APS April Meeting 2019

Quasi-Free Cross Section Measurements of the $\pi^+\pi^-$ Electroproduction off the Bound Proton in Deuterium

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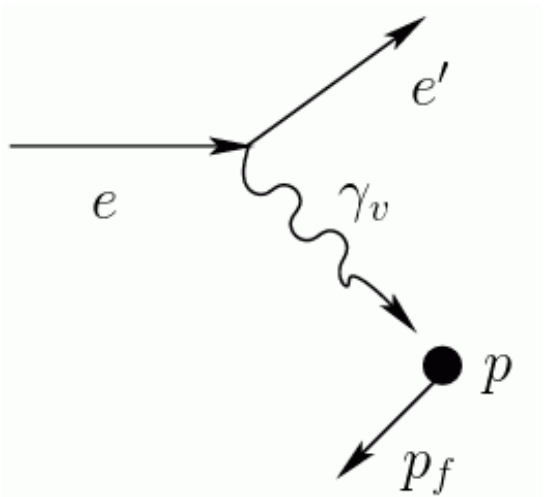
Supported by the South Carolina NSF grant PHY-1812382 and the JSA/JLab Graduate Fellowship

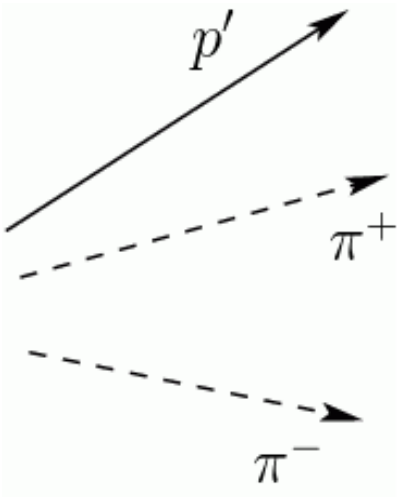
CLAS Deuteron Target Experiment

(e1e run, E_{beam} = 2.039 GeV)

$\gamma_v\, p(n)$



$p'(n')\pi^+\,\pi^-$



CLAS: B. A. Mecking et al., Nucl. Inst. Meth., Vol. A503, pp. 513-553, 2003.

Differences from the Free Proton Experiment

1) Considerably more complex effects of initial and final state interactions due to the presence of an additional nucleon → difficulties in exclusive event selection

2) Fermi motion of the target proton with the following consequences:

- Smearing of kinematic quantities (W, missing mass, etc.) if not all final particles are registered
- Different procedure of lab-to-cms transformation
- Moving proton experiment with fixed beam energy is equivalent to that on the proton at rest with varying beam energy

3) Off-shellness of the target proton

4) Possible modifications of reaction amplitudes

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Analysis Goals

- The integral and single-differential cross sections of the reaction $\gamma_v\, p(n) \rightarrow p'(n')\pi^+\,\pi^-$ are extracted

- The cross sections are extracted in the quasi-free regime

- Measurements were performed in the second resonance region for
  - 1.3 GeV < W < 1.825 GeV and
  - 0.4 GeV^2 < Q^2 < 1 GeV^2

$$\sigma_v^{int}(W,Q^2) = \int \frac{d^5\sigma_v}{\mathrm{d}^5\tau}\mathrm{d}M_{h_1h_2}\mathrm{d}M_{h_2h_3}\mathrm{d}\Omega_{h_1}\mathrm{d}\alpha_{h_1}$$

$$\frac{\mathrm{d}\sigma_v}{\mathrm{d}M_{p'\pi^+}} \quad \frac{\mathrm{d}\sigma_v}{\mathrm{d}M_{\pi^-\pi^+}} \quad \frac{\mathrm{d}\sigma_v}{\mathrm{d}M_{\pi^-p'}}$$

$$\frac{\mathrm{d}\sigma_v}{\mathrm{d}[-\cos\theta_{p'}]} \quad \frac{\mathrm{d}\sigma_v}{\mathrm{d}[-\cos\theta_{\pi^-}]} \quad \frac{\mathrm{d}\sigma_v}{\mathrm{d}[-\cos\theta_{\pi^+}]}$$

$$\frac{\mathrm{d}\sigma_v}{\mathrm{d}\alpha_{p'}} \quad \frac{\mathrm{d}\sigma_v}{\mathrm{d}\alpha_{\pi^-}} \quad \frac{\mathrm{d}\sigma_v}{\mathrm{d}\alpha_{\pi^+}}$$

- The extracted cross sections will be compared with the cross sections of the analogous reaction off the free proton [1]

[1] G.V. Fedotov, Iu. Skorodumina et al. [CLAS Collaboration], Phys. Rev. C 98 (2018) No.2, 025203 (2018), arXiv:1804.05136.

Monte Carlo Simulation with TWOPEG-D

- TWOPEG-D [2] is a new event generator for the quasi-free process of double-pion electroproduction off the moving proton

- The initial proton motion is accounted according to the Bonn potential [3]

- In this analysis TWOPEG-D was successfully used

  - ✔ To estimate the detector efficiency
  - ✔ To fill the kinematic cells with zero acceptance
  - ✔ To correct for the effects of the target motion

[2] CLAS12-Note-2017-014, arXiv:1712.07712
[3] R. Machleidt, K. Holinde, and C. Elster, Phys. Rept., Vol. 149, pp. 1-89, 1987

Topologies for the $\gamma_v\, p(n) \rightarrow p'(n')\pi^+\pi^-$ reaction

- All final particles are registered (~10%) – fully exclusive topology
- π^- is missing (~70%)

- π^+ is missing (~10%) $\rightarrow$ misidentification with
  $\gamma_v\, n(p) \rightarrow p'(n')\pi^-$ and
  $\gamma_v\, n(p) \rightarrow p'(n')\pi^-\pi^0$ channels
- p is missing (~10%) $\rightarrow$ misidentification with
  $\gamma_v\, n(p) \rightarrow n'(p')\pi^+\pi^-$ channel

} Not used

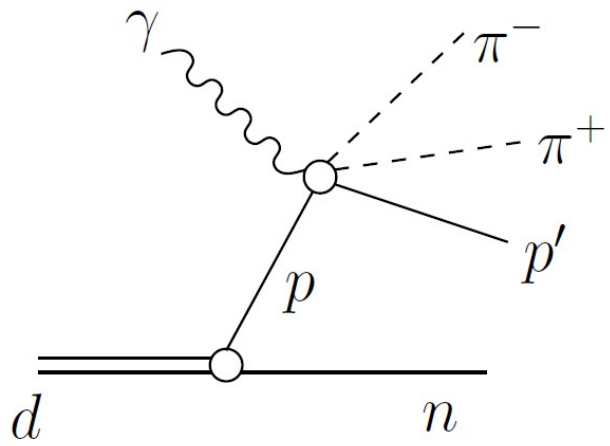
Selection of Double-Pion Events

Cuts	Data	Simulation
Fiducial	yes	yes
EC-cut → Electron identification	yes	yes
CC-cut	yes	no/yes
β vs. p → Hadron identification	yes	yes
θ vs. p	yes	yes
Electron momentum correction	yes	no
Proton energy loss correction	yes	yes
Exclusivity cut	yes	yes

Complicated by FSI

Quasi-Free Regime vs Final State Interactions

Quasi-free regime



Final state interactions

- Interaction of final hadrons with each other → *rather small effect as is known from the double-pion production off the free proton*
- Interaction of final hadrons with the additional nucleon (neutron) = rescattering under the influence of the strong interaction via resonant and/or non-resonant mechanisms → *noticeable effect*

FSI for $p(n)\pi^+\pi^-$ Final State

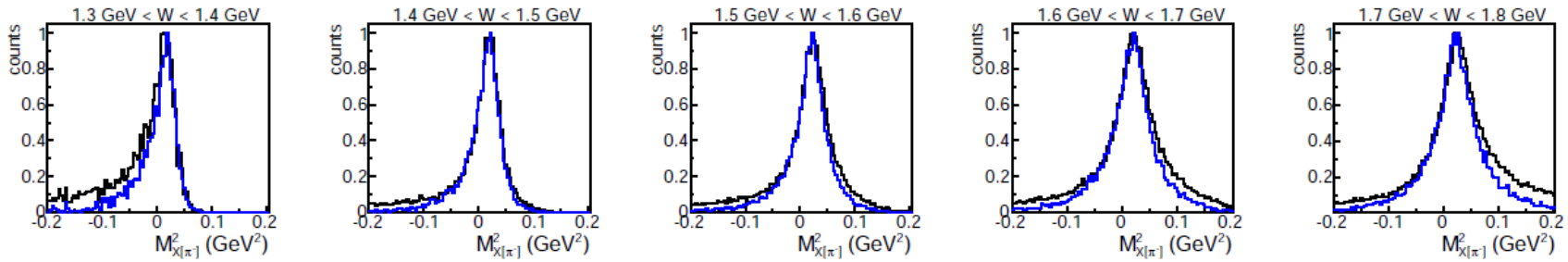
FSI strongly depend on:

- Invariant mass of final hadron system (W)
- Scattering angles of final hadrons.
  Hence FSI are topology dependent!

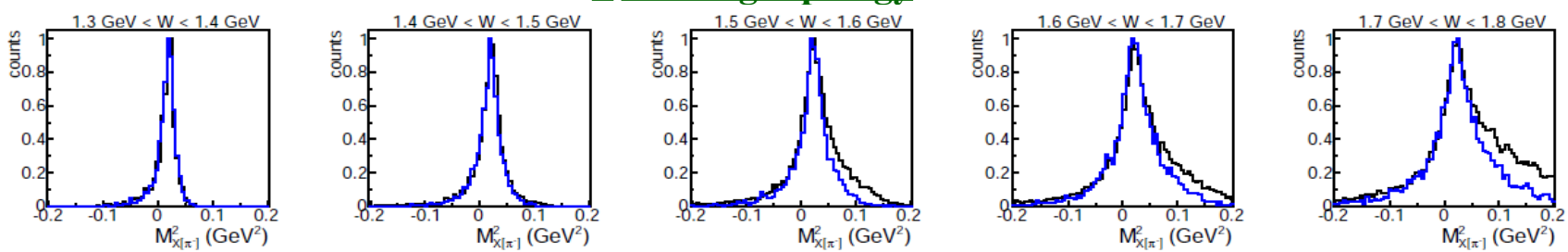
$$M^2_{X[\pi^-]} = [P^\mu_e + P^\mu_p - P^\mu_{e'} - P^\mu_{p'} - P^\mu_{\pi^+}]^2,$$

where P^μ_i are the four-momenta of the particle i.

Fully exclusive topology



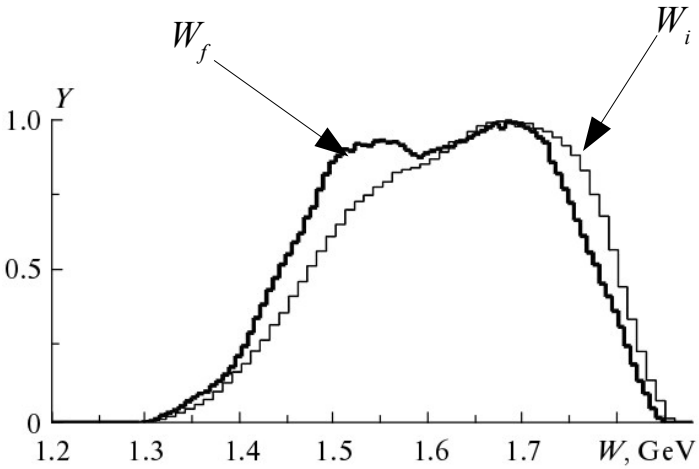
π^- missing topology



Black curve – data, **Blue curve** – simulation (FSI not included)

Smearing of the Reaction Invariant Mass (W)

Experimental event yield in the fully exclusive topology



$$W_i = \sqrt{(P^\mu_p + P^\mu_{\gamma_v})^2} \quad \text{(target-at-rest assumption)}$$

$$W_f = \sqrt{(P^\mu_{\pi^+} + P^\mu_{\pi^-} + P^\mu_{p'})^2}$$

- W_f is better suitable for the cross section extraction, but it is not available in the π^- missing topology
- The cross section is therefore binned in W_i and hence is folded with the effects of the initial proton motion
- The corresponding cross section inaccuracy is corrected
- The correction is based on the Monte Carlo simulation
- The multi-dimensional correction factor is estimated as

$$\mathcal{F}(\Delta W \Delta Q^2 \Delta \tau) = \frac{N_{rest}(\Delta W \Delta Q^2 \Delta \tau)}{N_{moving}(\Delta W \Delta Q^2 \Delta \tau)}$$

N_{rest} – from TWOPEG off proton at rest

N_{moving} – from TWOPEG-D off moving proton

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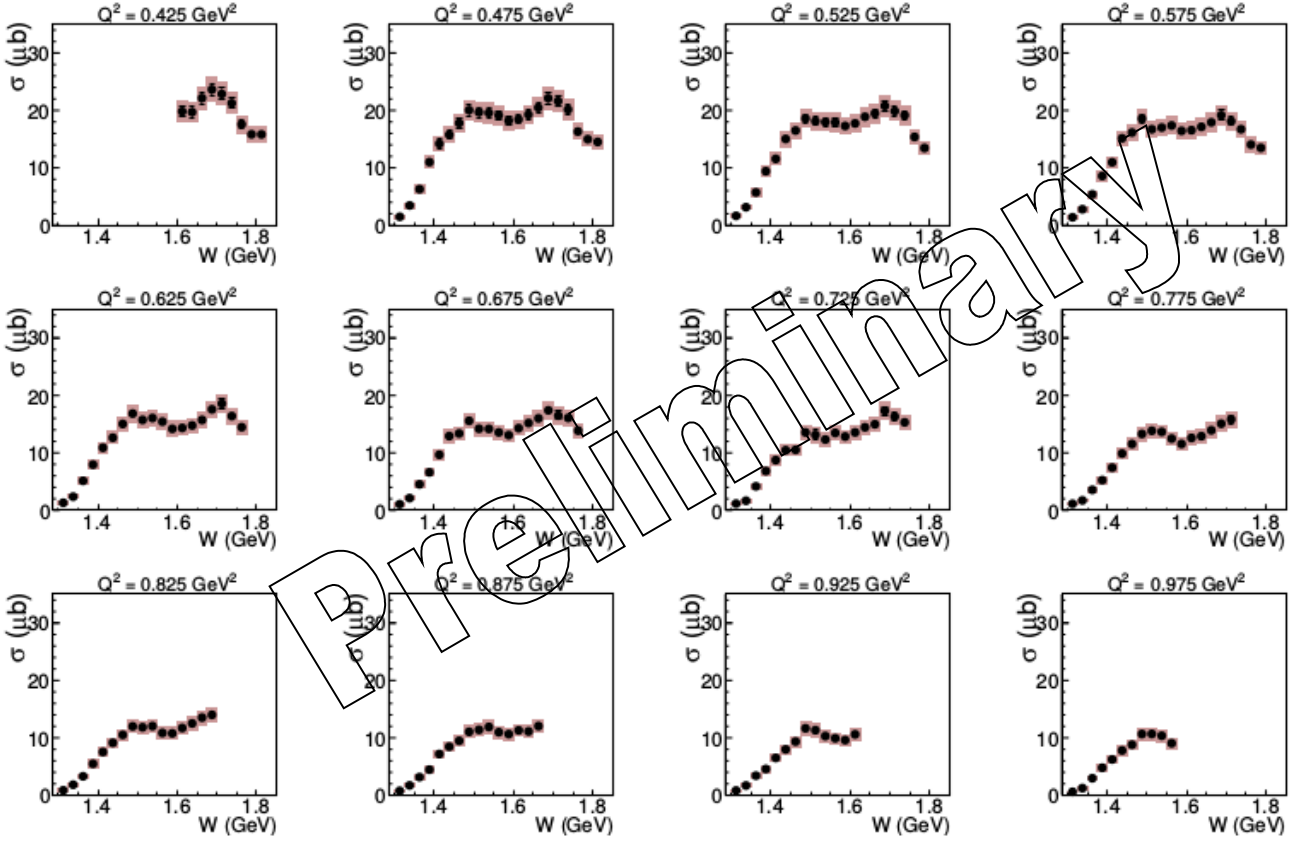
Integral Cross Sections (W dependence)



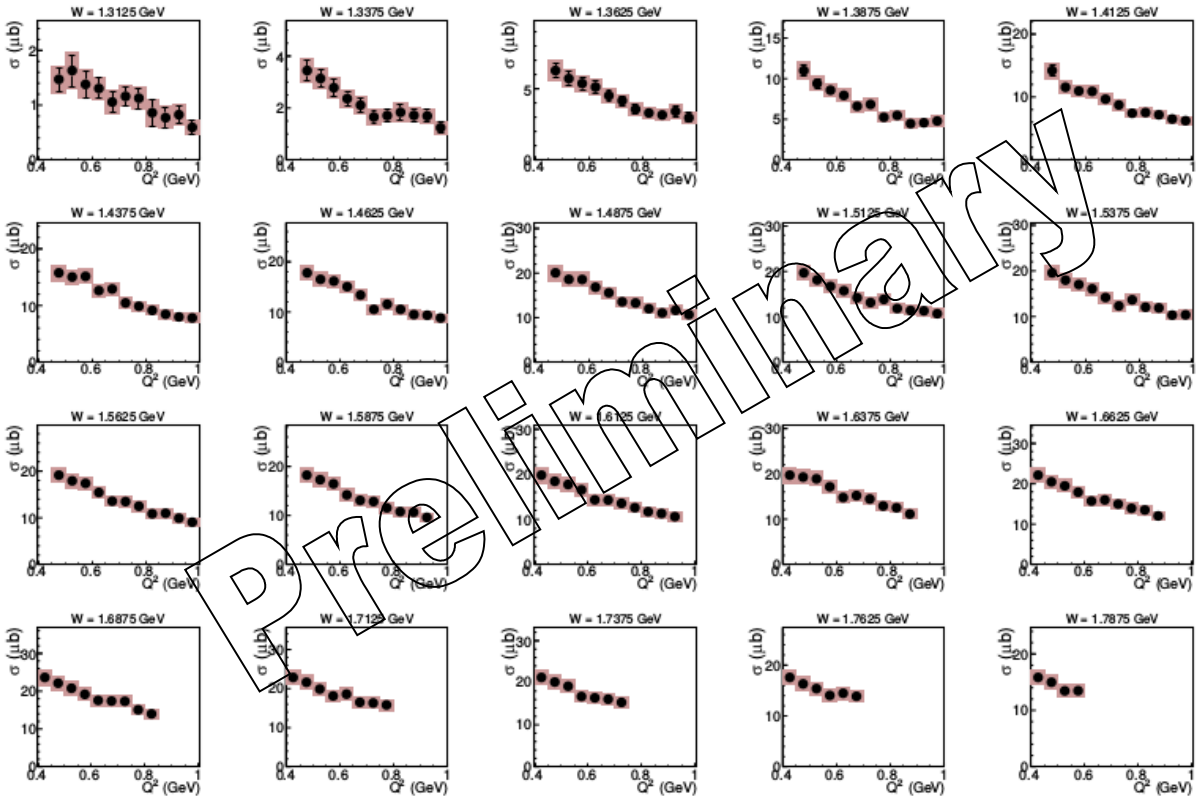
Black symbols – extracted integral cross sections.

Error bars correspond to the combination of the statistical and model dependence uncertainties.

Pink shadowed areas correspond to the total uncertainty, which is the combination of the statistical, model dependence, and systematic uncertainties.

$$\sigma_v^{int}(W,Q^2) = \int \frac{d^5\sigma_v}{\mathrm{d}^5\tau}\mathrm{d}M_{h_1h_2}\mathrm{d}M_{h_2h_3}\mathrm{d}\Omega_{h_1}\mathrm{d}\alpha_{h_1}$$

Integral Cross Sections (Q^2 Dependence)



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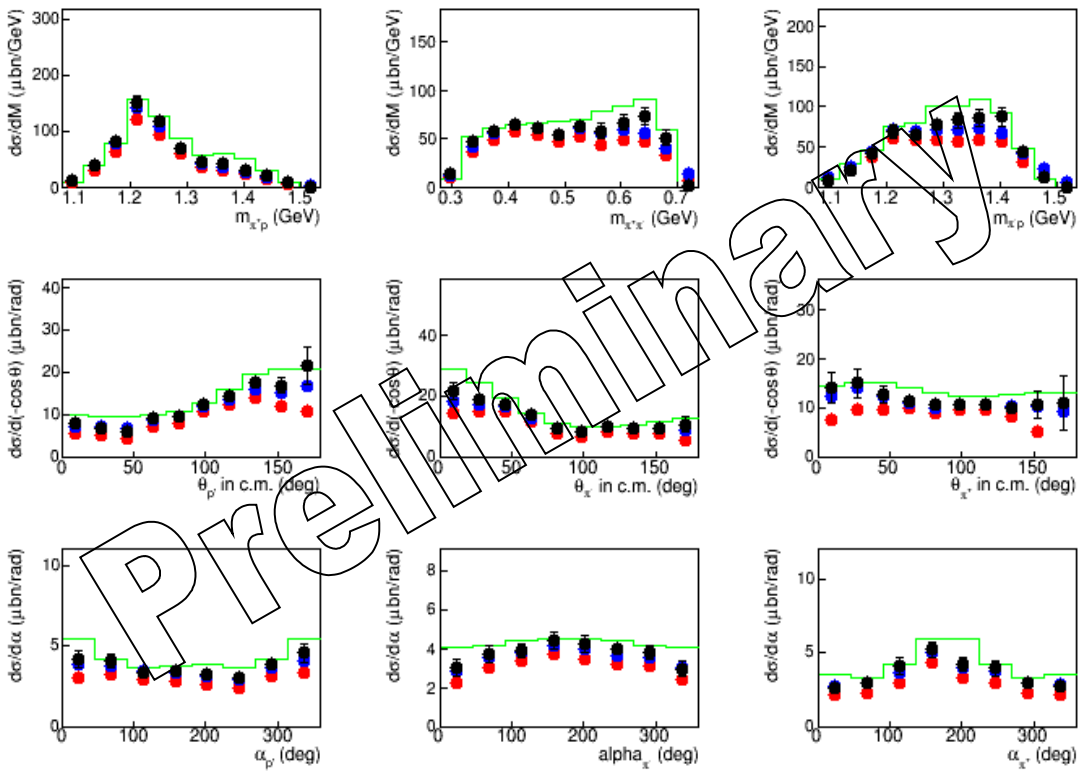
Differential Cross Sections



$W = 1.6375$ GeV, $Q^2 = 0.475$ GeV^2

Red symbols – empty cells are NOT filled
Blue symbols – empty cells are filled
Black symbols – Fermi correction is applied
Green curve – from EG off the free proton

$$\begin{array}{ccc} \frac{d\sigma_v}{dM_{p'\pi^+}} & \frac{d\sigma_v}{dM_{\pi^-\pi^+}} & \frac{d\sigma_v}{dM_{\pi^-p'}} \\ \frac{d\sigma_v}{d[-\cos\theta_{p'}]} & \frac{d\sigma_v}{d[-\cos\theta_{\pi^-}]} & \frac{d\sigma_v}{d[-\cos\theta_{\pi^+}]} \\ \frac{d\sigma_v}{d\alpha_{p'}} & \frac{d\sigma_v}{d\alpha_{\pi^-}} & \frac{d\sigma_v}{d\alpha_{\pi^+}} \end{array}$$

Conclusion

- Quasi-free integral and single-differential cross sections of the reaction $\gamma_v\, p(n) \rightarrow p'(n')\pi^+\,\pi^-$ are extracted for the first time

- Methods of selecting events in quasi-free kinematics and unfolding the effects of the proton motion are developed

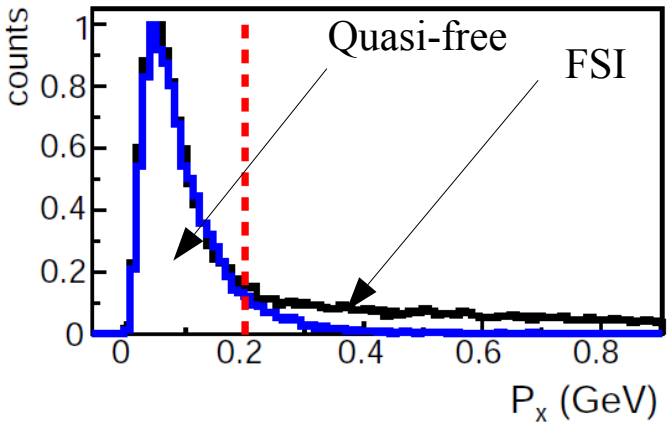
- The TWOPEG-D event generator was tested and for the first time used for the efficiency evaluation, filling cells with zero acceptance and unfolding the effects of the proton motion

- Further analysis will include the comparison of the obtained results with the corresponding results of the free proton experiment

- CLAS Analysis Note is almost ready for submission. The PhD thesis is in preparation

Thank you!

Exclusivity Cut in the Fully Exclusive Topology

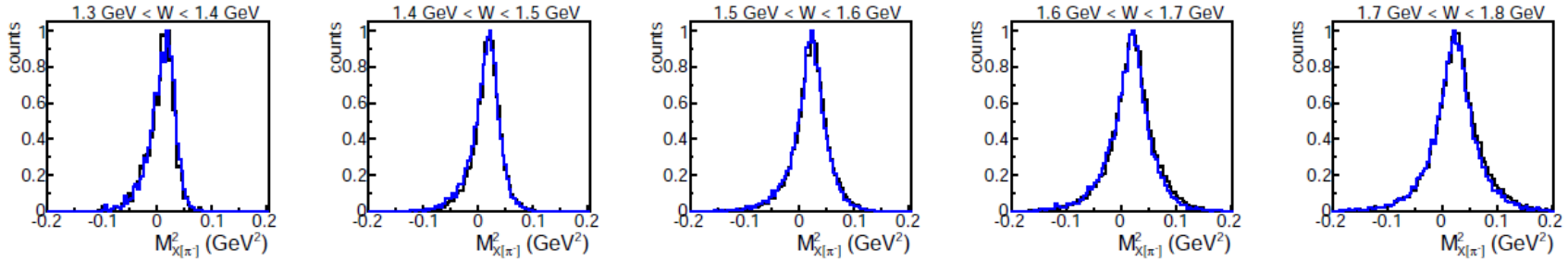


$$P_X = |\vec{P}_e - \vec{P}_{e'} - \vec{P}_{p'} - \vec{P}_{\pi^+} - \vec{P}_{\pi^-}|,$$

where $\vec{P}_i$ are the three-momenta of the particle i.

Cut P_x = 0.2 GeV selects quasi-free events.

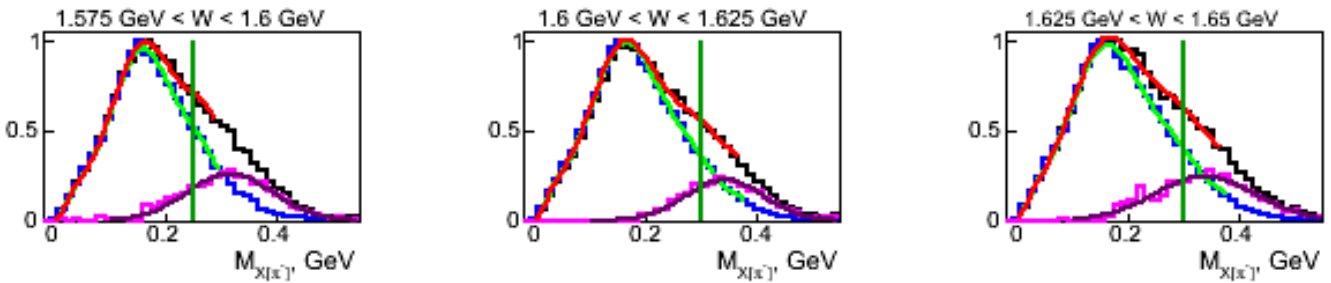
After the cut.



Black curve – data, **Blue curve** – simulation (FSI not included)

Exclusivity Cut in the π^- Missing Topology

$$M_{X[\pi^-]} = \sqrt{|M^2_{X[\pi^-]}|} = \sqrt{|[P^\mu_{\pi^-\ miss}]^2|} = \sqrt{|[P^\mu_e + P^\mu_p - P^\mu_{e'} - P^\mu_{p'} - P^\mu_{\pi^+}]^2|}.$$



Black histogram – experimental data, **Blue histogram** – simulation, **Purple histogram** – their difference. **Green curve** – fit to the simulation, **Purple curve** – fit to the difference, **Red curve** – their sum.

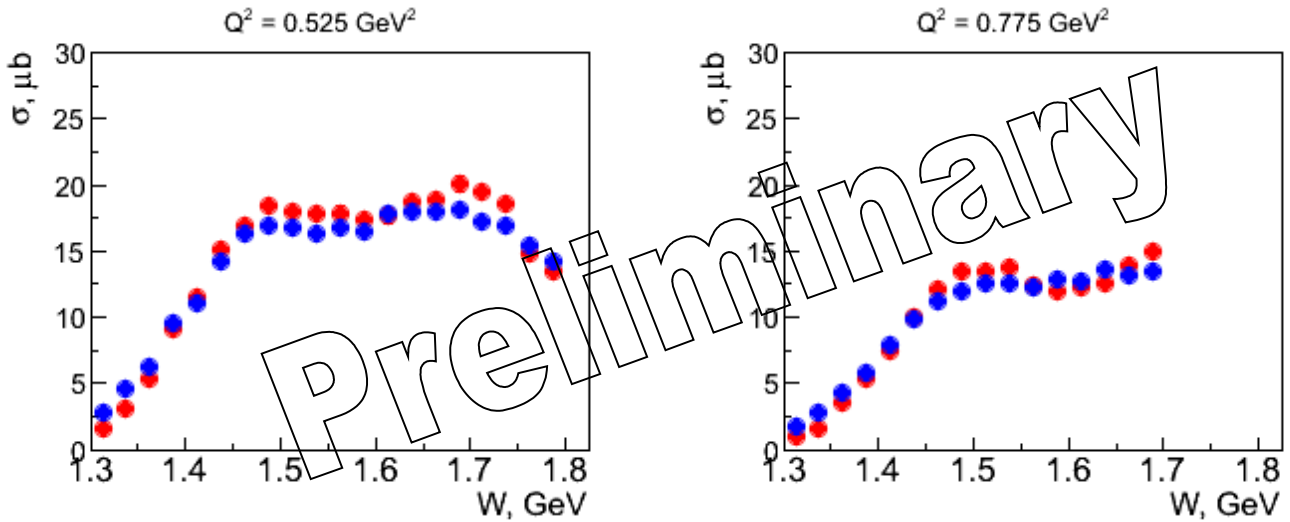
The corresponding correction factor

$$F_{fsi}(\Delta W) = \frac{Area\ under\ green}{Area\ under\ red}$$

Unfolding the Effects of the Proton Motion

$$\frac{d^7\sigma_{corr}}{dW dQ^2 d^5\tau} = \frac{d^7\sigma_{not\ corr}}{dW dQ^2 d^5\tau} \times \mathcal{F}(\Delta W \Delta Q^2 \Delta\tau) \qquad \mathcal{F}(\Delta W \Delta Q^2 \Delta\tau) = \frac{N_{rest}(\Delta W \Delta Q^2 \Delta\tau)}{N_{moving}(\Delta W \Delta Q^2 \Delta\tau)}$$

N_{rest} – from TWOPEG off proton at rest, N_{moving} – from TWOPEG-D off moving proton



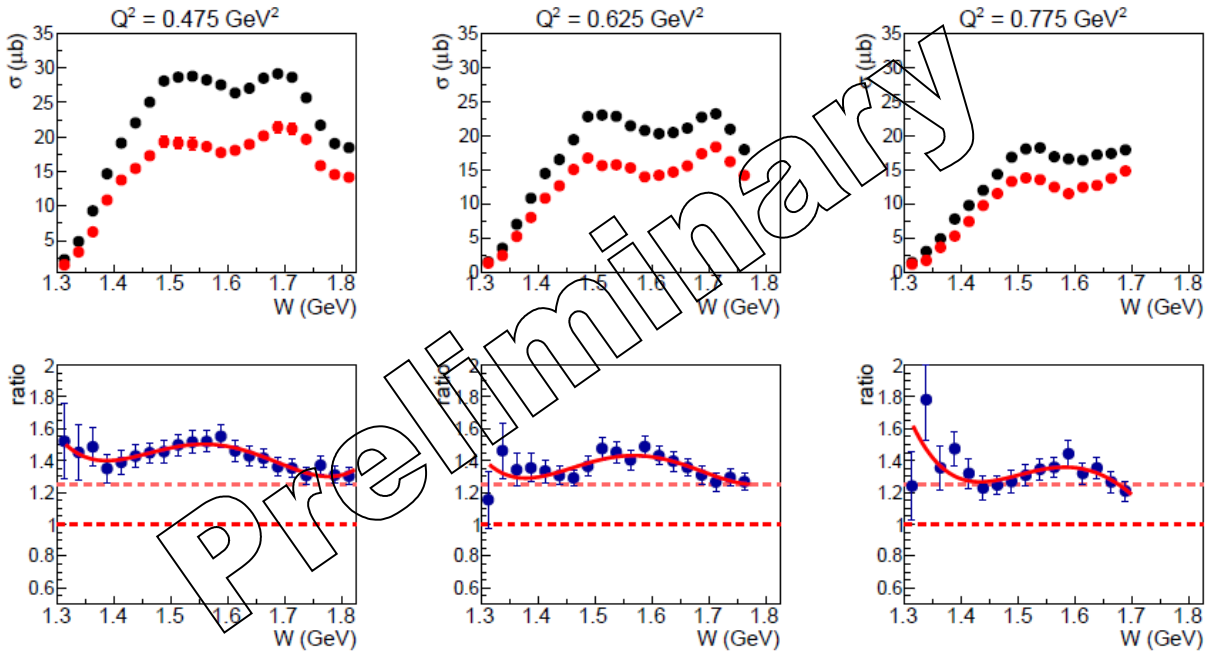
Red symbols – corrected experimental cross sections,
Blue symbols – not corrected experimental cross sections

Cross Section Uncertainties

- Statistical uncertainties
  - Due to the experimental statistics
  - Due to the Monte Carlo statistics
- Model dependence uncertainties
  - Due to the filling of the cells with zero acceptance
  - Due to the unfolding the effects of the proton motion
- Systematic uncertainties

Source	Average value
Electron identification and normalization	5%
Integration over three sets of hadron variables	1.6%
Relative efficiency uncertainty cut	0.8%
Correction due to FSI-background admixture	0.4%
Radiative corrections	5%
Total	**7.4%**

Comparison with Free Proton Cross Sections



Black symbols – *free* proton cross sections (e1e, E_{beam} = 2.039 GeV) [1]

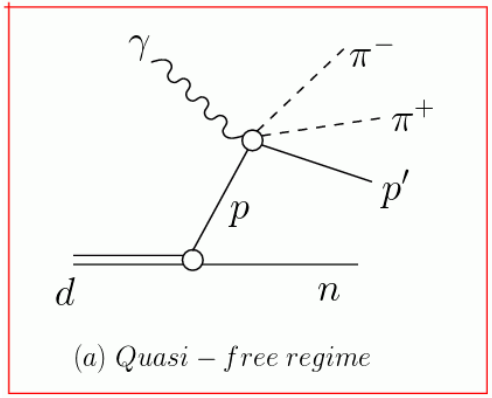
Red symbols – *quasi-free* cross sections on proton in the deuteron (e1e, E_{beam} = 2.039 GeV)

For both data-sets error bars show *statistical* and *model dependence* uncertainties combined

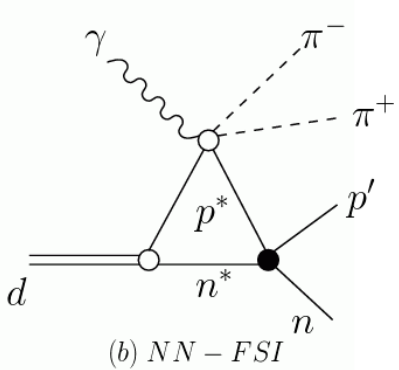
Blue symbols – their ratio

[1] G.V. Fedotov, Iu. Skorodumina et al. [CLAS Collaboration], Phys. Rev. C 98 (2018) No.2, 025203 (2018), arXiv:1804.05136.

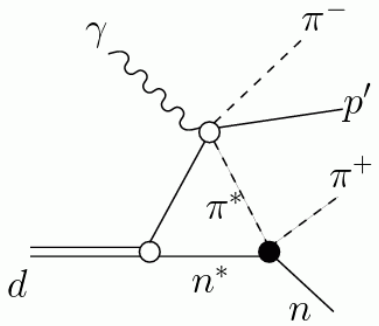
Quasi-Free Regime and FSI for $p(n)\pi^+\pi^-$ Final State



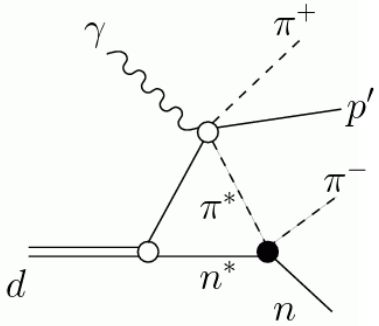
(a) Quasi − free regime



(b) NN − FSI



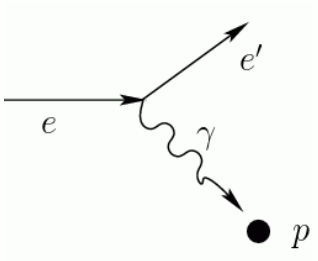
(c) πN − FSI



(d) πN − FSI

Invariant Mass of the Final Hadronic System

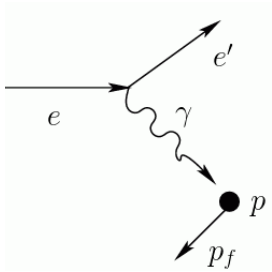
Proton at rest



$$P_p^{\,at\ rest} = (0, 0, 0, m_p)$$

$$W_{true} = \sqrt{(P_p^{\,at\ rest} + P_{\gamma_v})^2}$$

Moving proton



$$P_p^{\,moving} = (p_{fx}, p_{fy}, p_{fz}, \sqrt{m_p^2 + p_f^2})$$

$$W_{true} = \sqrt{(P_p^{\,moving} + P_{\gamma_v})^2}$$

P_f is unknown if π^- is missing

Target-at-rest assumption

$$W_{fsm} = \sqrt{(P_p^{\,at\ rest} + P_{\gamma_v})^2}$$

Double-Pion Kinematics