Color transparency in exclusive meson and proton production

Wim Cosyn

Florida International University
Ghent University, Belgium

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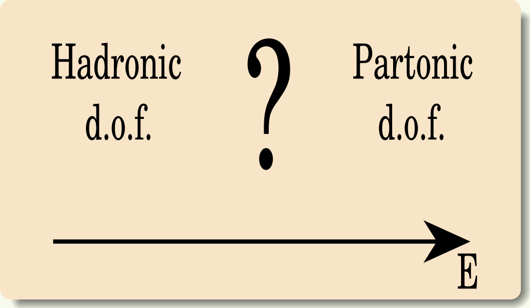
Outline

Motivation



When and in what way?

- Emergence of the concepts of “nuclear physics” (baryons and mesons) out of QCD (quarks and gluons) remains elusive
- Explore the limits of the shell model description of nuclei
- Use of exclusive removal reactions

Motivation

Fig. from Jefferson Lab

- Emergence of the concepts of "nuclear physics" (baryons and mesons) out of QCD (quarks and gluons) remains elusive
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Motivation (II)

- 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
- The possibility to use FSI based on an optical potential at low ejectile momenta (ROMEA)

Building a Model

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  NPA **A728** (2003) 226
- The possibility to use FSI based on an optical potential at low ejectile momenta (ROMEA)

- 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 $\longrightarrow$ OK for the performed experiments!
- Particles scatter over small angles and follow a linear trajectory
- Second order eikonal corrections have been computed $\longrightarrow$ small

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

$$f(\Delta, E) = \frac{K}{2\pi i}\int d\vec{b} e^{i\vec{\Delta}\cdot\vec{b}}\Gamma_{\pi N}(\vec{b})$$

- 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 $\longrightarrow$ short range

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

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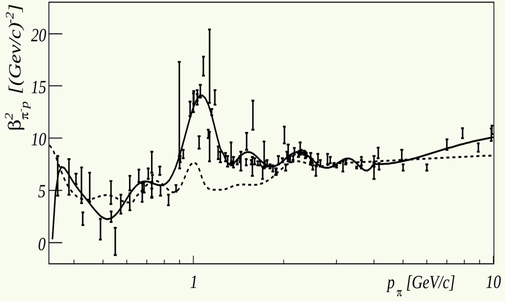

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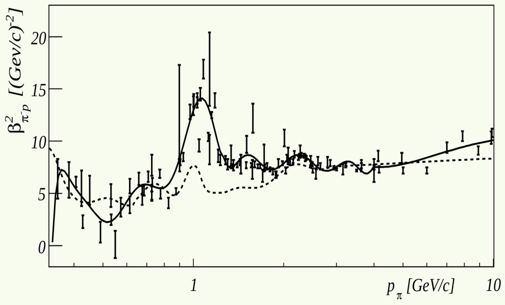

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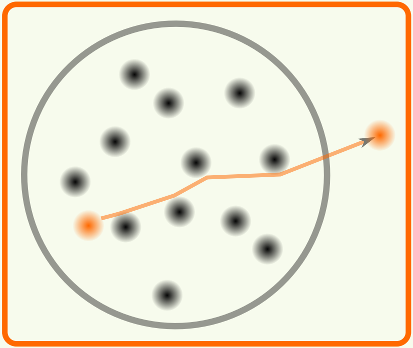
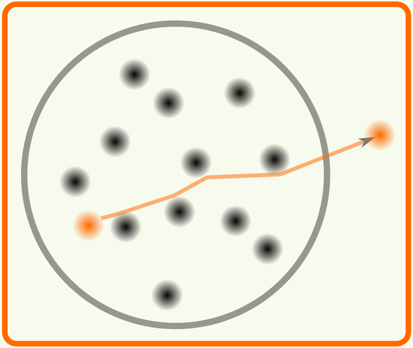


Multiple scattering

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

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

Relativistic Multiple-Scattering Glauber Approximation



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$\vec{b}, z \longrightarrow$ point of creation

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 $\vec{r} = (\vec{b}, z)$
- $\sqrt{2}\beta \sim 0.75$fm $\longrightarrow$ 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

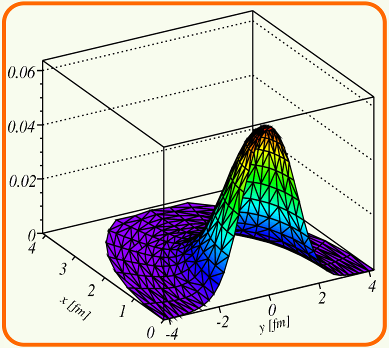
$$\rho_A^{[2]}(\vec{r}', \vec{r}) = \frac{A-1}{A} \gamma(\vec{r}) \rho_A^{[1]}(\vec{r}) \gamma(\vec{r}') \rho_A^{[1]}(\vec{r}') g(|\vec{r} - \vec{r}'|)$$

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

Densities in Glauber calculations (^{4}He case)

A nucleon or pion is created in the center of ^{4}He: how does the nuclear density looks like for this hadron?

^{4}He in IPM



^{4}He with SRC

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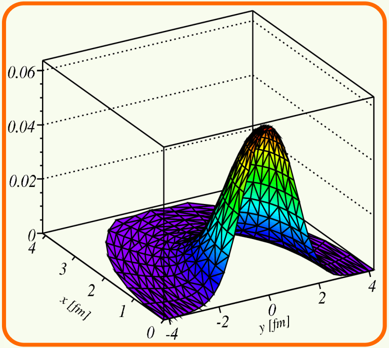

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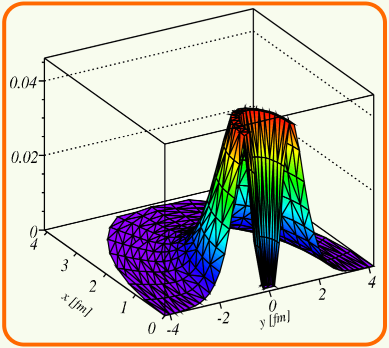

Color Transparency: Quantum diffusion parametrization

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

- 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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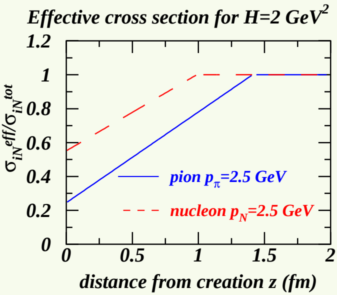

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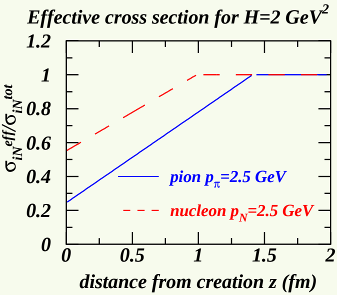
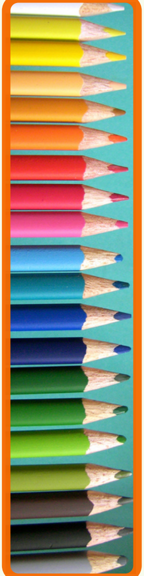


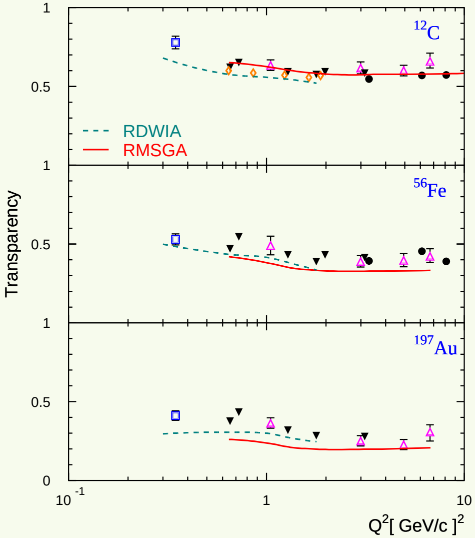
Applications



RMSGA can be applied to a variety of reactions, with incoming leptons or hadrons, outgoing nucleons or mesons, ...

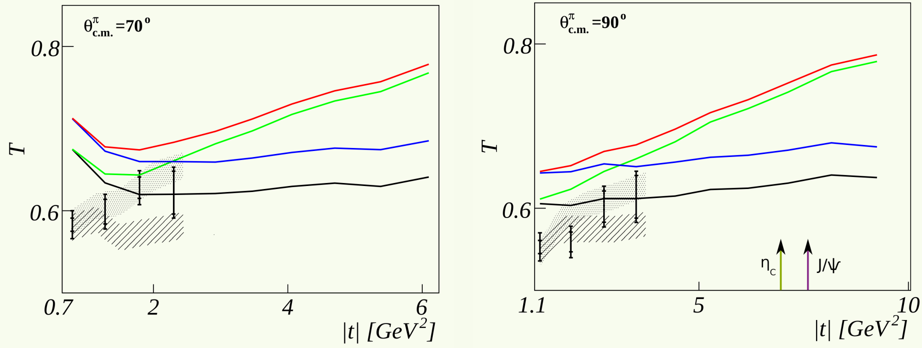
- $A(e, e'\pi)$
- $A(p, 2p)$
- $A(e, e'p)$
- $A(\nu, \nu'p)$
- $A(e, e'NN)$
- $\cdots$

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



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

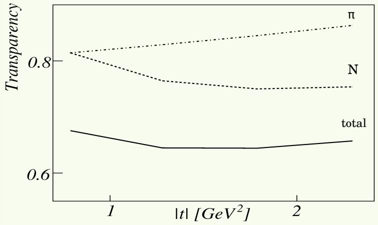
- Calculations tend to underestimate the measured proton transparencies
- In the region of overlap: RMSGA and RDWIA predictions are not dramatically different !!
- Data from MIT, JLAB and SLAC
- CT effects are very small for $Q^2 \leq 10$ GeV^2

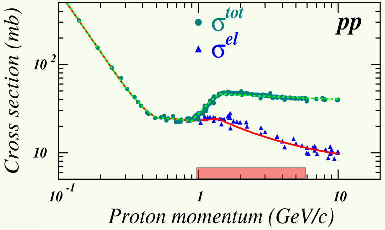


Glauber — Glauber + SRC — Glauber + CT — Glauber + SRC + CT

- 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]

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





- Pion transparency is larger than nucleon one
- Low energy behavior can be attributed to nucleon $\longrightarrow$ related to local minimum in σ_{NN}^{tot}
- How reliable are the transparency calculations? [robustness]
- Comparison with ROMEA model (based on nucleon-nucleus scattering) at very low momenta
- Difference about 5% and becomes smaller with rising energy

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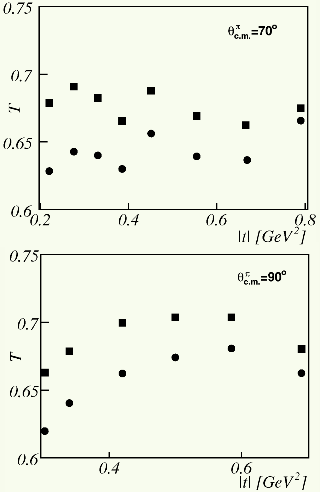

RMSGA ■

ROMEA ●

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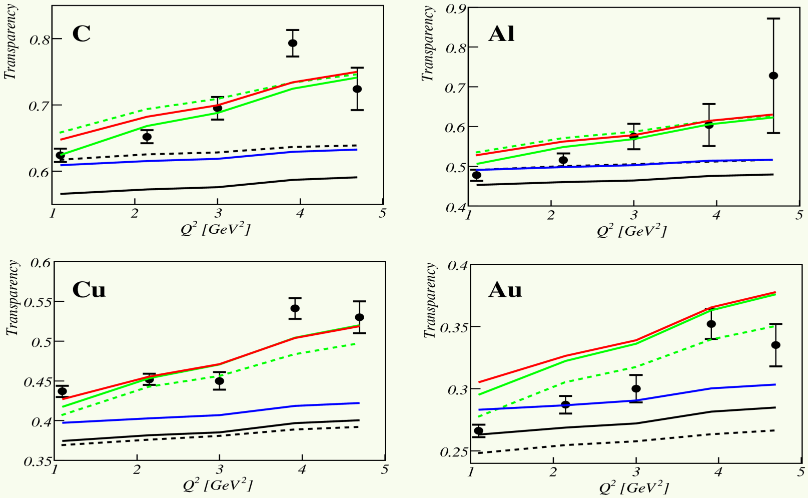
$A(e, e'\pi^+)$ transparencies: Q^2 dependence

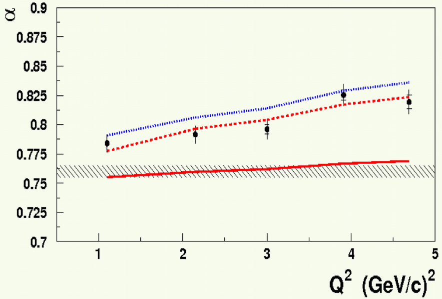


Glauber | Glauber + SRC | Glauber + CT | Glauber + SRC + CT

$A(e, e'\pi^+)$ 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



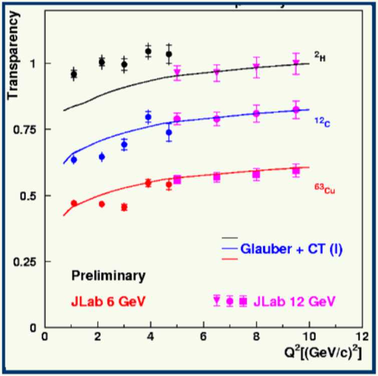
Gl.+SRC+CT

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

$A(e, e'\pi^+)$ transparencies: JLab 12 GeV



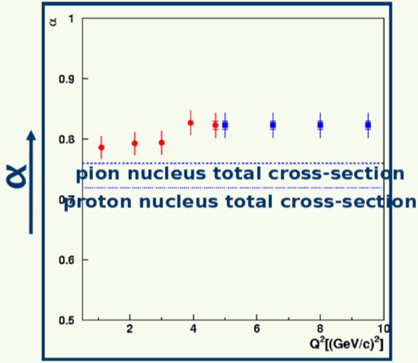
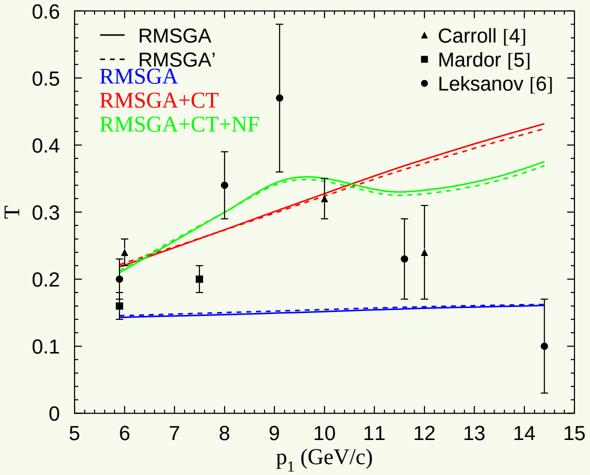


Fig from D. Dutta

Solid lines: Kundu et al., PRD 62, 113009 (2000)
Cu curve scaled to match data

$A(e, e'\pi)$ results will verify the strict applicability of factorization theorems for meson electroproduction

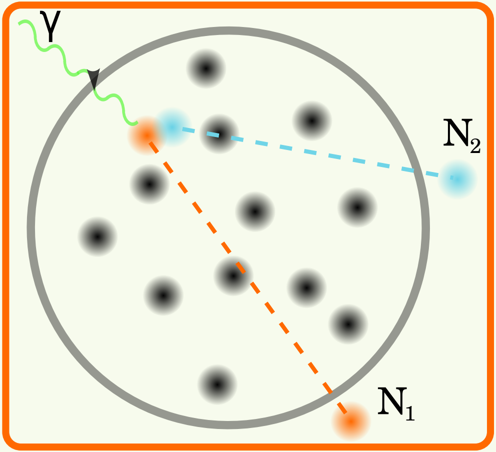
The nuclear transparency from $^{12}C(p,2p)$



Parameterization of the CT effects compatible with pion production results!

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

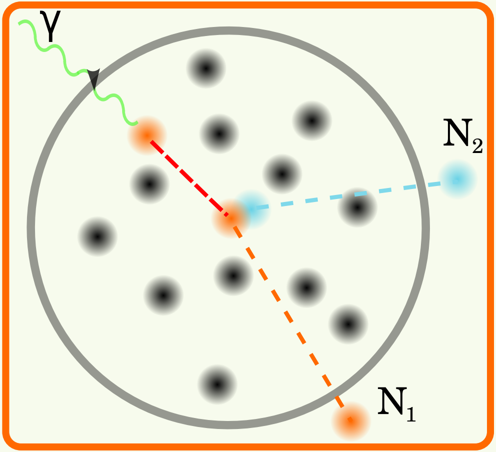
$A(\gamma, pp)$: two competing mechanisms



Knockout of a correlated pair

- One-step: beam interacts with one nucleon of the pair, the other nucleon is also ejected
- Two nucleons are assumed to reside in a relative S-state ($r_{12} \approx 0$)
- Cross section is unfactorized
- Calculations were done factorized to save computing time

$A(\gamma, pp)$: two competing mechanisms

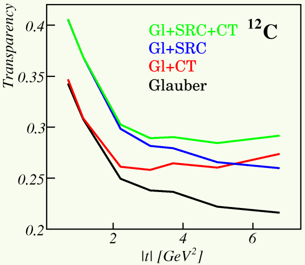


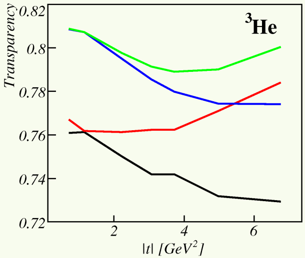
Hard rescattering

- Two-step: beam interacts with a nucleon, nucleon then hits a second one
- Propagator taken on the free nucleon mass shell
- Cross section and calculations unfactorized
- Propagator introduces extra degrees of freedom, a lot of nested integrations

Transparency calculations for $A(\gamma, pp)$

Corr. pair knockout

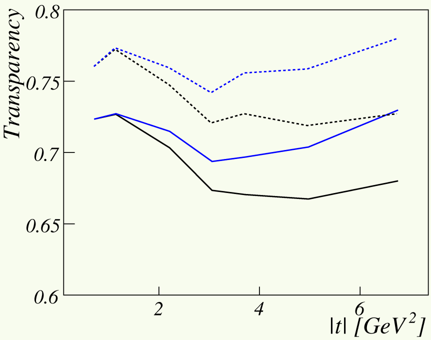




- Same dependence on the hard scale as the pion transparencies
- Low absolute values! $\longrightarrow$ probes high density regions of the nucleus
- HRM transparencies are a little bit lower
- FSI of the propagator lowers the transparency by 5%

Transparency calculations for $A(\gamma, pp)$

Hard rescatt. on ^{3}He



Glauber+CT Glauber

Dashed: without FSI for propagator

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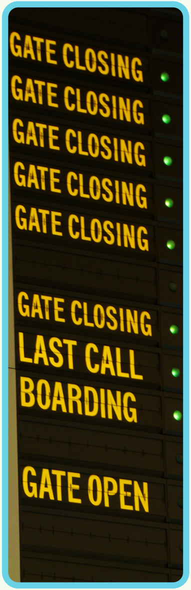
CT @ EIC

- EIC will probe color dipole size between hard & soft QCD regimes
- (More or less) Bi-weekly phone meetings with D. Dutta
- Focussing on VM production on light nuclei
- MC simulations for Rho production [L. El Fassi]
  [JLab6 Rho results show CT signs]
- $A(e,e'p)$ and $A(e,e'\pi)$: residual nucleus in final state with very small angle and energy loss for forward production
- Other processes [M. Strikman]:
  - $\gamma + A \rightarrow \rho + (N\pi) + A - 1$
  - Large c.m. angle
    $\gamma^* + A \rightarrow \pi^+ \pi^0 A^*$
    $\gamma^* + A \rightarrow \rho \pi^+ A^*$

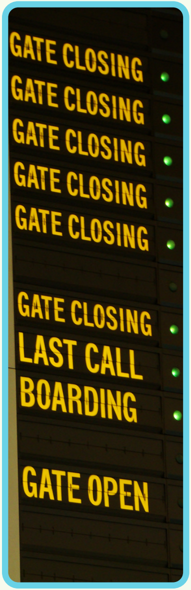
Conclusions



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

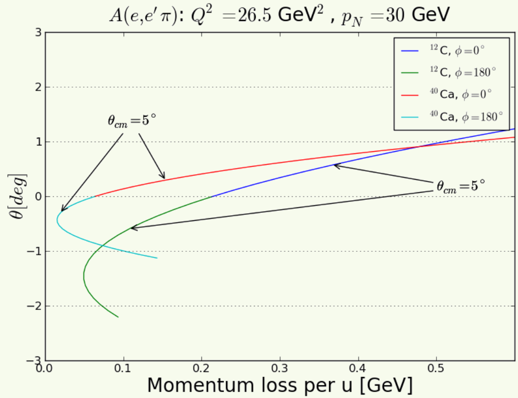
- Mean-field approach: can be applied to $A \geq 4$
- Can accommodate relativity (dynamics and kinematics).
- Can be used in combination with both optical potentials (pA) and Glauber Approach (pN).
- Glauber approach computes full $(A-1)$ multiple-scattering series and has no free parameters
- Provides 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

Conclusions (II)



- Good agreement with non-relativistic and optical potential calculations
- CT and SRC can be clearly separated, due to different hard scale dependence
- Pion electroproduction data in agreement with CT calculations
- Fair results for $A(p, 2p)$
- Double nucleon knockout probes high density regions
- EIC:
  - MC simulations for VM production
  - Recoil nucleus detection feasible?

$A(e, e'\pi^+)$ @ EIC: Recoil nucleus detection



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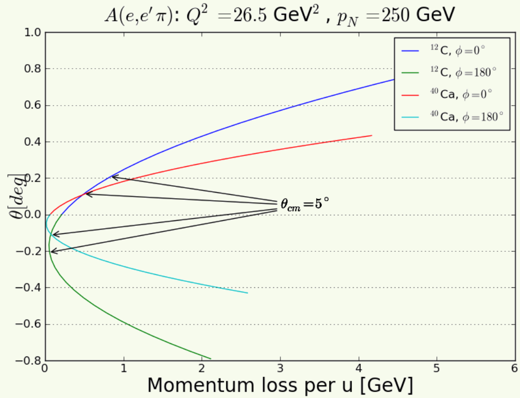

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