Short Distance Studies of the Deuteron

Werner Boeglin
Florida International University
Miami

Contents

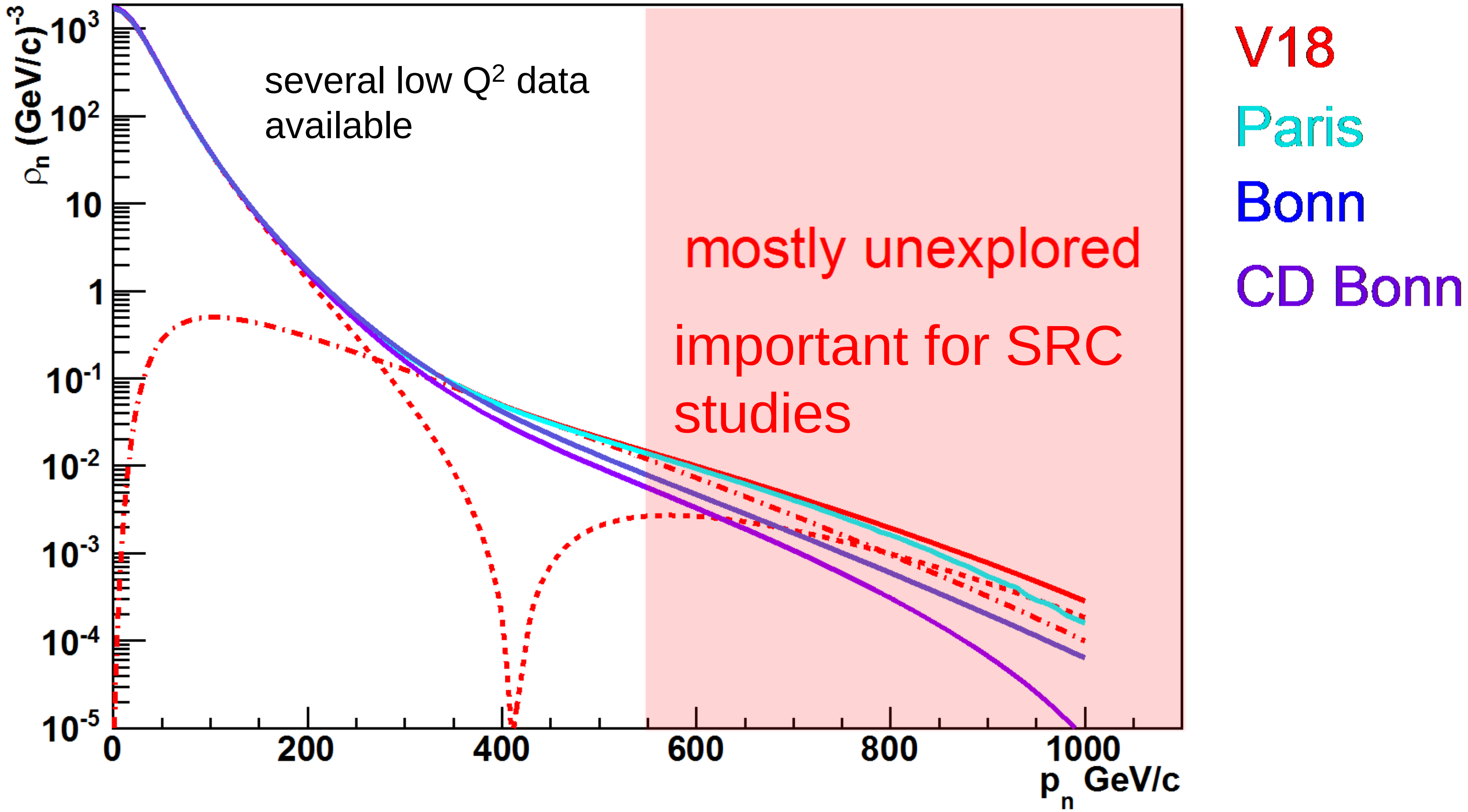
- Introduction
- Low Q^2 results
- Angular distributions
- Missing momentum dependences
- Lightcone momentum distribution
- A_{LT} measurements
- Future Plans
- Summary

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

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



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 ?
- Deuteron wave function
  - can one probe NN wave function at small distances ?
  - can one find evidence for new degrees of freedom ?
  - important for the interpretation of DIS data

All these problems are interconnected

New, high Q^2 data are necessary for progress!

D(e,e')

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} \left[A(Q^2) + B(Q^2)\tan^2(\theta/2) \right]$$

$$A = G_C^2 + \frac{2}{3}\eta G_M^2 + \frac{8}{9}\eta^2 G_Q^2$$

$$B = \frac{4}{3}\eta(1+\eta)G_M^2$$

G_Q Quadrupole form factor

G_M Magnetic form factor

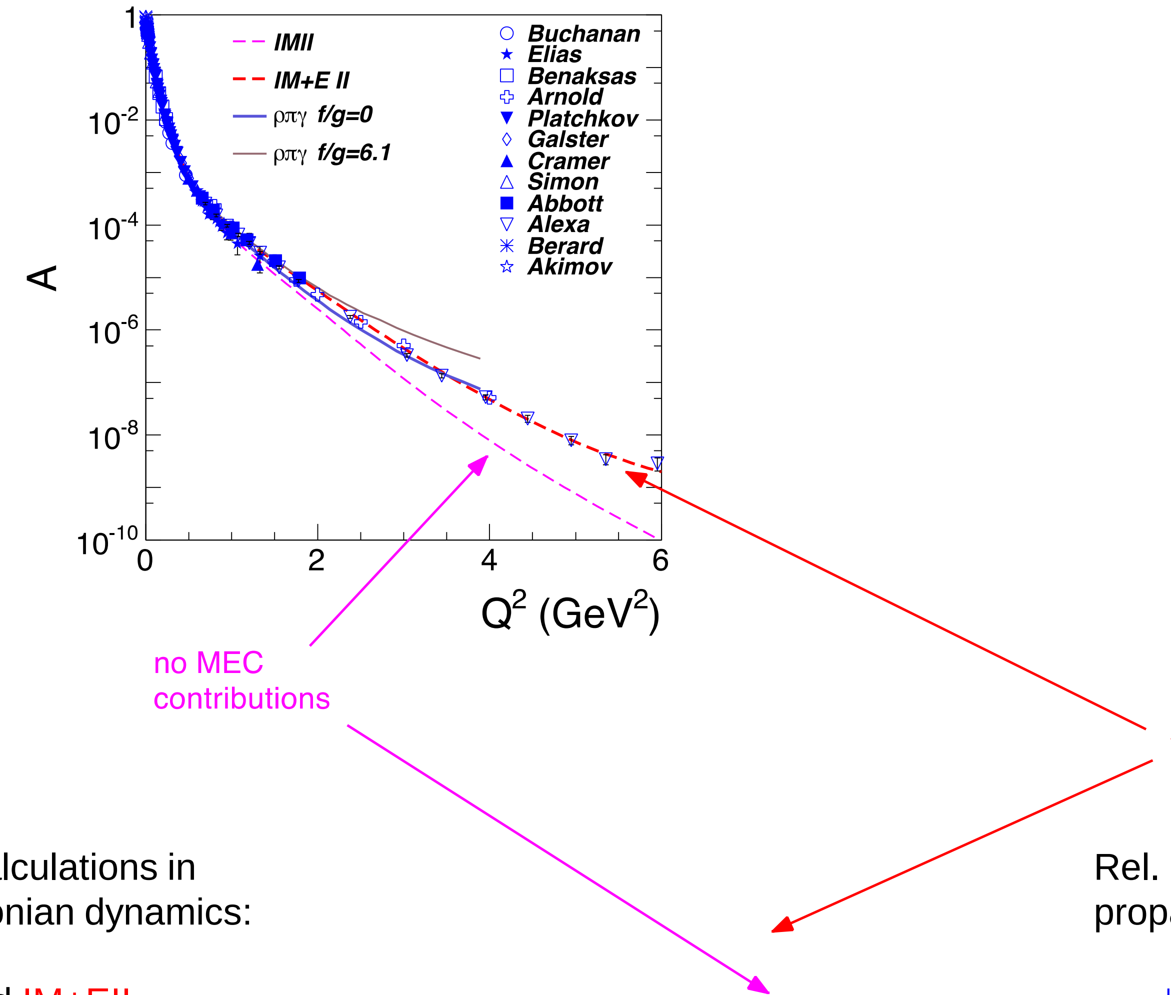
G_C Charge form factor

$$T_{20} = -\frac{\frac{8}{9}\eta^2 G_Q^2 + \frac{8}{3}\eta G_C G_Q + \frac{2}{3}\eta G_M^2 \left[\frac{1}{2} + (1+\eta)\tan^2(\theta/2) \right]}{\sqrt{2}\left[A + B\ \tan^2(\theta/2) \right]}.$$

$$\eta = Q^2/4M_D^2$$

Review Articles:

- M.Garcon and J.W. van Orden Adv.Nucl.Phys.26(2001)293
- R. Gilman and F. Gross, J. Phys. G: Nucl. Part. Phys. **28** (2002) R37–R116
- R.J.Holt and R. Gilman http://arxiv.org/abs/1205.5827v1



Rel. Calculations in Hamiltonian dynamics:

IMII and IM+EII

Y.Huang and W.N.Polyzou PRC80 (2009) 025503

Rel. Calculations in propagator dynamics:

$\rho\pi\gamma\ \phi/\gamma = 0$

$\rho\pi\gamma\ \phi/\gamma = 6.1$

D.R.Phillips et al. PRC72 (2005) 014006)

D(e,e’) summary:

- NR models cannot describe the form factors up to the highest Q^2 (RC are very important)
- Indications of dimensional scaling exist.
- Relativistic models successfully describe Deuteron form factors
- MEC contributions are very important
- $\rho\pi\gamma$ exchange current important and not well constrained

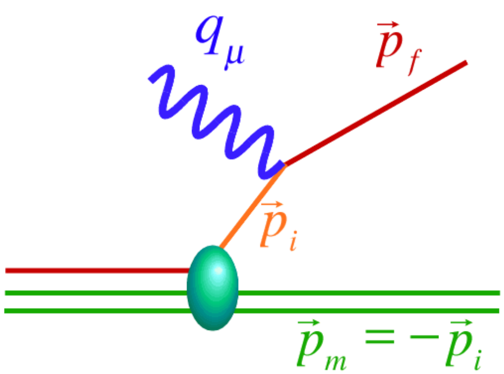
Experimental Goal:

Obtain data closely related to the deuteron wave function (momentum distribution) with a minimum of “other contributions” such as FSI, MEC, IC etc.

Ideally ‘measure’ the momentum distribution
$\Rightarrow$ study the d(e,e’p) reaction

D(e,e' p) Reaction Mechanisms

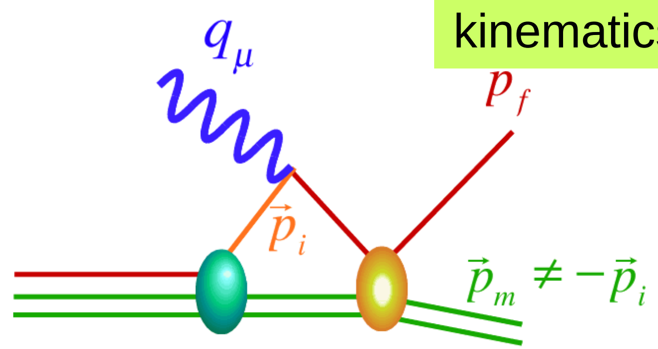
PWIA



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

FSI

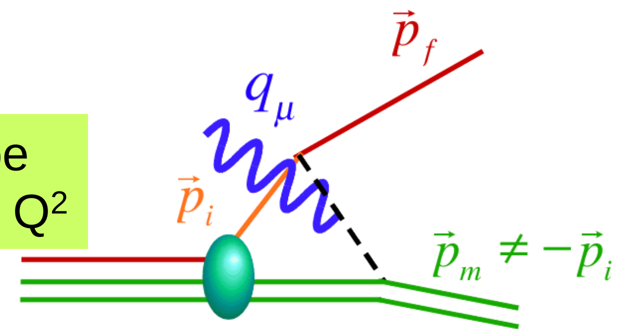
reduced at certain kinematics ?



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

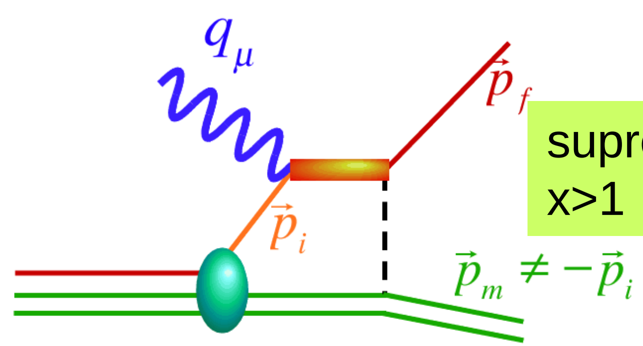
MEC

expected to be small at large Q^2

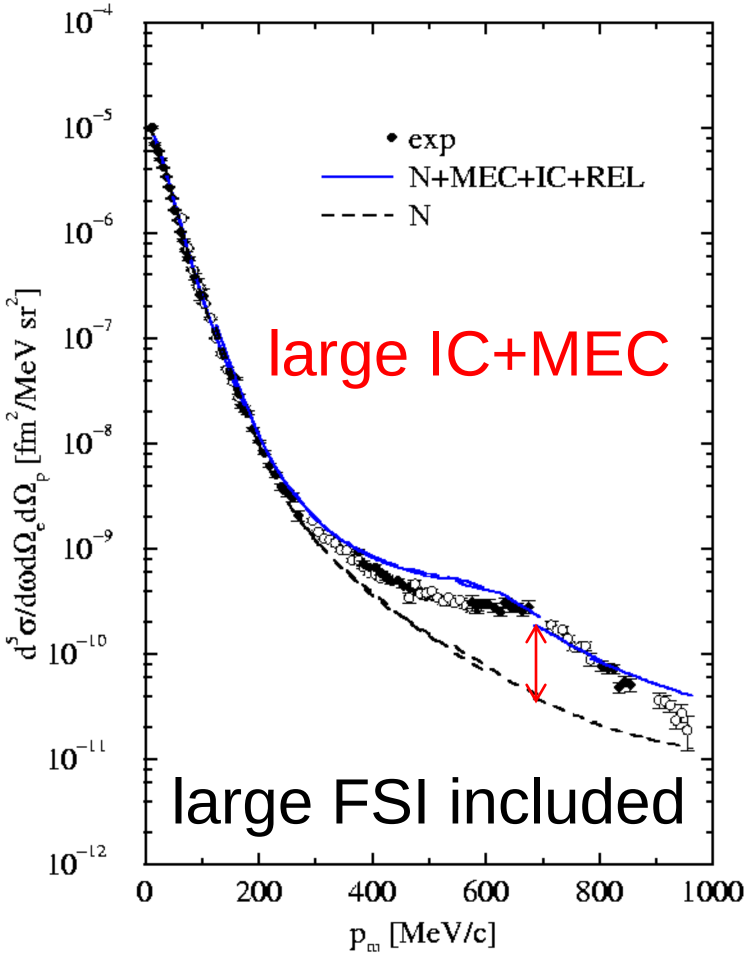


IC

supressed for x>1

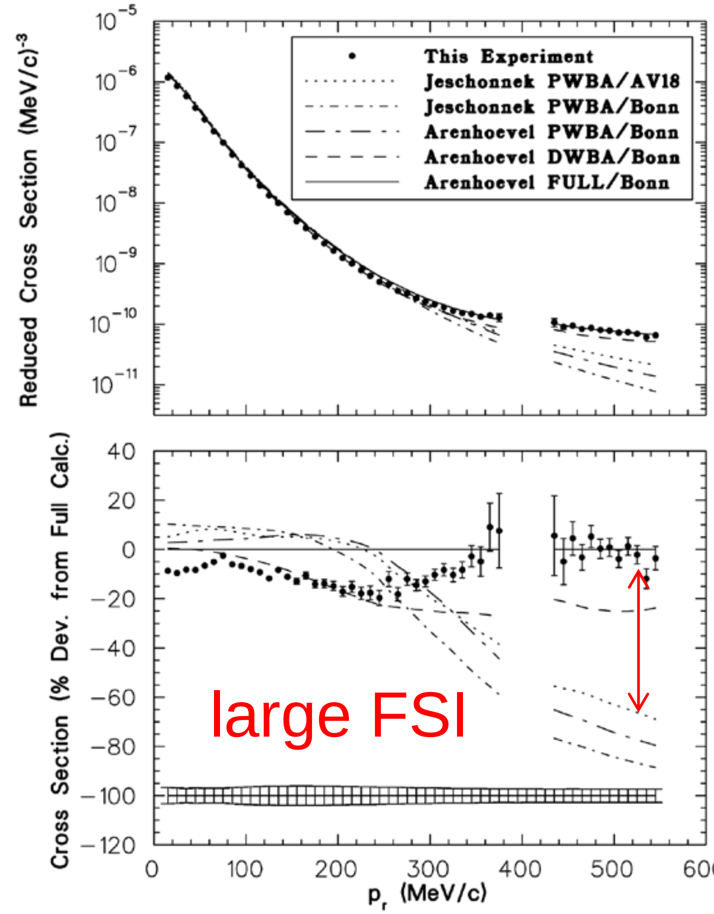


Missing Momentum Dependences



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

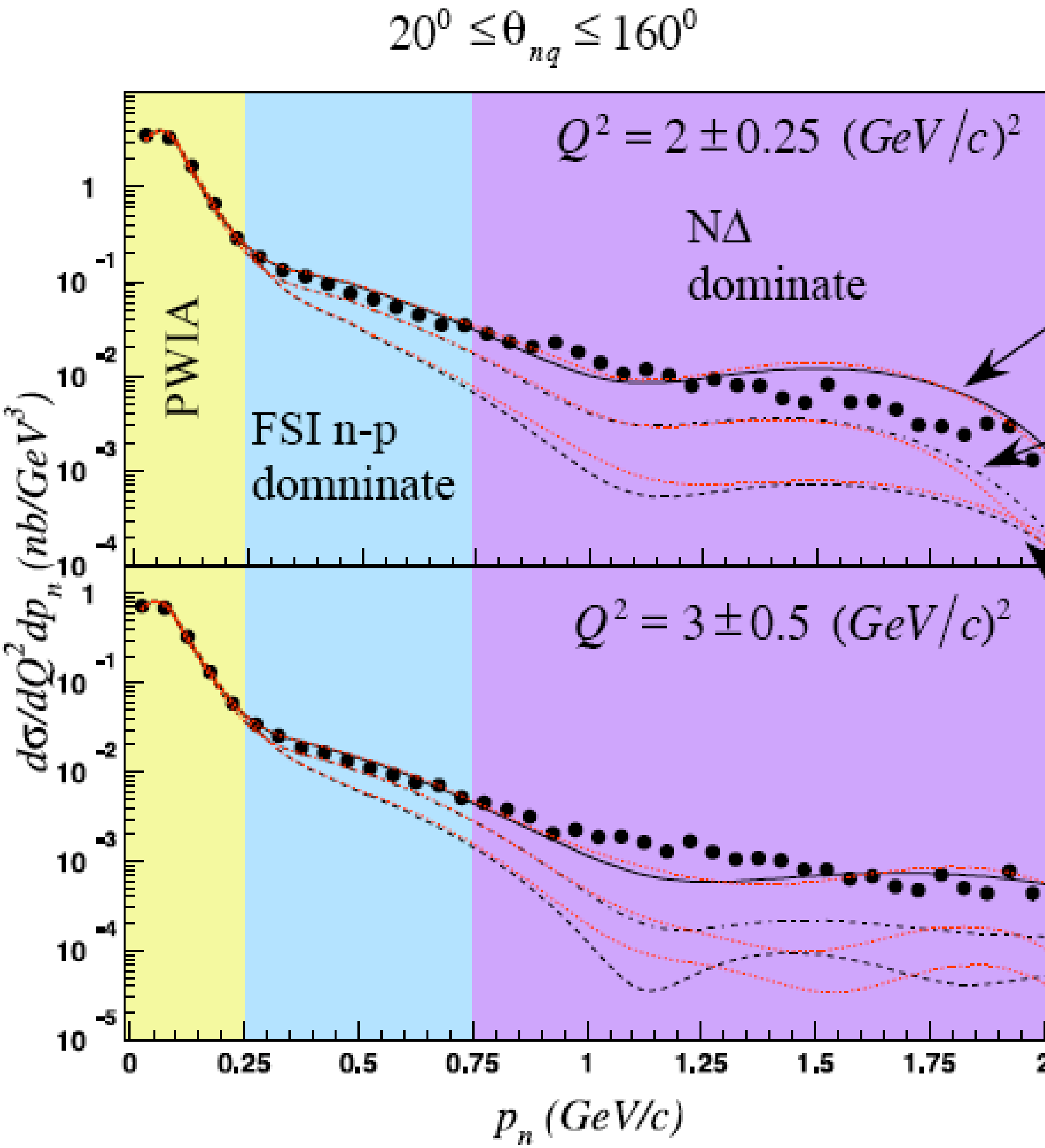
Blomqvist et al. PLB 429 (1998)



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

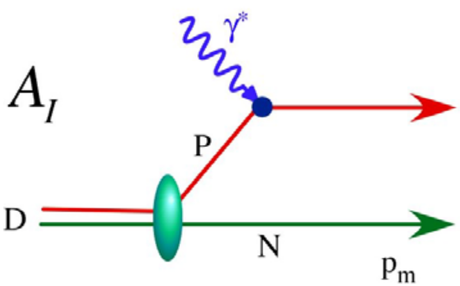
black: Paris potential

red: V18 potential

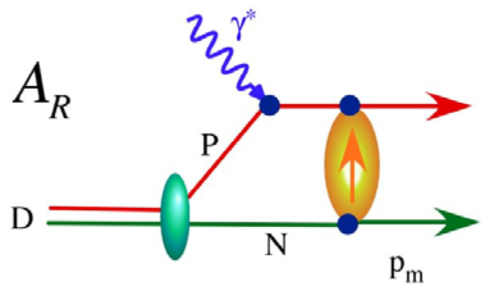
Egyian et al. (CLAS) PRL 98 (2007)

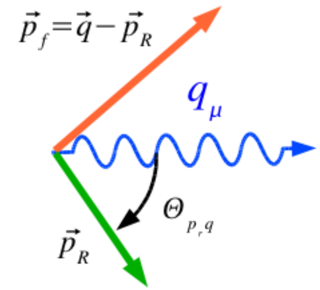
At high Q^2 FSI as Rescattering

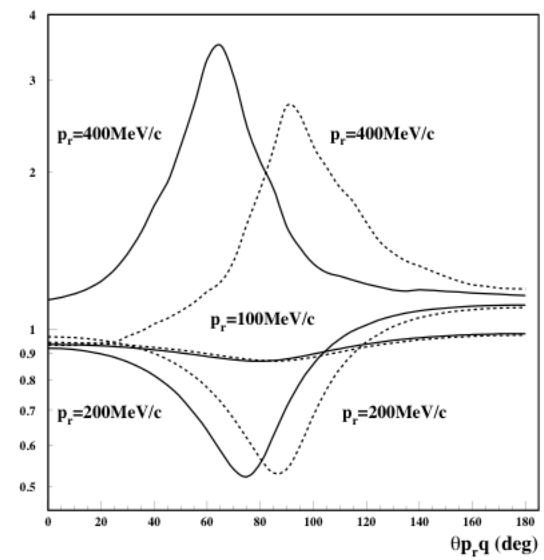
IA Amplitude (real):



Rescattering Amplitude
(at high energy mostly imaginary):







Total scattering amplitude: $A = A_I + iA_R$

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

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

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

JLAB: CLAS and Hall A

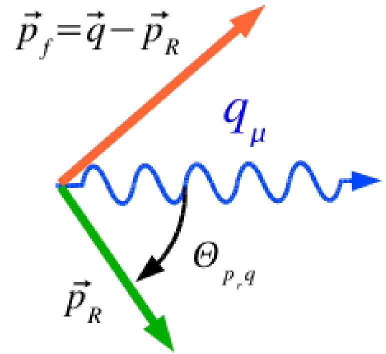
CLAS

- Simultaneous measurement of kinematics
- focus on Q^2 dependence
- e6 running period
- Q^2 = 2, 3, 4, 5 $(GeV/c)^2$
- Further analysis possible :Data Mining

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
- $20^o \leq \theta_{pq} \leq 140^o$
- angular range for each p_{miss} dependent on kinematics

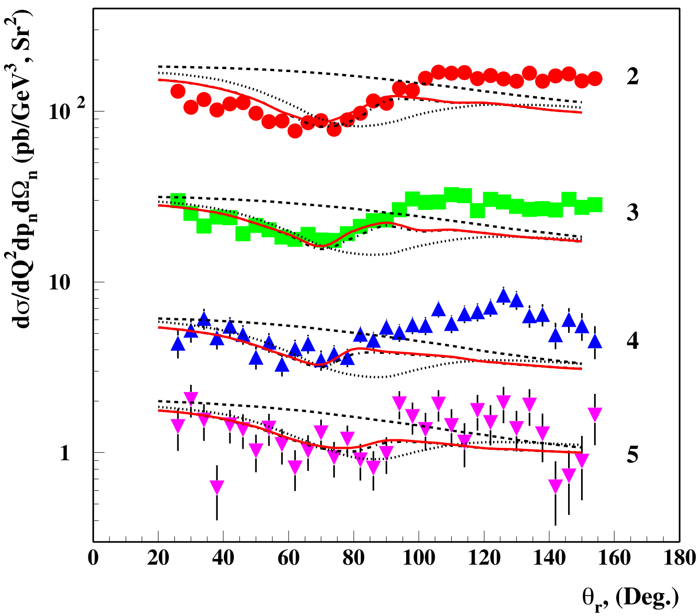
CLAS



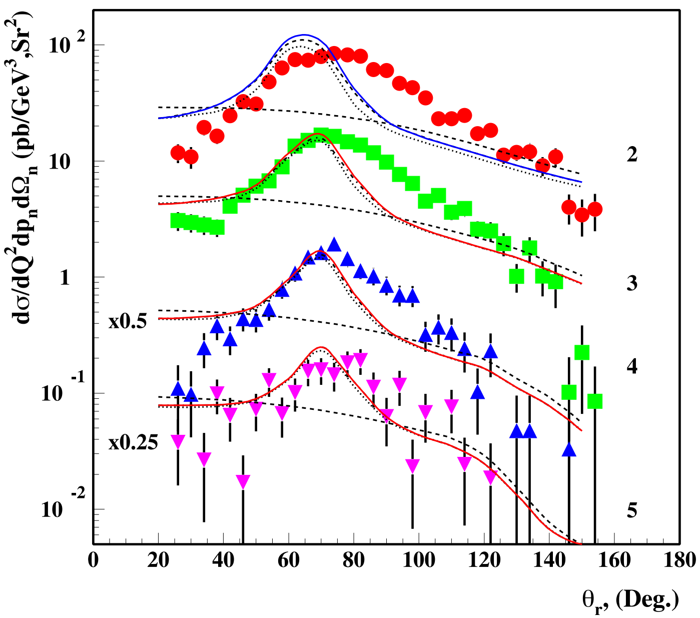
Data: Egyian et al. (CLAS) PRL 98 (2007)

Calculation M. Sargsian

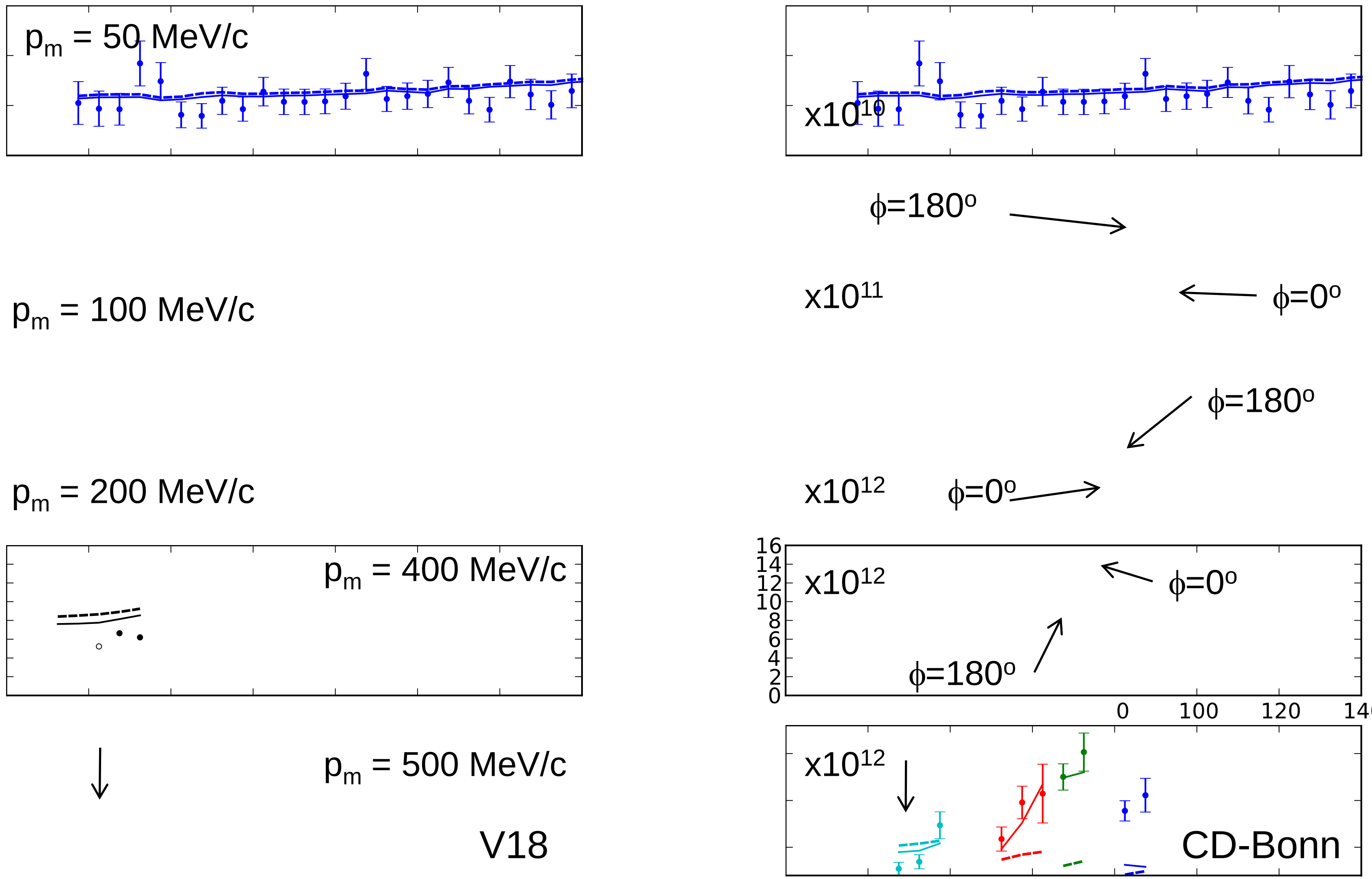
p_m = 250 ± 50 MeV/c



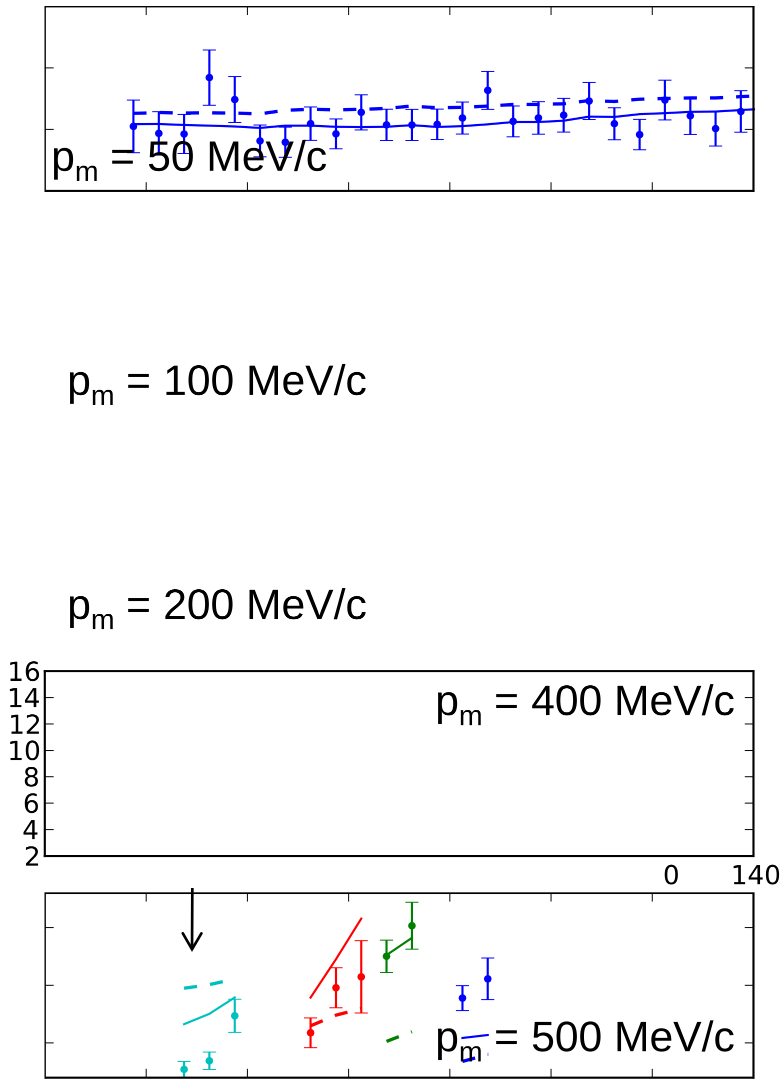
p_m = 500 ± 100 MeV/c

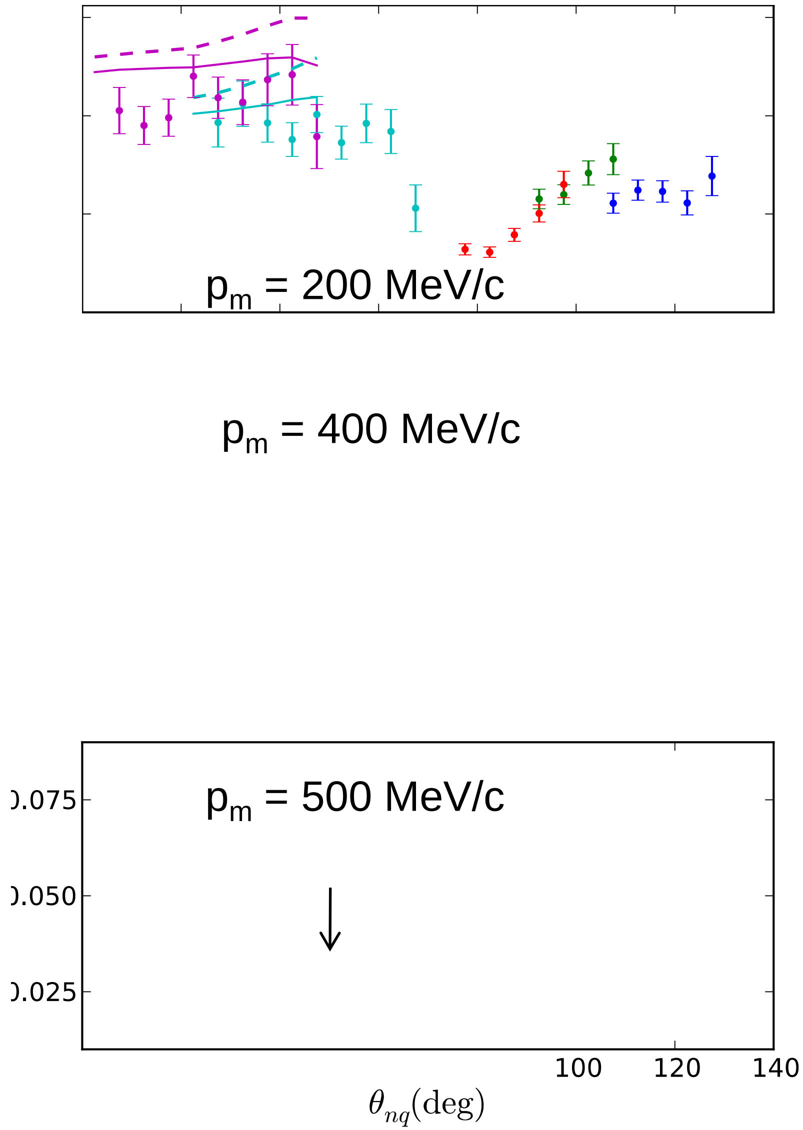


Hall A $Q^2 = 3.5(GeV/c)^2 \;\; \Delta p_m \pm 20 MeV/c$



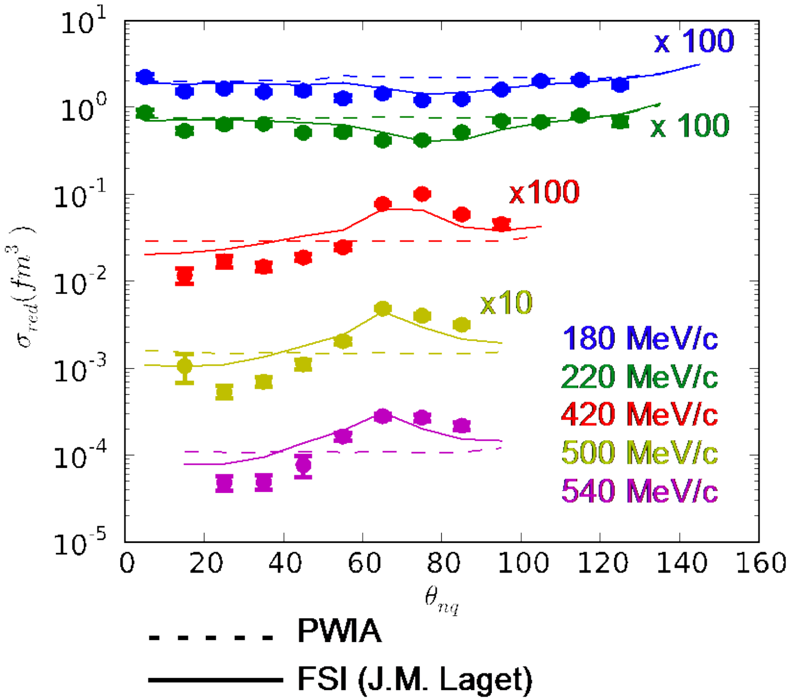
Calculations: M. Sargsian

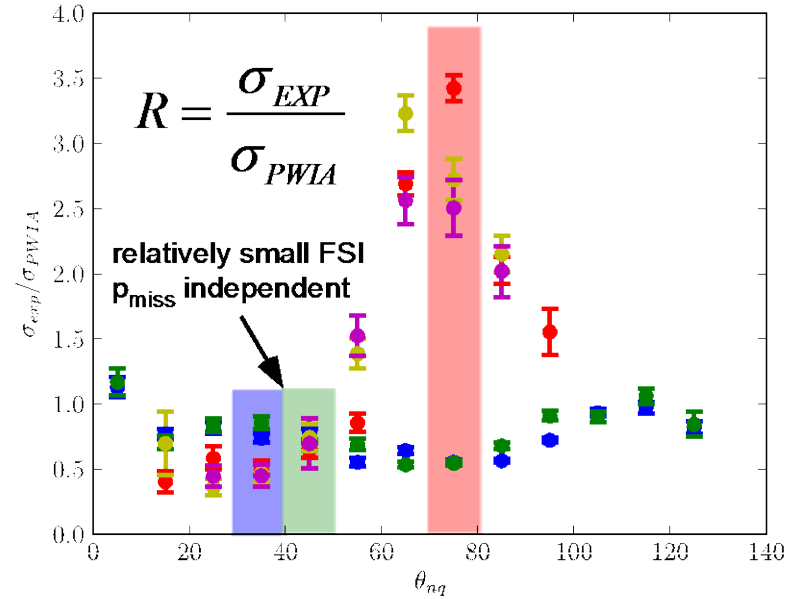


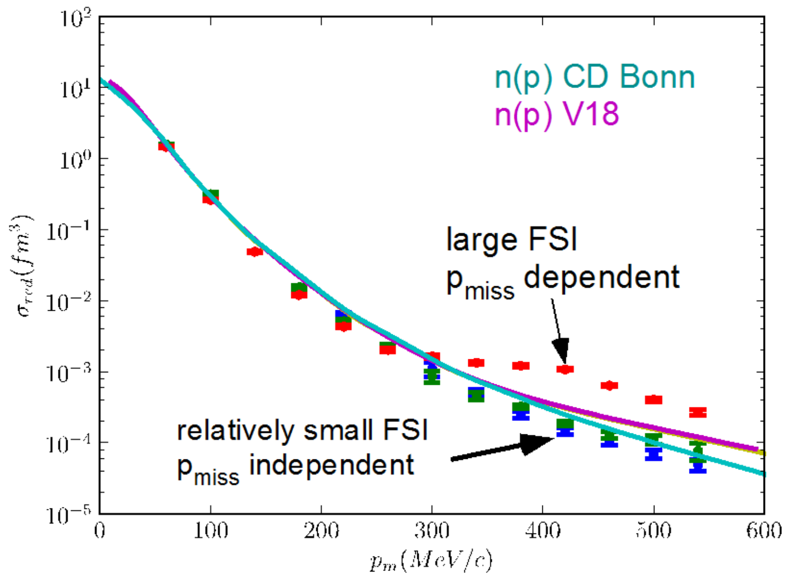


J.M.Laget

S. Jeschonnek J.W. van Orden

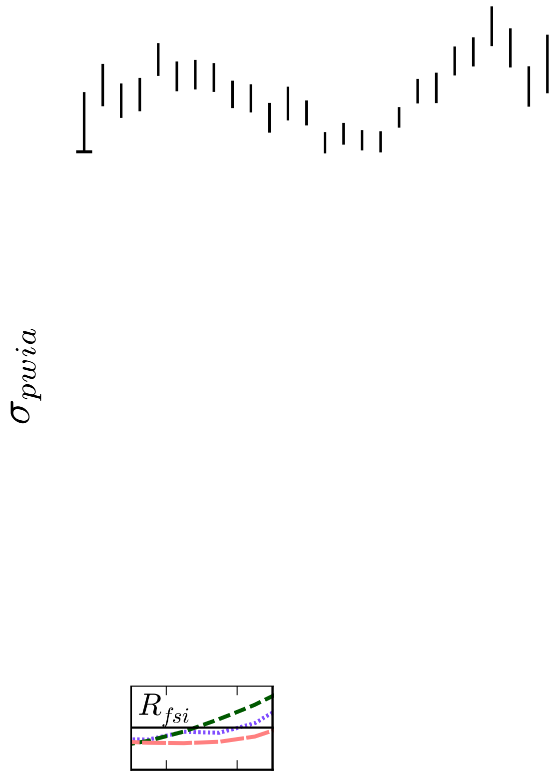






$$\sigma_{red} = \frac{\sigma_{exp}}{k\sigma_{cc1}}$$

for recoil angles around 40^o FSI seem to be minimal and independent of p_m

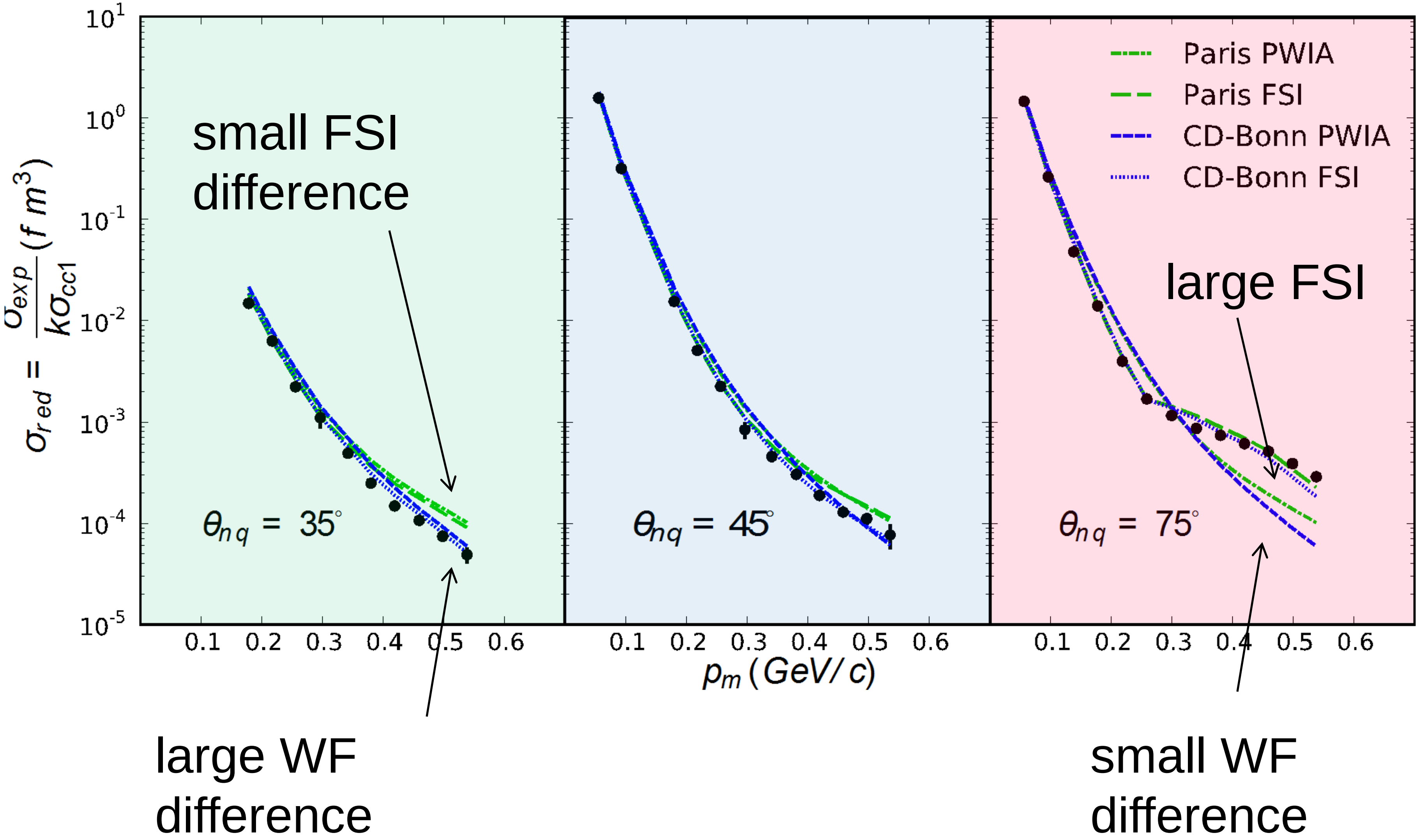


Summary of angular distributions At $Q^2 = 3.5\ (\text{GeV}/c)^2$

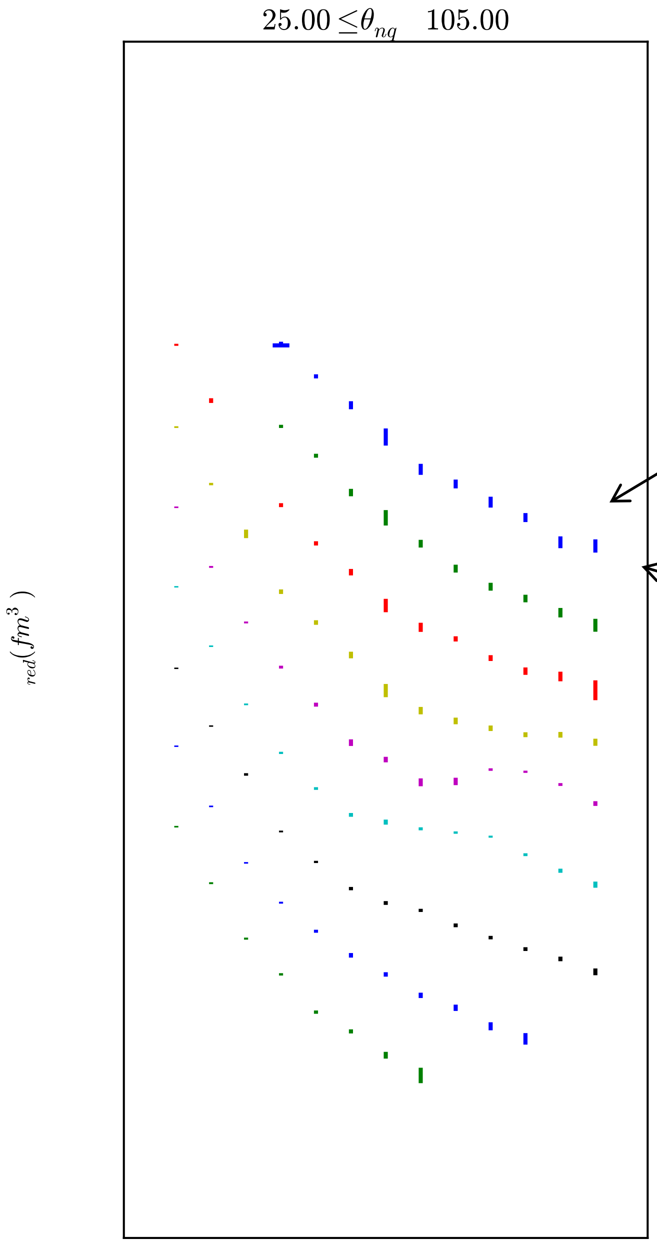
$$R = \frac{\sigma}{\sigma_{PWIA}}$$

σ Is experimental or calculated cross section

WB et al. PRL 107 (2011) 262501



small FSI difference
large FSI
large WF difference
small WF difference
Paris PWIA
Paris FSI
CD-Bonn PWIA
CD-Bonn FSI
$\sigma_{red} = \frac{\sigma_{exp}}{k\sigma_{cc1}} (f\,m^3)$
$\theta_{nq} = 35^\circ$
$\theta_{nq} = 45^\circ$
$\theta_{nq} = 75^\circ$
$p_m\,(GeV/c)$
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



each angle offset by 0.1

‘yellow’ n(p) Paris

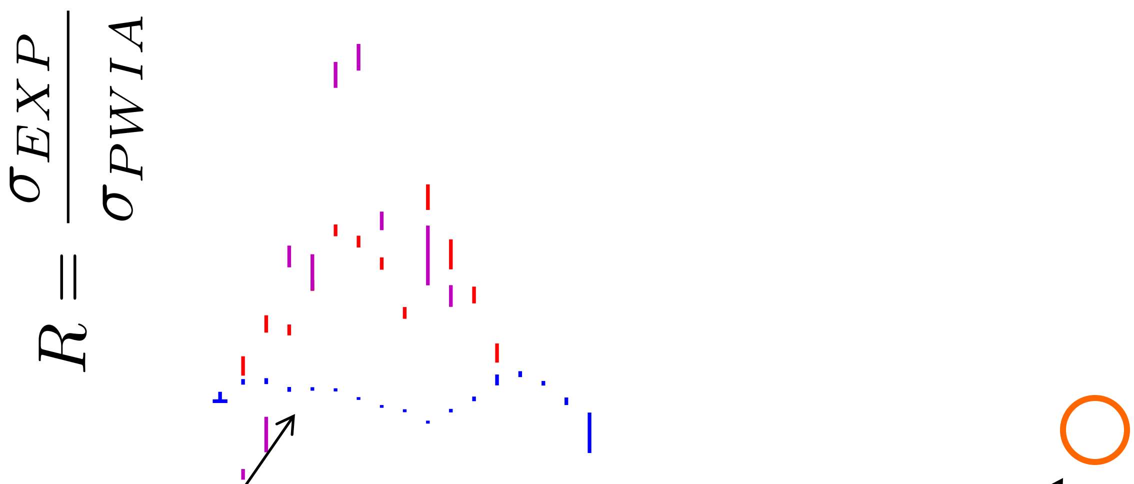
‘cyan’ n(p) CD Bonn

Lower Q^2

Thesis H. Khanal

Preliminary

$= 2.1$



No FSI ‘crossing’
Eikonal regime not yet reached

Crossing
Eikonal regime reached

Double Ratios

Preliminary

$= 2.1$ $Q^2 = 3.5$

Re-scattering increasing with Q^2

Extraction of $\rho(\alpha,p_t)$

- attempt to extract $\rho(\alpha, P_T)$ from experimental data
- Theoretical foundation:

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

Advantages of working on LC:

- at high Q^2, FSI is mostly transverse α is approx. conserved by FSI
- $\rho(\alpha)$ 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

$$F_{2d}(x) = \sum_N \int_x^2 F_{2N}(\frac{x}{\alpha})\rho(\alpha)\frac{d\alpha}{\alpha}$$

Light Cone Variables

Light cone variables for experimentalists:

4-vector: $V = (V^o, \vec{V})$ light cone: $V = (V^+, V^-, \vec{V}_T)$

$$V^{\pm} = V^o \pm V_z$$

Lorentz Transformation along z-axis: $V'^{\pm} = e^{\psi} V^{\pm}$ $\psi = \frac{1}{2} \ln\left(\frac{1+\beta}{1-\beta}\right)$

= scalar multiplication

Important property $\frac{V'^{\pm}}{V^{\pm}}$ boost invariant

Deuteron Momentum Distributions on the Light Cone (LC)

LC momentum $p^- = E - p_z$

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

analogous to "x" for quark distributions

α is frame independent for boosts along the z-axis

LC cross section

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

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

remember in lab: $P_D^- = M_D$ and $A = 2$

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

LC momentum

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

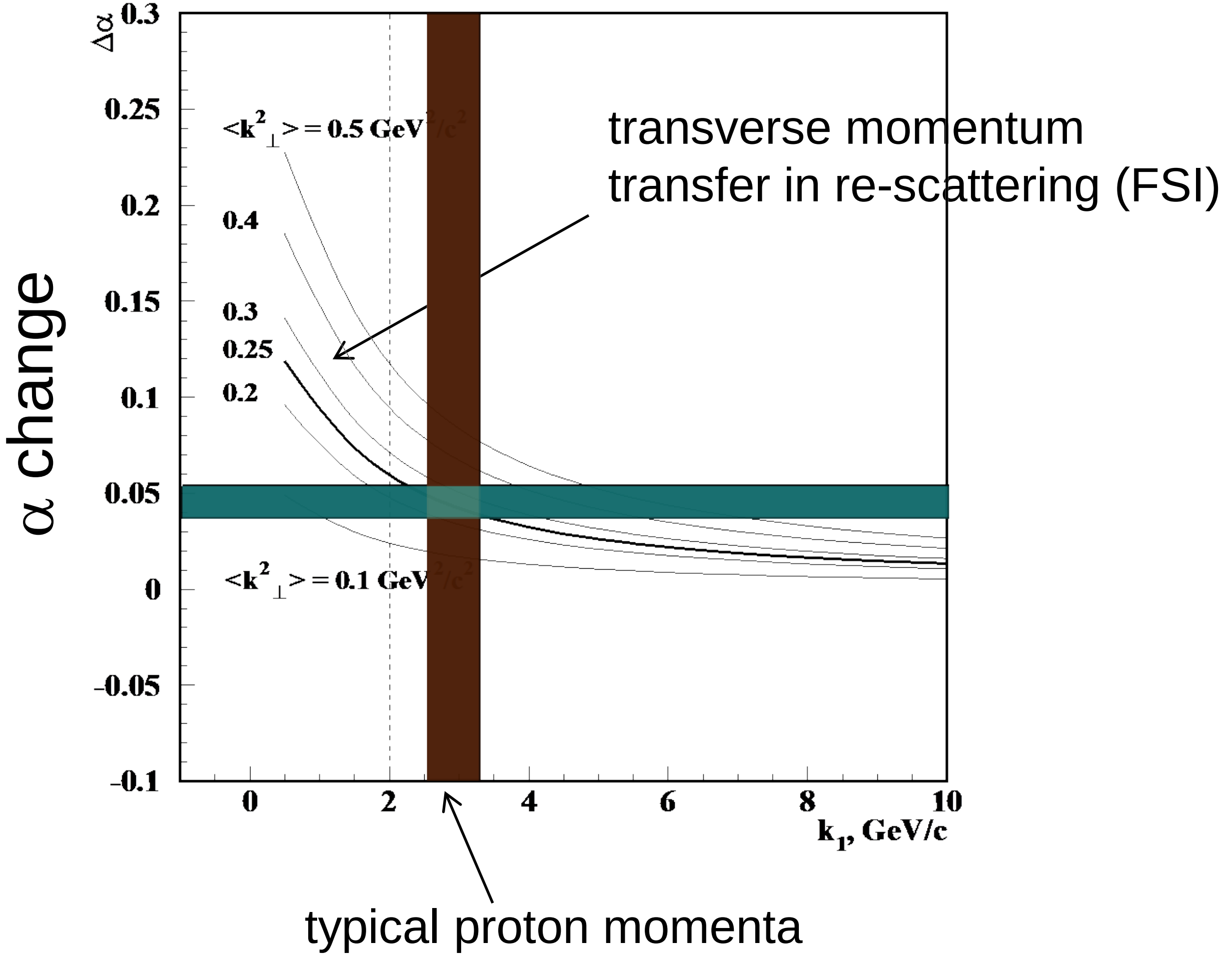
$$k = \sqrt{\frac{M_N^2 + p_t^2}{\alpha_s(2-\alpha_s)} - M_N^2} \qquad E_k = \sqrt{M_n^2 + p_t^2}$$

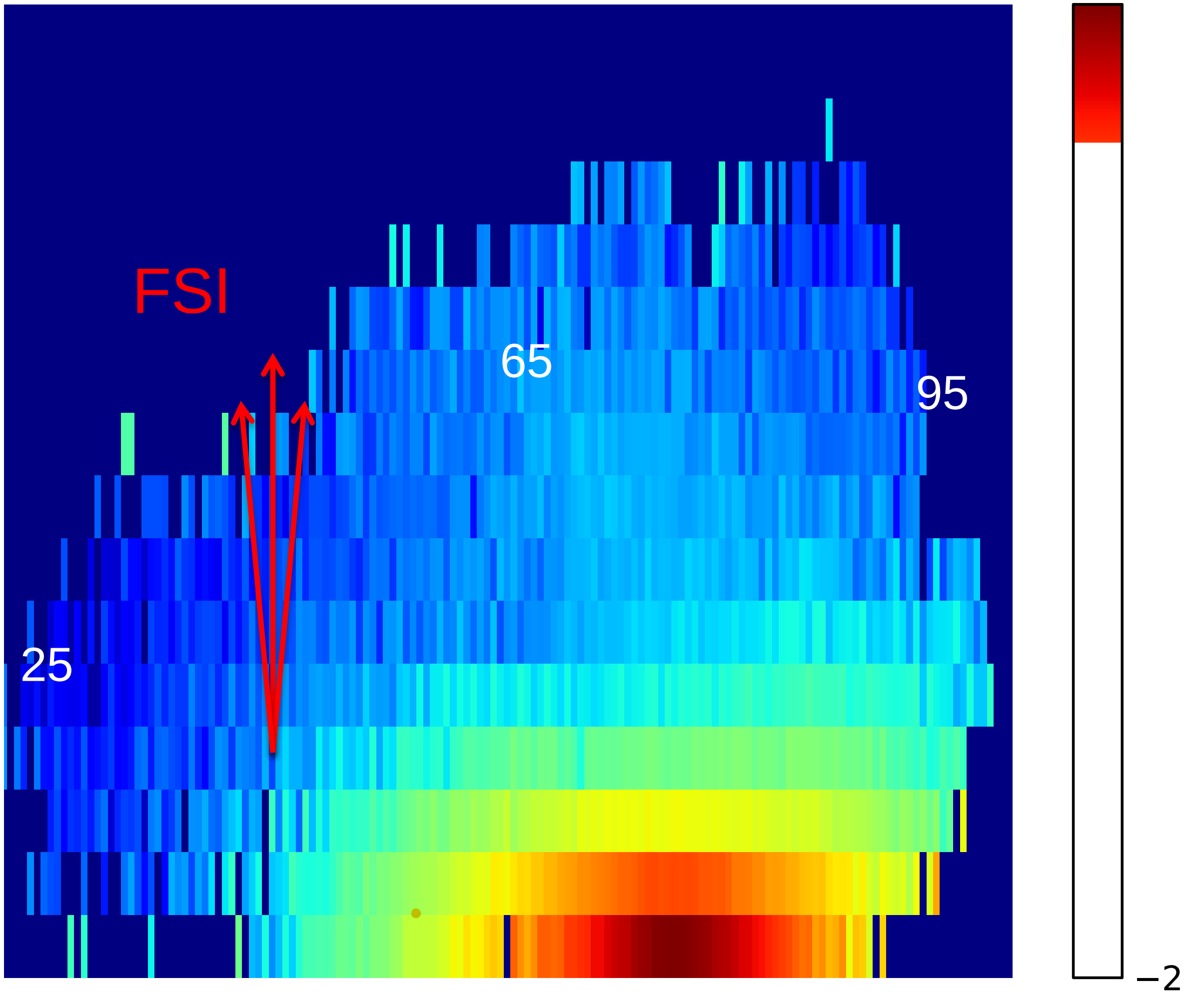
k relative nucleon momentum in *np* system in light cone

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

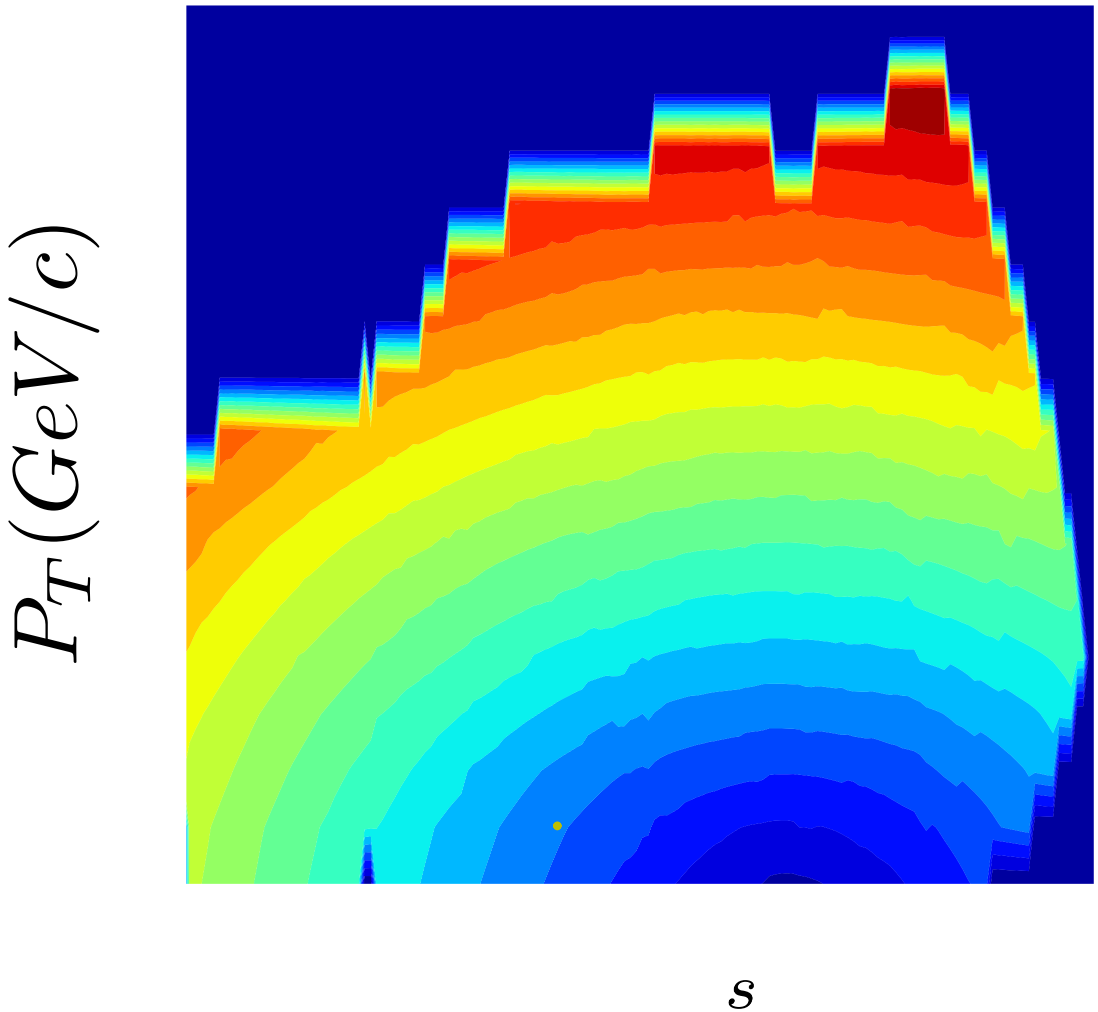
LC Momentum sum rule $\int \alpha\rho(\alpha)\frac{d\alpha}{\alpha}2\pi p_t dp_t = 1$

α conservation as function of nucleon momenta




FSI
65
95
25
−2

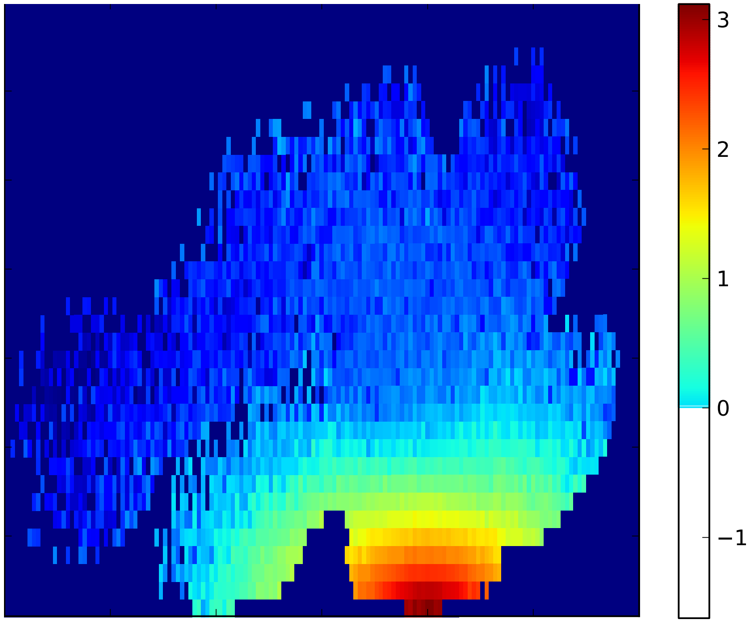
Contours of k = const



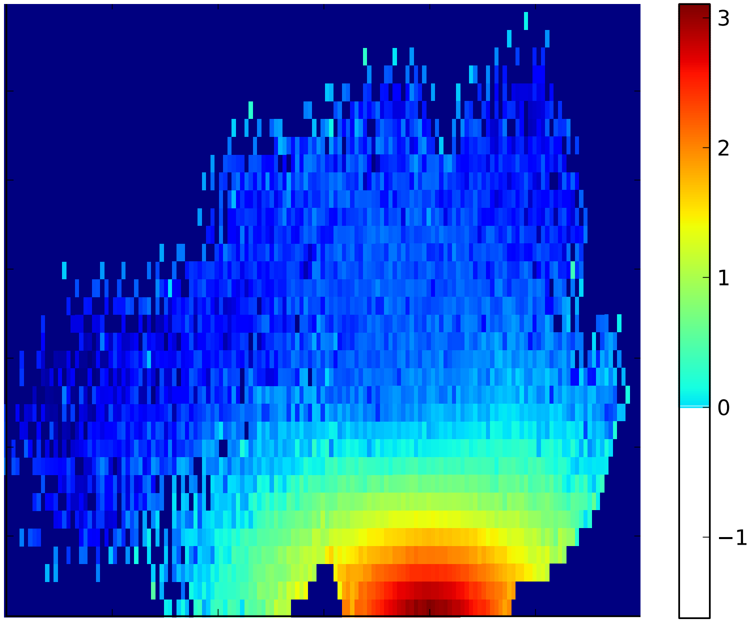
Experimental $\rho(\alpha, p_t)$ distributions

- Determine d(e,e'p)n cross section for each α_s, p_t bin
- Divide by $K\sigma_{eN}^{LC}$
- Problem: phase space acceptance
- Results should be as independent as possible of phase space cut
- Missing information due to cuts

Phase Space Coverage at $Q^2 = 3.5$

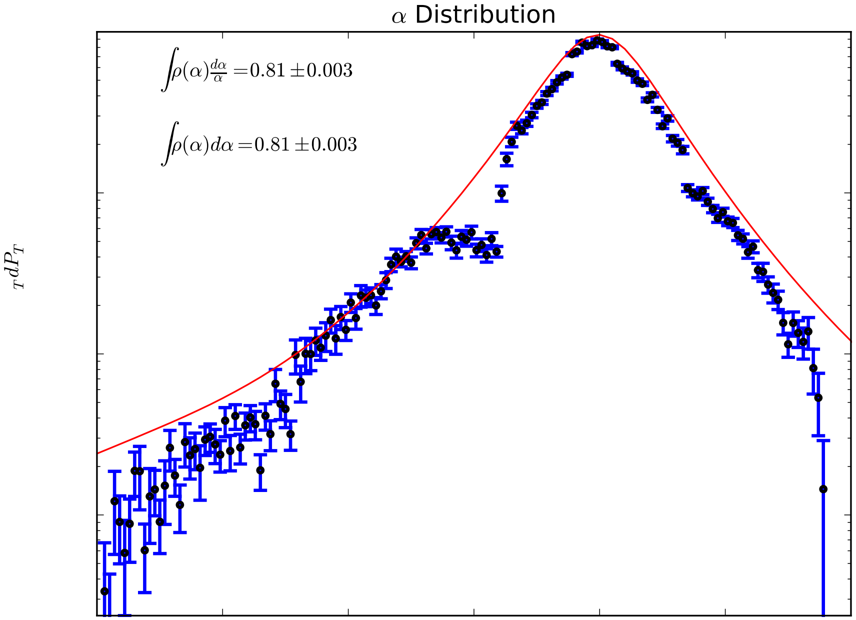


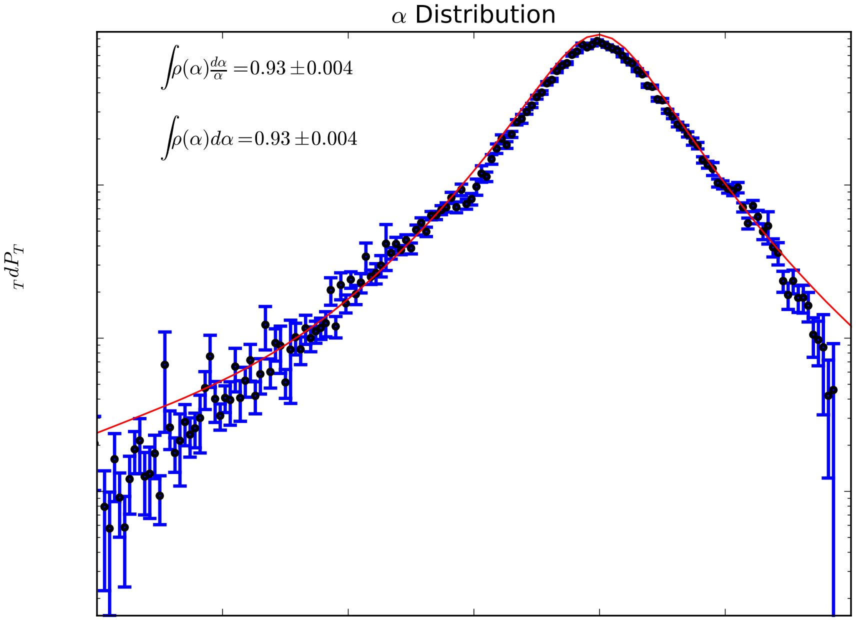
20% cut



2.5% cut

$$\int \rho(\alpha, P_T) 2\pi P_T dP_T \approx \sum \rho(\alpha, P_T) 2\pi P_T \Delta P_T$$





Interpolating missing data

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

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

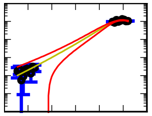
Parameters: $\alpha, \beta, \gamma, \delta_{s,l}, A$

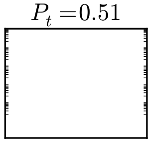
use δ_s for $\alpha < A$

use δ_l for $\alpha > A$

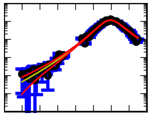
Calculated using model: $\rho_{LC}(\alpha)$
(e.g. Paris WF)

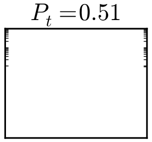
20% cut



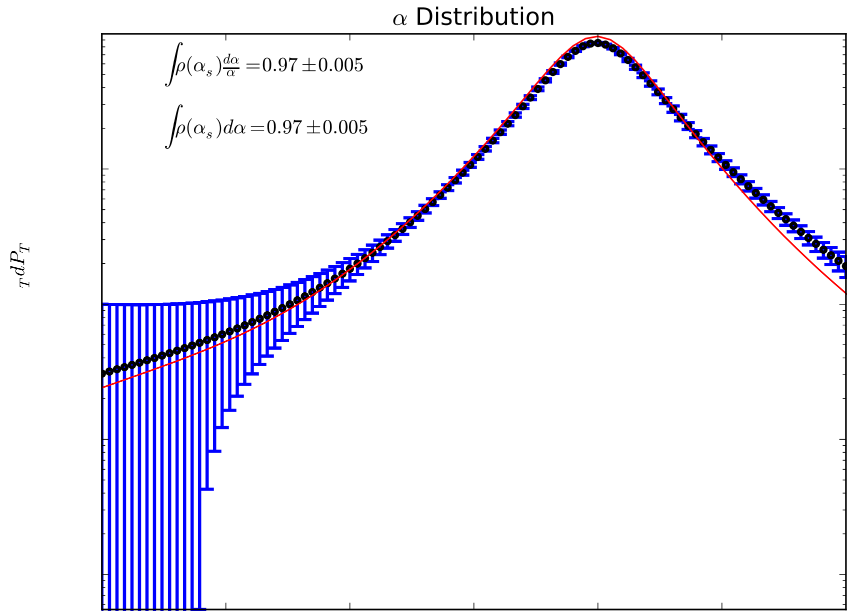


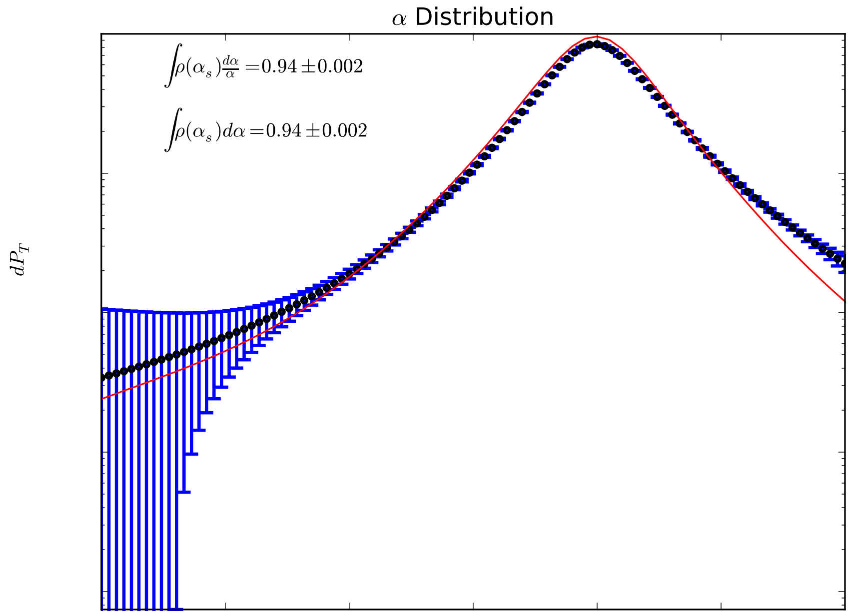
2.5% cut





ρ(α) using fit interpolation





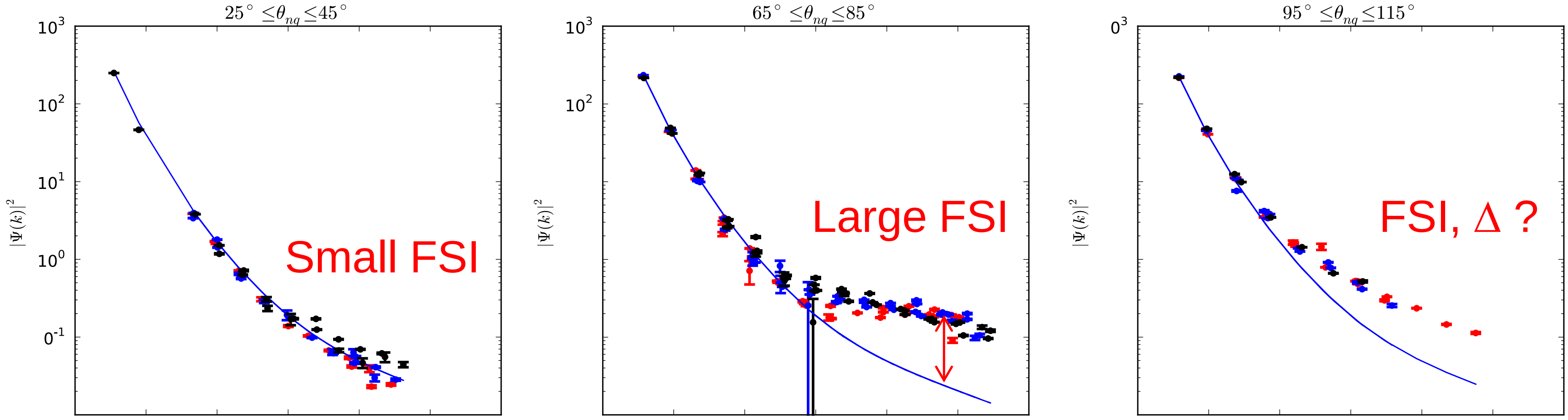
20% cut

2.5% cut

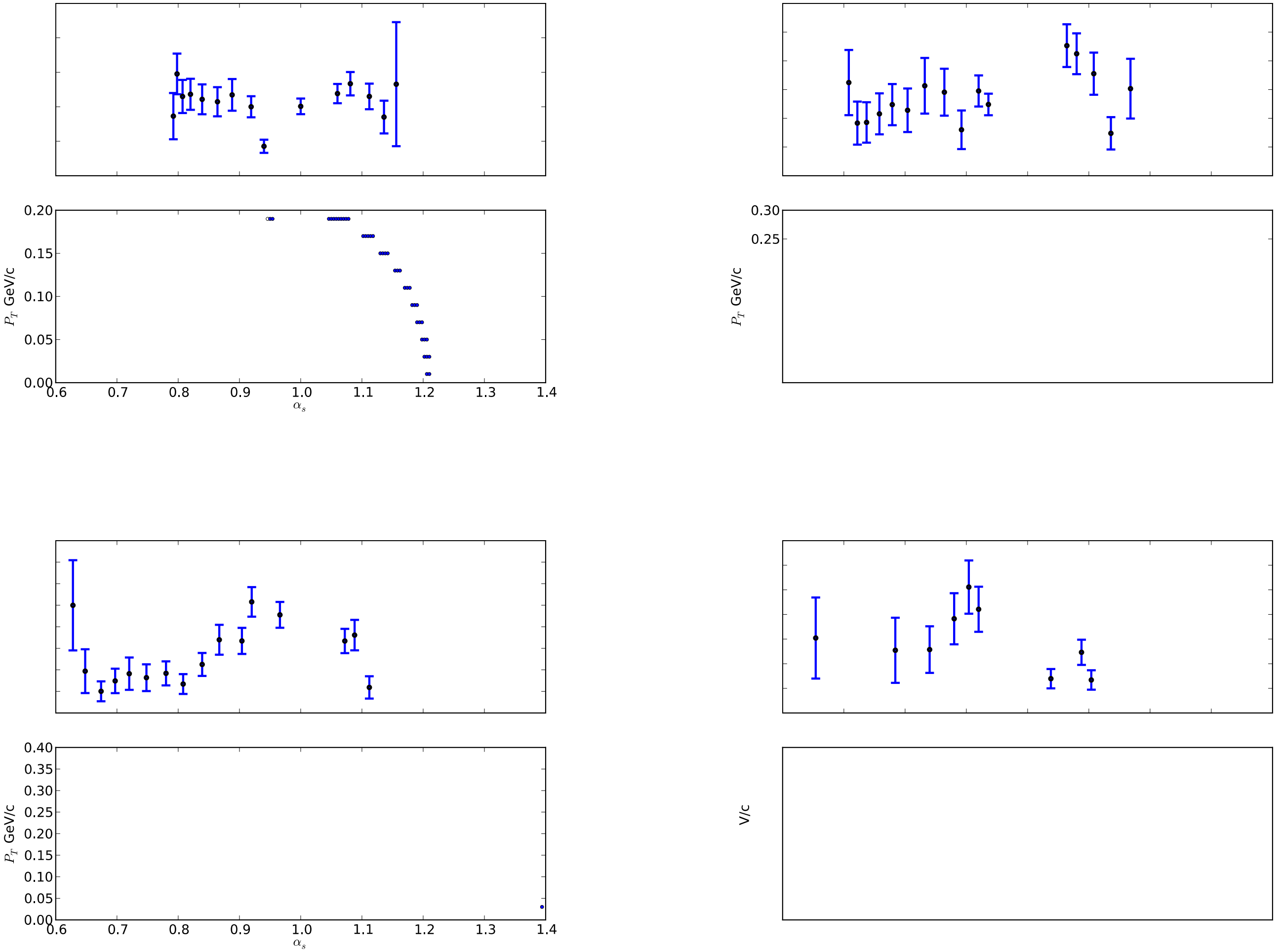
Experimental $|\psi(k)|^2$ distributions

- Determine d(e,e'p)n cross section for each θ_{nq}, p_m bin
- Divide by $K\sigma_{eN}^{LC}$
- Calculate $|\Psi_d(k)|^2$

Paris WF

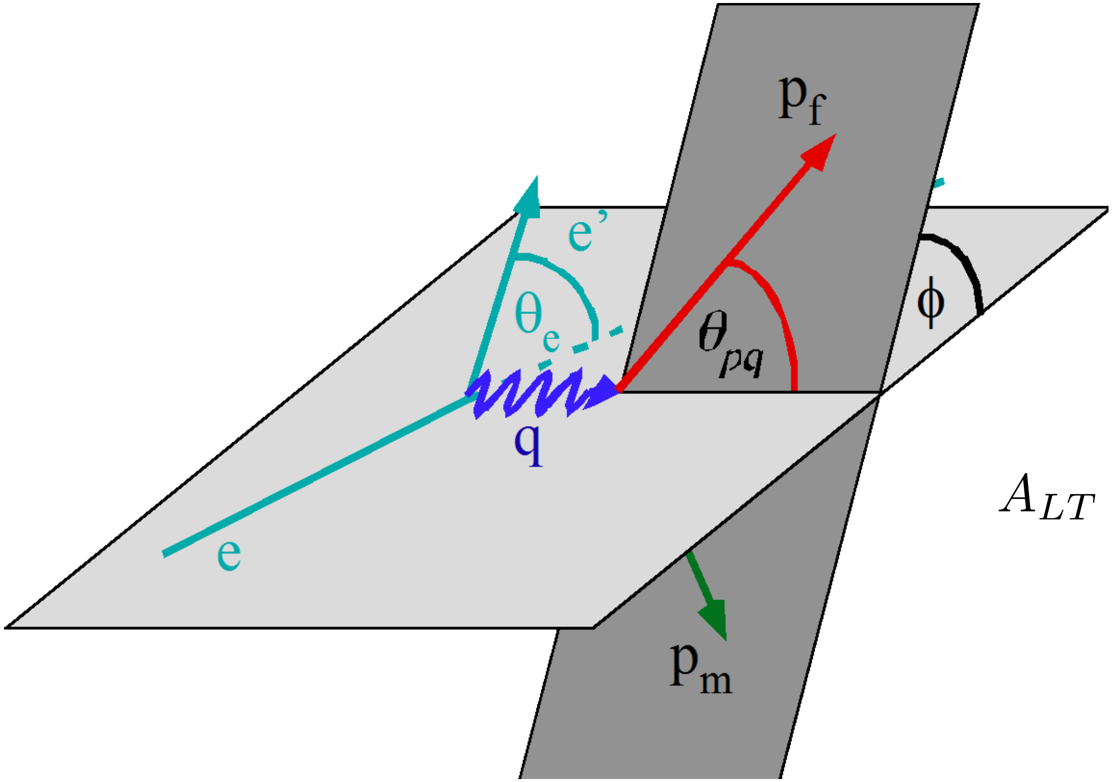


Rotational Invariance



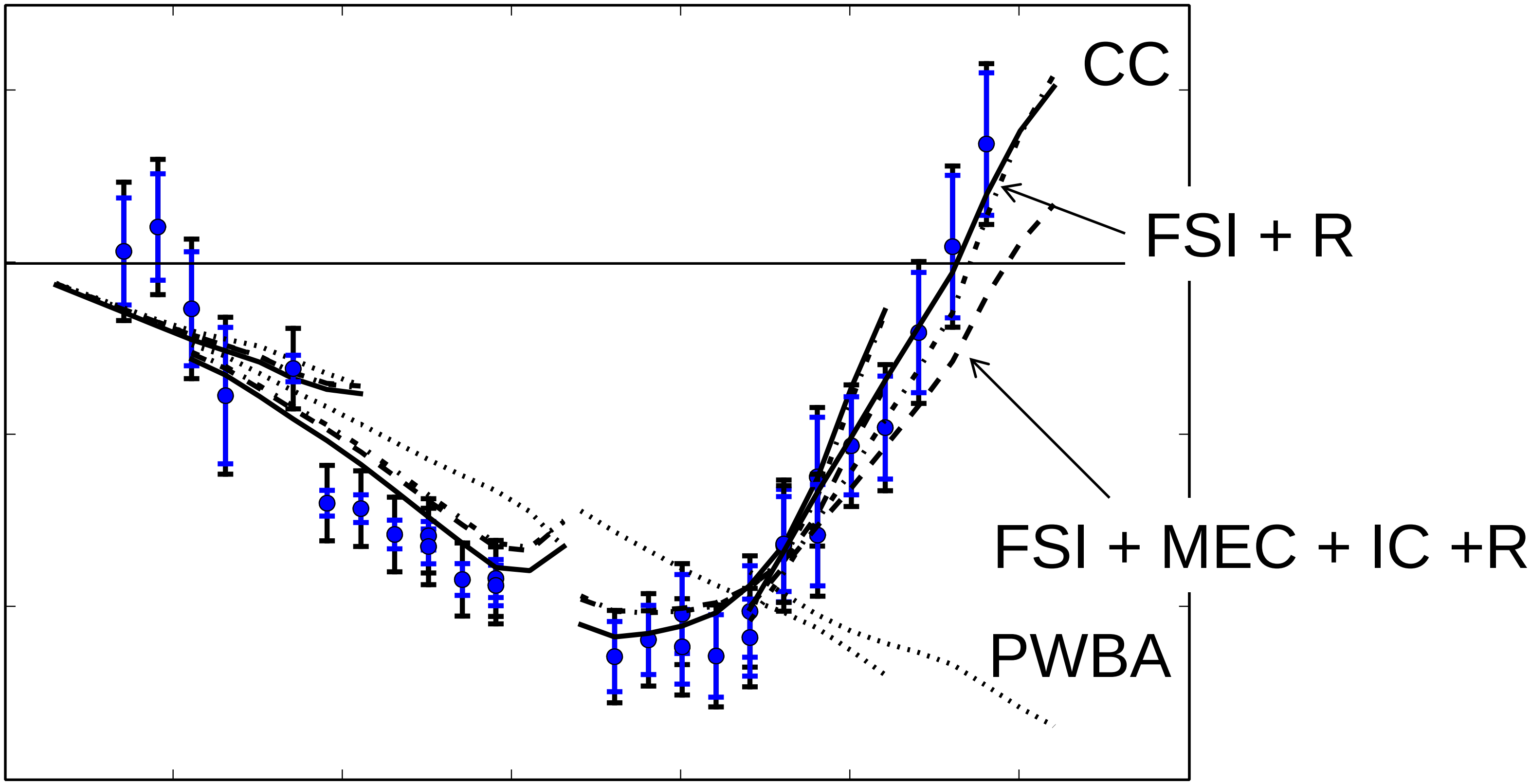
Response Functions

$$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = \sigma_M f_{rec} \left(v_L R_L + v_T R_T + v_{LT} R_{LT} \cos(\phi) + v_{TT} R_{TT} \cos(2\phi) \right)$$

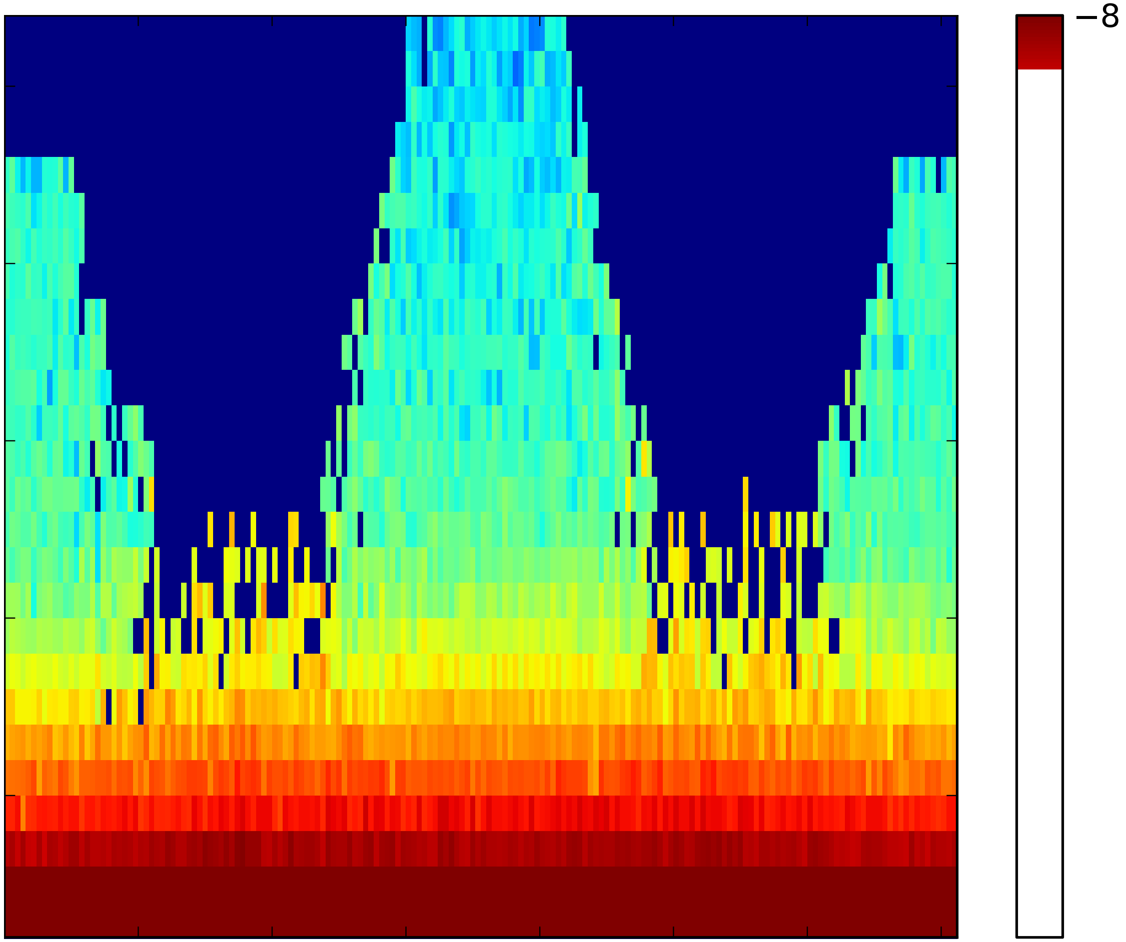


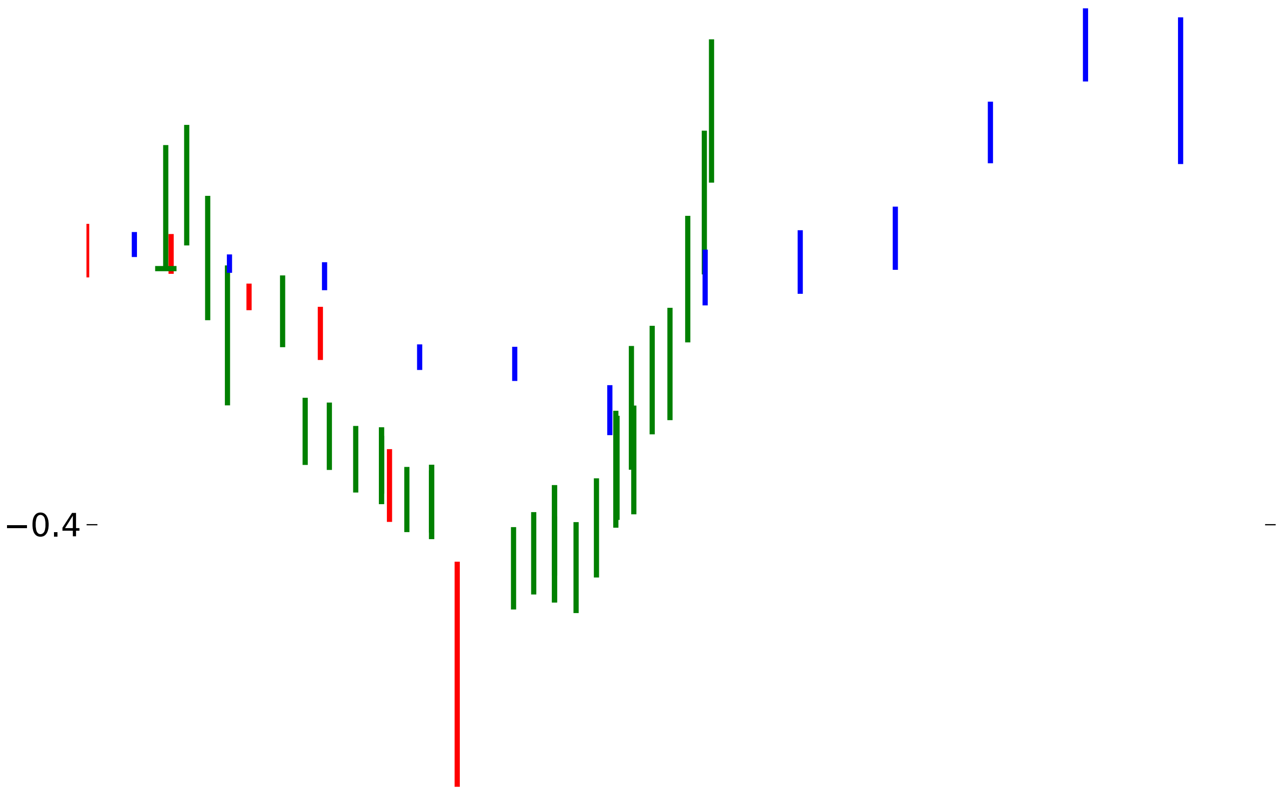
$$A_{LT} = \frac{\sigma(\phi = 0) - \sigma(\phi = 180)}{\sigma(\phi = 0) + \sigma(\phi = 180)}$$

At low Q^2 A_{LT} is well understood



WB et al.Phys. Rev C78 054001 (2008)


−8


−0.4

Future Experiment at 12 GeV

- 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

Measurements in Hall C

Beam:
Energy: 11 GeV
Current: 80μA

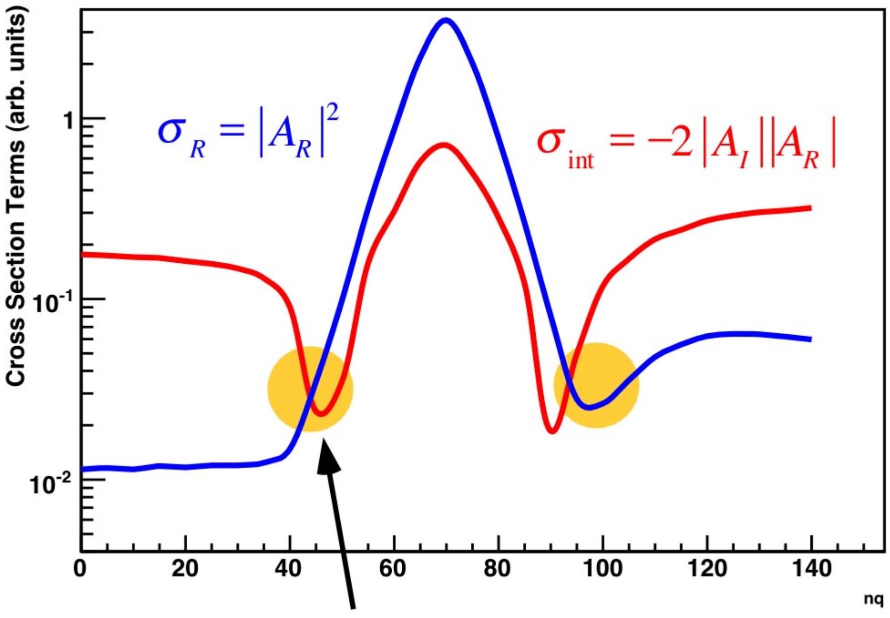
Electron arm *fixed* at:
SHMS at p_{cen} = 9.32 GeV/c
$\theta_e = 11.68^o$
$Q^2 = 4.25\ (GeV/c)^2$
x = 1.35

Vary proton arm to measure :
p_m = 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 GeV/c
HMS 1.96 d p_{cen} d 2.3 geV/c
Angles: 63.5^o e θ_p e 53.1

Target: 15 cm LHD

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:

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

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

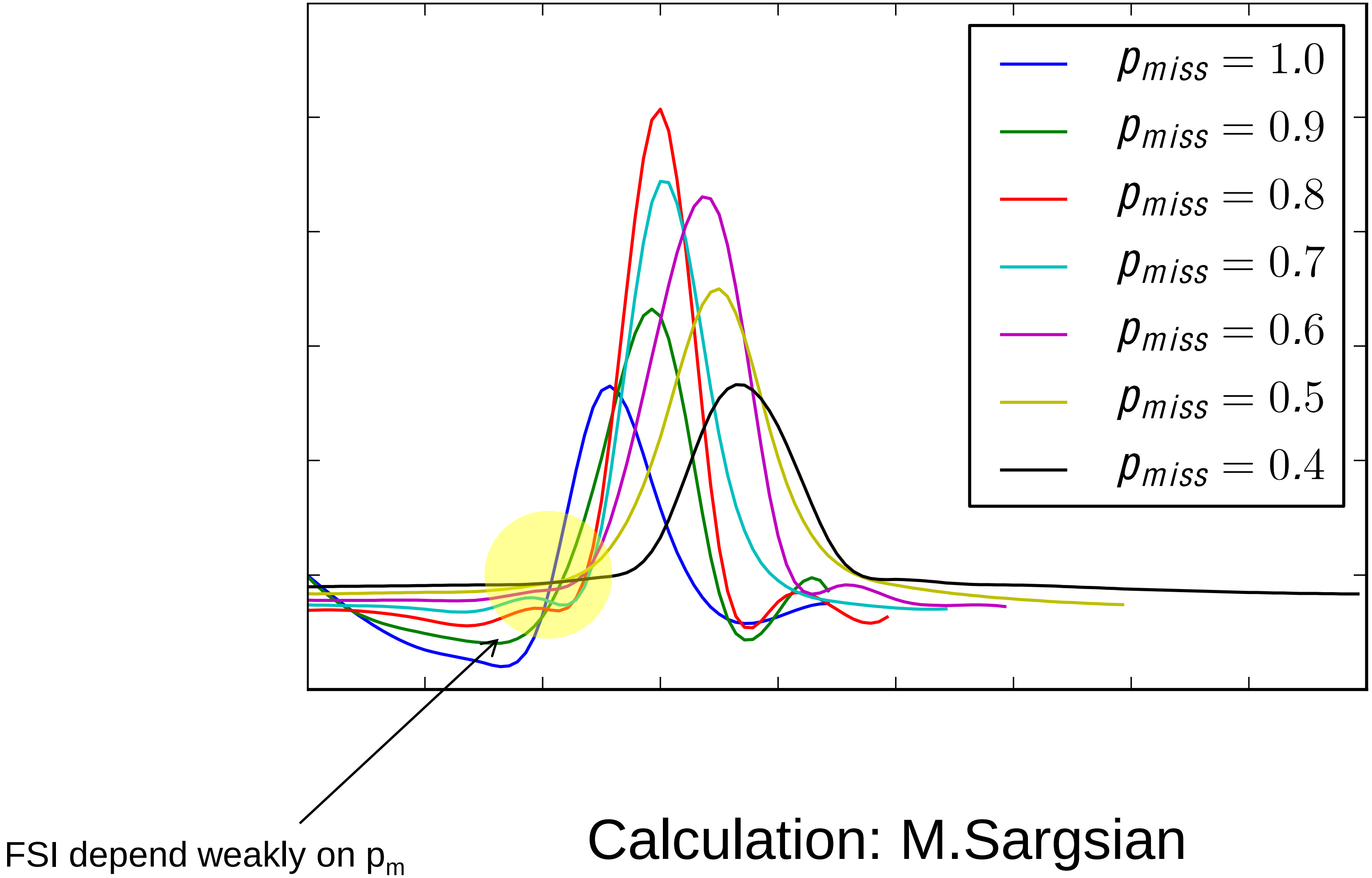
$$b \sim 6(GeV/c)^{-2}$$

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

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

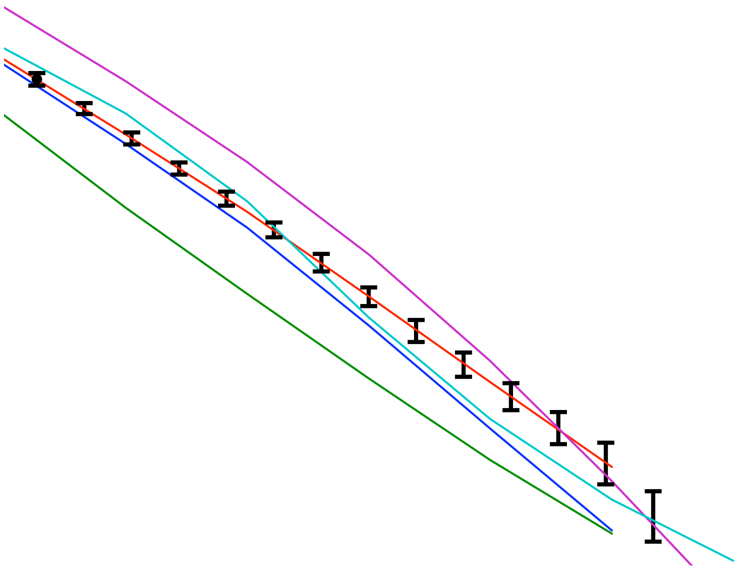
- b determined by nucleon size
- cancellation due to imaginary rescattering amplitude
- valid only for high energy (GEA)

Angular Distributions up to p_m = 1GeV/c



Calculation: M.Sargsian

Expected Results



- ✓ Measured cross sections for p_m up to 1 GeV/c
- ✓ Errors: dominated by statistics: 7% - 20%
- ✓ Estimated systematic error H5 %
- ✓ Very good theoretical support available
- ✓ JLAB uniquely suited for high p_m study
- ✓ Good coincidence commissioning experiment
- ✓ 21 days of beam time

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 window to study the Deuteron momentum distribution, CD Bonn seems OK
- current analysis of lower Q^2 data (H.Khanal thesis) soon complete
- first attempt to extract α distributions, Paris seems OK
- increase kinematics coverage for α determination
- high R_{LT} at high P_T cannot be reproduced
- 12 GeV: very high missing (up to 1GeV/c) momenta