June 7-10, 2021

Strong QCD from Hadron Structure Experiments

Teleworkshop at Nanjing University, China

June 2021

N→N* transition GPD measurements with CLAS12 at JLAB

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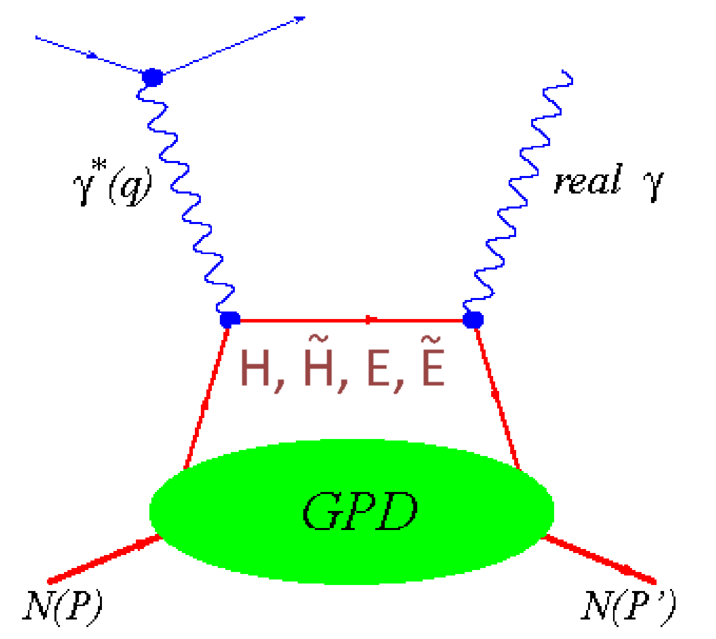
Introduction

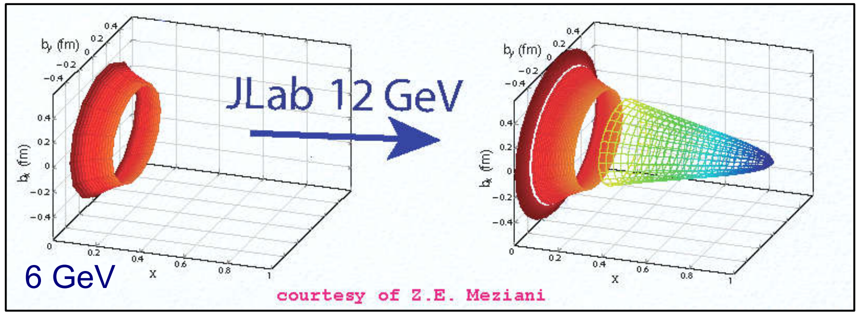
3D structure of the ground state nucleon: Classical GPDs

➔ Measured with processes like DVCS, DVMP, …



Deeply Virtual Compton Scattering (DVCS)

3D tomography of the nucleon:



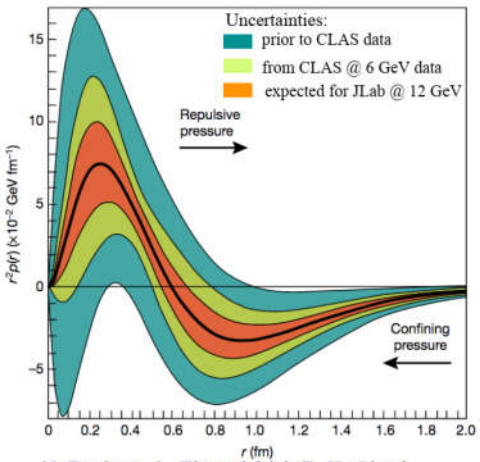
angular momentum

$$\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,dx = 2J(t)$$

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

mass

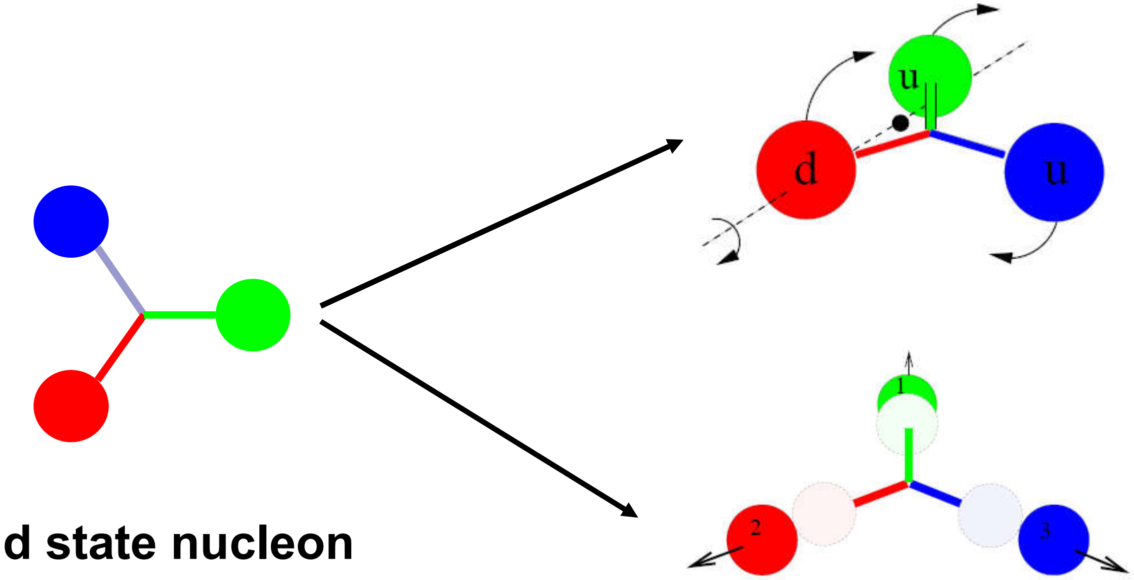
pressure and shear forces



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

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

Introduction



i.e. N(1535)

i.e. N(1440)

ground state nucleon
(classical GPDs)

3D structure of the excitation process / excited nucleon states
(N → N* transition GPDs)

➔ Investigate 3D dynamics of the excitation process (angular momentum-, pressure distributions, …)

➔ Map out the differences between orbital and radial excitations

Theoretical Description of Transition GPDs

Theoretical model so far only available for the N → Δ transition:

P.A.M Guichon, L. Mosse, M. Vanderhaeghen, Phys. Rev. D 68 (2003) 034018

8 twist-2 transition GPDs for the N → Δ transition:

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:

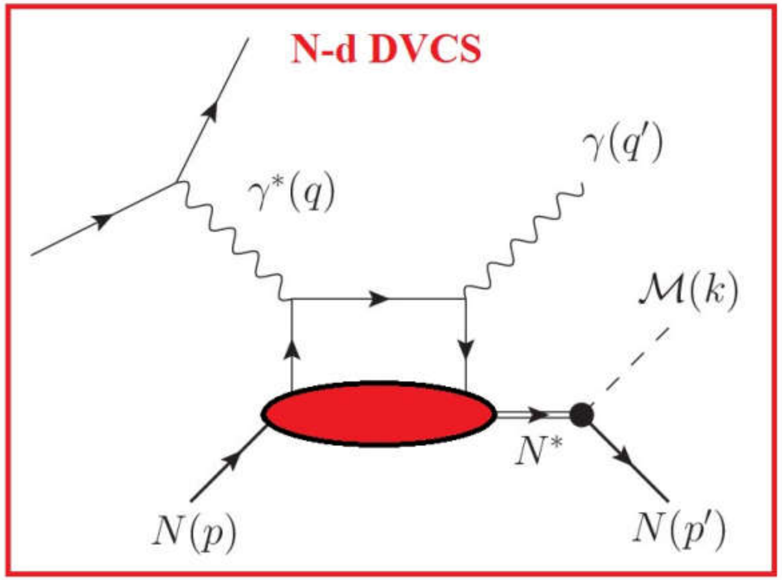
$$\left.\begin{aligned}\int_{-1}^{1} dx C_1(x;\xi;t) &= 2C_5^A(t)\\ \int_{-1}^{1} dx C_2(x;\xi;t) &= 2C_6^A(t)\\ \int_{-1}^{1} dx C_3(x;\xi;t) &= 2C_3^A(t)\\ \int_{-1}^{1} dx C_4(x;\xi;t) &= 2C_4^A(t)\end{aligned}\right\}$$

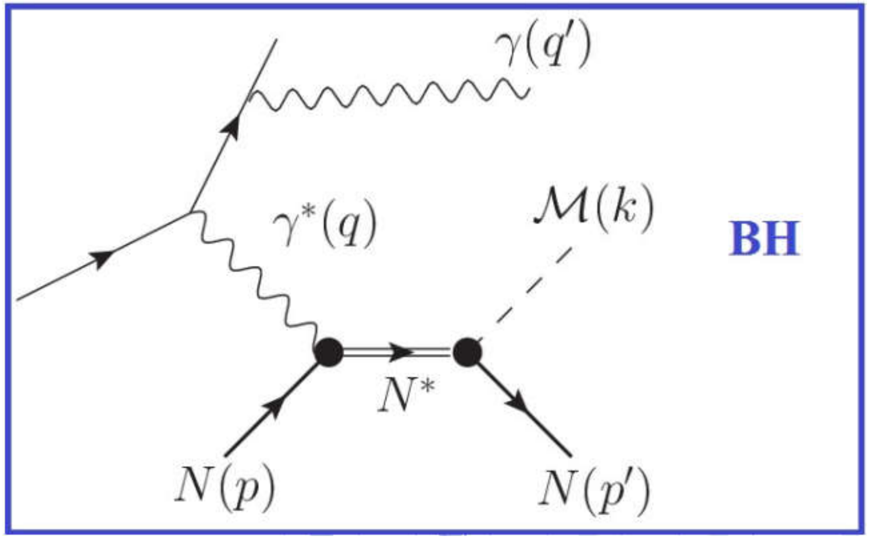
Adler form factors

Experimental Access to Transition GPDs

Non diagonal DVCS process

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





process factorizes for $Q^2 \rightarrow \infty, \ x_B \ \text{fixed}, \ t_\gamma/Q^2 \rightarrow 0, \ W^2/Q^2 \rightarrow 0$

Experimental Observables

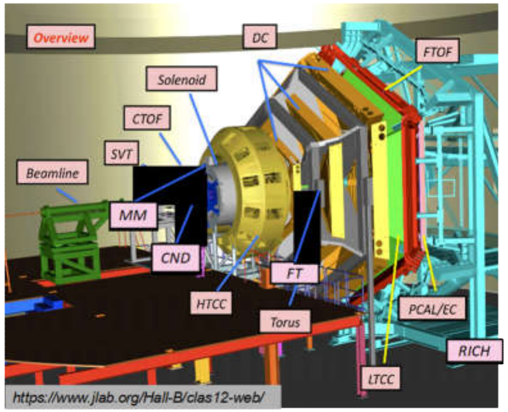
Two final states can be primarily studied:

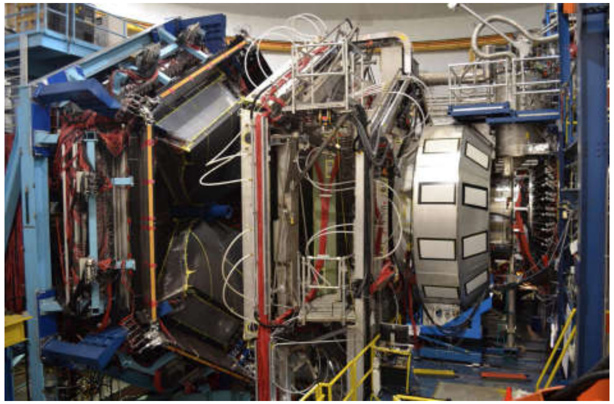
$$\gamma^* p \rightarrow N^* \gamma \rightarrow p\pi^0\gamma \rightarrow p\gamma\gamma\gamma$$

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

➔ Electron scattering in the DIS (high Q²) regime
➔ High rates
} 12 GeV CEBAF @ JLAB

➔ Detection of a multi particle final state (charged + neutral) under a large acceptance
} CLAS12



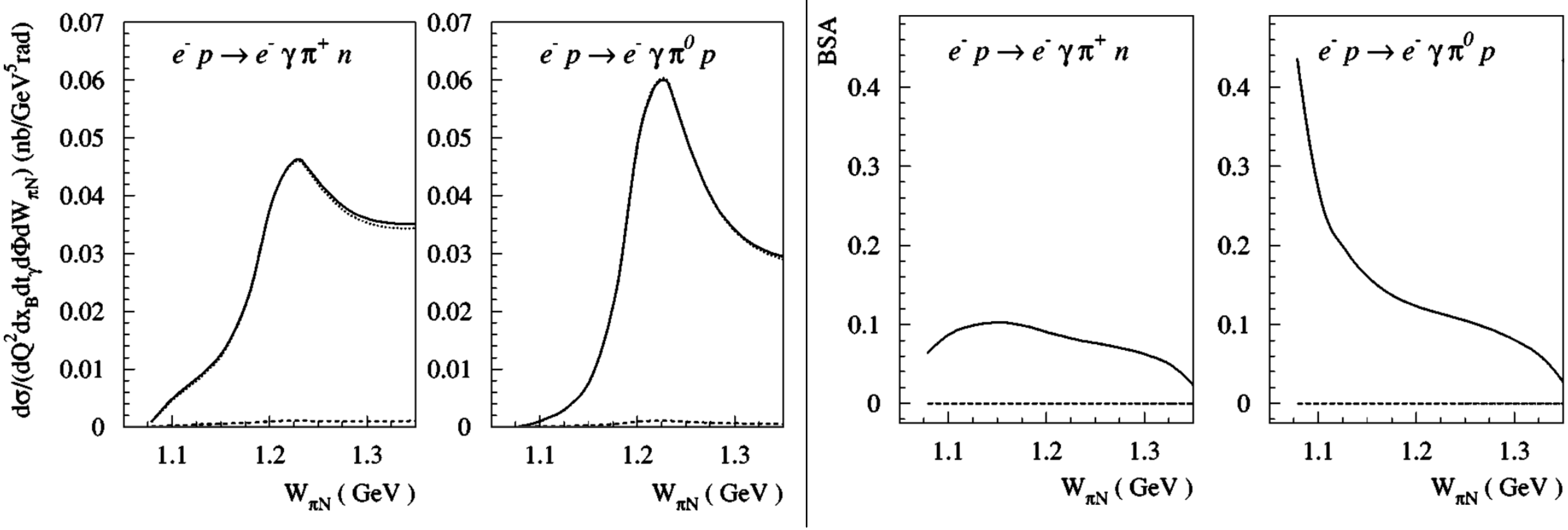


First Theoretical Description of the Δ Region

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

cross section | **BSA**



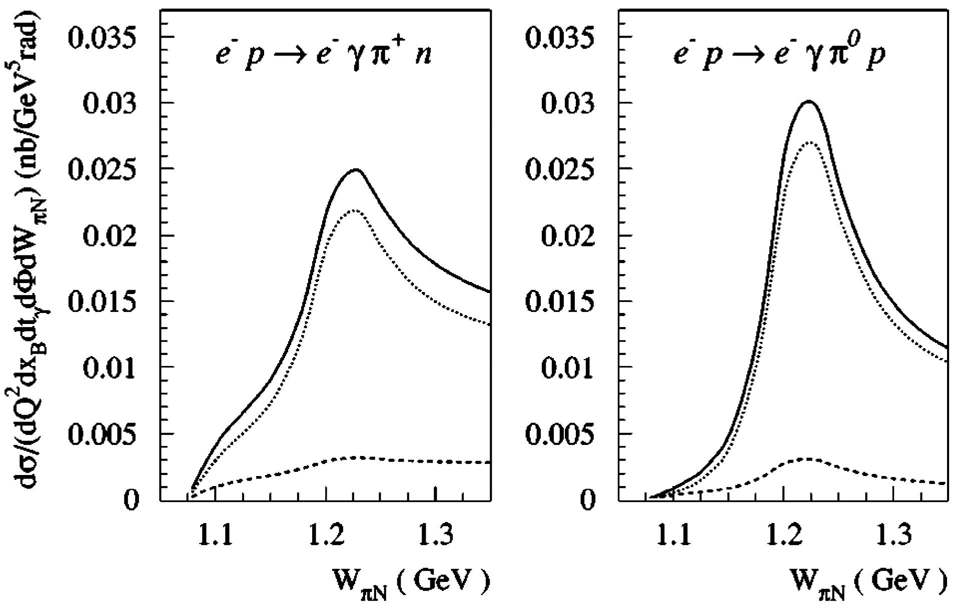
········ BH ········ nDVCS —— BH + DVCS

First Theoretical Description of the Δ Region

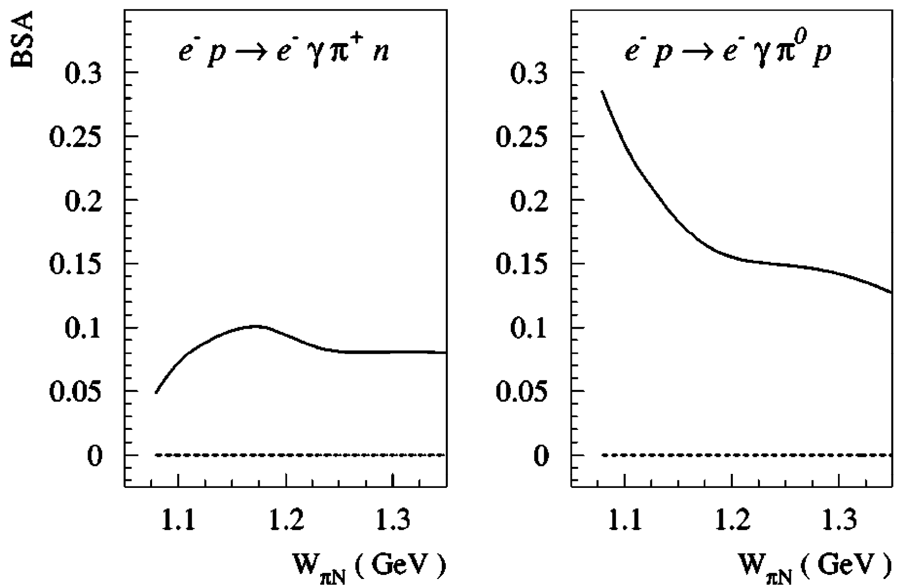
P.A.M Guichon, L.Mosse, M. Vanderhaeghen, Phys. Rev. D68 (2003) 034018

$\mathbf{E_e = 27\ GeV}$, $Q^2 = 2.5$ GeV, $x_B = 0.15$, $t_\gamma = -0.5$ GeV²

cross section



BSA



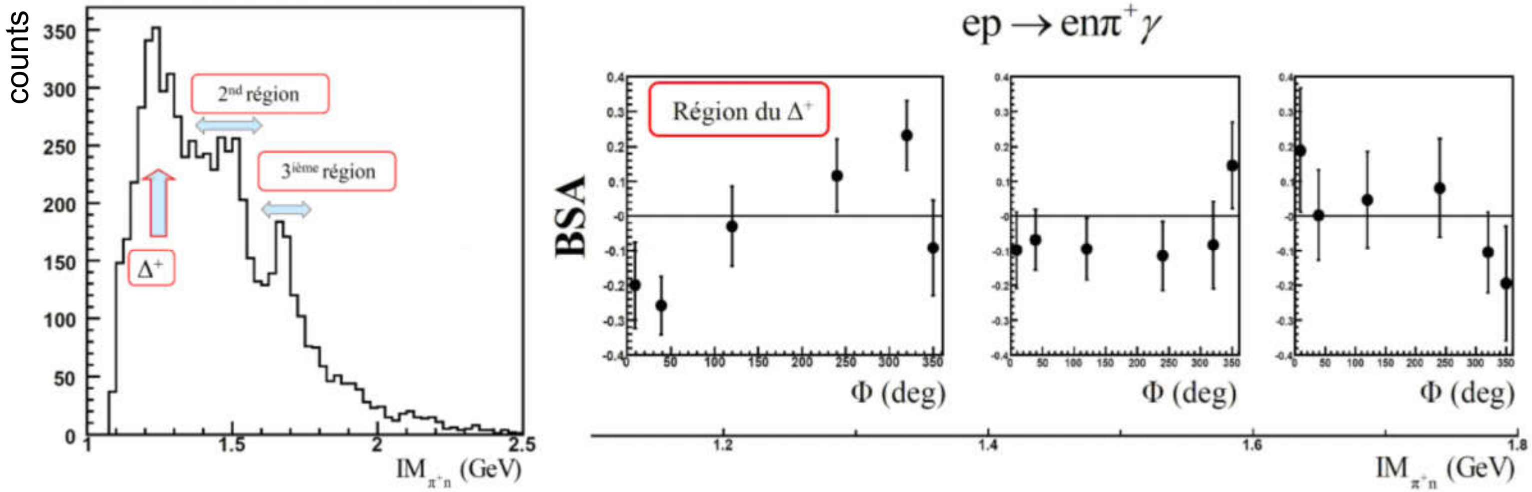
.... BH .... nDVCS —— BH + DVCS

Studies with CLAS at 6 GeV

Brahim Moreno, PhD thesis Universite Paris Sud XI (2009)
https://www.jlab.org/HallB/general/thesis/Moreno_thesis.pdf

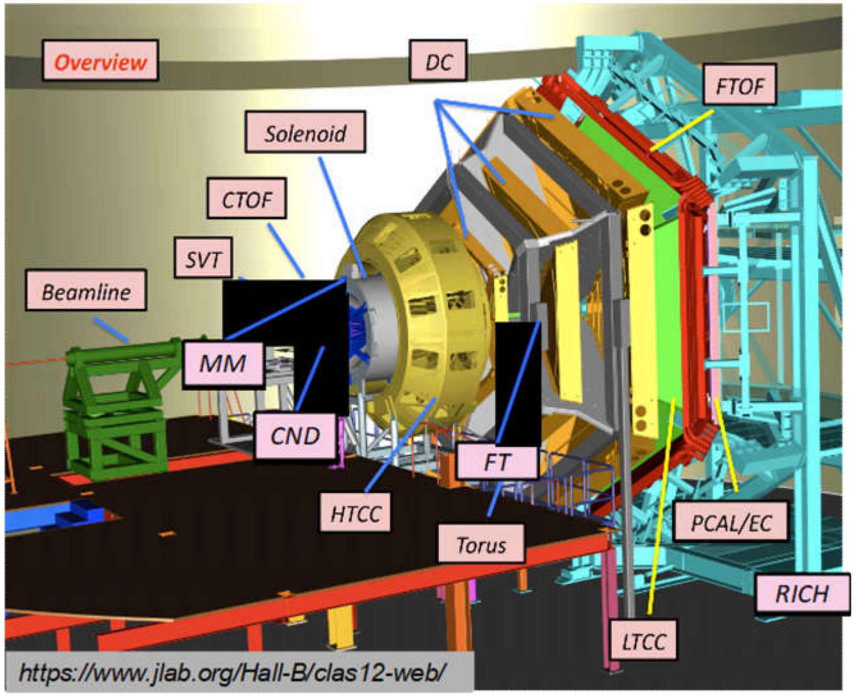
$$\gamma^* p \rightarrow N^* \gamma \rightarrow p\pi^0\gamma \rightarrow p\gamma\gamma\gamma$$

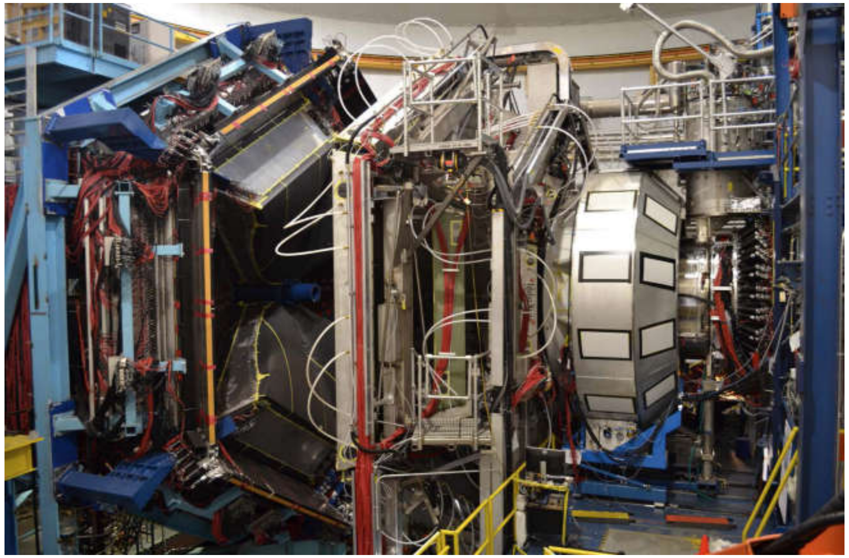
$$\gamma^* p \rightarrow N^* \gamma \rightarrow n\pi^+\gamma$$



➔ Promissing results but statistics not sufficient for further studies

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 of 2018

➔ 10.6 GeV electron beam ➔ 87 % average polarization ➔ liquid H_2 target

➔ Analysed data ~ 20 % of the approved RG-A beam time

Experimental Observables

Two final states have been studied:

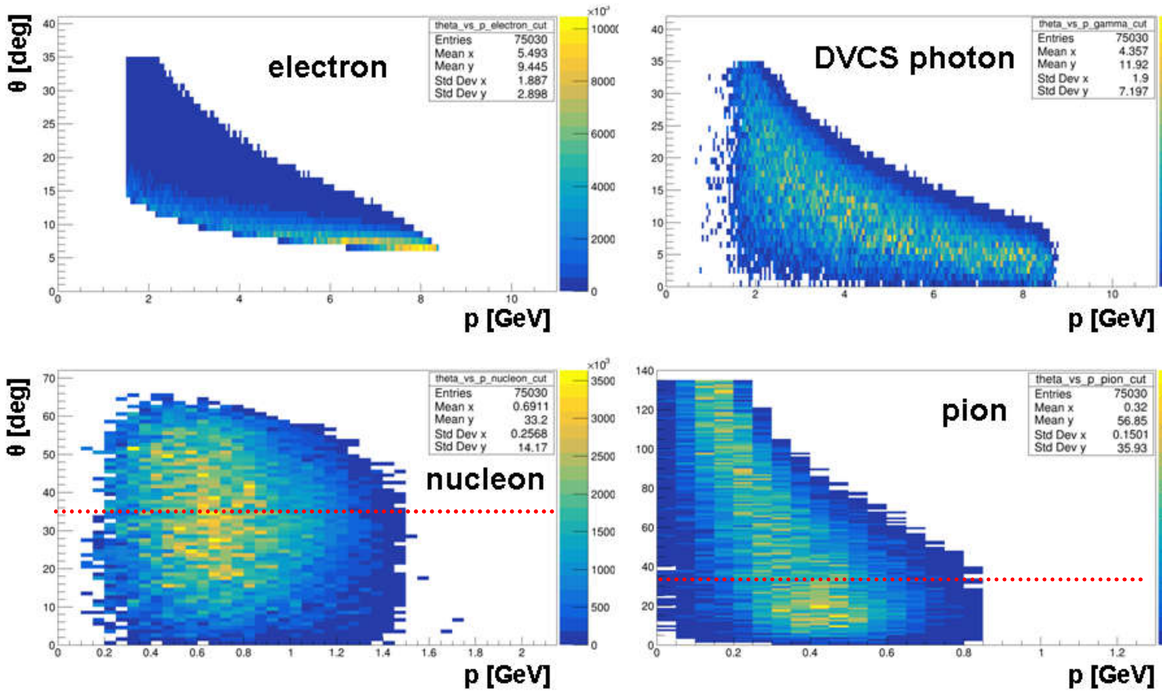
$$\gamma^* p \to N^* \gamma \to p\pi^0\gamma \to p\gamma\gamma\gamma$$

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

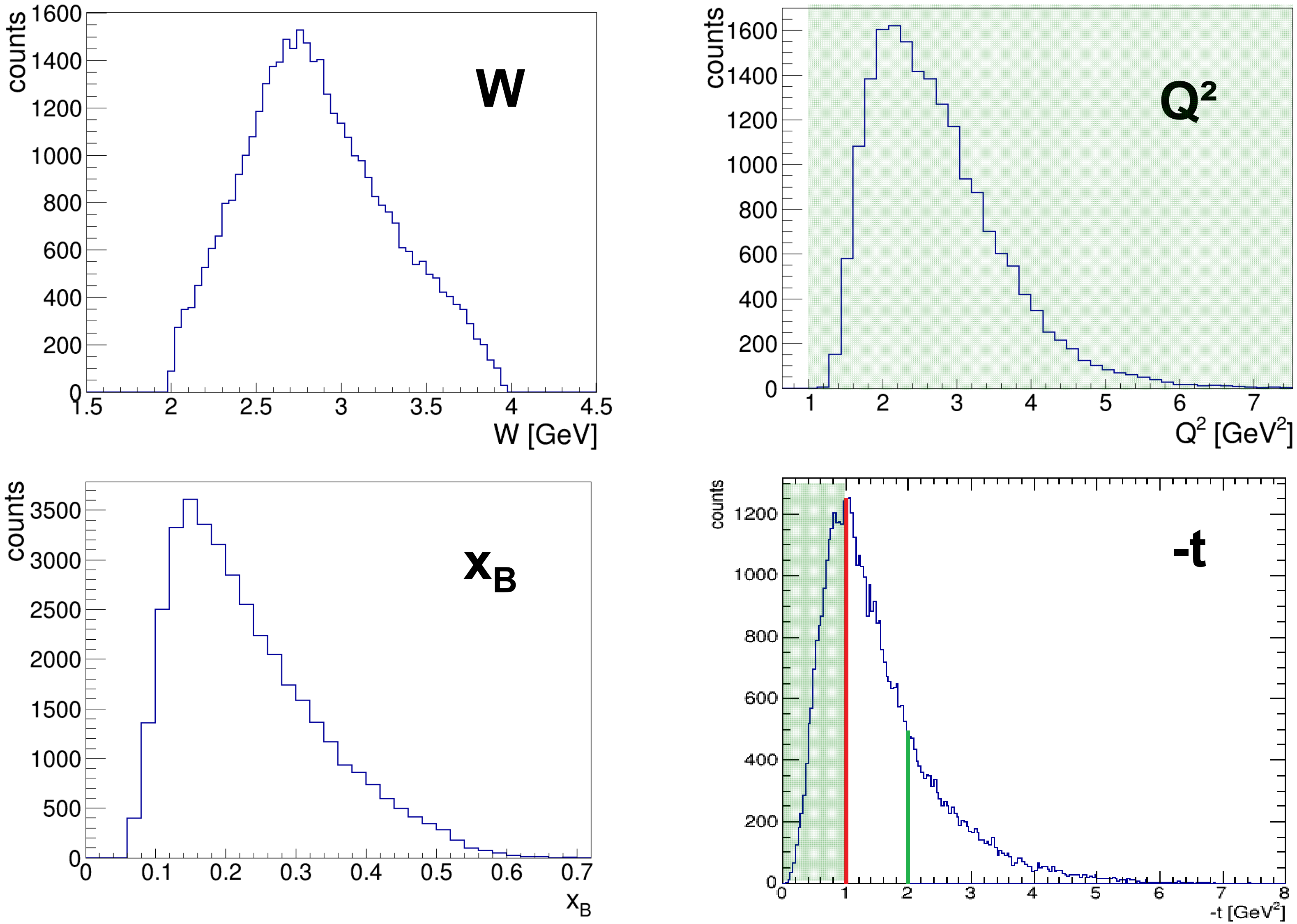
Kinematic cuts: $W > 2$ GeV $Q^2 > 1$ GeV² $y < 0.8$ $-t < 2$ GeV² $E_{DVCS} > 2$ GeV

➔ A series of exclusivity cuts has been applied to select fully exclusive events

Generated MC events for 10.6 GeV electrons:

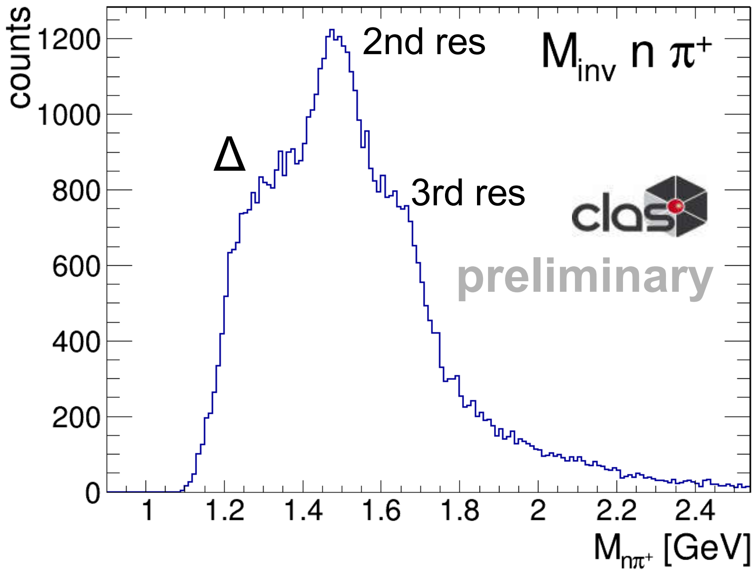


Accessible Kinematic Region with E_{beam} = 10.6 GeV

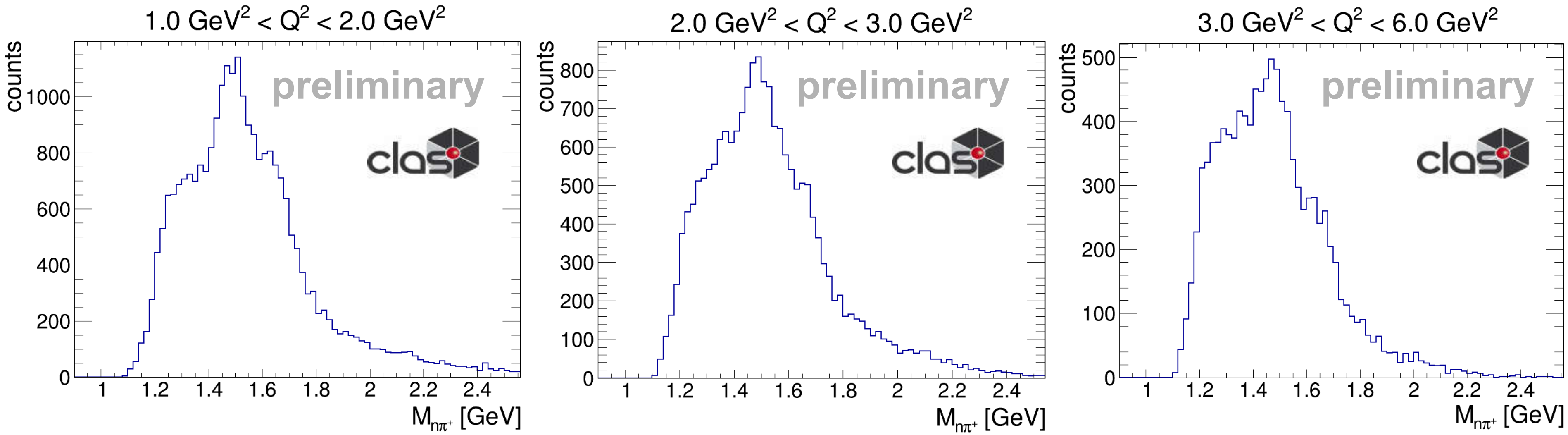


Resonance Mass Spectrum for $N^* \rightarrow n\pi^+$

$en\pi^+\gamma$

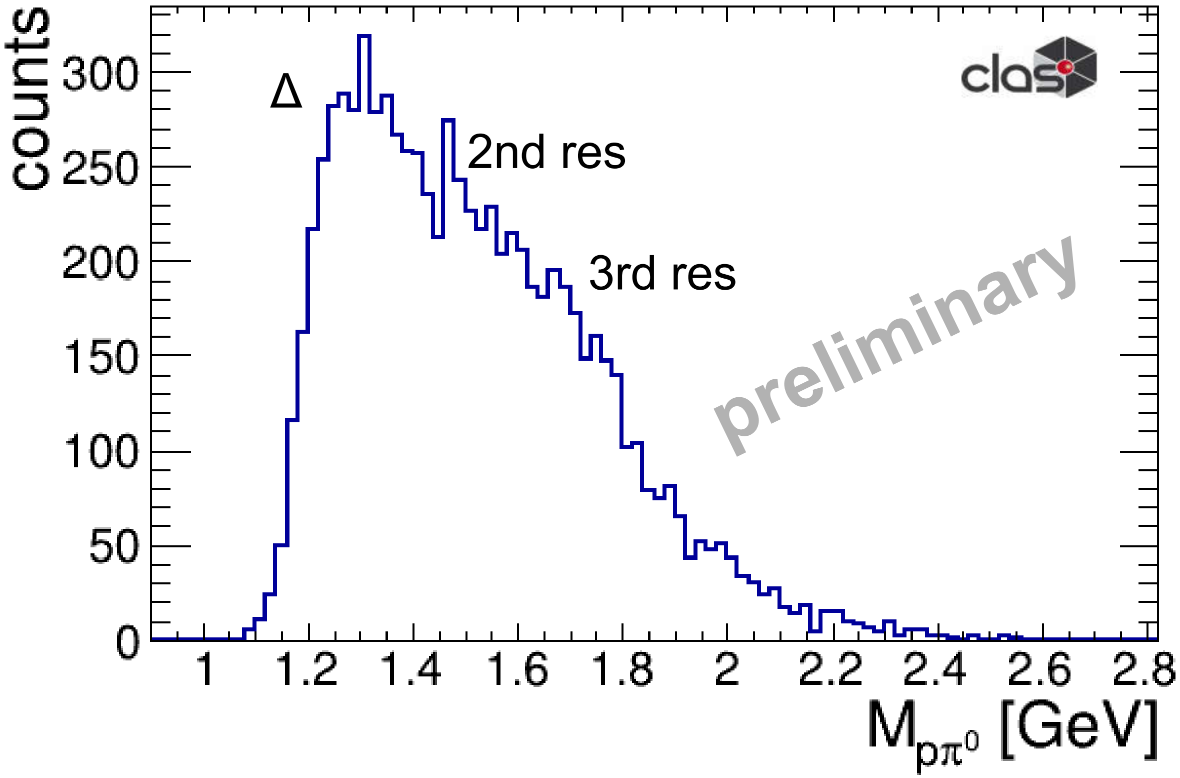


preliminary



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

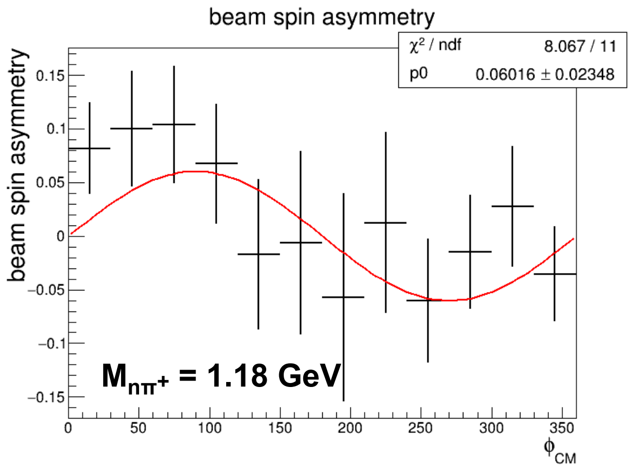
$ep\pi^0\gamma$



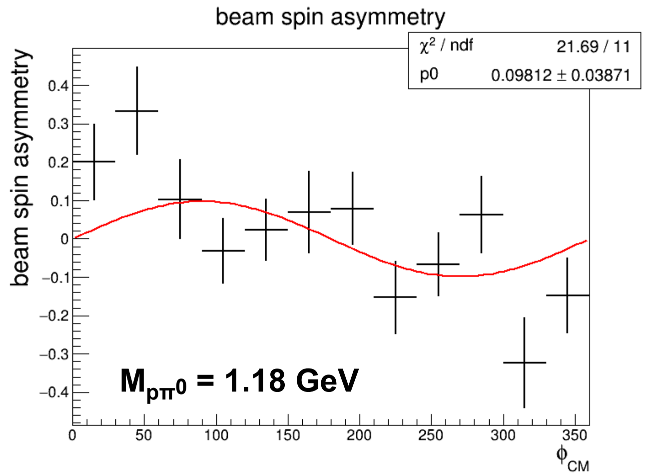
Beam spin asymmetries

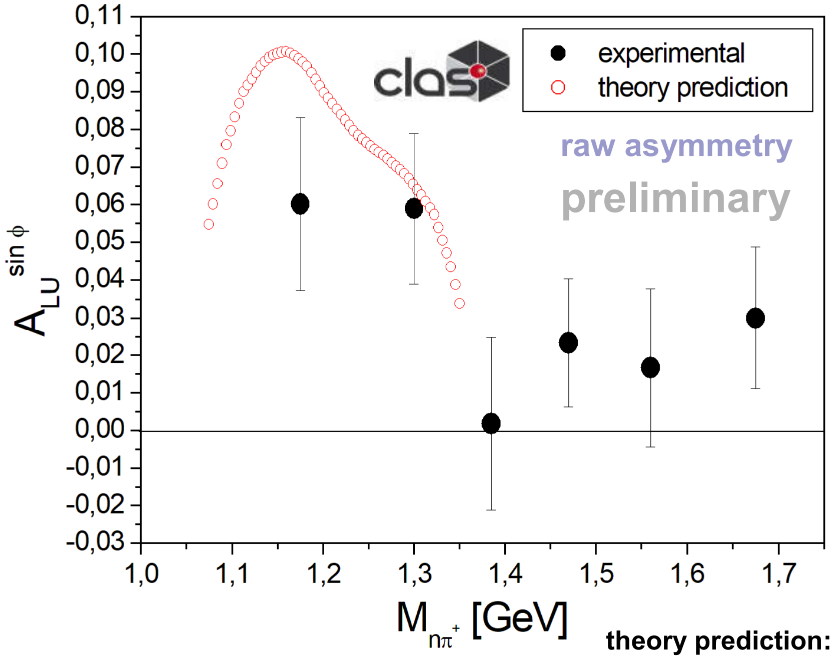
$$A = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-} \approx A_{LU}^{\sin\phi} \sin\phi$$

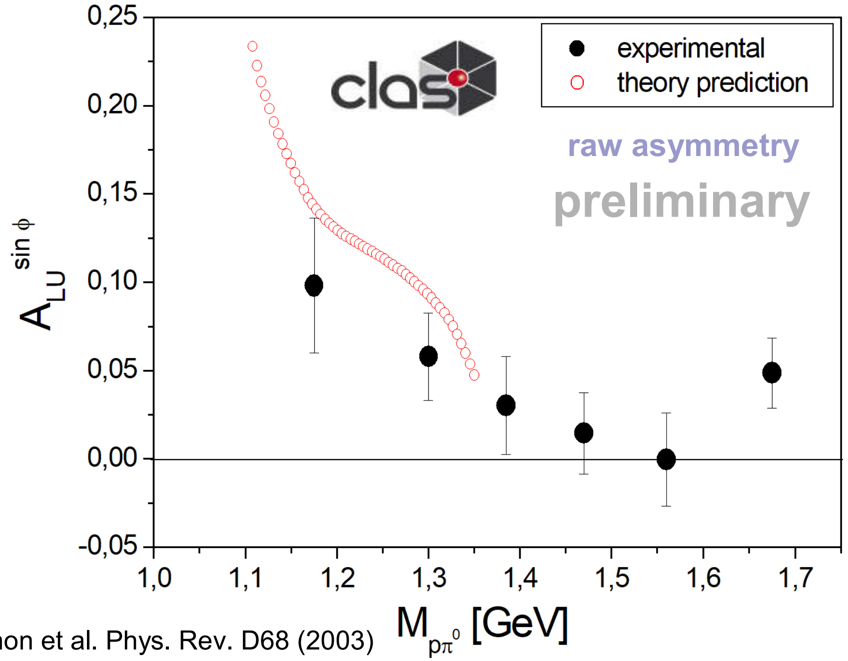
$en\pi^+\gamma$



$ep\pi^0\gamma$

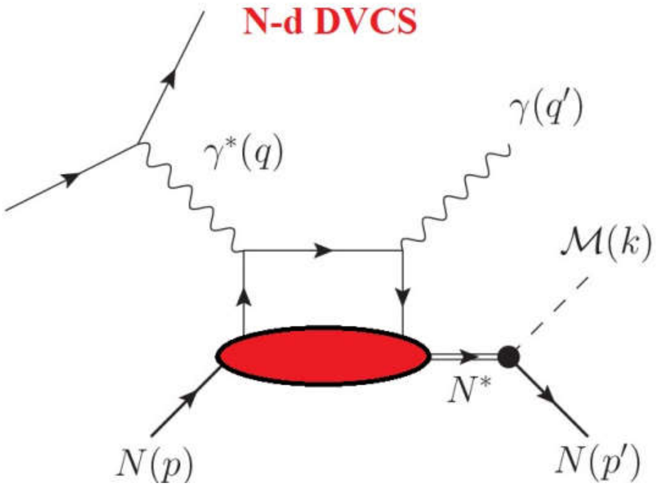




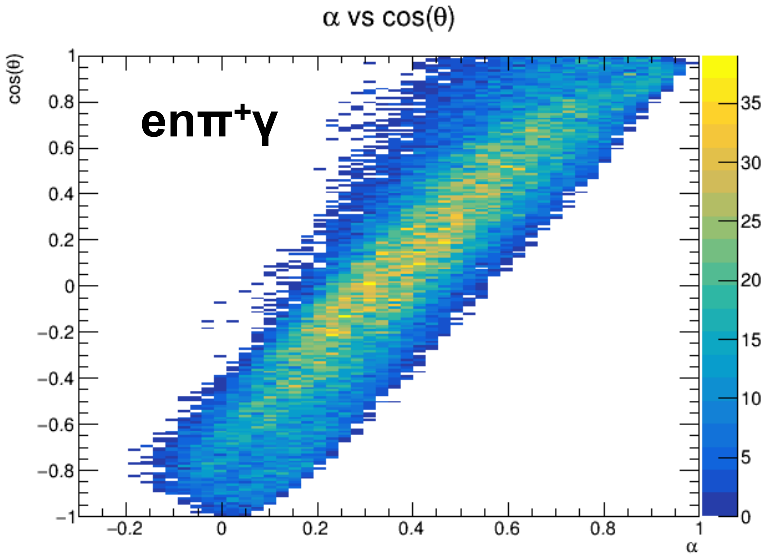


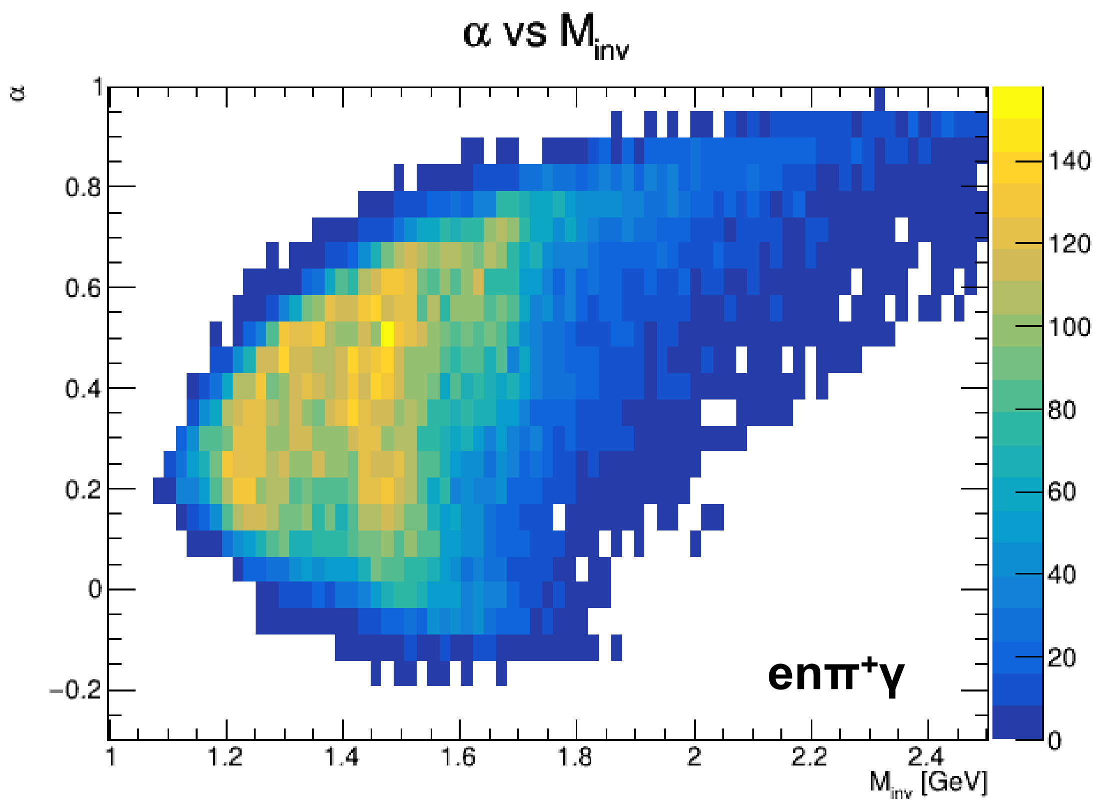
theory prediction: Guichon et al. Phys. Rev. D68 (2003)

The Pion Longitudinal Momentum Fraction

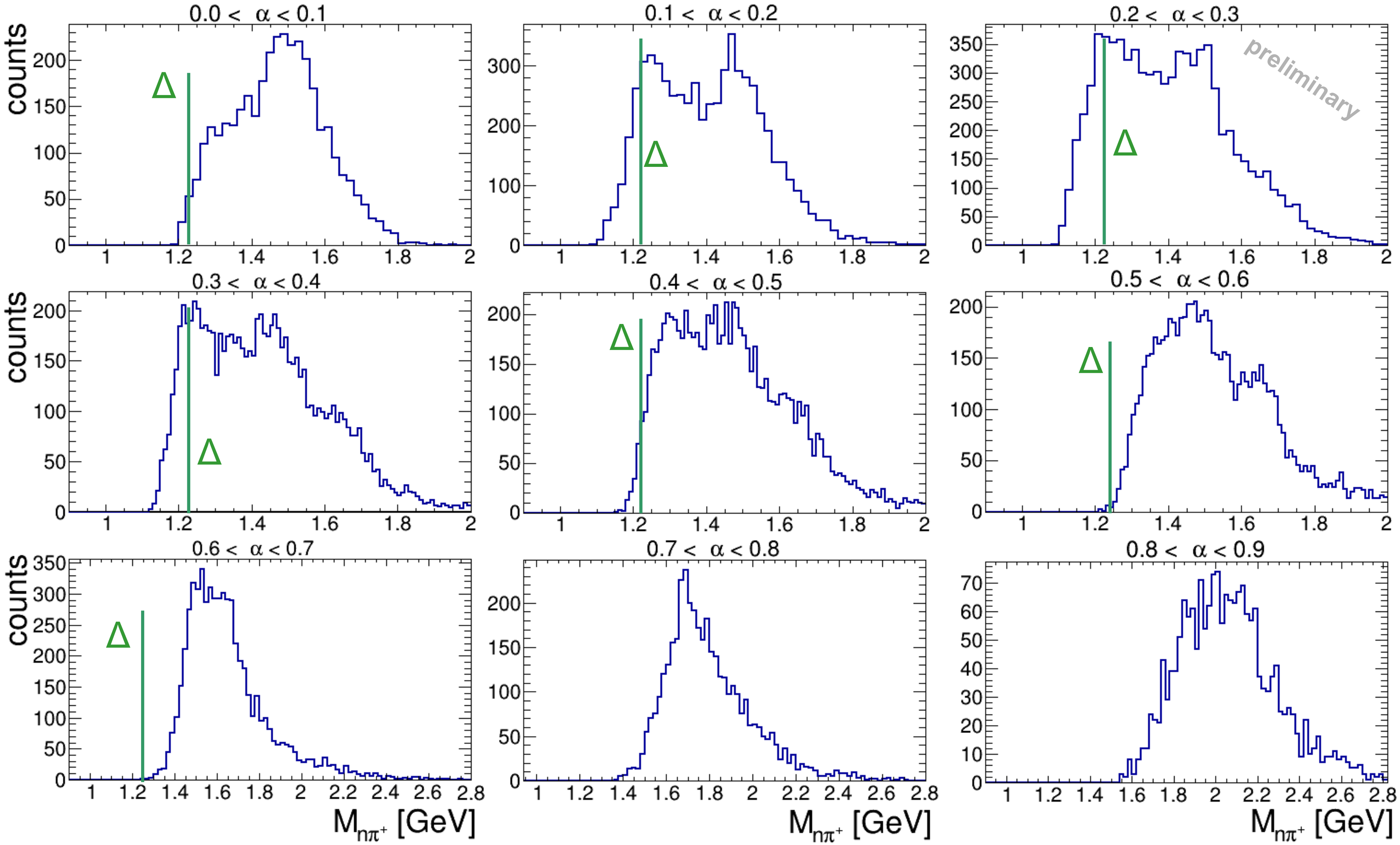


$$\alpha = \frac{(p'+k)\cdot k}{(p'+k)^2}$$



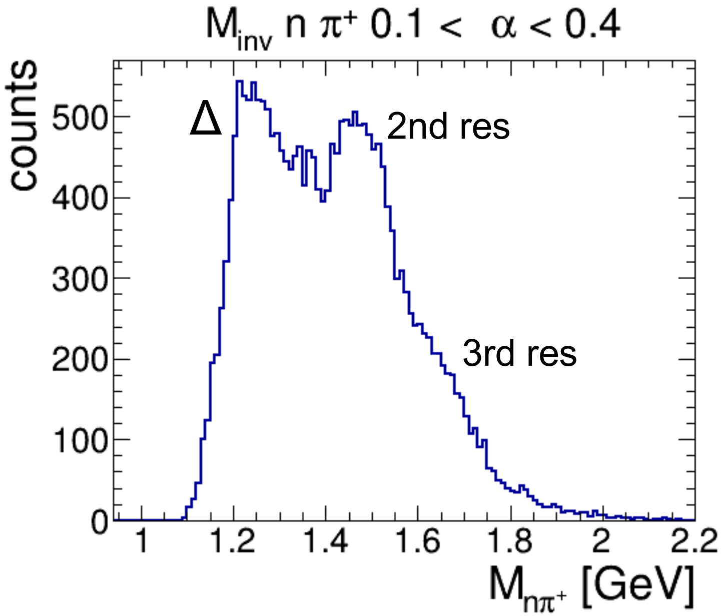


Resonance Mass Spectrum in Bins of α for $N^* \rightarrow n\pi^+$



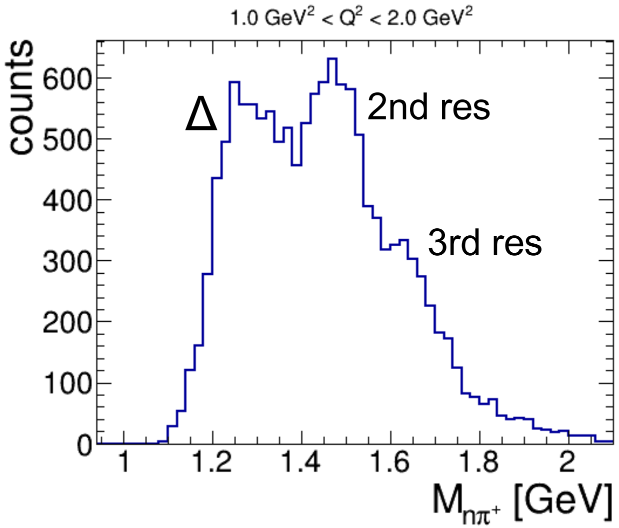
Resonance Mass Spectrum for 0.1 < α < 0.4

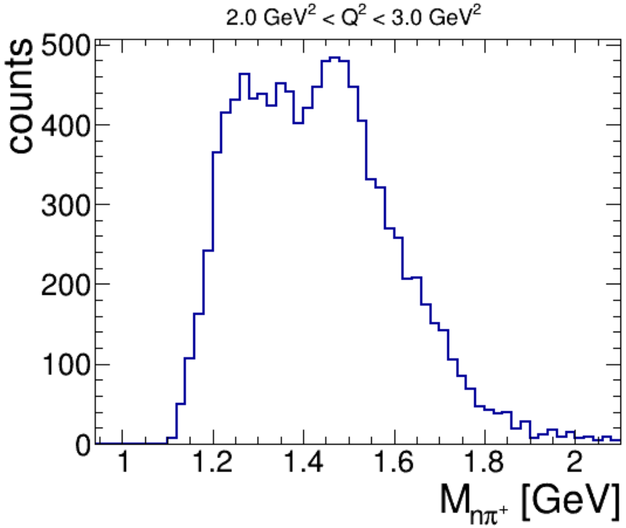
$en\pi^+\gamma$

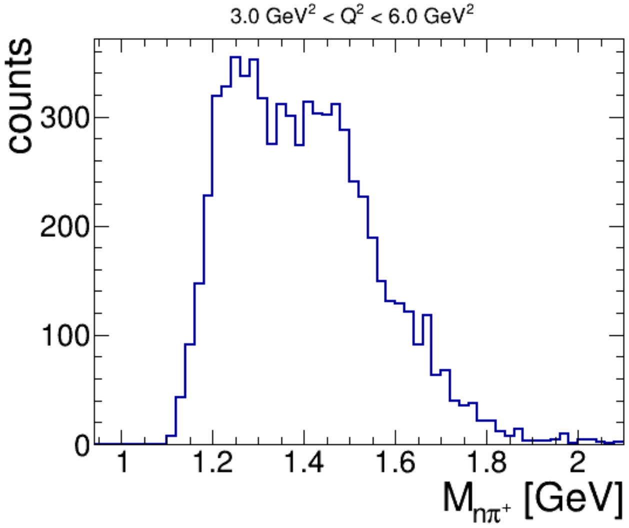


preliminary

Q² dependence:

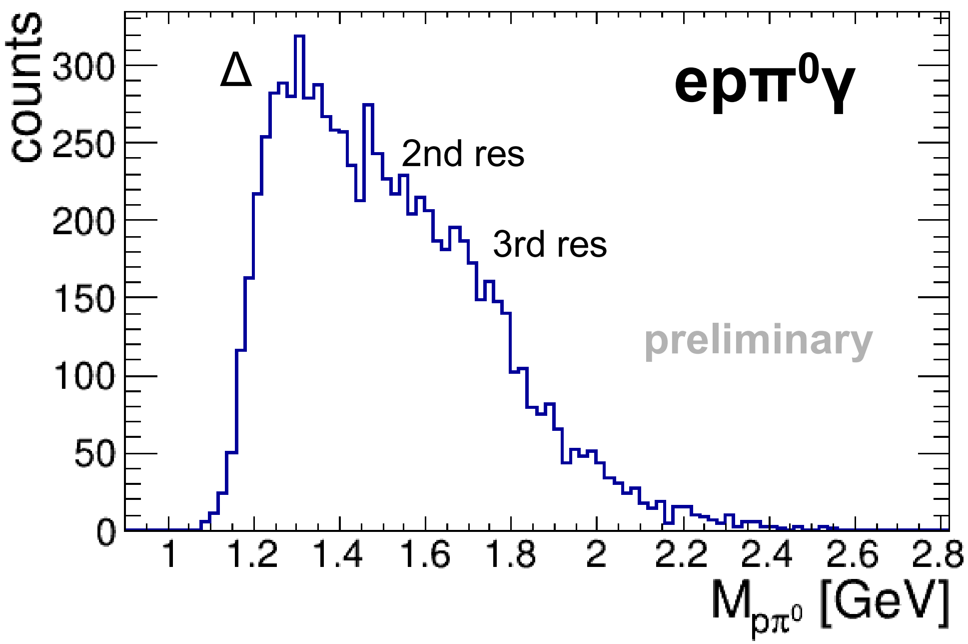




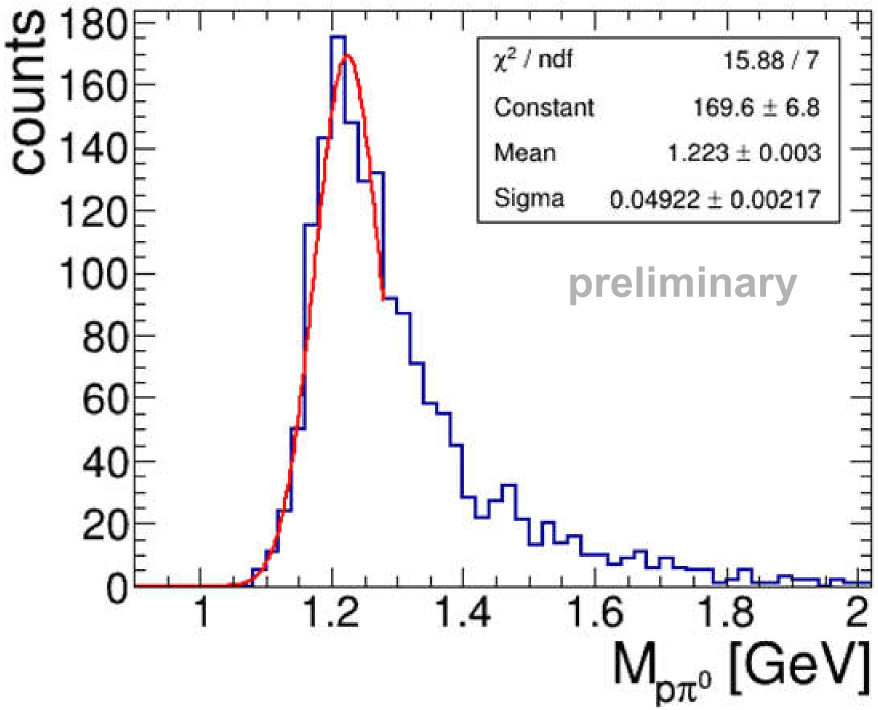


Resonance Mass Spectrum for $N^* \rightarrow p\pi^0$

full spectrum, no cuts



$0.1 < \alpha < 0.4$



➔ Also for the $p\pi^0$ final state, a cut on α helps to separate Δ events

Outlook

First stage: Insight into N→N* transition GPDs for the Δ(1232)$_{3/2+}$ resonance

Second stage: Extension to the N(1440)$_{1/2+}$, N(1520)$_{3/2-}$ and N(1535)$_{1/2-}$ resonances

Events in the complete resonance spectrum (W > 2 GeV Q^2 > 1 GeV^2 -t < 2 GeV^2)**:**

	20%	expected total events for RG-A with current reconstruction	with potential efficiency improvements
$e\,p\,\pi^0\,\gamma$	~ 40k	~ 200k	~300k
$e\,n\,\pi^+\gamma$	~ 56k	~ 280k	~400k

Fraction of events with -t < 1 GeV^2:   20 – 45 % (depending on the torus field)

➔ Statistics sufficient for a first extraction of cross sections and BSA

➔ Planings for a high luminosity run of CLAS12 are ongoing

➔ Possibility of studies at the EIC

Conclusion

- CLAS12 in combination with the upgraded CEBAF provides good conditions to measure the non-diagonal DVCS process
- Results will provide insight in the 3D image of the $N \rightarrow N^*$ transition for the first time
- Resonance structures can be identified in the pion – nucleon invariant mass spectrum
- A first BSA extraction provides a qualitative agreement with transition GPD based theory predictions

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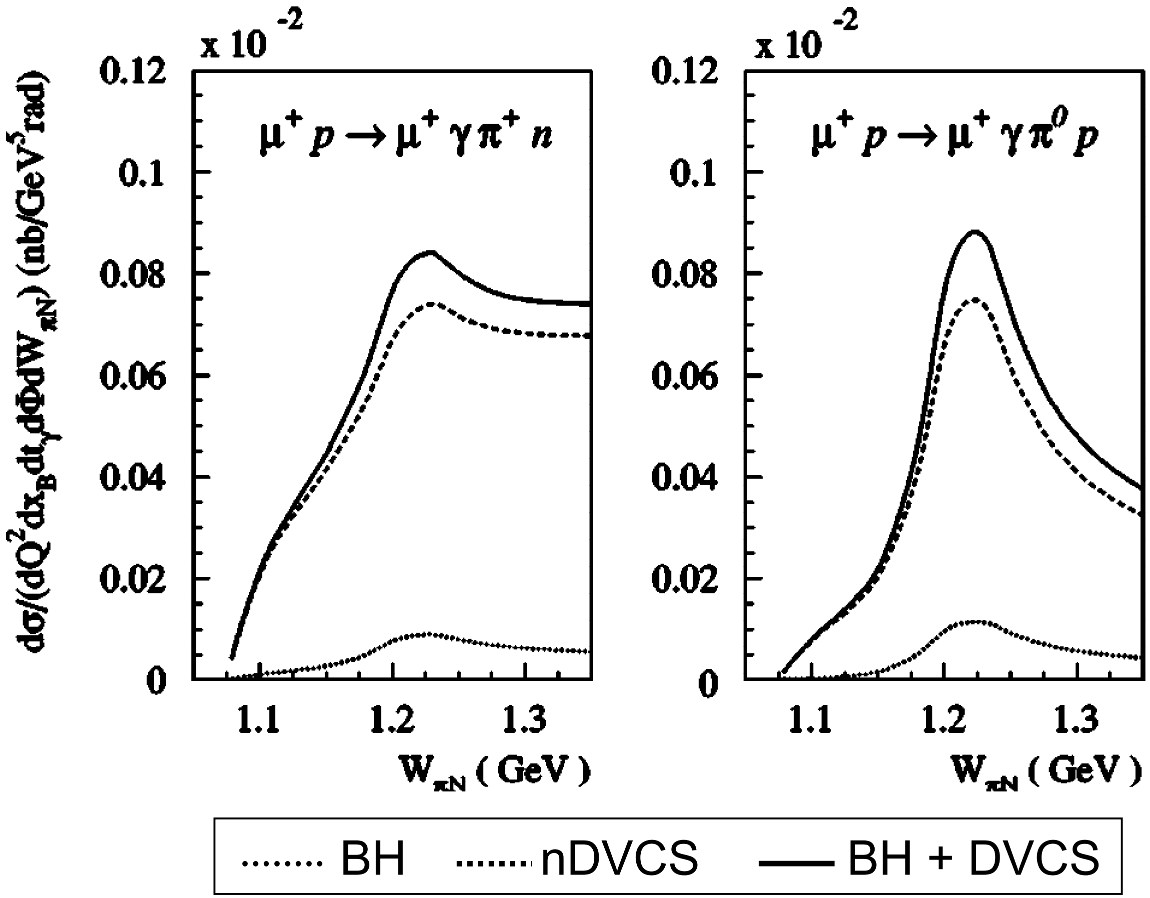
Perspectives for the EIC

E_e = 190 GeV, Q^2 = 4.0 GeV, x_B = 0.2, t_γ = -0.4 GeV²

COMPASS kinematics

EIC



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