Nuclear transparency of small-size configurations

Wim Cosyn

Florida International University
Ghent University, Belgium

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Outline

1. Motivation
2. Transparencies in a Glauber Model (Ghent group)
   - Model
   - Applications and Results
   - Density Dependence
3. Semi-inclusive DIS off deuteron (w M. Sargsian)
   - Model: Ingredients and approximations
   - Comparison with Deeps
   - Q^2, W evolution of rescattering parameters
4. Conclusions

Motivation

- Look for phenomena predicted in QCD that introduce deviations from traditional nuclear physics observations
- the nuclear transparency as a function of a tunable scale parameter (t or Q^2) is a good quantity to study the crossover between the two regimes

Nuclear transparency: effect of nuclear attenuations on escaping hadrons

$$T(A, Q^2) = \frac{\text{cross section on a target nucleus}}{A \times \text{cross section on a free nucleon}}$$

- Onset of color transparency (Brodsky,Mueller) will show as a rise in T
- Interpretation of the transparency experiments requires the availability of reliable and advanced traditional nuclear-physics calculations to compare the data with

Building a Model

- To interpret the data from experiments, comparison to results from up-to-date nuclear models is necessary to identify deviations originating from QCD effects
- Semi-classical models are available
- Develop a relativistic and quantum mechanical model

Ingredients

- Relativistic wave functions for beam, target and residual nucleus, outgoing particles
- Impulse approximation: incoming particle (leptonic or hadronic) interacts with one nucleon
- Describe the final state interactions of the ejected particles with Glauber scattering theory

NPA **A728** (2003) 226

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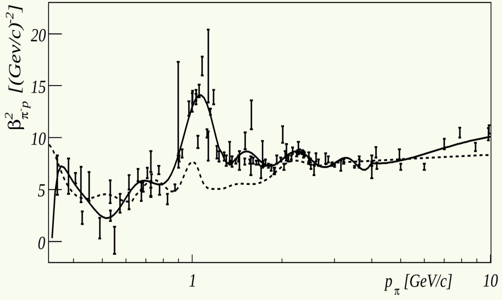
  NPA **A728** (2003) 226

Glauber scattering theory

- Uses the eikonal approximation, originating from optics:
  $\phi_{\text{out}}(\vec{r}) = e^{i\chi(\vec{r})}\phi_{\text{in}}(\vec{r}) = (1 - \Gamma(\vec{r}))\phi_{\text{in}}(\vec{r})$
- Works when the wavelength of the particle is a lot smaller than the range of the scattering potential $\rightarrow$ OK for the performed experiments!
- Particles scatter over small angles and follow a linear trajectory
- Second order eikonal corrections have been computed $\rightarrow$ small

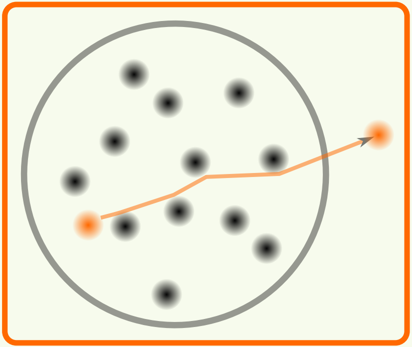
Profile function in $N - N$ and $\pi - N$ scattering

$$\Gamma_{\pi N}(\vec{b}) = \frac{\sigma_{\pi N}^{tot}(1 - i\epsilon_{\pi N})}{4\pi\beta_{\pi N}{}^2} exp\left(-\frac{\vec{b}^2}{2\beta_{\pi N}{}^2}\right)$$



- Profile function can be related to the scattering amplitude
- Three energy-dependent parameters
  - total cross section
  - slope parameter
  - real to imaginary ratio
- Fit parameters to $N - N$ and $\pi - N$ scattering data
- range $\sqrt{2}\beta$ is of the order 0.75 fm $\rightarrow$ short range

Relativistic Multiple-Scattering Glauber Approximation

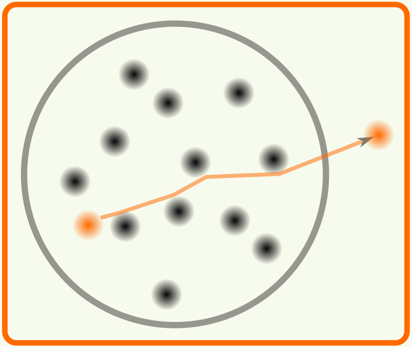


Multiple scattering

- Frozen approximation is adopted
- Phase-shift additivity
  $e^{i\chi_{tot}} = \prod_i \left(1 - \Gamma_i(\vec{b}_i)\right)$
- Profile functions are weighted with the Dirac wave function
- Only nucleons in forward path contribute

$$\mathcal{G}(\vec{b}, z) = \prod_{\alpha_{occ}\neq\alpha} \left[1 - \int d\vec{r}' \left|\phi_{\alpha_{occ}}(\vec{r}')\right|^2 \left[\theta(z' - z)\, \Gamma\left(\vec{b}' - \vec{b}\right)\right]\right]$$

Relativistic Multiple-Scattering Glauber Approximation



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Implementing Short-Range Correlations

- In standard Glauber: effect of intranuclear attenuations is computed as if the density remains unaffected by the presence of a nucleon at $\vec{r} = (\vec{b}, z)$
- $\sqrt{2}\beta \sim 0.75\text{fm} \rightarrow$ attenuations will be mainly affected by the short-range structure of the transverse density in the residual nucleus
- Mean field does not contain repulsive short-range behavior of the $N - N$ force
- Introduce correlated two-body density

$$\rho_A^{[2]}(\vec{r}', \vec{r}) = \frac{A-1}{A} \gamma(\vec{r}) \rho_A^{[1]}(\vec{r}) \gamma(\vec{r}') \rho_A^{[1]}(\vec{r}') g(|\vec{r} - \vec{r}'|)$$

- $\gamma(\vec{r})$ ensures normalization

Color Transparency: Quantum diffusion parametrization

$$\sigma^{\text{eff}}_{iN}(z) = \sigma^{\text{tot}}_{iN}\left\{\left[\frac{z}{l_h} + \frac{<n^2 k_t^2>}{\mathcal{H}}\left(1 - \frac{z}{l_h}\right)\theta(l_h - z)\right] + \theta(z - l_h)\right\} i = \pi \text{ or } N.$$

- Replace the total cross section with an effective one
- Parameters are based on theoretical grounds but values are educated guesses
- Pion cross section is more strongly reduced and formation length is longer

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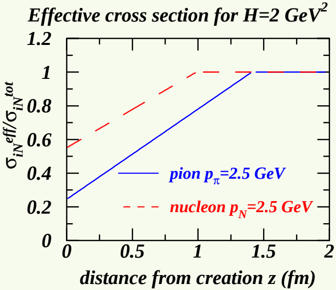

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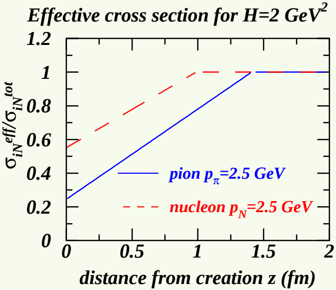
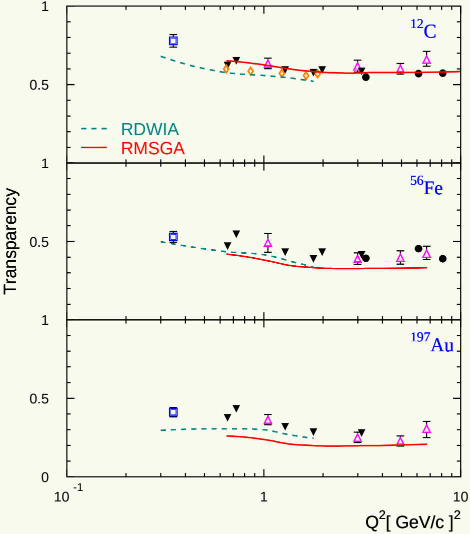


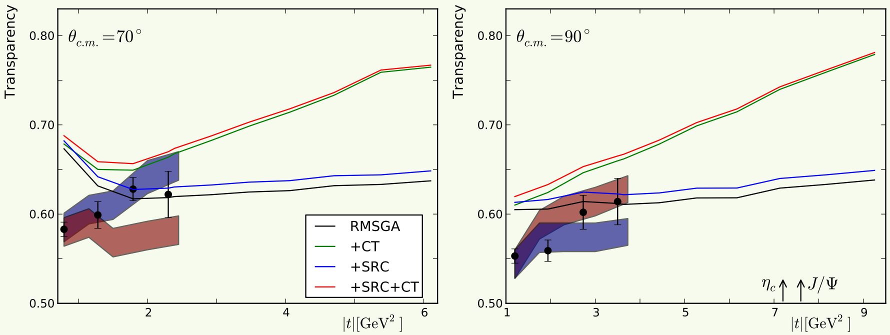
The nuclear transparency from $A(e, e'p)$



P. Lava *et al.* PLB595 (2004), 177–186

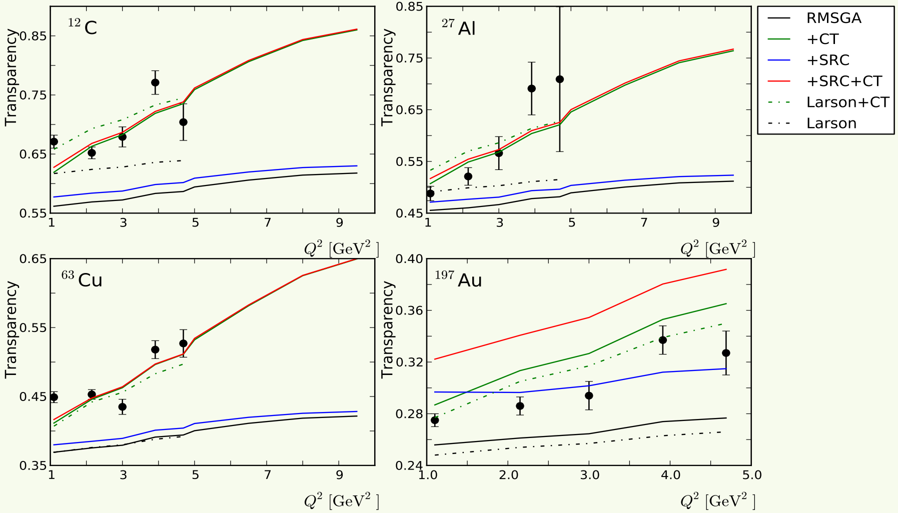
- Calculations tend to underestimate the measured proton transparencies
- In the region of overlap: RMSGA and RDWIA predictions are not dramatically different !!
- Data from MIT, JLAB and SLAC
- CT effects are very small for $Q^2 \leq 10$ GeV^2

$^4\text{He}(\gamma, p\pi^-)$ transparencies



- Theory: W. Cosyn et al., PRC74 (2006) 062201
- Data: D. Dutta et al., PRC68 (2003) 021001
- Semiclassical theory: H. Gao et al., PRC54 (1996) 2779 [normalized to first data point]

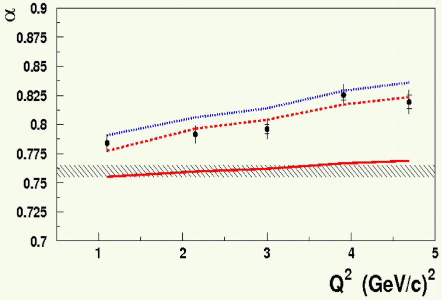
$A(e, e'\pi^+)$ transparencies: Q^2 dependence



$A(e, e'\pi^+)$ data from JLab, B. Clasie *et al.*, PRL99 (2007) 242502

Dashed lines from semi-classical calc. by A. Larson *et al.*, PRC79 (2006) 018201

$A(e,e'\pi^+)$ transparencies: A dependence



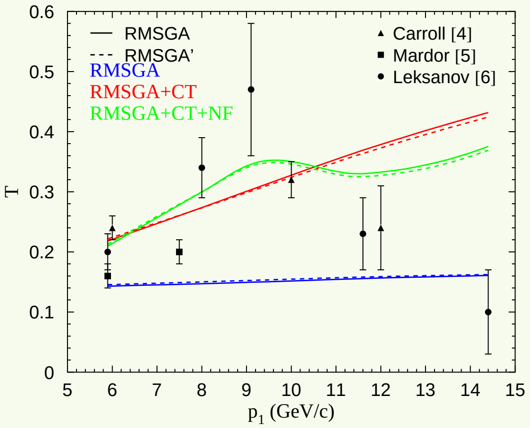
Gl.+SRC+CT

Semi-classical Larson

Hatched area: value from $\pi - A$ scatt.

- Parametrize $T = A^{\alpha-1}$
- Clear Q^2 dependence, deviates from expected value
- Models in good agreement

The nuclear transparency from $^{12}C(p, 2p)$



Parameterization of the CT effects compatible with pion production results!

B. Van Overmeire and J.R., PLB644 (2007) 304

Density Dependence

The RMSGA model provides an excellent basis to study the density dependence of removal reactions

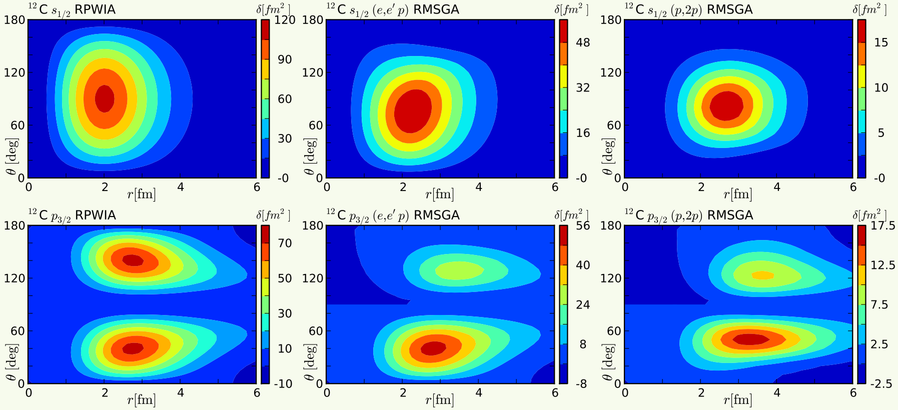
- Variety of reactions
- Scattering parameters are relatively smooth above 1 GeV → universal statements
- Density dependence of the attenuation will determine the effective nuclear density which can be probed

* Compare $A(e, e'p)$ (1 proton), $A(\gamma, pp)$ (2 protons) and $A(p, 2p)$ (3 protons) on ^{12}C and ^{56}Fe
* Outgoing particles have 1.5 GeV kinetic energy

J. Ryckebusch & WC arXiv:1102.0905

WC & JR, PRC80:011602 (2009)

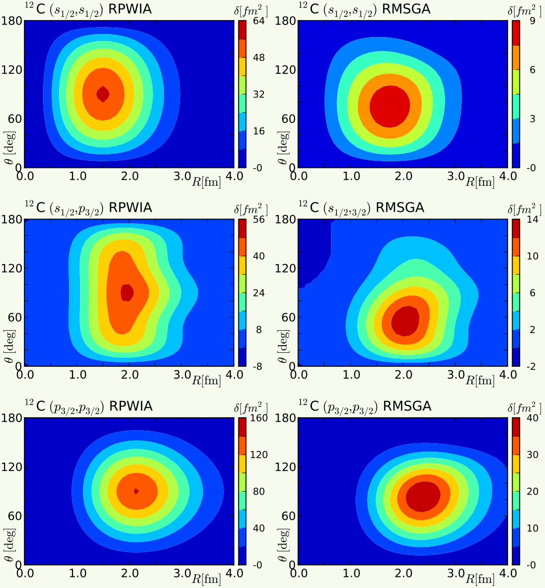
Density Dependence: $^{12}C(e,e'p)$ and $^{12}C(p,2p)$



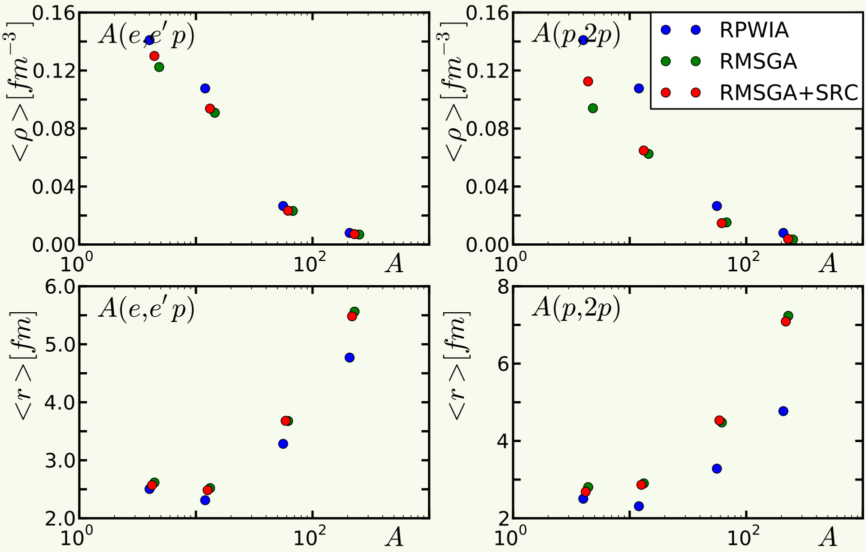
rms radius of ^{12}C $\rightarrow 2.464 \pm 0.012$ fm

- FSI shift contributions to larger r and upper hemisphere
- Larger effect for $A(p,2p) \rightarrow$ surface is probed

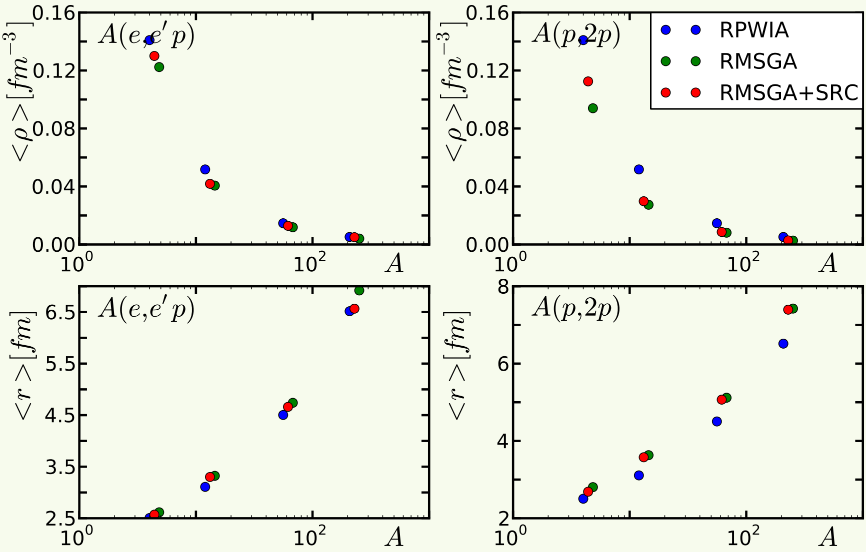
Density Dependence: ^{12}C(γ, *pp*)



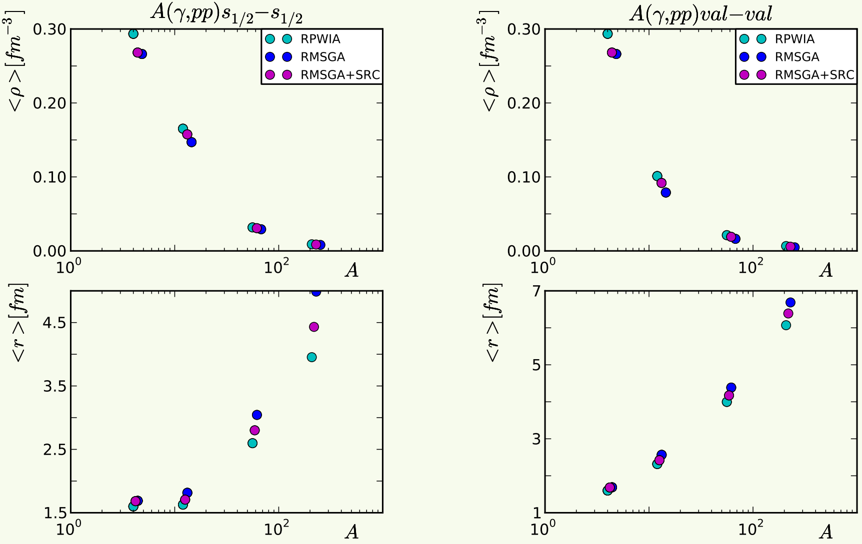
- Knockout of a correlated pair
- Strength remains in the high density regions of the nucleus


A(e,e′p)
A(p,2p)
RPWIA
RMSGA
RMSGA+SRC
<ρ> [fm^-3]
<r> [fm]
0.16
0.12
0.08
0.04
0.00
6.0
5.0
4.0
3.0
2.0
8
6
4
2
10^0
10^2
A

A dependence 1 nucl knockout: valence shell



A dependence 2 nucl knockout



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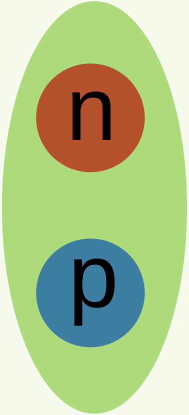
Model Ingredients

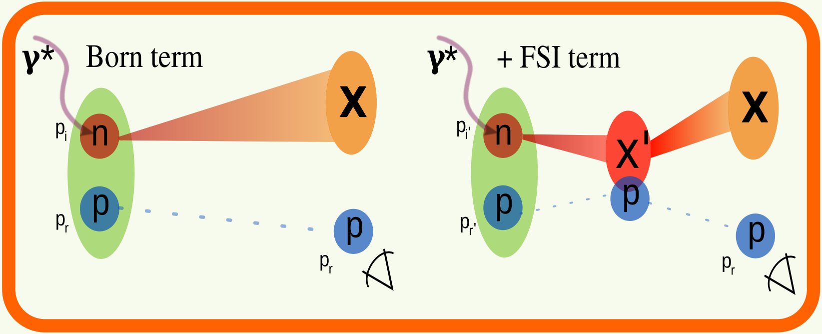
- Quantify effect of FSI
- X?: details about composition and space-time evolution (function of (x, Q^2)) of produced hadronic system after DIS unknown
- Use general properties of soft scattering theory, without specifying X
- Factorized approach: split photon interaction and rescattering part
  In $D(e, e'N)N$: works well up to $p_s \approx 400$ MeV

Virtual Nucleon Approximation



- Consider only *pn* component of Deuteron
- Spectator proton is on-shell
- Deuteron wf normalization obeys baryon number conservation $\int \alpha |\Phi_D(p)|^2 d^3p = 1$, but violates momentum sum rule $\int \alpha^2 |\Phi_D(p)|^2 d^3p < 1$
- Neglect negative energy contribution of virtual neutron propagator
  $\rightarrow p_s \leq 700$ MeV
- Photon interactions with exchanged mesons are neglected
  $\rightarrow Q^2 > 1\text{GeV}^2$

Reaction diagrams



$$\frac{d\sigma}{dxdQ^2 d\phi_{e'} \frac{d^3 p_s}{2E_s(2\pi)^3}} = \frac{2\alpha_{EM}^2}{xQ^4}(1-y-\frac{x^2y^2m_n^2}{Q^2})\left(F_L^D(x,Q^2) + v_T F_T^D(x,Q^2) + v_{TL}\cos\phi F_{TL}^D(x,Q^2) + \cos 2\phi F_{TT}^D(x,Q^2)\right)$$

Factorization

- Relate Deuteron structure functions to the neutron ones for a moving nucleon at $\hat{x} = \frac{Q^2}{2p_i \cdot q} \approx \frac{x}{2-\alpha_s}$...

$$F_T^D(x,Q^2) = [2F_{1N}(\hat{x},Q^2) + \frac{p_T^2}{m_i \hat{\nu}} F_{2N}(\hat{x},Q^2)] \times S^D(p_r)(2\pi)^3 2E_r$$

- ...times a distorted spectral function that contains a plane-wave and FSI part

$$S^D(p_r) = \frac{1}{3} \sum_{M,s_r,s_s} \left| \overbrace{\Phi_D^M(p_i s_i, p_s s_s)}^{PW} - \overbrace{\int \frac{d^3 p_{s'}}{(2\pi)^3} \chi(p_{s'}, m_{x'}) \langle p_r X | \mathcal{F} | p_{s'} X' \rangle \frac{\Phi_D^M(p_{i'} s_i, p_{s'} s_s)}{(p_{s'}^z - p_s^z + \Delta')}}^{FSI} \right|^2$$

FSI: Generalized eikonal approximation

- Scattering amplitude is parametrized with the standard diffractive form

$$\langle p_r, X|\mathcal{F}|p_{r'}X'\rangle = \sigma_{\text{tot}}(W,Q^2)(i+\epsilon(W,Q^2))e^{\frac{\beta(W,Q^2)}{2}t}\delta_{s_r,s_{r'}}\delta_{s_X s_{X'}}$$

- Eikonal regime gives approximate conservation law $p_s^- = p_{s'}^-$ in the high q limit. This leads to $m_X^2 > m_{X'}^2$, and yields pole values in the FSI integral of

$$\Delta' = \frac{\nu + M_D}{|\vec{q}\,|}(E_s - m_p) + \frac{m_X^2 - m_{X'}^2(p_{i'}=0)}{2\,|\vec{q}\,|} \quad \text{for } m_{X'}^2(p_{i'}=0) \leq m_X^2\,,$$

$$\Delta' = \frac{\nu + M_D}{|\vec{q}\,|}(E_s - m_p) \quad \text{for } m_{X'}^2(p_{i'}=0) > m_X^2\,.$$

Comparison with Deeps: approach

- Use SLAC parametrization for neutron structure functions (as in Deeps data analysis)
- Take $\sigma_{\text{tot}}(W, Q^2)$ (and $\beta(W, Q^2)$) as free parameter in the distorted spectral function. Fits are done for each W, Q^2 over the 5 measured spectator momenta (300-560 MeV).
- Deuteron wave function: $\Phi_D(p) = \Phi_D^{\text{NR}}(p)\sqrt{\frac{M_D}{2(M_D - E_s)}}$
  Obeys baryon number conservation $\int \alpha|\Phi_D(p)|^2 d^3p = 1$

Parametrization of the off-shell rescattering amplitude

Three approaches:

- no off-shell FSI: off-shell rescattering amplitude is zero

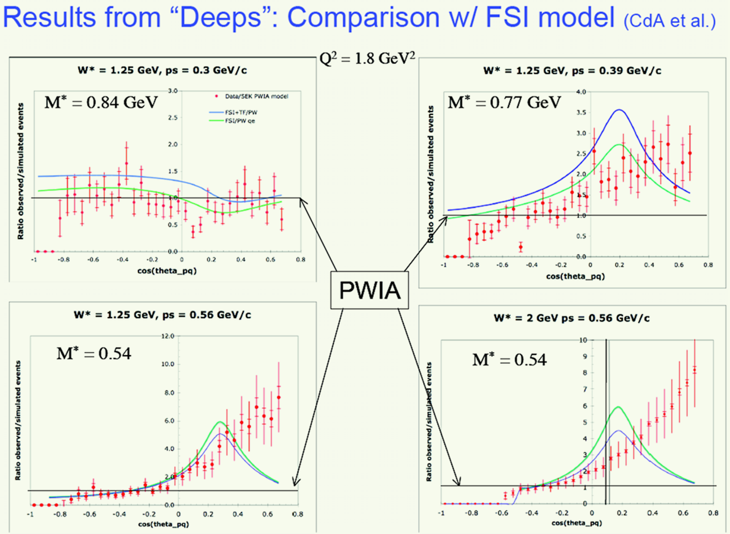
$$f^{\text{off}}_{X'N,XN} \equiv 0$$

- maximum off-shell FSI: off-shell amplitude is taken equal to the on-shell one

$$f^{\text{off}}_{X'N,XN} = f^{\text{on}}_{X'N,XN}$$

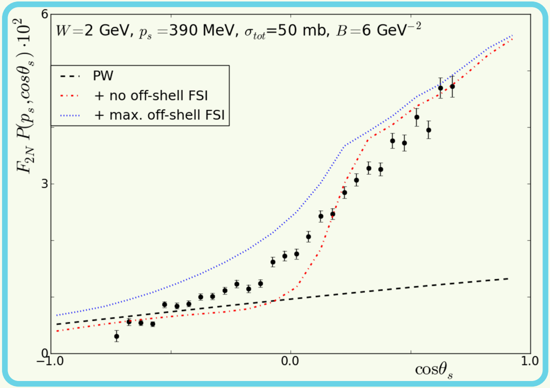
- fitted off-shell FSI: off-shell amplitude is parametrized as the on-shell one with a suppression factor dependent on (x, Q^2)

$$f^{\text{off}}_{X'N,XN} = f^{\text{on}}_{X'N,XN} e^{-\mu(x,Q^2)t}$$



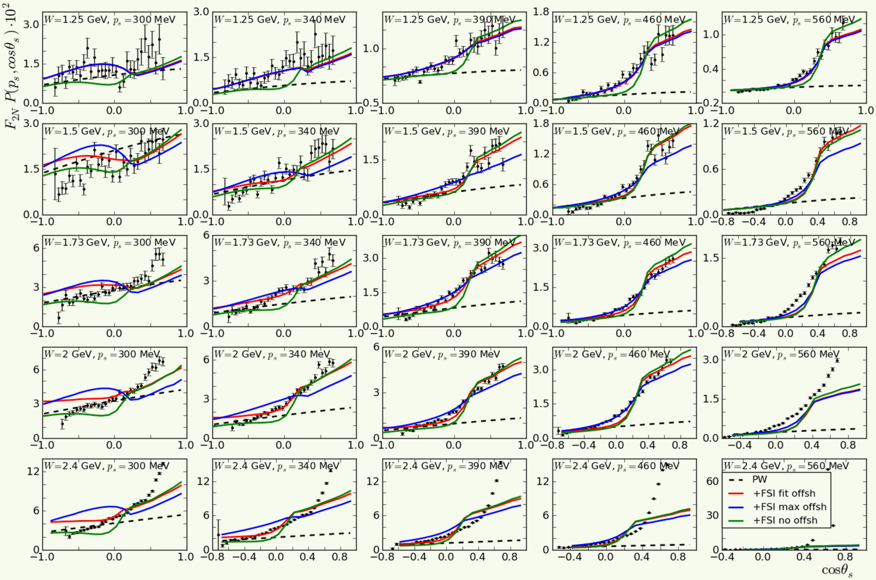
Calculation by `C. degli Atti et al.` [Slide from S. Kuhn]

Calculation without fits

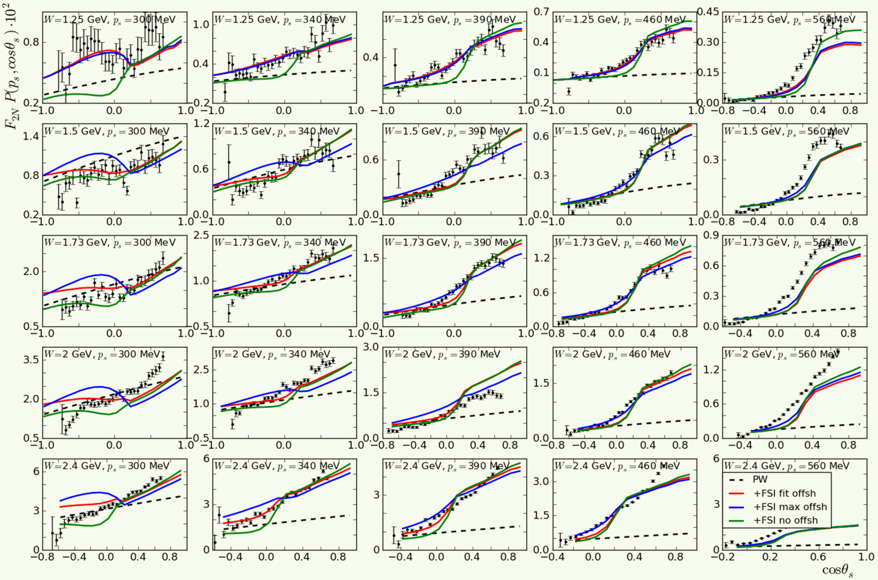


- Plain-wave calculation shows little dependence on spectator angle
- FSI effects grow in forward direction, different from quasi-elastic case
- Small contribution from off-shell amplitude

$Q^2 = 1.8\text{GeV}^2$: σ and β free, $\epsilon = -0.5$



$Q^2 = 2.8\text{GeV}^2$: σ and β free, $\epsilon = -0.5$

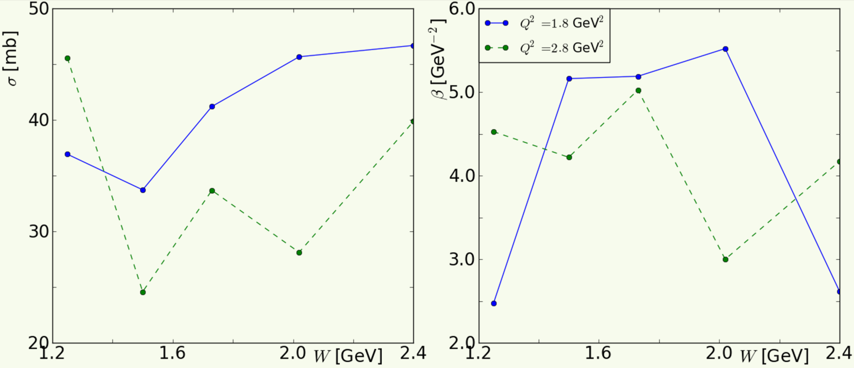


Results discussion

- Systematic underestimation of data at $p_s = 560$ MeV, breakdown of factorization
- Difference between off-shell desciptions diminishes with increasing p_s
- At lowest spectator momentum plain-wave and FSI amplitude comparable in magnitude, sensitive to small differences
- Fitted off-shell calculations correspond more with no off-shell ones, pointing to suppressed off-shell amplitude

σ and β parameters, $\epsilon = -0.5$

No off-shell FSI



- σ rises with W, no sign of hadronization plateau
- σ drops with Q^2, small-sized configuration?
- β largely correlated with σ

σ and β parameters, $\epsilon = -0.5$

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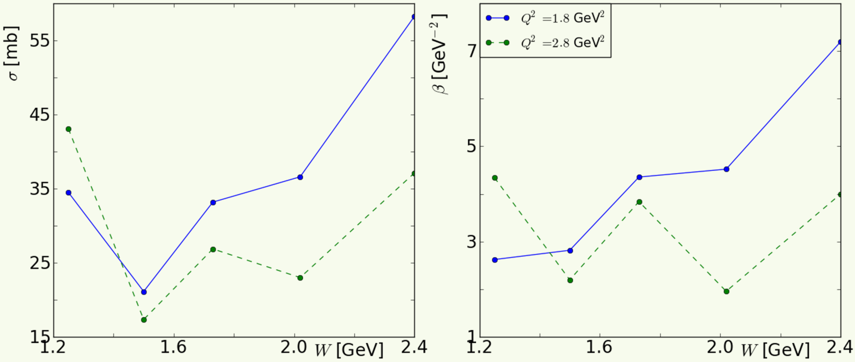

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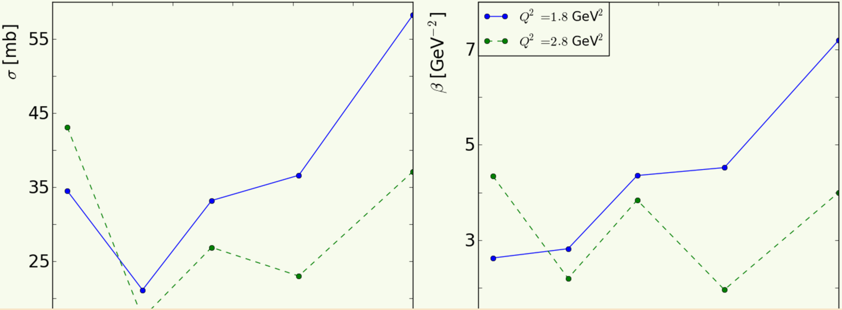

- More measurements at higher Q^2 needed to make more definite statements
- These values can be used as input in the computation of FSI effects in inclusive DIS

Conclusions

A "flexible" eikonal framework to model the propagation of fast nucleons and pions through the nuclear medium

- Glauber approach computes full $(A-1)$ multiple-scattering series and has no free parameters
- Provides common framework to describe a variety of nuclear reactions with electroweak and hadronic probes.
- Effect of central short-range correlations and color transparency can be implemented. The two can be clearly separated in results, due to different hard scale dependence
- Pion electroproduction data in agreement with CT calculations, Fair results for $A(p,pN)$
- Knockout of a correlated pair and s-shell knockout in $A(p,2p)$ probe the high density regions of the nucleus

Conclusions (II)

- Model for semi-inclusive DIS on the deuteron based on general properties of soft rescattering.
- Fair description of the Deeps data
- Discrepancies at $p_s = 300$ MeV with high W. Possible breakdown of factorization at highest $p_s = 560$ MeV.
- Cross section rises with W and shows no signs of a plateau (hadronization) yet, drops with Q^2.
- More measurements at higher Q^2 needed