Probing the Deuteron Structure at Short Distances

Werner Boeglin

Florida International University

Miami

Contents

- Introduction, History
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- Missing momentum dependences
- Light cone momentum distribution
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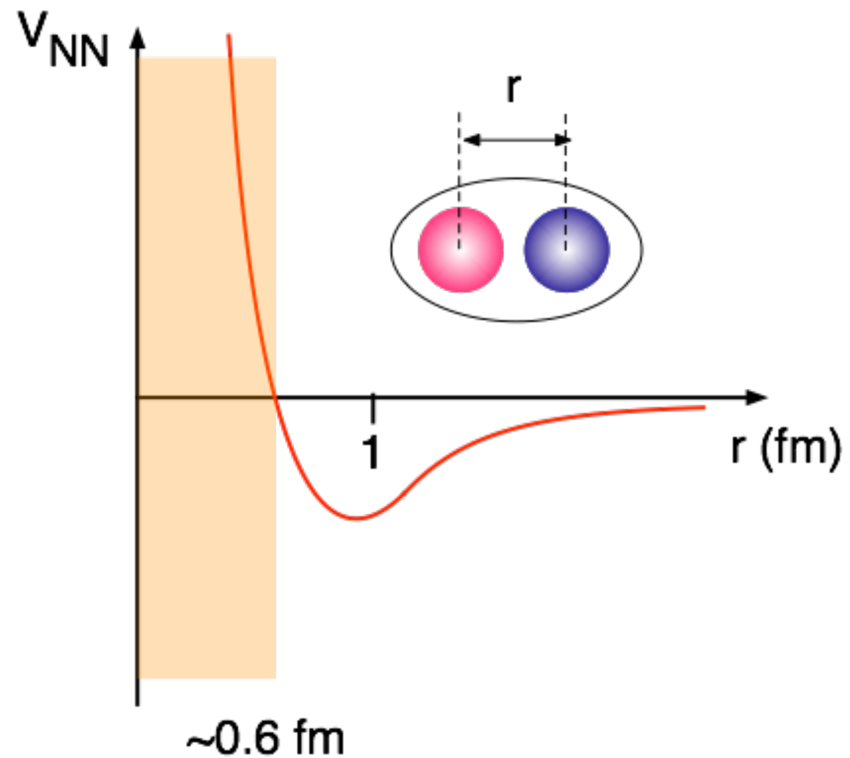
- Summary

Introduction: Role of the Deuteron

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

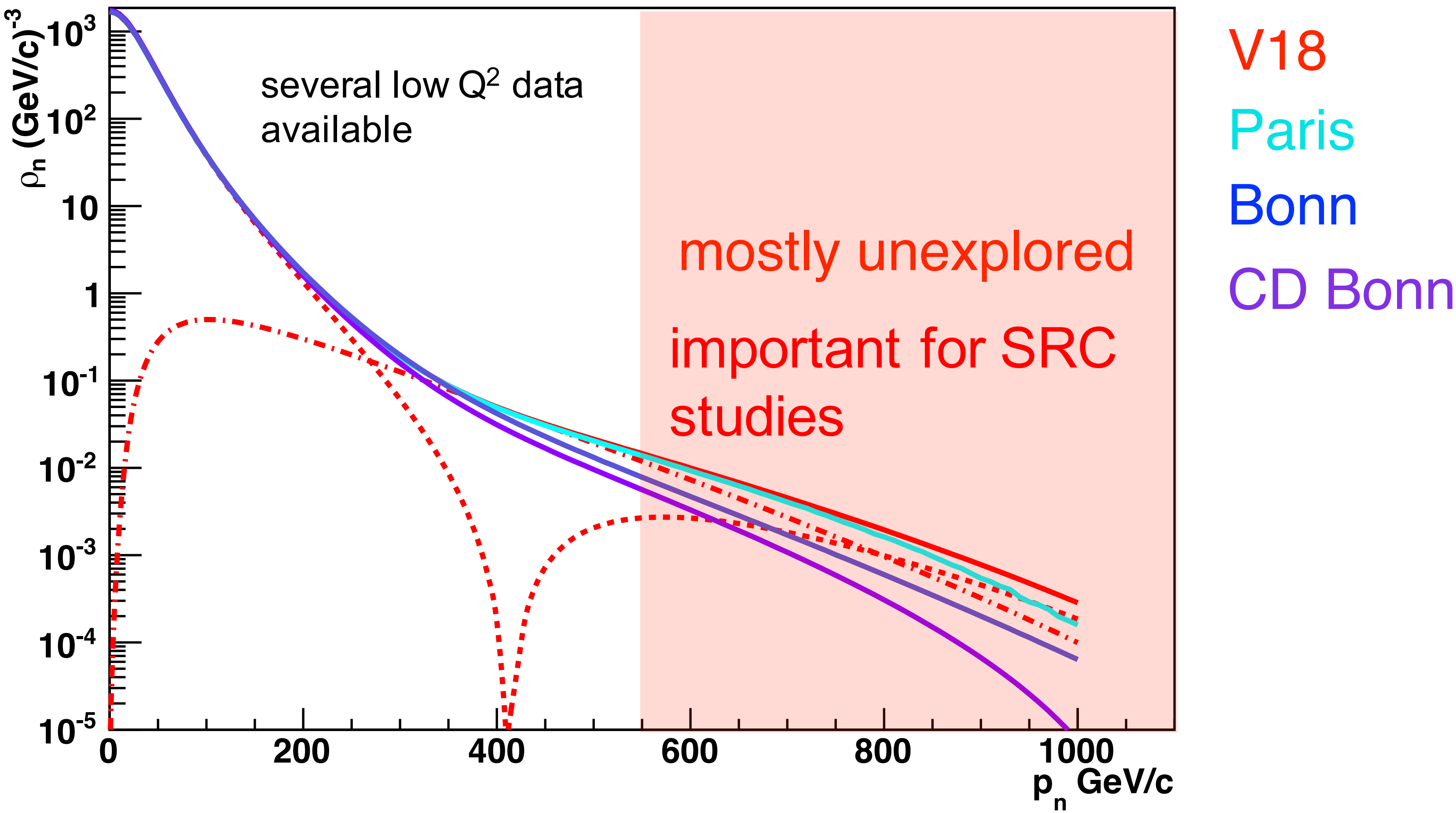


Ideally 'measure' the momentum distribution ⇒ study the d(e,e'p) reaction

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

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

High Q^2 data are necessary for progress!

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.

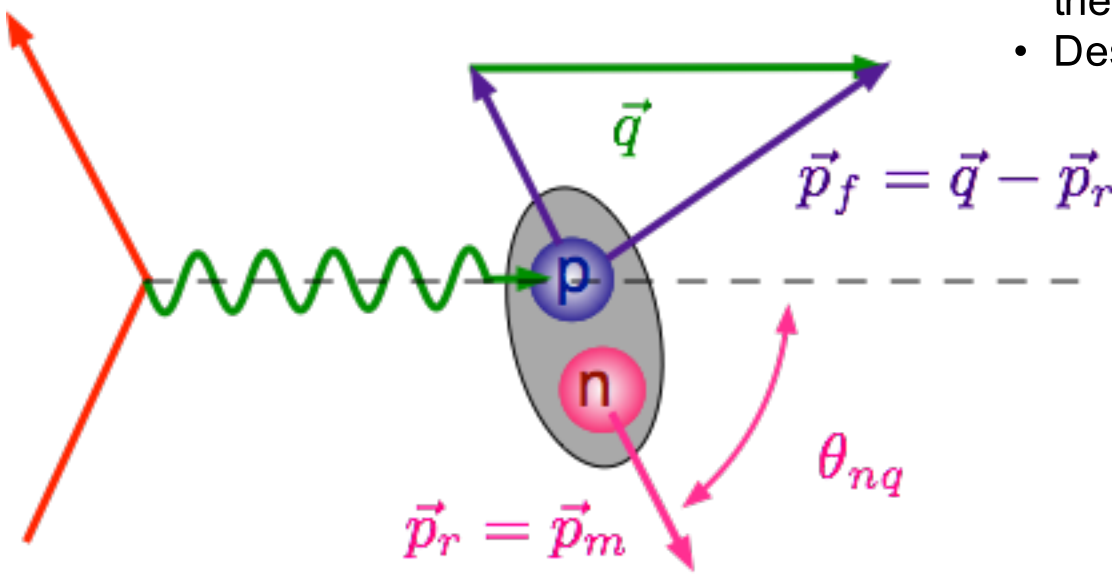
Ideally 'measure' the momentum distribution
$\Rightarrow$ study the d(e,e'p) reaction

D(e,e'p) 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

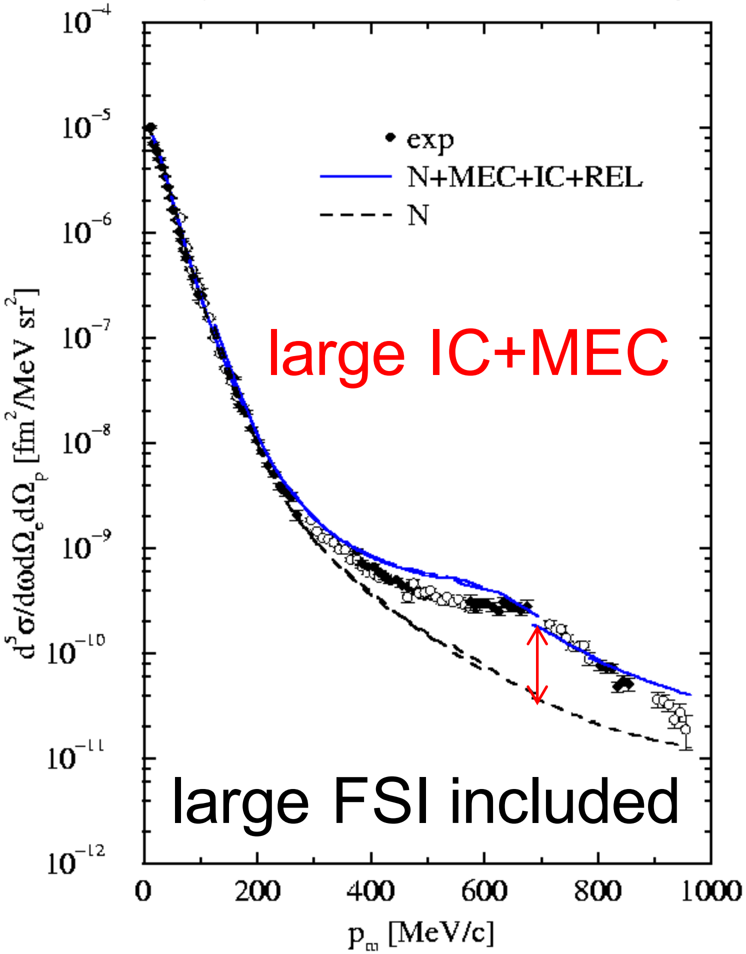


Experimental
Momentum distributions:

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

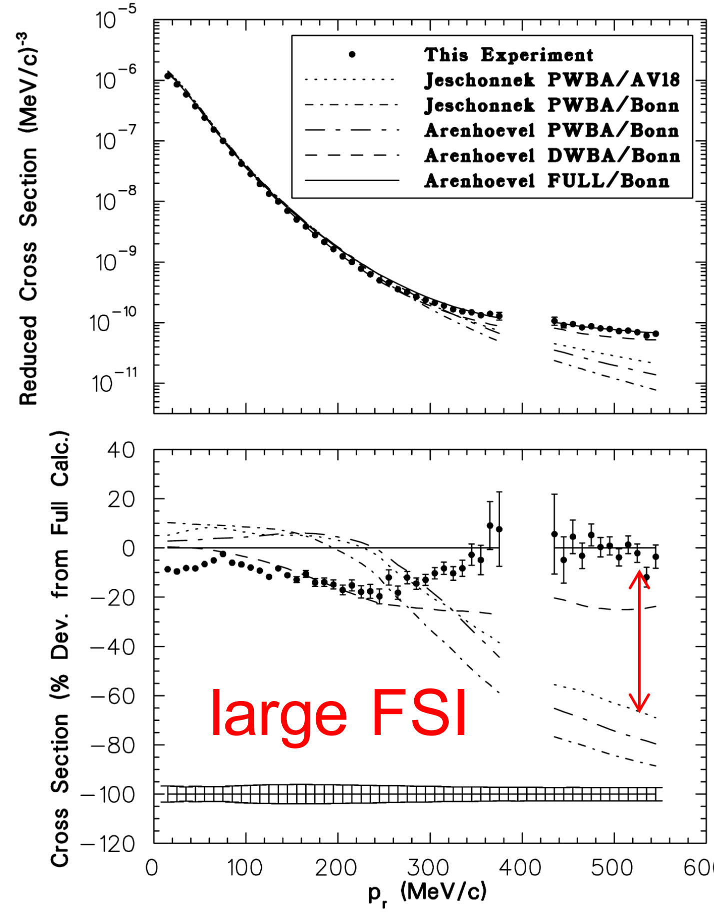
Missing Momentum Dependences

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

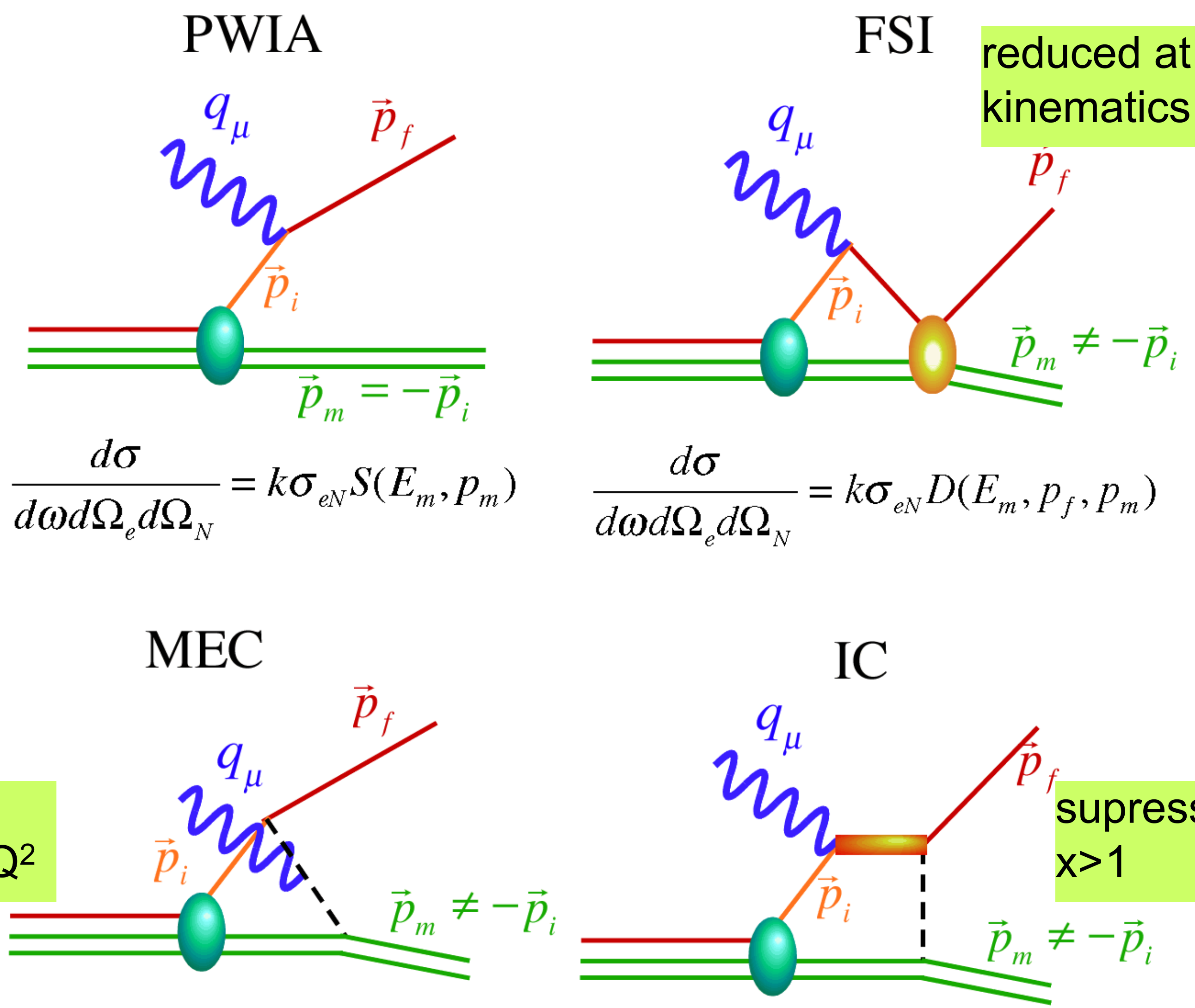
Blomqvist et al. PLB 429 (1998)



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

Ulmer et al. PRL89 (2002) 062301-1

D(e,e’p) Reaction Mechanisms



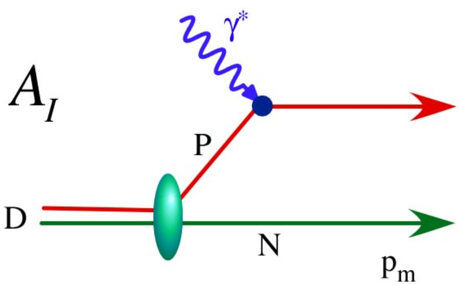
reduced at certain kinematics ?

expected to be small at large Q^2

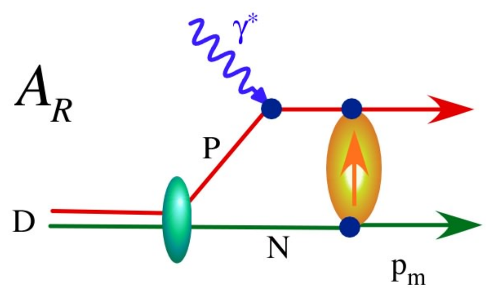
supressed for x>1

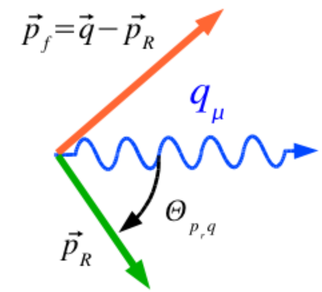
At high Q^2 FSI as Re-Scattering

IA Amplitude (real):



Rescattering Amplitude
(at high energy mostly imaginary):



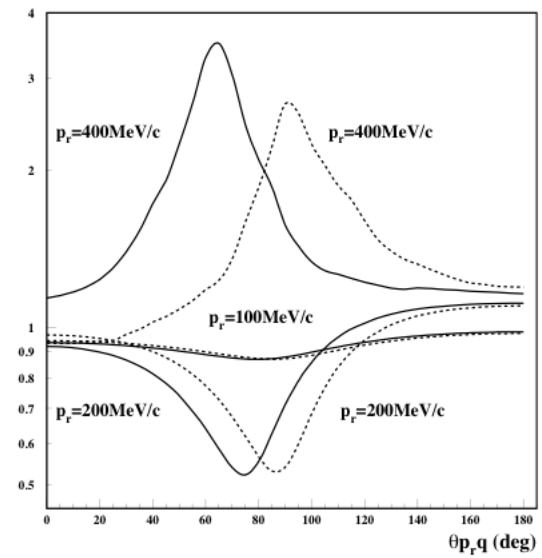


Total scattering amplitude: $A = A_I + iA_R$

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

Hall A

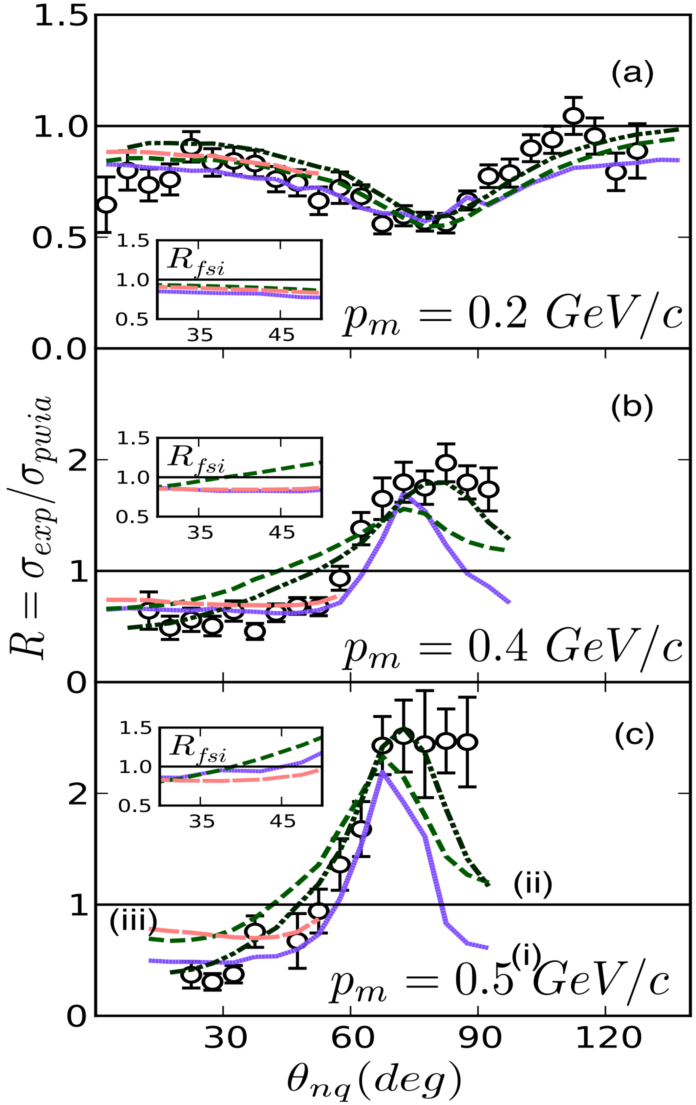
- Q^2 = 0.8, 2.1 and 3.5 $(GeV/c)^2$: constant for each set
- p_{miss} = 0.2, 0.4 and 0.5 GeV/c : angular distribution
- $20^\circ \leq \theta_{pq} \leq 140^\circ$
- angular range for each p_{miss} dependent on kinematics

Boeglin et al. PRL 107 (2011) 262501

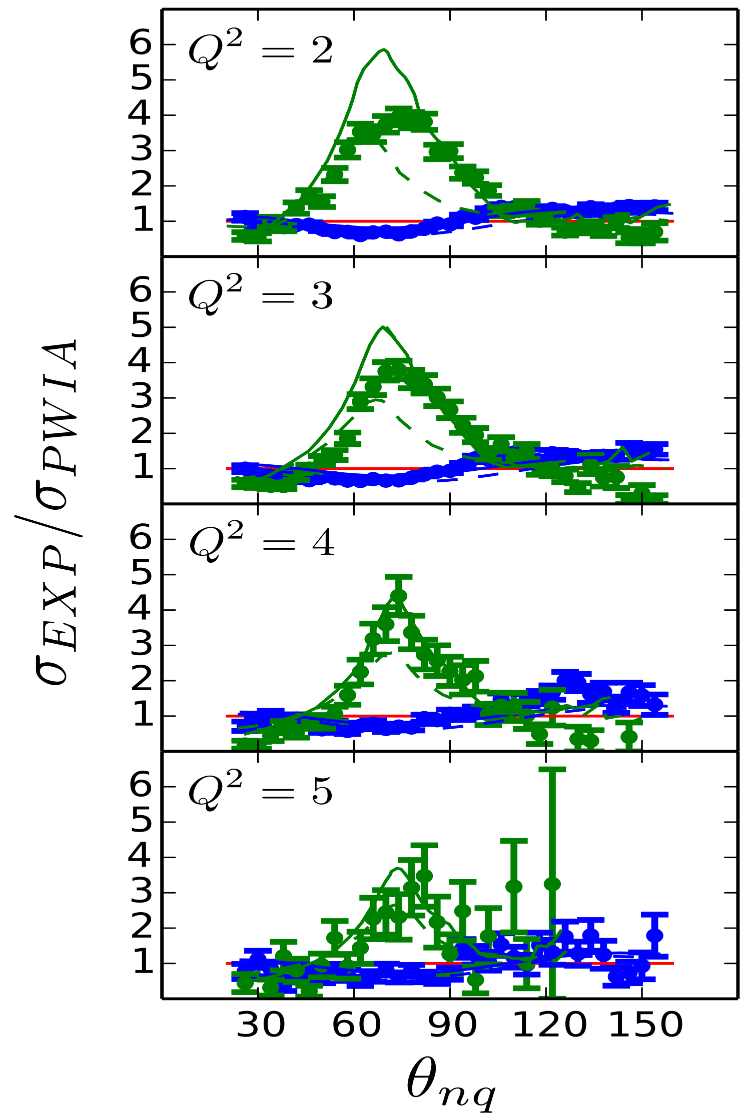
CLAS

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

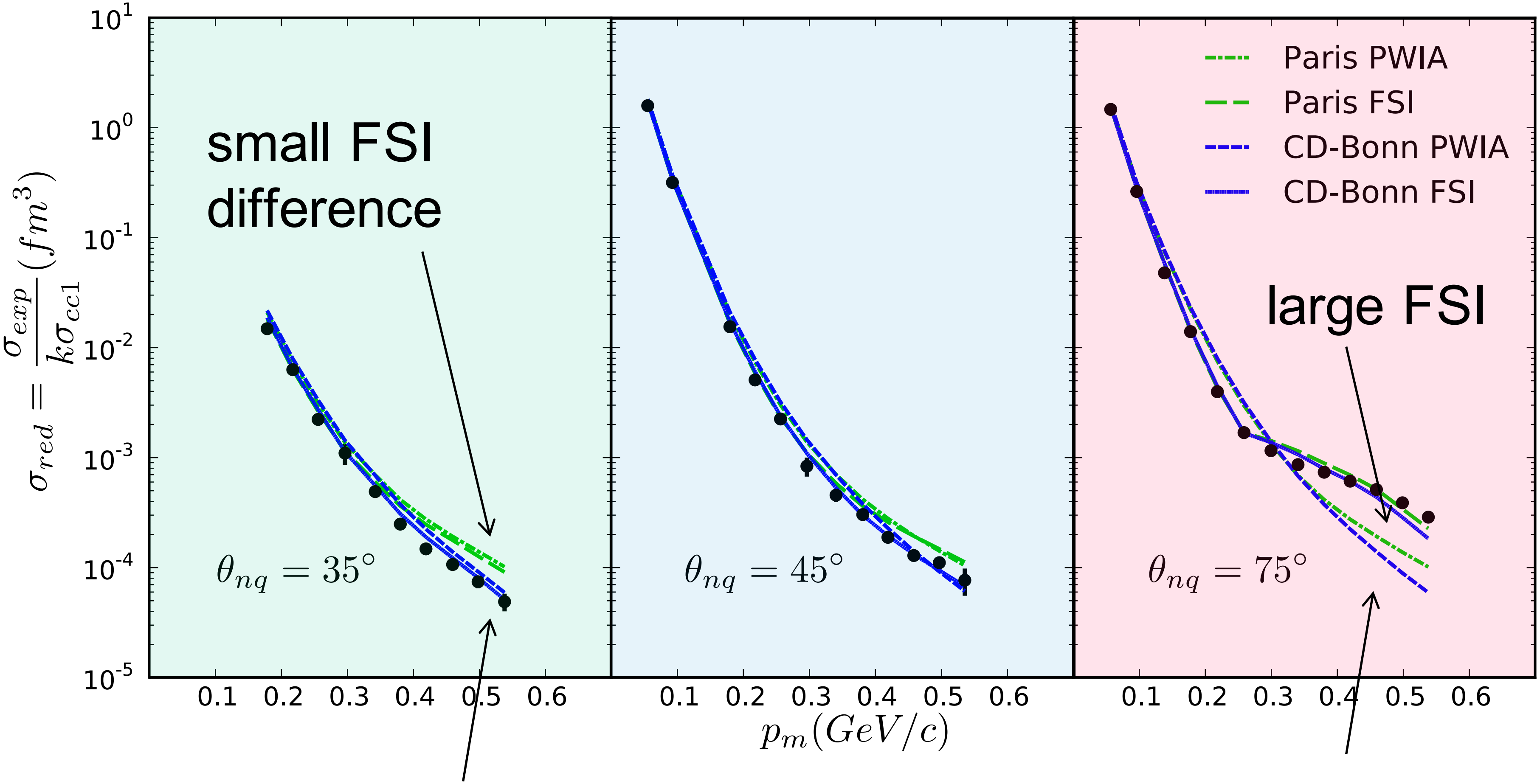
Egyian et al. (CLAS) PRL 98 (2007)



WB et al. PRL 107 (2011) 262501



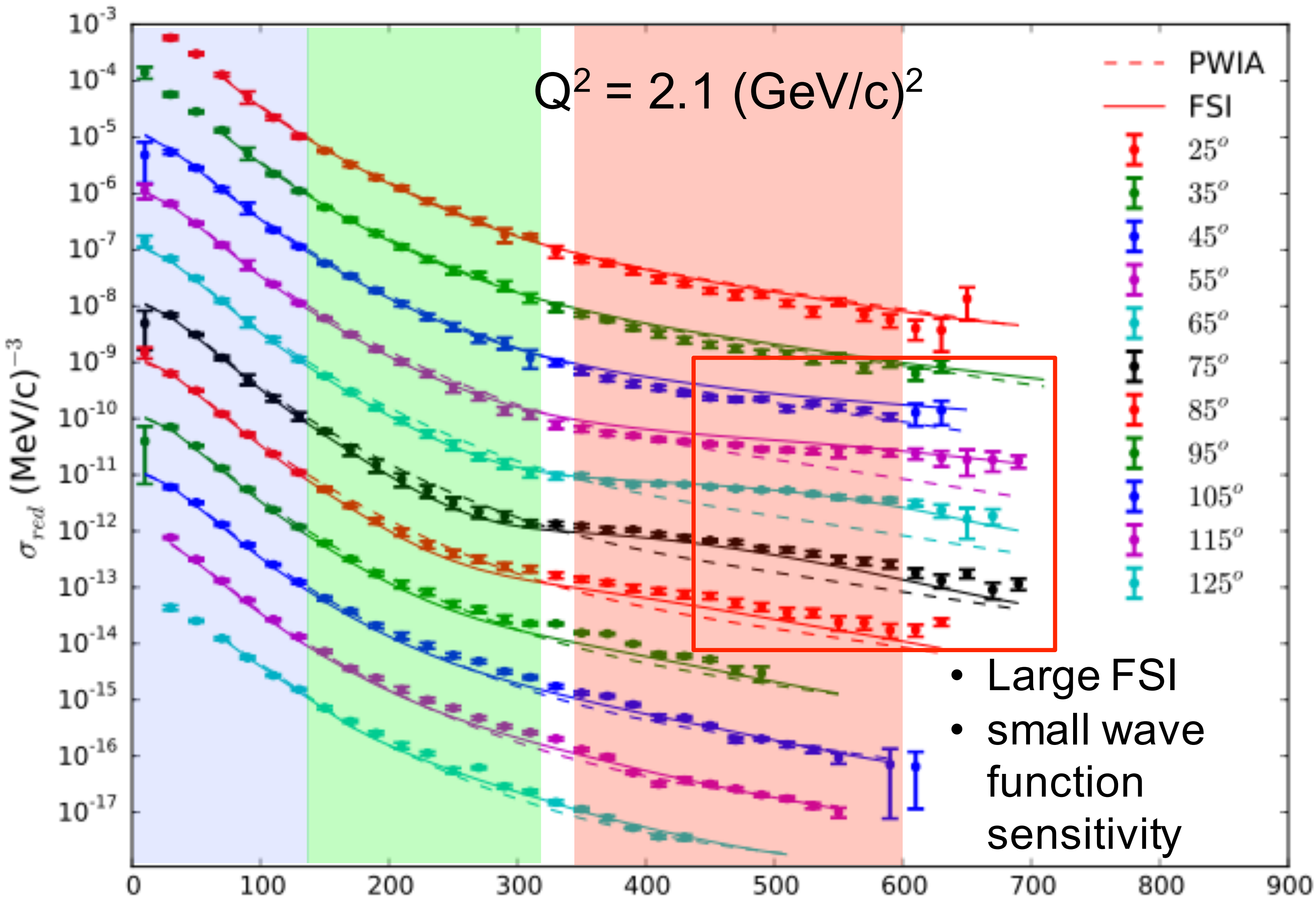
Egyian et al. (CLAS) PRL 98 (2007)



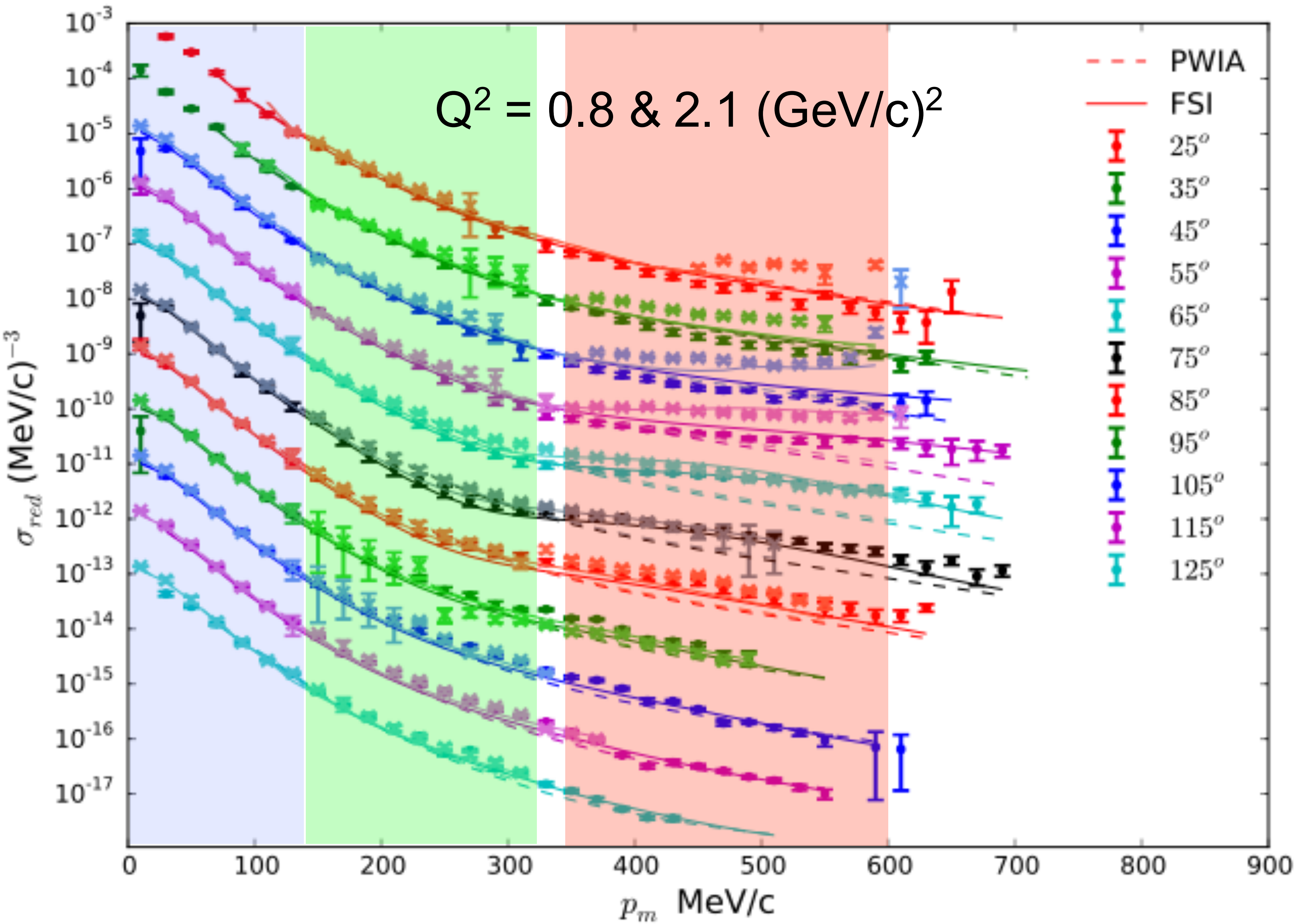
large WF difference

small WF difference

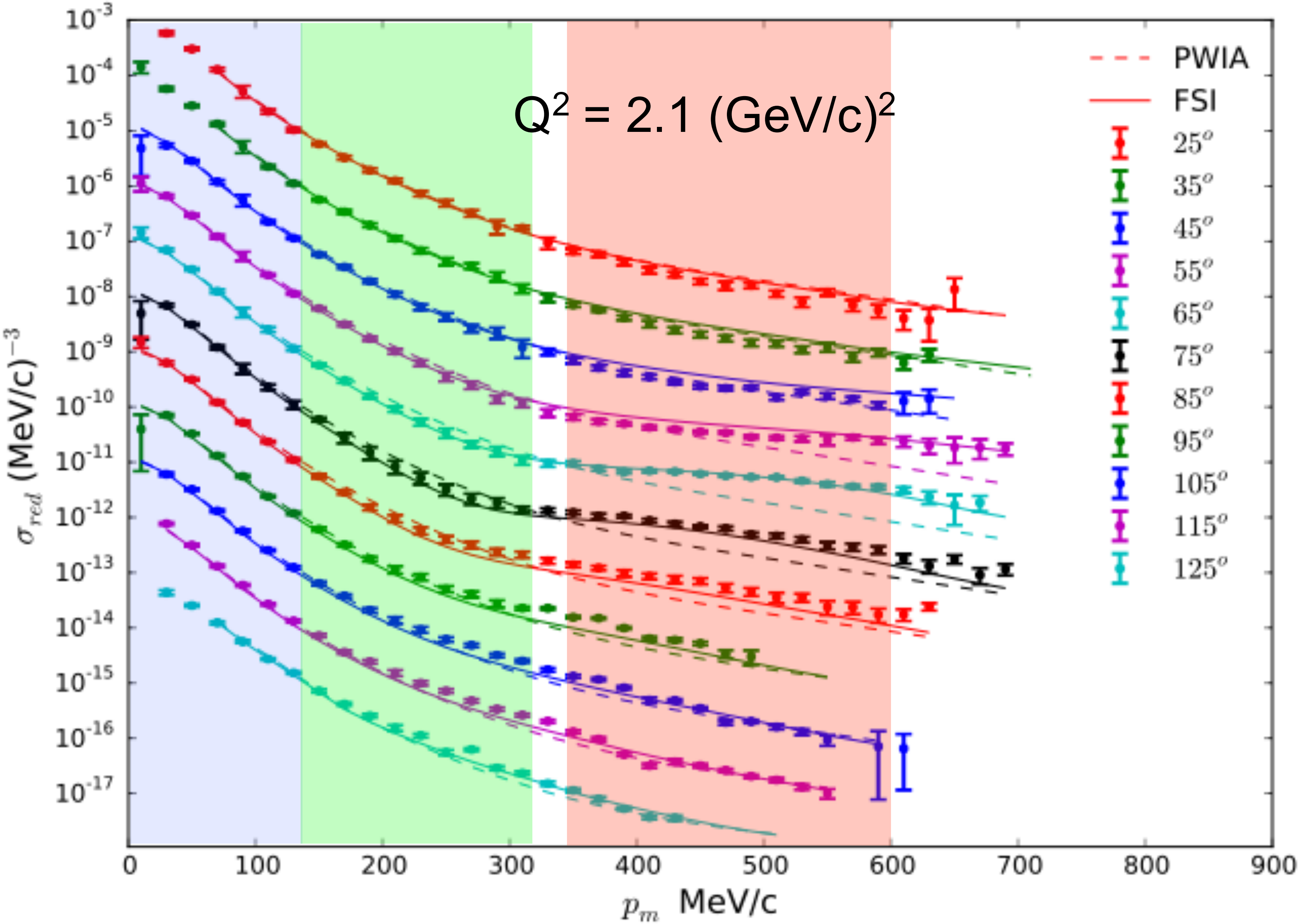
New Momentum Distributions

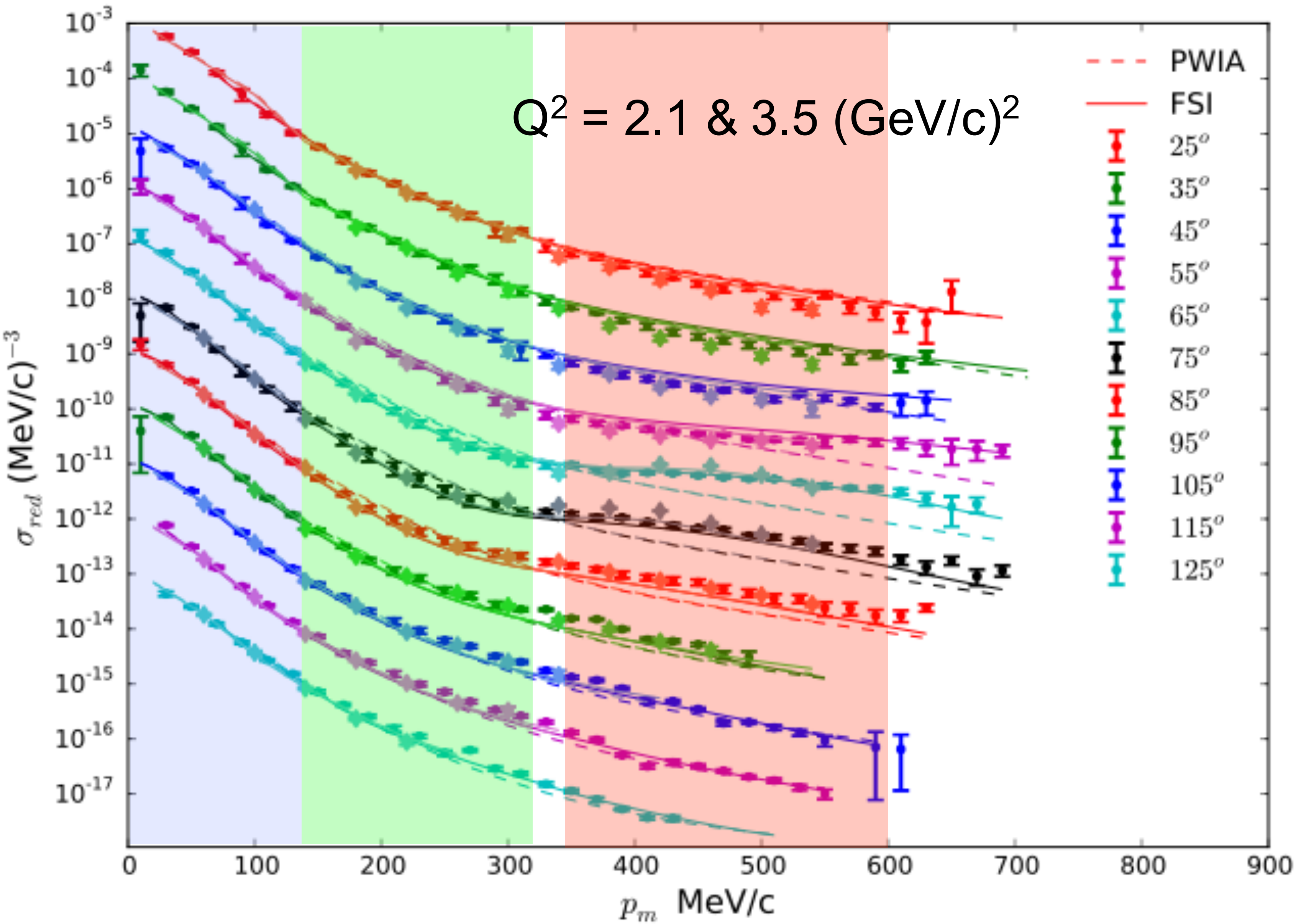


- Large FSI
- small wave function sensitivity



Q^2 = 0.8 & 2.1 (GeV/c)^2
PWIA
FSI
25^o
35^o
45^o
55^o
65^o
75^o
85^o
95^o
105^o
115^o
125^o
σ_{red} (MeV/c)$^{-3}$
p_m MeV/c

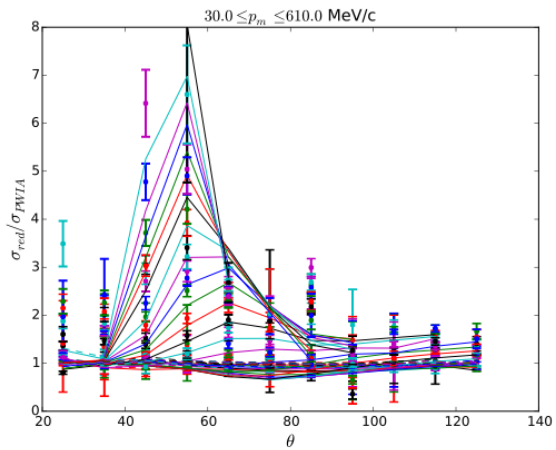

$Q^2 = 2.1\ (\mathrm{GeV/c})^2$
PWIA
FSI
25°
35°
45°
55°
65°
75°
85°
95°
105°
115°
125°
σ_{red} (MeV/c)$^{-3}$
p_m MeV/c

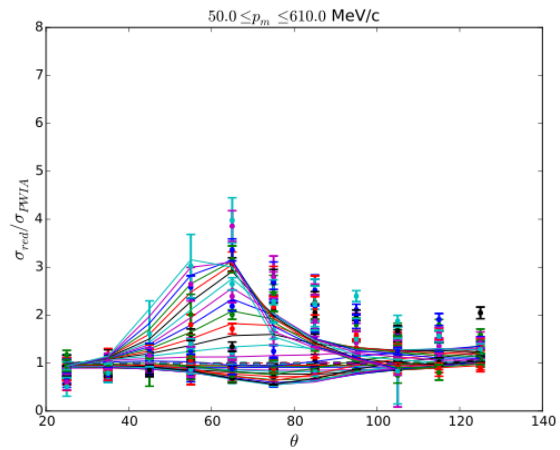


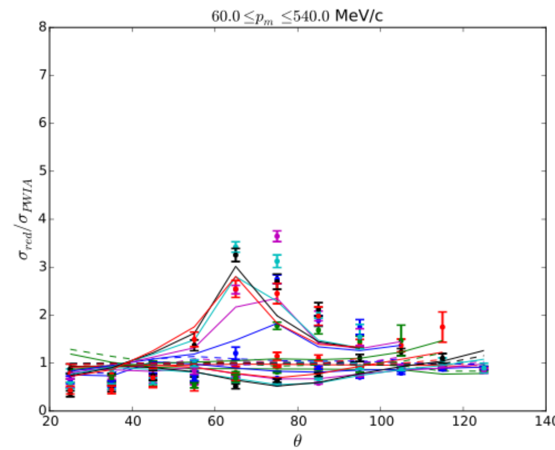
$Q^2 = 2.1$ & 3.5 (GeV/c)^2
PWIA
FSI
25°
35°
45°
55°
65°
75°
85°
95°
105°
115°
125°
σ_{red} (MeV/c)$^{-3}$
p_m MeV/c

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

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

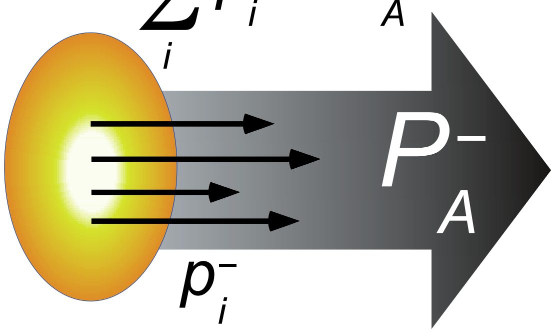
$$F_{2d}(x) = \sum_N \int_x^2 F_{2N}\left(\frac{x}{\alpha}\right)\rho(\alpha)\frac{d\alpha}{\alpha}$$

Deuteron Momentum Distributions on the Light Cone (LC)

LC momentum $p^- = E - p_z$

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

$\sum_i p_i^- = P_A^-$



analogous to "x" for quark distributions

α is frame independent for boosts along the z-axis

LC PWIA cross section

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

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 $A = 2$

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

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

LC momentum

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

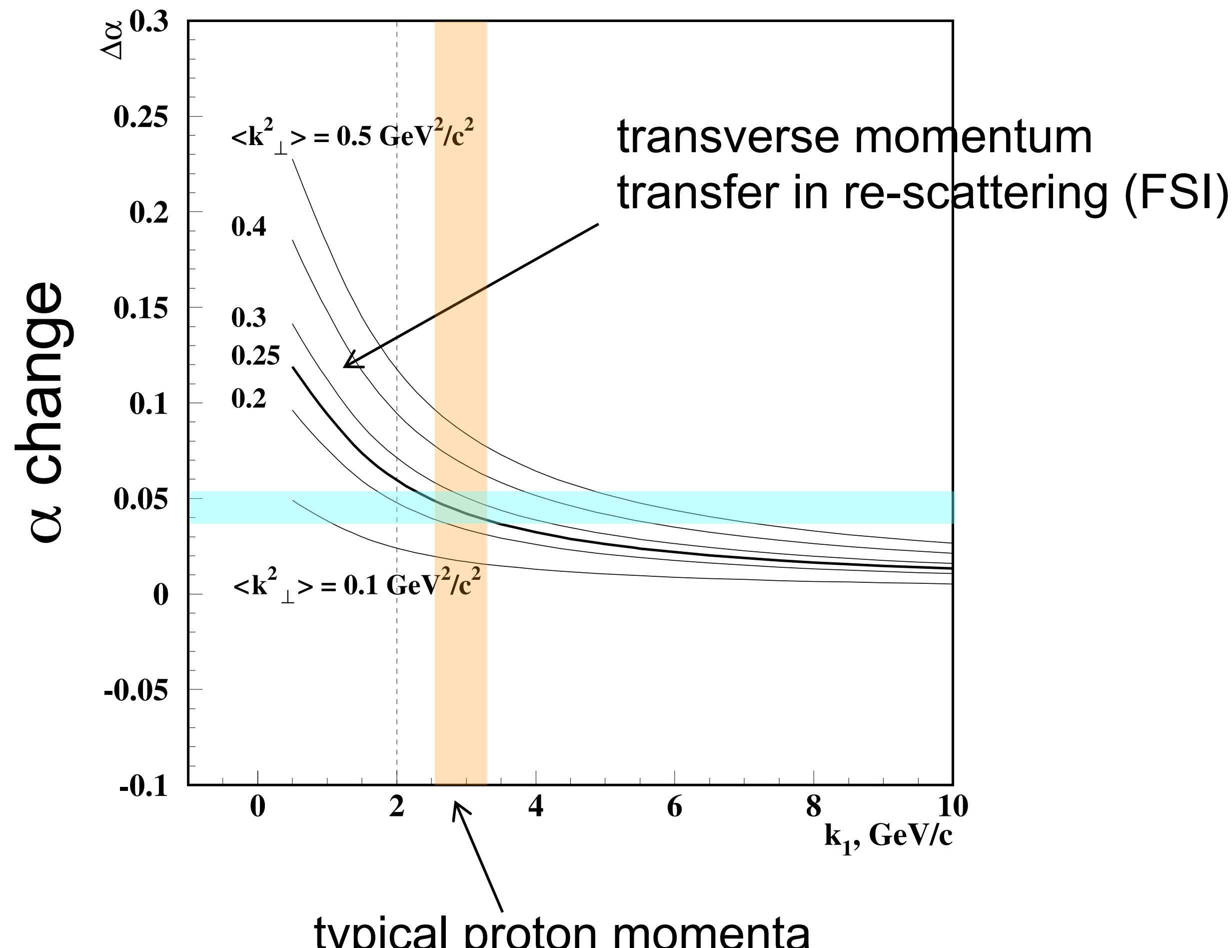
$$k = \sqrt{\frac{M_N^2 + p_t^2}{\alpha_s(2-\alpha_s)} - M_N^2} \qquad E_k = \sqrt{M_n^2 + p_t^2}$$

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

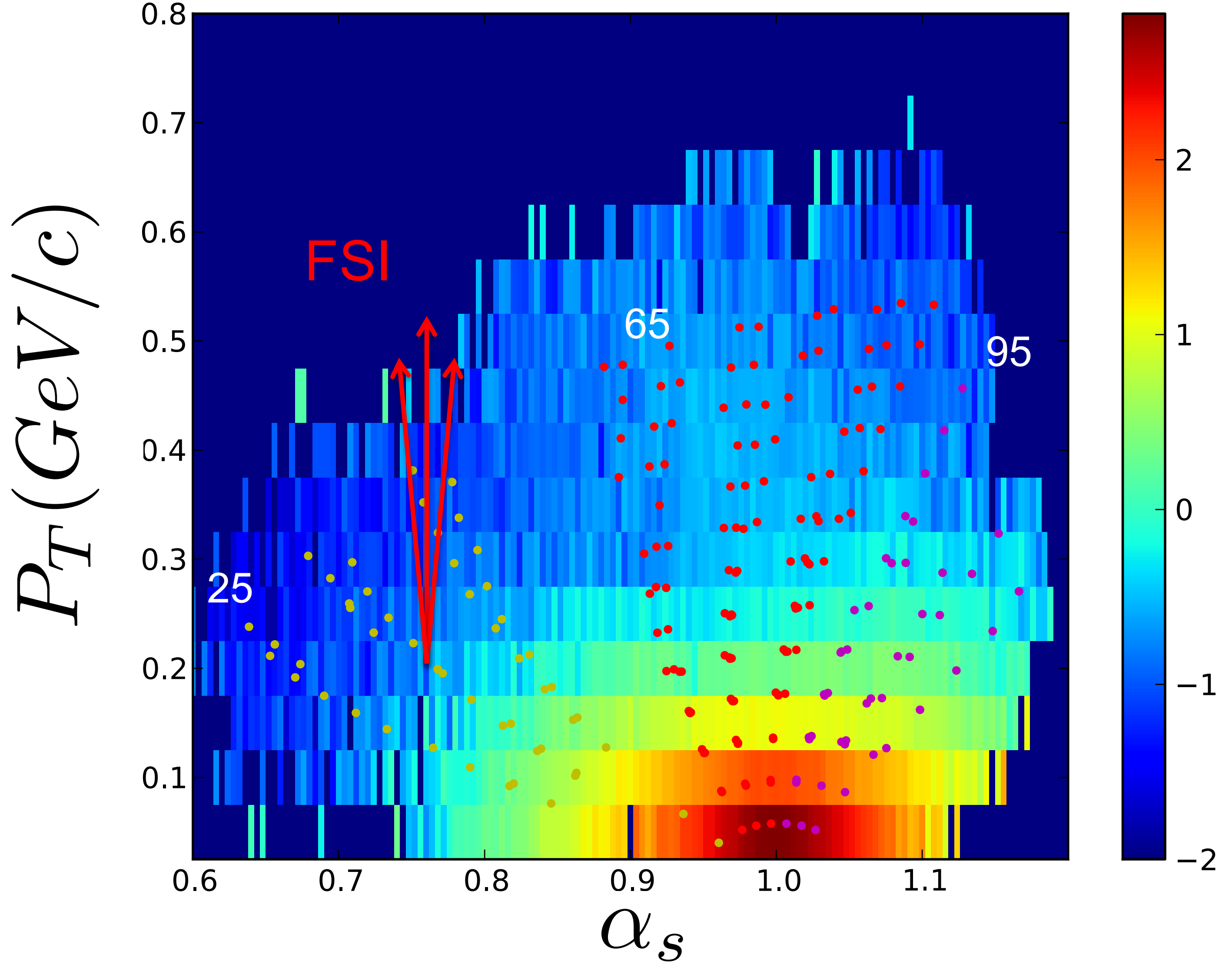
Normalization: $\displaystyle\int \rho(\alpha)\frac{d\alpha}{\alpha} 2\pi p_t dp_t = 1$

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

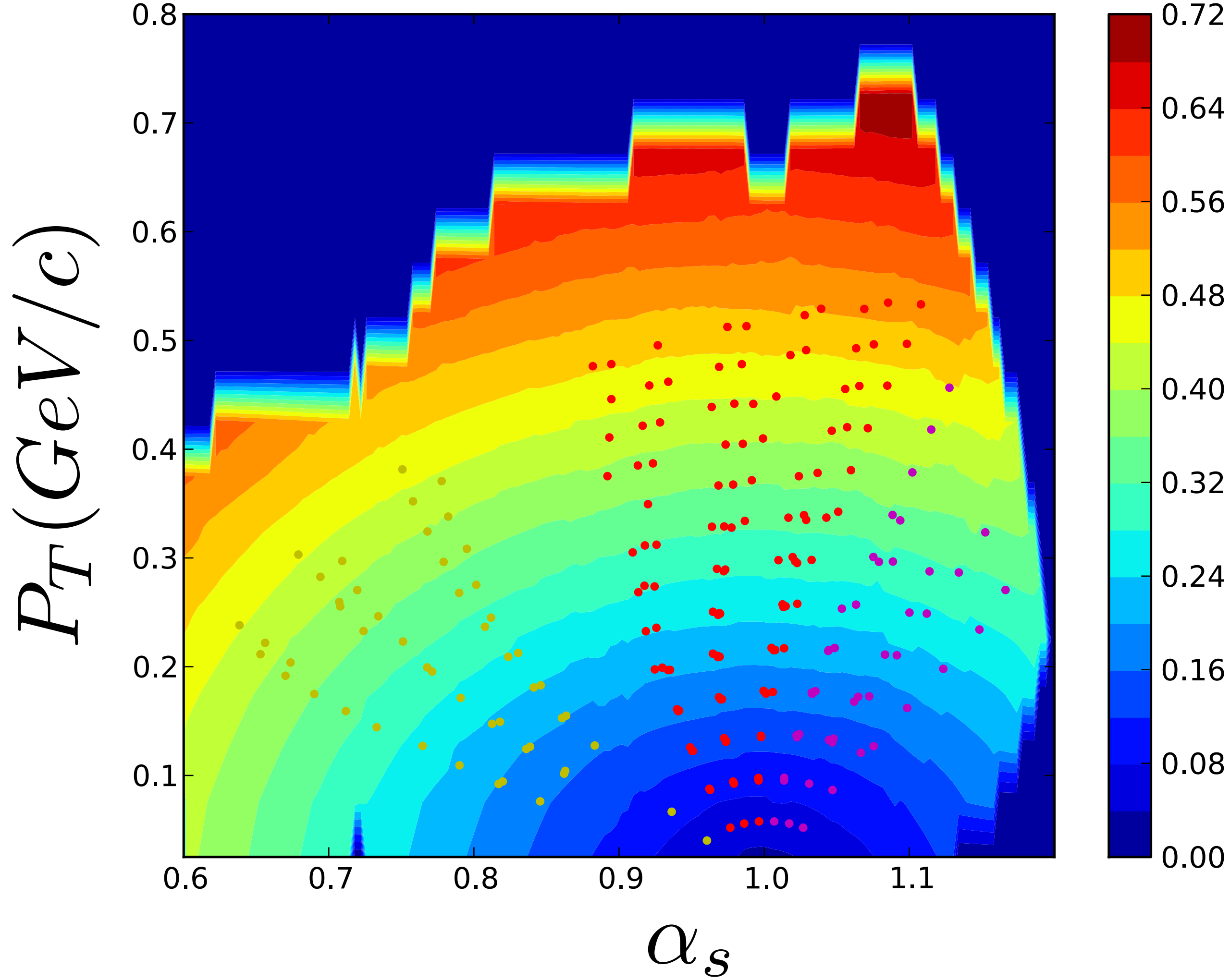
α conservation as function of nucleon momenta



$$log(\rho(\alpha_s, P_T))$$



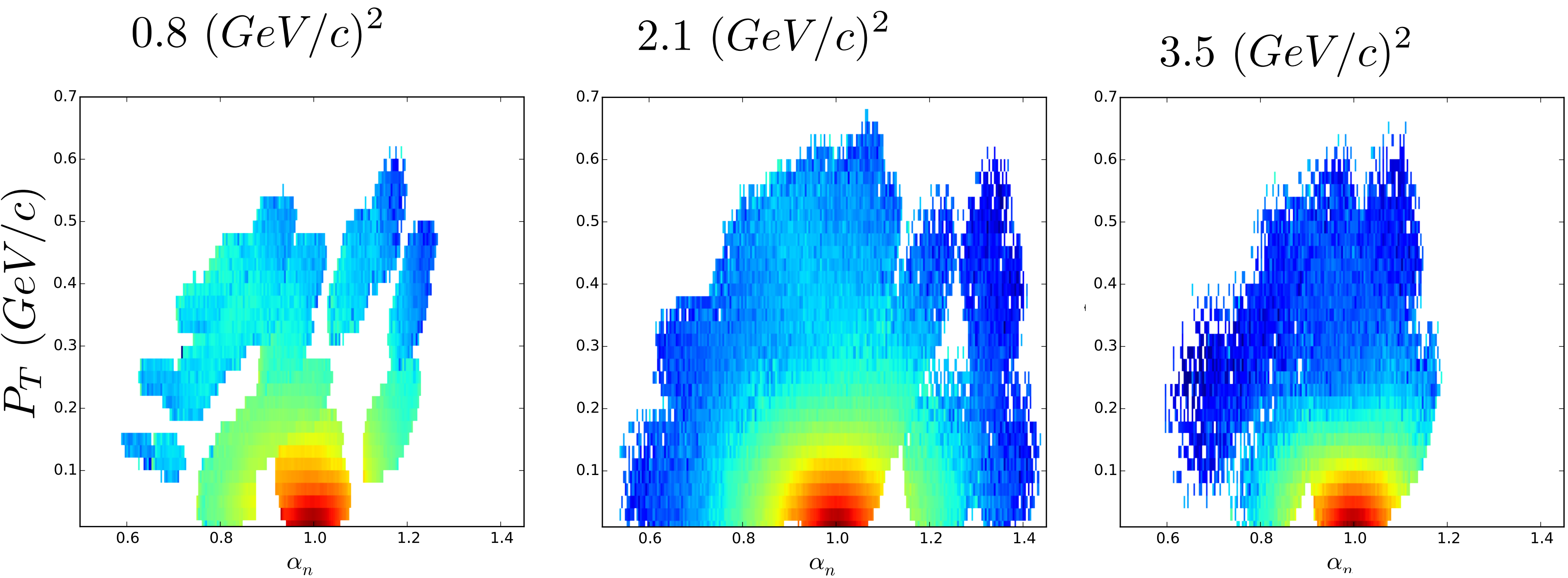
Contours of k = const



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

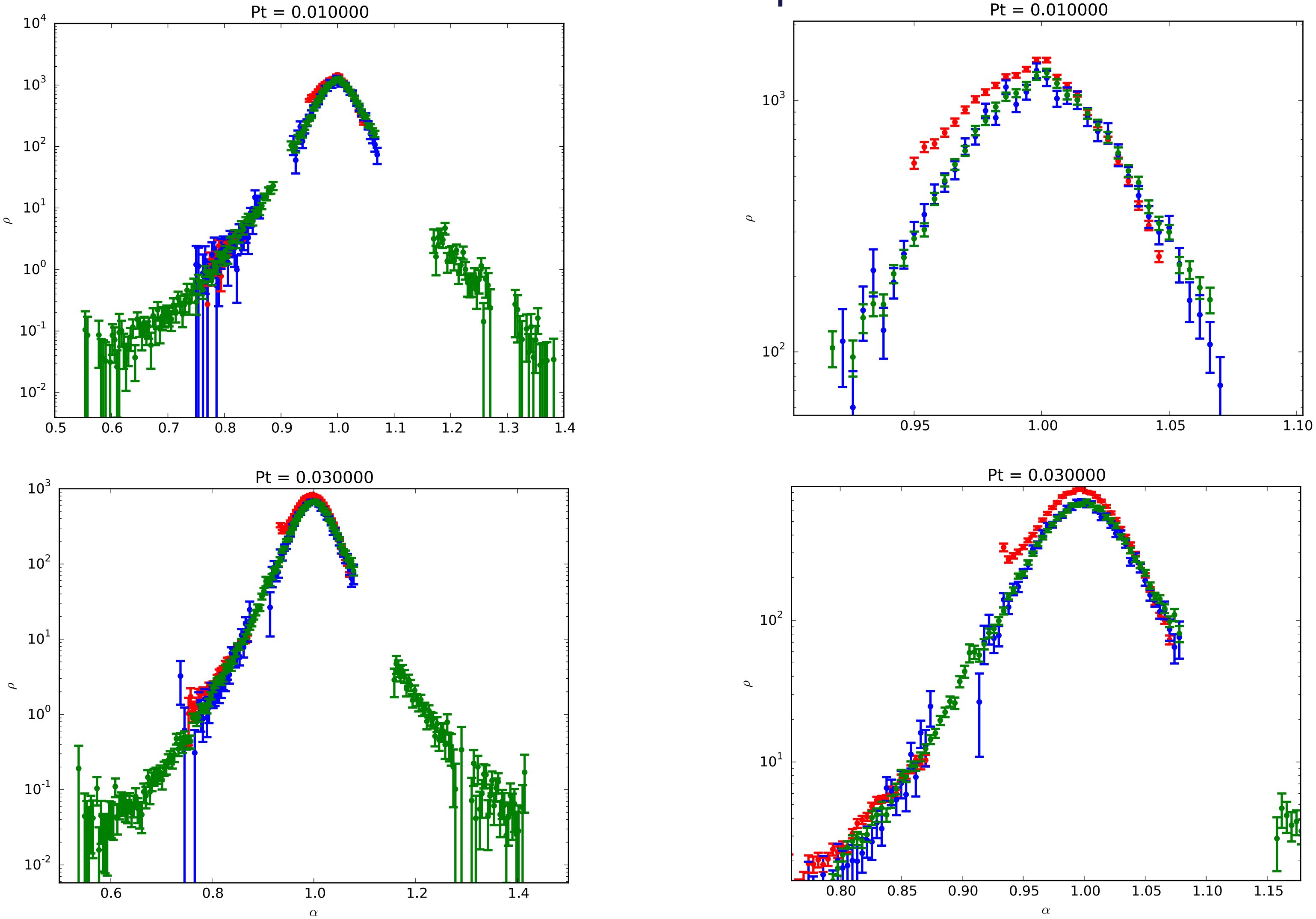
- Determine d(e,e'p)n cross section for each α_s, p_t bin
- Divide by $K\sigma_{eN}^{LC}$
- Problem: phase space acceptance
- Results should be as independent as possible of phase space cuts
- Missing information due to finite spectrometer acceptance
- Interpolation necessary for missing data

First Results (Preliminary)

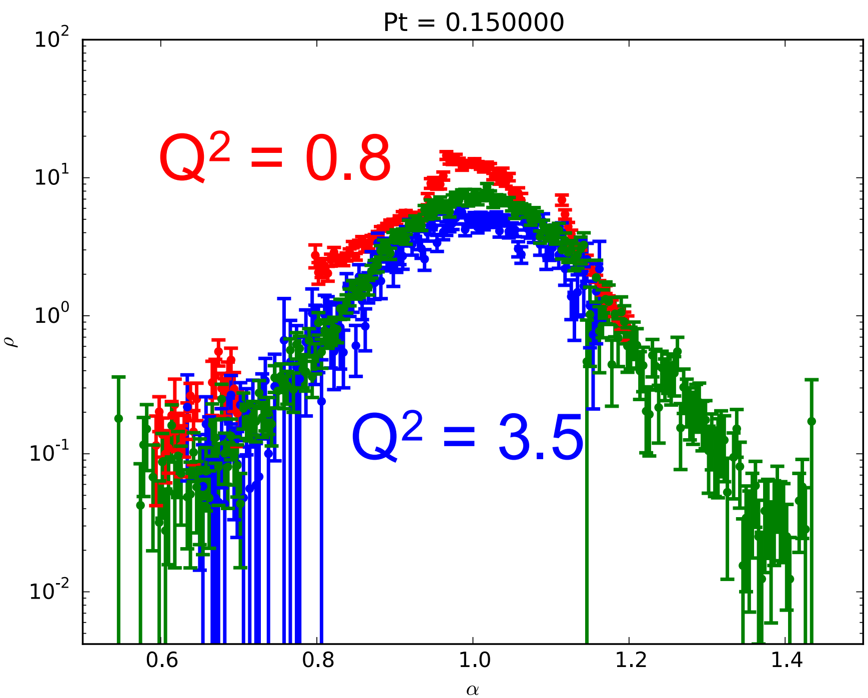


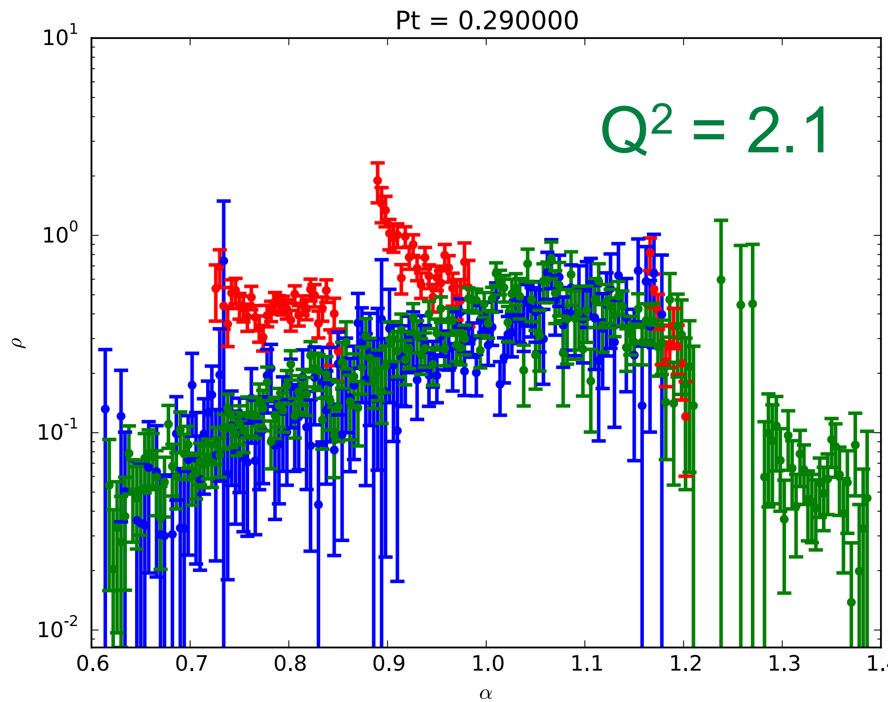
- 0.8 and 2.1 $(GeV/c)^2$ data normalized to 3.5 $(GeV/c)^2$ at low p_m (0.04- 1.2 GeV/c)
- Large FSI at small α and large P_T for small Q^2

Small P_T



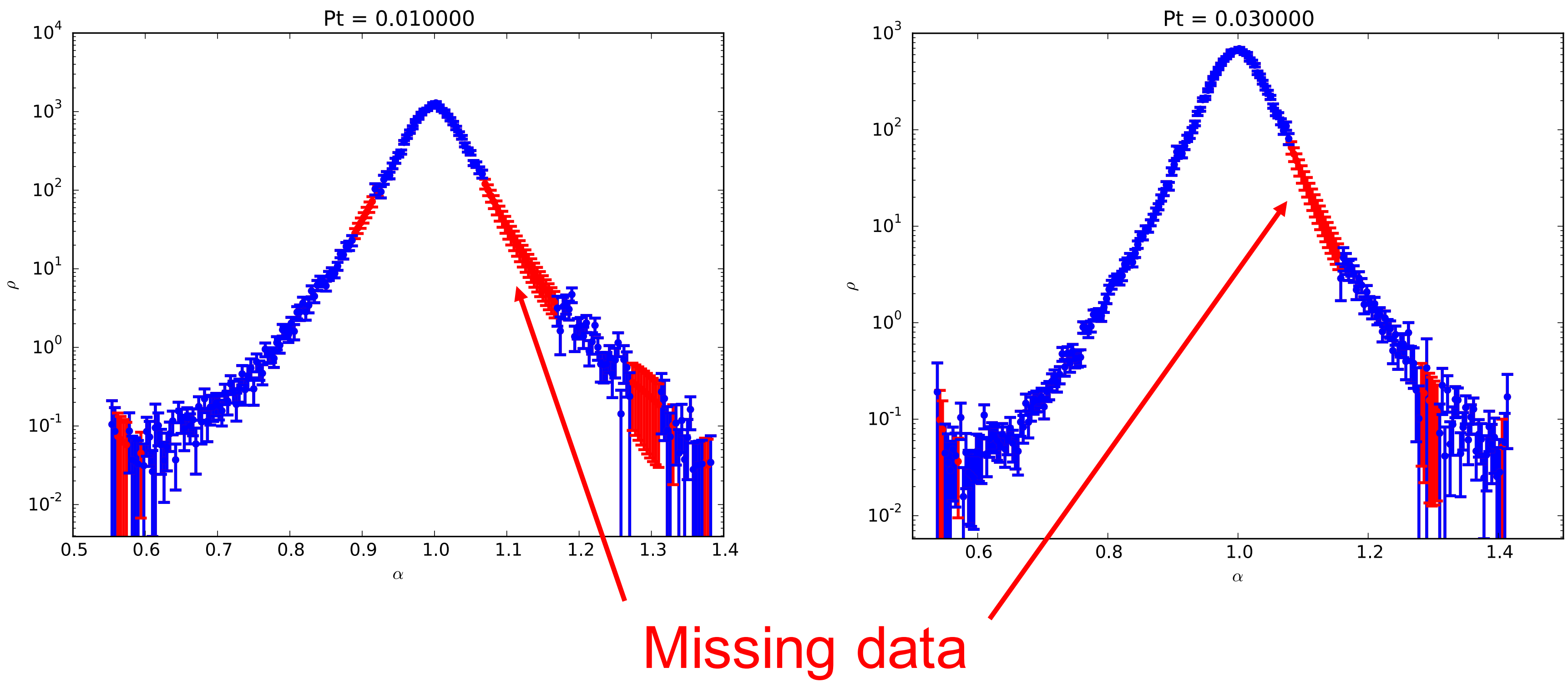
Larger P_T





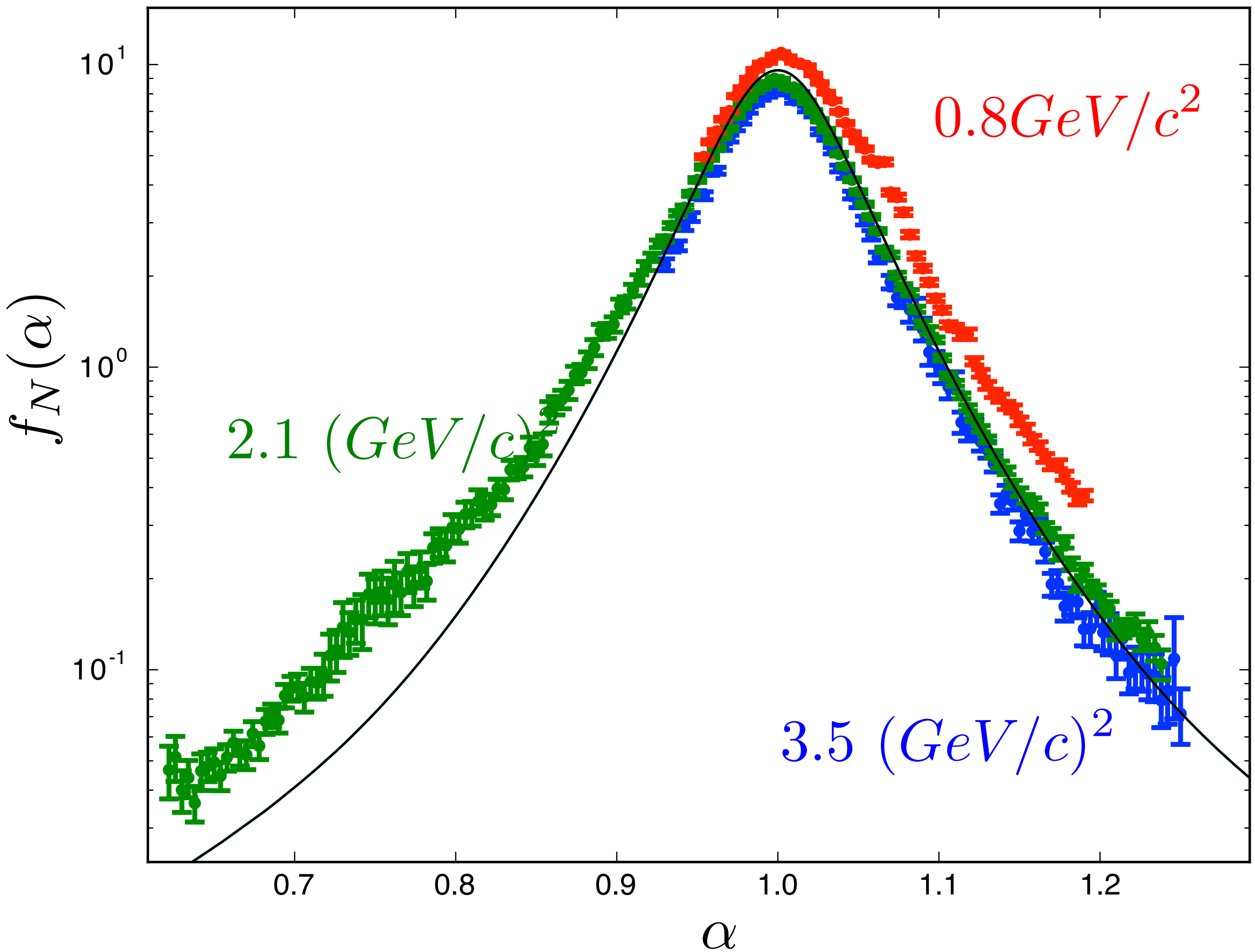
- $Q^2 = 0.8$ does not follow higher Q^2 behavior
- Qualitatively different (Large FSI etc.)

Missing Data



- Filled with fitting procedure
- Experimental data are not changed

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



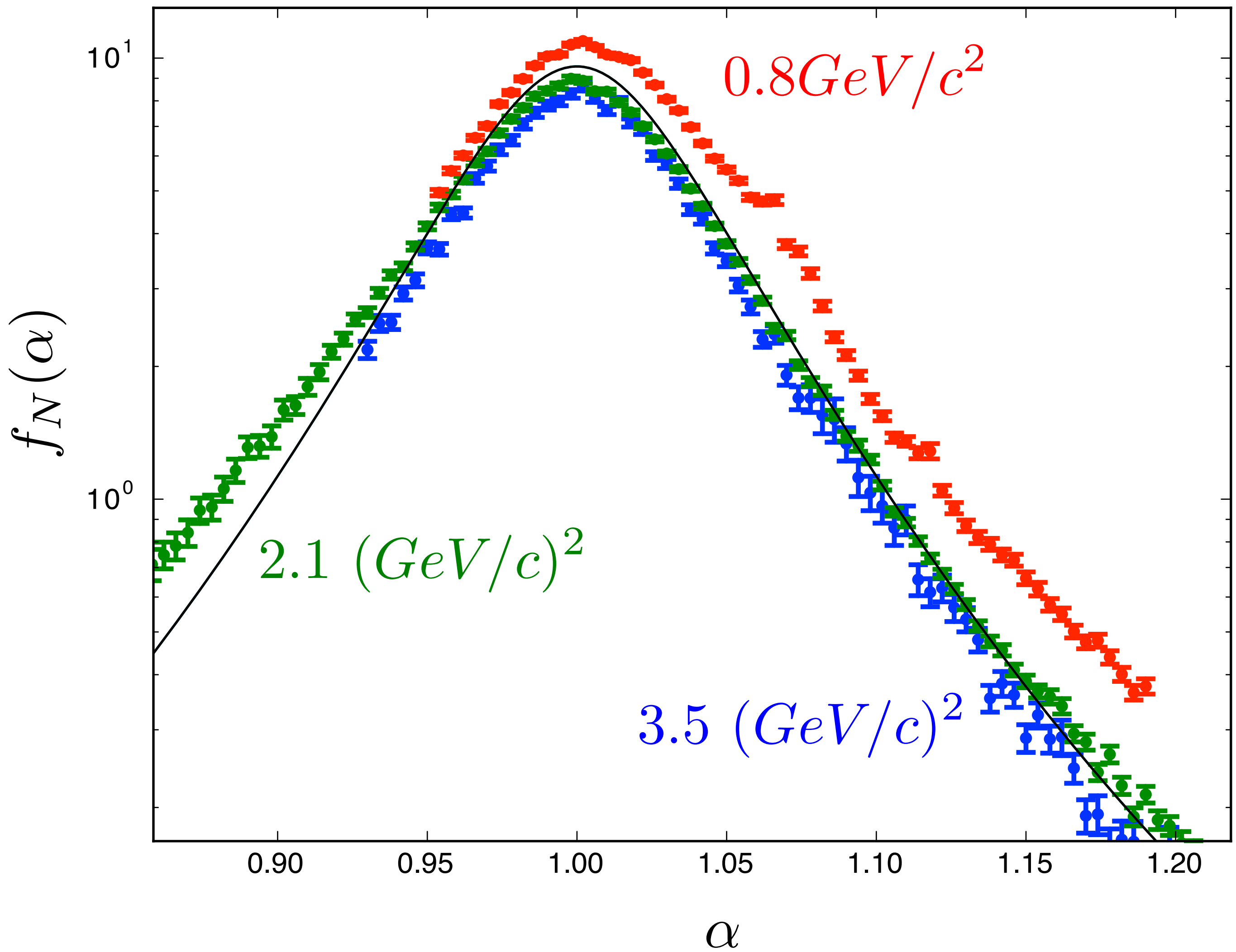
$$I = \int f_N(\alpha) d\alpha$$

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

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

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

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


10^1
10^0
$f_N(\alpha)$
$0.8 GeV/c^2$
$2.1\ (GeV/c)^2$
$3.5\ (GeV/c)^2$
0.90
0.95
1.00
1.05
1.10
1.15
1.20
α

- First steps in determining $\rho(\alpha)$
- Needs some more work
- Absolute normalization needs to be finalized
- But differences between experiment and calculation seem to remain

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

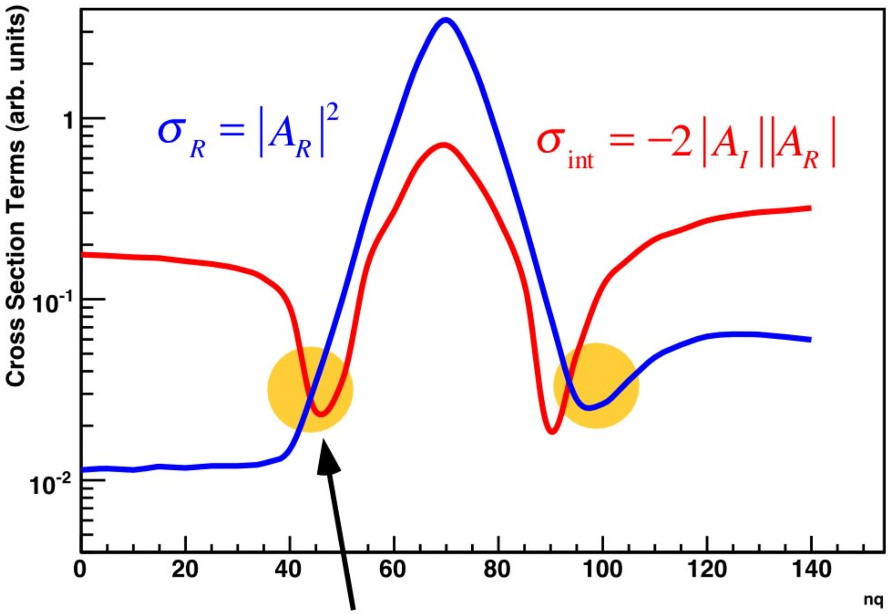
Electron arm *fixed* at:
SHMS at p_{cen} = 9.32 GeV/c
$\theta_e = 11.68^o$
$Q^2 = 4.25\ (GeV/c)^2$
x = 1.35

Vary proton arm to measure :
p_m = 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 GeV/c
HMS $1.96 \leq p_{cen} \leq 2.3$ geV/c
Angles: $63.5^o \geq \theta_p \geq 53.1$

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:

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

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

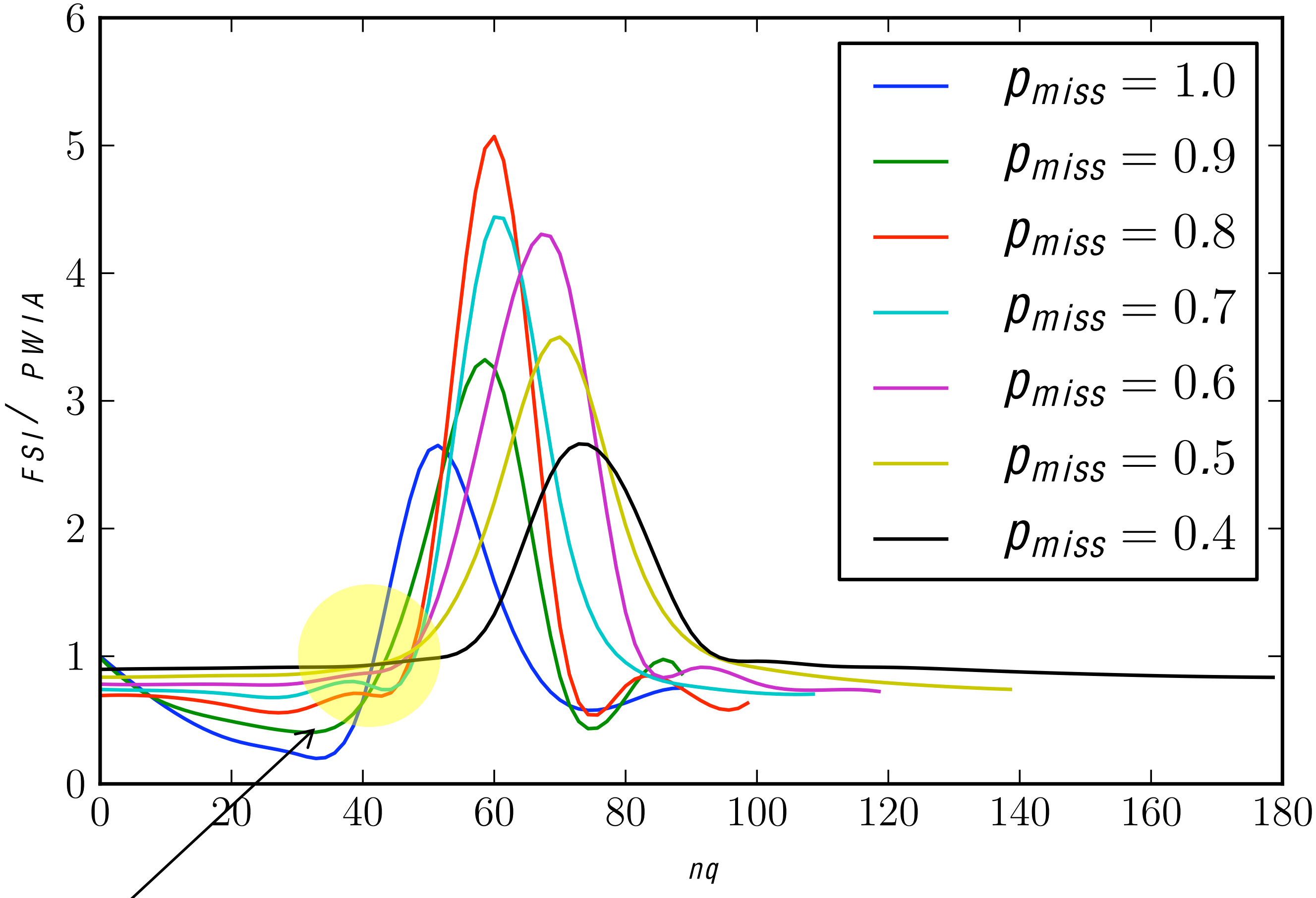
$$b \sim 6(GeV/c)^{-2}$$

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)

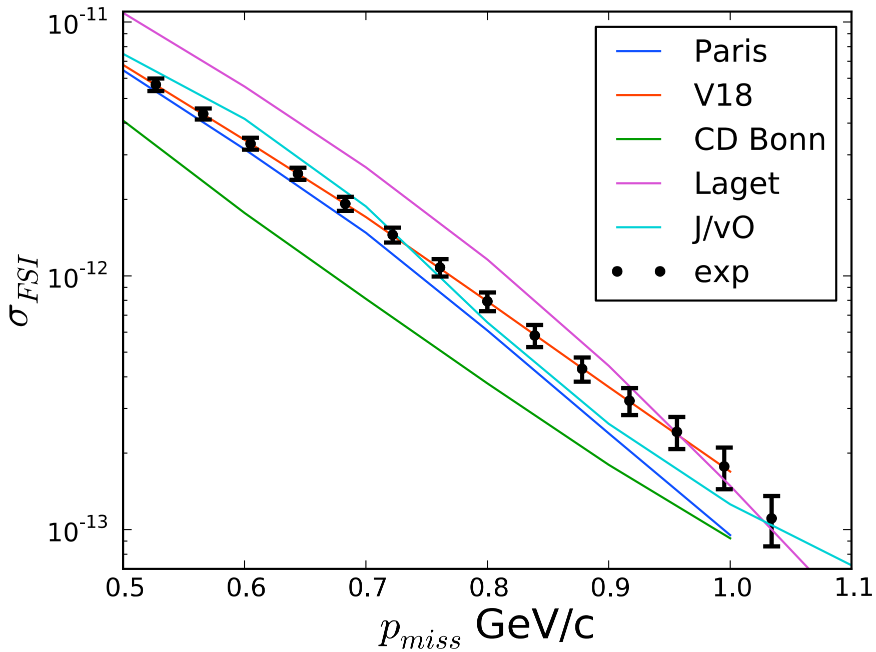
Angular Distributions up to p_m = 1GeV/c



FSI depend weakly on p_m

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 ≈ 5 %
- ✓JLAB uniquely suited for high p_m study

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
- publication of all Q^2 data nearing completion (some normalization issues)
- first attempt to extract α distributions
- increase kinematics coverage for α determination
- 12 GeV: very high missing (up to 1GeV/c) momenta coming soon (hopefully)

Interpolating missing data

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

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

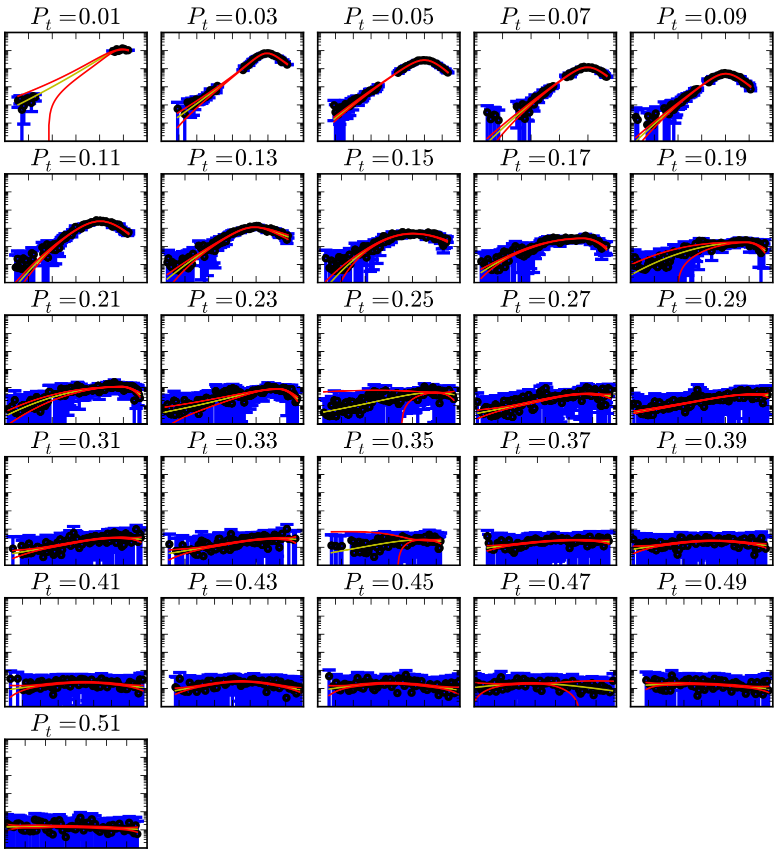
Parameters: $\alpha, \beta, \gamma, \delta_{s,l}, A$

use δ_s for $\alpha < A$

use δ_l for $\alpha > A$

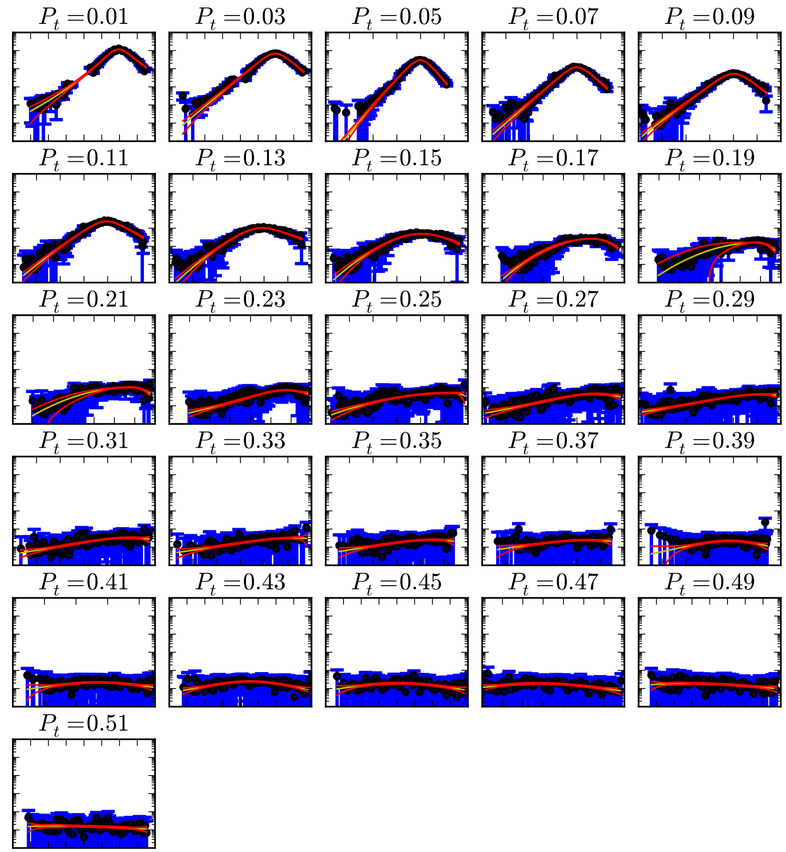
Calculated using model: $\rho_{LC}(\alpha)$
(e.g. Paris WF)

20% cut



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

2.5% cut



$P_t = 0.01$
$P_t = 0.03$
$P_t = 0.05$
$P_t = 0.07$
$P_t = 0.09$
$P_t = 0.11$
$P_t = 0.13$
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$P_t = 0.41$
$P_t = 0.43$
$P_t = 0.45$
$P_t = 0.47$
$P_t = 0.49$
$P_t = 0.51$

Light Cone Variables

Light cone variables for experimentalists:

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

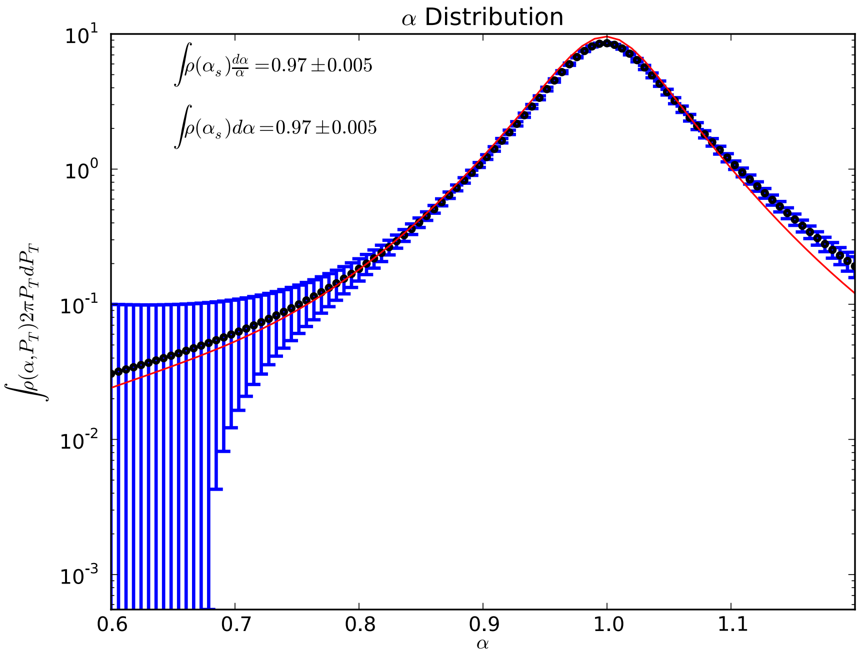
$$V^\pm = V^o \pm V_z$$

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

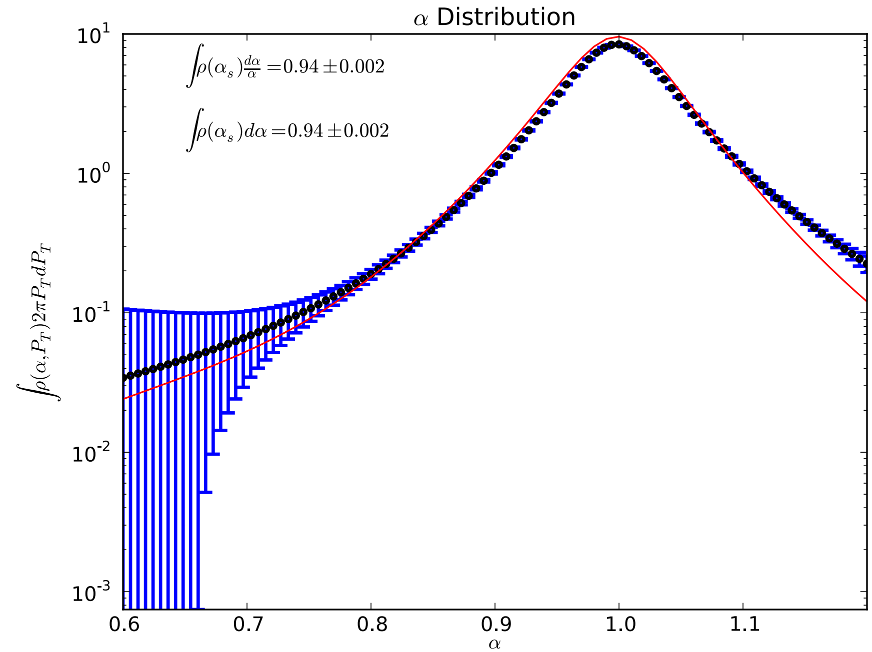
= scalar multiplication

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

ρ(α) using fit interpolation



20% cut



2.5% cut