Studies of Transition GPDs in Hall B

Towards improved hadron femtography with hard exclusive reactions 2023

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For the CLAS Collaboration

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clas

Generalized Parton Distributions (GPDs)

$$\rho(x, \vec{k}_T, \vec{b}_T)$$

$$\downarrow \int d^2 k_T \downarrow$$

Integrate over transverse ***momentum*** space

↓

Generalized Parton Distributions (GPDs)

↓

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

S. Liuti et al., Phys. Rev. D 84, 034007 (2011) (GGL)

P. Kroll et al., Eur. Phys. J. A 47, 112 (2011) (GK)

quark pol.

nucleon pol.

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

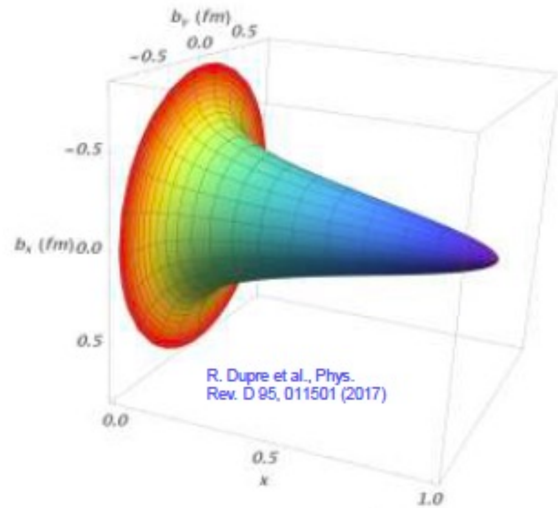
$$\bar{E}_T = 2\tilde{H}_T + E_T$$

Generalized Parton Distributions (GPDs)

$$\rho(x, \vec{k}_T, \vec{b}_T)$$

$$\downarrow \int d^2 k_T$$

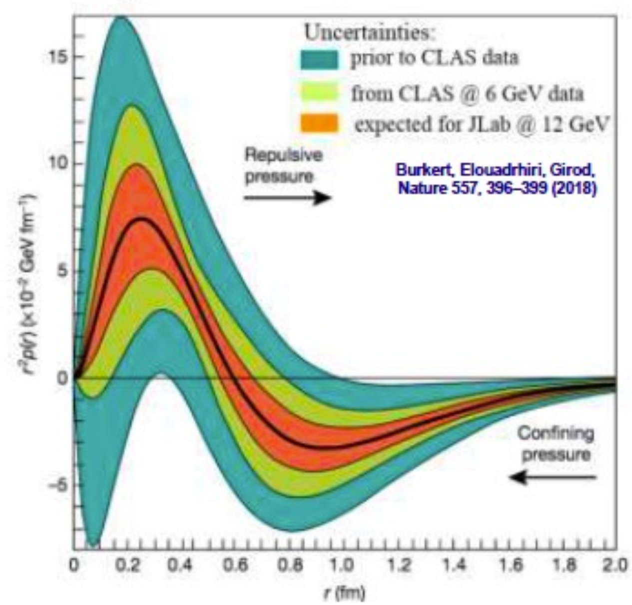
GPDs: 3-D nucleon images in the transverse coordinate and longitudinal momentum space



GPDs encode information on

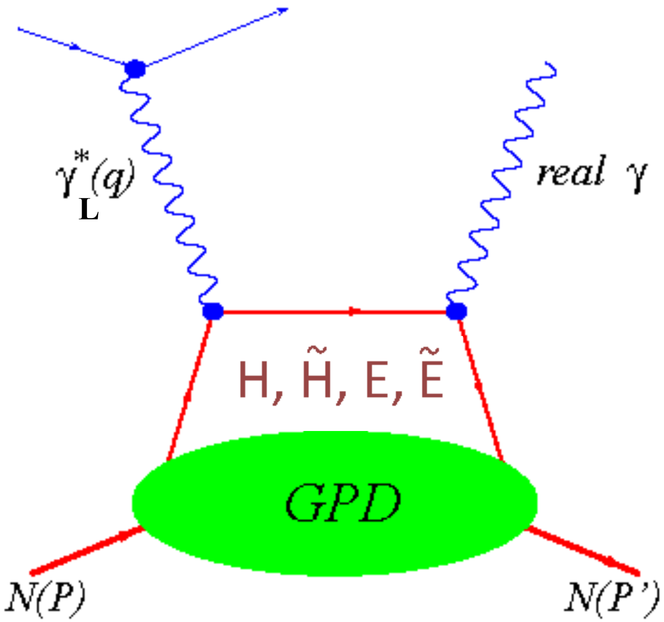
- ➔ **the distribution of pressure and shear forces via gravitational form factors**
- ➔ **the nucleon spin via Ji's sum rule**
- ➔ **the tensor charge**
- ➔ **the anomalous tensor magnetic moment**

....



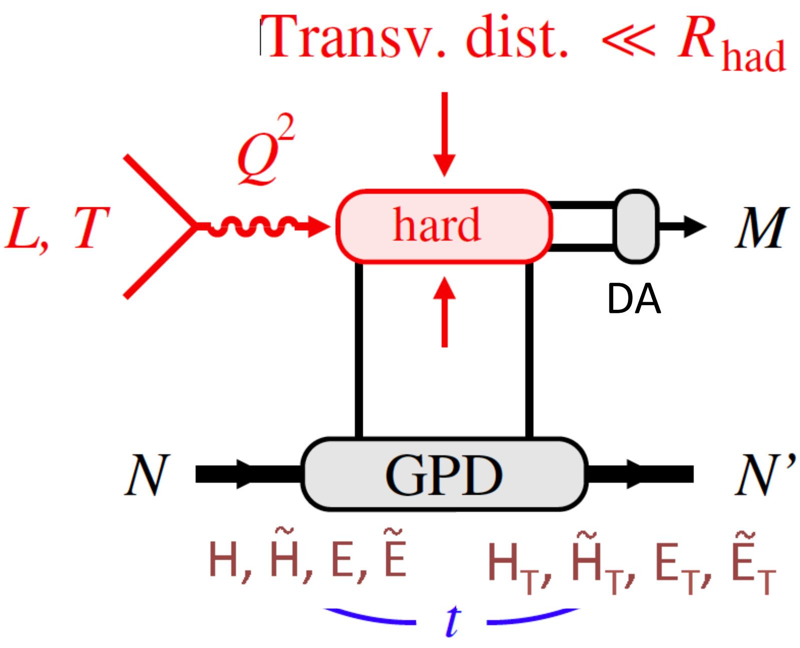
Study GPDs: Deeply Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



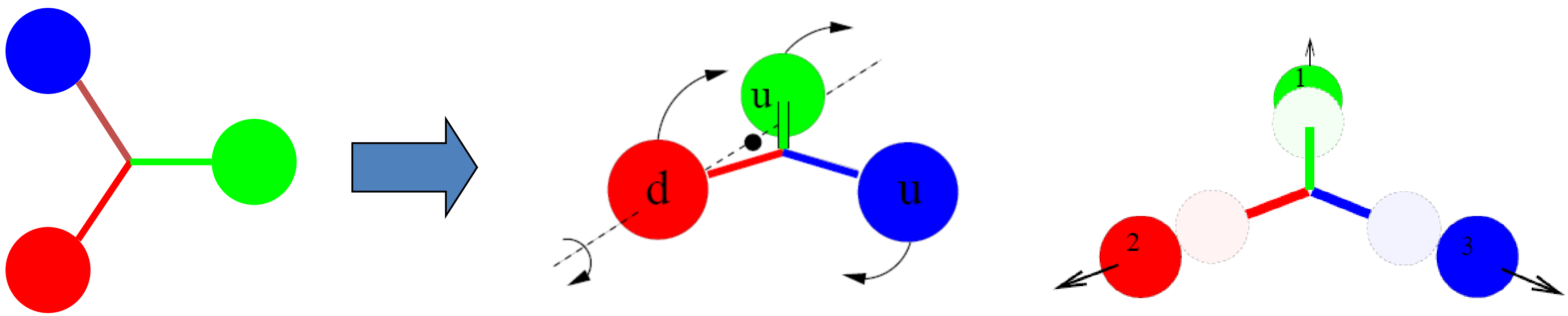
+ Clean process
- Only sensitive to chiral even GPDs

Deeply Virtual Meson Production (DVMP)



+ Access to transversity degrees of freedom described by chiral-odd GPDs
- Distribution Amplitude (DA) is involved as additional soft non pert. quantity

From the ground state nucleon to resonances



How does the exitation affect the 3D structure of the Nucleon?

→ Pressure distributions, tensor charge, … of resonances?

Traditional way: Study of transition form factors (**2D picture** of transv. position)

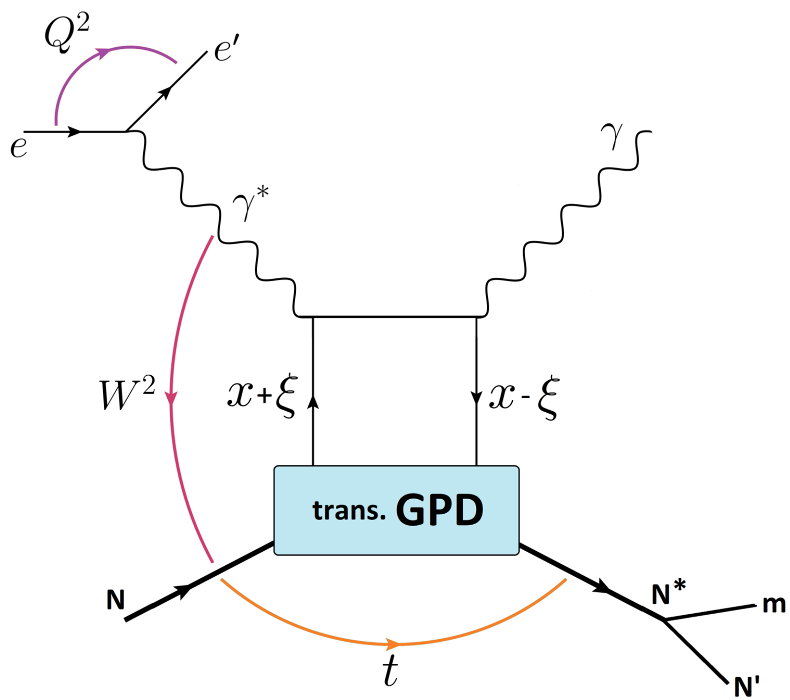
3D picture of the exitation process: Encoded in **transition GPDs**

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

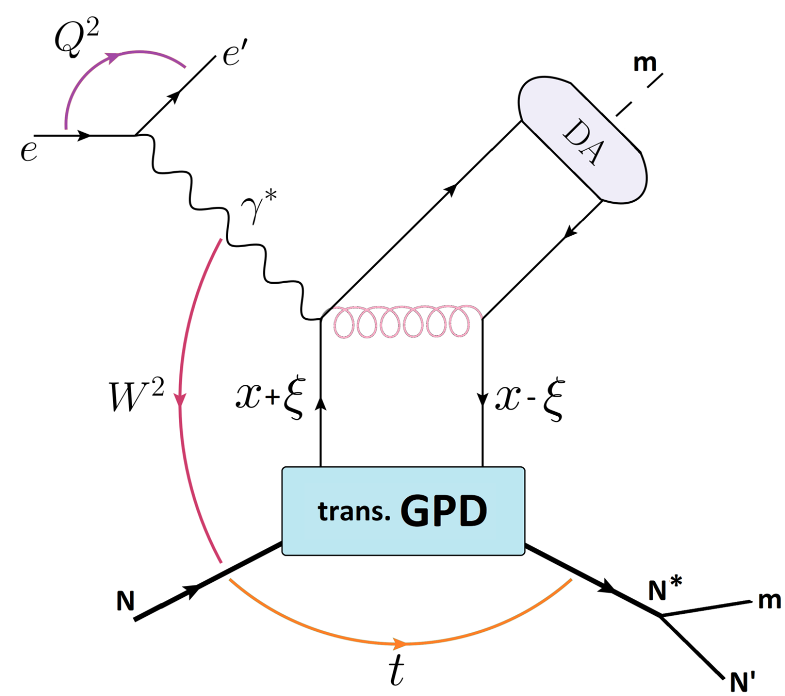
- **8 helicity non-flip transition GPDs (twist 2)**
  - Related to the Jones-Scardon and Adler EM FF for the N → Δ transition
- **8 helicity flip transition GPDs (transversity)**

Non-diagonal DVCS / DVMP

non-diagonal DVCS



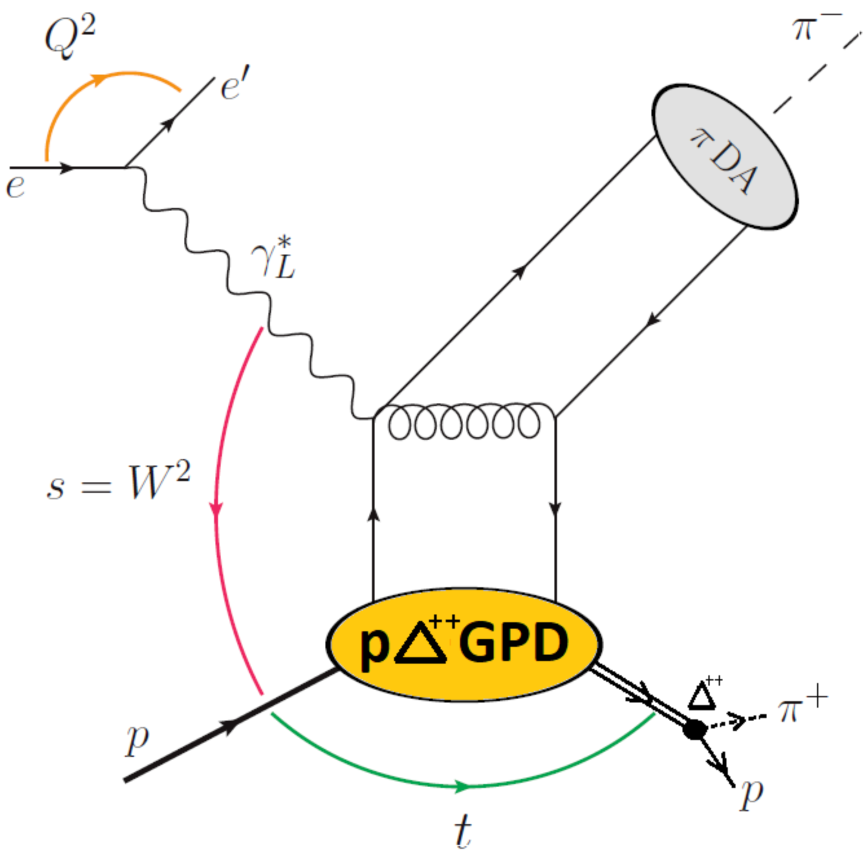
non-diagonal DVMP



factorization expected for: $-t/Q^2$ small, $Q^2 > M^2_{N*}$ x_B fixed

8 helicity non-flip trans. GPDs + 8 helicity flip trans. GPDs

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



Factorization expected for:

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

➔ Provides access to p-Δ transition GPDs

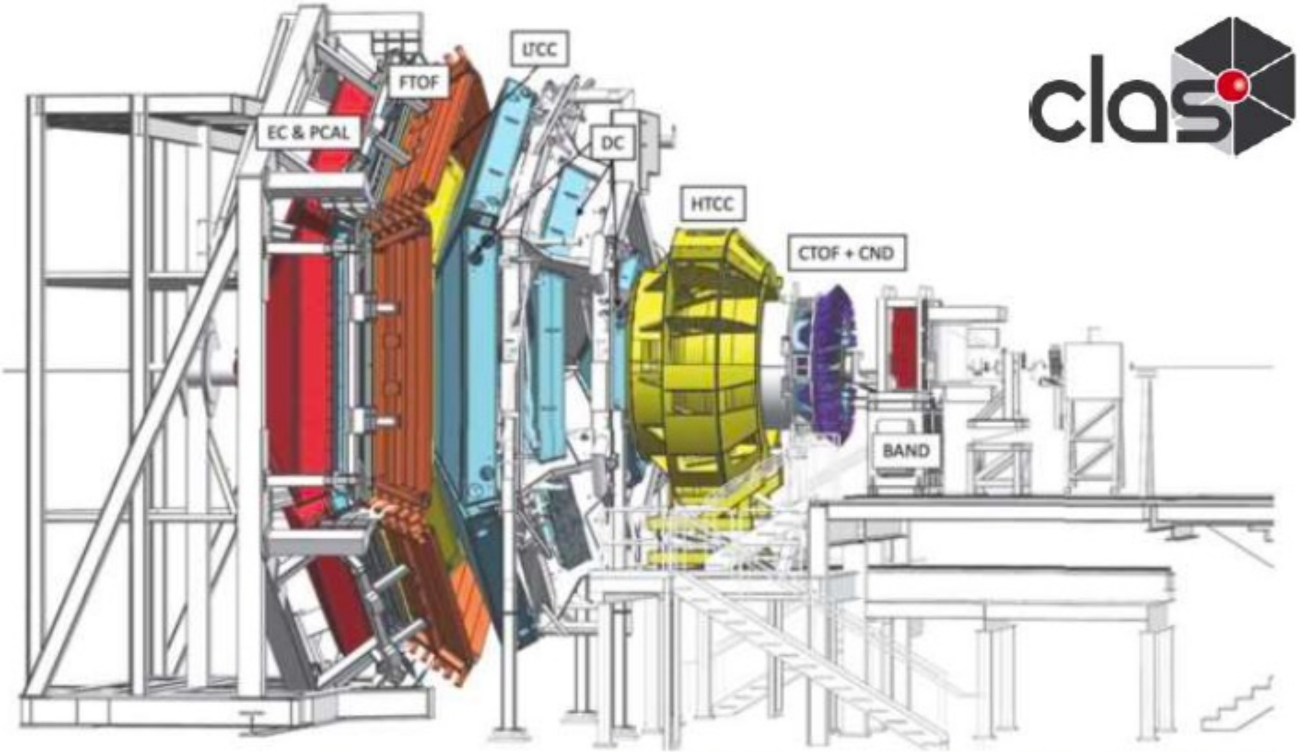
➔ 3D structure of the Δ resonance and of the excitation process

First Measurement of Hard Exclusive $\pi^-\Delta^{++}$ Electroproduction Beam-Spin Asymmetries off the Proton

S. Diehl,[34,6] N. Trotta,[6] K. Joo,[6] P. Achenbach,[39] Z. Akbar,[46,12] W. R. Armstrong,[1] H. Atac,[38] H. Avakian,[39] L. Baashen,[11] N. A. Baltzell,[39] L. Barion,[15] M. Bashkanov,[45] M. Battaglieri,[17] I. Bedlinskiy,[28] F. Benmokhtar,[8] A. Bianconi,[42,20] A. S. Biselli,[9] F. Bossù,[4] K.-T. Brinkmann,[34] W. J. Briscoe,[13] D. Bulumulla,[33] V. Burkert,[39] R. Capobianco,[6] D. S. Carman,[39] J. C. Carvajal,[11] A. Celentano,[17] G. Charles,[21,33] P. Chatagnon,[39,21] V. Chesnokov,[36] G. Ciullo,[15,10] P. L. Cole,[25] M. Contalbrigo,[15] G. Costantini,[42,20] V. Crede,[12] A. D'Angelo,[18,35] N. Dashyan,[48] R. De Vita,[17] A. Deur,[39] C. Djalali,[32,37] R. Dupre,[21] M. Ehrhart,[21,*] A. El Alaoui,[40] L. El Fassi,[27] L. Elouadrhiri,[39] S. Fegan,[45] A. Filippi,[19] G. Gavalian,[39] D. I. Glazier,[44] A. A. Golubenko,[36] G. Gosta,[42,20] R. W. Gothe,[37] Y. Gotra,[39] K. Griffioen,[47] K. Hafidi,[1] H. Hakobyan,[40] M. Hattawy,[33,1] T. B. Hayward,[6] D. Heddle,[5,39] A. Hobart,[21] M. Holtrop,[29] I. Illari,[13] D. G. Ireland,[44] E. L. Isupov,[36] H. S. Jo,[24] R. Johnston,[26] D. Keller,[46] M. Khachatryan,[33] A. Khanal,[11] A. Kim,[6] W. Kim,[24] V. Klimenko,[6] A. Kripko,[34] V. Kubarovsky,[39] S. E. Kuhn,[33] V. Lagerquist,[33] L. Lanza,[18,35] M. Leali,[42,20] S. Lee,[1] P. Lenisa,[15,10] X. Li,[26] I. J. D. MacGregor,[44] D. Marchand,[21] V. Mascagna,[42,41,20] G. Matousek,[7] B. McKinnon,[44] C. McLauchlin,[37] Z. E. Meziani,[1,38] S. Migliorati,[42,20] R. G. Milner,[26] T. Mineeva,[40] M. Mirazita,[16] V. Mokeev,[39] P. Moran,[26] C. Munoz Camacho,[21] P. Naidoo,[44] K. Neupane,[37] S. Niccolai,[21] G. Niculescu,[23] M. Osipenko,[17] P. Pandey,[33] M. Paolone,[30,38] L. L. Pappalardo,[15,10] R. Paremuzyan,[39,29] S. J. Paul,[43] W. Phelps,[5,13] N. Pilleux,[21] M. Pokhrel,[33] J. Poudel,[33,†] J. W. Price,[2] Y. Prok,[33] A. Radic,[40] B. A. Raue,[11] T. Reed,[11] J. Richards,[6] M. Ripani,[17] J. Ritman,[14,22] P. Rossi,[39,16] F. Sabatié,[4] C. Salgado,[31] S. Schadmand,[14] A. Schmidt,[13,26] Y. G. Sharabian,[39] U. Shrestha,[6,32] D. Sokhan,[4,44] N. Sparveris,[38] M. Spreafico,[17] S. Stepanyan,[39] I. Strakovsky,[13] S. Strauch,[37] M. Turisini,[16] R. Tyson,[44] M. Ungaro,[39] S. Vallarino,[15] L. Venturelli,[42,20] H. Voskanyan,[48] E. Voutier,[21] D. P. Watts,[45] X. Wei,[39] R. Williams,[45] R. Wishart,[44] M. H. Wood,[3] M. Yurov,[27] N. Zachariou,[45] Z. W. Zhao,[7,33] and M. Zurek[1]

(CLAS Collaboration)

CLAS12 at JLAB



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

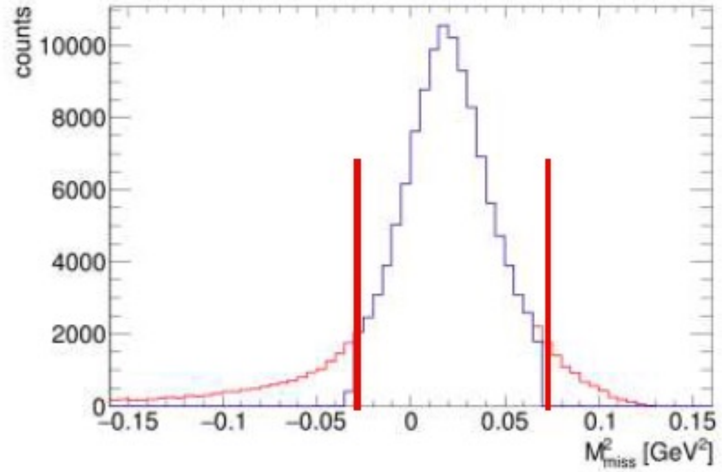
- ➔ Data recorded with CLAS12 during fall 2018 and spring 2019 (RG-A)
  - ➔ 10.6 GeV / 10.2 GeV electron beam ~ 86 % average polarization
  - ➔ liquid H_2 target

Event Selection and Kinematic Cuts

Event selection: $ep \rightarrow ep\pi^- X$

$$X = \pi^+$$

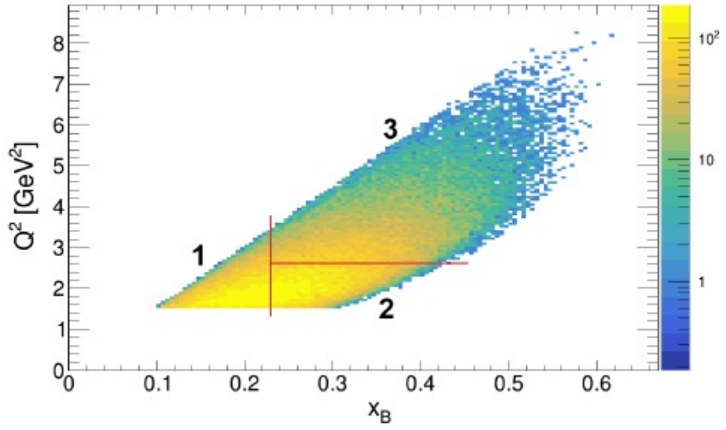
➔ 2 sigma cut around the missing π^+



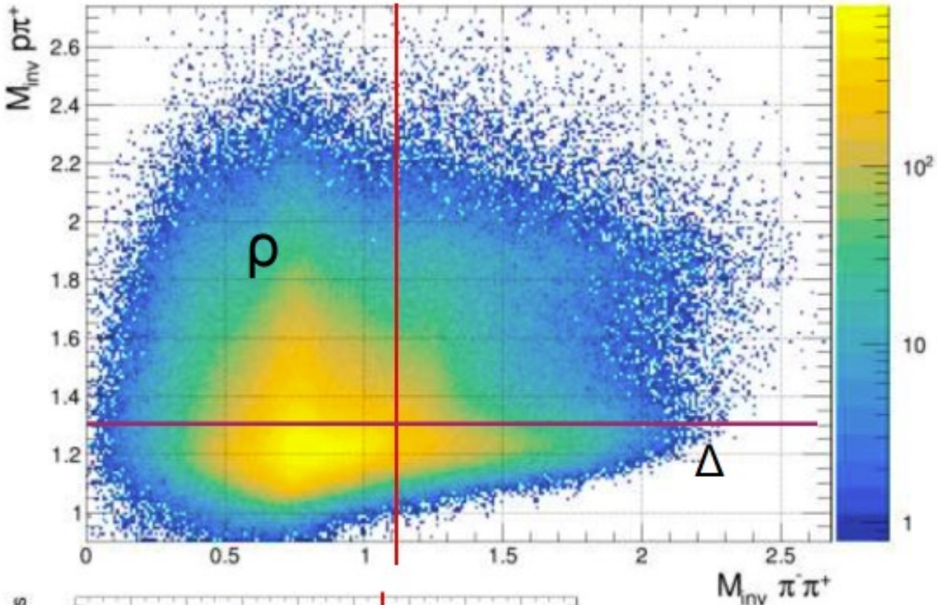
Kinematic cuts:

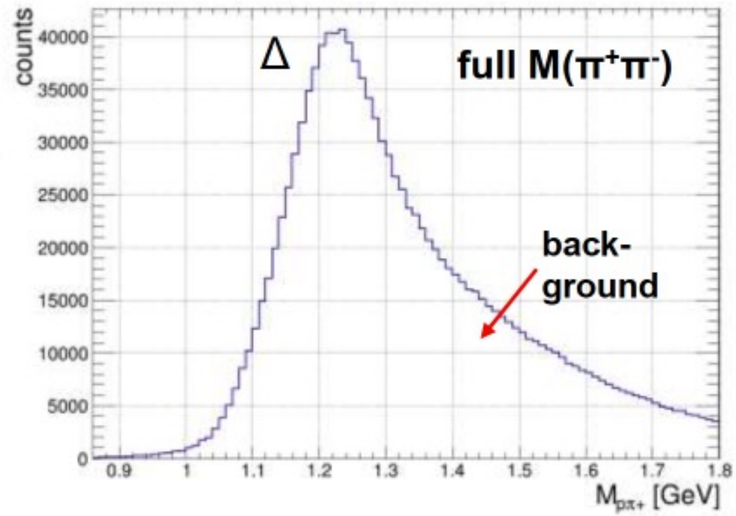
$Q^2 > 1.5$ GeV² $W > 2$ GeV

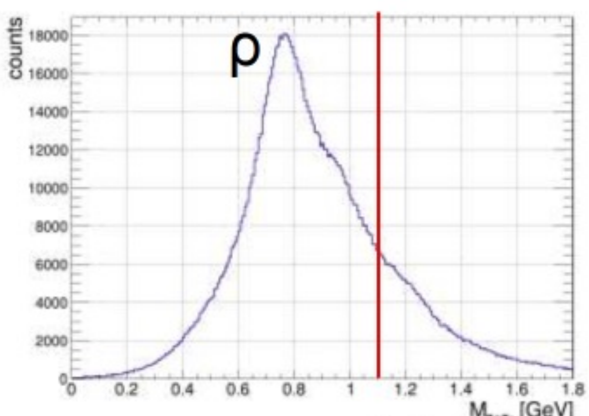
$y < 0.75$ $-t < 1.5$ GeV²



Event Selection and Background Rejection





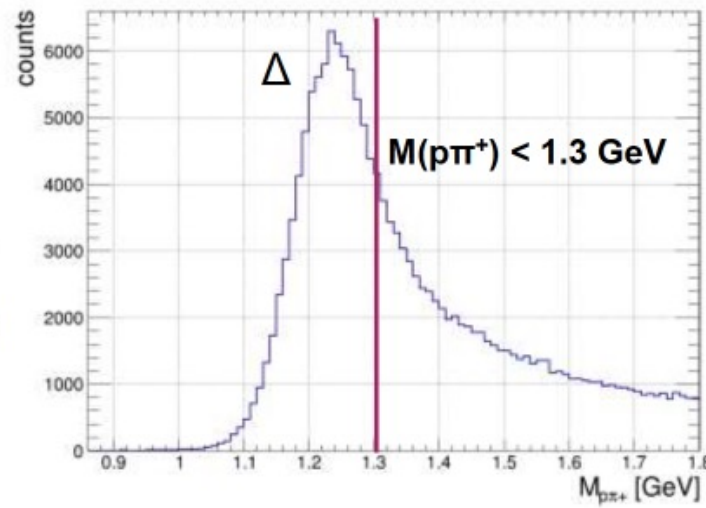


$$ep \to ep\rho \to ep\pi^+\pi^-$$

M(π⁺π⁻) > 1.1 GeV

ρ contamination

< 0.8 %



Monte Carlo Simulations

2 MC samples have been used:

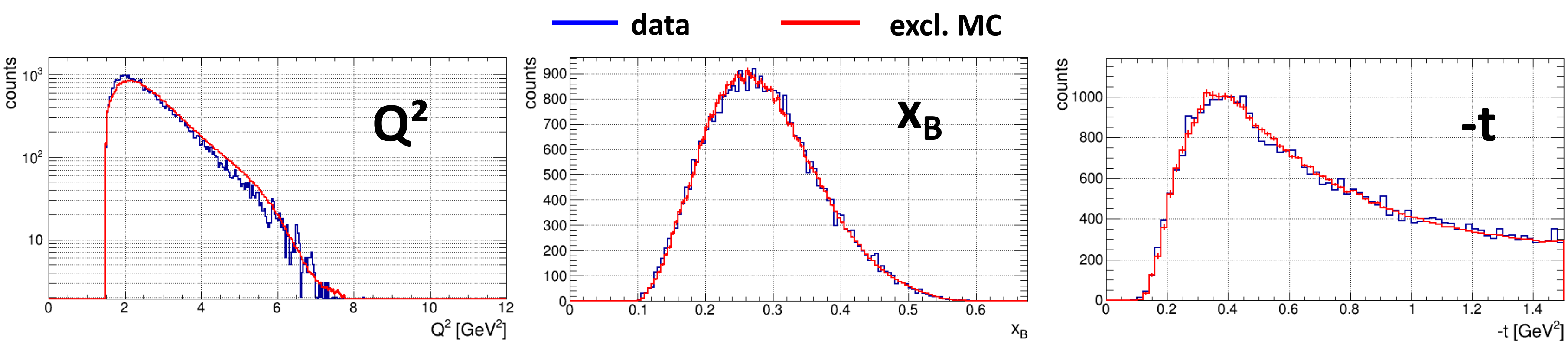
a) Background: Semi-inclusive DIS MC

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

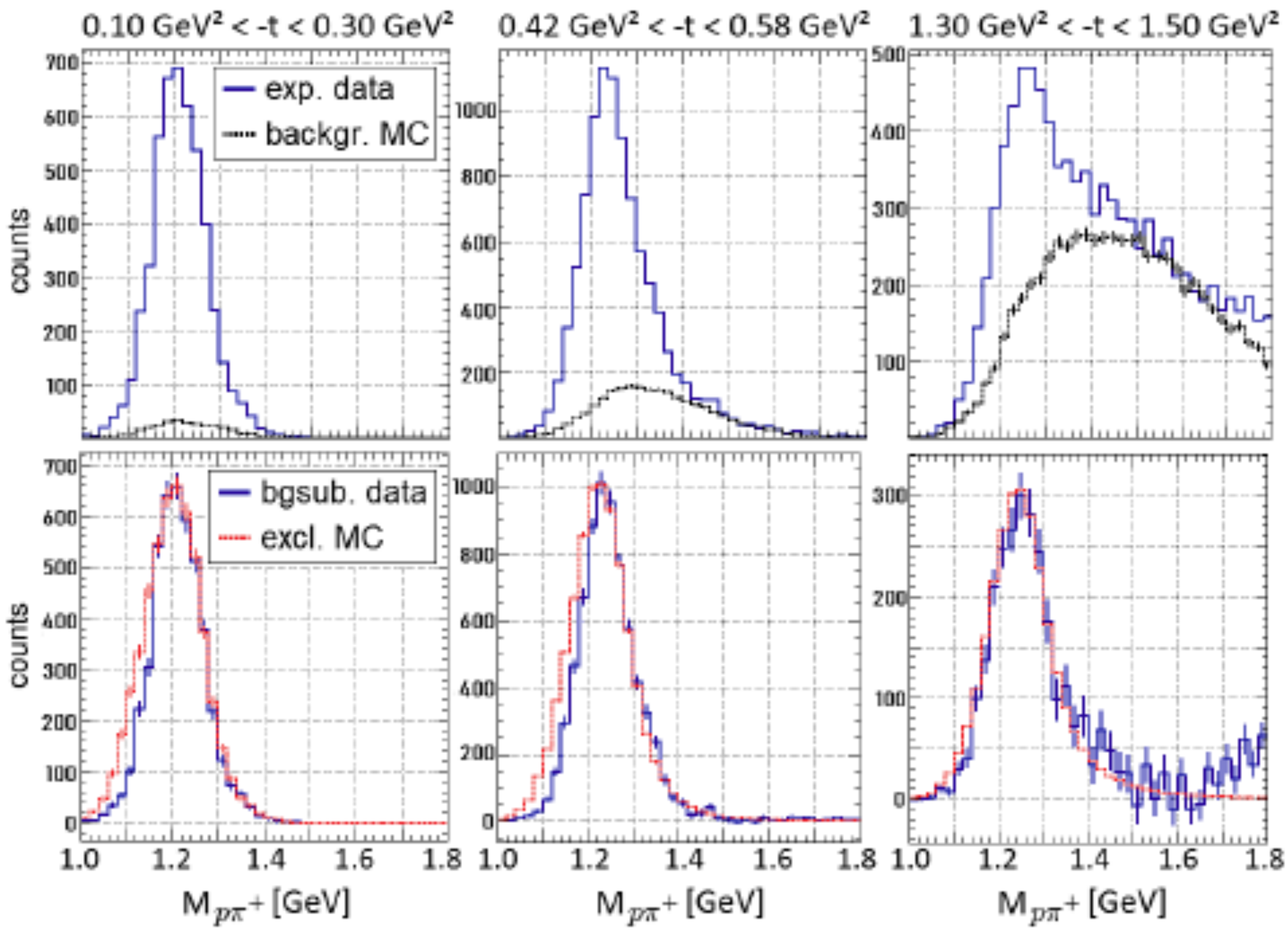
b) Signal: Exclusive $\pi^- \Delta^{++}$ MC

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

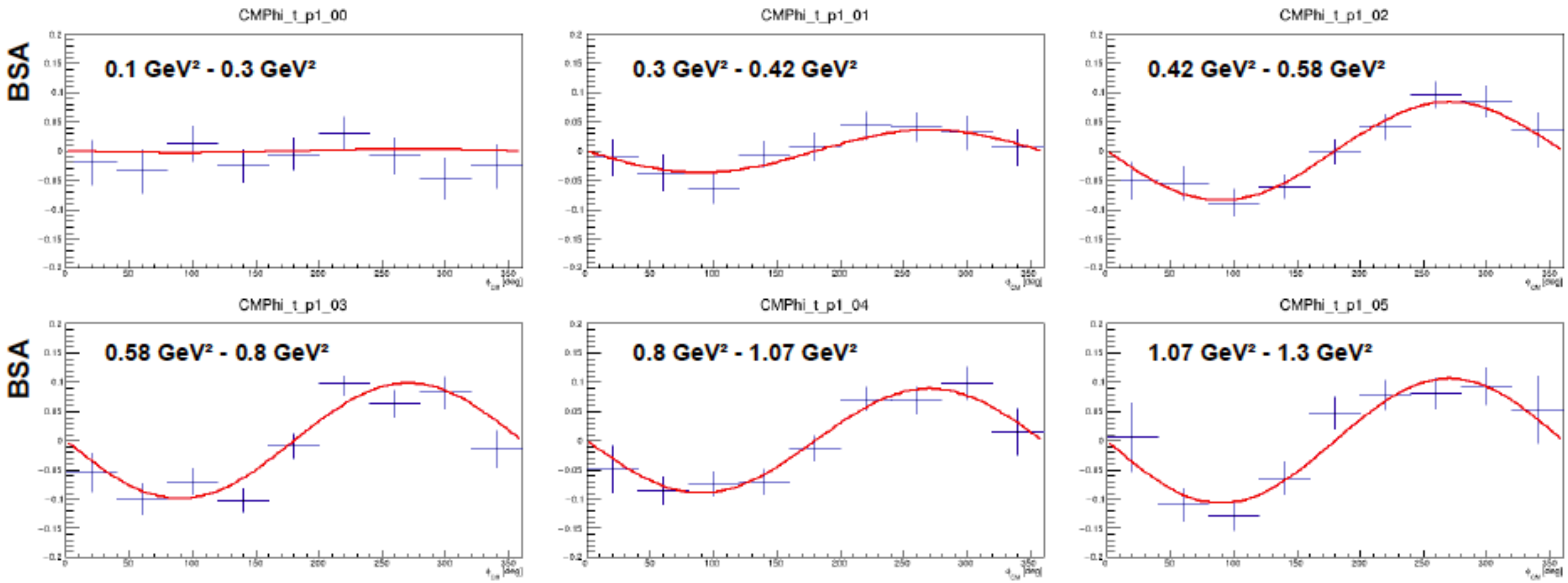
➔ Both MCs are processed through the full simulation and reconstruction chain

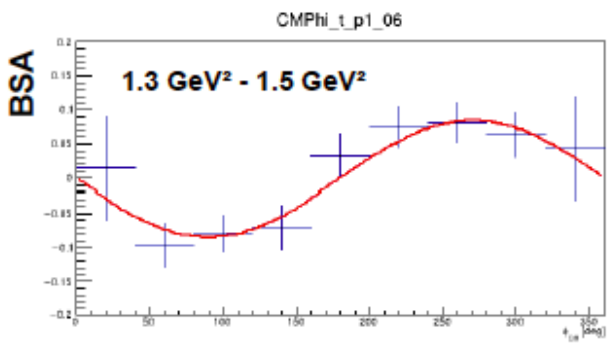


Signal and Background Separation



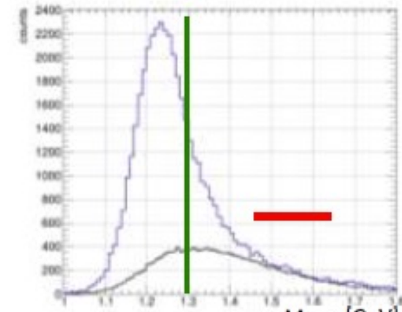
Resulting Beam Spin Asymmetries (Q^2-x_B integrated)





$$BSA_i = \frac{1}{P_e}\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-} \sim \sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi$$

Background Asymmetry Subtraction

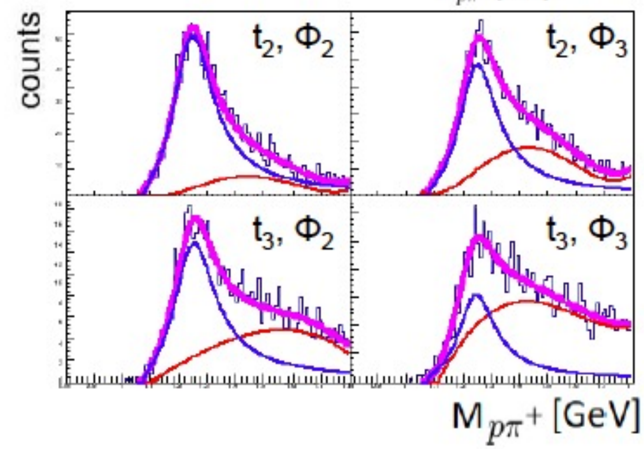


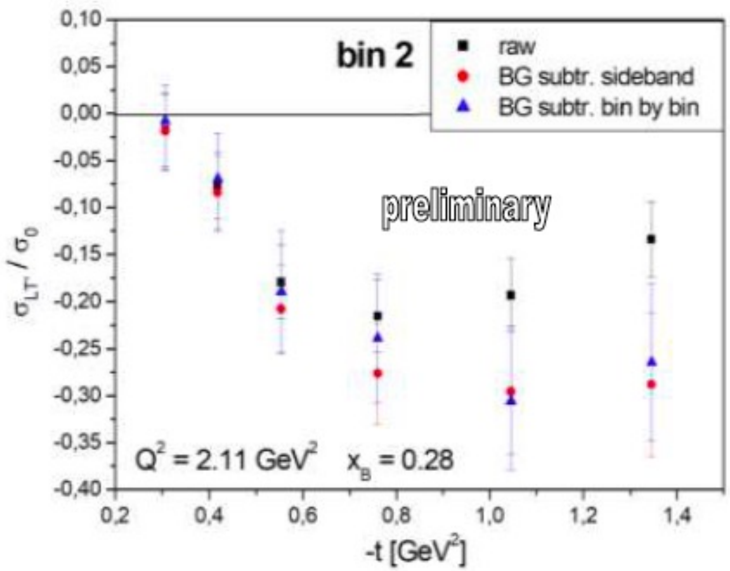
Method 1: **A sideband based background subtraction**

- S/B ratio from a fit of the signal shape and background asymmtry from the sideband

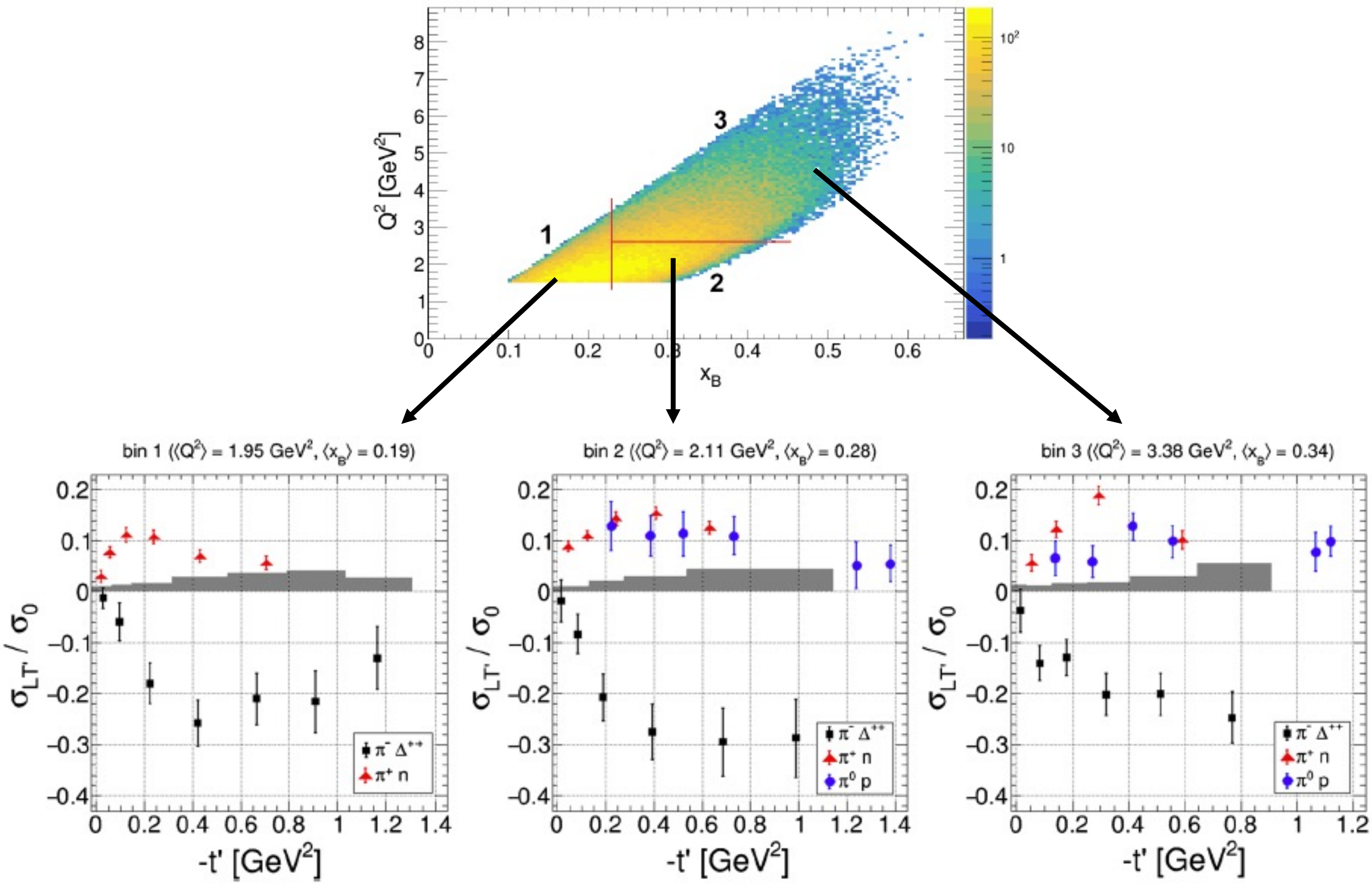
Method 2: **A bin-by-bin background subtraction**

- Fit of the $p\pi^+$ inv. mass with a „Sill“ function and a 5th order polynomial in each Q^2, x_B, -t, Φ bin.





Results

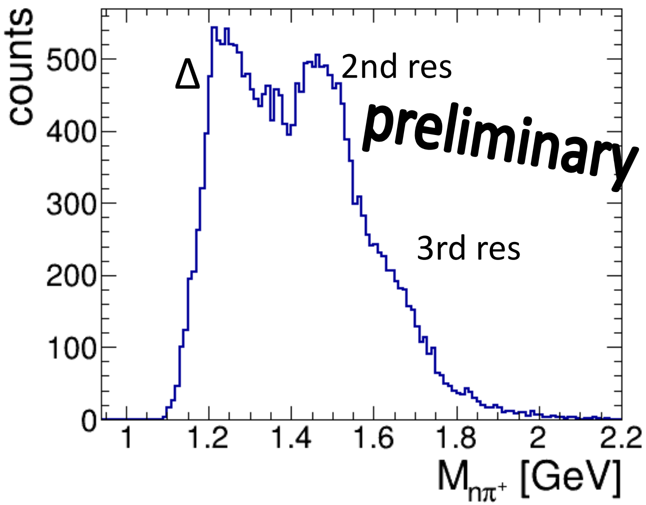


Q^2 [GeV^2]
x$_B$
1
2
3
bin 1 (⟨Q^2⟩ = 1.95 GeV^2, ⟨x$_B$⟩ = 0.19)
bin 2 (⟨Q^2⟩ = 2.11 GeV^2, ⟨x$_B$⟩ = 0.28)
bin 3 (⟨Q^2⟩ = 3.38 GeV^2, ⟨x$_B$⟩ = 0.34)
σ$_{LT'}$ / σ$_0$
-t' [GeV^2]
π$^-$ Δ^{++}
π$^+$ n
π^0 p

Outlook and Next Steps

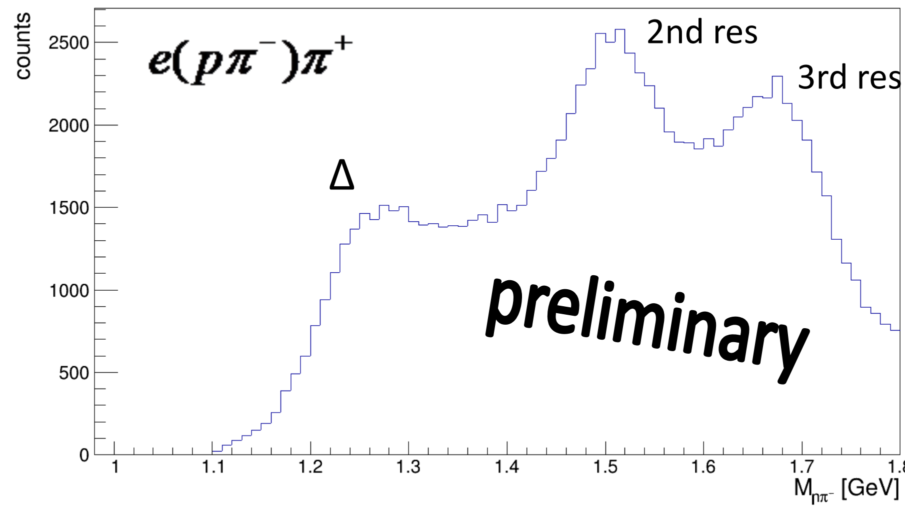
non-diagonal DVCS

$$e\,p \rightarrow e'\,\Delta^+\,\gamma \rightarrow e'\,n\,\pi^+\,\gamma$$



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**

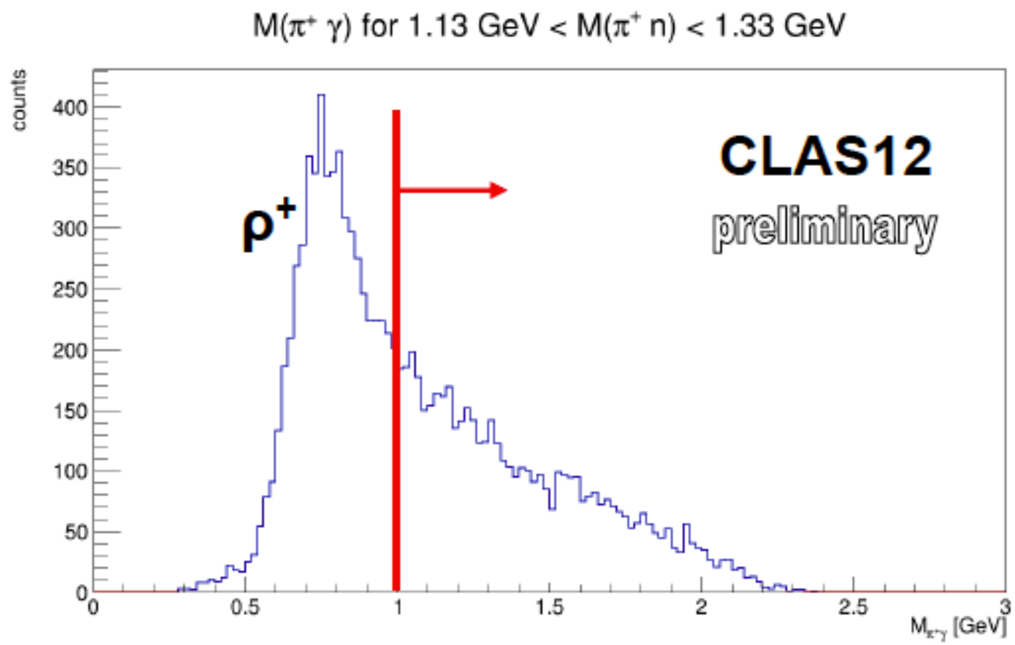
- Large gap between Δ(1232) and higher resonances

Non-Diagonal DVCS

$$e\,p \rightarrow e'\,\Delta^+\,\gamma \rightarrow e'\,n\,\pi^+\,\gamma$$

Kinematic cuts: $W > 2$ GeV $Q^2 > 1$ GeV² $y < 0.8$ $-t < 2$ GeV² $E_{DVCS} > 2$ GeV

Background:

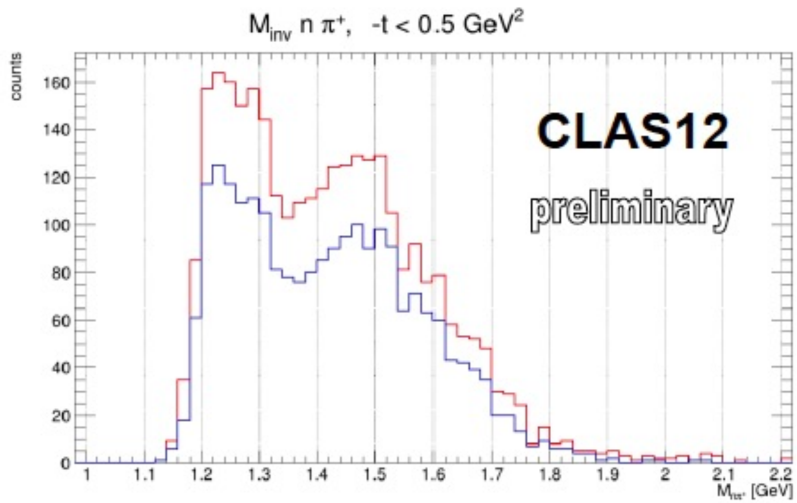


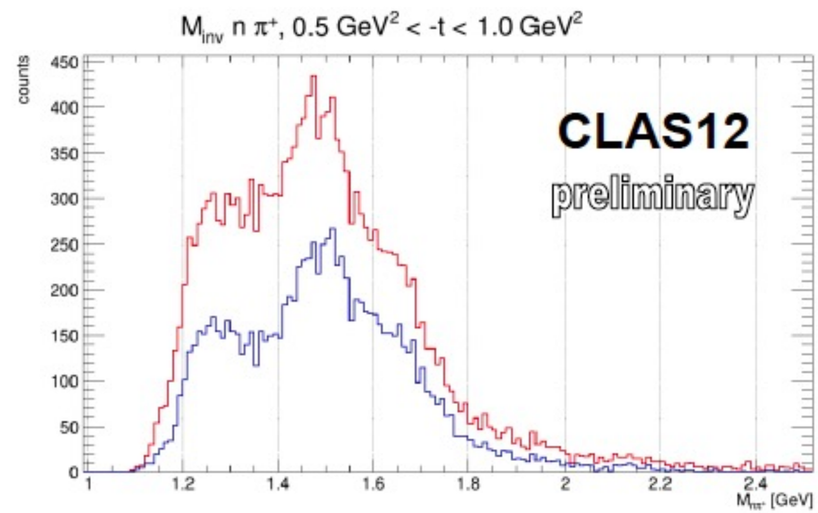
- Dominant background from $\rho^+ \rightarrow \pi^+\,\gamma$

$e\,p \rightarrow e'\,\Delta^+\,\gamma \rightarrow e'\,n\,\pi^+\,\gamma$

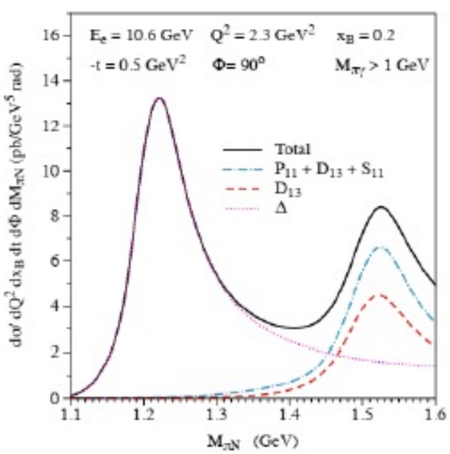
$e\,p \rightarrow e'\,\Delta^+\,\gamma \rightarrow e'\,n\,\pi^+\,\gamma$

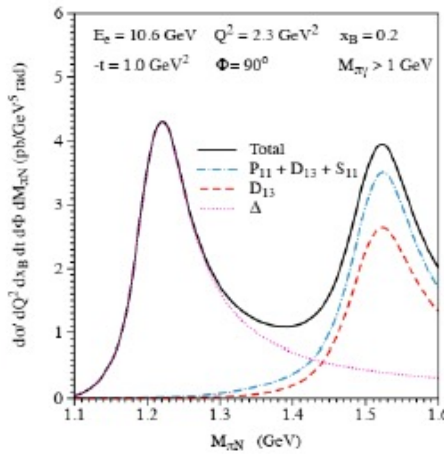
raw — $M(\pi^+\gamma) > 1.0$ GeV





Semenov-Tian-Shansky, Vanderhaeghen, arXiv:2303.00119 (2023)



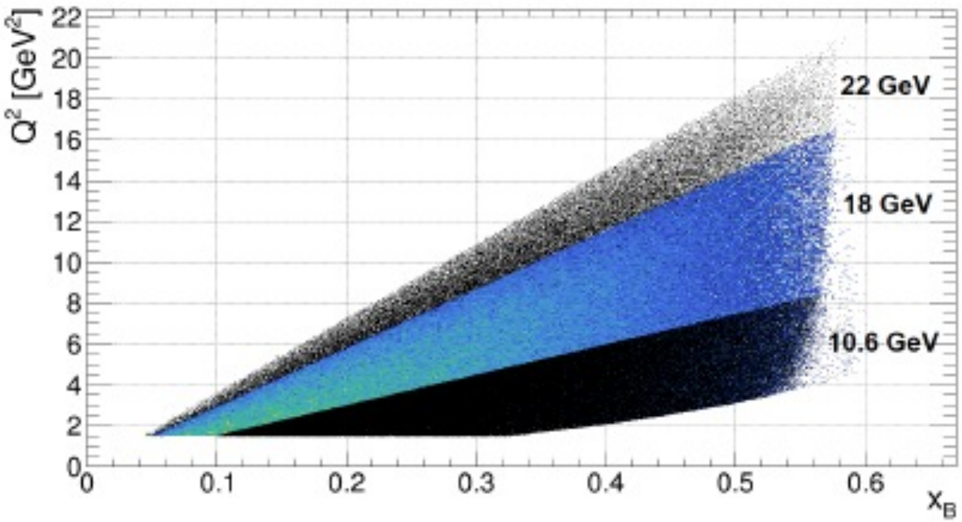


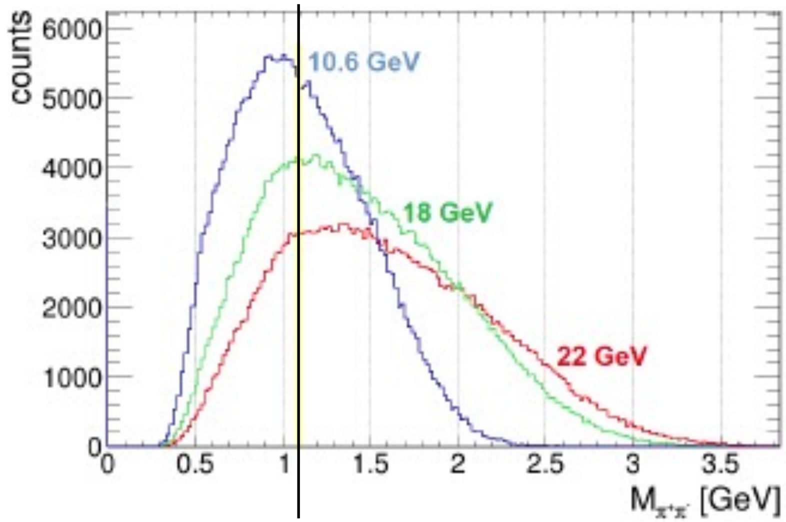
- study in progress
- π^+ mainly in CD and low momentum
- Good agreement of BSA
- awaiting pass 2

Studies of Transition GPDs at JLab 22 GeV

Q^2-x_B

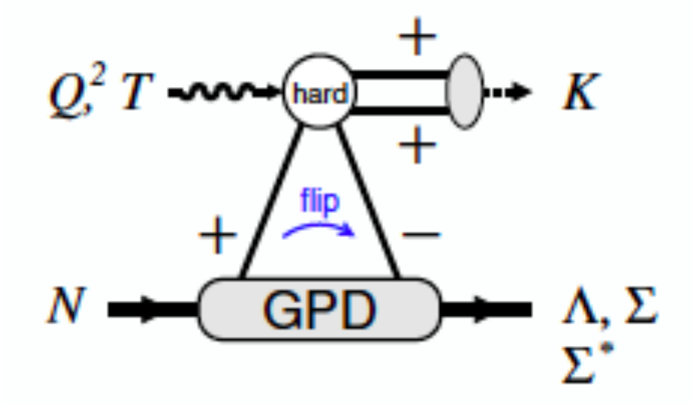
$M_{\pi+\pi-}$





- Comparison of the available phase space, accessible with the present CLAS12 setup, in $Q^2 - x_B$ or the $\pi^-\Delta$++ process under forward kinematics ($-t < 1.5$ GeV^2) (left) and for the $\pi+\pi-$ invariant mass of the same process.

N → Λ, Σ, Σ* GPDs in K production with CLAS12



Production mechanism

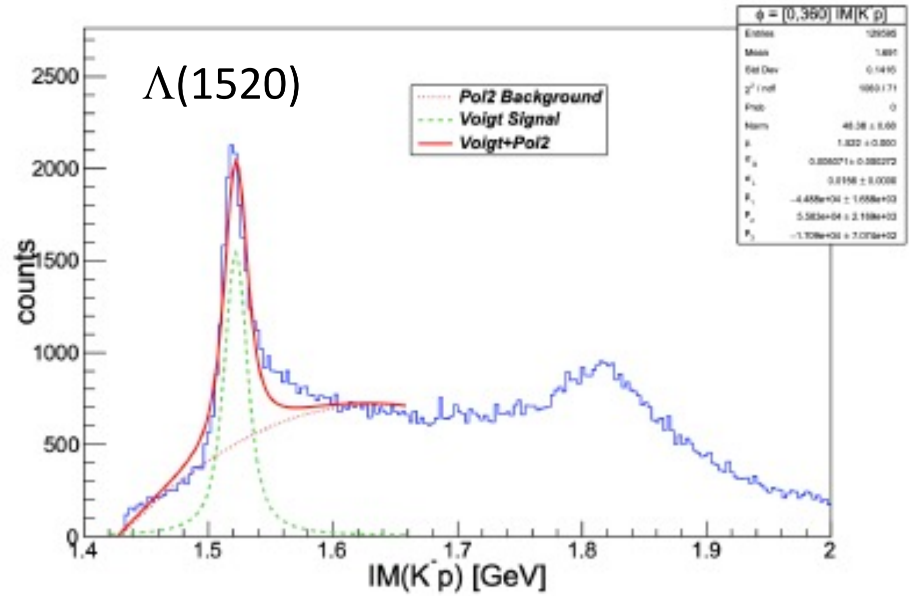
Same twist-3 mechanism with chiral-odd structures as π, η production

Symmetry relations for strange chiral-odd GPDs

$N \to \Lambda, \Sigma$ related to $N \to N$
by conventional SU(3) flavor symmetry

$N \to \Sigma^*$ related to $N \to N, \Lambda, \Sigma$
by SU(6) spin-flavor symmetry in large-N_c limit

Predictive power; quantitative predictions possible



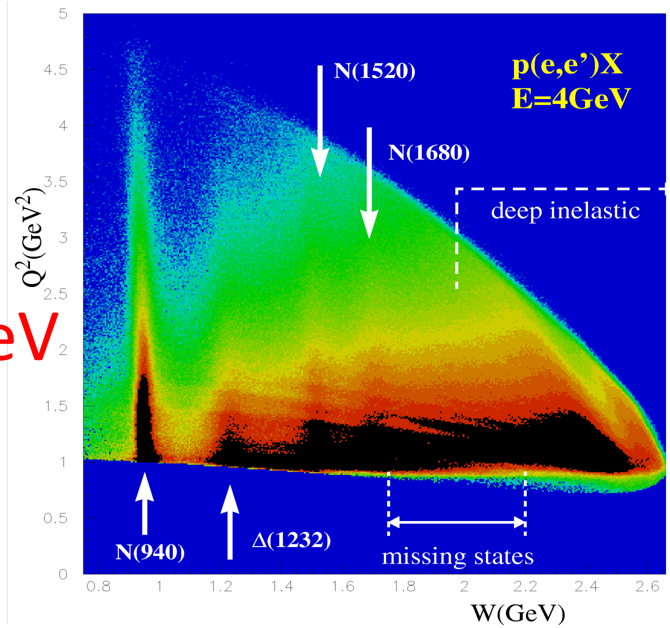
Invariant mass distribution of pK^- after $ep \to e'p'K^+K^-$ events are selected.

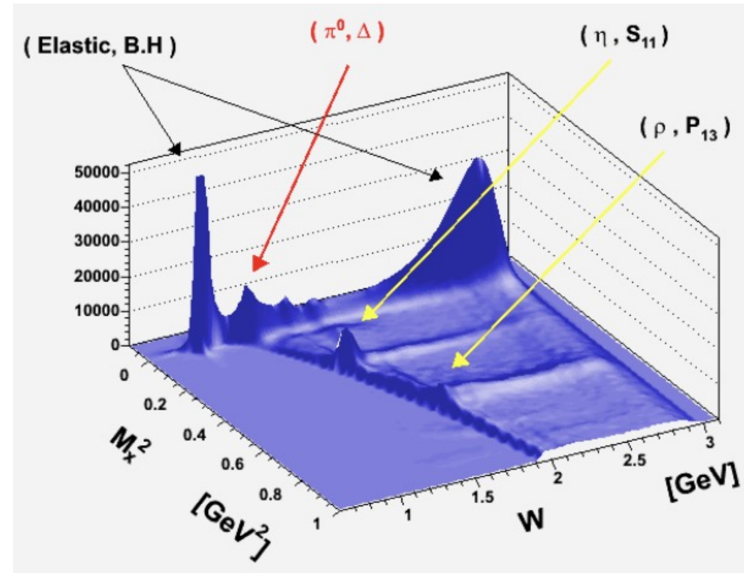
- 22 GeV kinematic coverage is similar to exlcusive $\Delta^{++}\,\pi^-$ production.

p(e,e')X

p(e,e'p)X

4-6 GeV

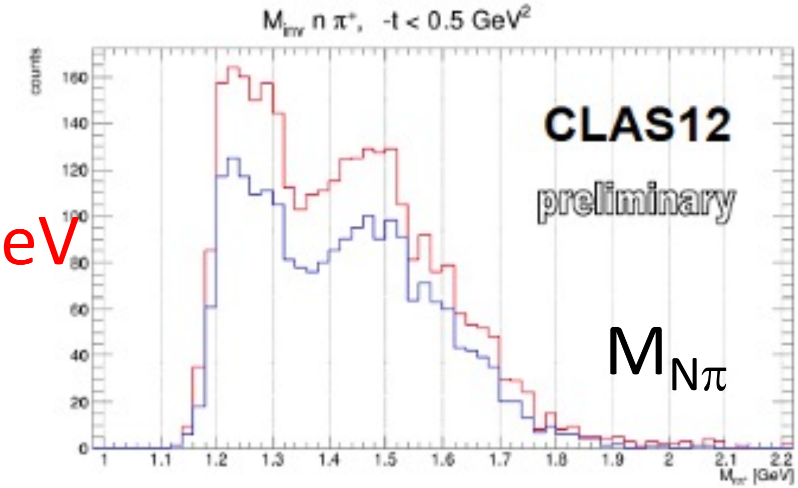


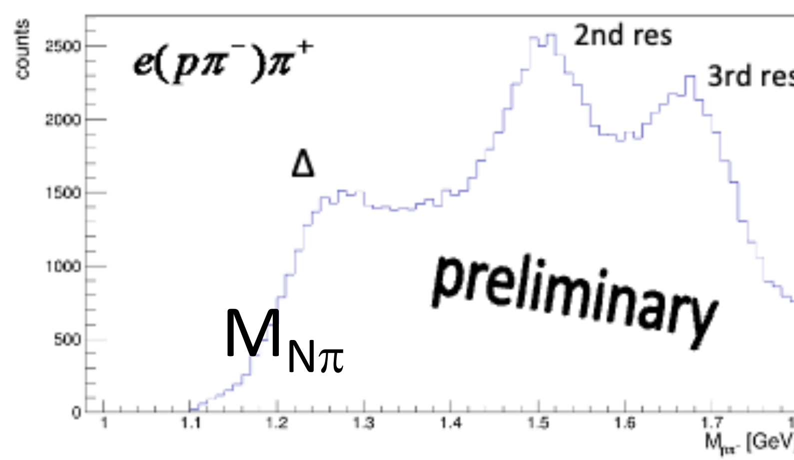


$$e\,p \rightarrow e'\,\Delta^+\,\gamma \rightarrow e'\,n\,\pi^+\,\gamma$$

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

11 GeV





Conclusion and Outlook

1. Hard exclusive $\pi^-\Delta^{++}$ production has been measured with CLAS12 and provides a first observable sensitive to p->D transition GPDs. (Phys. Rev. Lett. 131, 021901 (2023))
2. The obtained BSA is clearly negative and ~ 2 times larger that for π^+
3. A transition GPD based description of the reaction exists by P. Kroll and K. Passek-Kumericki (Phys. Rev. D 107, 054009 (2023)), but a reliable prediction of BSAs is not possible due to missing experimental constraints to the transversity transition GPDs.

Outlook

1. Cross sections and A_{LL} of $\pi^-\Delta^{++}$ (Run Group C) will provide further constraints to the transition GPDs.
2. Other N->N* DVMP processes are under investigation by scanning invariant mass of $N\pi$
3. The N->N* DVCS process will further constrain the twist-2 transition GPDs. K. Semenov, M. Vanderhaeghen, arXiv:2303.00119 (2023)

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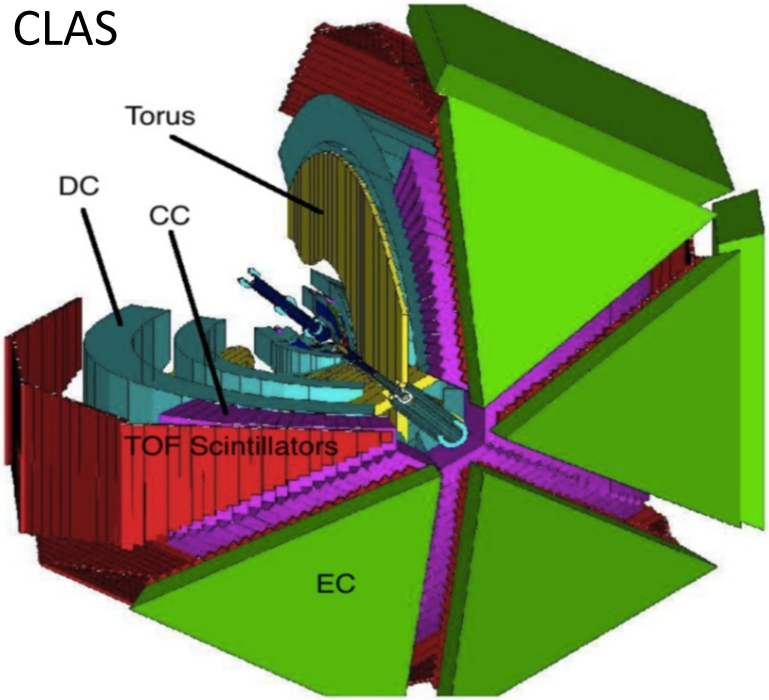
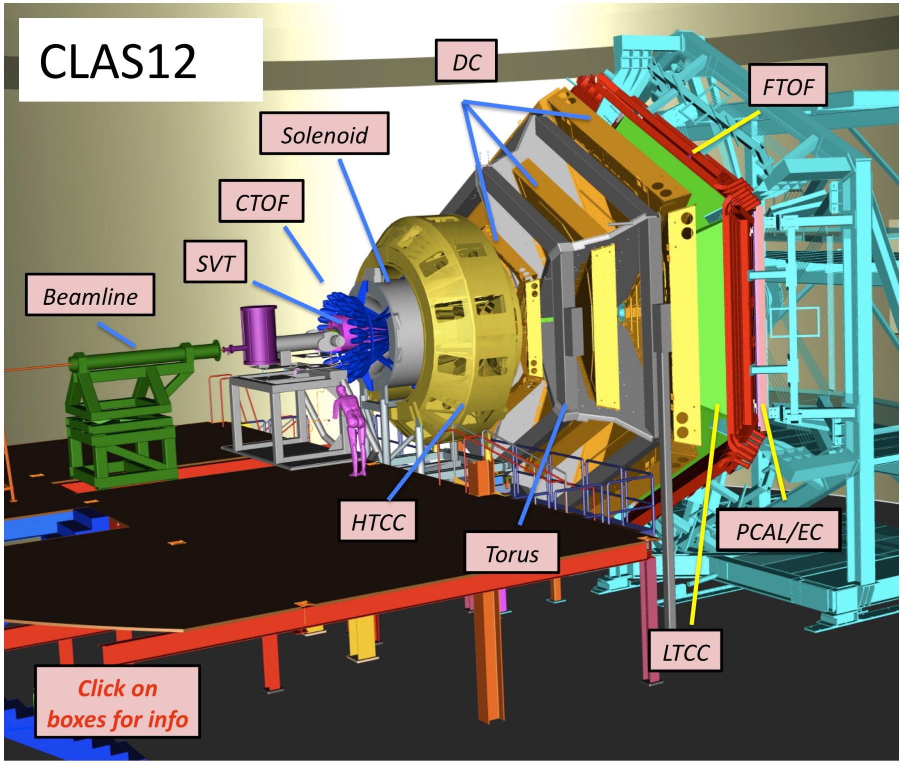




Transition Form Factors (N* Physics) at 6 GeV JLab Era → Transition GPDs (3D N* Physics) at 12-22 GeV JLab Era

Sources of Systematic Uncertainty

1. Uncertainty of the background subtraction

→ 2 sources of uncertainty: S/B ratio and sideband asymmetry

→ Both sources were varied within their uncertainty range

➔ Typically in the order of 1.5 % (low -t) - 12.5 % (high -t) (stat. ~ 12 – 25 %)

➔ Dominant sys. uncertainty for the high -t bins

2. Uncertainty of the beam polarization ~ 3.1 %

3. Effect of the extraction method and the denominator terms ~ 2.8 %

4. Acceptance and bin-migration effects ~ 2.9 %

→ Comparison of injected and reconstructed BSA in the MC

5. Radiative effects ~ 3.0 %

6. Other sources (particle ID, fiducial cuts, …) < 2.0 %

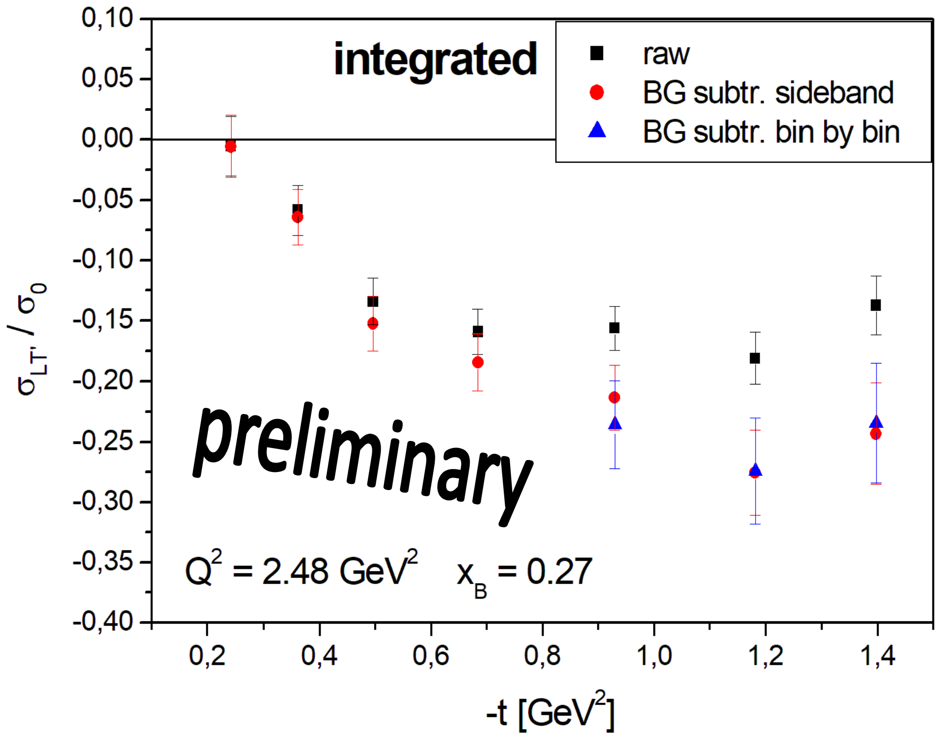
Total: 7.1 - 14.3 %

Background Subtraction

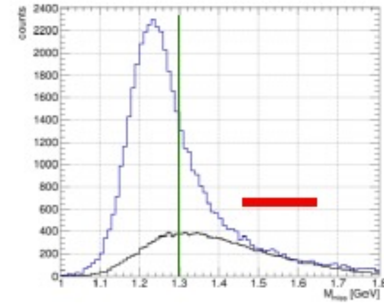
- Based on the obtained S/B ratio and based on the asymmetry of the sideband, the contribution of the non-resonant background has been subtracted.

- 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.

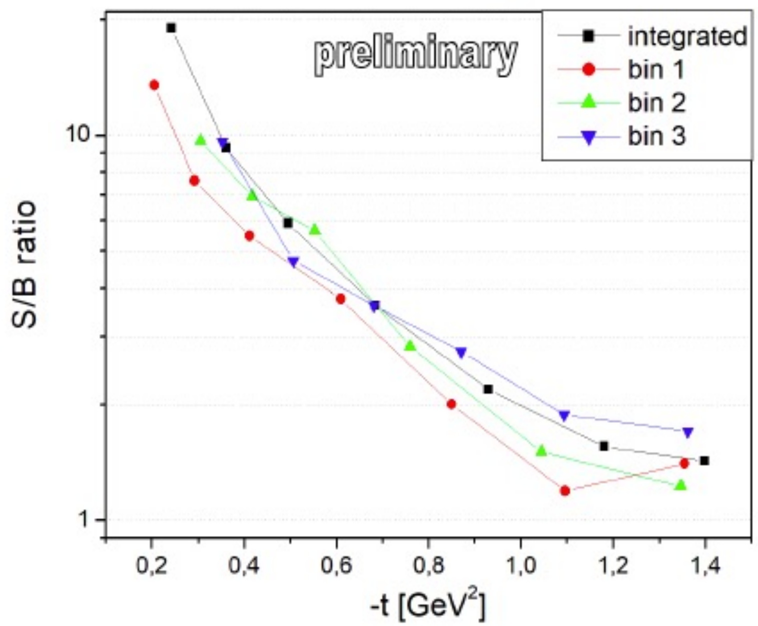


Background Subtraction

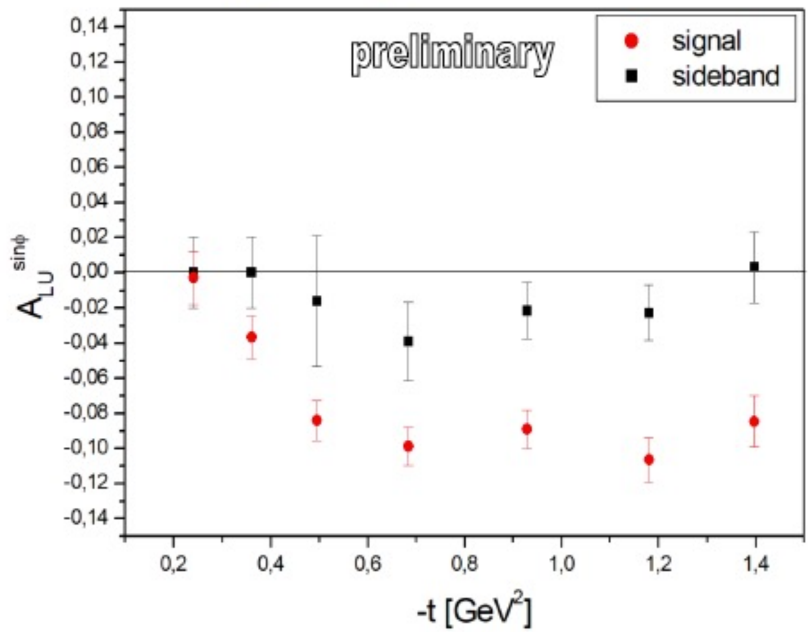


<u>Method 1</u>: A sideband based background subtraction

S/B ratio based on data - MC comparison



asymmetry of the sidebands



Background Subtraction

Method 2: A bin-by-bin background subtraction

- Fit of the $p\pi^+$ inv. mass with a „Sill" function and a 5th order polynomial in each Q^2, x_B, $-t$, Φ bin.