A study of neutron structure with (un)polarized deuterons and forward spectator tagging at EIC

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Motivation → Electron Ion Collider

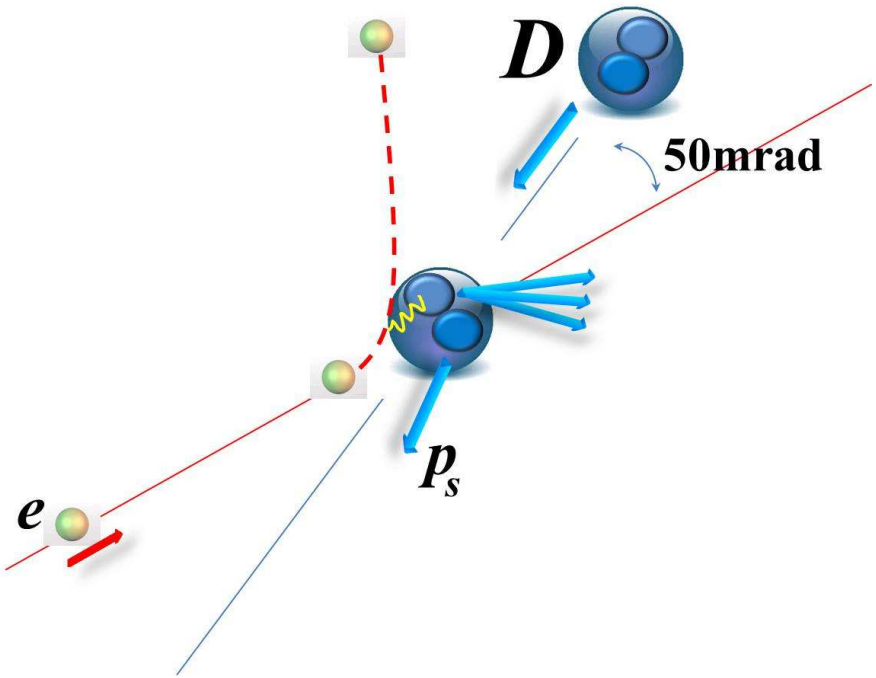


Figure: A Schematic of Reaction $eD \to e' p_s X$

- **No Free Neutron Target**
  - Neutron Structure
  (flavor decomposition of quark spin, sea quarks, gluon pol.)
  - Spectator Nucleon Tagging
  (forward detection/unique for collider)
  - (Pol.) Deuterium
  (a simple wave function/pol. neutron spin/limited FSI/coherence $N = 2$,...)

- **Gluon and sea quarks**
  - Transverse imaging of the nucleon
  - Nucleon Spin
  (ΔG vs. log Q^2, transverse momentum)
  - Nucleon QCD
  (gluons in nuclei, quark/gluon energy loss)
  - Hadron Structure and formation

Tagging with unpolarized and polarized light ions

^2H:

unpolarized

- A simple wave function, Two-body object
- Understanding how the free nucleon quark/gluon distribution are modified in the nucleus
- Neutron structure function F_2^n
- Dependence of bound single nucleon structure (EMC effect)
- Spin-flavor dependence of EMC effect

polarized

- Neutron spin structure function g_1^n
- Map out g_1^n cleanest/most precise/ nearly model-independent
- with ^3He to test isospin dependent nuclear modification
- **F_2^n, g_1^n, EMC effect disentangled !**
- **In this talk, Demonstrate that use of the spectator tagging MC simulation ($\vec{e}\vec{D} \rightarrow e' p_s X$) in feasibility of these observations**

^3He:

unpolarized

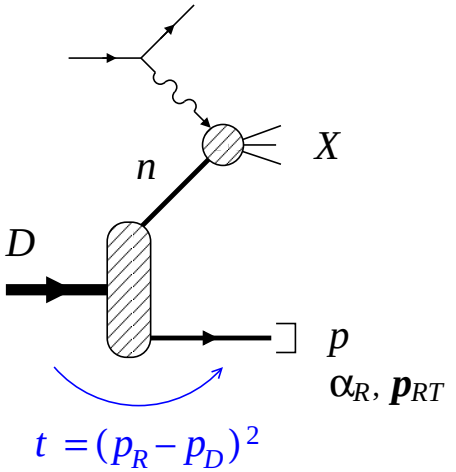
- Three-body object
- Bound nucleon structure and coherent quark/gluon fields
- Neutron structure function F_2^n
- Dependence of bound single nucleon structure (EMC effect)
- Spin-flavor dependence of EMC effect

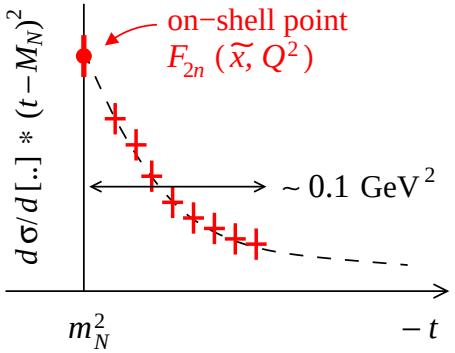
polarized

- Neutron spin to test of the universality of g_1^n
- Three-nucleon system is much complex
- with ^2H to test isospin dependent nuclear modification

[Talks by R. Ent & C. Hyde]

Spectator Tagging → Extrapolating Neutron Structure





[Talk by C. Weiss, W. Cosyn]

- Light-Cone momentum fraction, Transverse momentum of recoil proton:

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

- Cross-section in the IA

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

- On-shell extrapolation: $t \to M_N^2 \quad (t - M_N^2 \equiv t' \to 0)$
  - Free neutron structure at pole
  - FSI does not affect to pole value
  - Model-independent method

Spectator Tagging MC event generator

JLAB LDRD2014-2015 Project

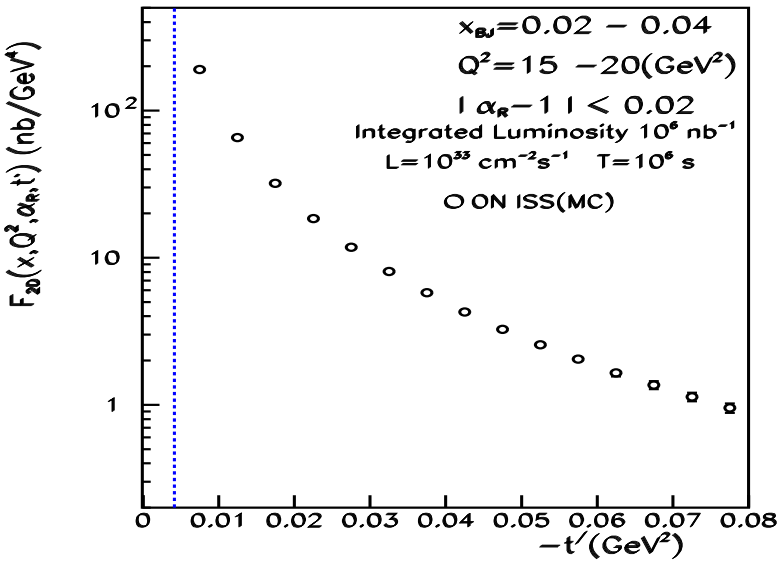
- Develop code for stand-alone event generator / physics model
  - C. Hyde, D. W. Higinbotham, P. Nadel-Turonski, K. Park, C. Weiss, M. Strikman, M. Sargsian, V. Guzey, W. Cosyn.....[Talk by C. Weiss]
- Modular code allows easy to maintain and extend
  - e.g. fixed target/collider, various physics model,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

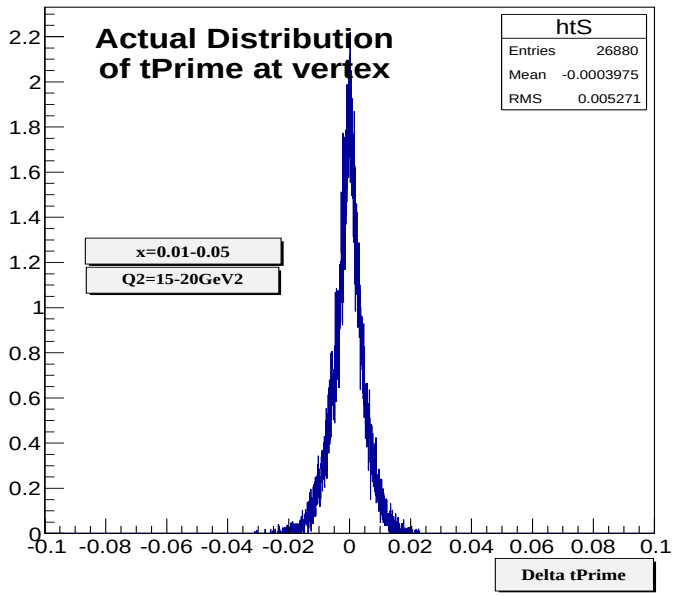
INGREDIENTS

- Implementing accelerator info
  - Cross-angle: 50 mrad, $[E_e : E_D] = [5{:}100]$ GeV, $p_R < 300$ MeV
  - Longitudinal p and angular spread of the beam: $dp/p = 3 \times 10^{-4}$, $d\theta = 2 \times 10^{-4}$
  - Luminosity($\mathcal{L}$)= $10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, Time($\mathcal{T}$)= $10^6(\mathrm{sec})$
- 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
  - FSI (on-going work) .....[Talk by W. Cosyn]
- F_{2n} structure function on-shell extrapolation with experimental uncertainty estimation

$$\Delta\sigma_{MC} = \sum N_i \Delta t' \frac{d\sigma}{dx dQ^2 dt'} \Gamma \cdot J/N_0 \ , \ count = L \cdot T \cdot \Delta\sigma_{MC} \ , \ \sigma(\Delta\sigma_{MC}) = \frac{\Delta\sigma_{MC}}{\sqrt{count}} = \sqrt{\frac{\Delta\sigma_{MC}}{L \cdot T}}$$

MC Simulation → Cross-sections

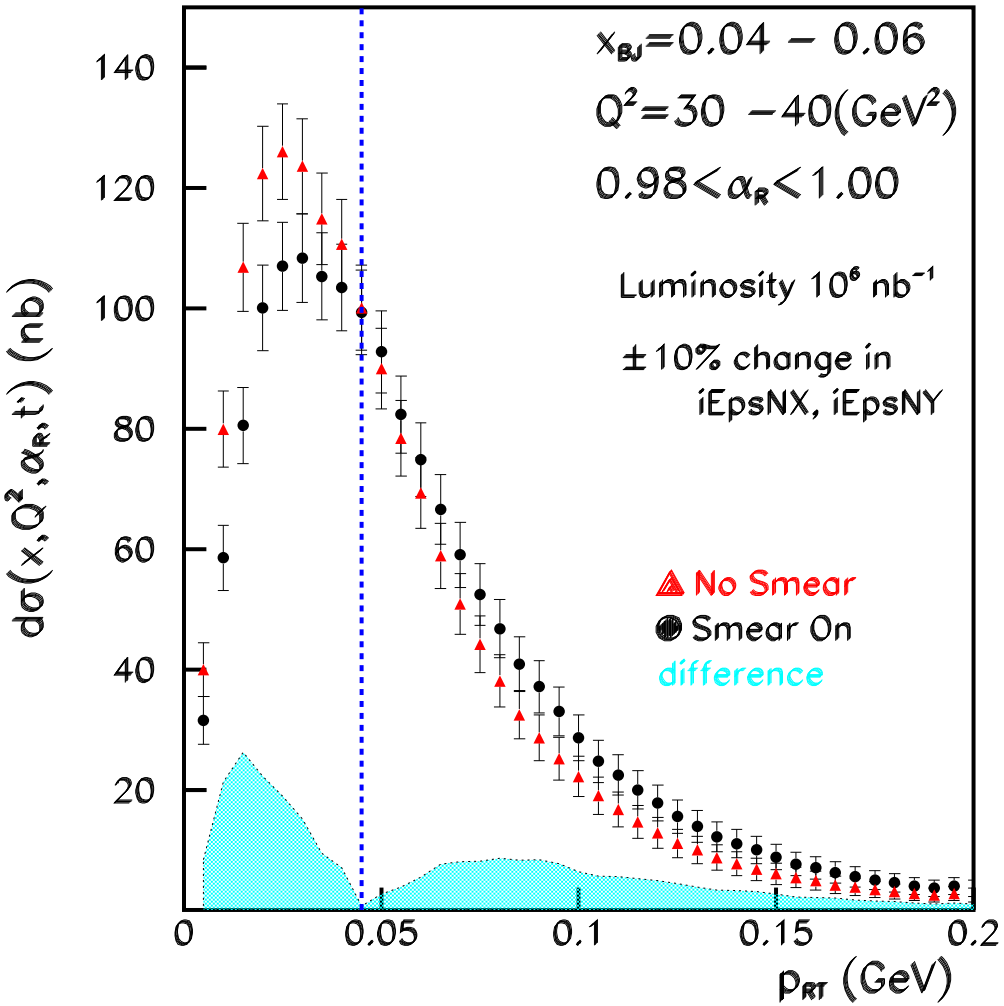




- F_{2n} vs. t' : take out f_{Flux}
- α_R : cut around 1.0 $\pm$ 0.02
- Excellent resolution allows to reach lower t'
- Feasible on-shell extrapolation
- Vertical dash line: $t'_{min} = 0.00416$ GeV^2

- t' **resolution: RMS=0.005**
- Intrinsic momentum spread in **Ion beam** smears recoil momentum
- Dominant uncertainty for MEIC
- Effect on t' (angular spread)
- Smearing $<$ t' bin-size

Beam momentum smearing



- Smearing: Ion beam Transv.Emittances
- Ion beam p_T spread : $\sigma \approx 20$ MeV
- Width is known by $\delta\sigma/\sigma \approx 10\%$
- No smearing (Red) and nominal smearing (Black)

  p_{RT}(vertex) $\neq$ p_{RT}(measure)
- Up to 30% difference at lower p_{RT} (light-blue shade)
- Systematic uncertainty: 10% of difference ($\approx$ 1-3%)
- $p_{RT} = 0.45 GeV$ (vertical dashed line)

MC Simulation / GEMC - Event Display -

$[x_{BJ}:Q^2]$=[0.01-0.1:10-20] phase-space event

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

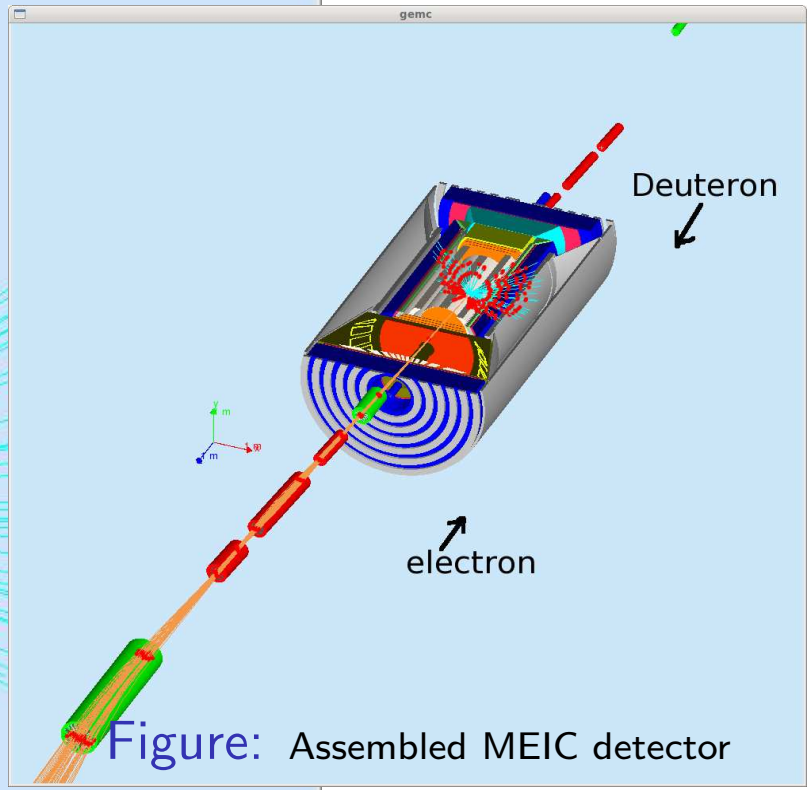


Figure: Assembled MEIC detector

- 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

[Far-forward detectors, Talk by C. Hyde]

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

- $E_e = 5$ GeV, $E_D = 100$ GeV, $\mathcal{L} = 10^{33} cm^{-2} s^{-1}$, $\mathcal{T} = 3 \times 10^6 s$
- 10 bins per decade in x_{BJ}, Q^2
- Cross-section weighted in each bin

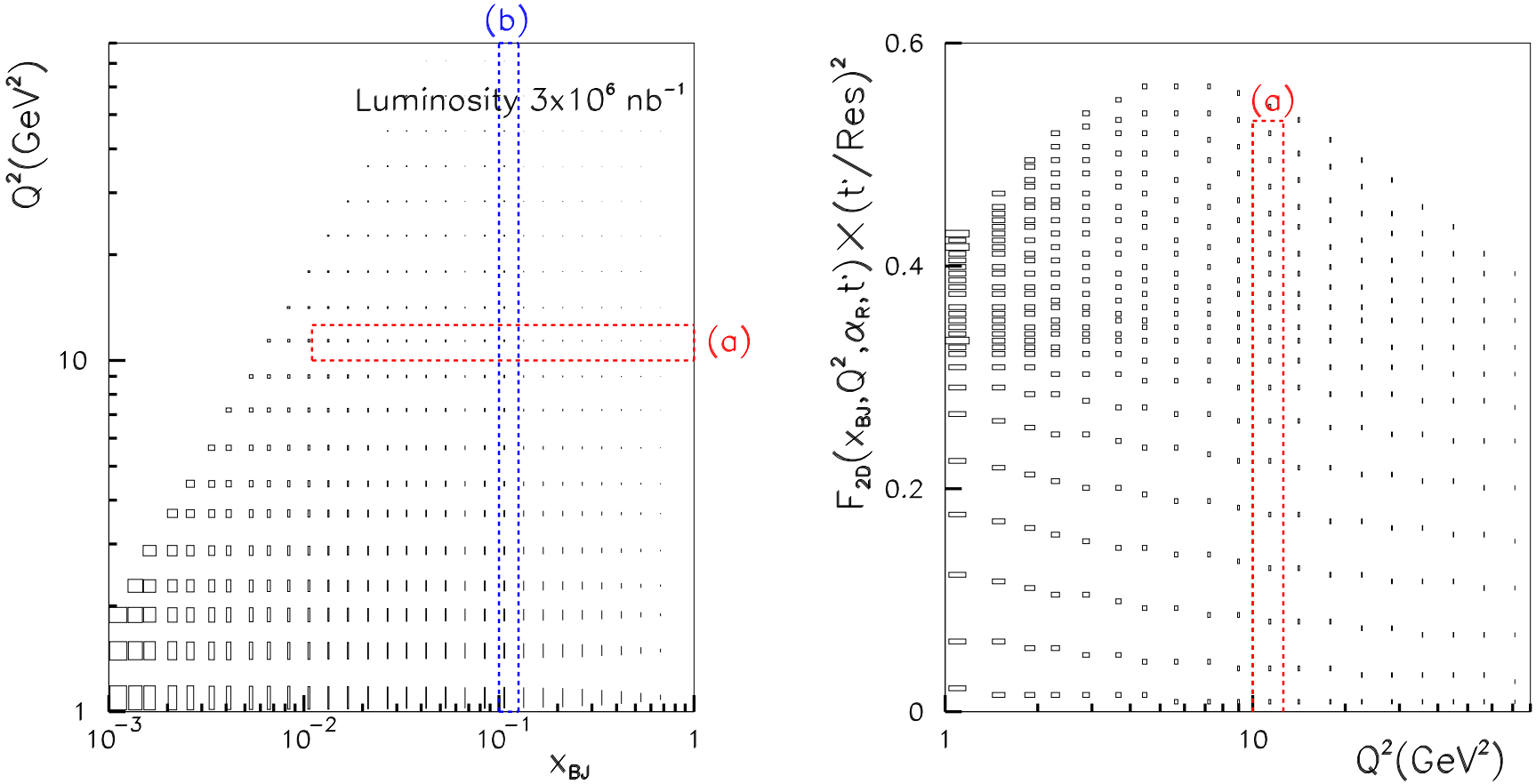
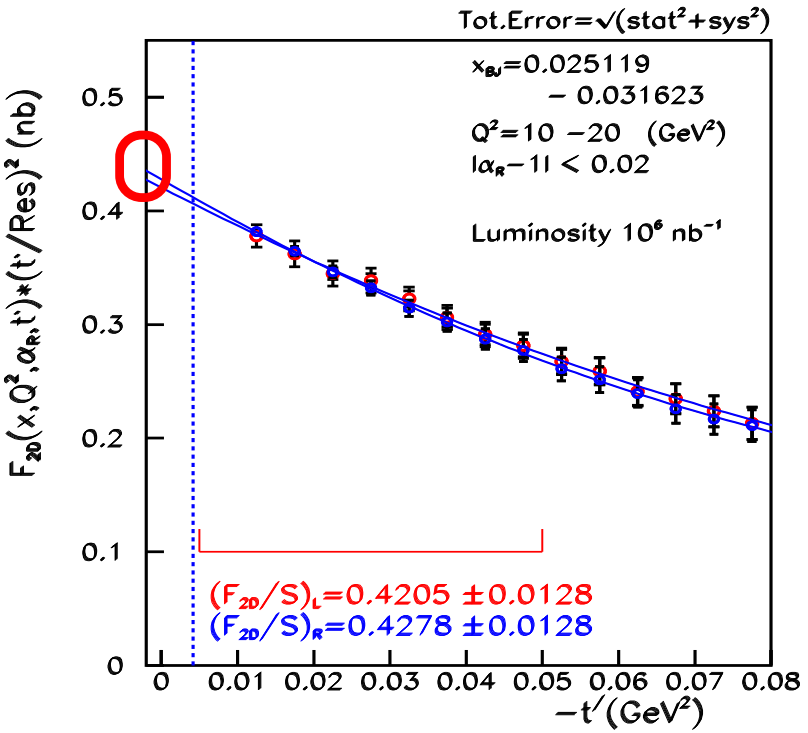
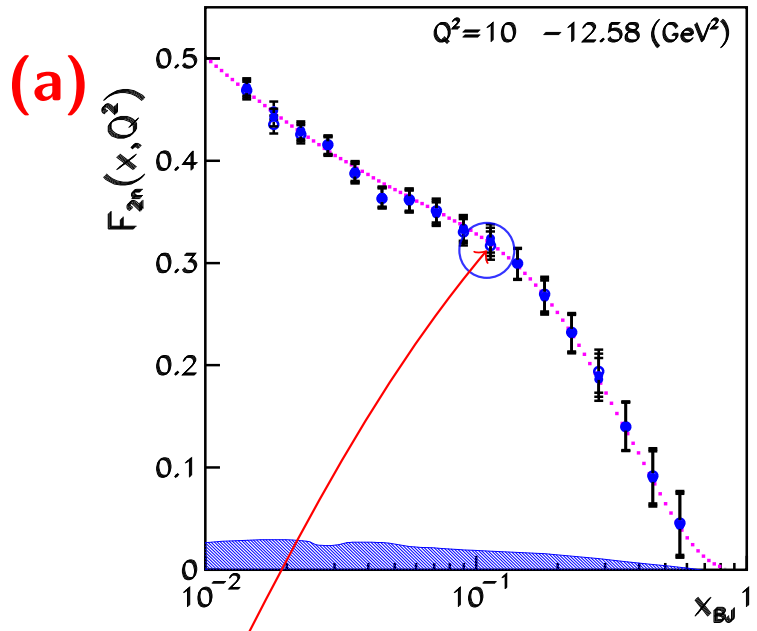


Figure: (Left) Kinematic map of F_{2n} ($\hat{z}$-axis) in terms of x_{BJ}, Q^2, (right) F_{2n} vs. Q^2. Band-(a): x_{BJ} dependence at fixed $Q^2 = 10.0 - 12.58$ GeV^2, band-(b): Q^2 dependence at fixed $x_{BJ} = 0.1 - 0.126$

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





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

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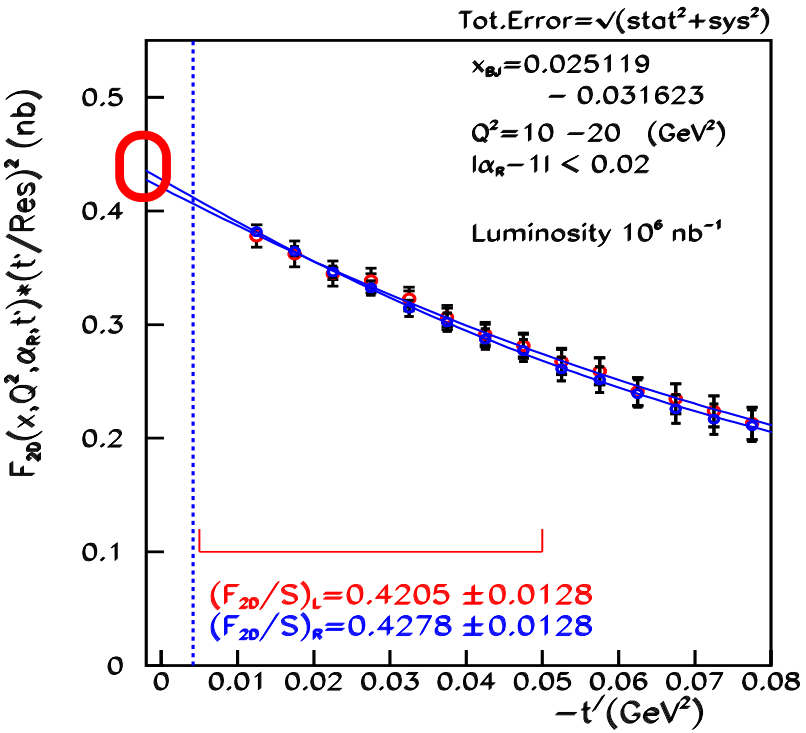
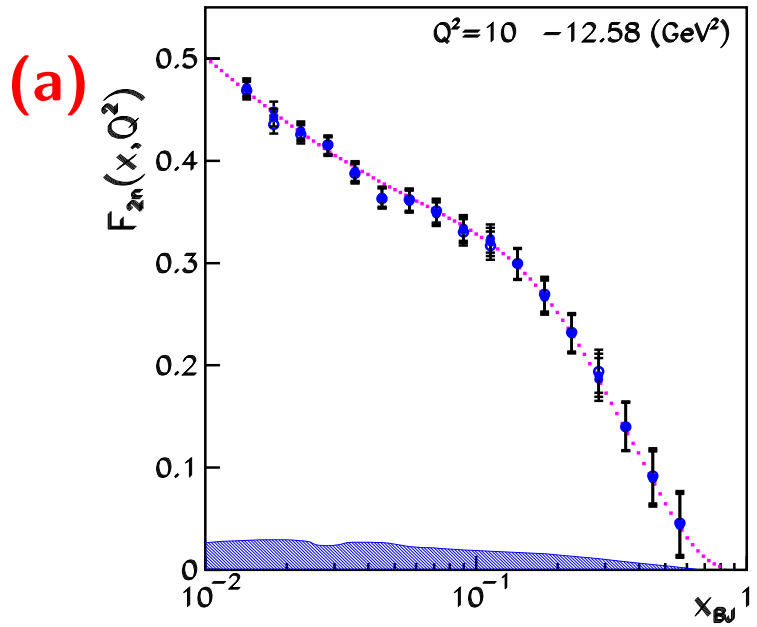
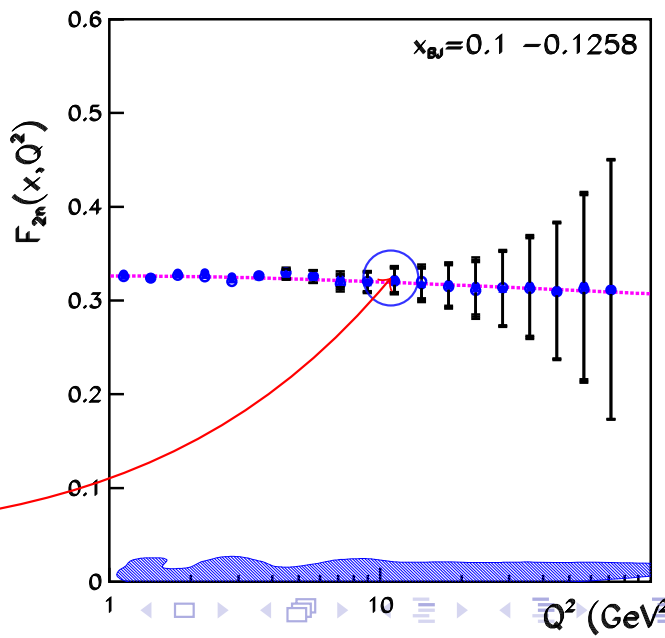
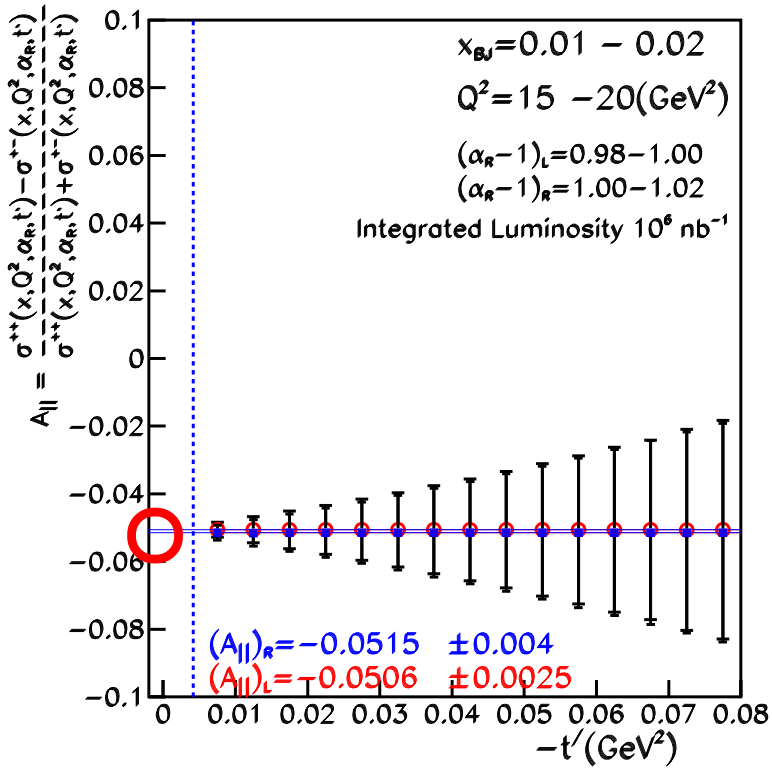


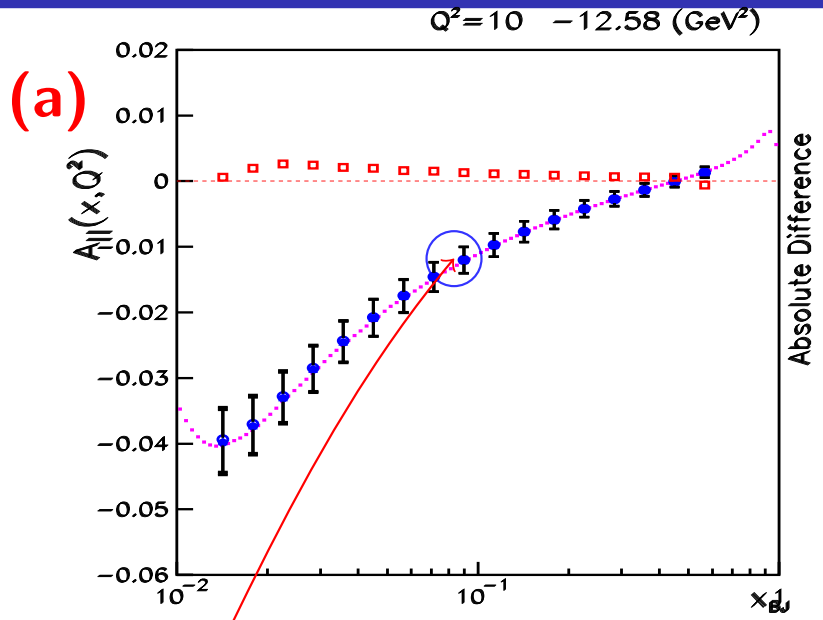




- Systematic uncertainty is dominated at lower t'
- Intrinsic momentum spread: Ion beam smears recoil momentum $-t' \approx 2p_R^2$
- Systematic uncertainty is NOT sensitive to Q^2
- On-shell extrapolation F_{2n} for each (x_{BJ}, Q^2) bin

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





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

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

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

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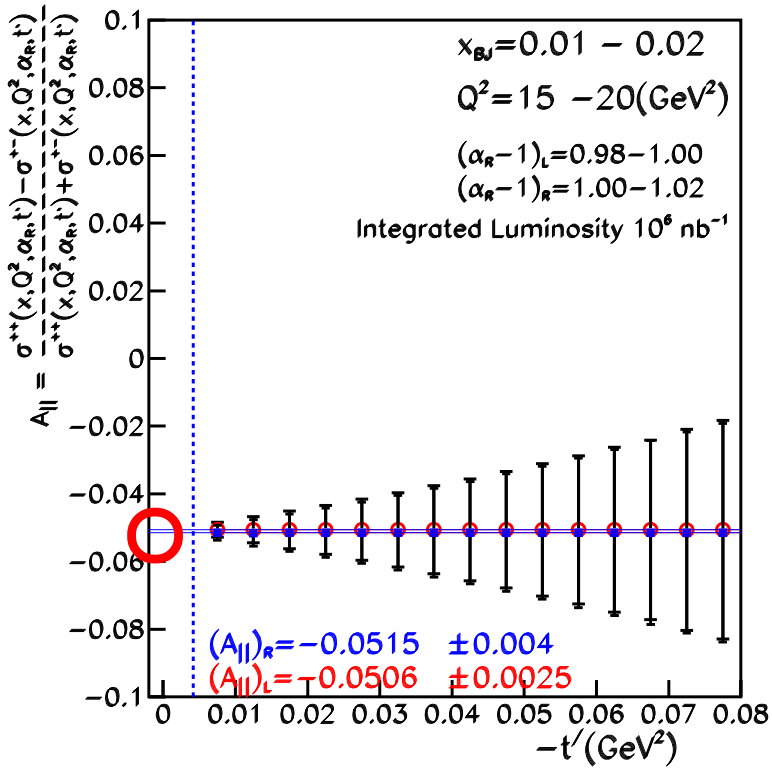

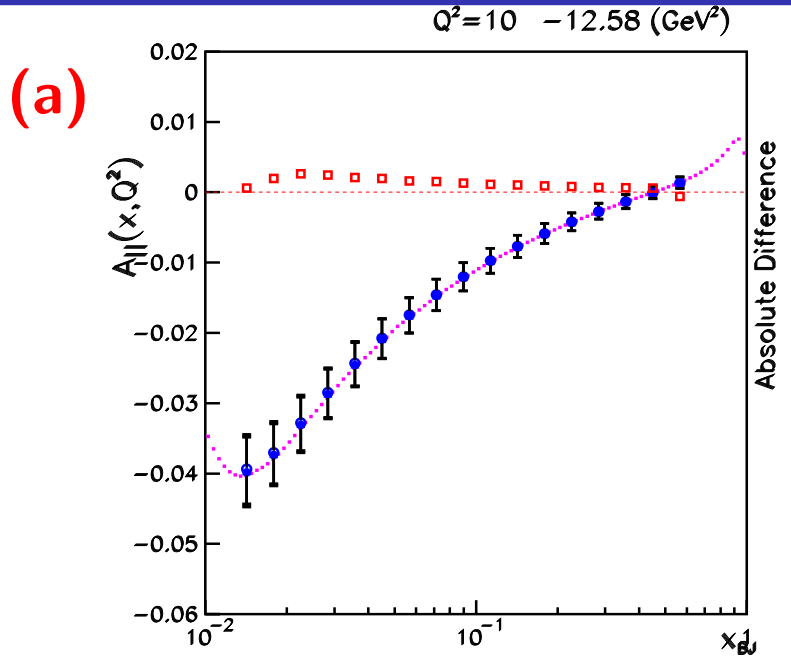

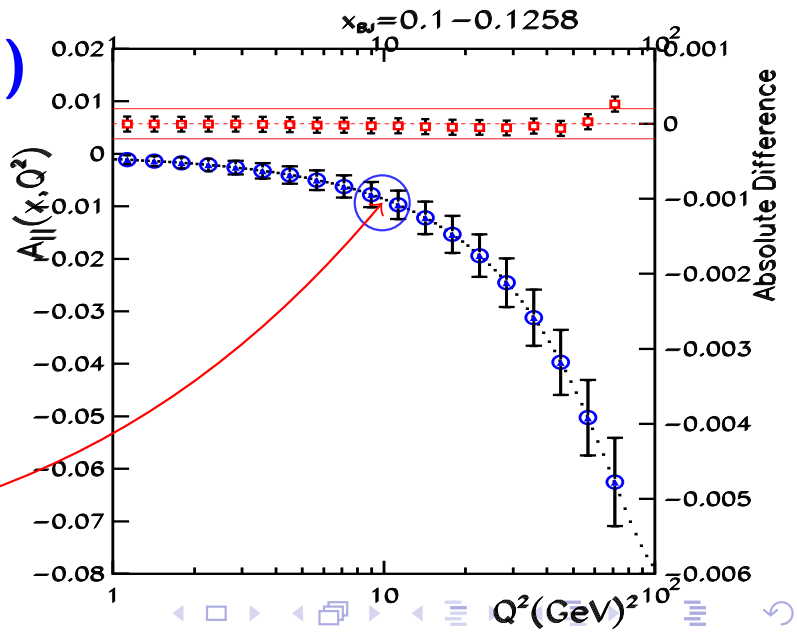

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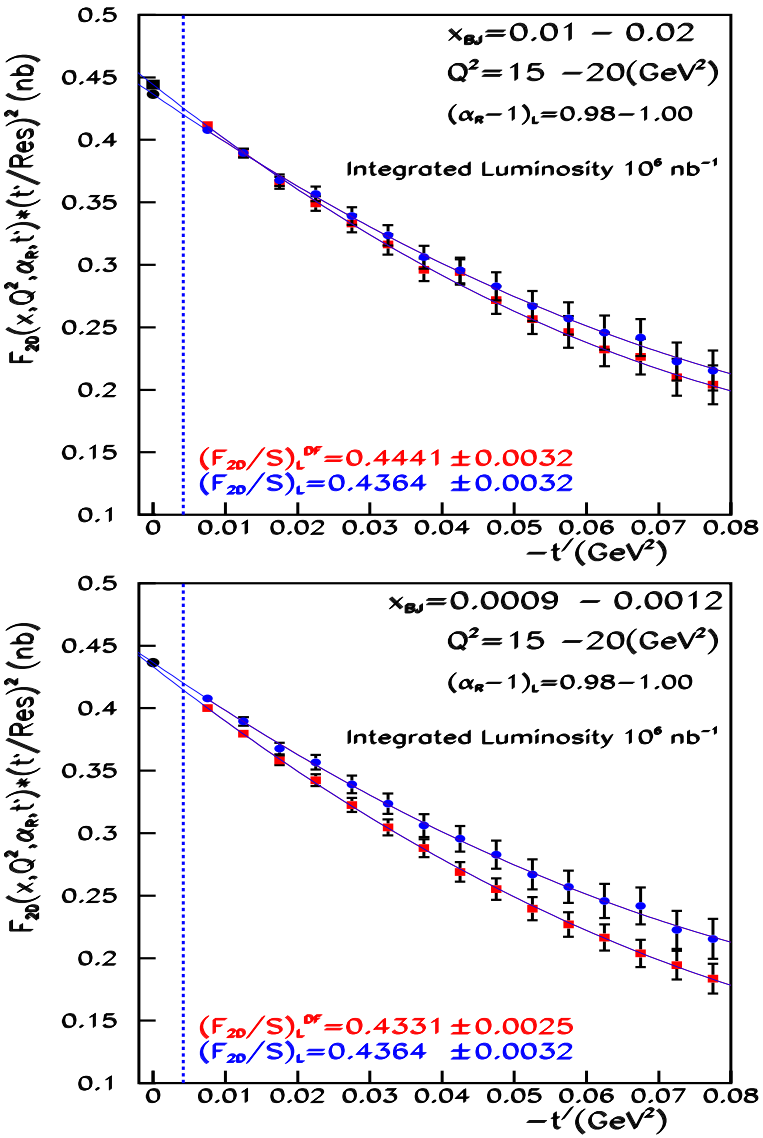
Tagging: Coherent Effects (e.g.: Shadowing correction)



- 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-left)
  $x_{BJ} = 0.01 - 0.02$,
  $Q^2 = 15 - 20$ GeV^2
- Diffractive effect 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)

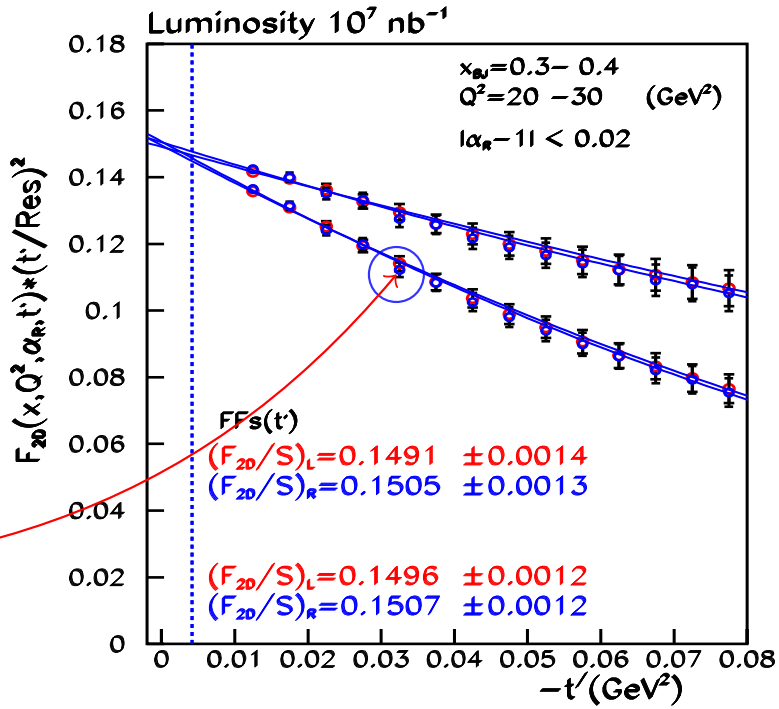
- **Kinematics II**: (bottom-left)
  $x_{BJ} = 0.0009 - 0.0012$,
  $Q^2 = 15 - 20$ GeV^2
- Diffractive effect shows a **stronger impact in lower** x_{BJ}
  -19% at $t' = 0.08$ GeV^2, -1.8% at $t' = 0.01$ GeV^2

[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 pol. D

- $x_{BJ} = 0.3 - 0.4$, $Q^2 = 20 - 30$ 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]

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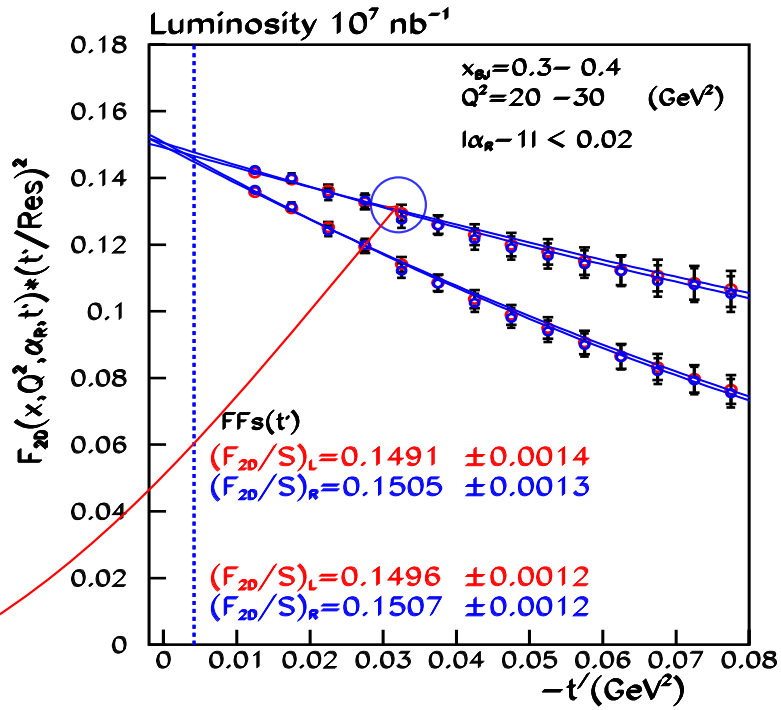

[Interested kinematic region for EMC, M. Strikman]

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

Summary

- Developed Spectator Tagging Event Generator MC with EIC configuration
- On-shell extrapolation of F_{2n} & $A_{||}$ have been obtained
- Overall 1% level of statistical uncertainty
  - 10 bins per decade in x_{BJ}, Q^2 and $\mathcal{L} = 10^{33} cm^{-2} s^{-1}$
- 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

  $\rightarrow$ https://www.jlab.org/theory/tag/

  $\rightarrow$ https://github.com/JeffersonLab/LightIonEIC