

Forward Tagging as a Probe of Hadronic and Nuclear Dynamics

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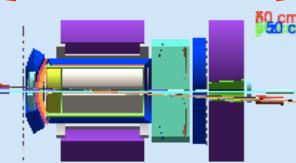
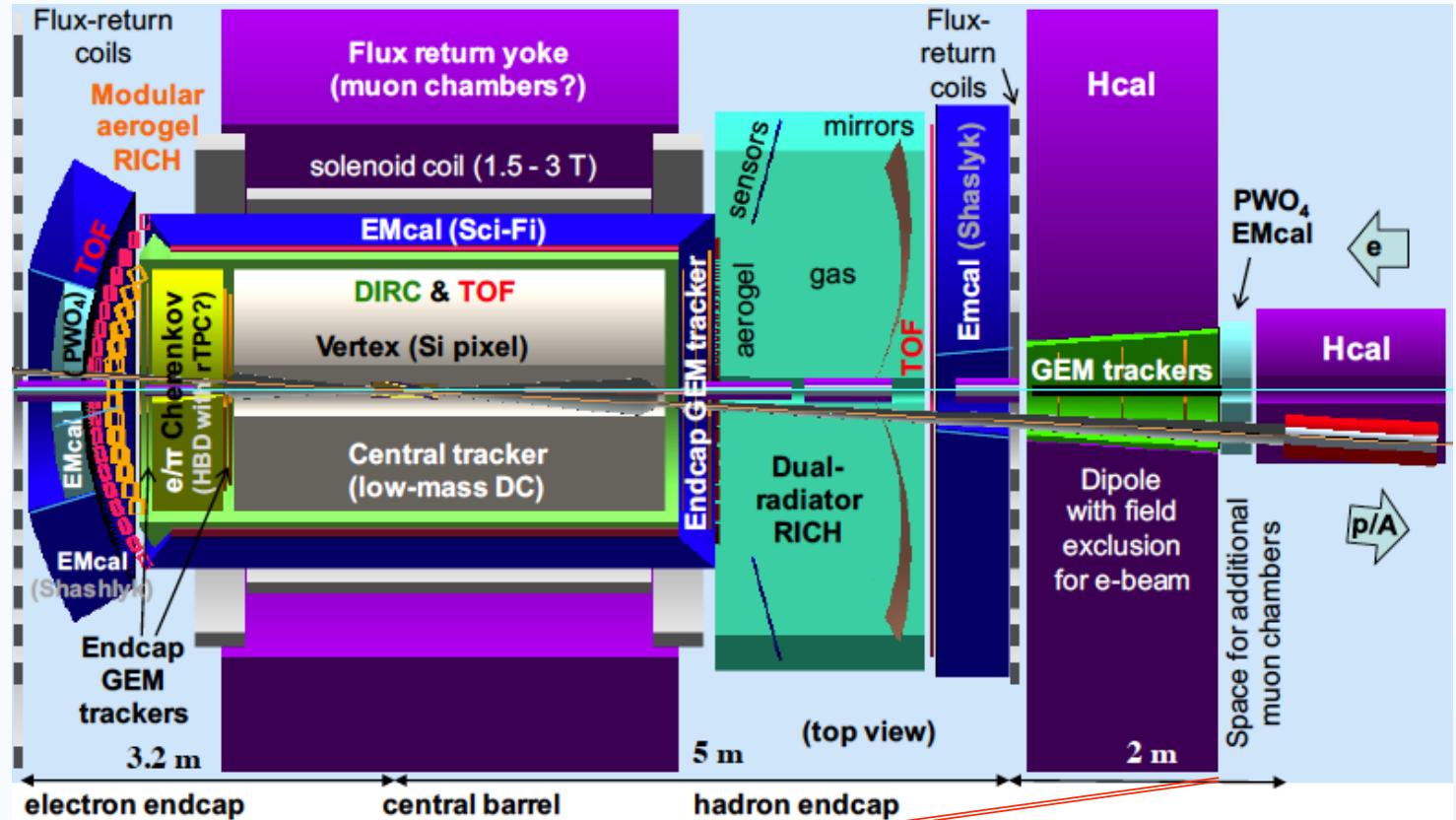


EIC Users Group Meeting



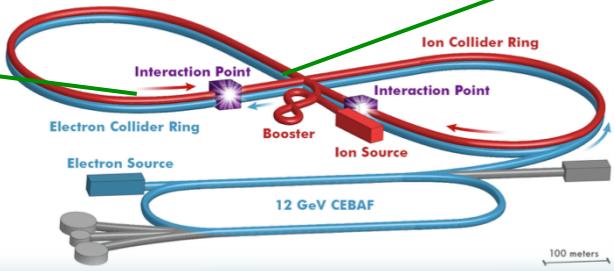
7-9 July 2016

JLEIC



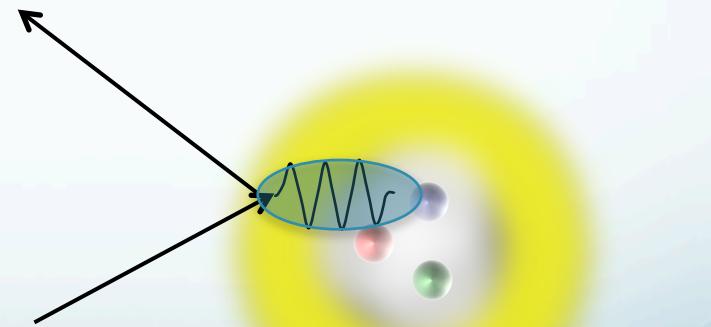
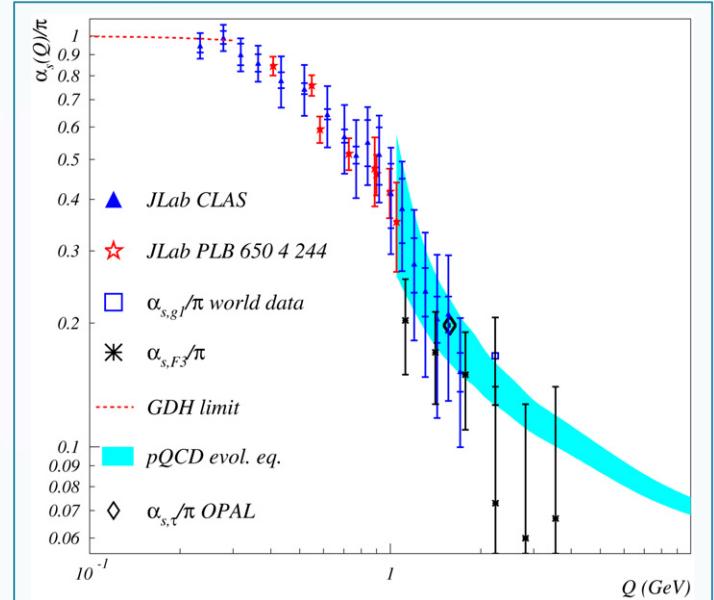
Forward Spectrometer: $\Delta p/p = \pm 0.5$, $\theta = \pm 8\text{mrad}$

ZDC



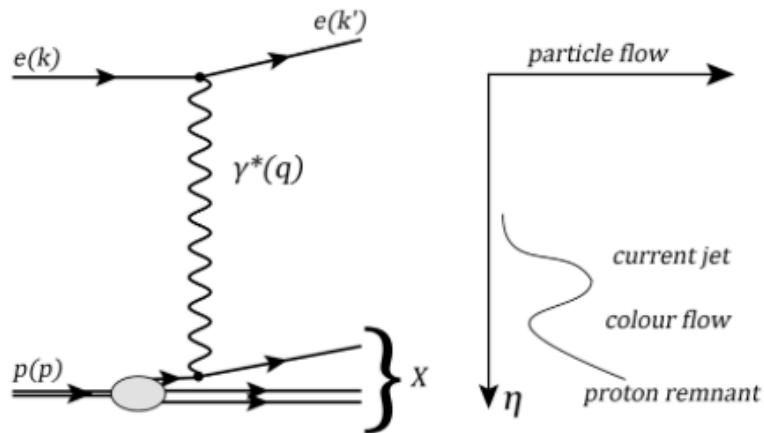
The Tools of DIS

- Basic Variables: Q^2 , x_{Bj}
 - $\alpha_s(Q^2) < 0.5$ for $Q^2 > 1 \text{ GeV}^2$
 - Transverse spatial resolution
 $\delta b \sim 1/[Q^2]^{1/2}$
- Longitudinal coherence length
of virtual photon $\lambda \approx 1/(2Mx_{Bj})$
 - $x < 0.1 \leftrightarrow \lambda \geq 1 \text{ fm}$



Final States: DIS & Diffractive DIS

Deep Inelastic Scattering (DIS)

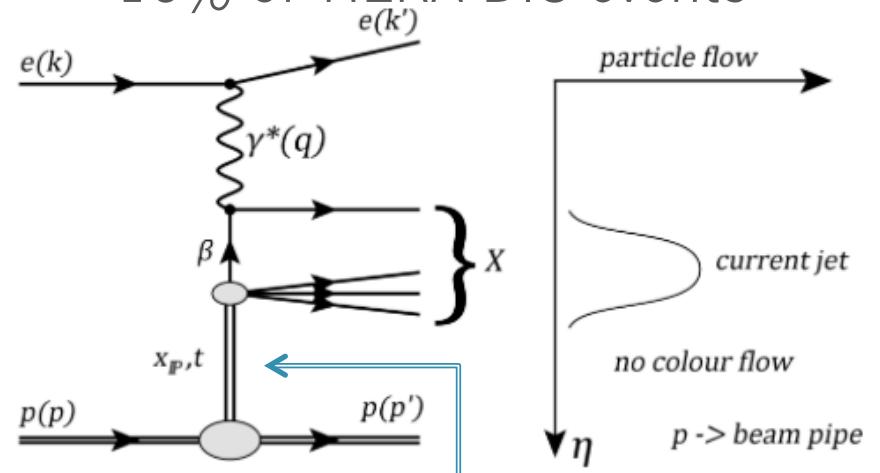


Proton Remnant:

- Di-quark/ tetra-quark color triplet
- Color octet

Diffractive Scattering (DDIS)

- ~10% of HERA DIS events

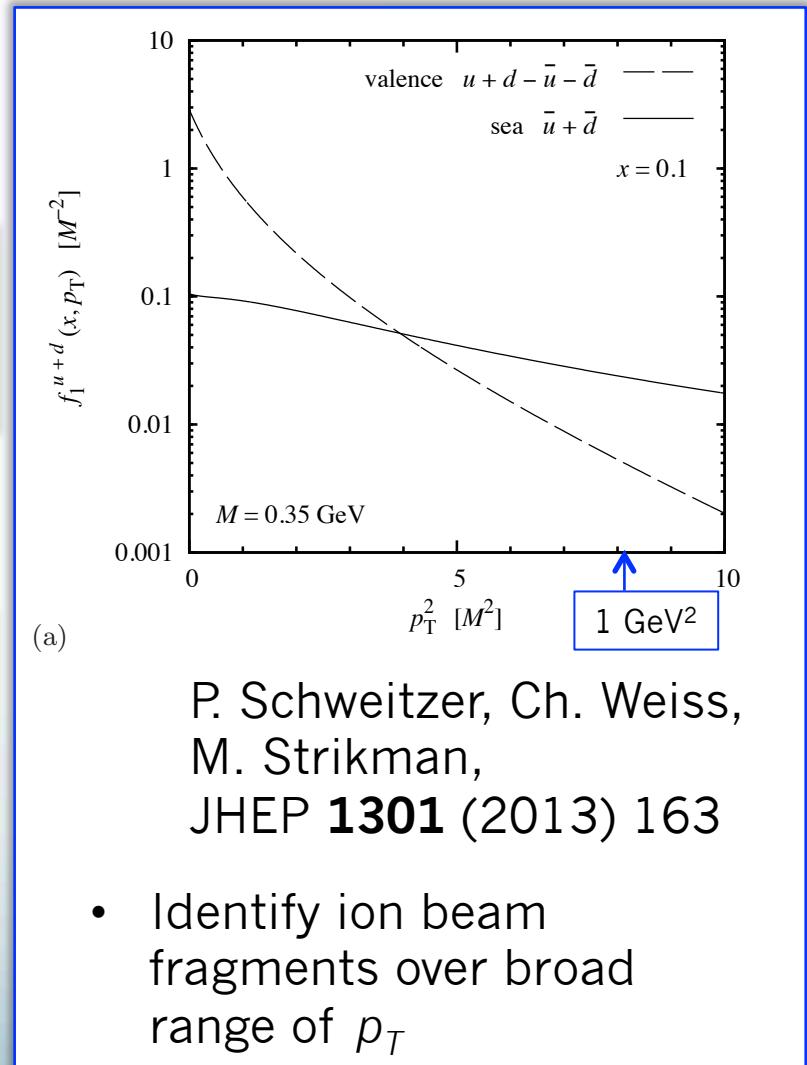
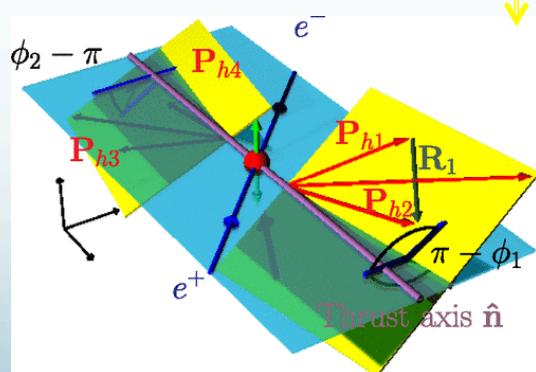


Rapidity Gap: $\Delta\eta \geq 2$

Correlations between Current & Target fragments

- Chiral Symmetry Breaking:
Parton-parton correlations at $p_T \sim \Lambda \chi \sim 1 \text{ GeV}$. 
- Coincident hadrons in target and current fragments, with correlated & spin-dependent p_T .
- Multiparton interactions in LHC pp collisions do not scale as average density

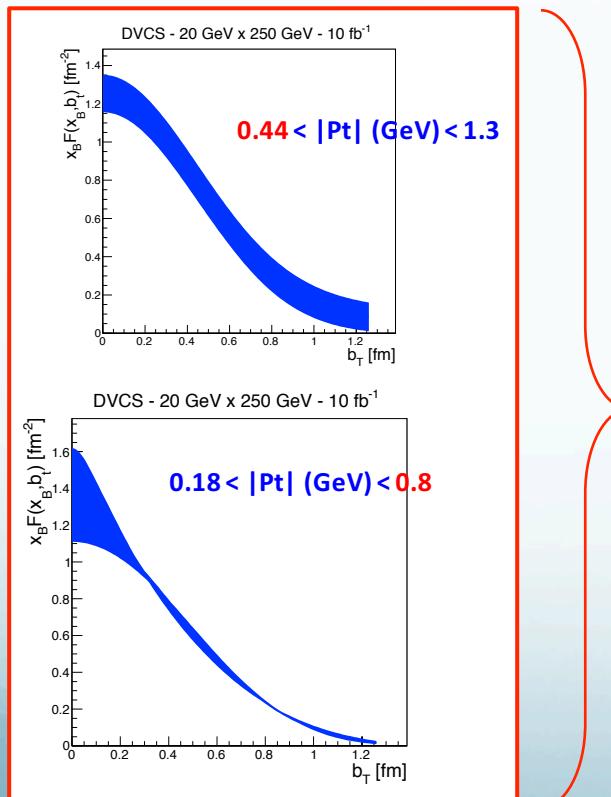
Interference Fragmentation Functions measured in BELLE:
A Vossen et al,
PRL **107**, 072004
(2011)



Deep Virtual Exclusive Scattering Transverse Spatial Imaging vs. x_{Bj}

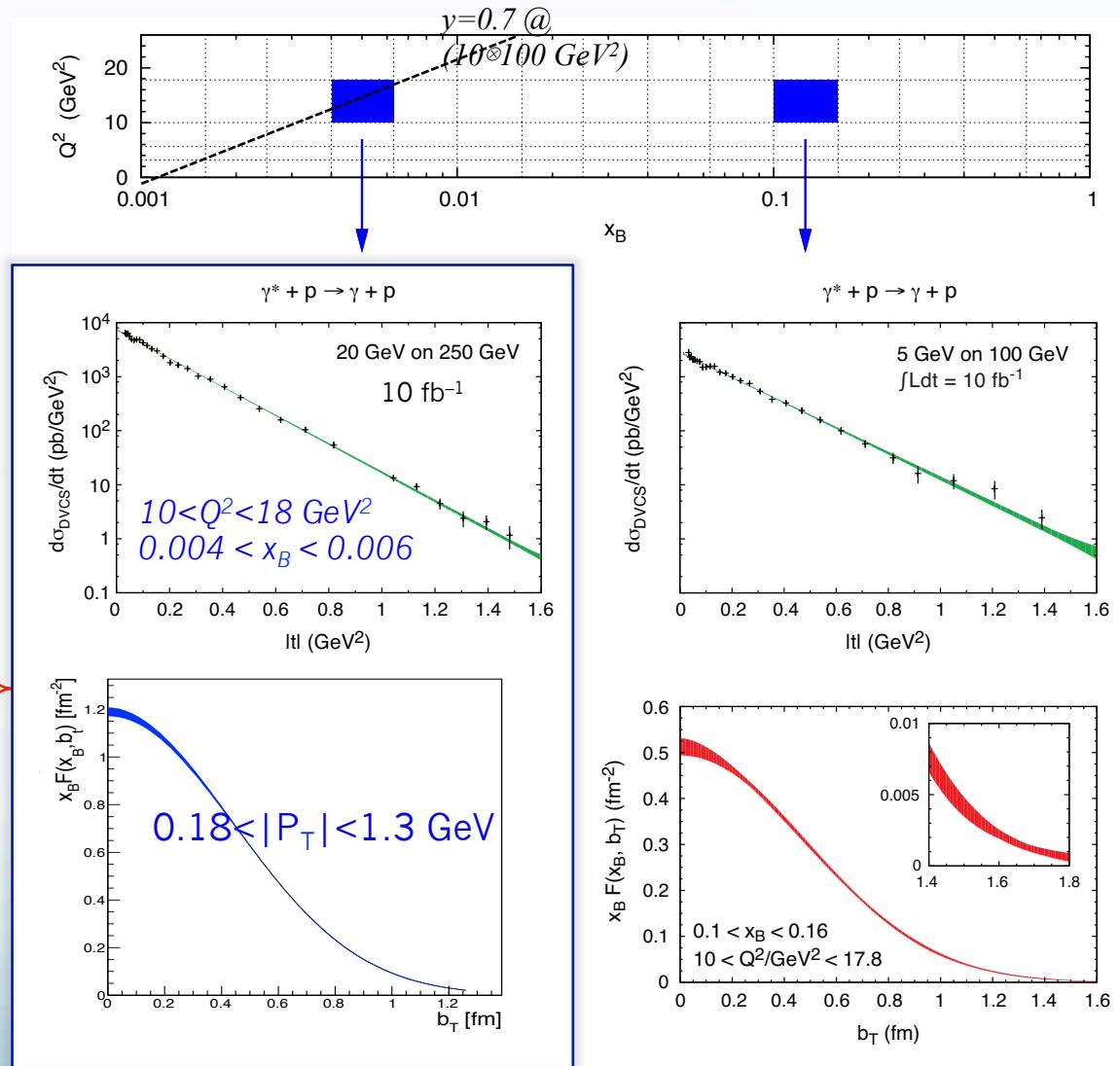
- Detector Acceptance

- eRHIC: new IR design:
 $0.18 \leq p_T$
- JLEIC: Far-Forward spectr.
 $0.0 \leq p_T$ for $x_{Bj} > 0.003$



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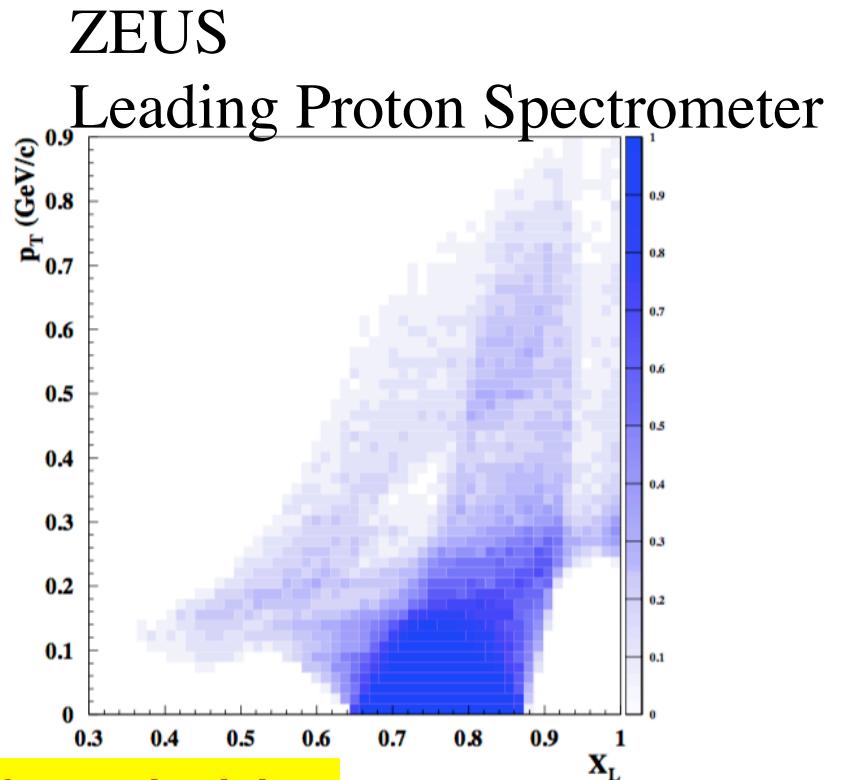
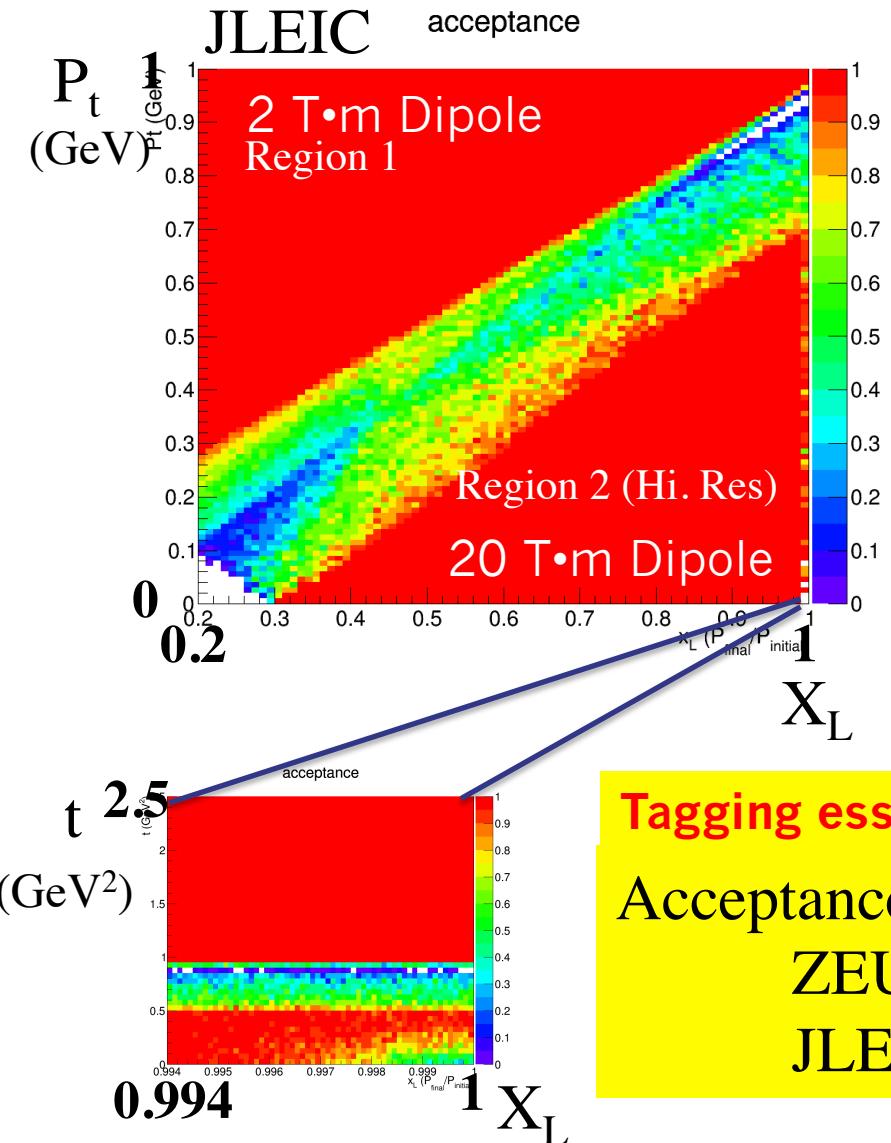
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Acceptance for p' in DDIS/DVES



Tagging essential for exclusivity

Acceptance in diffractive peak ($X_L > \sim .98$)

ZEUS: ~2%

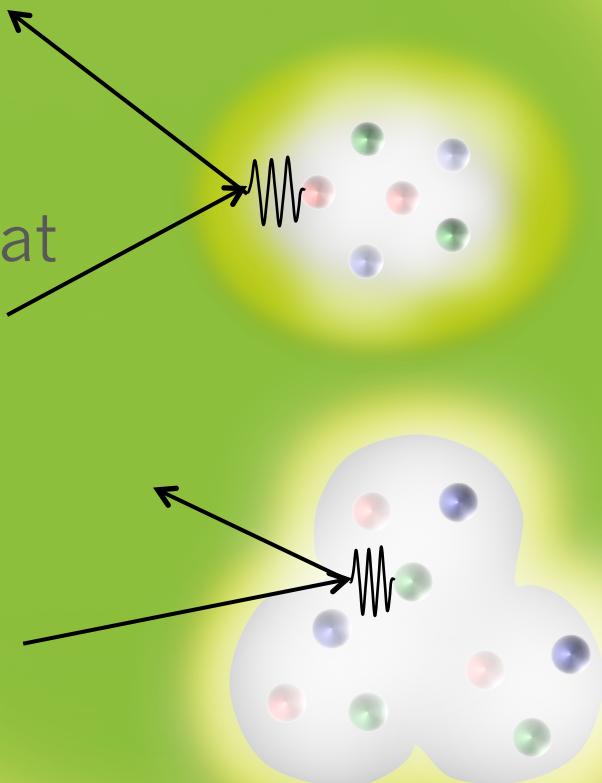
JLEIC: ~100%

DIS and Many Body Nuclear Dynamics

- DIS at different x , Q^2 ranges probes particular configurations in the nucleus
- Forward tagging of spectator/recoil nucleons... to observe the dynamics of the active configurations.
- Illustrative Examples:
 - $x > 1$ ~6-quark bags
 - $0.2 < x < 0.7$ Nuclear Binding, Short Range Correlations
 - $x \approx 0.1$ Anti-shadowing: Hard Core on NN Force
 - $x < 0.1$ Coherent Diffraction: Multiple nucleons
 - $x \lll 0.1$, $Q^2 \gg 1 \text{ GeV}^2$ Coherence \rightarrow Saturation Transition

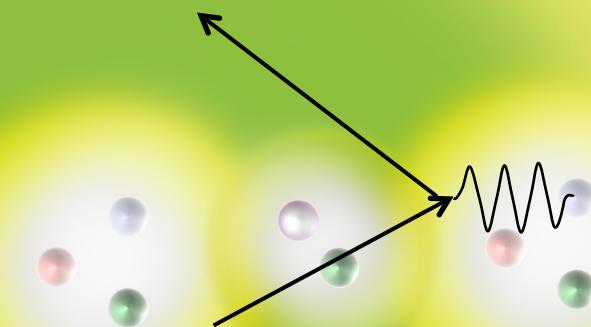
Nuclear Dynamics Probed by DIS: I

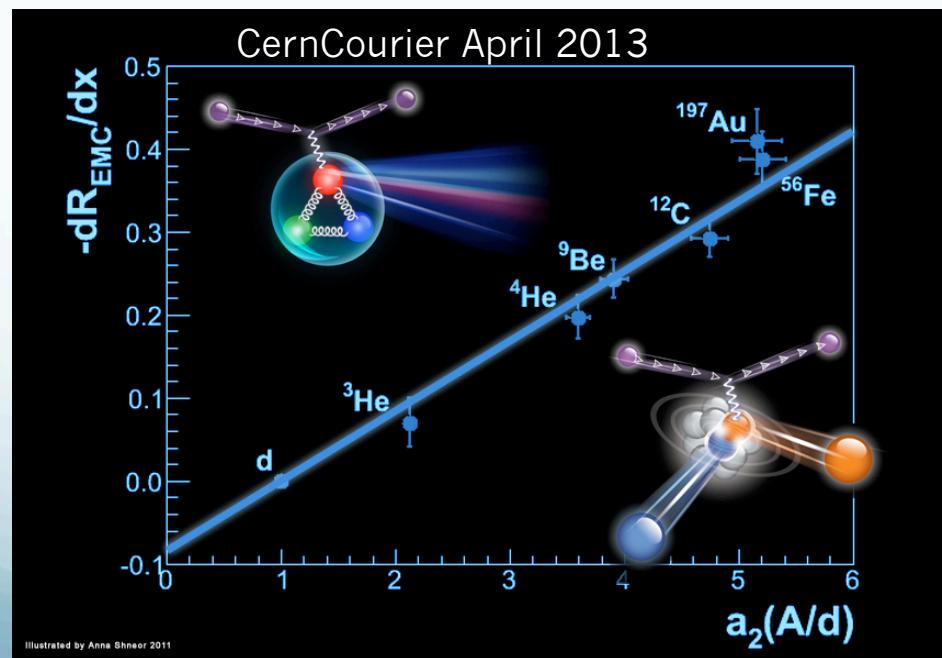
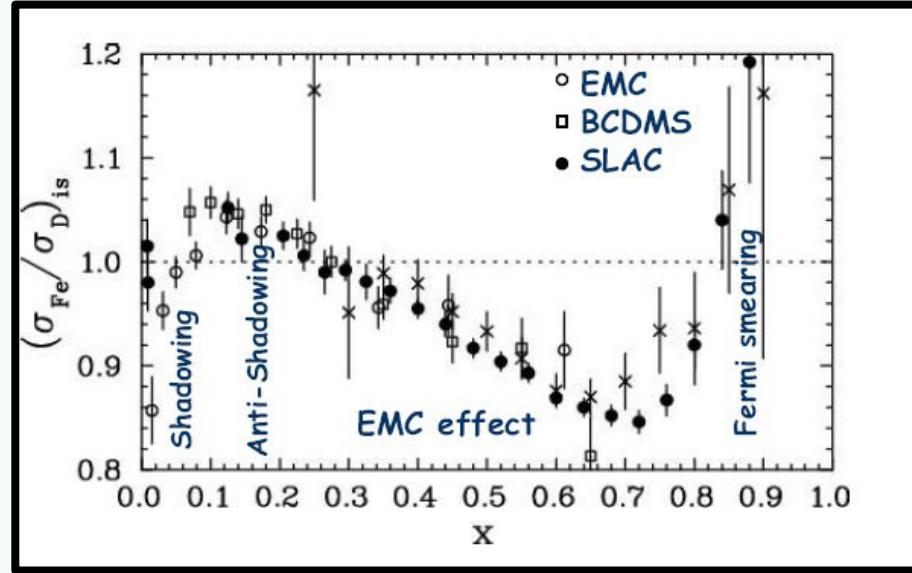
- Kinematic bound: $x_{Bj} < A$
- $x_{Bj} > 1$
 - Parton momentum fraction generated by interaction of at least two nucleons
 - [Color Octet]² states ?
- $x_{Bj} > 2$
 - Probe three body forces.



Nuclear Dynamics Probed by DIS: II

- $0.2 < x_{Bj} < 0.8$
EMC Effect
- Quark-Gluon structure of nuclear binding at scale $1/(2x_B M) \leq 0.5$ fm
 - Incoherent over quarks in different nucleons or exchanged mesons





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The EMC Effect

- Quark-gluon imprint of Nuclear Binding
- NN Correlations

N. Fomin, et al,

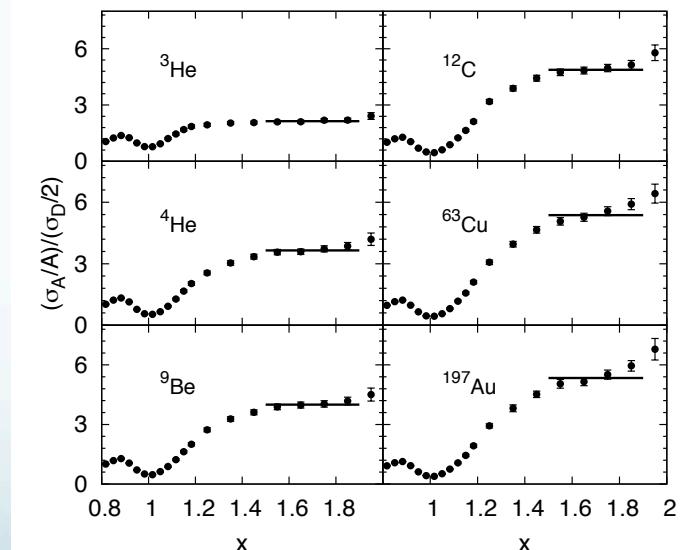


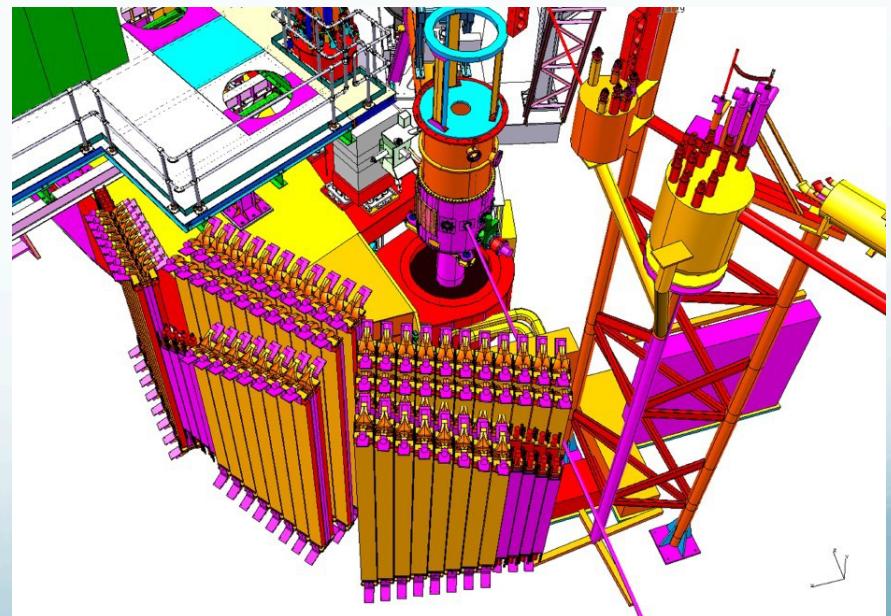
FIG. 2: Per-nucleon cross section ratios vs x at $\theta_e=18^\circ$.

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Nuclear Final State in DIS

- Active program at JLab12 to study NN pairs emitted in nuclear DIS
 - isospin structure
 - Low p_{Rel} vs high p_{Rel}
 - Forward nucleons from $^3\text{H}/^3\text{He}$ (Hall A 2017)
 - Backward nucleons in heavy nuclei:
Hall B, Hall C →

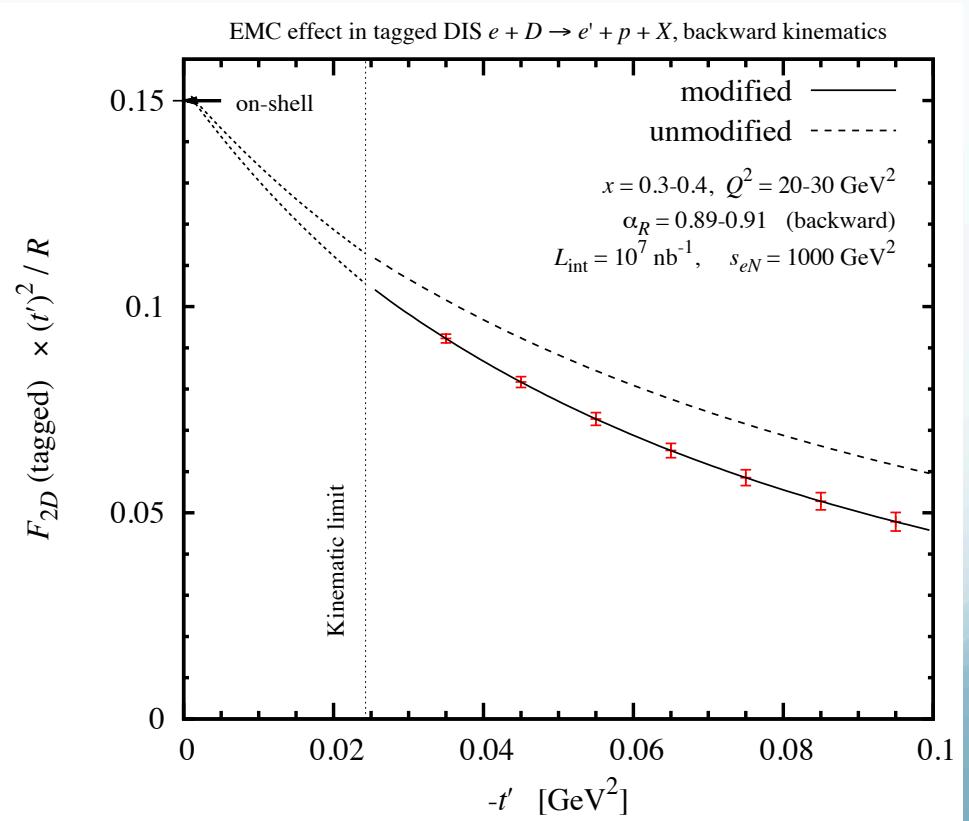


Nuclear Final State at EIC

- Naive spectator kinematics:
$$p_i^\mu = \left[\frac{\alpha_i}{A} P_A^+, \mathbf{p}_{i,T}, p_i^- \right]$$
$$\sum_{i=1}^A \alpha_i = A \quad \sum_{i=1}^A \mathbf{p}_{i,T} = 0$$
- Fermi gas: $|\alpha_i - 1| \approx p_F/M \approx 0.25$ $\mathbf{p}_{i,T} \leq p_F$
- In a heavy nucleus of momentum $Z \cdot (100 \text{ GeV}/c)$, spectator neutrons, protons have laboratory momenta $(p_{||}, p_T) \approx [\alpha_i(40 \text{ GeV}/c), \mathbf{p}_{i,T}]$
 - Forward Tagging!

DIS on the Deuteron: Spectator Tagging

- $\alpha_p \approx 1, \mathbf{p}_{p,T} \approx 0$
→ on-shell extrapolation of DIS on neutron
- Calibrate with ZDC tagging of spectator neutron
 - $30\% / E_n^{1/2} \approx 4\% @ 50 \text{ GeV}$
 $\delta\alpha_p \approx 0.04 \rightarrow$
Rest frame resolution of initial NN relative momentum
~ 40 MeV/c for DIS on nearly on-shell proton
 - $|1 - \alpha_P| > 0.2$
 - EMC effect in Deuterium!

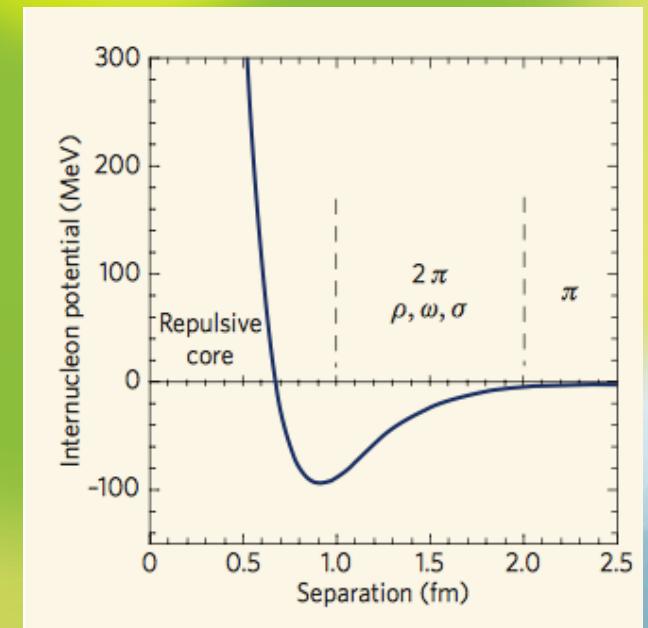
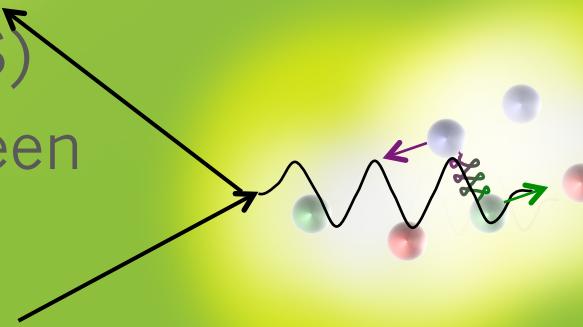


DVES on Deuteron

- Coherent $d(e, e'd V)$
 - Tensor polarized beam: Observe quark-gluon structure of tensor interaction.
- Incoherent $d(e, e'pnV)$
 - *Miller, Sievert, Rajugopalan,*
[www.arXiv.org/1512.03111](https://arxiv.org/abs/1512.03111)
 - Low mass NN final state \approx independent nucleons
 - High mass NN final state \rightarrow probe spatial size of interacting pair

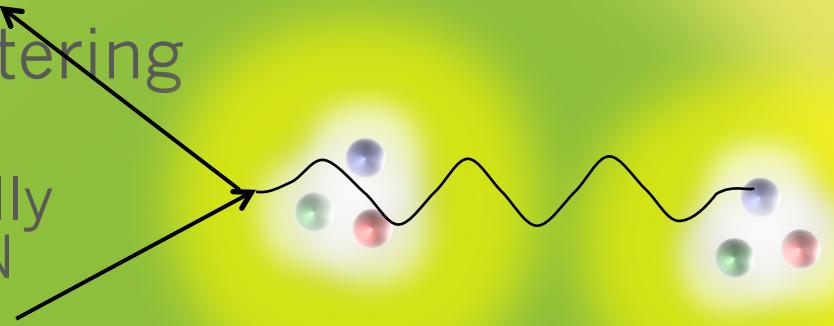
Nuclear Dynamics Probed by DIS: III

- $x_{Bj} \approx 0.1$: “Anti-Shadowing”
 - $q(x) + \bar{q}(x)$ enhanced (DIS)
 - No $\bar{q}(x)$ enhancement seen in Drell-Yan.
- Hard Core of NN-interaction from q - q - g exchange?
- Expect gluon anti-shadowing (enhancement in nuclei)
 - JLab LDRD program to study open-charm in nuclear DIS



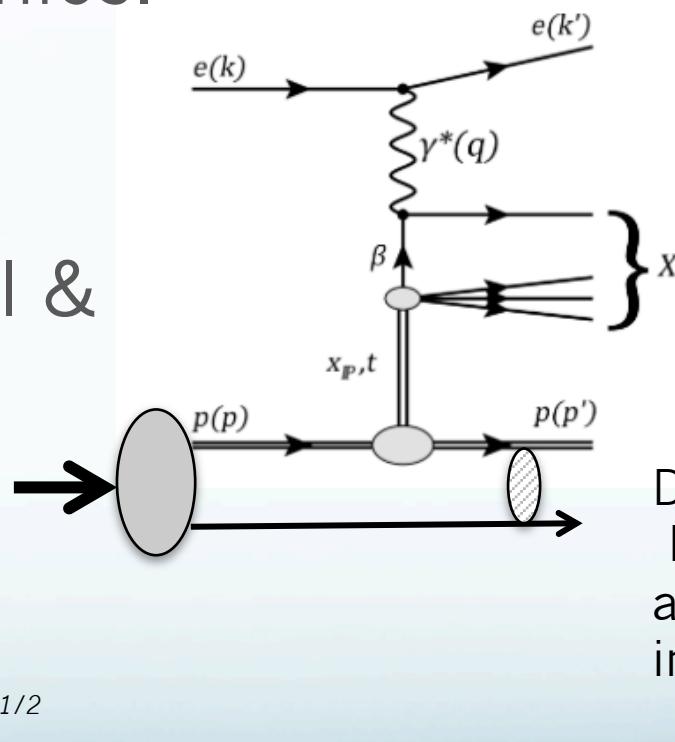
Nuclear Dynamics Probed by DIS: IV

- $x_{Bj} < 0.05$: “Shadowing”
- Coherent diffractive scattering from ≥ 2 nucleons
 - Interference is automatically destructive by virtue of NN antisymmetry
 - NN pair must be back-to-back
 - Transverse resolution $1/Q^2$ post-selects nuclear state
 - Shadowing is a $\sim 100\%$ effect on the $\sim 10\%$ of DIS events that are diffractive



Nuclear Initial and Final States in Diffractive DIS.

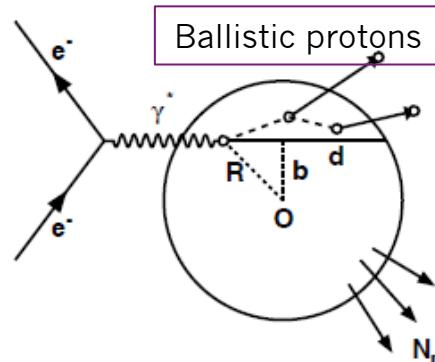
- Incoherent Diffraction: A clean probe of multi-nucleon dynamics.
 - Only low-energy NN, NNN... FSI
- Event-by-event initial & final state:
 - Elliptical source ≥ 2 nucleons
 $\longleftrightarrow \frac{1}{(2x_B M)}$
 - Elliptic flow?



Color-neutral
 $\delta b > 1/[Q^2]^{1/2}$
No FSI!

Destructive Interference:
active/spectator in NN pair

Geometry tagging (w/o shadowing)

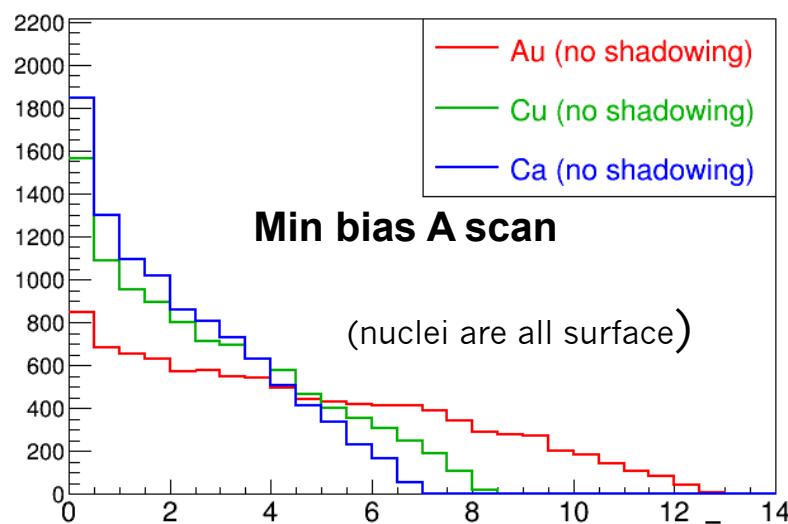


Ballistic protons
Intra-nuclear cascading increases with d (forward particle production)

Leads to more evaporation of nucleons from excited nucleus (very forward)

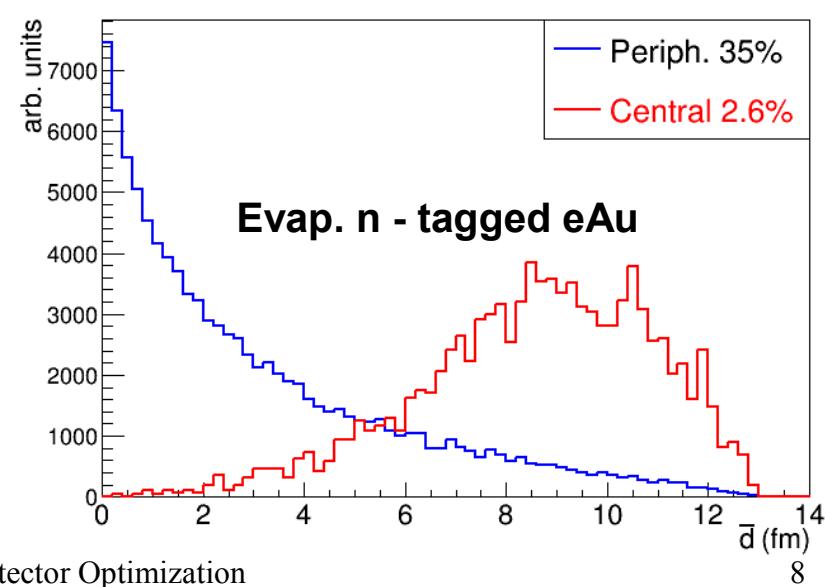
JLab LDRD FY2017 proposal
Nadel-Turronski, Baker et al

Role of ballistic nucleons:
Lappi, Mäntysaari,
R. Venugopalan, PRL **114**



06-July-2016

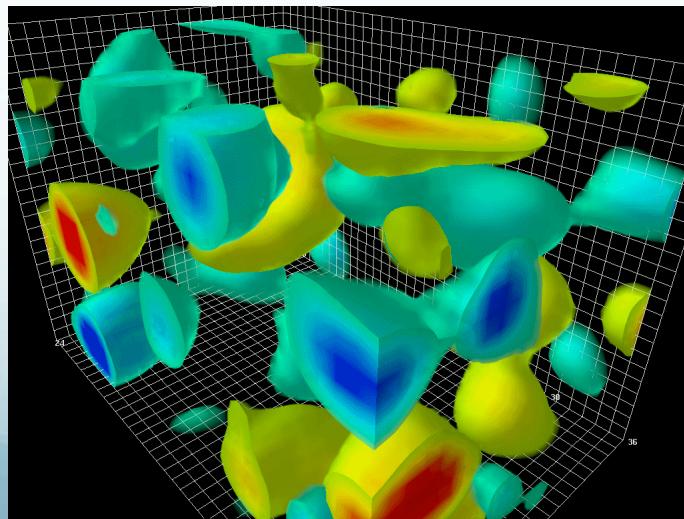
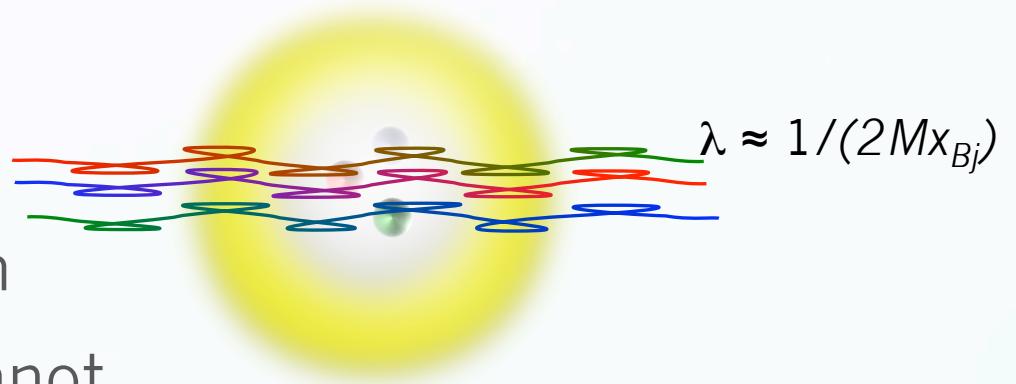
MDB - Forward Detector Optimization



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DIS @ $x_{Bj} \ll 0.1$

- DIS probes fluctuations with coherence length λ much greater than nucleon or even nuclear size.
- Precursor to saturation
- Low energy probes cannot distinguish these from vacuum fluctuations



Animations at
www.physics.adelaide.edu.au/theory/staff/leinweber

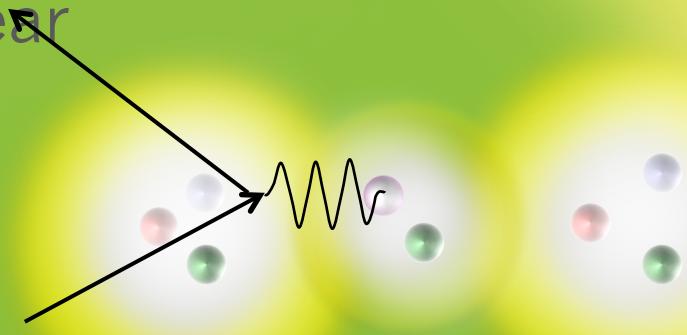
Conclusion

- A High Luminosity Polarized Electron Ion Collider is an unprecedented tool to quantitatively explore the quark-gluon dynamics of
 - the Origin of the Mass of mesons and baryons
 - The creation of mass as a quark or gluon propagates through cold QCD matter
 - Vacuum
 - Nucleus
 - Nuclear Binding
 - NN Force
 - NNN Force
- These are exciting, challenging questions.
 - We can make progress
 - This will resonate with the larger scientific community

Backup Slides

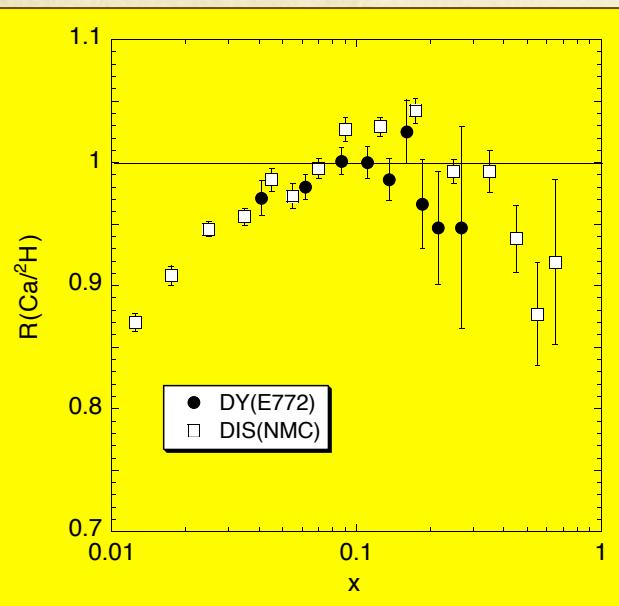
Nuclear Dynamics Probed by DIS: II

- $0.2 < x_{Bj} < 0.8$ EMC Effect
- Quark-Gluon structure of nuclear binding at scale ≤ 0.5 fm
- Nucleons modified by strong scalar+vector fields
- Quark-gluon structure modified by short range NN correlations
 - $q\bar{q}$ -bar condensates modified from free nucleon:
Nuclear Mean Field
+ rms fluctuations
(NN... Correlations)

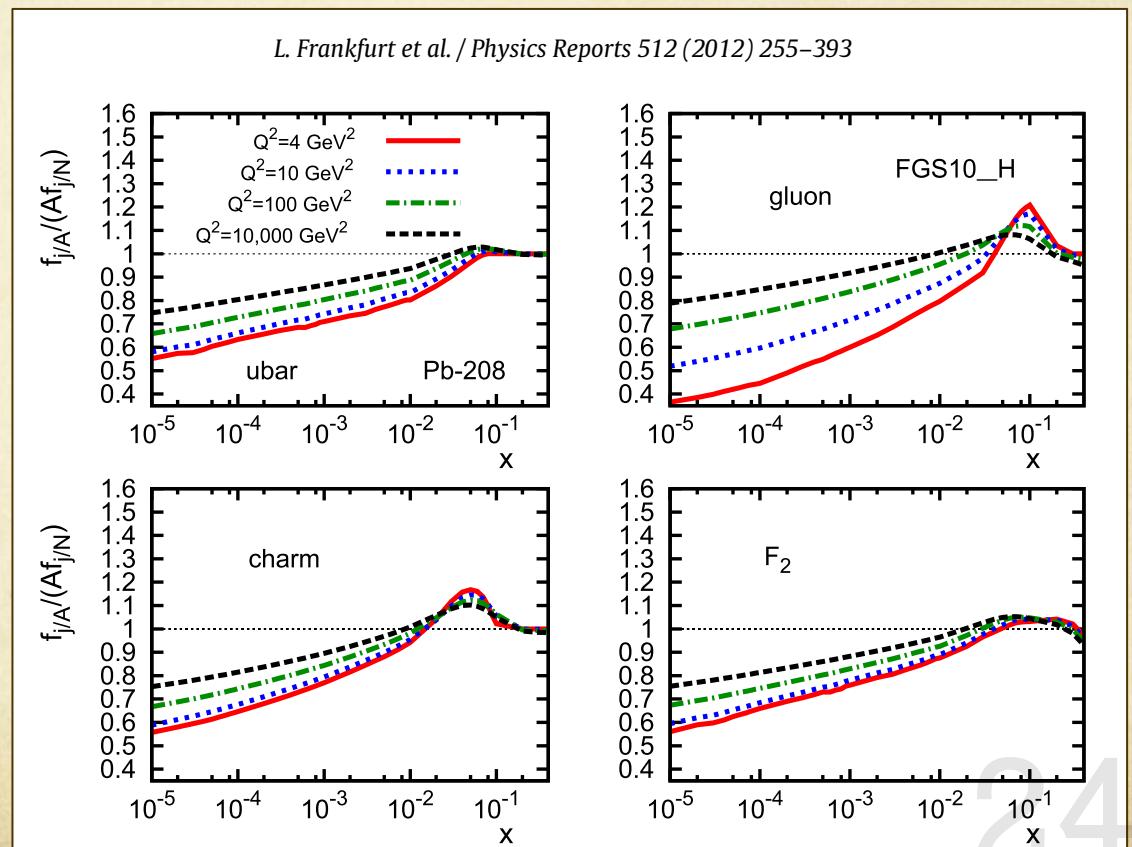


EMC Effect': Anti-Shadowing

- Anti-shadowing is not anti-quarks!
FermiLab Drell-Yan
E722



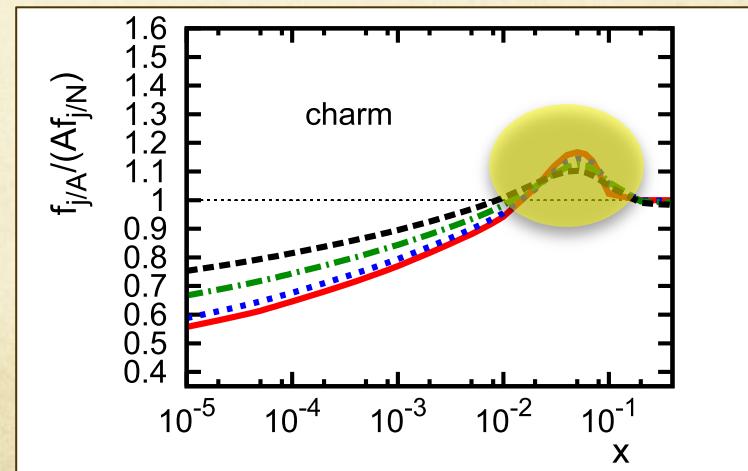
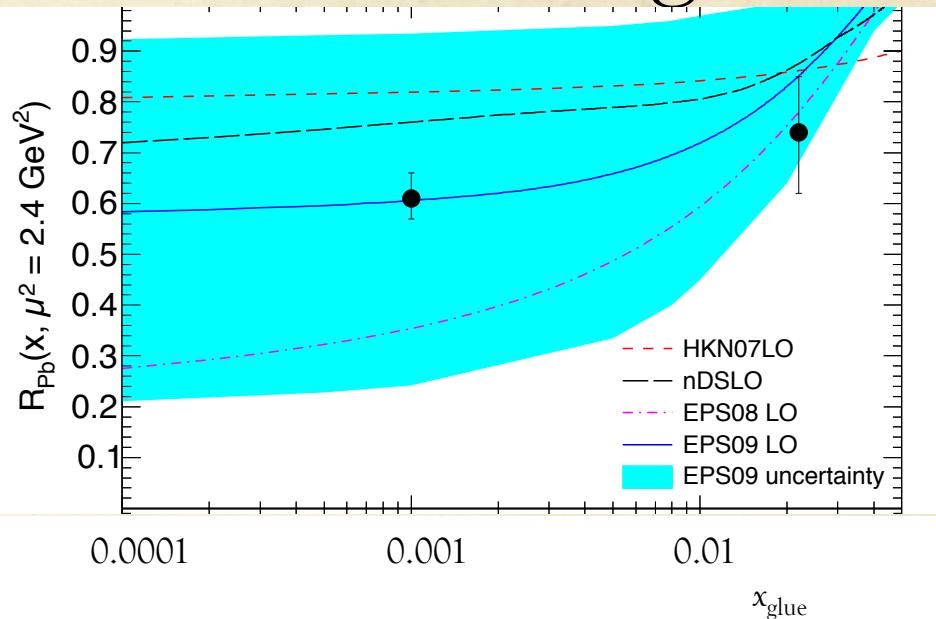
- Anti-shadowing is glue



Gluons & Nuclear Binding

- Shadowing (coherent gluons from NN, NNN ...)
- ALICE PLB718 (213) ultra-peripheral AA → AA J/ Ψ ...CMS 2016
Fig. from Guzey, Zhalov, arXiv.org/ 1404.6101
- $x = 0.001 - 0.01$
- Expectation of gluonic anti-shadowing at $x \approx 0.1$

$$R = \frac{G_A(x)}{AG_N(x)}$$



SPECTATOR TAGGING

- Spectator Tagging:

$$p_R = p_p^{\{+, \perp, -\}} = \left[\frac{\alpha}{2} P_D^+, \mathbf{p}_{R\perp}, \frac{M^2}{\alpha P_D^+} \right] \approx P_D^\mu / 2$$

- Impulse Approximation:

$$p_n^2 = (P_D - p_R)^2 = t = M_n^2 + t'$$

$$-t' > M_D B + B^2 / 2 = 4.1 \cdot 10^{-3} \text{ GeV}^2$$

- In Deuteron rest-frame:

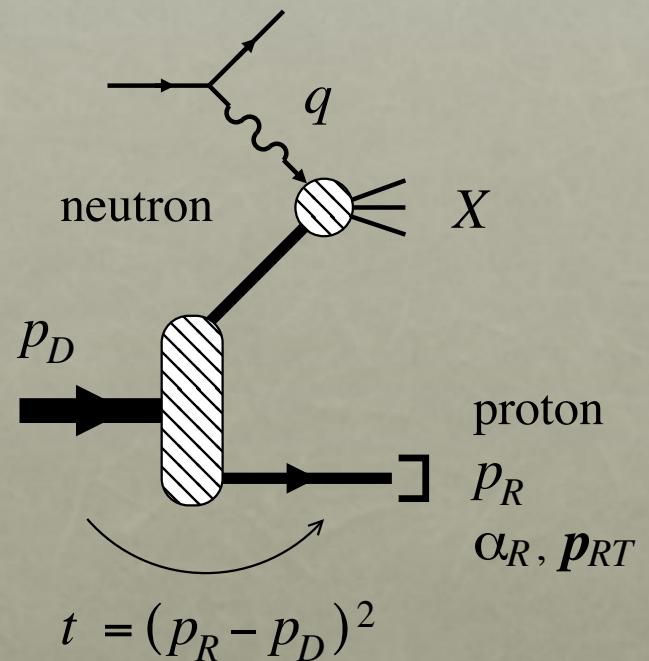
$$\mathbf{p}_p \rightarrow \frac{(\alpha-1)}{2} M_N \hat{z} + \mathbf{p}_\perp$$

for $\alpha \approx 1$ and $|\mathbf{p}_\perp| \ll M_N$

- In Collider Frame:

$$\mathbf{p}_p \approx \frac{1}{2} \mathbf{P}_D + \mathbf{p}_\perp$$

$$\mathbf{p}_p \approx \frac{\alpha}{2} \mathbf{P}_D + \mathbf{p}_\perp$$



$$t = (p_R - p_D)^2$$

ON-SHELL EXTRAPOLATION

- Spectator Tagging in Impulse Approximation:

$$p_n^2 = (P_D - p_R)^2 = t = M_n^2 + t'$$

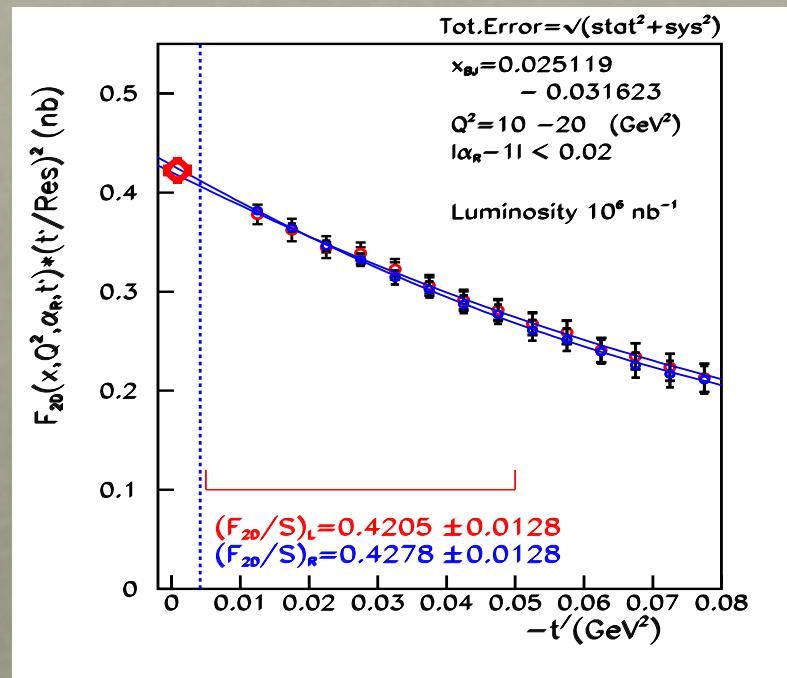
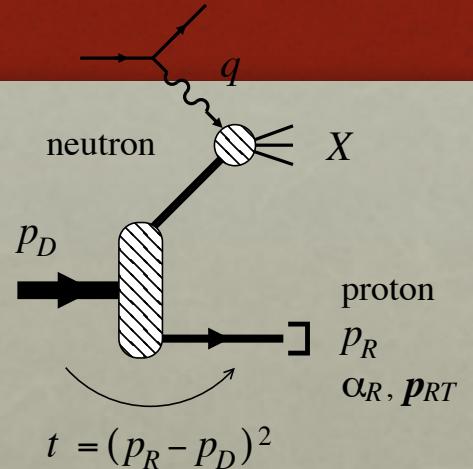
$$-t' > M_D B + B^2/2 = 4.1 \cdot 10^{-3} \text{ GeV}^2$$
- Example on-shell extrapolation

$$k_e \otimes P_D = 5 \otimes 100 \text{ (GeV/c)}^2$$

$$\int \mathcal{L} dt = 1 / \text{fb}$$

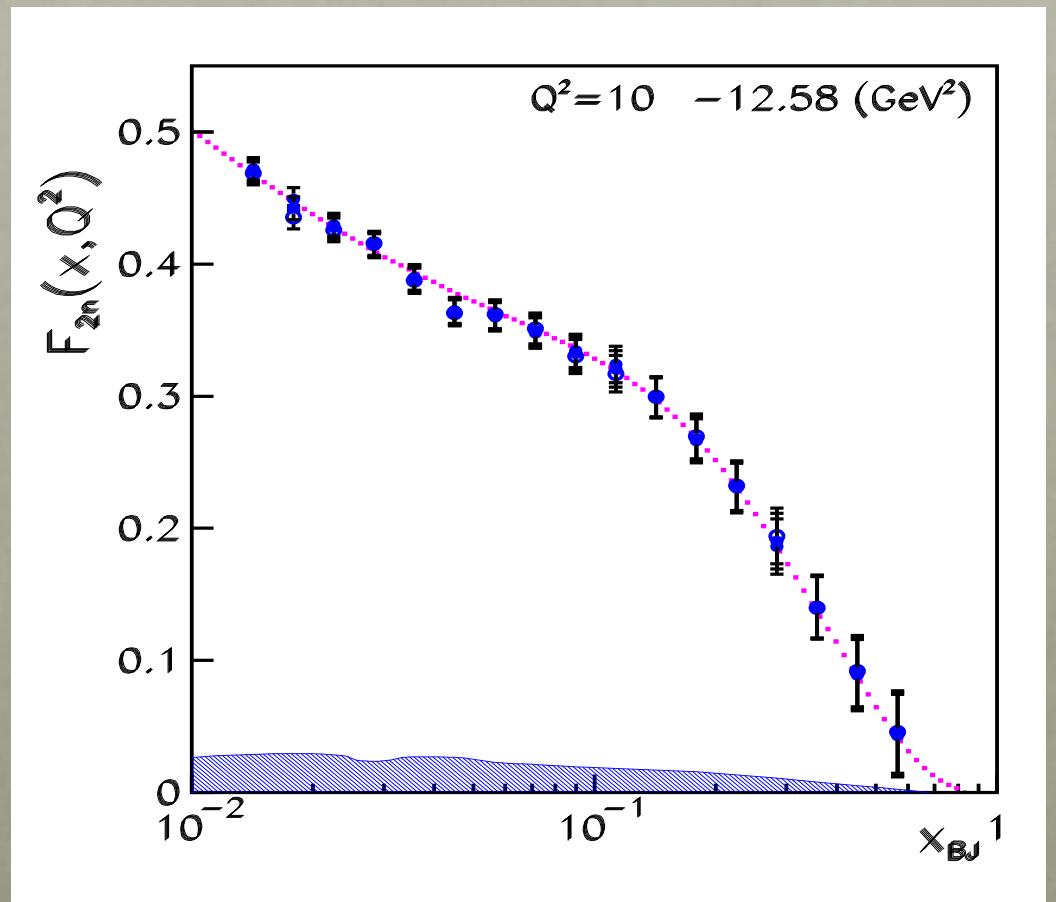
$$x_{\text{Bj}} \in [0.025, 0.032], Q^2 \in [10, 20] \text{ GeV}^2$$

$$0.98 \leq \alpha < 1 \quad 1.0 < \alpha \leq 1.02$$



NEUTRON F_2 FROM ON-SHELL EXTRAPOLATION

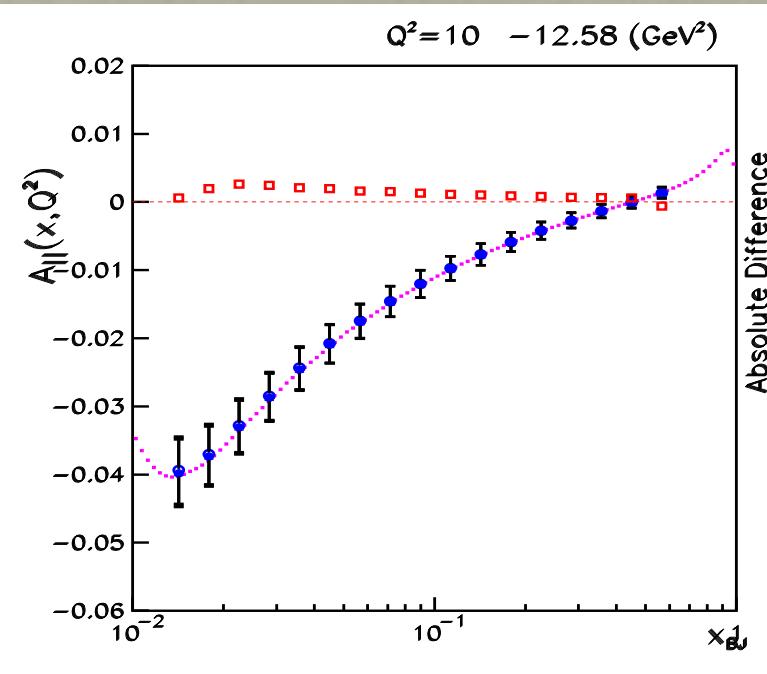
- A sample bin in Q^2
 - Error bars are statistical
 - Error band is systematic error from assumed 10% uncertainty in incident beam emittance
- Radiative effects not yet included.
- QCD Evolution not yet included.



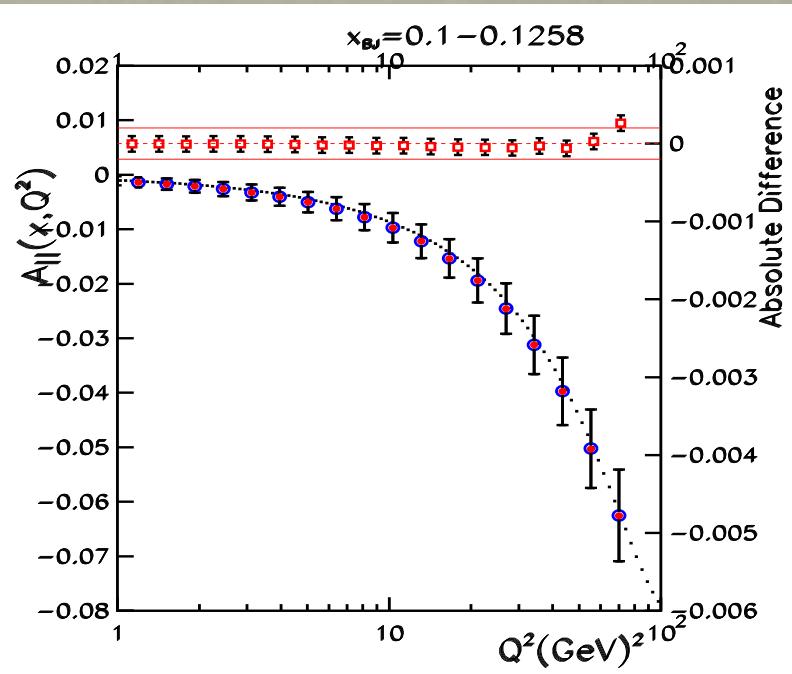
NEUTRON SPIN STRUCTURE

- Longitudinal Double Spin Asymmetry on the Neutron

x -dependence at fixed Q^2



Q^2 -dependence at fixed x



THE EMC EFFECT IN THE DEUTERON

In a given bin in (x_{Bj} , Q^2):

- First extrapolate to the on-shell point for $\alpha \approx 1$
- Compare IA (dashed) with pseudo- data (solid) at ‘large’ negative $\alpha - 1$
 - $\alpha < 1$ minimizes FSI
 - EMC Effect modeled via t' - dependent form factor
- Illustrated Luminosity is 10 / fb

