# Theoretical Perspective on Electron-Ion Collider

**Jianwei Qiu**
**Brookhaven National Laboratory**

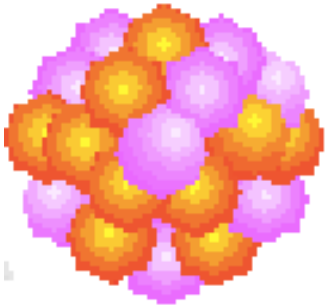
- ✧ What is the fundamental structure of all visible matter?
- ✧ Why do we need an Electron-Ion Collider?

  New questions, new opportunities, and new discoveries
- ✧ Why cannot be achieved by other facilities?
- ✧ Summary

POETIC 2012: *Physics Opportunities @ an Electron Ion Collider*
Indiana University, Bloomington, IN, August 20-22, 2012

# Fundamental structure of all visible matter

- The nucleus – in the heart of all atoms:




Proton (1919) Neutron (1931)

Held together by the color force of QCD – the strong force!

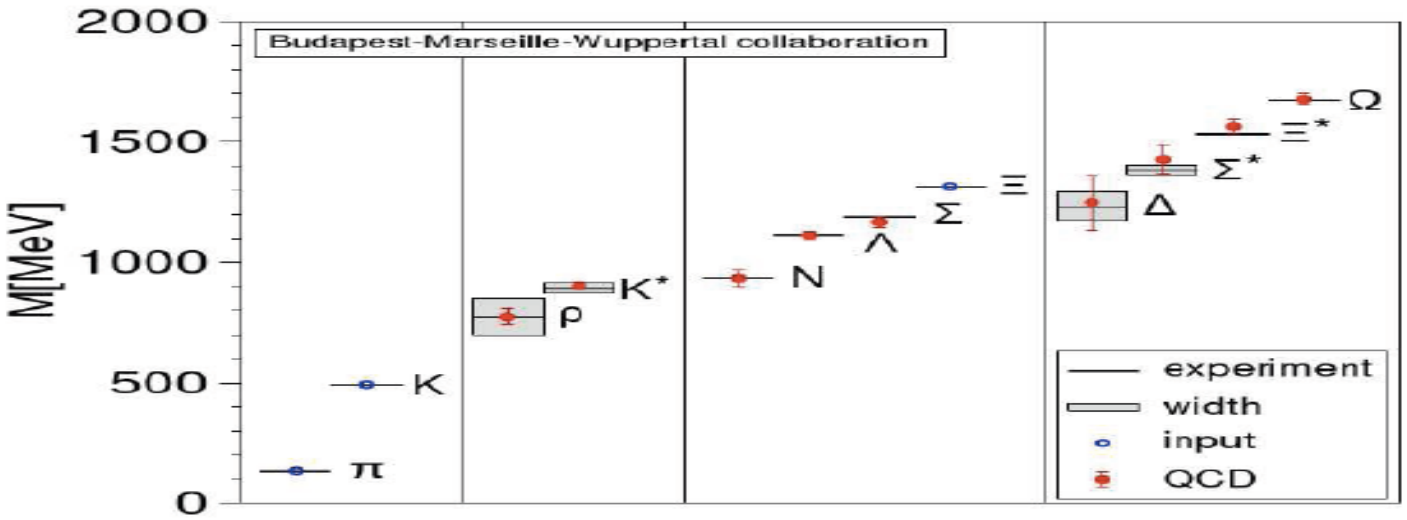
- Challenges:

| Hadron properties | | QCD | | |
|---|---|---|---|---|
| Charge,<br>Mass,<br>Spin,<br>Magnetic moment,<br>… | ⟷ | Quarks<br>Color,<br>Flavor,<br>Charge,<br>Mass,<br>Spin,<br>… | + | Gluons<br>Color,<br>Spin,<br>… |

Emergence of hadrons from the properties and dynamics of quarks and gluons in QCD?

# We believe QCD – Lattice calculation

- **Hadron mass:**

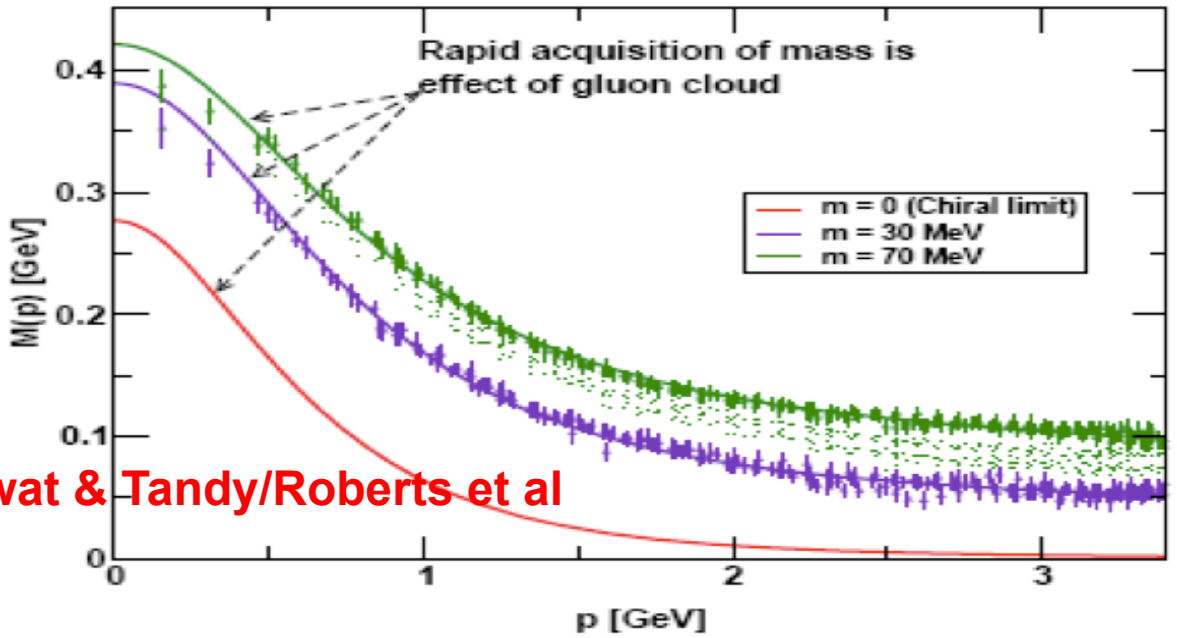



**But,**

It does not reveal the space-time distribution of partons inside a hadron, details of interactions, reasons of confinement, nuclear force, …

- **"Quark" mass:**

**Mass function:**




**Mystery:**

**Bhagwat & Tandy/Roberts et al**

**"Mass without mass!"**

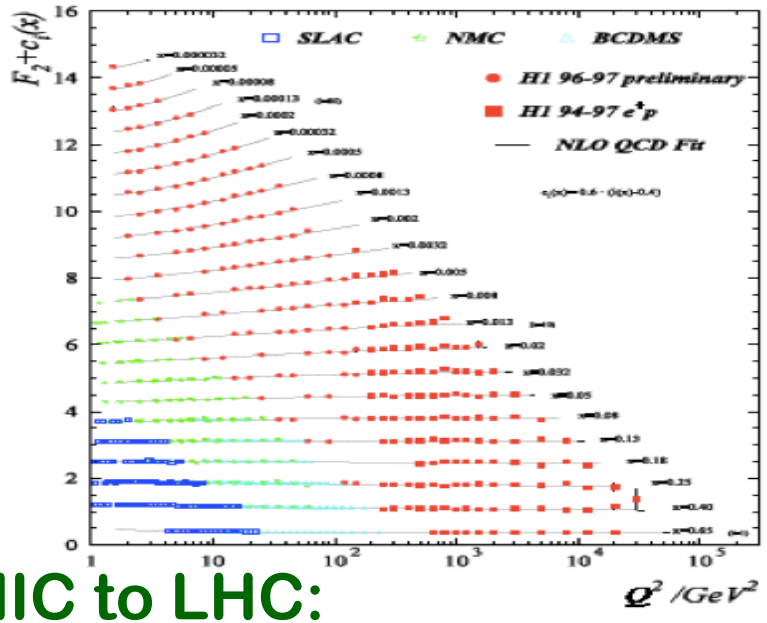
Critical role of gluons and sea quarks in hadron physics – not in quark model!

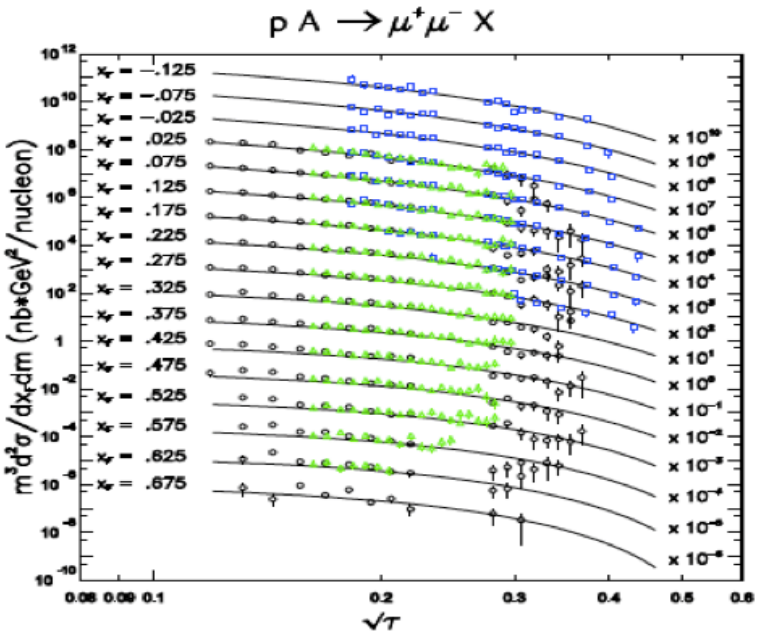
# We believe QCD – Experimental tests

## ❑ From DIS to Drell-Yan:

**The probe:**

**< 0.1 fm**

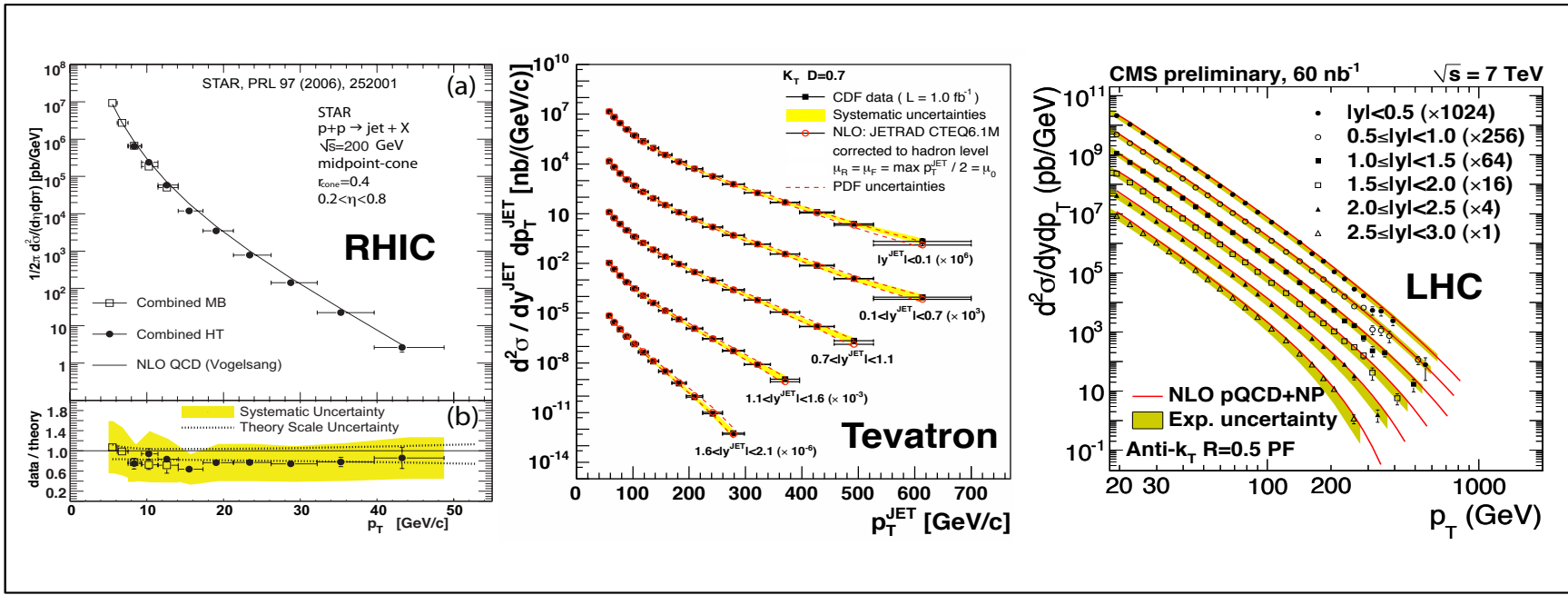



## ❑ From RHIC to LHC:

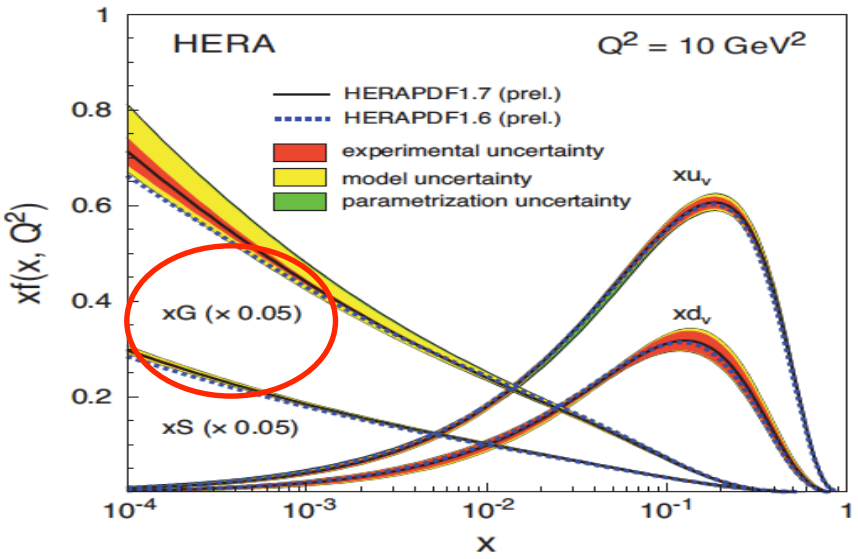
**The probe:**

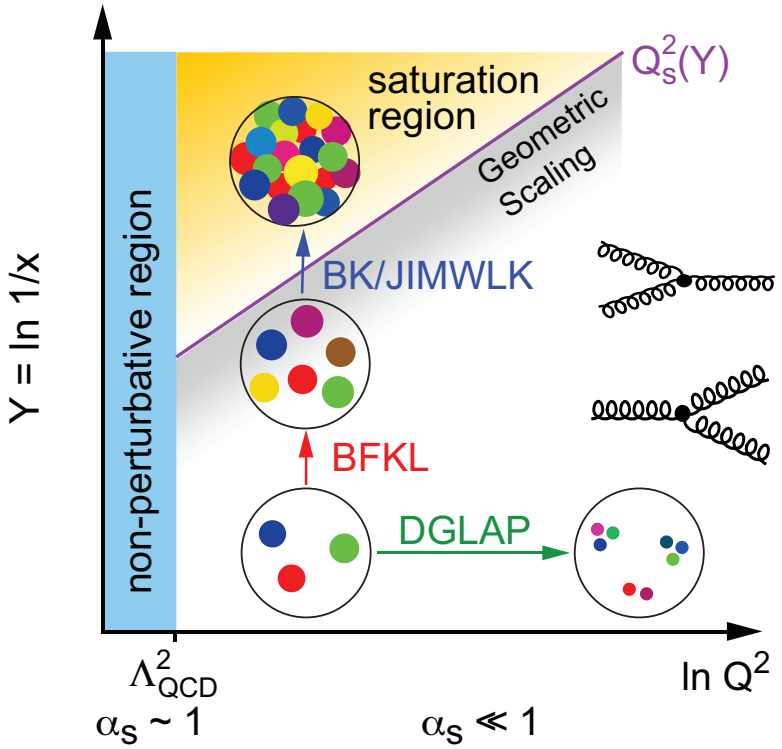
**<< 0.1 fm**



# New regime of QCD matter

## ❑ Proliferation of soft gluons:




## ❑ Indefinite rise at low x?

- ✧ Immediate consequence of gluon self-interaction
- ✧ Violation of the unitary of hadronic cross sections
- ✧ Recombination of soft gluons – result of the same gluon self-interaction

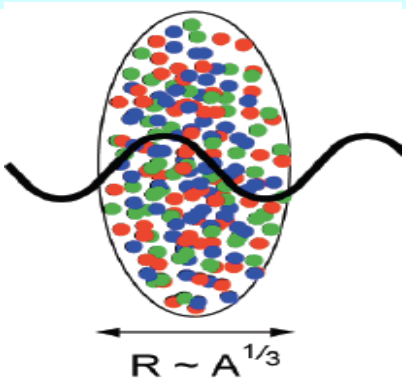
## ❑ New matter of condensed and saturated gluons?

- ✧ Does the density of soft gluons saturate? Where does it set in?
- ✧ Is there a simple boundary between the dilute and the saturated?
- ✧ Matter of universal properties in the nucleon and all nuclei?

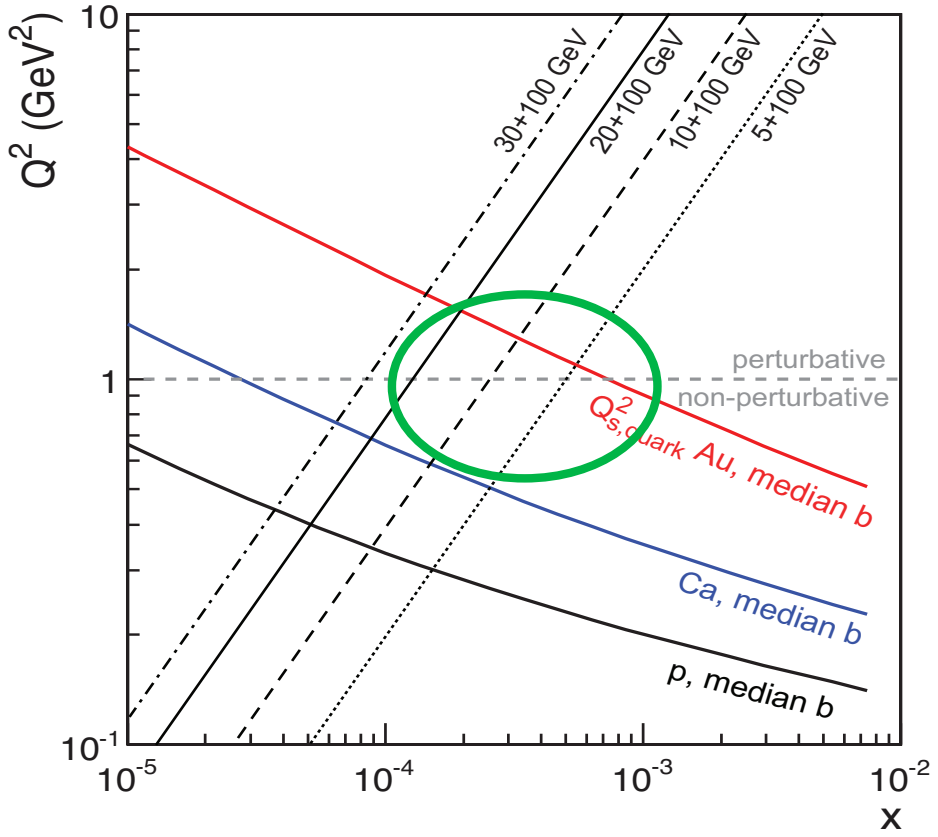
# Nucleus, a laboratory for QCD

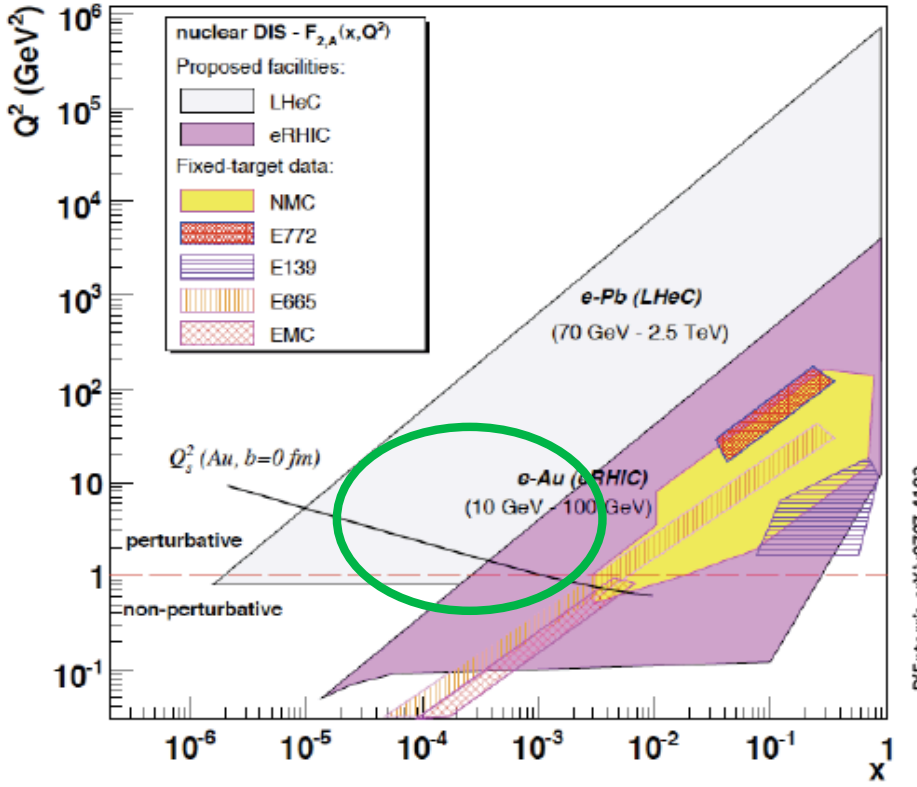
- **Many more soft gluons in nucleus at the same impact parameter:**

$$Q_s^2(eA) \propto Q_s^2(ep)\, A^{1/3}$$




Mueller's talk



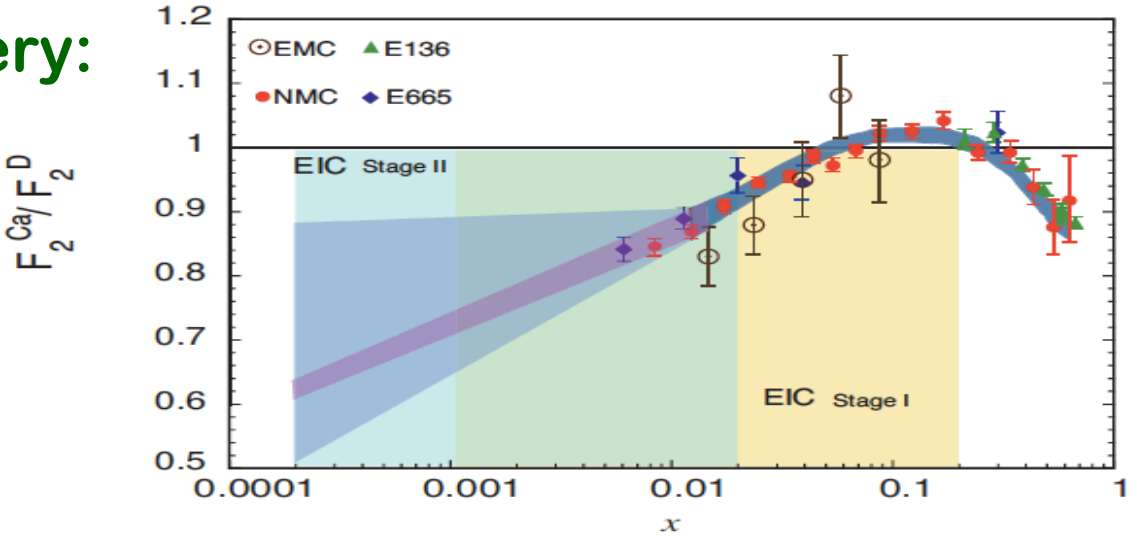






**Need an EIC to reach the saturation regime at a lower energy, and to explore the transition region by varying the ion species**

# Quarks and gluons in nuclei?

## ❑ EMC discovery:



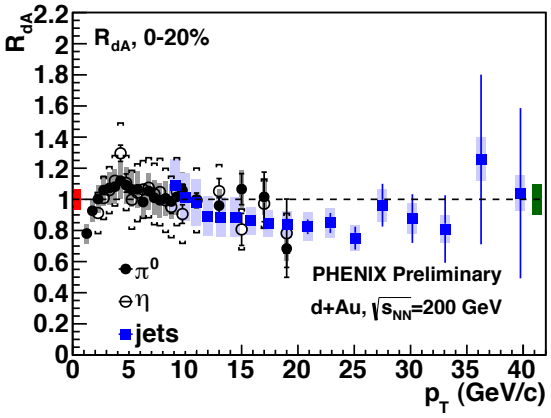

See talks by Weiss, Brooks, …

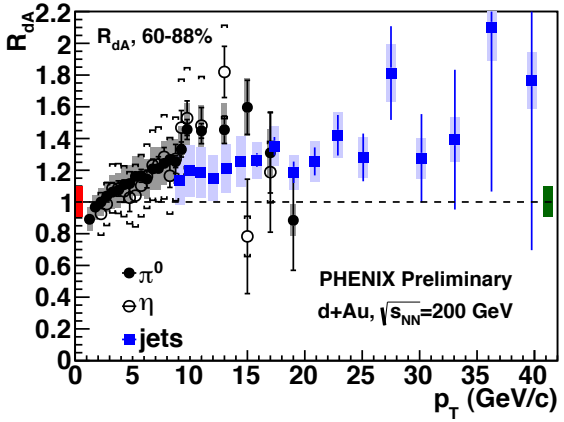
**How does nuclear environment affect the quark-gluon distributions?**

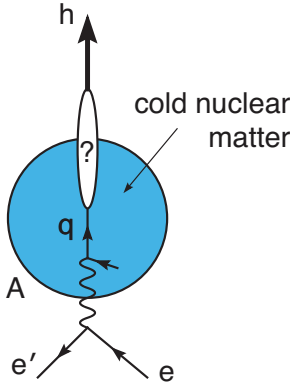
Lump around the "nucleons"?
A property of whole nucleus?

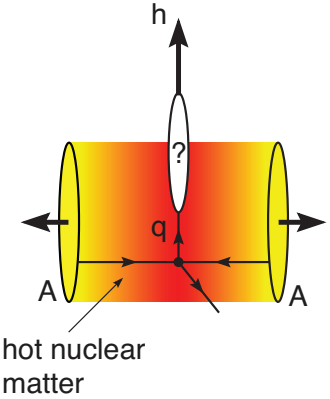
QED: molecule/crystal

## ❑ How does nuclear matter respond to a fast moving charge?



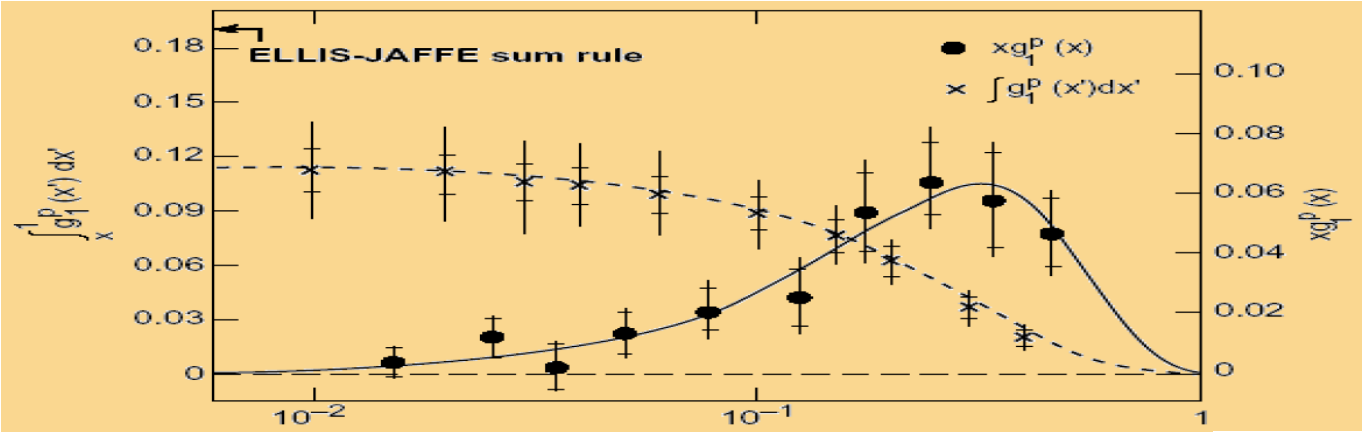




**Strange nuclear effect in dA at RHIC?!** ➡ **Need an EIC**

# Proton spin and proton structure?

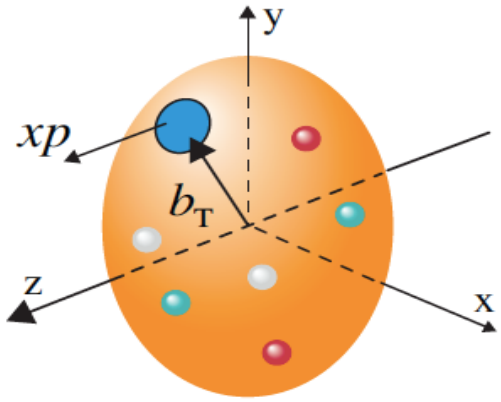
## ❑ EMC measurement – "the plot":




See talks by Stratmann, Perdekamp, Wissink, Burkhart

## ❑ Over 20 years effort:

- ✧ Quark (valence + sea) helicity: $\sim 30\%$ of proton
- ✧ Gluon helicity (RHIC data): Not zero, but, sn




➡ Need a polarized EIC to explore the gluon and sea

## ❑ New opportunities at an EIC – tomographic images of partons:

- ✧ How are the sea quarks and gluons inside the nucleon distributed in space, momentum, spin and favor?
- ✧ How do they correlated with nucleon's properties, such as spin?
- ✧ What is the role of orbital motion of quarks and gluons in proton spin?

# Golden measurements at an Electron-Ion Collider

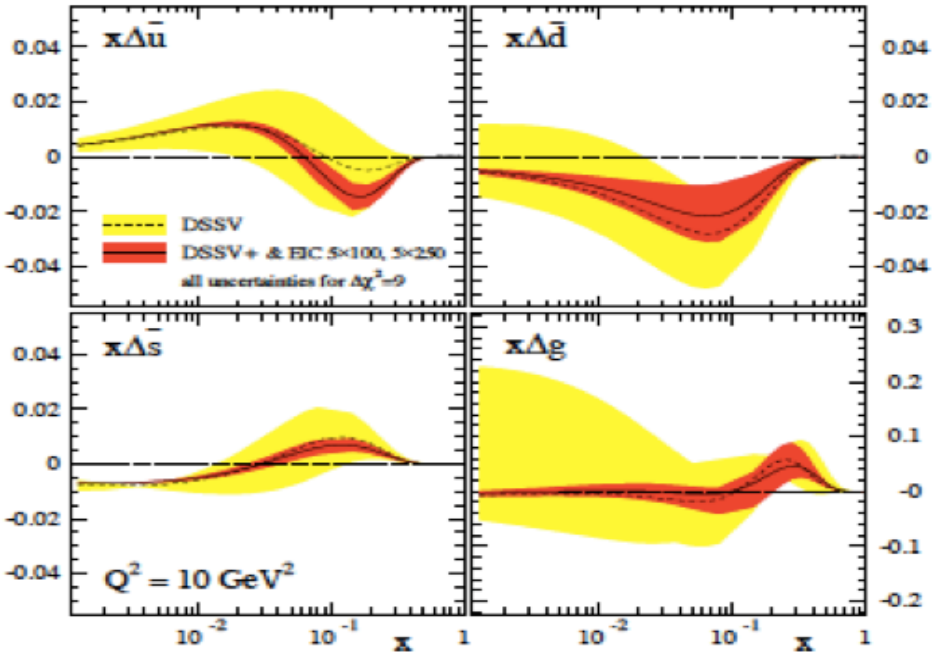
See talks by Deshpande, Aschenauer, Nadel-Turonski, Xu, …

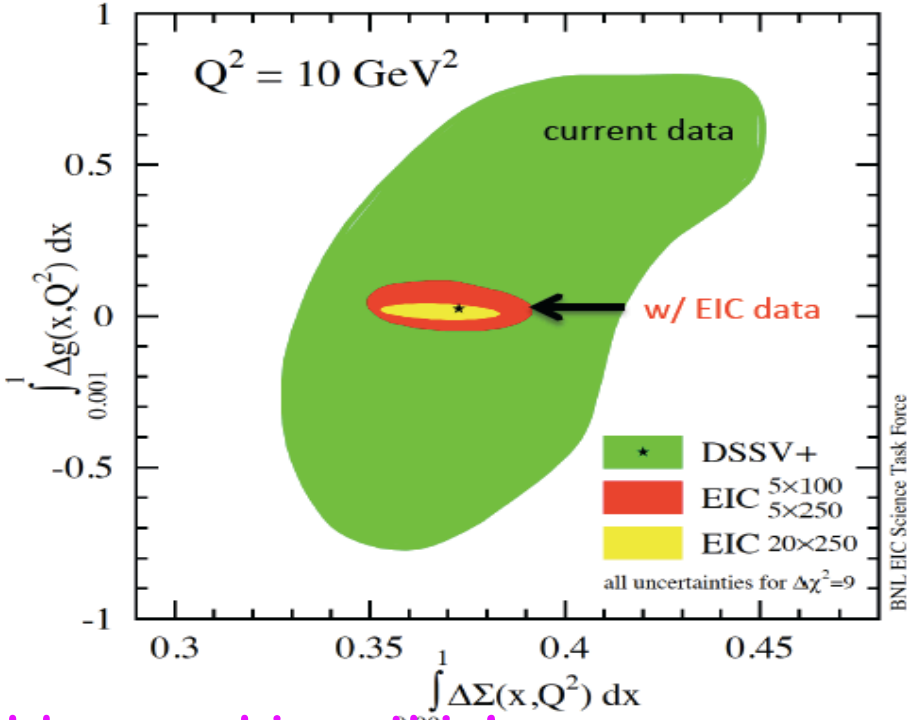
# The spin and flavor structure of the nucleon

- **Proton – composite particle of quarks and gluons:** Stratmann's talk

  **Spin = intrinsic (parton spin) + motion (orbital angular momentum)**

- **The EIC – the decisive measurement (two months running):**




**No other machine in the world can achieve this!**

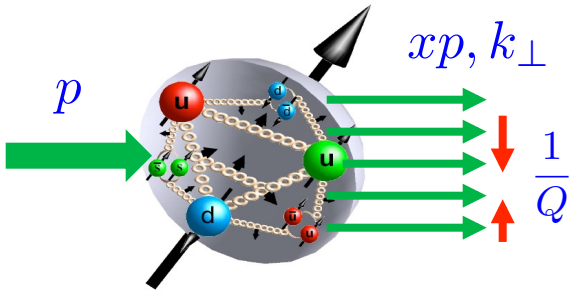
- **The proton spin:**

  **Adding the Δg, is there still a deficit to the proton spin?**

  **If yes, we will have to investigate the orbital motion of quarks and gluons – the motion transverse to the proton's momentum**

# 1+2D confined motion in a nucleon

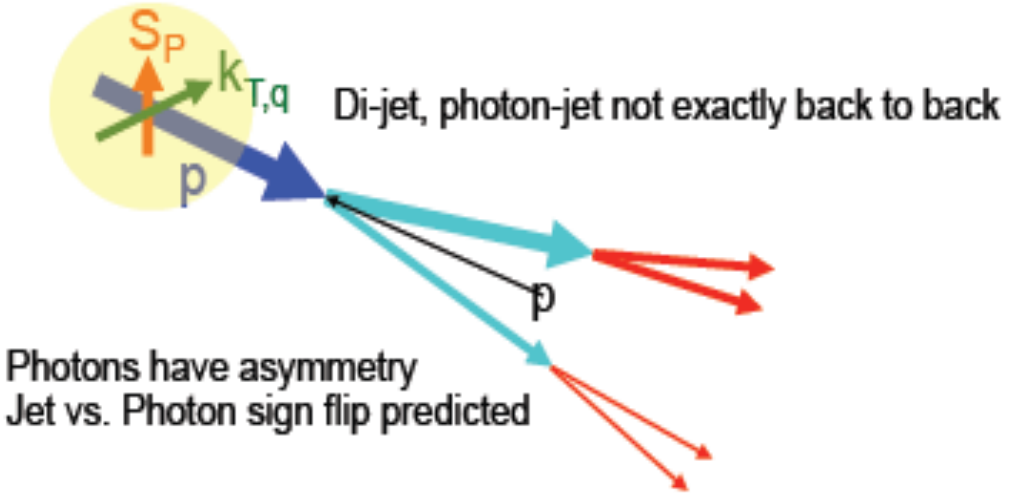
## ❑ Motion at the confining scale (<< Q) – partonic structure:




- ✧ Transverse momentum dependent parton distributions (TMDs)
- ✧ Two scale observables
- ✧ SIDIS – Q, $p_T$

See talks by Gao, Schiegel, Prokudin, Goldstein, …

## ❑ Quantum correlation between hadron spin and parton motion:




Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

## ❑ Single-spin asymmetry:

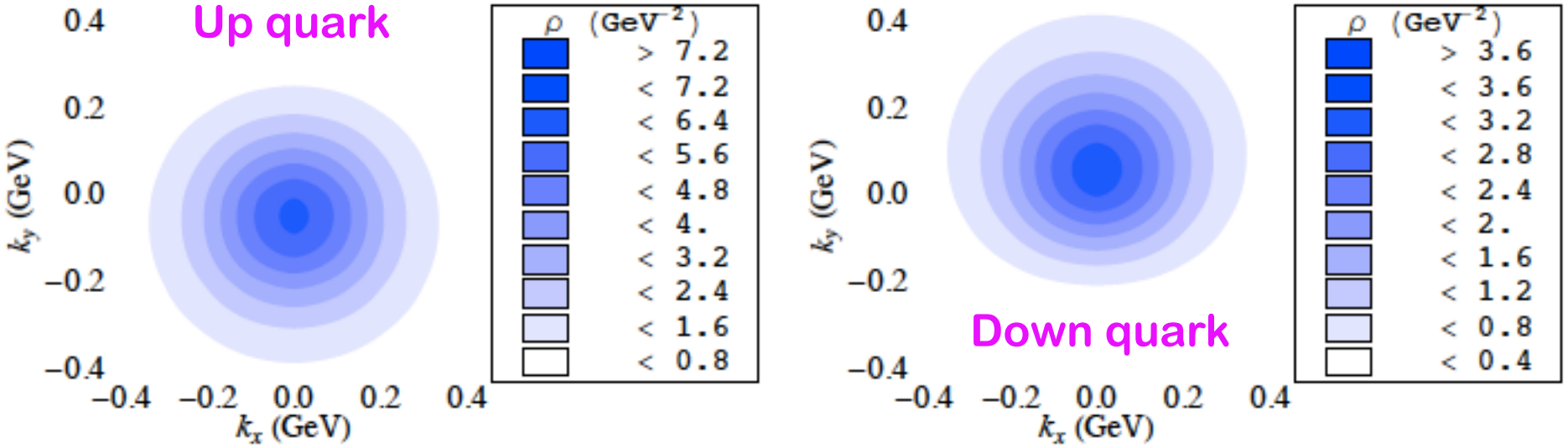
$$A(\ell, \vec{s}) \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$

Enhance the role of transverse motion – confined motion!

Only EIC can cover the sea and gluon, and separate various TMDs!

# What EIC can do to Sivers function?

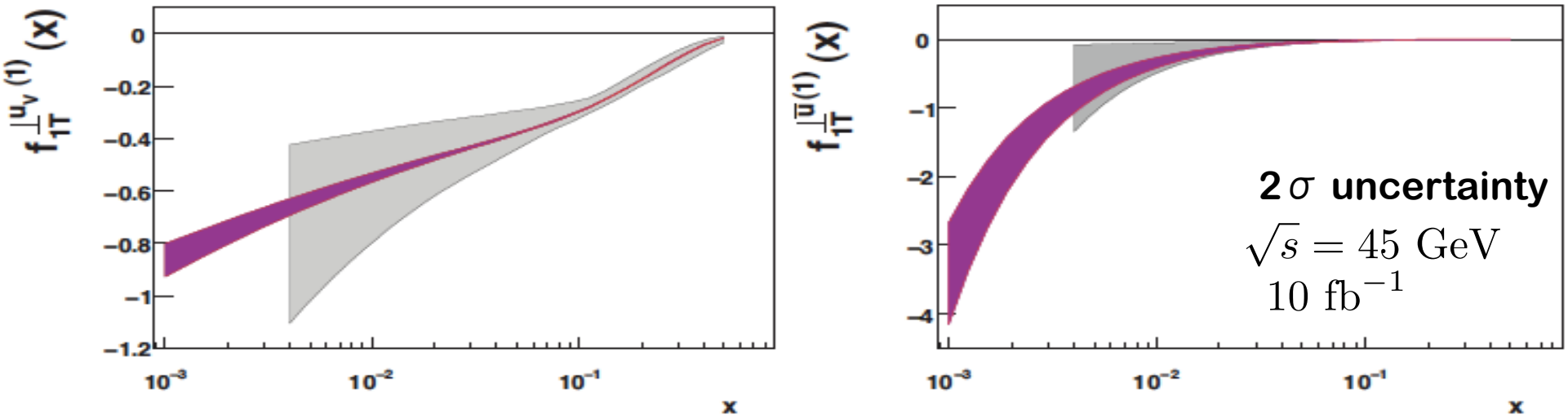
## ❑ Unpolarized quark inside a transversely polarized proton:




Color confined radius at different x?

See talks by Gao, Prokudin, …

## ❑ Role of momentum fraction – x:



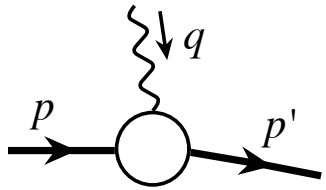
# 1+2D spatial imaging of color?

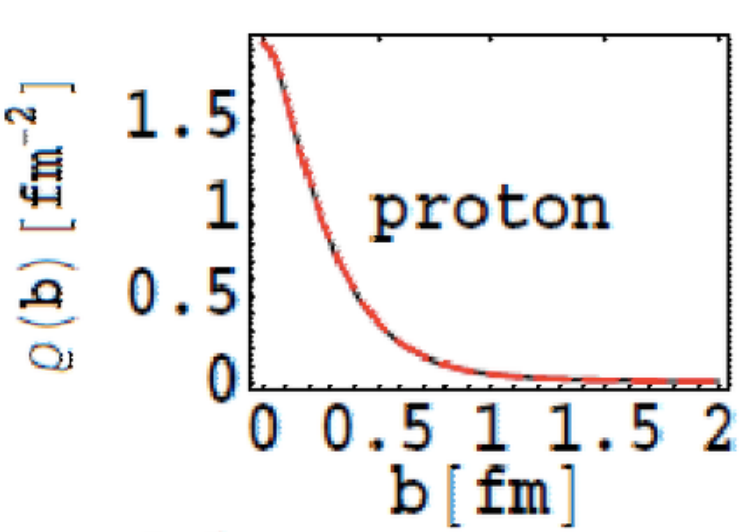
- **The "big" question:**

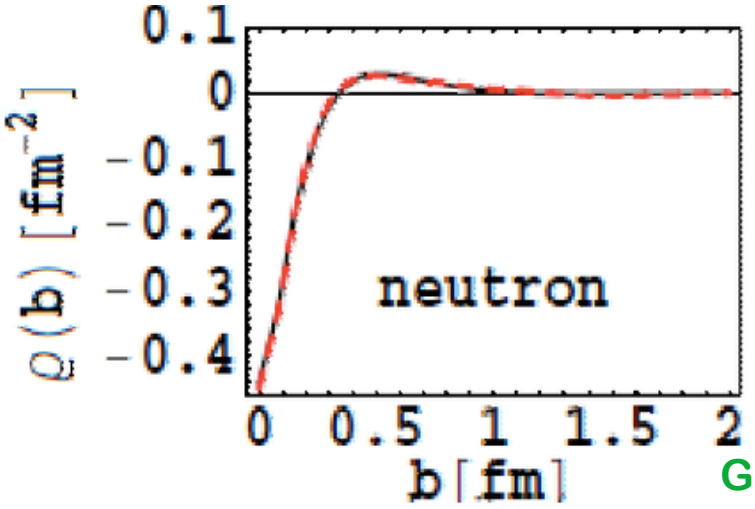
  How color is distributed inside a hadron? (clue for color confinement?)

- **Electric charge distribution:**

  Elastic electric form factor ➡ Charge distributions



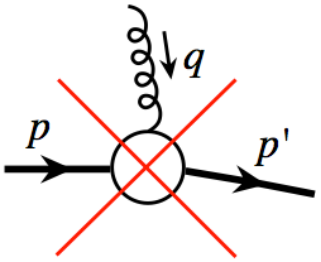




G.A. Miller (2007)

- **But, NO color elastic nucleon form factor!**

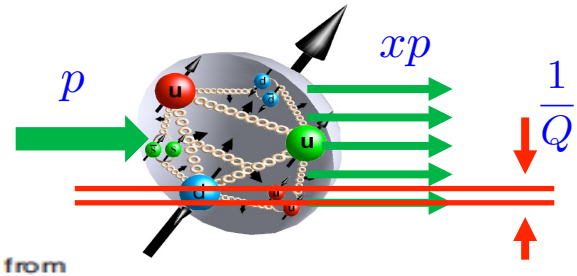
  Hadron is colorless and gluon carries color

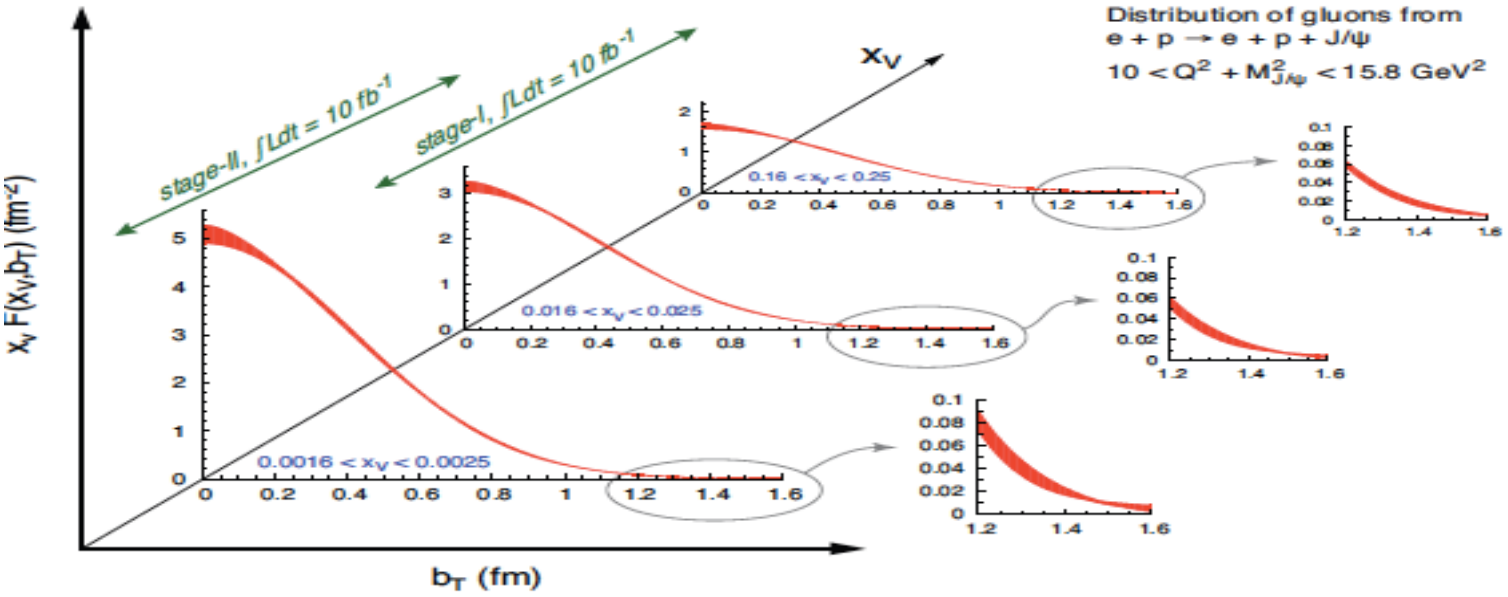


# 1+2D spatial imaging of parton density

## ❑ 2D Fourier transformation:

$$q(x, |\vec{b}|, Q^2) = \frac{1}{4\pi} \int_0^\infty d|t|\, J_0(|\vec{b}|\sqrt{|t|})\, H(x, \xi = 0, t, Q^2)$$




See talks by Hasch, Liuti, Fazio, …

**Images of gluons Only at an EIC**

## ❑ Quark GPDs and its orbital contribution to proton's spin:

$$J_q = \frac{1}{2} \lim_{t\to 0} \int dx\, x\, [H_q(x, \xi, t) + E_q(x, \xi, t)] = \frac{1}{2}\Delta q + L_q$$

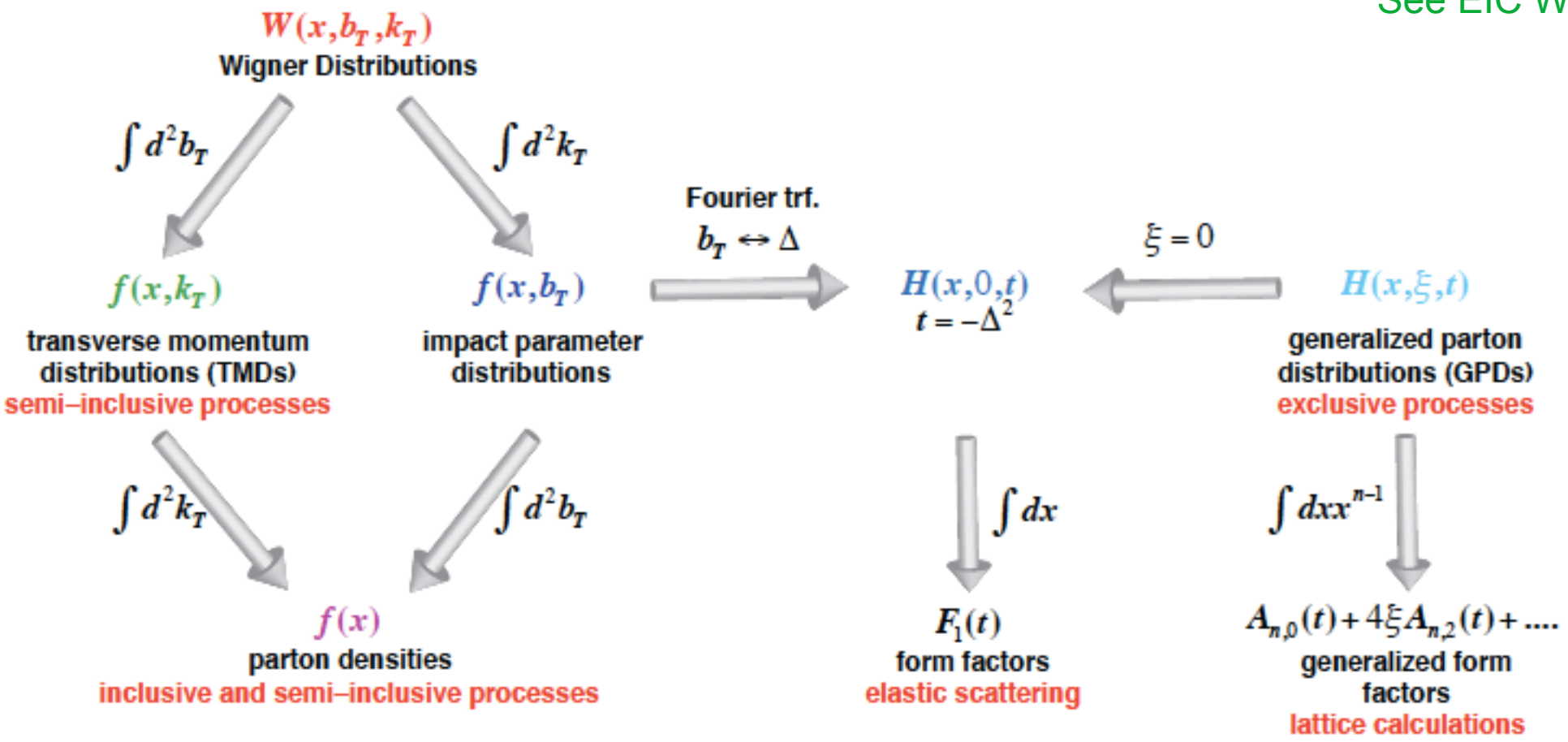
**The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab 12**

**Should this be consistent with Lattice QCD?**

# The Wigner functions

- A beautiful description of all distributions and their relations:

See EIC WP




- It is not clear if we can measure these Wigner functions in high energy scatterings

# Nucleus, a Laboratory for QCD

- **The nucleus:**

  See talks by Mueller, Stasto, …

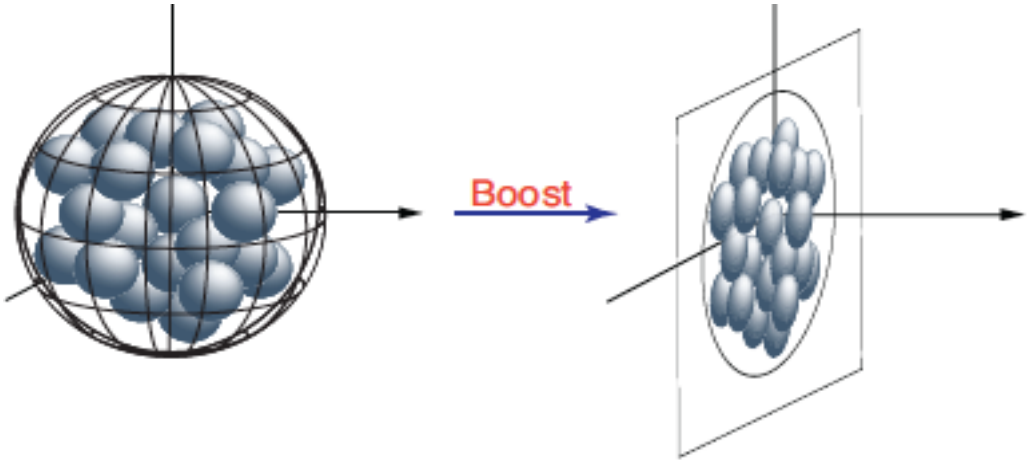
  Binding energy/nucleon ~ 8 MeV << Q < a few GeV

  → Nuclear landscape = superposition of nucleon landscape

- **EMC effect:**

  Nuclear landscape =\= superposition of nucleon landscape

- **"Snapshot" does not have a "sharp" depth at small $x_B$**



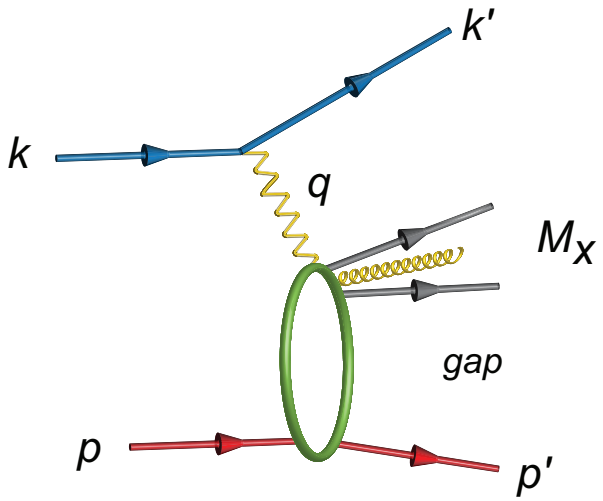

Probe size: transverse - $\frac{1}{Q} \ll 1\ \mathrm{fm}$, longitudinal size - $\frac{1}{xp} \sim \frac{1}{Q} \ll 1\ \mathrm{fm}$

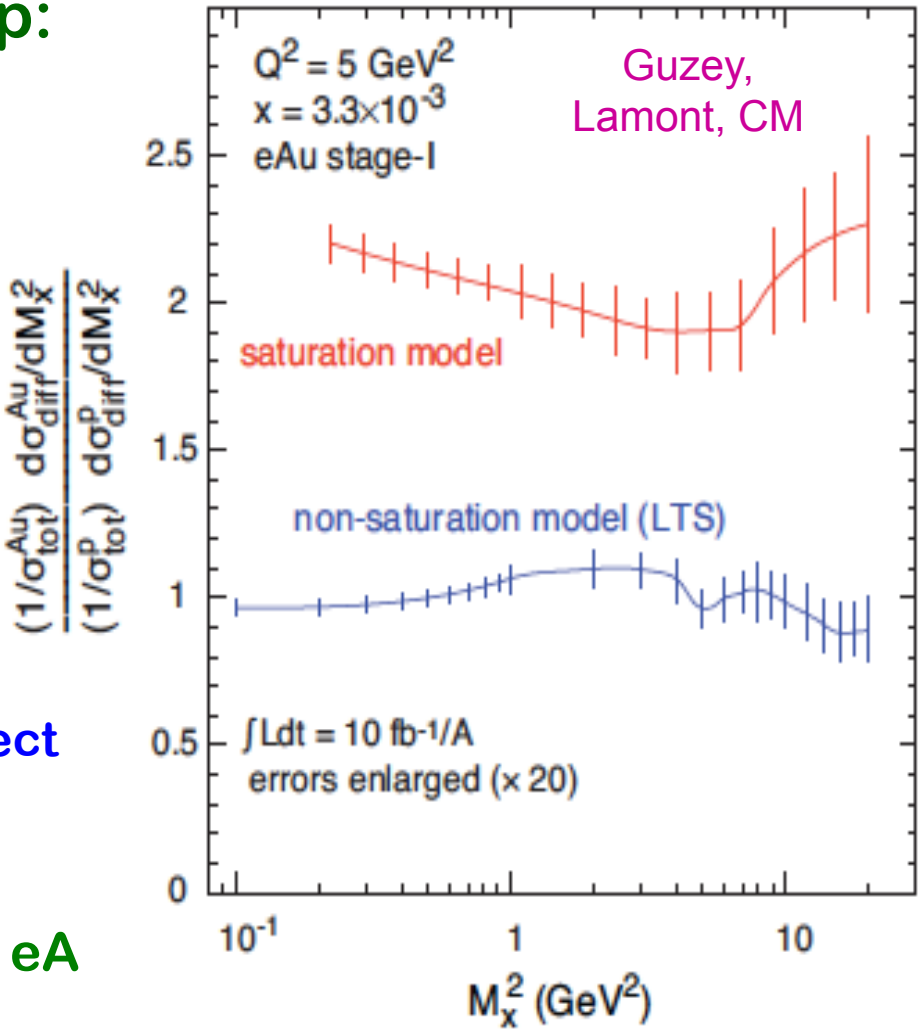
Longitudinal size > Lorentz contracted nucleon: $\frac{1}{xp} > 2R\frac{m}{p}$

$$x < x_c = \frac{1}{2mR} \sim 0.1$$

# Hard diffractive at an EIC

## ❑ Hard scattering with a rapidity gap:




- ✧ Color singlet exchange, trong non-linear effect
- ✧ Factorization works in DIS, not in pp, pA, AA

**The factor of 2 enhancement is only for eA (no equivalent in pA!)**

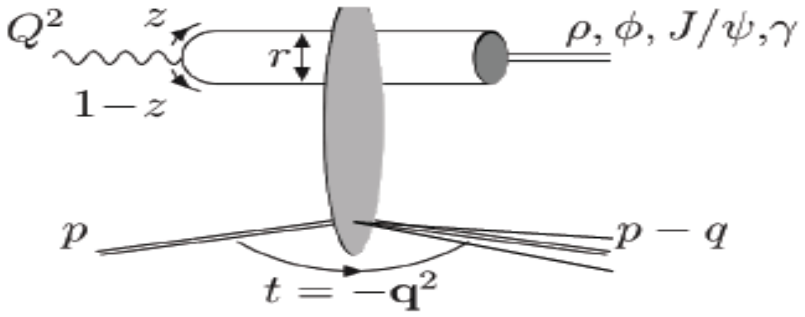
See talks by Kovchegov, Strikman, Surrow, …

**This is a clean and unambiguous signal of saturation physics already at EIC stage-1**

C. Marquet @ QM2012

# Exclusive vector meson production

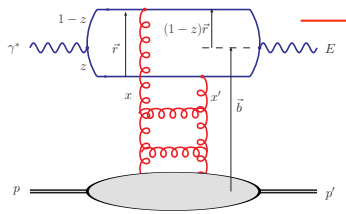
## ❑ Diffractive vector mesion (Φ, J/ψ, ..) production:

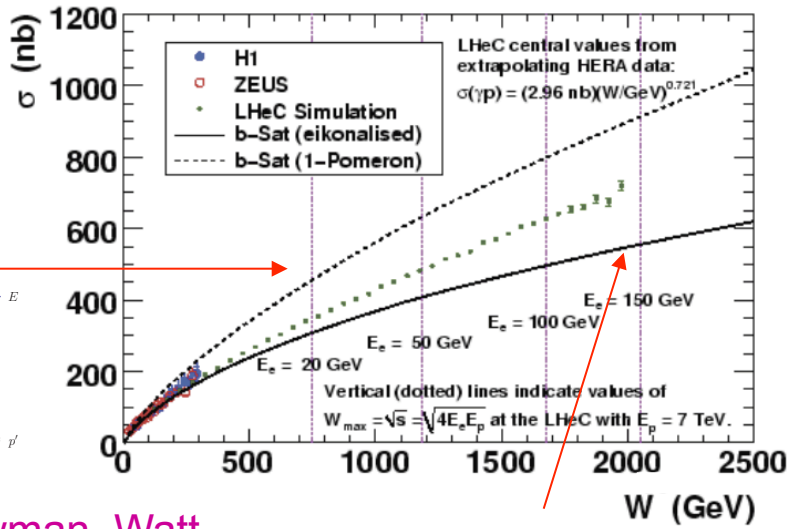



- as a function of **t**

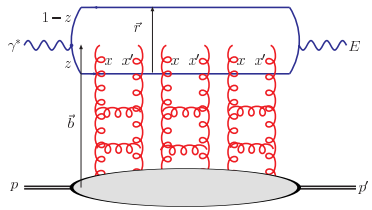
$e + p \rightarrow e + J/\Psi + p$ @ LHeC

energy dependence

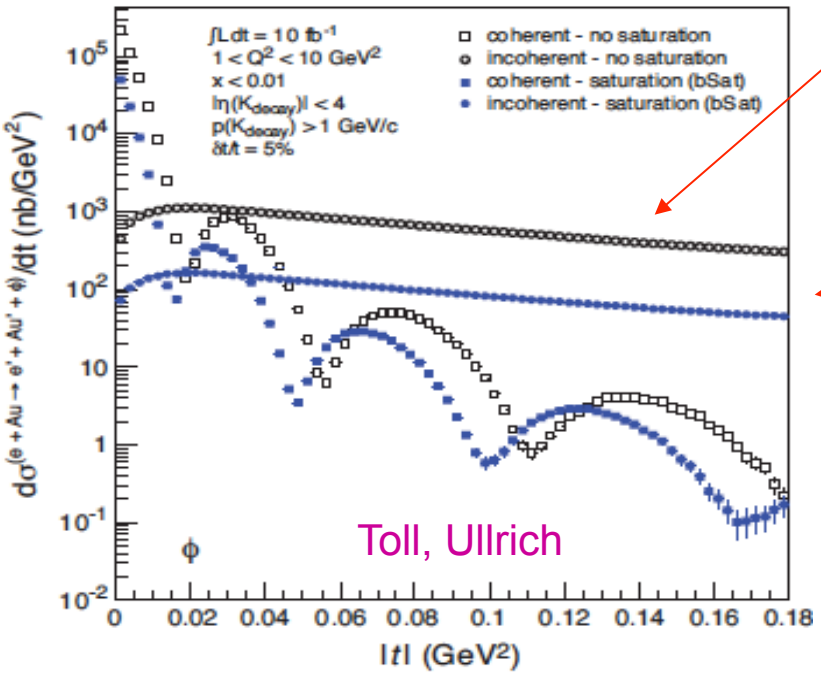





Newman, Watt



## ❑ ϕ–production:




Toll, Ullrich

## ❑ Images in nuclei:

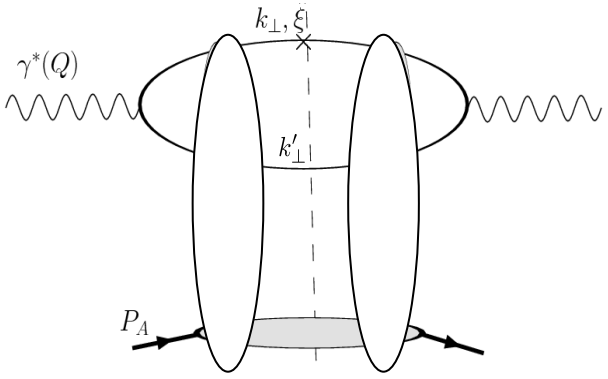
**Spatial gluon distribution from a Fourier transformation in |t|**

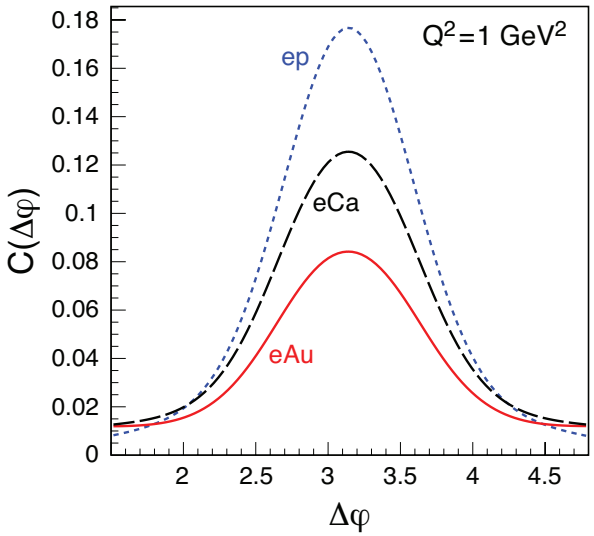
**Not feasible in p+A**

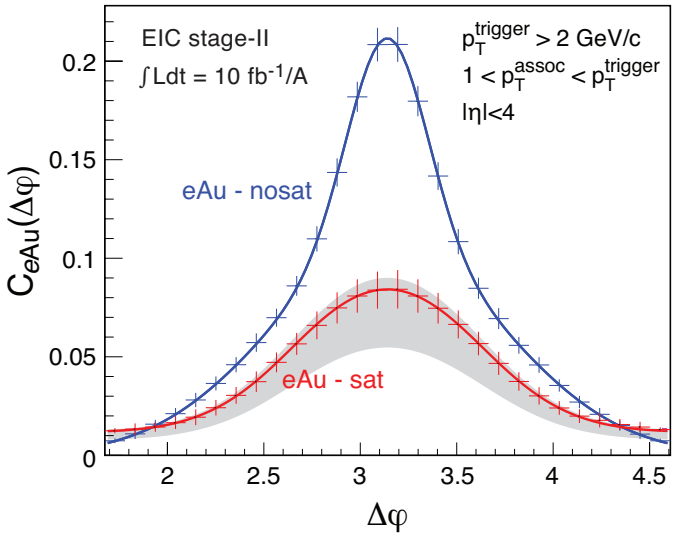
C. Marquet @ QM2012

# Di-hadron correlation at an EIC

## ❑ Direct access to the $k_T$ dependence of gluon distribution:



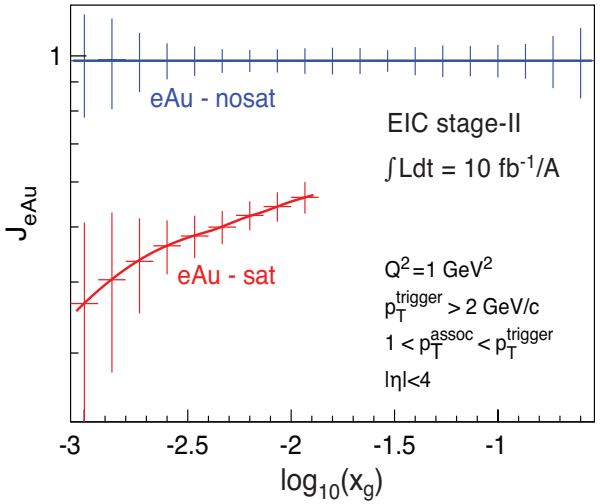



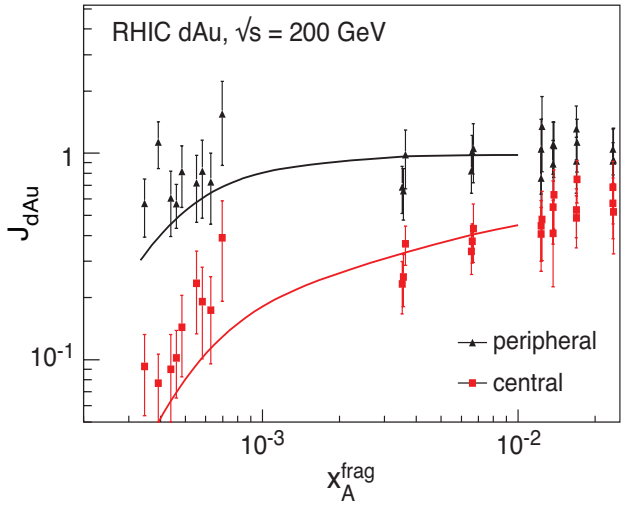

**At the qualitative level:**

**similar effects as in p+A**

Lee, Xiao, Zheng

**But, at the qualitative level, this process involves a different unintegrated gluon distribution**




**Unique access to Weizsacker-Williams "gluon" distribution**

**(a different operator definition is involved in p+A)**

Xiao's talk

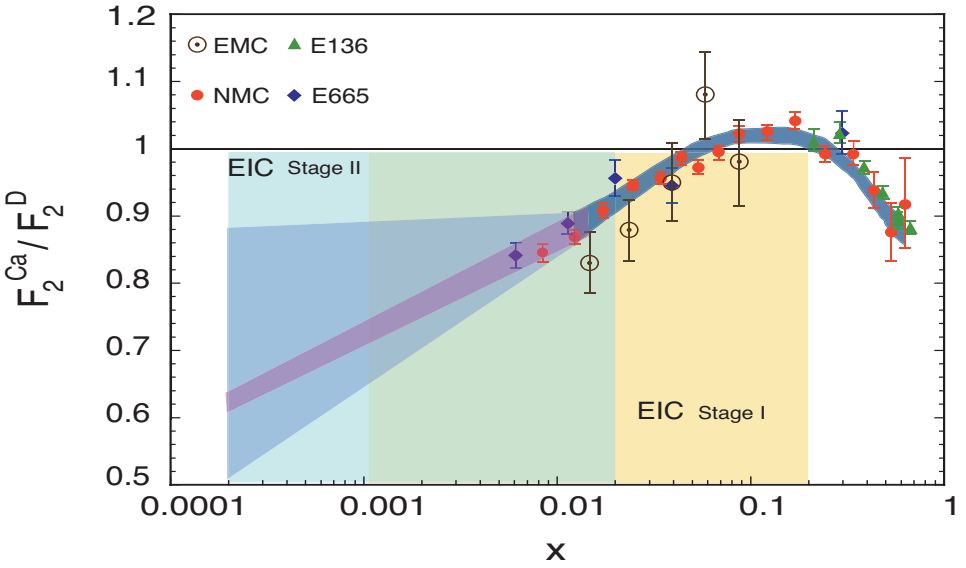
C. Marquet @ QM2012

# Nuclear parton distributions

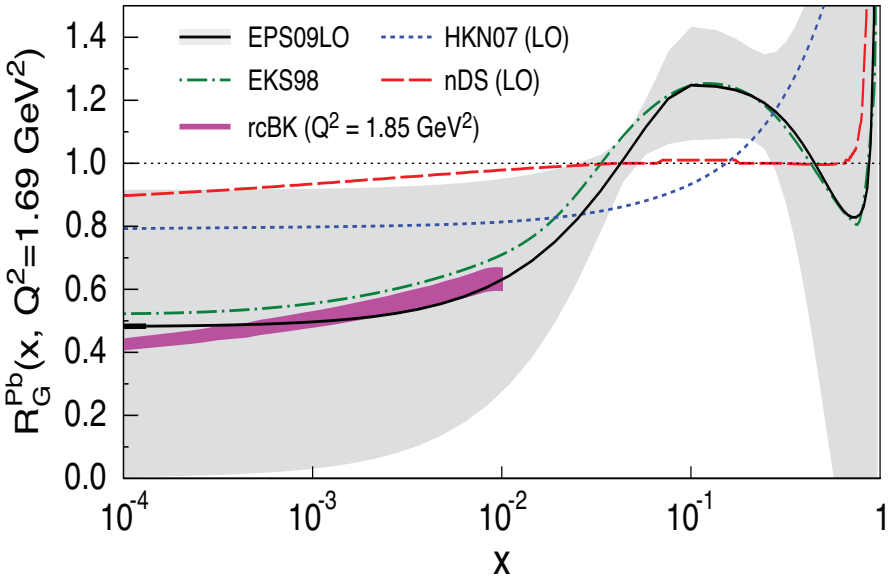
## ❑ The EICs are ideal for exploring the transition region:

$0.0001 < x < 0.1,\ 1\ \text{GeV}^2 < Q^2$

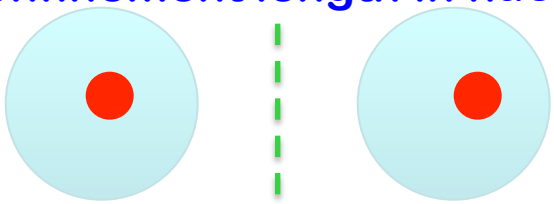
**$F_2$ structure function**




**"Gluon" distribution – not physical!**




- ✧ Saturation of the ratio for x > 0.001 =\= saturation of nuclear structure function
- ✧ Color confinement length in nuclei?



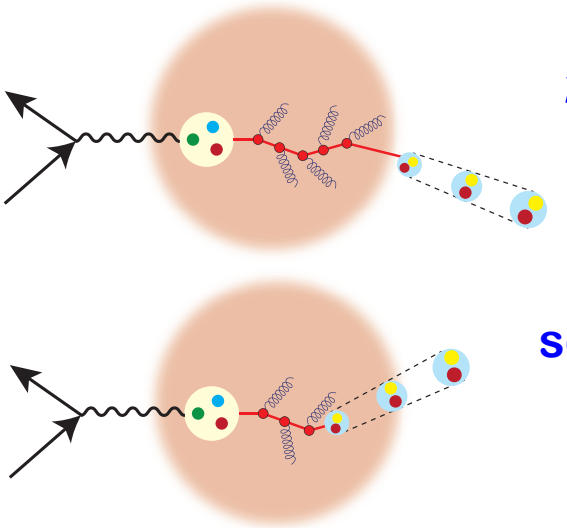
Nucleon size – top of the shade area?
Nuclear size – bottom of the shade area?

- ✧ DGLAP cannot predict the region below the "x" where there are data!
- ✧ Evolution of $Q^2$, or $F_L$ measurement
- ✧ BK equation predict "x"-dependence from the boundary $G(x_0,Q^2)$ at all $Q^2$

C. Marquet @ QM2012

# Hadronization – energy loss

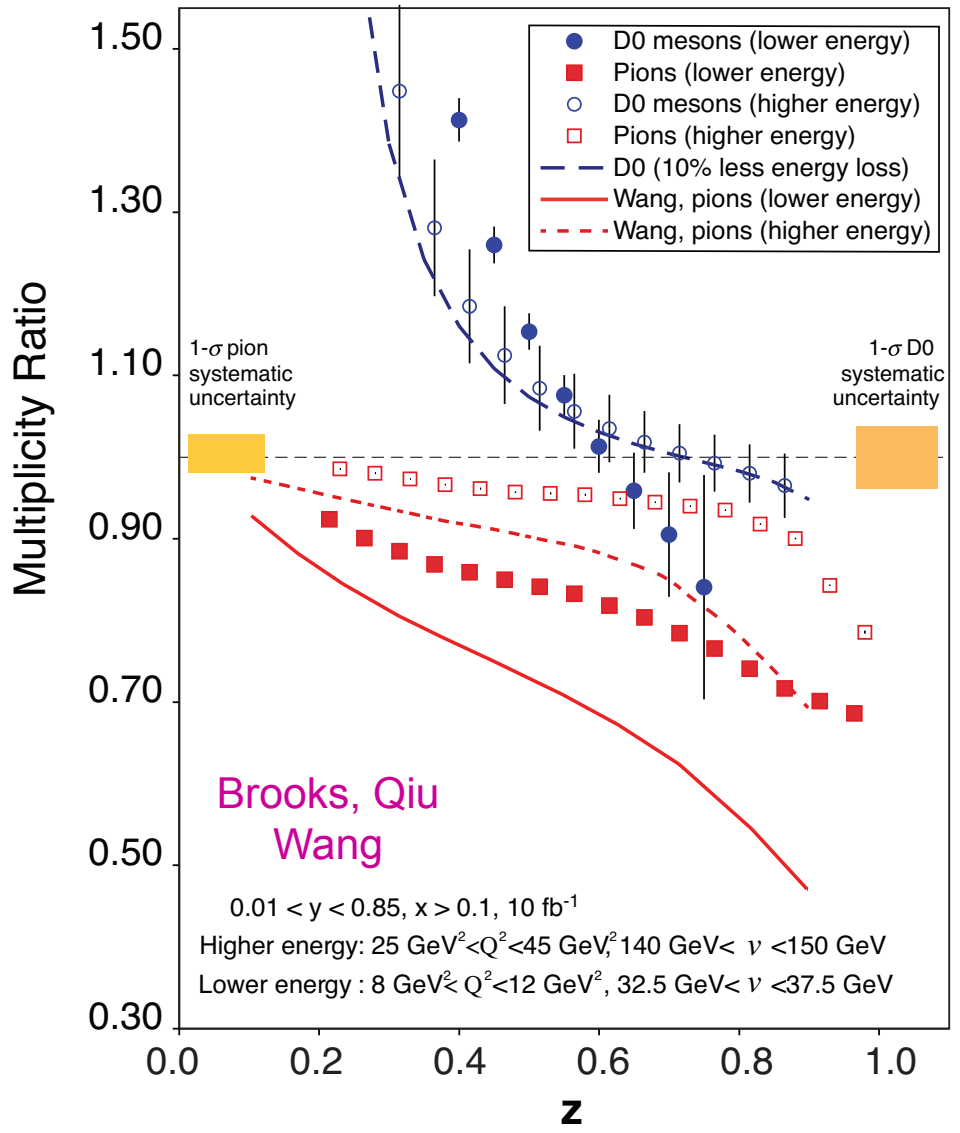
## ❑ Unprecedented ν range at EIC:



$$\nu = \frac{Q^2}{2mx}$$

**semi-inclusive DIS**

- ✧ **Small $\nu$ - in medium hadronization:**
  - dynamics of confinement
  - stages of hadronization and their time scales
- ✧ **Large $\nu$ - parton multiple scattering:**
  - Parton propagation in medium
  - Energy loss and broadenning, $\hat{q}$
  - Direct access to fragmentation

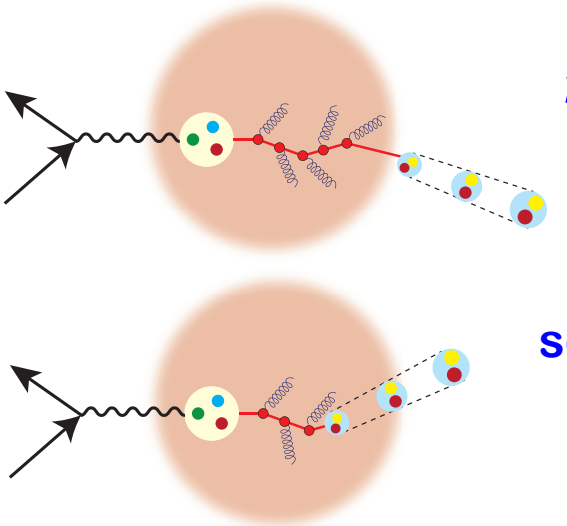



Brooks' talk

C. Marquet @ QM2012

# Hadronization – energy loss

## ❑ Unprecedented ν range at EIC:

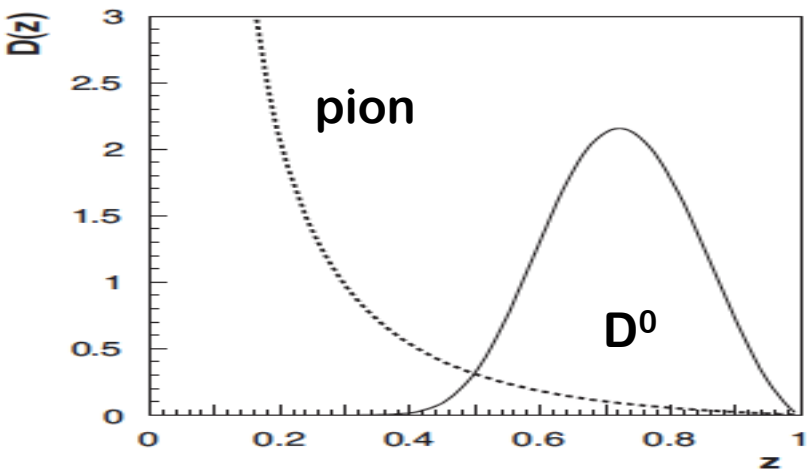


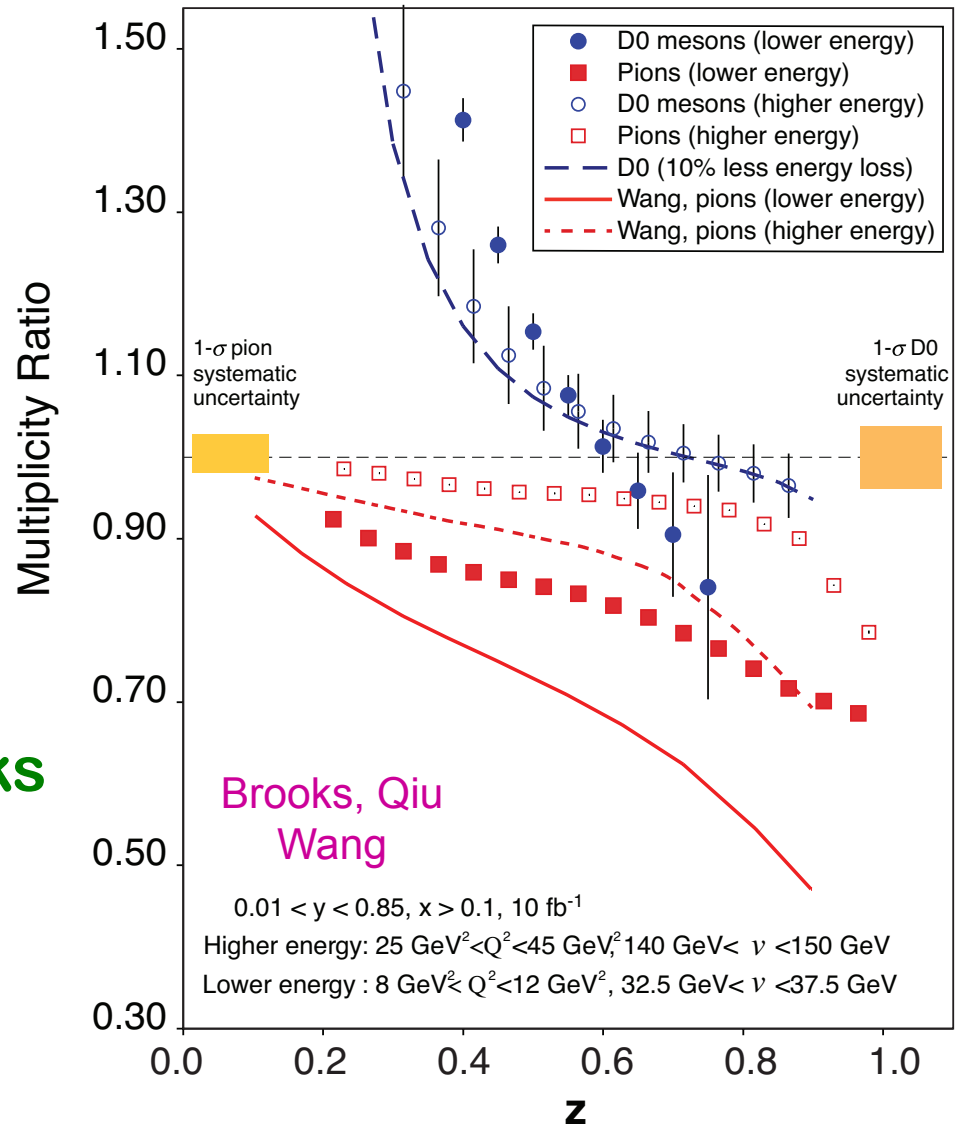
$$\nu = \frac{Q^2}{2mx}$$

**semi-inclusive DIS**

## ❑ First time access to heavy quarks

- **Mass dependence of fragmentation**




**Need the collider energy of EIC**

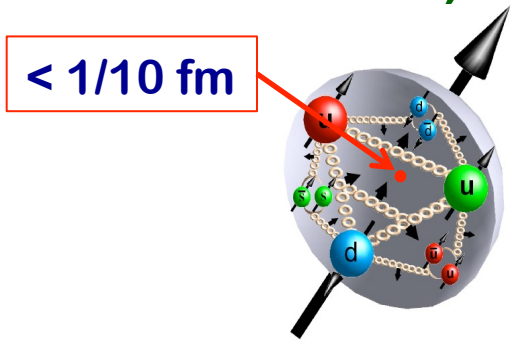
C. Marquet @ QM2012

# Summary

- We have learned a lot of QCD dynamics in last 40 years, but, mainly in its most trivial asymptotic regime (less than 0.1 fm)

- What about the hadron structure?

  **Not much!**




- Many aspects of hadron's partonic structure can be naturally addressed by EIC, but, not other machines: e+e-, pp, pA, AA

- The EIC with polarization was designated in the 2007 Nuclear Physics Long Range Plan as,
  "embodying the vision for reaching the next QCD frontier"

It will extend the QCD science programs established at both the CEBAF accelerator at JLab and RHIC at BNL in dramatic and fundamentally important ways

Thank you!