Absolute d(e,e'p)n Cross Section Studies

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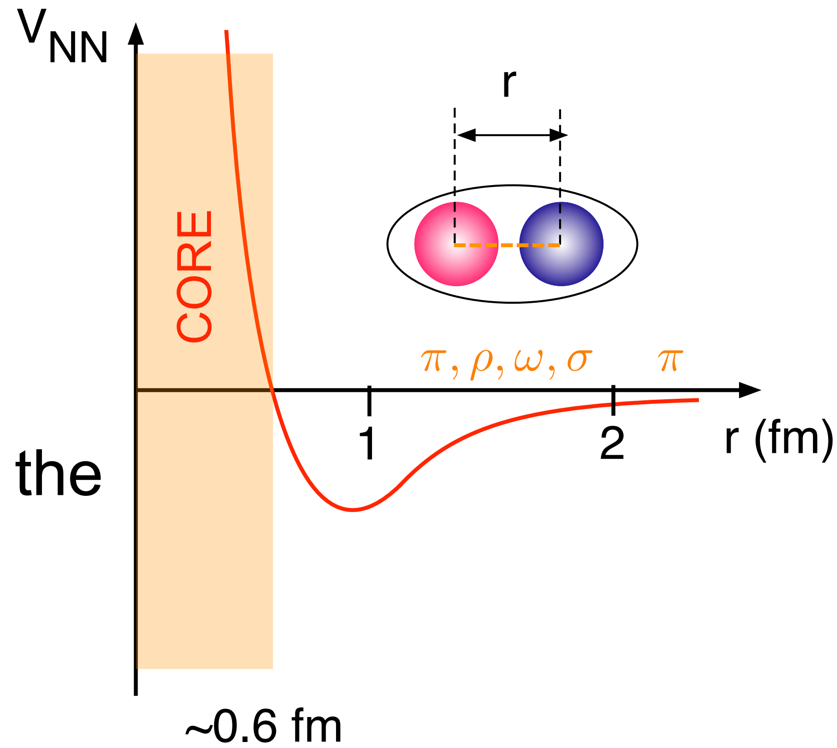
Jefferson Lab

Newport News, VA

Contents

Introduction

- A key system to investigate the core of the NN interaction
- Prime nucleus to test NN models
- Basis for SRC (structure) studies



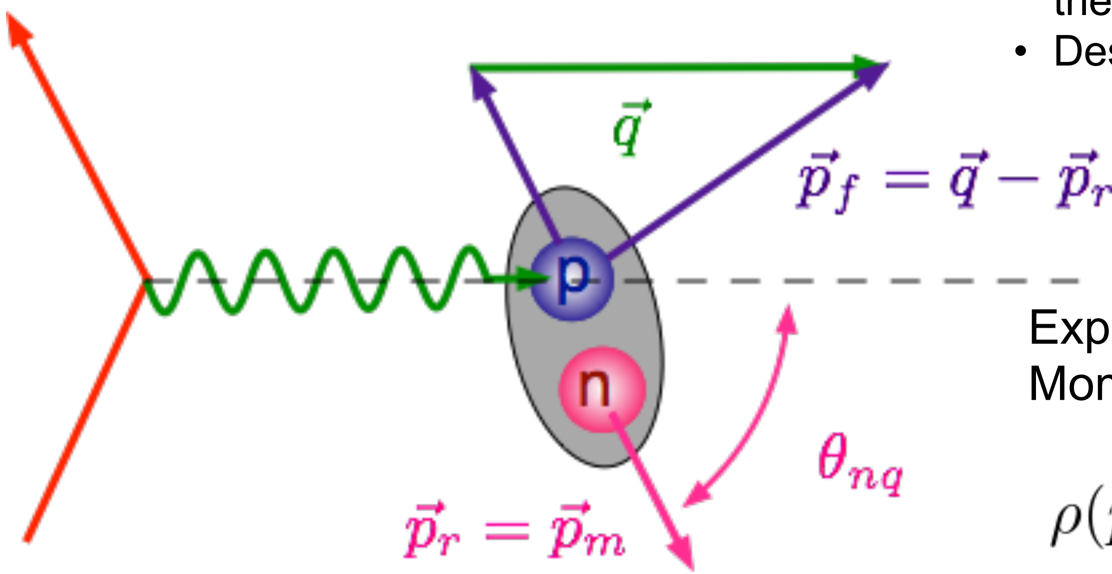
Ideal method: ‘measure’ the momentum distribution ⇒ study the d(e,e’p) reaction

$$\rho(\vec{p}) = C \int \psi(\vec{r}) e^{-i\vec{r}\cdot\vec{p}} d^3 r$$

Very small $\vec{r}$ $\Rightarrow$ very large $\vec{p}$

D(e,e'p) in PWIA

$$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = k\sigma_{ep}\rho(p_r)$$



Plane Wave IA:

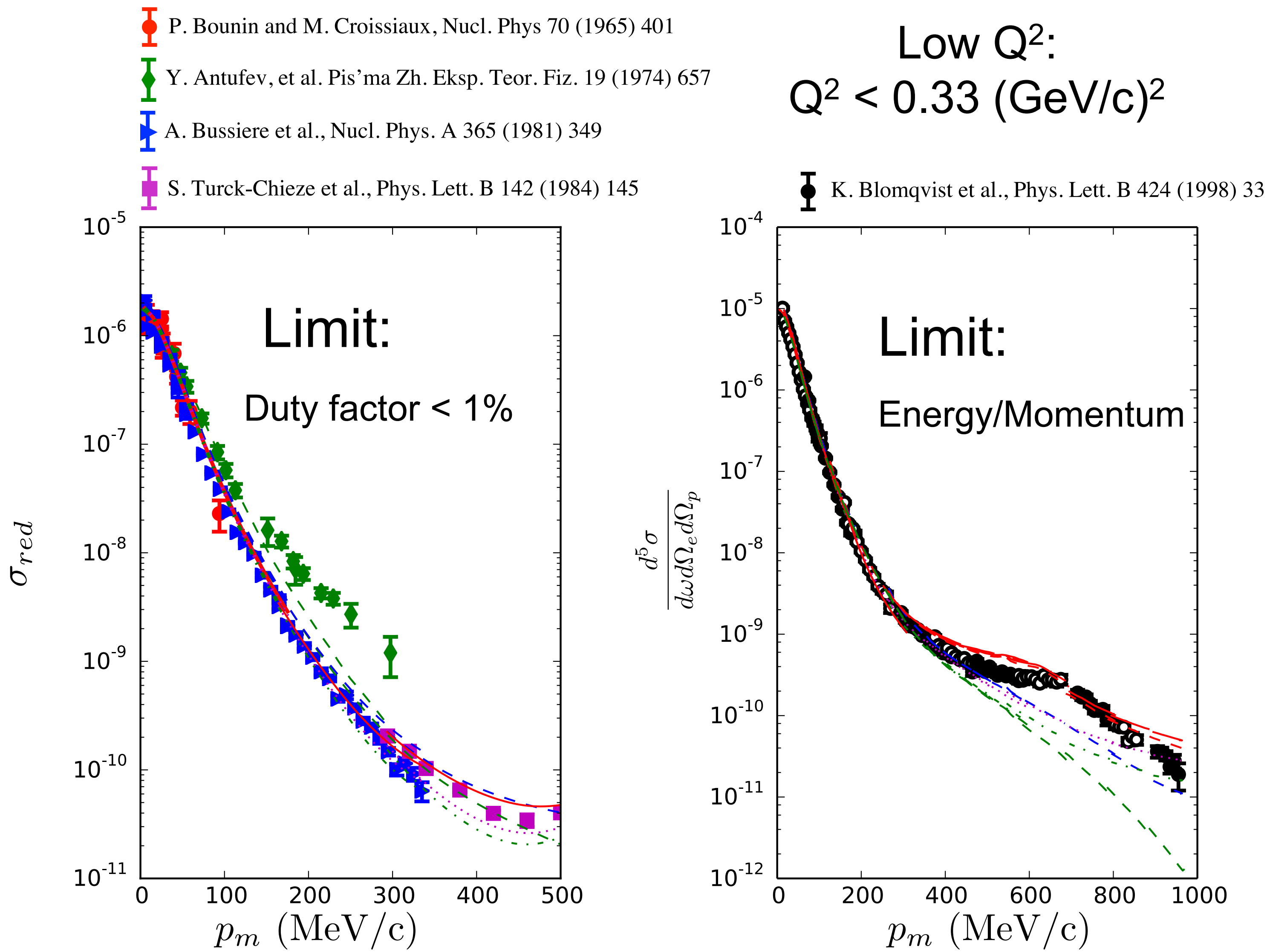
- Hit nucleon does not interact with the recoiling system
- Described by a plane wave

Experimental
Momentum distributions:

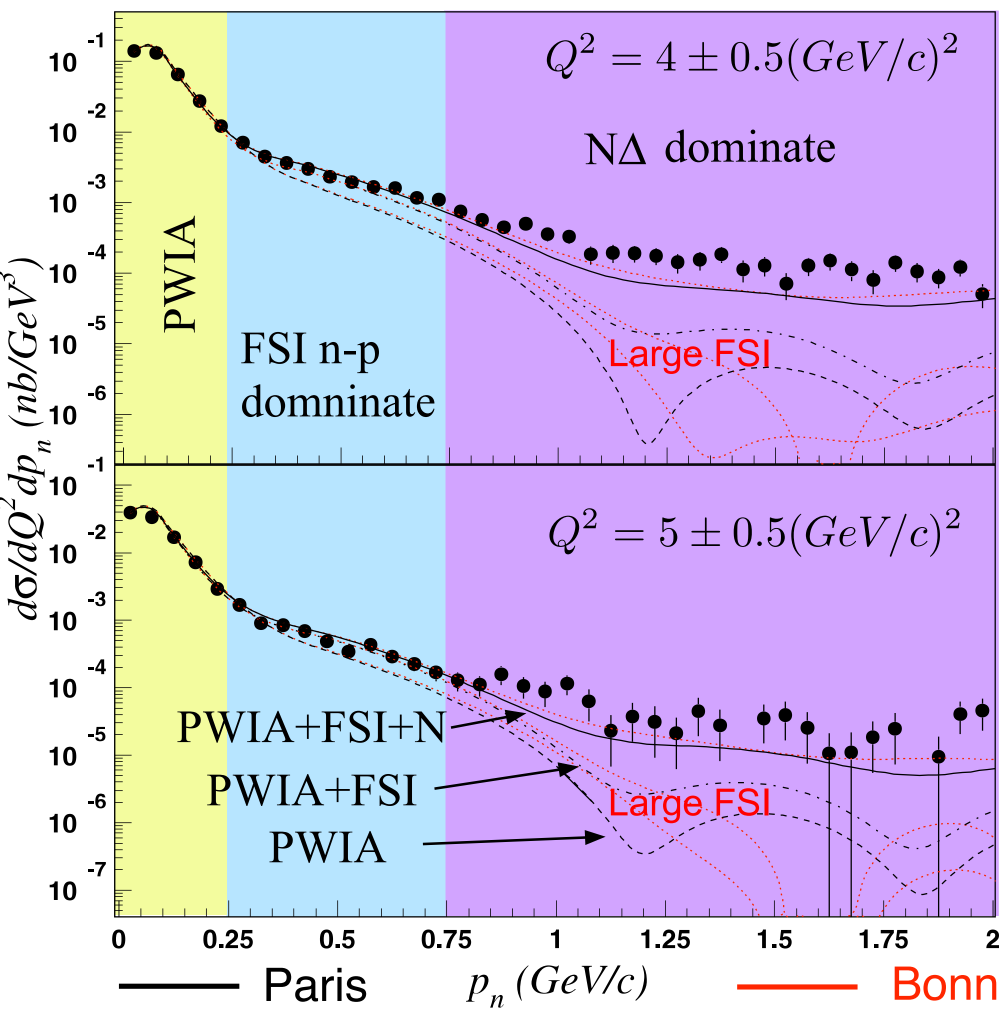
$$\rho(p_r)_{exp} = \sigma_{red} = \frac{\sigma_{exp}}{k\sigma_{ep}}$$

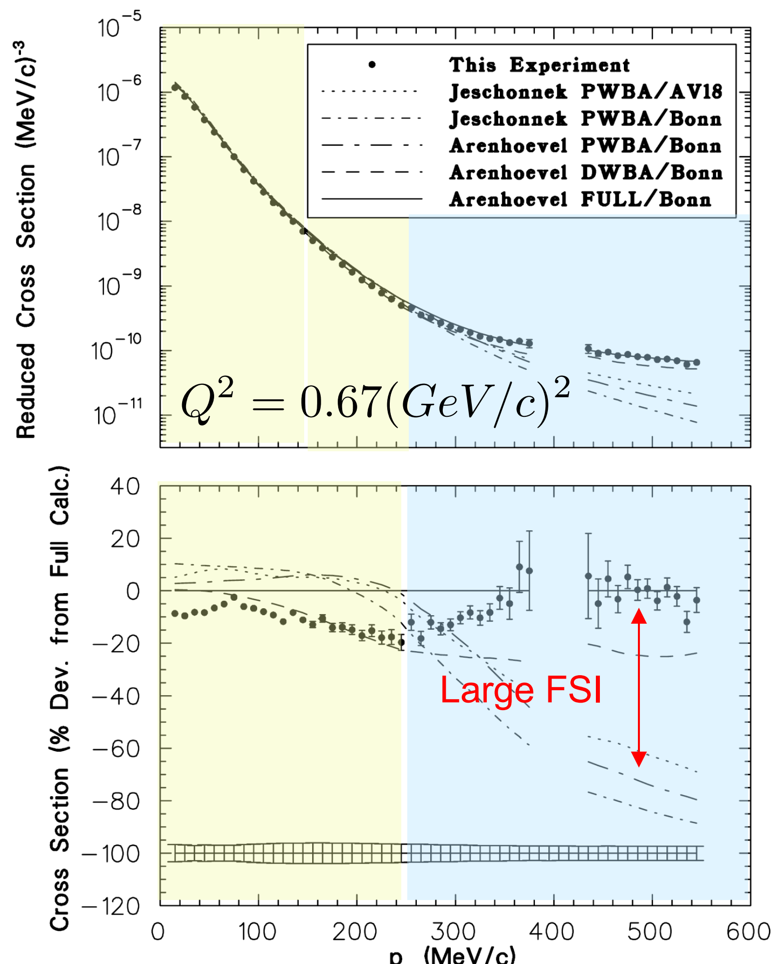
also called reduced cross sections

History of Missing Momentum Dependences



CLAS Egyian et al. PRL 98 (2007) Hall A Ulmer et al. PRL89 (2002) 062301-1

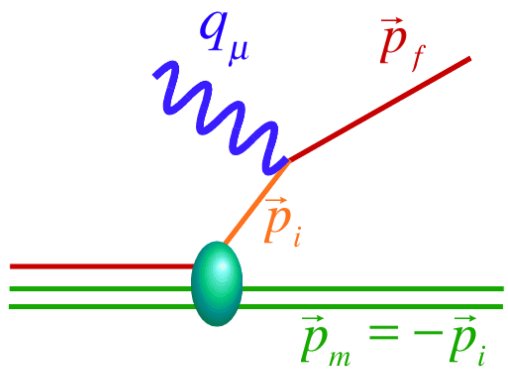




Cross sections integrated over full CLAS acceptance, all recoil angles and wide range of kinematic settings

Introduction: D(e,e' p) Reaction Mechanisms

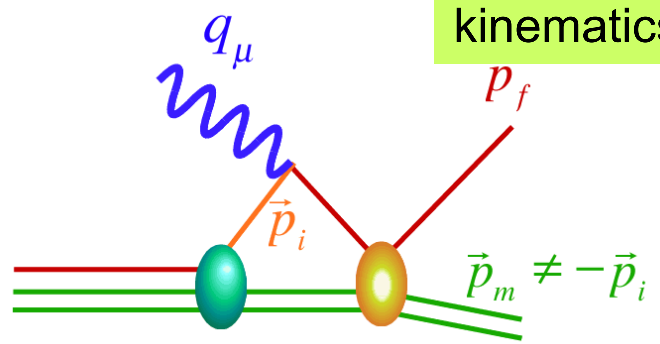
PWIA



$$\frac{d\sigma}{d\omega d\Omega_e d\Omega_N} = k\sigma_{eN} S(E_m, p_m)$$

FSI

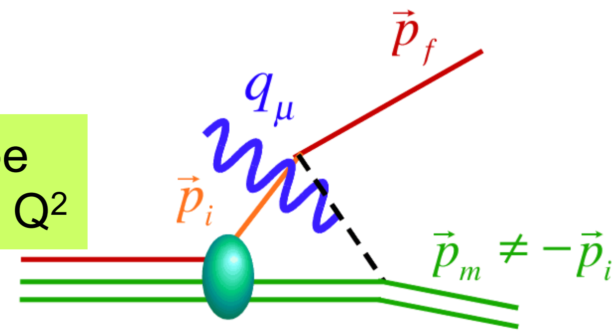
reduced at certain kinematics ?



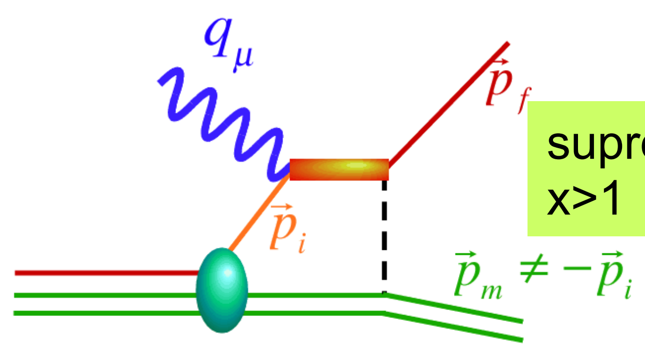
$$\frac{d\sigma}{d\omega d\Omega_e d\Omega_N} = k\sigma_{eN} D(E_m, p_f, p_m)$$

MEC

expected to be small at large Q^2



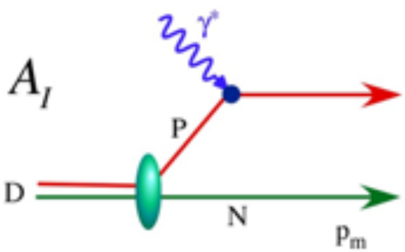
IC



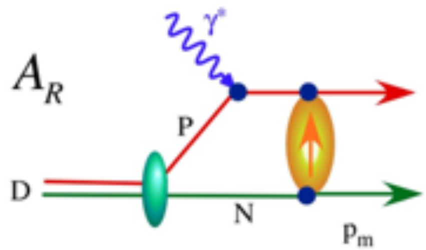
supressed for x>1

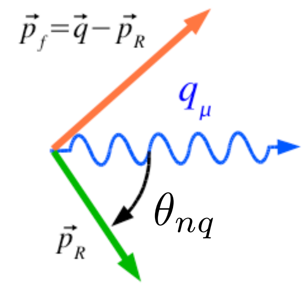
At High Q^2 FSI Anisotropic

IA Amplitude (real):



Rescattering Amplitude
(at high energy mostly imaginary):



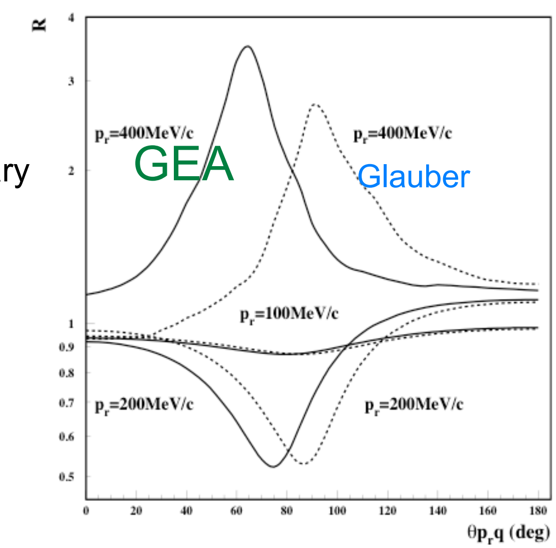


TotalScattering Amplitude: $A = A_I + iA_R$ $\quad A_R \approx i\,|A_R|$ mostly imaginary

Cross Sections: $\sigma \sim |A|^2 = |A_I + iA_R|^2$

$$\sigma \sim |A_I|^2 - 2\,|A_I|\,|A_R| + |A_R|^2$$

Ratio to PWIA $\quad R = \frac{\sigma}{\sigma_I} = 1 - 2\frac{|A_I|\,|A_R|}{|A_I|^2} + \frac{|A_R|^2}{|A_I|^2}$



M.Sargsian, PRC **82**, 014612 (2010)

Glauber: spectator nucleons frozen

GEA: spectator nucleon moving

Modern Calculations

Theoretical Calculation	Final State Interactions (np parametrization)	Nucleon Form Factors (parametrization)	Deuteron Wave Function
J.M. Laget	SAID	Galster: GEn Hall A Exp: GEp	Paris
M.M. Sargsian	SAID	JJK	CD-Bonn AV18
S. Jeschonnek & J.W.V. Orden	SAID/Regge	GKex05 AMT	WJC2 CD-Bonn AV18

J.M. Laget, Phys. Lett. B609, 49 (2005) (JML)

M.M. Sargsian, Phys. Rev. C82, 014612 (2010) (MS)

W.P. Ford, S. Jeschonnek and J.W.V. Orden, Phys. Rev. C90, 064006 (2014) (JVO)

JML: diagrammatic approach
MS: effective Feynman diagrams
JVO: Bethe-Salpeter based model

Form Factors

S. Galster, et al., Nucl. Phys. B32 (1971) 221 (Galster, neutron electric form factor, GEn)

O. Gayou, et al., Phys. Rev. Lett. 88 (2002) 092301 (Hall A Exp. proton electric form factor, GEp)

J.J. Kelly, Phys. Rev. C70, 068202 (2004) (JJK)

E.L. Lomon, Phys. Rev. C66, 045501 (2002) (GKex05)

J. Arrington, W. Melnitchouk, and J.A. Tjon, Phys. Rev. C76, 035205 (2007) (AMT)

FSI NN Parameterizations

R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, and R.L. Workman, Phys. Rev. C76, 025209 (2007) (SAID)

W.P. Ford, S. Jeschonnek, and J.W.V. Orden, Phys. Rev. C 87, 054006 (2013) (Regge)

NN Potential/WF

M. Lacombe, B. Loiseau, J. M. Richard, R. Vinh Mau, J. Côté, P. Pirès, and R. de Tourreil Phys. Rec. C21, 861 (1980) (Paris Potential)

R.B. Wiringa, V.G.J. Stoks, and R. Schiavilla, Phys. Rev. C51, 38 (1995) (AV18)

R. Machleidt, Phys. Rev. C63, 024001 (2001) (CD-Bonn)

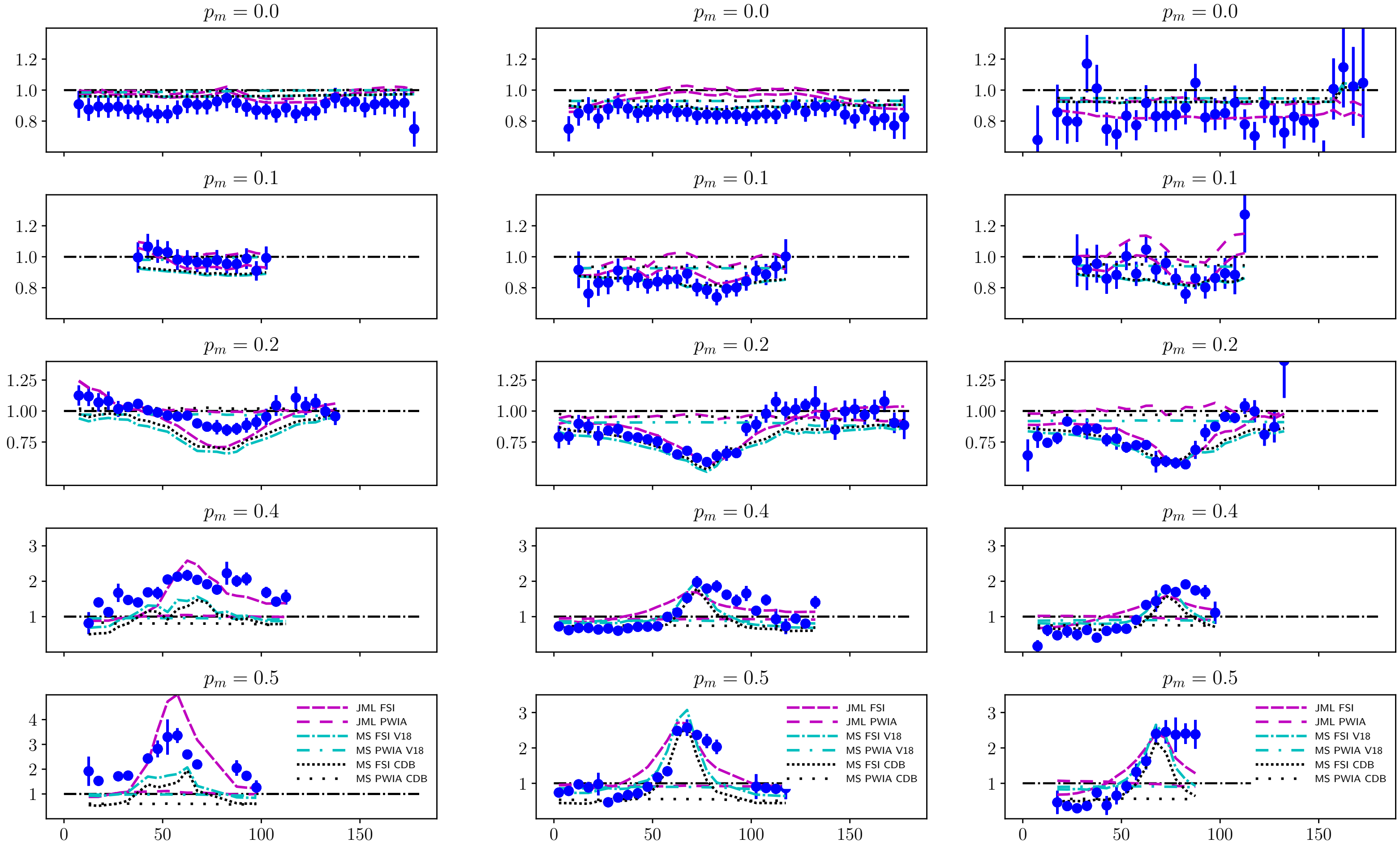
F. Gross and A. Stadler, Few Body Syst. 44, 295 (2008) **(WJC2)**

$$R = \frac{\sigma_{EXP}}{\sigma_{PWIA}}$$

Hall A

WB et al. PRL 107 (2011) 262501

$Q^2 = 0.8$ $Q^2 = 2.1$ $Q^2 = 3.5$



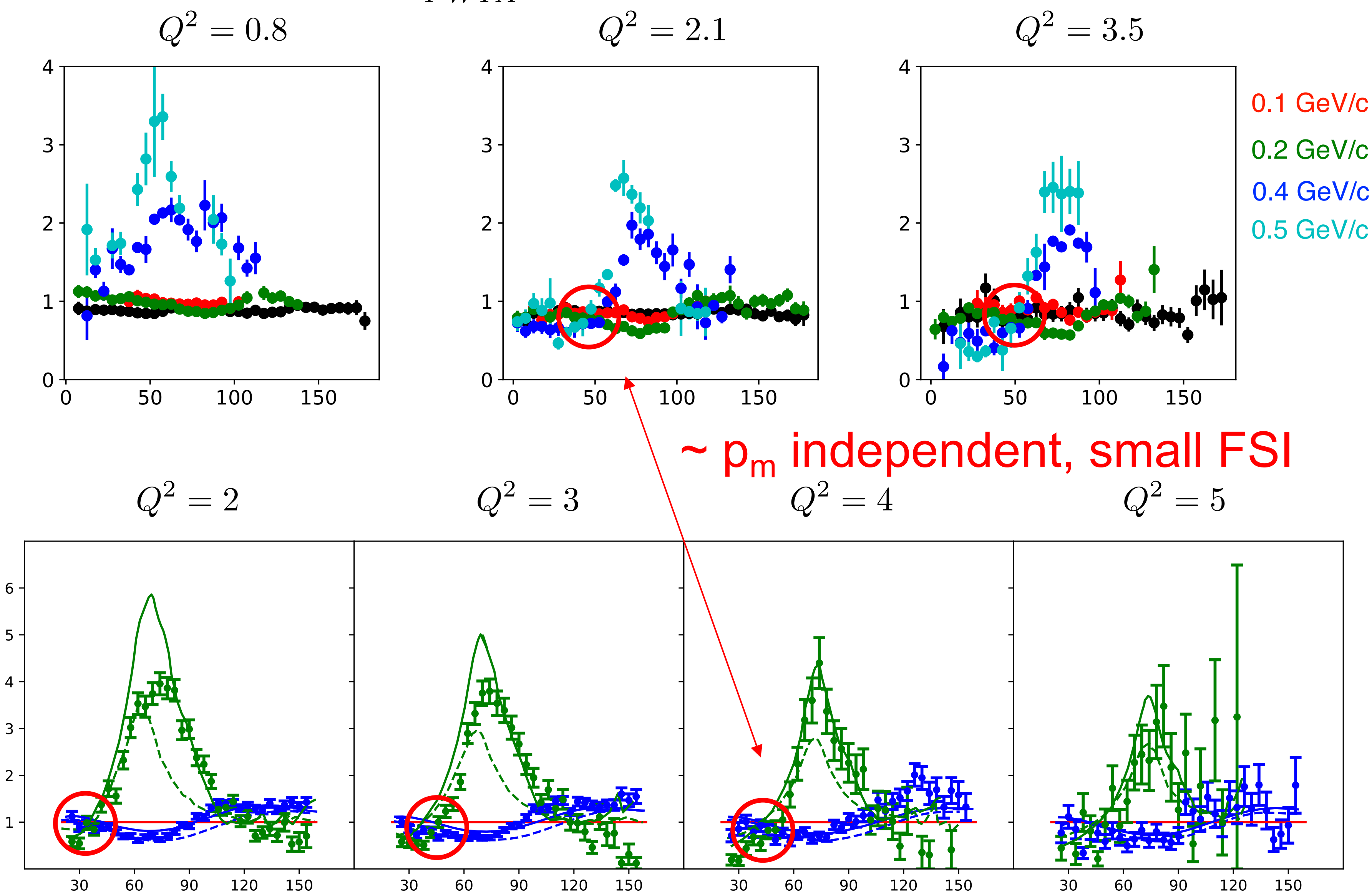
FSI
CD Bonn
PWIA

FSI
V18
PWIA

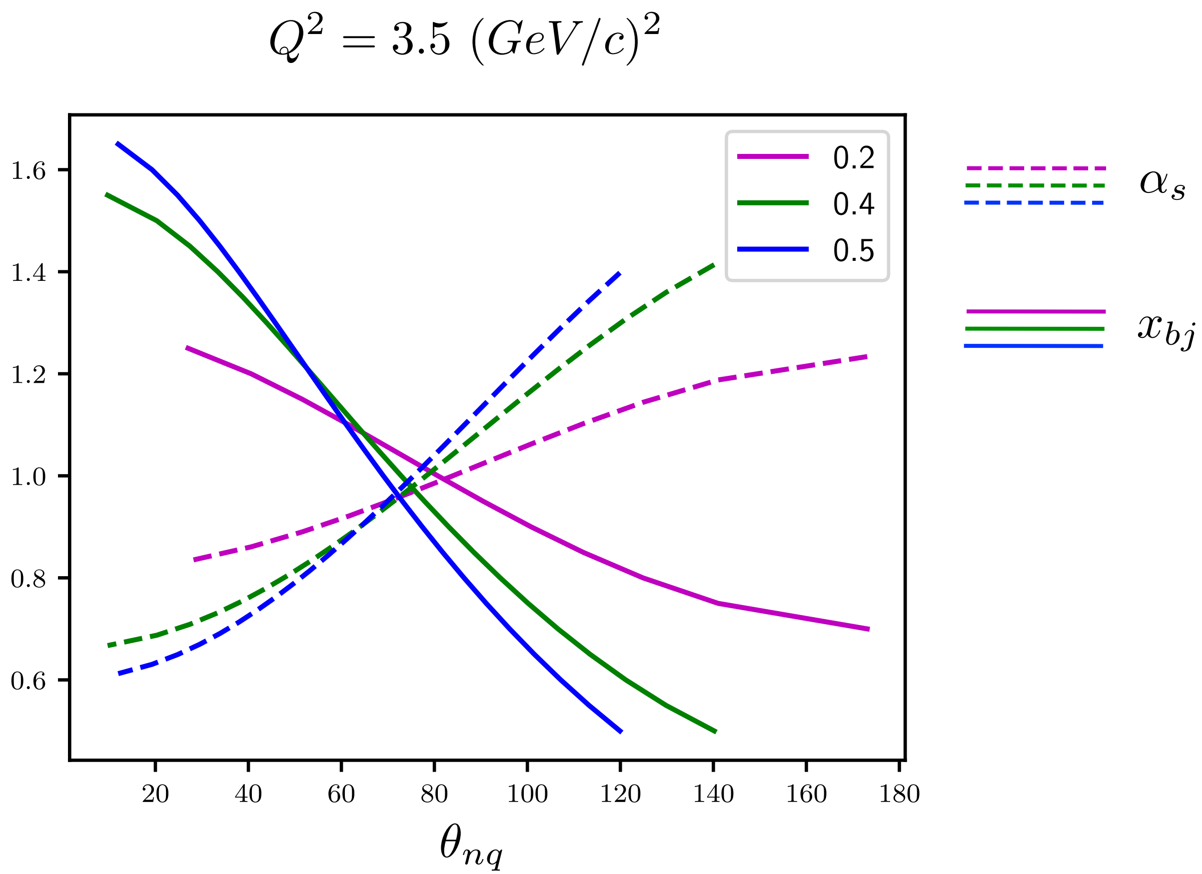
FSI
Laget
PWIA

$\Delta p_m = \pm 0.02$ GeV/c

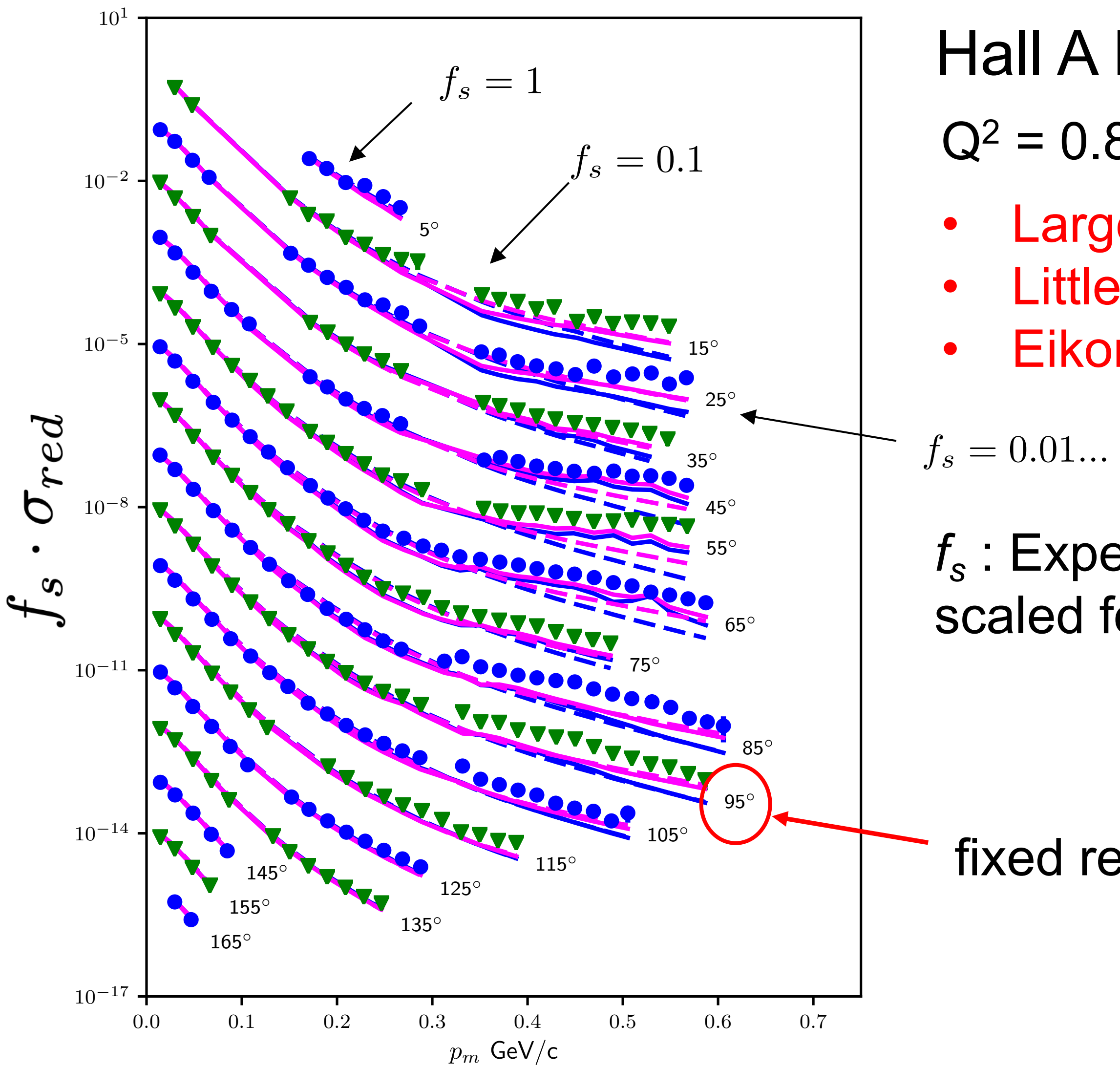
$$R = \frac{\sigma_{EXP}}{\sigma_{PWIA}}$$



Relations between various kinematic variables



‘Experimental’ Momentum Distributions



Hall A Experiment E01-020

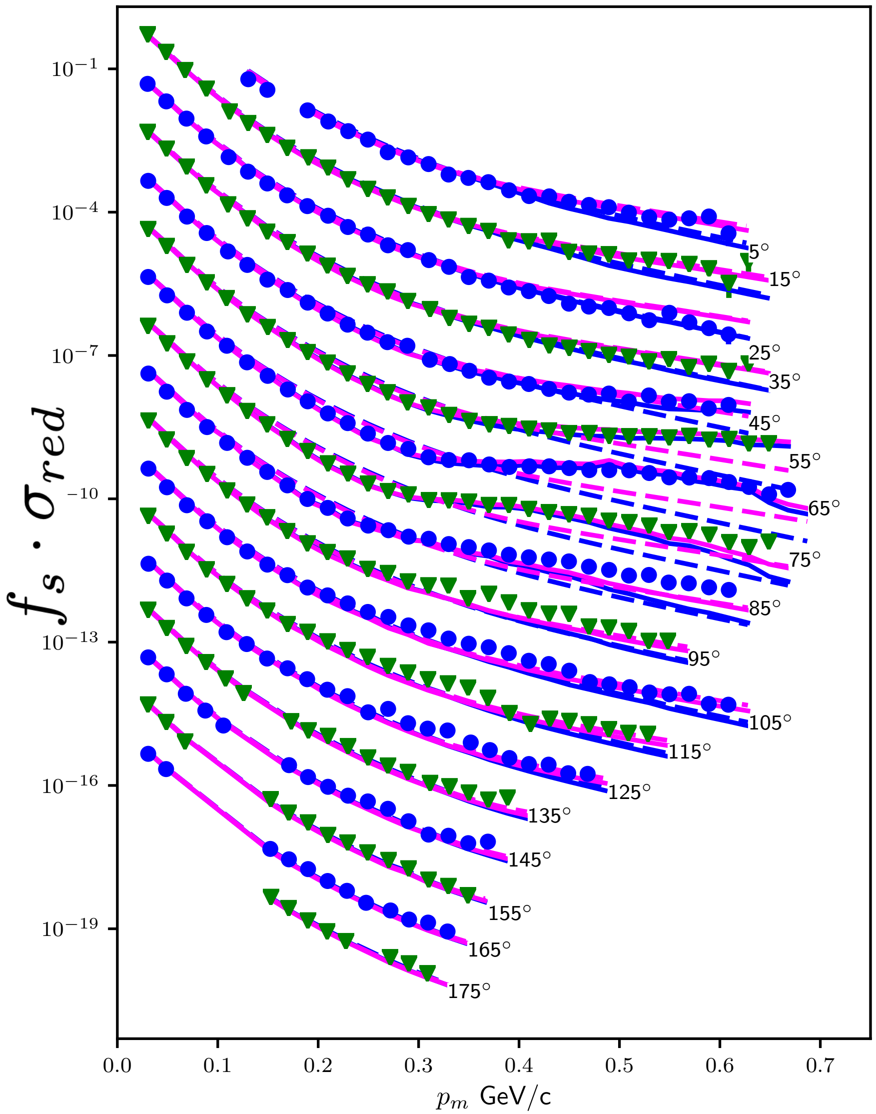
$Q^2 = 0.8\ (GeV/c)^2$

- Large FSI for pm >0.25 GeV/c
- Little sensitivity to W.F.
- Eikonal regime not yet reached

f_s : Experimental data are scaled for display purposes

fixed recoil angles θ_{nq}

Experimental data are scaled for display purposes



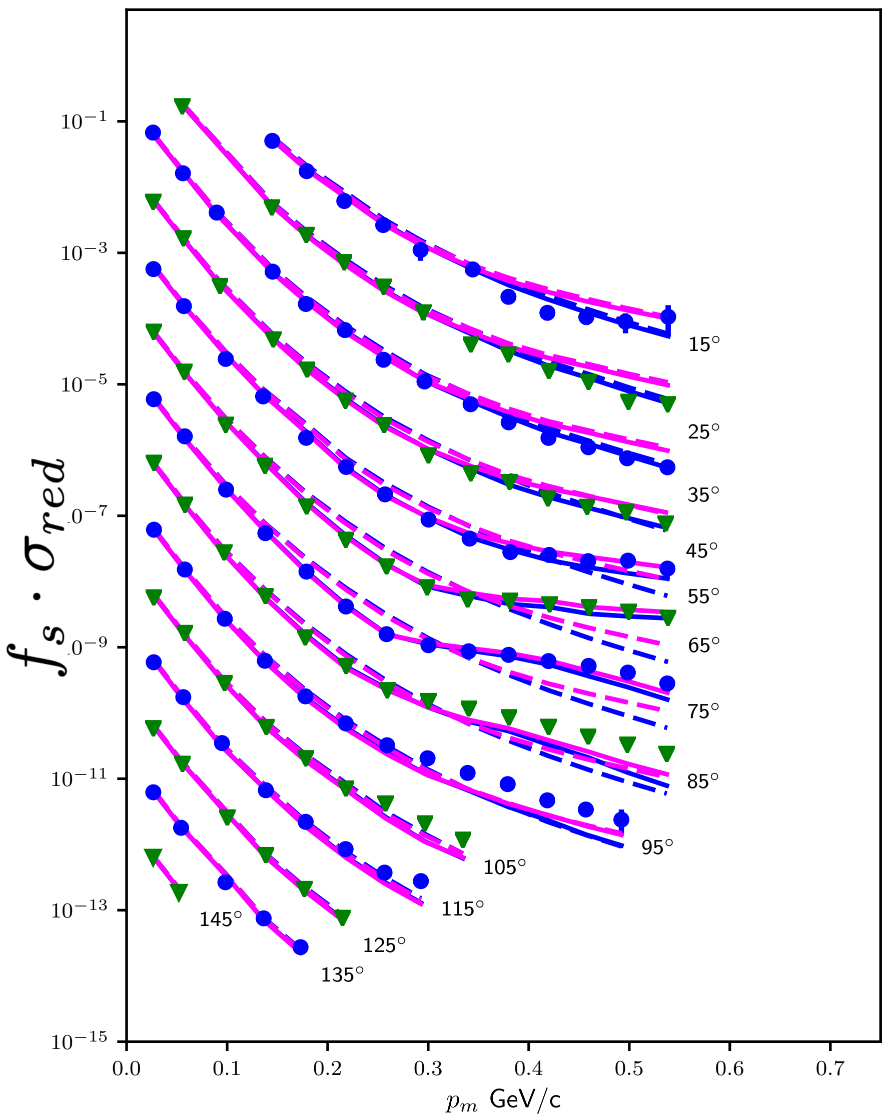
$Q^2 = 2.1\ (GeV/c)^2$

Small FSI

Large FSI

Small FSI, Resonances ?

Experimental data are scaled for display purposes



$Q^2 = 3.5\ (GeV/c)^2$

Small FSI

Large FSI

Small FSI, Resonances ?

Experimental data are scaled for display purposes

The Next Step: Toward p_m = 1 GeV/c

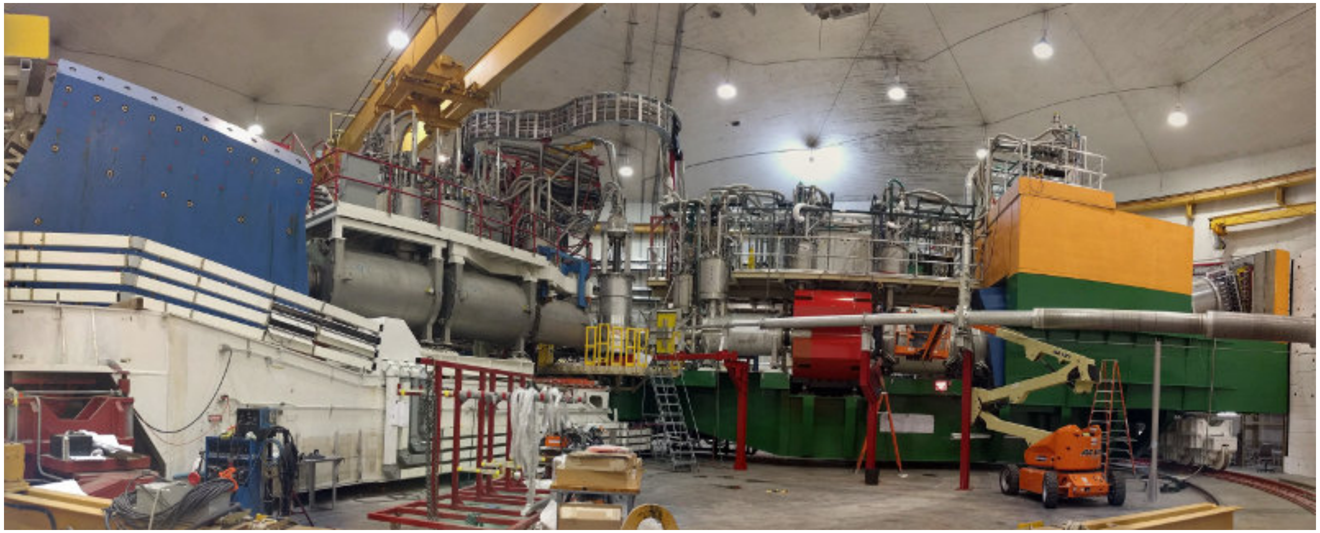
- Hall A and Hall B experiments established validity of GEA based calculations

- Determine cross sections at missing momenta up to 1 GeV/c (and beyond if possible)
- Measure at well defined kinematic settings:
    - to minimize contributions from FSI
    - to minimize effects of delta excitation

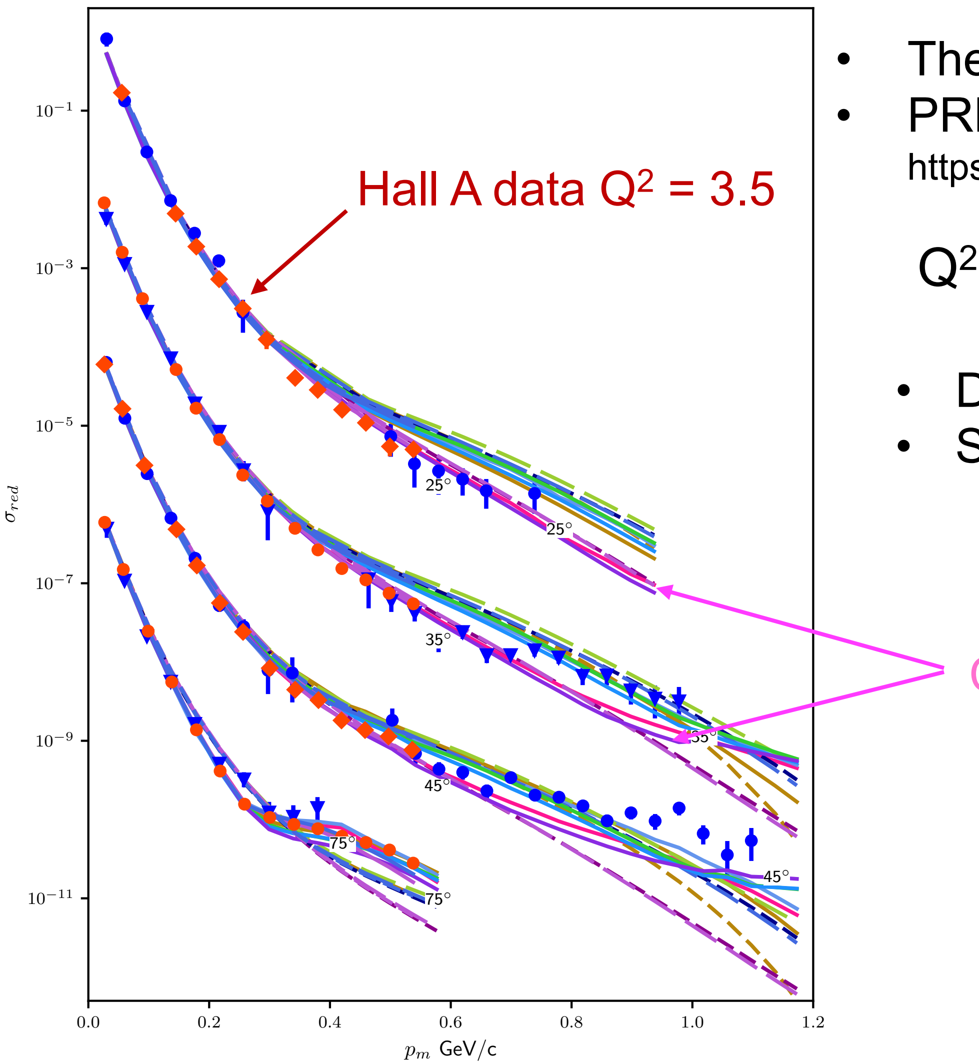
Parameters

- Beam: 10.6 GeV, ~40 - 50μA
- Electron Detector: SHMS at p_{cen} = 8.534GeV/c
  - $\theta_e = 12.19^o$, $Q^2 = 4.25$ (GeV/c)^2, x = 1.35
- Proton Detector: HMS 2.1 ≤ p_{cen} ≤ 2.8 GeV/c
  - p_m = 0.08, 0.58, 0.75 GeV/c
  - Angles: $58.5^o \geq \theta_p \geq 38.8$

- Target: 10 cm LHD
- First data as part of series of Hall C Commissioning Experiments



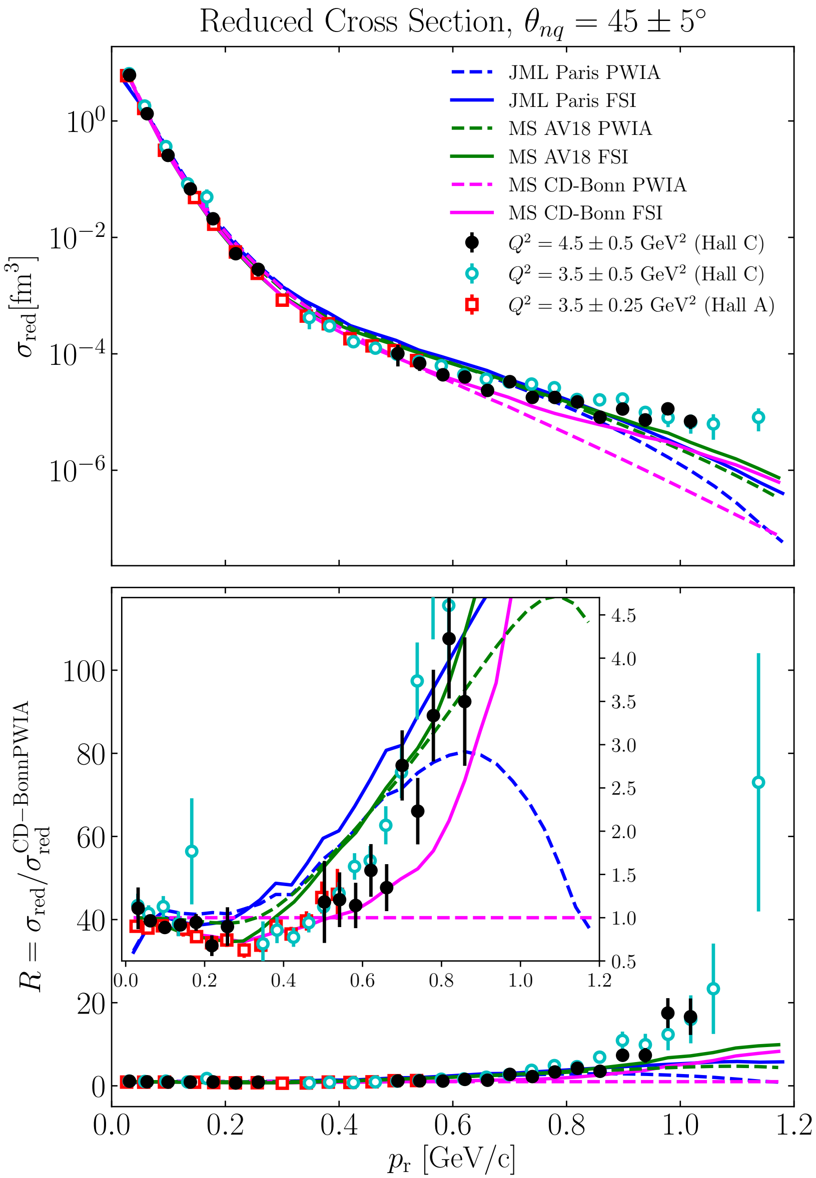
New Results



- Thesis C. Yero
- PRL 125, 262501 (2020)
  https://doi.org/10.1103/PhysRevLett.125.262501

Q^2 = 4.25 $(GeV/c)^2$

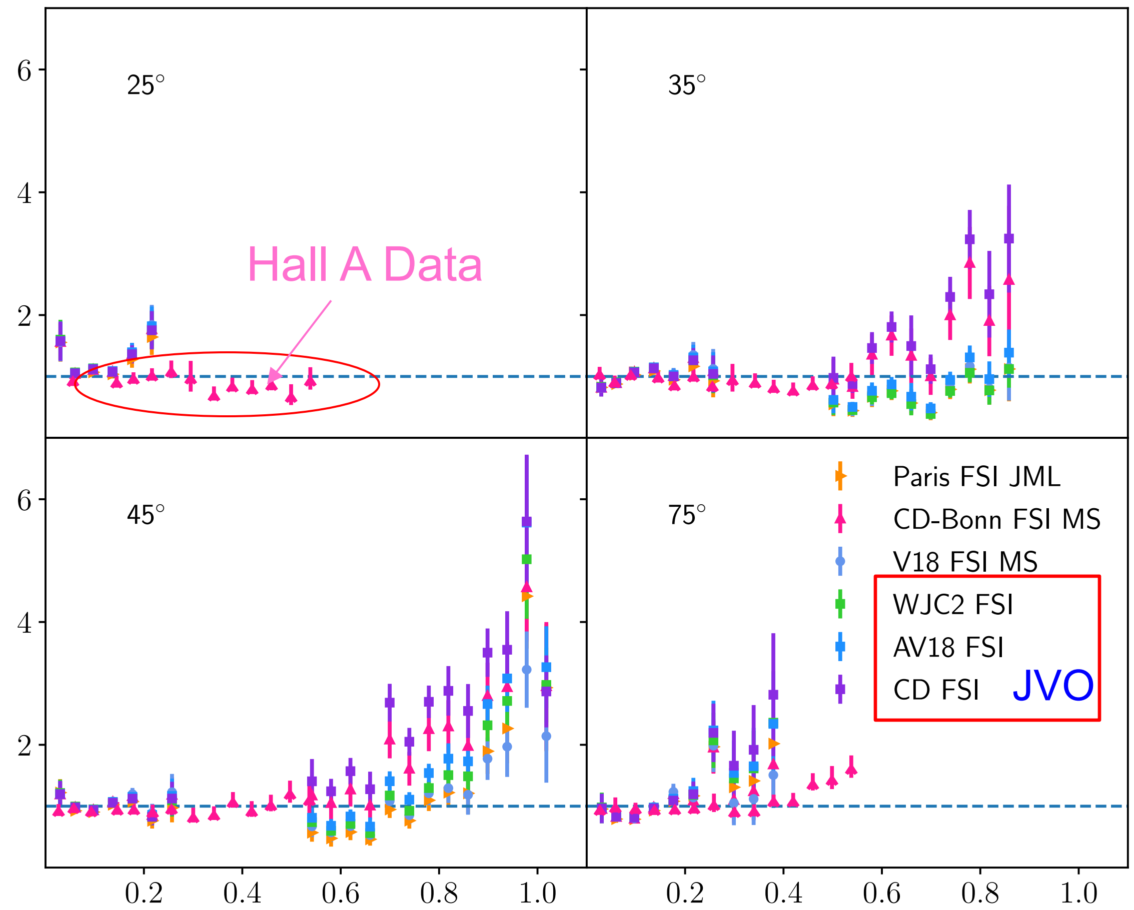
- Dashed lines: PWIA
- Solid lines: FSI



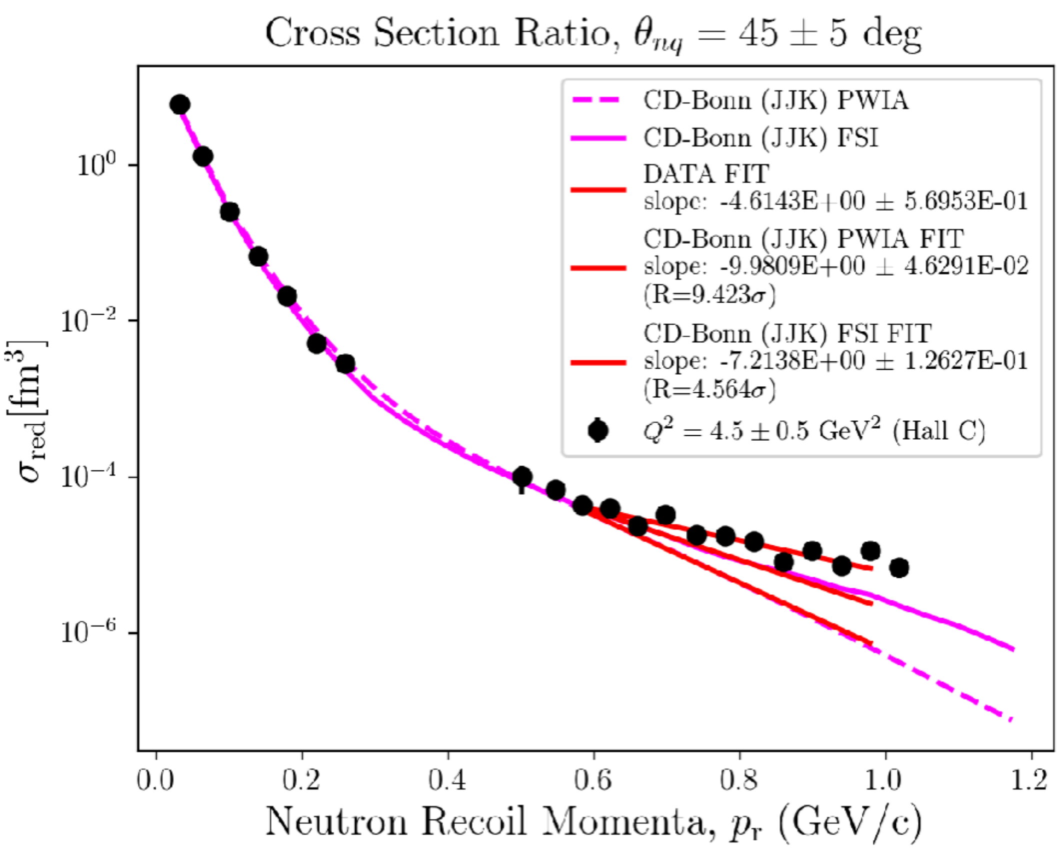
- Hall C data at 3.5 and 4.5 (GeV/c)^2
- Self consistent
- Agree witjh Hall A data

C.Yeros thesis FIU
http://digitalcommons.fiu.edu/etd/4479

$$\sigma_{exp}/\sigma_{calc}$$



High p_m Fall-Off



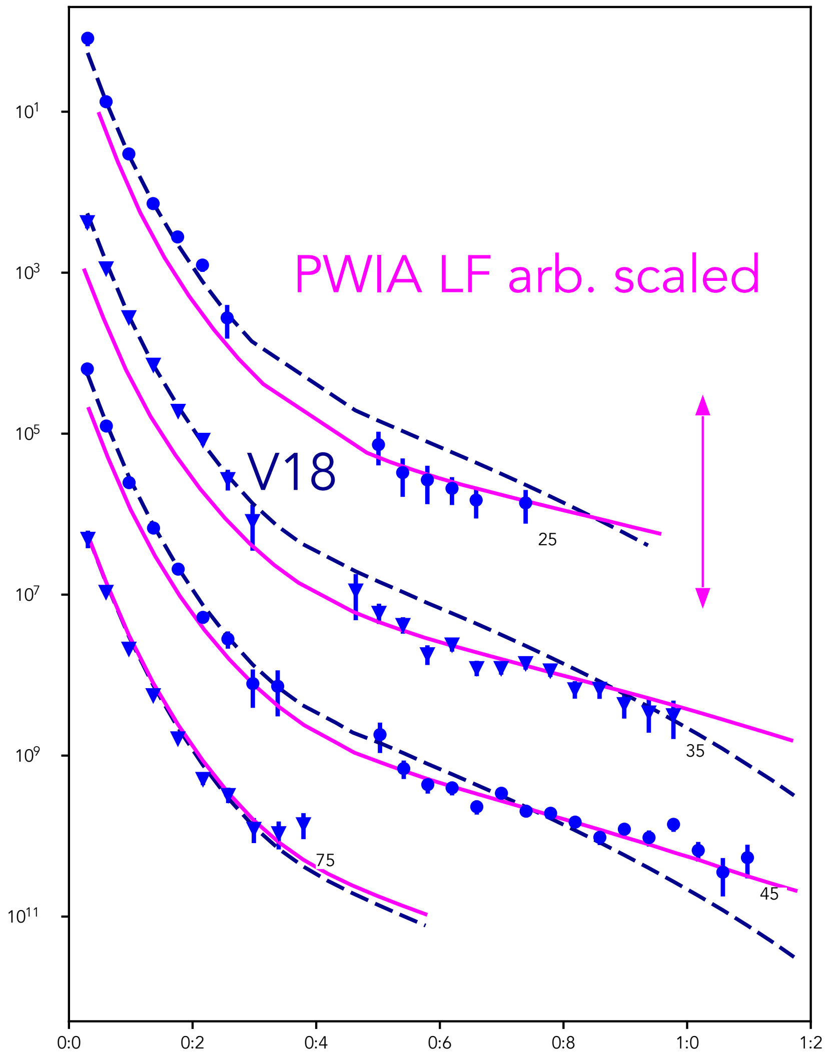
- Fit: $\sigma_{red}(p_m) = Ae^{-\mu p_m}$

- $0.6 < p_m < 1.0$ GeV/c
- Fit exp. data
- Fit model calculations
- Z-score:

$$Z = \frac{\mu_{exp} - \mu_{calc}}{\sigma_{\mu_{exp}}}$$

- P-value: probability for Z as a statistical fluctuation

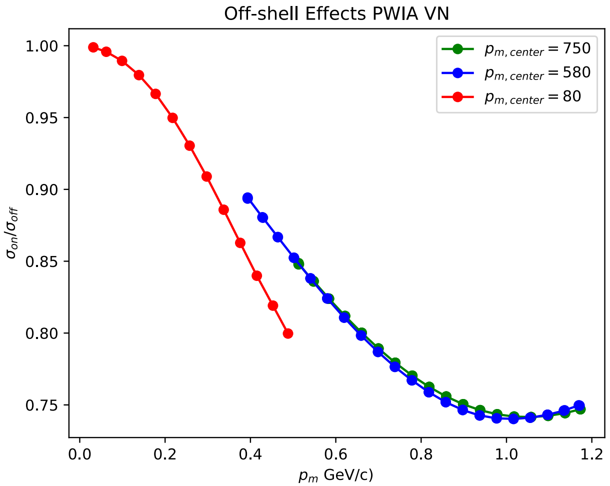
Light Front Calculation



M. Sargsian and F. Vera in progress

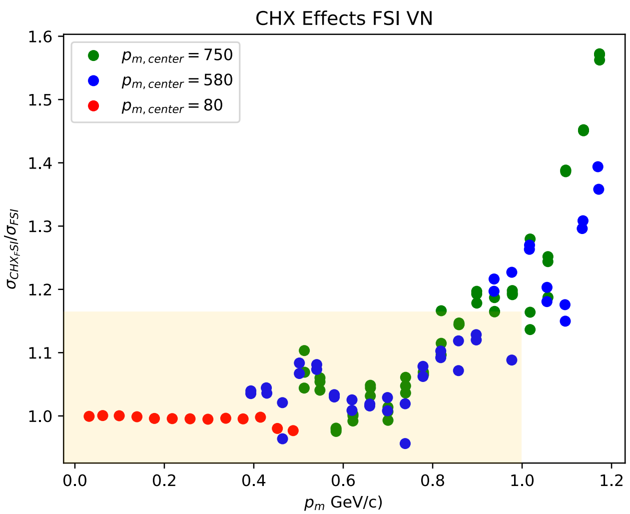
LC shape closer than other calculations for pm > 0.6 GeV/c

p_m dependence at p_m>0.6 GeV/c agrees

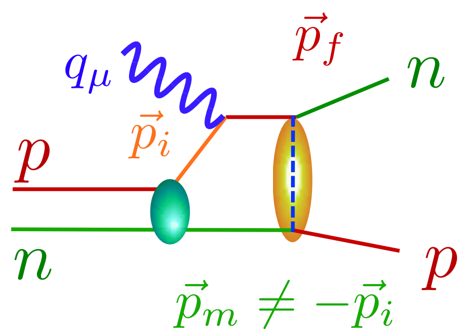


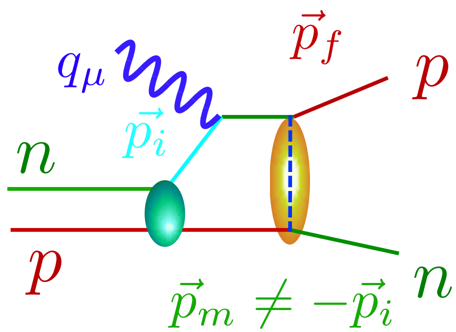
Off-shell effects:
included in calculations

Overall too small to explain differences



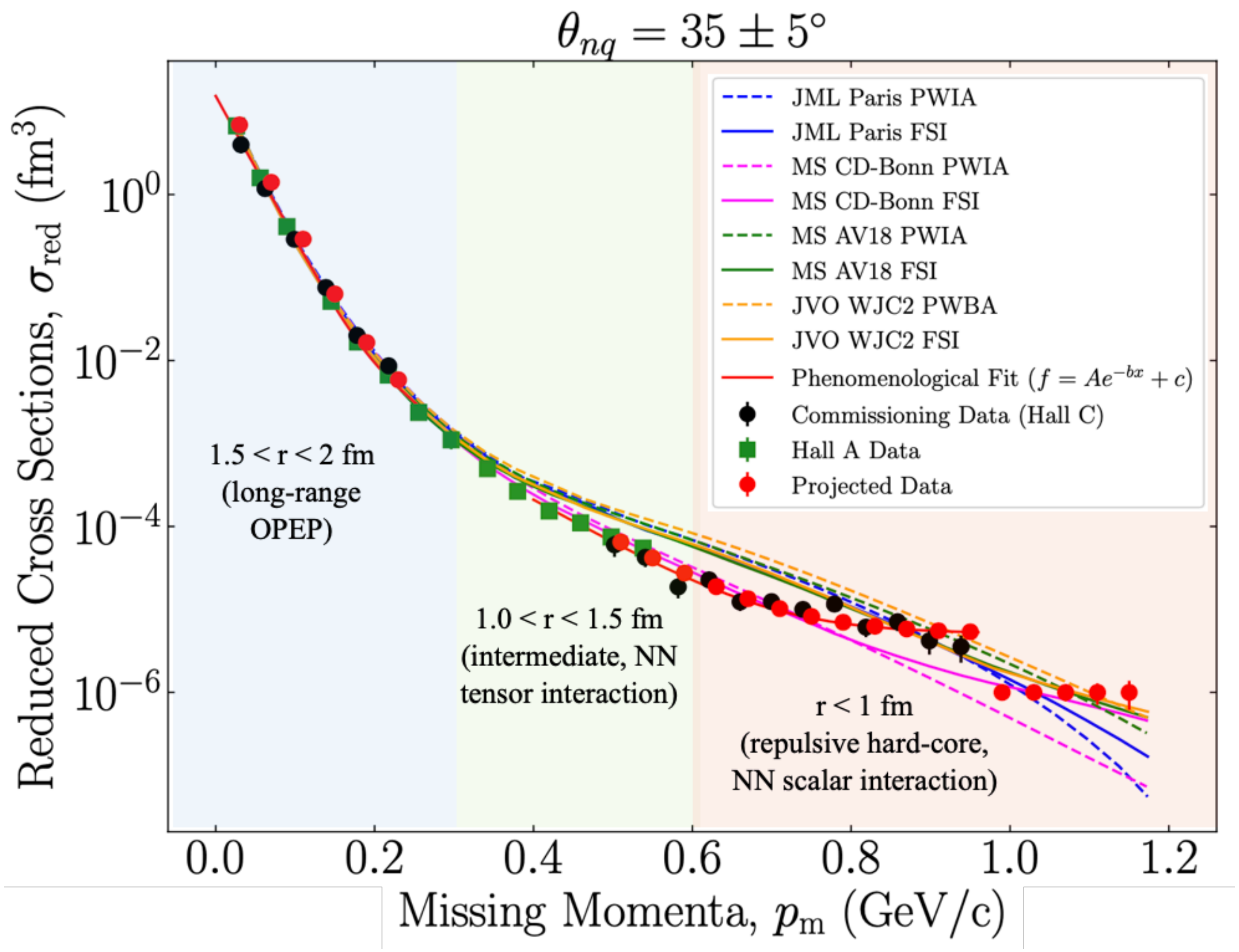
Charge Exchange Effects:
NOT included

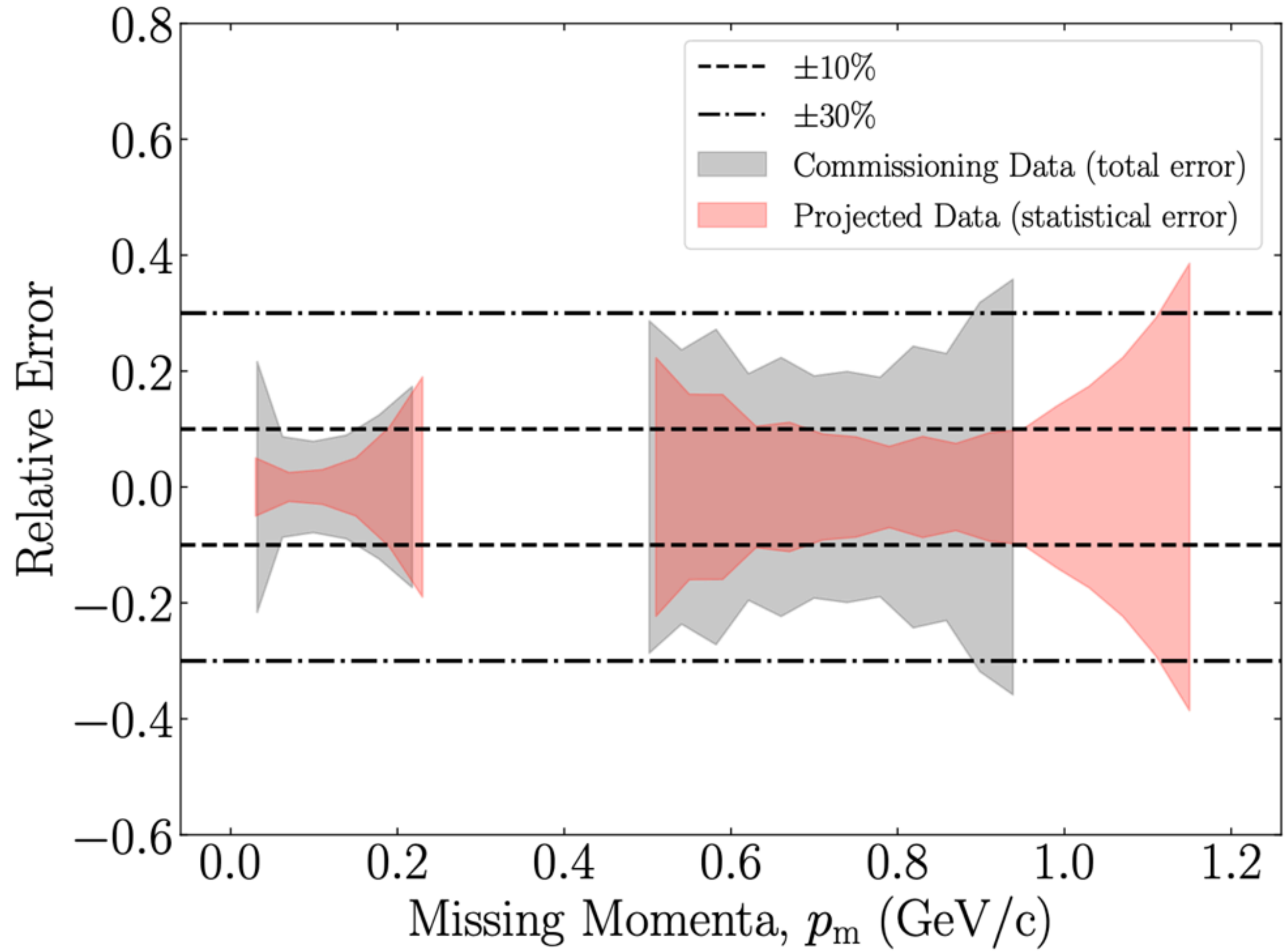




Near Future

- Part II of experiment starts end pf February/March 2023
- Improve statistics: 10% for $0.6 \leq \ p_m \leq 1.0$ GeV/c





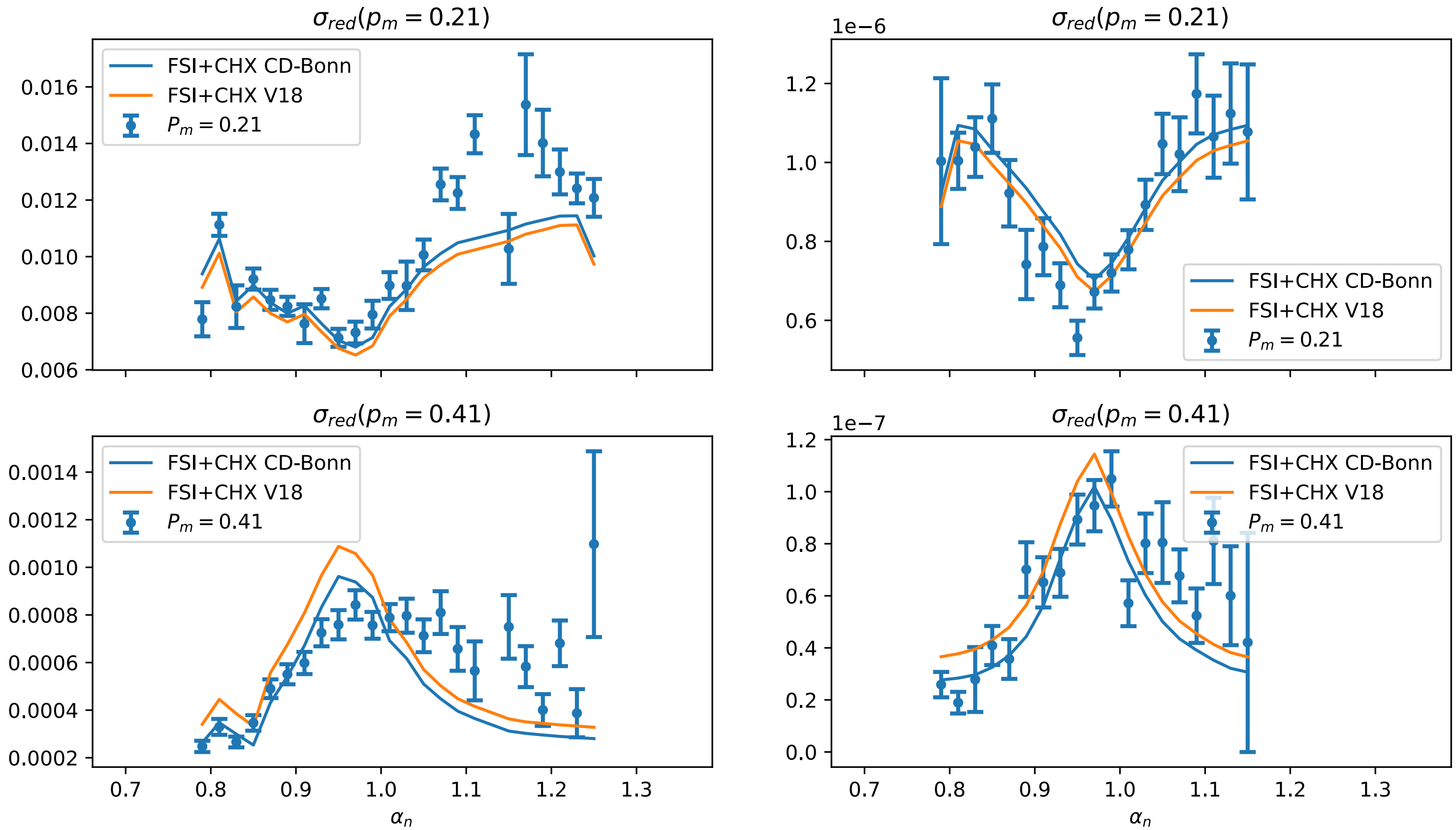
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Relative Error
±10%
±30%
Commissioning Data (total error)
Projected Data (statistical error)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Missing Momenta, p_m (GeV/c)

A closer Look at Rescattering

- Re-scattering maximal for $\alpha \sim 1$
- Kinematics must be in Eikonal regime
- Analyze α-distributions for constant p_m
- Cross section ratios to enhance re-scattering
- Potential for CT studies at higher Q^2 values

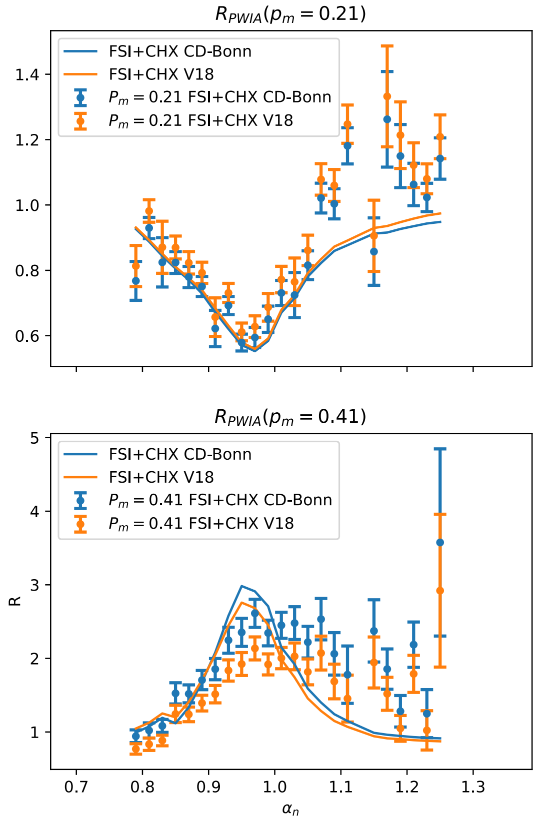
Reduced Cross sections

Should be constant if PWIA only

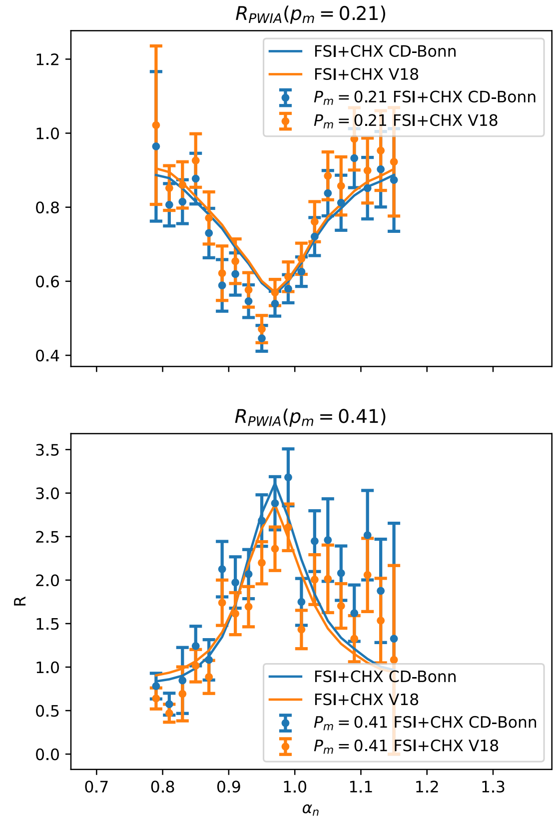


$Q^2 = 2.1$ $\quad$ $Q^2 = 3.5$

$R_{PWIA} = \sigma_{EXP}/\sigma_{PWIA}$

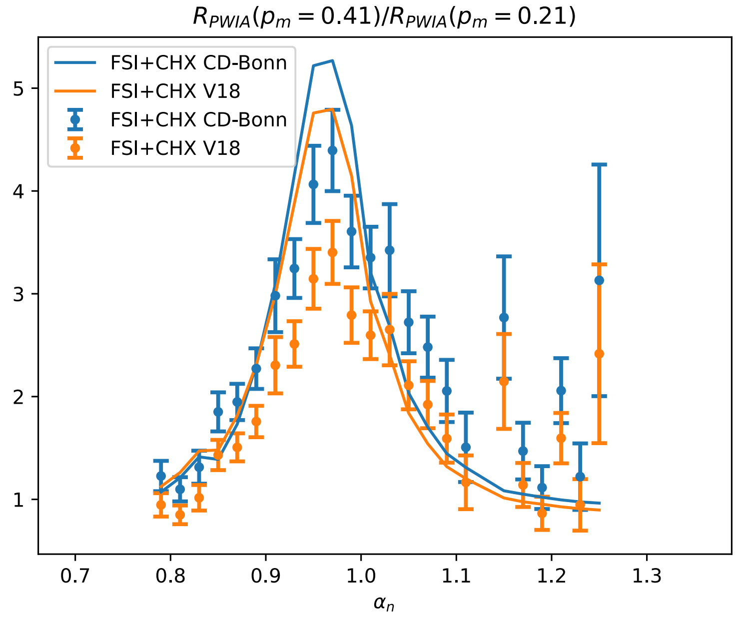


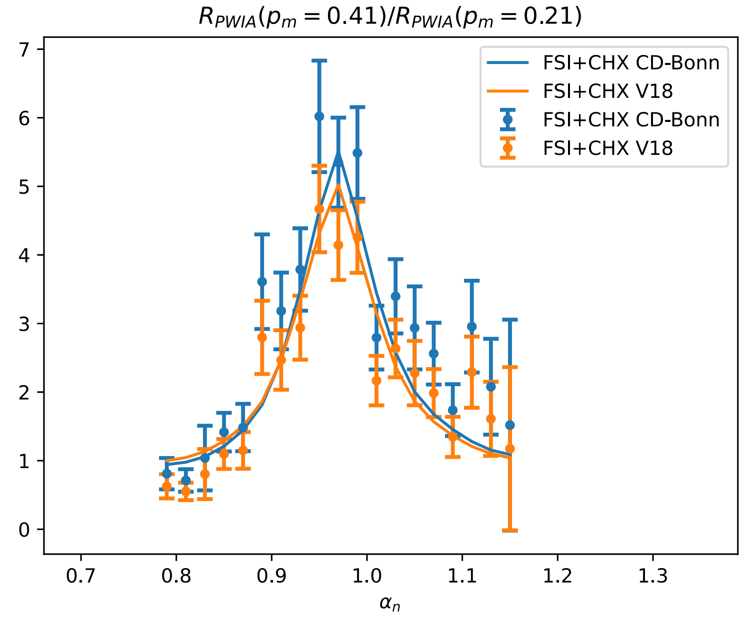
$Q^2 = 2.1$



$Q^2 = 3.5$

Double Ratios

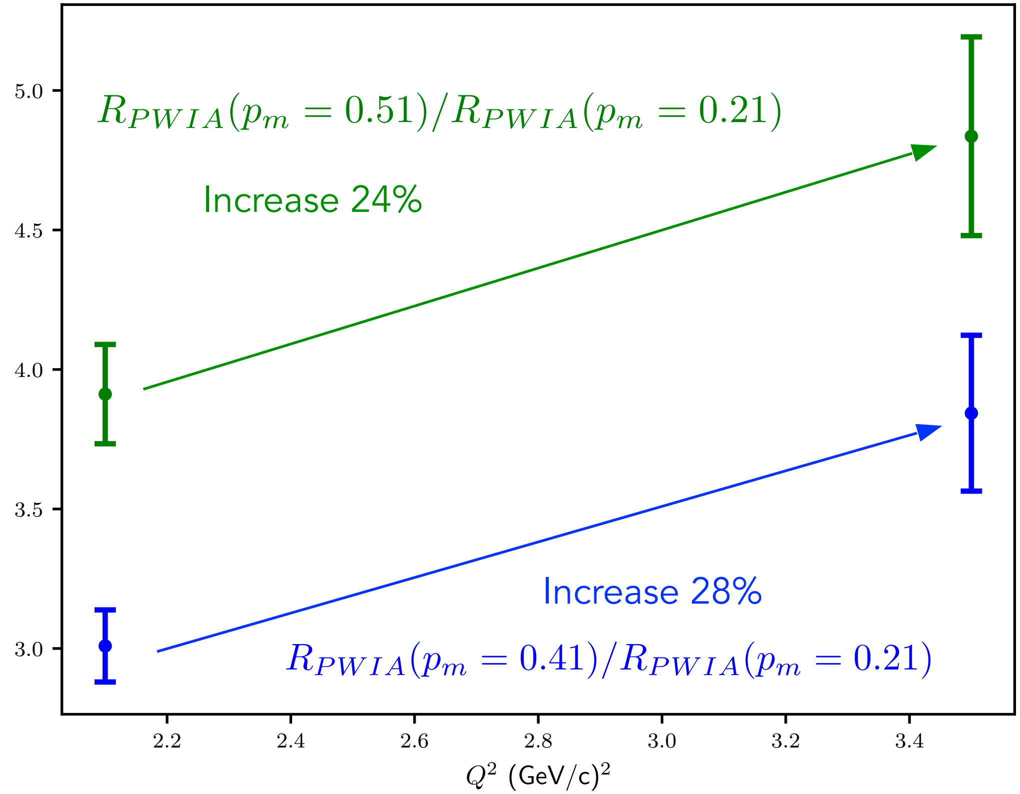




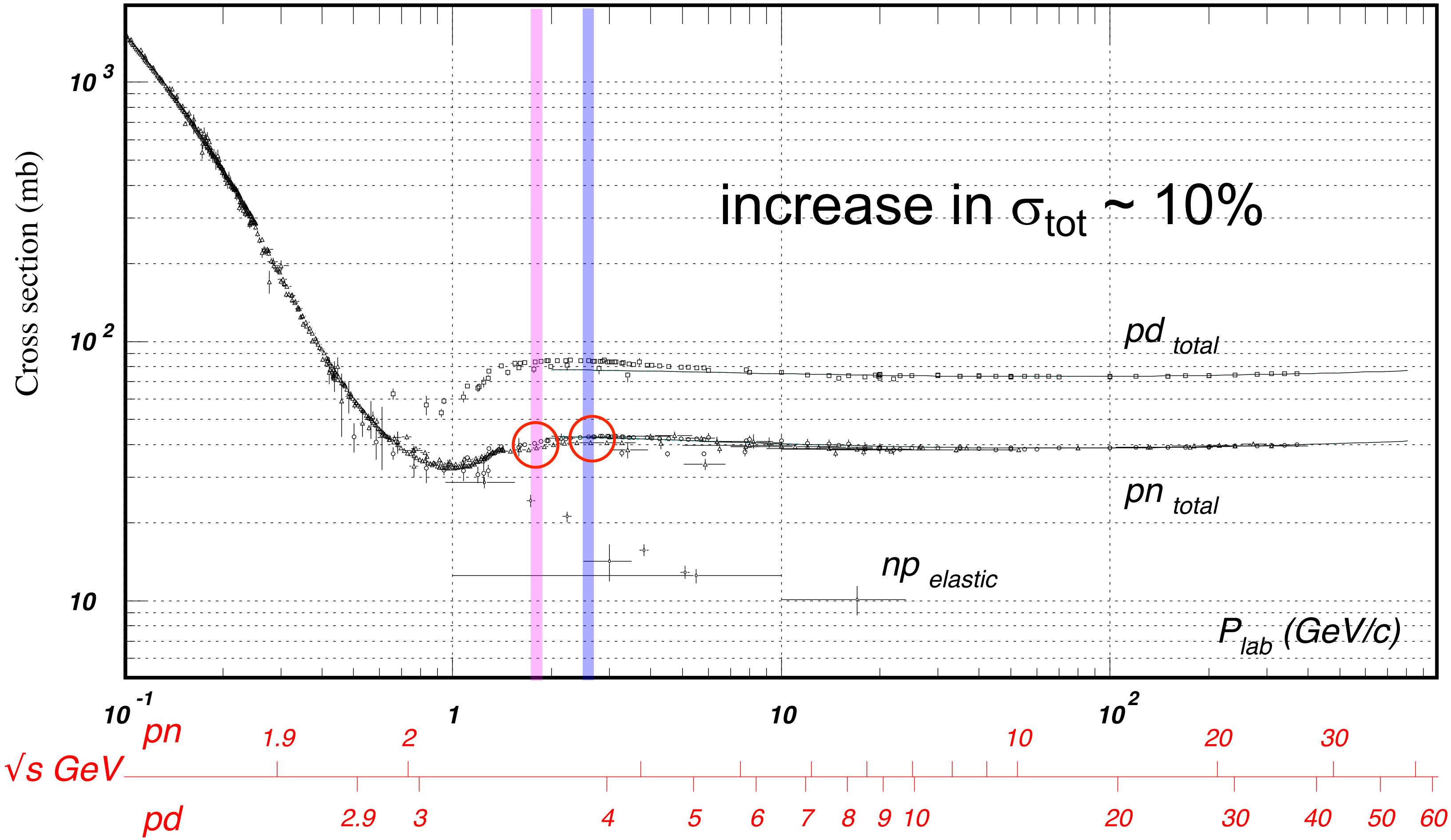
$Q^2 = 2.1$ $Q^2 = 3.5$

Peak height : measure of rescattering strength

Q^2 Dependence of maximal rescattering



2.1 3.5 $(\mathrm{GeV/c})^2$



since $f^{NN} = \sigma_{tot}^{NN}(i+\alpha)e^{-\frac{B}{2}(p_3-p_1)_\perp^2}$ increase in rescattering ~ 20%

from M.Sargsian Intl. Journal of Modern Physics E, Vol. 10, No. 6 (2001)

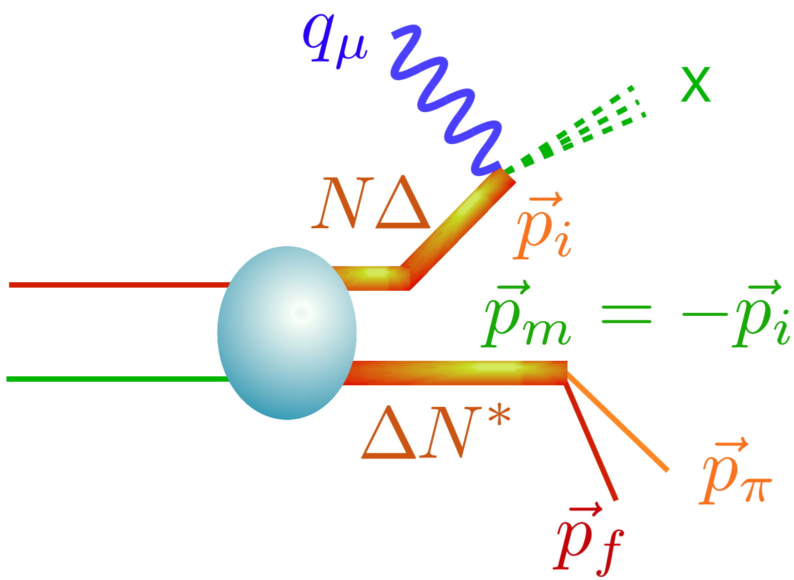
Summary

- High Q^2 d(e,e' p)n best described by generalized eikonal approximation for $Q^2 > 2$ GeV/c
- FSI can be controlled and is understood for $p_m < 0.5$ GeV/c
- **Reduced cross section behavior at $p_m > 0.6$ GeV/c still cannot be reproduced by current calculations.**
- Off-shell & Charge exchange not enough to explain difference
- Other e.g. relativistic contributions needed?
- Better statistics is coming this spring
- angular distribution at pm = 0.8 GeV/c needed
- inelastic channels should be studied
- Graduate students: Luminita Coman, Hari Khanal and Carlos Yero

Supported by the Department of Energy, contract DESC0013620

Backup

Outlook: Improve statistics, explore NN interaction core using inelastic channels: Jlab, EIC

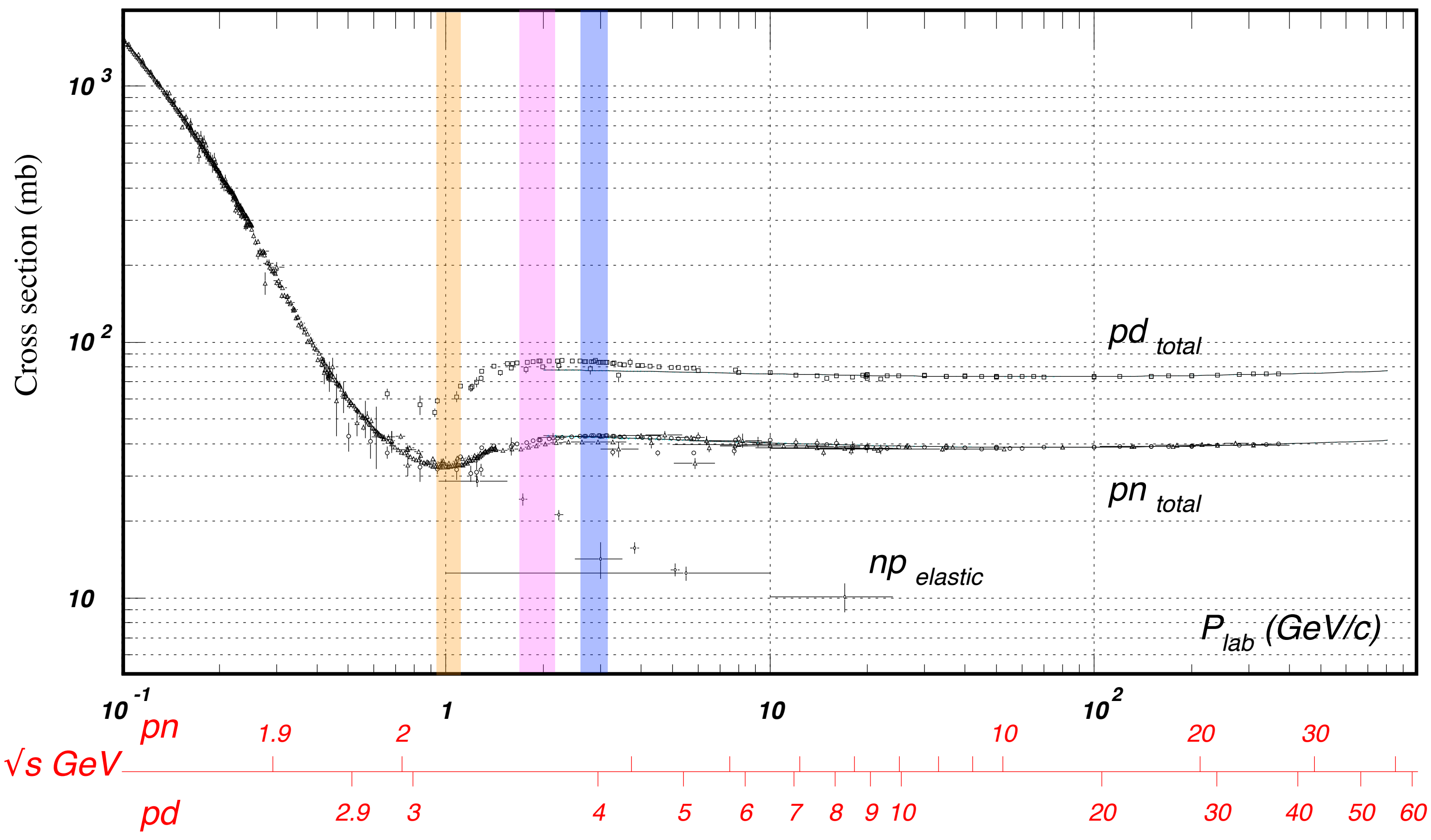


- Backwards Δ or N*
- Large momentum ~ 1GeV/c

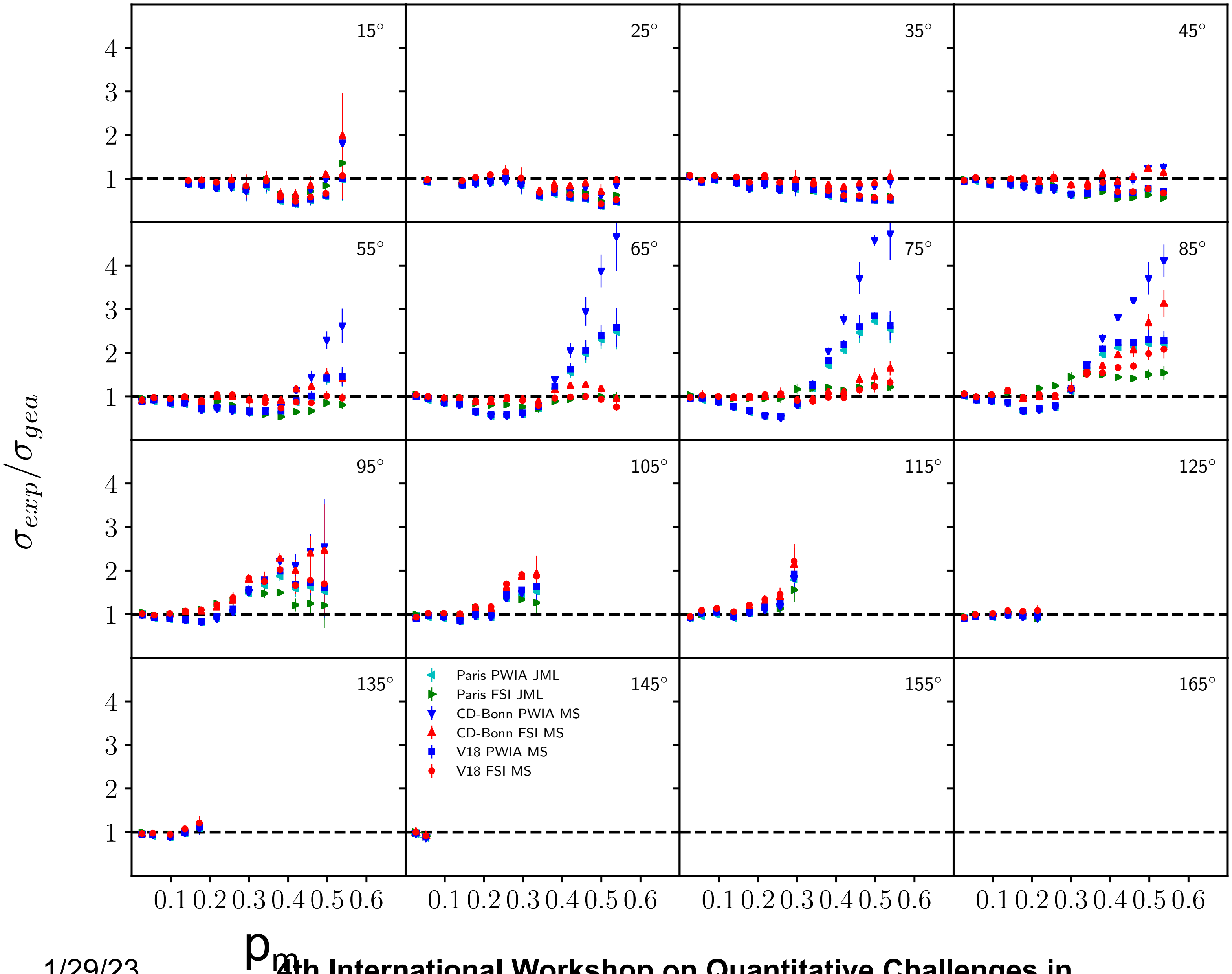
Theoretical Model	PWIA (35 deg) Z-score	p-value	PWIA (45 deg) Z-score	p-value	FSI (35 deg) Z-score	p-value	FSI (45 deg) Z-score	p-value
Paris (Galster)	**4.929**	**4.1E-07**	**6.541**	**3.0E-11**	**4.791**	**8.2E-07**	**5.355**	**4.2E-08**
AV18 (JJK)	**4.373**	**6.1E-06**	**5.632**	**8.9E-09**	**5.184**	**1.0E-07**	**4.721**	**1.1E-06**
AV18 (GKex05)	**4.623**	**1.9E-06**	**6.079**	**6.0E-10**	**5.616**	**9.7E-09**	**5.889**	**1.9E-09**
AV18 (AMT)	**4.598**	**2.1E-06**	**6.066**	**6.5E-10**	**5.597**	**1.0E-08**	**5.976**	**1.1E-09**
CD-Bonn (JJK)	**7.321**	**1.2E-13**	**9.423**	**2.1E-21**	**6.648**	**1.4E-11**	**4.564**	**2.5E-06**
CD-Bonn (GKex05)	**7.611**	**1.3E-14**	**9.895**	**2.1E-23**	**7.484**	**3.6E-14**	**5.383**	**3.6E-08**
CD-Bonn (AMT)	**7.586**	**1.6E-14**	**9.882**	**2.4E-23**	**7.460**	**4.3E-14**	**5.516**	**1.7E-08**
WJC2 (GKex05)	**4.241**	**1.1E-05**	**5.575**	**1.2E-08**	**5.133**	**1.4E-07**	**5.519**	**1.7E-08**
WJC2 (AMT)	**4.217**	**1.2E-05**	**5.561**	**1.3E-08**	**5.110**	**1.6E-07**	**5.598**	**1.0E-08**

Systematically different p_m dependence

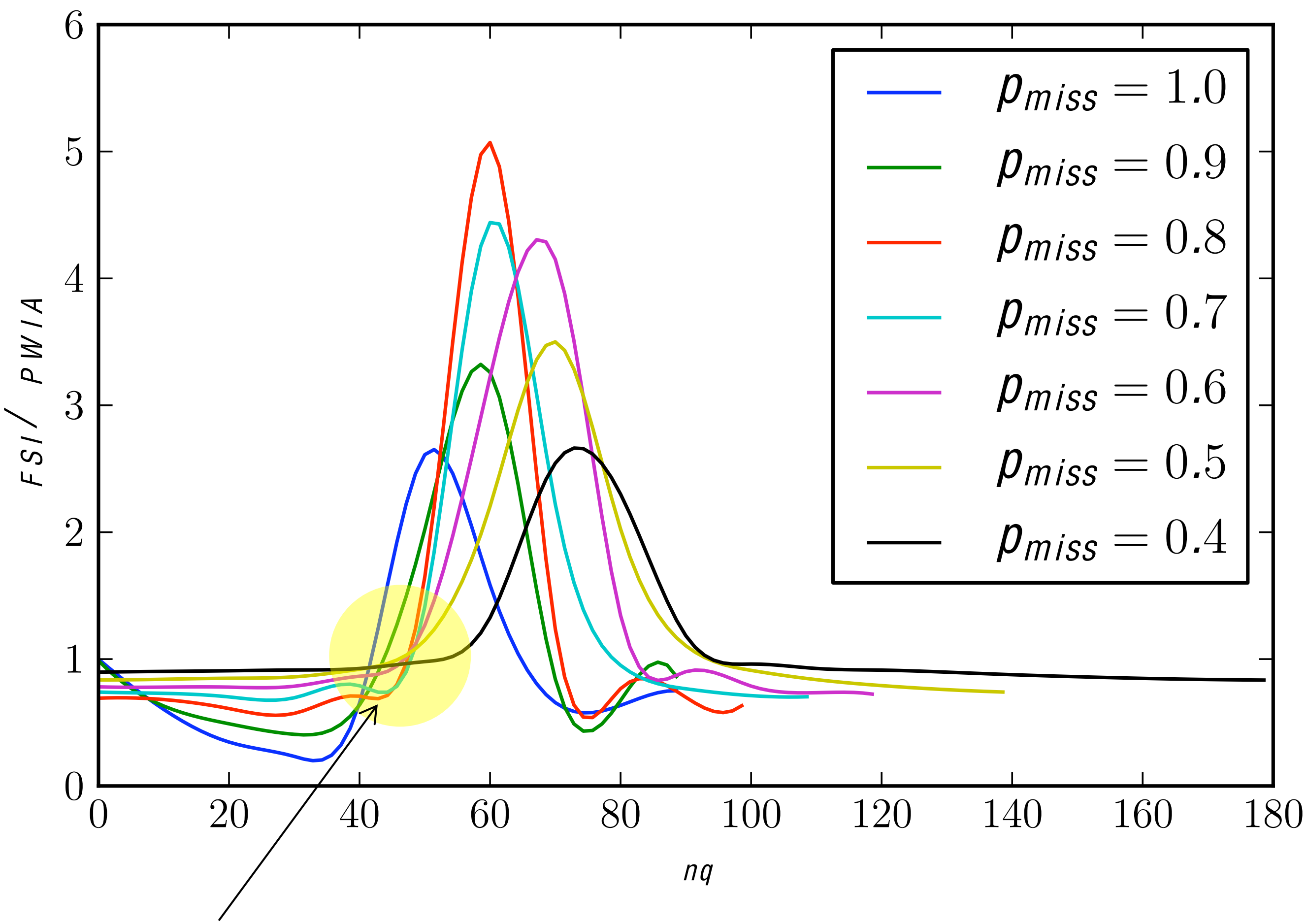
0.8 2.1 3.5 (GeV/c)^2


Cross section (mb)
10^3
10^2
10
pd total
pn total
np elastic
P lab (GeV/c)
10^-1
1
10
10^2
pn
√s GeV
pd
1.9
2
10
20
30
2.9
3
4
5
6
7
8
9
10
20
30
40
50
60

Q^2 = 3.5 (GeV/c)^2 GEA M.Sargsian



Estimated Angular Distributions up to p_m = 1GeV/c

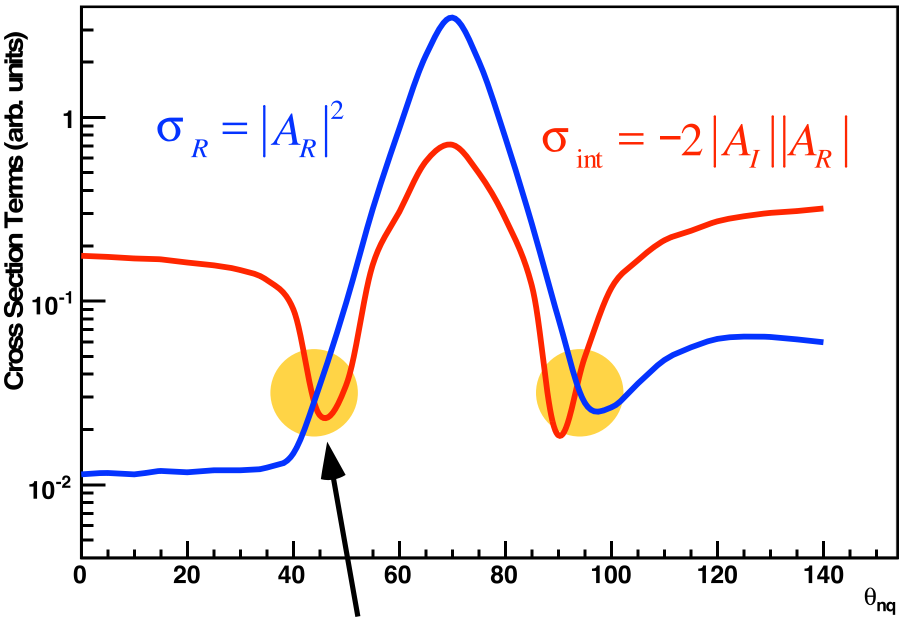


FSI depend weakly on p_m

Calculation: M.Sargsian

FSI Reduction

Reduction of FSI: $\sigma \sim |A_I|^2 - 2|A_I||A_R| + |A_R|^2$



Rescattering determined by slope factor:

$$f_s = e^{-\frac{b}{2}k_t^2}$$

$$k_t = p_m \sin(\theta_{p_m q})$$

$$b \sim 6(GeV/c)^{-2}$$

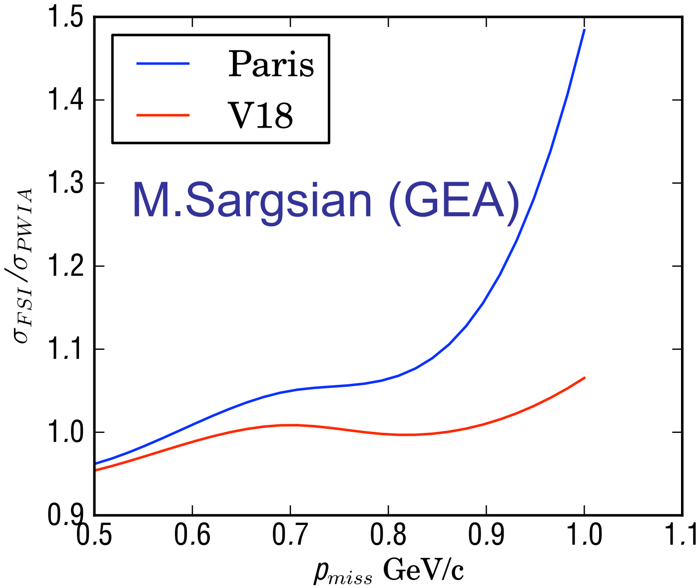
f_s relatively flat up to $k_t \approx 0.5(GeV/c)$

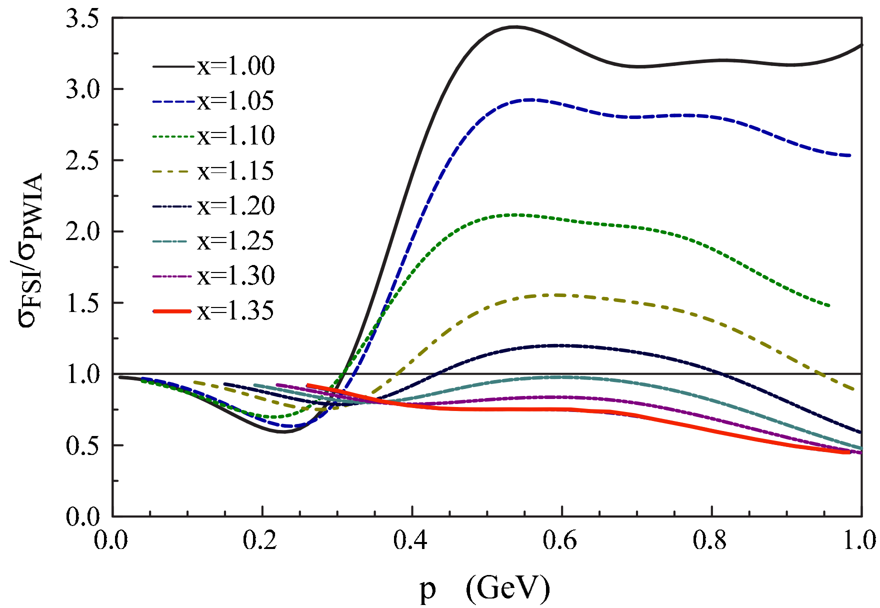
$$\Rightarrow p_m \approx 0.8(GeV/c)$$

both terms are equal $\Rightarrow$ interference and rescattering cancel

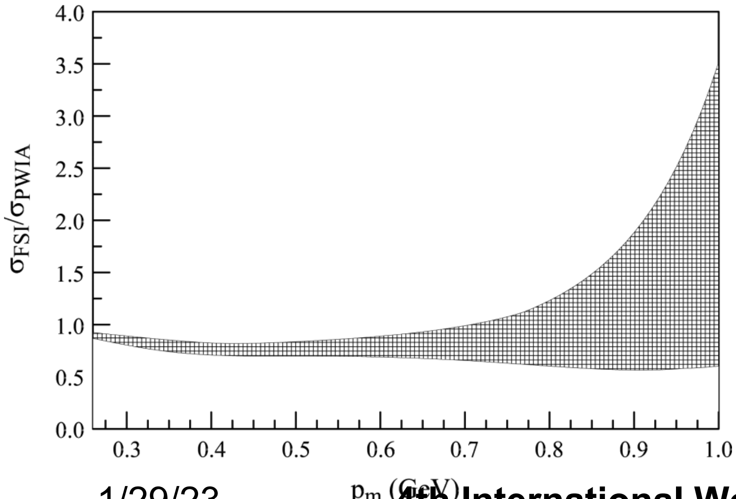
- b determined by nucleon size
- cancellation due to imaginary rescattering amplitude
- valid only for high energy (GEA)

FSI uncertainties





W.P.Ford et al. PRC 90 064006 (2014)



range of possible values of R for all form factor and W.F. used