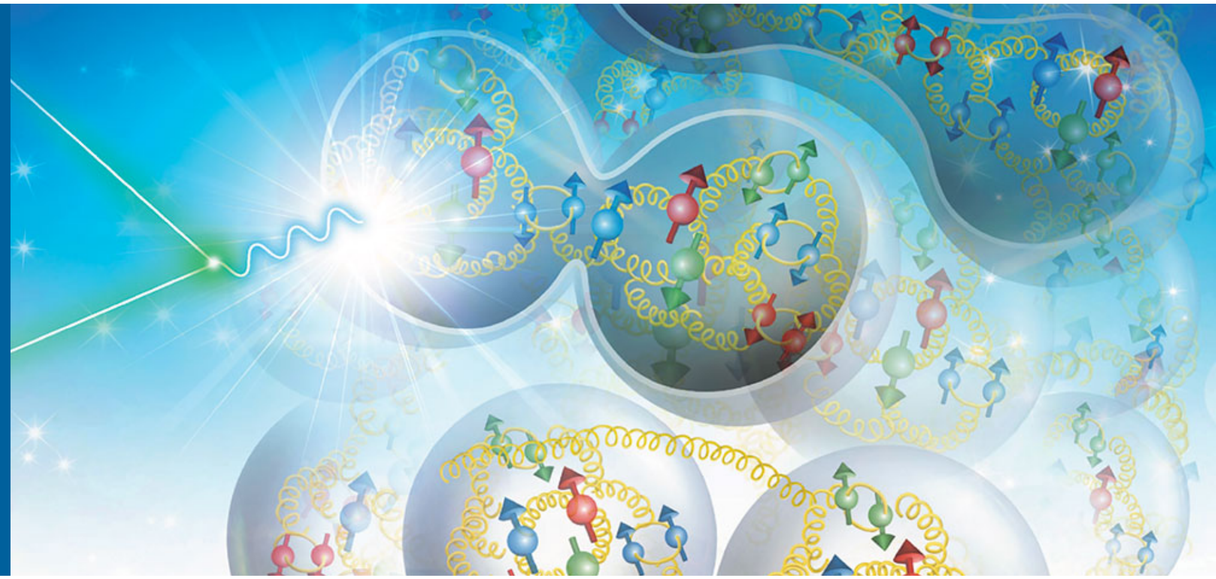
Argonne NATIONAL LABORATORY

## EXPERIMENTAL OVERVIEW

# *eA* PHYSICS AT THE EIC



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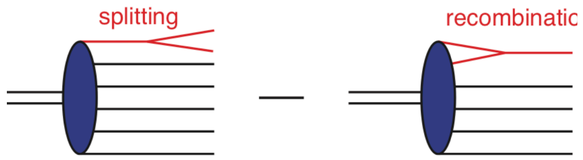
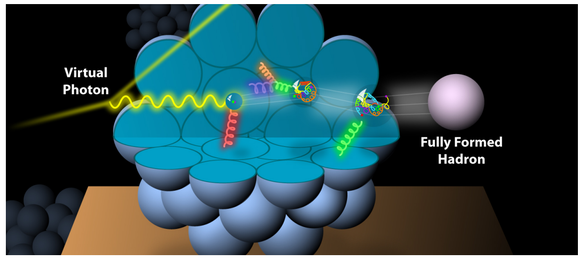
RHIC&AGS Annual User's Meeting
June 5, 2019

# CENTRAL QUESTIONS

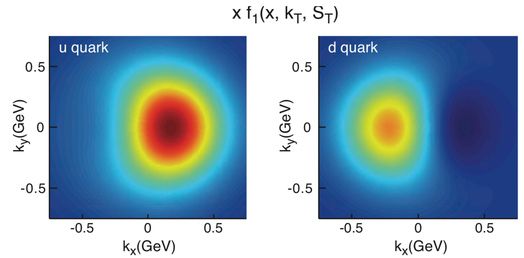
## Physics reach of *eA* program at EIC




- **Saturation:**
  Is the high-energy/low-*x* limit governed by a universal dense saturated gluon matter?

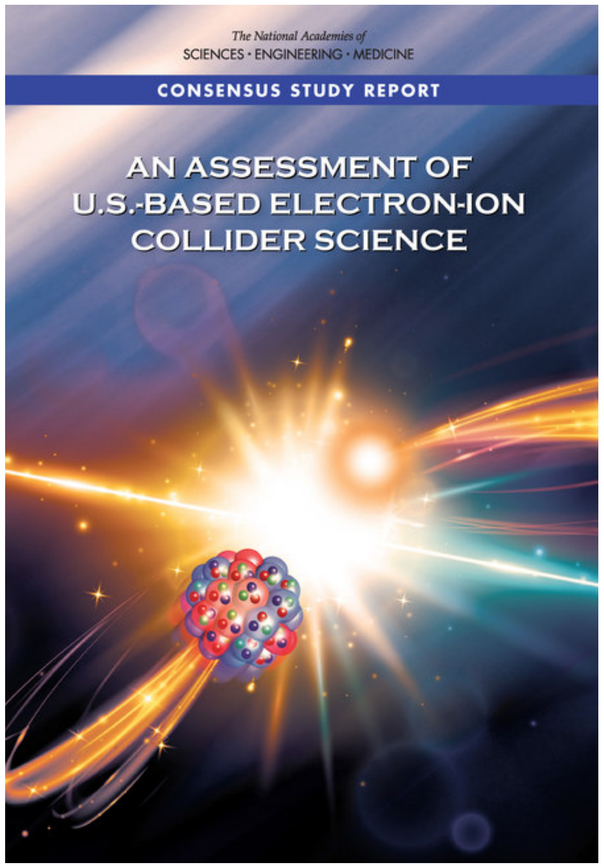



- **Confinement & Hadronization:**
  What are the space-time dynamics for hadronization?
  How do quarks and gluons interact with a nuclear medium?



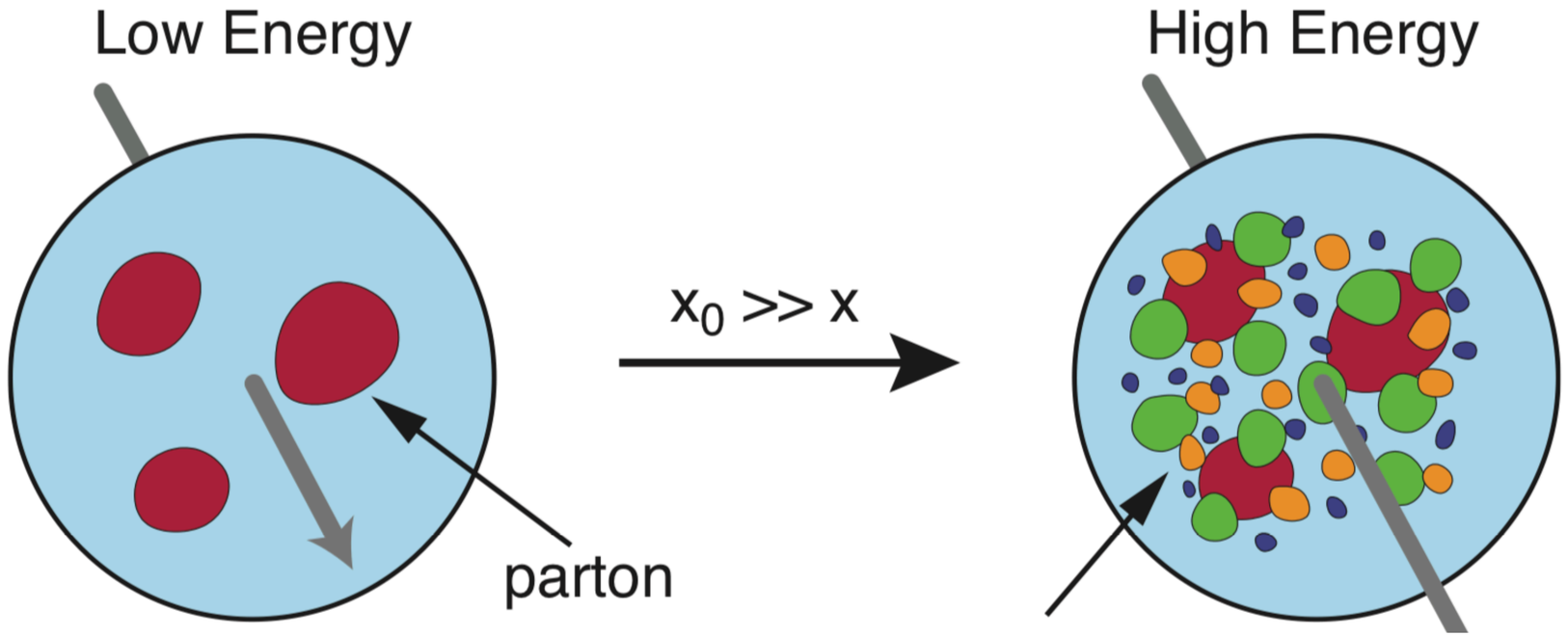

- **Partonic Structure of the Nucleus**
  What is the partonic origin of the EMC effect?
  What is the role of collective gluon excitations?
  A full 5D description of the partonic structure & dynamics?

# NAS CHARGE FOR EIC




- An EIC can uniquely address three profound questions about nucleons - neutrons and protons - and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - **What are the emergent properties of dense systems of gluons?**

*[…] The third question is perhaps the most exciting to nuclear scientists because it offers the opportunity for the most surprises, including new phases of matter and deep insights about quantum field theory.*



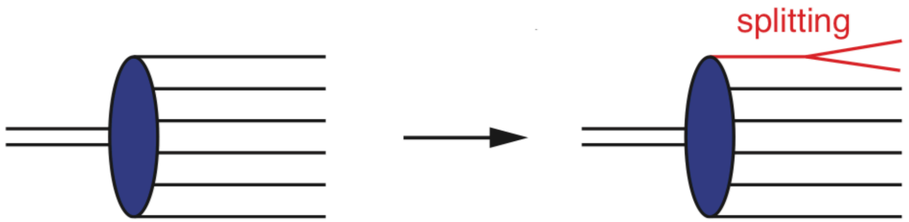

# SATURATION

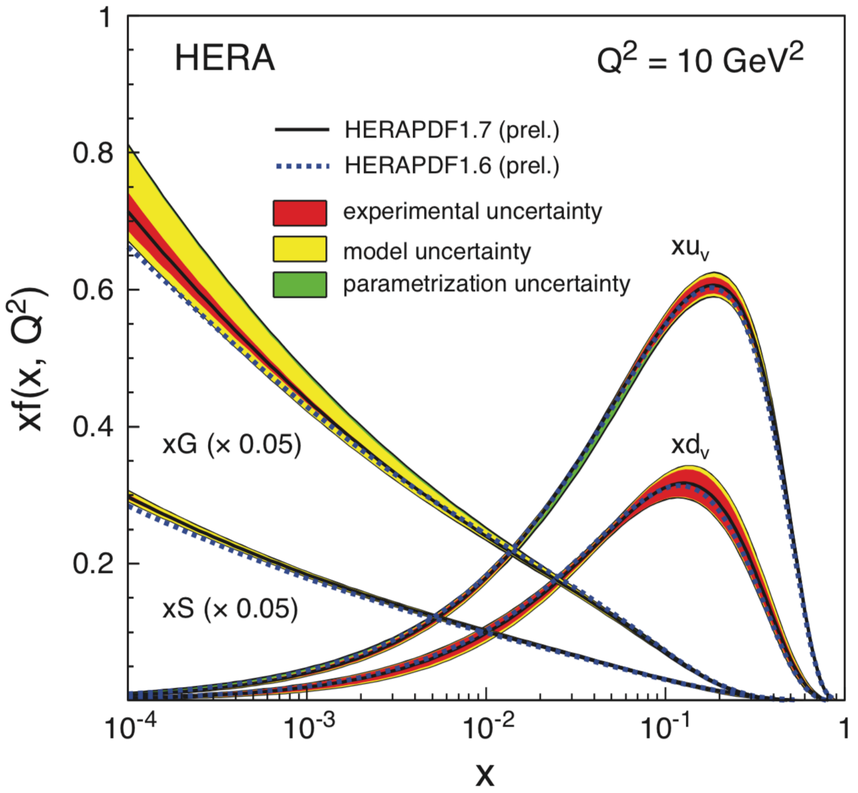
- Is the high-energy/low-*x* limit governed by a universal dense saturated gluon matter?

# PROTON STRUCTURE AT LOW X

## Linear evolution has problems!

- Gluons and sea quarks dominant at low x
- Distributions rise quickly at low x
- According to BFKL evolution, single gluon emission diverges (~ 1/x)

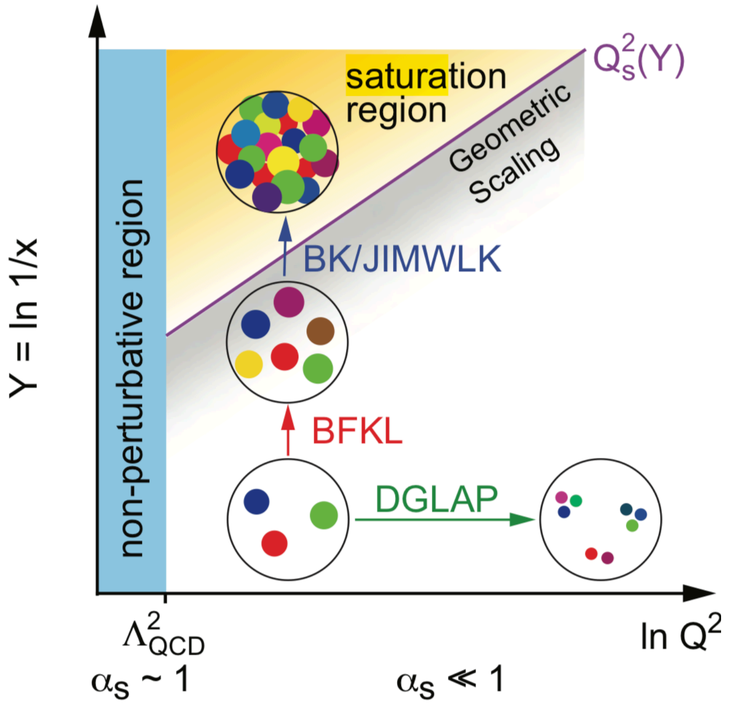


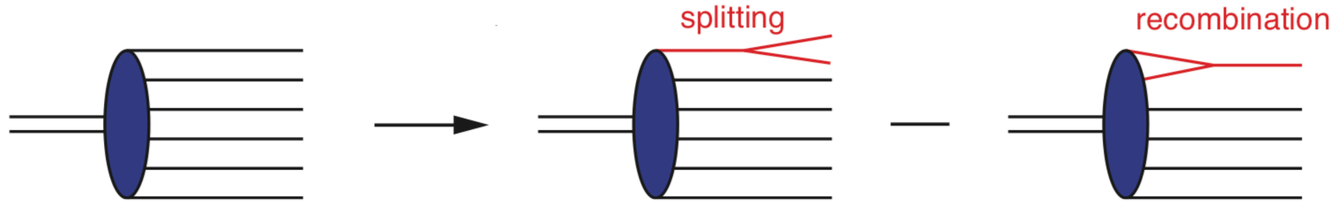

**Divergent behavior violates the black disk limit from QM**

# PROTON STRUCTURE AT LOW X

## Non-linear effects lead to saturation.



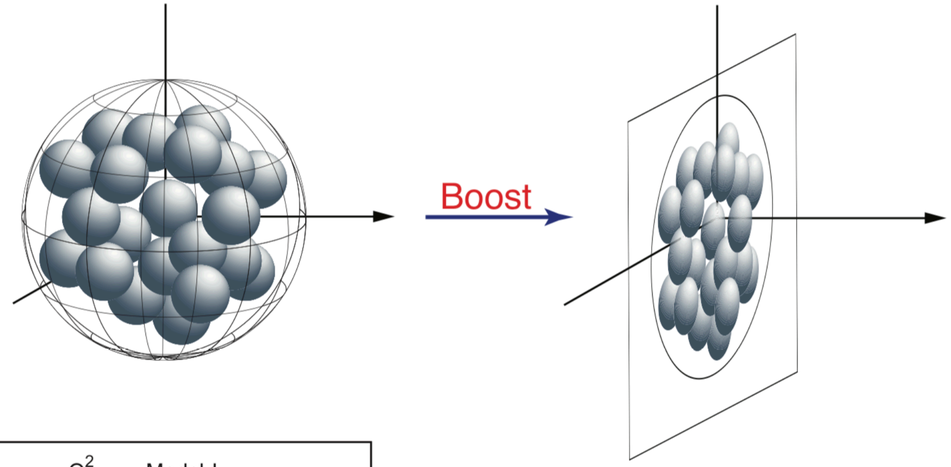

- Saturation caused by gluon recombination
- Non-linear behavior described by BK/JIMWLK-based models
- Equilibrium point between splitting and recombination defines new scale $Q_s(x) >> \Lambda_{QCD}$
- Color fields in this Color Glass Condensate extremely strong, but perturbative regime!

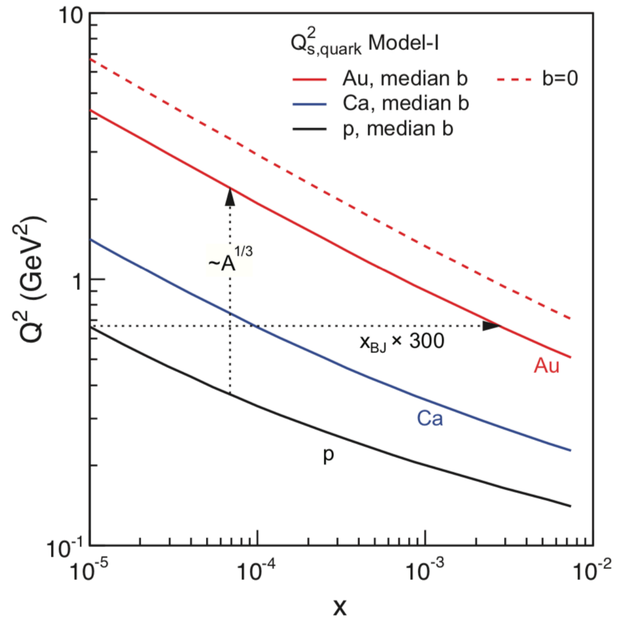


# WHY EIC?

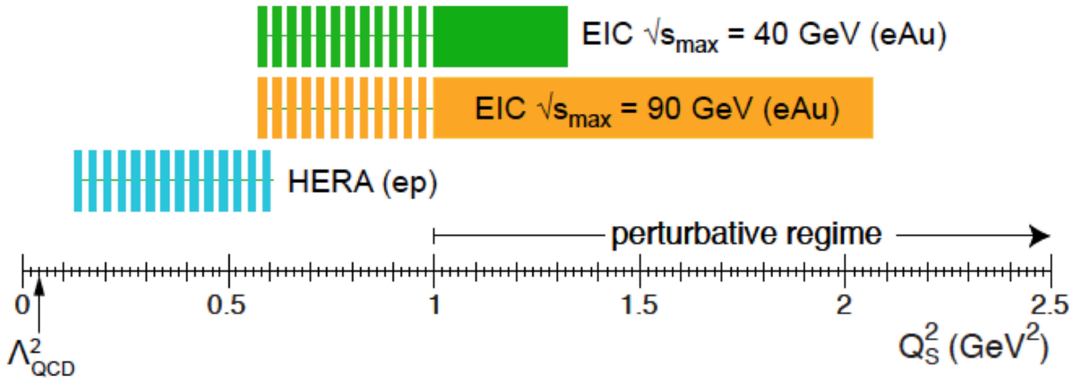
## The ideal place to study saturation!

- First hints of possible onset of saturation seen at HERA, RHIC and LHC
- Advantages at EIC: clean initial state and strong nuclear enhancement (nuclear “Oomph” factor)



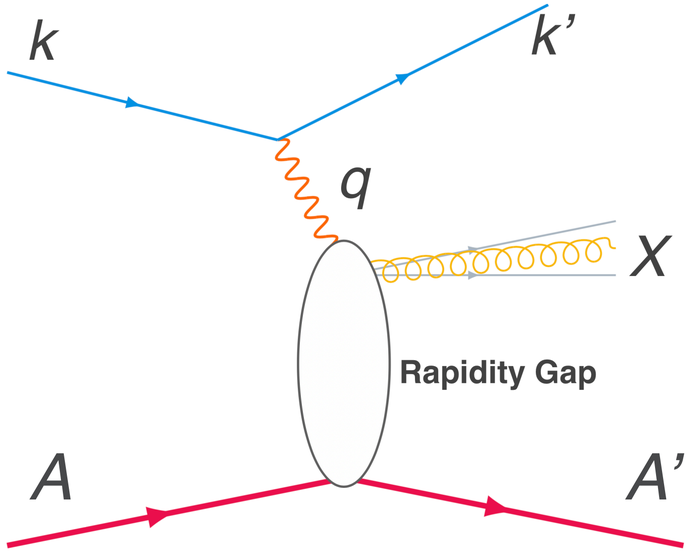

$$Q_S^2(x) \propto \left(\frac{A}{x}\right)^{\frac{1}{3}}$$

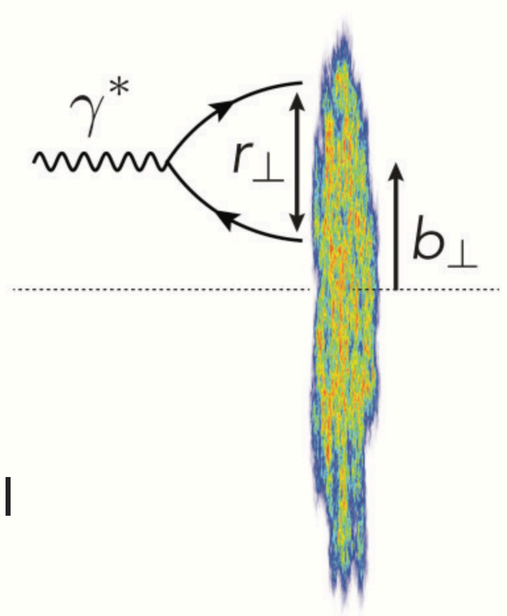



**Saturation scale for Au as large as for proton at 197x smaller value of x**

# KEY OBSERVABLES FOR SATURATION

## Golden channels: diffractive processes

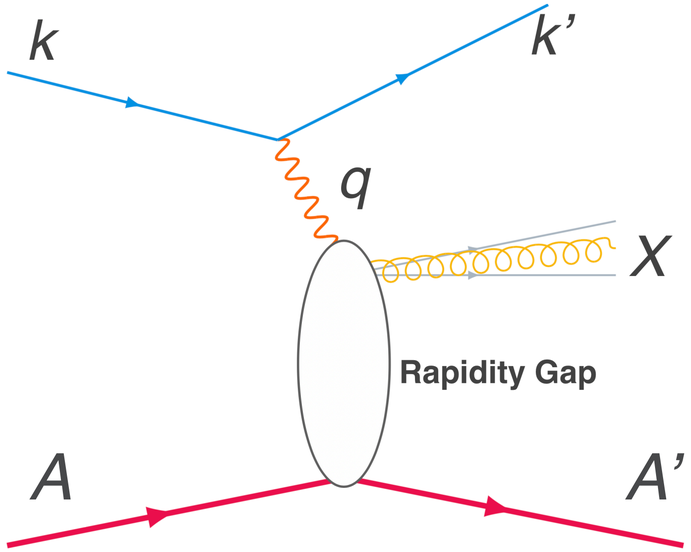


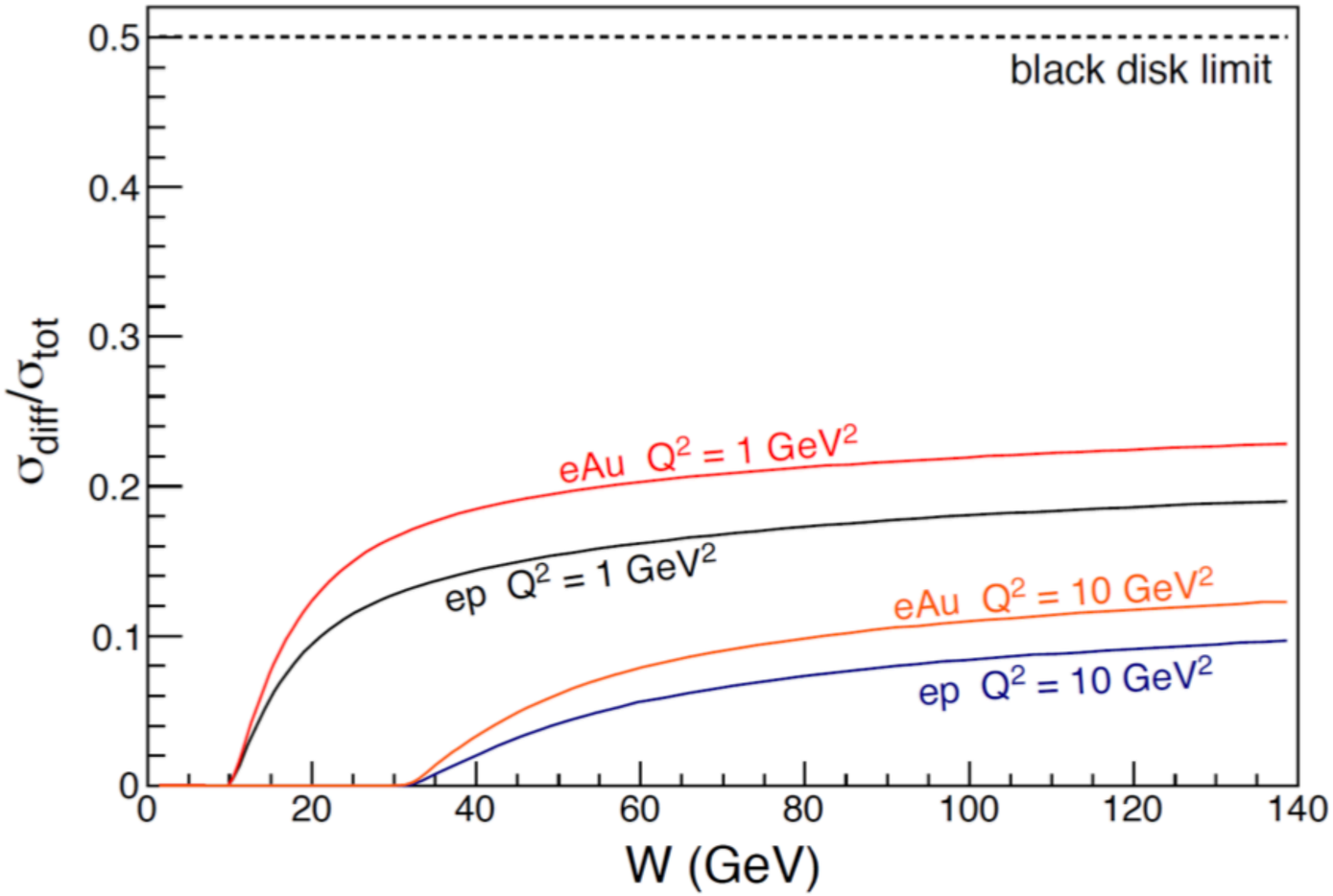




- Diffractive scattering can be described as interaction of color dipole with nucleus.
- Only class of events sensitive to the spatial distribution of gluons.
- Cross section depends quadratically on gluon momentum distribution
- At HERA, 15% of DIS events was diffractive
- In *eA* we have both coherent and incoherent scattering

# KEY OBSERVABLES FOR SATURATION

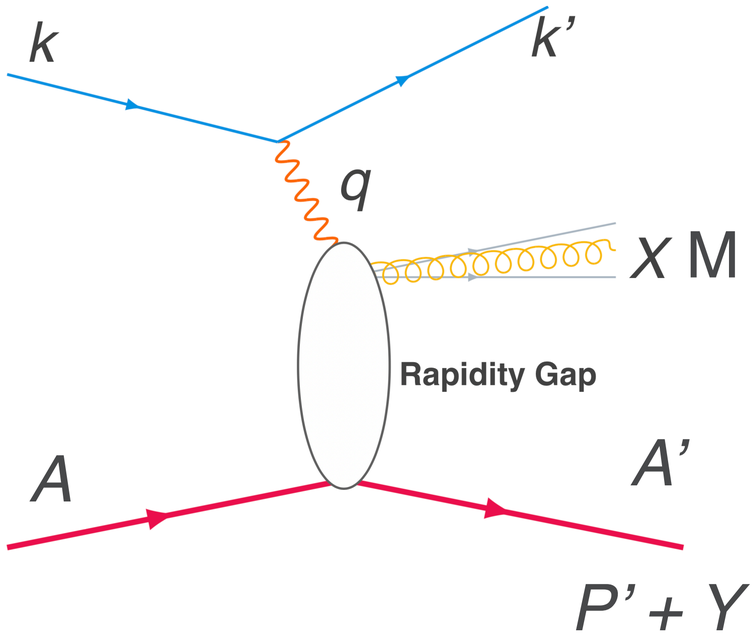
## Ratio of diffractive to total cross-section

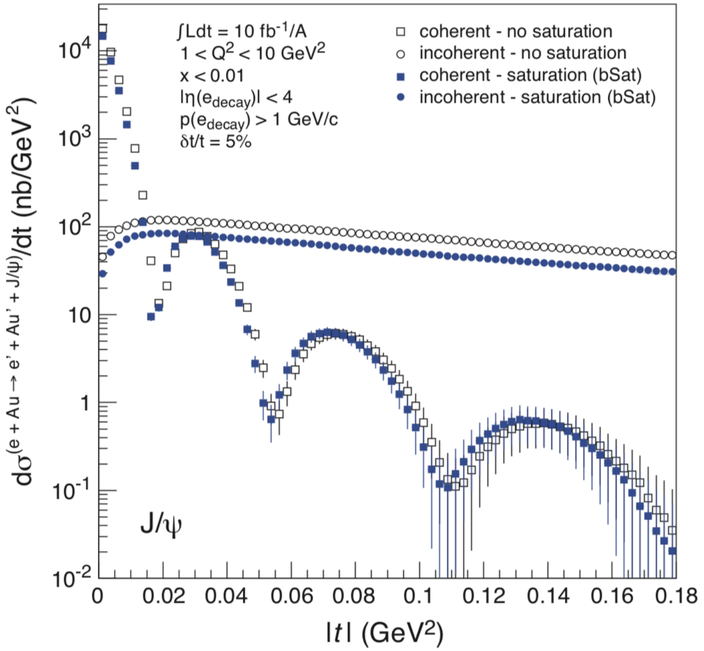


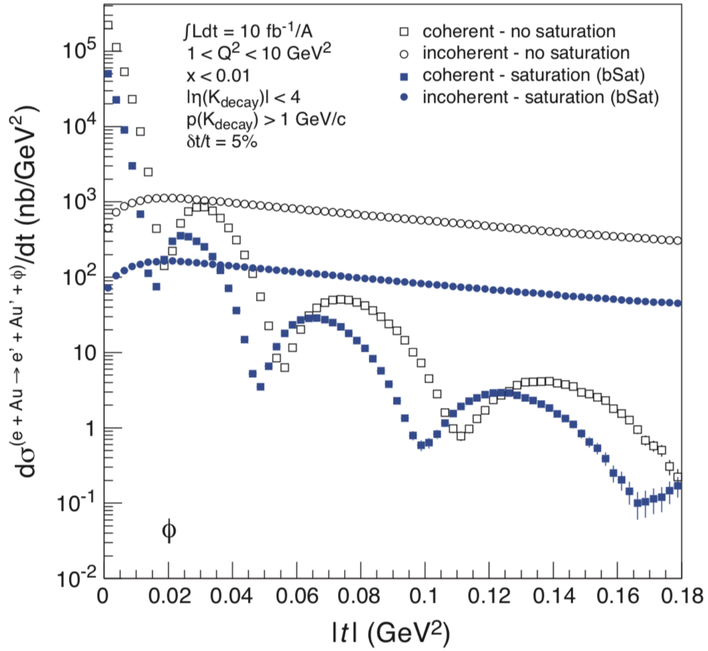



# KEY OBSERVABLES FOR SATURATION

## Diffractive vector meson production



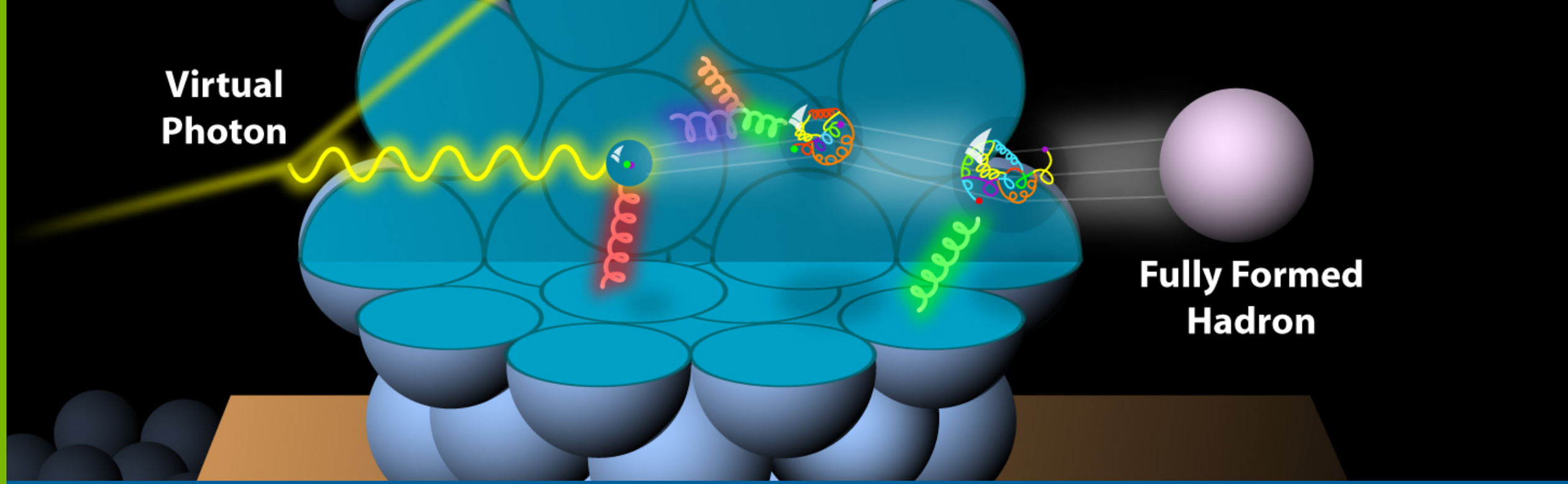




- *J/ψ* smaller and less sensitive to non-linear effects compared to *φ*

# EIC WELL-PLACED TO MEASURE SATURATION

## Many complimentary channels available!

- **Primary channels:**
  - Ratio diffractive DIS to DIS
  - Diffractive meson production
- **…But also:**
  - Nuclear structure functions compared to proton
  - Di-hadron correlations
  - Saturation effects in nuclear GPDs
  - …



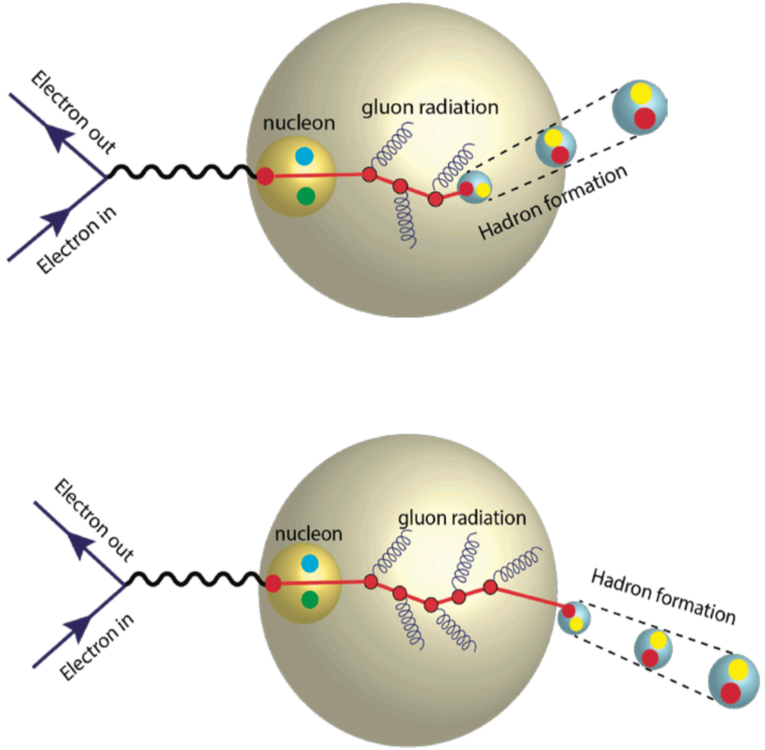

# CONFINEMENT AND HADRONIZATION

- How do quarks and gluons interact with a nuclear medium?
- What are the space-time dynamics for hadronization?

# HADRONIZATION IN SIDIS

## *eA* collision provides for ultimate control

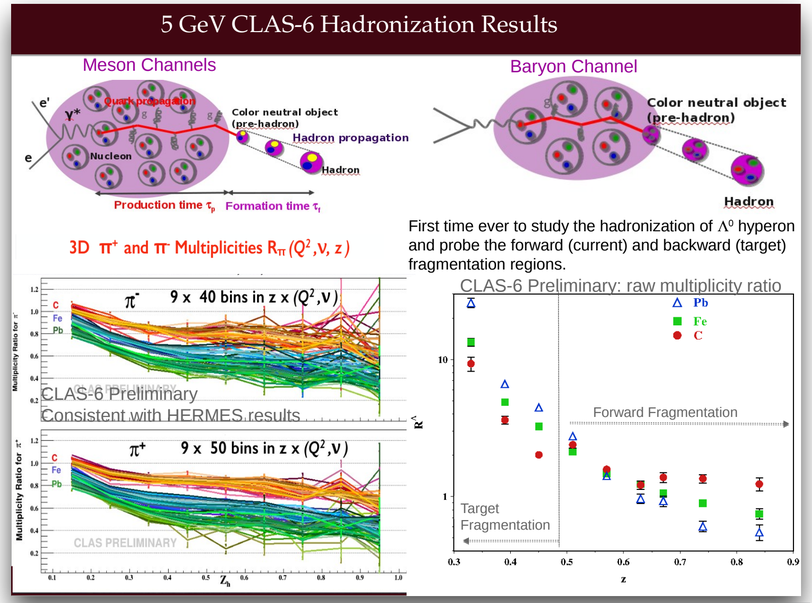
- Well controlled hard-scattering kinematics
- Well known final state
- Able to go from production inside medium (low-energy) to production outside of medium (high energy)
- New handle on surprising heavy-meson suppression at RHIC
- Topics of momentum broadening and color transparency can also be explored



# ISSUES WITH EXISTING LOW-ENERGY DATA

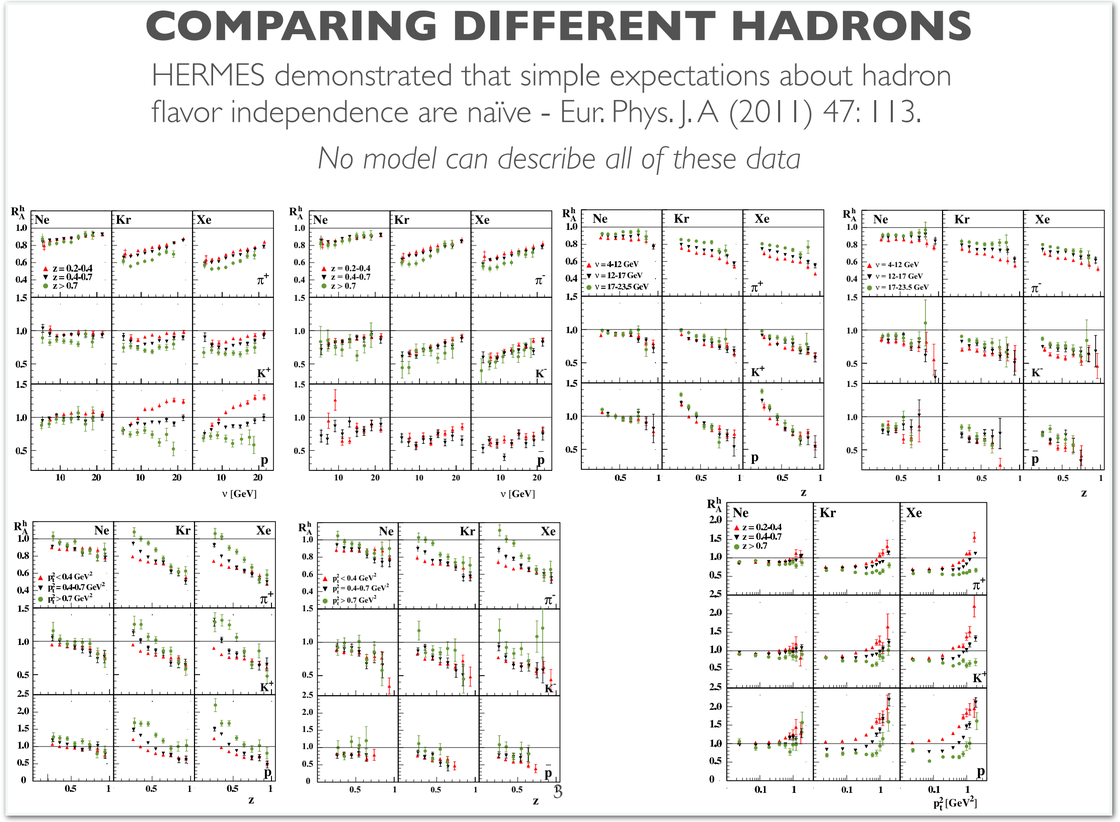
## How well do we understand the data we already have?

- Identified hadrons
- Low energy scale
- HERMES and CLAS-6 data currently not described by any models




Slide by Lamiaa El Fassi

Slide by Will Brooks

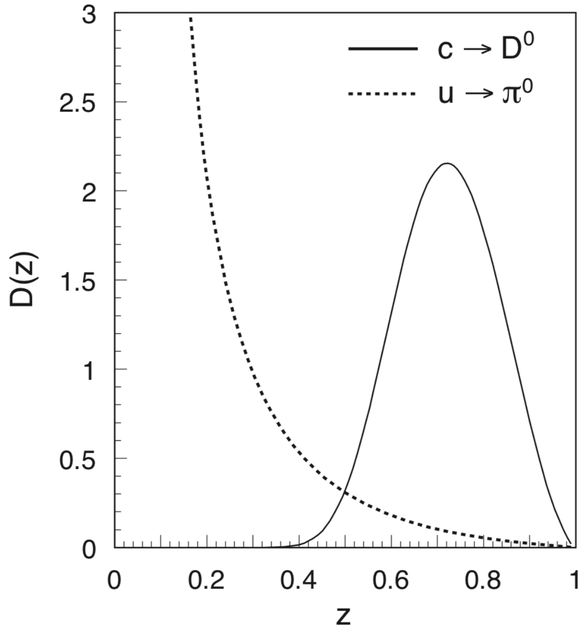


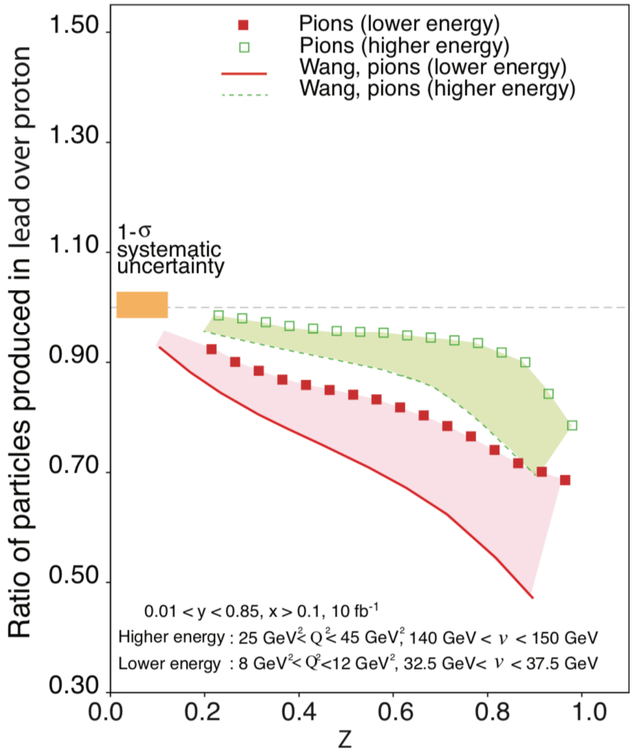

- EIC can do these measurements at large $W/Q^2$ without issues with factorization

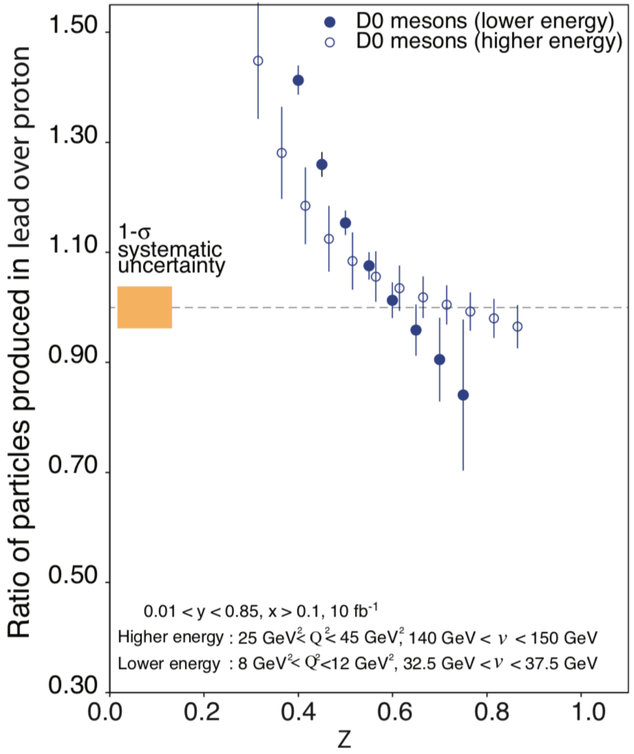
# COMPARISON OF LIGHT AND HEAVY QUARKS

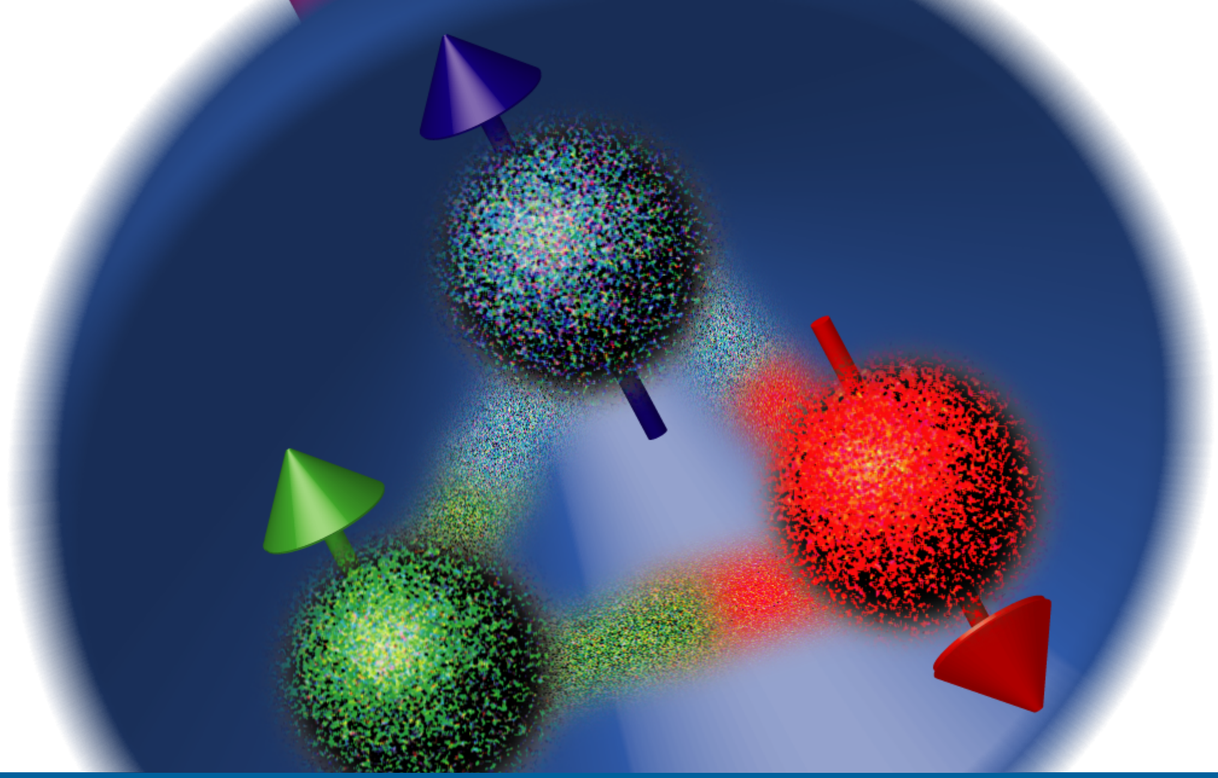
## EIC year-1 result!

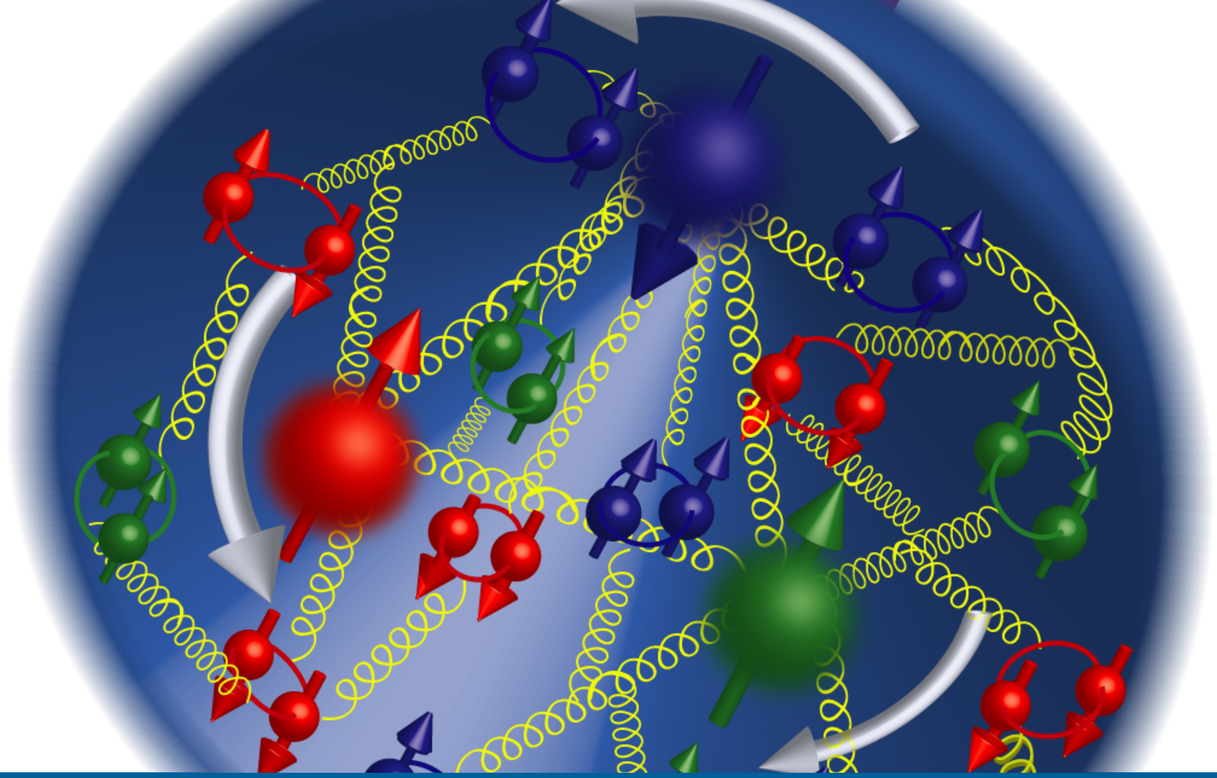
- Only 2 of many mesons that will be fully identified!







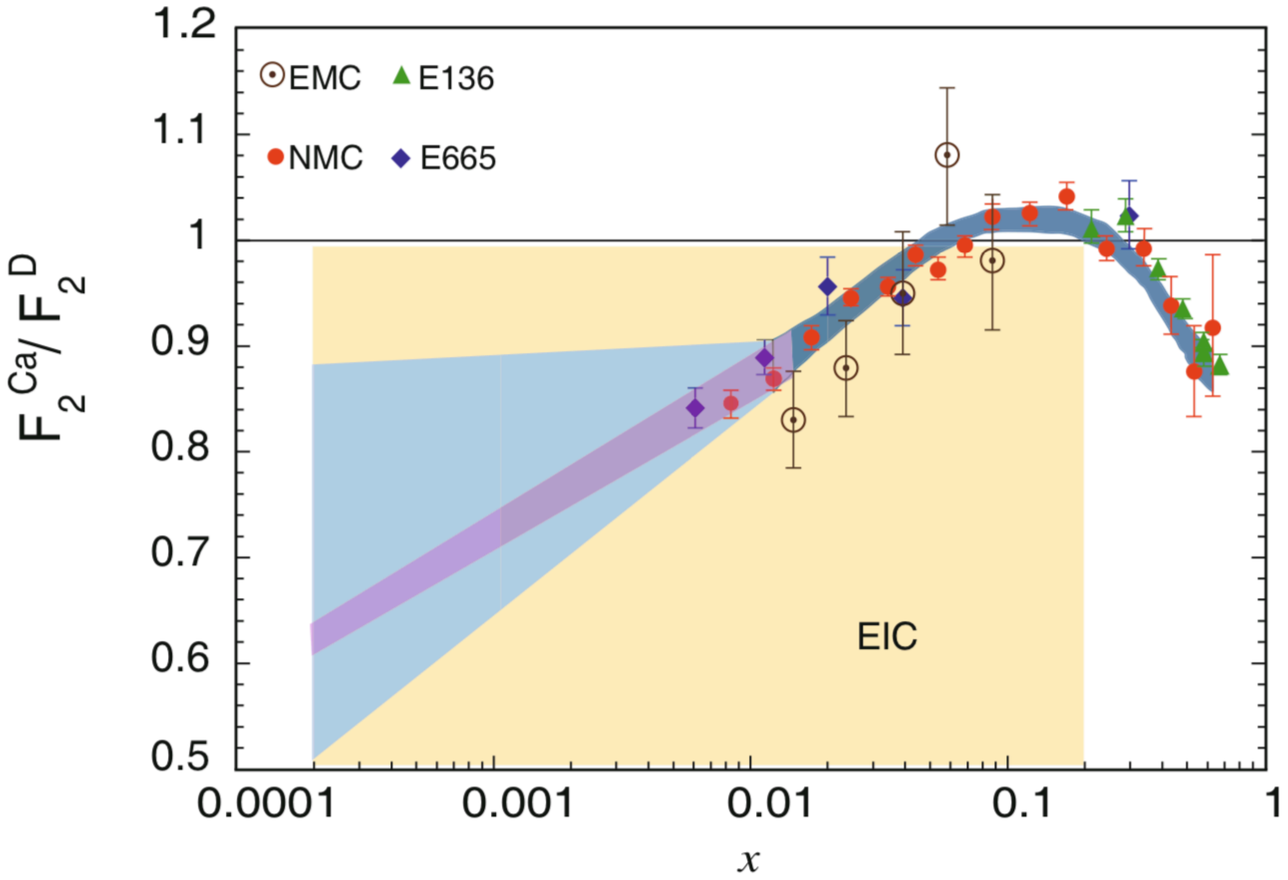
## PARTONIC STRUCTURE OF THE NUCLEUS

- What is the partonic origin of the EMC effect?
- What is the role of collective gluon excitations?
- A full 5D description of the partonic structure & dynamics?

# EMC EFFECT

## What happens below the shadowing region?

- Ratio of nuclear over nucleon structure function
- Different behavior depending on the nature of the soft gluons.
- EIC ranges from deep sea to valence region!



# FREE NEUTRON STRUCTURE

## Tagged deuteron DIS

- From “Nuclear FSI in tagged deuteron DIS at EIC”, Christian Weiss

### Tagging: Free neutron structure

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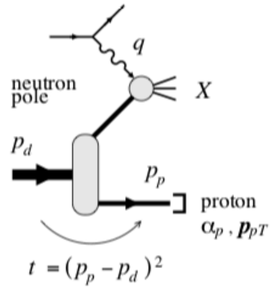


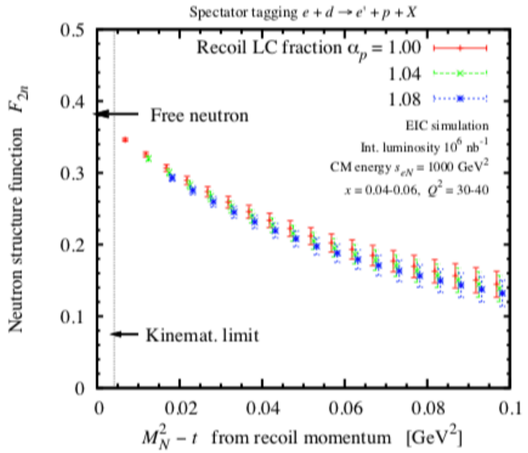


- On-shell extrapolation

  Proton momentum defines invariant $t - M_N^2 = -2|\boldsymbol{p}_p|^2 + t_{\min}$ “neutron off-shellness”

  Free neutron at pole $t - M_N^2 = 0$: On-shell extrapolation

  Eliminates nuclear binding effects and FSI Sargsian, Strikman 05

- Free neutron structure $F_{2n}$

  Uncertainty mainly systematic
  JLab LDRD: Detailed estimates

- Extension to spin structure $g_{1n}$

  On-shell extrapolation of asymmetry

  D-wave suppressed at $\boldsymbol{p}_p = 0$: Neutron 100% polarized

### Tagging: Neutron spin structure

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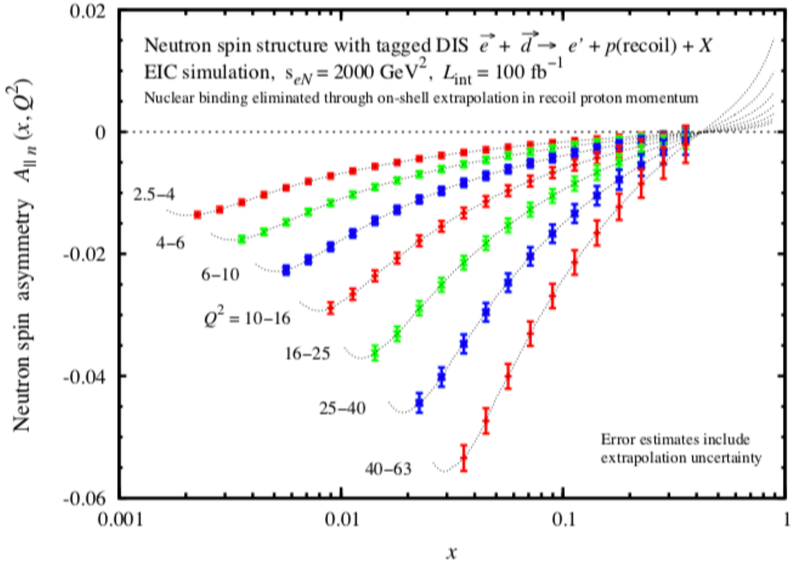



$$A_{\parallel n} = \frac{\sigma(+-) - \sigma(++)}{\sigma(+-) + \sigma(++)} = D\,\frac{g_1}{F_1} + \ldots$$

$$D = \frac{y(2-y)}{2 - 2y + y^2}$$ depolarization factor

$$y = \frac{Q^2}{x s_{eN}}$$

- Precise measurement of neutron spin structure

  Wide kinematic range: Leading $\leftrightarrow$ higher twist, nonsinglet $\leftrightarrow$ singlet QCD evolution

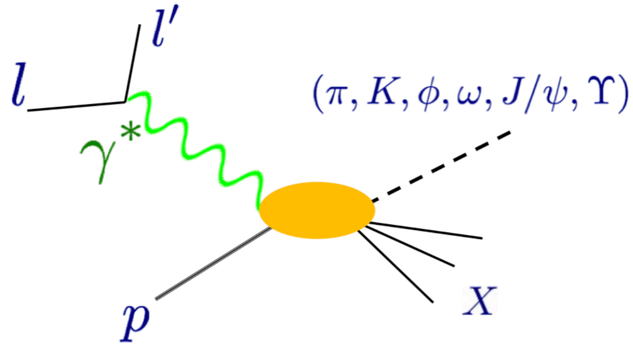
  Parton density fits: Flavor separation $\Delta u \leftrightarrow \Delta d$, gluon spin $\Delta G$

  Nonsinglet $g_{1p} - g_{1n}$ and Bjorken sum rule

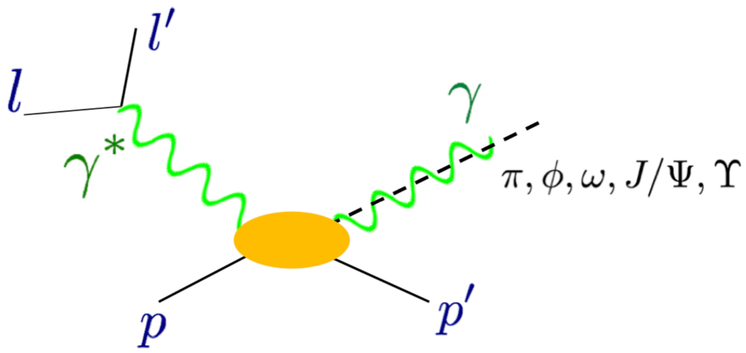
# NUCLEON AND NUCLEAR TOMOGRAPHY

## Experimental tools

- Semi-inclusive reactions: *e+p/A —> e' + h + X*
  - ➥ High polarized luminosity combined with large acceptance detectors
  - ➥ 5 key variables x,$Q^2$, z, $p_T$ and angle between leptonic and hadronic plane
  - ➥ Fine binning needed

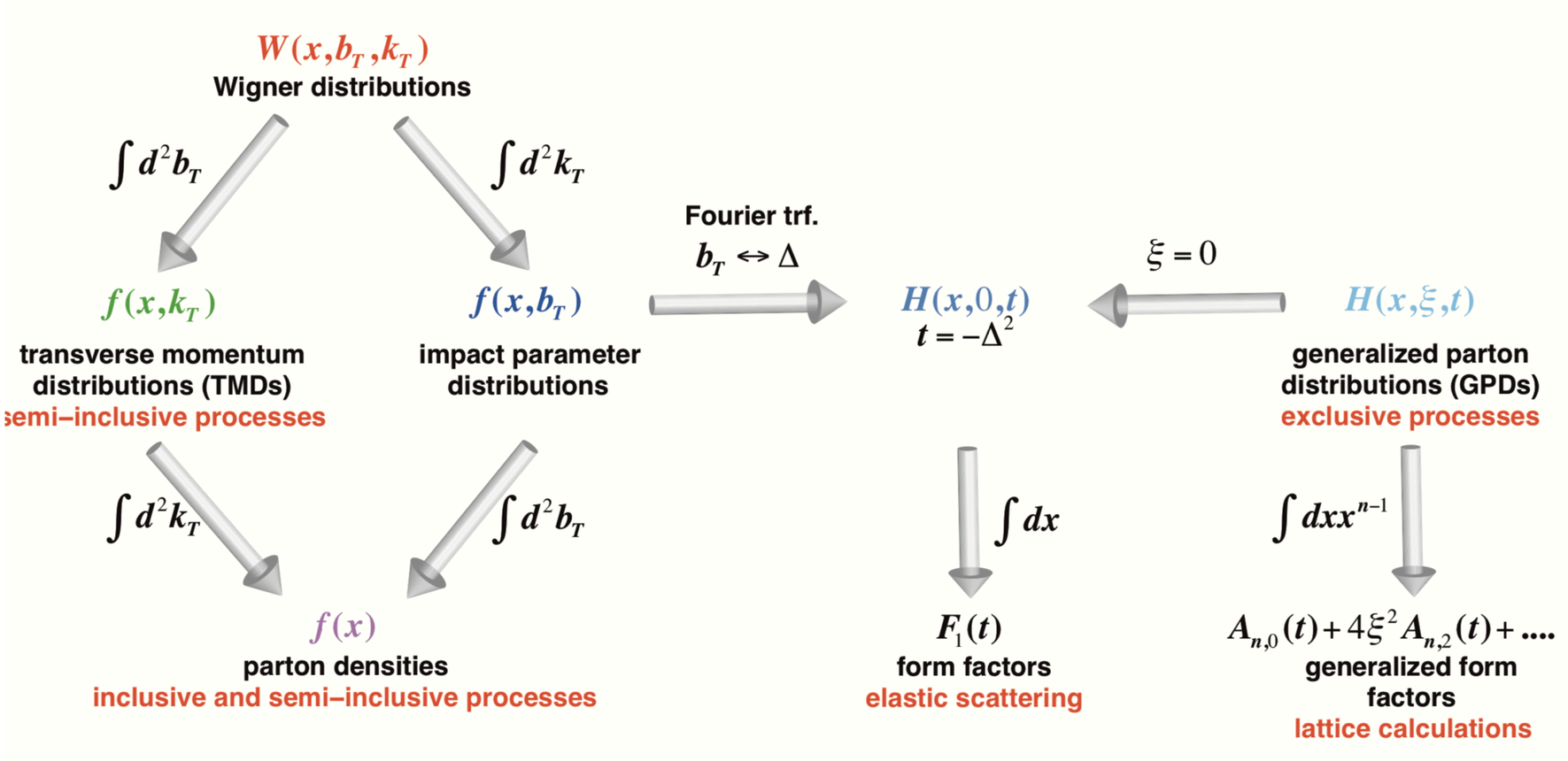



- Exclusive reactions: *e+p/A —> e' + p'/A' + h/γ* (DVCS and DVMP)
  - ➥ High polarized luminosity combined with large acceptance detectors
  - ➥ 4 key variables x,$Q^2$,t and angle between leptonic and production plane ($\phi$)
  - ➥ Fine binning needed



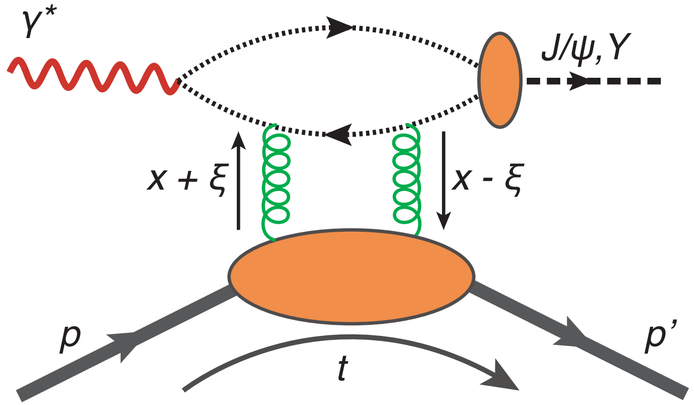
# NUCLEON AND NUCLEAR TOMOGRAPHY

## Wigner distributions and 2+2+1D imaging



# EXAMPLE: ACCESSING THE GLUON GPD

## 2+1D imaging with exclusive processes




Hard scale: $Q^2 + M_V^2$

Modified Bjorken-x: $x_V = \dfrac{Q^2 + M_V^2}{2p \cdot q}$

average unpolarized gluon GPD related to t-dependent cross section (LO)

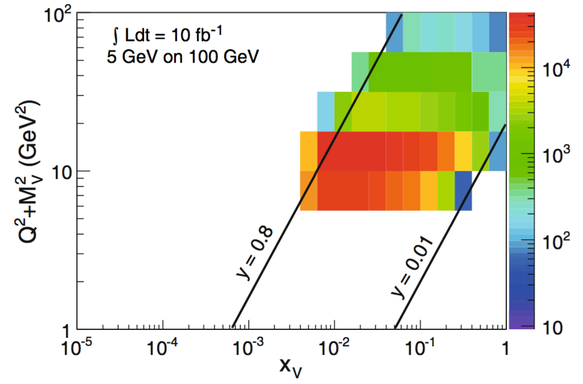
$$|\langle \mathcal{H}_g \rangle|(t) \propto \sqrt{\frac{d\sigma}{dt}(t) / \frac{d\sigma}{dt}(t=0)}$$

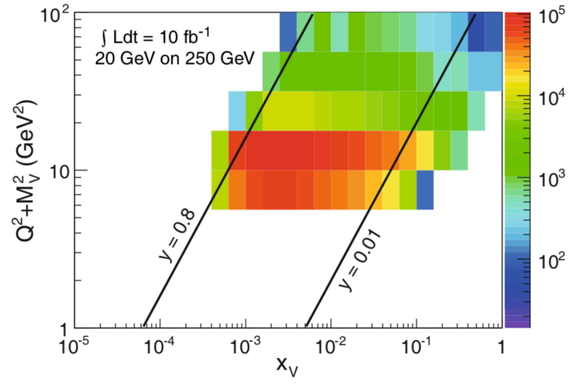
Fourier transform:
transverse gluonic profile

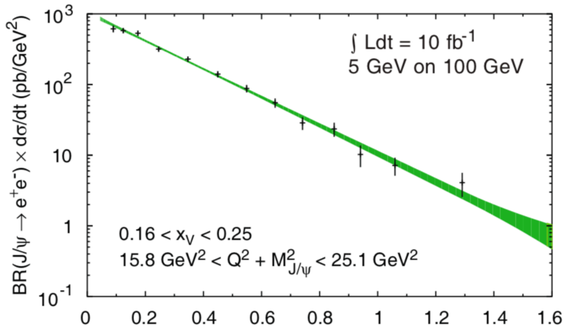
$$\rho(|\vec{b}_T|, x_V) = \int \frac{d^2\vec{\Delta}_T}{(2\pi)^2} e^{i\vec{\Delta}_T \vec{b}_T} |\langle H_g \rangle|(t = -\vec{\Delta}_T^2)$$

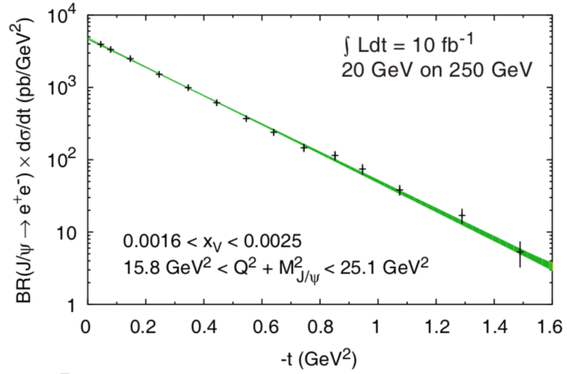
- Remarks:
  - **Simplest** possible GPD extraction
  - Intrinsic systematic uncertainty due to **extrapolation** outside of measured *t*-range
  - **NLO effects** could be significant
    - Corrections expected to be smaller for *Υ(1s)* than for *J/ψ*

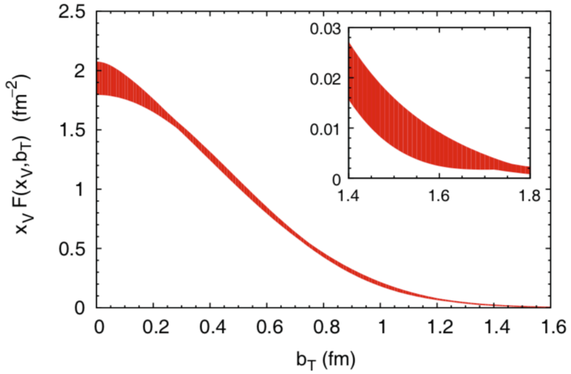
# NUCLEON TOMOGRAPHY WITH *J/Ψ*

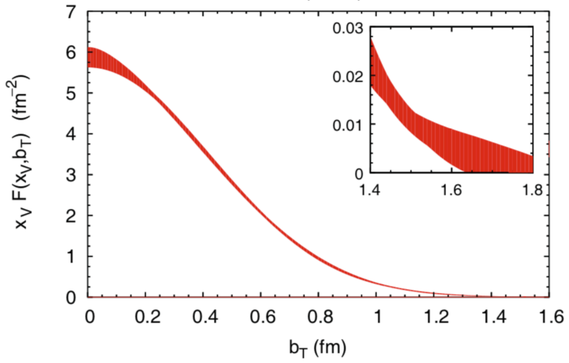


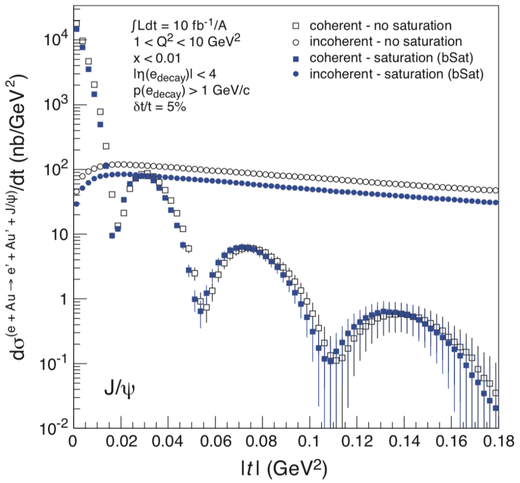

**Only possible at an EIC:**
from the valence region deep into the sea!

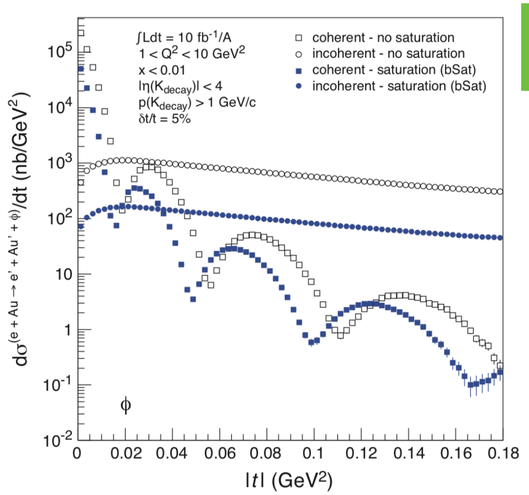
***t*-spectra**

**Normalized average gluon density**

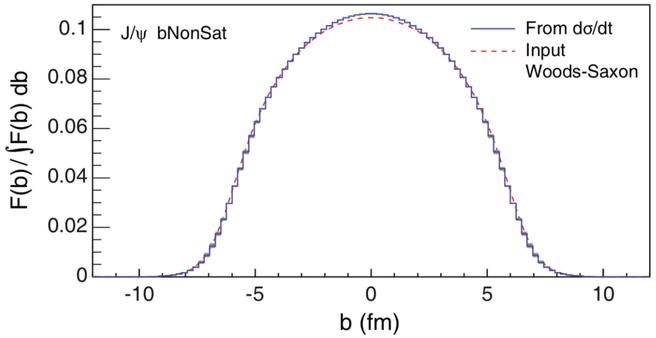
# NUCLEAR TOMOGRAPHY WITH *J/Ψ* AND *φ*

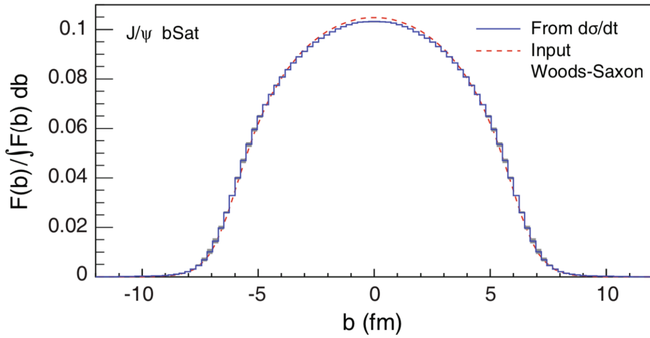
## Diffractive vector meson production

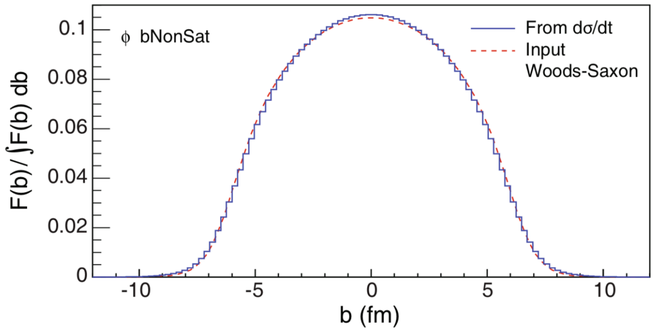


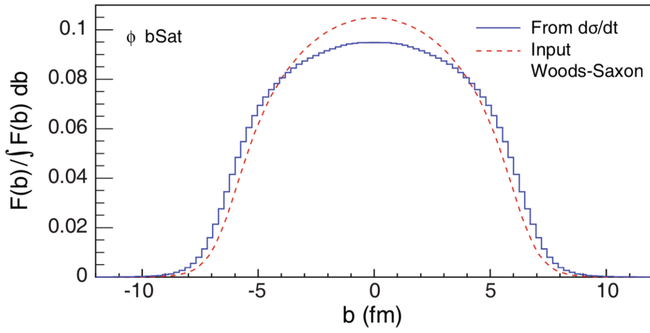




***t*-spectra** → **Normalized average gluon density**



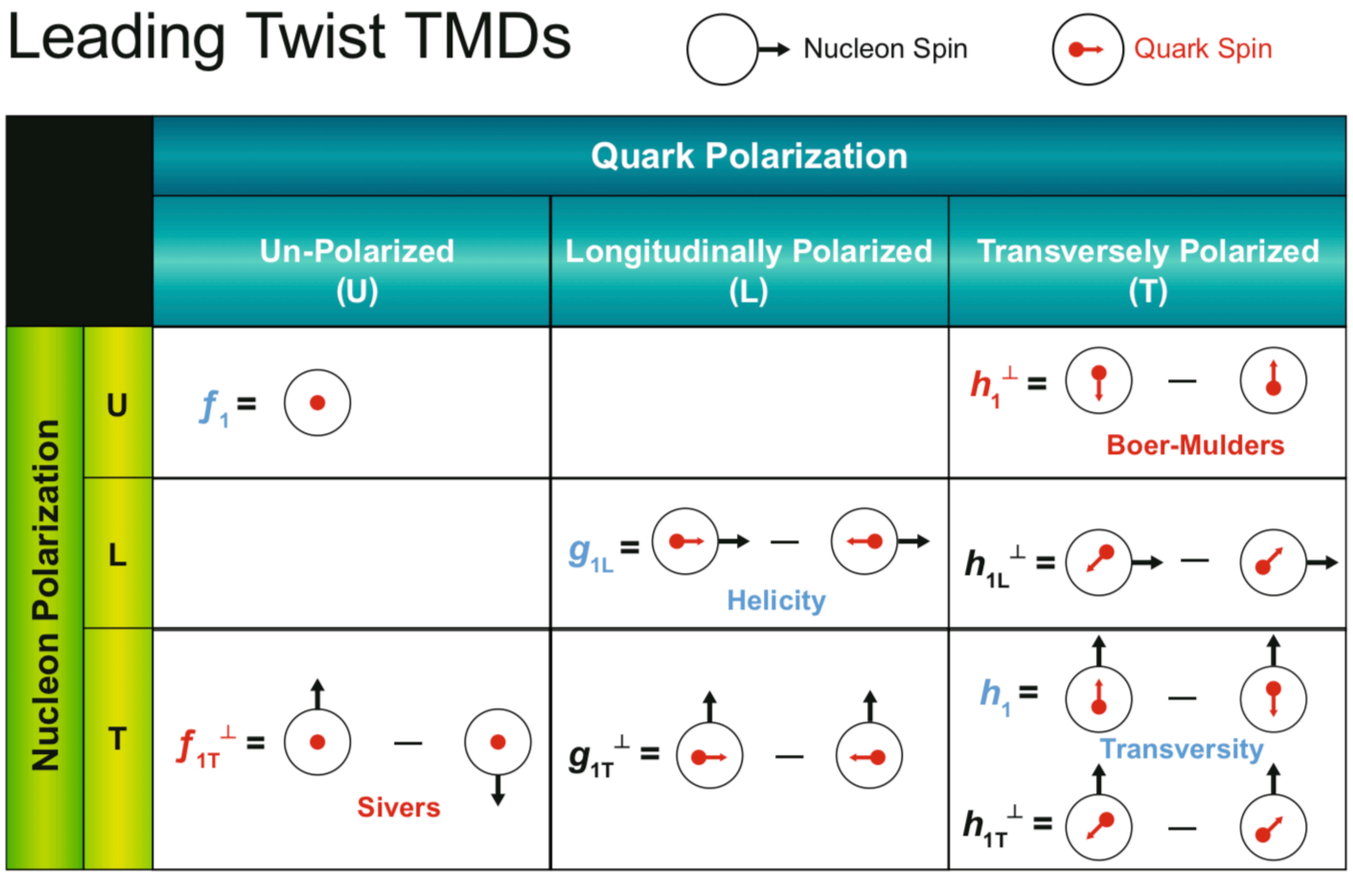




- *J/ψ* smaller and less sensitive to non-linear effects compared to *φ*
- Coherent part probes nuclear structure
- Incoherent part probes structure of nucleon in nuclear potential, including “lumpiness”.
- Can select coherent by veto on breakup

# PARTON DYNAMICS INSIDE NUCLEI

## What can we do with TMDs?




- Especially useful: unpolarized TMD and Boer-Mulders function because no need to separate spin from structure
- Boer-Mulders function describes correlation of transverse quark polarization in unpolarized nucleon
- Access EMC effect in transverse direction

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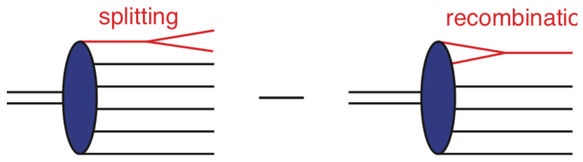
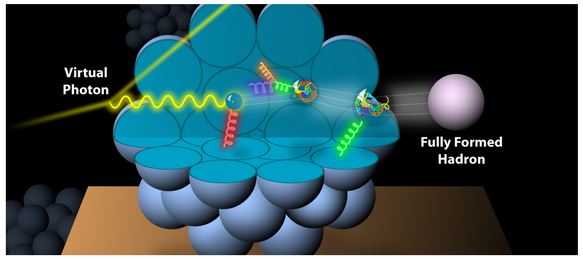
# SUMMARY

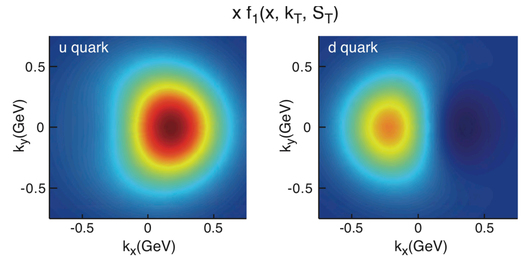
## Physics reach of *eA* program at EIC




- **Saturation:**
  Is the high-energy/low-*x* limit governed by a universal dense saturated gluon matter?




- **Confinement & Hadronization:**
  What are the space-time dynamics for hadronization?
  How do quarks and gluons interact with a nuclear medium?




- **Partonic Structure of the Nucleus**
  What is the partonic origin of the EMC effect?
  What is the role of collective gluon excitations?
  A full 5D description of the partonic structure & dynamics?