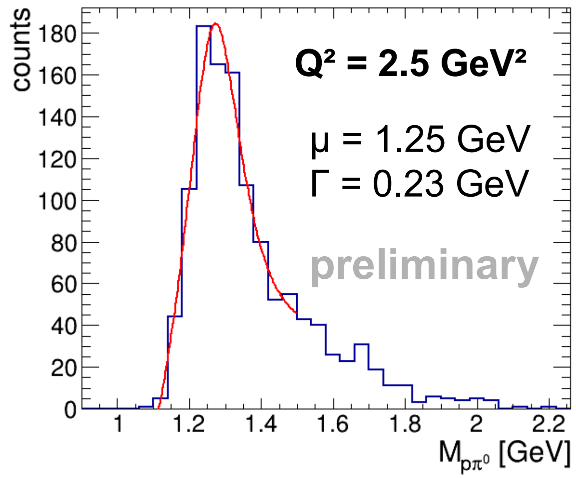
Resonance Mass Spectrum for N* → pπ⁰

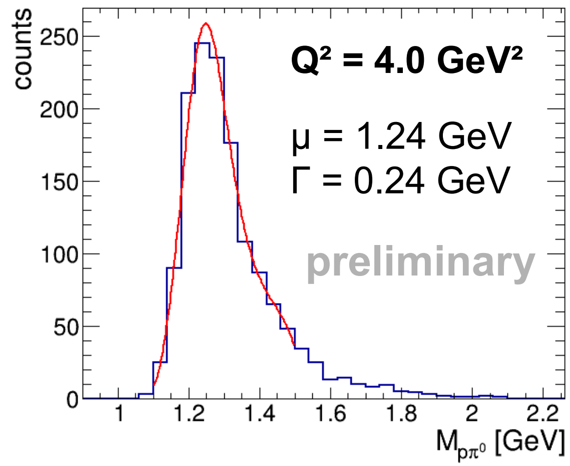




0.1 < α < 0.4



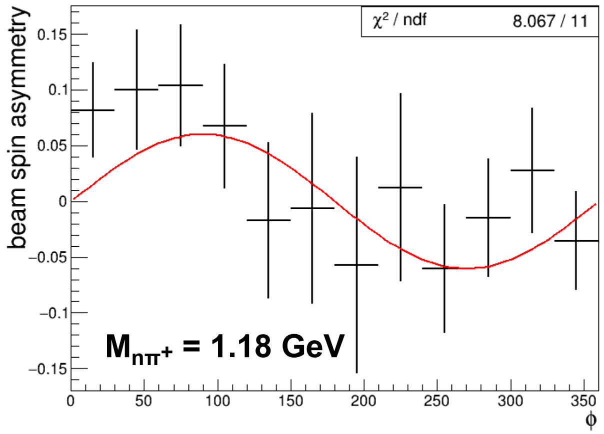




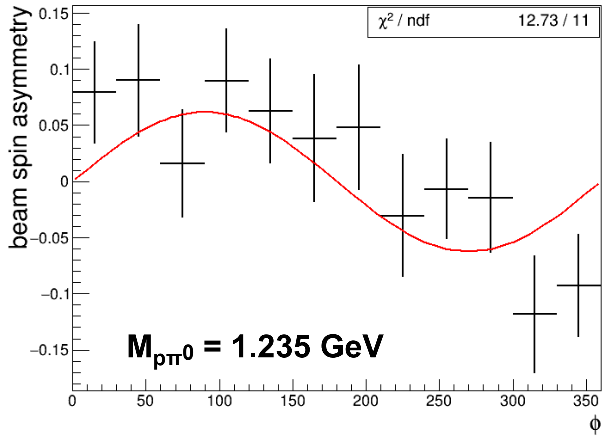
Raw beam spin asymmetries

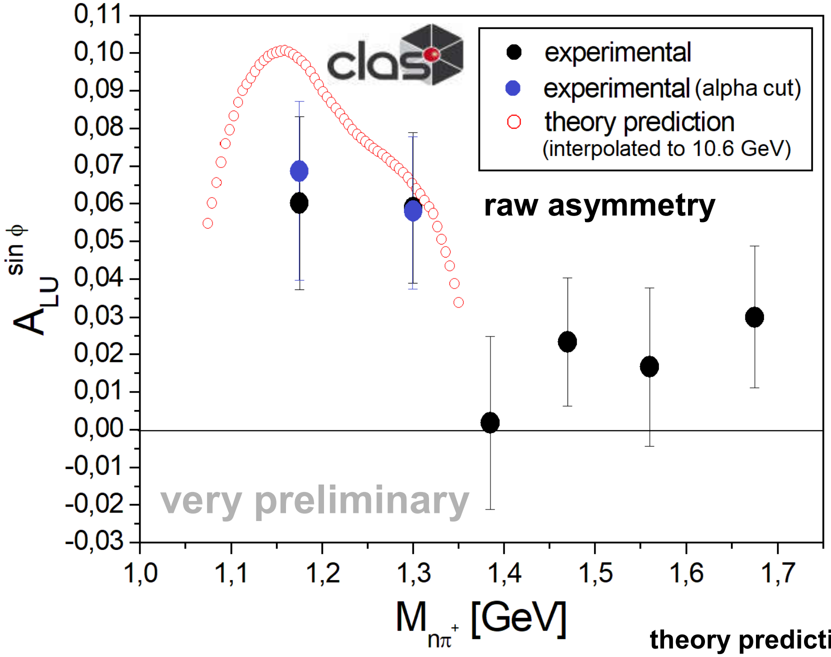
$$A = \frac{1}{P}\frac{N^{+} - N^{-}}{N^{+} + N^{-}} \approx A_{LU}^{\sin\phi} \sin\phi$$

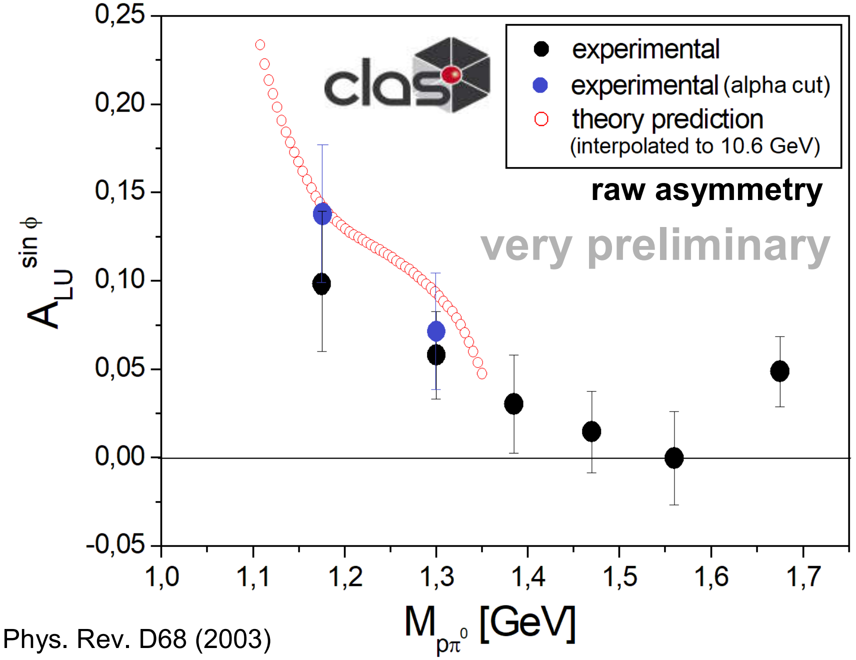
$en\pi^{+}\gamma$



$ep\pi^{0}\gamma$

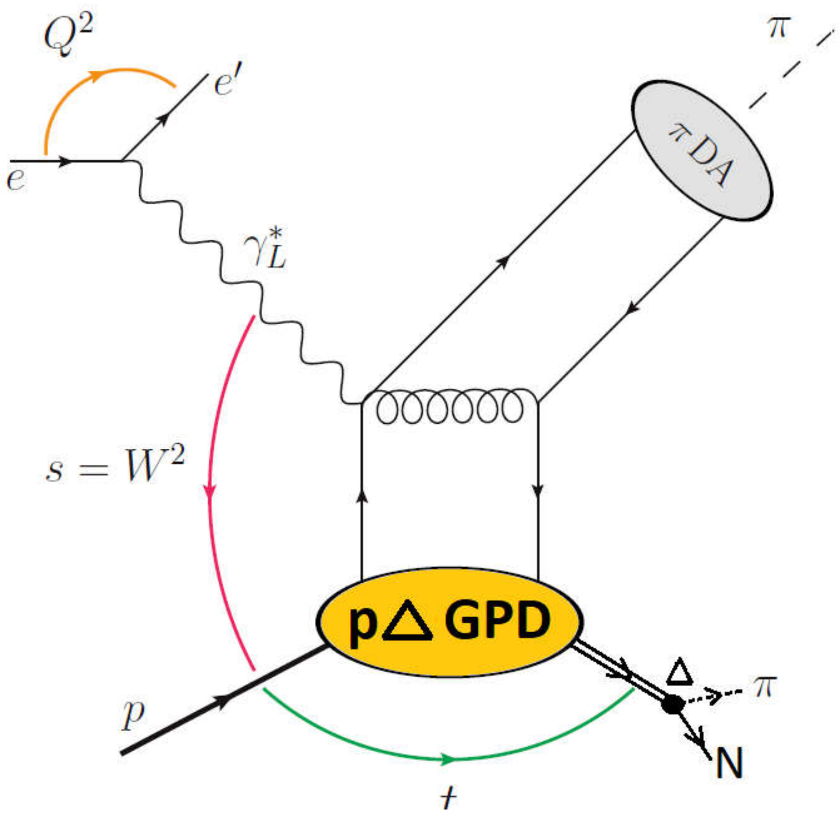






theory prediction: Phys. Rev. D68 (2003)

The non-diagonal DVMP processes



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

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

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

8 helicity non-flip trans. GPDs

+

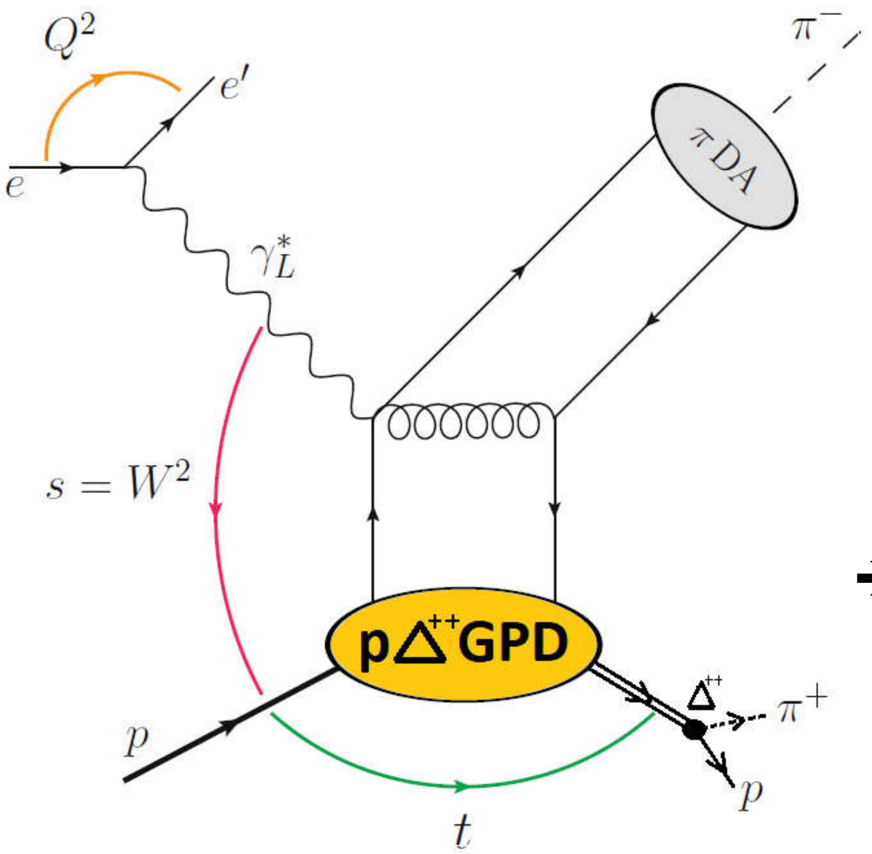
8 helicity flip trans. GPDs

→ Needed for twist-3 sector

→ No publications so far

Hard exclusive π⁻Δ⁺⁺ production

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



Factorisation expected for:

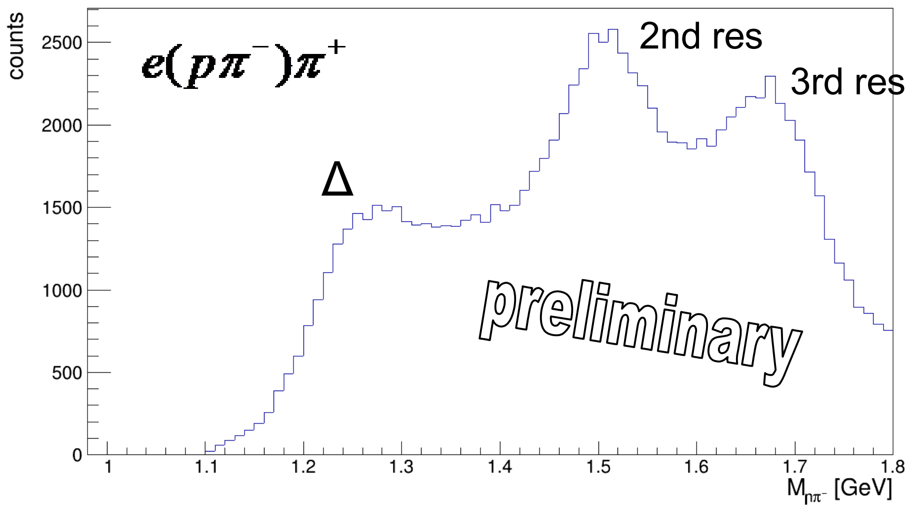
$-t / Q^2 << 1$ and $Q^2 > M_\Delta^2$

x_B fixed

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

Why is π⁻Δ⁺⁺ special?

Other non - diagonal DVMP channels, i.e. $ep \rightarrow e\Delta^0\pi^+ \rightarrow e(p\pi^-)\pi^+$



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

➔ The pπ⁺ final state can **only** be populated by **Δ-resonances**

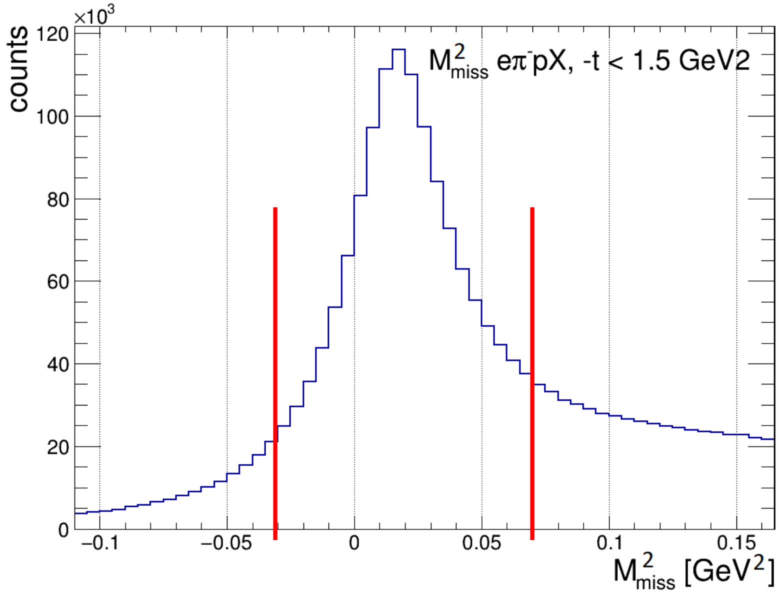
➔ Large gap between Δ(1232) and higher resonances

Event Selection and Kinematic Cuts

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

$$X = \pi^+$$

➔ 2 σ cut around the missing π^+

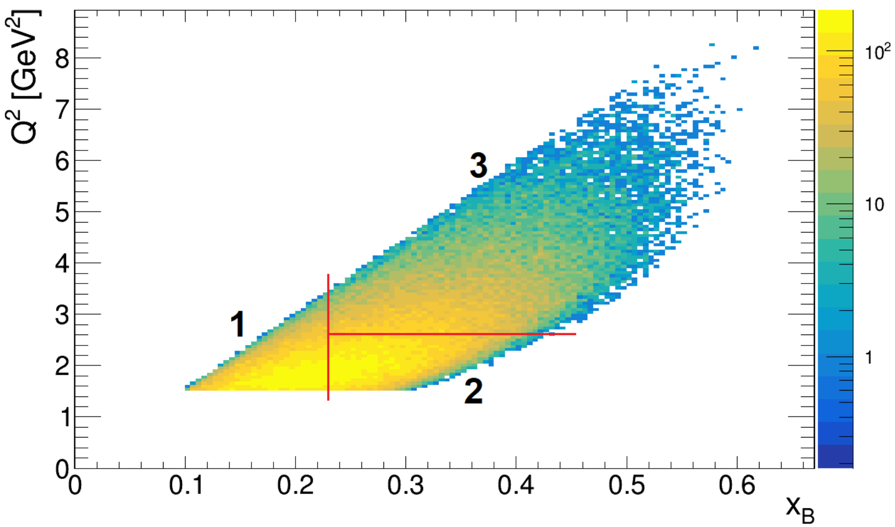


Kinematic cuts:

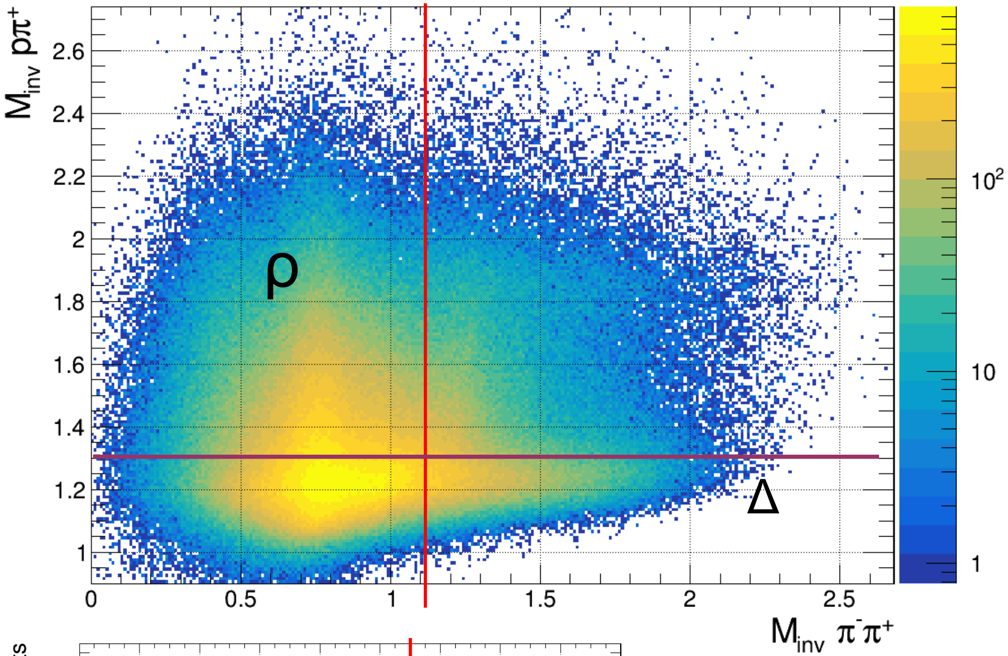
$Q^2 > 1.5$ GeV² W > 2 GeV

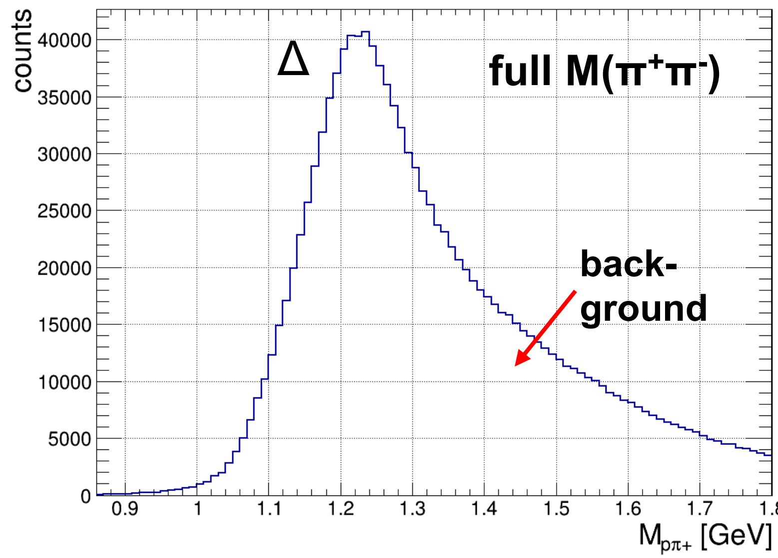
$y < 0.75$

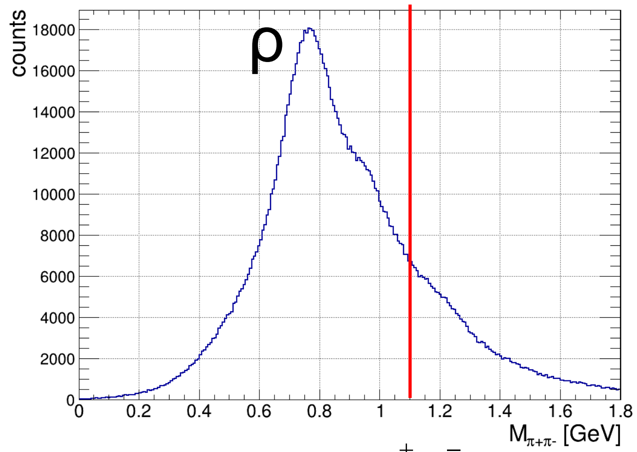
$-t < 1.5$ GeV² (forward region)



Event Selection and Background Rejection





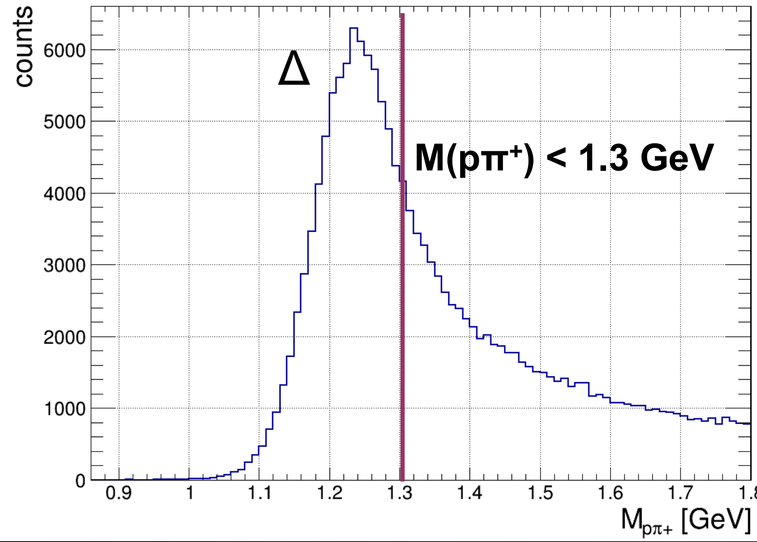


$$ep \rightarrow ep\rho \rightarrow ep\pi^+\pi^-$$

M(π⁺π⁻) > 1.1 GeV

ρ contamination

< 0.8 %



Monte Carlo Simulations

<u>2 MC samples have been used</u>:

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

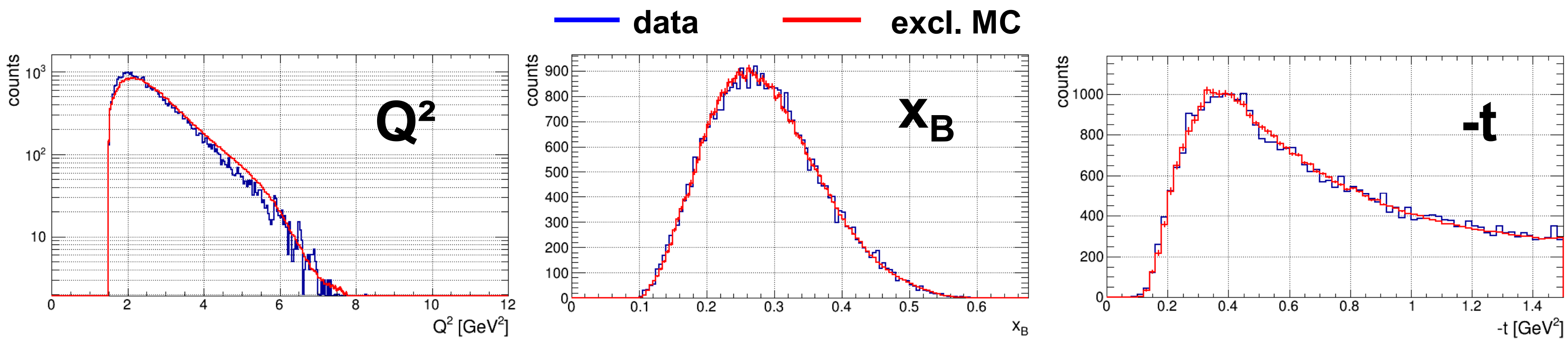
➔ Used to estimate background shape and contaminations

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

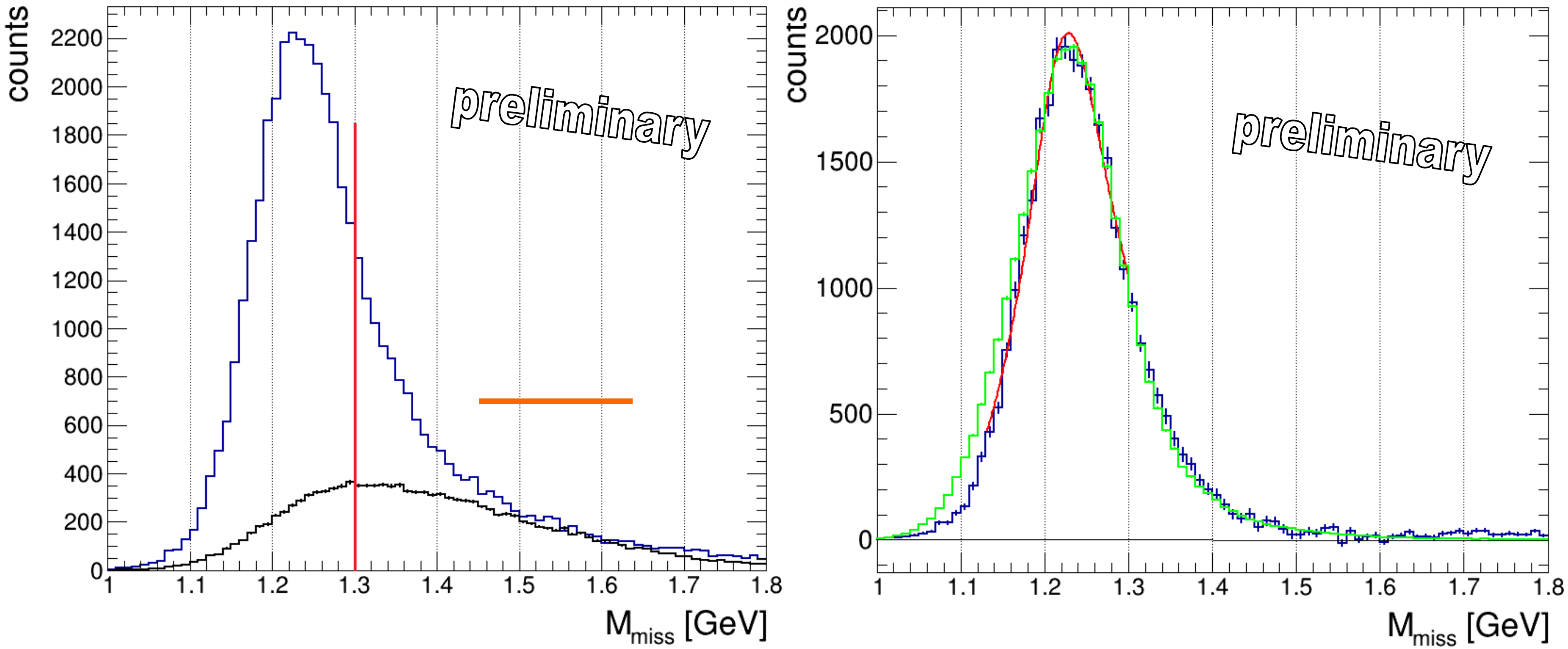
→ Phase space simulation with a weigth added to match experimental data

→ 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)

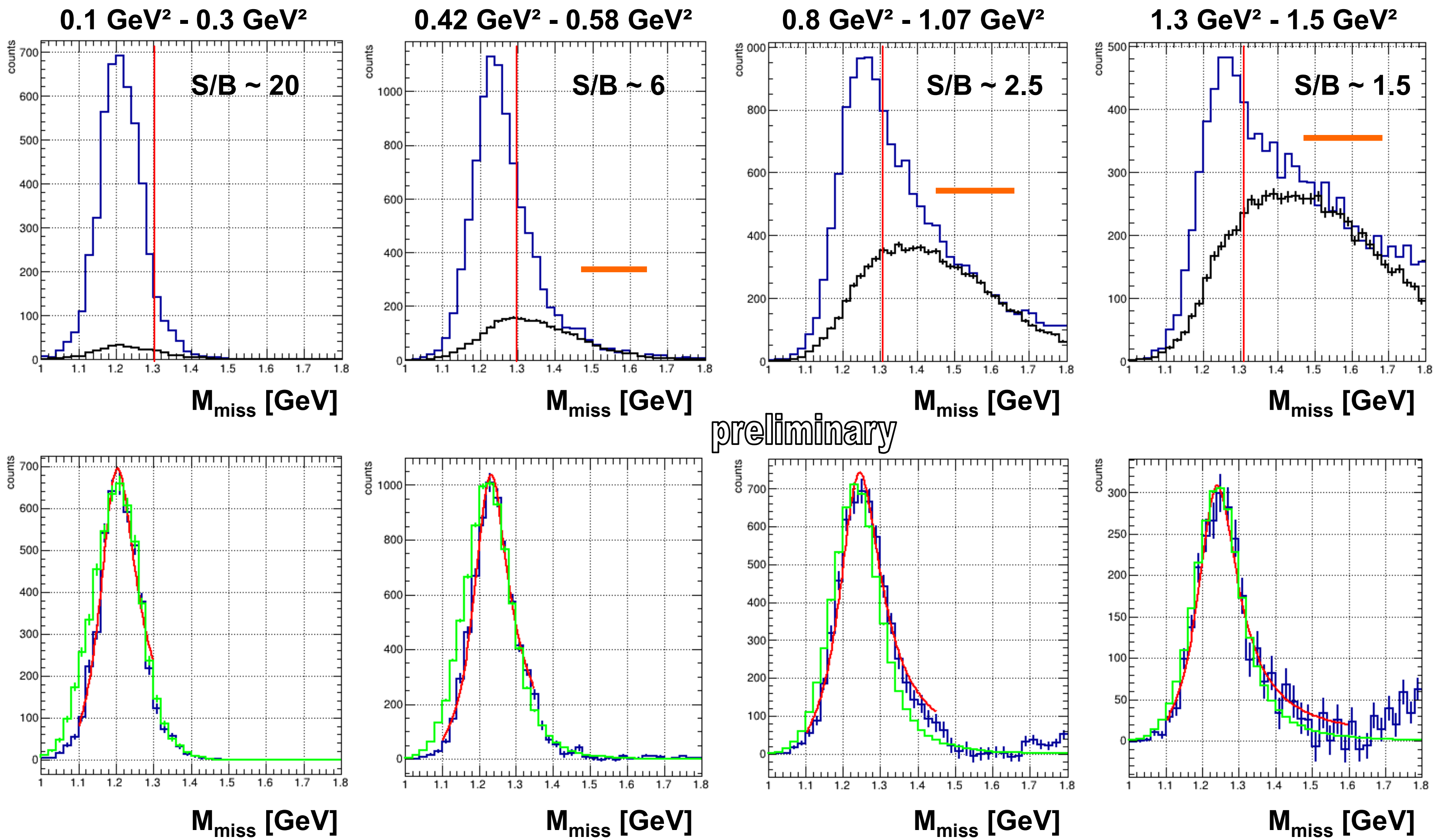
data after SIDIS MC subtraction

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

exclusive MC (for comparison)

<u>Background:</u> 98 – 99 % non-resonant events

Event Selection and Background Estimate



experimental data

SIDIS MC (same cuts)

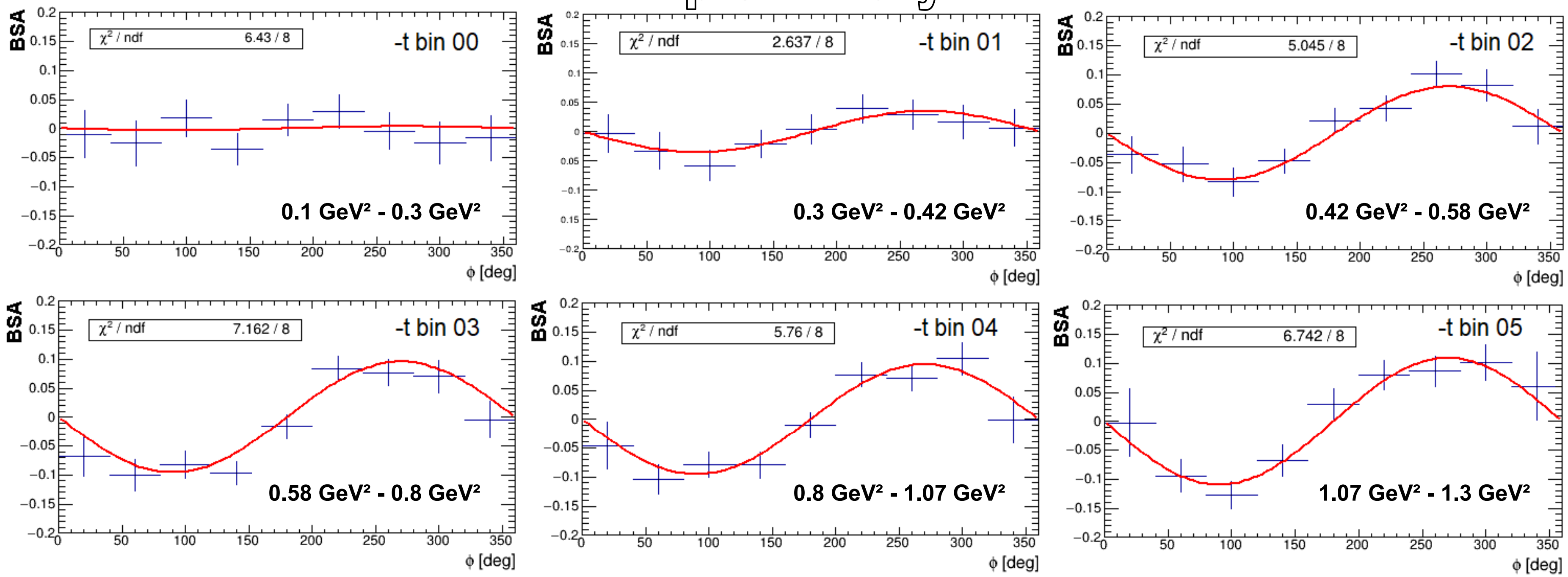
data after SIDIS MC subtraction

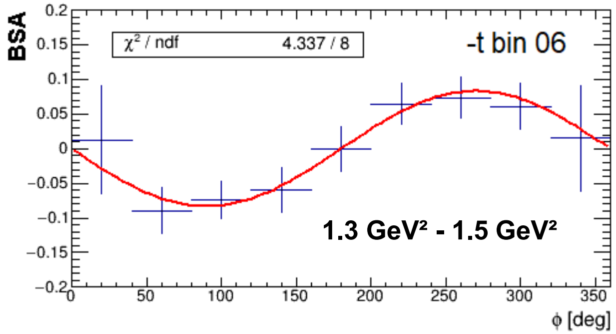
fit of a Sill function (BW with thr. effects)

exclusive MC (for comparison)

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

preliminary

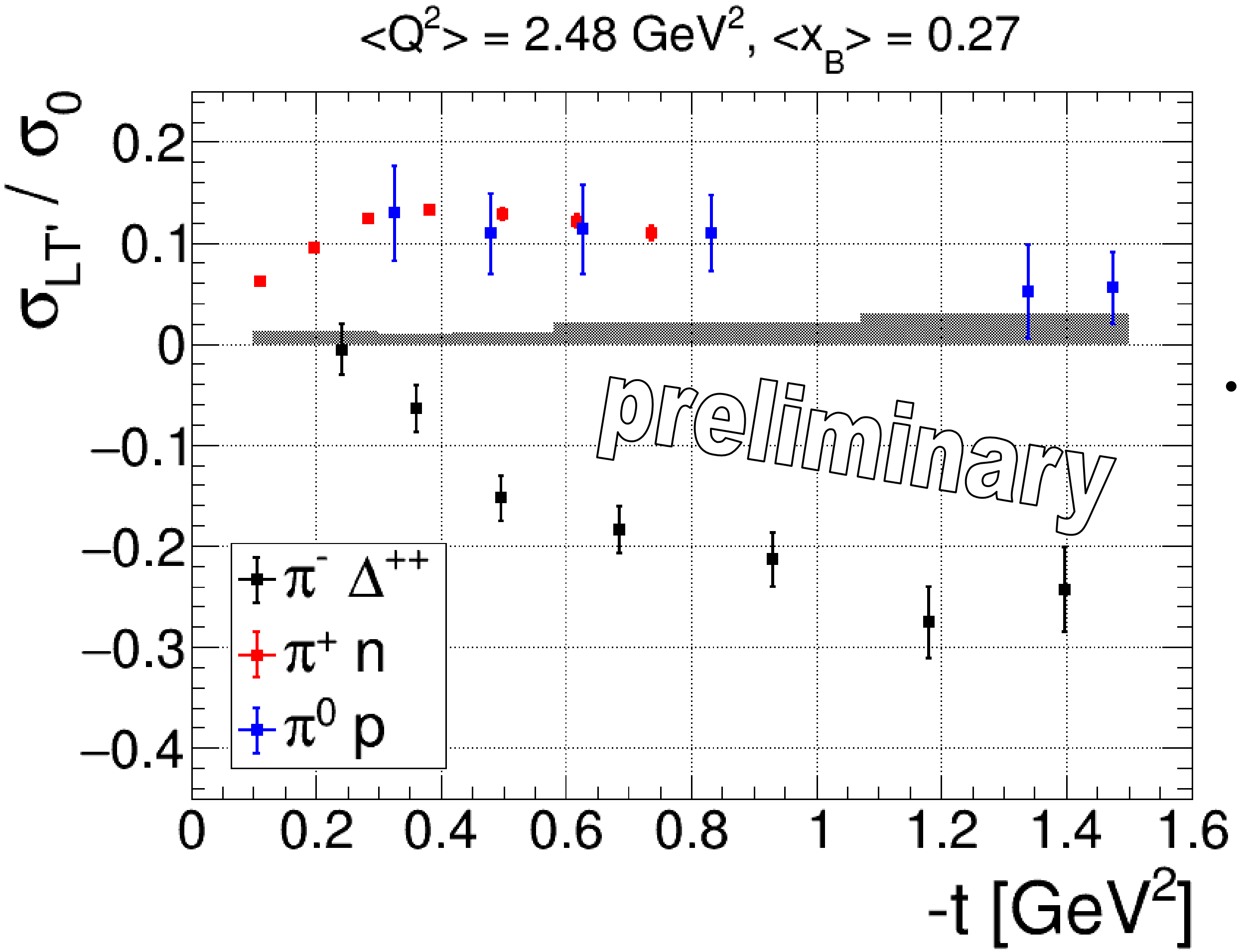




$$BSA(t,\phi,x_B,Q^2) \sim \sqrt{2\epsilon(1-\epsilon)}\boxed{\frac{\sigma_{LT'}}{\sigma_0}}\sin\phi$$

preliminary

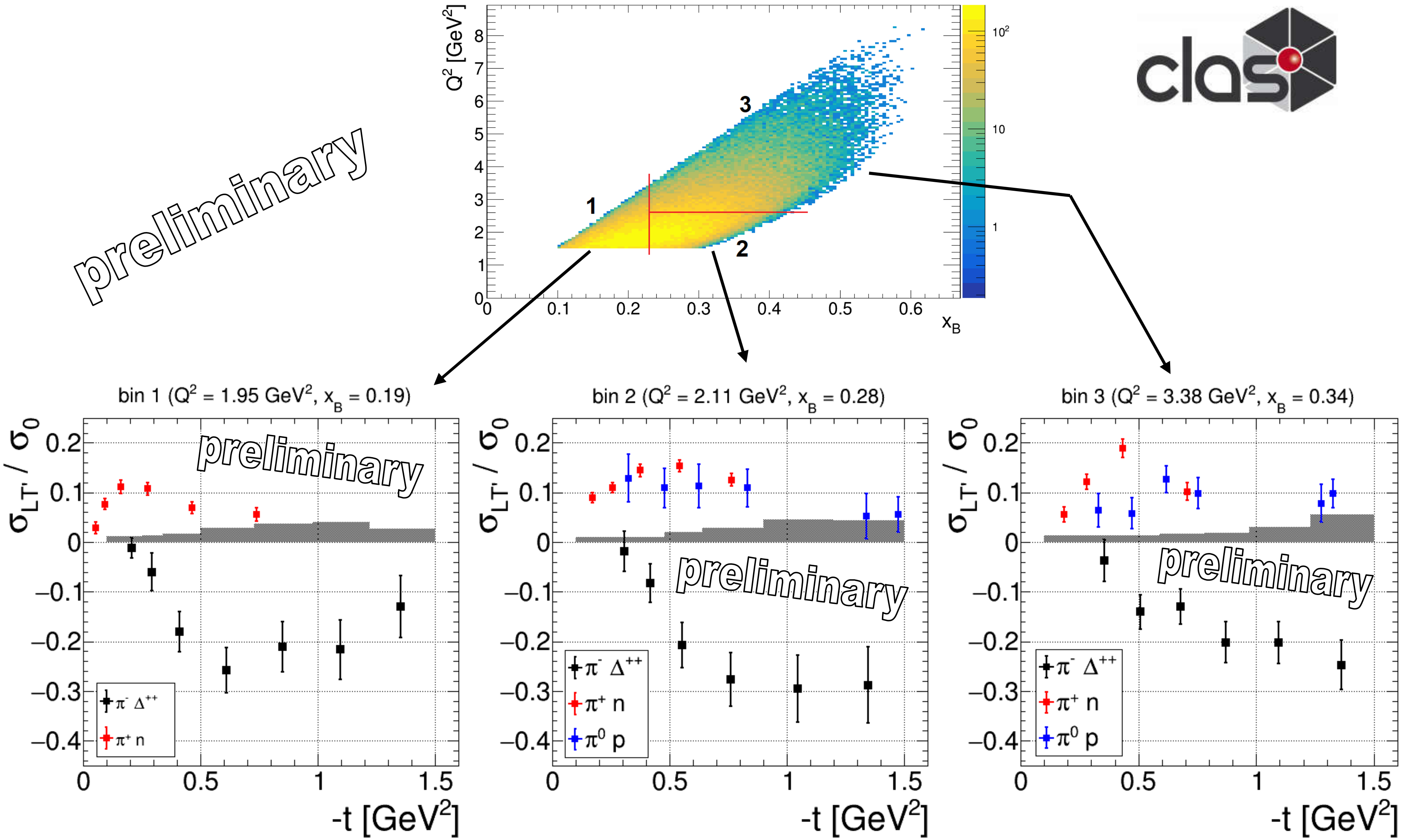
Q^2 - x_B Integrated Result



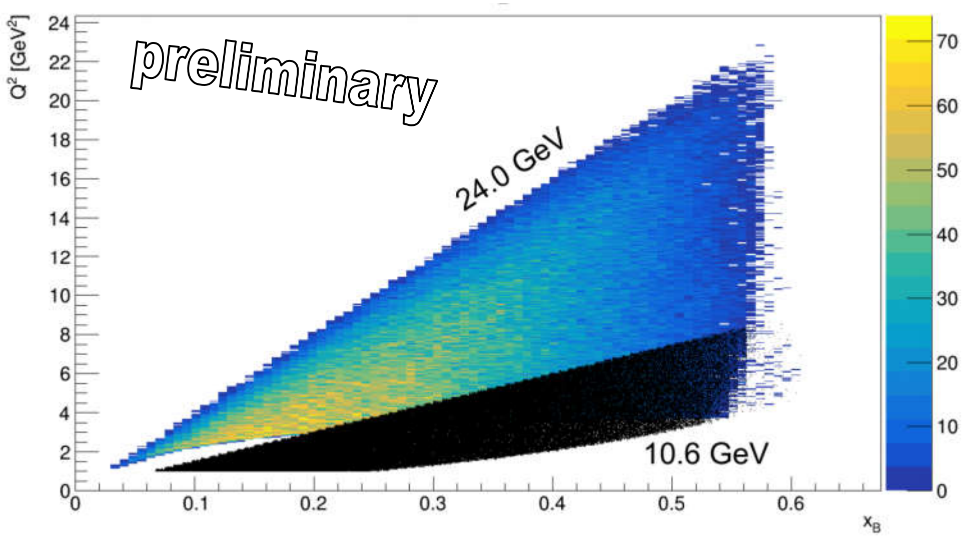
- The contribution of the non-resonant back-ground has been subtracted

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



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

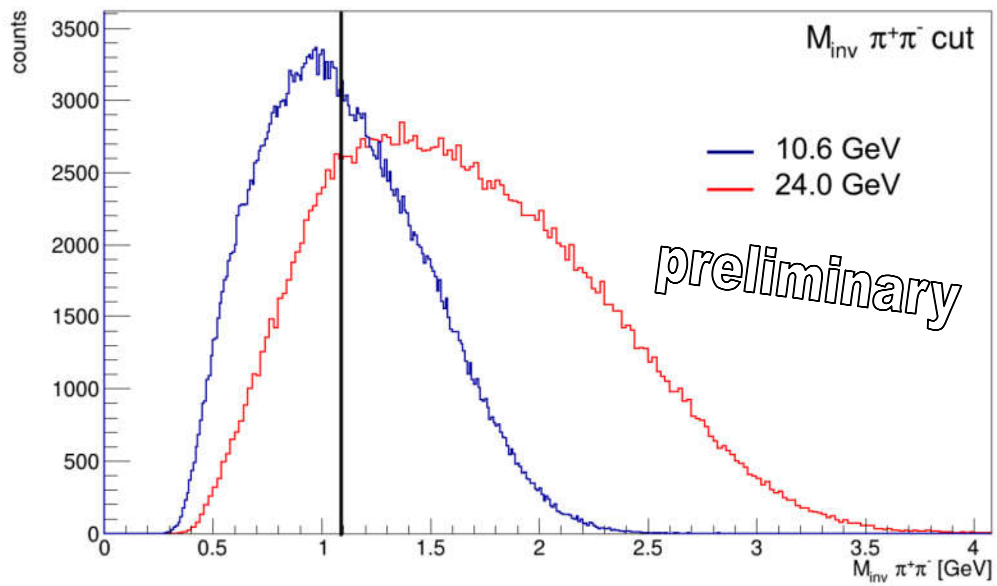
Extended Q² range

→ 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 needed

  ➔ Connection of transition GPDs to physics properties (sum rules etc.) needed

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