Neutron spin structure with tagging at EIC

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Feb. 10-13, 2016

Next generation nuclear physics with JLab12 and EIC
at Florida International University, FL, USA

Outline

- Neutron spin structure: Why spectator tagging
- Spectator tagging with EIC
  - Simulation tools
  - Forward detection
  - Momentum resolution
- Simulation results
  - Unpolarized F_{2n} with on-shell extrapolation
  - Polarized g_{1n} ($A^n_{||}$) with on-shell extrapolation
- Outlook
  - Shadowing/EMC/FSI

Neutron spin structure: Spectator tagging

- Challenges in neutron spin structure extraction
  - Dilution: Eliminate scattering on proton
  - Effective polarization: Large spin effects from Δs in ^{3}He
  - Nuclear modifications: Fermi motion, EMC effect

- Advantages of spectator tagging $\vec{e} + \vec{D} \rightarrow e' + p_s + X$
  - Deuteron wave function simple and well-known
  - Non-nucleonic degrees of freedom suppressed, $|D\rangle = |NN\rangle + \epsilon|\Delta\Delta\rangle$
  - Recoil momentum dependence allows one to eliminates nuclear binding
    - On-shell extrapolation
  - Uniquely suited for collider
    - Forward proton detection
    - Full acceptance down to $p_R \sim 0$
    - Sufficient resolution

Tagging with unpolarized and polarized light ions

^{2}**H**:

unpolarized

- Two-body object
- Neutron structure function F_{2n}
- Dependence of bound single nucleon structure (EMC effect)

polarized

- Neutron spin structure function g_{1n}
- Map out g_{1n} cleanest/most precise/ nearly model-independent
- with ^{3}He to test isospin dependent nuclear modification

^{3}**He**:

unpolarized

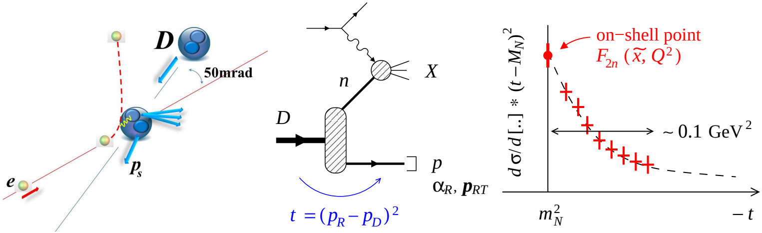
- Three-body object
- Bound nucleon structure and coherent quark/gluon fields
- Neutron structure function F_{2n}
- Dependence of bound single nucleon structure (EMC effect)
- Spin-flavor dependence of EMC effect

polarized

- Neutron spin to test of the universality of g_{1n}
- Three-nucleon system is much complex
- with ^{2}H to test isospin dependent nuclear modification
- **JLEIC: polarized D and ^{3}He with figure-8 ring layout**

- [1] F_{2n}, g_{1n}, **EMC effect disentangled !**
- [2] **Demonstrate that use of the spectator tagging MC simulation ($\vec{e}\vec{D} \rightarrow e' p_s X$) in feasibility of these observations !**

Spectator tagging → Extrapolating neutron structure
On-shell extrapolation → Unique technique



- Light-Cone momentum fraction, Transverse momentum of recoil proton: [M. Sargsian, C. Weiss]

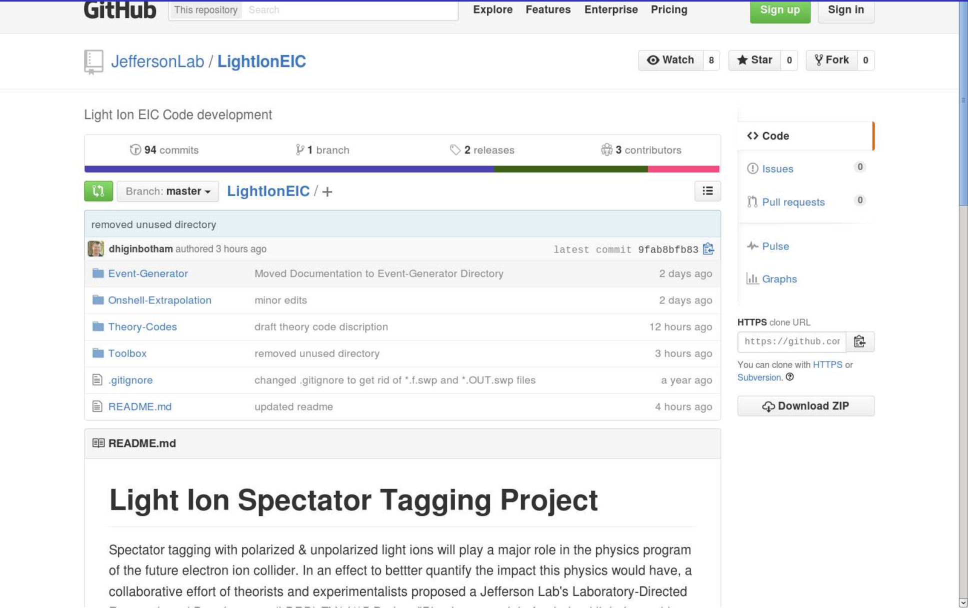
$$\alpha_R = 2\frac{E_R + p_R^z}{M_D}, \qquad |\vec{P_R}|^2 = \frac{-t'}{2}\left(1 - \frac{t'}{2M_D^2}\right) + \frac{M_D^2}{4} - M_N^2$$

- Cross-section in the IA

$$\frac{d\sigma}{dxdQ^2 d\alpha_R d^2 p_{RT}} = f_{Flux} \times S_D(\alpha_R, p_{RT}) \times F_{2n}\left(\frac{x}{2-\alpha_R}, Q^2\right)$$

- On-shell extrapolation: $t \to M_N^2 \quad (t - M_N^2 \equiv t' \to 0)$

https://github.com/JeffersonLab/LightionEIC



Spectator tagging MC event generator

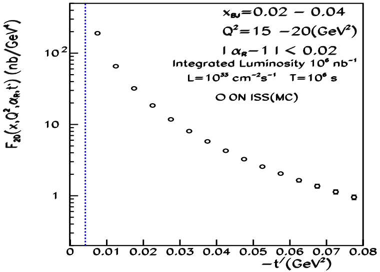
JLAB LDRD2014-2015 Project

- Develop code for stand-alone event generator / physics model
  - C. Hyde, D. W. Higinbotham, P. Nadel-Turonski, K. Park (Experimentalists)
  - C. Weiss, M. Strikman, M. Sargsian, V. Guzey, W. Cosyn (Theorists)
- Modular code allows easy to maintain and extend
  - e.g. fixed target/collider, various physics model, etc...

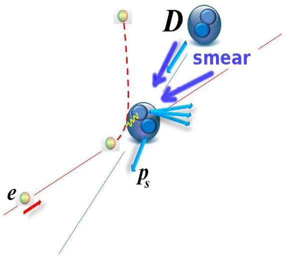
CONTENTS

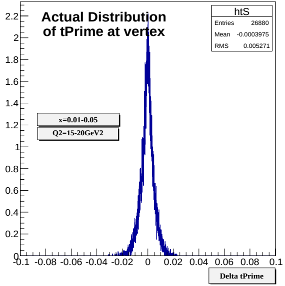
- Implementing accelerator info
  - Cross-angle: 50 mrad, $[E_e : E_D] = [5{:}100]$ GeV, $p_R < 300$ MeV in D rest frame
  - Longitudinal p_L and angular spread of the beam: $dp/p = 3 \times 10^{-4}$, $d\theta = 2 \times 10^{-4}$
  - Various luminosities: $\int \mathcal{L} dt = 1\ \mathrm{fb}^{-1}$, $10\ \mathrm{fb}^{-1}$, $50\ \mathrm{fb}^{-1}$
- User inputs: cross-section model
  - nucleon Struc.Func./deuteron Wav.Func./deuteron Residue Spect.Func.
- Resolution and Uncertainty
  - Initial State Smearing (ISS) is $\ll \pm 1\%$
  - Intrinsic MC Statistical Uncertainty is $\leq 1\%$
  - Sufficient t' resolution for the extrapolation
  - Final State Interactions [Talk by W. Cosyn]
- Estimation of the experimental uncertainty for F_{2n} on-shell extrapolation

MC Simulation → Cross-sections



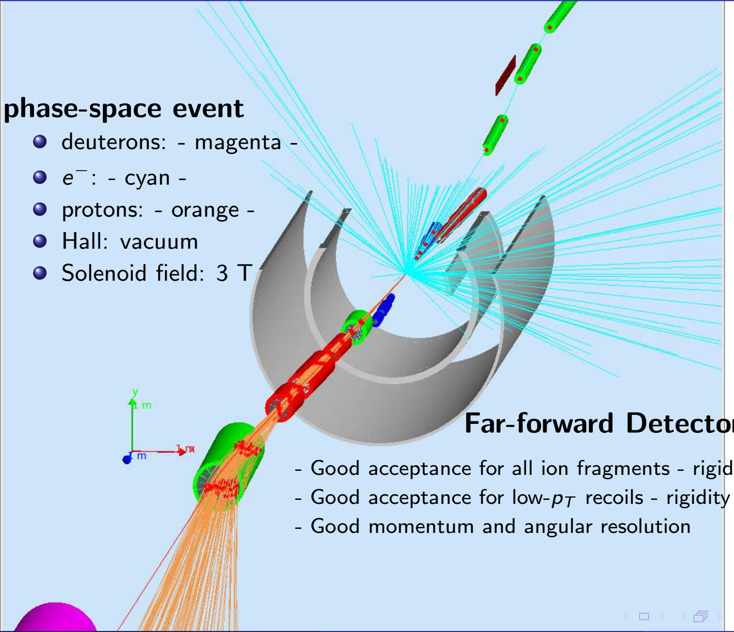
- Reduced xsection vs. t' : take out f_{Flux}
- α_R cut around 1.0 ± 0.02
- Excellent resolution allows to reach lower t'
- Feasible on-shell extrapolation
- Vertical dash line: $t'_{min} = 0.00416$ GeV^2





- t' **resolution: RMS=0.005**
- Intrinsic momentum spread in **Ion beam** smears recoil momentum
- Dominant uncertainty for JLEIC
- Effect on t' (angular spread)
- t' bin-size > smearing

MC Simulation / GEMC - Event display -



phase-space event

- deuterons: - magenta -
- e^-: - cyan -
- protons: - orange -
- Hall: vacuum
- Solenoid field: 3 T

Far-forward Detector in EIC

- Good acceptance for all ion fragments - rigidity different from beam
- Good acceptance for low-p_T recoils - rigidity similar to beam
- Good momentum and angular resolution

MC Simulation / GEMC - Event display -

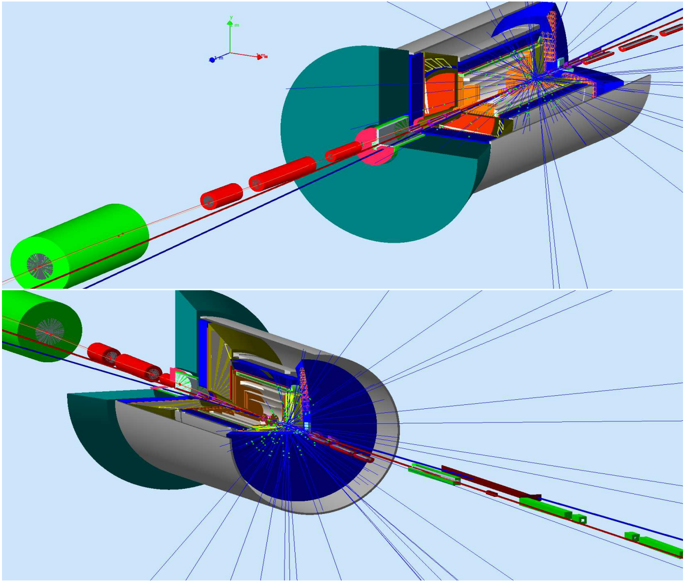


Figure: Assembled JLEIC IP1 detector with single event

On-shell extrapolation F_{2n} in the grid of x_{BJ}, Q^2

- $E_e = 5$ GeV, $E_D = 100$ GeV, $\int \mathcal{L}dt = 1fb^{-1}$
- 10 bins per decade in x_{BJ}, Q^2
- Cross-section weighted in each bin

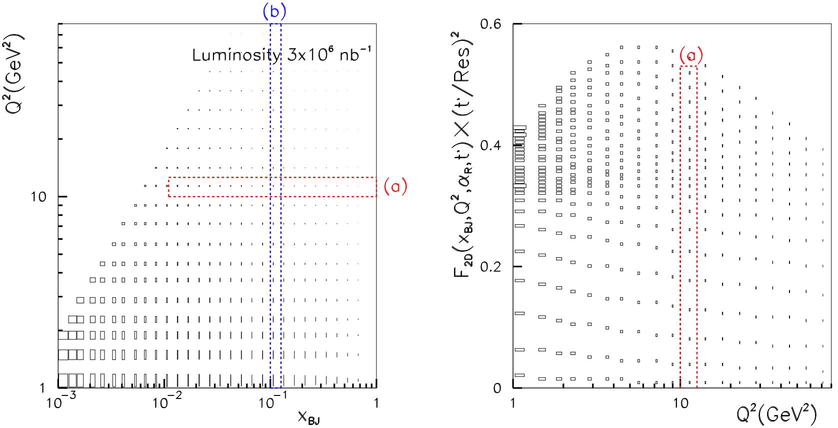
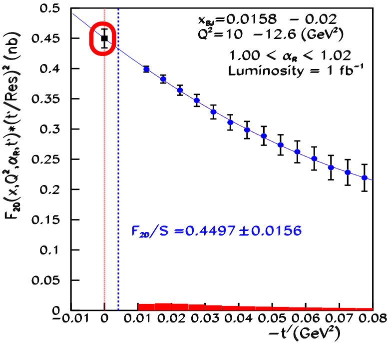
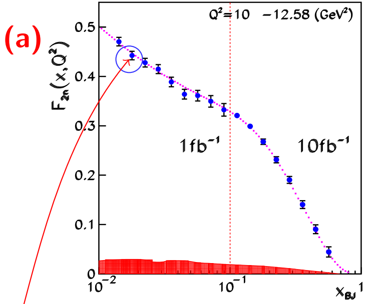


Figure: (Left) Kinematic map of F_{2n} ($\hat{z}$-axis) in terms of x_{BJ}, Q^2, (right) F_{2n} vs. Q^2. Band-(a): x_{BJ} dependence at fixed $Q^2 = 10.0 - 12.58$ GeV^2, band-(b): Q^2 dependence at fixed $x_{BJ} = 0.1 - 0.126$

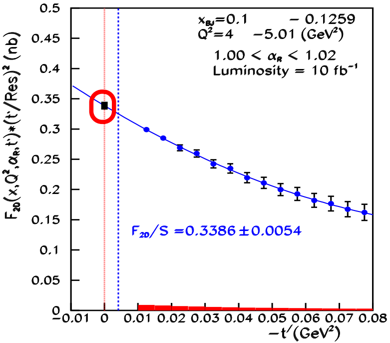
Unpolarized $(e, D) \rightarrow F_{2n}(x, Q^2)$

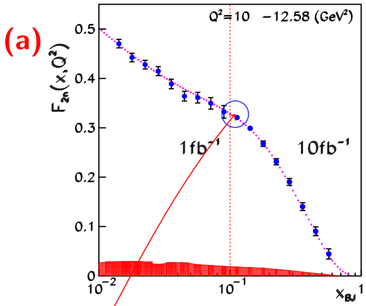




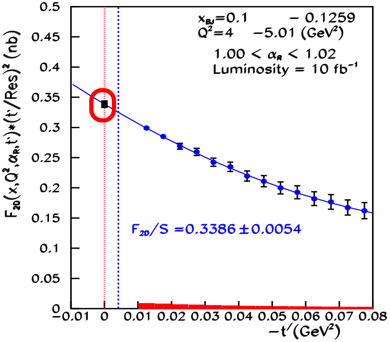
- Luminosity $= 1\ \mathrm{fb}^{-1}$ for low $x_{BJ} < 0.1$
- Systematic uncertainty is dominant at lower t', lower x_{BJ}
- Intrinsic momentum spread: Ion beam smears recoil momentum $-t' \approx 2p_R^2$
- On-shell extrapolation F_{2n} for each $(x_{BJ},\ Q^2)$ bin

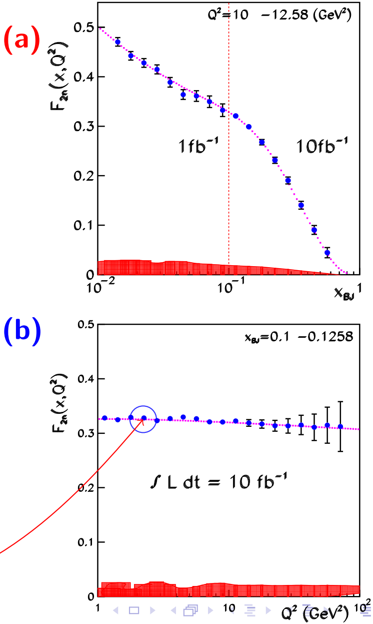
Unpolarized $(e, D) \rightarrow F_{2n}(x, Q^2)$





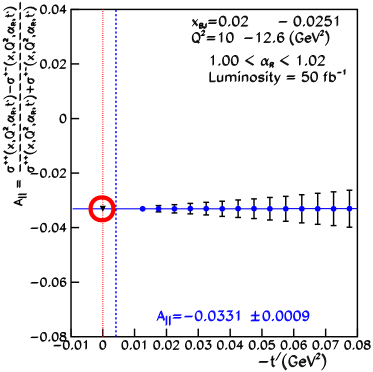
- Luminosity $= 10\ \text{fb}^{-1}$ for high $x_{BJ} > 0.1$
- Systematic uncertainty is dominant at lower t', lower x_{BJ}
- Intrinsic momentum spread: Ion beam smears recoil momentum $-t' \approx 2p_R^2$
- On-shell extrapolation F_{2n} for $(x_{BJ},\ Q^2) = (0.1,\ 10.)$!

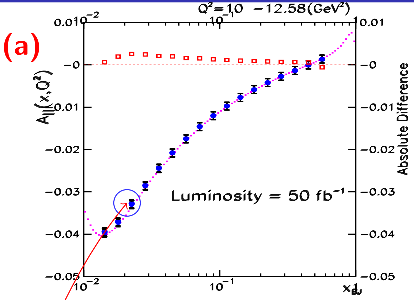




- Luminosity $= 10\ \mathrm{fb}^{-1}$ for high $x_{BJ} > 0.1$
- Systematic uncertainty is dominant at lower t', lower x_{BJ}
- Intrinsic momentum spread: Ion beam smears recoil momentum
  $-t' \approx 2p_R^2$
- Systematic uncertainty is NOT sensitive to Q^2
- On-shell extrapolation F_{2n}

Polarized $(\vec{e}, \vec{D})$, $hel = \pm 1$ along each beam





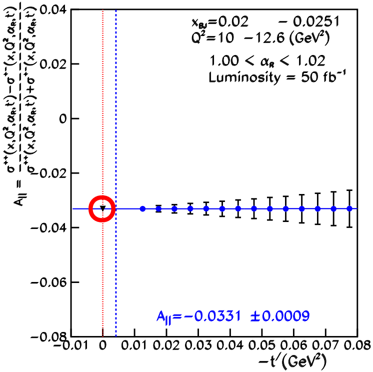
- Asymmetry ($A^n_{||}$);

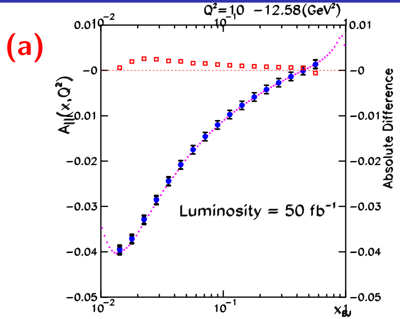
$$A = \left(\frac{N_+ - N_-}{N_+ + N_-}\right), \quad \delta A = \sqrt{\frac{1-A^2}{N_+ + N_-}}$$

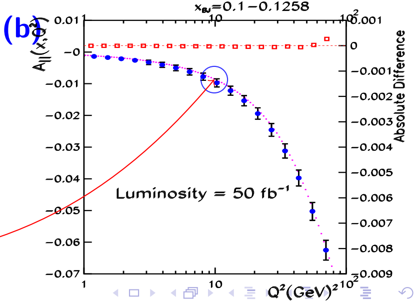
- Depolarization (D'); $= \frac{(1-\epsilon)(2-y)}{y(1+\epsilon R)}$, where $y = Q^2/x_D/(s_{eD} - M_D^2)$, $R = \sigma_L/\sigma_T$
- On-shell extrapolation $A_{||}$ for each (x_{BJ}, Q^2) bin

- $A^n_{||} \sim$ (-0.05 : +0.01)
- Effective polarization $P_e * P_D \sim 0.9 * 0.7$
- Higher luminosity; $\mathcal{L}$=50 fb^{-1}

Polarized $(\vec{e}, \vec{D})$, $hel = \pm 1$ along each beam







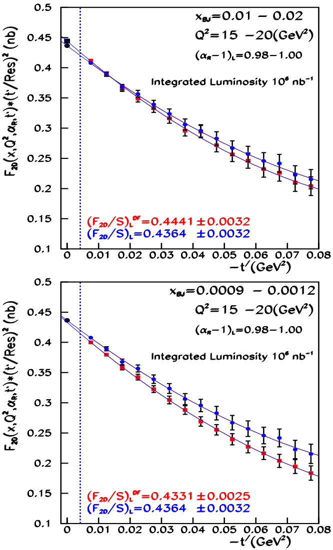
- Asymmetry ($A^n_{||}$) with high $\mathcal{L}$=50 fb^{-1};

  $A = \left(\frac{N_+ - N_-}{N_+ + N_-}\right)$, $\delta A = \sqrt{\frac{1-A^2}{N_+ + N_-}}$

- Depolarization (D'); $= \frac{(1-\epsilon)(2-y)}{y(1+\epsilon R)}$, where $y = Q^2/x_D/(s_{eD} - M_D^2)$, $R = \sigma_L/\sigma_T$

- On-shell extrapolation $A_{||}$ at $(x_{BJ}, Q^2) = (0.1, 10.)$ bin

Tagging: Coherent effects (e.g.: Shadowing correction)



- Coherence in Tagged DIS
- Coherent effect is clean (e.g. $N = 2$)
- FSI between p and $n \rightarrow$ distortion of p_T, spin

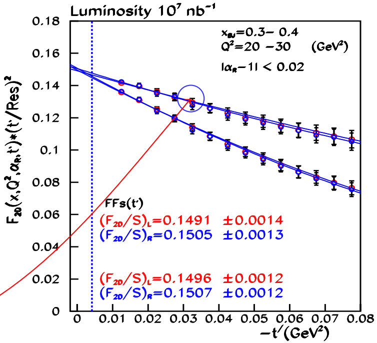
- **Kinematics I**: (top)
  $x_{BJ} = 0.01 - 0.02$,
  $Q^2 = 15 - 20$ GeV^2
- Diffractive shows a **stronger impact in larger** t'
  -9% at $t' = 0.08$ GeV^2, $+1\%$ at $t' = 0.01$ GeV^2
- With diffrac.(red), without diffrac.(blue)

- **Kinematics II**: (bottom)
  $x_{BJ} = 0.0009 - 0.0012$,
  $Q^2 = 15 - 20$ GeV^2
- Diffractive shows a **stronger impact in lower** x_{BJ}
  -19% at $t' = 0.08$ GeV^2, -1.8% at $t' = 0.01$ GeV^2

[Vadim's shadowing corrections]

Tagging: EMC effect

- **EMC effect in tagged DIS**
- Study modification as function of recoil momentum $\rightarrow$ off-shellness
- EIC : Q^2-evolution, spin dependence with $\vec{D}$

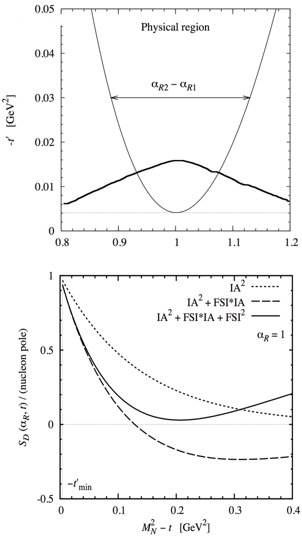


- $x_{BJ} = 0.3 - 0.4,\ Q^2 = 20 - 30\ \text{GeV}^2$, two α_R cuts
- $F_{2n}(x_{BJ}, Q^2)$ (no FF in t')
- $F_{2n}(x_{BJ}, Q^2) \cdot FF(t')$, dipole FF type: $\left(\frac{\Lambda^2}{\Lambda^2 - t'}\right)^2$, where $\Lambda^2 \sim 0.5$

[Interested kinematic region for EMC, M. Strikman]

** Given statistical uncertainty, observation of EMC effect is feasible ! **

Final state interaction



- Model dependence !
- Dependence of Q^2, α_R (t', p_R), weak dependence of x_{BJ}
- $\alpha_R \sim 1$ cut allows to access the smallest t' bin
- FSI is maximum α_R is closed to 1
- (TOP) Thin solid line: kinematic limit of minimumum of $-t'$, thick solid line: naive α_R dependent FSI
- (BOTTOM) No modify nucleon pole, distort p_R at $-t' \neq 0$, emperical hadron distributions/ NN interactions
- Proper choice of α_R cut makes minimize the systematic uncetainty for on-shell extrapolation

[On-going work, M. Strikman, C. Weiss 15]

→ Minimize the systematic uncertainty of FSI with consistent on-shell extrapolation !

Summary

- Developed Spectator Tagging Event Generator MC with EIC configuration
- On-shell extrapolation of F_{2n} & $A^n_{||}$ have been obtained
  → various luminosities
- Overall 1% level of statistical uncertainty
  → 10 bins per decade in x_{BJ}, Q^2 and $\int \mathcal{L} dt = 1\ fb^{-1}$
- Global systematic uncertainty $\delta\sigma/\sigma = 2.5\%$, $\delta A/A = 1.7\%$
  → point-to-point: (Gaussian random) $\sim 0.5\%$
- Spectator Tagging Event Generator and Physics models are available for detector simulations

  → https://www.jlab.org/theory/tag/
  → https://github.com/JeffersonLab/LightIonEIC