Deuteron Structure Studies at High Q^2

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Introduction

- Only bound 2 nucleon system
- Reference systems for SRC and EMC studies
- Prime testing ground models: where is the limit for the description in terms of nucleons and mesons
- At short ranges (< nucleon size), what happens when nucleons overlap ?

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

Challenges

- Reaction dynamics
    - photon interacts with a bound nucleon
    - what is the EM current structure at high Q^2 and large virtuality
- Final State Interactions
    - high Q^2 : are eikonal approximations valid ?
- Deuteron wave function
    - probe NN wave function at small distances
    - search for manifestations of new degrees of freedom

All these problems are interconnected

New, high energy, high Q^2 data will provide new information!

Reactions

- D(e,e'): elastic scattering including recoil polarization (T_{20})
- D(γ,p)n at high energy (but $Q^2 = 0$)
- D(e,e'p) at moderate and high Q^2

D(e,e')

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

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

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

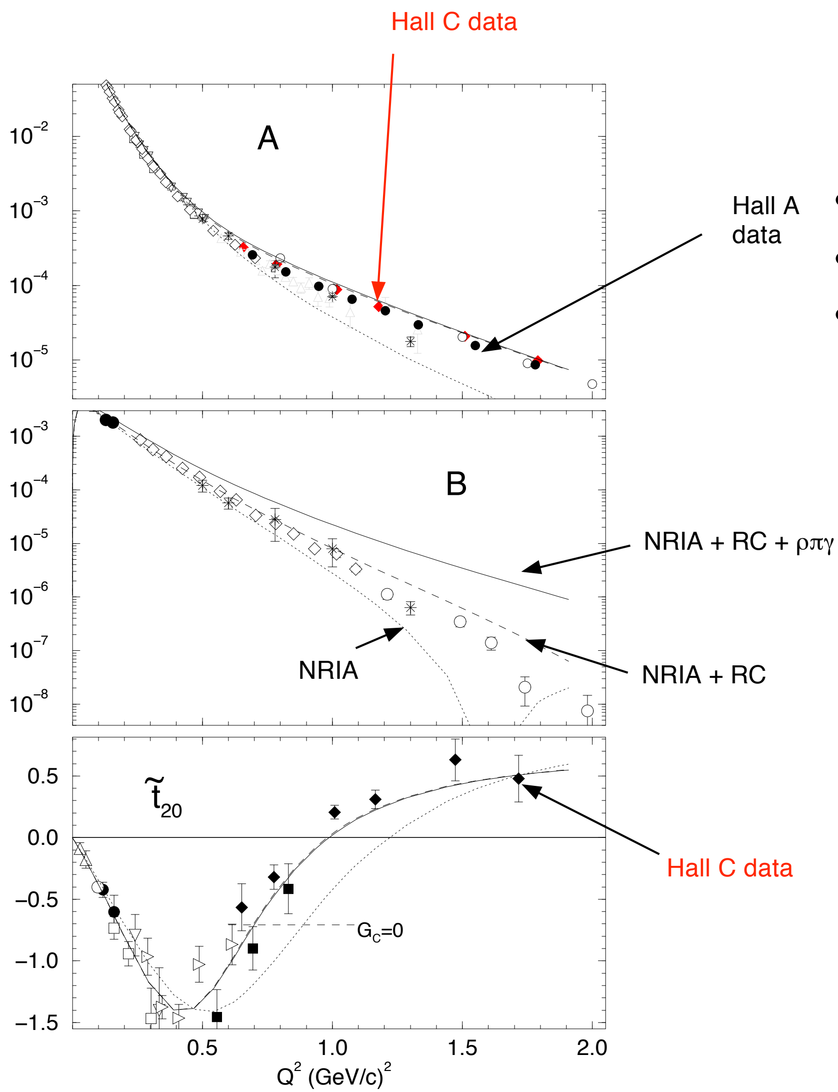
G_Q Quadrupole form factor

G_M Magnetic form factor

G_C Charge form factor

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

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

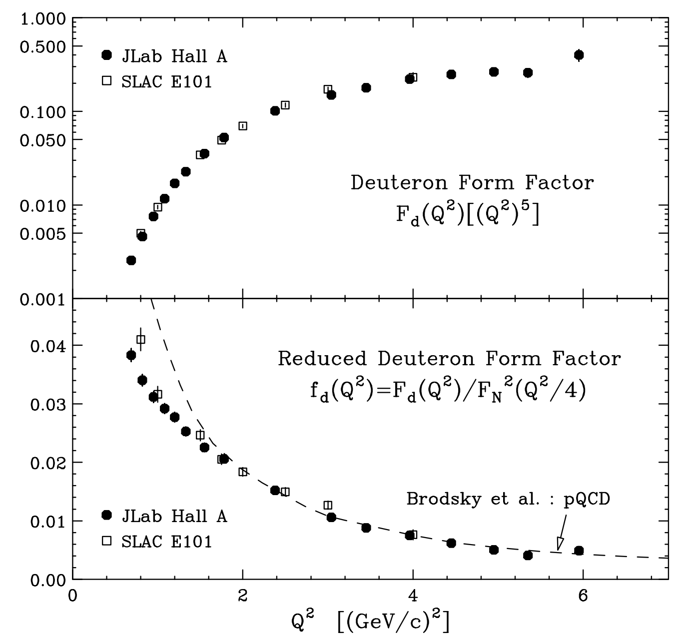


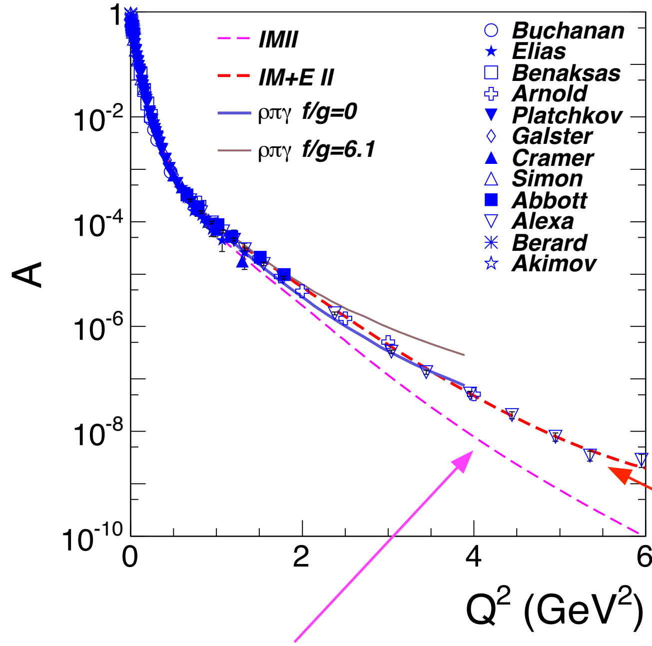
Calculation: H.Arenhövel et al. PRC 61, 034002

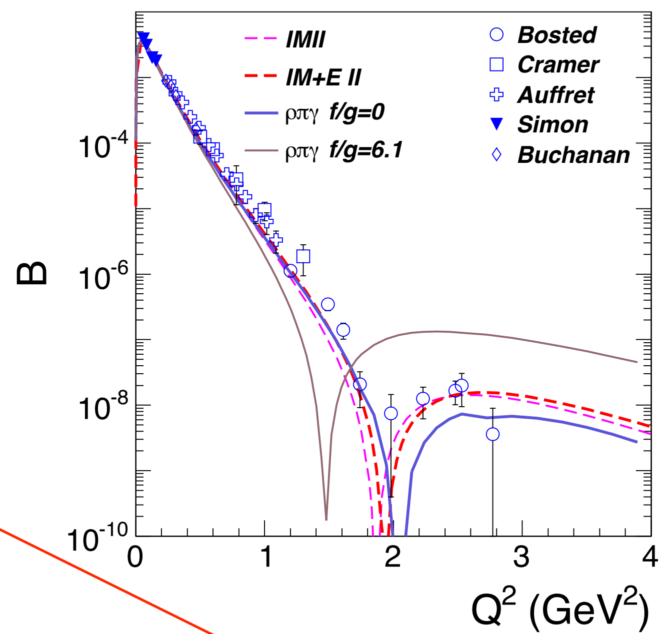
Experiments:

- Hall A : L.C.Alexa et al. PRL 82 (1999) 1374
- Hall C: D.Abbott et al. PRL 82 (1999) 1379
- Hall C: D.Abbott et al. PRL 84 (2000) 5053

Onset of Dimensional Scaling ?







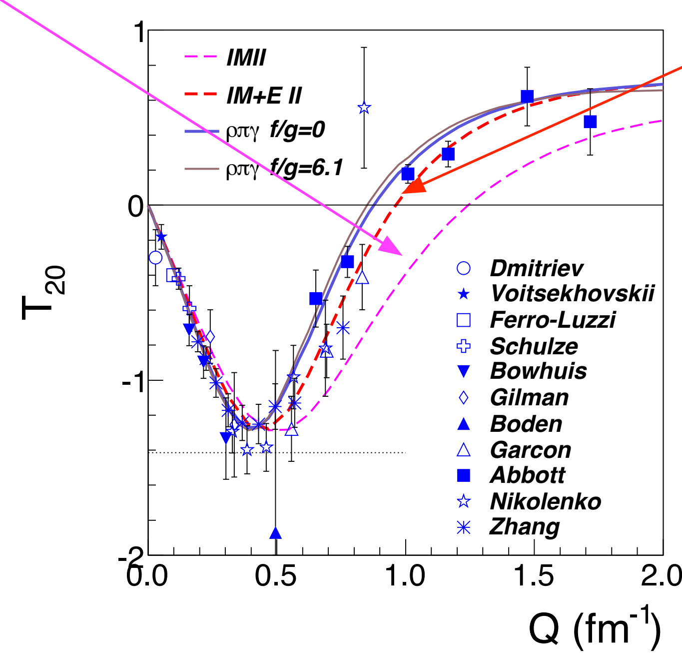
no MEC contributions

with MEC

Rel. Calculations in Hamiltonian dynamics:

IMII and IM+EII

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



Rel. Calculations in propagator dynamics:

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

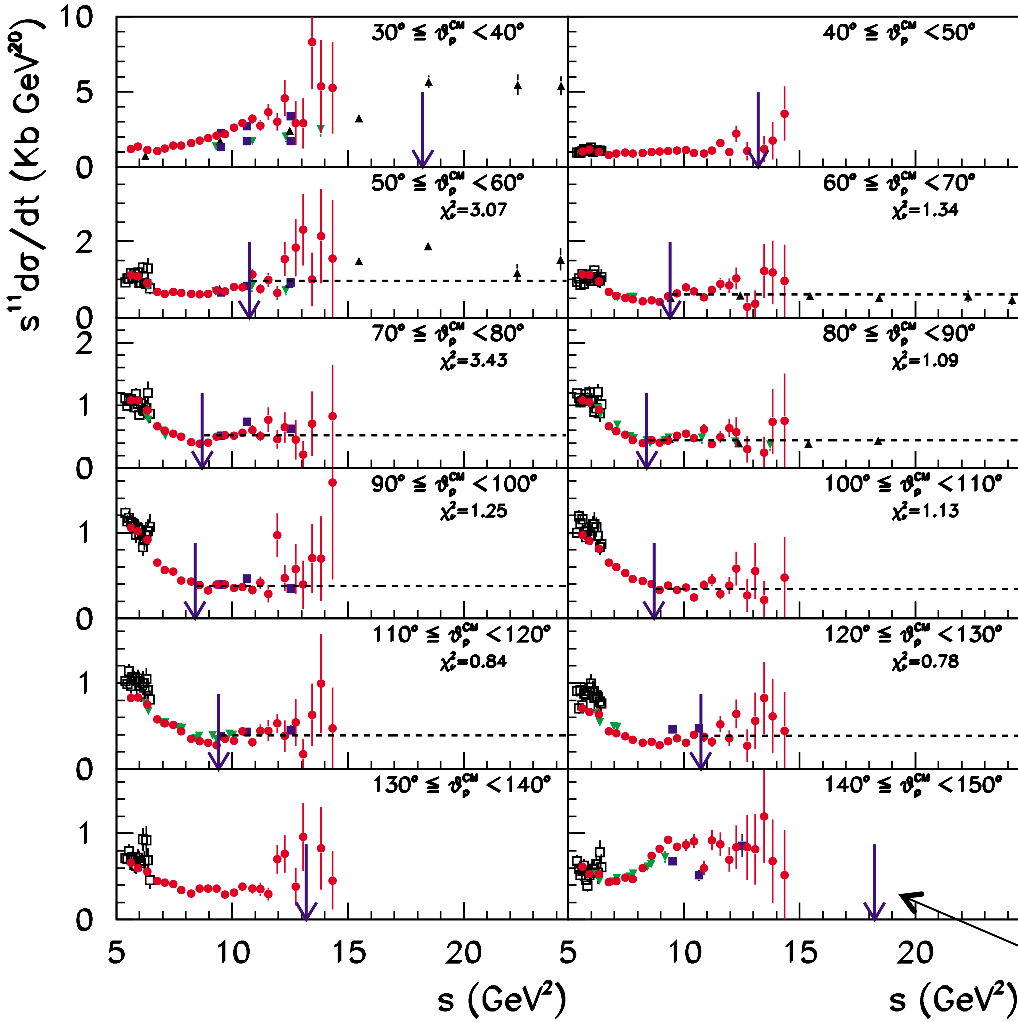
$\rho\pi\gamma\ \phi/\gamma = 6.1$

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

Summary:

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

D(γ,pn)



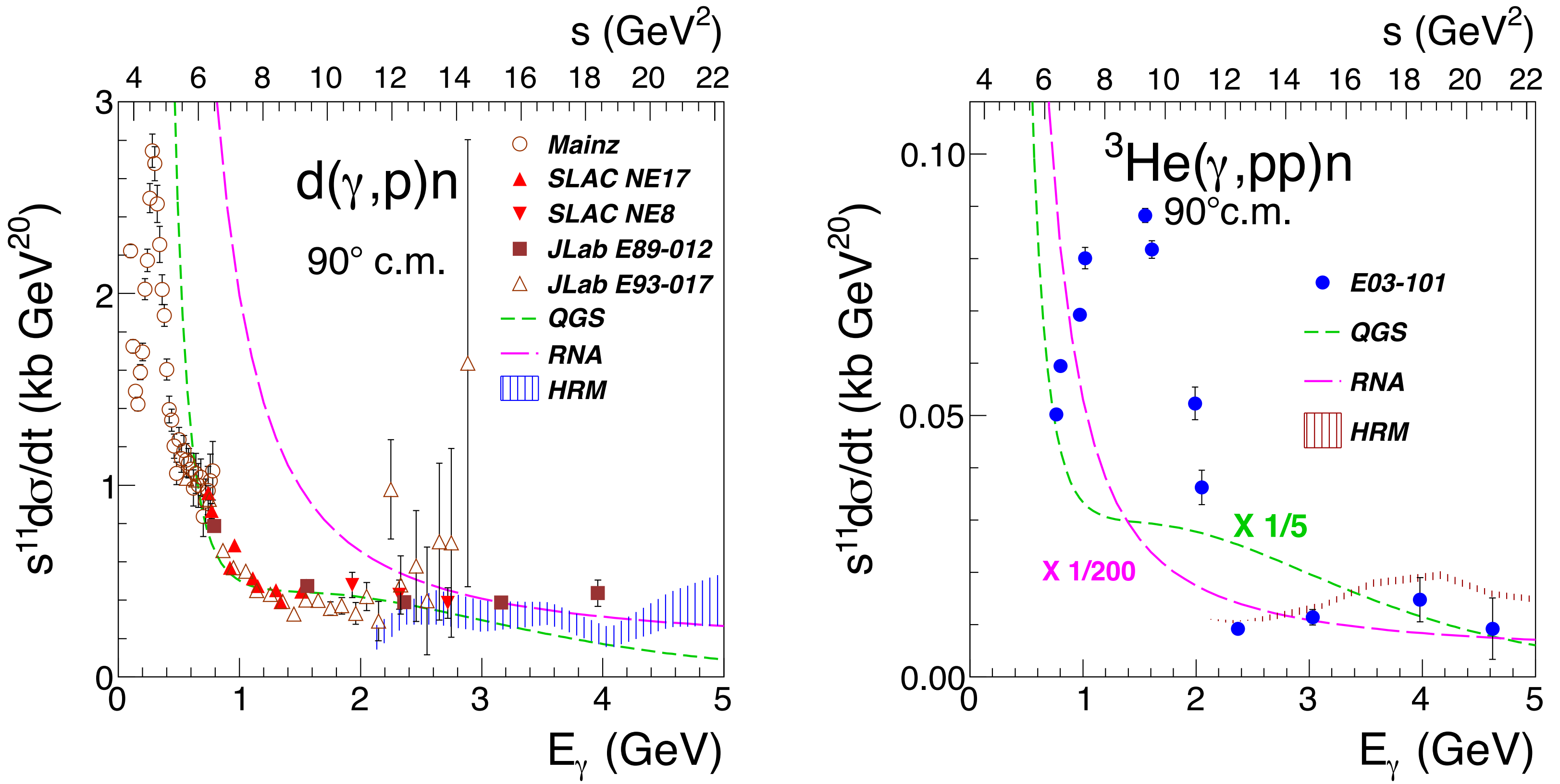
Constituent counting rule seems to hold for P_T>1.1 GeV/c:

$$\frac{d\sigma}{dt} \sim s^{-11} f(\theta_{CM})$$

P.Rossi et al. PRL 94 (2005) 012301

M.Mirazita et al. PRC 70 (2004) 014005

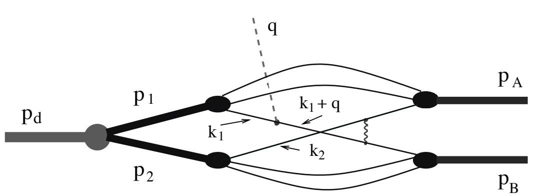
P_T>1.1 GeV/c



QGS: Quark Gluon String Model (L.A.Kondratyuk et al., PRC 48, 2491(1993))

RNA: Reduced Nuclear Amplitudes (S.J. Brodsky and J.R.Hiller PRC 48, 475 (1983))

HRM: Hard Rescattering Model (L.L.Frankfurt et al., PRL 84 3045 (2000))



E.C.Schulte et al. PRL 87 (2001) 102302
C.Bochna et al. PRL 81 (1998) 4576
I.Pomerantz et al. PLB 684 (2010) 106)

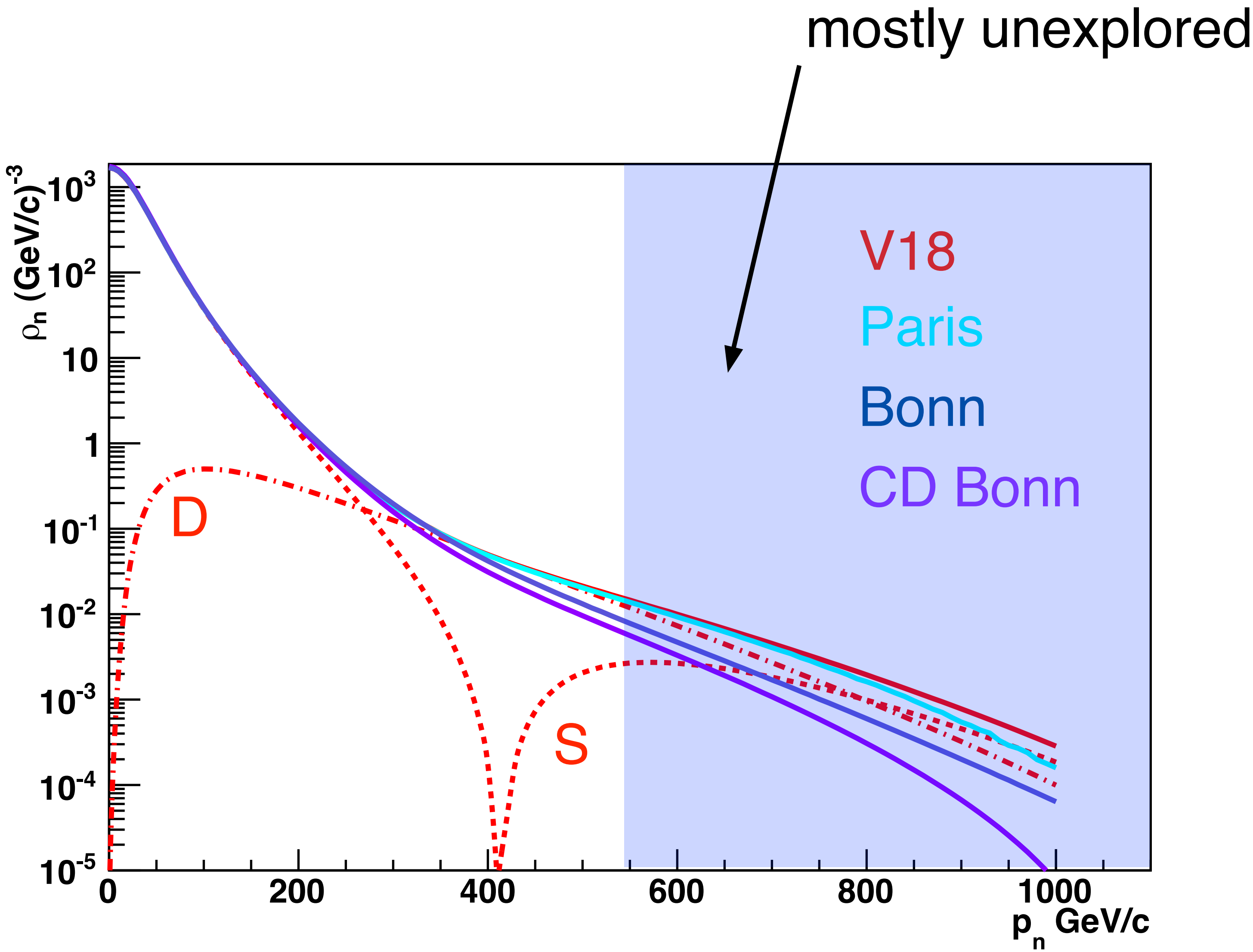
Summary:

- Very challenging to calculate
- Indication of dimensional scaling but pQCD and RNA cannot reproduce absolute cross sections
- Hard re-scattering model reproduces data above 2GeV
- QGS reproduces general trend
- Photo disintegration does not give access to high momentum components of deuteron wave function

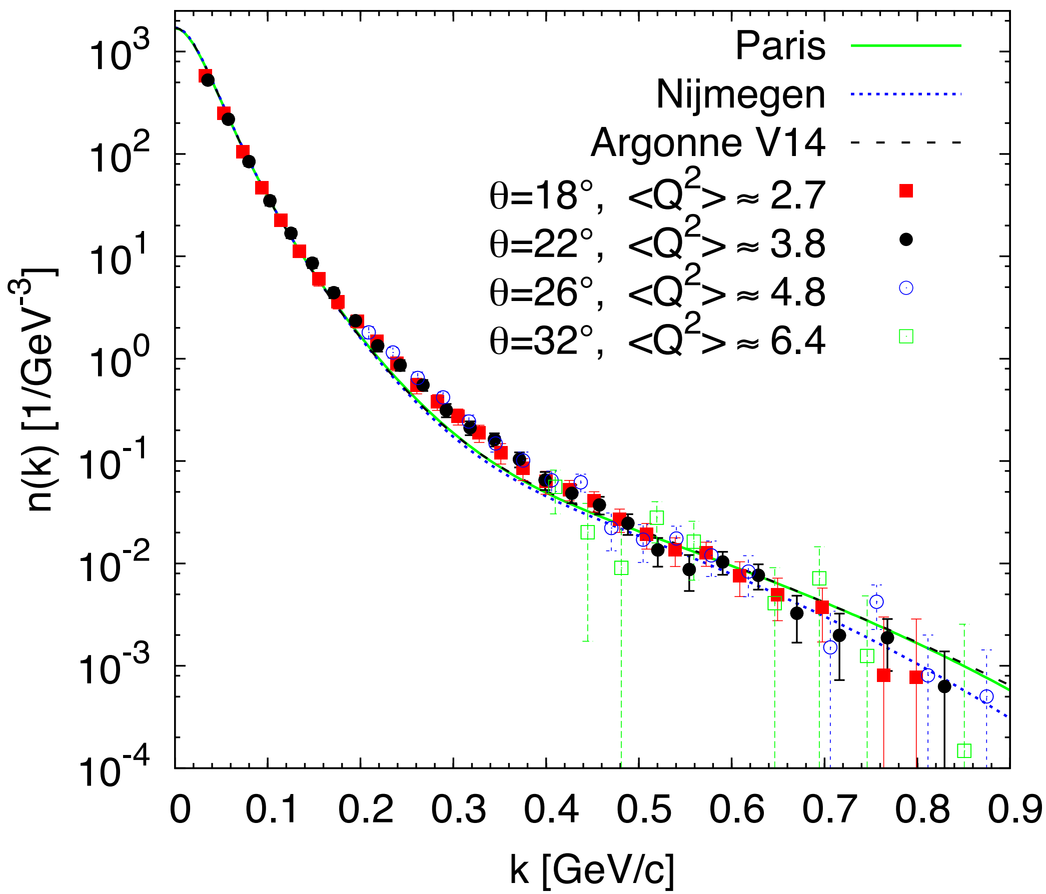
Problem

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


mostly unexplored
V18
Paris
Bonn
CD Bonn
D
S
ρ_n (GeV/c)$^{-3}$
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
200
400
600
800
1000
p_n GeV/c

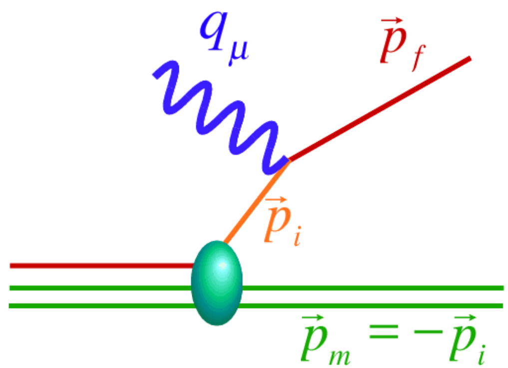
Momentum distribution from scaling analysis



N. Fomin, et al., PRL 108 (2012) 095202

D(e,e’ p) Reaction Mechanisms

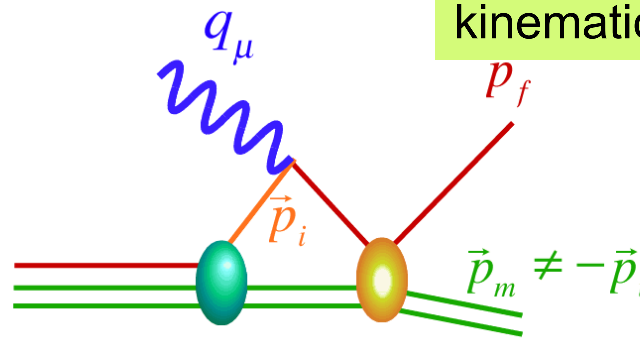
PWIA



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

FSI

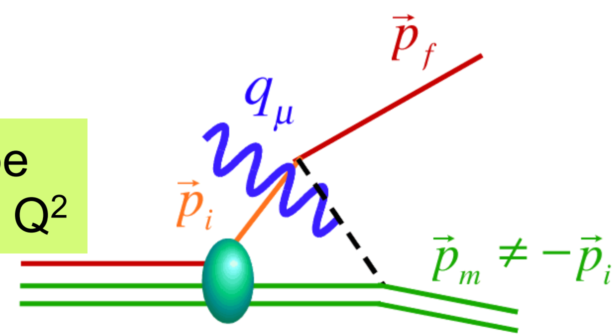
reduced at certain kinematics ?



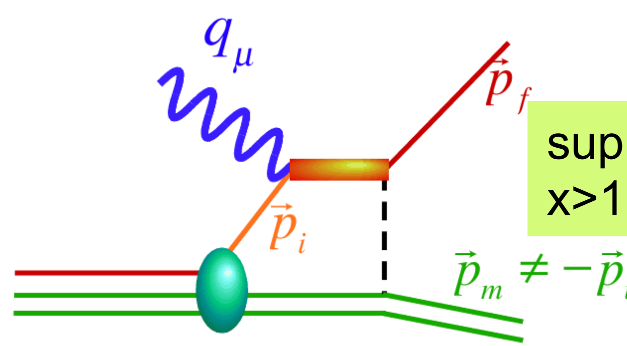
$$\frac{d\sigma}{d\omega d\Omega_e d\Omega_N} = k\sigma_{eN} D(E_m, p_f, p_m)$$

MEC

expected to be small at large Q^2

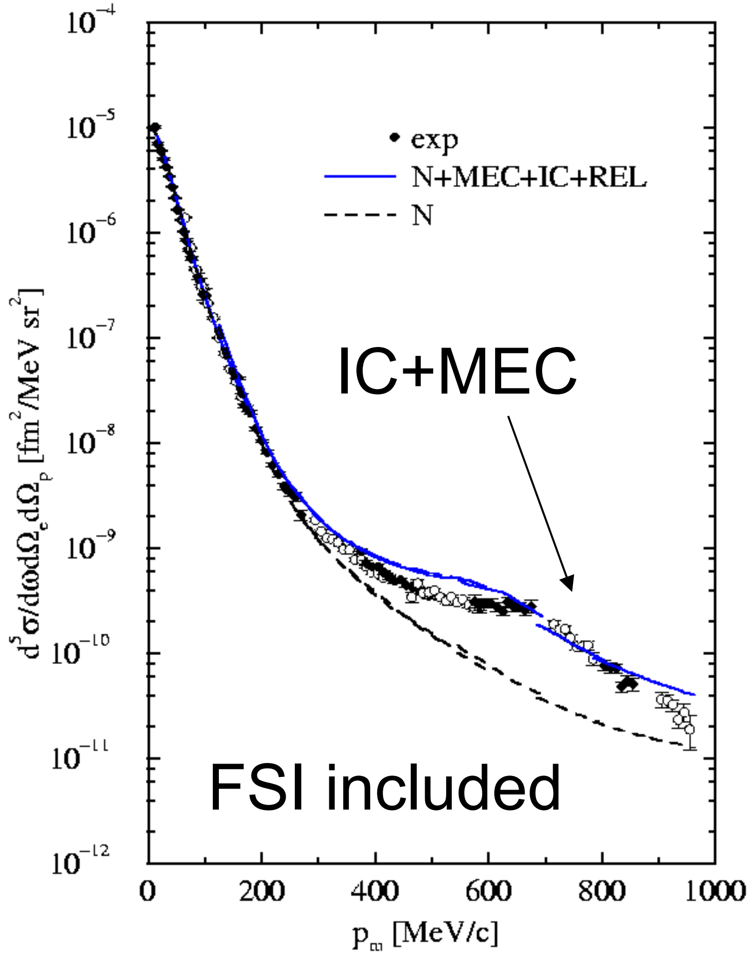


IC

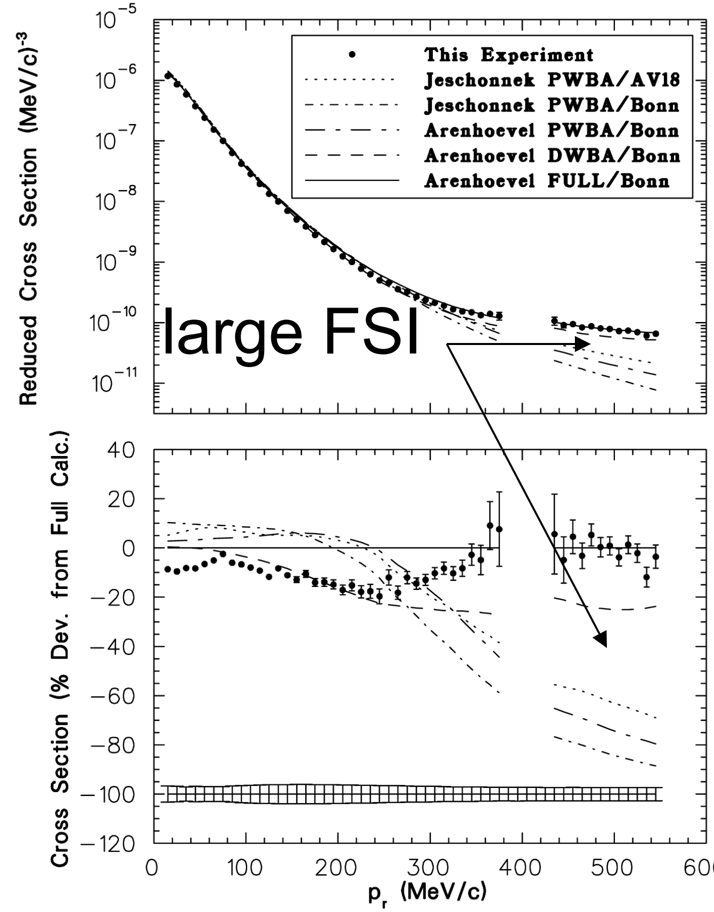


supressed for x>1

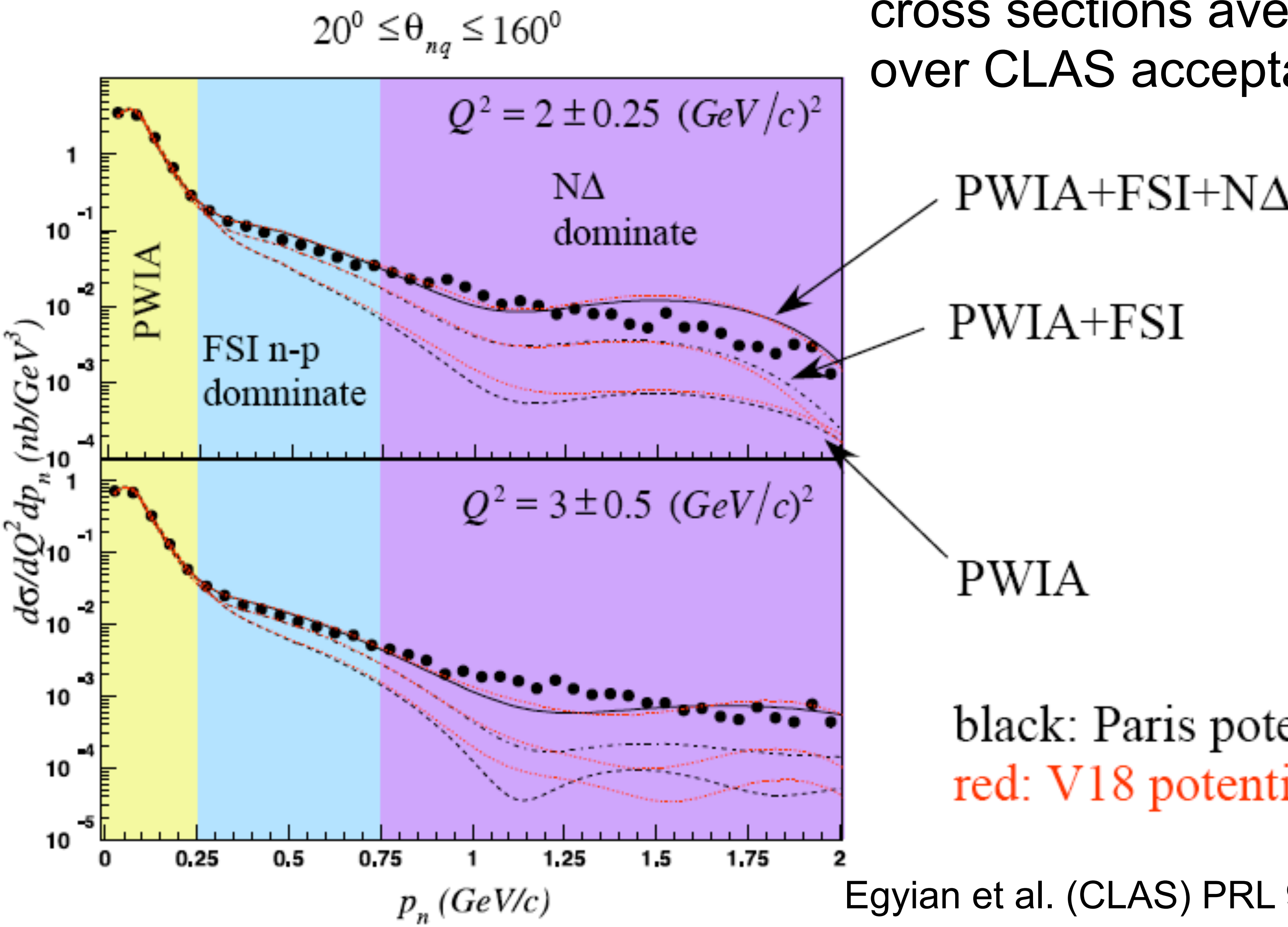
Missing Momentum Dependence



MAMI $Q^2 = 0.33$ (GeV/c)^2
Blomqvist et al. PLB 424 (1998) 33



JLAB $Q^2 = 0.67$ (GeV/c)^2
Ulmer et al. PRL 89 (2002) 062391



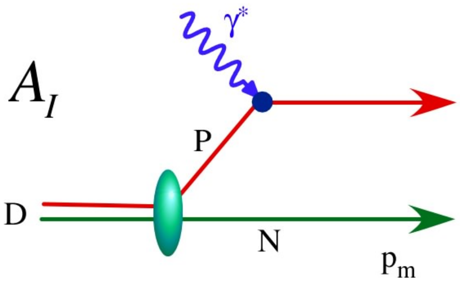
cross sections averaged over CLAS acceptance !

black: Paris potential
red: V18 potential

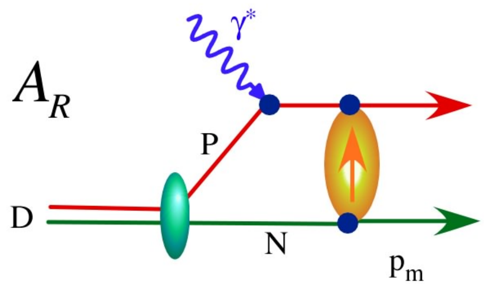
Egyian et al. (CLAS) PRL 98 (2007)

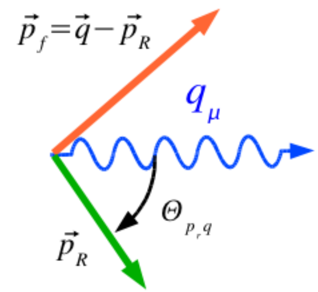
FSI as Rescattering

IA Amplitude (real):



Rescattering Amplitude
(at high energy mostly imaginary):



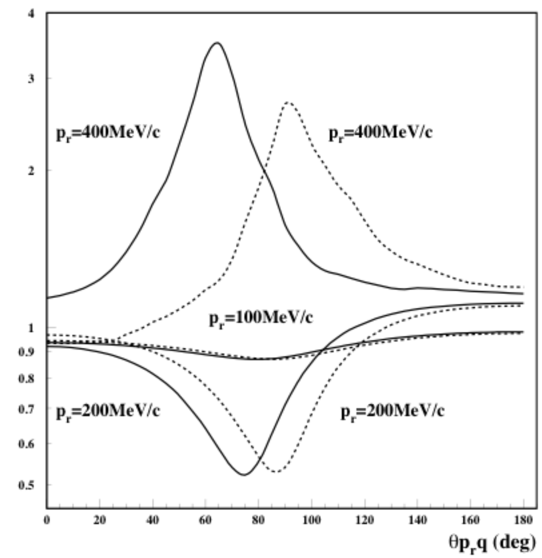


Total scattering amplitude: $A = A_I + iA_R$

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

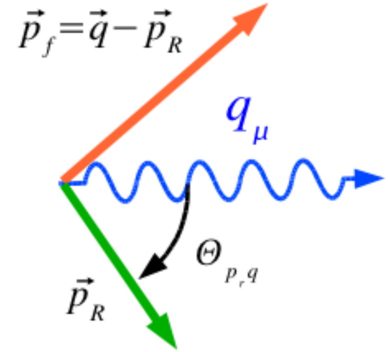
CLAS

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

Hall A

- $Q^2 = 0.8, 2.1$ and $3.5\ (\text{GeV}/c)^2$: 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

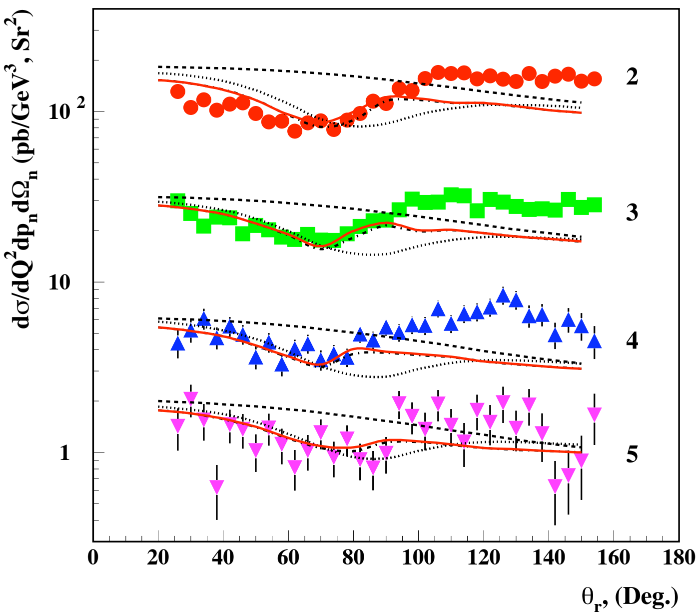
CLAS



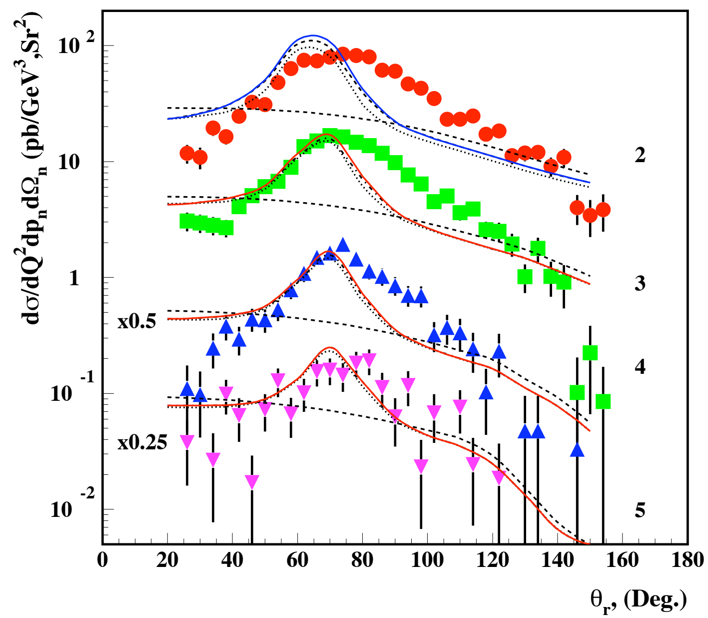
Data: Egyian et al. (CLAS) PRL 98 (2007)

Calculation: M. Sargsian PRC 82 (2010) 014612

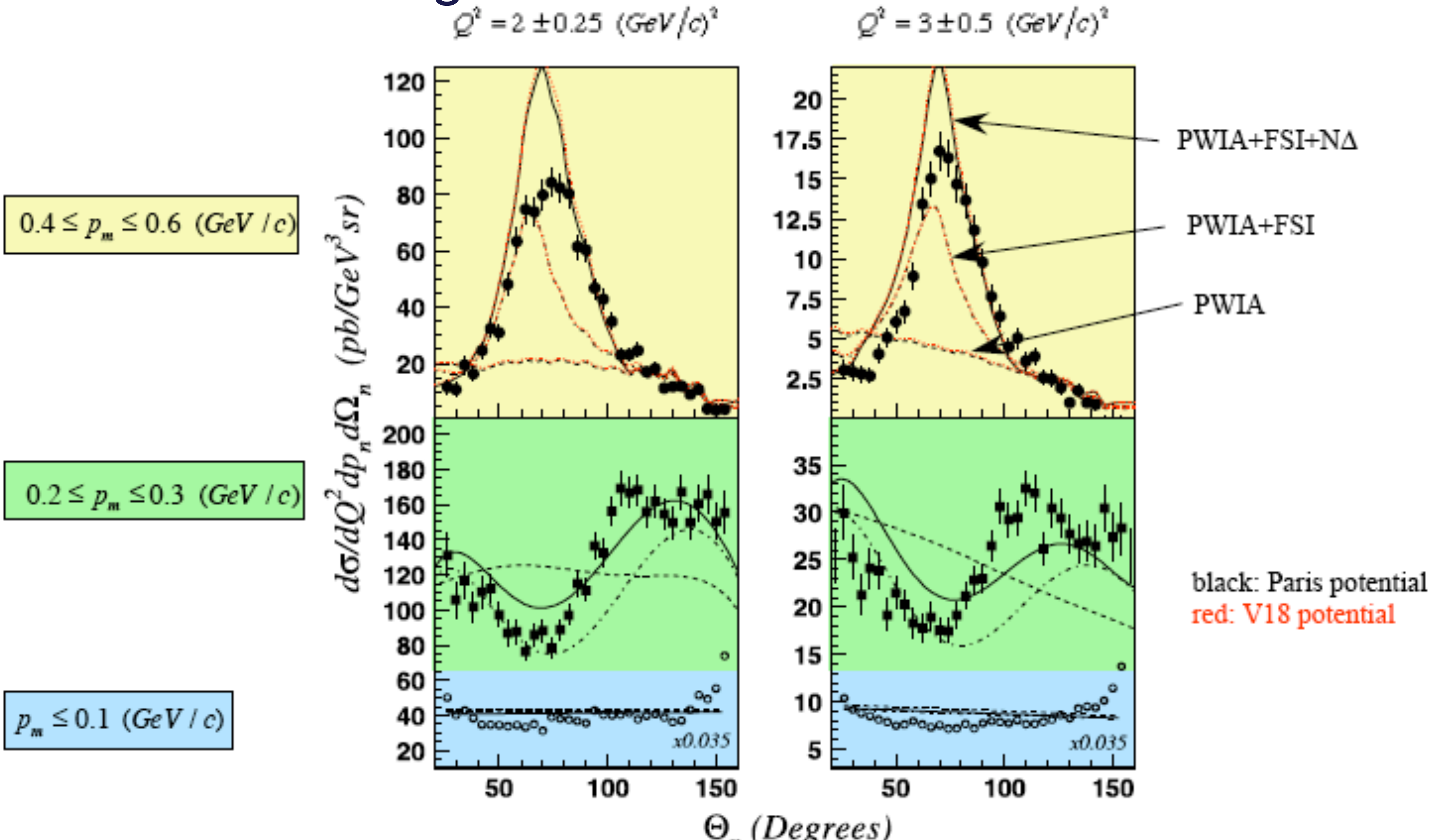
p_m = 250 ± 50 MeV/c



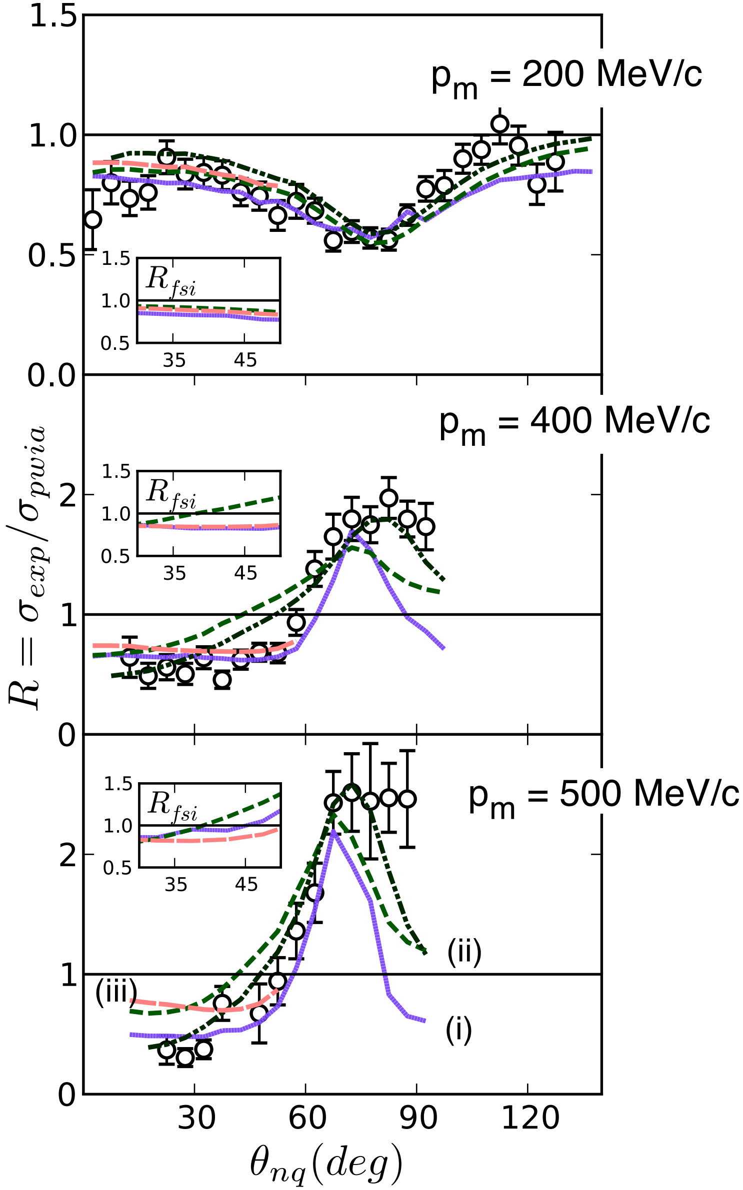
p_m = 500 ± 100 MeV/c



Angular Distribution lower Q^2



Hall A



Selection of angular distributions

$$\Delta p_m = \pm 20 MeV/c$$

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

σ Is experimental or calculated cross section

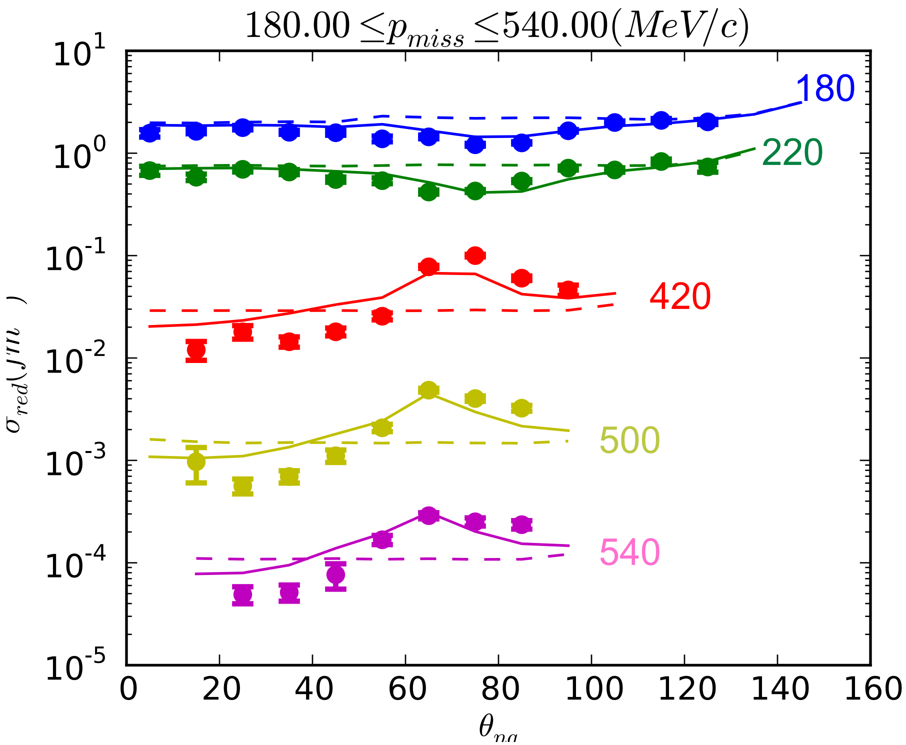
Calculations:

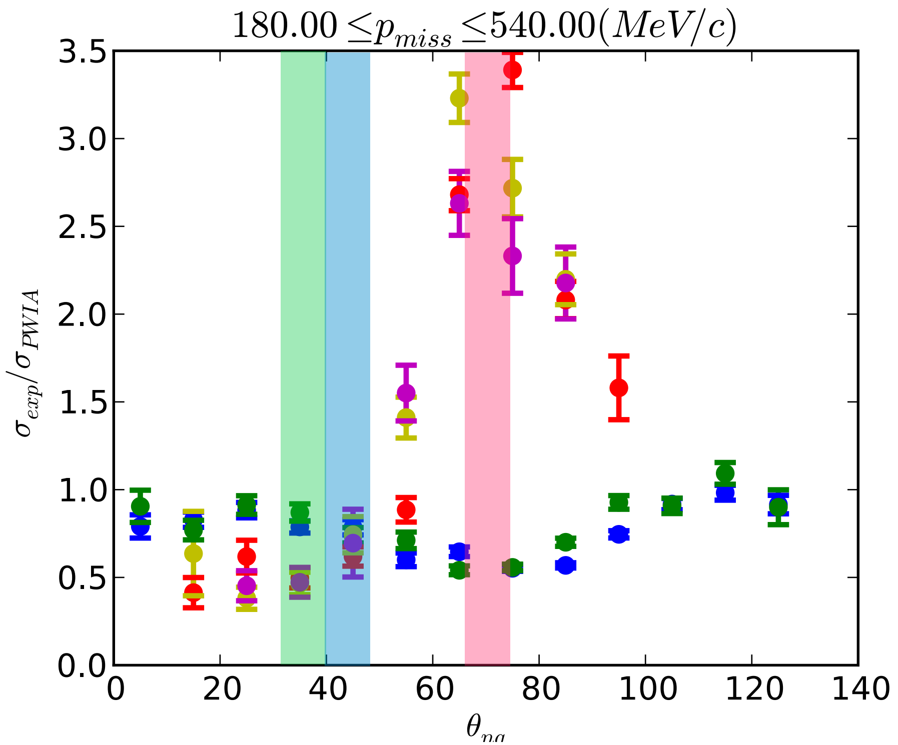
M. Sargsian PRC 82 (2010) 014612

J.M.Laget PLB 609 (2005) 49

S.Jeschonnek and J.W.van Orden PRC 78 (2008) -14007

W.U.Boeglin et al. PRL 107(2011)262501

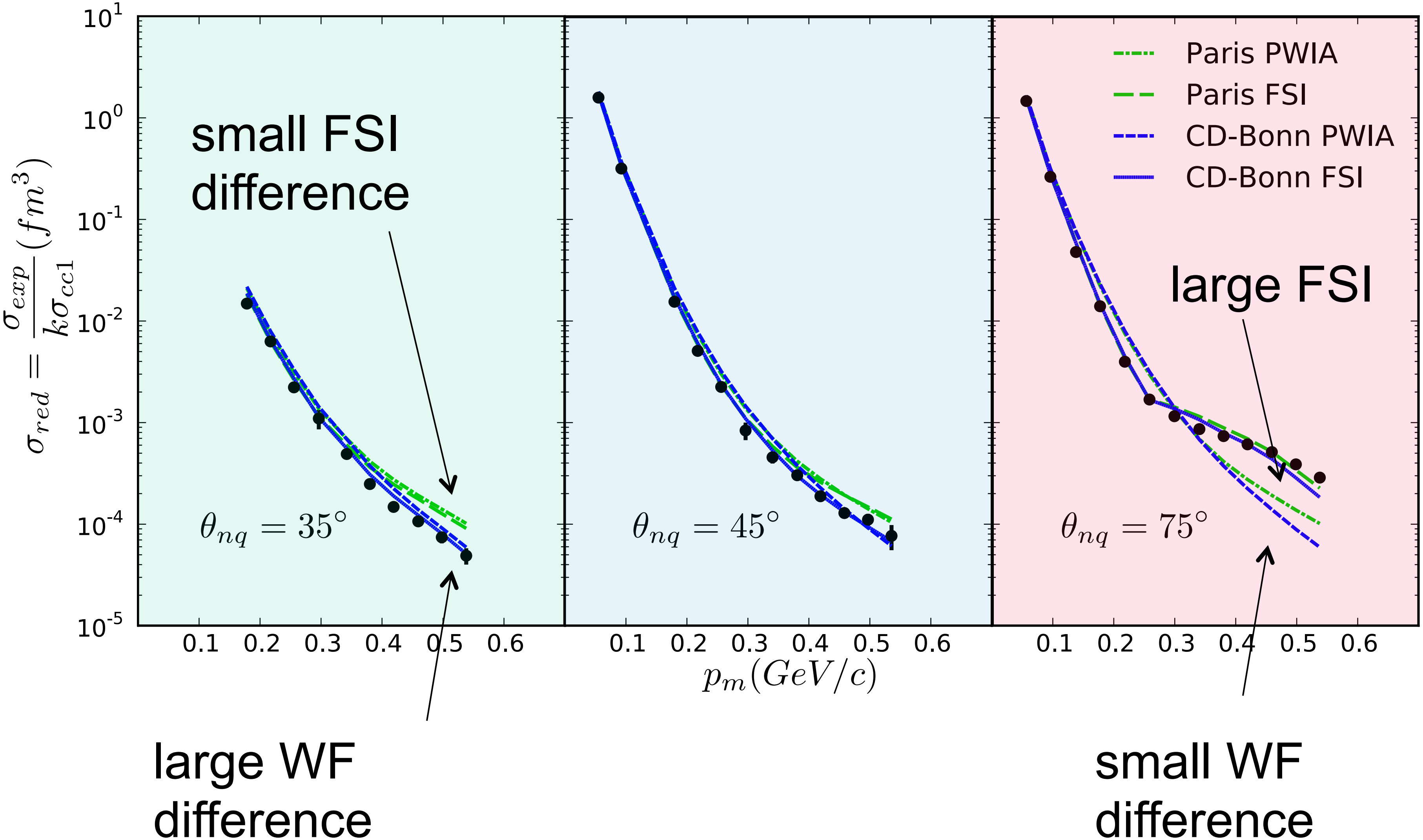




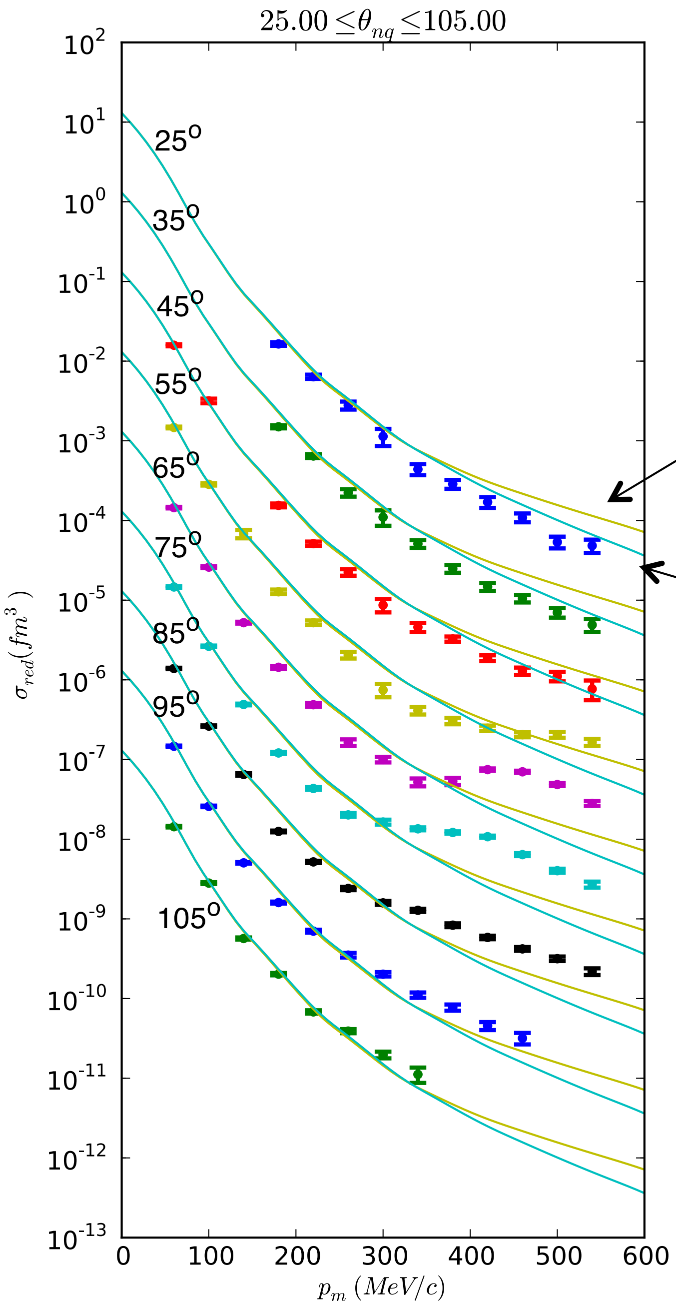
$$\sigma_{red} = \frac{\sigma_{\exp}}{k\sigma_{cc1}}$$

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

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



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



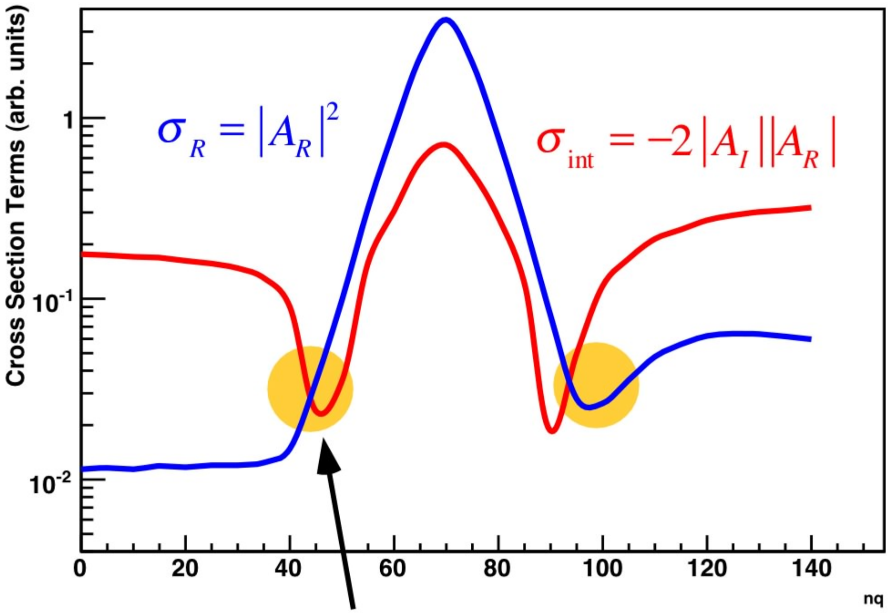
each angle offset by 0.1

'yellow' n(p) Paris

'cyan' n(p) CD Bonn

Why the 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)

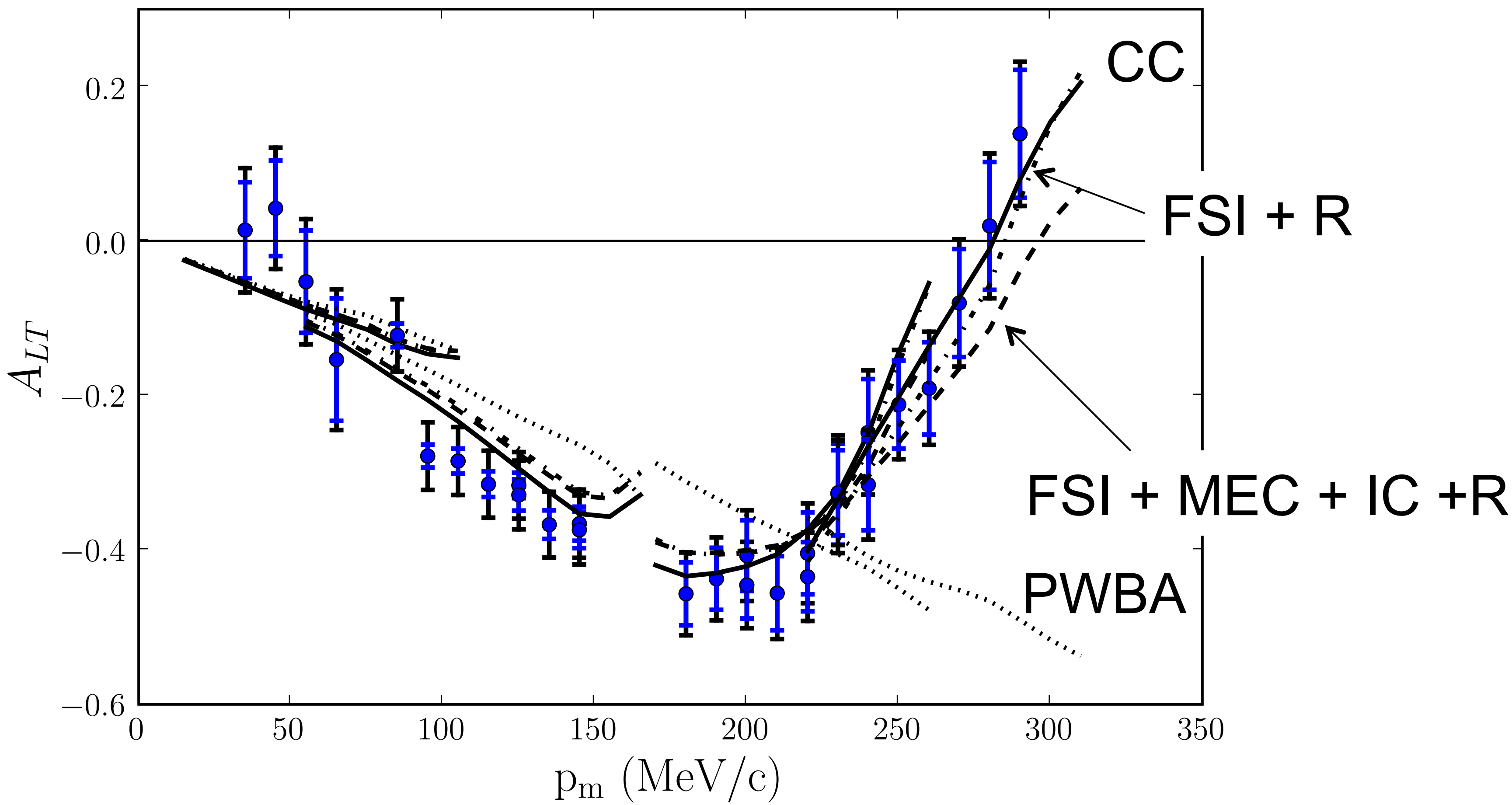
R_{LT} determination

- Data for $\phi = 0^o$ and $\phi = 180^o$
- New analysis: first results

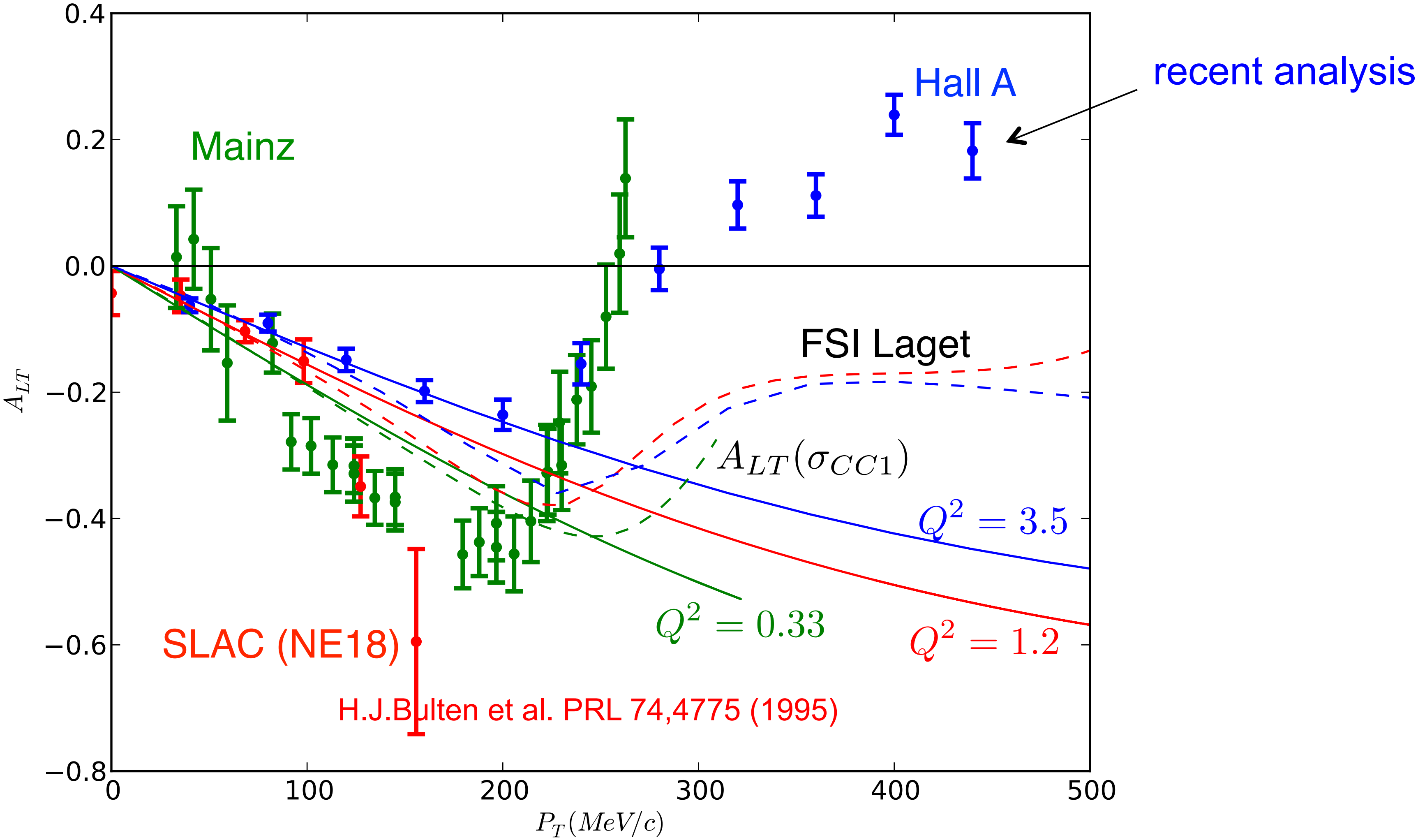
$$A_{LT} = \frac{\sigma_0 - \sigma_{180}}{\sigma_0 + \sigma_{180}}$$

- PWIA: A_{LT} determined by σ_{ep}

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



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

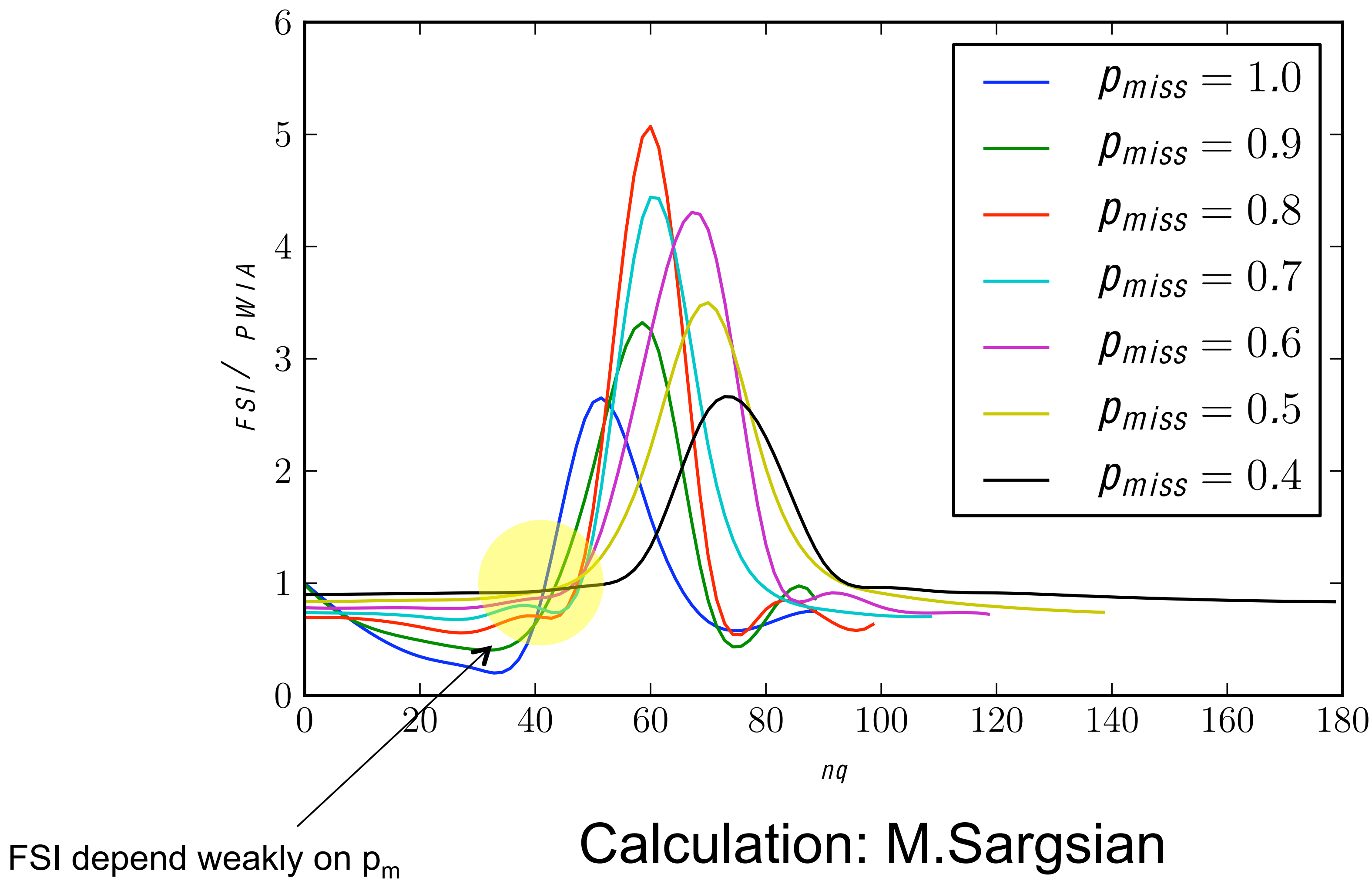


recent analysis
Hall A
Mainz
FSI Laget
$A_{LT}(\sigma_{CC1})$
$Q^2 = 3.5$
$Q^2 = 0.33$
$Q^2 = 1.2$
SLAC (NE18)
H.J.Bulten et al. PRL 74,4775 (1995)
A_{LT}
$P_T(MeV/c)$
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
0
100
200
300
400
500

Future Experiment at 12 GeV

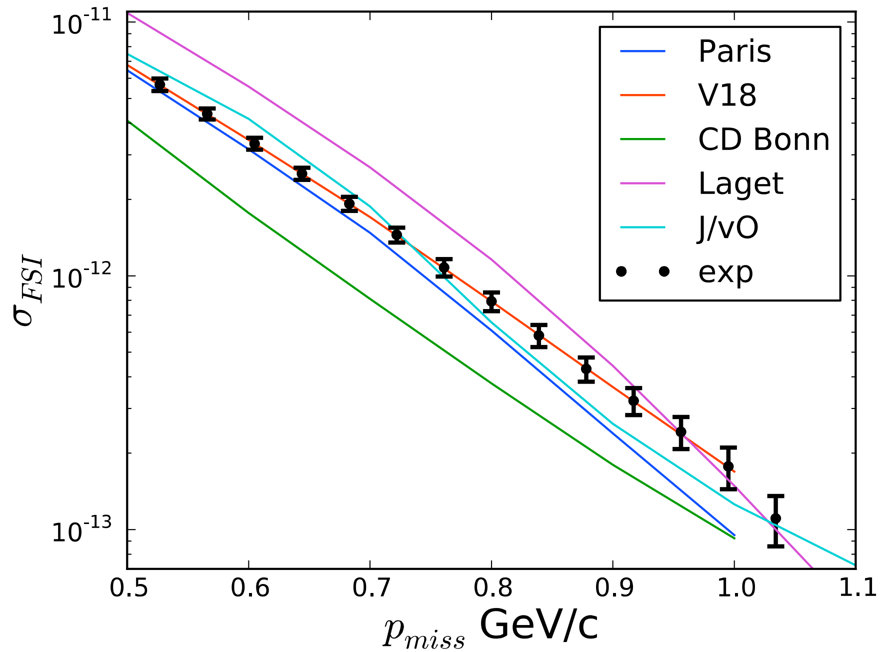
- SHMS,HMS coincidence experiment to determine cross sections at missing momenta up to 1 GeV/c
- Q2 = 4.25 $(\mathrm{GeV/c})^2$
- Selected kinematics to minimize contributions from FSI
- Selected kinematics to minimize effects of delta excitation

Angular Distributions up to p_m = 1GeV/c



Calculation: M.Sargsian

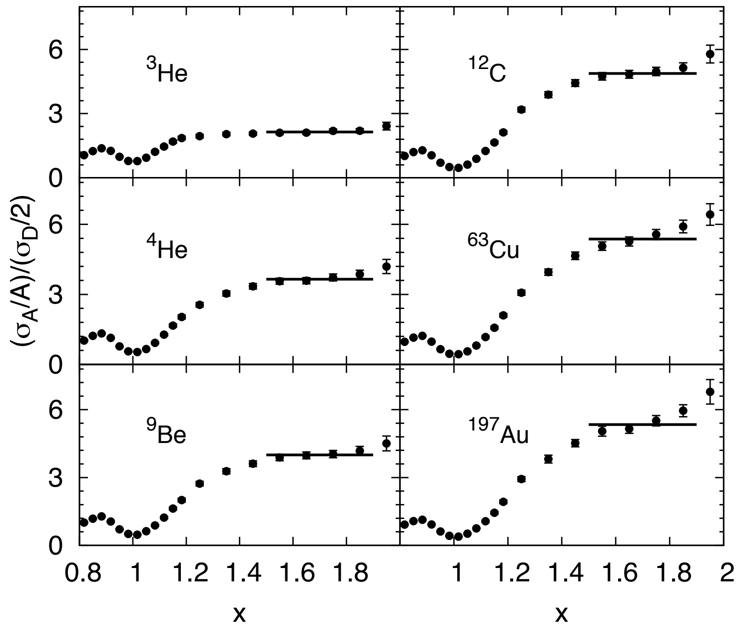
Expected Results



- ✓ Measured cross sections for p_m up to 1 GeV/c
- ✓ Errors: dominated by statistics: 7% - 20%
- ✓ Estimated systematic error ≈ 5 %
- ✓ Very good theoretical support available
- ✓ JLAB uniquely suited for high p_m studies

Summary

- Elastic Scattering is well reproduced by new, relativistic models.
- MEC dominate at large Q^2
- Photo disintegration dominated by hard re-scattering in final state. Successful models need explicit quark-gluon degrees of freedom.
- Dimensional scaling behavior indicative of the emergence of new degrees of freedom.
- High Q^2 d(e,e' p)n can be described using the generalized eikonal approximation
- High Q^2 provides a window to study the Deuteron momentum distribution with small FSI



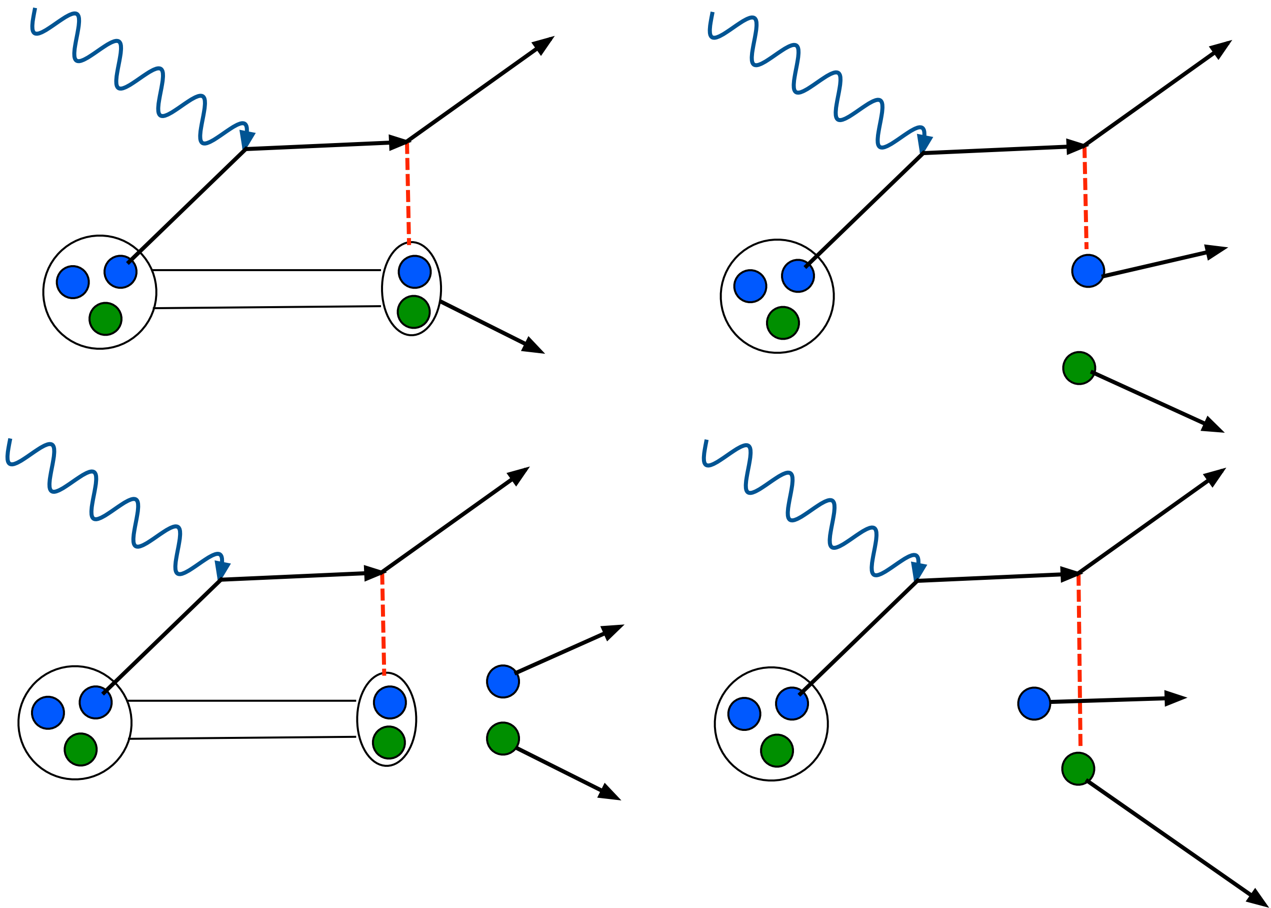
N. Fomin, et al., PRL 108 (2012) 095202

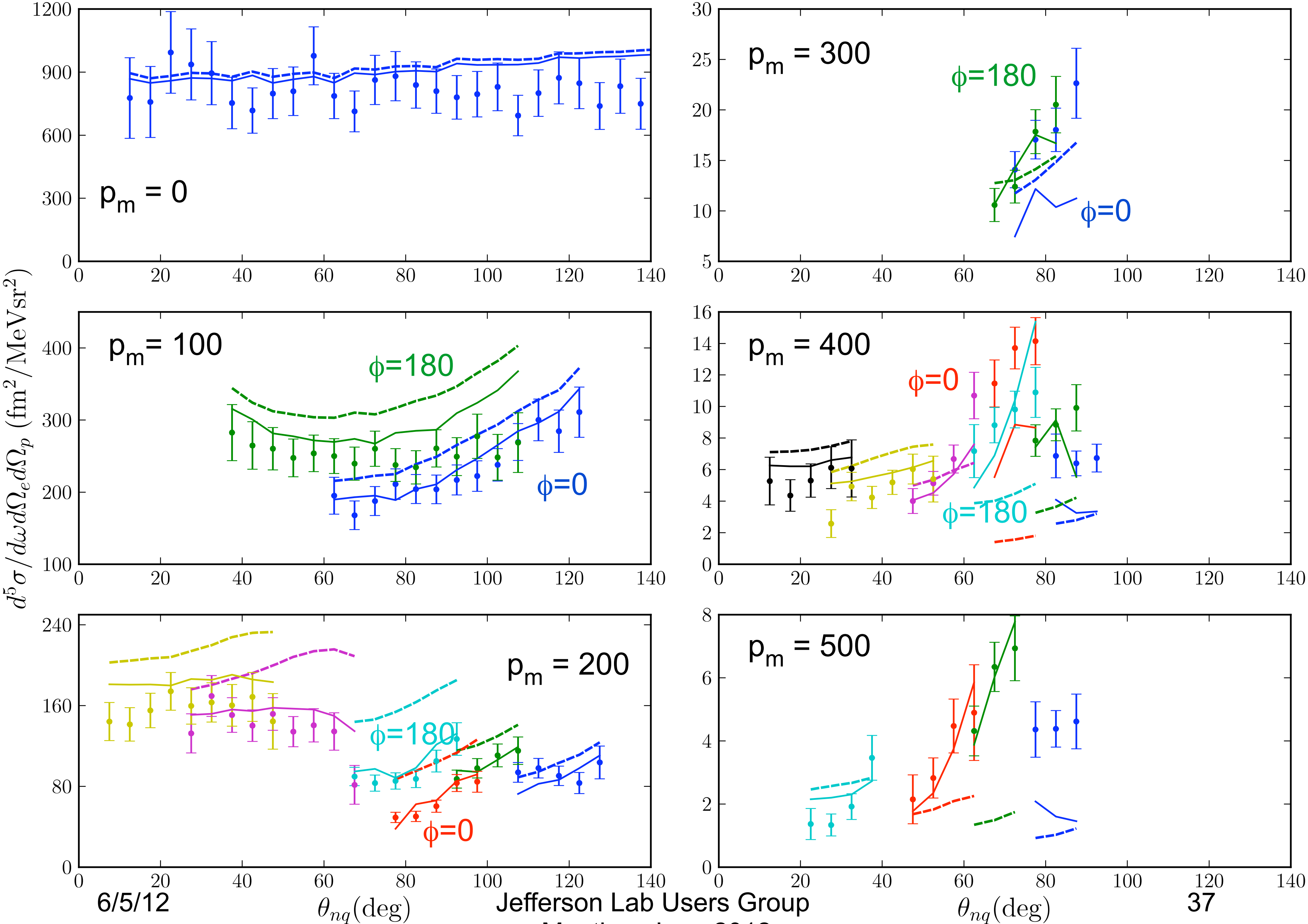
Other systems

All e,e'p measurements of ^{3}He are dominated by FSI at high p_m

- Are there 'windows' with small FSI in other systems ?
- ^{3}He a natural case
- How does re-scattering in a 2-body break up differ from the deuteron case
- What about 3 body break up
- Should we measure angular distributions ?

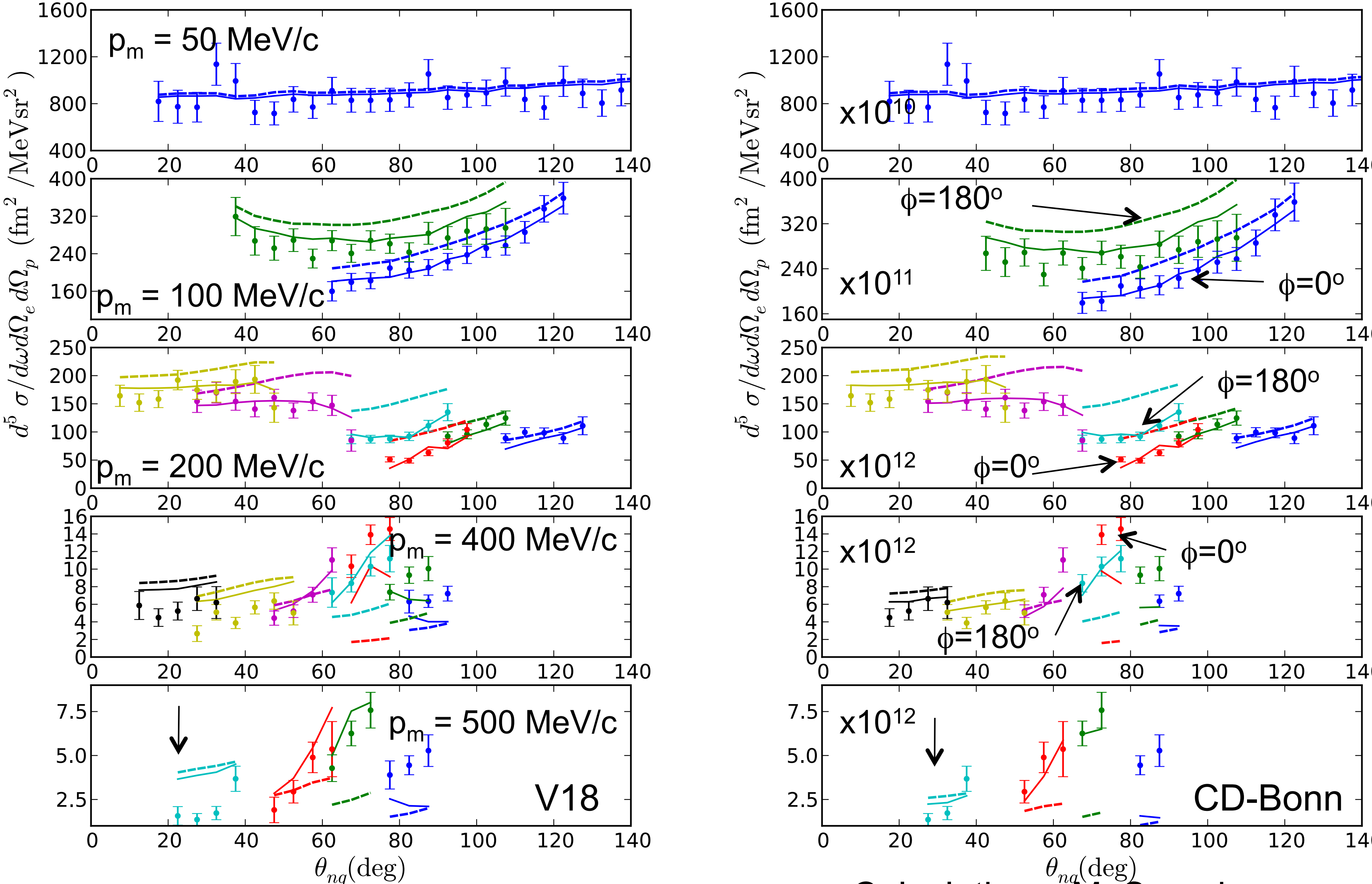
Rescattering in ^{3}He e,e'p



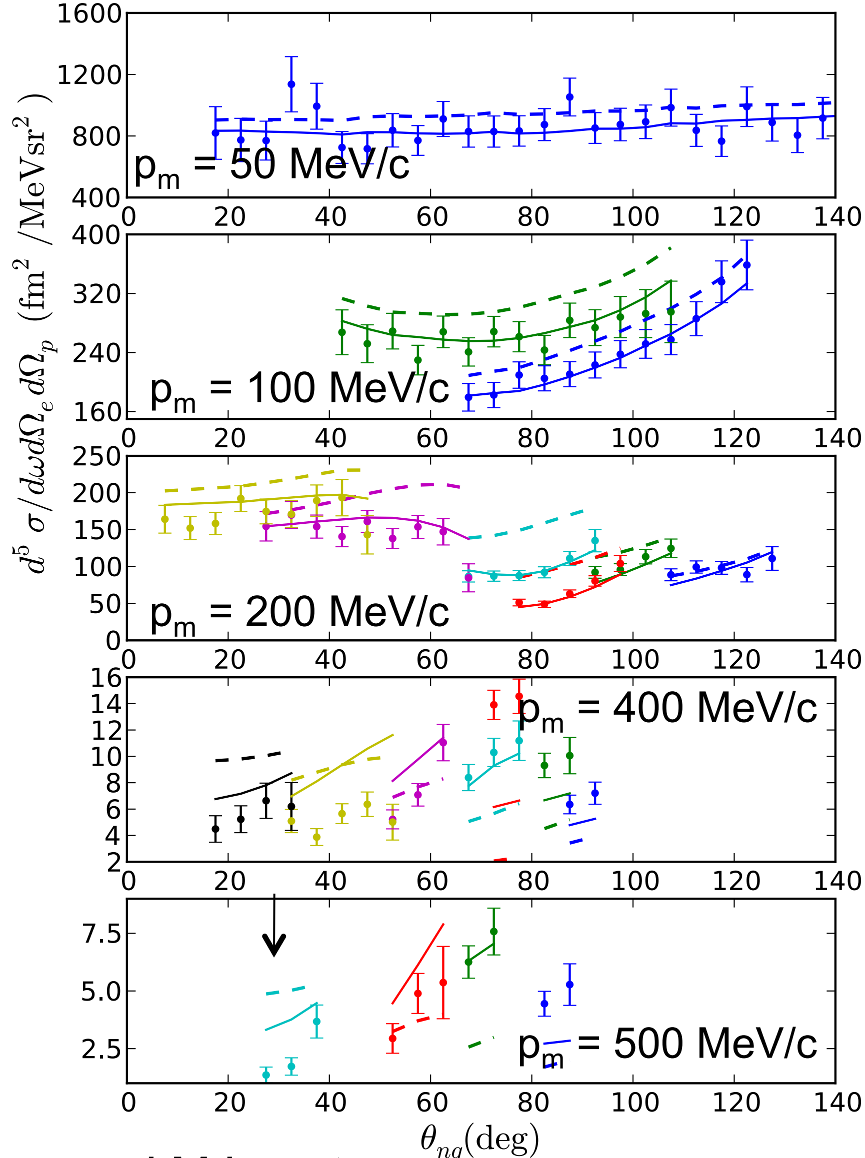


$p_m = 0$
$p_m = 300$
$\phi=180$
$\phi=0$
$p_m = 100$
$\phi=180$
$\phi=0$
$p_m = 400$
$\phi=0$
$\phi=180$
$p_m = 200$
$\phi=180$
$\phi=0$
$p_m = 500$
$d^5\sigma/d\omega d\Omega_e d\Omega_p$ (fm^2/MeVsr^2)
θ_{nq}(deg)
θ_{nq}(deg)

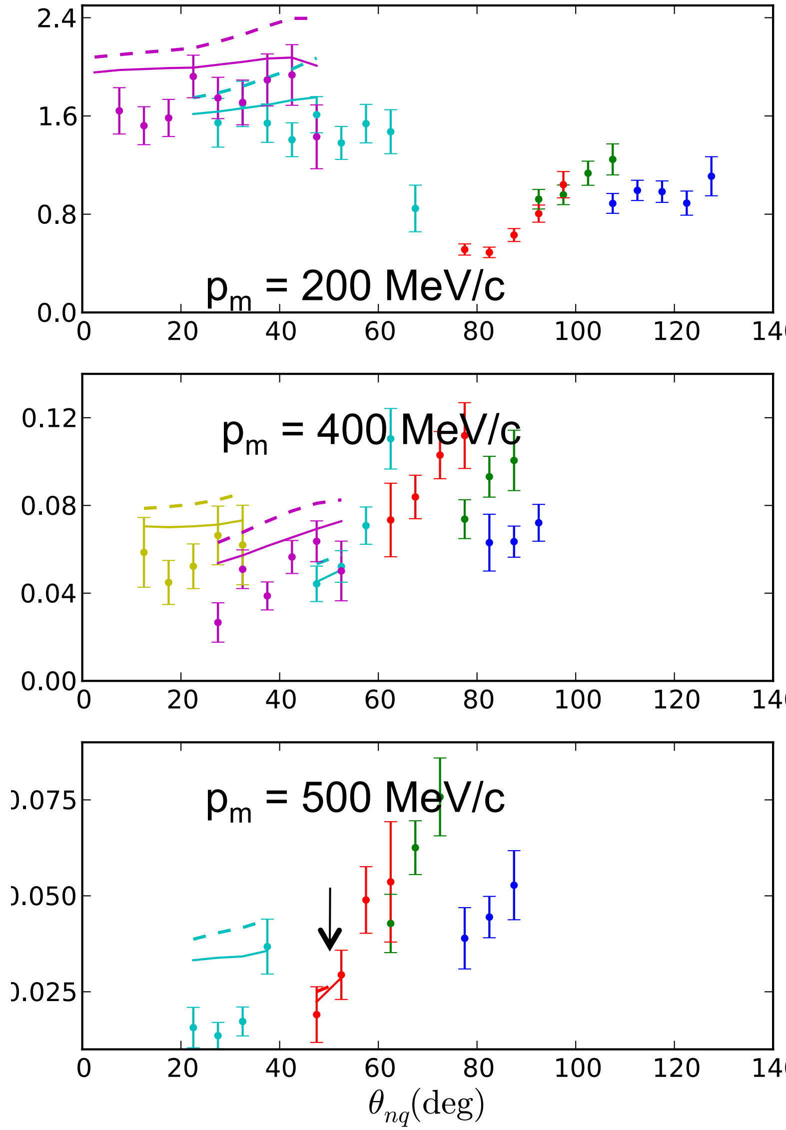
Hall A



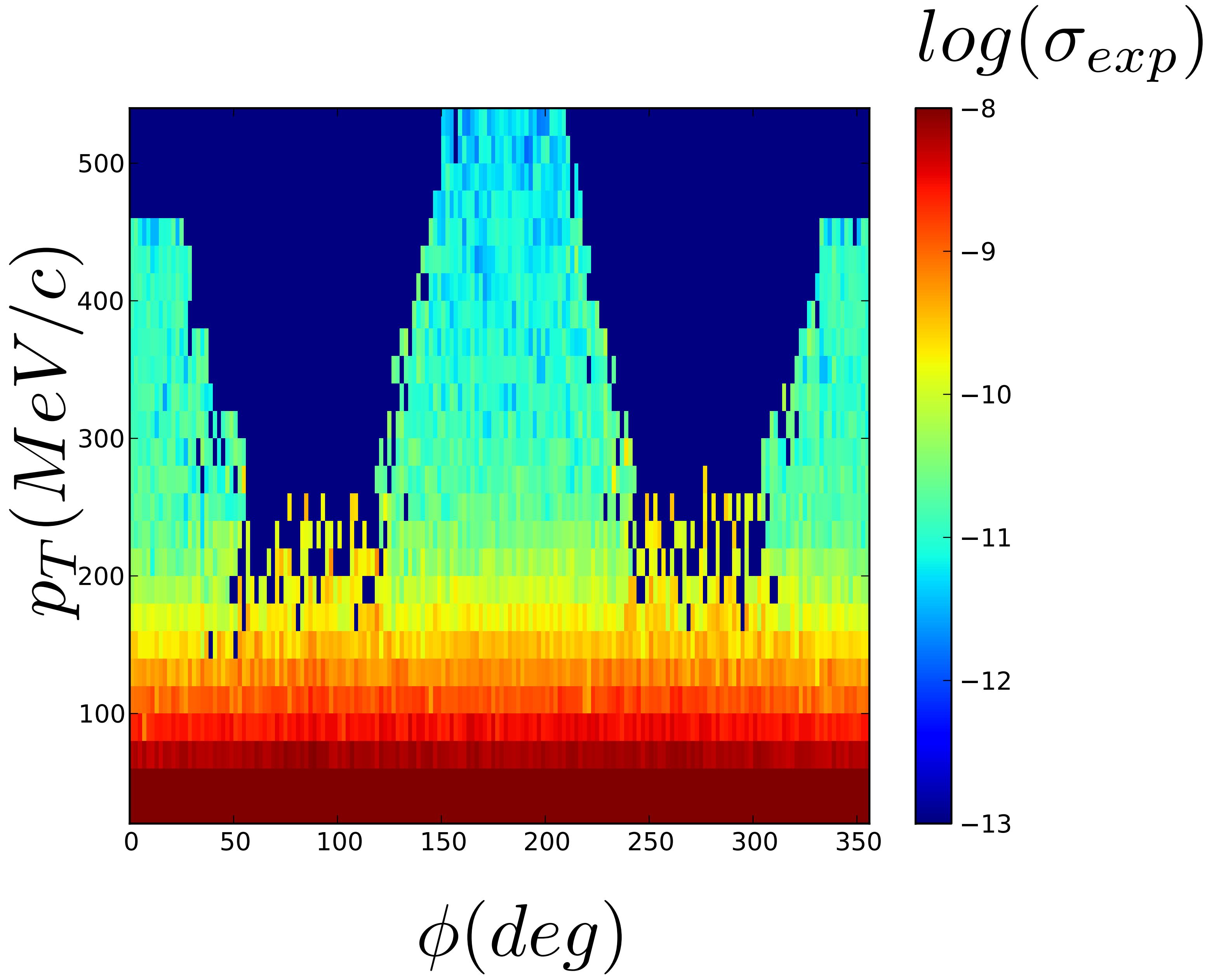
Calculations: M. Sargsian



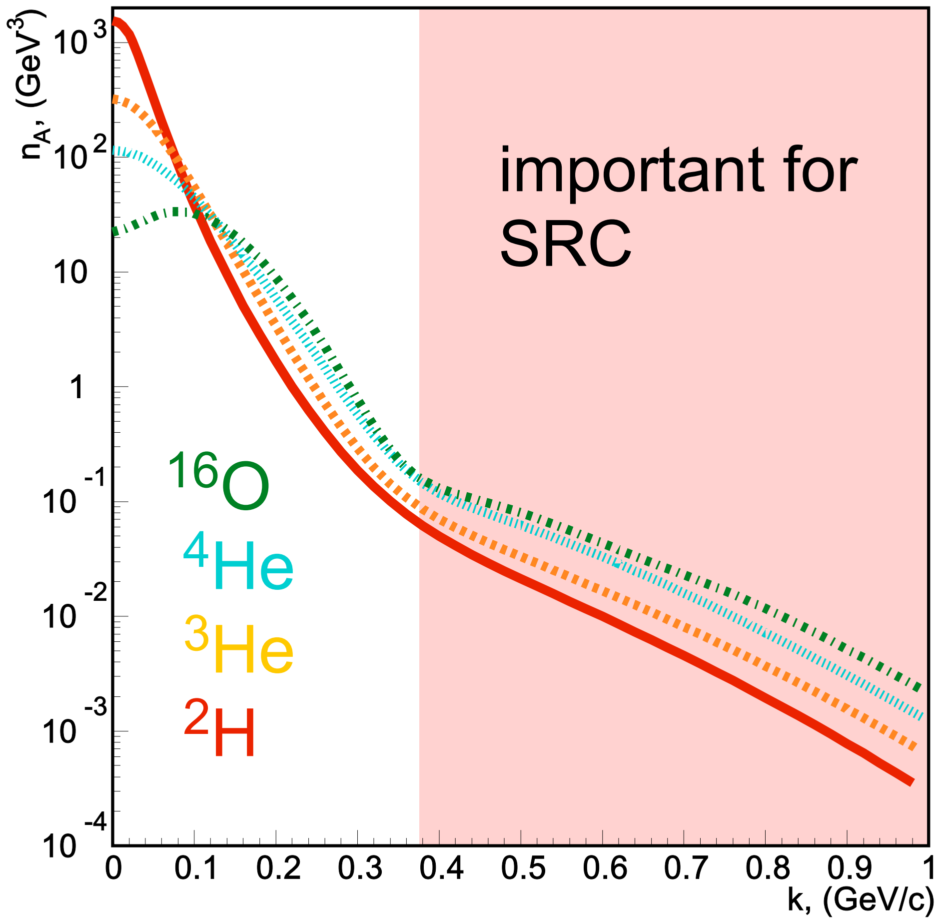
J.M.Laget



S. Jeschonnek J.W. van Orden


$log(\sigma_{exp})$
−8
−9
−10
−11
−12
−13
$p_T(MeV/c)$
500
400
300
200
100
0
50
100
150
200
250
300
350
$\phi(deg)$

Momentum Distributions



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

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