Probing the deuteron at extremely large internal momenta

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- Introduction
- History and previous Results
- Angular distributions for fixed p_m
- Missing momentum dependences for fixed neutron angle
- New Hall C Results
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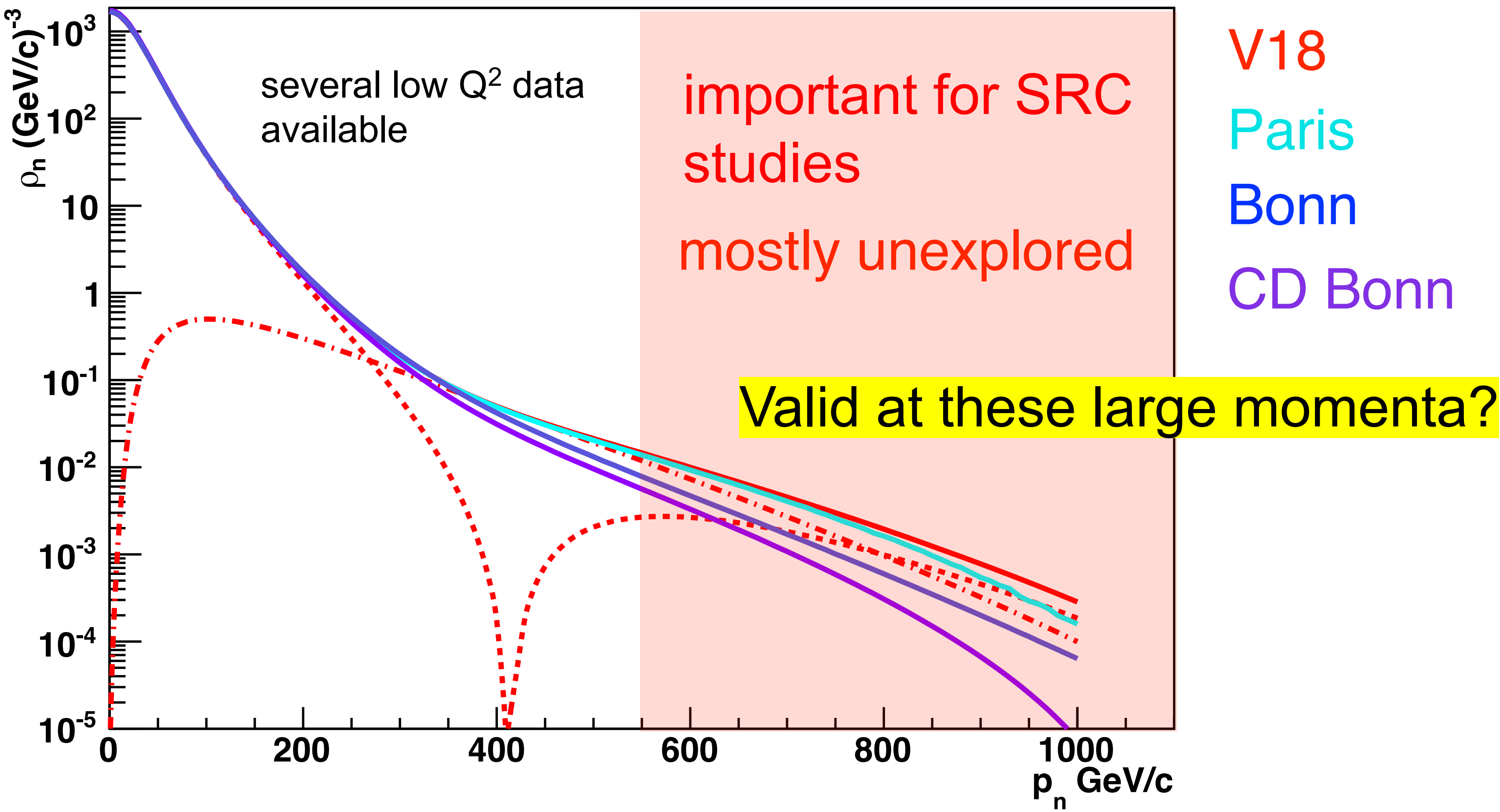
- Inelastic Channels
- Summary

Introduction: Role of the Deuteron

- Key system to investigate the (repulsive) core of the NN interaction.
- Basis for SRC (structure) studies
- Prime nucleus to test NN models
- Structure needs to be understood in detail at all length scales

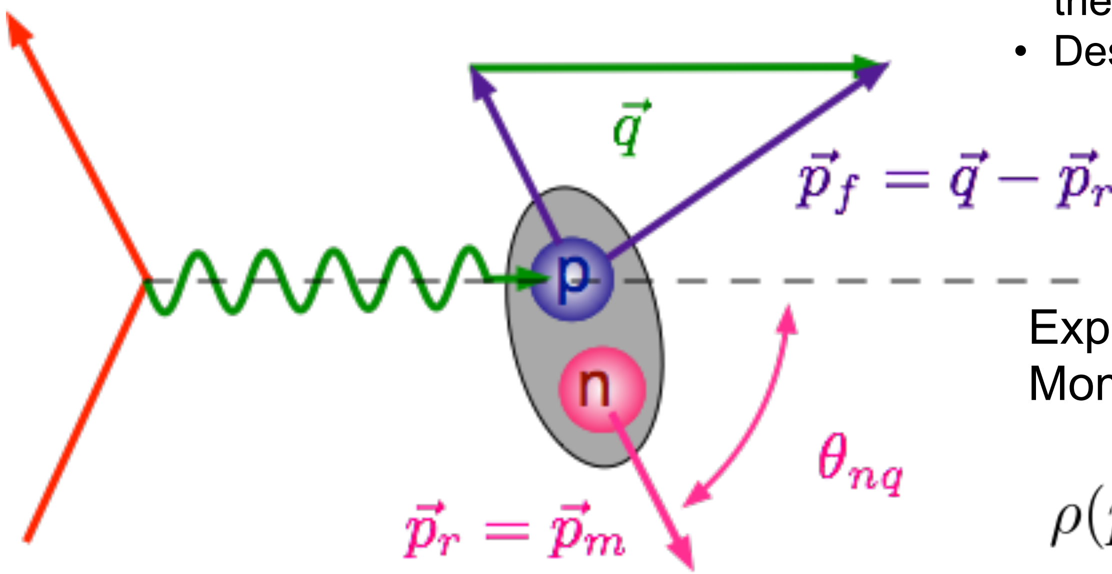
Introduction: Momentum Distribution

virtually no experimental d(e,ep)n data exist for p_m > 0.5 GeV/c without large contributions of FSI, MEC and IC



Introduction: 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

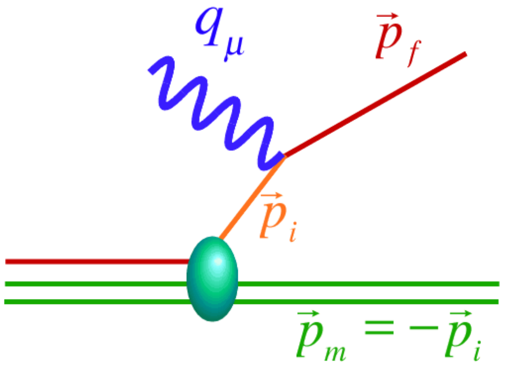
Experimental Momentum distributions:

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

also called reduced cross sections

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

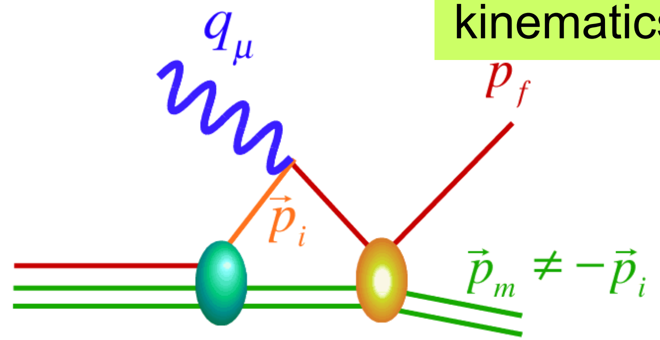
PWIA



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

FSI

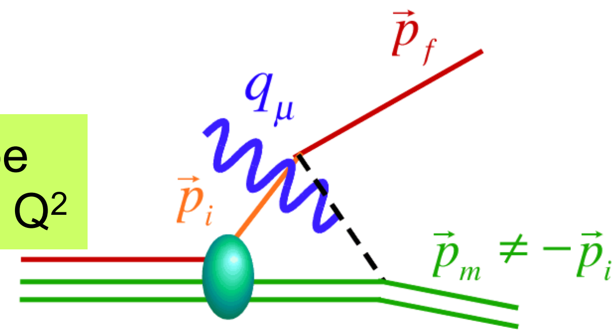
reduced at certain kinematics ?



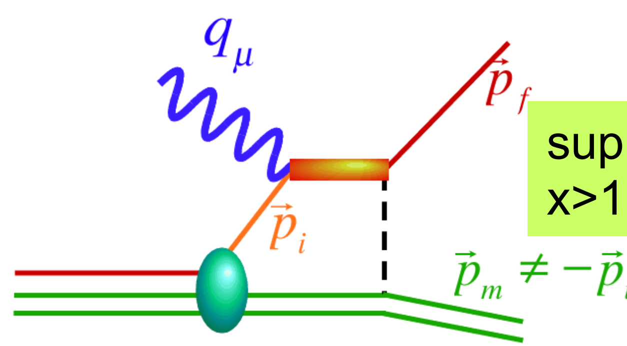
$$\frac{d\sigma}{d\omega d\Omega_e d\Omega_N} = k\sigma_{eN} D(E_m, p_f, p_m)$$

MEC

expected to be small at large Q^2

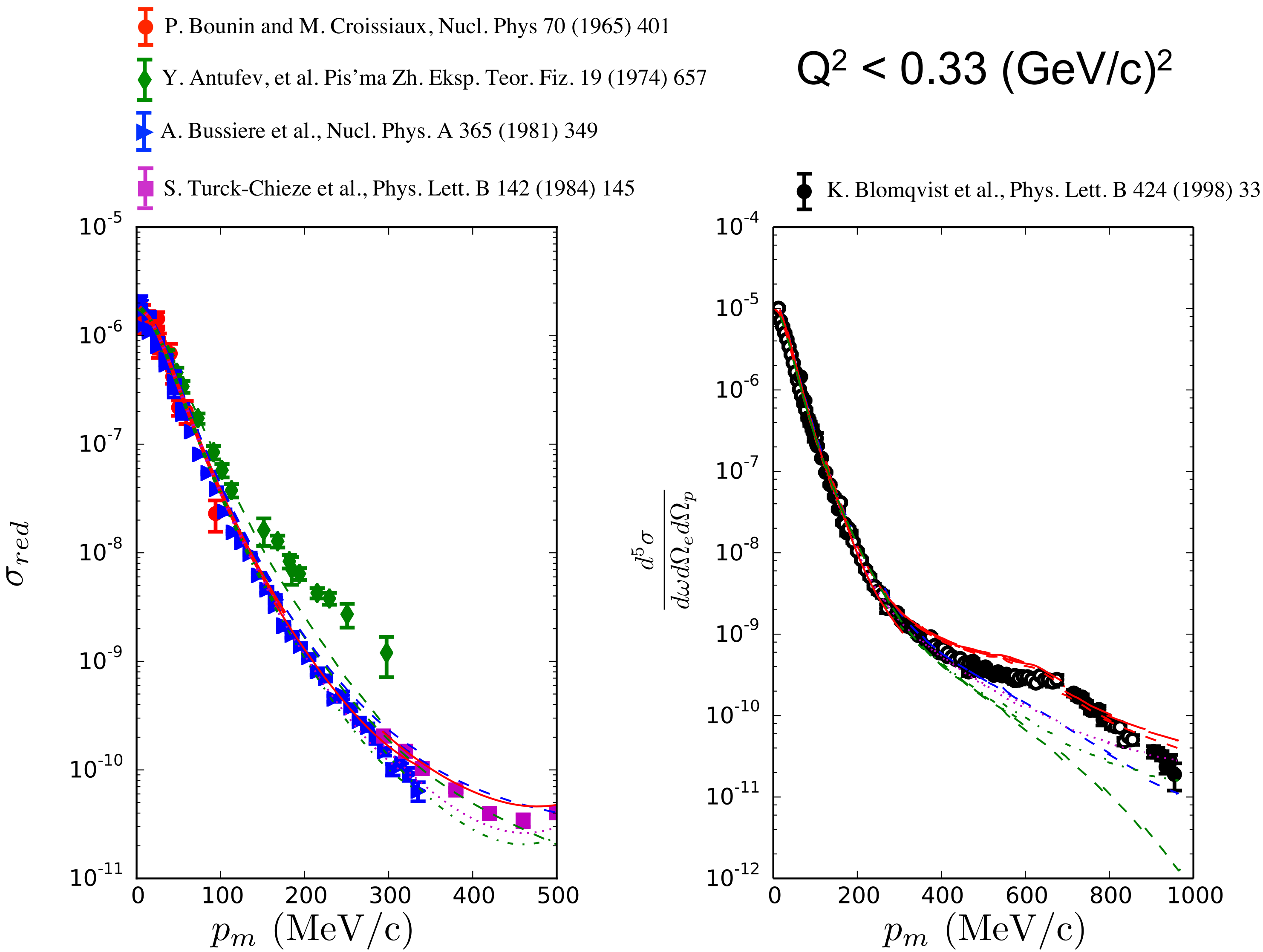


IC

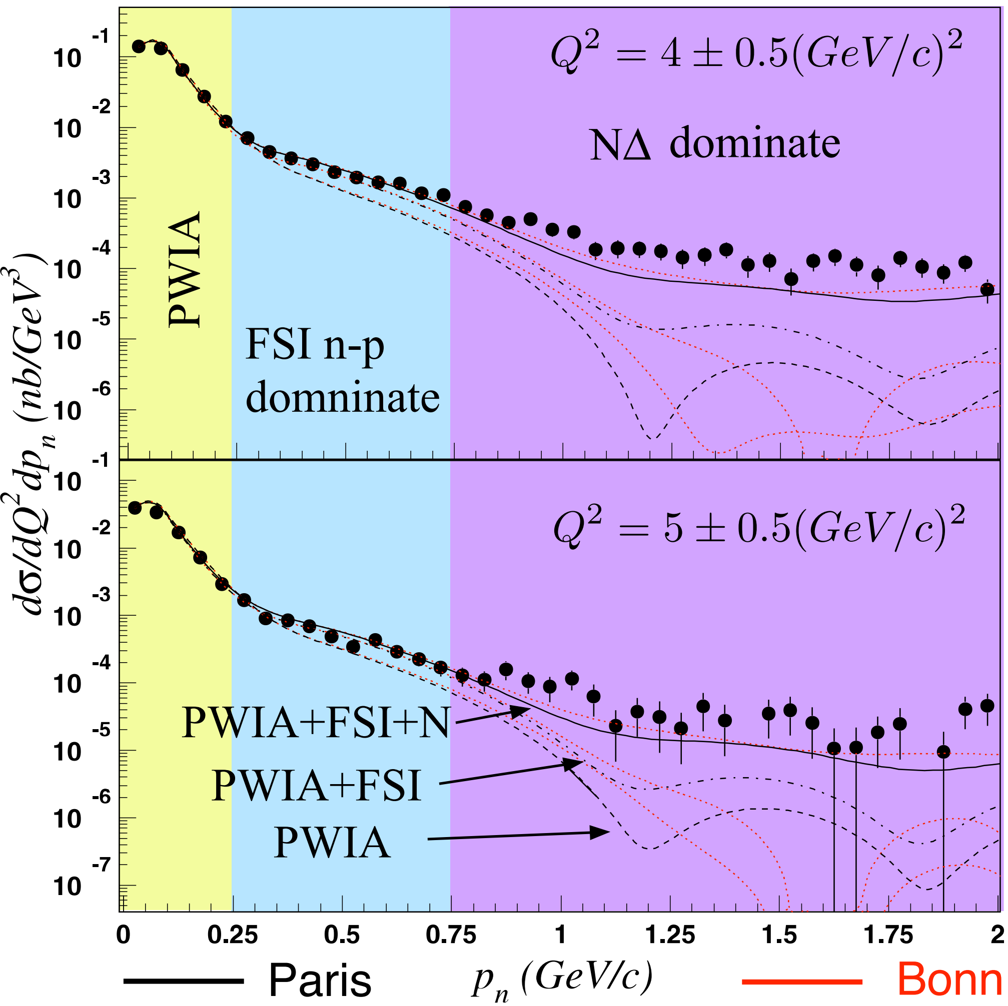


supressed for x>1

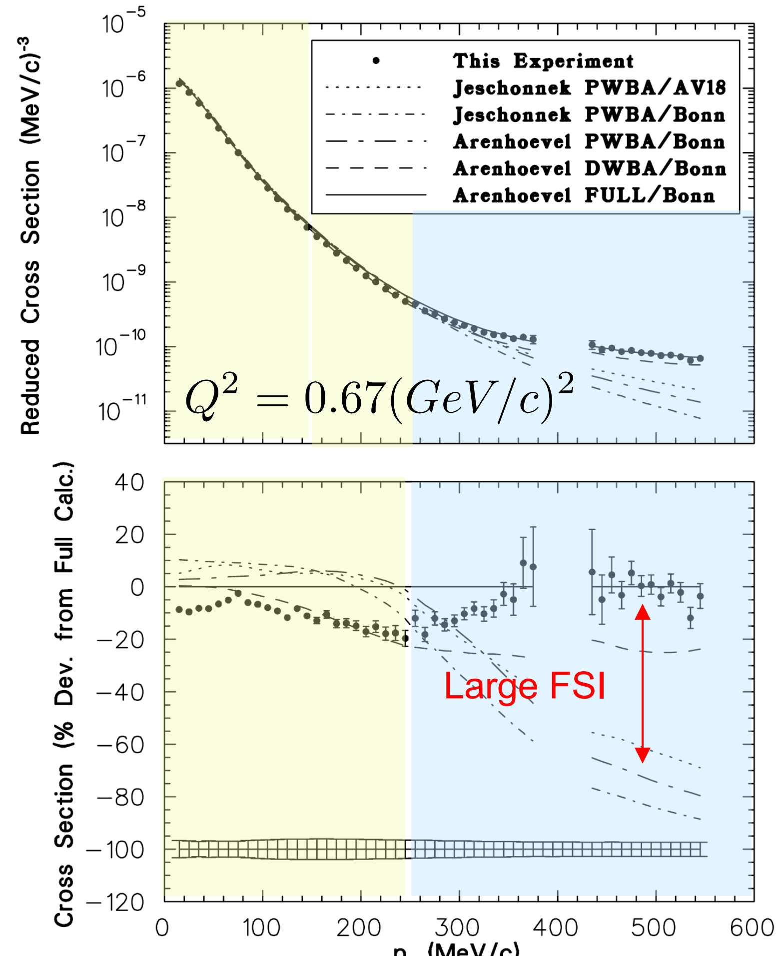
History of Missing Momentum Dependences



CLAS Egyian et al. PRL 98 (2007)



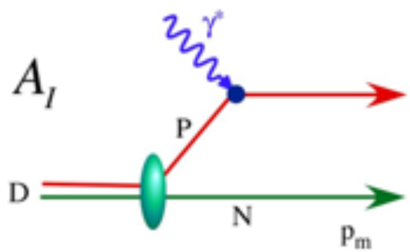
Hall A Ulmer et al. PRL89 (2002) 062301-1



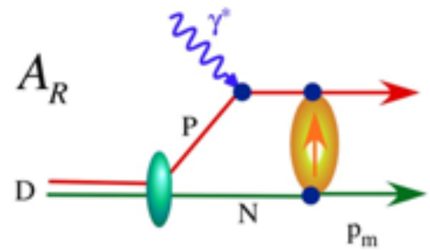
Cross sections integrated over full CLAS acceptance, all recoil angles and wide range of kinematic settings

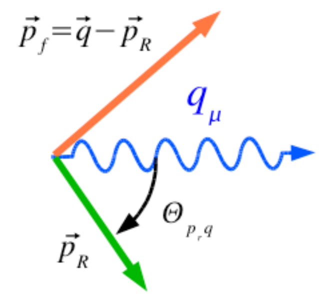
At high Q² FSI as Nucleon Re-Scattering

IA Amplitude (real):



Rescattering Amplitude
(at high energy mostly imaginary):



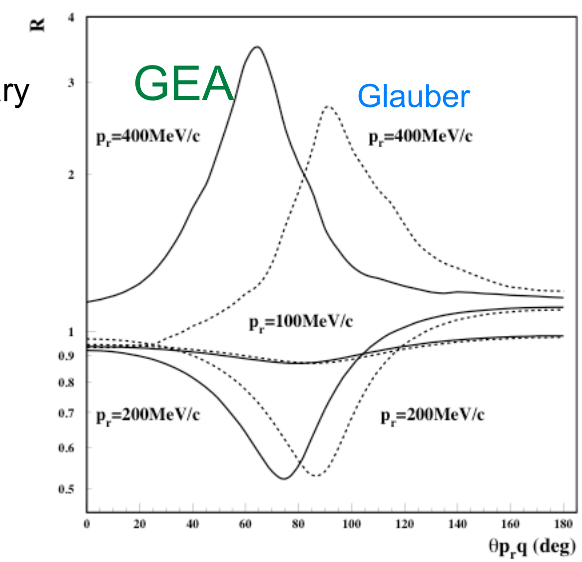


TotalScattering Amplitude: $A = A_I + iA_R$ $\quad A_R \approx i\,|A_R|$ mostly imaginary

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

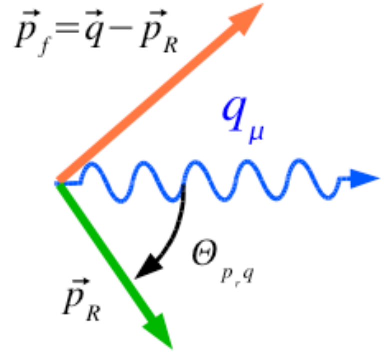


Glauber: spectator nucleons frozen

GEA: spectator nucleon moving

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

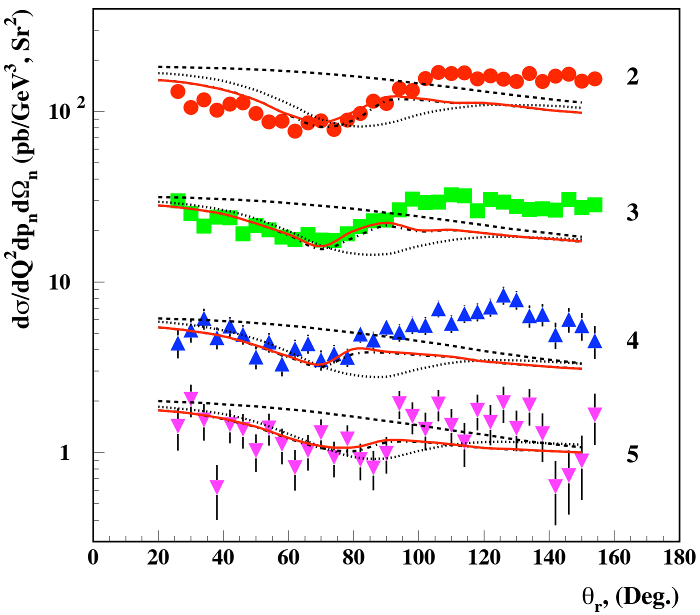
CLAS



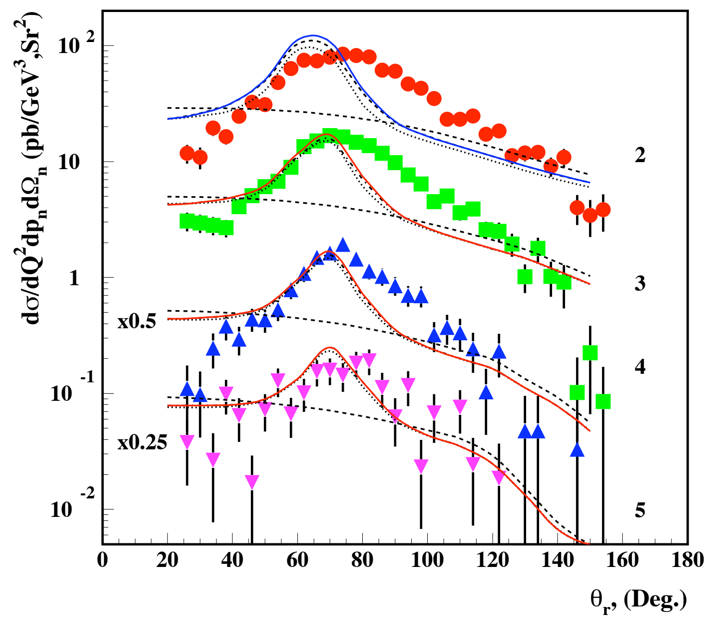
Data: Egyian et al. (CLAS) PRL 98 (2007)

Calculation M. Sargsian

$p_m = 0.25 \pm .05$ GeV/c



$p_m = 0.5 \pm 0.1$ GeV/c



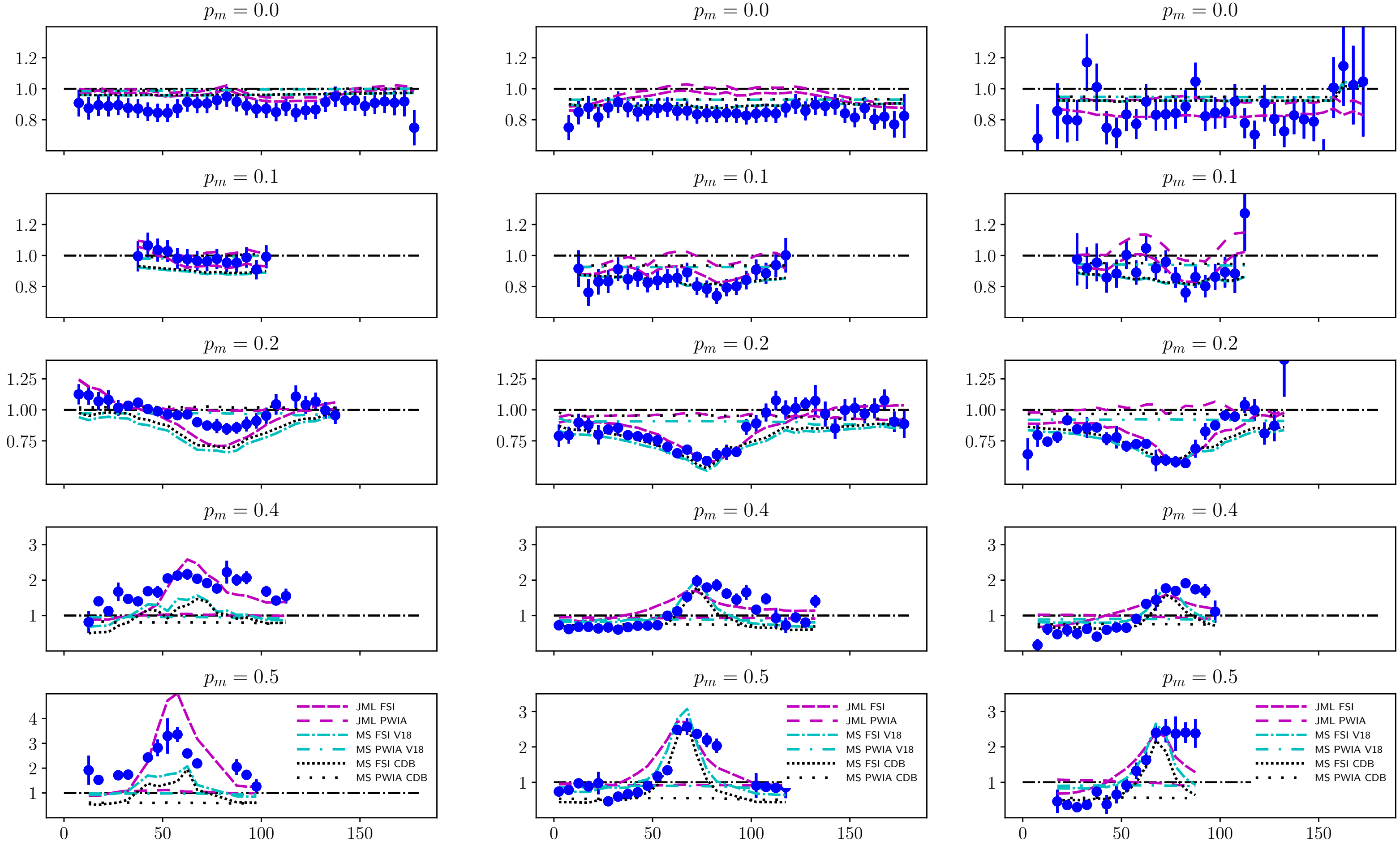
M.Sargsian, PRC **82**, 014612 (2010)

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

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

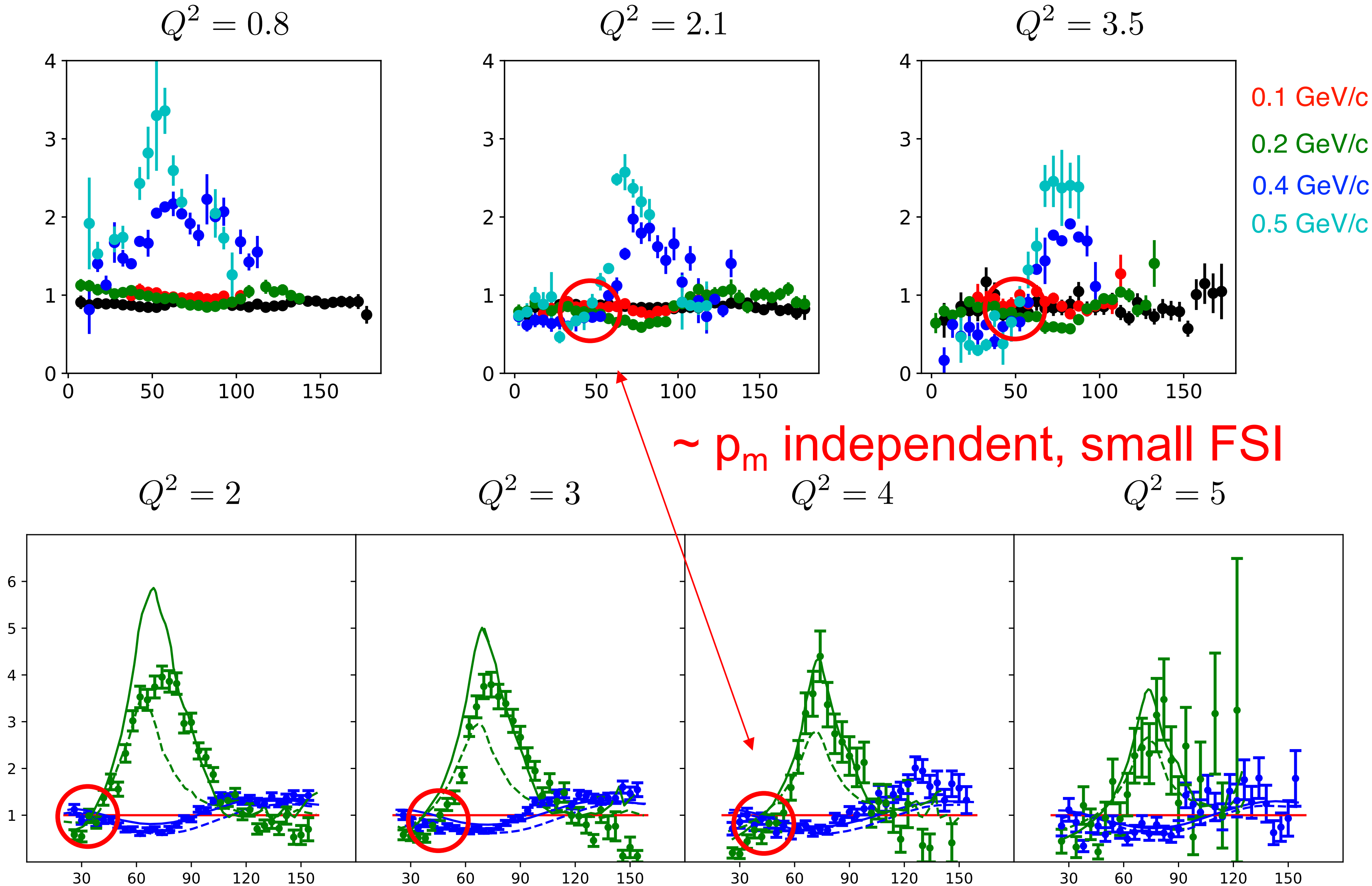
FSI

Laget

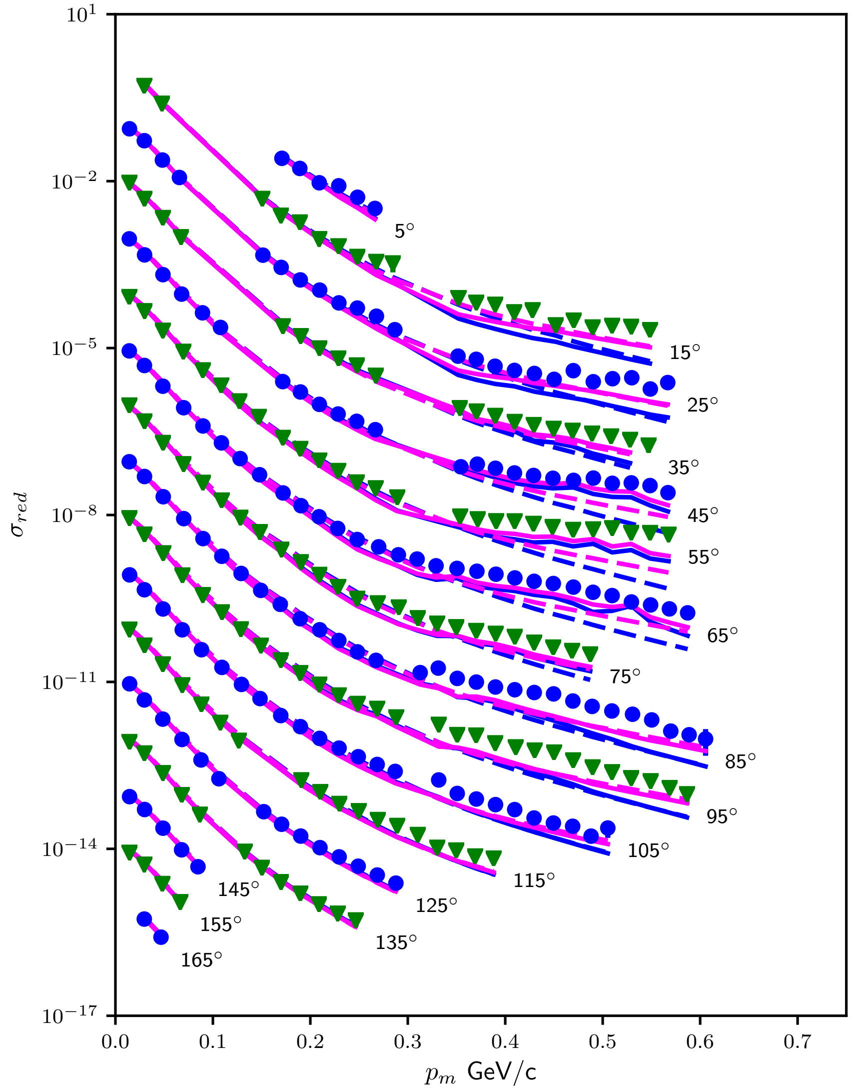
PWIA

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

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



Momentum Distributions

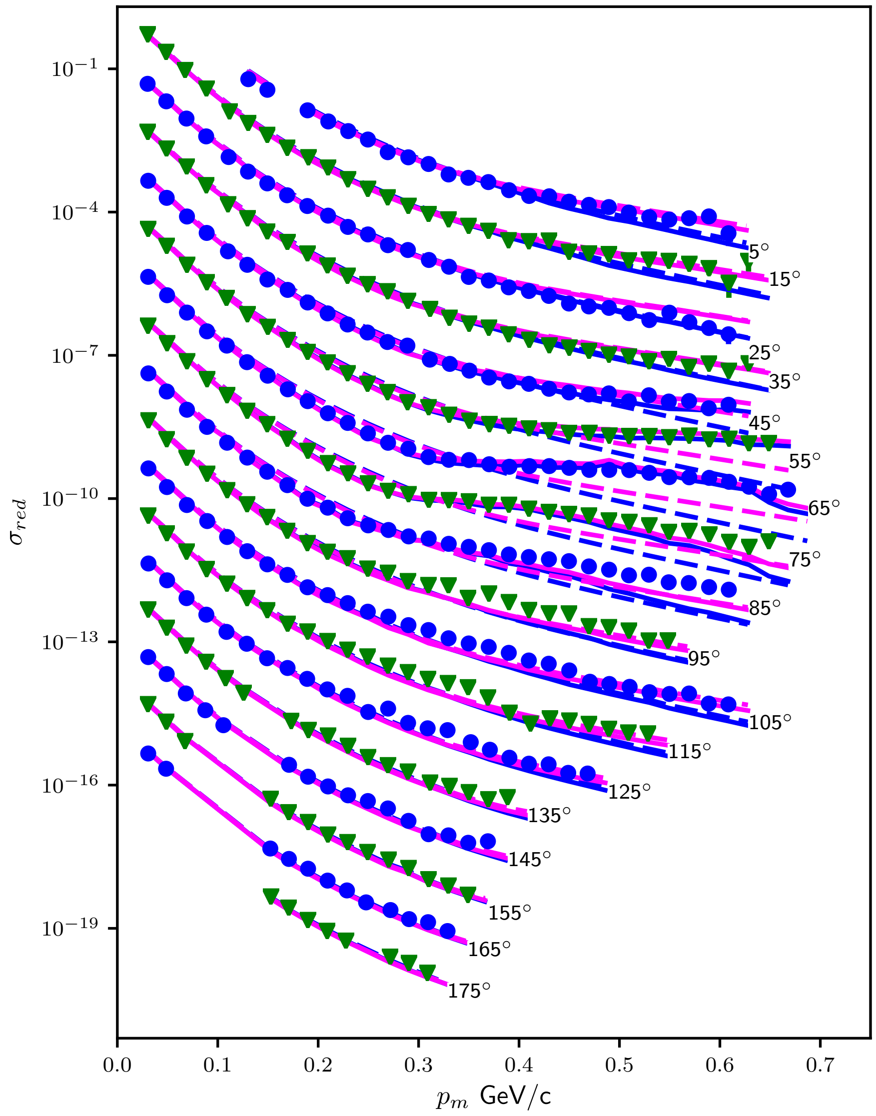


$Q^2 = 0.8\ (\mathrm{GeV/c})^2$

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

Experimental data are scaled for display purposes

Experimental data are scaled for display purposes

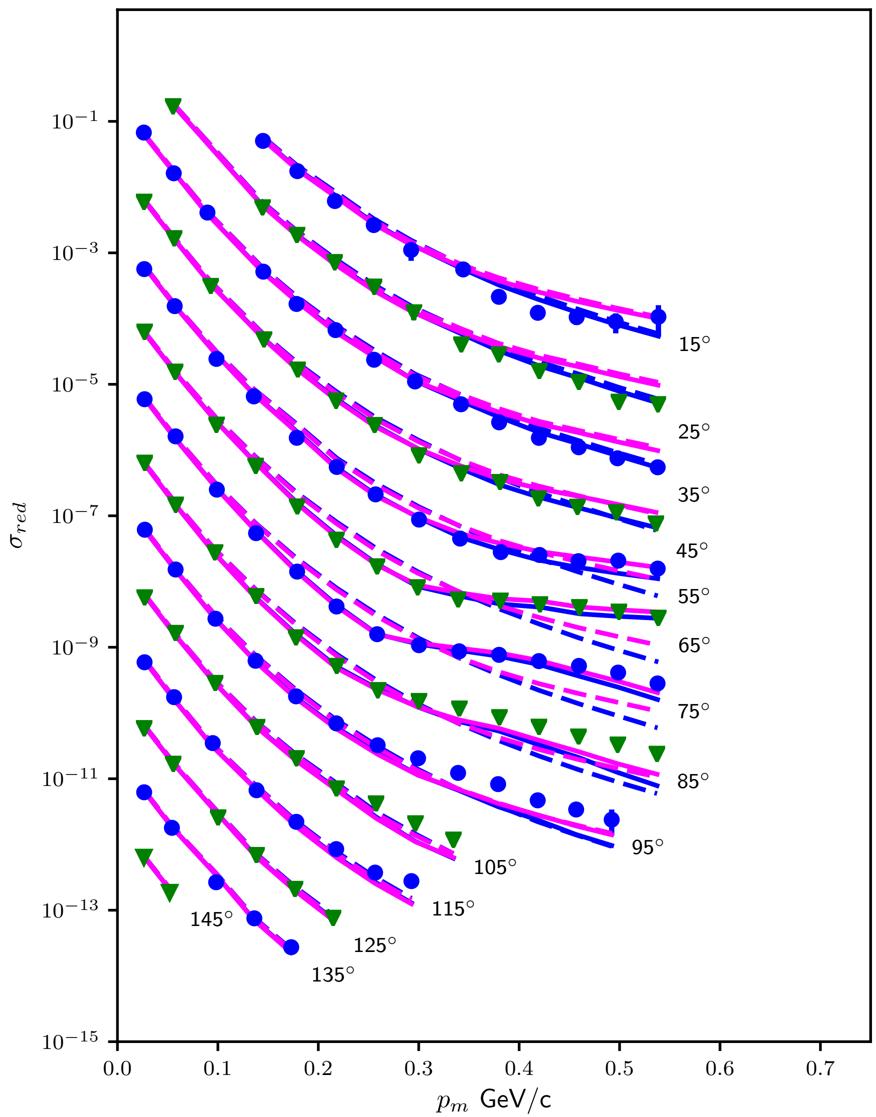


$Q^2 = 2.1\ (\mathrm{GeV}/c)^2$

Small FSI

Large FSI

Small FSI, Resonances ?



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

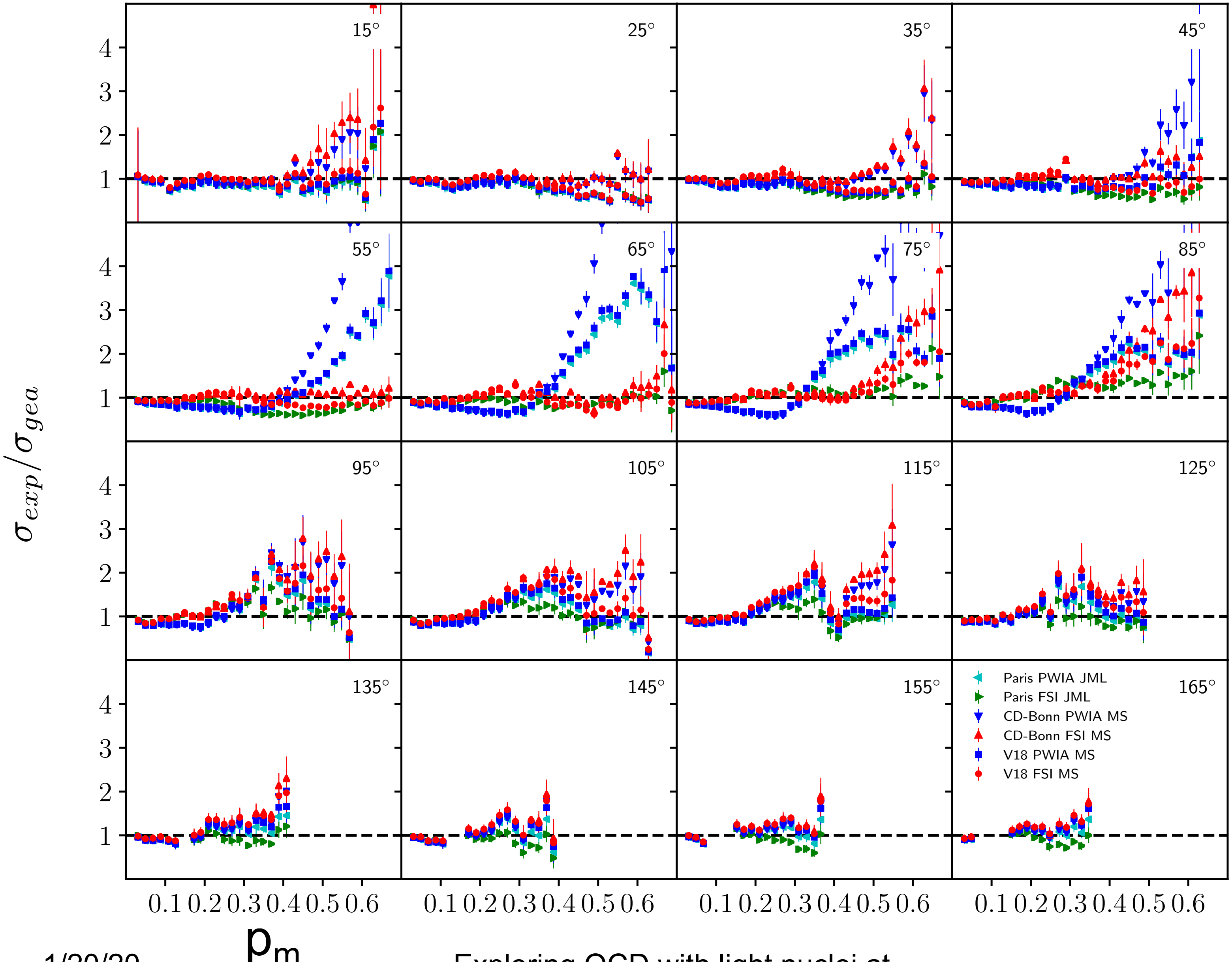
Small FSI

Large FSI

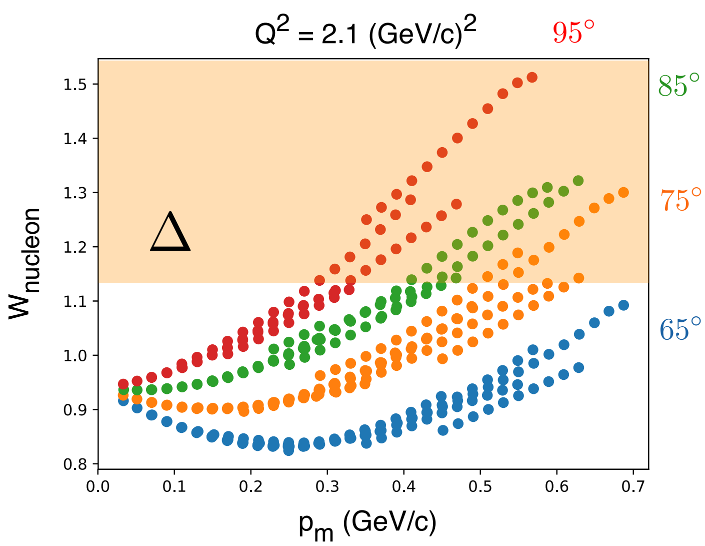
Small FSI, Resonances ?

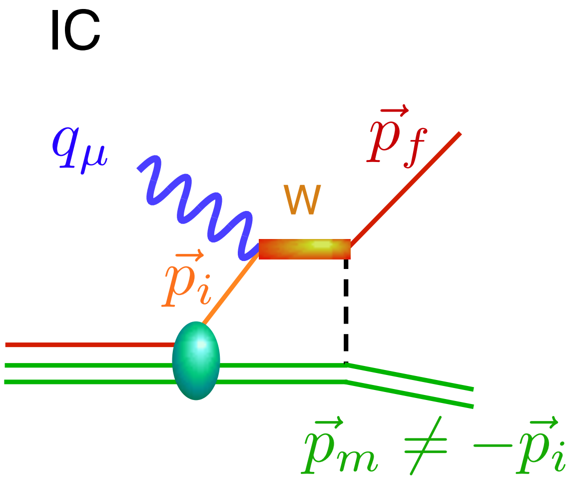
Experimental data are scaled for display purposes

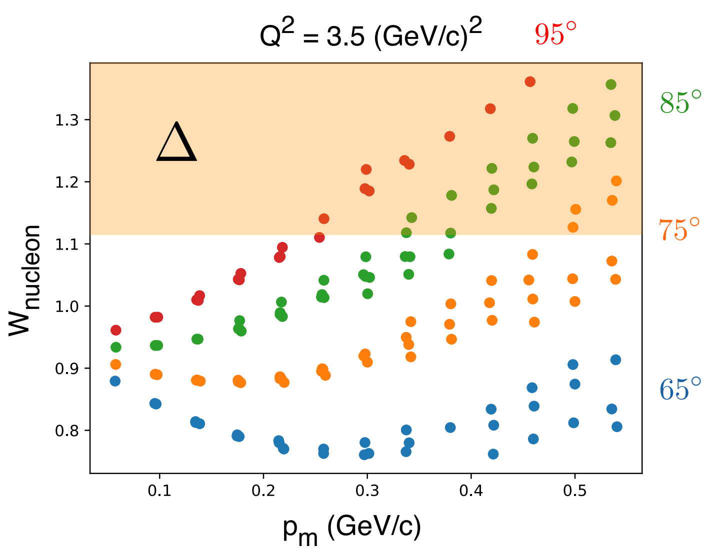
Q^2 = 2.1 $(GeV/c)^2$ GEA M.Sargsian



Resonance Contributions to Re-Scattering ?







Pushing the p_m limit: Experiment at 12 GeV in Hall C

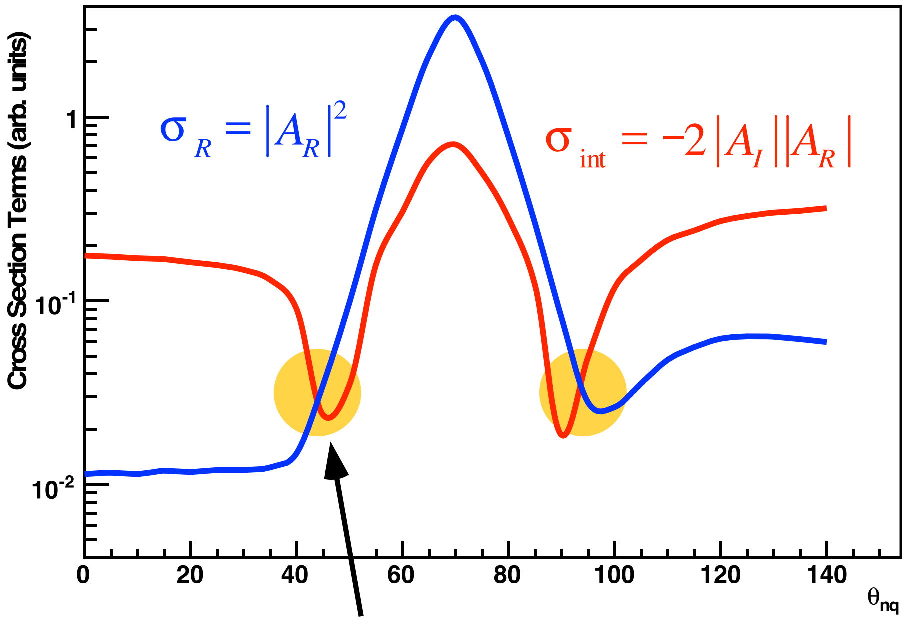
- Determine cross sections at missing momenta up to 1 GeV/c
- Measure at well defined kinematic settings
- Selected kinematics to minimize contributions from FSI
- Selected kinematics to minimize effects of delta excitation

Original Parameters

- Beam: 11 GeV, ~50μA
- 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: 10 cm LHD

FSI Reduction

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



Rescattering determined by slope factor:

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

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

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

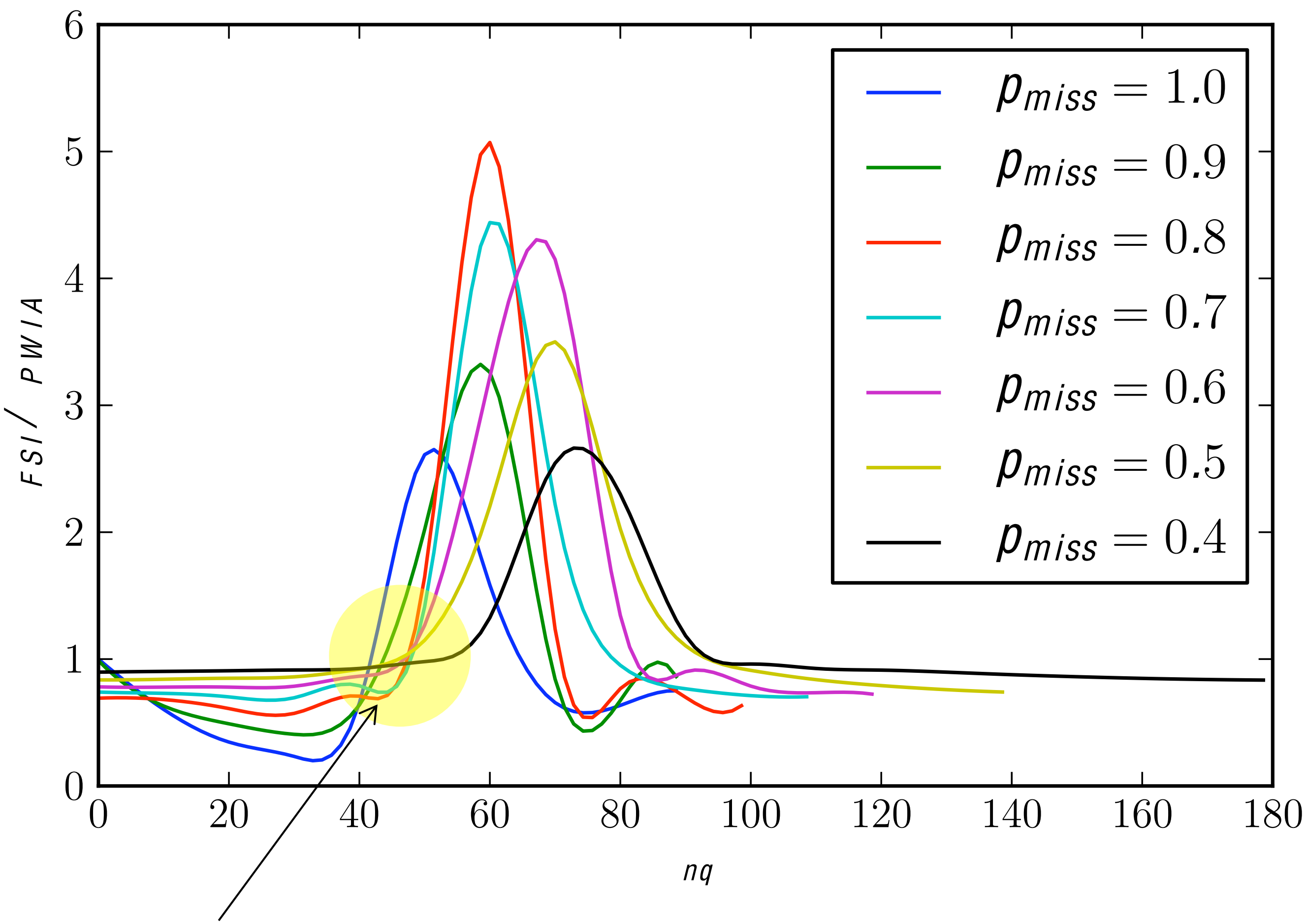
f_s relatively flat up to $k_t \approx 0.5(GeV/c)$

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

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)

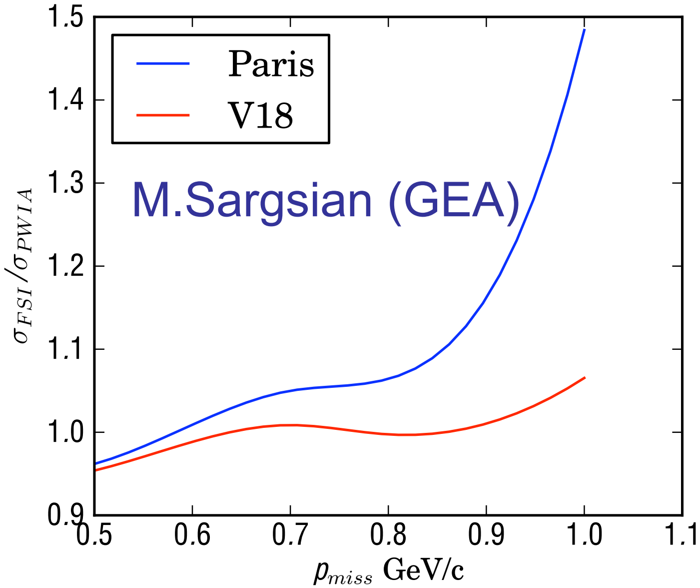
Estimated Angular Distributions up to p_m = 1GeV/c

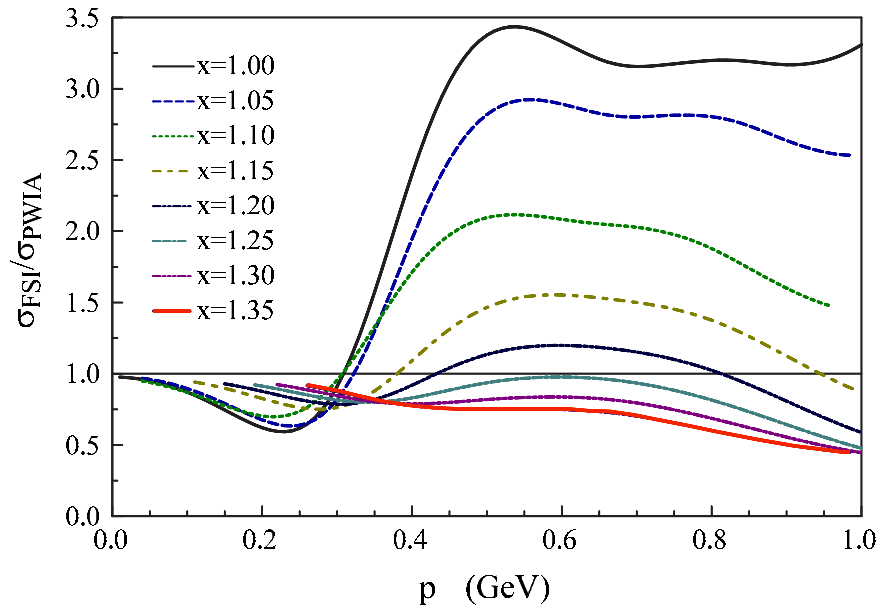


FSI depend weakly on p_m

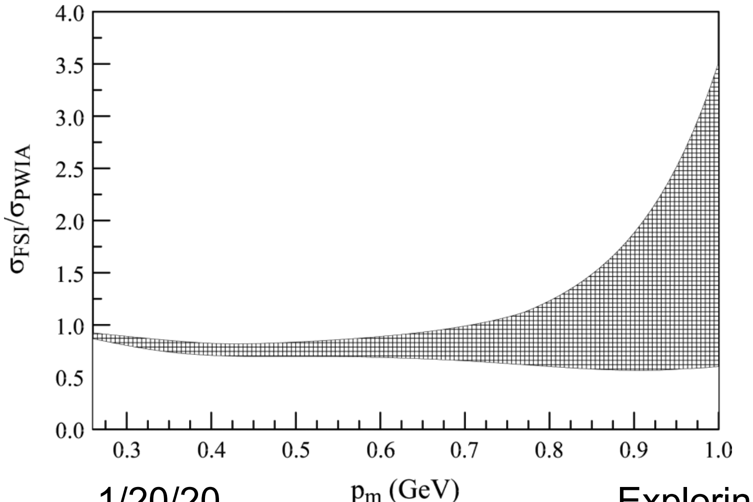
Calculation: M.Sargsian

FSI uncertainties



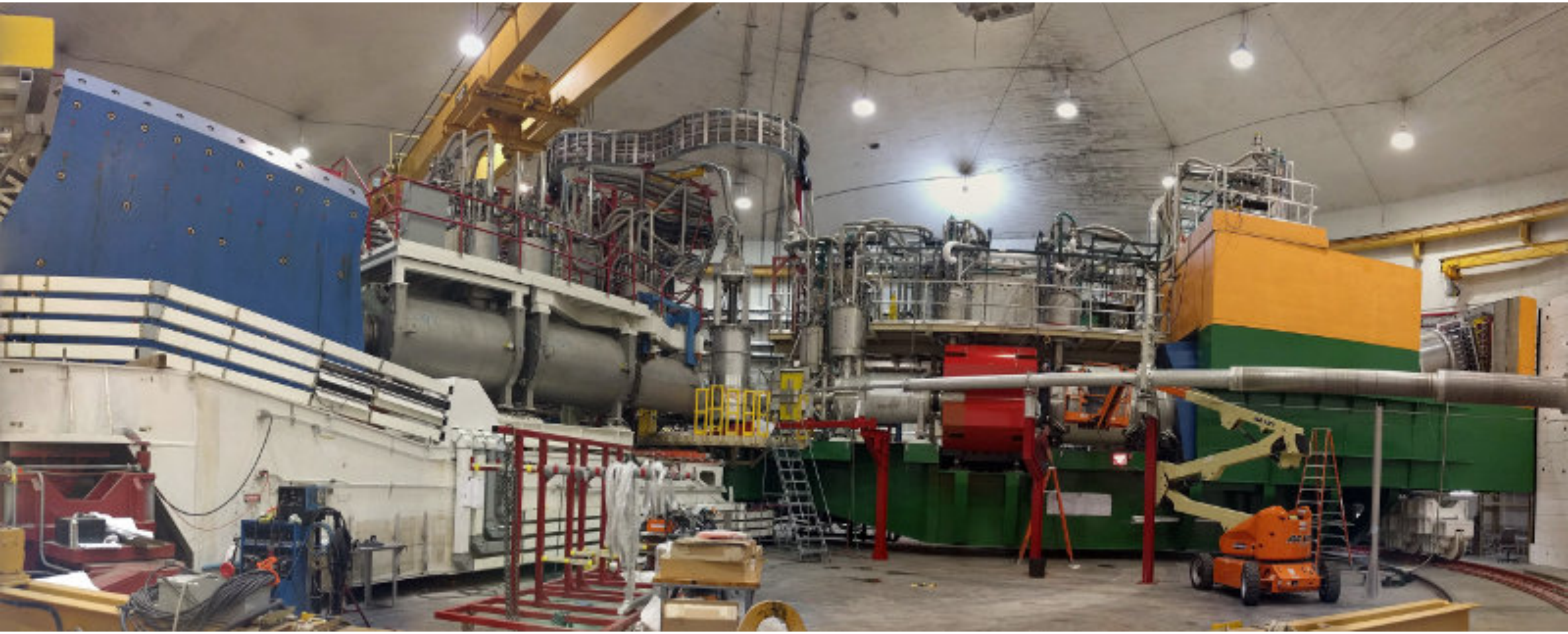


W.P.Ford et al. PRC 90 064006 (2014)

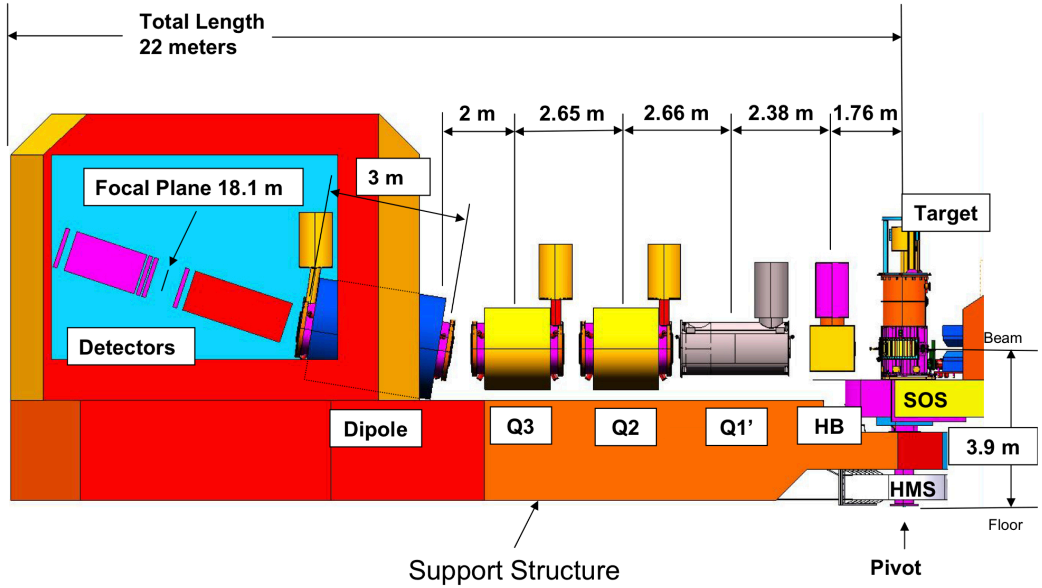


range of possible values of R for all form factor and W.F. used

First Results of Commissioning Experiment

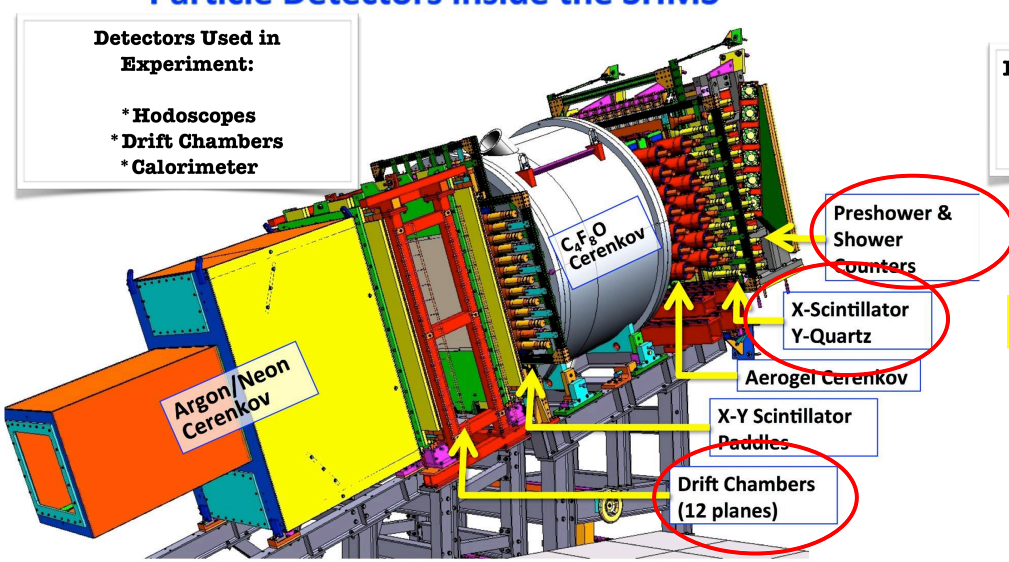


SHMS Overall Dimensions

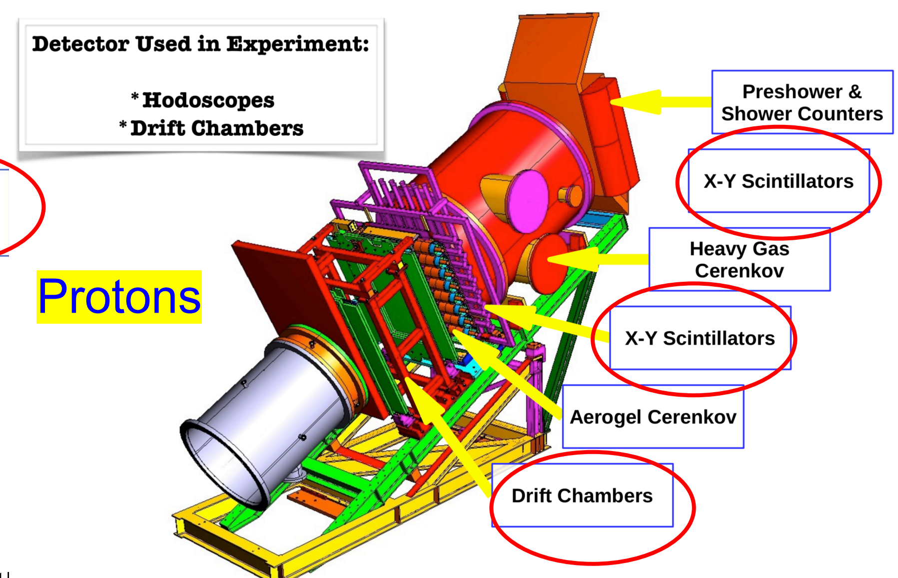


Electrons

Particle Detectors inside the SHMS

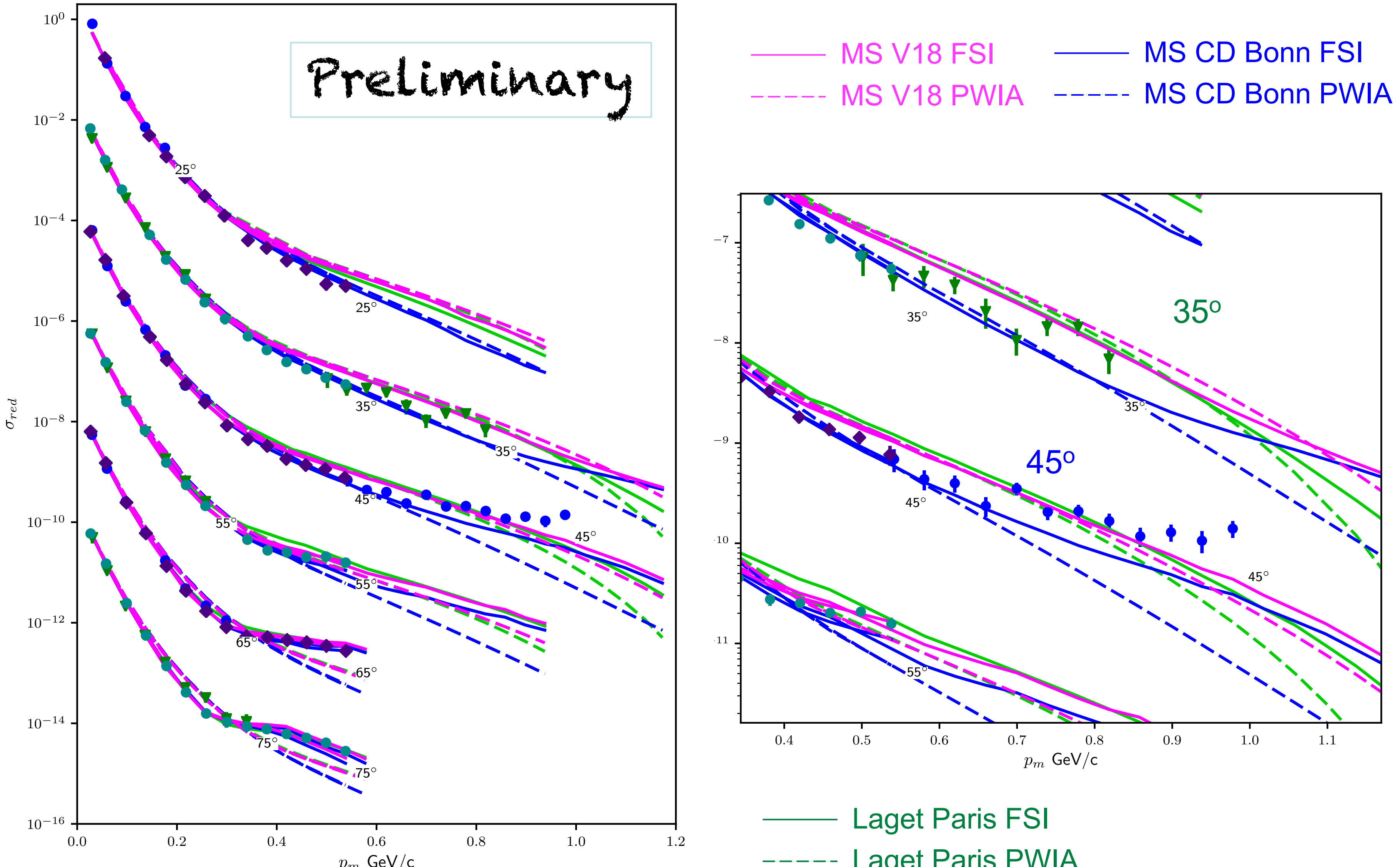


Particle Detectors inside the HMS

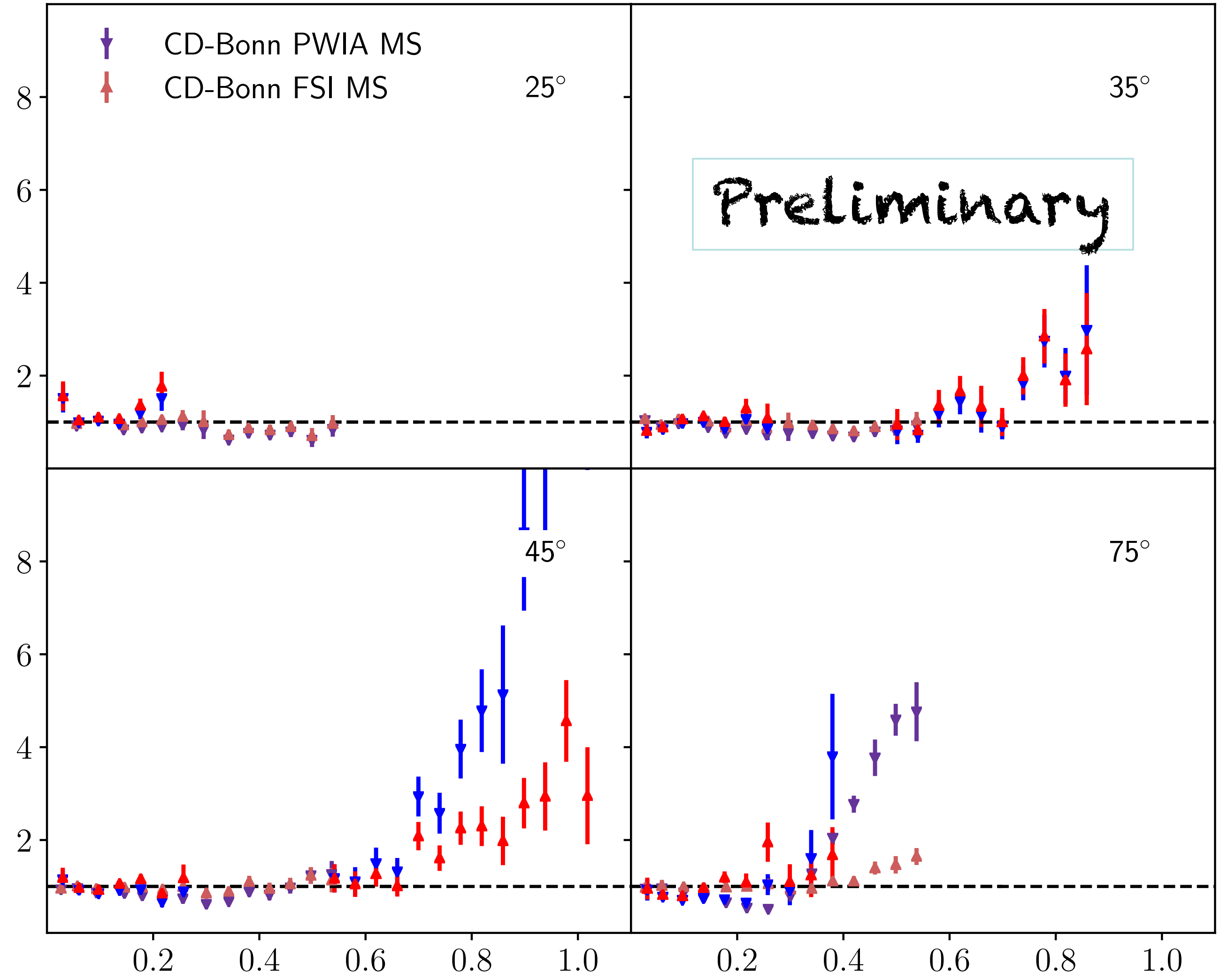


Protons

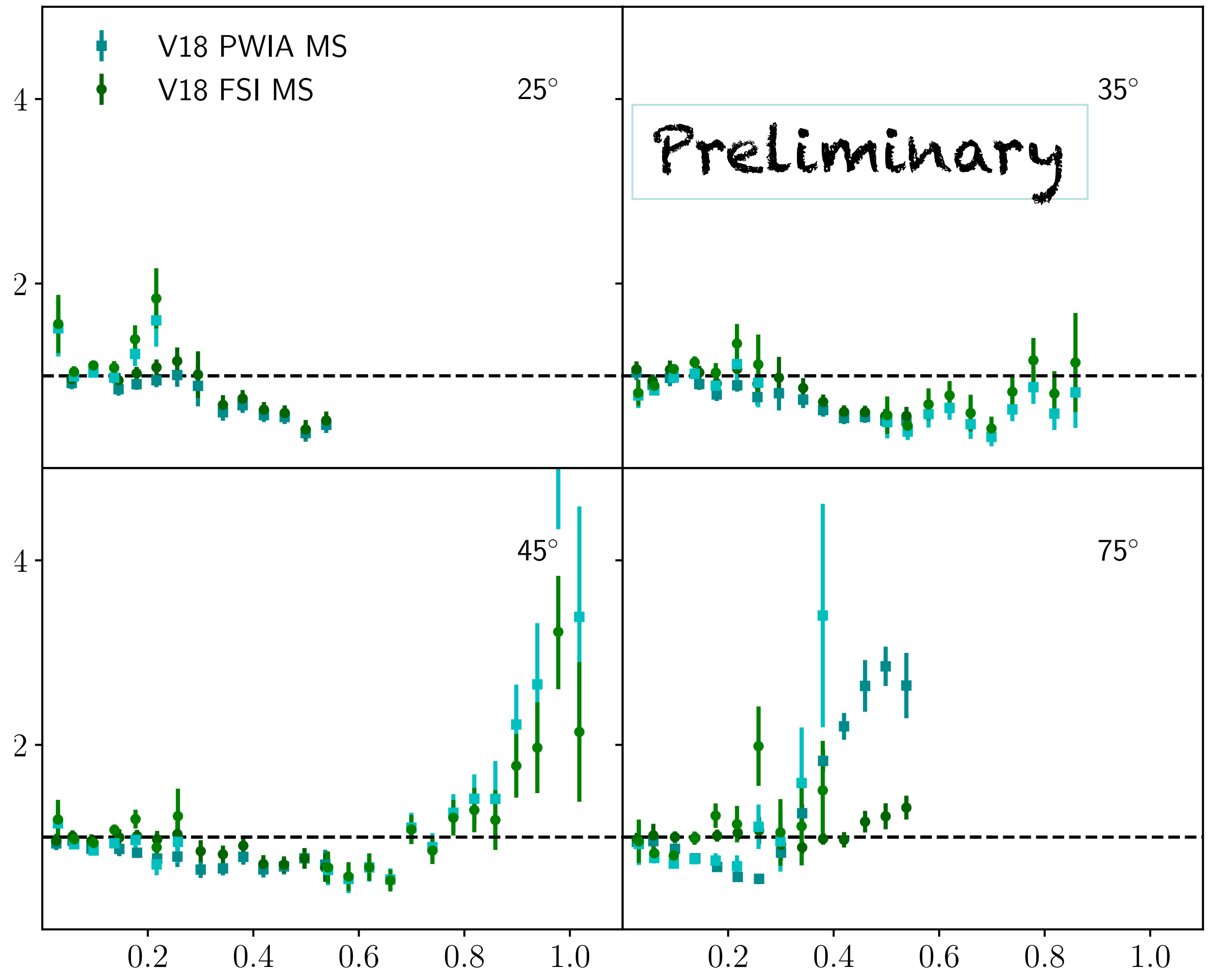
New Results


Preliminary
σ_{red}
p_m GeV/c
25°
35°
45°
55°
65°
75°
MS V18 FSI
MS V18 PWIA
MS CD Bonn FSI
MS CD Bonn PWIA
35°
45°
Laget Paris FSI
Laget Paris PWIA

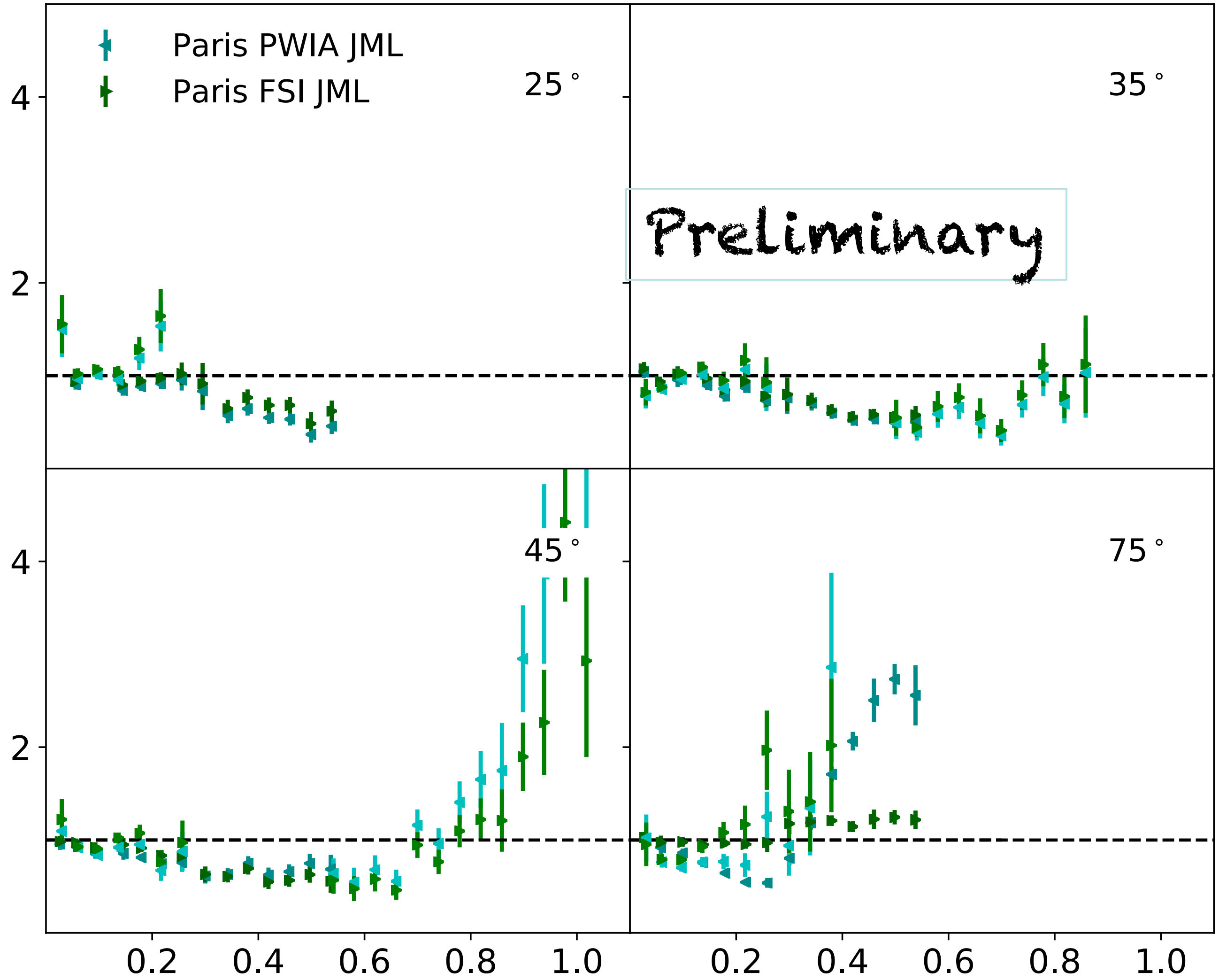
$$\sigma_{exp}/\sigma_{calc}$$



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



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



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
- Large FSI at small α and large P_T for small Q^2

LC PWIA cross section

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

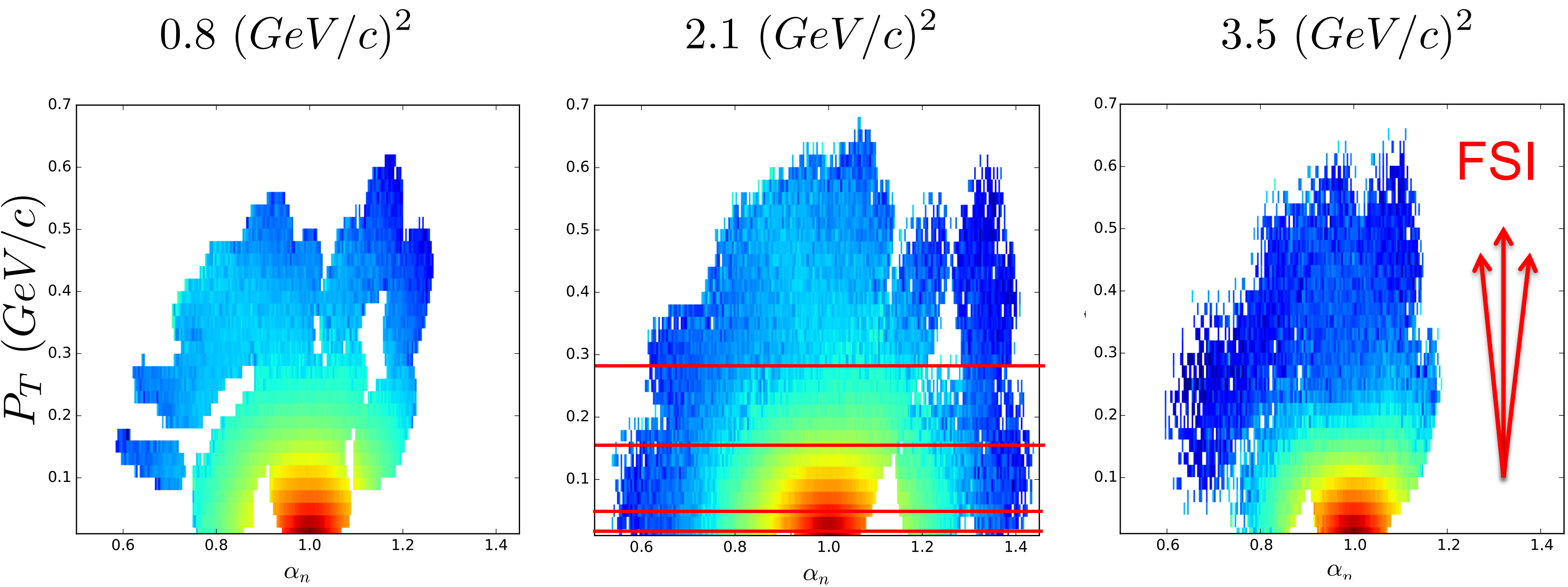
Nuclear analog to parton distribution $$f_N(\alpha) = \rho(\alpha) = \int \frac{\rho(\alpha, p_t)}{\alpha} d^2 p_t$$

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

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

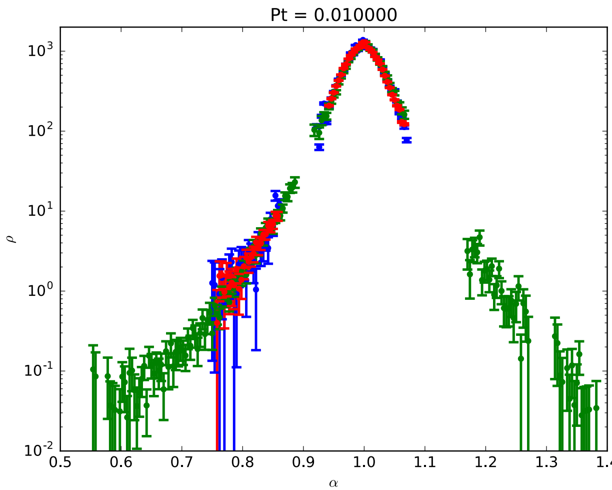
Problem: how do FSI affect $f_N(\alpha)$

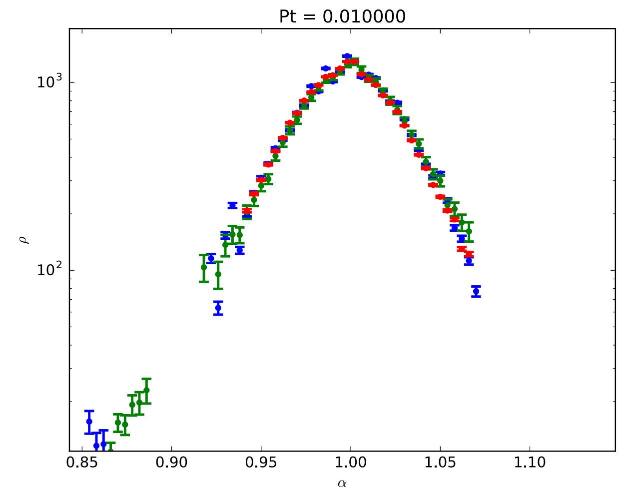
First Results

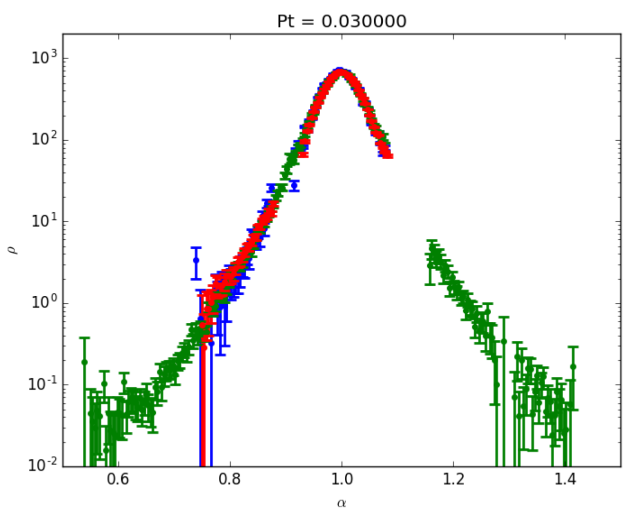


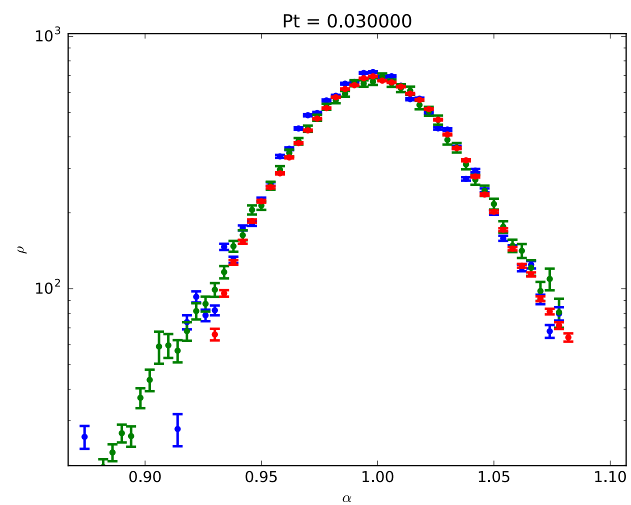
- Systematic error ~7%
- Original experiment design to measure angular distributions

Small P_T <0.05 GeV/c

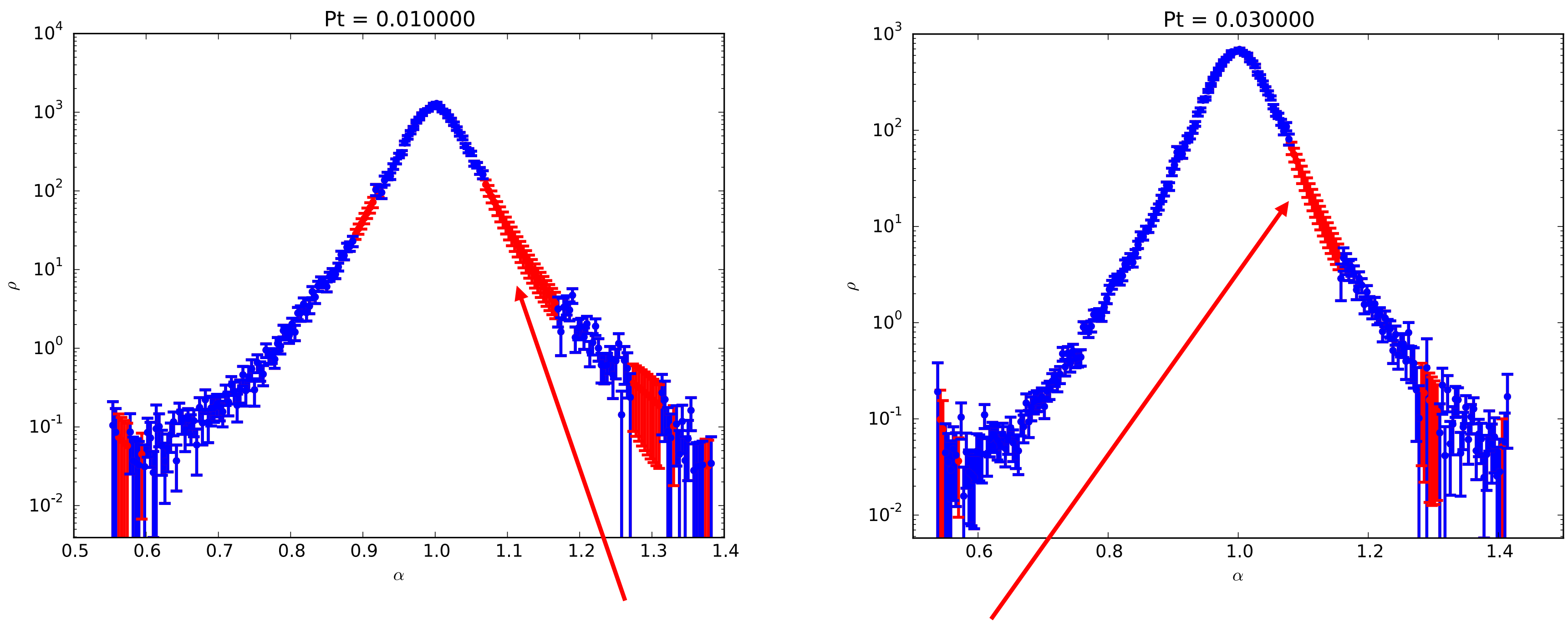








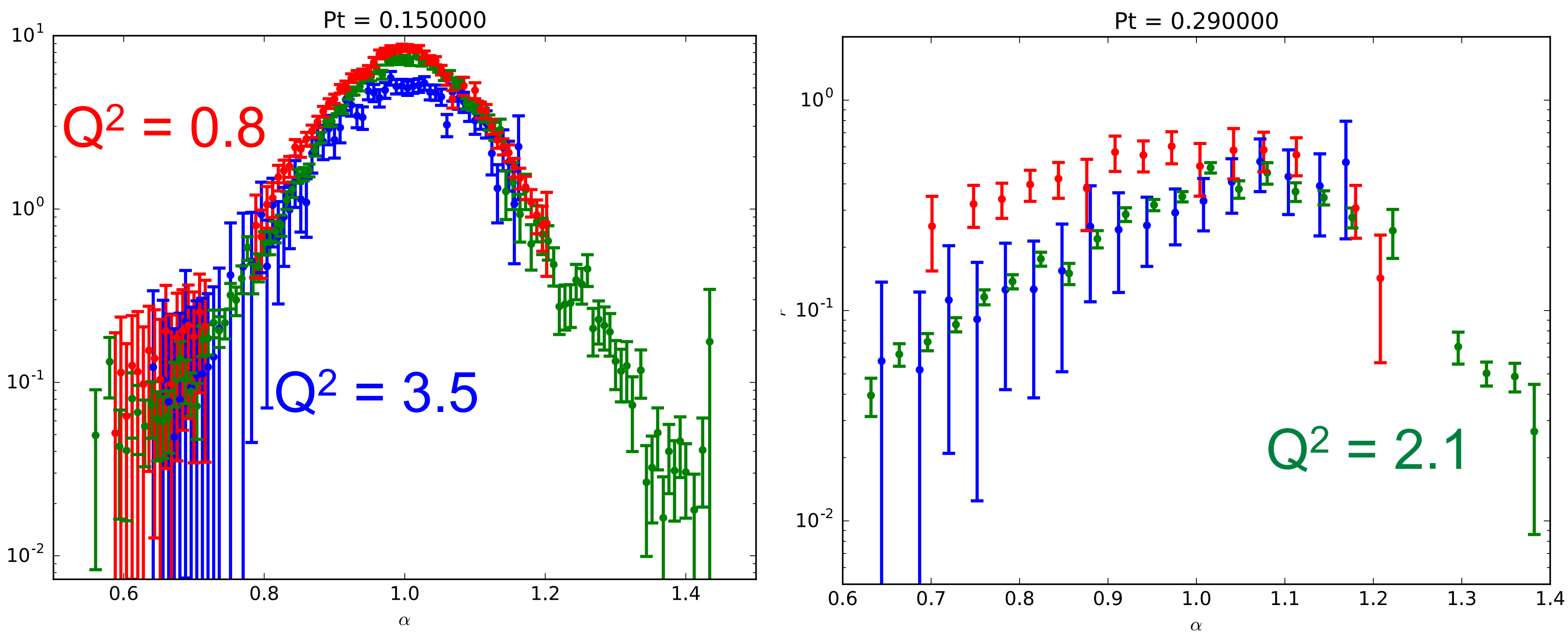
Missing Data



Missing data

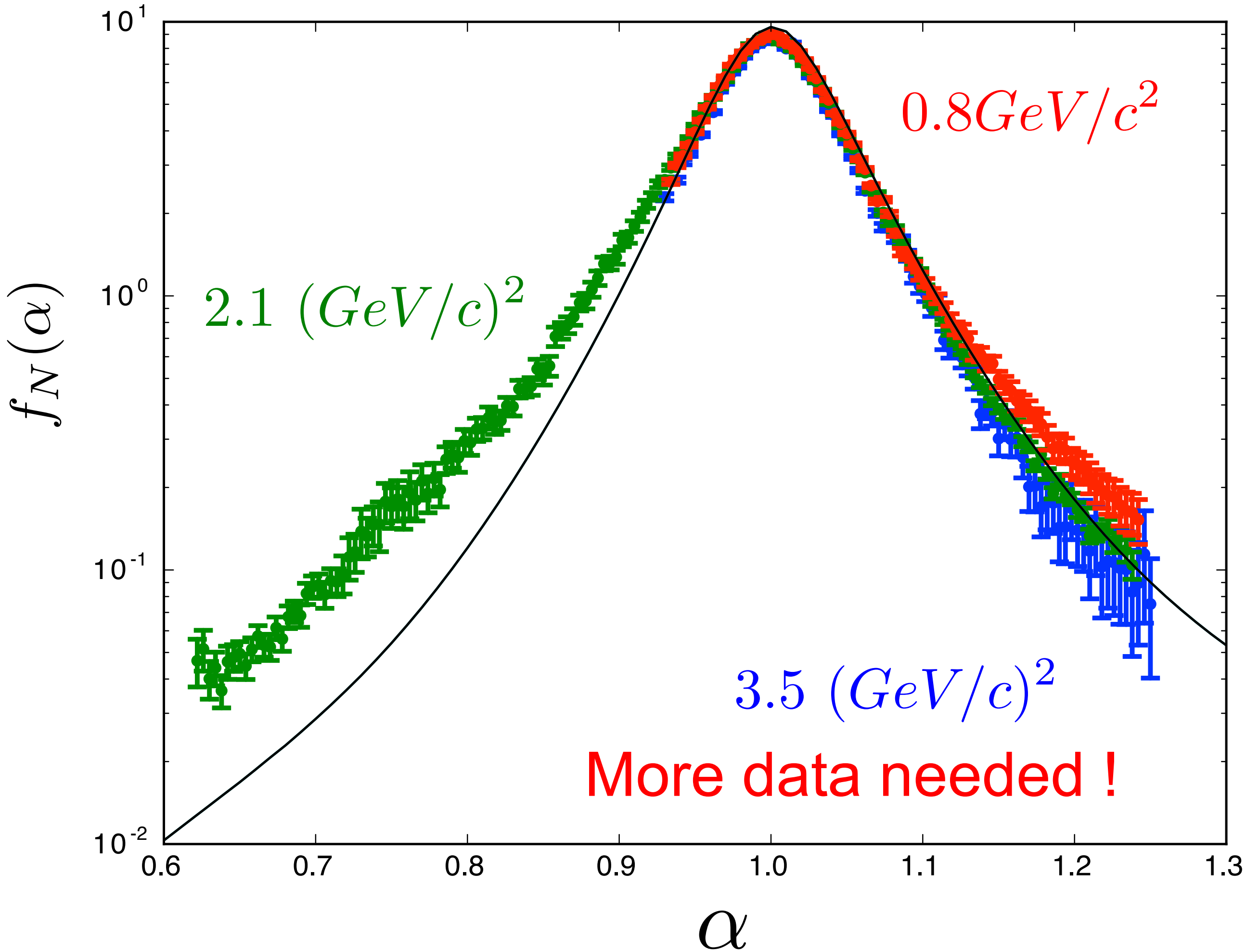
- Filled with fitting procedure
- Experimental data are not changed
- No extrapolation

Larger P_T



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

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



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

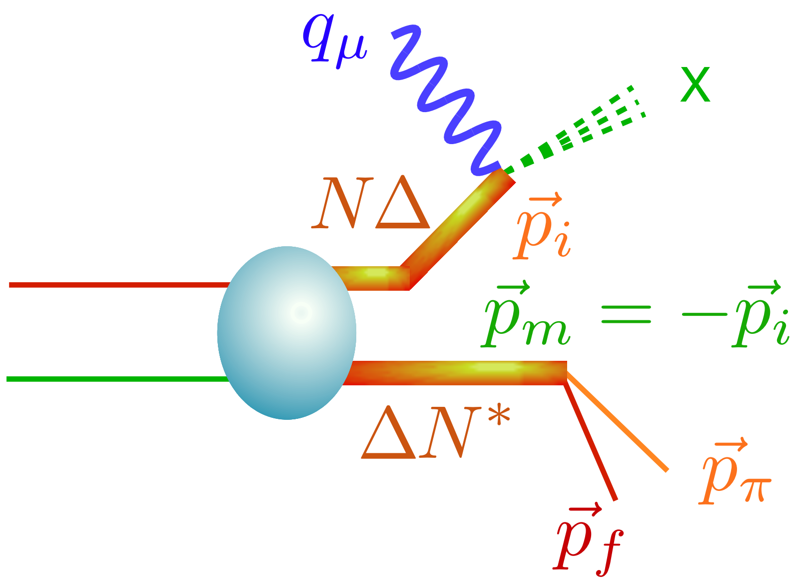
$$\frac{I_{exp}}{I_{PWIA}} \approx 1.3$$

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

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

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

Explore NN interaction core using inelastic channel: EIC



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

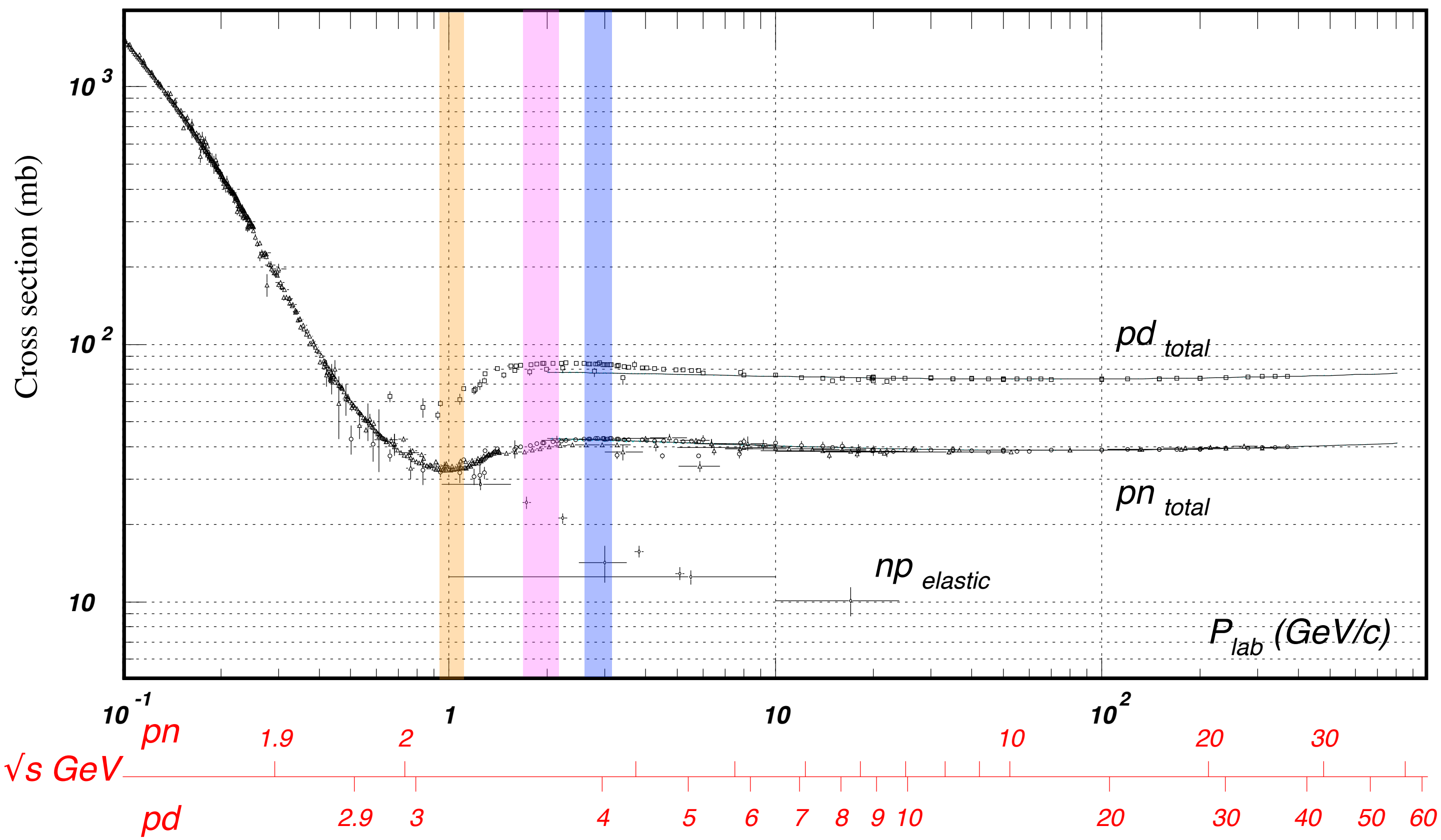
Summary

- High Q^2 d(e,e' p)n can be described using generalized eikonal approximation for Q^2 > 2 GeV/c
- There is a kinematic window to study the Deuteron momentum distribution.
- 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 different from Paris, V18 or CD-Bonn prediction
- LC momentum distribution determination needs more data
- Inelastic channels should be included (EIC)

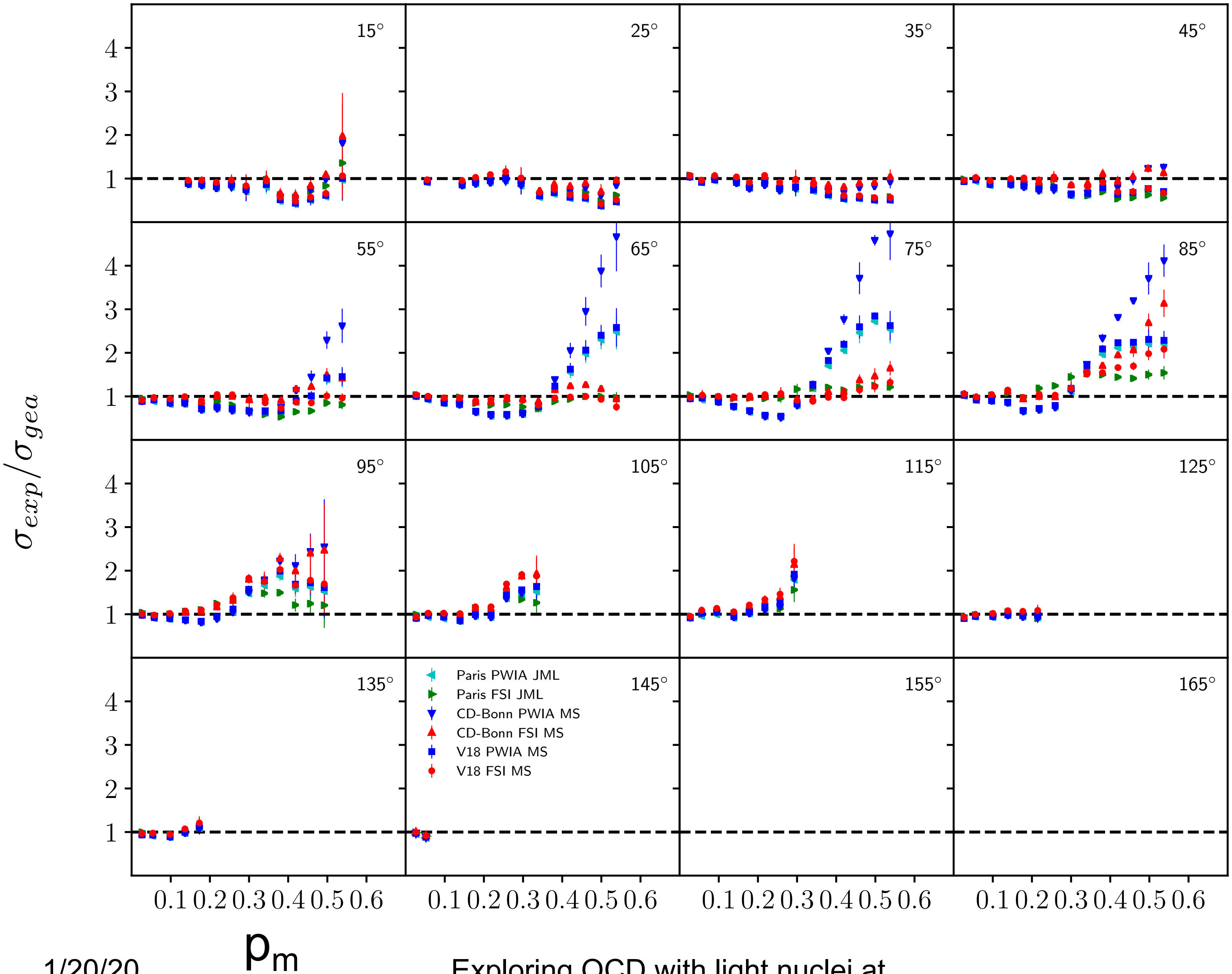
Supported by the Department of Energy, contract DESC0013620

Backup

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



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



Extracting ρ_{LC}

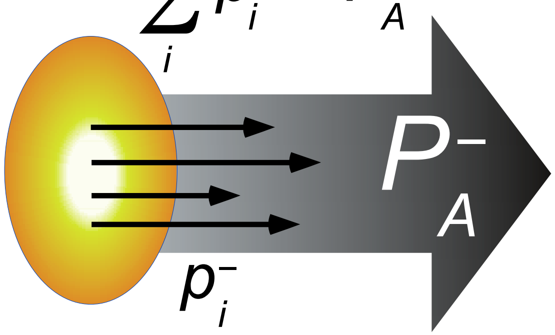
Relativistic Description of the Deuteron, L.L Frankfurt and M. Strikman, Nuclear Physics **B148** (1979) 107

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 $\quad \alpha = A\dfrac{p_i^-}{P_A^-}$

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



α is frame independent for boosts along the z-axis

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

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

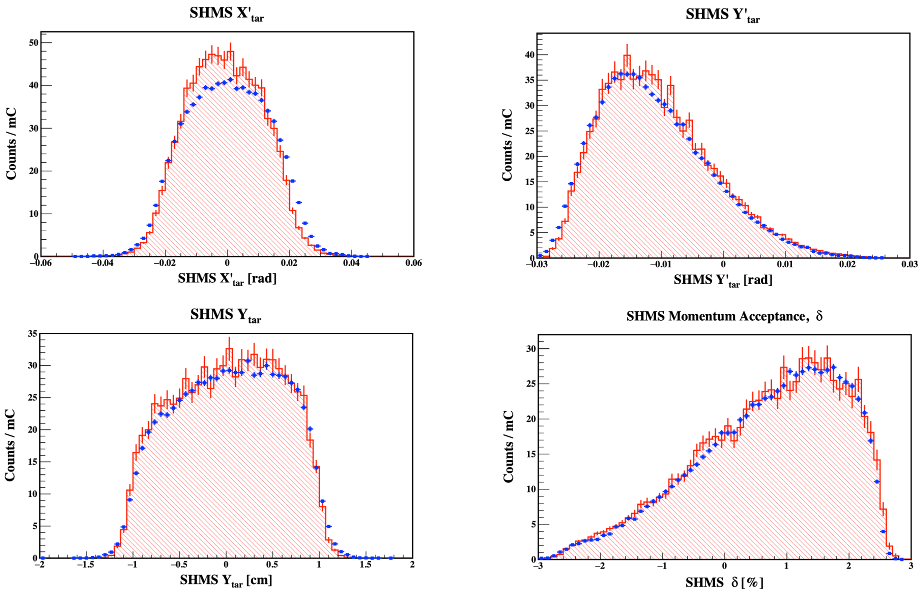
Advantages of working on LC:

- 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

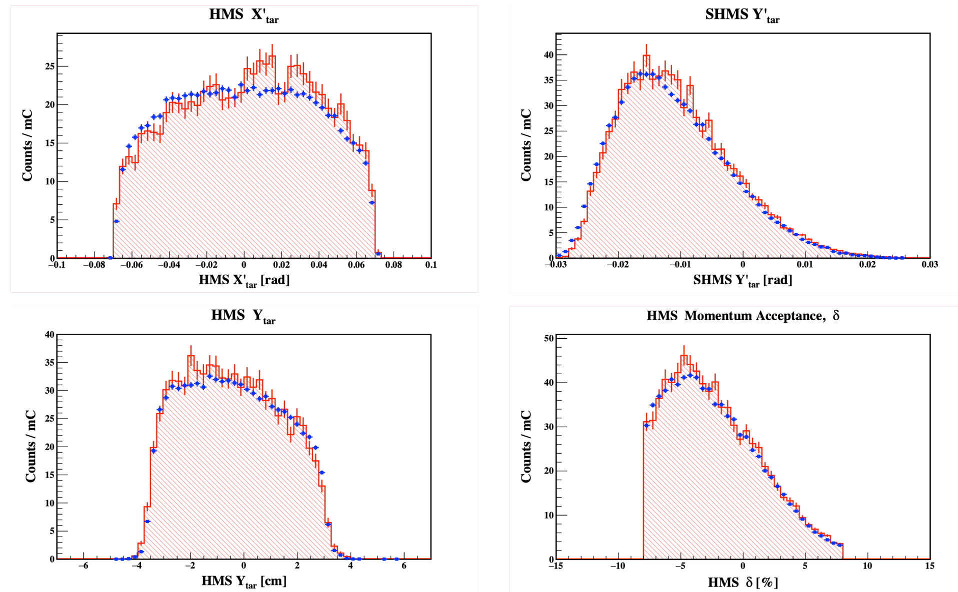
Detector Performance

SHMS

HMS



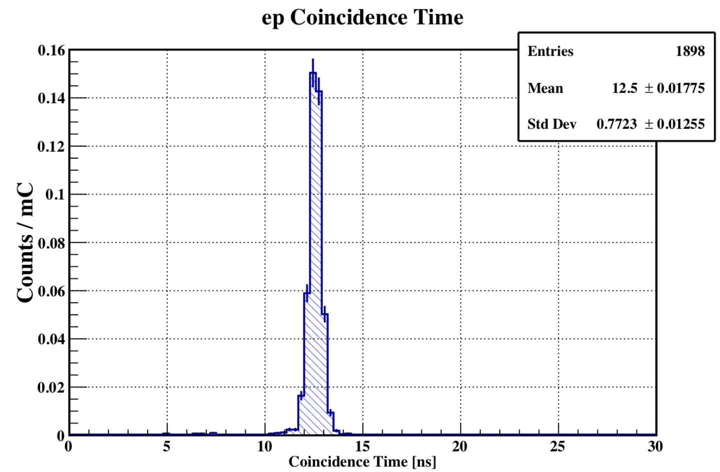
Data
SIMC

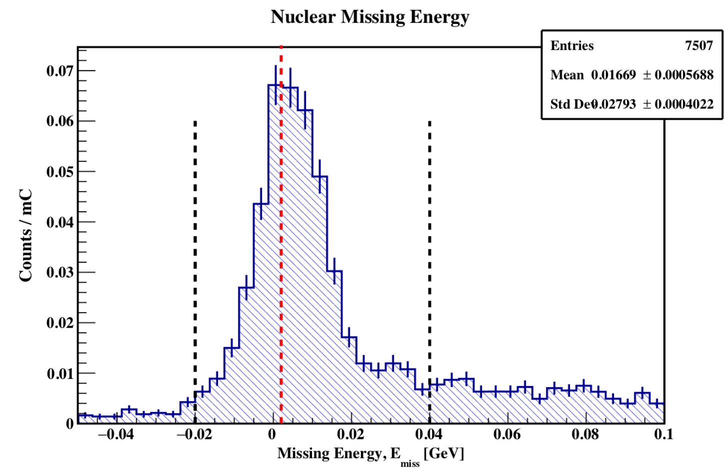


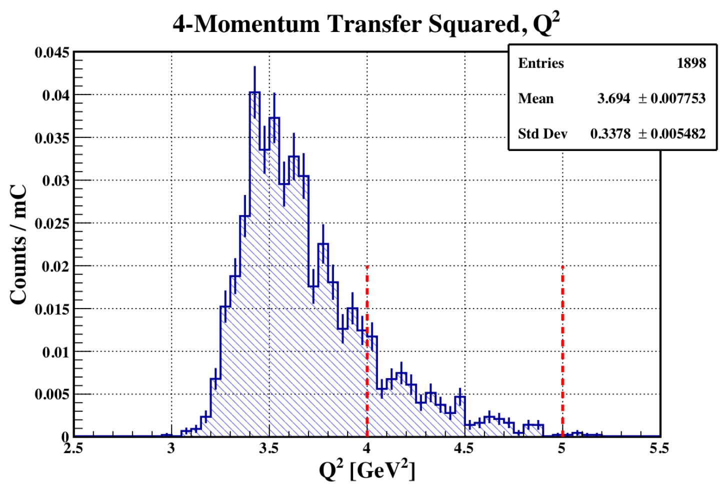
Data
SIMC

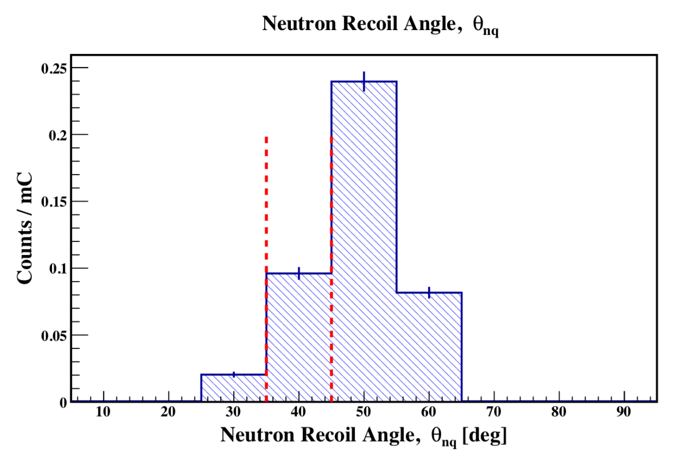
Kinematic Variables

p_m = 750 MeV/c









- Data

Problems

- Reaction dynamics:
  - how does the photon interact with a deeply bound nucleon ?
  - what is the EM current structure ?
- Final State Interactions
  - high Q^2 : eikonal approximations valid ?
    (Answer: yes for $Q^2>2$ $(GeV/c)^2$)
- Deuteron wave function
  - can one probe NN wave function at small distances ?
  - can one find evidence for new degrees of freedom ?

All these problems are interconnected
High Q^2 data are necessary for progress!