NN Core Studies in d(e,e'p)n

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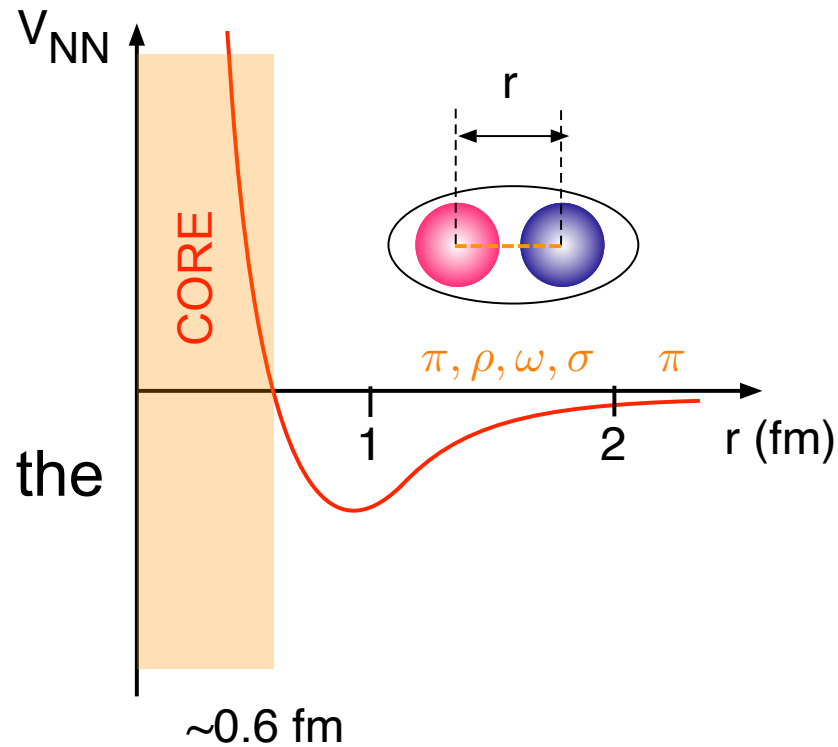
- Introduction
- History and previous results
- Angular distributions for fixed p_m
- ‘Experimental’ momentum distributions
- Approaching the Core
- Outlook
- Summary

Introduction

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



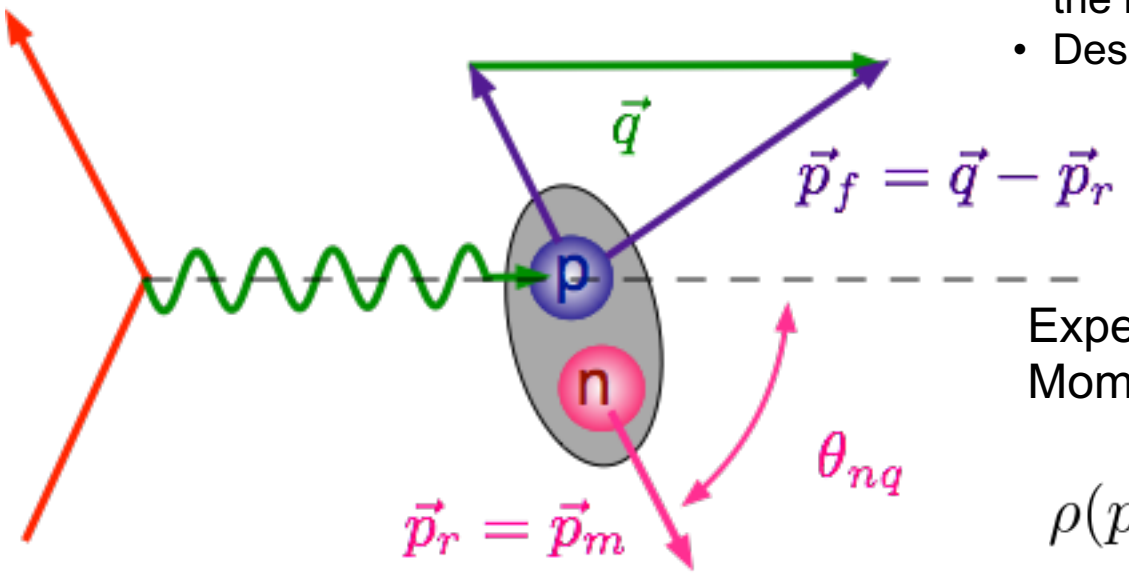
Ideal method: 'measure' the momentum distribution ⇒ study the d(e,e'p) reaction

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

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:

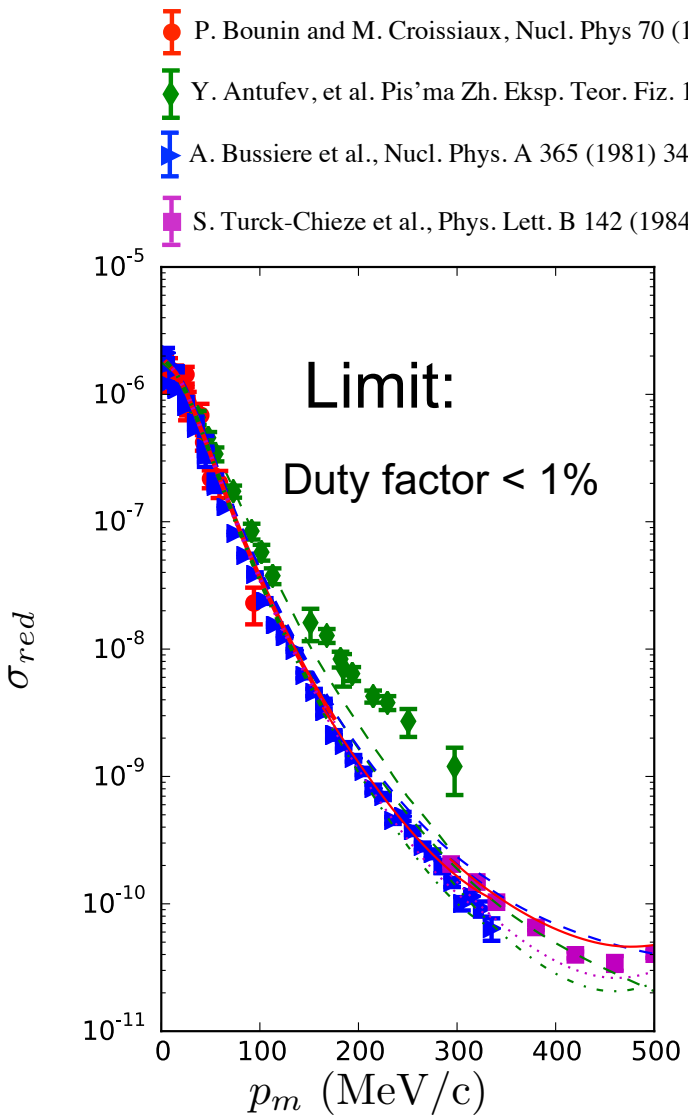
- Hit nucleon does not interact with the recoiling system
- Described by a plane wave

Experimental
Momentum distributions:

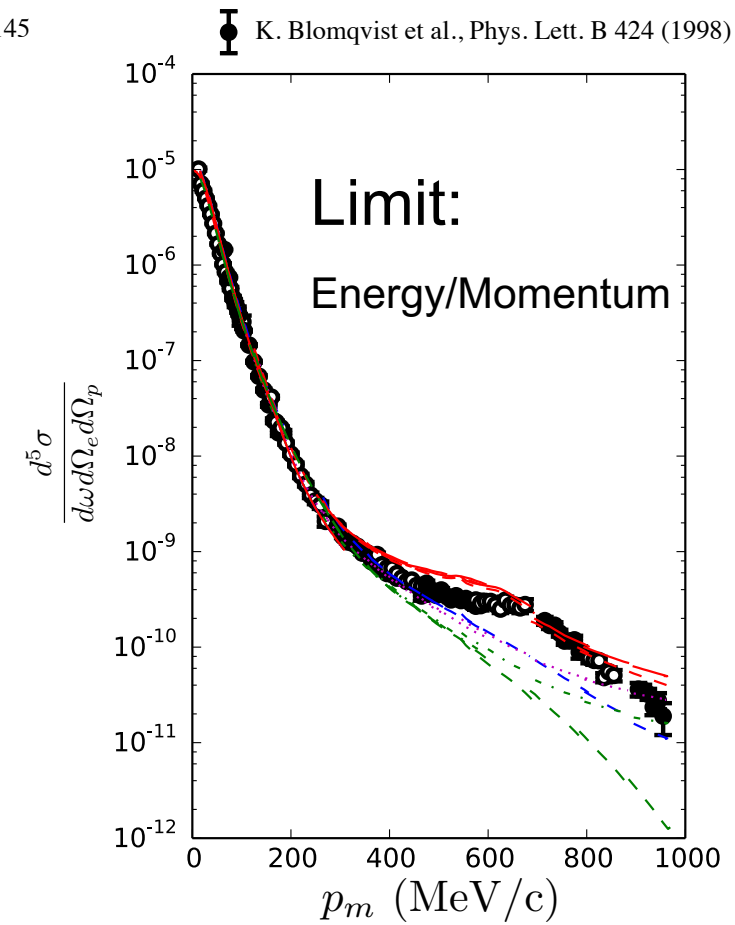
$$\rho(p_r)_{exp} = \sigma_{red} = \frac{\sigma_{exp}}{k\sigma_{ep}}$$

also called reduced cross sections

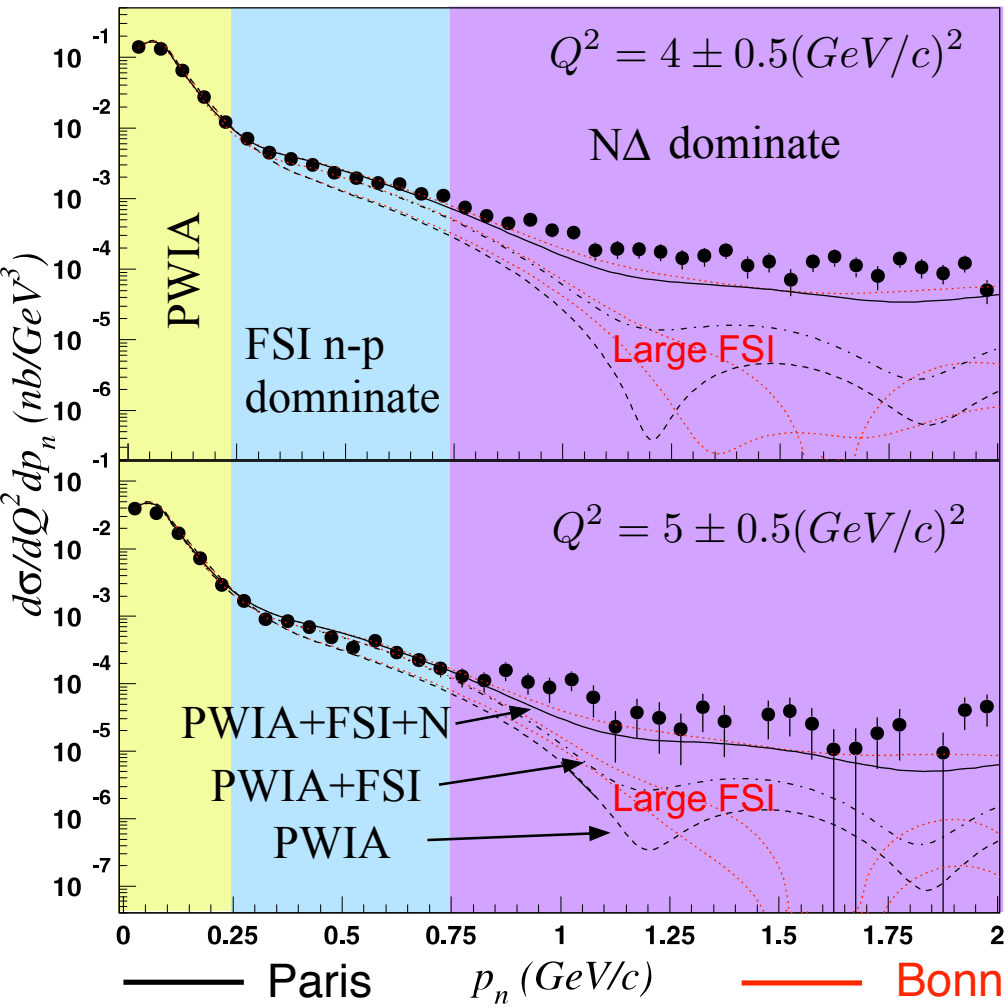
History of Missing Momentum Dependences



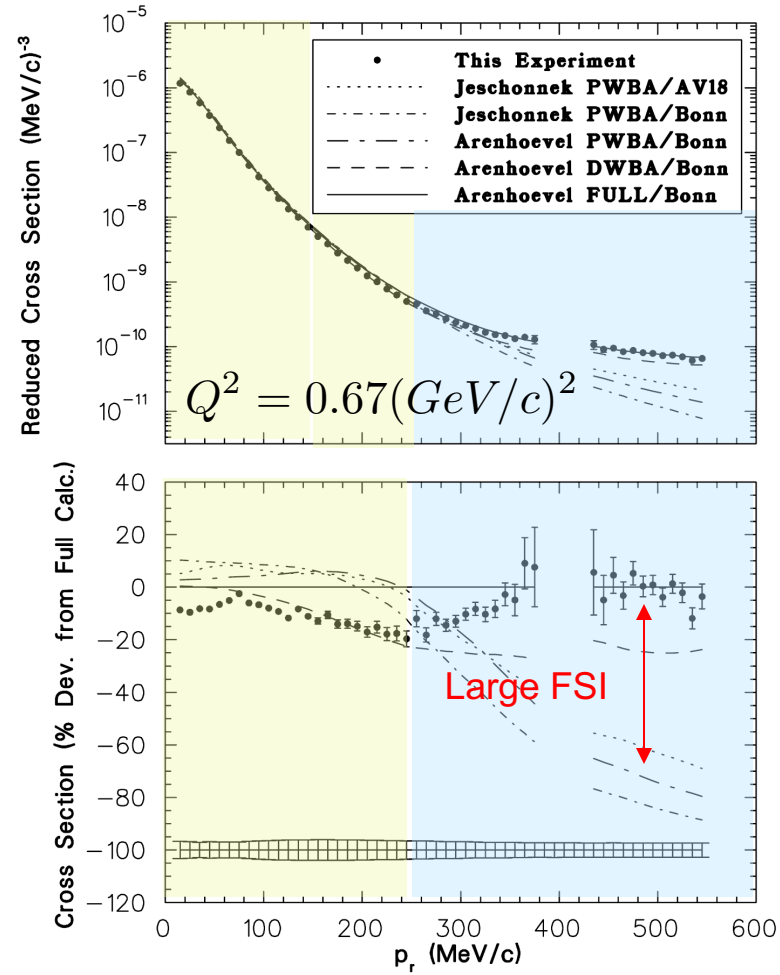
Low Q^2:
$Q^2 < 0.33\ (\mathrm{GeV/c})^2$



CLAS Egyian et al. PRL 98 (2007)



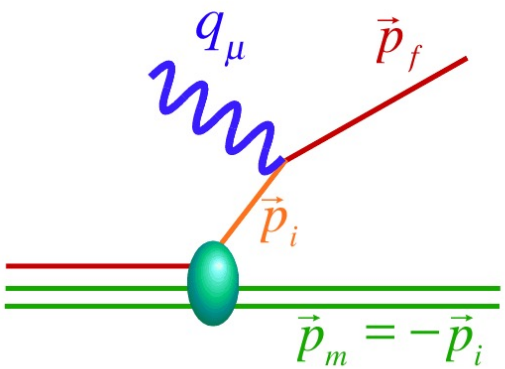
Hall A Ulmer et al. PRL89 (2002) 062301-1



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

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

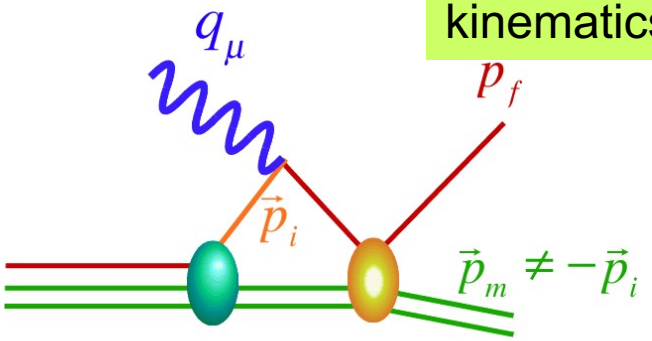
PWIA



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

FSI

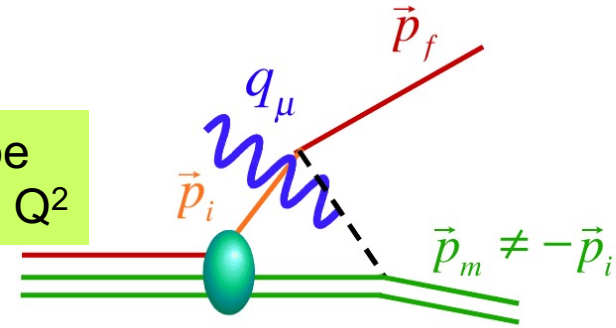
reduced at certain kinematics ?



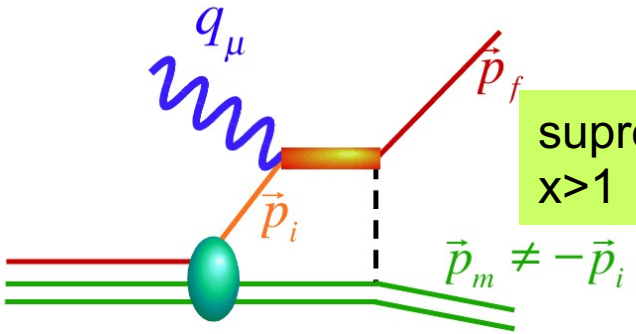
$$\frac{d\sigma}{d\omega d\Omega_e d\Omega_N} = k\sigma_{eN} D(E_m, p_f, p_m)$$

MEC

expected to be small at large Q^2



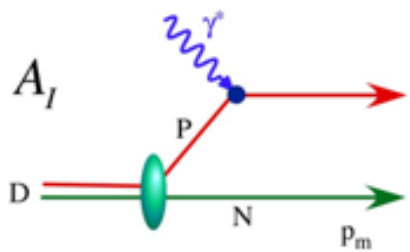
IC



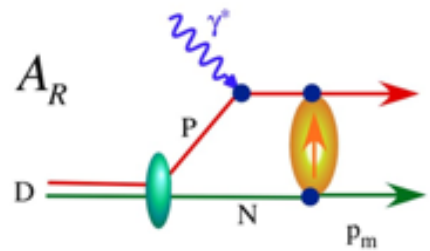
supressed for x>1

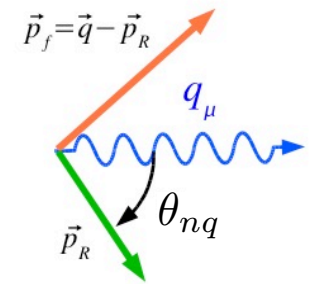
At High Q^2 FSI Anisotropic

IA Amplitude (real):



Rescattering Amplitude
(at high energy mostly imaginary):



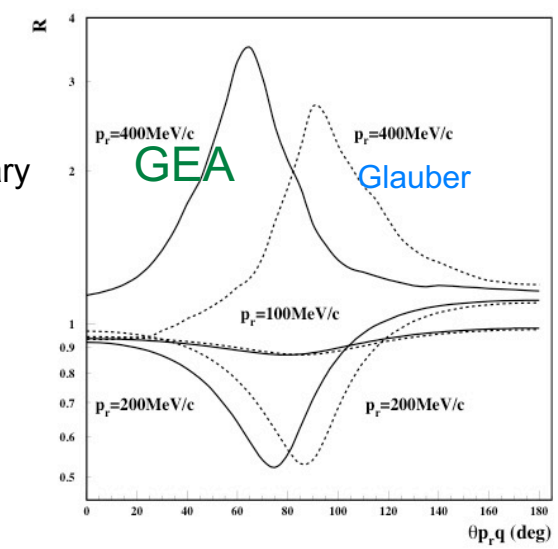


TotalScattering Amplitude: $A = A_I + iA_R$ $\quad A_R \approx i\,|A_R|$ mostly imaginary

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 $\quad R = \dfrac{\sigma}{\sigma_I} = 1 - 2\dfrac{|A_I|\,|A_R|}{|A_I|^2} + \dfrac{|A_R|^2}{|A_I|^2}$



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

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)

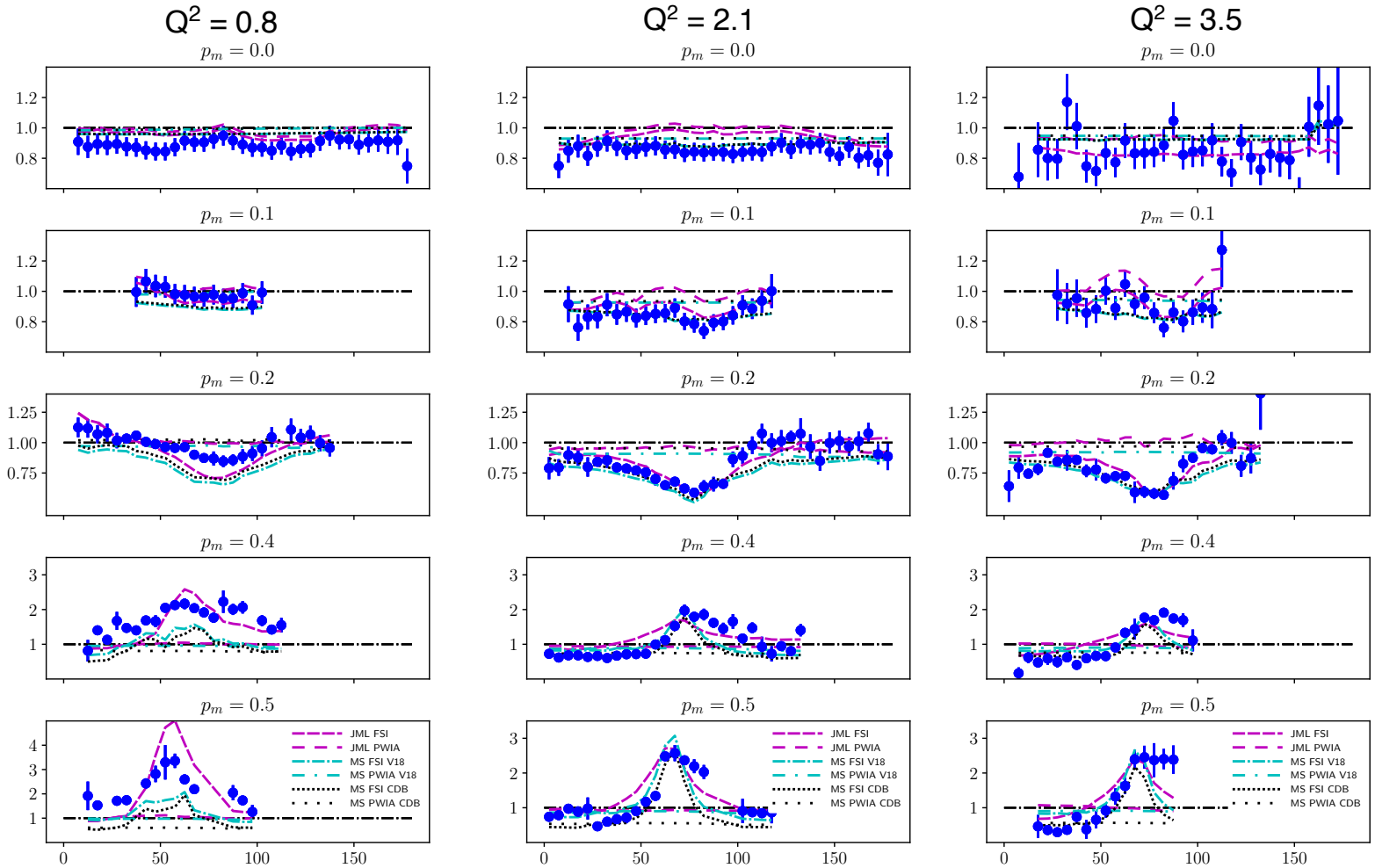
R. Machleidt, Phys. Rev. C63, 024001 (2001) (CD-Bonn)

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



FSI

CD Bonn

PWIA

FSI

V18

PWIA

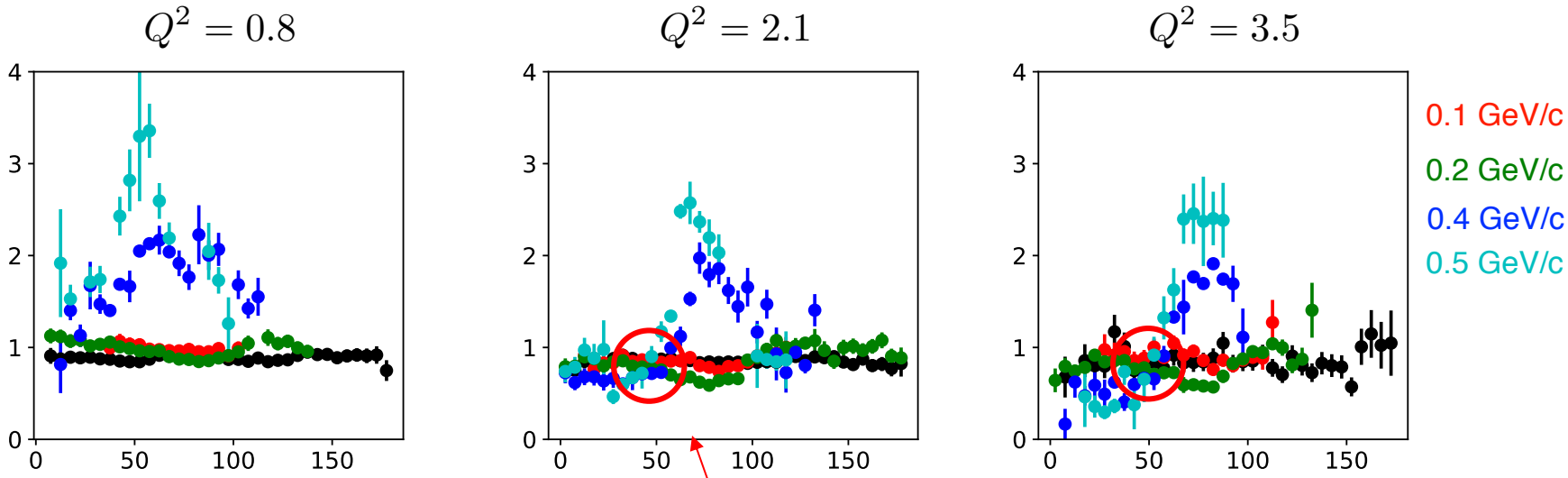
FSI

Laget

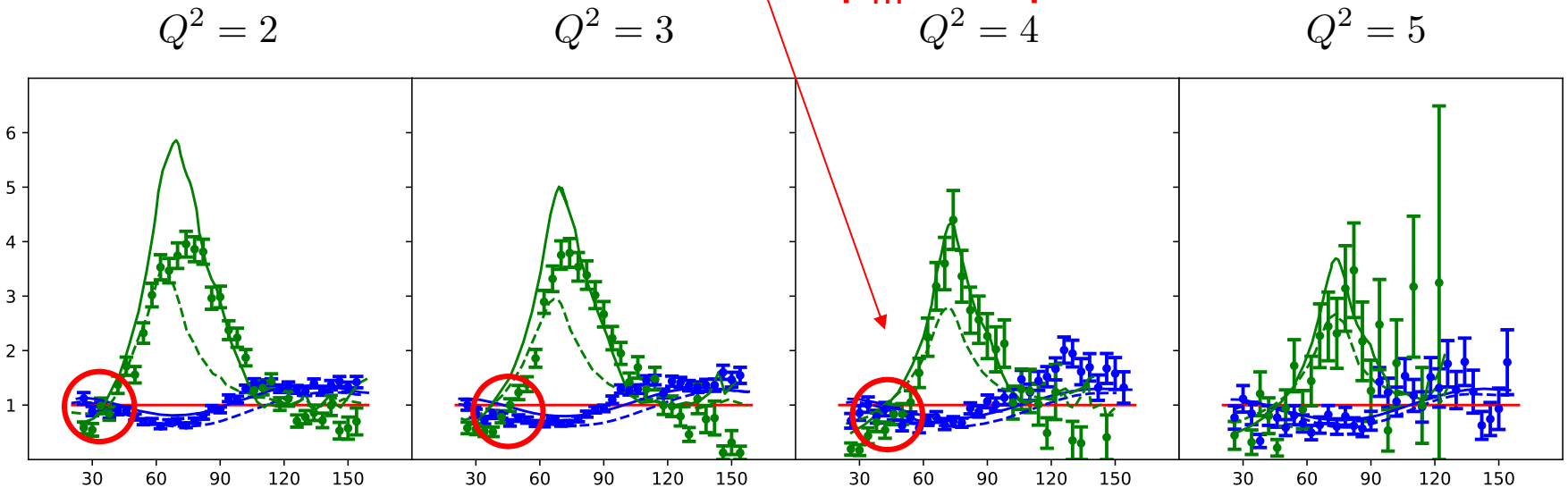
PWIA

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

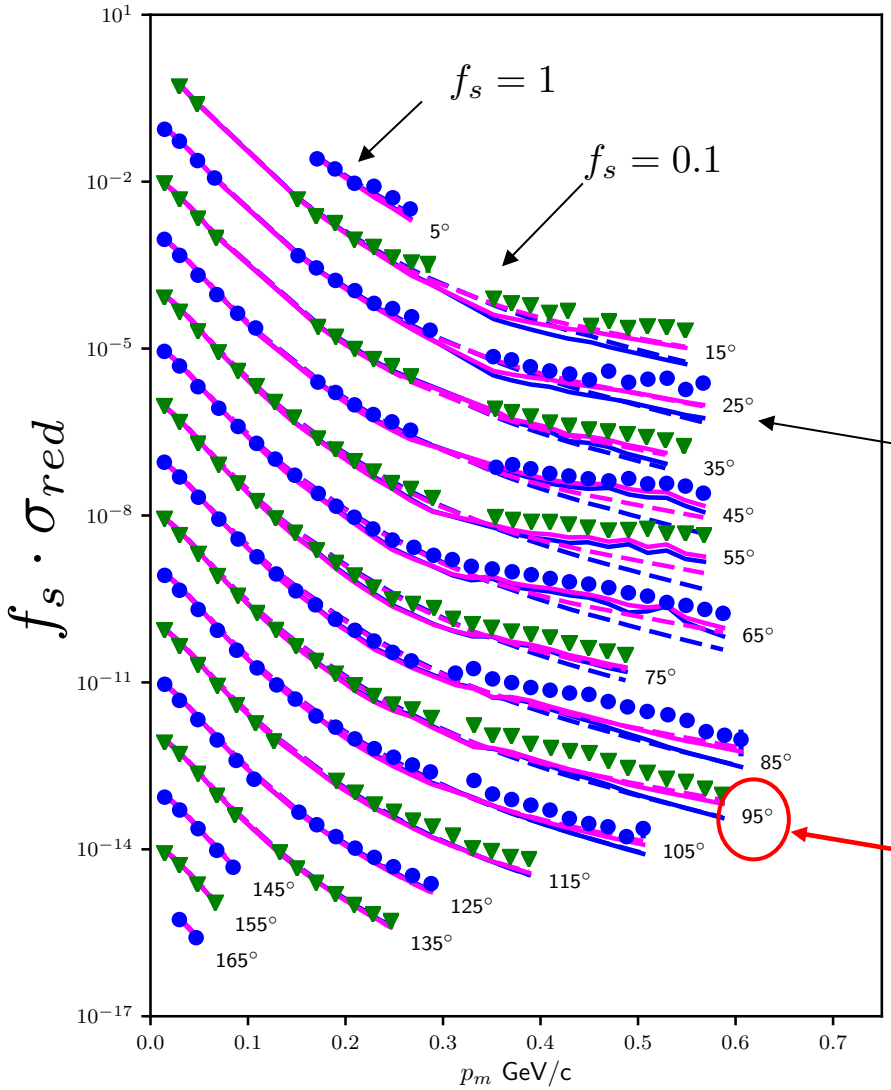
$$R = \frac{\sigma_{EXP}}{\sigma_{PWIA}}$$



~ p_m independent, small FSI



‘Experimental’ Momentum Distributions



Hall A Experiment E01-020

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

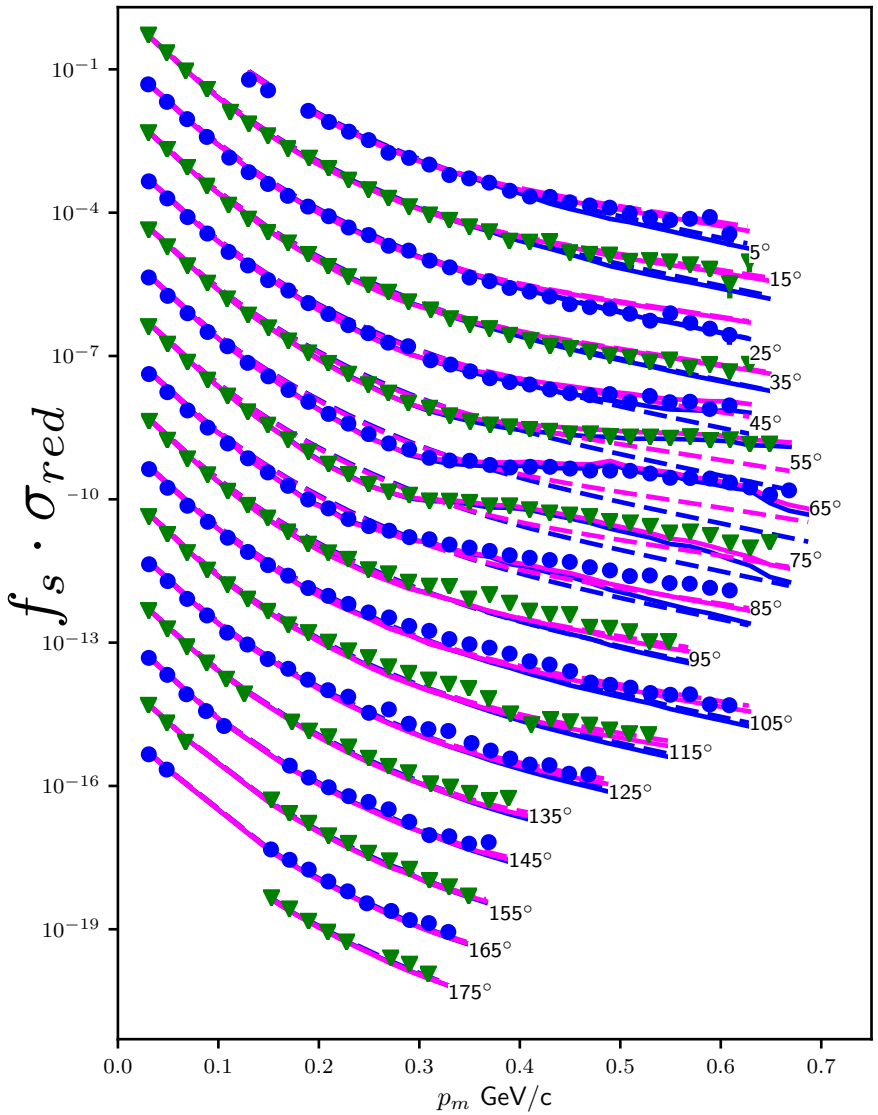
- Large FSI for pm >0.25 GeV/c
- Little sensitivity to W.F.
- Eikonal regime not yet reached

$f_s = 0.01...$

f_s : Experimental data are scaled for display purposes

fixed recoil angles θ_{nq}

Experimental data are scaled for display purposes



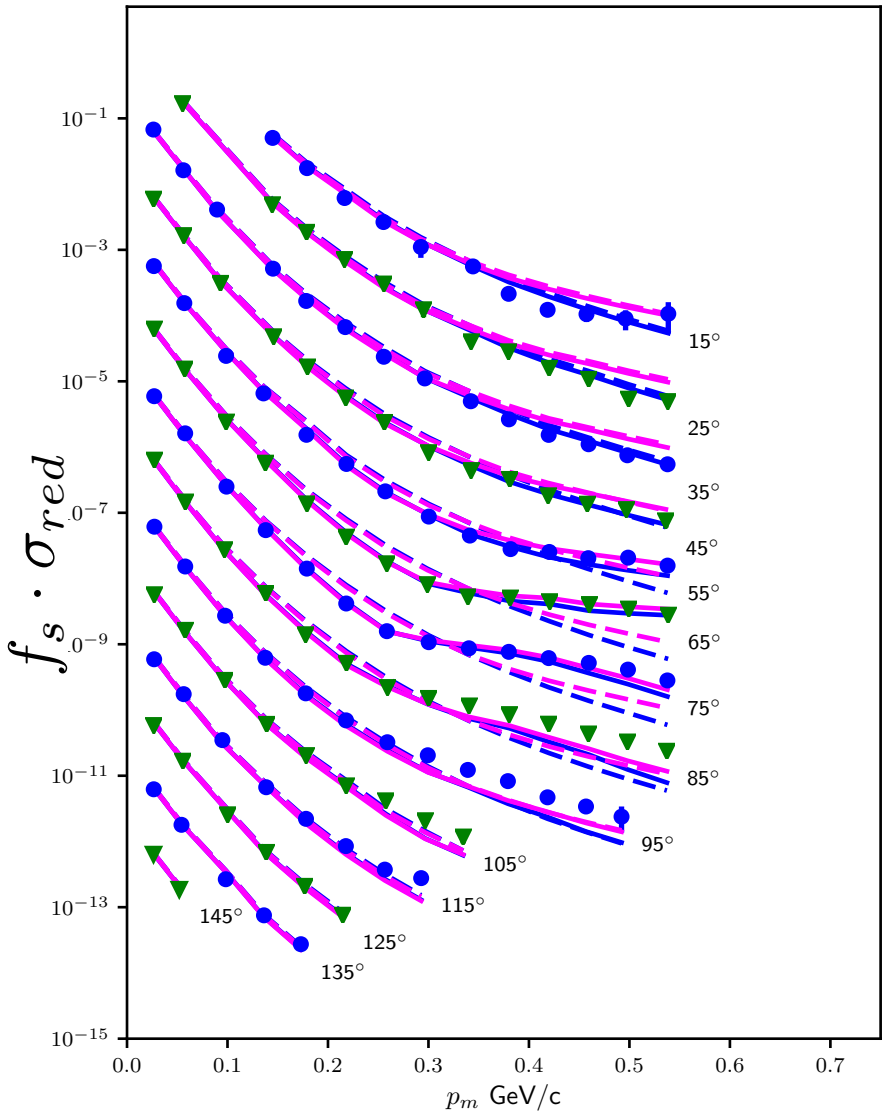
$Q^2 = 2.1\ (\mathrm{GeV/c})^2$

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

Approaching the Core

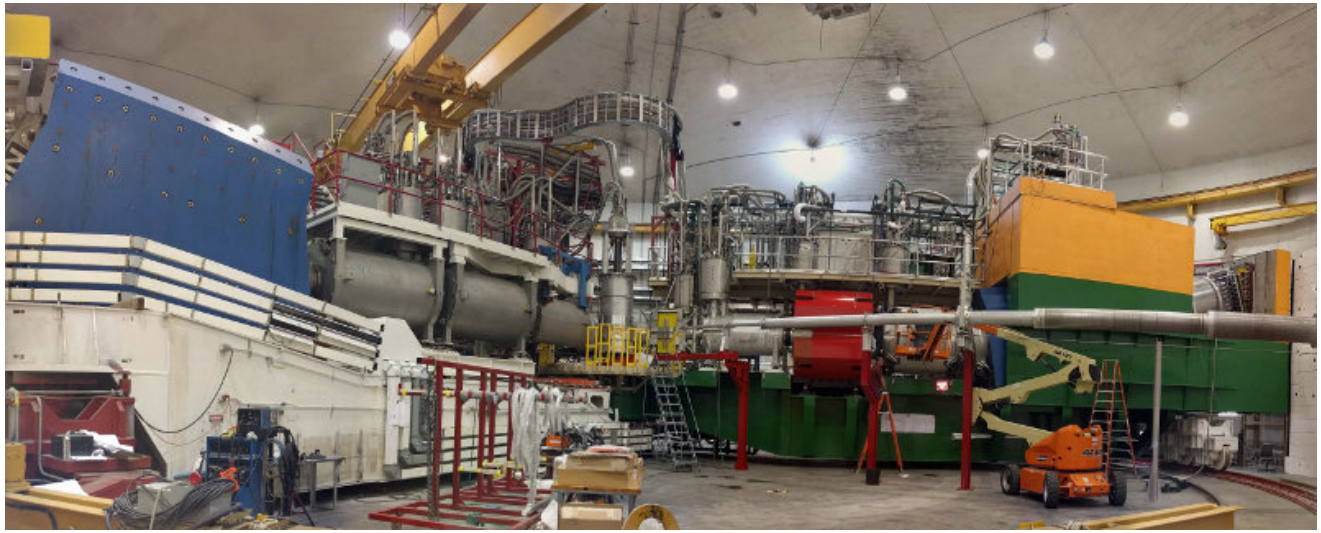
- Hall A and Hall B experiments established validity of GEA based calculations

- Determine cross sections at missing momenta up to 1 GeV/c
- Measure at well defined kinematic settings
- Selected kinematics to minimize contributions from FSI
- Selected kinematics to minimize effects of delta excitation

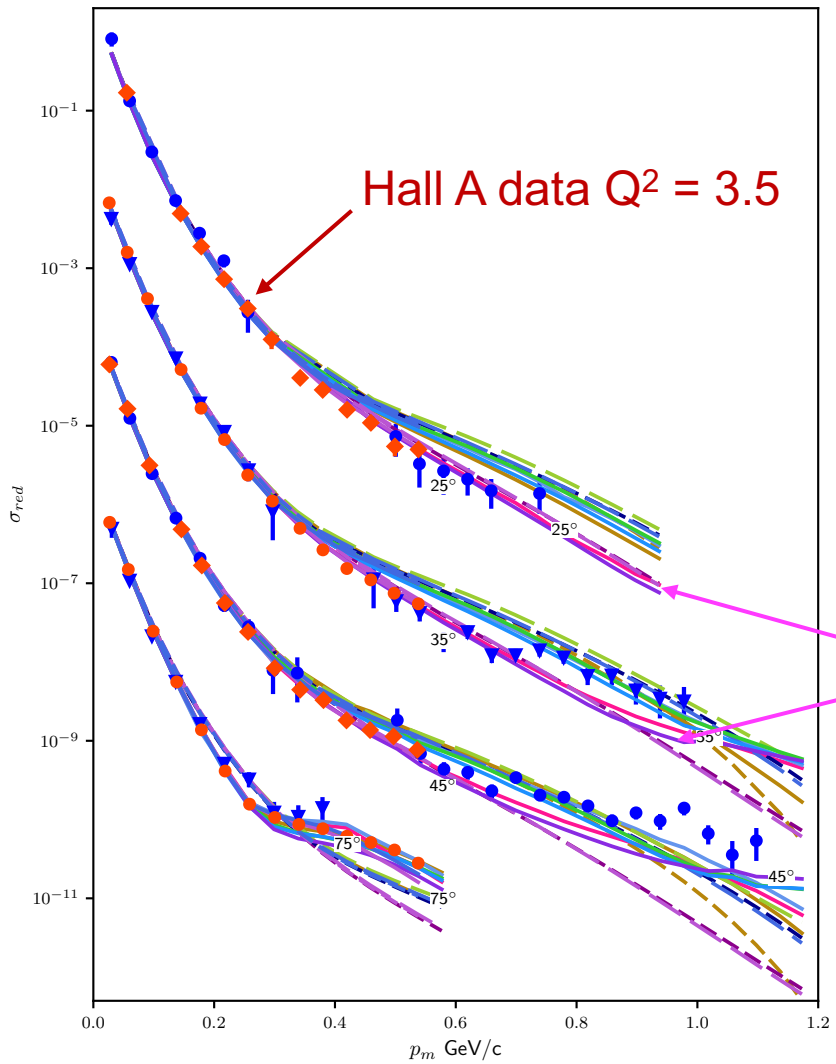
Parameters

- Beam: 10.6 GeV, ~40 - 50μA
- Electron Detector: SHMS at p_{cen} = 8.534GeV/c
  - θ_e = 12.19°, 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° ≥ θ_p ≥ 38.8

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



New Results



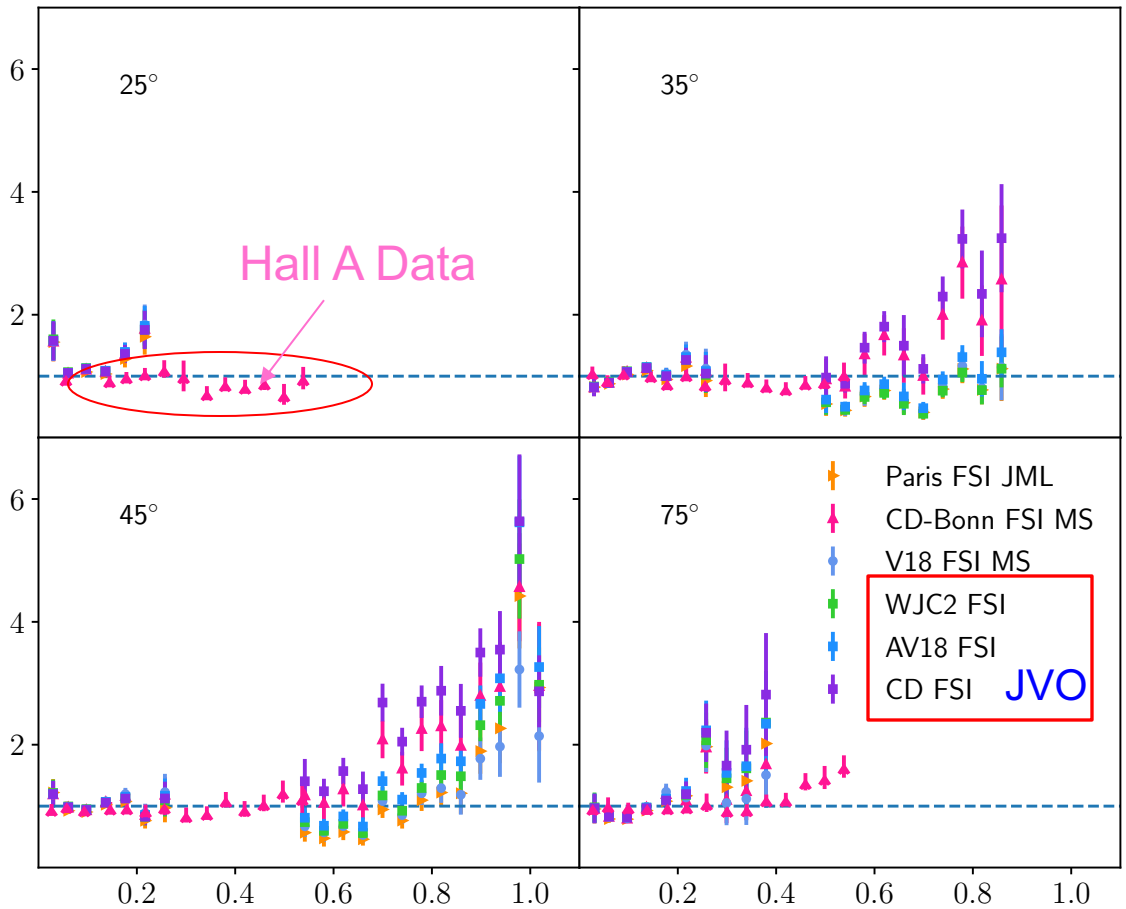
- Thesis C. Yero
- PRL 125, 262501 (2020)
  https://doi.org/10.1103/PhysRevLett.125.262501

$Q^2 = 4.25\ (\mathrm{GeV}/c)^2$

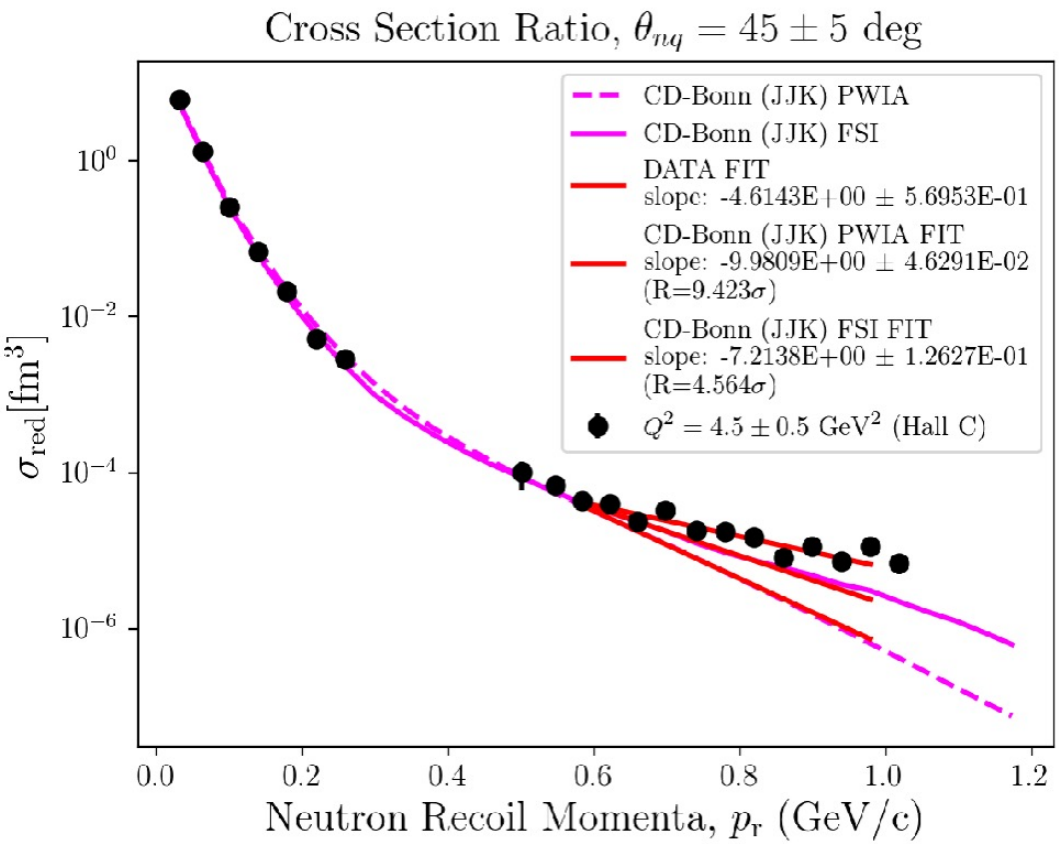
- Dashed lines: PWIA
- Solid lines: FSI

CD Bonn based calculations

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



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:

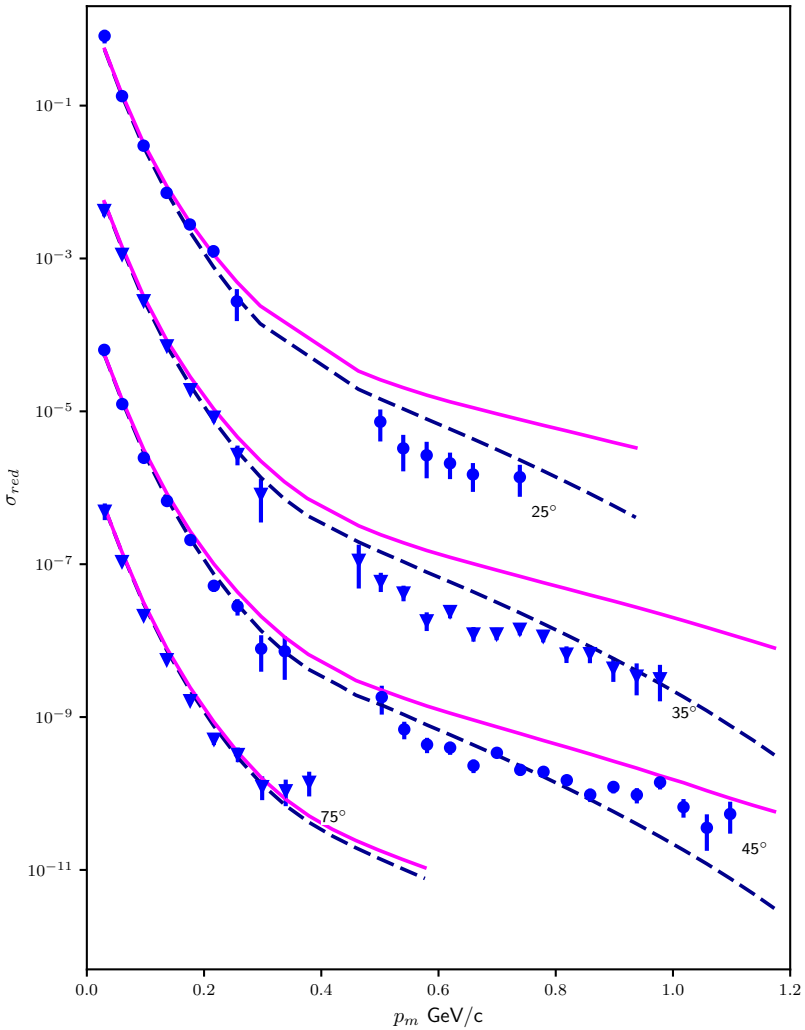
$$Z = \frac{\mu_{exp} - \mu_{calc}}{\sigma_{\mu_{exp}}}$$

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

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

Light Cone Calculation

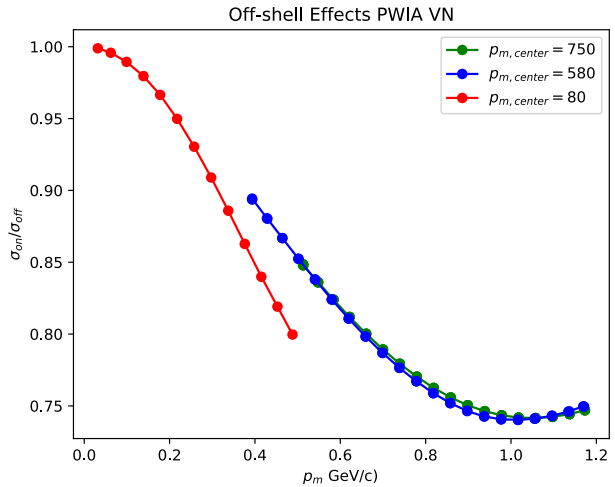


M. Sargsian and F. Vera in progress

Z_{35} = 3.8e-4 p-value = 1.

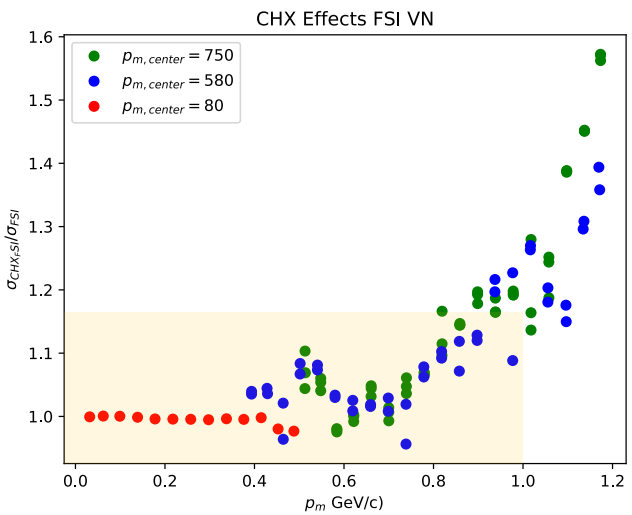
Z_{45} = 3.9 p-value = 9e-5

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

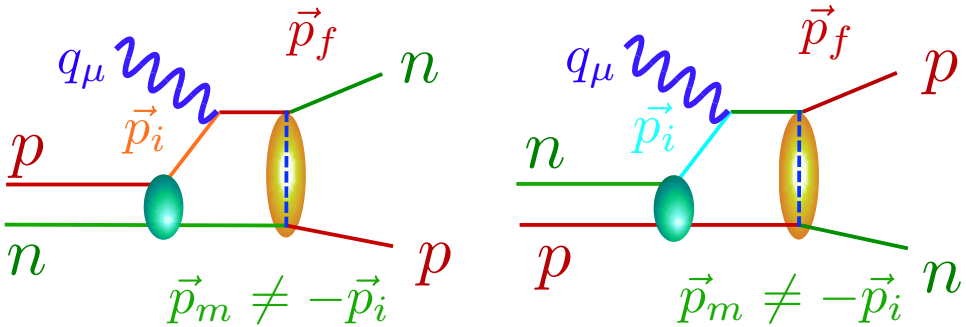


Off-shell effects:
included in calculations

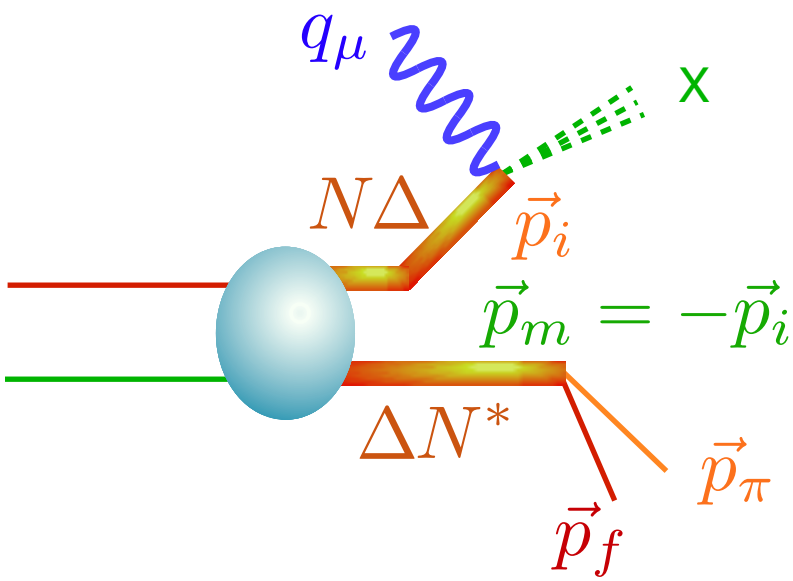
Too small to explain differences



Charge Exchange Effects:
NOT included



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



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

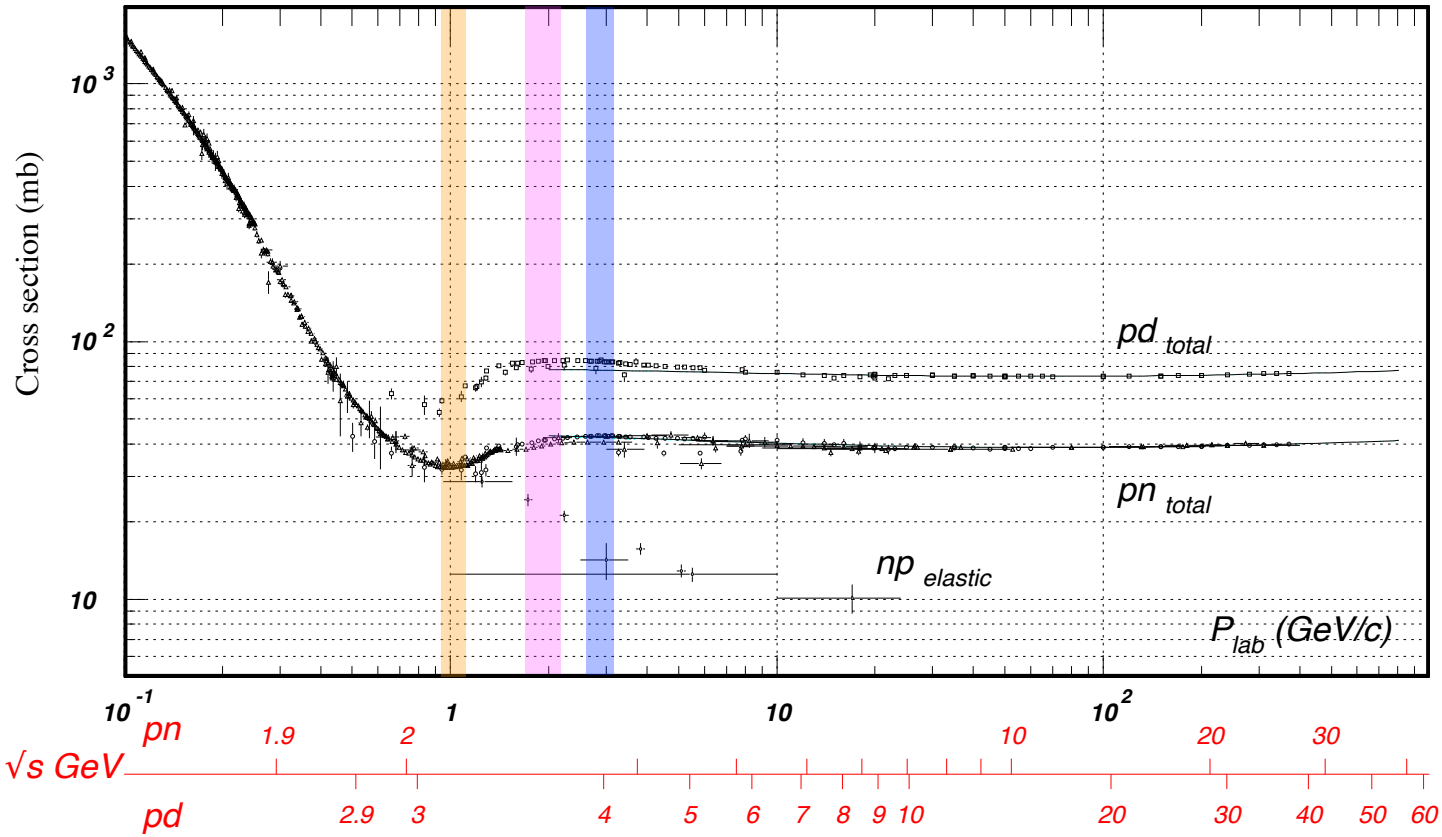
Summary

- High Q^2 d(e,e' p)n best described by generalized eikonal approximation for $Q^2 > 2$ GeV/c
- FSI can be controlled
- First new data on very high missing momenta obtained in Hall C at JLAB for $Q^2 > 4$ $(GeV/c)^2$ up to $p_m = 0.98$ GeV/c
- Reduced cross section behavior at $p_m > 0.6$ GeV/c cannot be reproduced by current calculations.
- Off-shell & Charge exchange not enough to explain difference
- Better statistics is needed
- Future : inelastic channels should be studied

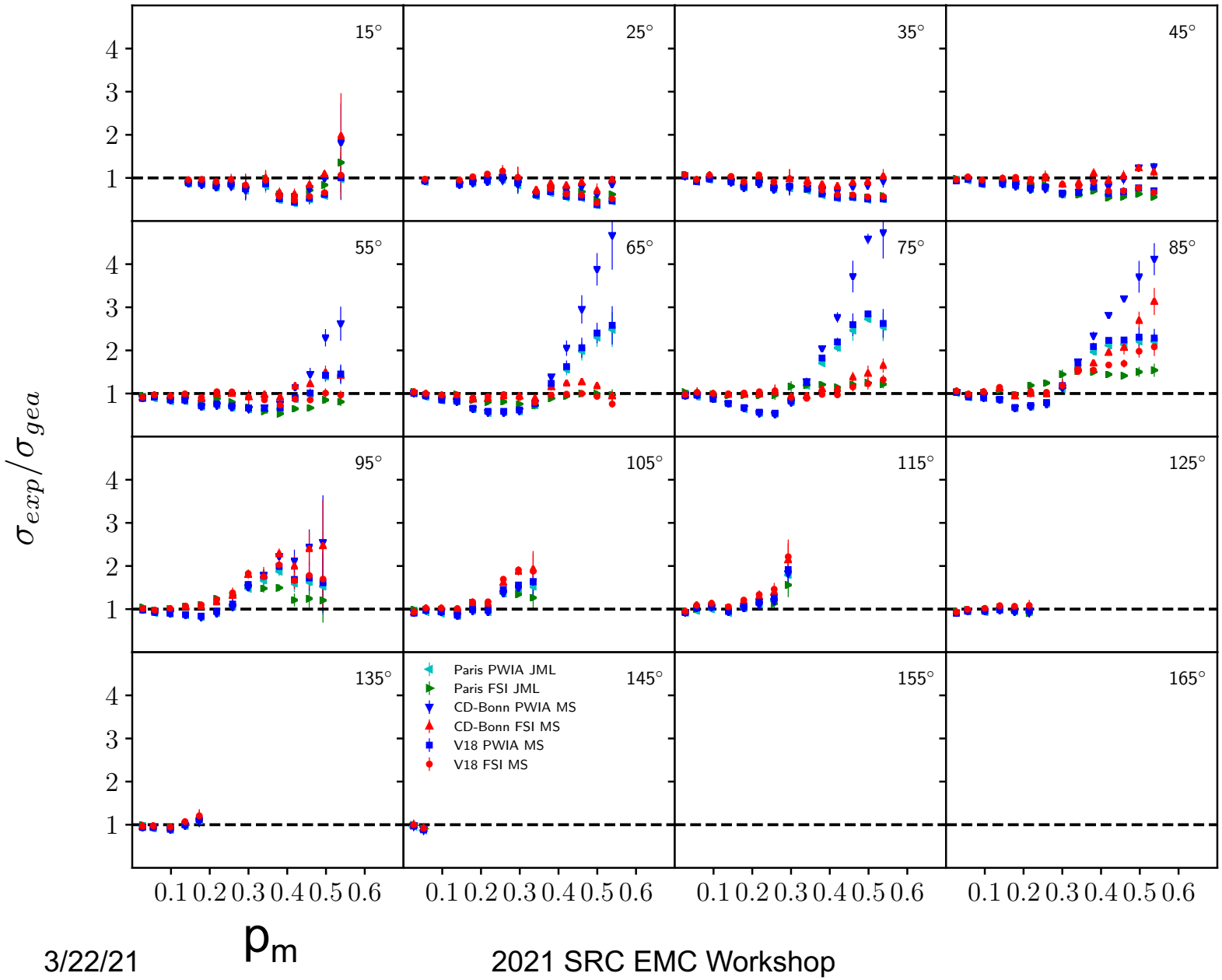
Supported by the Department of Energy, contract DESC0013620

Backup

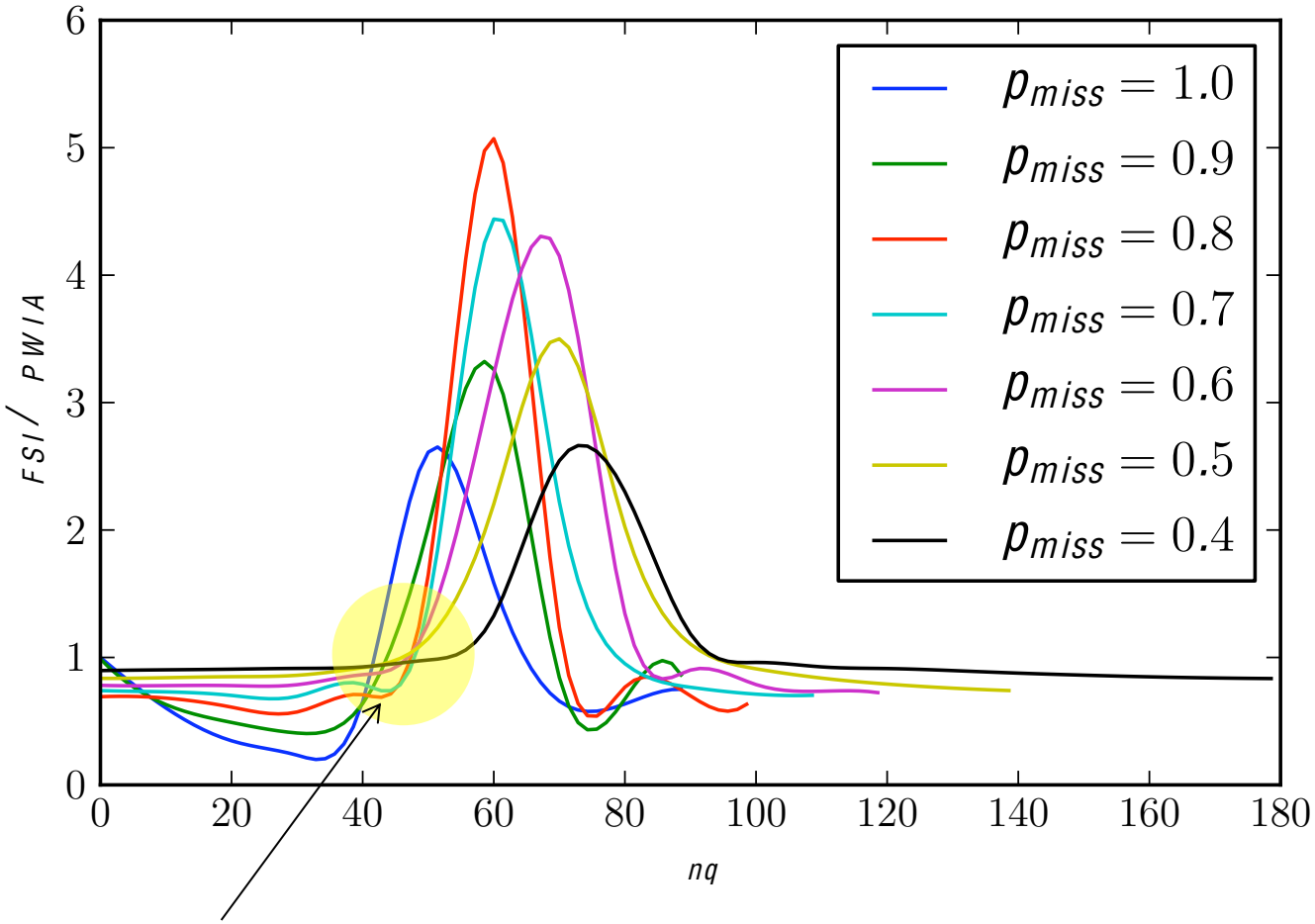
0.8 2.1 3.5 $(GeV/c)^2$



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



Estimated Angular Distributions up to p_m = 1GeV/c

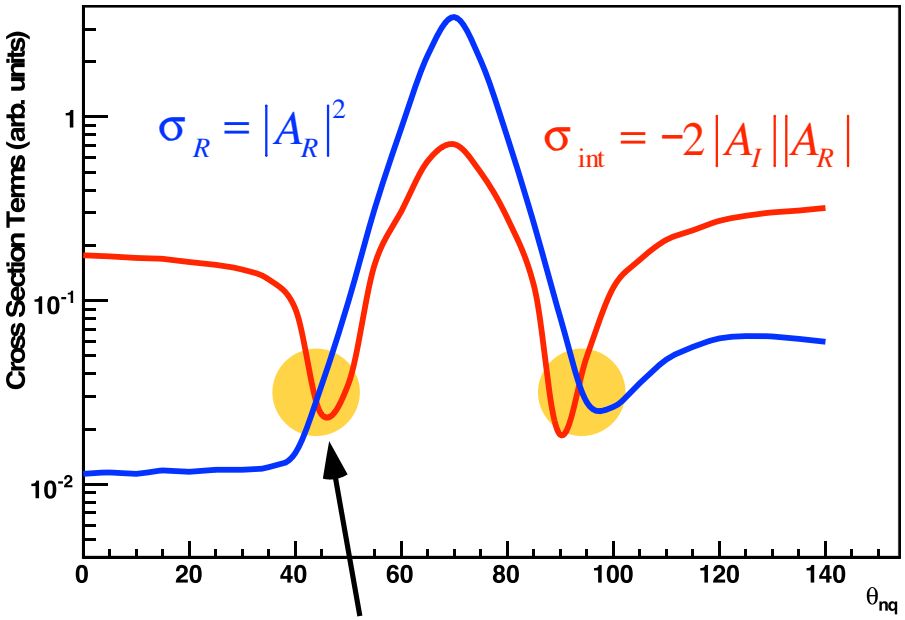


FSI depend weakly on p_m

Calculation: M.Sargsian

FSI Reduction

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



Rescattering determined by slope factor:

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

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

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

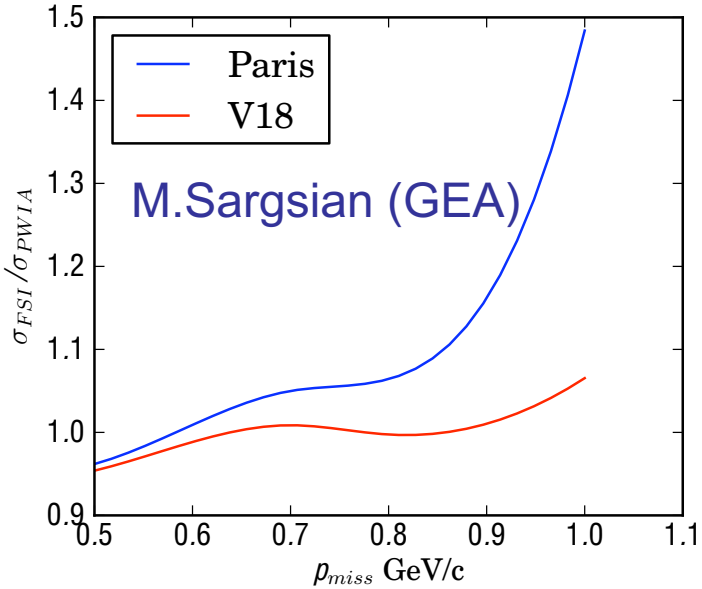
f_s relatively flat up to $k_t \approx 0.5(GeV/c)$

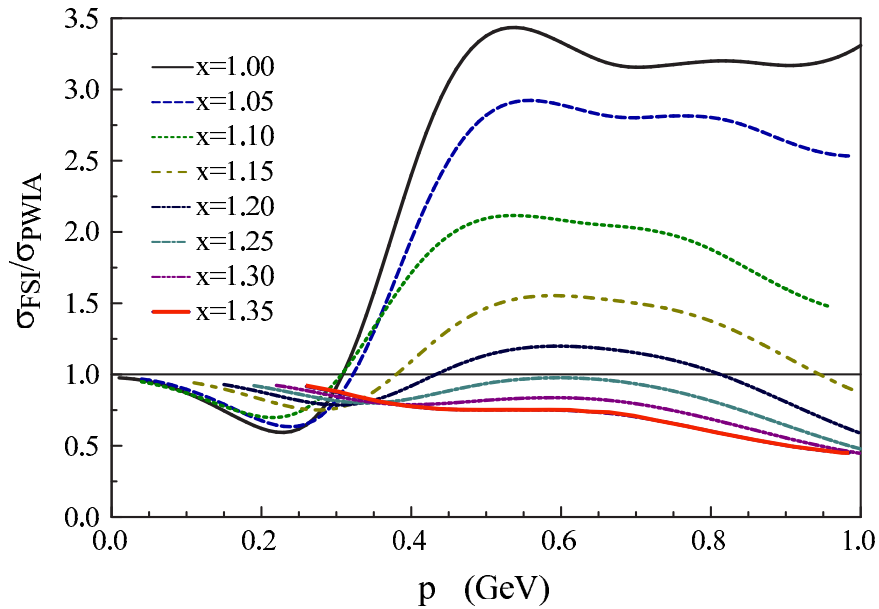
$$\Rightarrow p_m \approx 0.8(GeV/c)$$

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

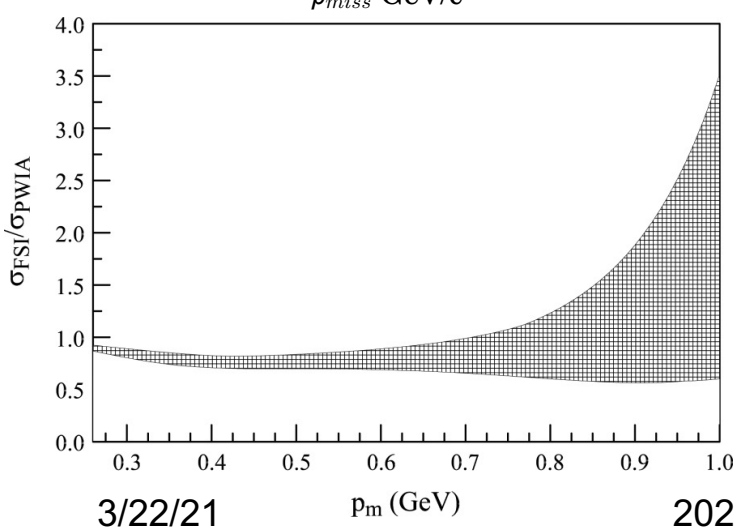
- b determined by nucleon size
- cancellation due to imaginary rescattering amplitude
- valid only for high energy (GEA)

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