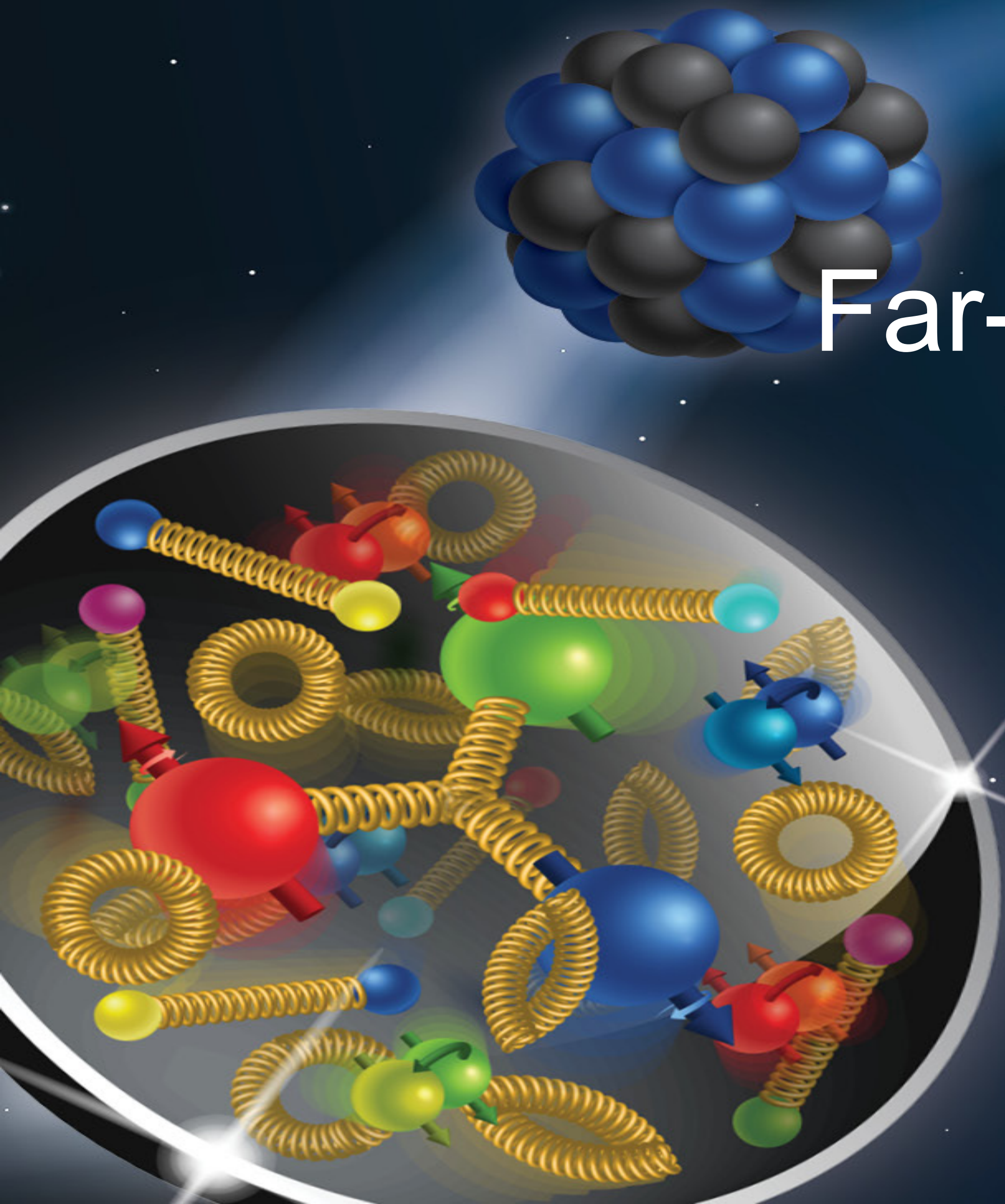

Far-Forward Physics @ the EIC: Lecture 1

Alex Jentsch, *Brookhaven National Lab*

ajentsch@bnl.gov

EIC Summer School

July 11th - 22nd , 2022

Stony Brook University

BROOKHAVEN NATIONAL LABORATORY　Jefferson Lab　U.S. DEPARTMENT OF ENERGY | Office of Science

About me

- PhD from UT Austin in 2019 – studying heavy-flavor in heavy-ion collisions @ STAR.
  - Found heavy-ion a bit difficult w.r.t. disentangling fundamental physics from phenomenology.
- Moved to BNL 3 days after graduation with my spouse and animals to work on the EIC.
  - Became heavily involved in the development of the FF physics program and associated detectors.
  - Also work on p+p spin analysis in STAR.
- Served as a convener for the FF detector development during the Yellow Report, the ATHENA detector proposal, and now for the EIC detector 1 collaboration.

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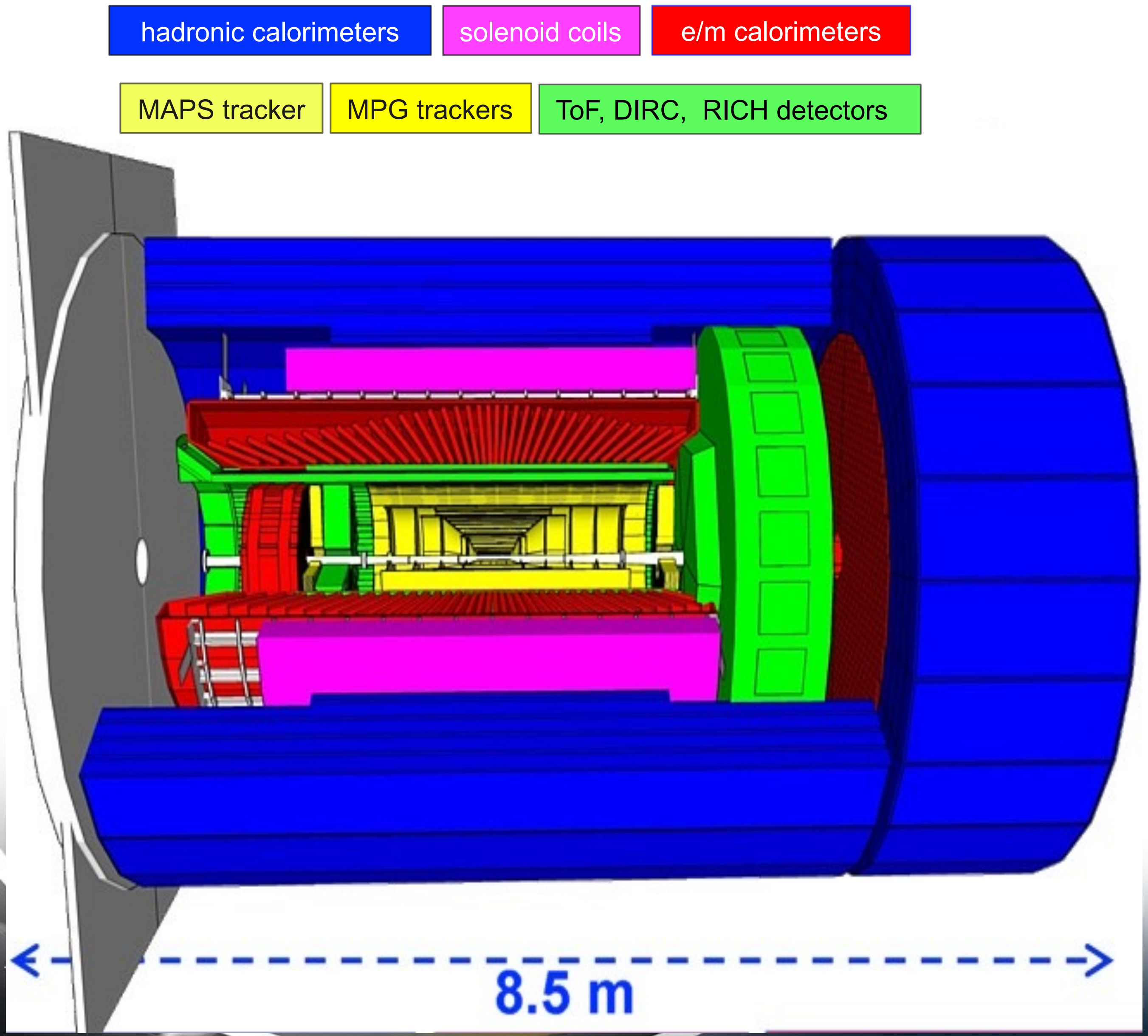
- Trivia: I play in an 80s cover band on Long Island (VHS).

I hate outlines

- Lecture 1 (today)
  - Introduce basic idea of “far-forward” physics, with great damage done to proper terminology.
    - Pardon me, I am an experimentalist ☺
  - Discuss some examples which I find interesting, and for which a direct observable can be described.
  - These are *biased* discussions – I cannot cover everything, so the things I leave out should reflect on the general physics program.
- Lecture 2 (tomorrow)
  - Discuss the “how” for measuring these final-states.
  - Bludgeon you with a few details to provide more than just an overview.

What is meant by Far-Forward?



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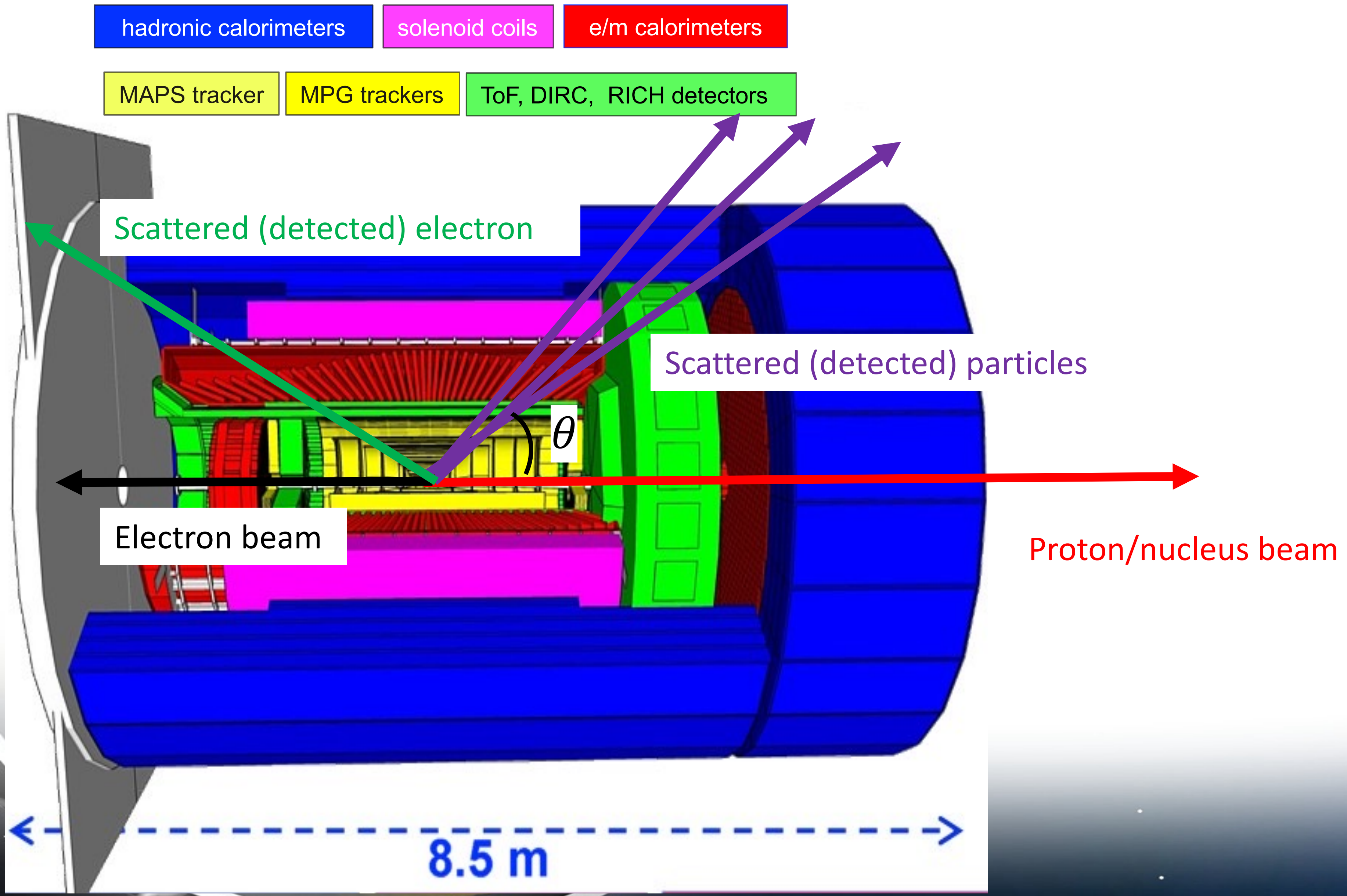

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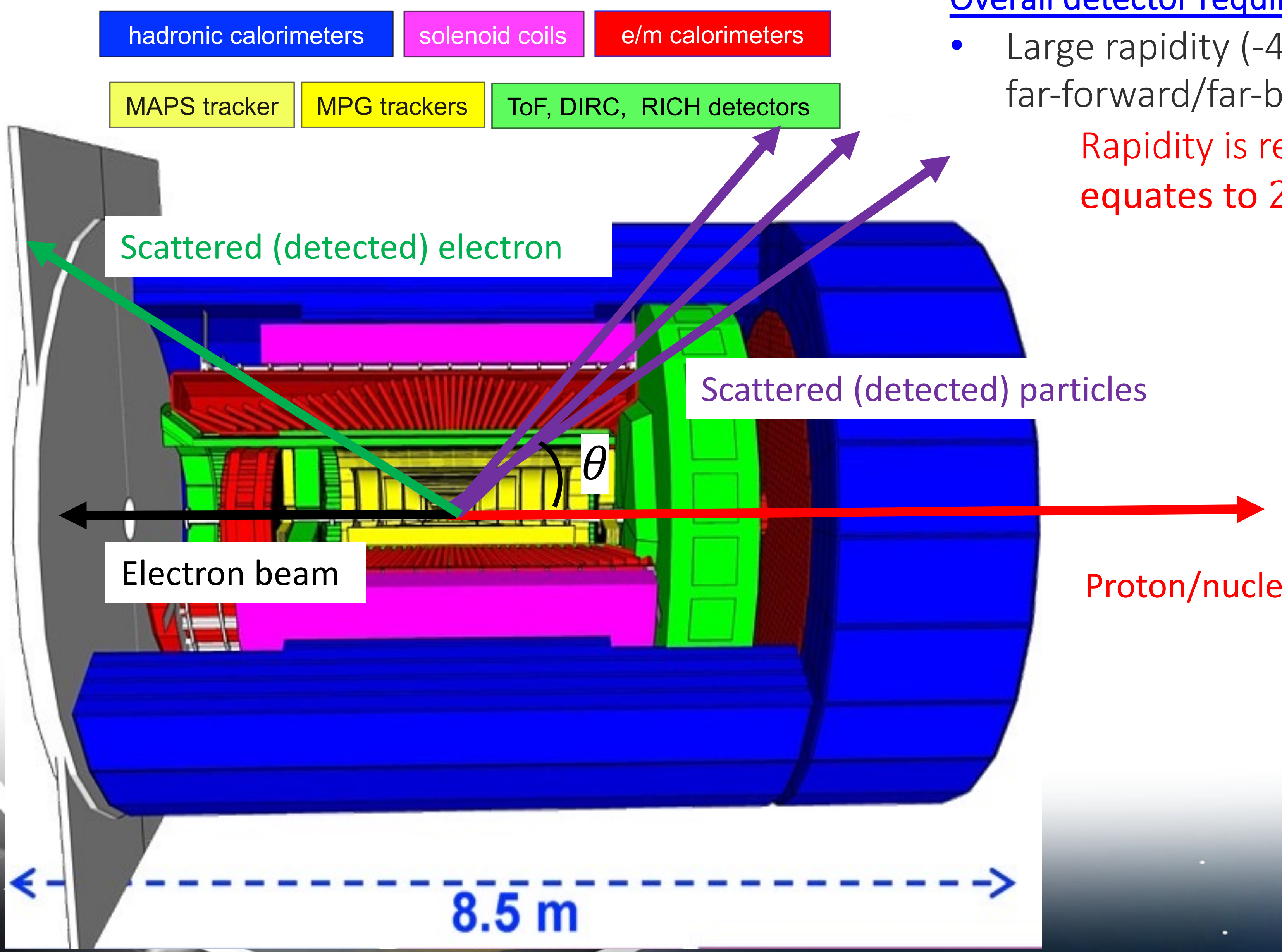


Overall detector requirements:

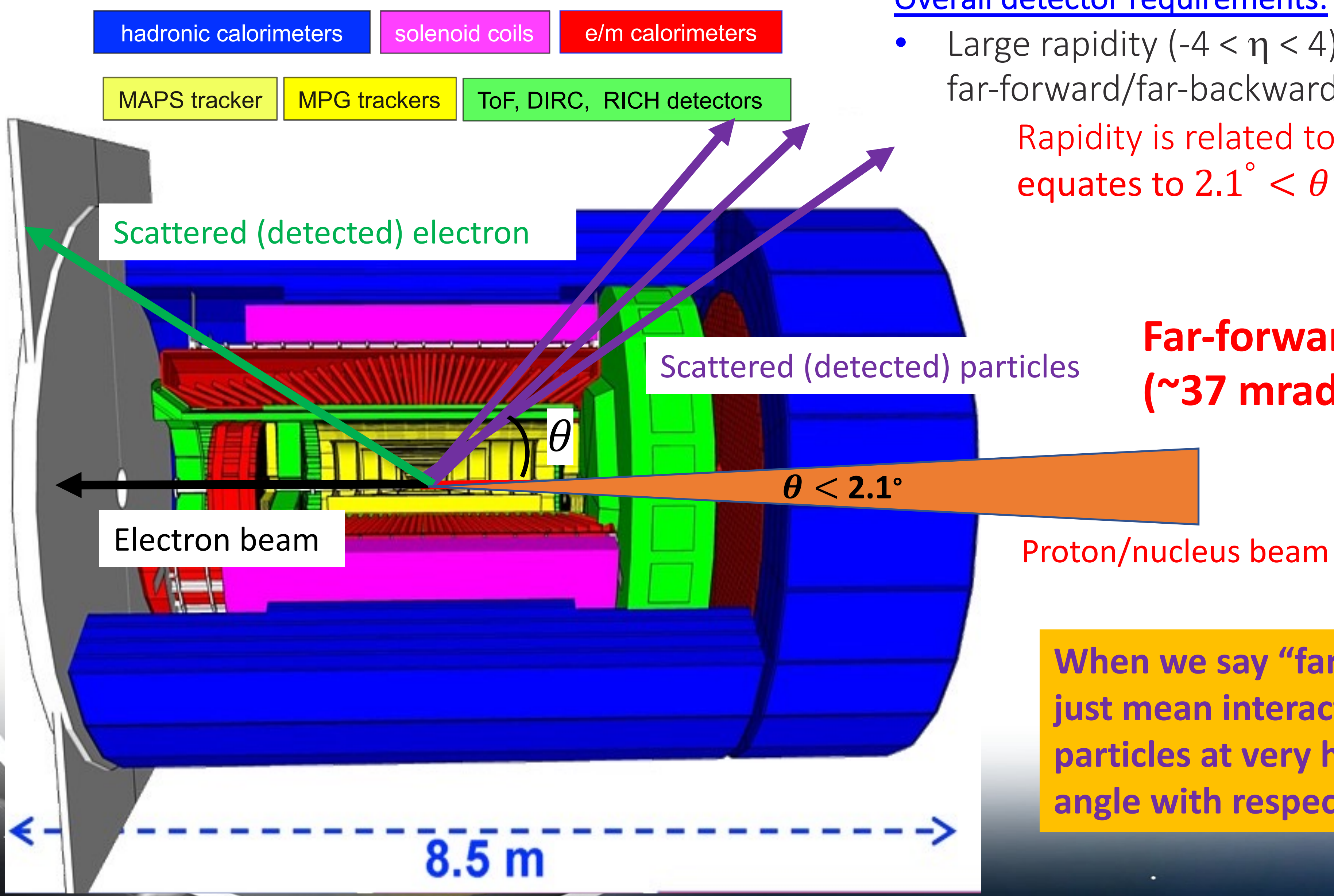
- Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions

Rapidity is related to the polar angle → 0 < η < 4 equates to $2.1^\circ < \theta < 90^\circ$

$$\eta = -ln(tan(\theta/2))$$

pseudorapidity

What is meant by Far-Forward?



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Rapidity is related to the polar angle → 0 < η < 4 equates to $2.1^{\circ} < \theta < 90^{\circ}$

$\eta = -ln(tan(\theta/2))$

pseudorapidity

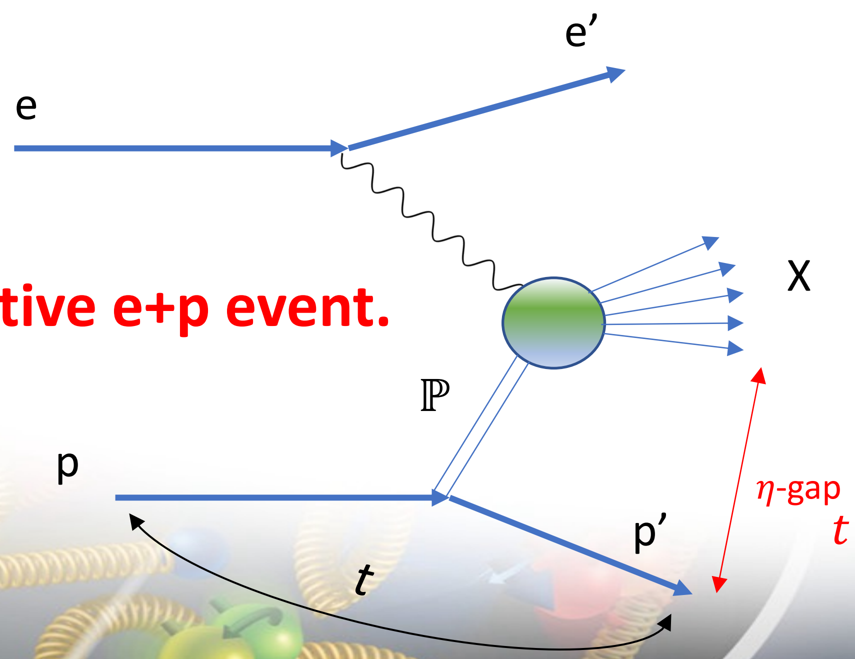
Far-forward here means $\theta < 2.1°$ (~37 mrad)

When we say "far-forward" physics, we really just mean interactions with some final state particles at very high pseudorapidity (or small angle with respect to the beam).

Diffractive + Exclusive Final States

- Diffractive events characterized by an "η-gap" between jet and scattered proton → proton scattered at high pseudorapidity!

Diffractive e+p event.



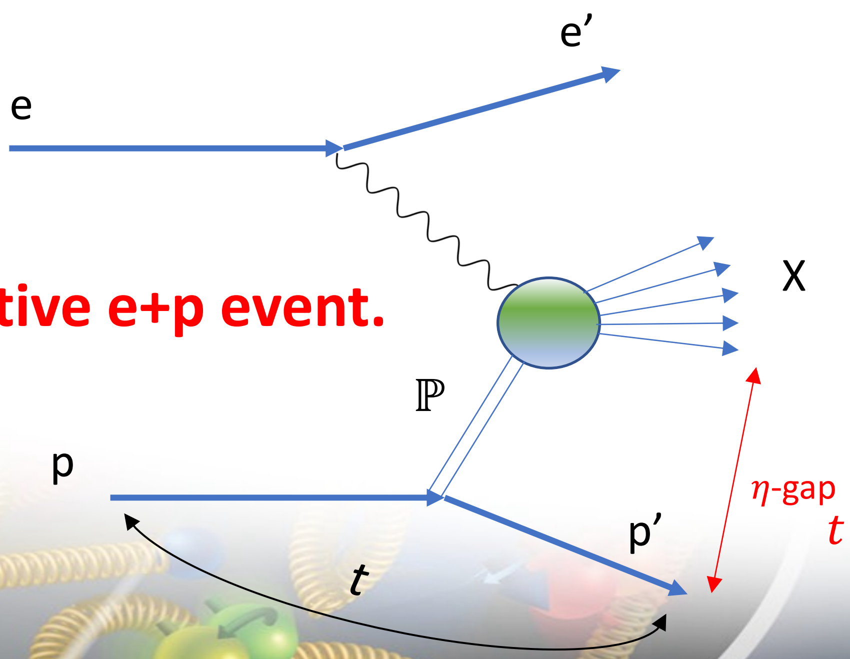
$t = -(p - p')^2 \approx -p_{t,p'}^2$

Mandelstam t

Diffractive + Exclusive Final States

- Diffractive events characterized by an "η-gap" between jet and scattered proton → proton scattered at high pseudorapidity!
- Can be described by color-singlet "pomeron" exchange in Regge theory.
  - Accounts for ~15% of the total e + p cross section at HERA and non-perturbative!
  - HERA: the rest-frame proton was seeing a *50 TeV* electron – and 15% of the time the proton didn't break up!

Diffractive e+p event.

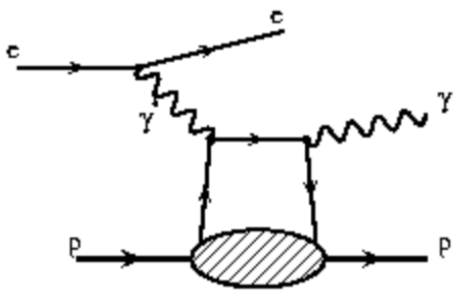


$t = -(p - p')^2 \approx -p_{t,p'}^2$

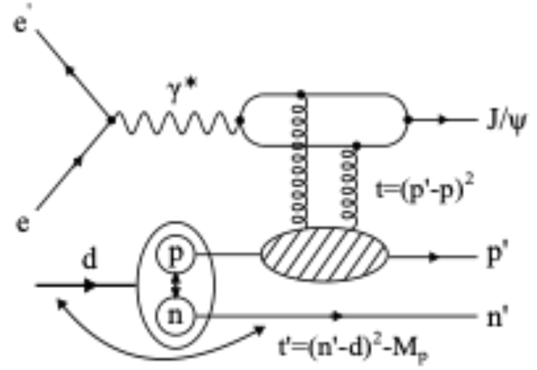
Mandelstam t

Far-Forward Processes at the EIC

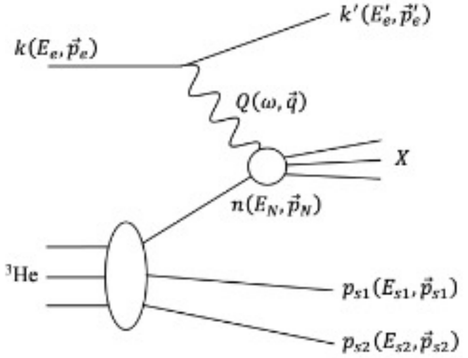
e+p DVCS



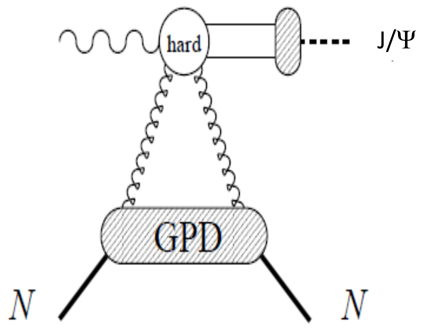
e+d exclusive J/Psi with p/n tagging



e+He3 spectator tagging

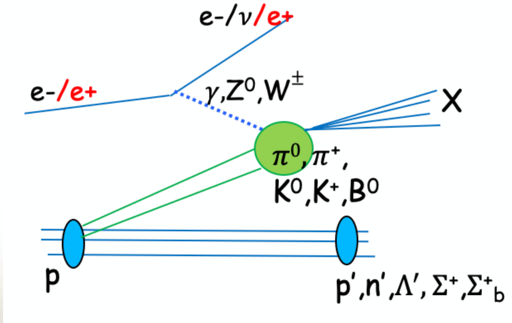


coherent/incoherent J/ψ production in e+A

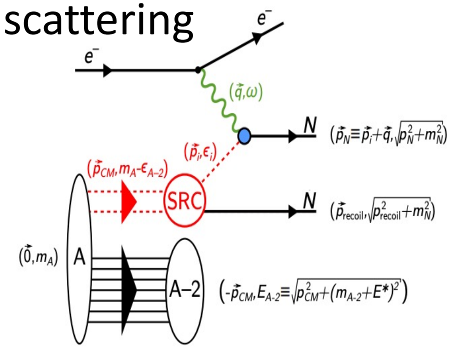


Meson structure:

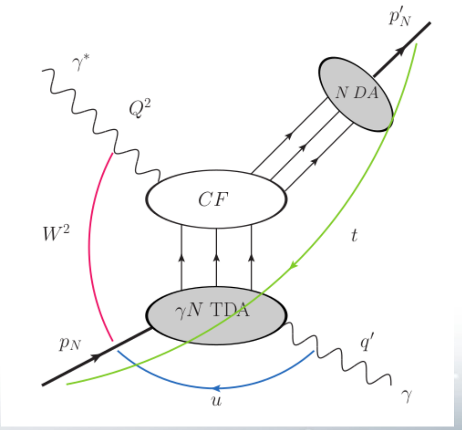
- ep→ (π) →e' n X
- Λ →pπ^- and $\Lambda \rightarrow n\pi^0$



Quasi-elastic electron scattering



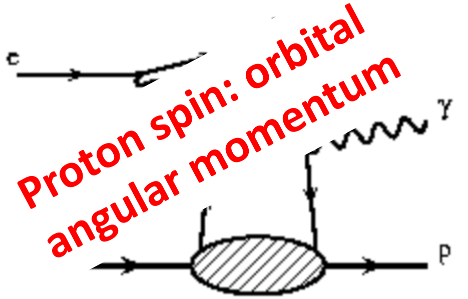
u-channel backward exclusive electroproduction



…and MANY more!

Far-Forward **Physics** at the EIC

e+p DVCS



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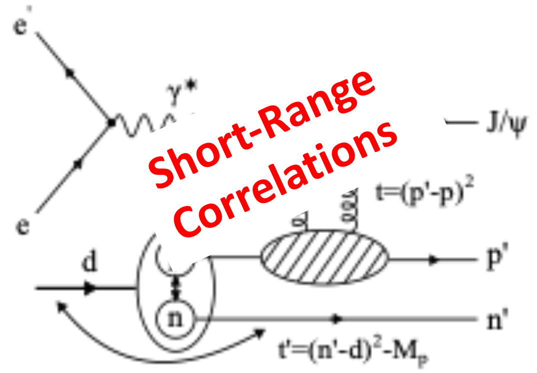

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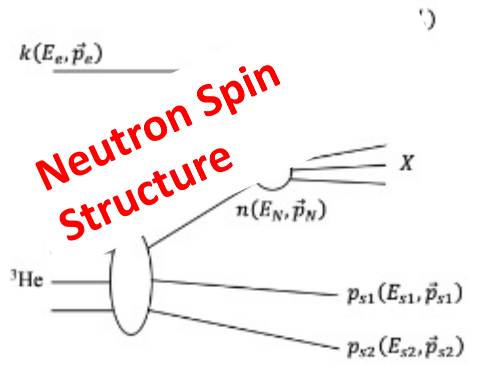

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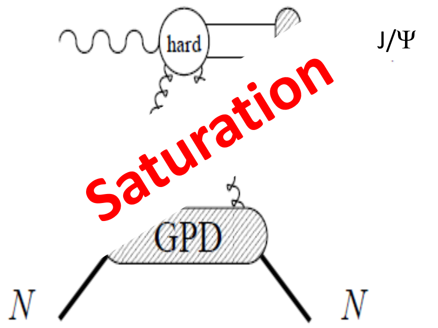
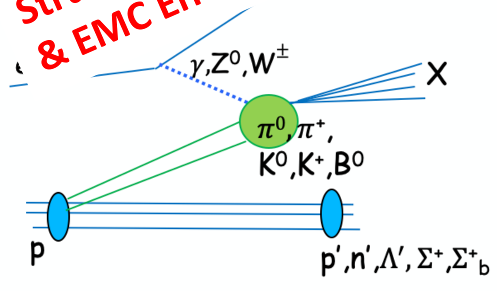


Meson structu...

- ep→ ...
- ... $n\pi^0$



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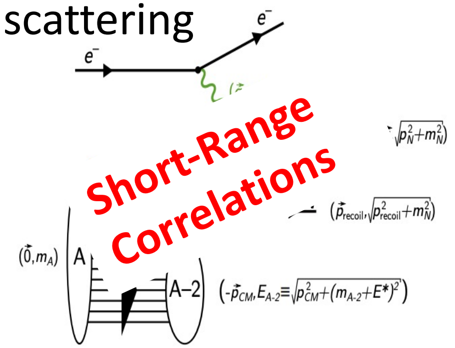

[1] Z. Tu, A. Jentsch, et al., Physics Letters B, (2020)
[2] I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)
[3] W. Chang, E.C. Aschenauer, M. D. Baker, A. Jentsch, J.H. Lee, Z. Tu, Z. Yin, and L.Zheng, Phys. Rev. D **104**, 114030 (2021)
[4] A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

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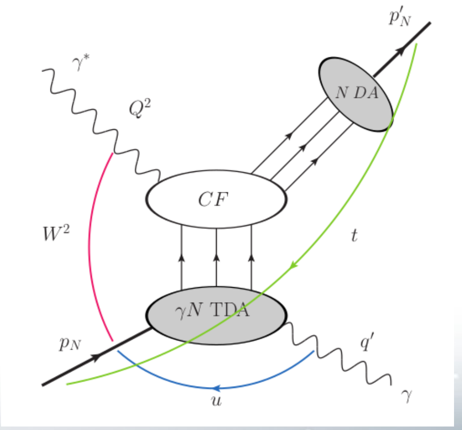
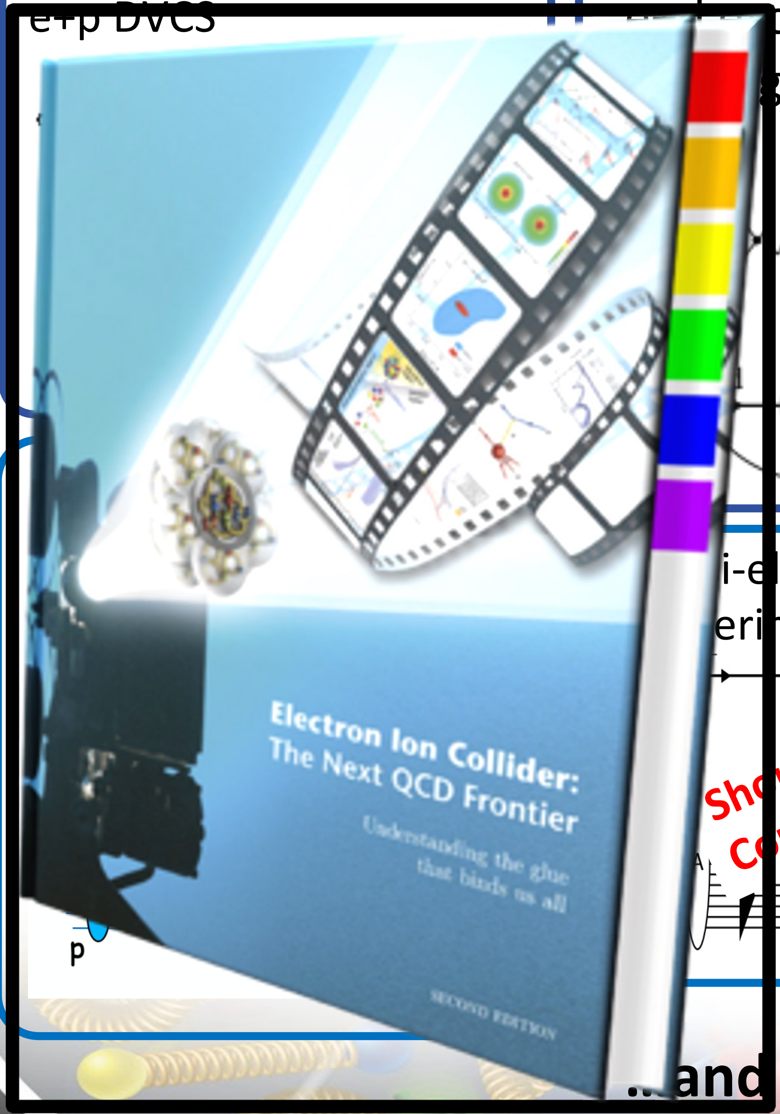
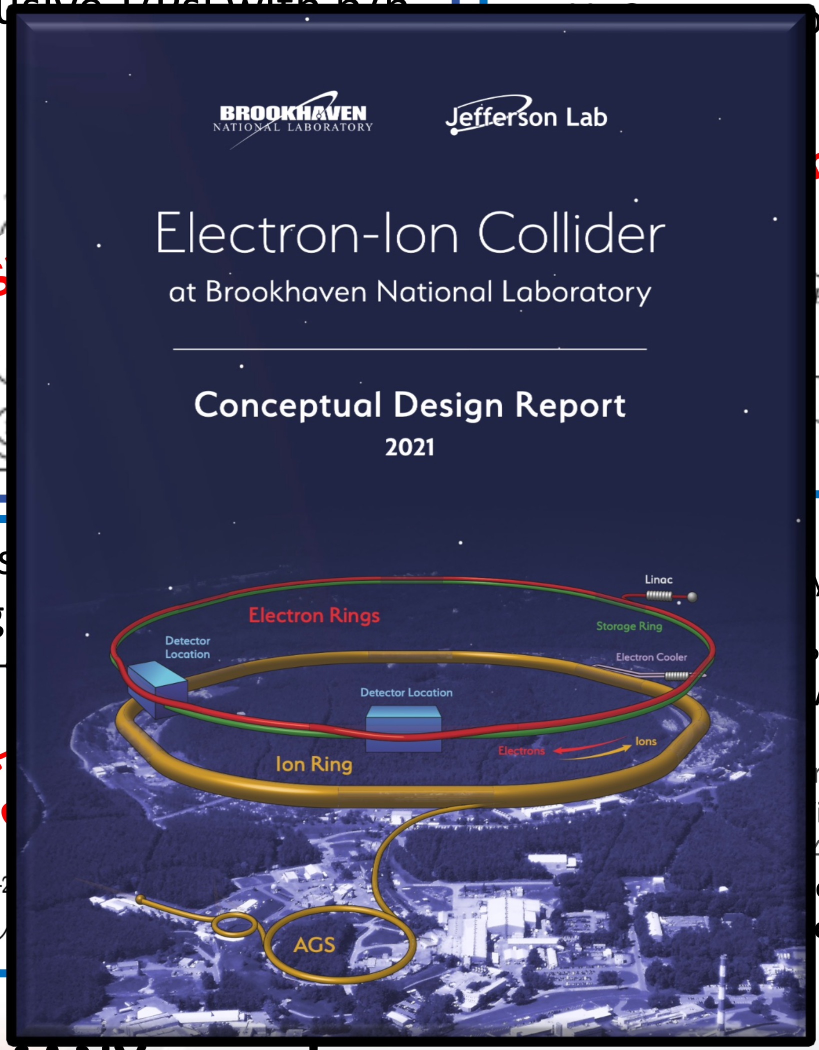
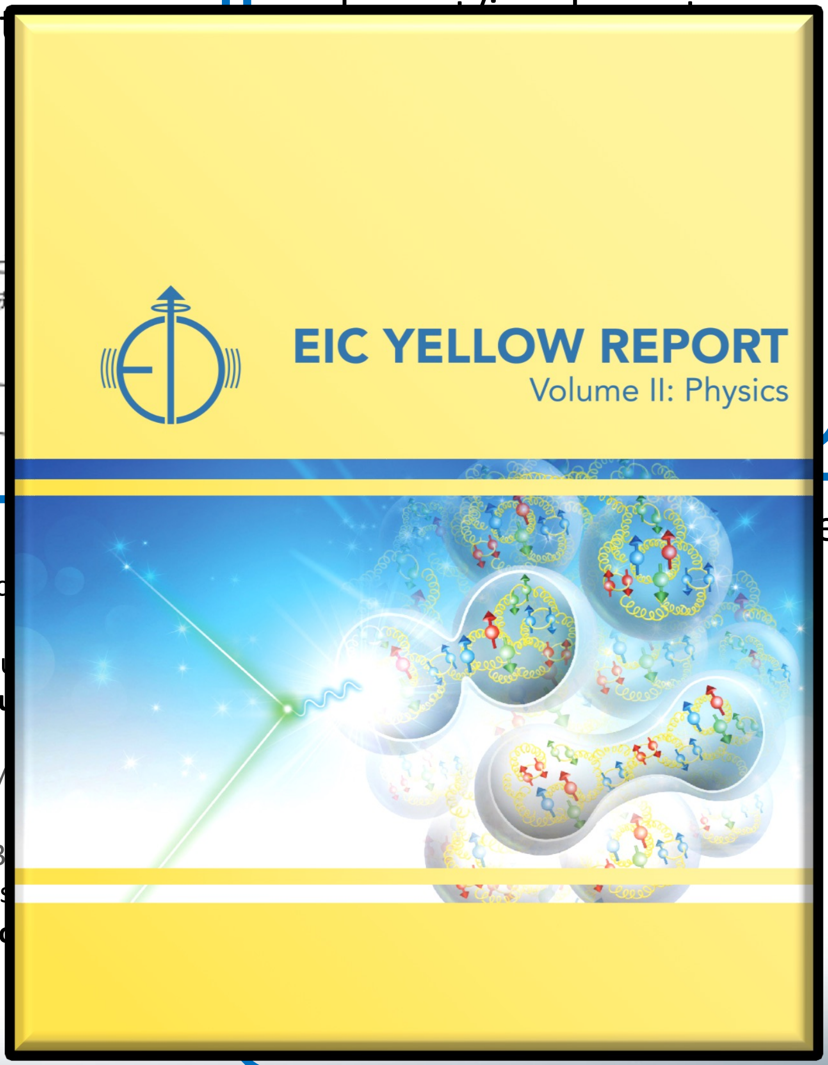


...and MANY more!

Far-Forward Physics at the EIC







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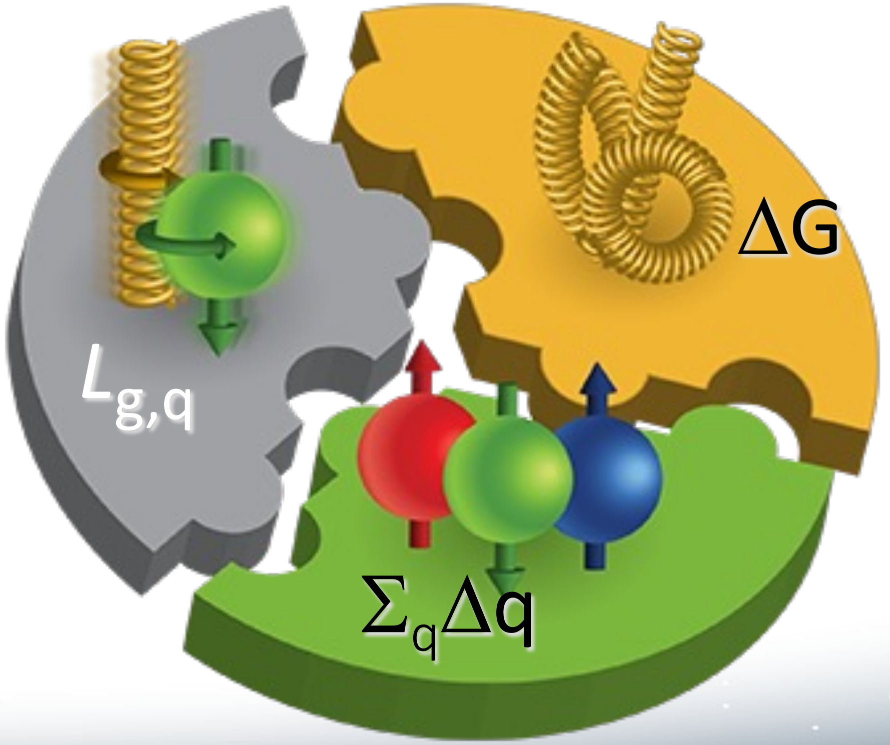
Overall EIC physics goals (non-exhaustive)

- The overall physics goals of the EIC are to study nuclear structure from high to low-x and low to high-Q^2.
  - Spin structure – the three "valence" quarks do not account for the total spin of the proton!

Proton spin: $\frac{1}{2} = \frac{1}{2}\Sigma_q \Delta q + \Delta G + L_{g,q}$



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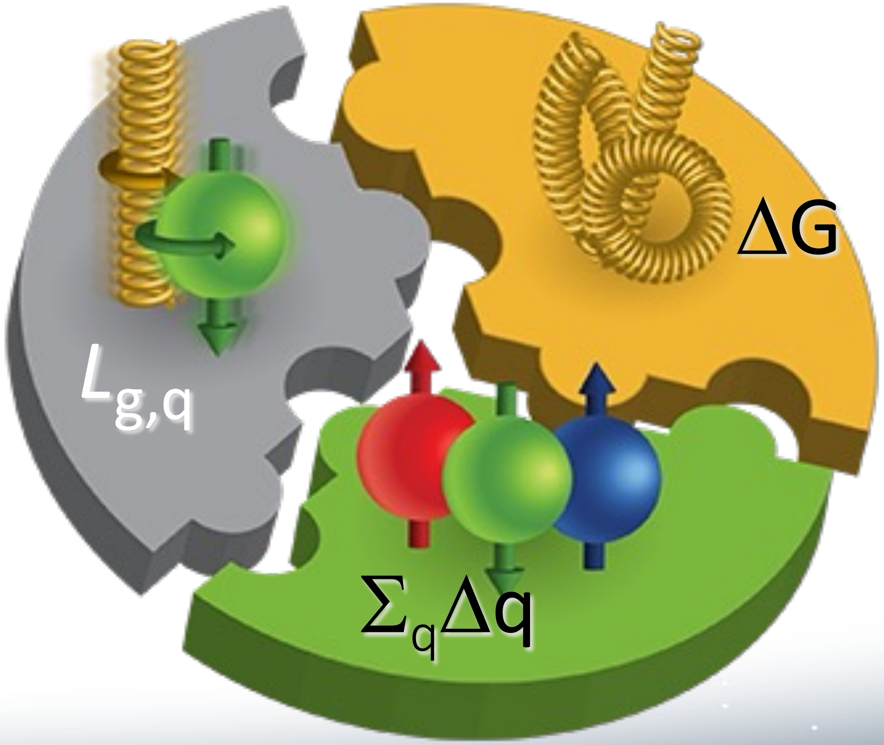
~20-30% from polarized DIS experiments.

RHIC jet asymmetry measurements constrain ΔG down to $x \sim 0.015$.

Not at all constrained! – need an EIC!!



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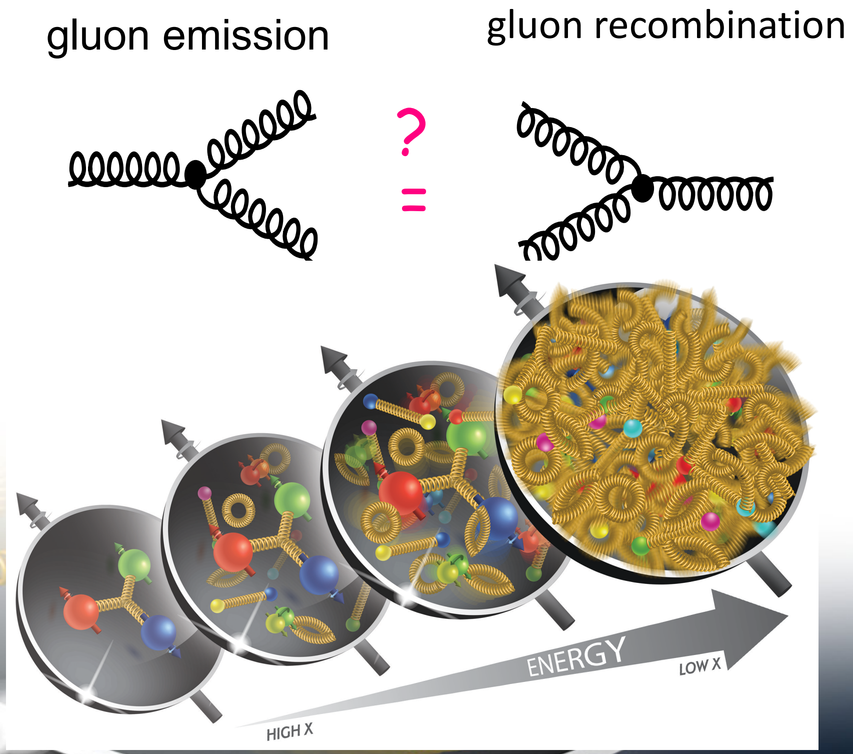

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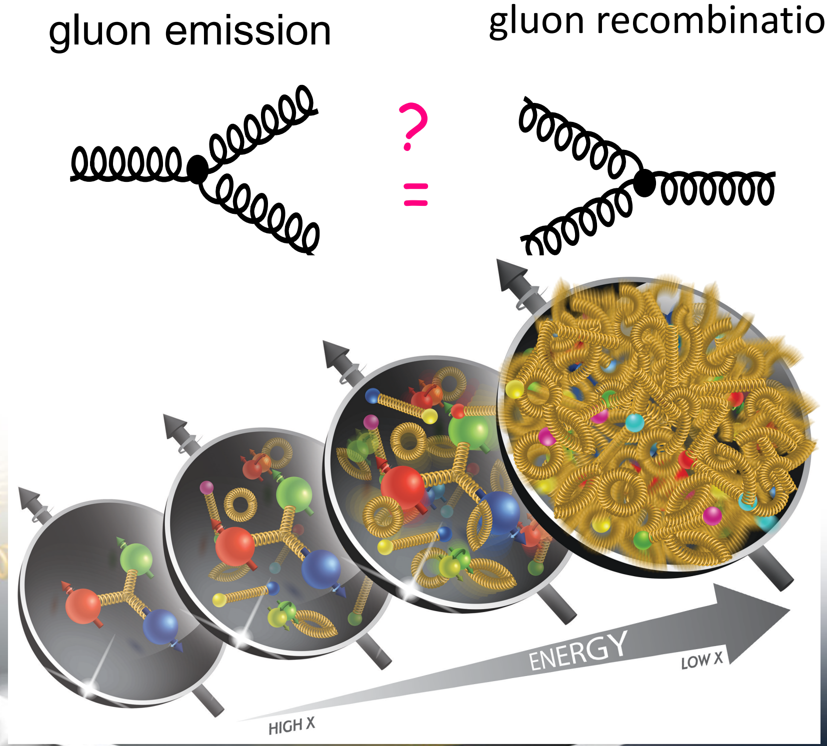

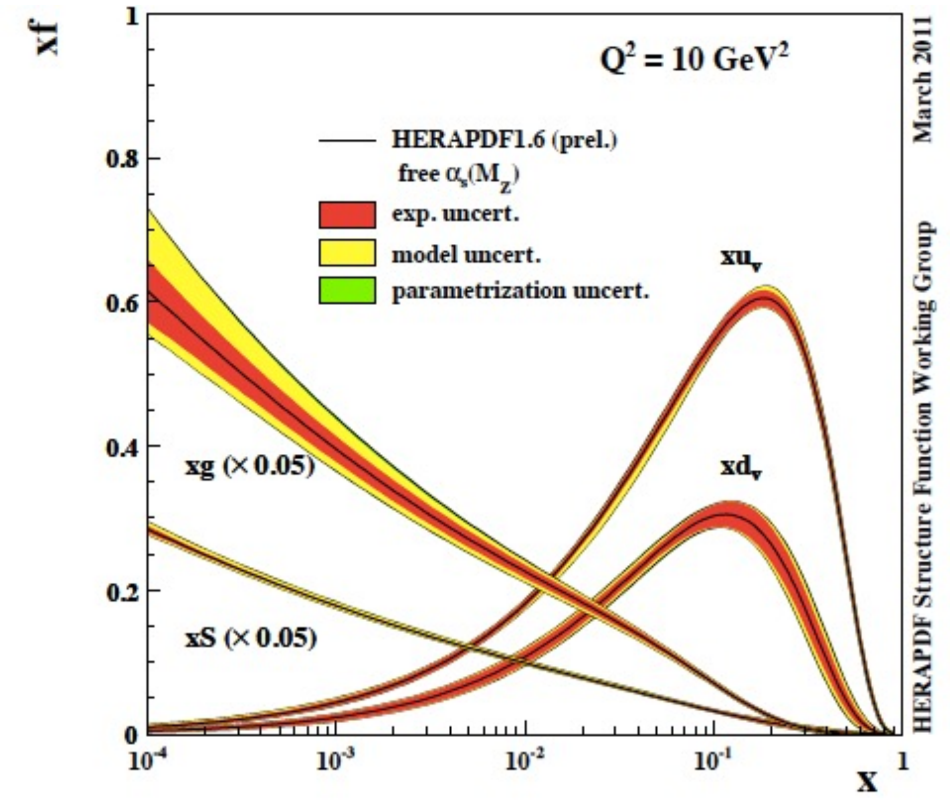

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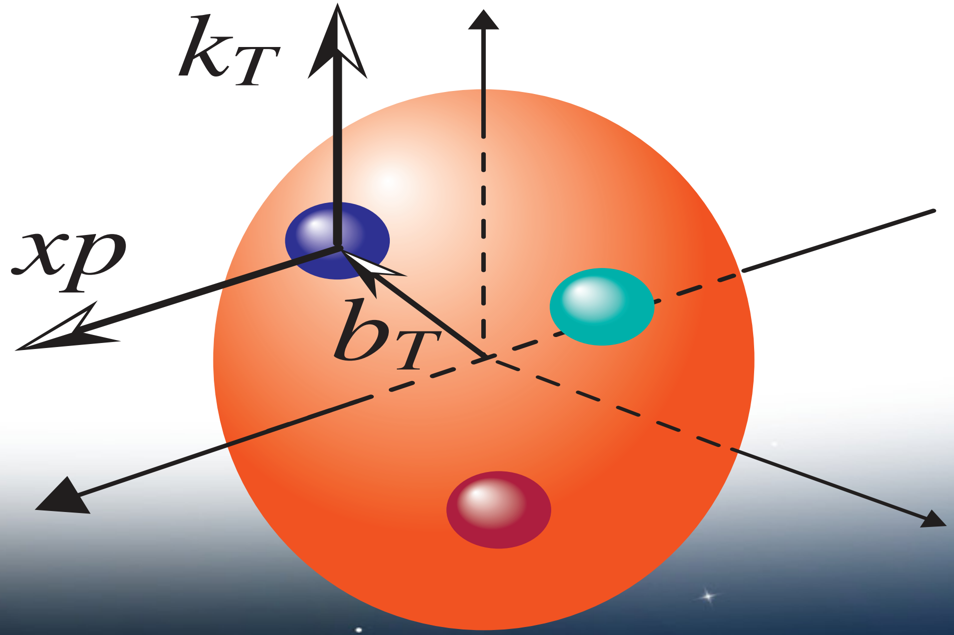
  - Saturation – eventually the growing gluon density at very low-x and high-Q^2 will lead to gluons recombining.
  - Structure of partons in coordinate and momentum space – how are partons distributed inside nucleons?
  - …and there is more!



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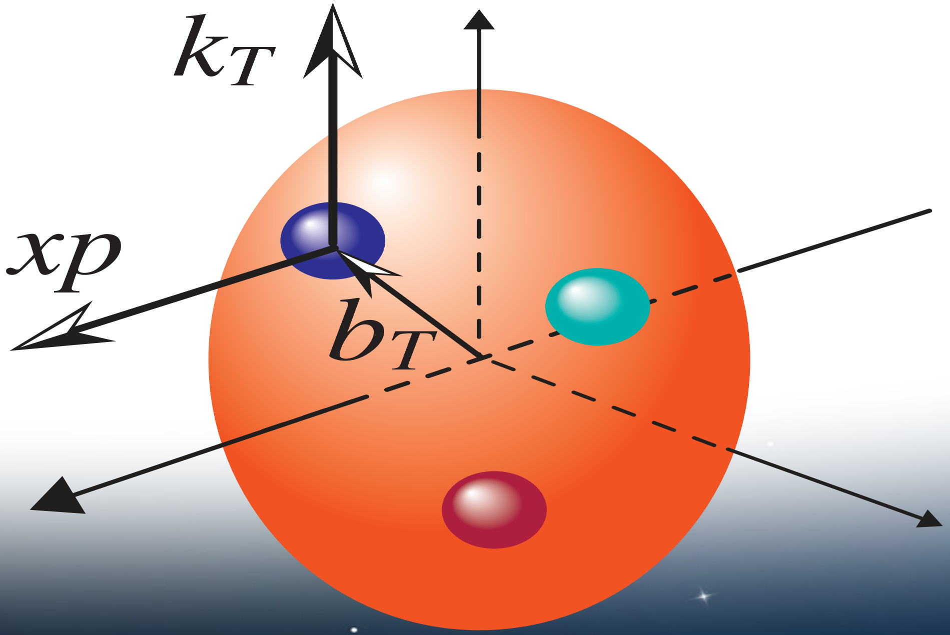
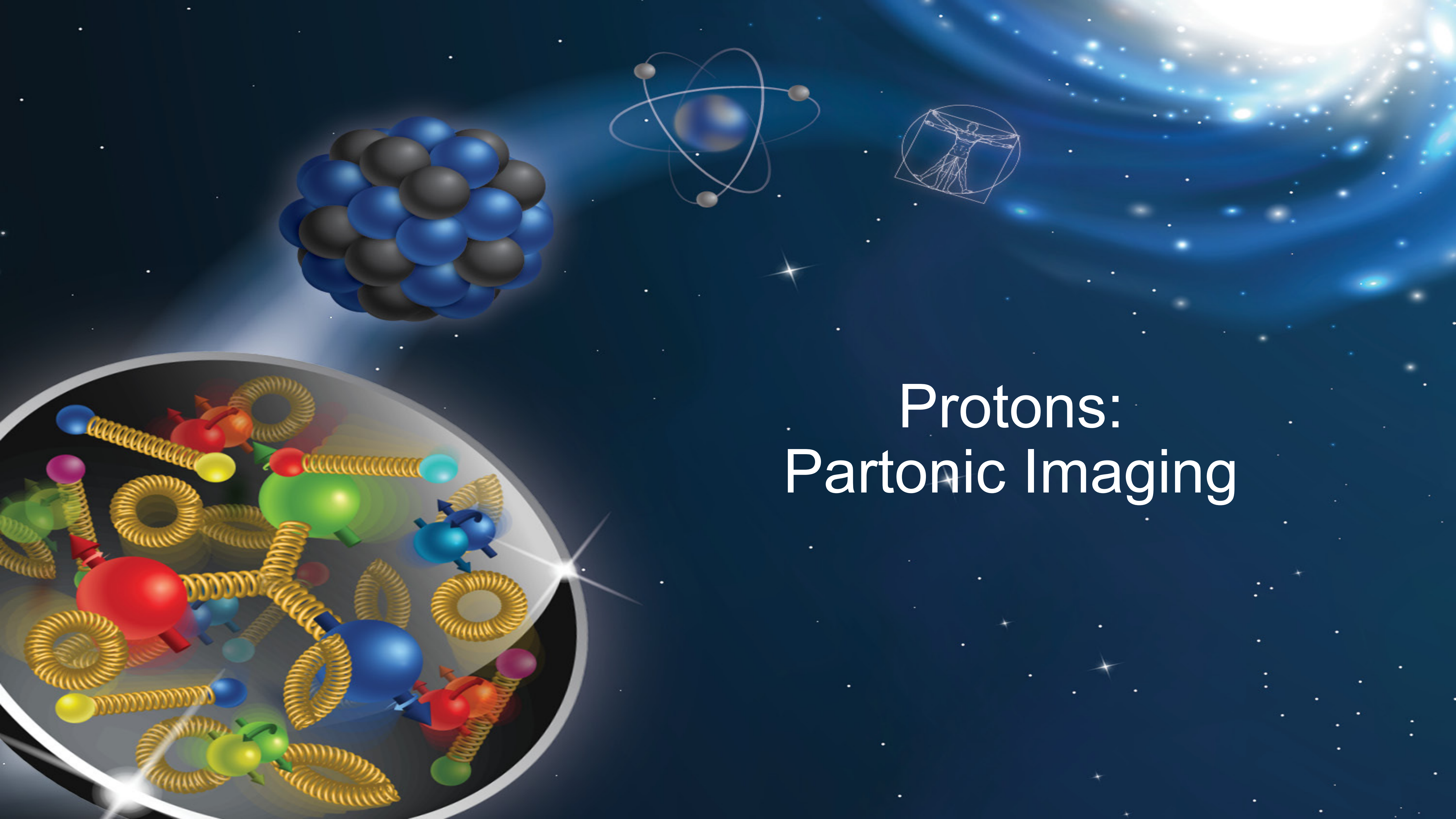
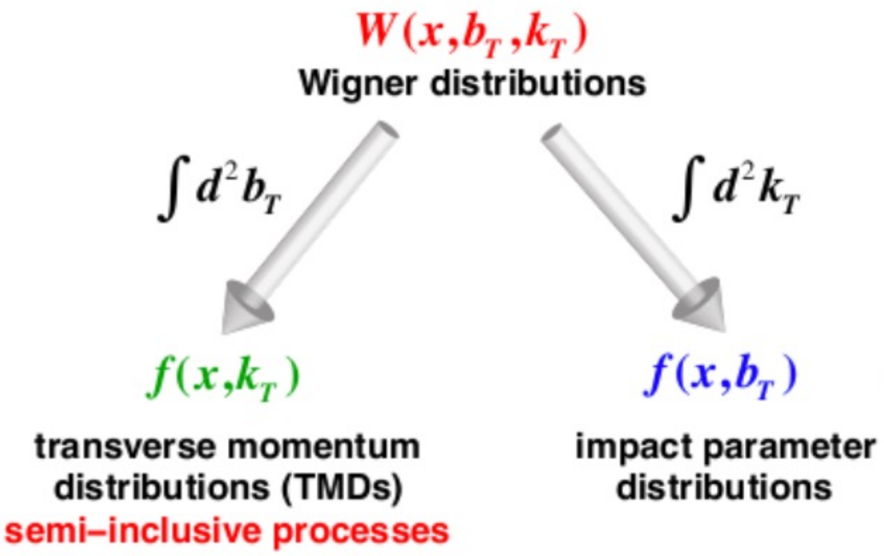
Each of these topics can be studied, in part, using final-states which produce far-forward particles.





Protons:
Partonic Imaging

Partonic Imaging of Nucleons



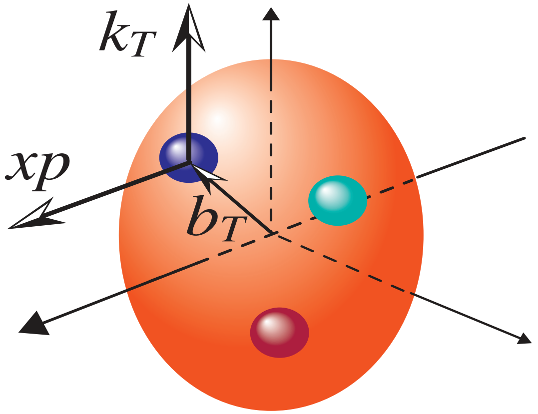
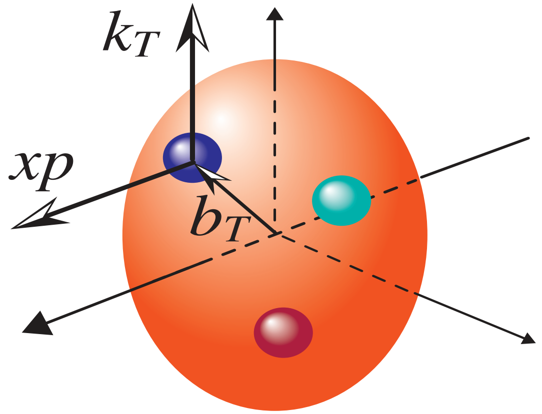
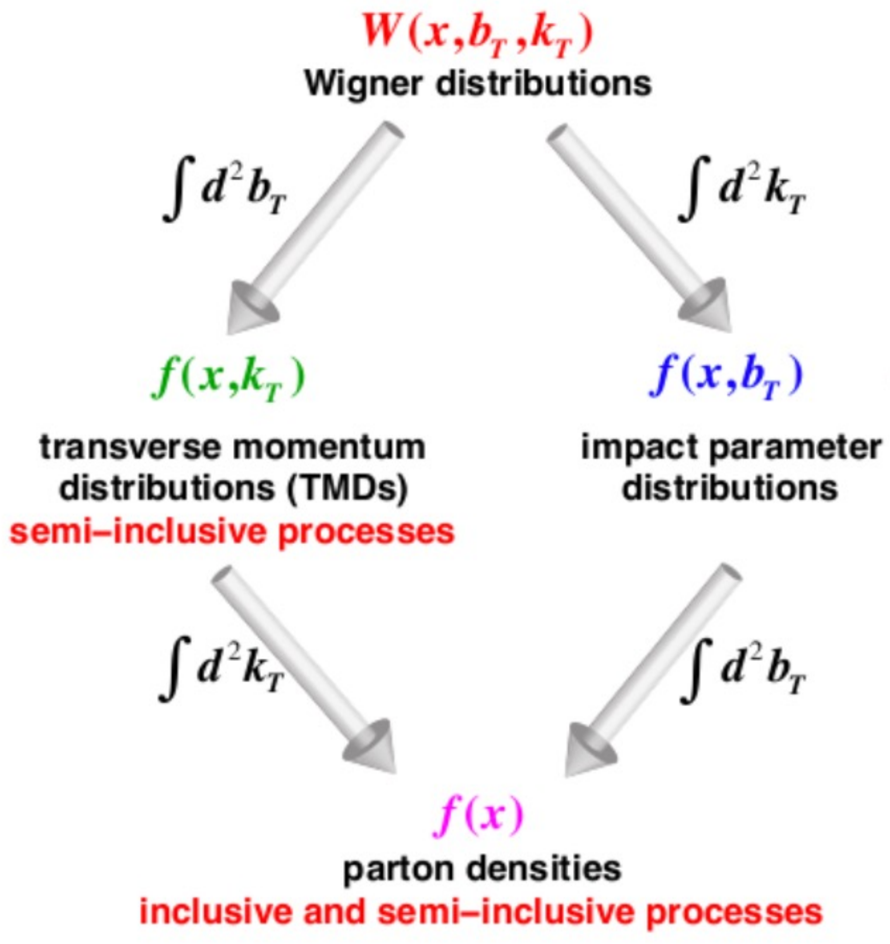


Fig. 2.2 from the EIC White Paper

Partonic Imaging of Nucleons





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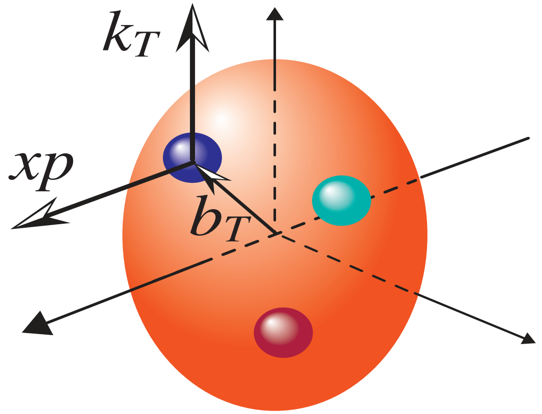

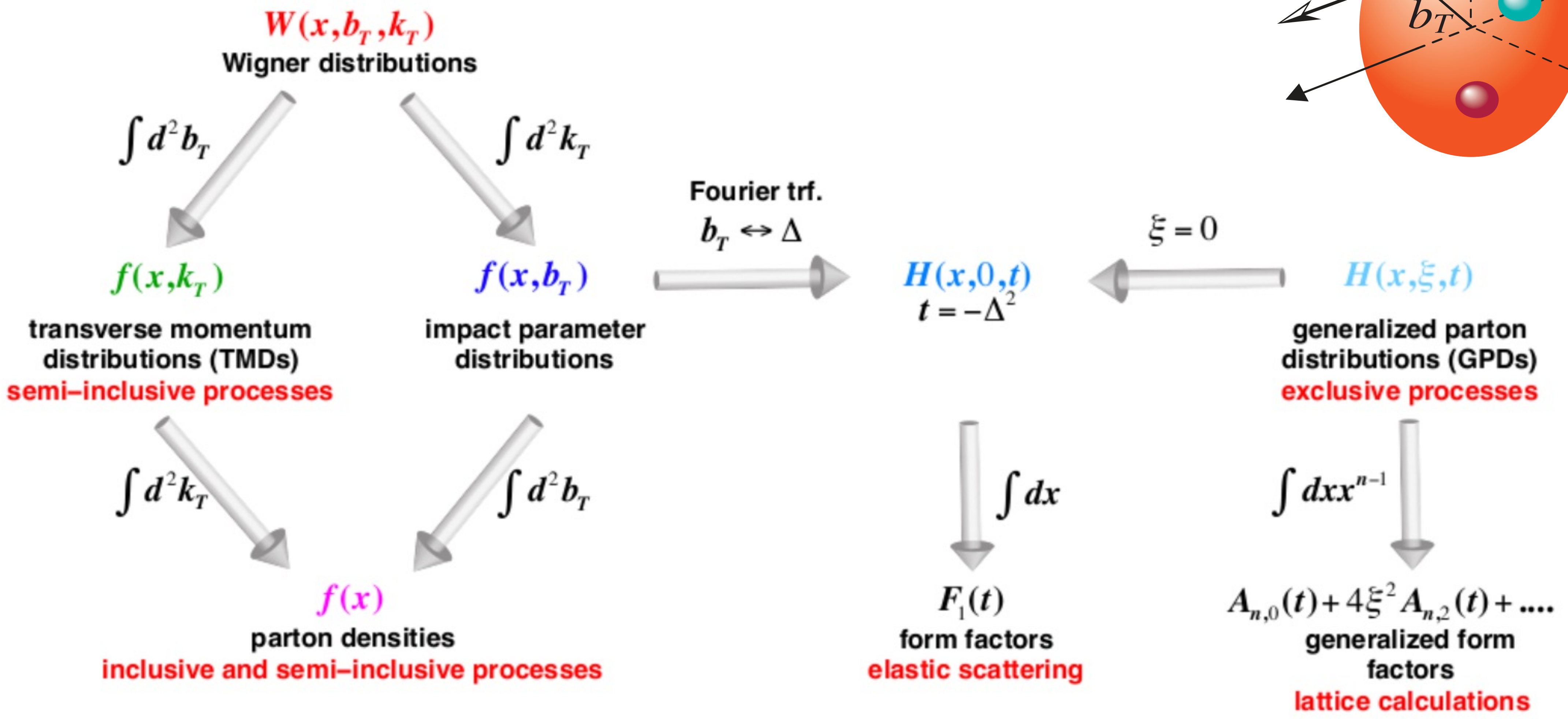

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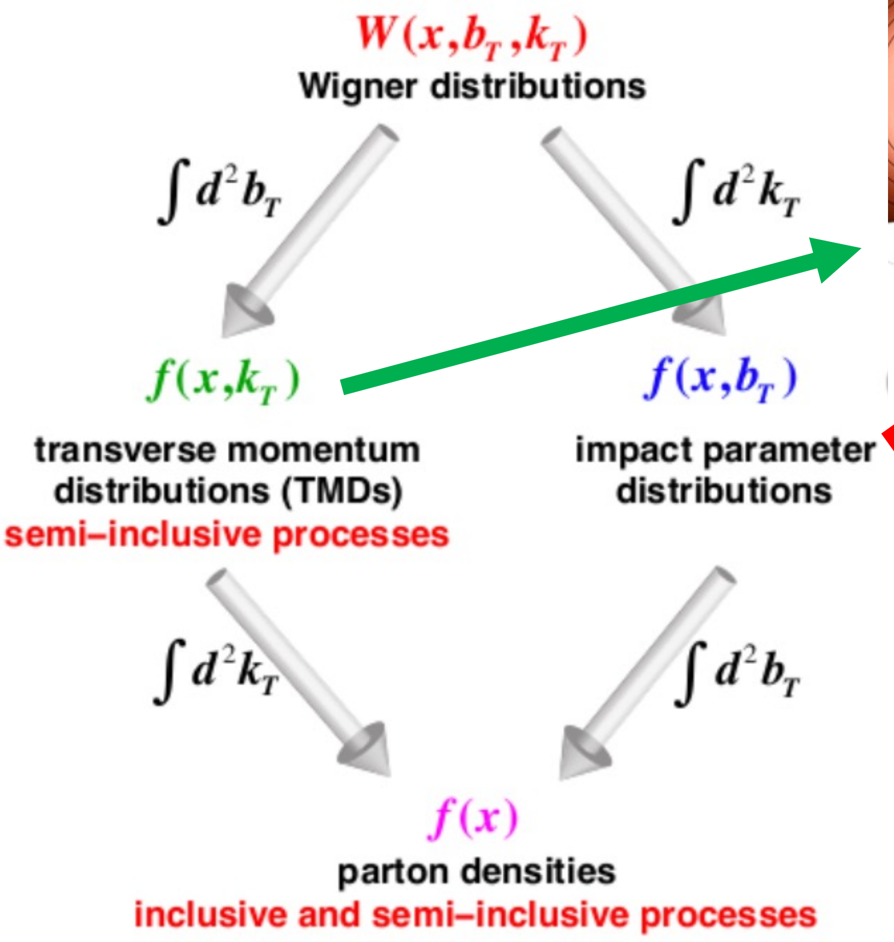

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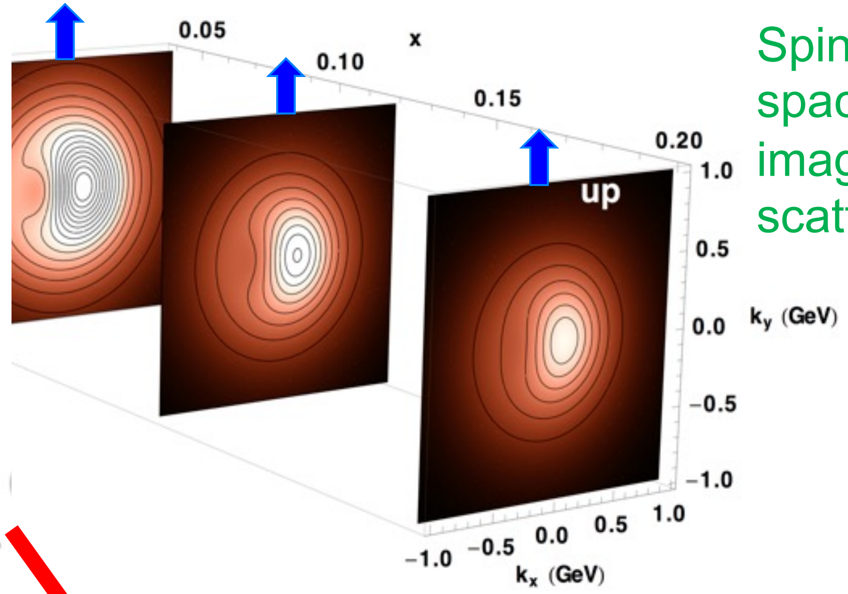
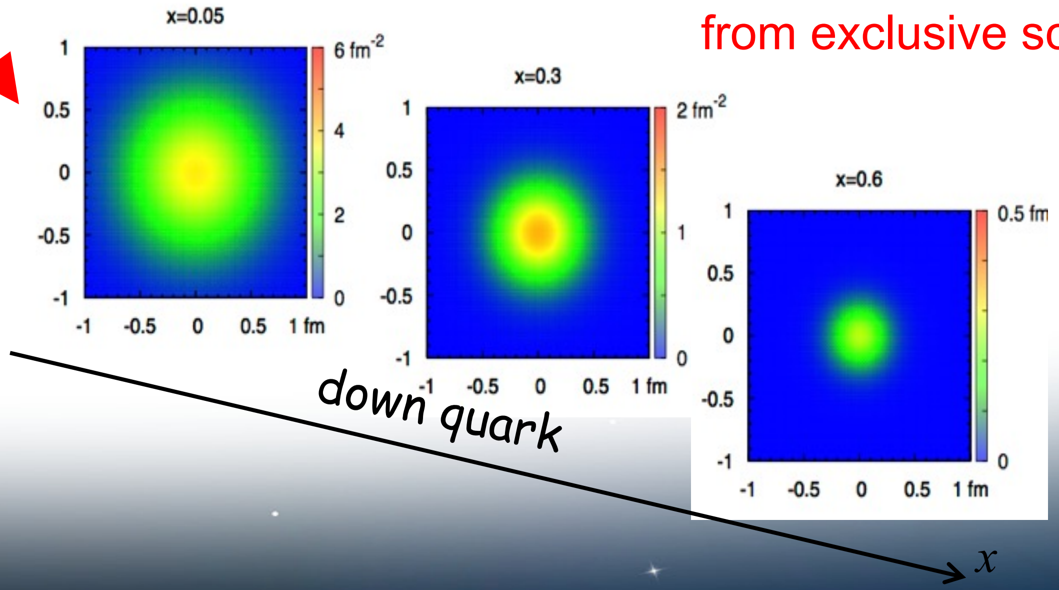
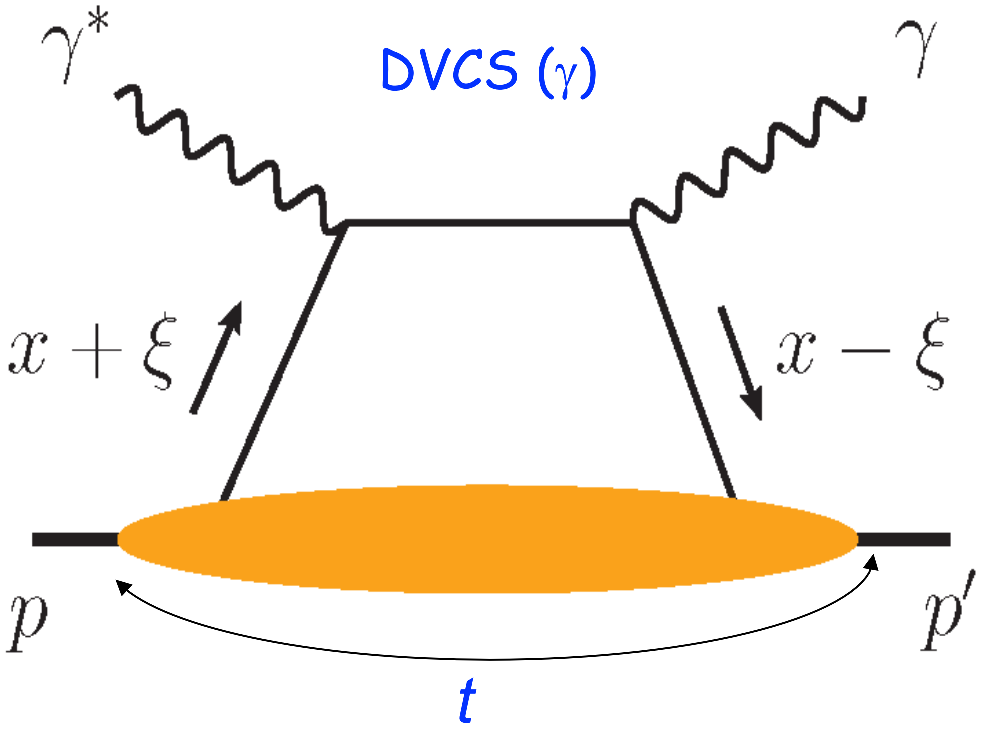


Spin-dependent 3D momentum space images from semi-inclusive scattering

Spin-dependent 2+1D coordinate space images from exclusive scattering



Deeply Virtual Compton Scattering (DVCS)



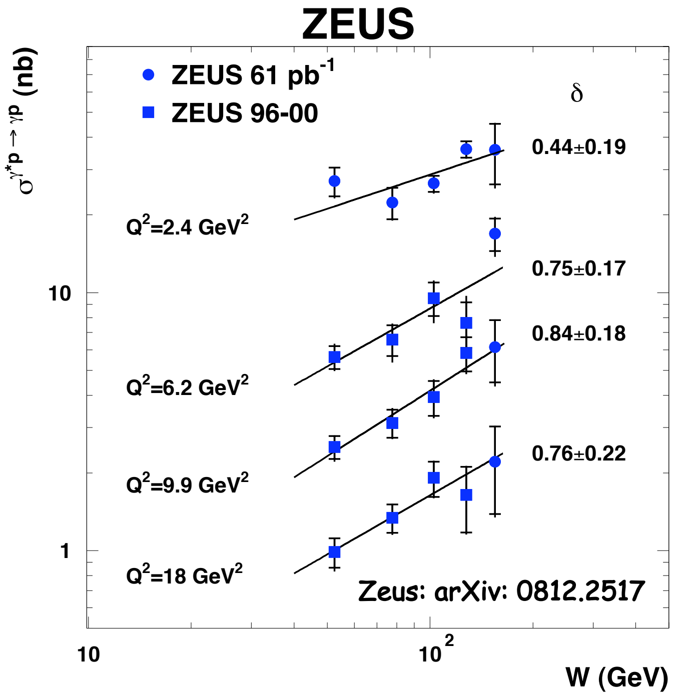
- Exclusive process with all final state particles detected in the event.
- Sensitive to the proton GPD.

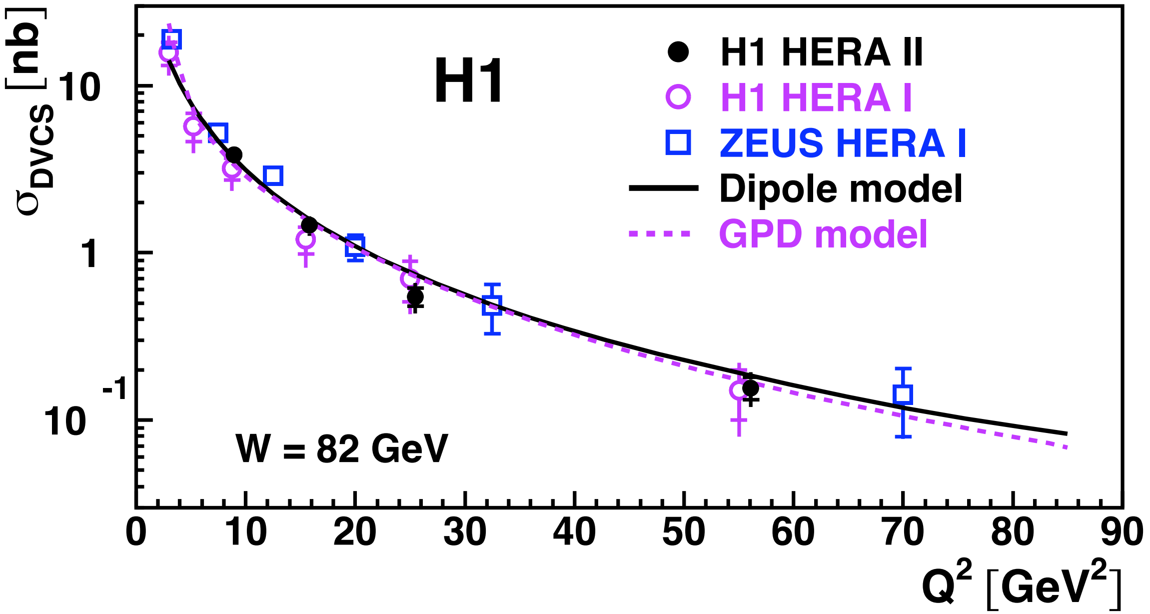
$$t = -(p-p')^2 \approx -{p'}_t^2$$

p_T and b_T are conjugate variables!

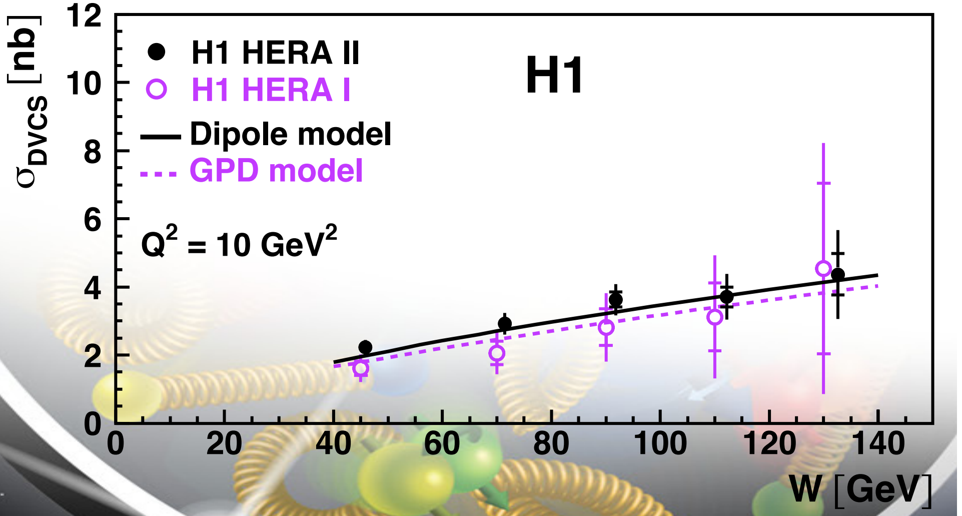
Measuring the cross-section differential on the momentum transfer yields access to spatial imaging!!

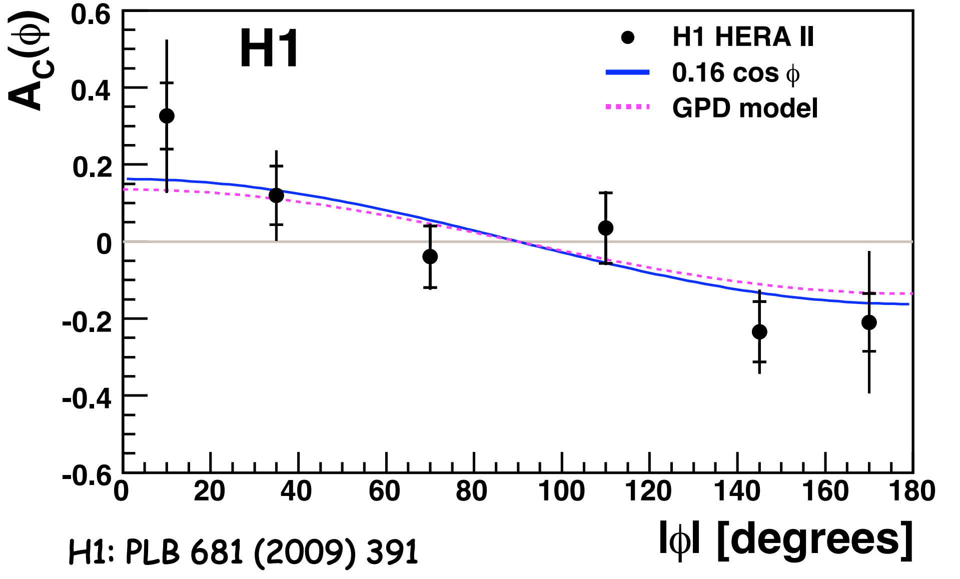
Results from HERA





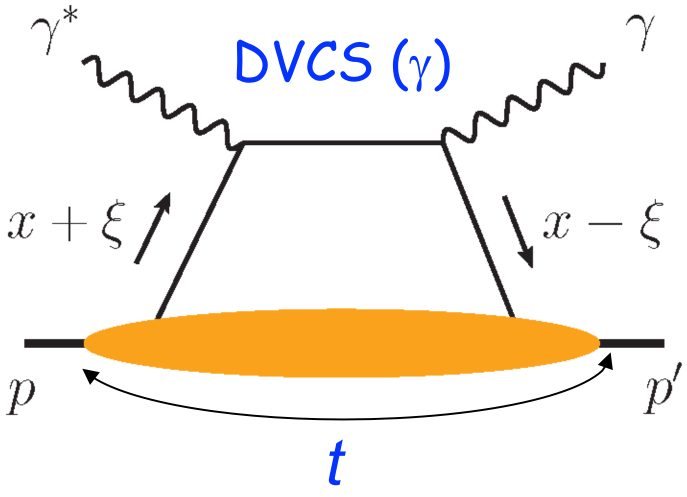
- Not enough data or acceptance to differentiate GPD models from others.
- No proton beam polarization to study spin-dependence!





EIC gives us the tools to solve both problems!!

Deeply Virtual Compton Scattering



- Exclusive process with all final state particles detected in the event.
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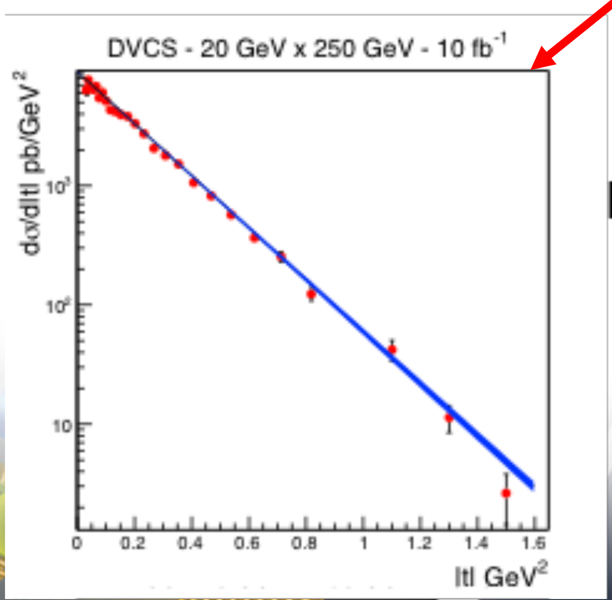
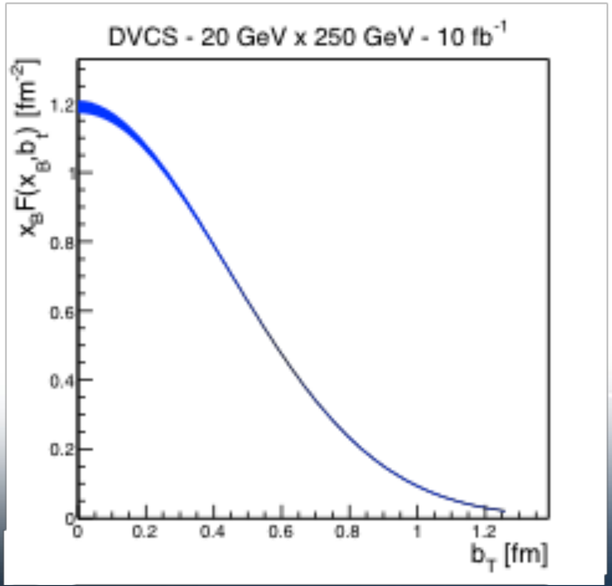
Measurement



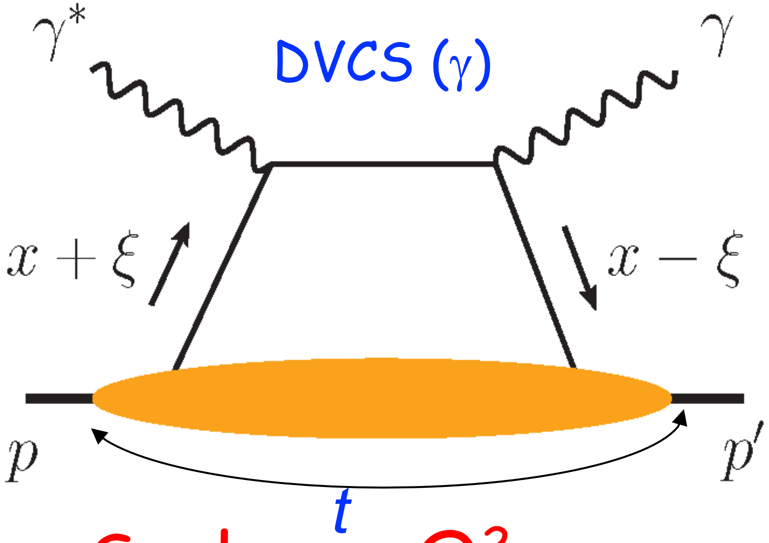
Plots from EIC White Paper:

Fourier transform

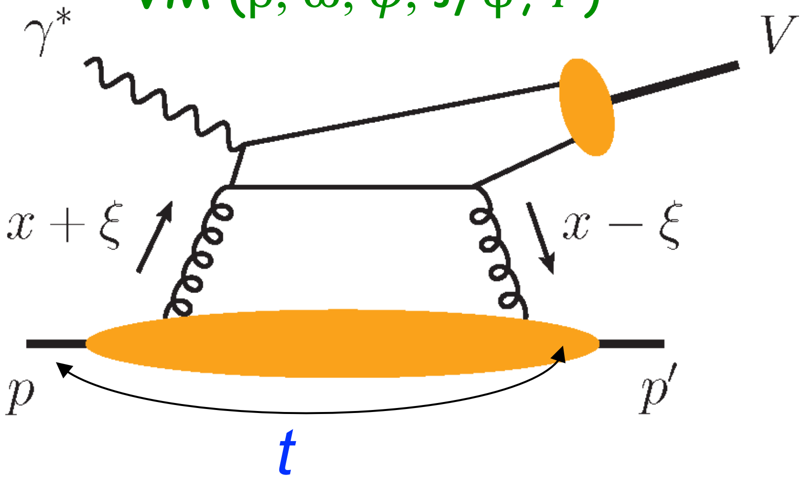
Physics observable (Impact parameter distribution)



Exclusive Vector Meson and Real Photon Production



square 4-momentum at *p*-vertex: *t=(p'-p)²*



Scale: Q^2 $Q^2 + M^2$

DVCS:

- Very clean experimental signature
- No VM wave-function uncertainty
- Hard scale provided by Q^2
- Sensitive to both quarks and gluons Q^2 dependence of cross section

VMP:

- Uncertainty of wave function
- J/Psi → direct access to gluons, c+cbar pair production
- Light VMs → quark-flavor separation

Small GPD Primer

unpolarized	polarized
$H^q(x,\xi,t)$	$\tilde{H}^q(x,\xi,t)$
$E^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$

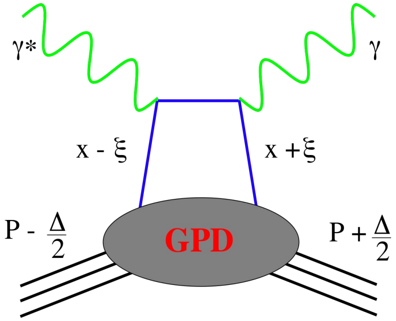
conserve nucleon helicity

$$H^q(x,0,0) = q, \tilde{H}^q(x,0,0) = \Delta q$$

flip nucleon helicity
not accessible in DIS

quantum numbers of final state ⟹ select different GPD

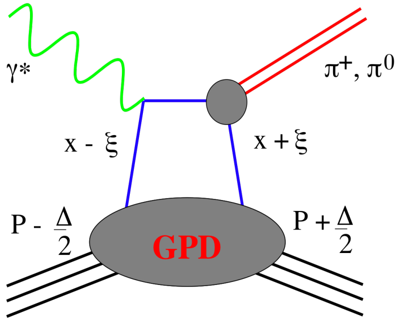
How are GPDs characterized?



DVCS

$H^q \quad E^q \quad \tilde{H}^q \quad \tilde{E}^q$

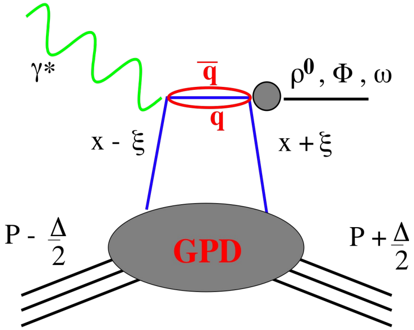
- $Q^2 = 2E_eE_e'(1-\cos q_{e'})$
- $x_B = Q^2/2Mn \quad n = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = (p-p')^2$
- $x \cong x_B/(2-x_B)$



pseudo-scaler mesons

$\tilde{H}^q, \tilde{E}^q$

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$



vector mesons

H^q, E^q

ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

Small GPD Primer

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

$$\frac{d\sigma}{dt} \sim A_0\left[|H|^2(x,t,Q^2) - \frac{t}{4M_p^2}|E^2|(x,t,Q^2)\right]$$

Dominated by H
slightly dependent on E

$$A_{UT} \propto \sqrt{\frac{-t}{4M^2}}\left[F_2(t)H(\xi,\xi,t,Q^2) - F_1(t)E(\xi,\xi,t,Q^2) + \ldots\right]$$

sin(*$\Phi_T - \phi_N$*)
governed by E and H
Requires a polarized proton-target

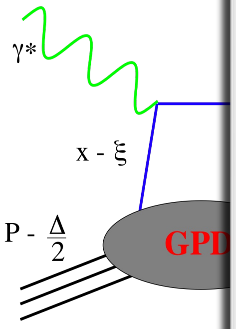
responsible for total orbital angular momentum through Ji sum rule
a window to the SPIN physics

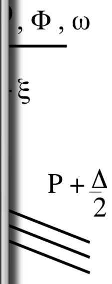
Small GPD Primer

How are GPDs characterized?

unpolarized	polarized	
$H^q(x,\xi,t)$	$\tilde{H}^q(x,\xi,t)$	conserve nucleon helicity: $H^q(x,0,0) = q,\ \tilde{H}^q(x,0,0) = \Delta q$
$E^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$	flip nucleon helicity, not accessible in DIS

quantum numbers of final state ⟹ select different GPD





the way to 3D imaging of the proton and access the orbital angular momentum

Spin-Sum-Rule in PRF:

$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z \qquad J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,g}\right)\right)_{t\to 0}$$

responsible for orbital angular momentum

DVCS

H^q E^q $\tilde{H}^q$ $\tilde{E}^q$ … $\tilde{H}^q, \tilde{E}^q$

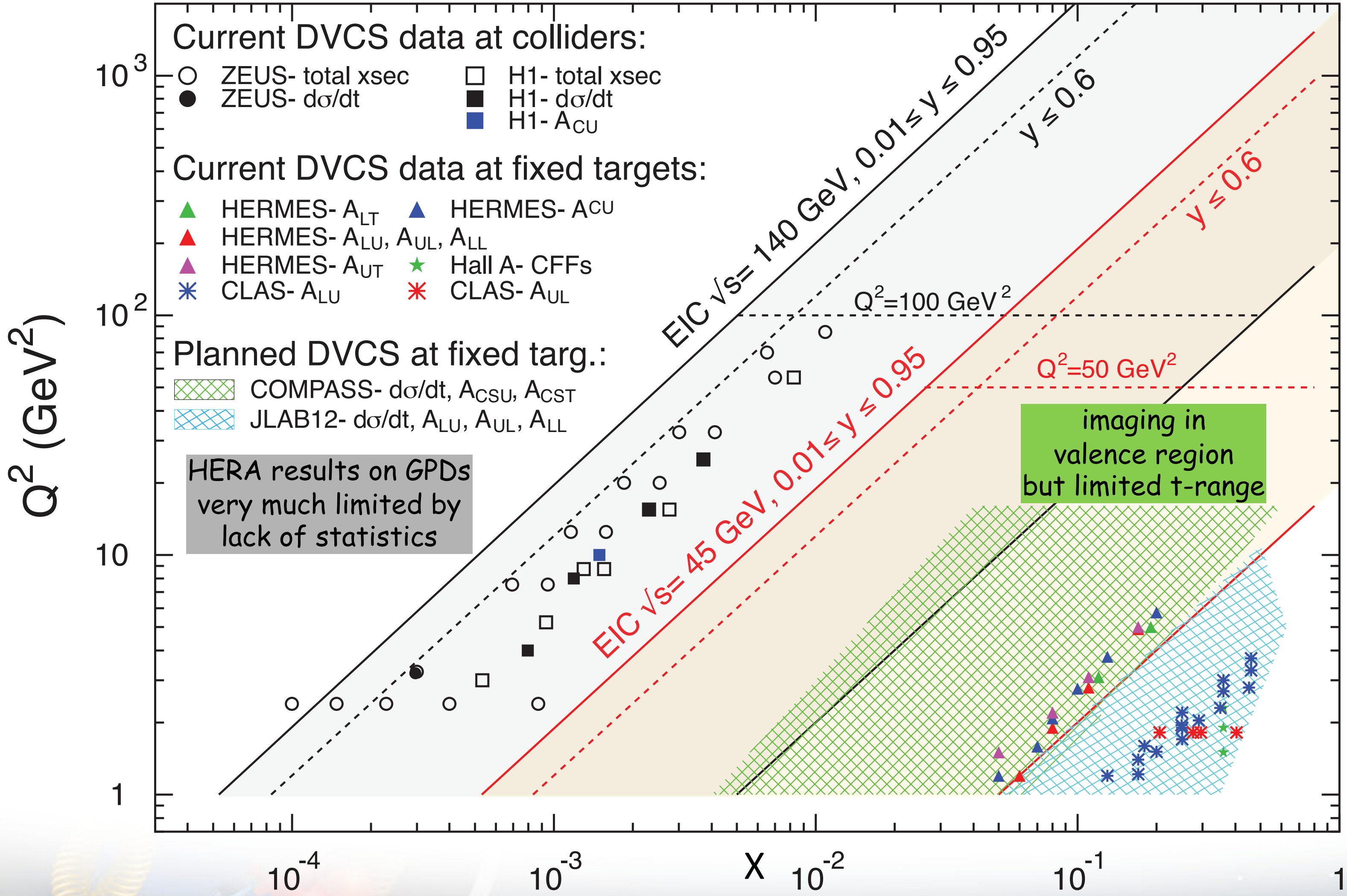
ns

- $Q^2 = 2E_eE_e'(1-\cos q_{e'})$
- $x_B = Q^2/2Mn \quad n = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = (p-p')^2$
- $x \cong x_B/(2-x_B)$

π^0	2Δu+Δd
η	2Δu–Δd

ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
φ	s, g
ρ^+	u–d
J/ψ	g

The DVCS Phase Space



quantum numbers of final state → selects different GPD

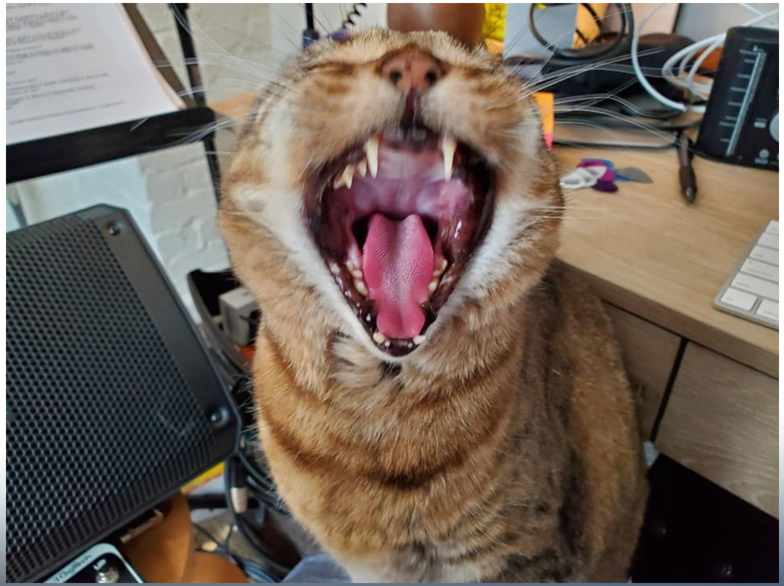
DVCS: wide range of observables (σ, A_{UT}, A_{LU}, A_{UL}, A_C) to disentangle GPDs

Intermission: I have very cute animals

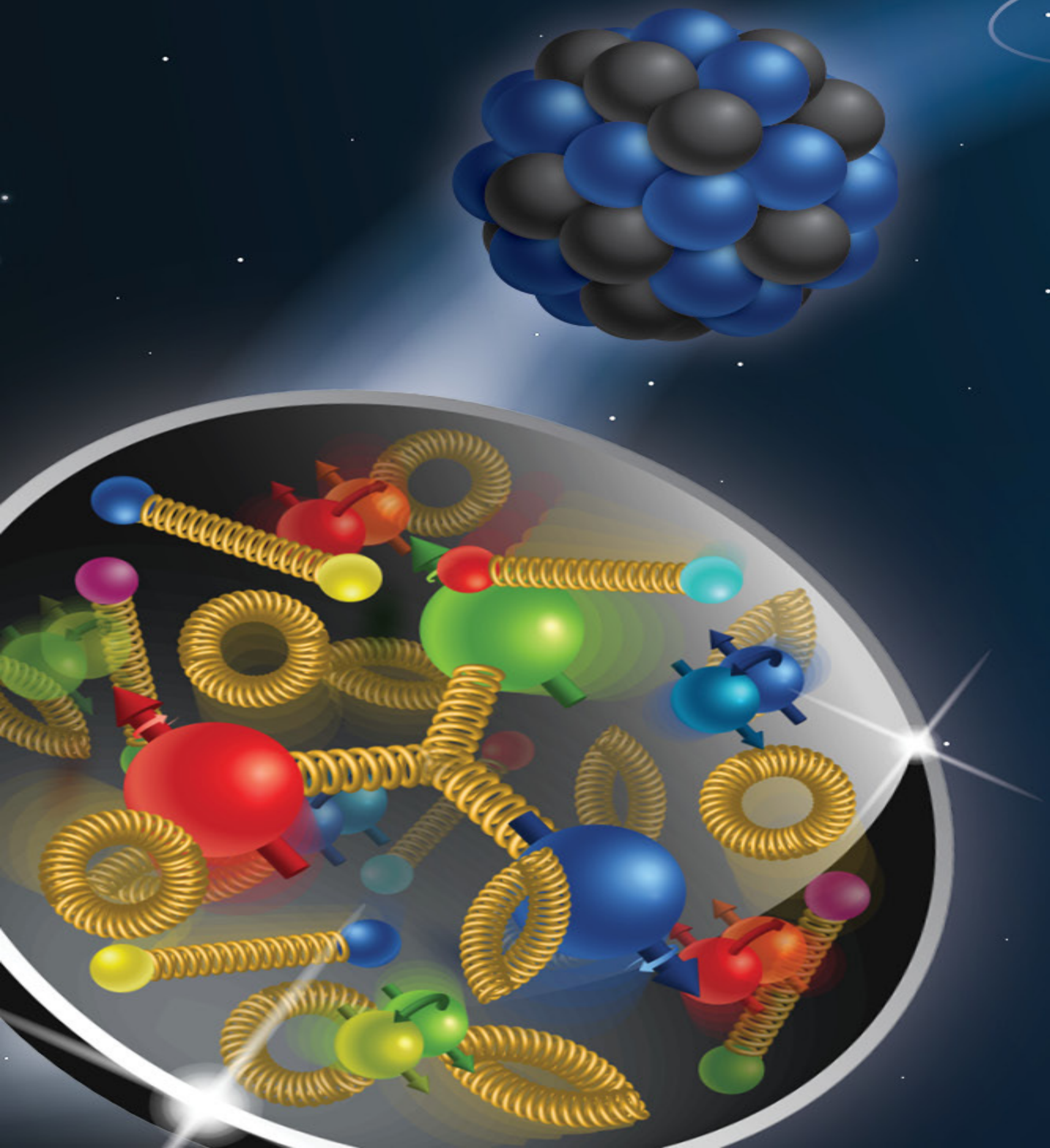
Julep

They (mostly) get along.

Lilu



She's in a death metal band.

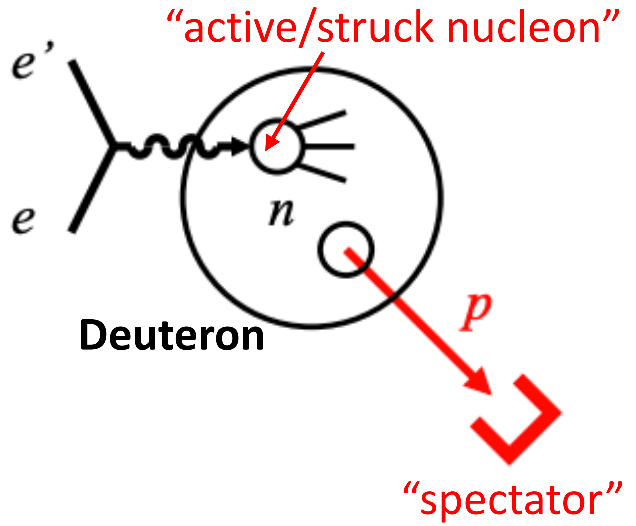


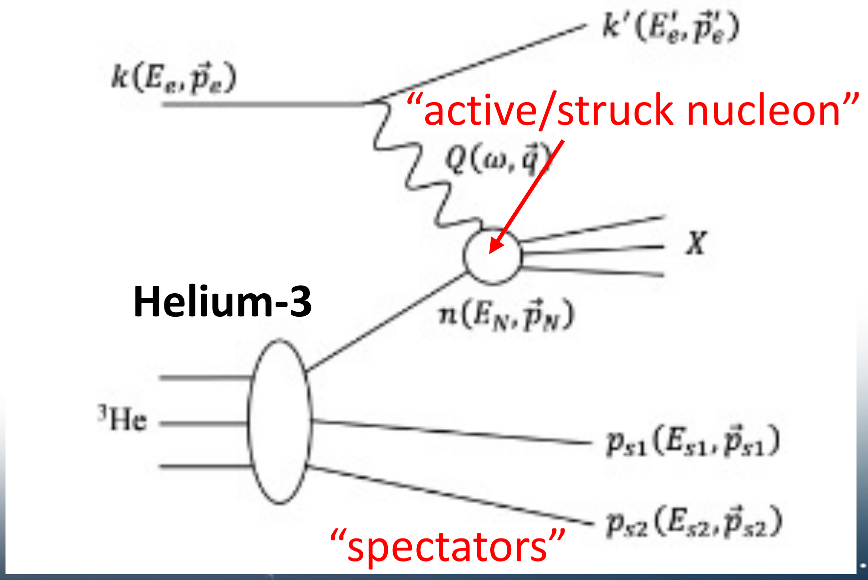
What about (light) nuclei?

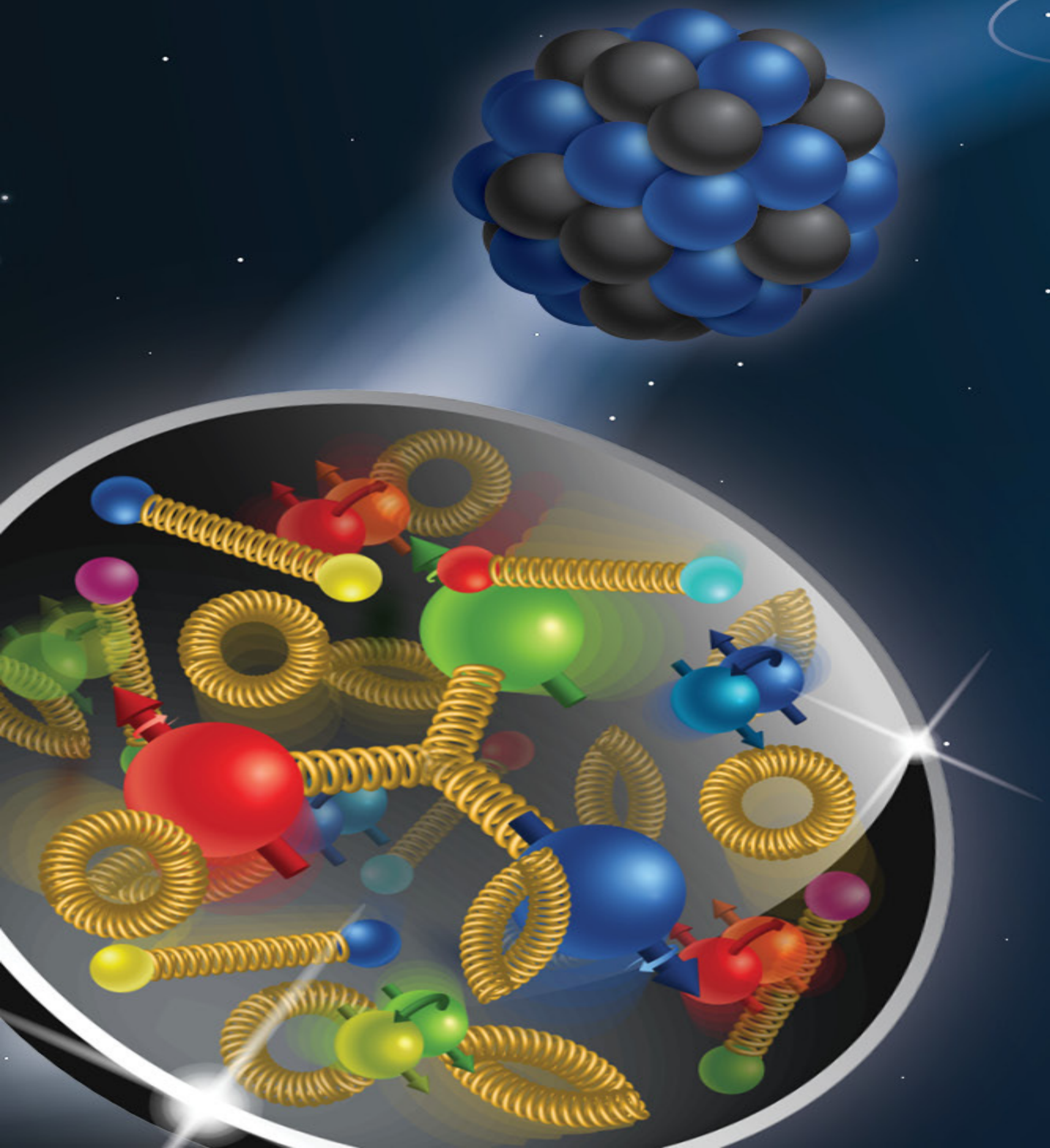
Tagged DIS at the EIC

- **Tagged DIS** measurements on light nuclei → ”tag” (generally) far-forward particles in final state for useful kinematic information!
  - Provides more information than inclusive cross sections!
- Lots of topics!
  - Short-range correlations.
  - Gluon distributions in nuclei.
  - Free neutron structure functions.
  - Nuclear modifications of nucleons in light nuclei.
    - EMC effect, anti-shadowing, etc.

Tagged spectator nucleon momentum → experimental variable for selecting nuclear configurations with free and modified nucleons.







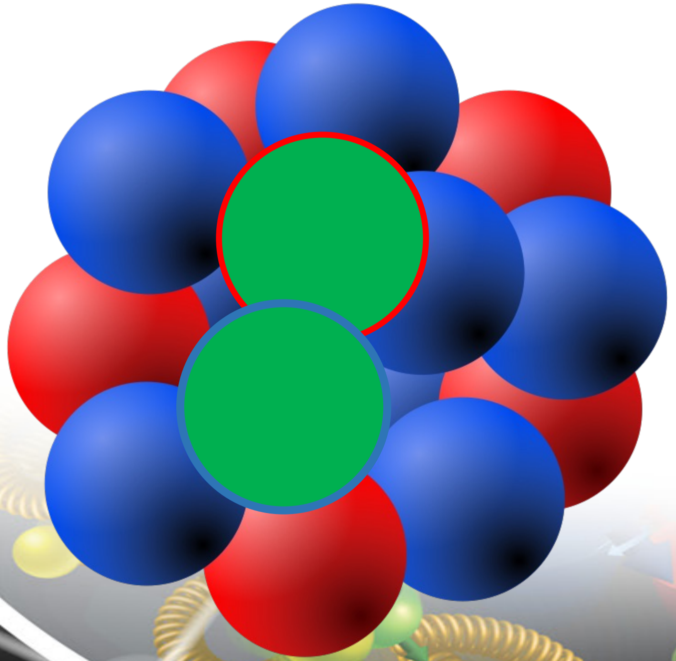
Light nuclei - deuterons: Short-Range Correlations

Short-Range Correlations

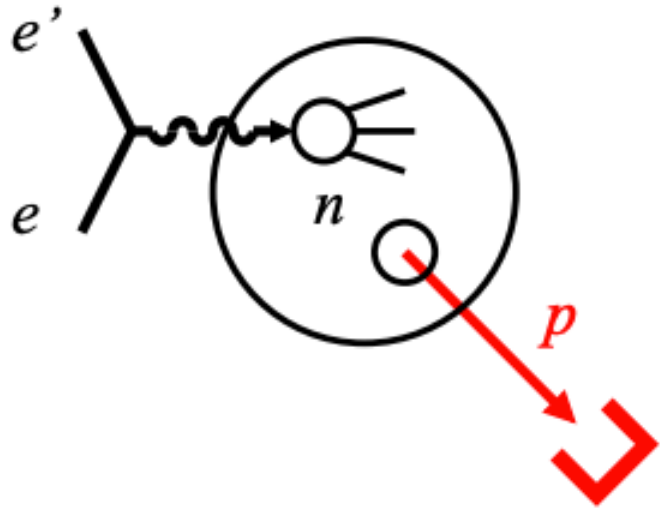
"The nucleus can often be approximated as an independent collection of protons and neutrons confined in a volume, but for short periods of time, the nucleons in the nucleus can strongly overlap. This quantum mechanical overlapping, known as a nucleon-nucleon short-range correlation, is a manifestation of the nuclear strong force, which produces not only the long-range attraction that holds matter together, but also the short-range repulsion that keeps it from collapsing."

Excerpt from: https://www.jlab.org/research/nucleon_nucleon

Lots of SRC pairs!!! -> Really tough!



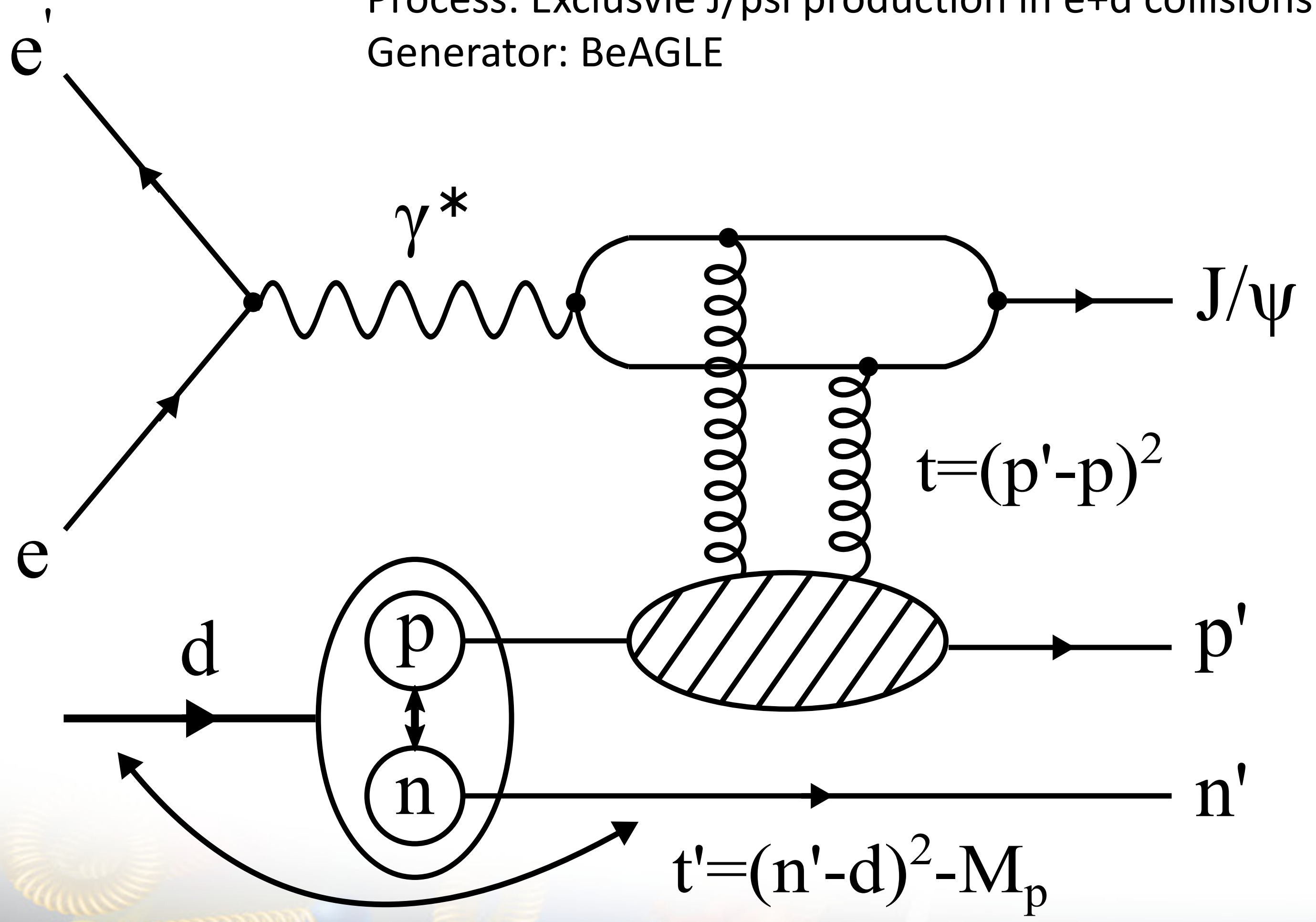
Use deuteron as "SRC laboratory", where nucleon kinematics are readily accessible.



Short-Range Correlations in Deuterons

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

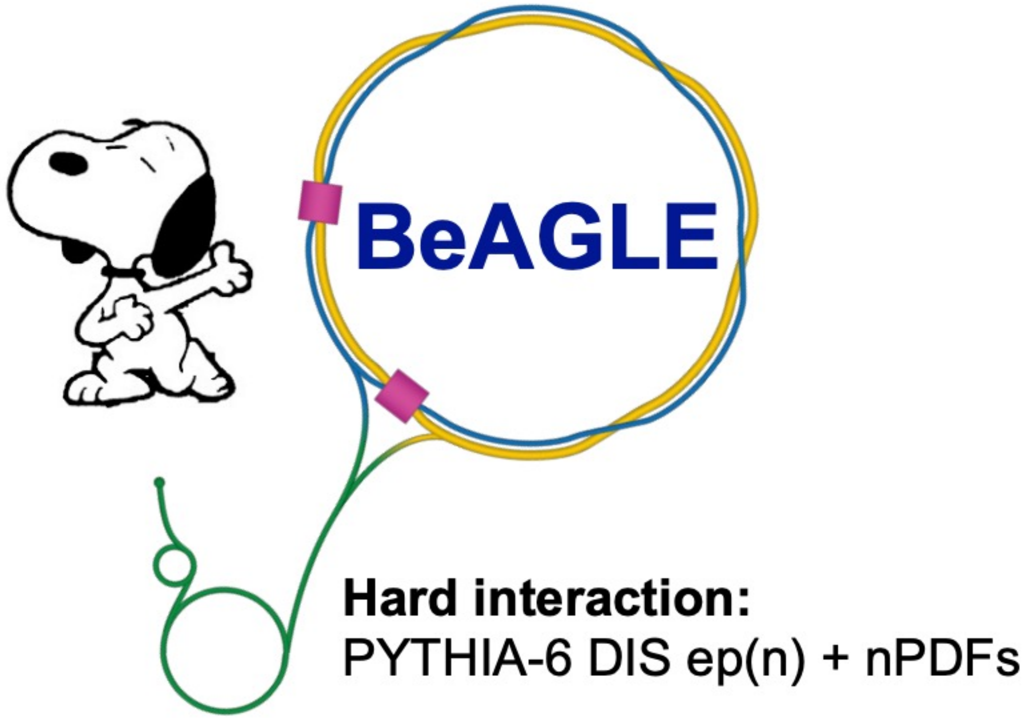
Process: Exclusvie J/psi production in e+d collisions.
Generator: BeAGLE



- J/psi produced at mid-rapidity.
  - Sensitive to gluon structure!
- Tagging active and spectator nucleons allow for experimental control of nuclear configuration -> study transition into SRC region (e.g. where nuclear effects become larger).

Monto-Carlo sample for all e+d studies presented here

General-purpose eA DIS MC generator
https://eic.github.io/software/beagle.html



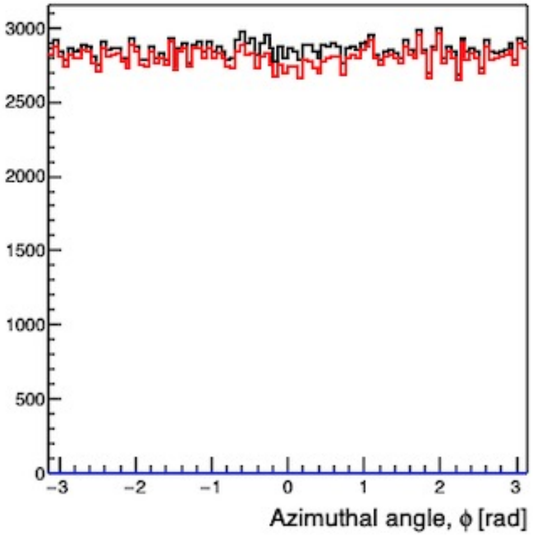
Recent comprehensive overview of BeAGLE, (arXiv:2204.11998)

- Use BeAGLE to simulate the hard e + (active) nucleon scattering and primary process (e.g. J/psi production, DIS, etc.)
- Spectator momentum spectra calculated via deuteron spectral function, using parametrization of Ciofi and Simula.
  - C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53, 1689 (1996)

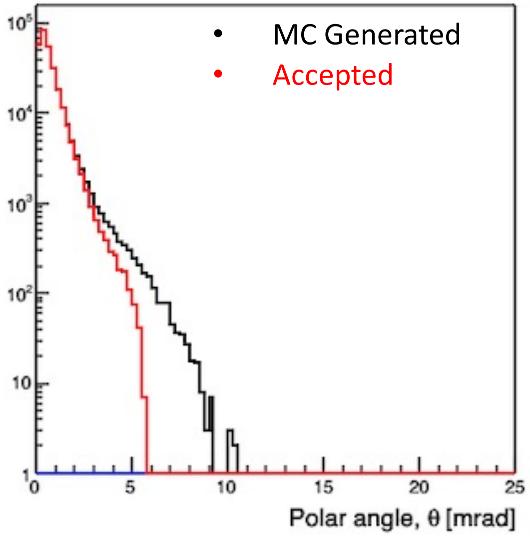
Short-Range Correlations in Deuterons

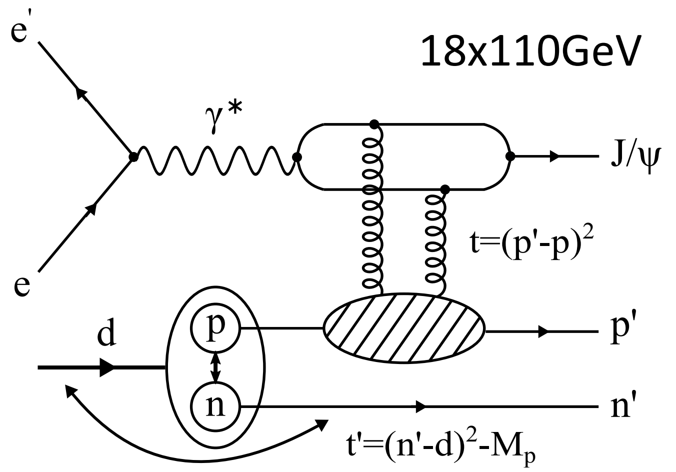
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

Protons



Protons





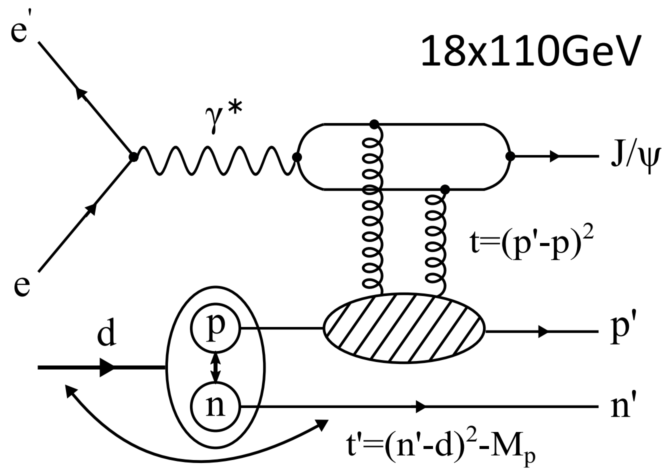
Proton "spectator" case.

Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

MC generated events shown in black – "accepted" protons in red.
Acceptance refers to particles which are actually captured by the detector.

Short-Range Correlations in Deuterons

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)



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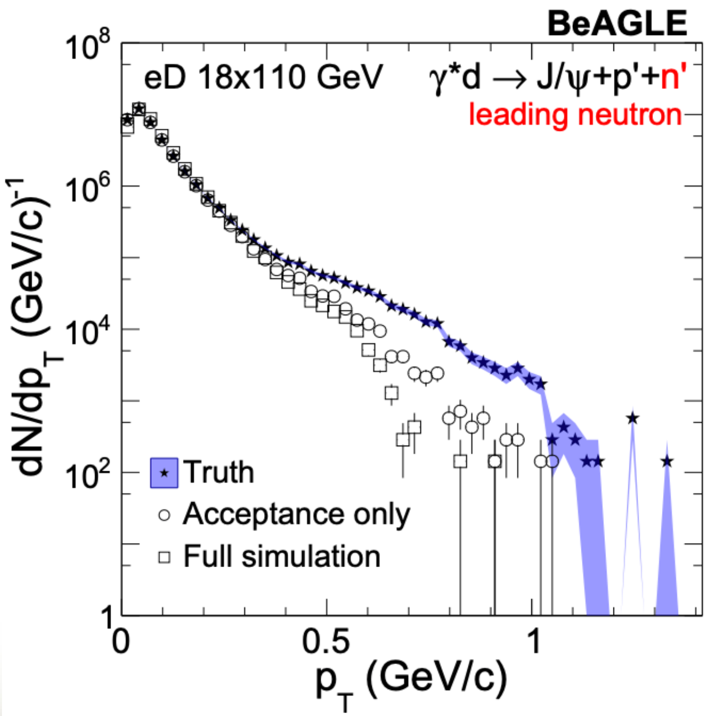
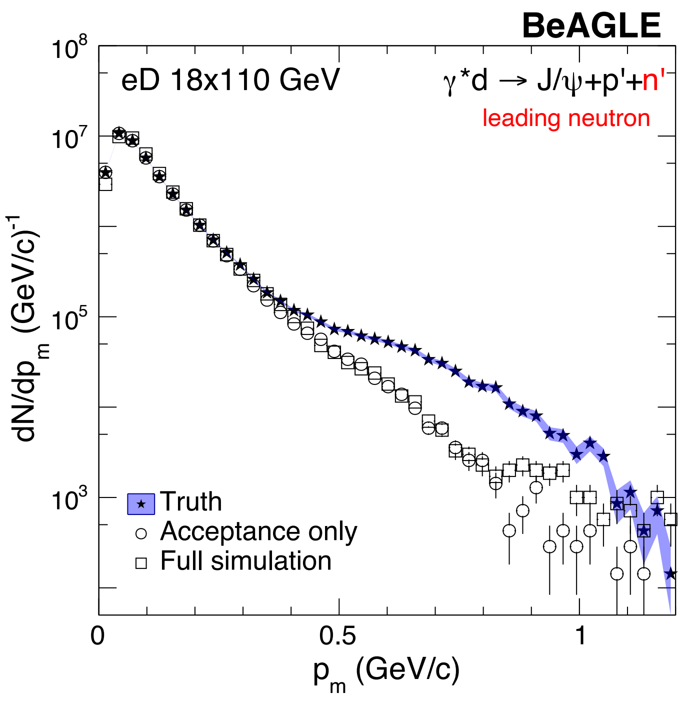
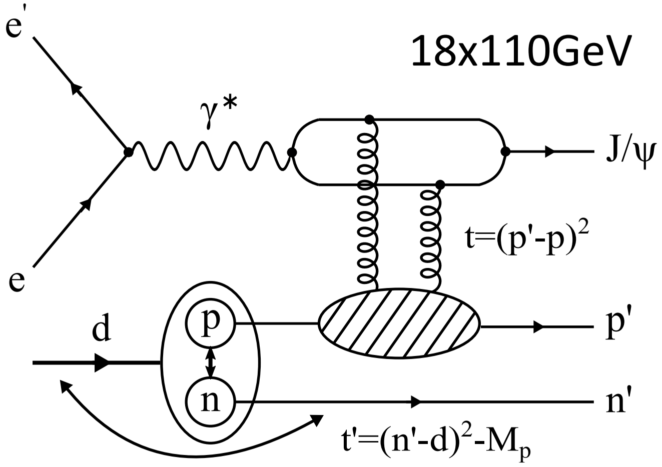




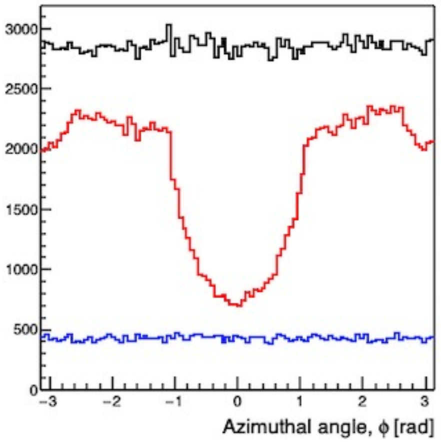
- Spectator kinematic variables reconstructed over a broad range.
- Bin migration is observed due to smearing in the reconstruction.
- Each plot shows the MC (closed circles), acceptance effects only (open circles), and full reconstruction (open squares).

Short-Range Correlations in Deuterons

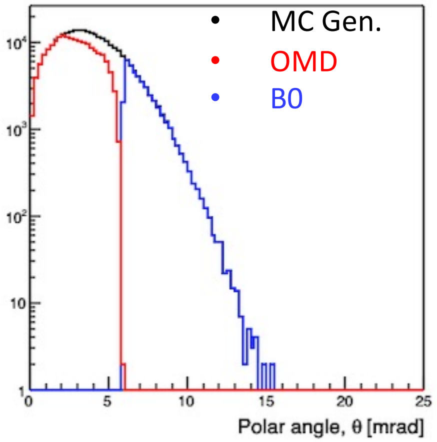
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)



Protons

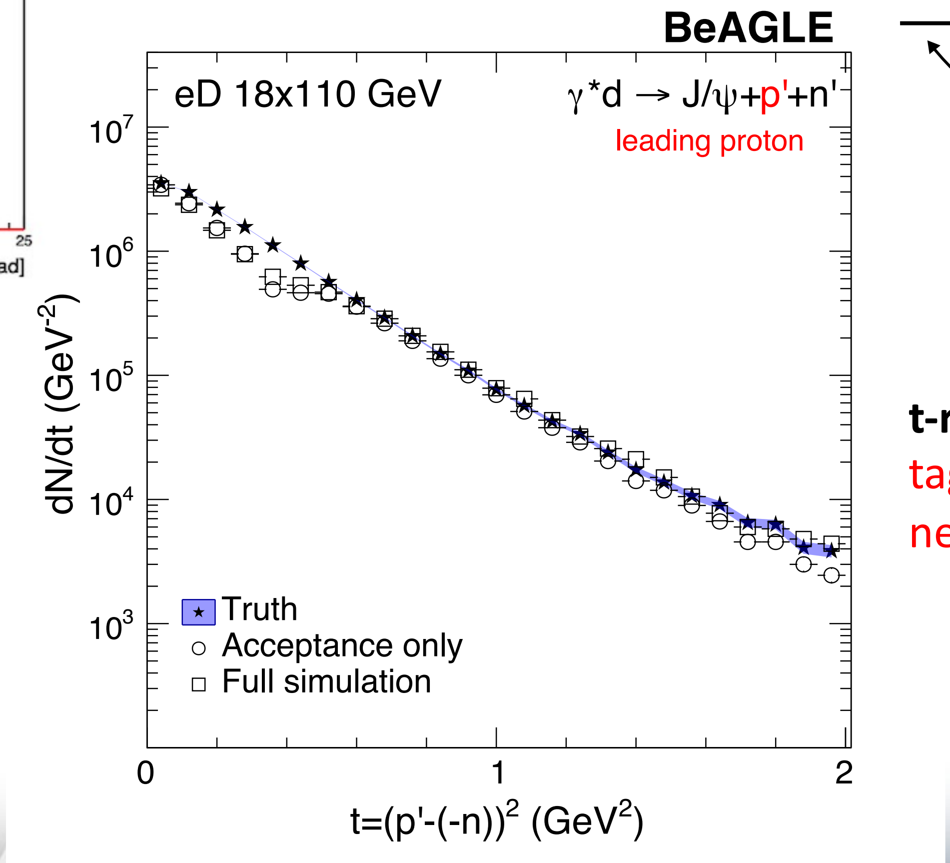


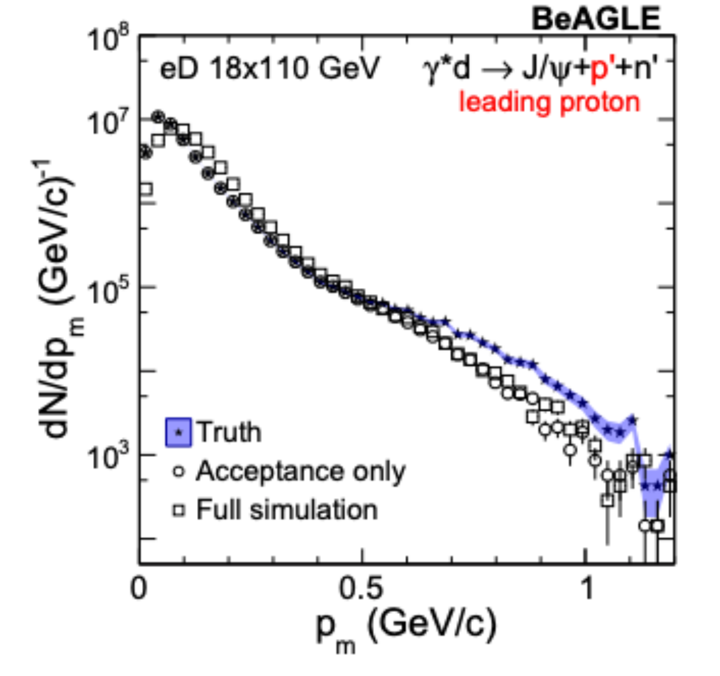
Protons



Neutron spectator case.

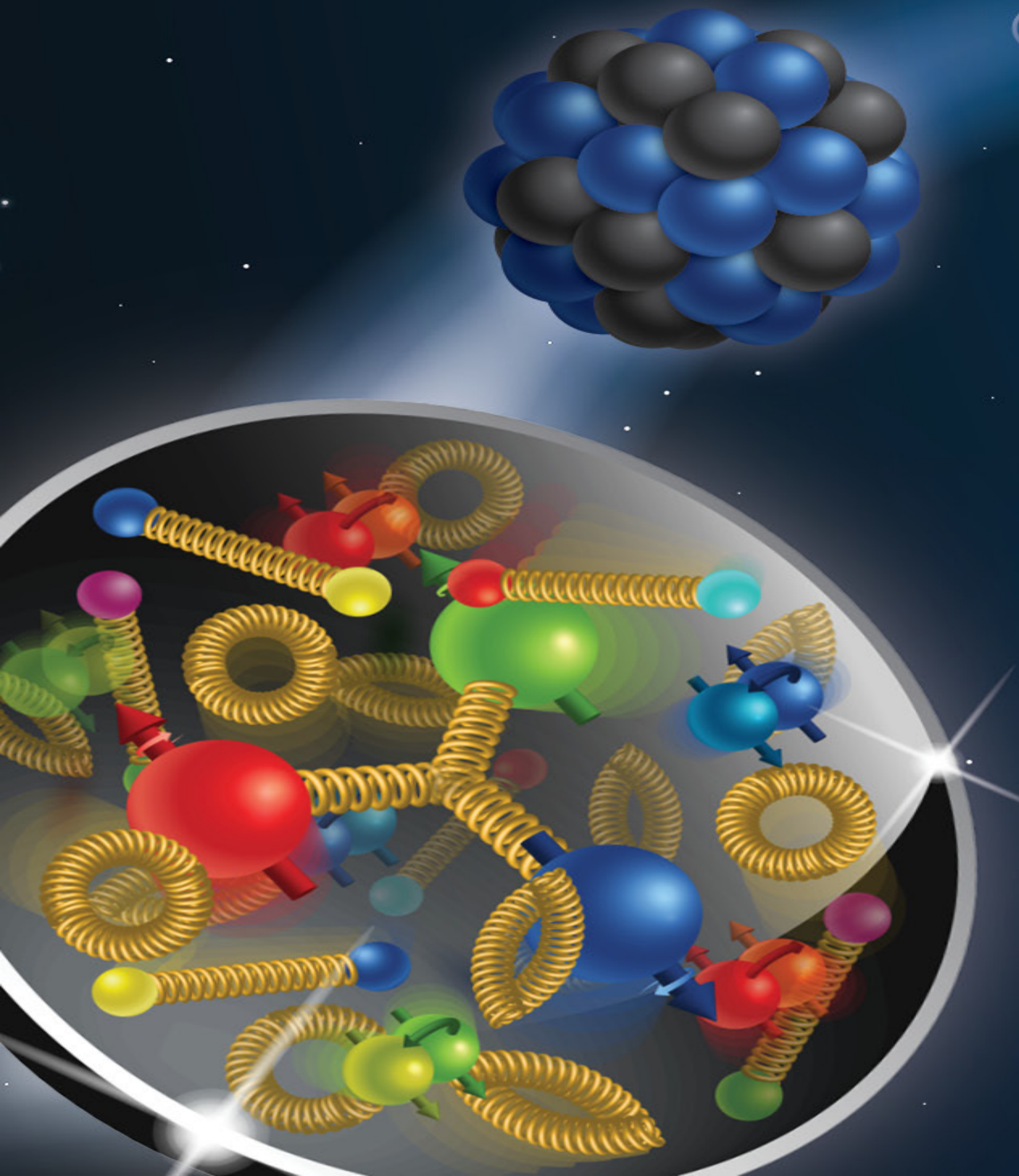
Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.





t-reconstruction using double-tagging (both proton and neutron).

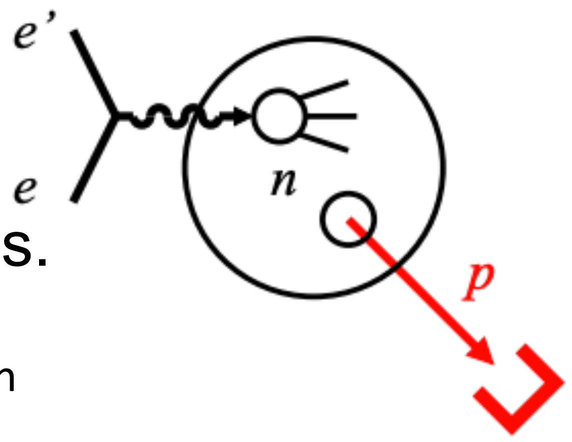
➢ **Spectator information is the "dial" for the SRC region.**



Light nuclei - deutrerons: Free Neutron Structure

Neutron Structure

- Protons well-studied at HERA -> So…why the neutron?
  - Flavor separation, baseline for studies of nuclear modifications.



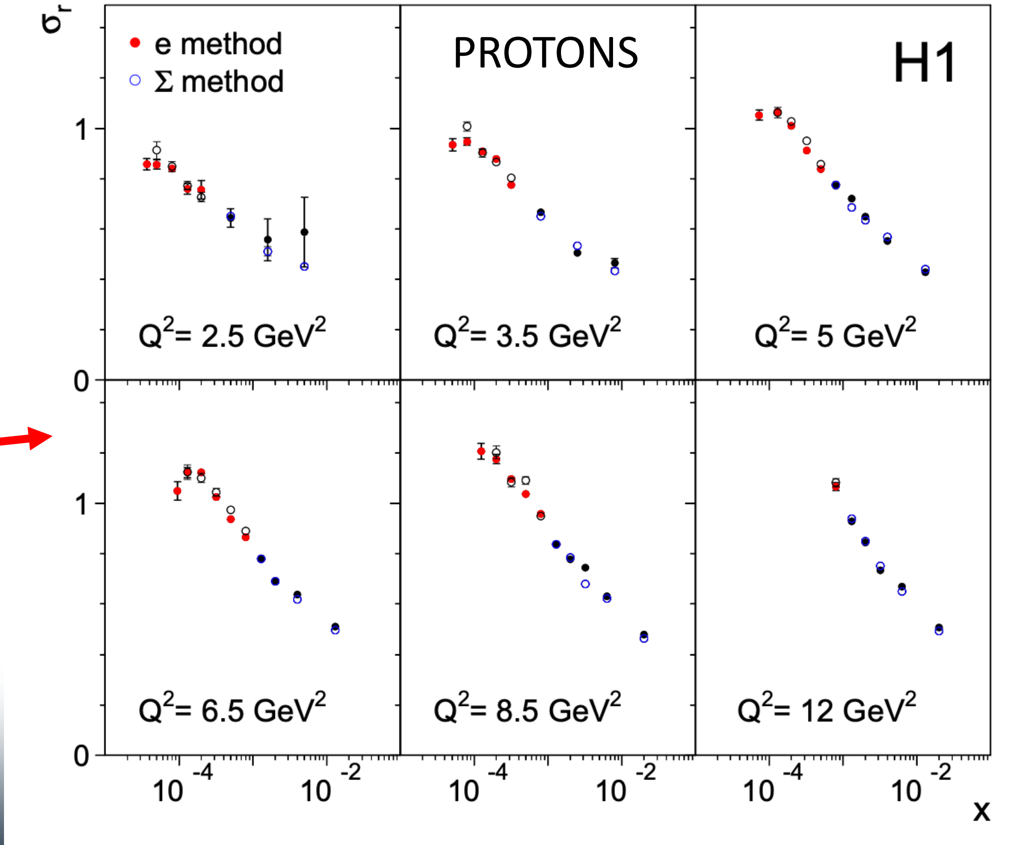
$$\sigma_r = \frac{Q^4 x}{2\pi\alpha^2[1+(1-y)^2]} \cdot \frac{d^2\sigma}{dx\,dQ^2} = F_2(x,Q^2) - f(y)\cdot F_L(x,Q^2)$$

Reduced cross section

"Flux factor"

Differential cross section

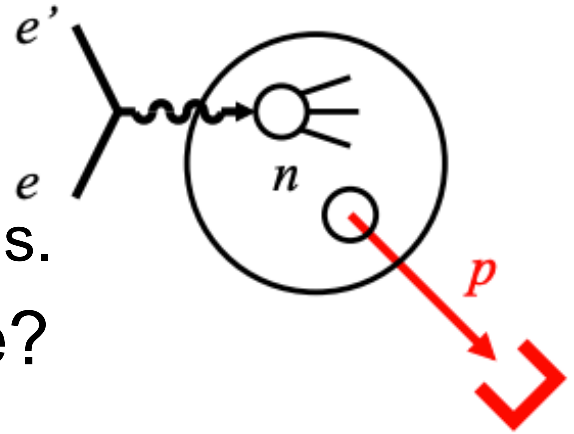
Structure functions



Some useful HERA references for measurements on proton

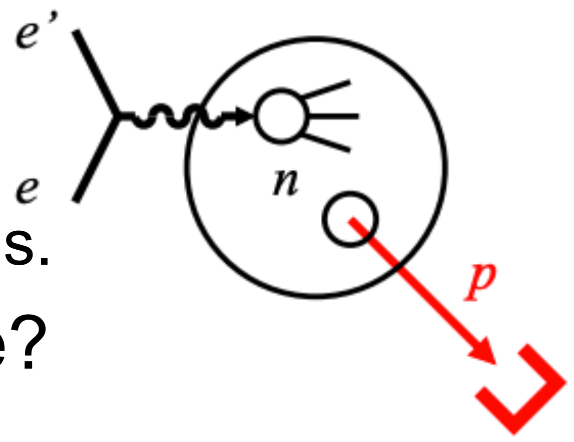
- F. Aaron *et al.* (H1 Collaboration), The European Physical Journal C volume 63, Article number: 625 (2009)
- V. Andreev *et al.* (H1 Collaboration), *Eur.Phys.J.C* 74 (2014) 4, 2814
- H. Abramowicz *et al.* (H1 and ZEUS Collaborations) *The European Physical Journal C* **volume 75**, Article number: 580 (2015)

Neutron Structure



- Protons well-studied at HERA -> So…why the neutron?
  - Flavor separation, baseline for studies of nuclear modifications.
- What makes the free neutron structure hard to measure?
  - Can only access neutrons *in a nucleus.*
  - Includes nuclear binding effects, Fermi motion, etc.

Neutron Structure



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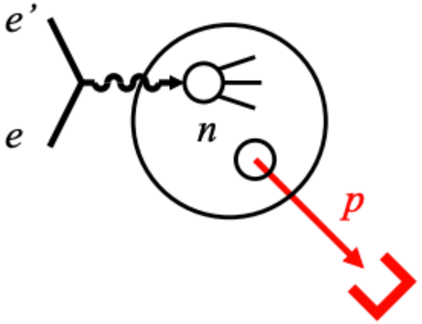
  - Flavor separation, baseline for studies of nuclear modifications.
- What makes the free neutron structure hard to measure?
  - Can only access neutrons *in a nucleus.*
  - Includes nuclear binding effects, Fermi motion, etc.

- <u>Two options:</u>
  1. Inclusive measurements → Average over all nuclear configurations, use theory input to correct for nuclear binding effects.
  2. Tagged measurements → Select nuclear configuration via spectator kinematics, allows for differential study.
     - Spectator kinematics provide a knob to dial in different regions of interest for study (i.e. high p_T → SRC physics; very low p_T ~ 0 GeV/c yields access to on-shell extrapolation).
     - On-shell extrapolation enables access to **free** nucleon structure.
       - M. Sargsian, M. Strikman PLB **639** (iss. 3-4) 223231 (2006)

Neutron Structure

- Previous fixed target experiments with tagging have measured the neutron F_2 at high-x.
  - CLAS - Phys. Rev. Lett. **108**, 199902 (2012)
  - CLAS + BONUS - Phys. Rev. C 89, 045206 (2014)
    - measurement had a lower p_T cutoff ~ 70 MeV/c.
- Future JLAB 12 GeV studies planned.
  - ALERT - https://arxiv.org/abs/1708.00891
  - CLAS - https://www.jlab.org/exp_prog/proposals/10/PR12-06-113-pac36.pdf
- **<u>Tagged DIS @ the EIC</u>:**
  - In a collider, can tag spectators down to p_T ~ 0 MeV/c → Enables extraction of free neutron structure function via pole extrapolation.
  - Can extend tagged DIS measurement to $x \lesssim 0.1$.

Basic Method - Tagging



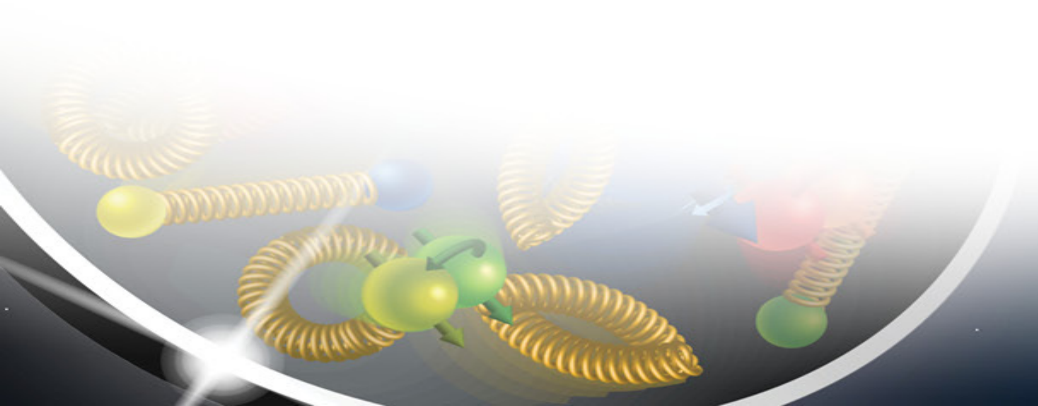
spectator nucleon (p_{pT}, α_p)

α_p: light-cone momentum fraction

$$\alpha_p \equiv \frac{2p_p^+}{p_d^+} = \frac{2(E_p + p_{z,p})}{M_d}$$

S_d: deuteron spectral function pole

Total cross section $$d\sigma = Flux(x, Q^2) \times \sigma_{red,d} \times \frac{dx}{2} dQ^2 \frac{d\phi_{e'}}{2\pi} [2(2\pi)^3]^{-1} \frac{d\alpha_p}{\alpha_p} \frac{dp_{pT}^2}{2} d\phi_p$$



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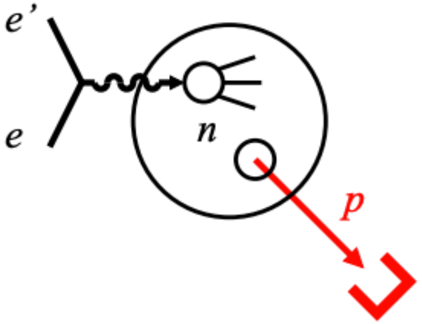

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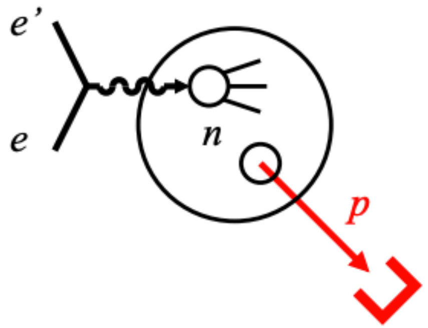
- Measure the cross-section differential on the spectator kinematics.
  - Spectator kinematics provide control knob on the nuclear configuration.
- Solve for the deuteron reduced cross section.

Basic Method - Tagging



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- Measure the cross-section differential on the spectator kinematics.
  - Spectator kinematics provide control knob on the nuclear configuration.
- Solve for the deuteron reduced cross section.
- Deuteron reduced cross section related to the struck nucleon reduced cross section via the deuteron spectral function.

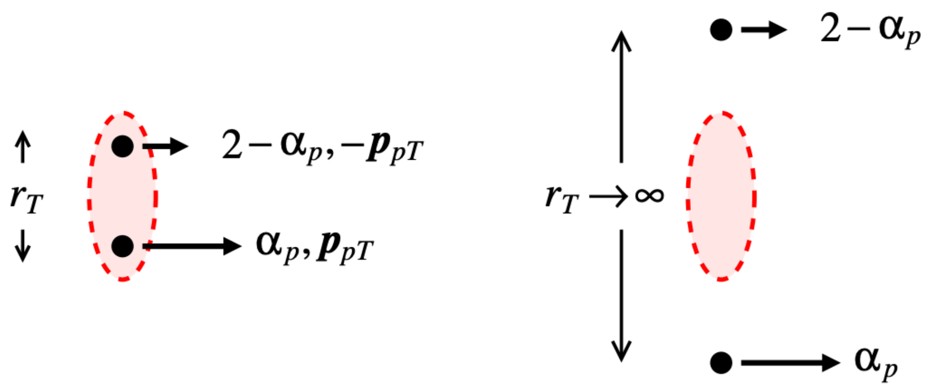
$$\sigma_{red,d}\left(x, Q^2; p_{pT}, \alpha_p\right) = [2(2\pi)^3] \times S_d(p_{pT}, \alpha_p)[pole] \times \sigma_{red,n}(x, Q^2)$$

Measurement of the deuteron reduced cross section yields access to the struck nucleon structure via the tagged spectator!

M. Strikman and C. Weiss, Phys. Rev. C 97, 035209 (2018)

Basic Method - Pole Extrapolation

C. Weiss and W. Cosyn
Phys. Rev. C **102**, 065204 (2020)



$p_{pT}^2 > 0$
physical region

$p_{pT}^2 \to -a_T^2$
pole extrapolation

- Divide by deuteron spectral function (nucleon pole).
  - The resulting distribution is the active nucleon reduced cross section as a function of p_{pT}^2.

$$\sigma_{red,n}(x, Q^2) = \frac{\sigma_{red,d}(x, Q^2;\ p_{pT}, \alpha_p)}{[2(2\pi)^3] S_d(p_{pT}, \alpha_p)[pole]}$$

$$S_d(p_{pT}, \alpha_p)[pole] = \frac{R}{\left(p_{pT}^2 + a_T^2\right)^2}$$ Deuteron spectral function

$$R = 2\alpha_p^2 m_N \Gamma^2(2-\alpha_p)$$

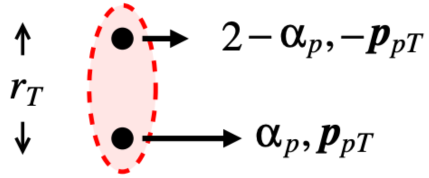
$$a_T^2 = m_N^2 - \alpha_p(2-\alpha_p)\frac{M_d^2}{4}$$

$R = residue\ of\ spectral\ function$

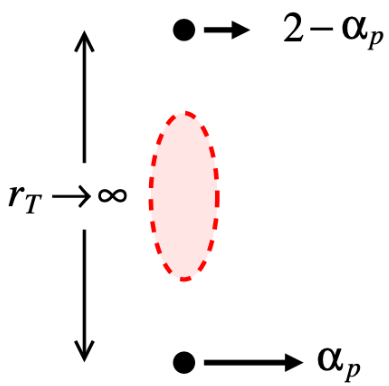
$a_T^2 = position\ of\ pole$

Basic Method - Pole Extrapolation

C. Weiss and W. Cosyn
Phys. Rev. C **102**, 065204 (2020)



$p_{pT}^2 > 0$
physical region



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- Divide by deuteron spectral function (nucleon pole).
  - The resulting distribution is the active nucleon reduced cross section as a function of p_{pT}^2.

$$\sigma_{red,n}(x, Q^2) = \frac{\sigma_{red,d}(x, Q^2;\ p_{pT}, \alpha_p)}{[2(2\pi)^3] S_d(p_{pT}, \alpha_p)[pole]}$$

$$S_d(p_{pT}, \alpha_p)[pole] = \frac{R}{\left(p_{pT}^2 + a_T^2\right)^2}$$ Deuteron spectral function

$$R = 2\alpha_p^2 m_N \Gamma^2 (2 - \alpha_p)$$

$$a_T^2 = m_N^2 - \alpha_p (2 - \alpha_p) \frac{M_d^2}{4}$$

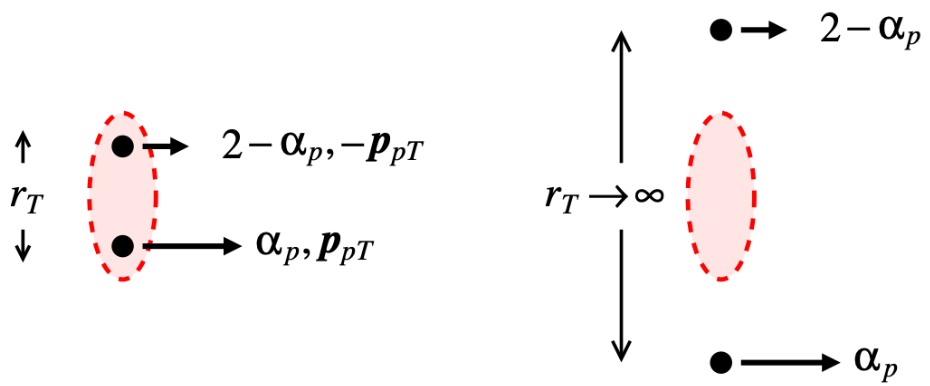
$R = residue\ of\ spectral\ function$

$a_T^2 = position\ of\ pole$

- Extrapolate to $p_{pT}^2 \to -a_T^2$ to extract F_2 to extract free nucleon F_2.
  - Pole extrapolation selects large-size pn configurations where nuclear binding and FSI are absent.

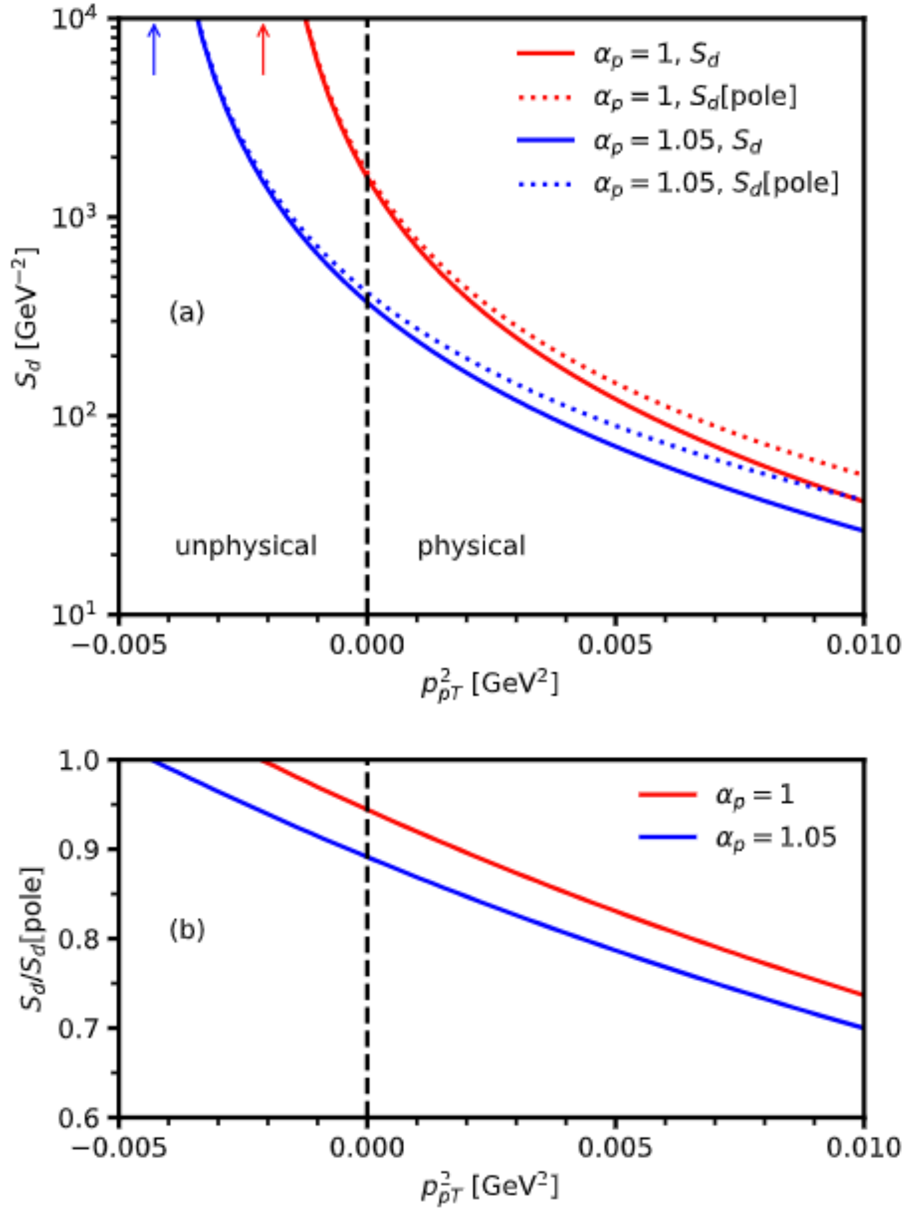
Basic Method - Pole Extrapolation

C. Weiss and W. Cosyn
Phys. Rev. C **102**, 065204 (2020)



$p_{pT}^2 > 0$
physical region

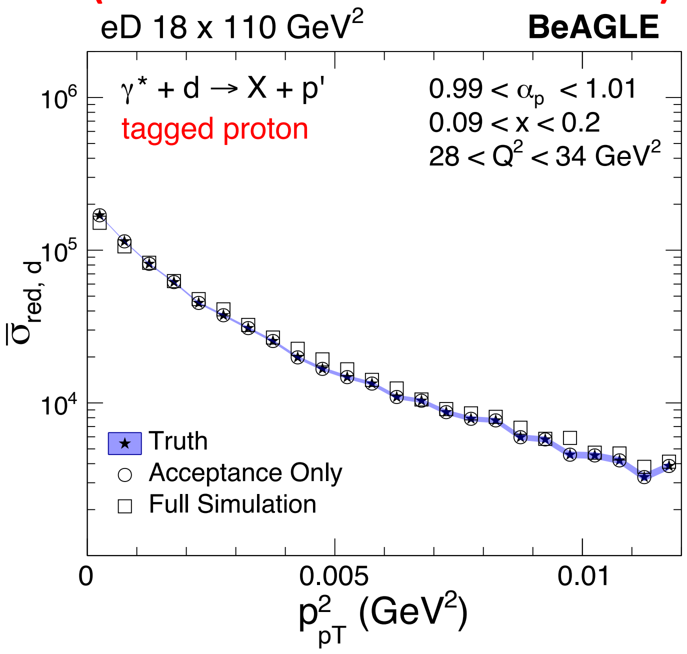
$p_{pT}^2 \to -a_T^2$
pole extrapolation



Free Neutron F_2 Extraction

A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

(deuteron reduced cross section)



- Start with the deuteron reduced cross section → **direct measurement!**

Free Neutron F_2 Extraction

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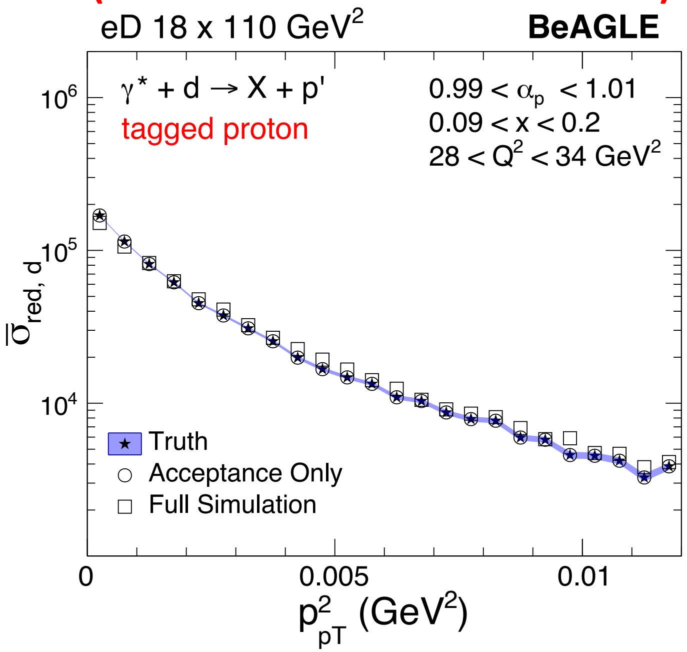

- Start with the deuteron reduced cross section → direct measurement!
- Multiply by the inverse of the deuteron spectral function pole.

$$\frac{1}{S_d(p_{pT}, \alpha_p)[pole]}$$

(inverse pole of deuteron spectral function)

Free Neutron F_2 Extraction

A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104**, 065205, (2021) **(Editor's Suggestion)**

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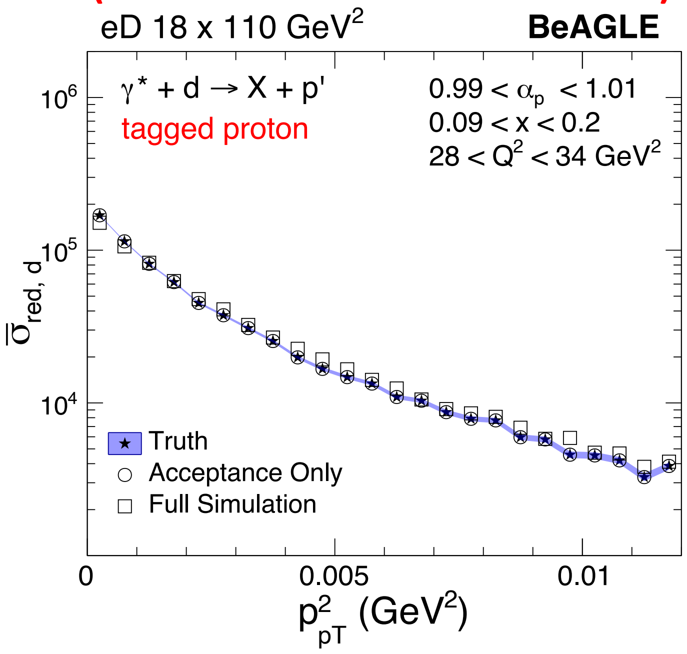
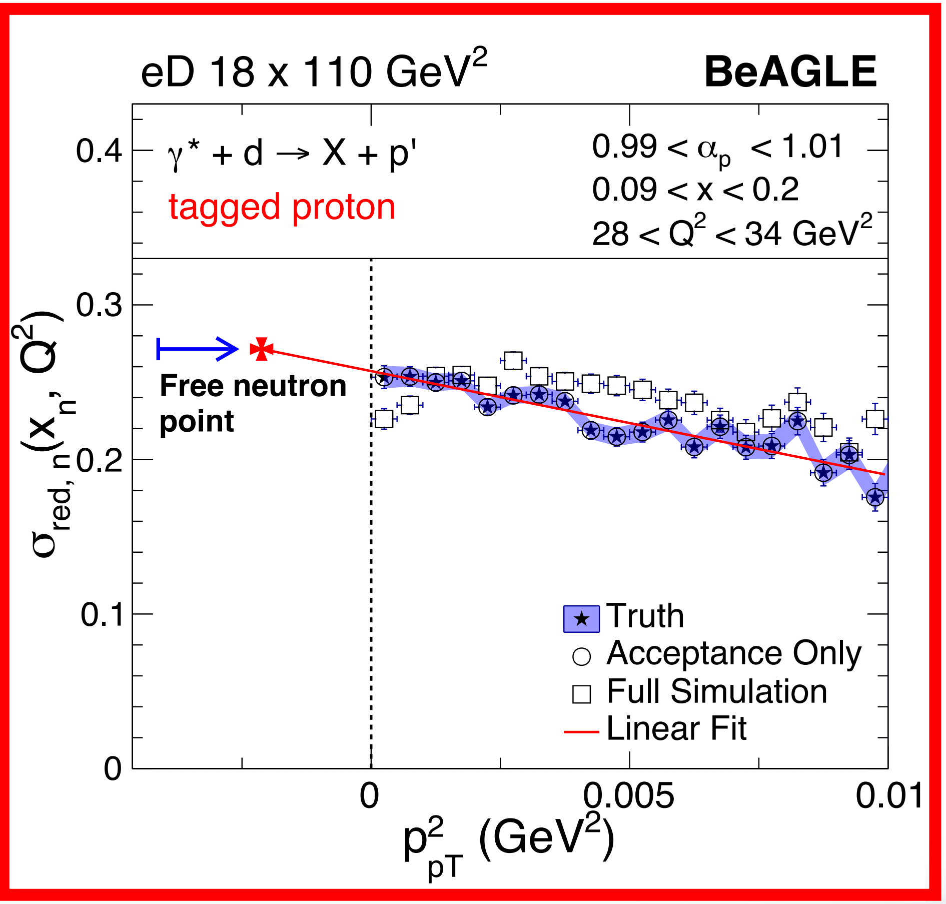


RESULT: Reduced cross section on the **active nucleon.**

$$\times \quad \frac{1}{S_d(p_{pT}, \alpha_p)[pole]}$$

(inverse pole of deuteron spectral function)



(Active nucleon reduced cross section)

$$\sigma_{red,n}(x, Q^2) = \frac{\sigma_{red,d}}{[2(2\pi)^3]S_d(p_{pT}, \alpha_p)}$$

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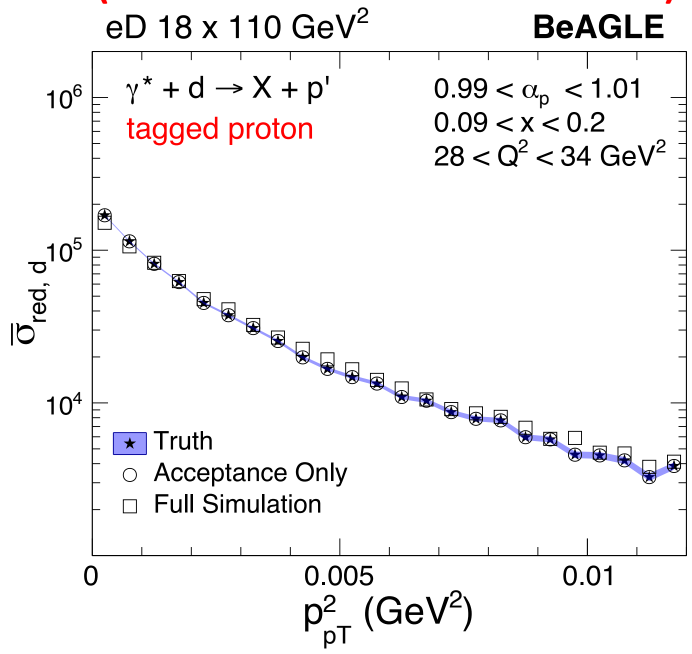

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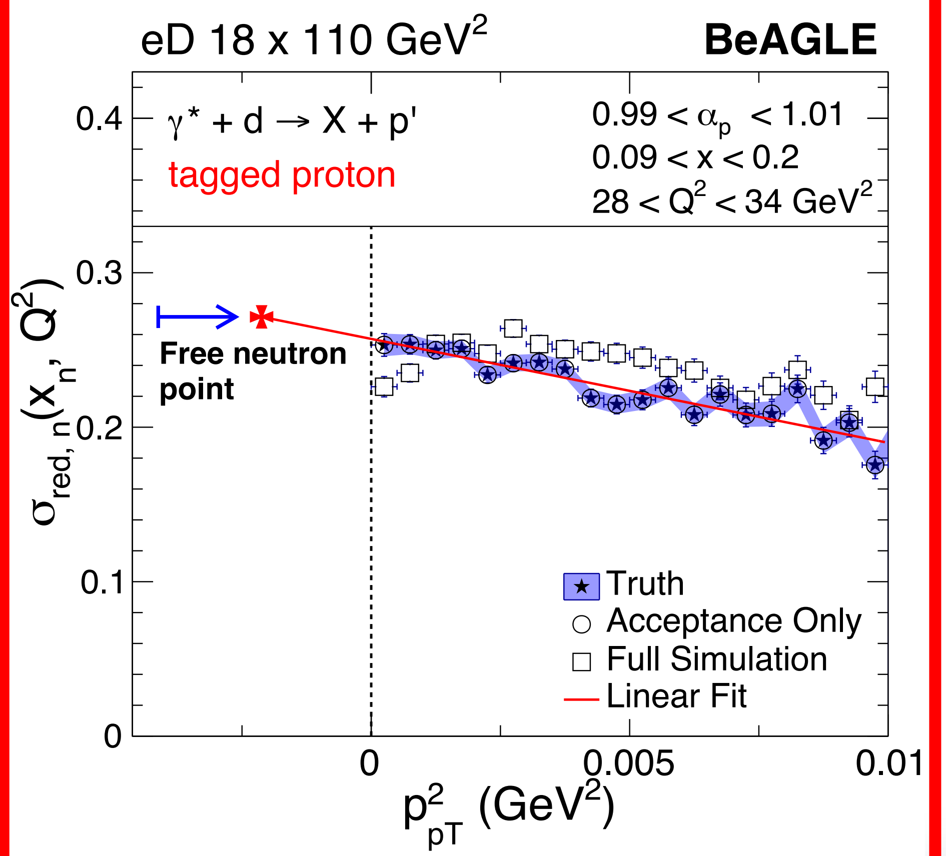


(Active nucleon reduced cross section)

- Resulting dependence on p_{pT}^2 is very weak and the extrapolation can be performed with a 1st-degree polynomial fit.
- Extrapolation only performed for the generator-level distribution.

$$R = 2\alpha_p^2 m_N \Gamma^2 (2 - \alpha_p)$$

$$a_T^2 = m_N^2 - \alpha_p(2 - \alpha_p)\frac{M_d^2}{4}$$

$$R = residue\ of\ spectral\ function$$

$$a_T^2 = position\ of\ pole$$

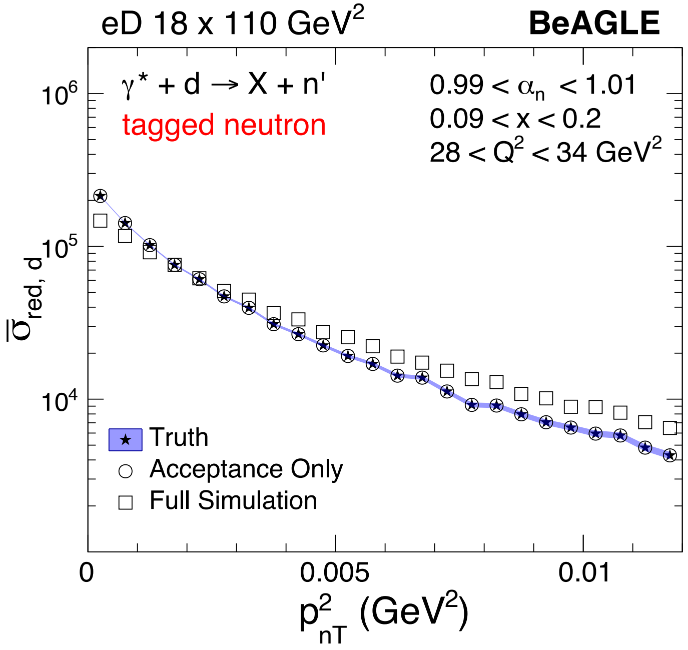
$$S_d(p_{pT}, \alpha_p)[pole] = \frac{R}{(p_{pT}^2 + a_T^2)^2}$$

$$\sigma_{red,n}(x, Q^2) = \frac{\sigma_{red,d}}{[2(2\pi)^3]S_d(p_{pT}, \alpha_p)}$$

Free Proton F_2 Extraction

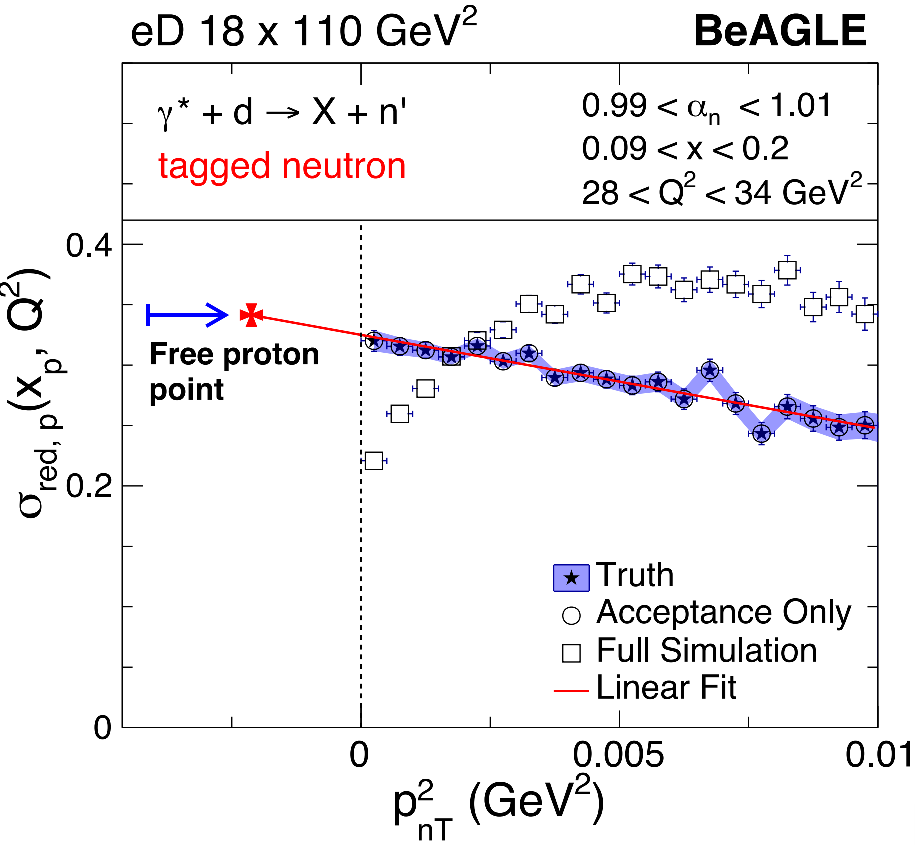
A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104**, 065205, (2021) **(Editor's Suggestion)**

(deuteron reduced cross section)



$$\frac{1}{S_d(p_{pT},\alpha_p)[pole]}$$

(inverse pole of deuteron spectral function)



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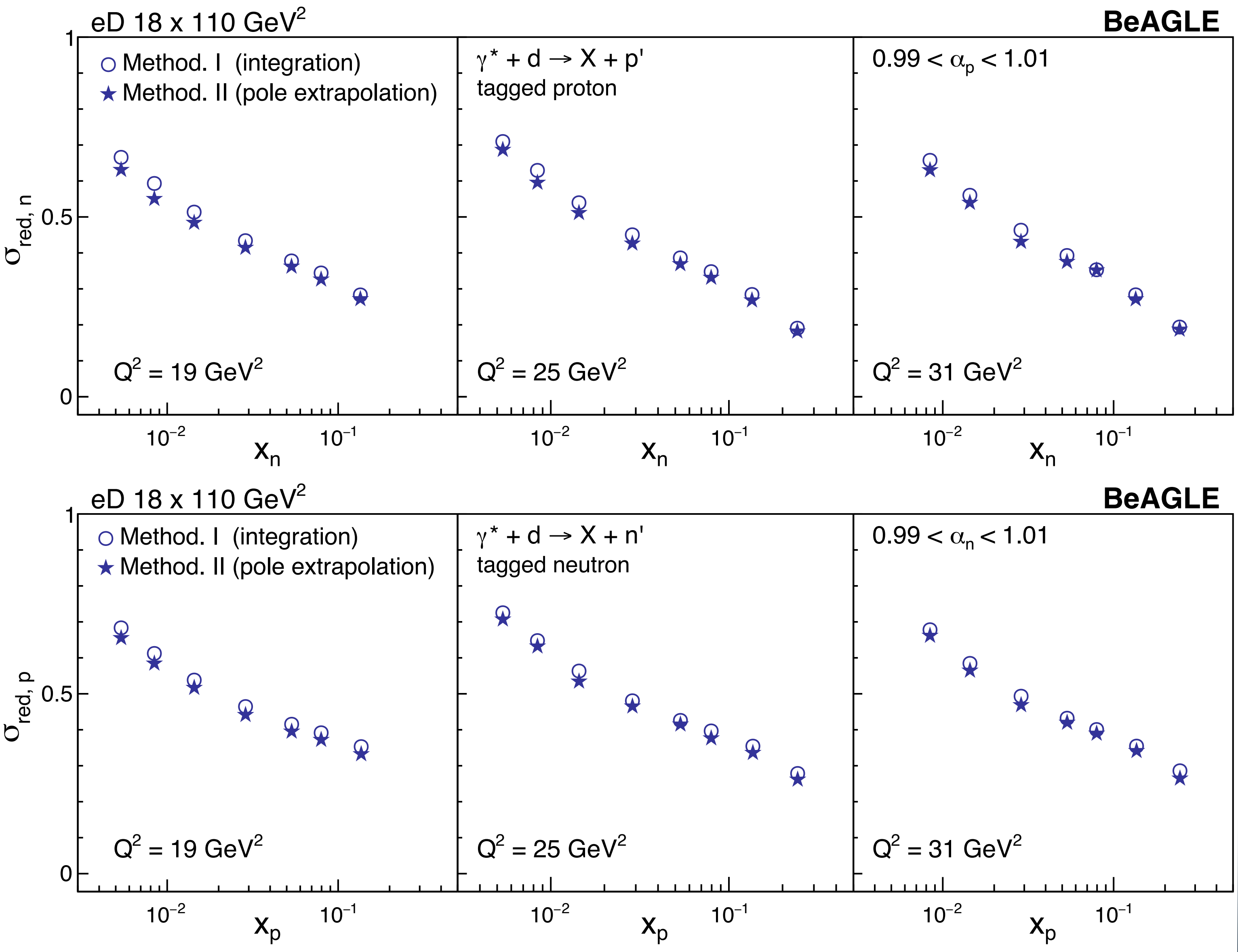
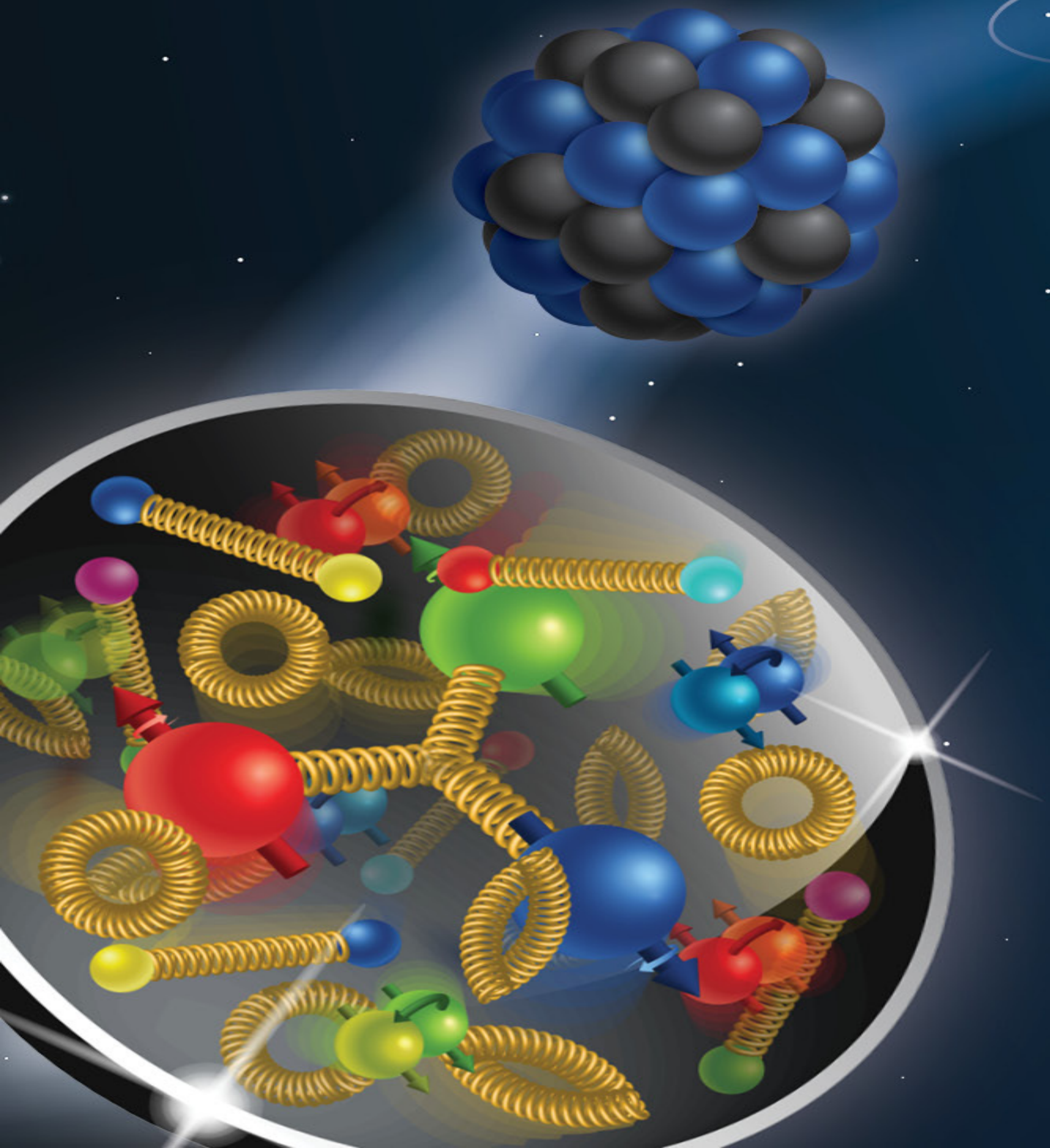
Free Nucleon Structure

A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**



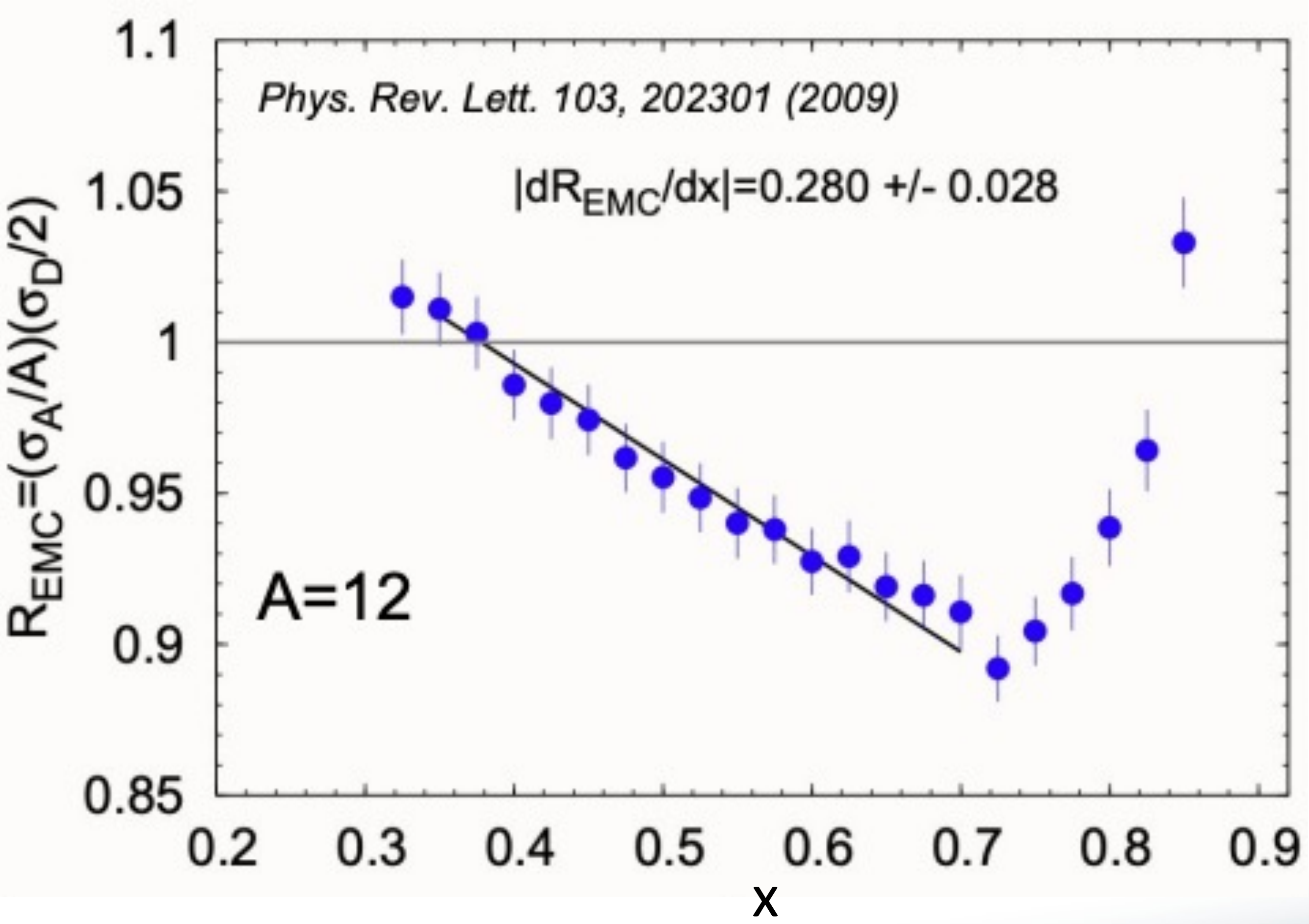
- Pole factor removed using "average" approach.
  - Pole factor calculated in each (α, Q^2, x) bin – shows sensitivity of pole factor to different nuclear configurations.
  - Difference between "stars" and open circles due to the approach in removing the pole factor.
  - This method leads to ~ few percent percent discrepancy between the inclusive and pole extrapolated results.



Light nuclei – deuterons: The EMC Effect (on-going study)

The EMC Effect

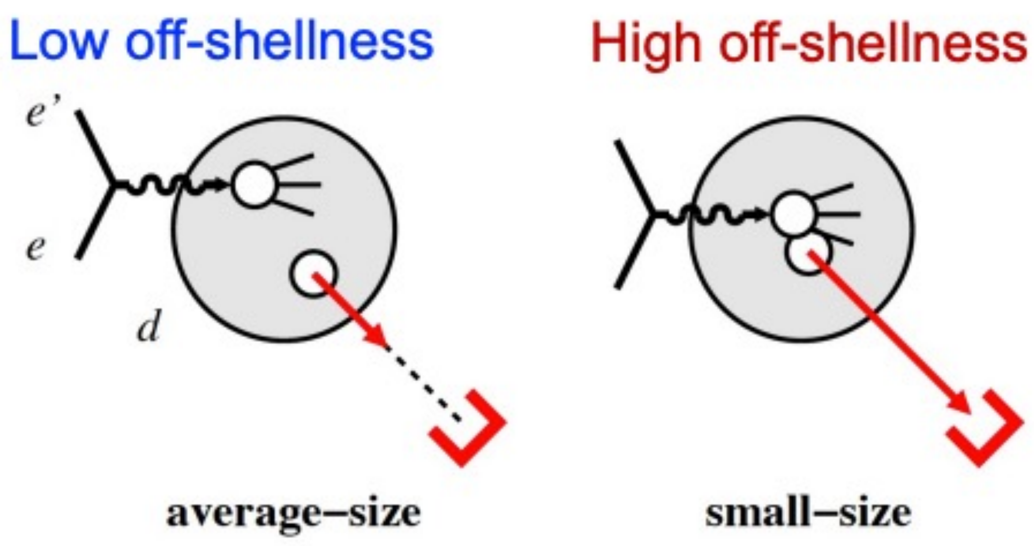
- Discovered by the European Muon Collaboration ~40 years ago.
  - Puzzle: why the dip?
- Still an unanswered question, and one we hope the EIC can aid in answering.

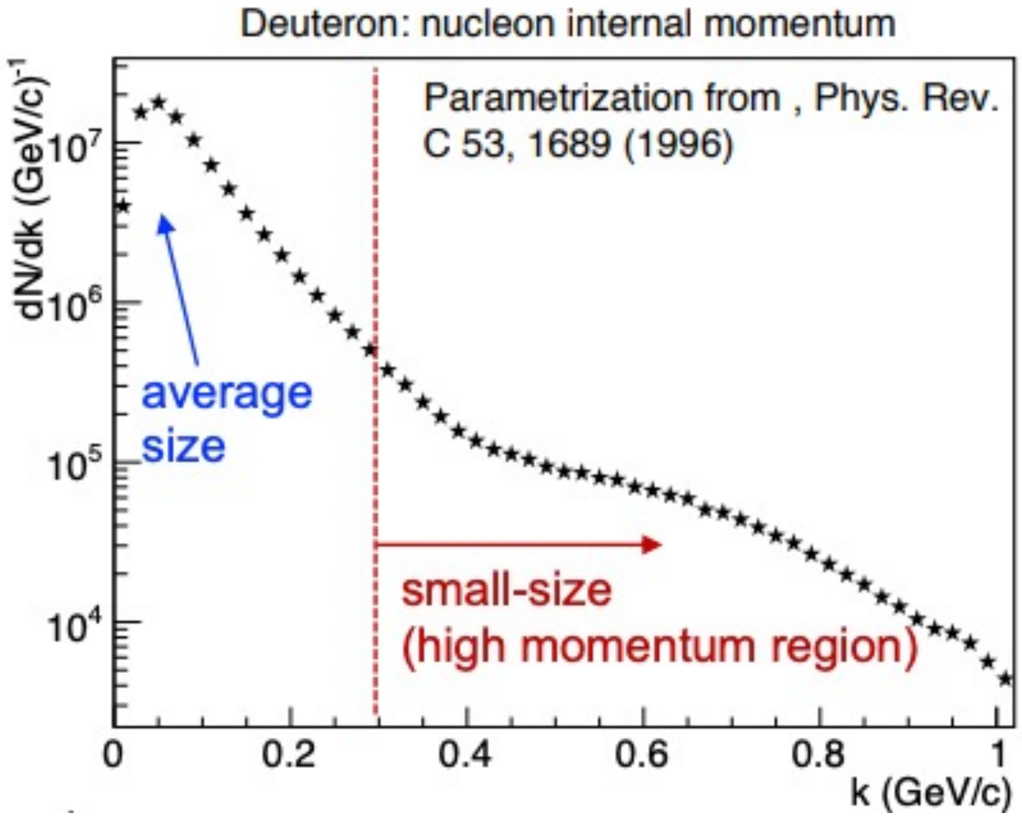


The EMC Effect

- Potential pathway forward – study off-shell effect in deuterons.

Tagged DIS Process: e + d → e' + X + p' or n'



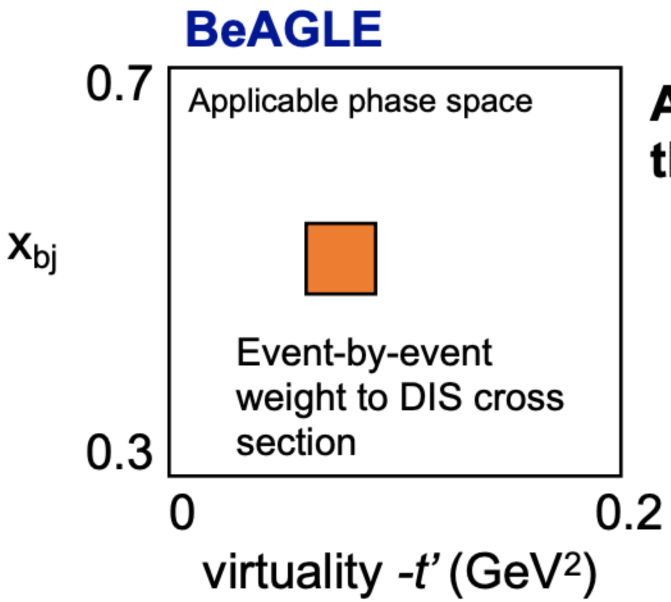


$$-t'^2 = M_N^2 - (p_d - p_p)^2$$

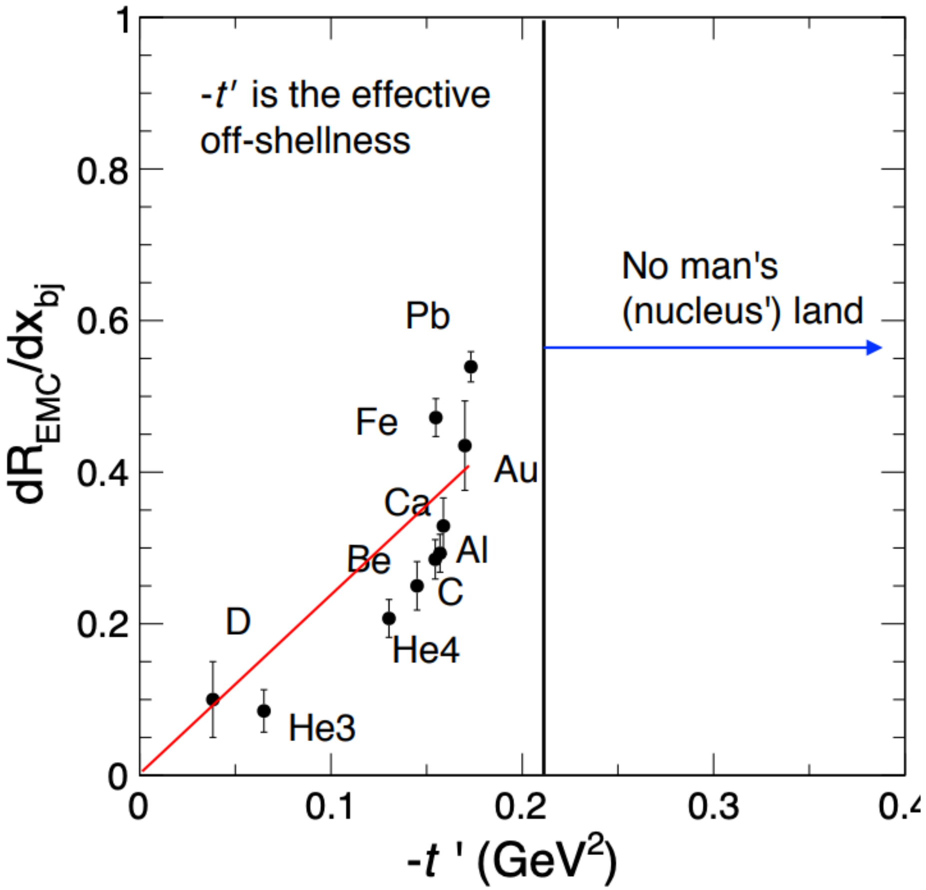
Virtuality/off-shellness in the deuteron

Question: can the EMC effect be controlled via the off-shellness without altering the colliding system?
Our goal: establish experimental prospects to see if we will be sensitive enough to study this!

The EMC Effect



Add EMC effect according to the linear parametrization



- Only apply to $0.3 < x_{bj} < 0.7$
- Q^2 independent
- Weight = F_2 (bound)/ F_2 (free)

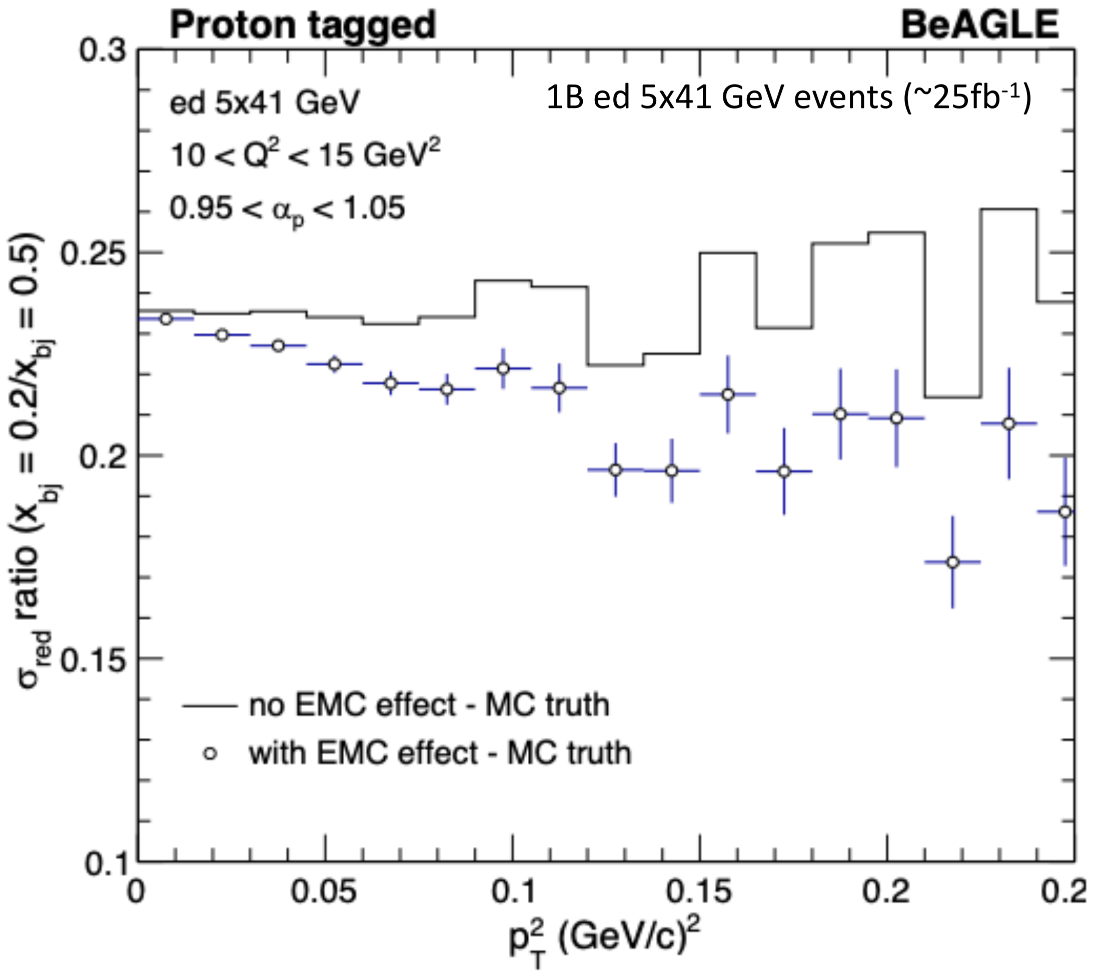
Minimal parametrization (linear)

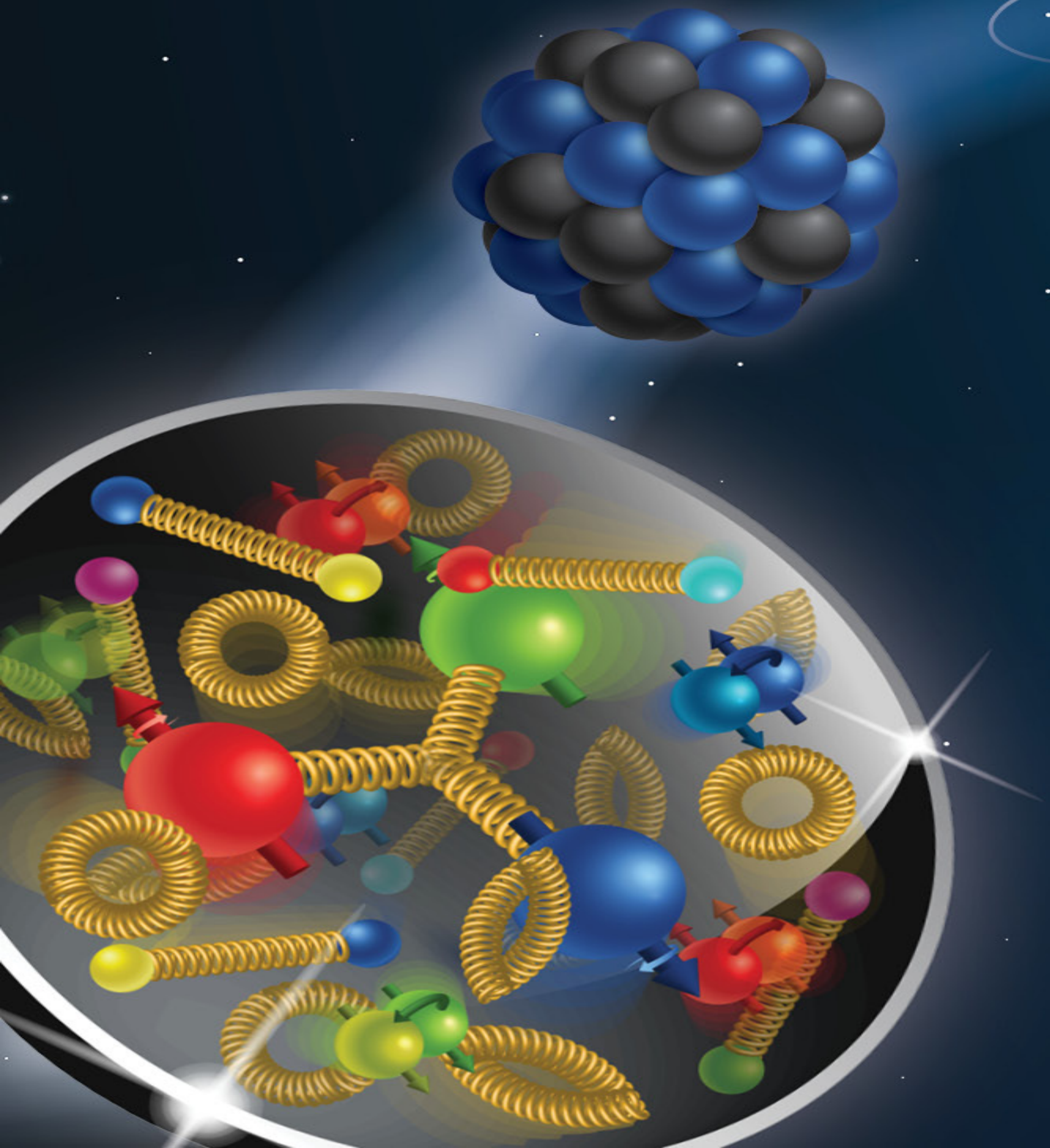
Linear offshell dependence on the EMC effect.
(Frankfurt, Strikman 80’, Weiss)

The EMC Effect

Reduced cross section ratio $\frac{\sigma_{red}^{x=0.2}}{\sigma_{red}^{x=0.5}}$

- Basic method:
  - Introduce off-shell dependence using linear parametrization in BeAGLE.
  - Measure reduced cross-section as in the free neutron study, with and without the off-shell effects included.
  - Take ratio of reduced cross sections in both cases of x-bins inside and outside the EMC region (e.g. x ~ 0.5)
  - See if integrated luminosity allows for separation of distributions with and without off-shell effects.



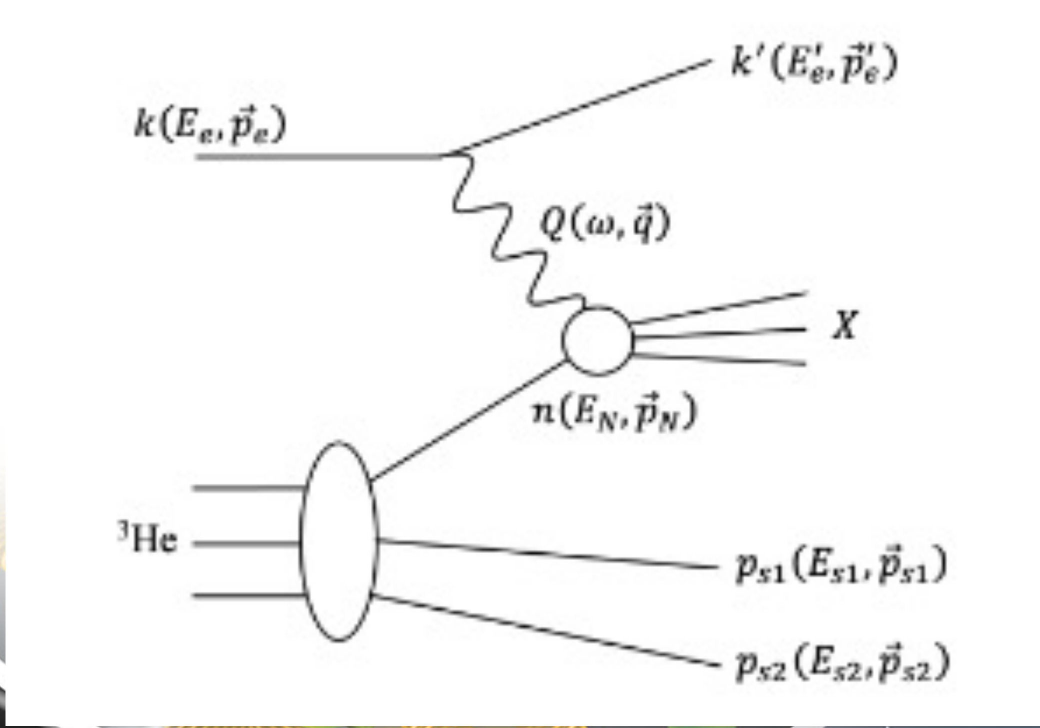


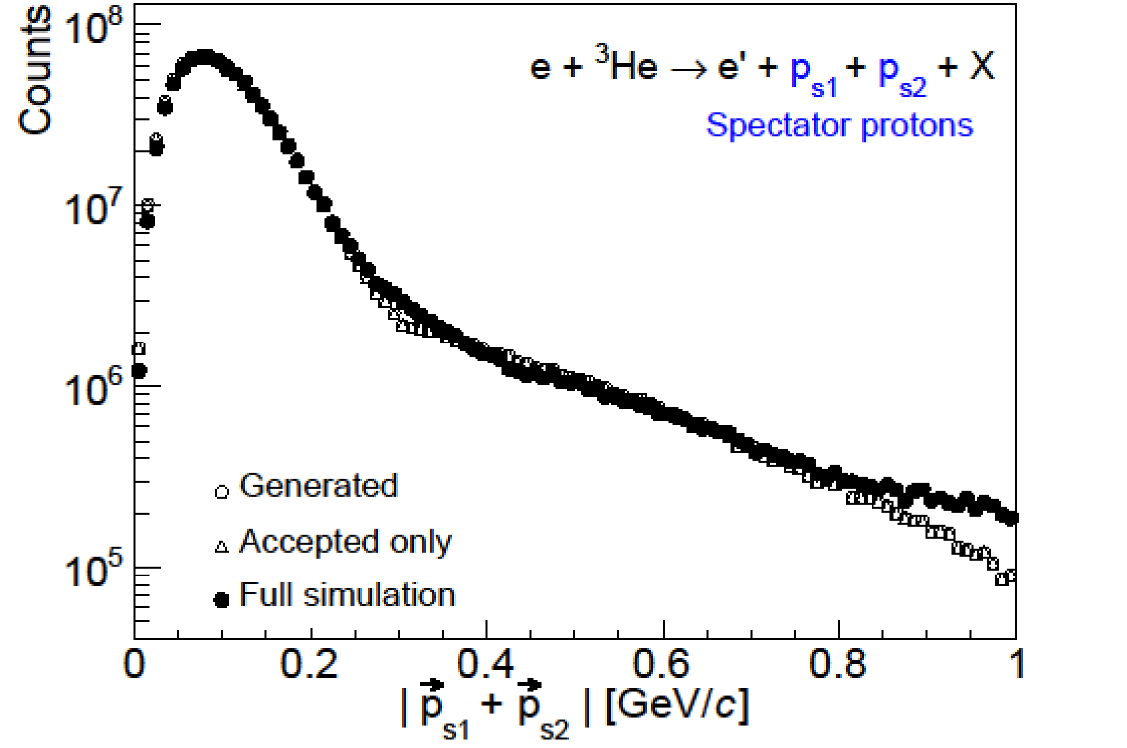
Light nuclei – Helium-3: Neutron Spin Structure

Neutron Spin Structure in He3

I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*,
Phys. Lett. B, **Volume 823**, 136726 (2021)

- Studies of neutron structure with a *polarized* neutron.
- More challenging final state tagging since *both* protons must be tagged.
- MC events generated with CLASDIS in fixed-target frame, and then boosted to collider frame.



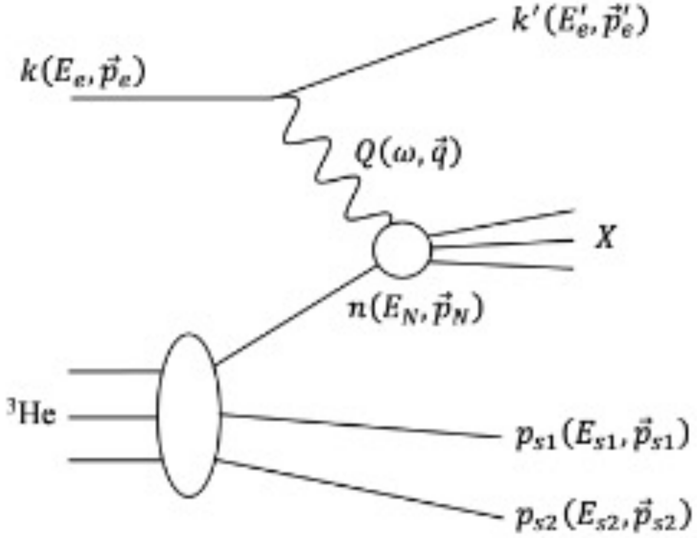


Neutron Spin Structure in He3

I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)

- Spin structure probed via spin asymmetries!

$$A_1^{^3\text{He}} = \underbrace{P_n \frac{F_2^n}{F_2^{^3\text{He}}} A_1^n}_{\text{Neutron}} + \underbrace{2P_p \frac{F_2^p}{F_2^{^3\text{He}}} A_1^p}_{\text{Protons}}$$



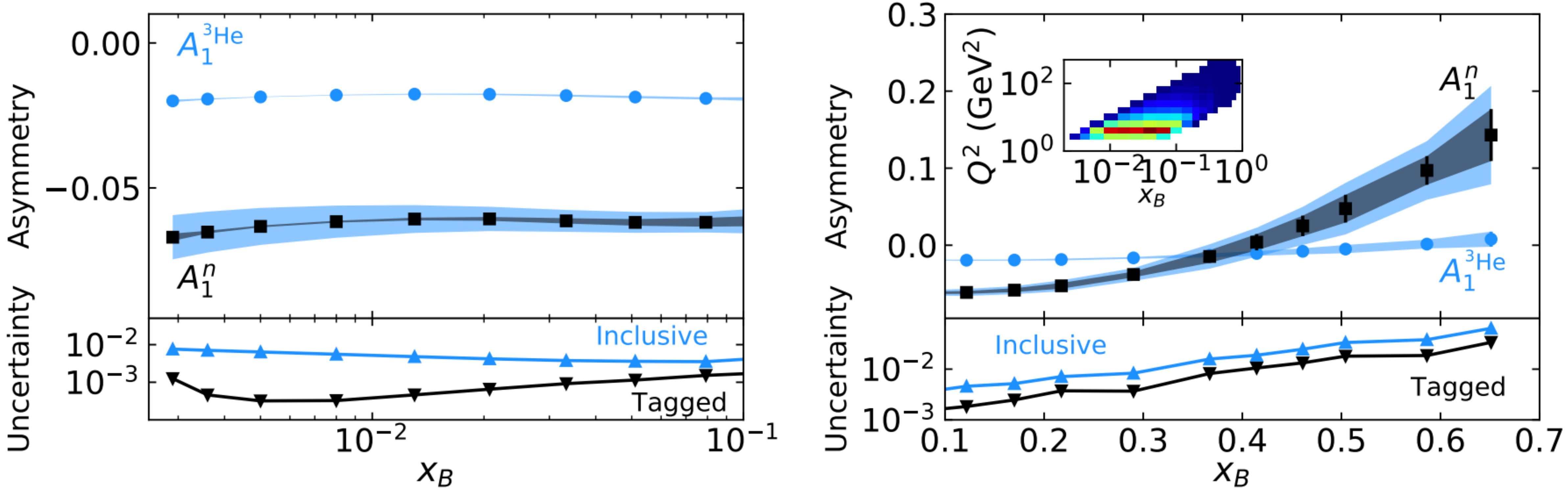
- (double) Tagged DIS measurement capable of measuring A_1^n directly!
- Complementary to measurements at JLAB.

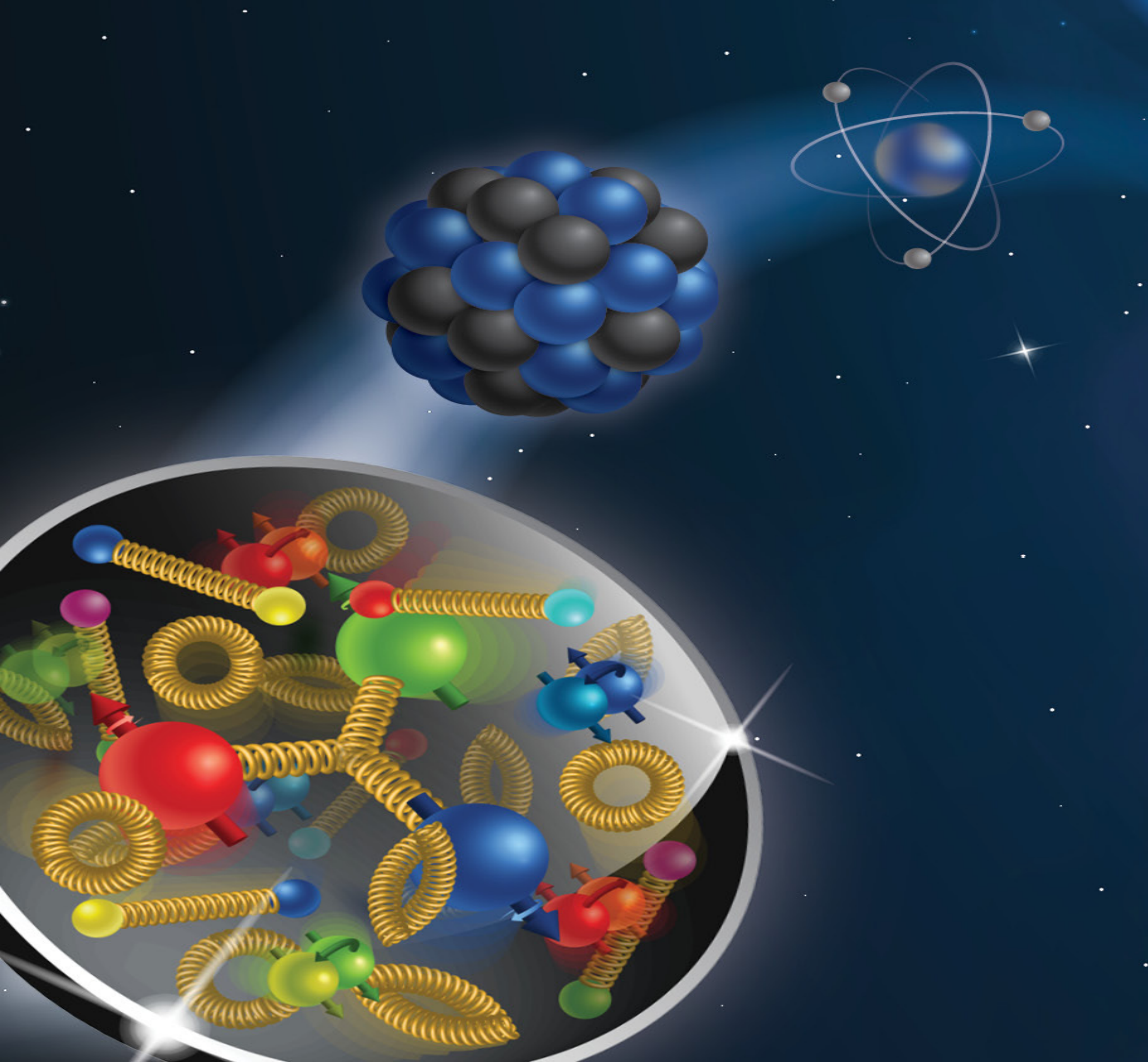
Neutron Spin Structure in He3

I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)

- Neutron spin asymmetries can be measured from kinematics of the tagged protons.
- EIC can build upon measurements at JLAB by reducing polarization uncertainties, and opening a broader Q^2 range for study.
- Can aid in our understanding of quark orbital angular momentum in nucleons.

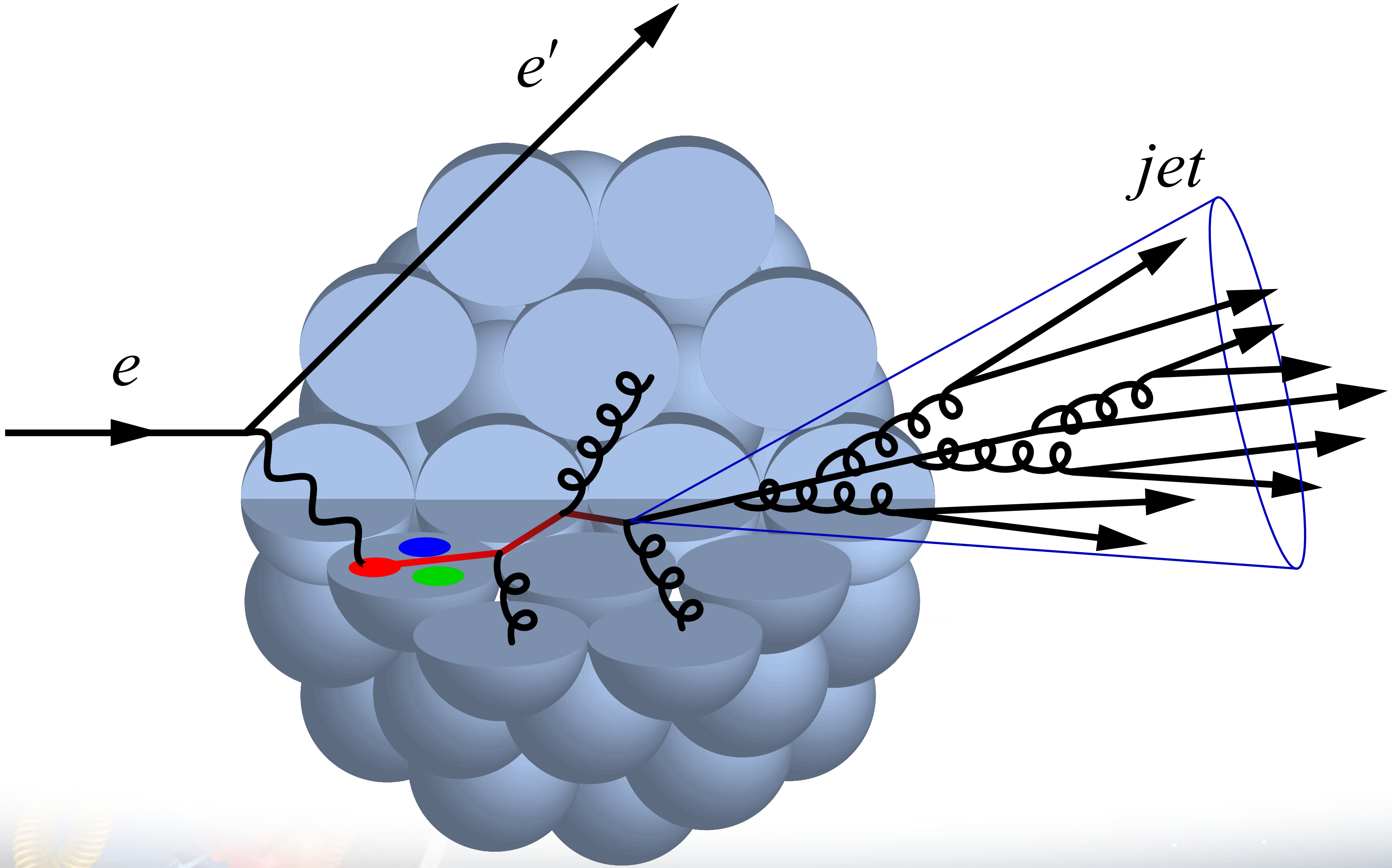
Low-x High-x



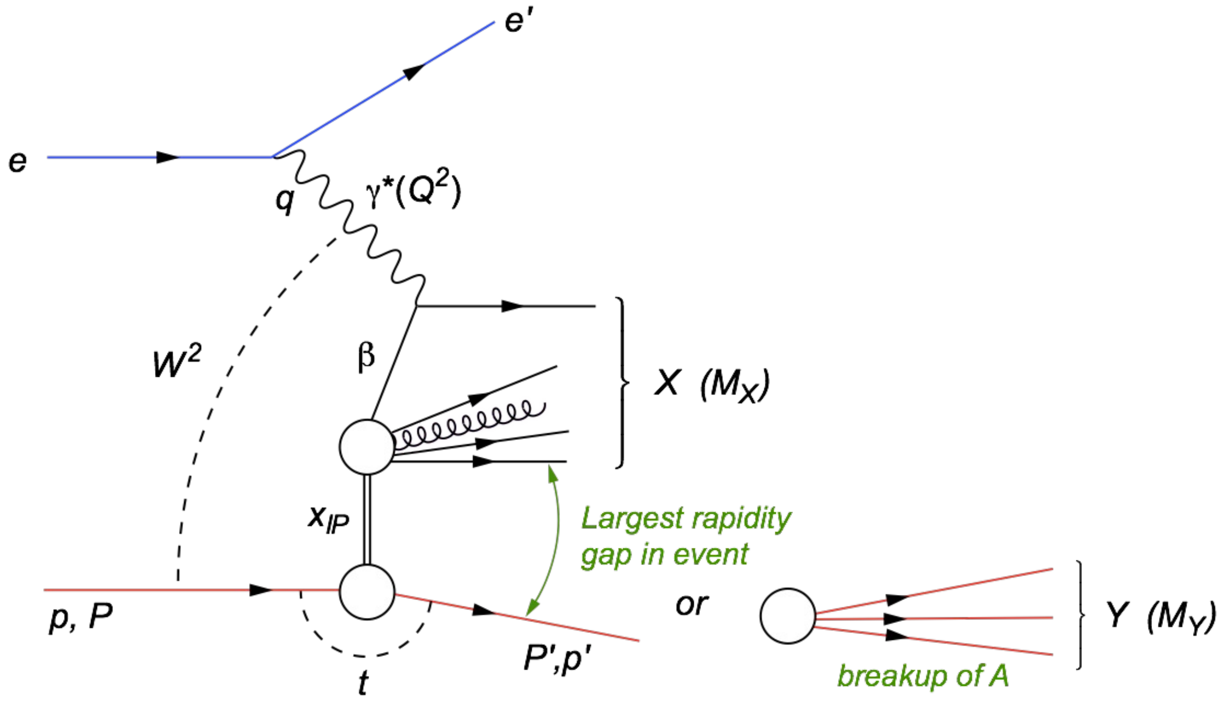


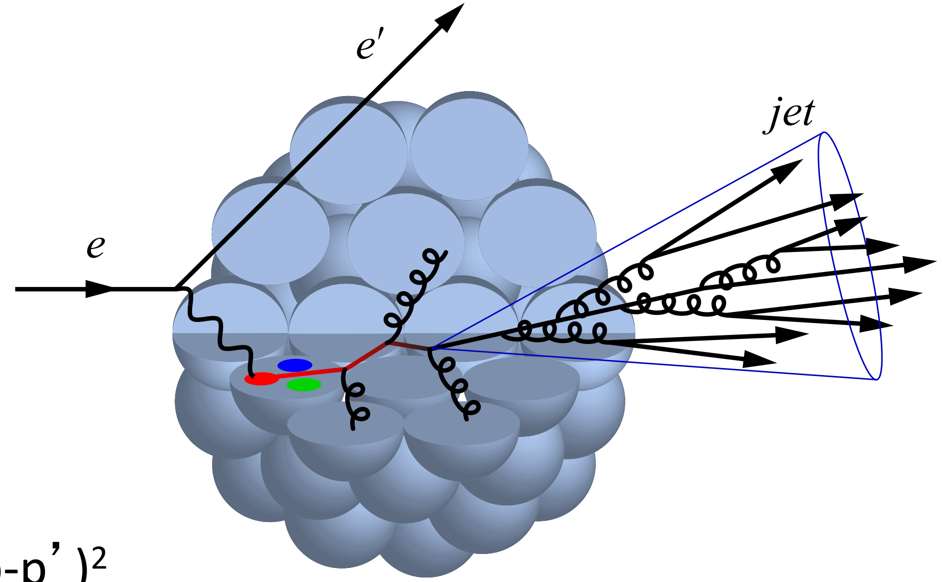
Time permitting:
Heavy Nuclei

What about (light) Nuclei?



Diffraction in Nuclei





- $t = (p-p')^2$
- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

$$\frac{d^4\sigma^{eh\to eXh}}{dx dQ^2 d\beta dt} = \frac{4\pi\alpha_{em}^2}{\beta^2 Q^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2^{D,4}(x,Q^2,\beta,t) - \frac{y^2}{2}F_L^{D,4}(x,Q^2,\beta,t)\right]$$

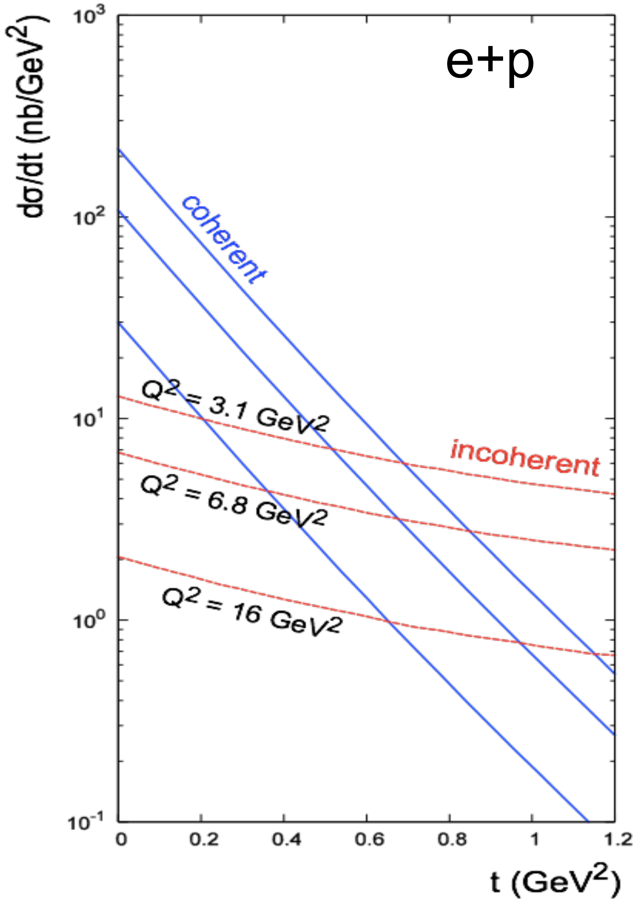
Diffraction in e+p:

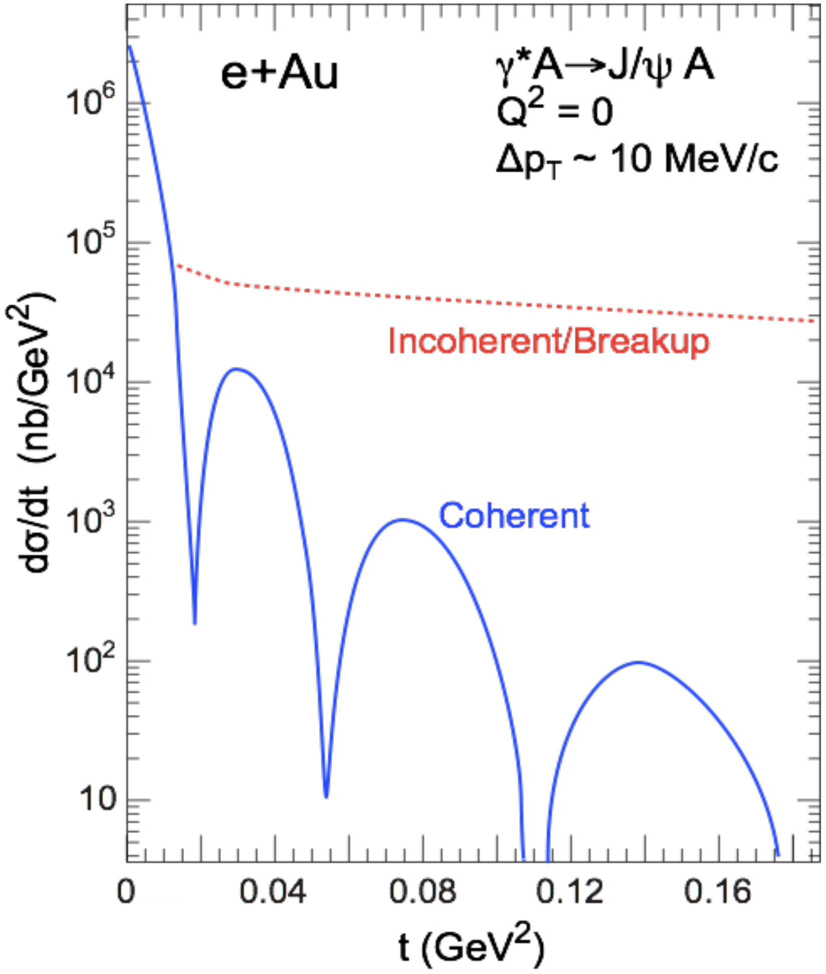
- coherent ⇔ p intact
- incoherent ⇔ breakup of p
- HERA: 15% of all events are hard diffractive

Diffraction in e+A:

- coherent diffraction (nuclei intact)
- breakup into nucleons (nucleons intact)
- incoherent diffraction
- Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%

Diffraction in Nuclei





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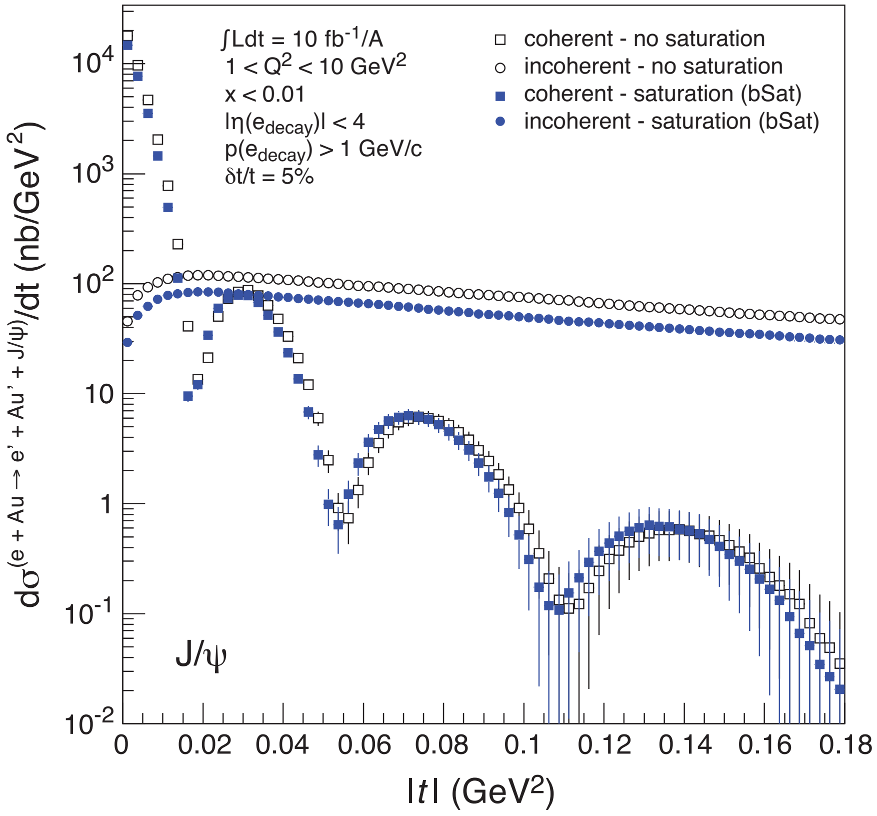
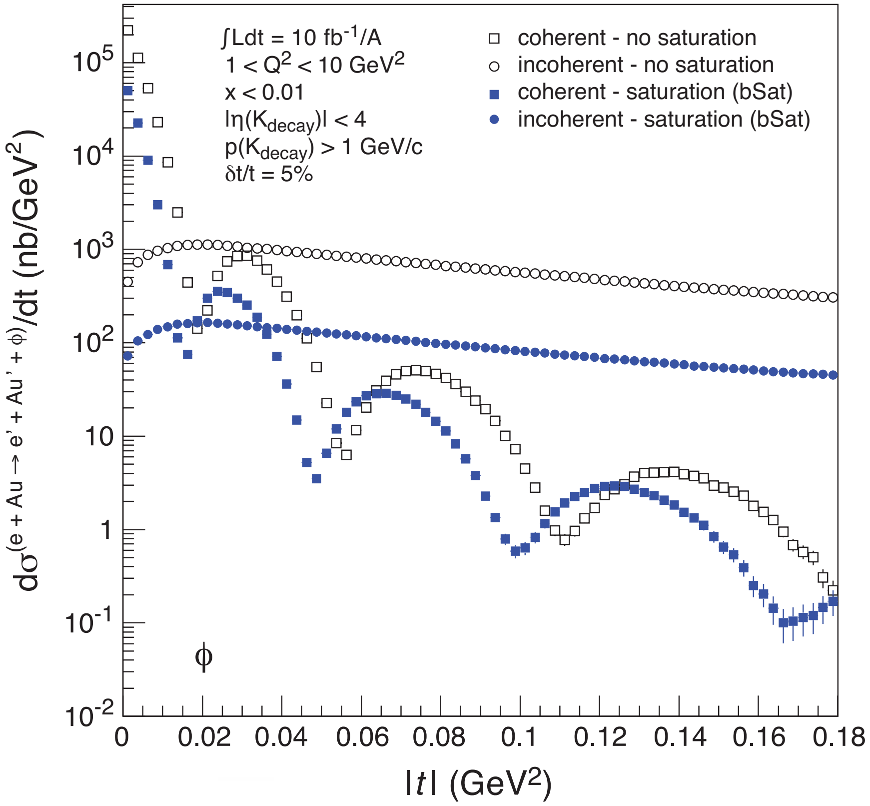
Spatial Gluon Distribution from dσ/dt

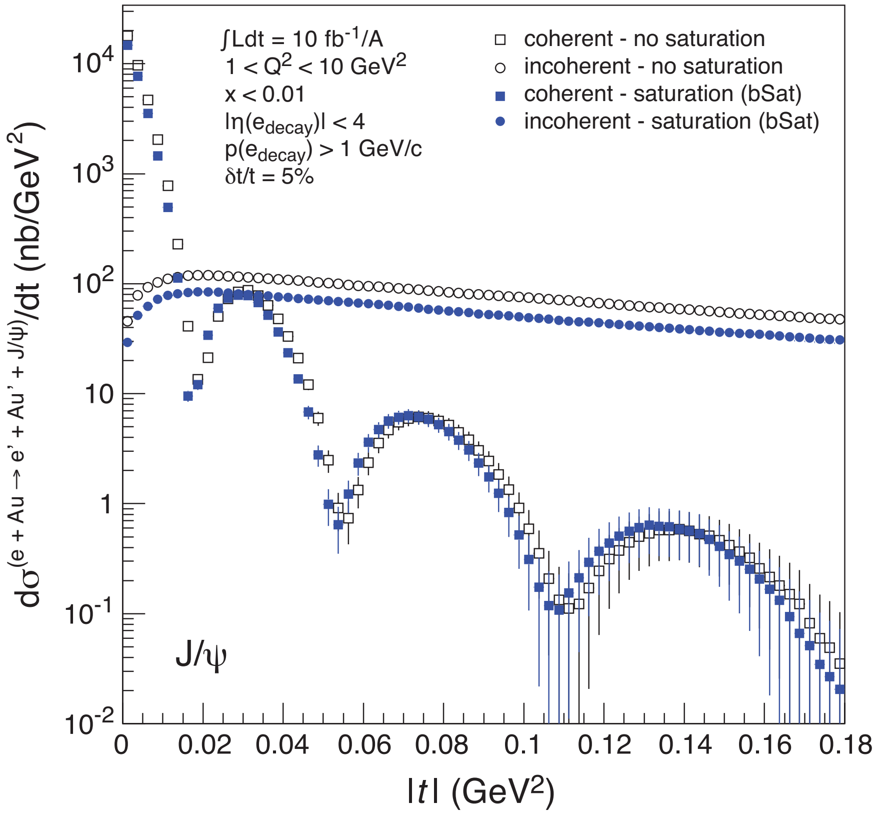




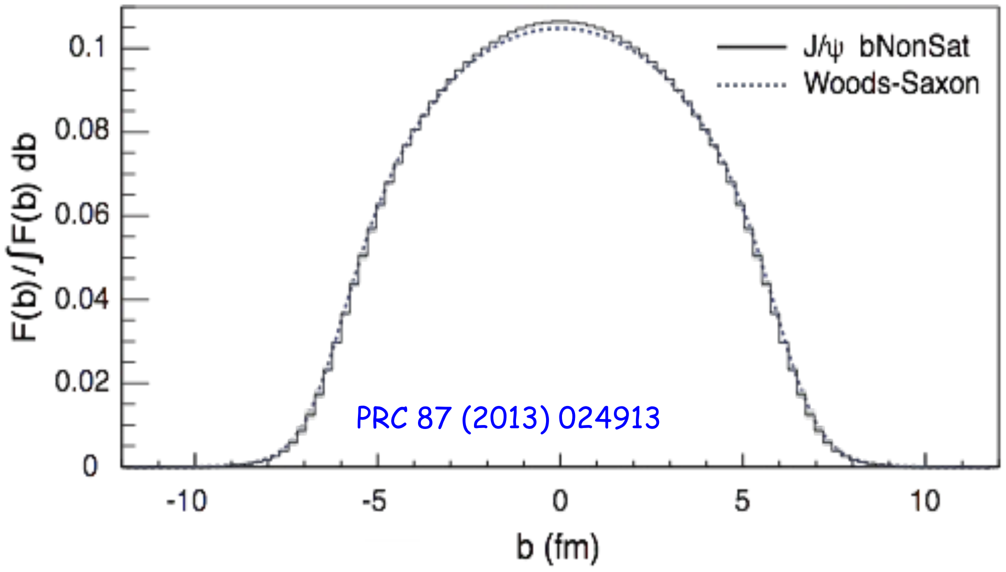
- Converges to input F(b) rapidly: $|t| < 0.1$ almost enough
- Recover accurately any input distribution used in model used to generate pseudo-data (here Wood-Saxon)
- Systematic measurement requires ∫*Ldt* >> 1 fb^{-1}/A

> - *dσ/dt:* diffractive pattern known from wave optics
> - *φ* sensitive to saturation effects, smaller *J/ψ* shows no effect
> - *J/ψ* perfectly suited to extract source distribution

Spatial Gluon Distribution from dσ/dt



Fourier Transform



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- *dσ/dt:* diffractive pattern known from wave optics
- *φ* sensitive to saturation effects, smaller *J/ψ* shows no effect
- *J/ψ* perfectly suited to extract source distribution

Lecture 1 summary

- Far-forward physics characterized by exclusive+diffractive final states.
  - Lots to unpack! – proton spin, neutron structure, saturation, partonic imaging, meson structure, etc.
- There is lots of interest in the EIC community in studying this physics via these final states!
  - Exciting time to get involved!!
- Special thanks to Elke Aschenauer, Salvatore Fazio, and Kong Tu for some slides!!

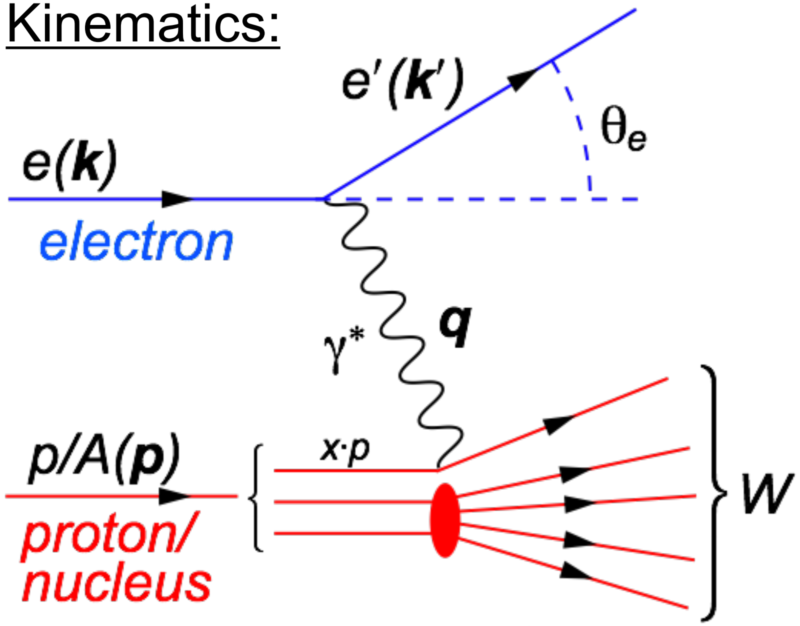
Email me if you have any questions: ajentsch@bnl.gov

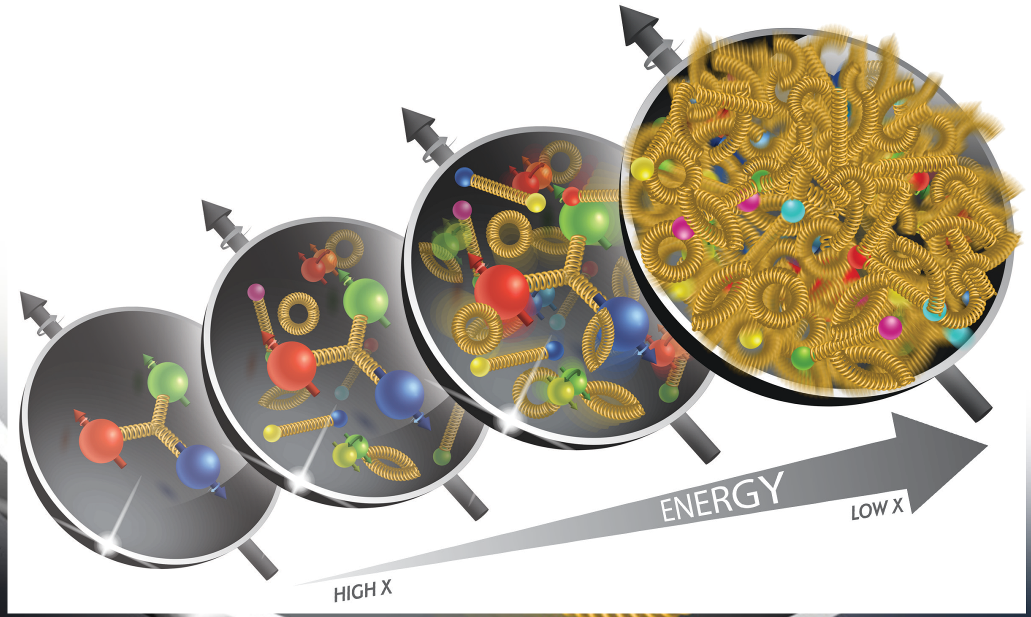
Now…*how* do we do this physics program?
See tomorrow's lecture!

Backup

Primer on Deep Inelastic Scattering (DIS)

Kinematics:





$$Q^2 = 2E_e E'_e(1 - cos\theta'_e) = -q^2$$

Measure of resolution power

$$y = 1 - \frac{E'_e}{E_e} cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq}$$

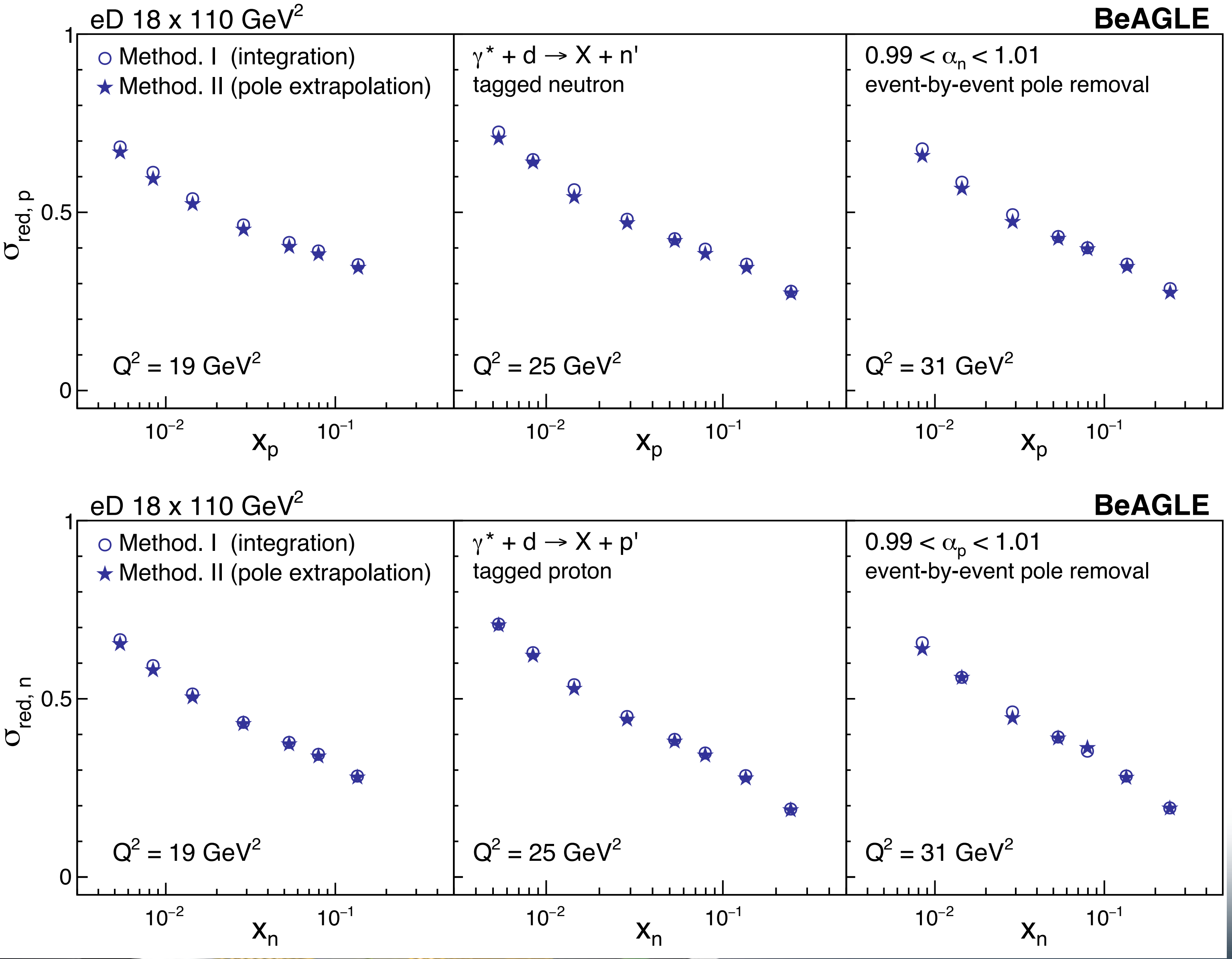
Measure of momentum fraction of struck quark

$$\sqrt{s} = 2\sqrt{E_e E_p}$$

Center-of-mass energy of electron-hadron system

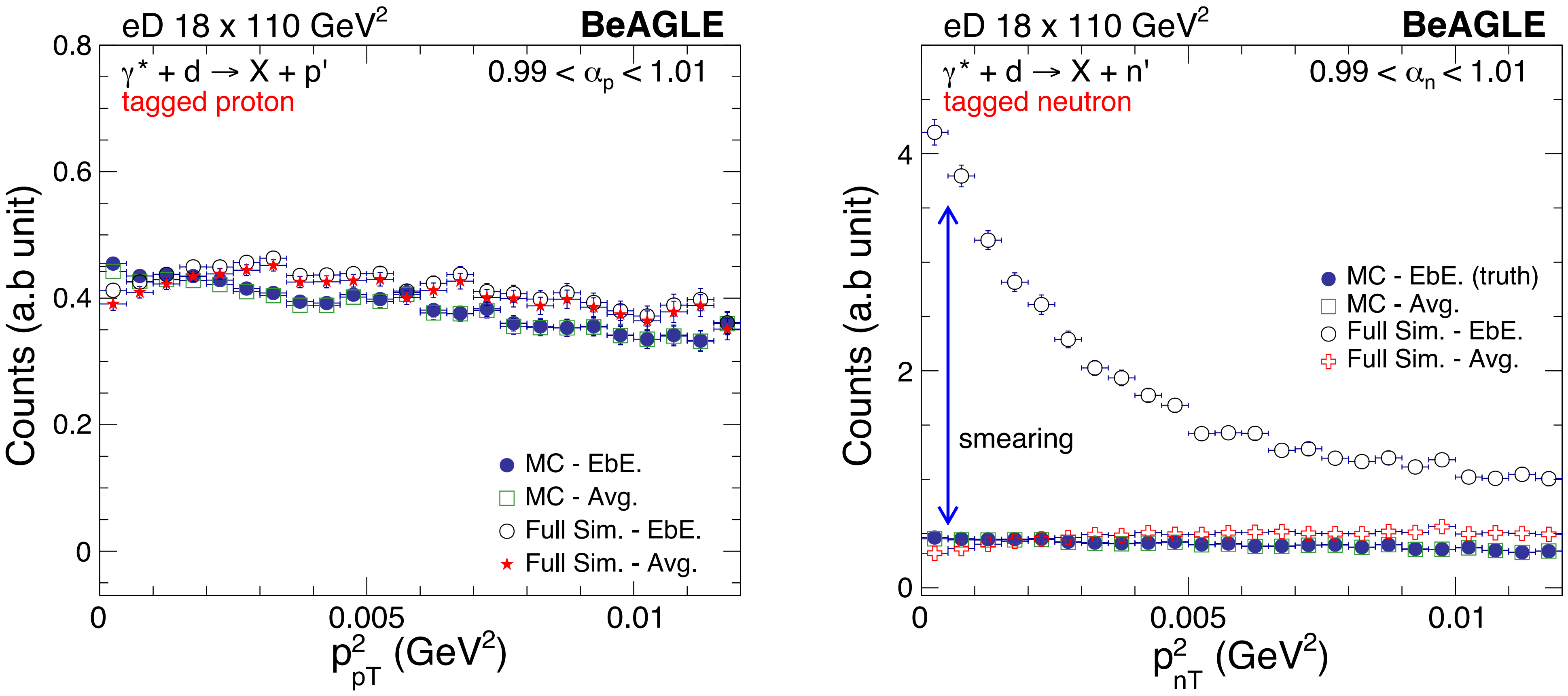
$$Q^2 = s \cdot x \cdot y$$

Closure Test – Event by Event Pole Removal



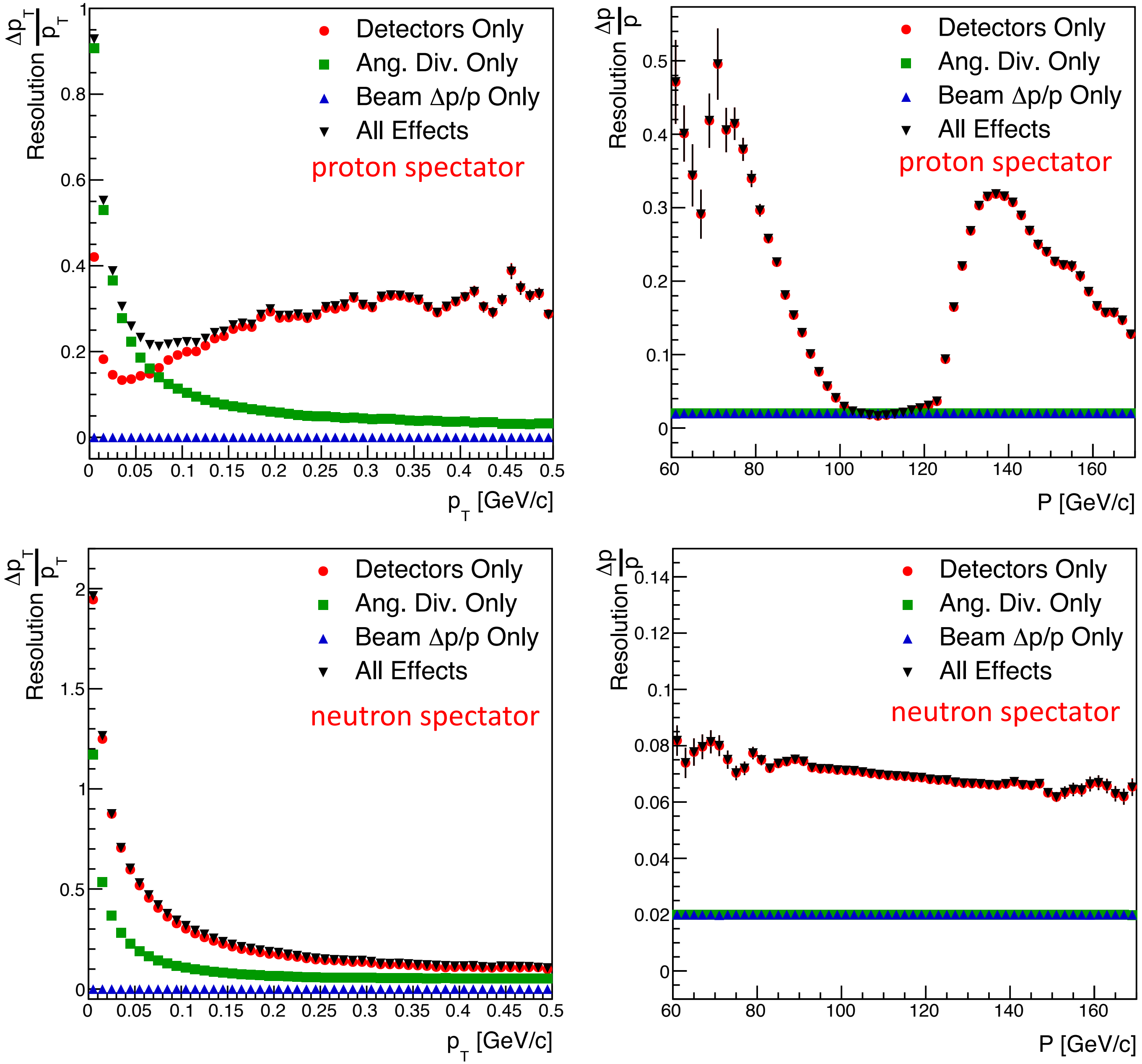
- Pole factor removed using "event by event (EbE)" approach.
  - Pole factor calculated and applied for each event (i.e. pole factor calculated for each exact nuclear configuration).
  - Solved discrepancy at generator level.
    - This was also checked using an independent toy MC to confirm there was nothing related to our analysis code causing an issue.
  - Remaining differences due to fitting and statistics.

Effects of momentum smearing on pole factor



- Detector smearing has a drastic impact when the EbE method is used.
  - If you calculate the pole factor on an EbE basis with *smeared* spectator kinematic values, you now remove the pole factor for the wrong nuclear configuration!

Kinematic Distributions and Smearing



- Event sub-sample passed through full GEANT4 simulations.
  - Smearing parametrizations extracted for (p_x, p_y, p_z, E).
- Larger overall smearing observed for neutrons, consistent with previous study.
- Anomalous proton smearing at high pT and p > 120 GeV/c and p < 100 GeV/c due to linear transfer matrix assumption.
  - Will be fixed in the future for TDR studies.

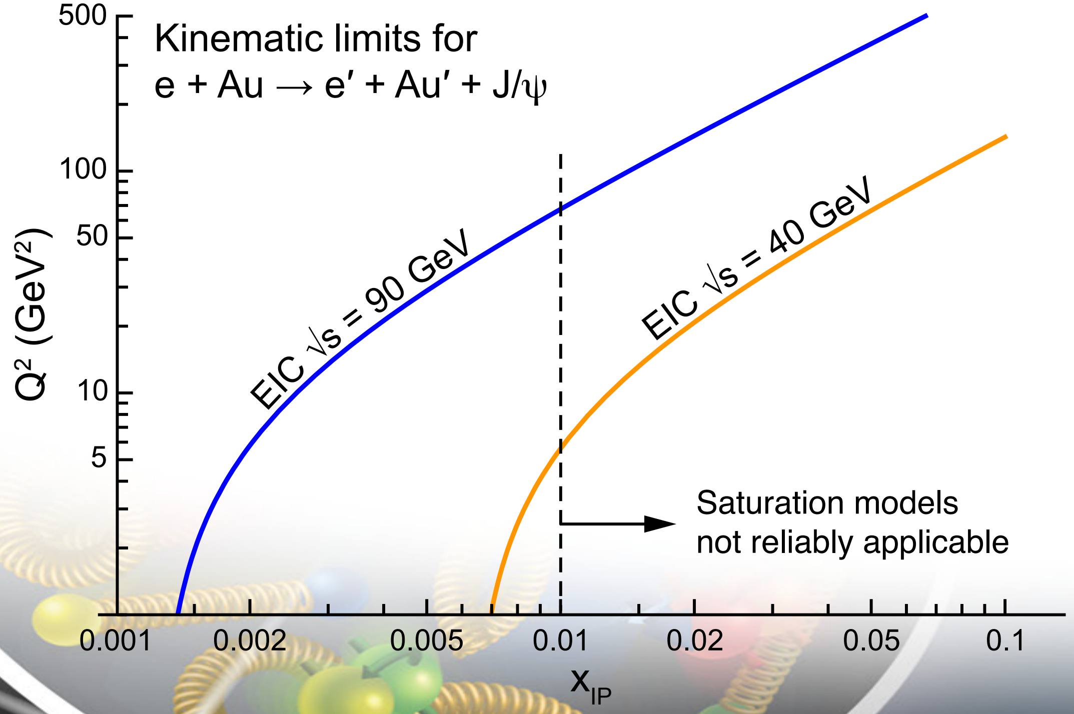
3D-Imaging of Nuclei

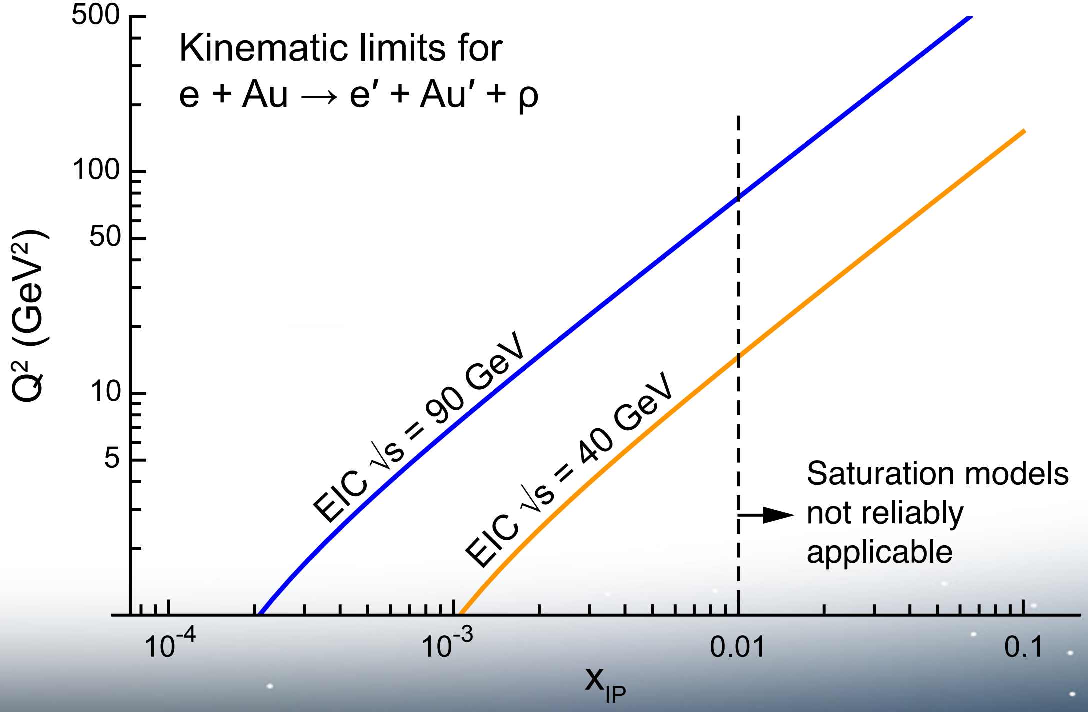
1950-60: Measurement of charge (proton) distribution in nuclei
Ongoing: Measurement of neutron distribution in nuclei
EIC ⇒ spatial gluon distribution in nuclei → Saturated or non-saturated ?

Method:

Diffractive vector meson production: e + Au → e′ + Au′ + J/ψ, ϕ, ρ

- Momentum transfer $t = |\mathbf{p}_{Au}-\mathbf{p}_{Au'}|^2$ conjugate to b_T





Neutron Spin Structure in He3

See Dien's talk later today!!!

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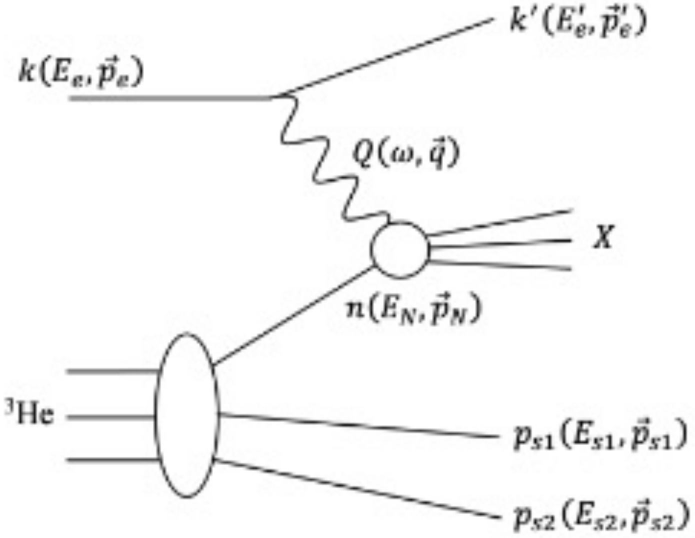
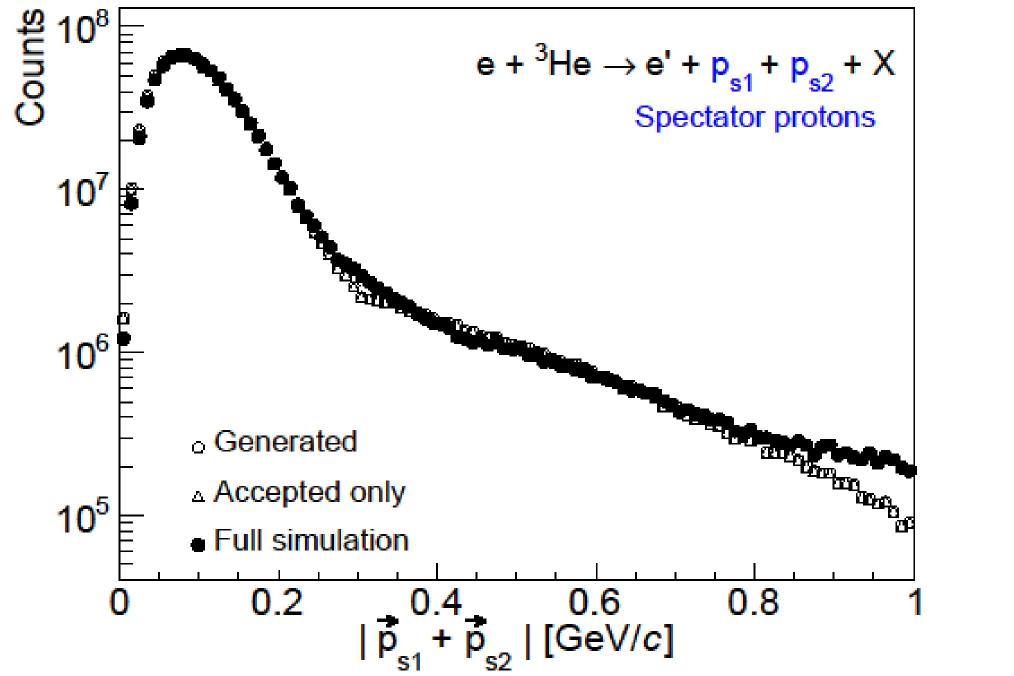
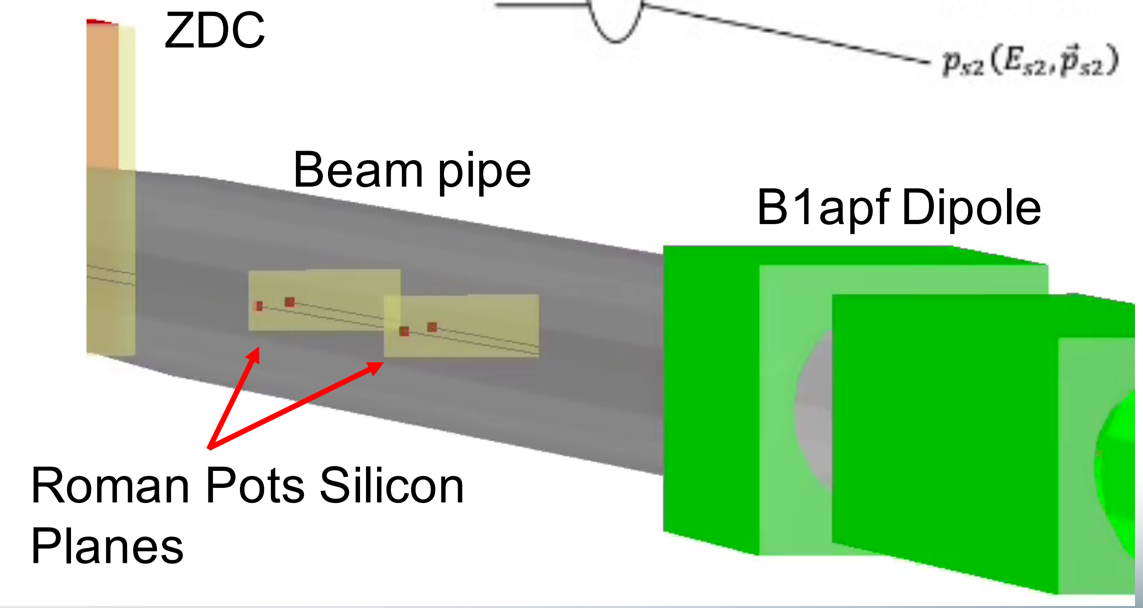
- More challenging final state tagging since *both* protons must be tagged in the FF region.
- MC events generated with CLASDIS in fixed-target frame, and then boosted to collider frame.

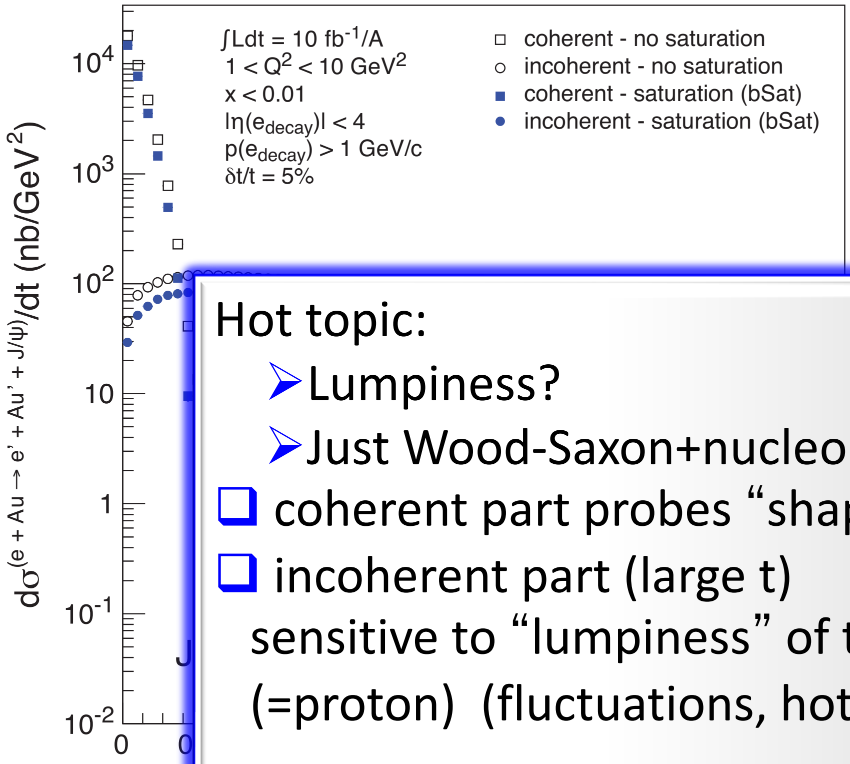






https://arxiv.org/abs/2106.08805
Accepted by Phys. Lett. B just last week!

Spatial Gluon Distribution from dσ/dt



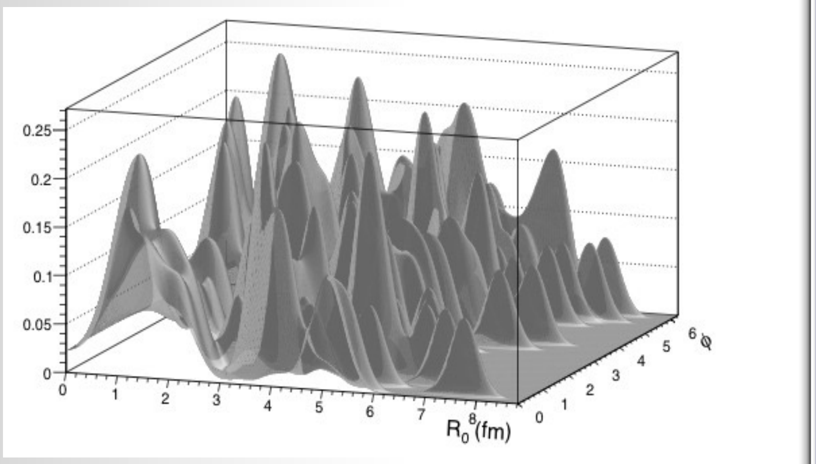
Fourier Transform

Hot topic:

- Lumpiness?
- Just Wood-Saxon+nucleon $g(b_T)$

- coherent part probes "shape of black disc"
- incoherent part (large t) sensitive to "lumpiness" of the source (=proton) (fluctuations, hot spots, ...)

possible Source distribution with b_T^g = 2 GeV^{-2}

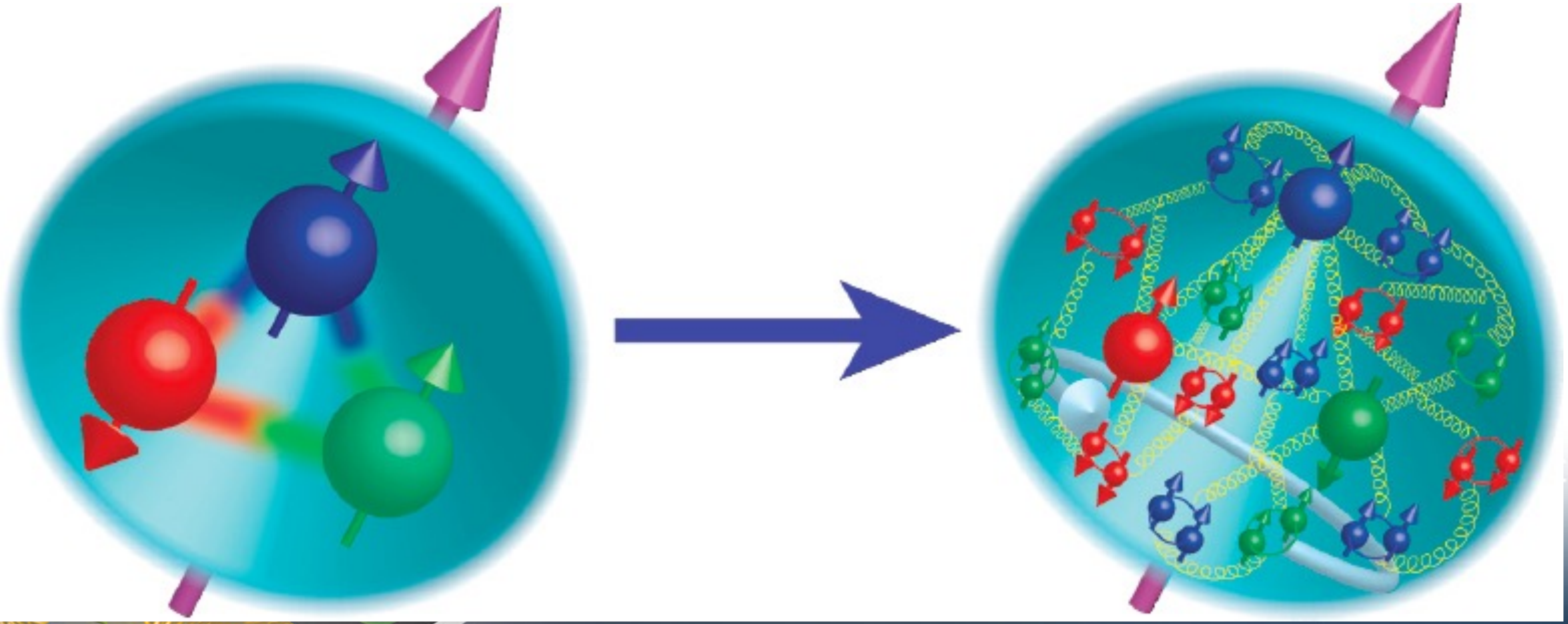


- Converges to input F(b) rapidly: $|t| < 0.1$ almost enough
- Recover accurately any input distribution used in model used to generate pseudo-data (here Wood-Saxon)
- Systematic measurement requires $\int Ldt >> 1$ fb^{-1}/A

- *dσ/dt:* diffractive pattern known from wave optics
- *φ* sensitive to saturation effects, smaller *J/ψ* shows no effect
- *J/ψ* perfectly suited to extract source distribution

Why an EIC? (non-exhaustive)

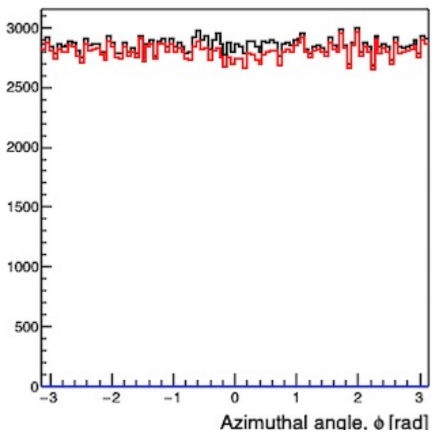
- Deep Inelastic Scattering (DIS) of electrons on protons at SLAC led to discovery of valence quarks inside protons. (1969)
  - QCD was formalized with the discovery of confinement a few years later.
  - Sea quarks (fluctuating pairs of quarks/antiquarks) and gluons also present in nucleons.



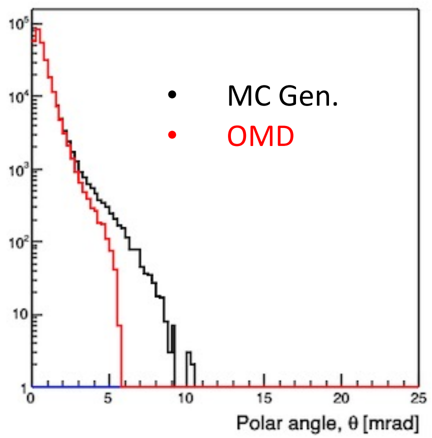
e+d Spectator Tagging

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

Protons

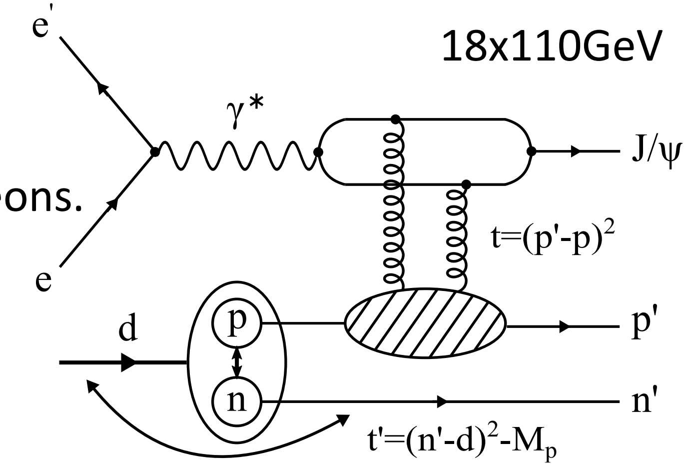


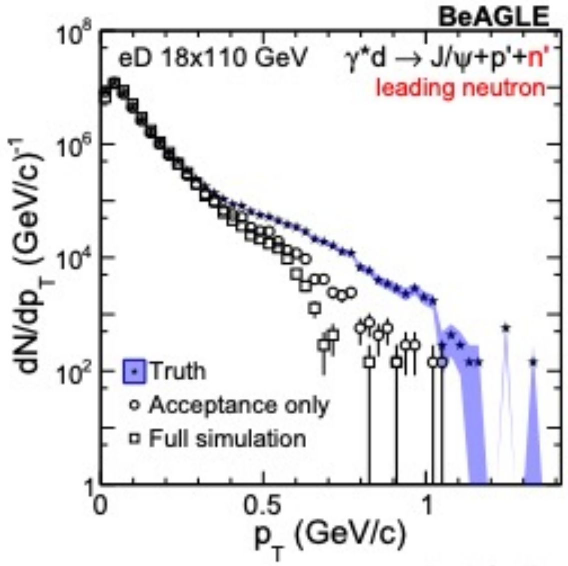
Protons

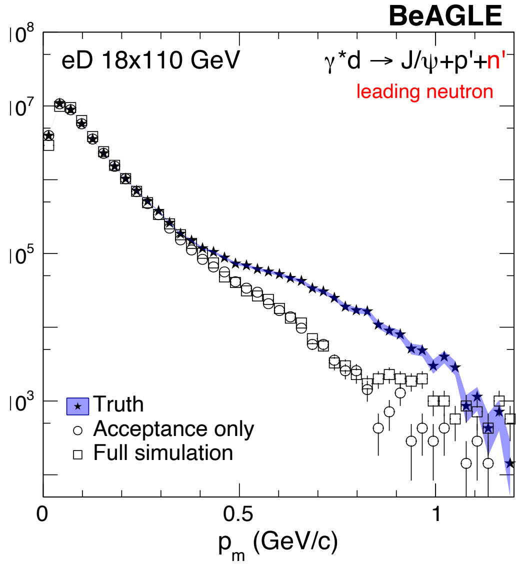


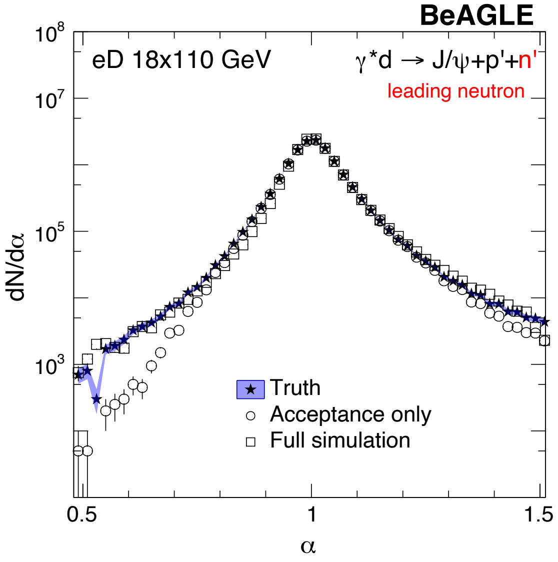
Proton spectator case.

Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.









Spectator kinematic variables reconstructed over a broad range. Bin migration is observed due to smearing in the reconstruction. Each plot shows the MC (closed circles), acceptance effects only (open circles), and full reconstruction (open squares).

- **In the proton spectator case, essentially all spectators tagged.**
- **Active neutrons only tagged up to 4.5 mrad.**