Probing the deuteron at very short distances

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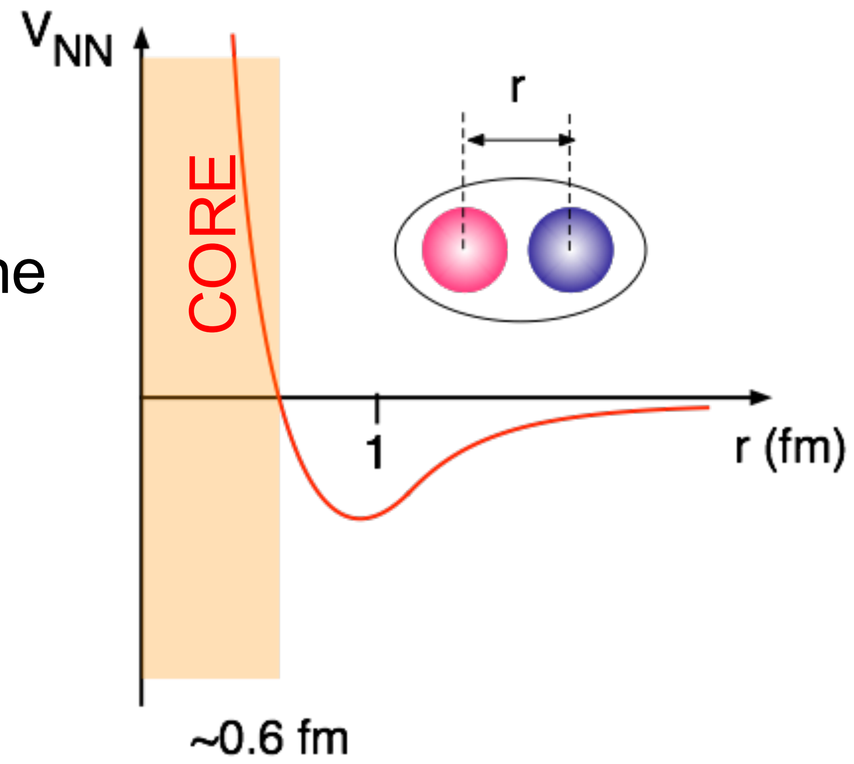
Introduction: Role of the Deuteron

A key system to investigate the core of the NN interaction

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

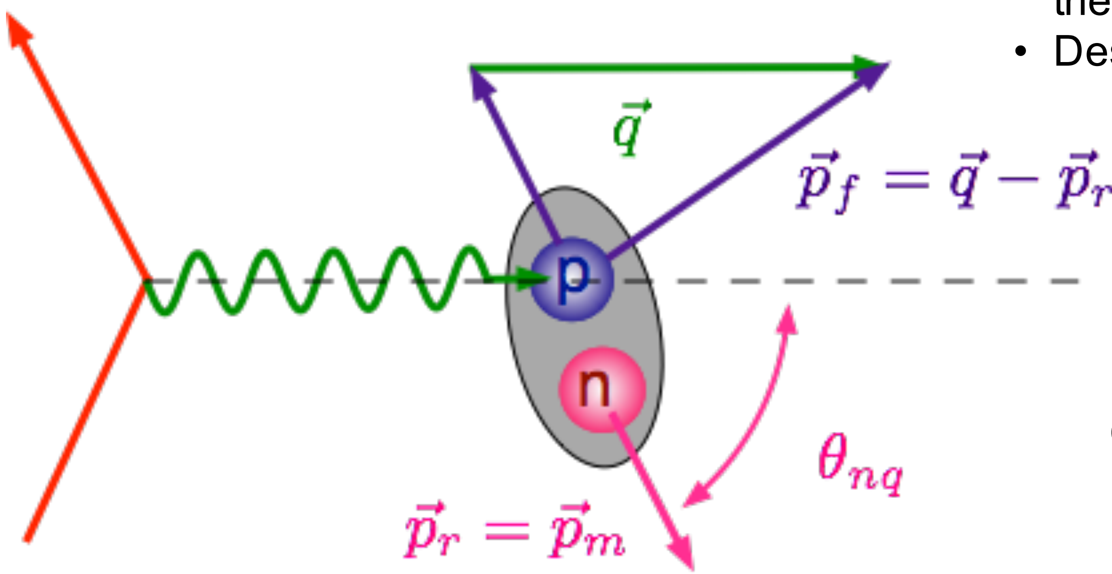
$$\rho(\vec{p}) = C \int \psi(\vec{r}) e^{-i\vec{r}\cdot\vec{p}} d^3 r$$

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



D(e,e'p) in PWIA

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



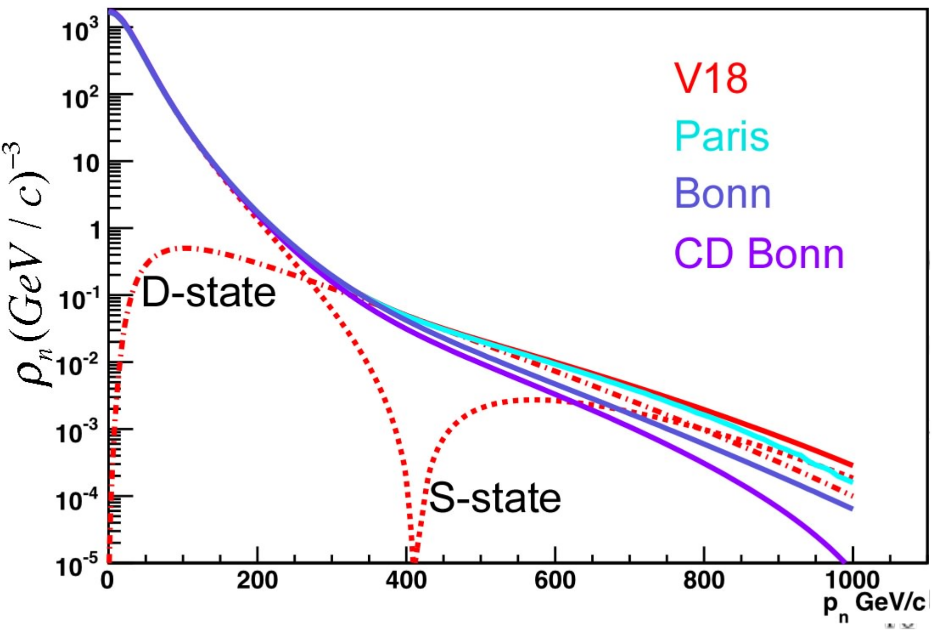
Plane Wave IA:

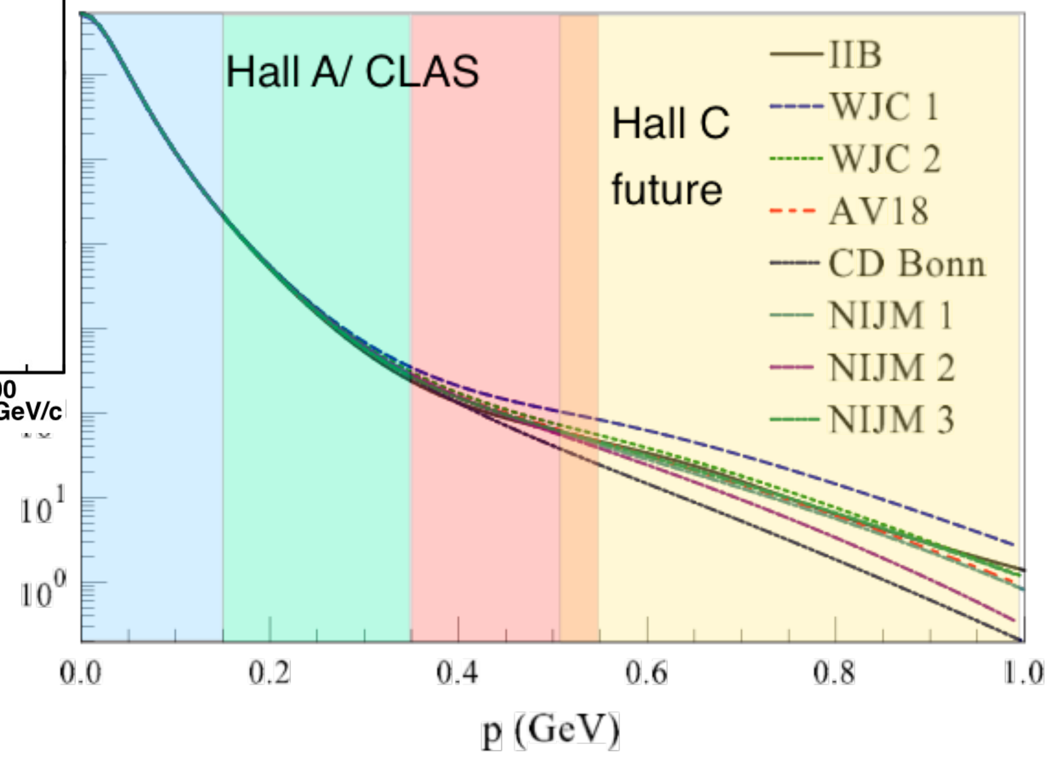
- Hit nucleon does not interact with the recoiling system
- Described by a plane wave

Conventional Experimental Momentum distributions:

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

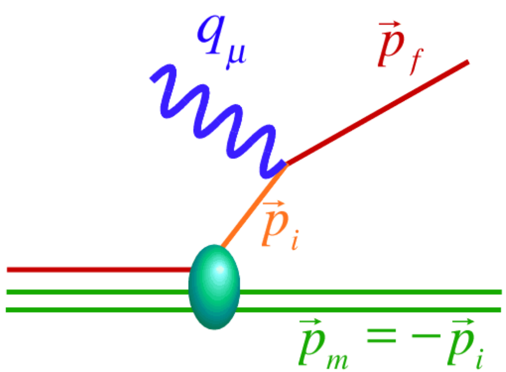
Momentum Distributions





D(e,e’p) Reaction Mechanisms

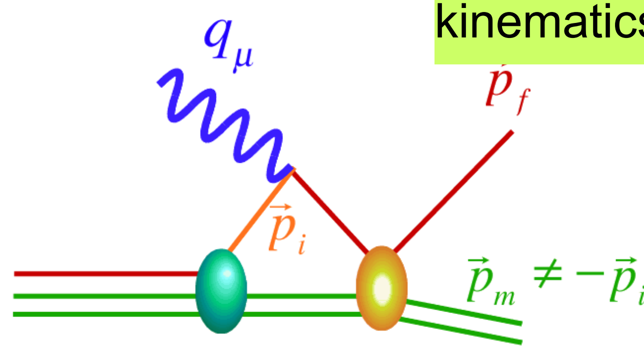
PWIA



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

FSI

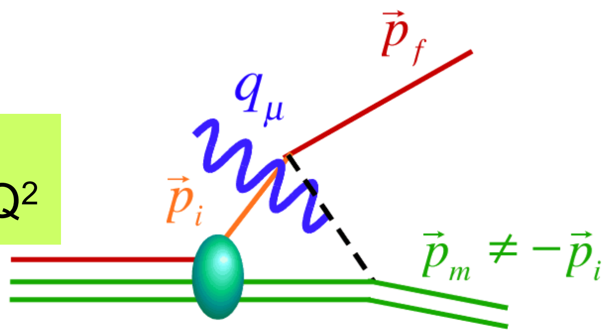
reduced at certain kinematics ?



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

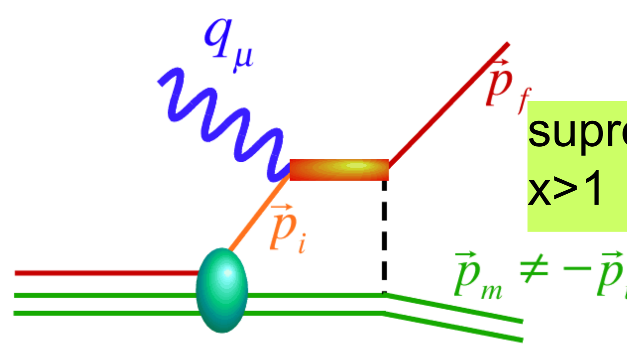
MEC

expected to be small at large Q^2



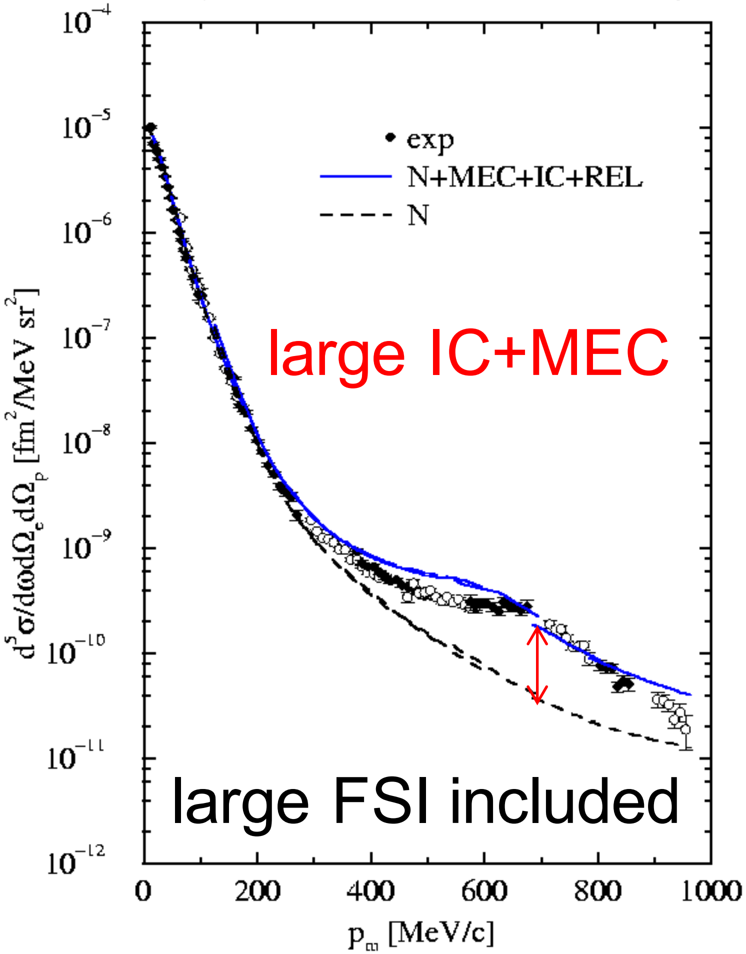
IC

supressed for x>1



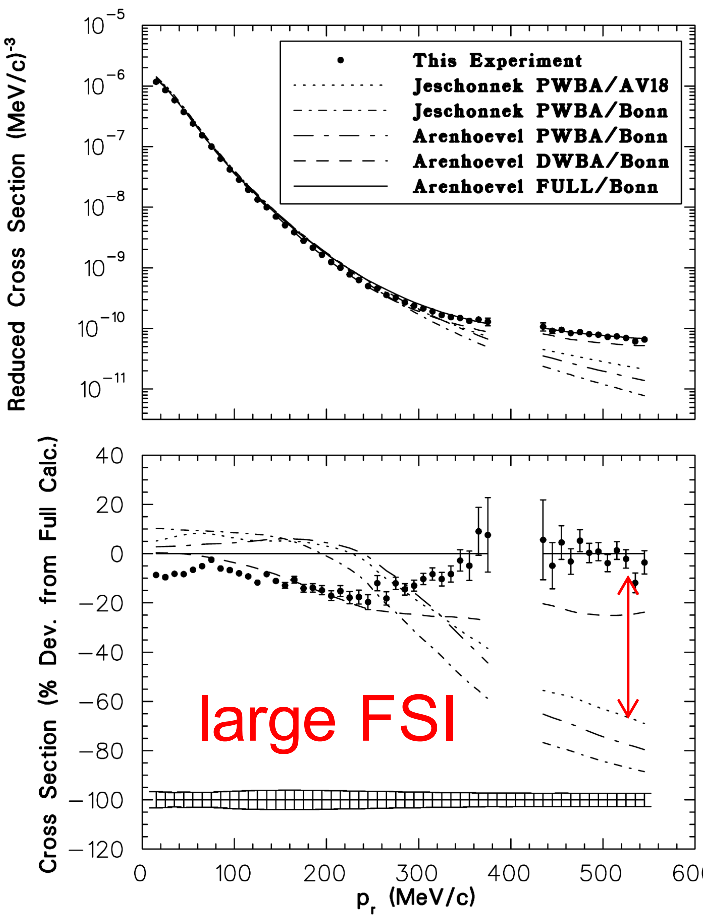
Missing Momentum Dependences

Mini-Review: W.B. and M.Sargsian, International Journal of Modern Physics E Vol. 24, No. 3 (2015) 1530003



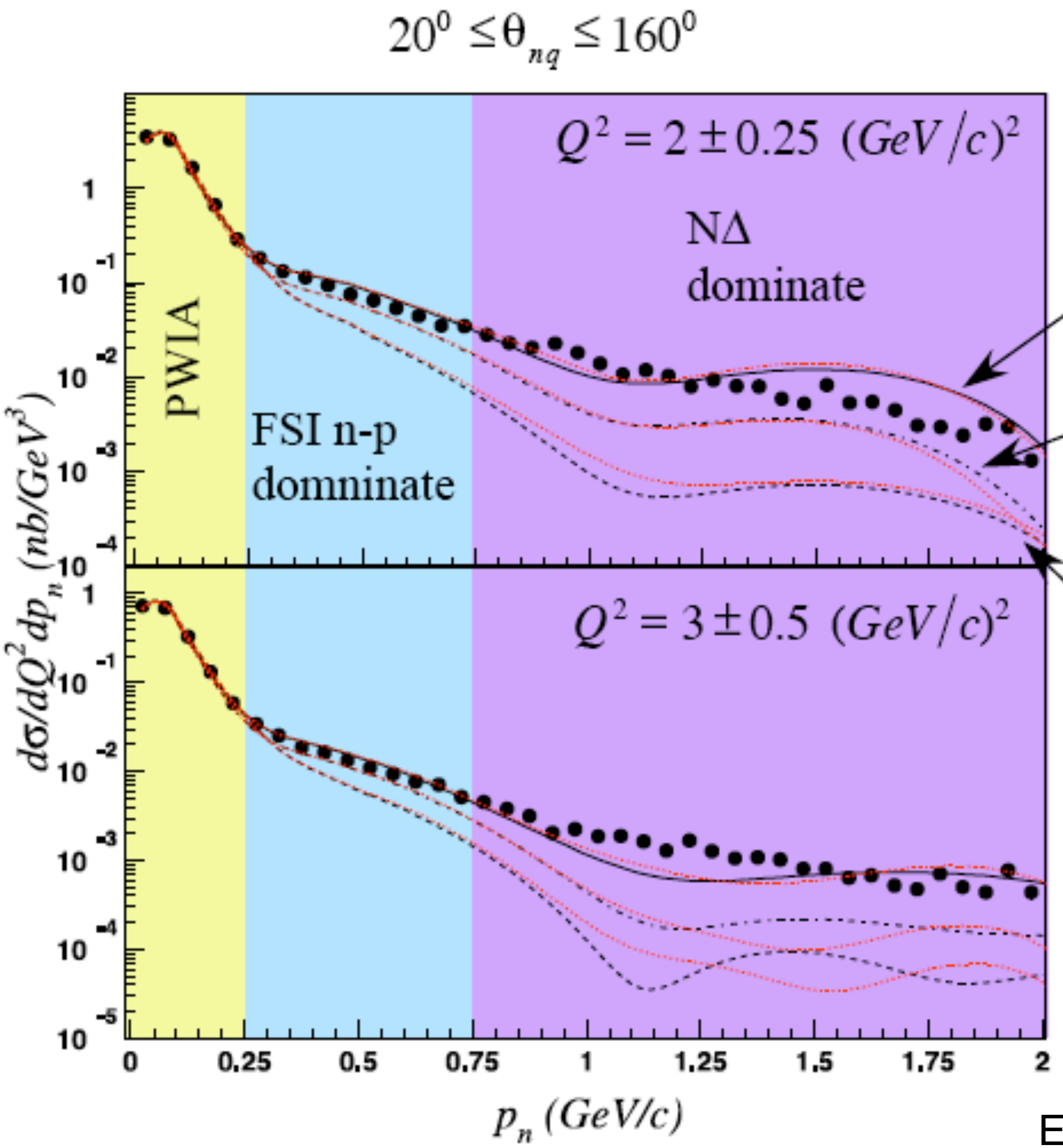
MAMI $Q^2 = 0.33\ (GeV/c)^2$

Blomqvist et al. PLB 429 (1998)



JLAB $Q^2 = 0.67\ (GeV/c)^2$

Ulmer et al. PRL89 (2002) 062301-1



cross sections averaged over CLAS acceptance !

PWIA+FSI+NΔ

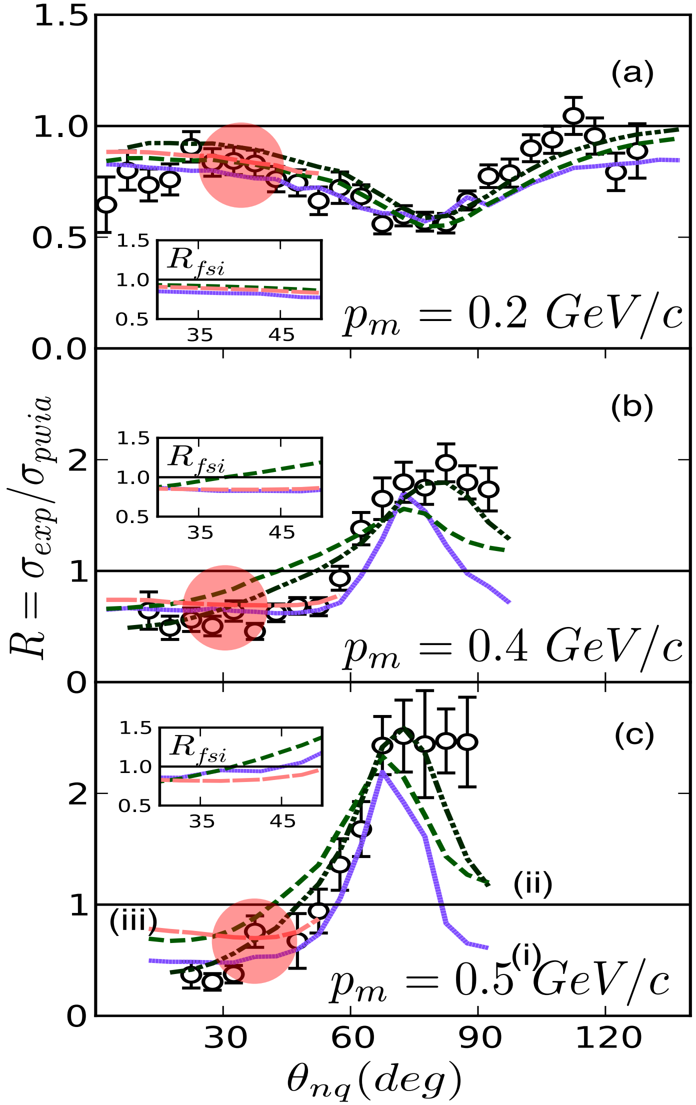
PWIA+FSI

PWIA

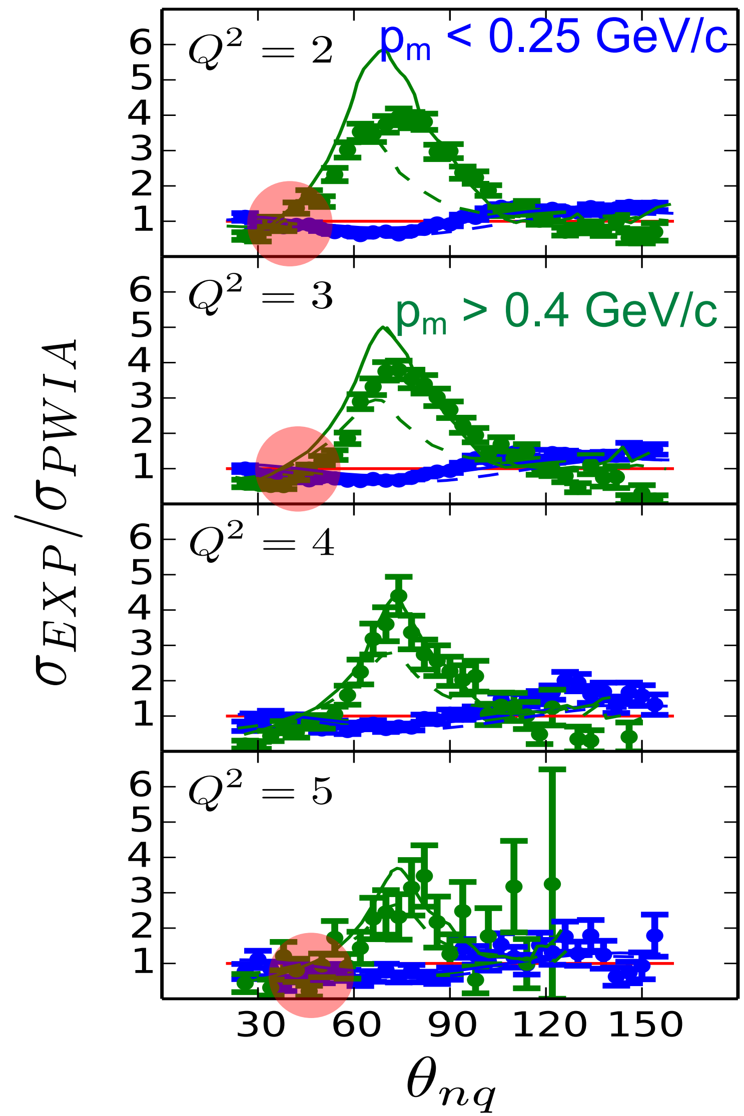
black: Paris potential

red: V18 potential

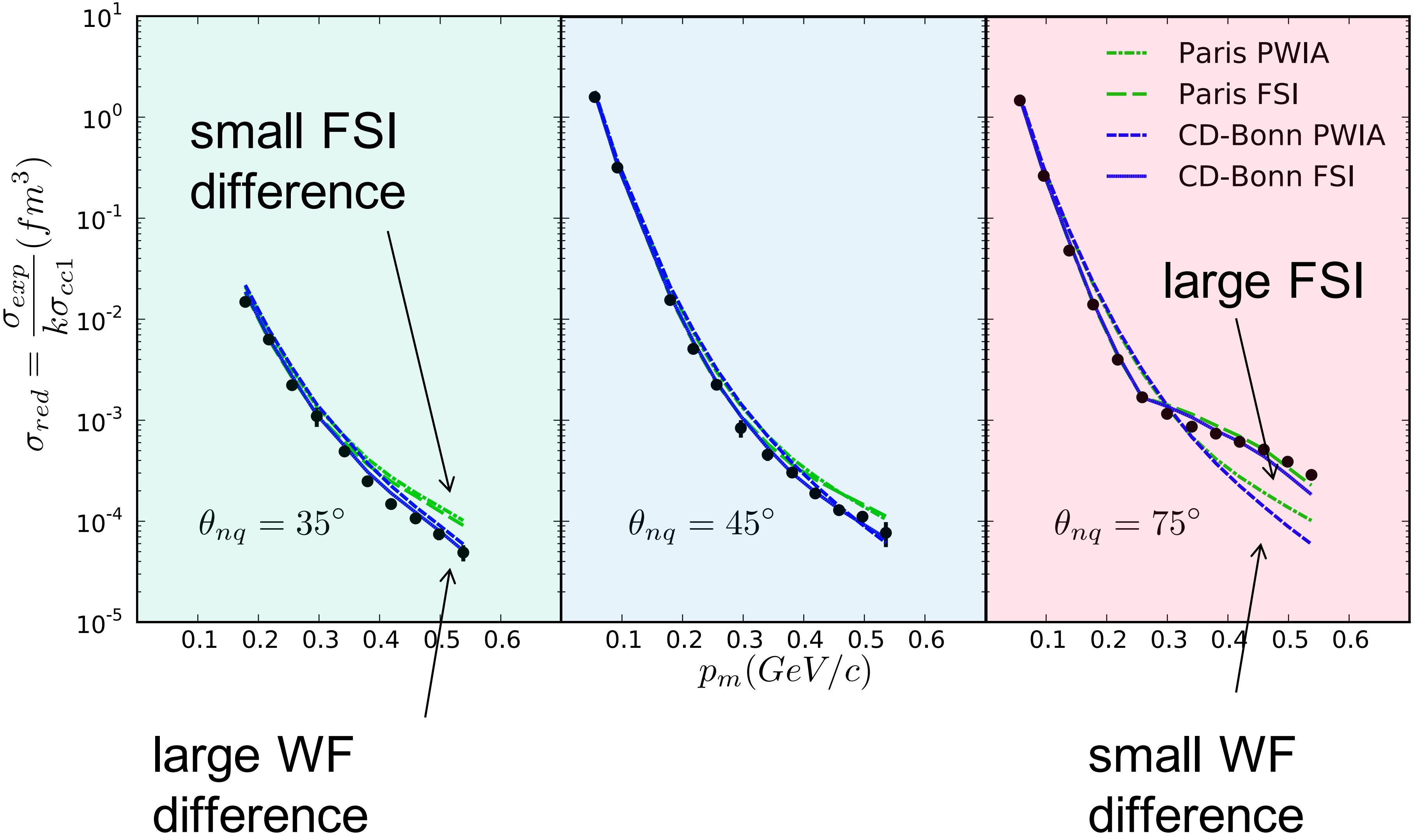
Egyian et al. (CLAS) PRL 98 (2007)



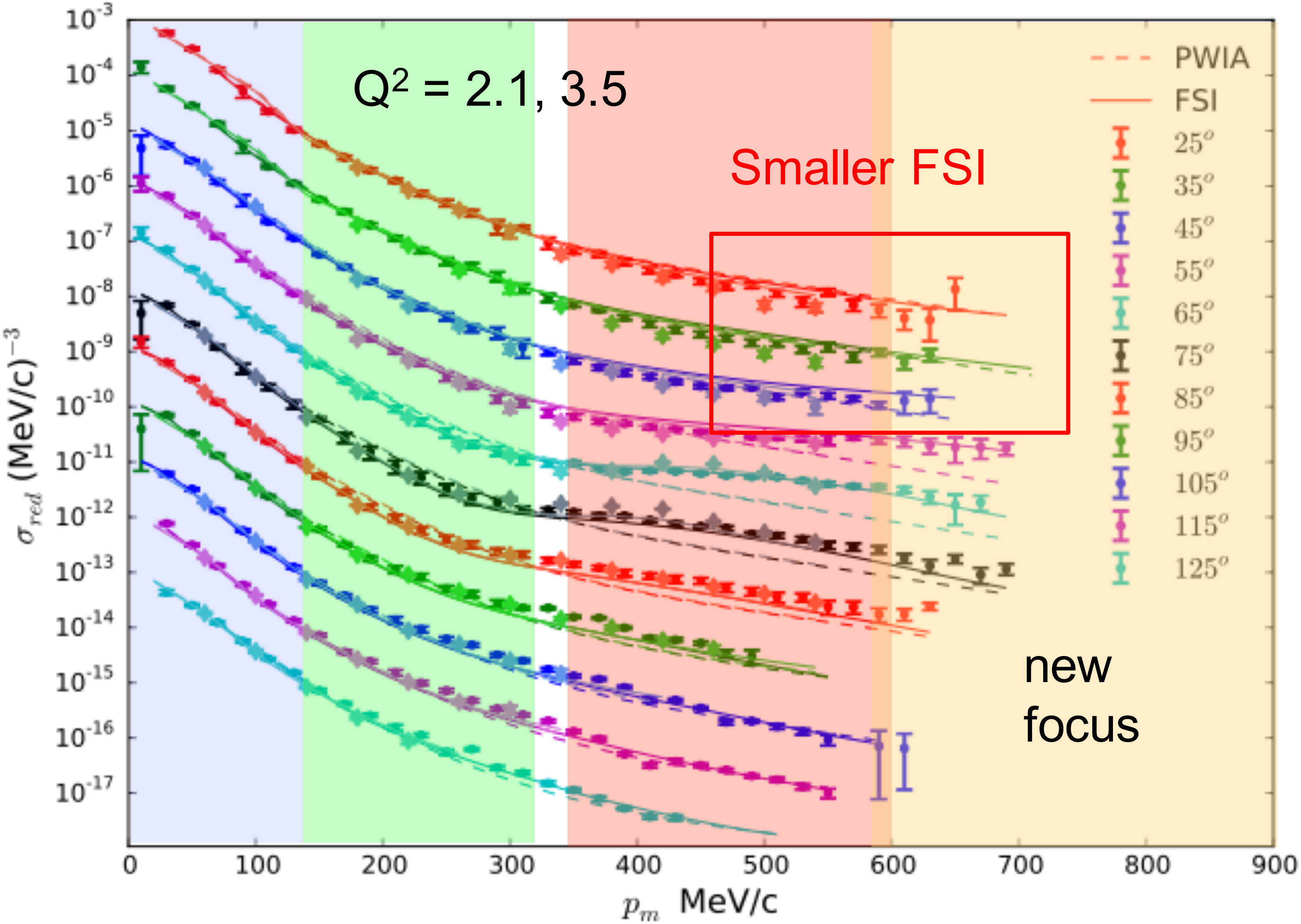
WB et al. PRL 107 (2011) 262501



Data: Egyian et al. (CLAS) PRL 98 (2007)


small FSI
difference
large WF
difference
large FSI
small WF
difference
Paris PWIA
Paris FSI
CD-Bonn PWIA
CD-Bonn FSI
$\sigma_{red} = \frac{\sigma_{exp}}{k\sigma_{cc1}}(fm^3)$
$p_m(GeV/c)$
$\theta_{nq} = 35^\circ$
$\theta_{nq} = 45^\circ$
$\theta_{nq} = 75^\circ$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.1
0.2
0.3
0.4
0.5
0.6

σ_{red} scaled by factors of 10 for display



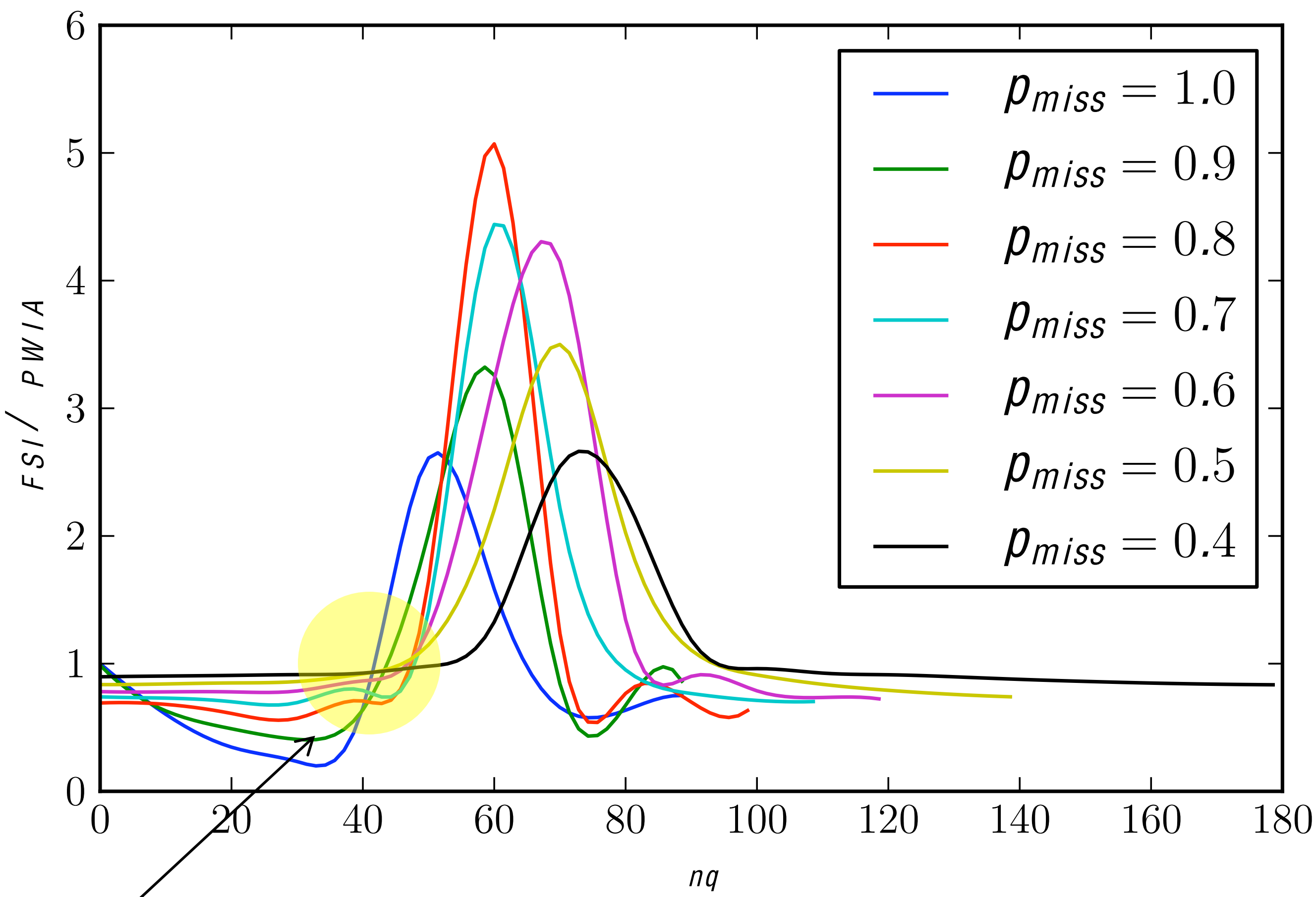
Future Experiment at 12 GeV in Hall C

- 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

  - Beam: 11 GeV, 80μA
  - Electron Detector: SHMS at $p_{cen} = 9.32$ GeV/c
    - $\theta_e = 11.68^o$, $Q^2 = 4.25\ (GeV/c)^2$, $x = 1.35$
  - Proton Detector: HMS $1.96 \leq p_{cen} \leq 2.3$ GeV/c
    - $p_m = 0.5, 0.6, 0.7, 0.8, 0.9, 1.0$ GeV/c
    - Angles: $63.5^o \geq \theta_p \geq 53.1$

  - Target: 15 cm LHD

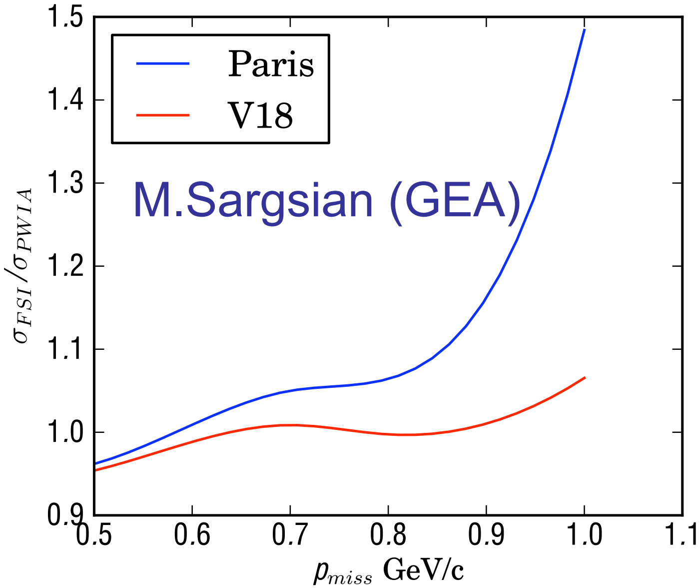
Angular Distributions up to p_m = 1GeV/c

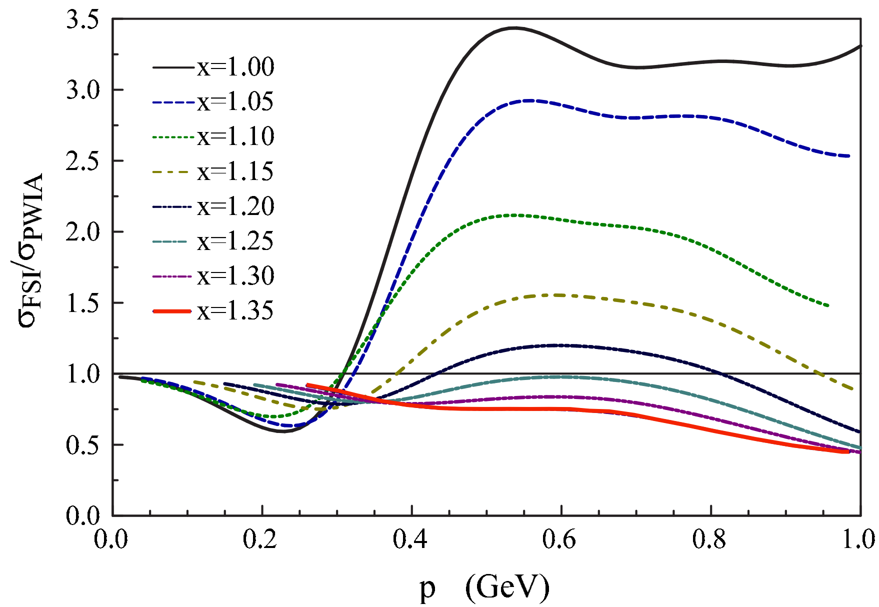


FSI depend weakly on p_m

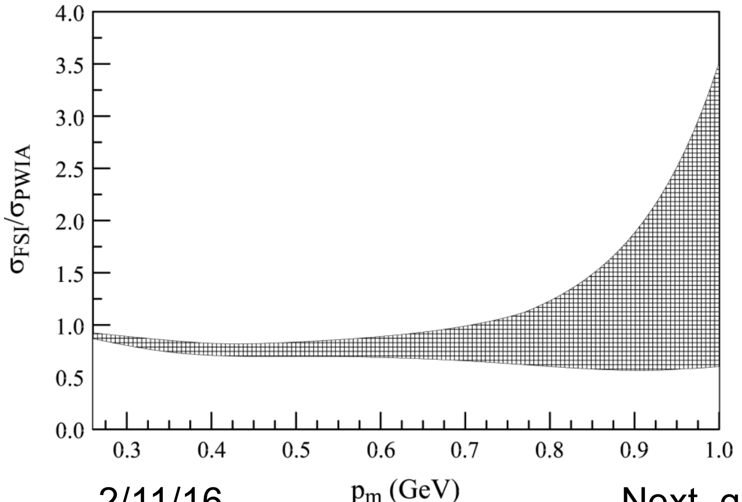
Calculation: M.Sargsian

FSI uncertainties



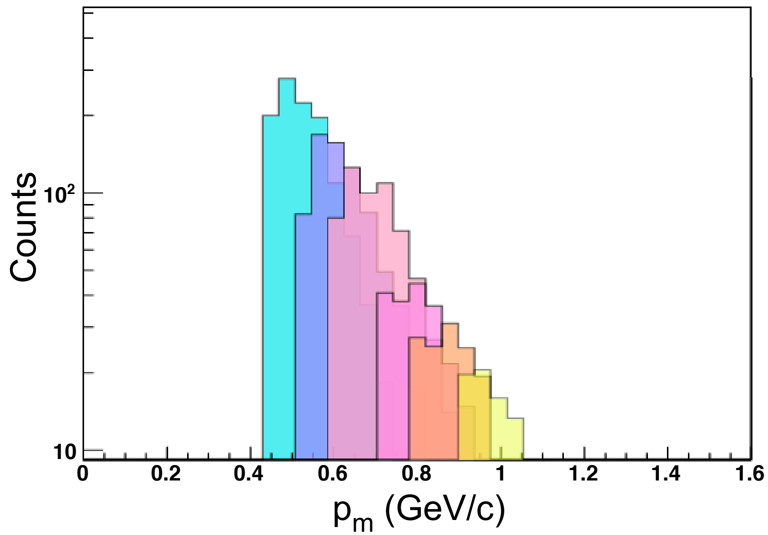


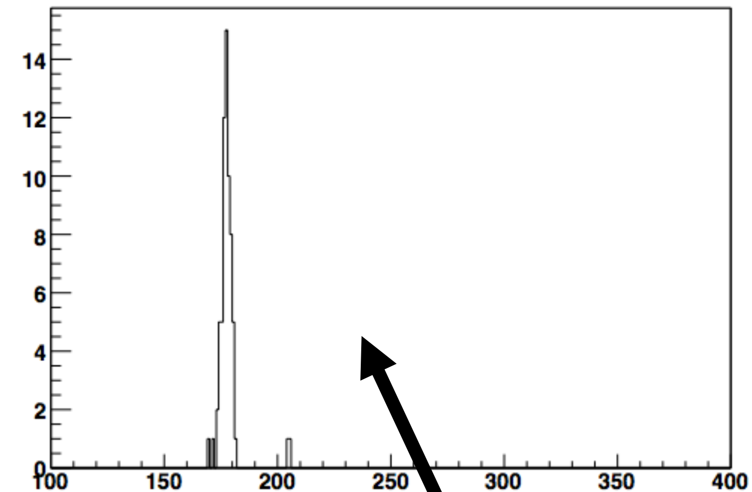
W.P.Ford et al. PRC 90 064006 (2014)

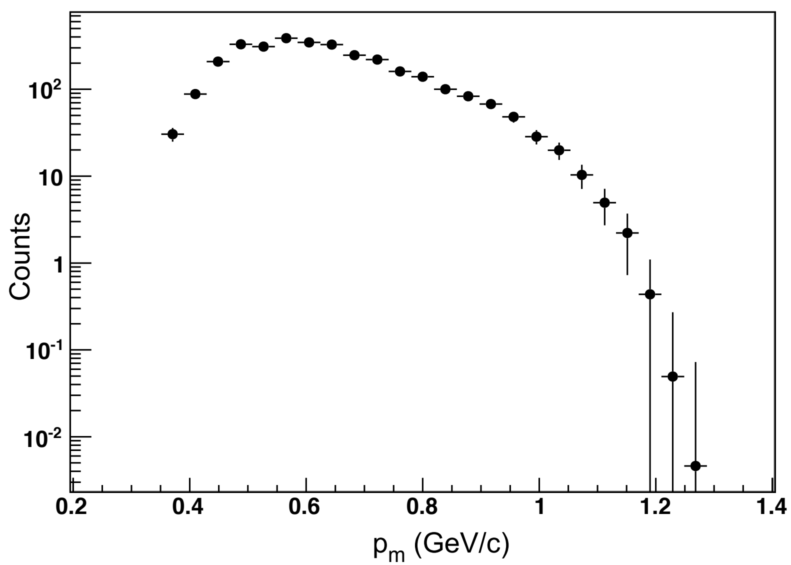


range of possible values of R for all form factor and W.F. used

Rates







Applied Cuts:

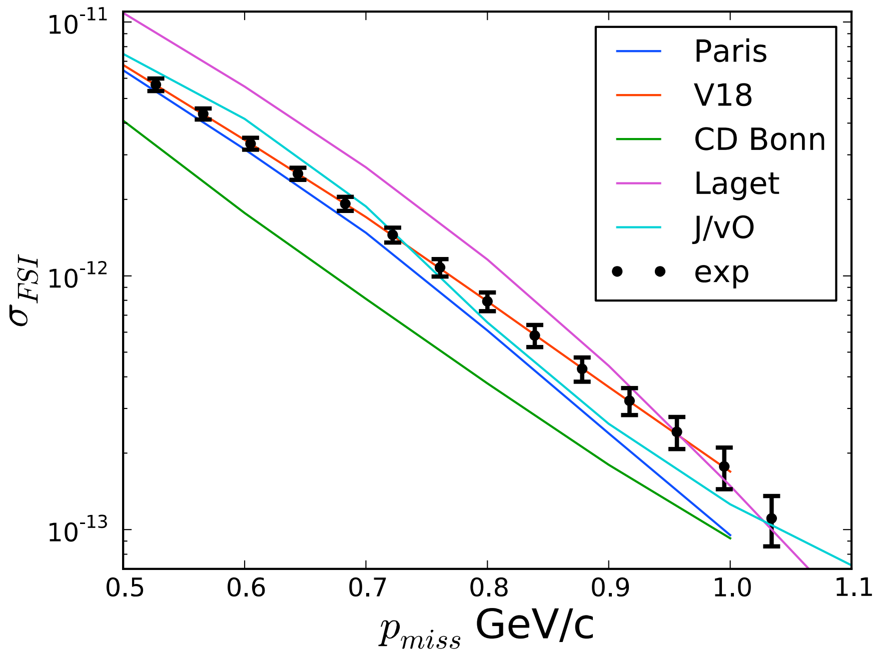
$-0.05 \leq \theta_e \leq 0.05$
$-0.025 \leq \phi_e \leq 0.025$
$-0.08 \leq \Delta p/p \leq 0.04$

$-0.06 \leq \theta_p \leq 0.06$
$-0.035 \leq \phi_p \leq 0.035$
$-0.1 \leq \Delta p/p \leq 0.1$

$1.3 \leq x_{Bj} \leq 1.4$

Previous d(e,e'p) exp.
$Q^2 = 3.5$ (GeV/c)^2
$p_m = 0.5$ GeV/c , I = 90μA
15 cm LD

Expected Results



- ✓ Measured cross sections for p_m up to 1 GeV/c
- ✓ Errors: dominated by statistics: 7% - 20%
- ✓ Estimated systematic error ≈ 5 %
- ✓JLAB uniquely suited for high p_m study
- ✓First data expected Spring 2017

Alternative method: extracting of ρ_{LC}

Relativistic Description of the Deuteron, L.L Frankfurt and M. Strikman, Nuclear Physics **B148** (1979) 107

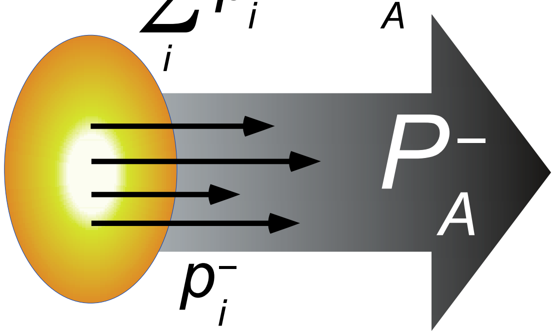
High-Energy Phenomena, Short-Range Nuclear Structure and QCD, L.L Frankfurt and M. Strikman, Physics Reports **76**, (1981) 215

LC momentum $\quad p^- = E - p_z$

LC momentum fraction $\quad \alpha = A\frac{p_i^-}{P_A^-}$

α is frame independent for boosts along the z-axis

$$\sum_i p_i^- = P_A^-$$



analogous to “x” for quark distributions

Spectator (neutron) momentum fraction from experiment $\alpha_s = 2\frac{E_s - p_s^z}{M_D}$

remember in lab: $P_D^- = M_D$ and

Proton momentum fraction $\alpha = 2 - \alpha_s$

Small α large p_z

$\alpha_s \to 2 \quad p_{pz} \to \infty$

Advantages of working on LC:

- at high Q^2, FSI is mostly transverse α is approx. conserved by FSI (M.Sargsian Int. J. Mod. Phys. E10 2001)
- $\rho(\alpha)$ is very little affected by re-scattering
- at high energies: $N\bar{N}$ become important but
- unimportant on LC (photon energy is 0)
- $\rho(\alpha)$ necessary for interpretation of DIS data of nuclei

LC PWIA cross section

$$\frac{d\sigma}{dE'_e d\Omega_e d\Omega_p} = K\sigma_{eN}^{LC}(\alpha, p_t)\rho(\alpha, p_t)$$

Nuclear analog to parton distribution

$$f_N(\alpha) = \rho(\alpha) = \int \frac{\rho(\alpha, p_t)}{\alpha} d^2 p_t$$

Normalization:

$$\int \rho(\alpha, p_t)\frac{d\alpha}{\alpha} 2\pi p_t dp_t = 1$$

LC Momentum sum rule:

$$\int \alpha\rho(\alpha, p_t)\frac{d\alpha}{\alpha} 2\pi p_t dp_t = 1$$

Problem: how do FSI affect $f_N(\alpha)$

Experimental $\rho(\alpha, p_t)$ distributions

$$\rho_{EXP}(\alpha, p_T) = \frac{\sigma_{EXP}(\alpha, p_T)}{K \sigma_{eN}^{LC}(\alpha, p_T)}$$

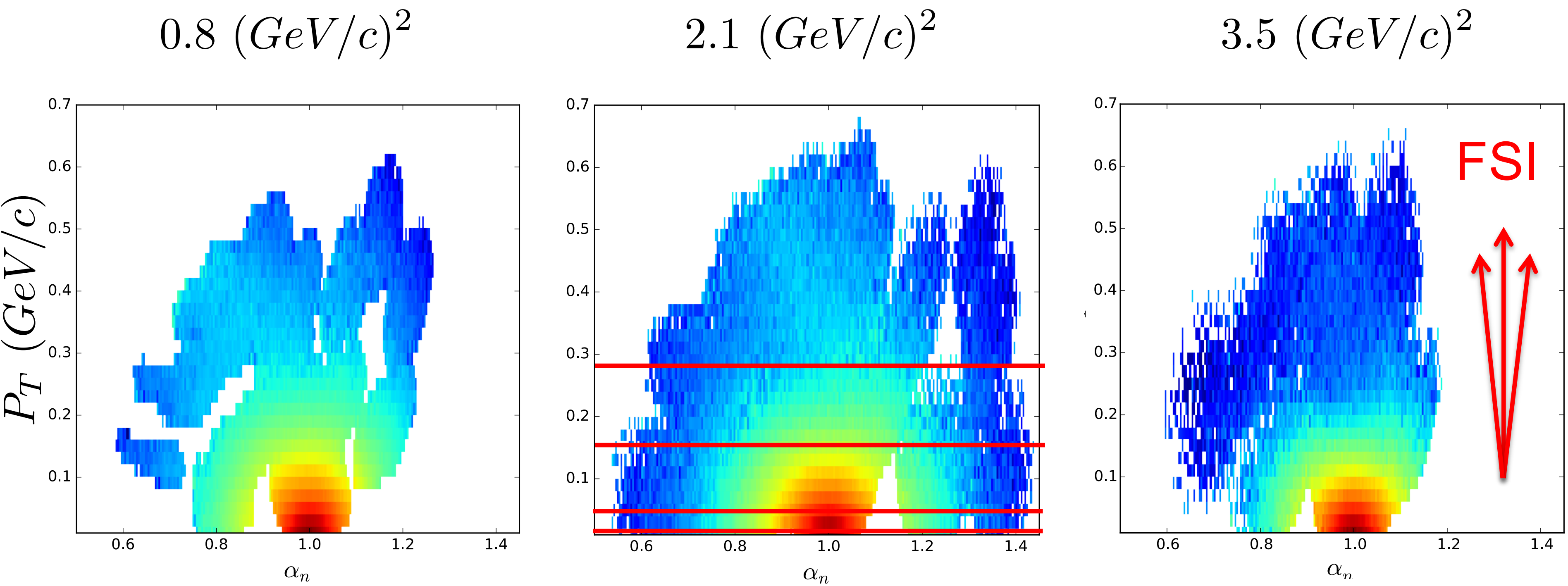
Hall A

- Q^2 = 0.8, 2.1 and 3.5 $(GeV/c)^2$: constant for each set
- p_{miss} = 0.2, 0.4 and 0.5 GeV/c : angular distribution
- $20^\circ \leq \theta_{nq} \leq 140^\circ$
- angular range for each p_{miss} dependent on kinematics

Boeglin et al. PRL 107 (2011) 262501

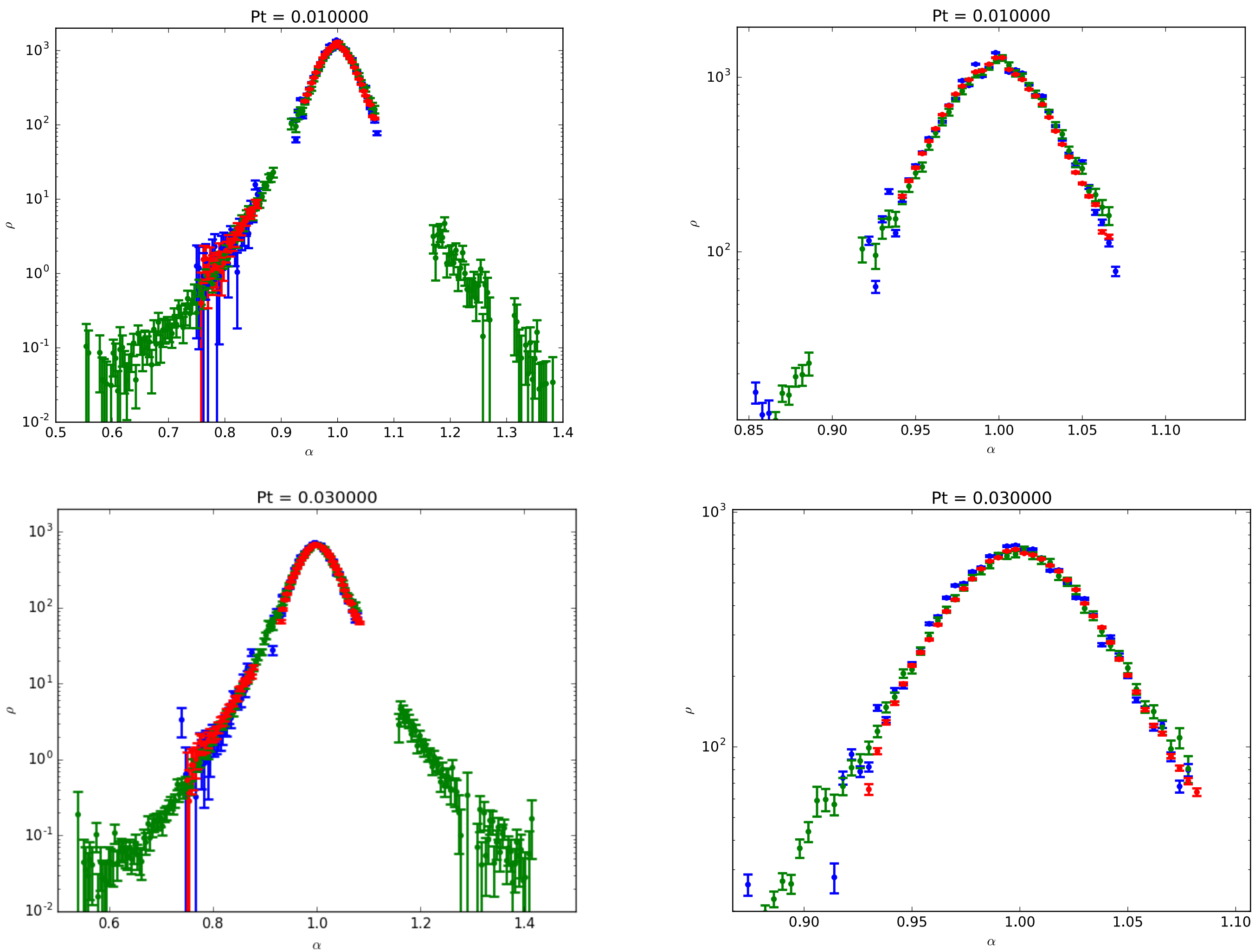
- Missing information due to finite spectrometer acceptance
- Interpolation necessary for missing data
- Various methods possible
- 0.8 and 2.1 $(GeV/c)^2$ data normalized to 3.5 $(GeV/c)^2$ at low p_m (0.04 - 0.12 GeV/c)
- Large FSI at small α and large P_T for small Q^2

First Results (Preliminary)

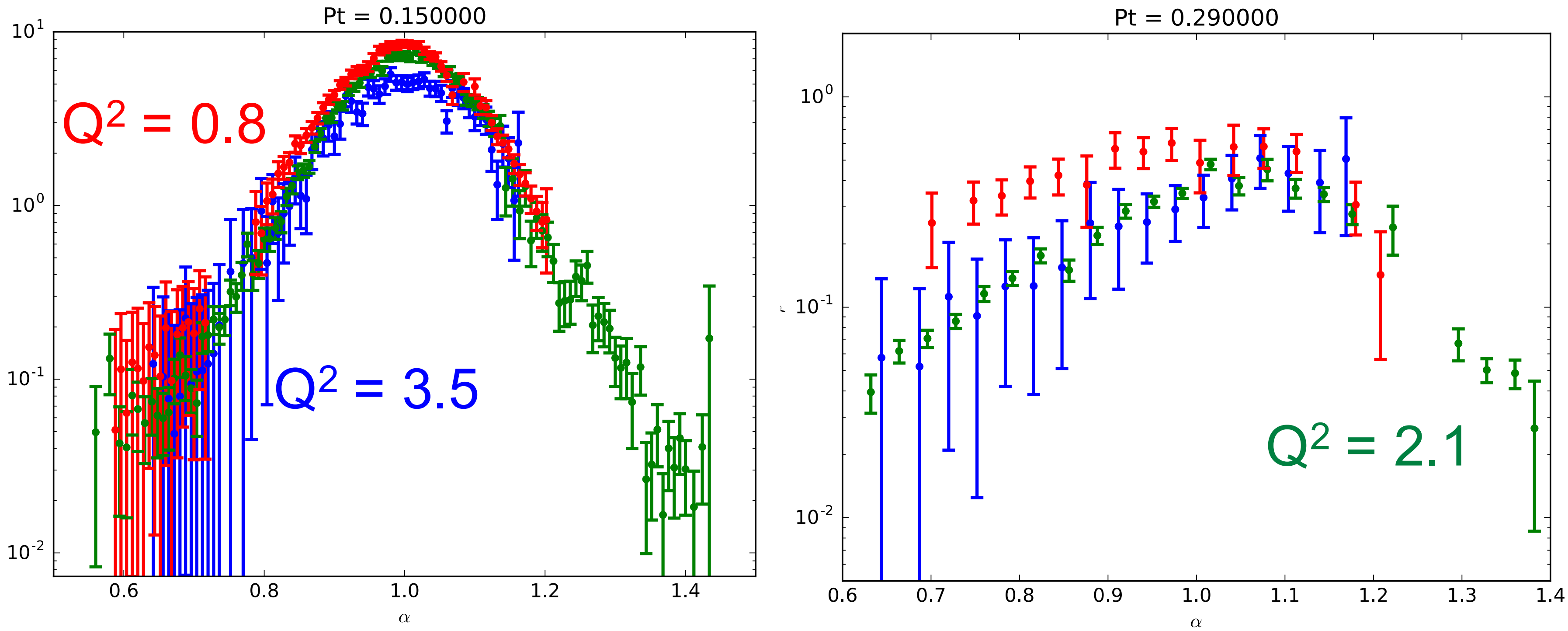


- Systematic error ~7%
- Original experiment design to measure angular distributions

Small P_T

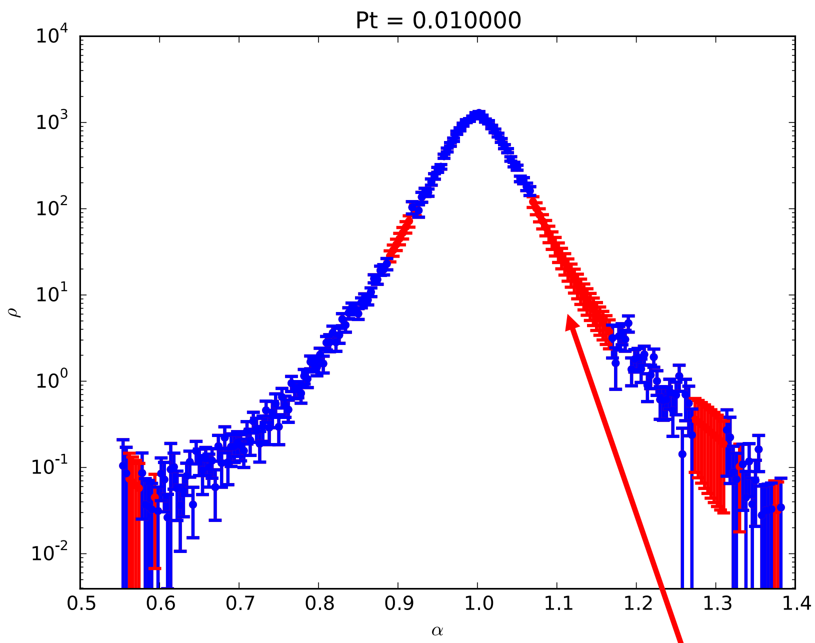


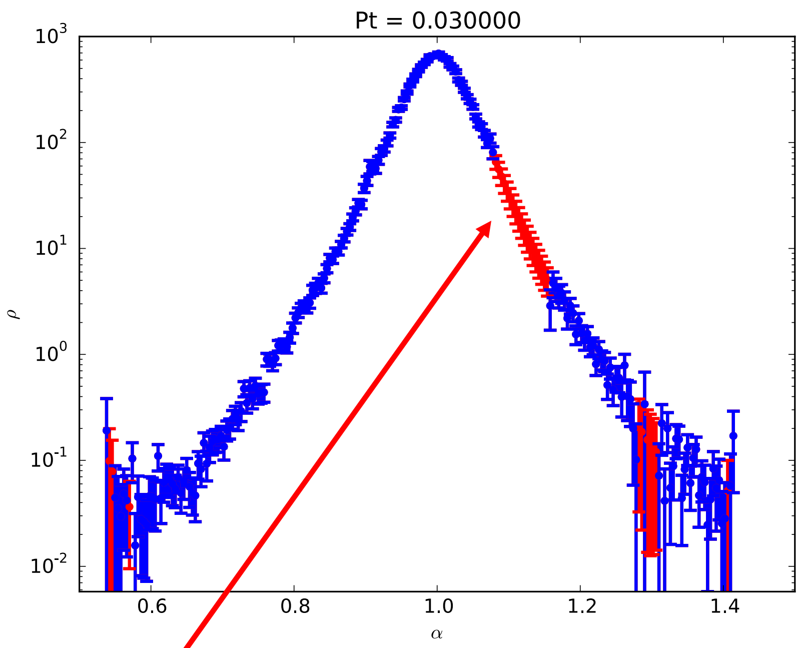
Larger P_T



- $Q^2 = 0.8$ does not follow higher Q^2 behavior
- Qualitatively different (Large FSI etc.)

Missing Data

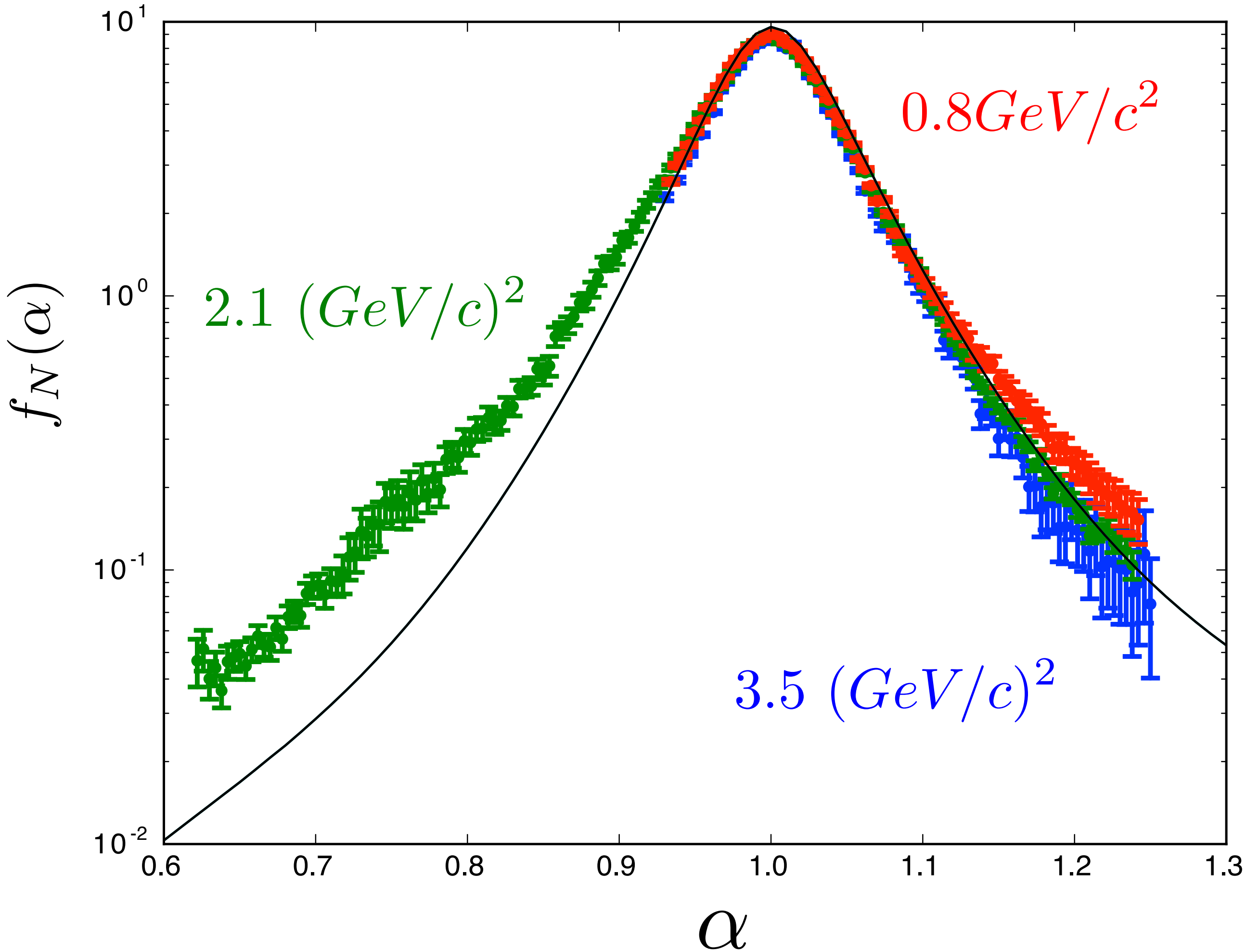




Missing data

- Filled with fitting procedure
- Experimental data are not changed

$$f_N(\alpha) = \rho(\alpha) = \int \frac{\rho(\alpha, p_t)}{\alpha} 2\pi p_t dp_t$$



$$I = \int f_N(\alpha) d\alpha$$

$$\frac{I_{exp}}{I_{PWIA}} \approx 1.3$$

$$\frac{I_{exp}}{I_{PWIA}} \approx 1.$$

$$\frac{I_{exp}}{I_{PWIA}} \approx 0.9$$

$$\Delta I / I \approx 0.1$$

Summary

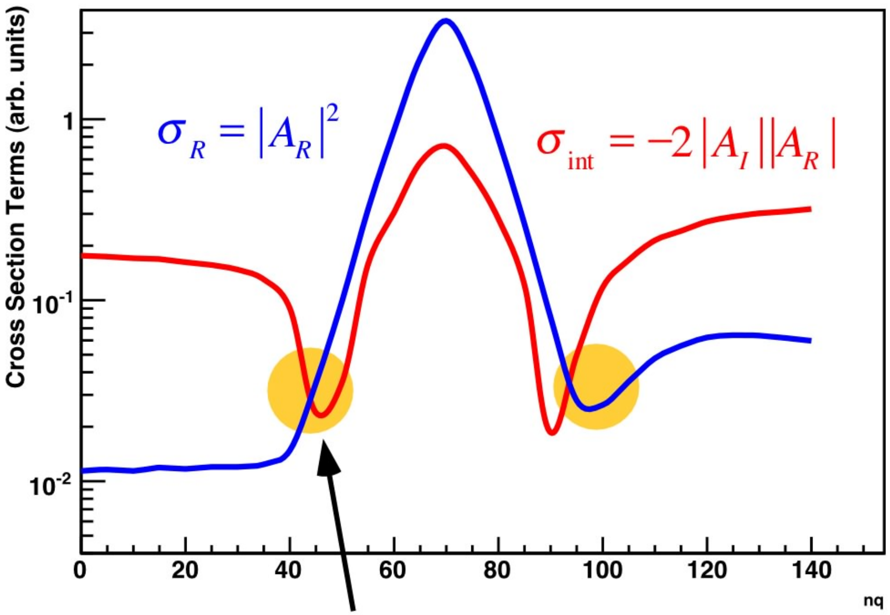
- High Q^2 d(e,e' p)n can be described using generalized eikonal approximation for $Q^2 > 2$ GeV/c
- Minimal FSI expected even at high p_m
- Angular distribution should be measured at pm ~ 0.8 GeV/c for verification
- New experiment at 11 GeV determines d(ee'p)n cross section up to p_m = 1GeV/c
- First experimental extraction of $\rho(\alpha)$ from Q^2 = 2.1 and 3.5 $(GeV/c)^2$ data
- Various interpolation methods need to be assessed
- Sum rules satisfied within 10%
- Consequence for parton distributions functions need further analysis
- Experimental determination requires large kinematic coverage in α and p_T

Support

This work was supported in part by the Department of Energy under Contracts No. DE-AC02-06CH11357 and DE-SC0013620

FSI Reduction

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



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

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 $k_t \approx 0.5(GeV/c)$

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

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

Interpolating missing data with modified model fit for Q^2 = 3.5 (GeV/c)^2

Fit function: $\rho(\alpha) = \gamma \rho_{LC}(\alpha^*) e^{-(\delta_{s,l}(\alpha - A))^2}$

$$\alpha^* = 1 + \beta(\alpha - A)$$

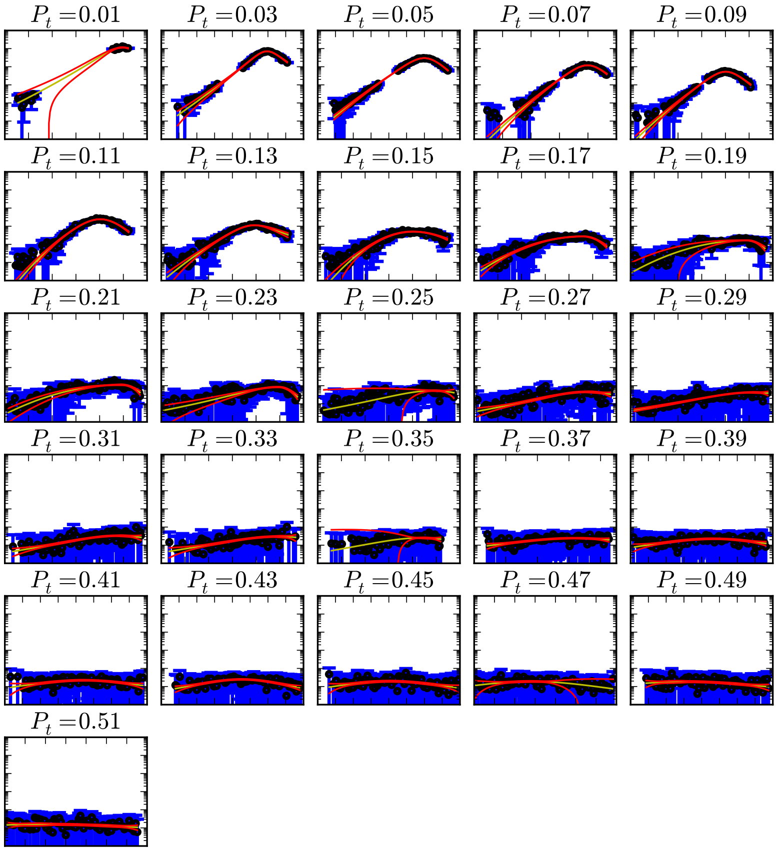
Parameters: $\alpha, \beta, \gamma, \delta_{s,l}, A$

use δ_s for $\alpha < A$

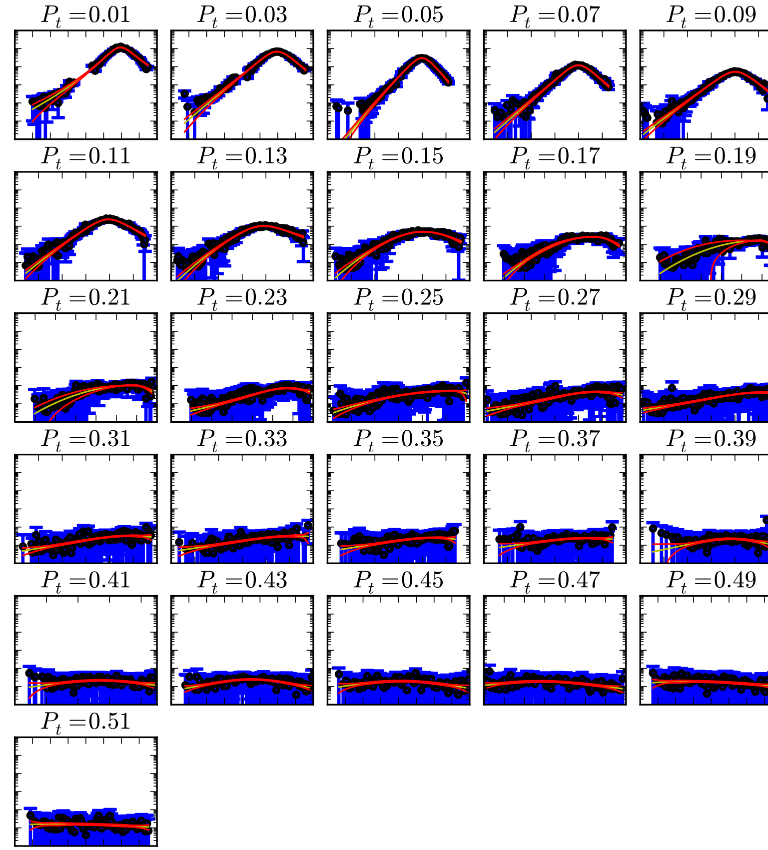
use δ_l for $\alpha > A$

Calculated using model: $\rho_{LC}(\alpha)$
(e.g. Paris WF)

20% cut


$P_t = 0.01$
$P_t = 0.03$
$P_t = 0.05$
$P_t = 0.07$
$P_t = 0.09$
$P_t = 0.11$
$P_t = 0.13$
$P_t = 0.15$
$P_t = 0.17$
$P_t = 0.19$
$P_t = 0.21$
$P_t = 0.23$
$P_t = 0.25$
$P_t = 0.27$
$P_t = 0.29$
$P_t = 0.31$
$P_t = 0.33$
$P_t = 0.35$
$P_t = 0.37$
$P_t = 0.39$
$P_t = 0.41$
$P_t = 0.43$
$P_t = 0.45$
$P_t = 0.47$
$P_t = 0.49$
$P_t = 0.51$

2.5% cut


$P_t = 0.01$
$P_t = 0.03$
$P_t = 0.05$
$P_t = 0.07$
$P_t = 0.09$
$P_t = 0.11$
$P_t = 0.13$
$P_t = 0.15$
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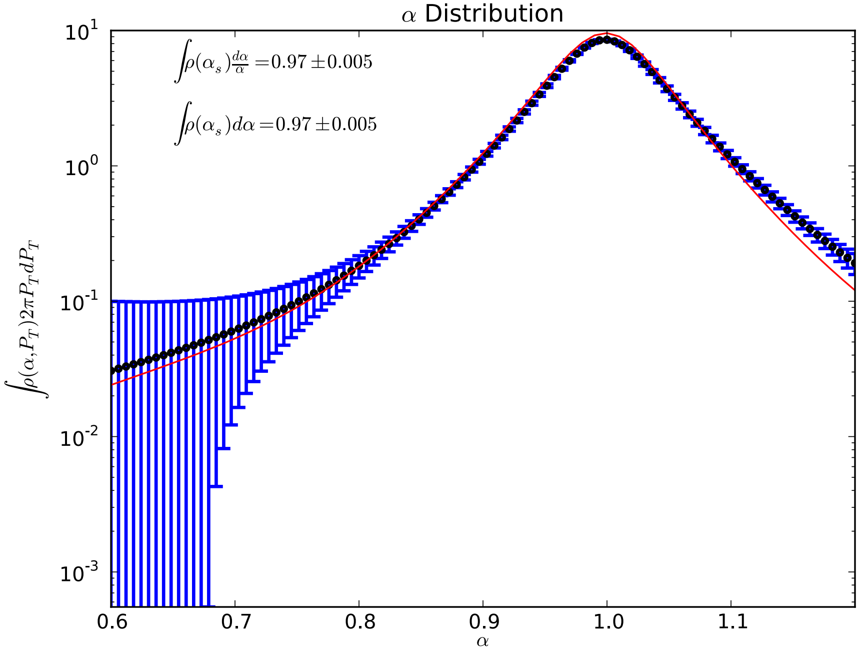
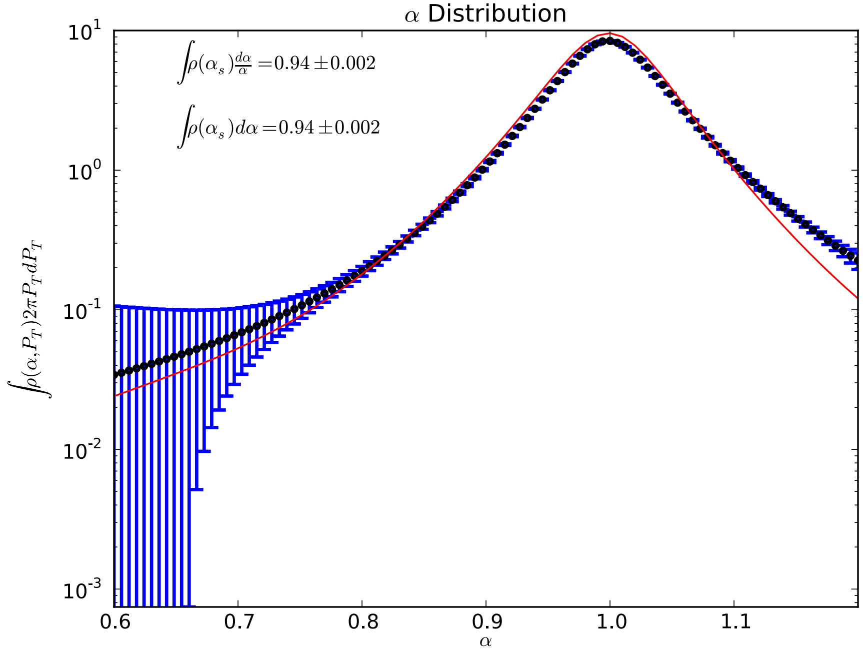
$P_t = 0.43$
$P_t = 0.45$
$P_t = 0.47$
$P_t = 0.49$
$P_t = 0.51$

ρ(α) using fit interpolation

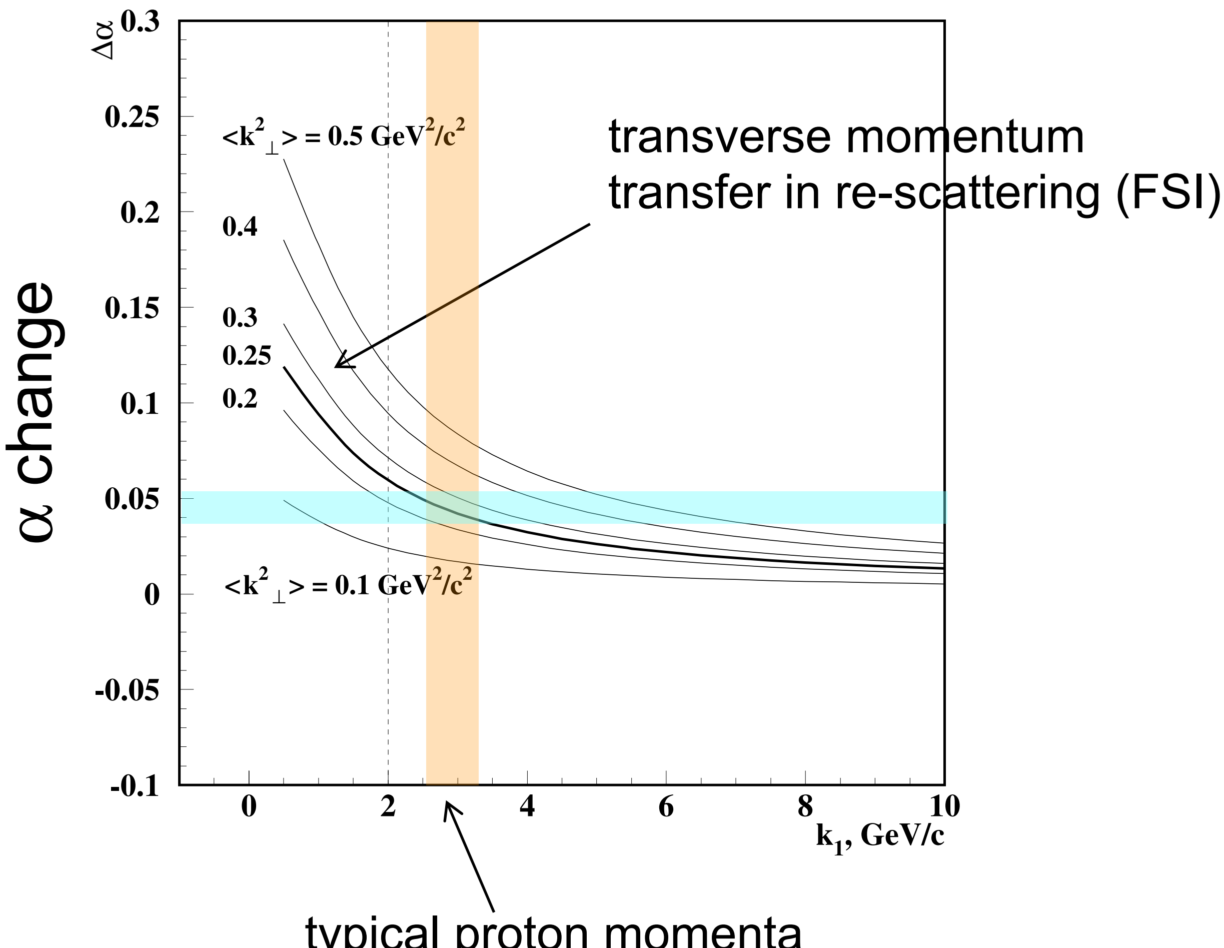




20% cut

2.5% cut

α conservation as function of nucleon momenta



LC momentum

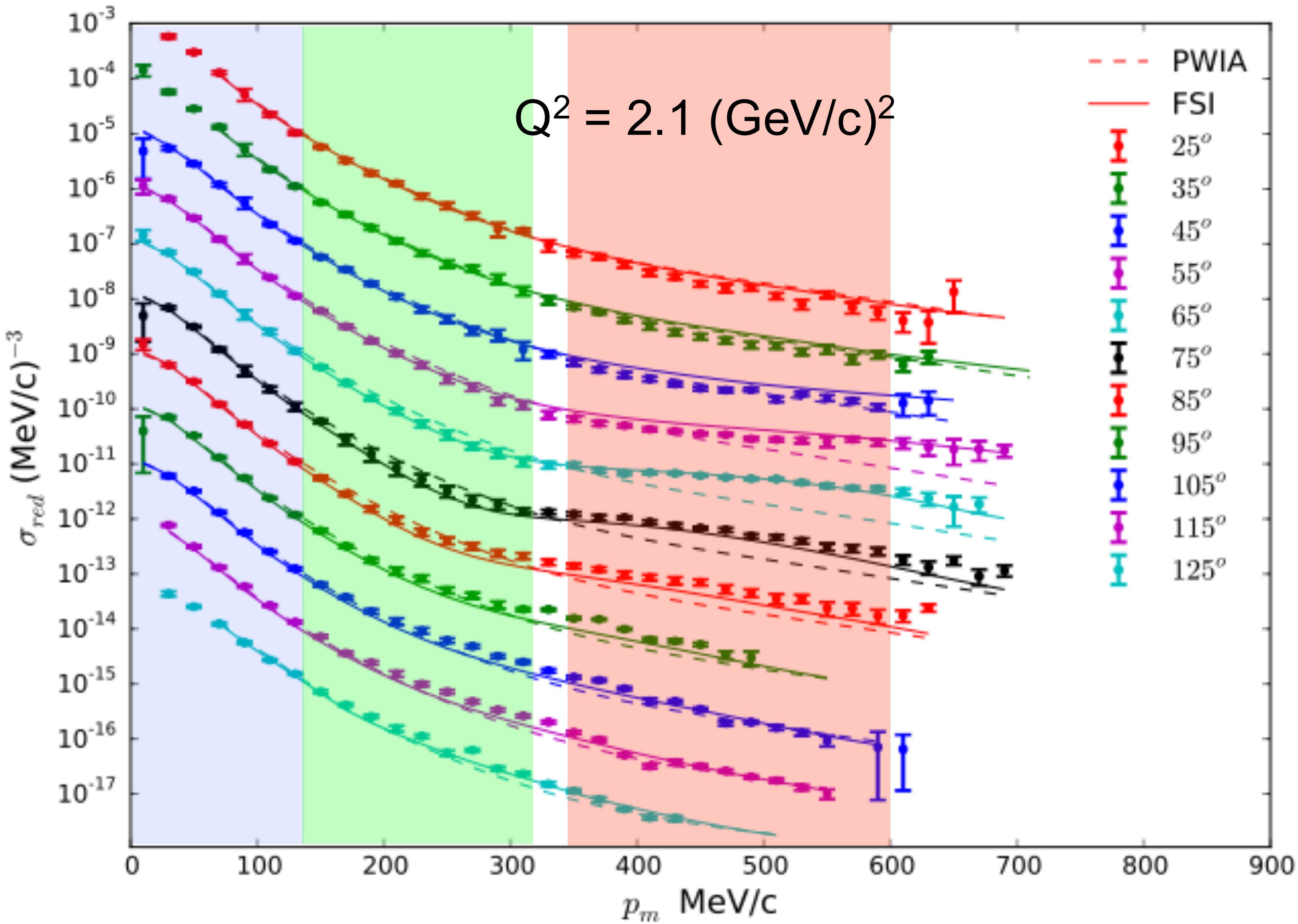
LC momentum distribution $\rho(\alpha, p_t) = \dfrac{|\Psi_d(k)|^2 E_k}{2-\alpha}$

$$k = \sqrt{\frac{M_N^2 + p_t^2}{\alpha_s(2-\alpha_s)} - M_N^2} \qquad E_k = \sqrt{M_n^2 + p_t^2}$$

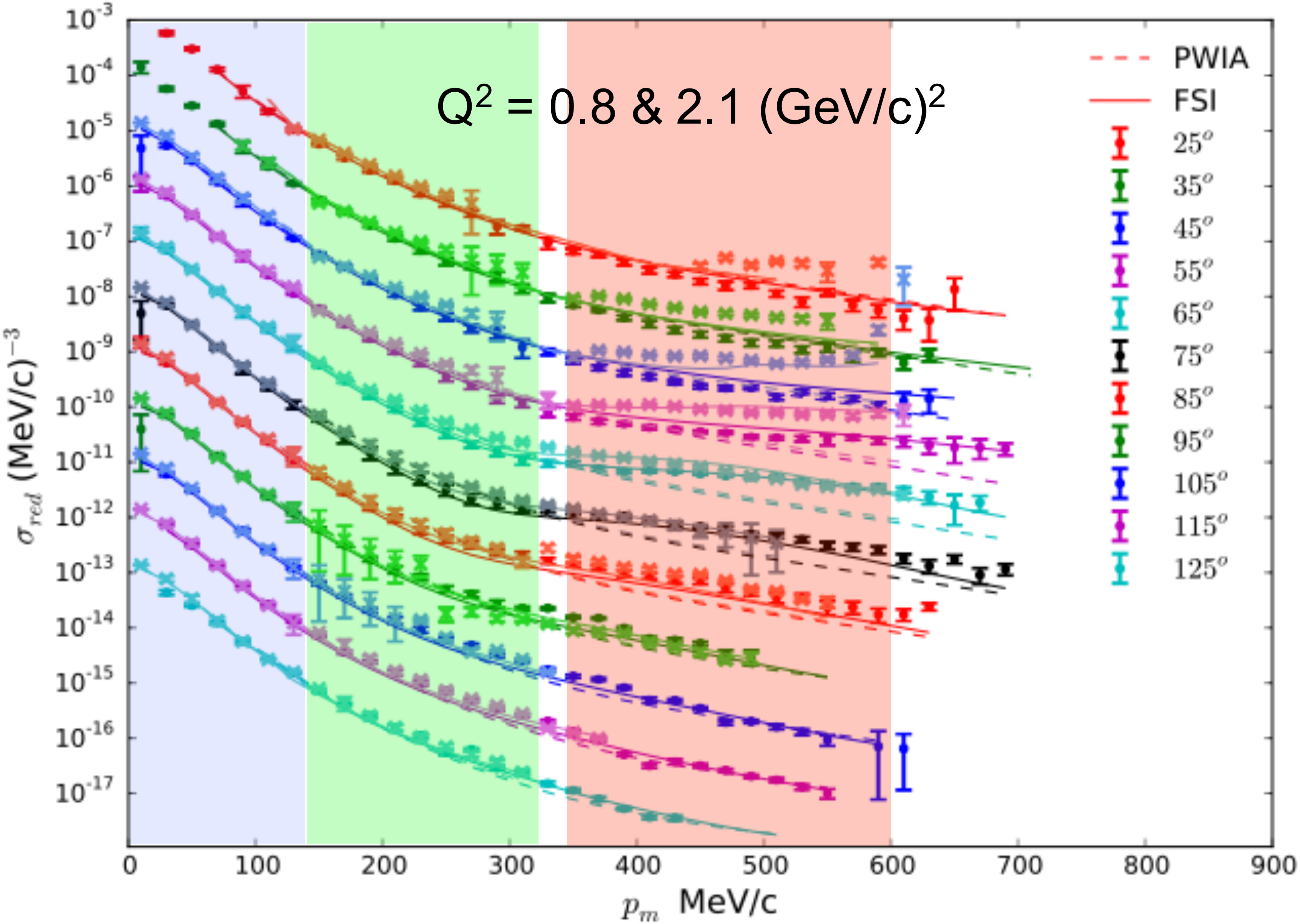
k relative nucleon momentum in *np* system on the light cone

Normalization: $\displaystyle\int \rho(\alpha, p_t)\frac{d\alpha}{\alpha} 2\pi p_t dp_t = 1$

LC Momentum sum rule $\displaystyle\int \alpha\rho(\alpha, p_t)\frac{d\alpha}{\alpha} 2\pi p_t dp_t = 1$



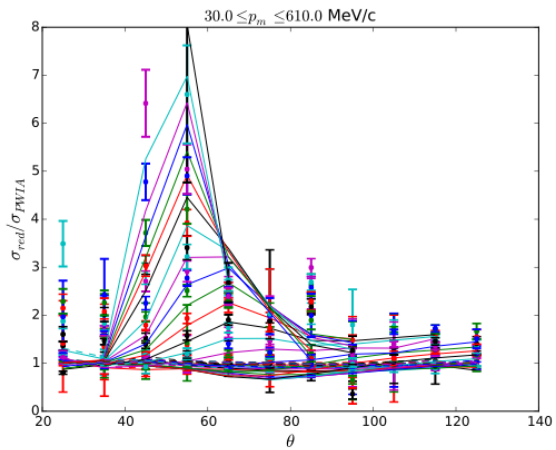
PWIA
FSI
25°
35°
45°
55°
65°
75°
85°
95°
105°
115°
125°
Q² = 2.1 (GeV/c)²
σ_red (MeV/c)^-3
p_m MeV/c



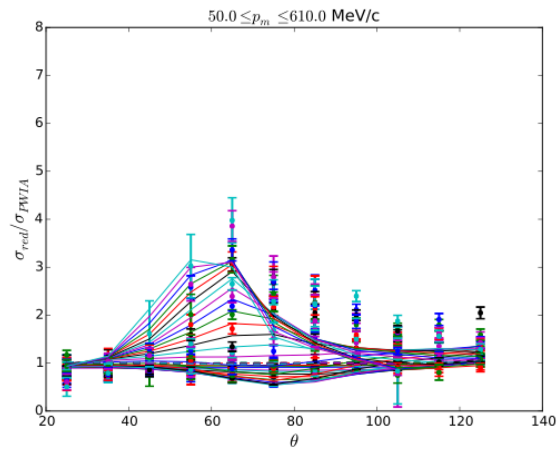
Q² = 0.8 & 2.1 (GeV/c)²
PWIA
FSI
25°
35°
45°
55°
65°
75°
85°
95°
105°
115°
125°
σ_red (MeV/c)^-3
p_m MeV/c

Angular Distributions

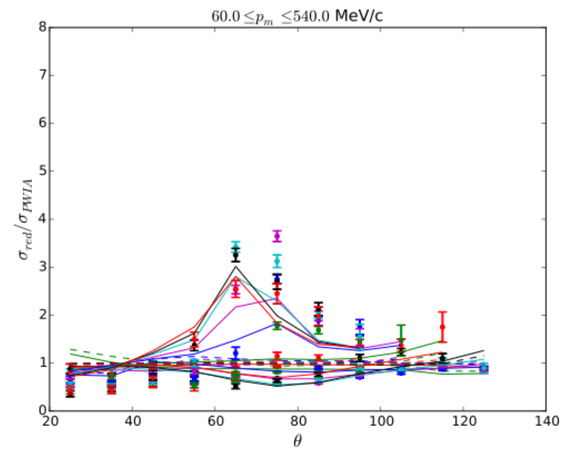
$Q^2 = 0.8$



$Q^2 = 2.1$



$Q^2 = 3.5$



large FSI over wide angular range

small FSI at small angles

small FSI at small angles

Eikonal regime seems to be reached