CFNS Stony Brook

Deep Virtual Production of Pion Pairs

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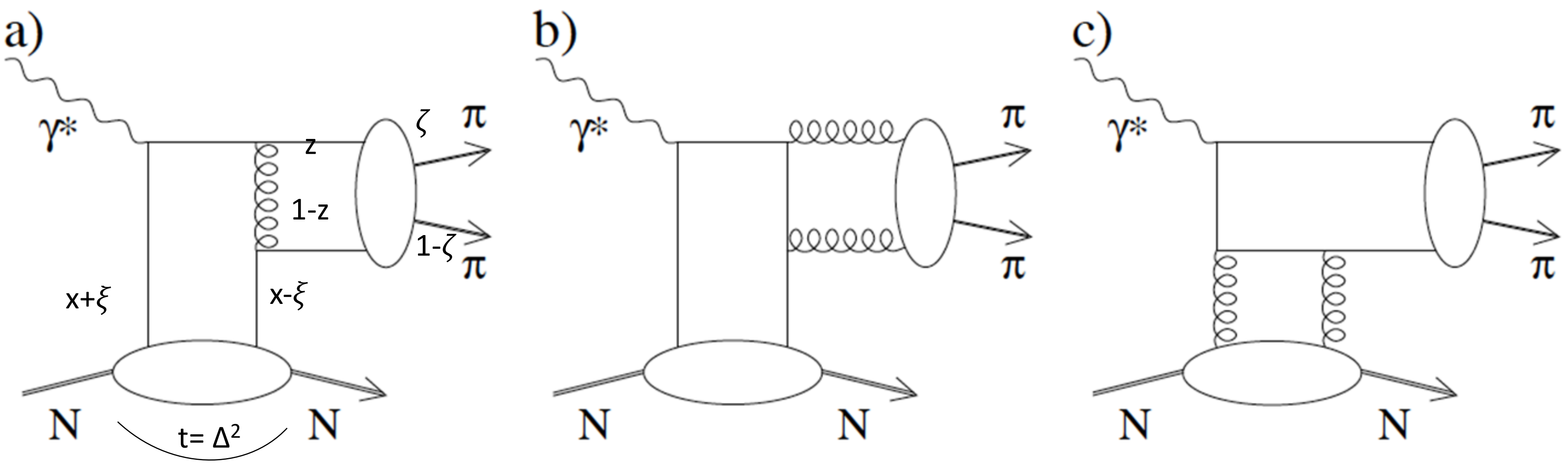
Project

- We are mainly considering two reactions, Charged and Neutral Pion Pairs

- $ep \rightarrow e'p'\pi^{+}\pi^{-}$
  - Isospin I=1, angular momentum J=1
    - $\boldsymbol{\rho(770)}$
  - Isospin I=0, angular momentum J=0
    - $\boldsymbol{f_0(500) = \sigma, f_0(980)}$
- $ep \rightarrow e'p'\pi^{0}\pi^{0}$
  - Isospin zero, spin zero channel (I:J=0:0)
    - $\boldsymbol{f_0(500) = \sigma, \quad f_0(980)}$

Deep Virtual Factorization

- Leading order diagrams for exclusive deep virtual production of two pions



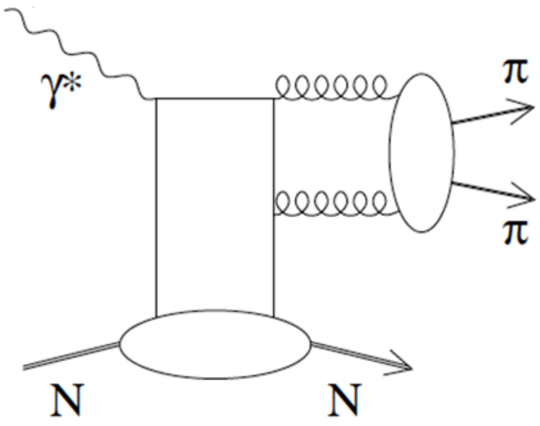
B. Lehmann-Dronke *et al.*, Phys Lett B **475** (2000) 147

B. Lehmann-Dronke *et al.*, Phys Rev D, **63** (2001) 114001

Neutral mesonic final state: $\pi^+\pi^-$ *or* $\pi^0\pi^0$

a) [Flavor-Diagonal quark-GPD]⊗ [$q\bar{q}$ -Two-Pion Distribution Amplitude (DA)]
b) [Flavor-Diagonal quark-GPD] ⊗[gluon-Two-Pion Distribution Amplitude(DA)]
c) [Gluon-GPD] ⊗[$q\bar{q}$ -Two-Pion Distribution Amplitude (DA)]

Deep sigma



J.R.Peláez

- σ-meson Asymptotic Distribution Amplitudes:
  - $\phi_{gluon} = 2\,\phi_{qq}$
- σ-meson: $f_0(500)$ well established.
  - ***Pole = (450±20)MeV – i(275±12) MeV)***
- Microscopic structure of $f_0(500)$ not well understood.
  - $q\bar{q}$: $^3P_0$
  - Tetraquark
  - $\pi\pi$ -molecule
  - Glueball
  - Superposition of all of the above
- Deep sigma-production offers intriguing probe of gluonic content of $f_0(500)$.

- **Deep Virtual $\pi\pi$ Production Amplitude**

$$\mathcal{M} = \sum_{\substack{I \\ \lambda_N,\lambda_\pi \in (q\bar{q},g)}} \int d\tau dz \mathrm{GPD}_{\lambda_N}(\tau,\xi,t) \odot S_{\lambda_N,\lambda_\pi}(\tau,z,\xi) \odot \mathrm{DA}^{I}_{\lambda_\pi}(z,\zeta;m_{\pi\pi}:\theta^*)$$

$$\mathcal{M} = \sum_{\substack{J^\pi:I \\ \lambda_N,\lambda_\pi \in (q\bar{q},g)}} \int d\tau dz \mathrm{GPD}_{\lambda_N}(\tau,\xi,t) \odot S_{\lambda_N,\lambda_\pi}(\tau,z,\xi) \odot \mathrm{DA}^{I}_{\lambda_\pi}(z,\zeta) P_J(\cos(\theta^*)\Omega_{J:I}(m_{\pi\pi})$$

- **Kinematics**

$$\xi \sim \frac{x_B}{2-x_B}$$

$$t = (q - p_{\pi\pi})^2 = (P'_p - P_p)^2$$

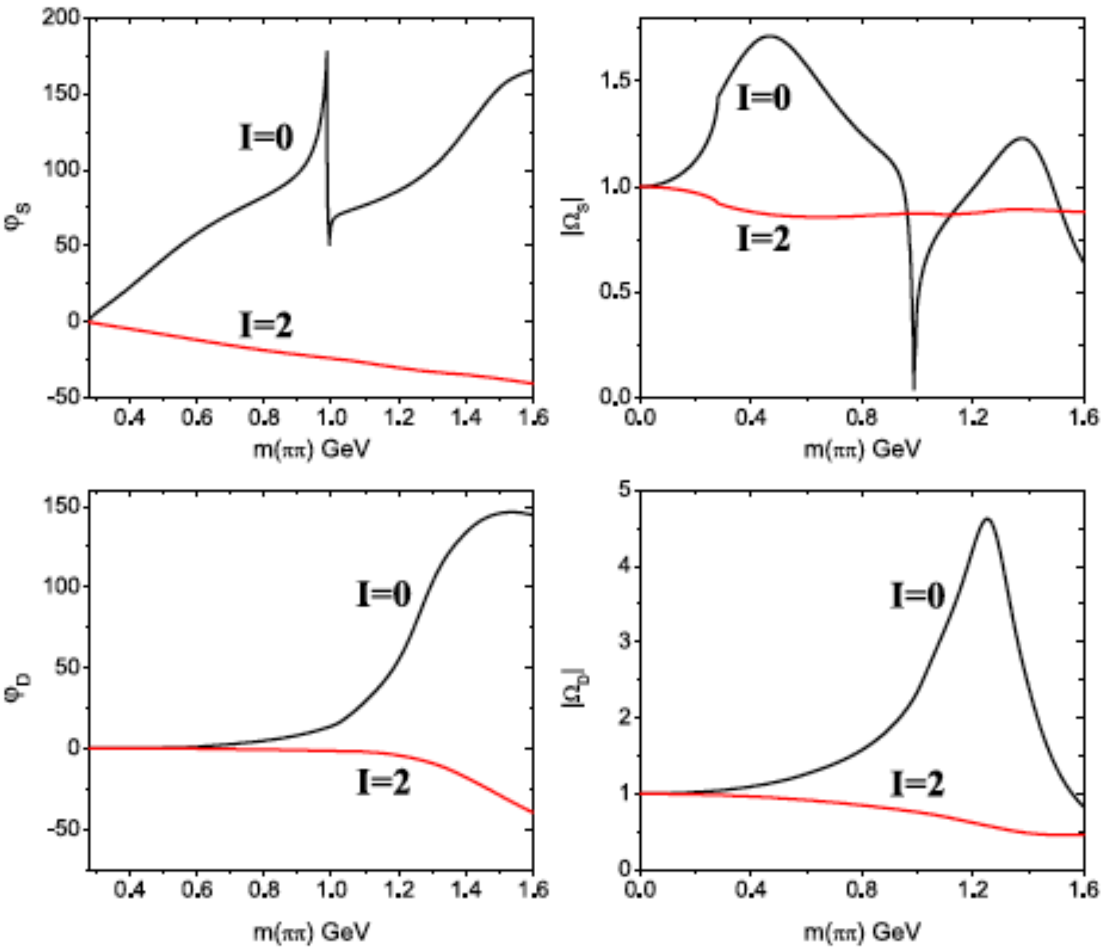
$$\zeta,\ (1-\zeta) = \frac{1}{2}[1 \pm \beta^* \cos\theta^*] = \text{ pion lightcone momentum fractions}$$

$$\beta^* = \text{ pion velocity in } \pi\pi \text{ rest frame}$$

$$\theta^* = \text{ pion polar angle in } \pi\pi \text{ rest frame}$$

- **Dynamics**
  - $S(\tau,z;\xi)$ = Hard scattering amplitude (quark-gluon propagators)
  - $\Omega_{J;I}$ = Omnès-function, derived from $\pi\pi$ phase shifts
  - τ = average momentum fraction of parton in nucleon
  - z = momentum fraction of parton in $\pi\pi$ DA

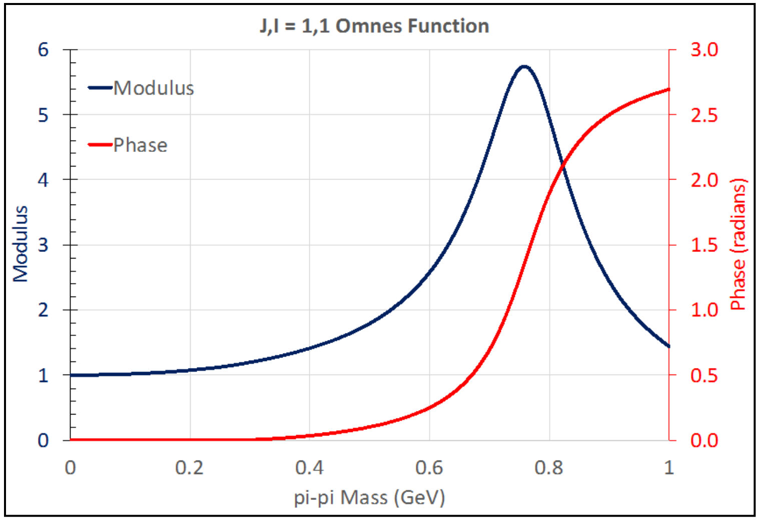
$\pi\pi$ Mass Distribution (Omnès F'n)



- L.Dai, M.Pennington, Phys Rev D **90** 036004 (2014)
- L=0
  - *f_0(500)*
  - *f_0(980)*
  - *Small I=2 non-resonant*
- L=2
  - f_2(1270)
  - *Small I=2 non-resonant*

$$\Omega_l^I(m_{\pi\pi}) = \exp\left\{ i\delta_l^I(m_{\pi\pi}) + \frac{m_{\pi\pi}^2}{\pi}\Re\mathrm{e}\left[\int_{4m_\pi^2}^{\infty} ds \frac{\delta_l^I(s)}{s(s - m_{\pi\pi}^2 - i\epsilon)}\right]\right\}$$

$\pi\pi$ Omnès F'n I;J = 1;1 (ρ-meson)



- L.Dai, M.Pennington, Phys Rev D **90** 036004 (2014)

$$\Omega_l^I(m_{\pi\pi}) = \exp\left\{ i\delta_l^I(m_{\pi\pi}) + \frac{m_{\pi\pi}^2}{\pi}\Re e\left[\int_{4m_\pi^2}^{\infty} ds \frac{\delta_l^I(s)}{s(s-m_{\pi\pi}^2-i\epsilon)}\right]\right\}$$

Simulation : Event Generation

- **Monte-Carlo Generation of Phase Space Variables**
  - There are eight independent kinematic variables in the final state of the $ep \rightarrow e'p'\pi\pi$ reaction.

Total kinematic variables in final state (four 4-vectors)	16
Mass constraint of the four final state particles	-4
Four-Momentum Conservation, initial to final state	-4
Total number of independent variables in final state	8

- These are,
  - $Q^2, x_B, \phi_e, M_{1,2}^2, t, \phi_{1,2}^*, cos\theta_{\sigma\_Rest}, \phi_{\sigma\_Rest}$

Reactions

1. First consider the reaction $\boldsymbol{e} + \boldsymbol{p} \rightarrow \boldsymbol{e}' + \boldsymbol{p}' + \boldsymbol{\pi}^{+} + \boldsymbol{\pi}^{-}$
   - Four Particles in final state
2. Secondly consider the reaction $\boldsymbol{e} + \boldsymbol{p} \rightarrow \boldsymbol{e}' + \boldsymbol{p}' + \boldsymbol{\pi}^{\mathbf{0}} + \boldsymbol{\pi}^{\mathbf{0}}$,

   its primary mode of decay is $\boldsymbol{\pi}^{\mathbf{0}} \rightarrow \boldsymbol{\gamma}\,\boldsymbol{\gamma}$

   6 particles in final state

   - Scattered electron
   - Recoil Proton
   - Two $\boldsymbol{\pi}^{\mathbf{0}}$ s $\Rrightarrow$ Four gamma-rays

Simulation and Reconstruction

- For my simulation and reconstruction, I used

  GEMC version 4a.2.1

  COATJAVA version 4a.8.2

Steps :

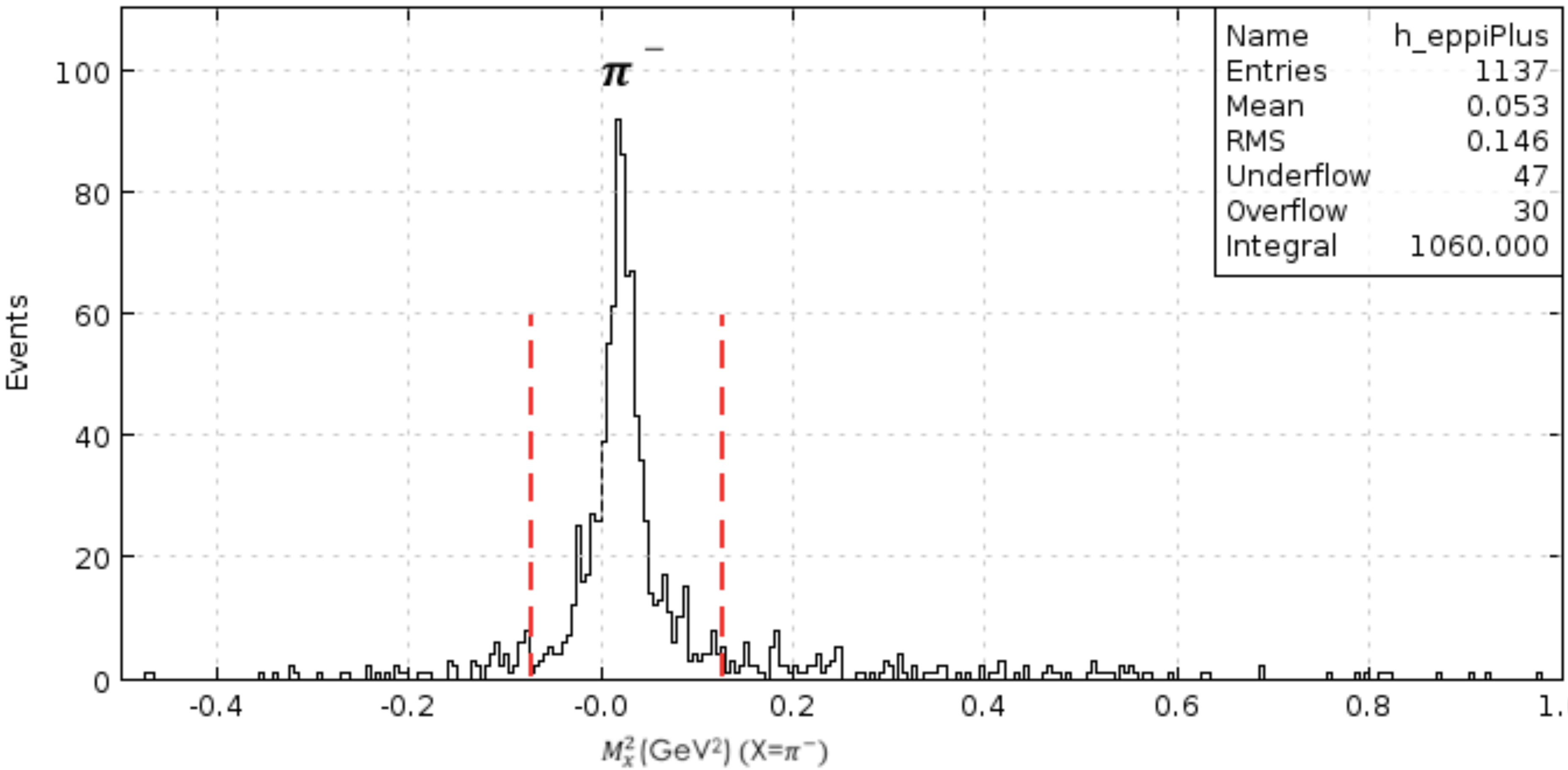
- After generation monte-carlo data is passed through the GEMC in the form of LUND format.
- Reconstruction is done with coatjava.

- CLAS12 analyses are done with **groovy** scripts (java).

- This method ties well with the coatjava framework and provides standard tools for reading EVIO files and reconstructed banks.

Missing mass for $ep \to e\ p\ \pi^+ X$

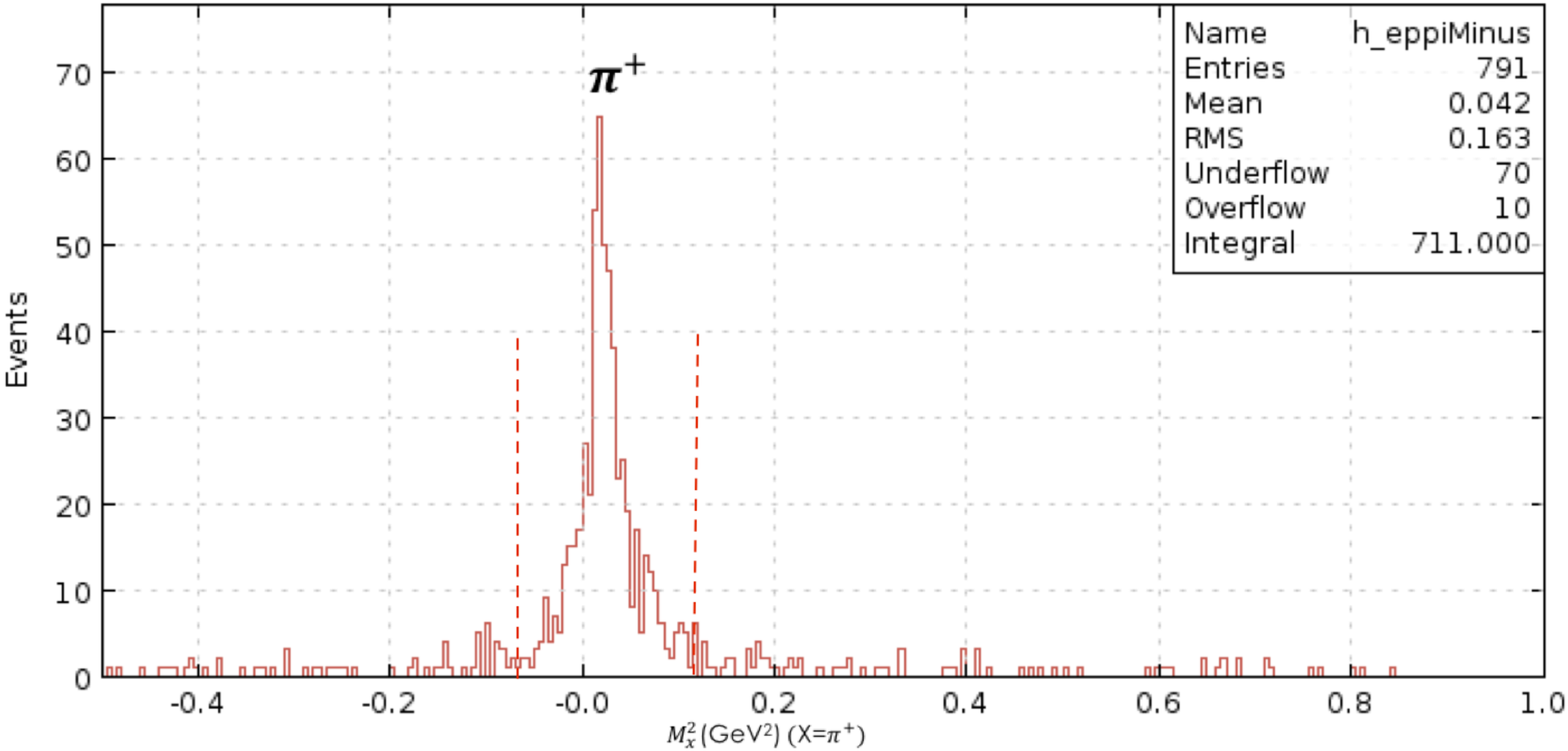
- Missing mass squared reconstruction of $\boldsymbol{\pi}^-$



CLAS12 Detection ⊗ reconstruction efficiency ≈ 14%

Missing mass for $ep \rightarrow e\ p\ \pi^{-}\ X$

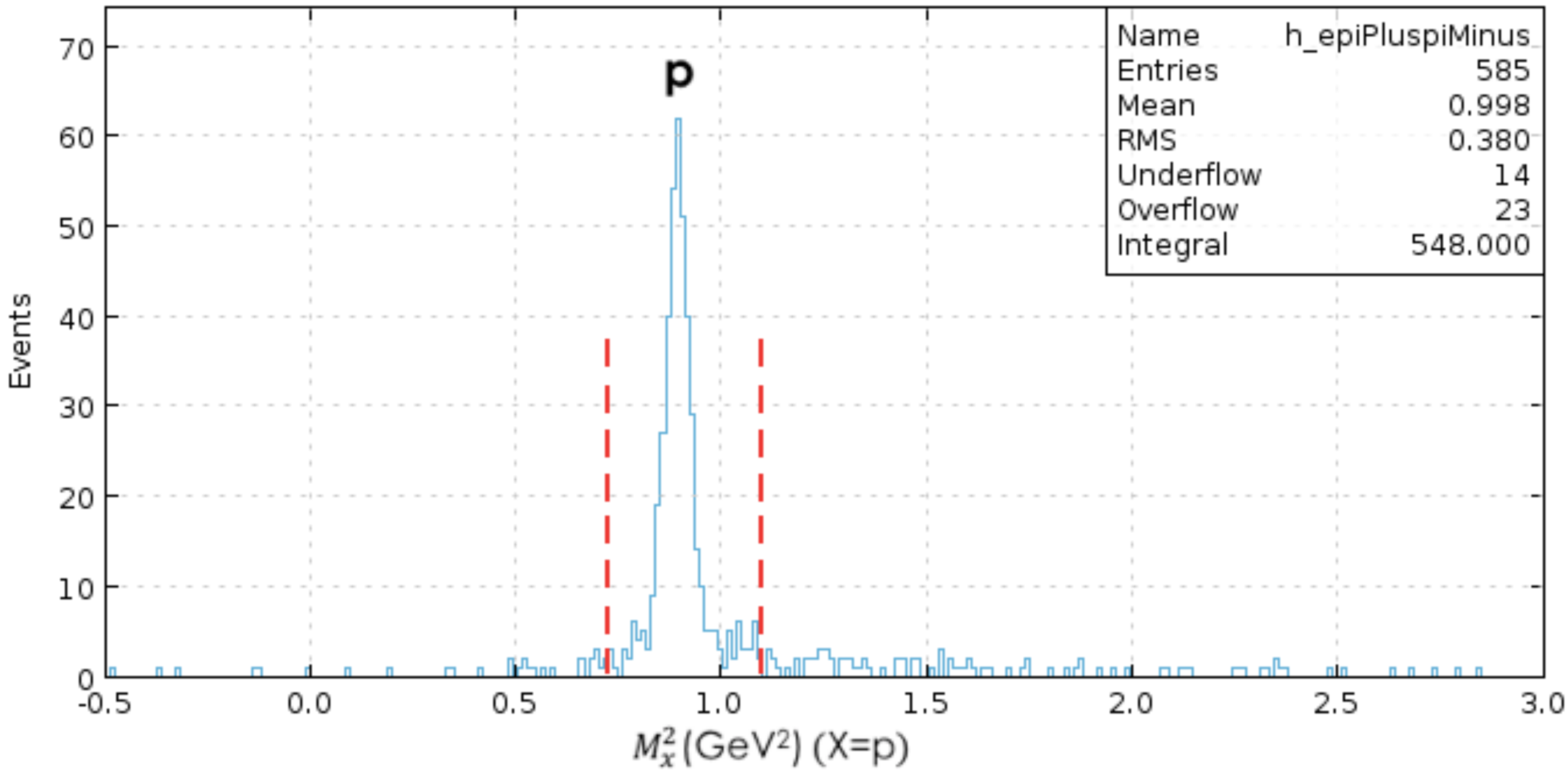
- Missing mass squared reconstruction of $\boldsymbol{\pi}^{+}$



CLAS12 Detection ⊗ reconstruction efficiency ≈ 11%

Missing mass for $ep \rightarrow e\ \pi^+\ \pi^-\ X$

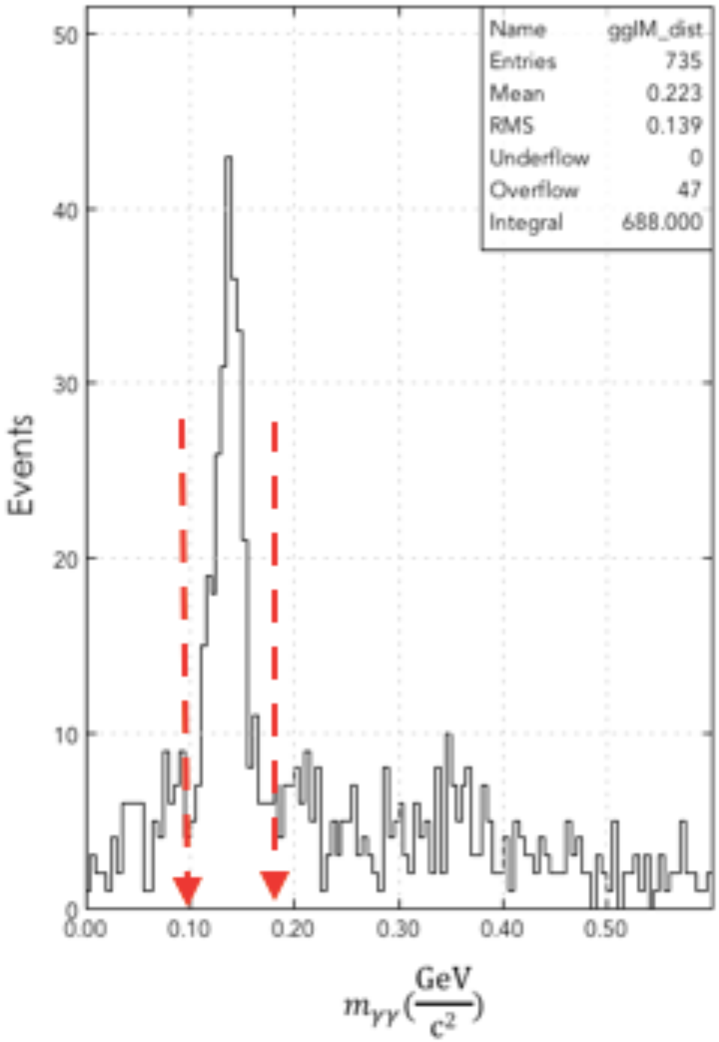
- Missing mass squared reconstruction of *p*



CLAS12 Detection ⊗ reconstruction efficiency ≈ 8%

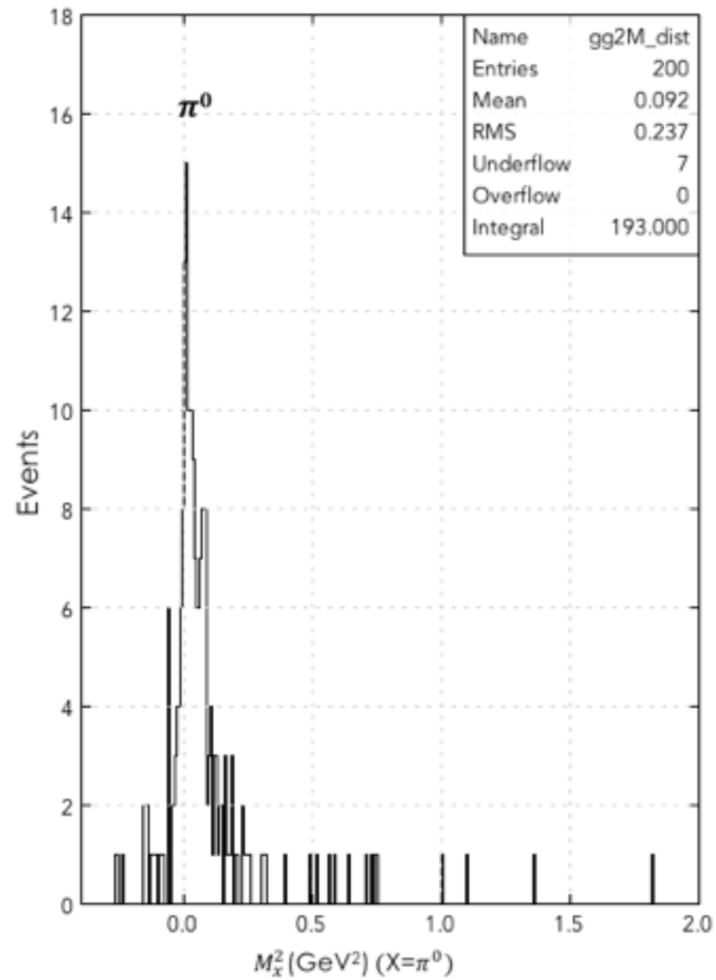
$\gamma\gamma$ Invariant mass for $ep \rightarrow e' p' \pi^0 \pi^0$

- Secondly, consider the reaction, $\boldsymbol{ep \rightarrow e'p'\pi^0\ \pi^0}$, and $\boldsymbol{\pi^0}$ decays into two gammas ($\boldsymbol{\pi^0 \rightarrow \gamma\gamma}$).
- Expected two photon invariant mass peak



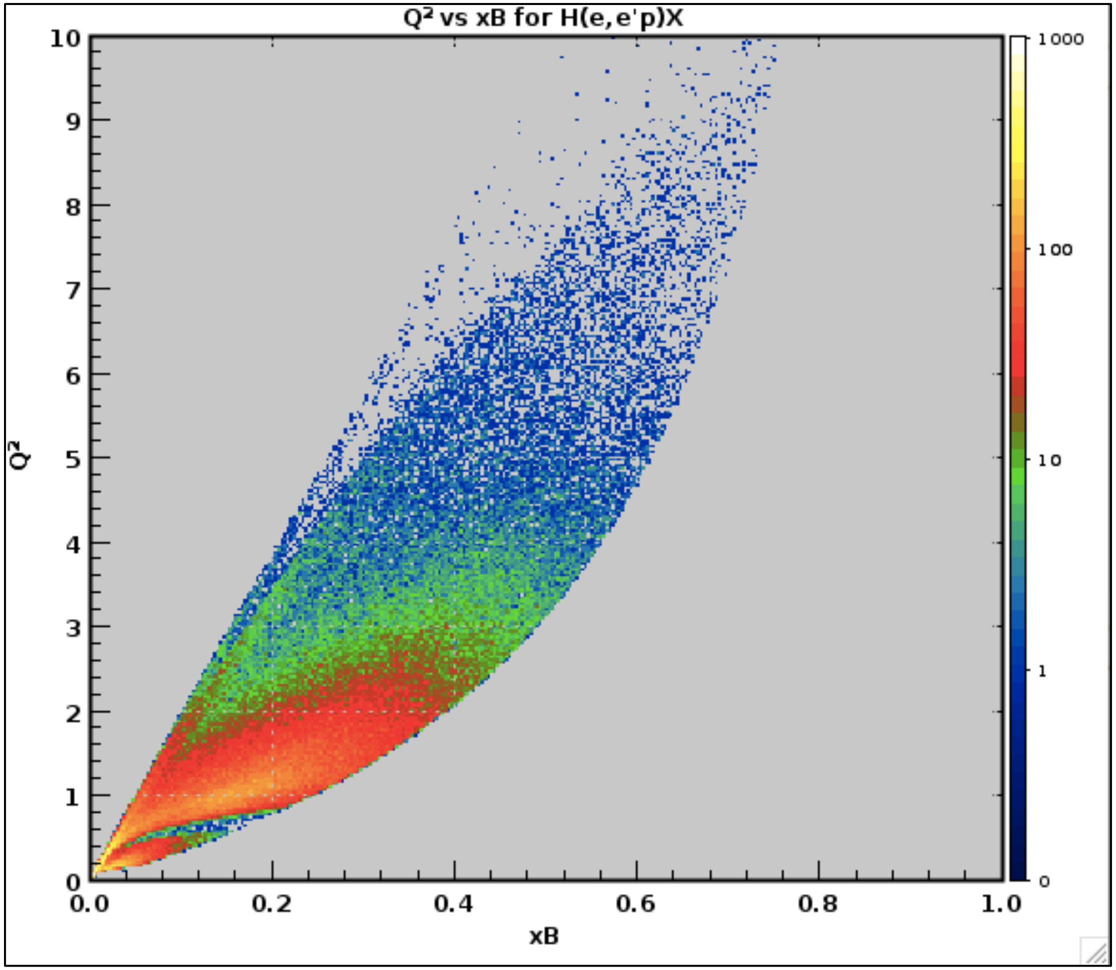
Missing mass for $ep \to e'p'\pi^0 X$

- Reconstruct (missing) second π^0
- Apply a cut on $\gamma\gamma$ invariant mass : $0.10 < m_{\gamma\gamma} < 0.17$ GeV
- Second π^0 reconstructing by peak in H(e,e′p π^0)X missing mass squared at 0.02 GeV^2



CLAS12 Detection ⊗ reconstruction efficiency ≈ 2%

Q^2 vs x_B for H(e , e′ p)X



- Data from Spring 2018 CLAS12, 4 hours of run.
- Apply a cut on :

  $W^2 > 4\ GeV^2$

  $M_X^2 < 2\ GeV^2$

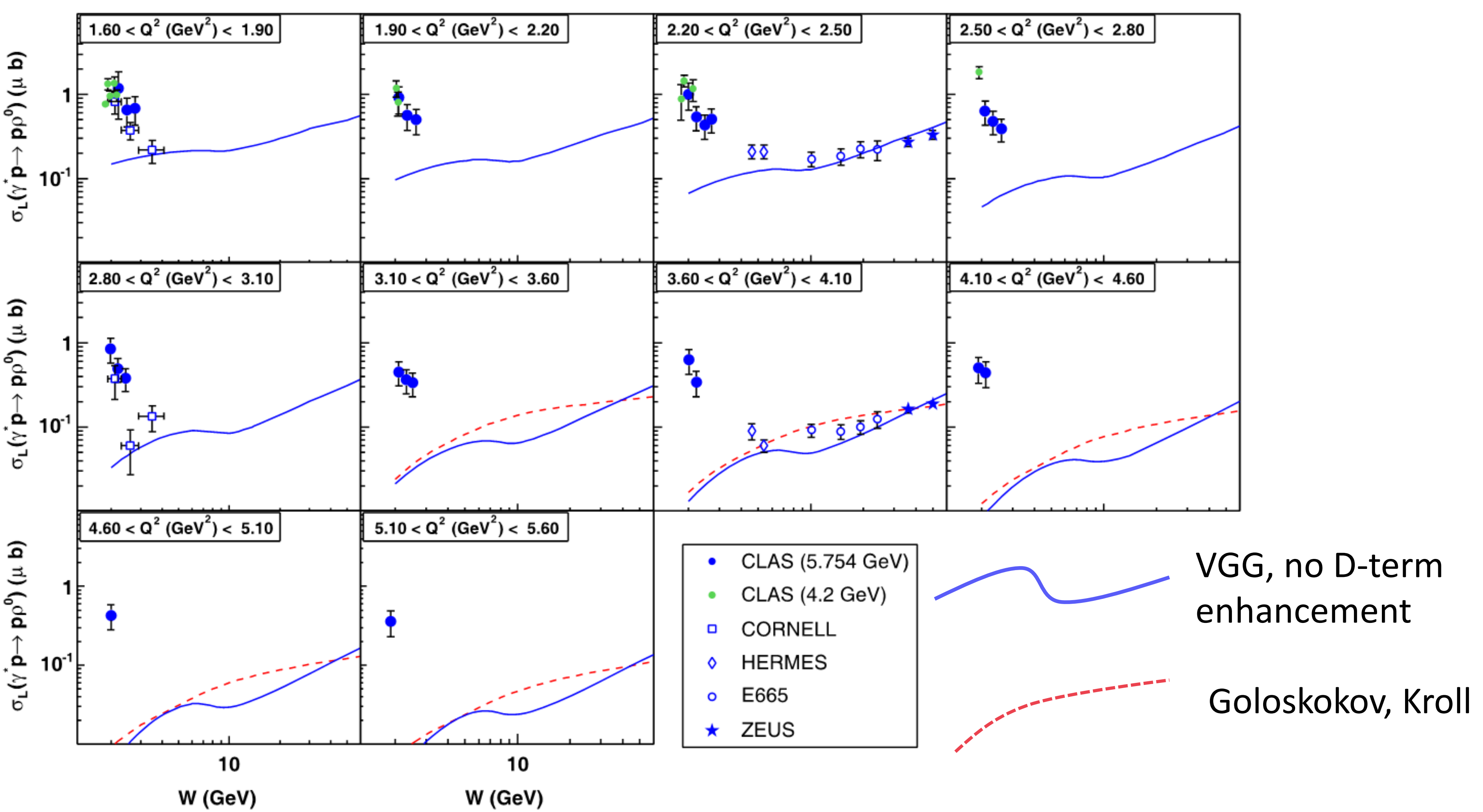
Conclusion

- Calibration/analysis of Spring 2018 CLAS12 data in progress
- Data taking (CLAS12 Run Group A/K) will continue in Fall 2018
  - 10.6, 7.5, 6.5 GeV electrons
- Preparing a run group proposal
  - Implementing Lehmann-Dronke Model in simulation
  - Need improved model for e.g. rho-production
    - SCHC violating amplitudes?
  - Theory work on deep ρ
    - Goloskokov, Kroll Eur.Phys.J. C74 (2014) 2725
      - Predictions for 11GeV? (W~3 GeV)
    - C.Weiss: Instanton dynamics as source of s-channel helicity violation?

Back up Slides

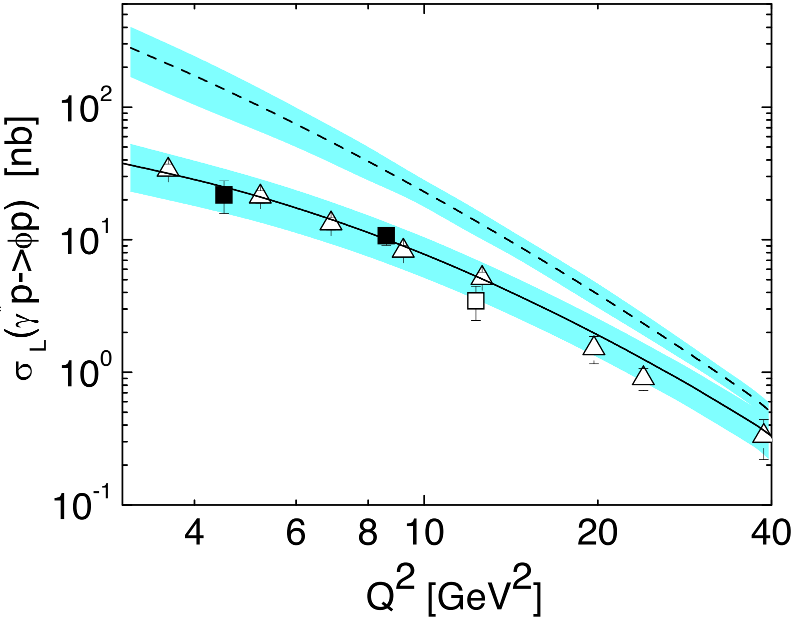
Deep ρ meson Problem

- S-channel helicity conservation violated
- Cross section is anomalously large at low W



The Deep ϕ-meson

- Corrections up to factor of 10 to leading-order factorization at Jlab kinematics
- Successful phenomenology with finite-size/χSB in $\gamma \rightarrow$meson amplitud and kinematic higher twist in proton GPD.
  - Deep π^0, η: χSB Twist-3 DA$\otimes$GPD$_T$
    - $d\sigma_T >> d\sigma_L$
    - (Recent Hall A and CLAS results)
- Deep ϕ : Sudakov form factor (finite-size) suppression:
  - CLAS/HERMES/HERA data ➔

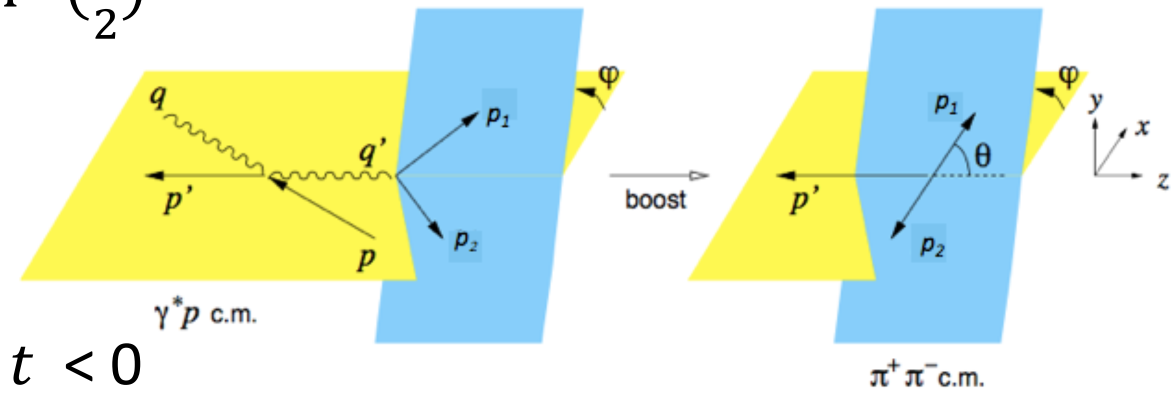


Basic Kinematics and Observables

- Here are the exclusive two-pion electroproduction kinematics on a proton using the following momentum variables:

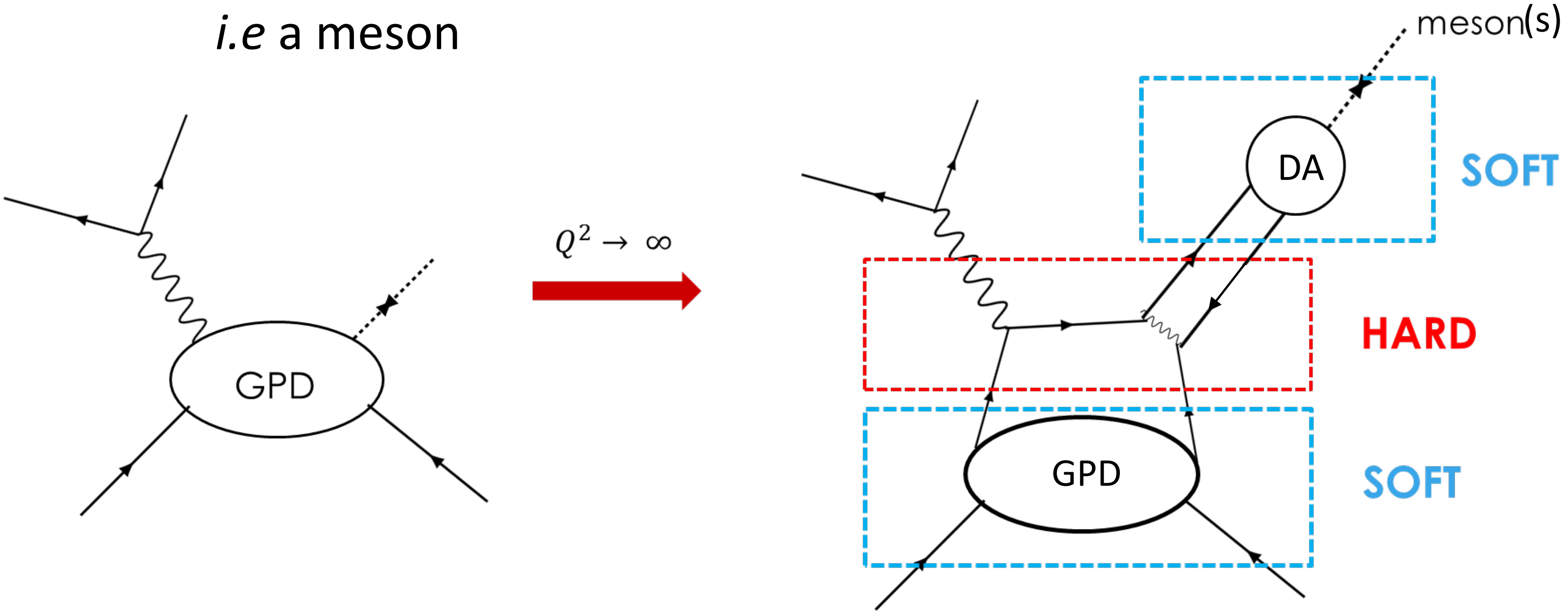
$$\boldsymbol{e}(\boldsymbol{k}) + \boldsymbol{P}(\boldsymbol{P}) \rightarrow \boldsymbol{e}(\boldsymbol{k}') + \boldsymbol{\pi}_1(\boldsymbol{p}_1) + \boldsymbol{\pi}_2(\boldsymbol{p}_2) + \boldsymbol{P}(\boldsymbol{P}') \,.$$

- $q = k - k'$
- $q^2 = -Q^2 = 4EE' \sin^2(\frac{\theta}{2})$
- $\nu = E - E'$
- $W^2 = (P + q)^2$
- $x_B = \frac{\boldsymbol{Q^2}}{\boldsymbol{2P.q}}$
- $\Delta = P' - P$ and $\Delta^2 = t < 0$
- $(p_1 + p_2)^2 = m_{\pi\pi}{}^2$
- $q' = p_1 + p_2$ (e.g. σ or ρ meson)



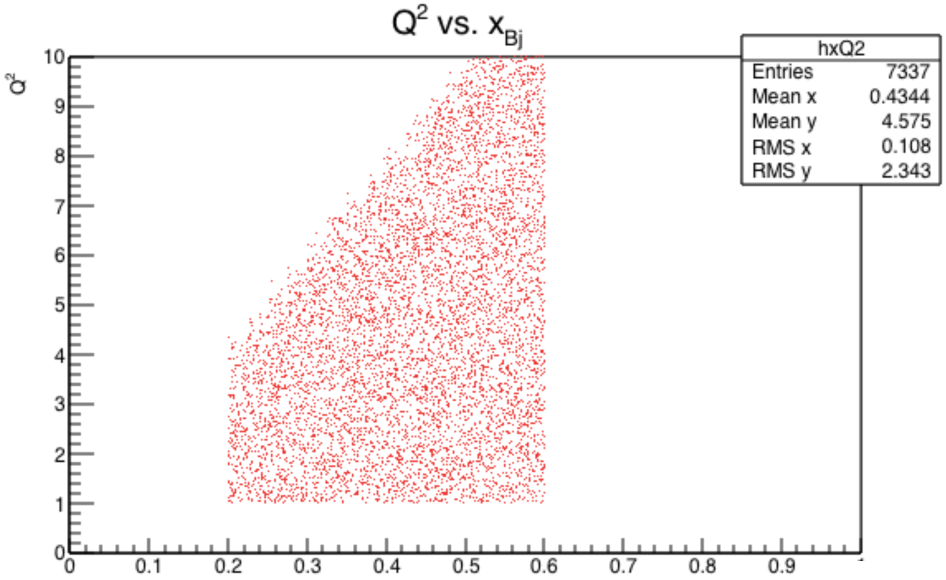
Deep Virtual Exclusive Scattering (DVES)

- $ep \rightarrow e'p'h$ where h is the hadronic system *i.e* a meson



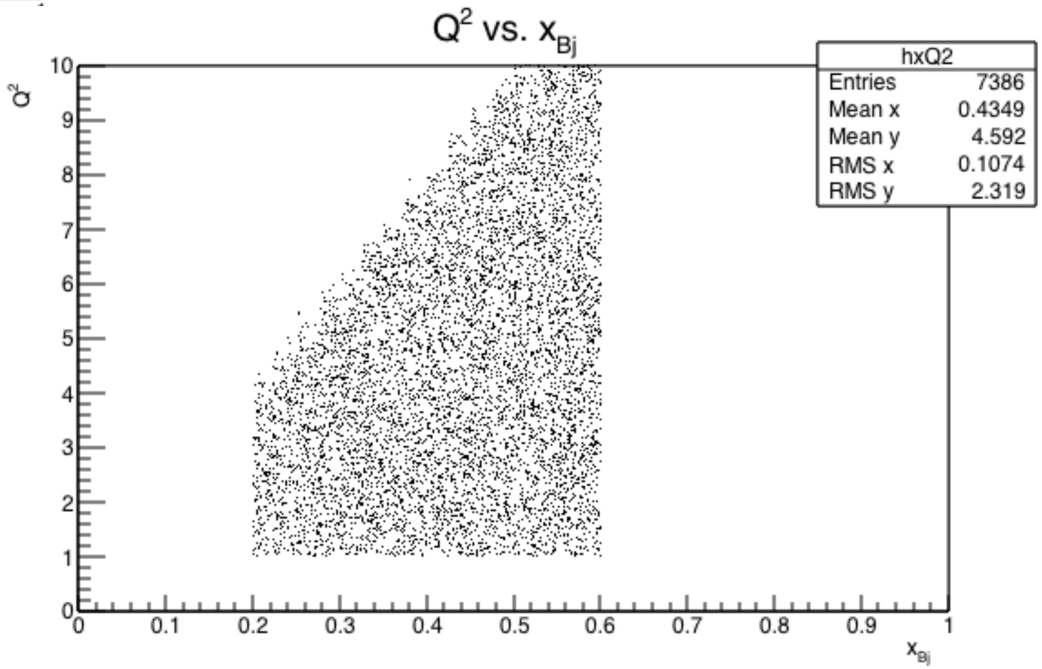
- The interaction of the scattered electron with a parton (HARD), calculable through perturbative QCD, and the parton interaction with the proton (SOFT), described in terms of GPDs and another soft part describes the meson production.

Event Generator Results



$ep \rightarrow e'p'\pi^+\pi^-$

$ep \rightarrow e'p'\pi^0\pi^0$



Analysis

- Treat pi-minus as "missing" even if detected
- Here is the cosine distribution of detected pi+ in rest frame
- piplus is always forward, if detected.