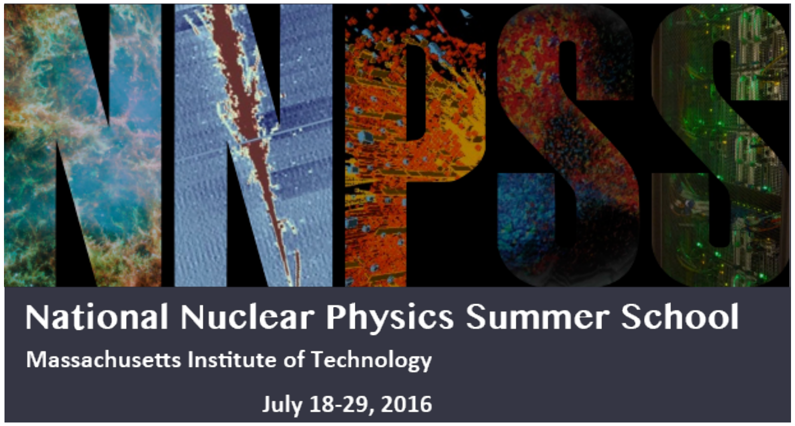


The Electron Ion Collider (EIC)

Abhay Deshpande

Lecture 3:

How the EIC will "solve" the nucleon spin puzzle

Open questions in high density cold QCD matter & how will the EIC address them?

Stony Brook University

Study of internal structure of a watermelon:

A-A (RHIC)

1) Violent collision of melons

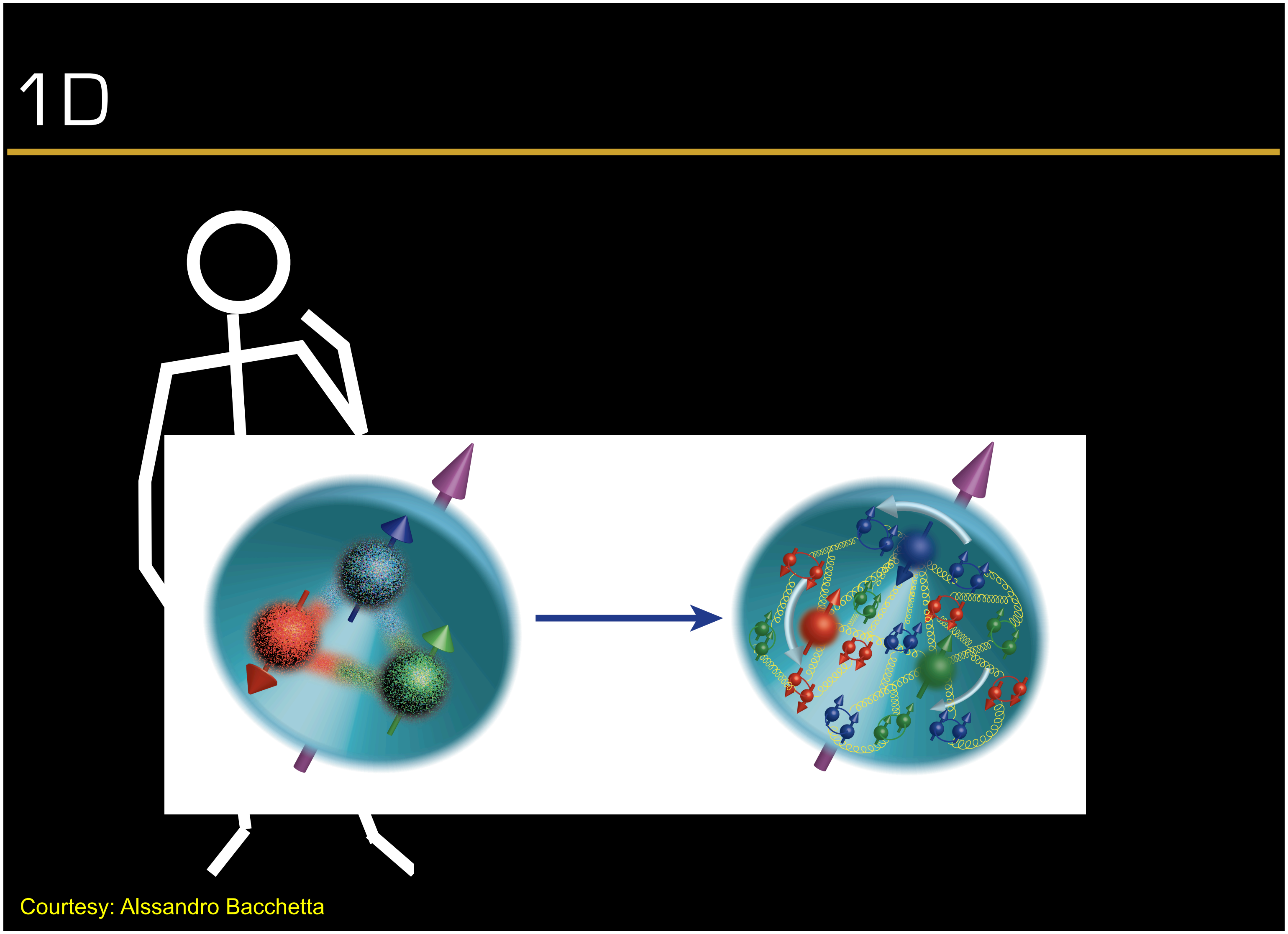
2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

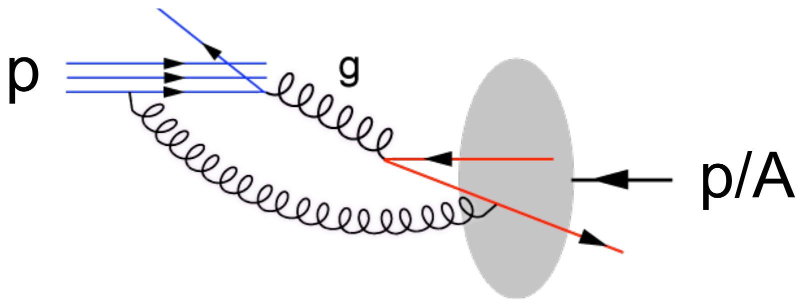
3) MRI of a watermelon

Non-Violent e-A (EIC)

What does we look like?



Hadron-Hadron

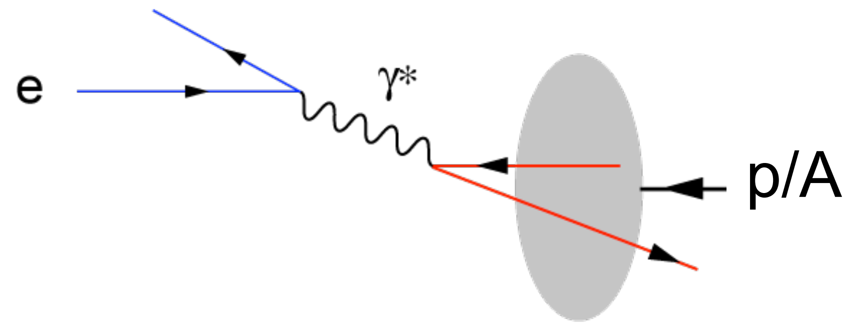


Probe & target complex

Soft interactions <u>before</u> collisions can destroy factorization, i.e. nuclear wave function affected

Kinematics imprecisely determined

Electron-Hadron (DIS)



Probe point like

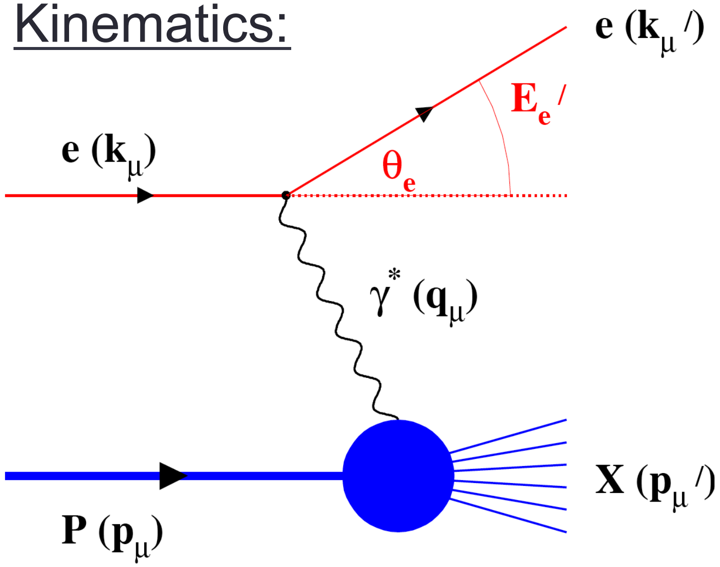
No <u>initial state</u> soft interactions, factorization preserved

Kinematics precisely determined

Deep Inelastic Scattering

$$s = 4E_pE_e$$

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_eE'_e(1 - \cos\Theta_{e'})$$

Measure of resolution power

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

Measure of inelasticity

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{Q^2}}$$

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

Measure of momentum fraction of struck quark

Hadron :

$$z = \frac{E_h}{\nu}; p_t$$ with respect to γ

Inclusive measurements:

e+p/A → e'+X

Detect only the scattered lepton in the detector

Semi-inclusive measurements:

e+p/A → e'+h(π,K,p,jet)+X

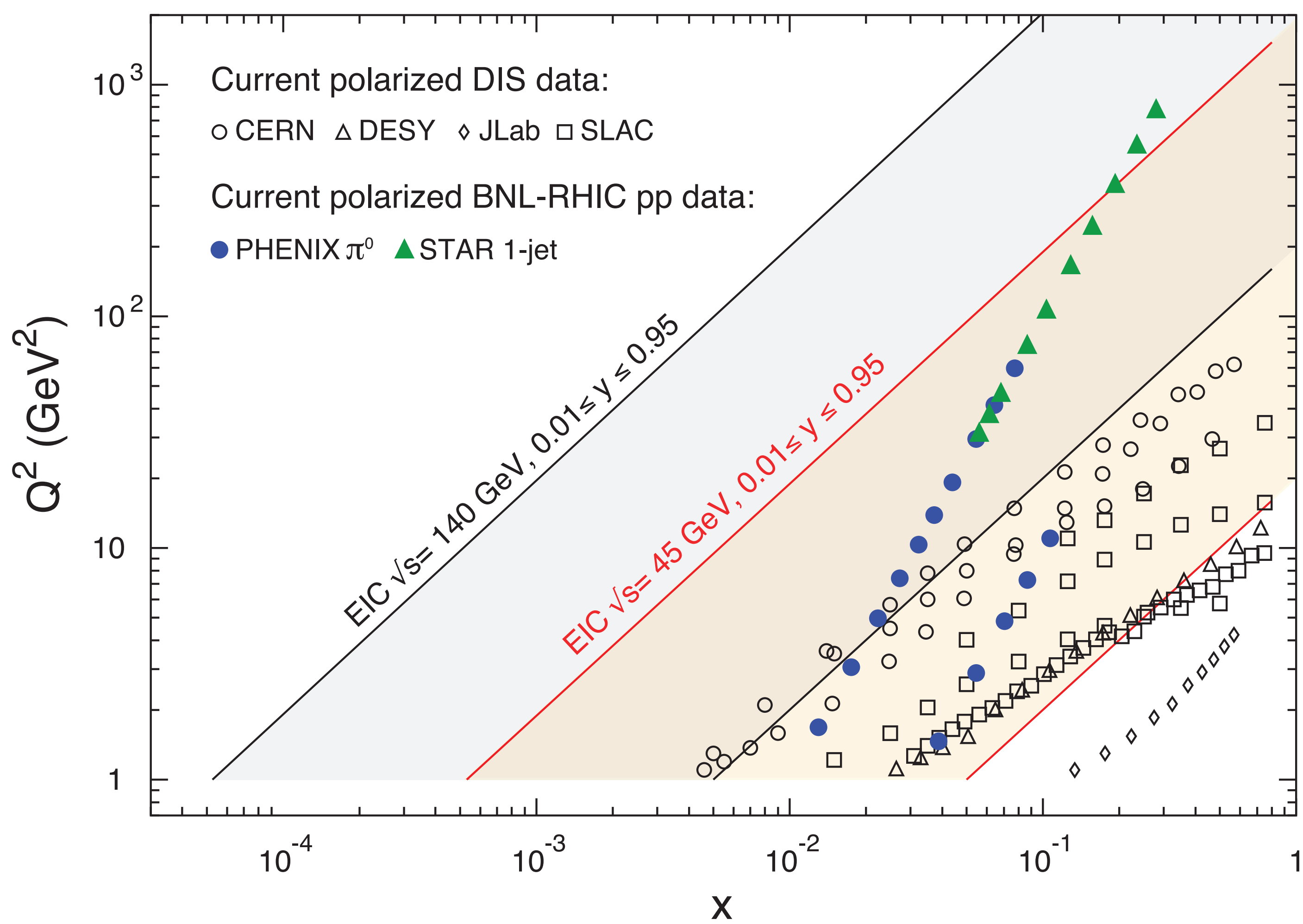
Detect the scattered lepton in coincidence with identified hadrons/jets

Exclusive measurements:

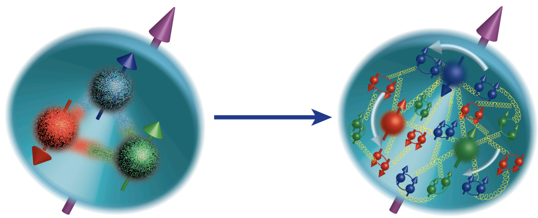
e+p/A → e'+h(π,K,p,jet)+p'/A'

Detect scattered lepton, identify produced hadrons/jets and measure target remnants

EIC: widens the x-Q^2 phase space!

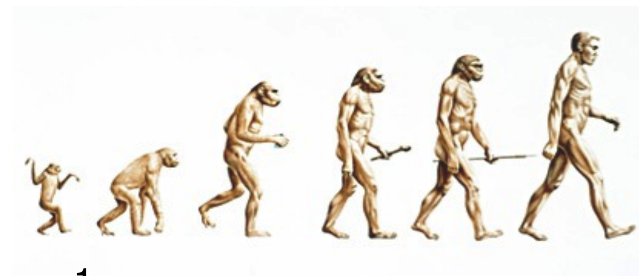


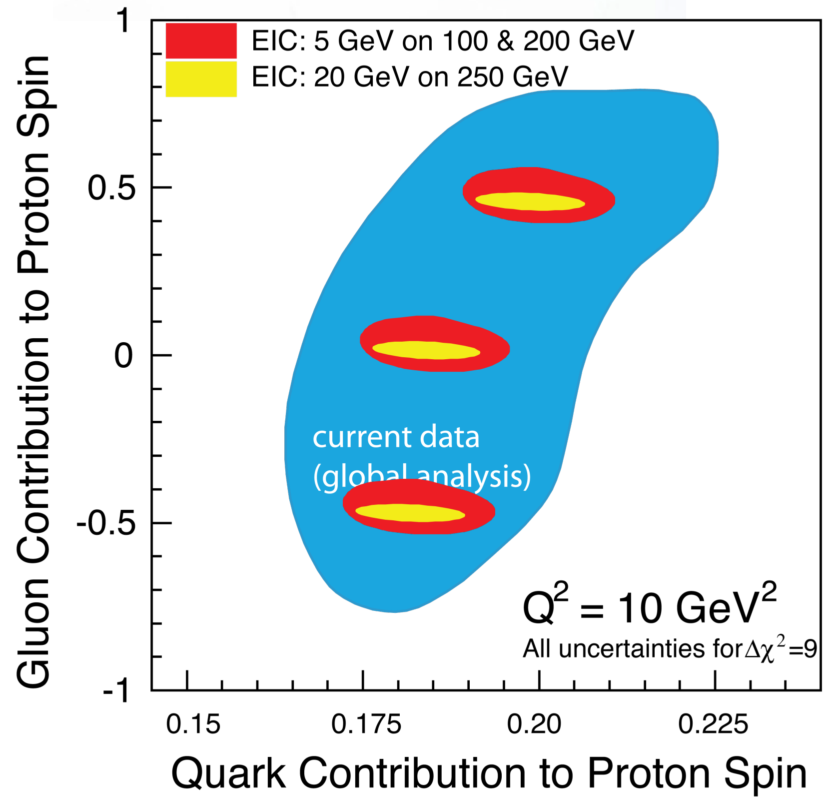
Our Understanding of Nucleon Spin



$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

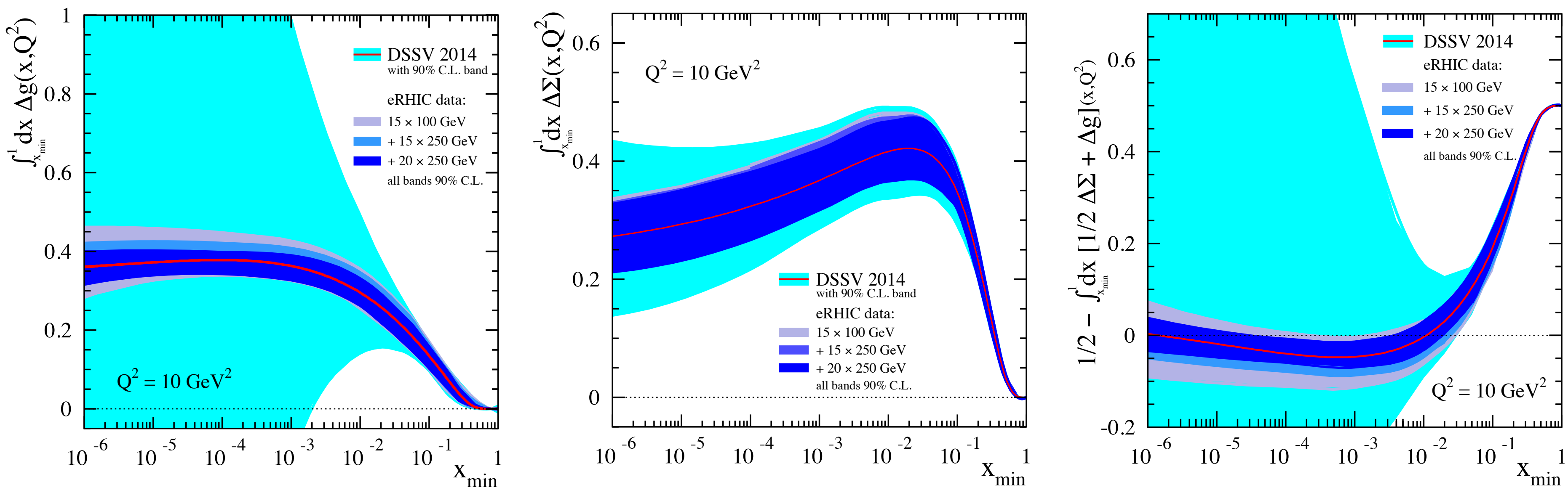




Precision in $\Delta\Sigma$ and Δg ➔ A clear idea Of the magnitude of L_Q+L_G

Toward solving nucleon spin:

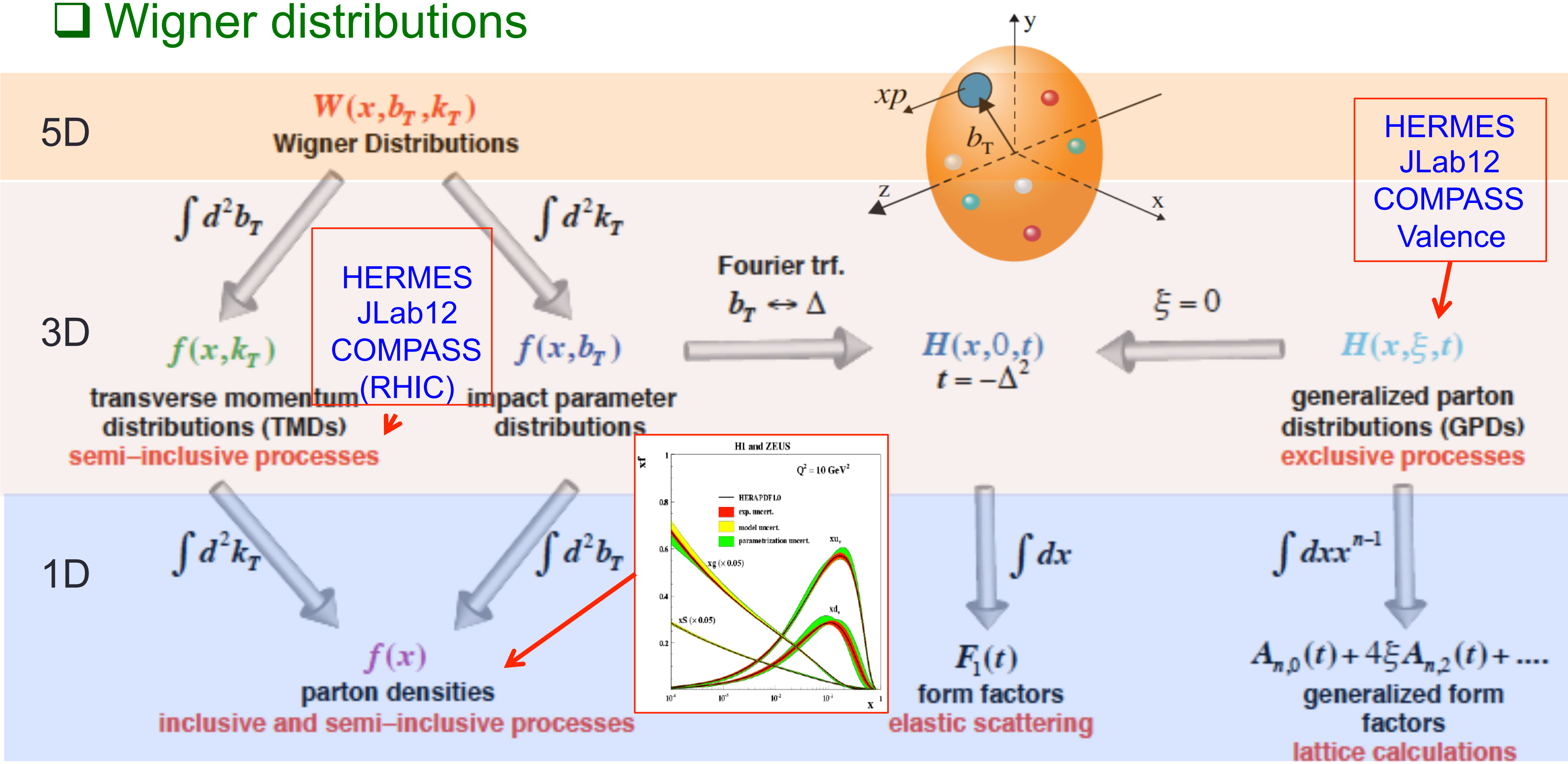
ΔΣ ΔG $L_{Q,G}$ = ½ - (ΔΣ + ΔG)



But, theory & experimental techniques have also evolved, now so we can do better than this….

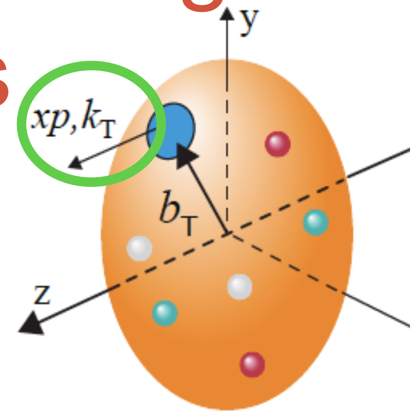
Unified view of the Nucleon Structure

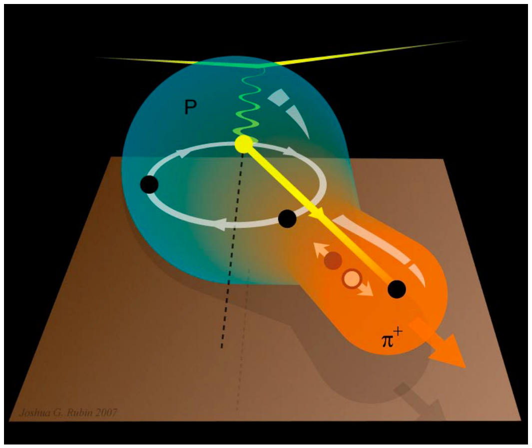
- ❑ Wigner distributions



- ❑ (2+1)D imaging Quarks (Jlab/COMPASS) , **Gluons (EIC)**
  - ✧ TMDs – confined motion in a nucleon (semi-inclusive DIS)
  - ✧ GPDs – Spatial imaging of quarks and gluons (exclusive DIS & diffraction)

Semi-Inclusive DIS → Best for measuring Transverse Momentum Distributions





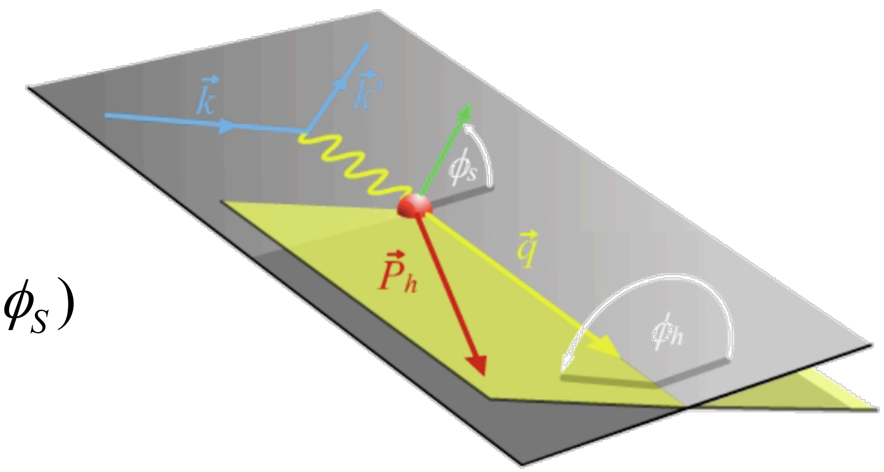
- Naturally, two scales:
  - high Q – localized probe
    To "see" quarks and gluons
  - Low p_T – sensitive to confining scale
    To "see" their confined motion
  - *Theory – QCD TMD factorization*

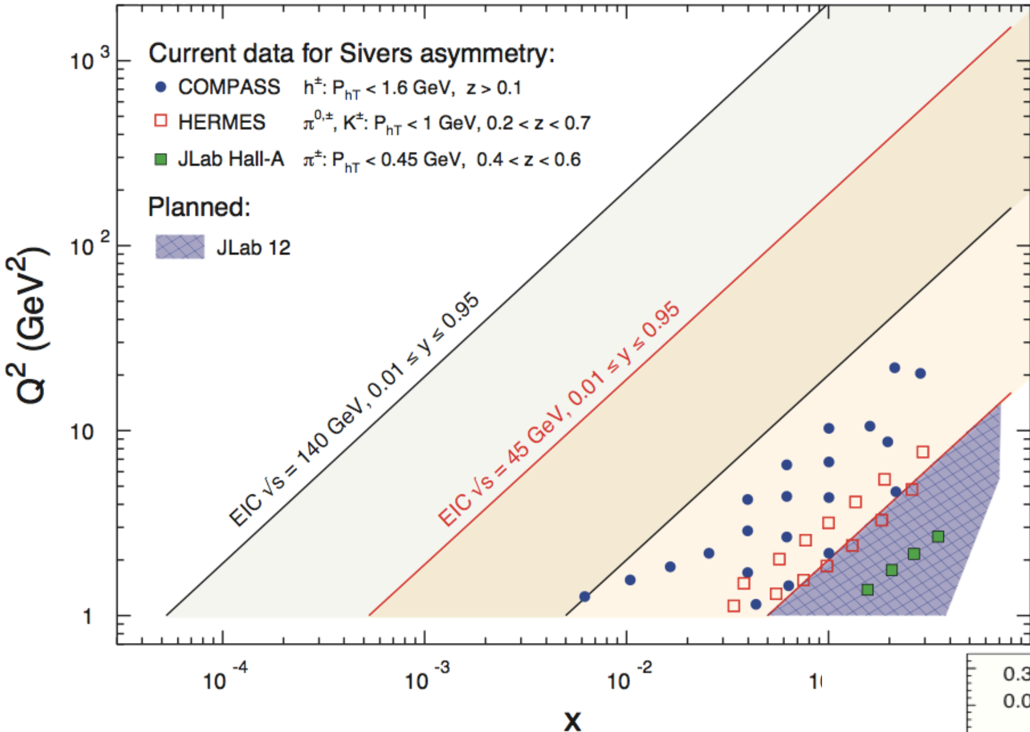
- Naturally, two planes:

$$A_{UT}(\varphi_h^l,\varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}$$

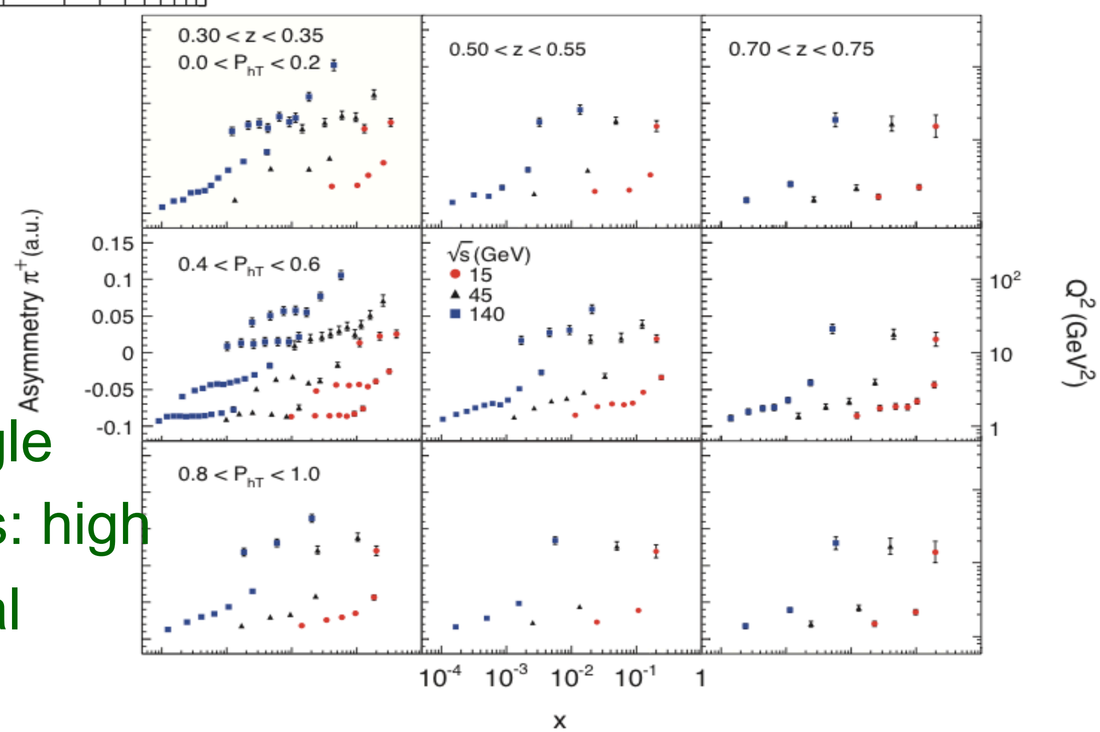
$$= A_{UT}^{Collins}\sin(\phi_h+\phi_S) + A_{UT}^{Sivers}\sin(\phi_h-\phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h-\phi_S)$$





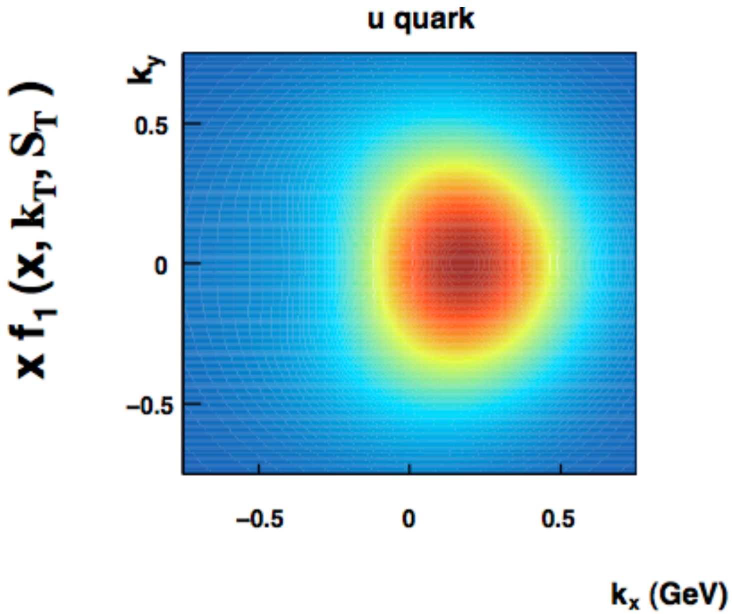
First, maybe the only, measurement of polarized sea and gluon TMDs

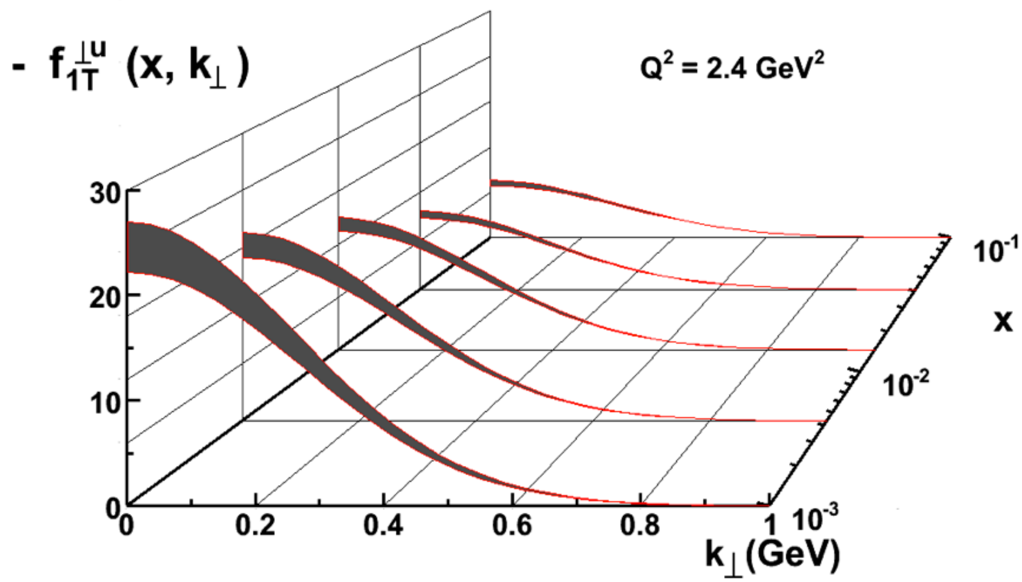


- High luminosity implies: Single transverse-spin asymmetries: high resolution & multidimensional

Momentum tomography of the nucleon

- Tomographic images of K_X/K_y of partons as functions of Bjorken-x: u quark distribution for transversely polarized proton.
- ***With EIC: low x partonic plots like these possible!***



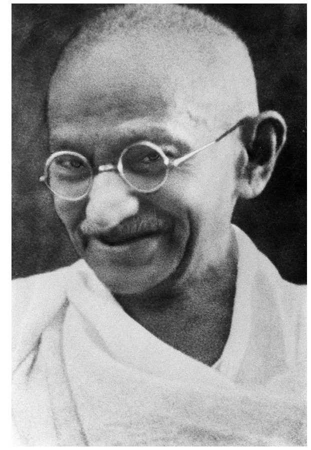


Spatial Imaging of quarks & gluons

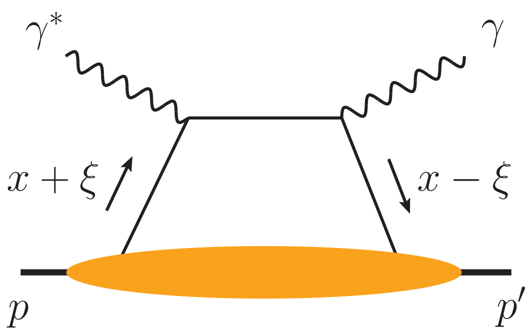
Generalized Parton Distributions

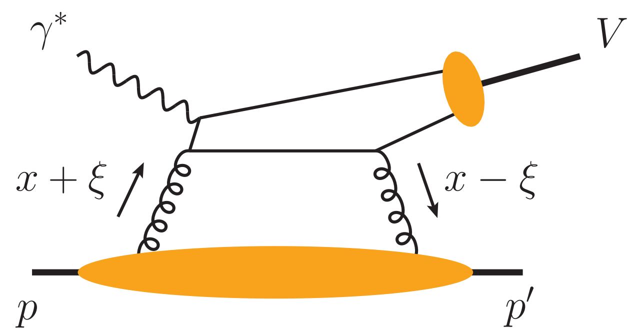
Historically investigations of nucleon structure and dynamics involved breaking the nucleon….

To get to the **orbital motion** of quarks and gluons we need **non-violent collisions**



Quarks Motion





Gluons: Only @ Collider

Deeply Virtual Compton Scattering

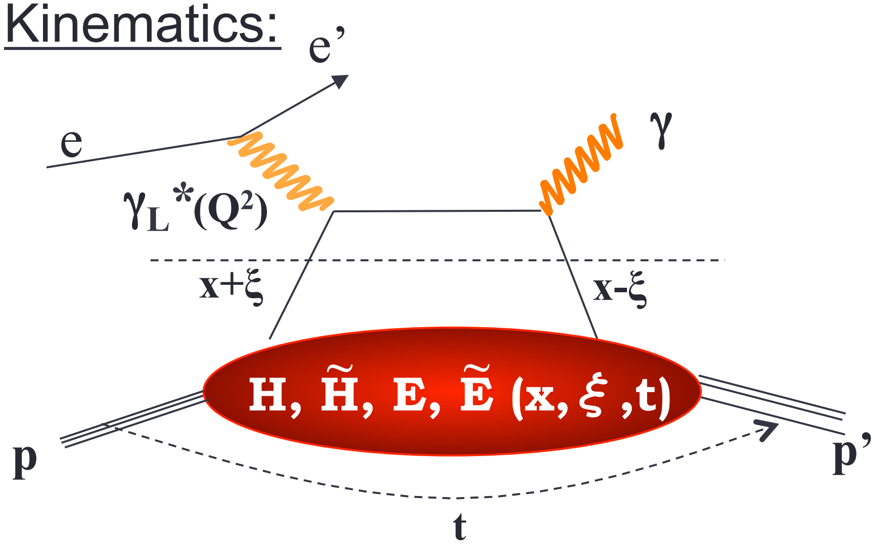
Measure all three final states

e + **p** → e'+ **p'**+ γ

Fourier transform of momentum transferred=(p-p') → Spatial distribution

Exclusive DIS

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e(1-\cos\Theta_{e'})$$

Measure of resolution power

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

Measure of inelasticity

$$x_B = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

$$t = (p-p')^2, \xi = \frac{x_B}{2-x_B}$$

Exclusive events:

e + **(p/A)** → e'+ **(p'/A')**+ γ / J/ψ / ρ / φ

detect **all** event products in the detector

Allow access to the spatial distribution of partons in the nucleon

Fourier transform of spatial distributions → GPDs

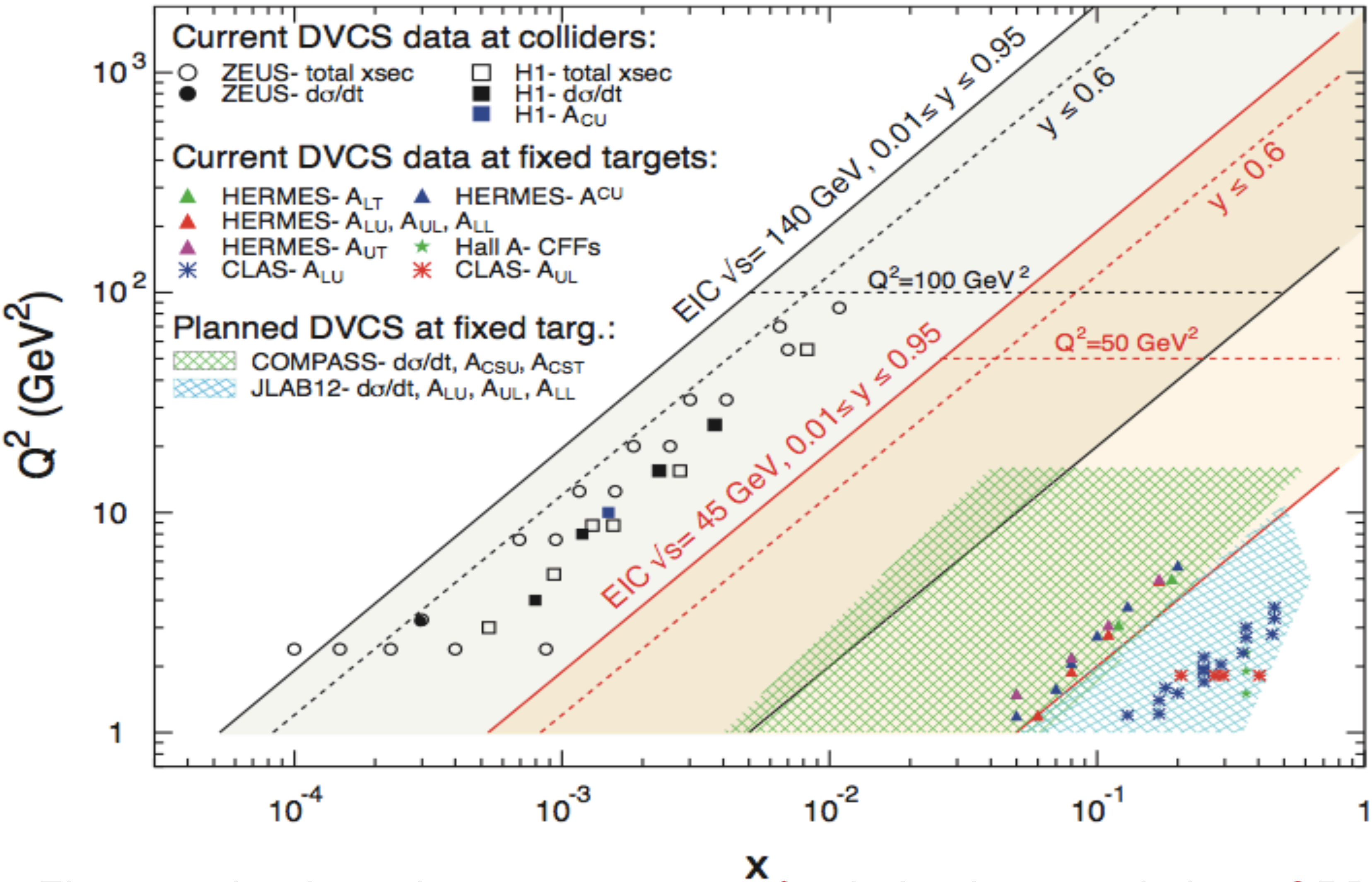
GPDs → Orbital Angular Momenta!

$$\frac{1}{2} = J_Q + J_G$$

$$J_Q = \frac{1}{2}\Delta\Sigma + L_Q$$

$$J_G = \Delta G + L_G$$

EIC coverage for GPDs



First, maybe the only, measurement of polarized sea and gluon GPDs

GPDS: Transverse spatial gluon distribution from exclusive J/Ψ production

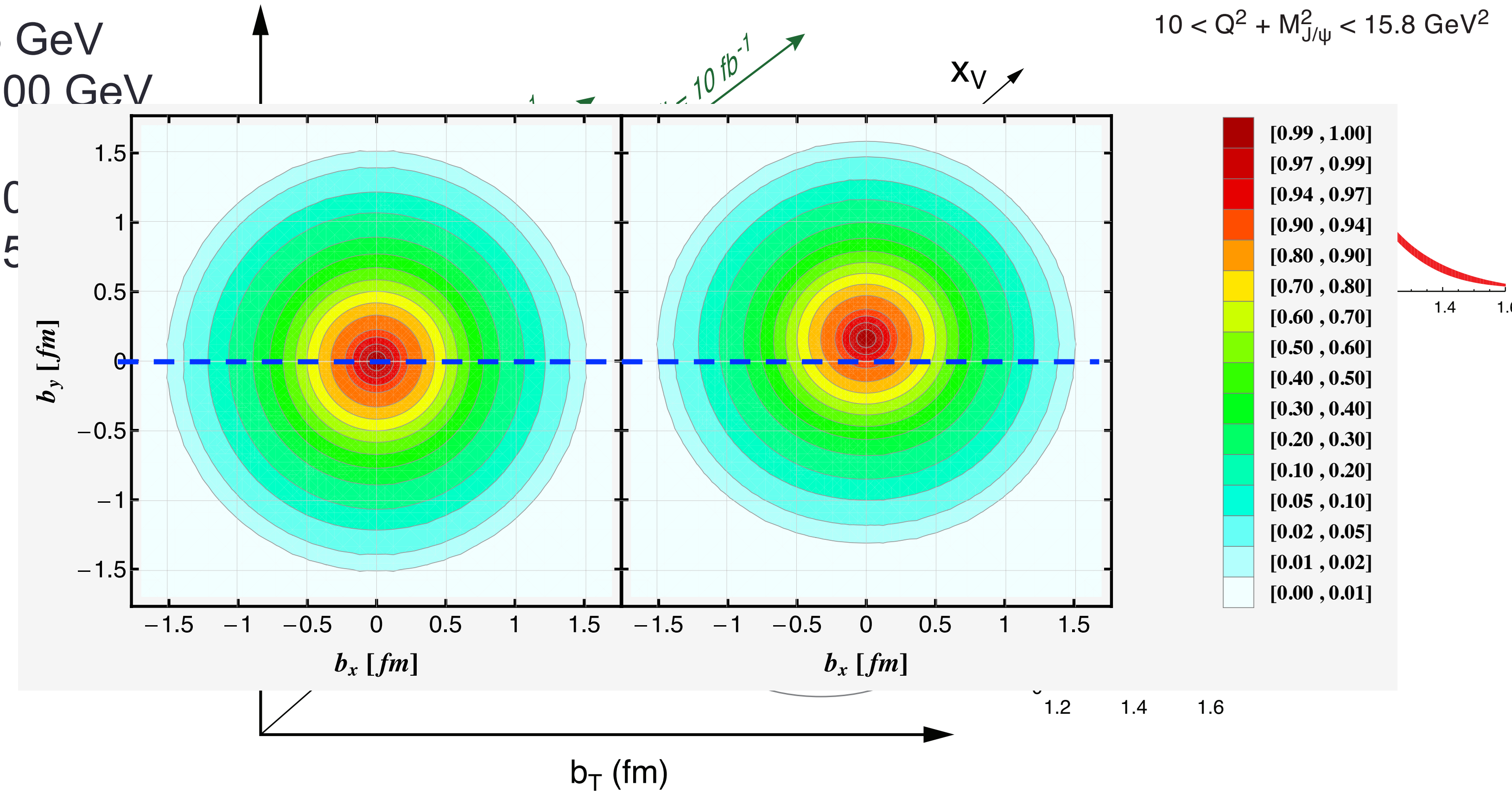
b_T is the distance of the gluon from the center of the proton
x_V determines the gluon momentum fraction

$$x_V = \frac{M_{J/\psi}^2 + Q^2}{W^2 + Q^2 + M_N^2}$$

$$W^2 = (p+q)^2; \qquad M_N^2 = p^2$$

$10 < Q^2 + M_{J/\psi}^2 < 15.8$ GeV^2

E_e = 5 GeV
E_p = 100 GeV



An immediate check/impact:

- **Quark GPDs and its orbital contribution to proton's spin:**

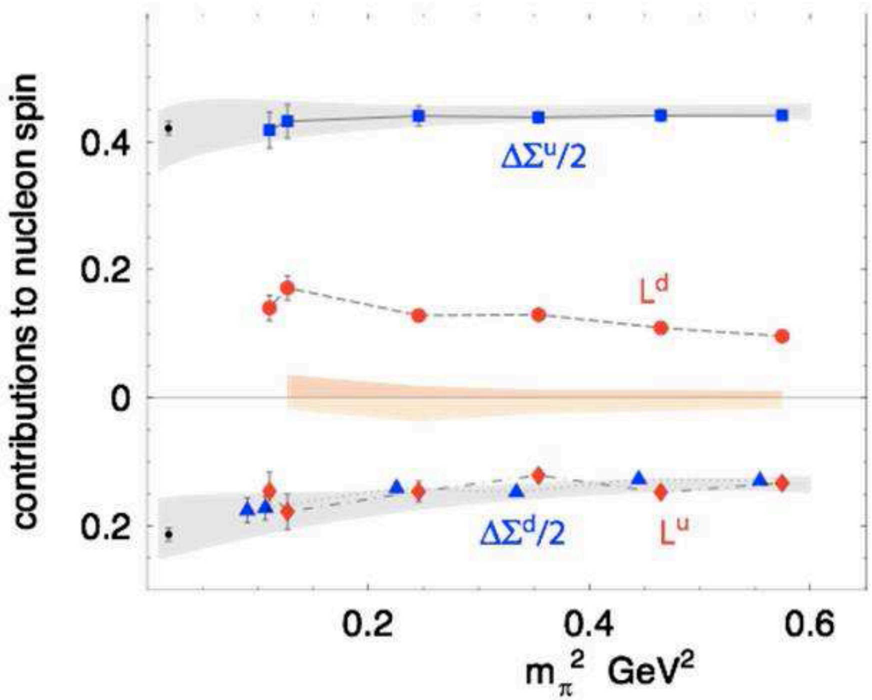
$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\,[H_q(x,\xi,t) + E_q(x,\xi,t)] = \frac{1}{2}\Delta q + L_q$$

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

This could be checked by Lattice QCD

$L_u + L_d \sim 0$?

There are also more recent ideas Of calculating parton distribution functions on Lattice:
X. Ji et al. arXiv 1310.4263; 1310.7471; 1402.1462
& Y.-Q. Ma, J.-W. Qiu 1404.6860

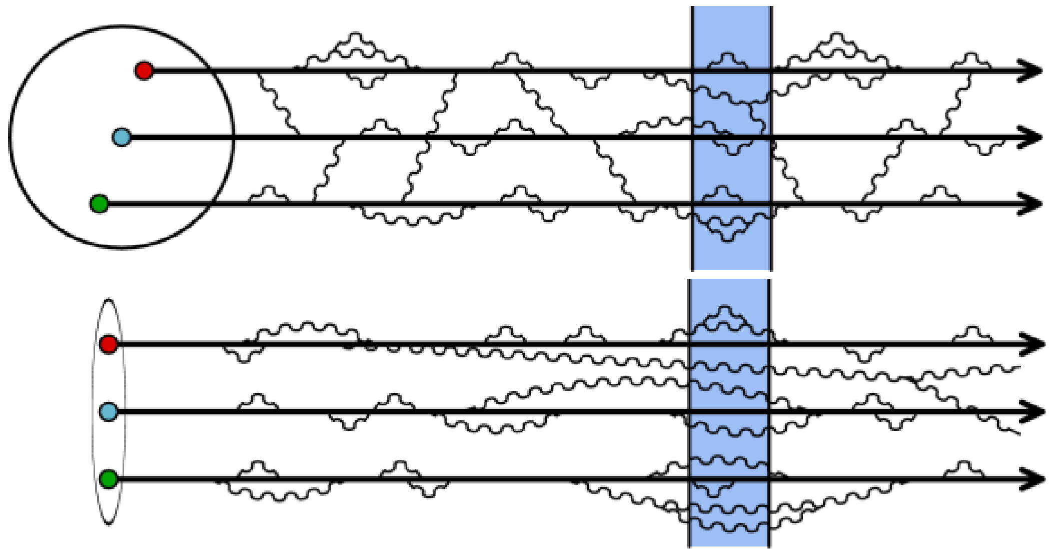


What Can We Learnt From The Nuclei At The EIC?

How does a Proton look at low and high energy?

Low energy
High x
Regime of fixed target exp.

High energy
Low- x
Regime of a Collider



At high energy:

- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate further smaller x gluons ➔ which intern radiate more……. Leading to a **runaway growth?**

Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with other gluons!

"…The result is a self catalyzing enhancement that leads to a runaway growth. A small color charge in isolation builds up a big color thundercloud…."

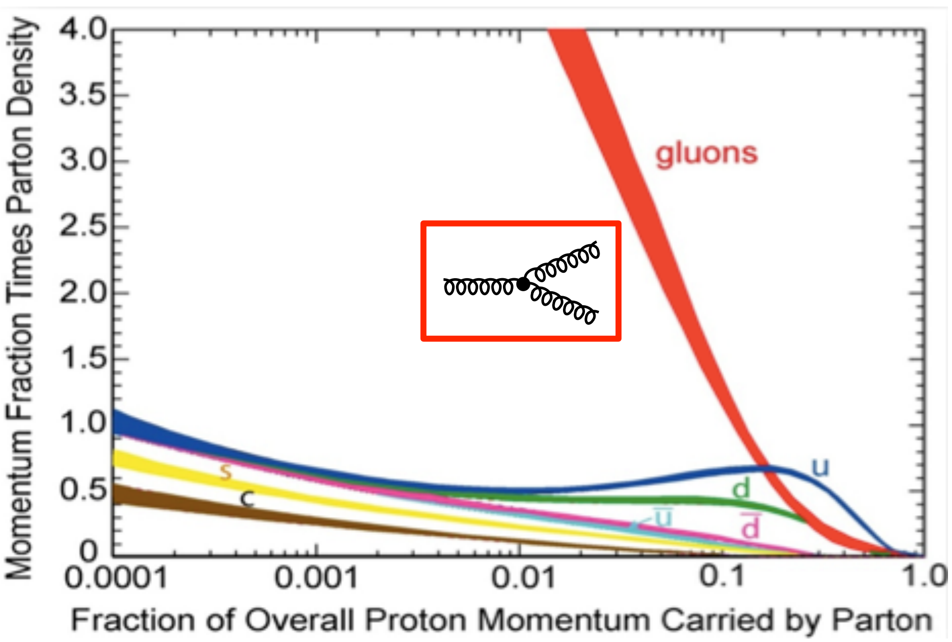
F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004

Gluon and the consequences of its interesting properties:

Gluons carry color charge → Can interact with oth

QCD
Terra-
incognita!

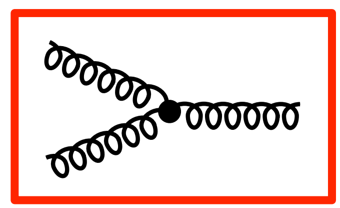
High Potential for Discovery



Apparen… ” in gluon distribut…

What… ndefinite **rise?** → saturation of soft gluon densities via gg→g recombination must be responsible.

recombination



Where? No one has unambiguously seen this before!

If true, effective theory of this →“Color Glass Condensate”

McLerran & Venugopalan et al

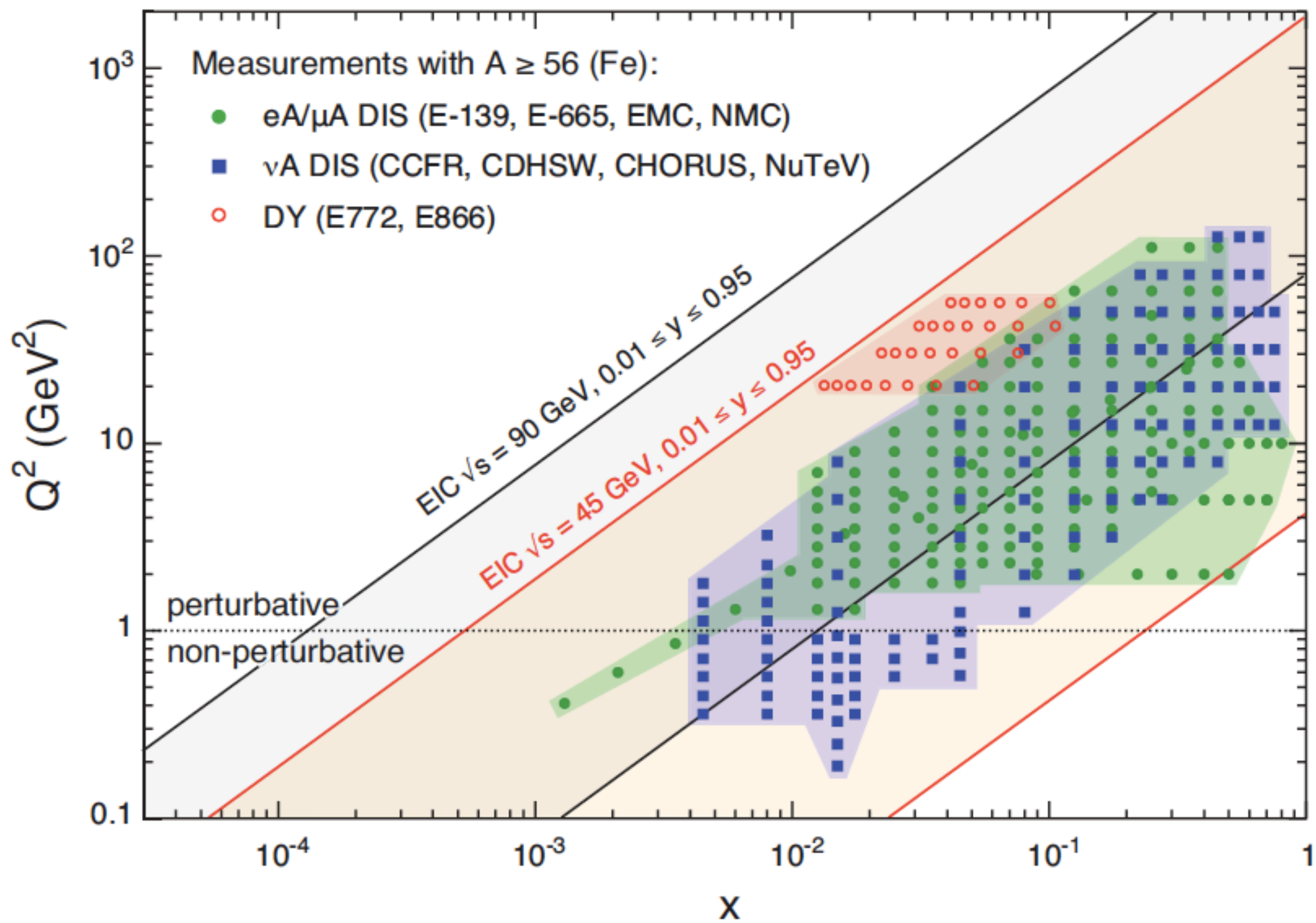
Nucleus: A laboratory for QCD

What do we know about the gluons in nuclei? Very little!

Does gluon density saturate? Does it produce a unique and universal state of matter?

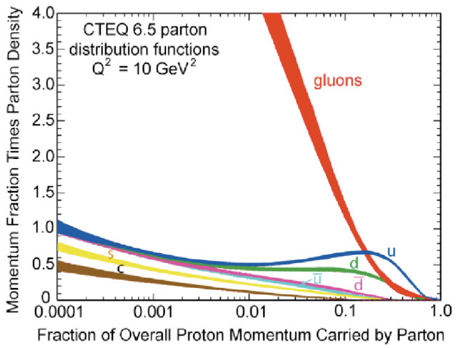
Parton propagation and interaction in nuclei (vs. protons)

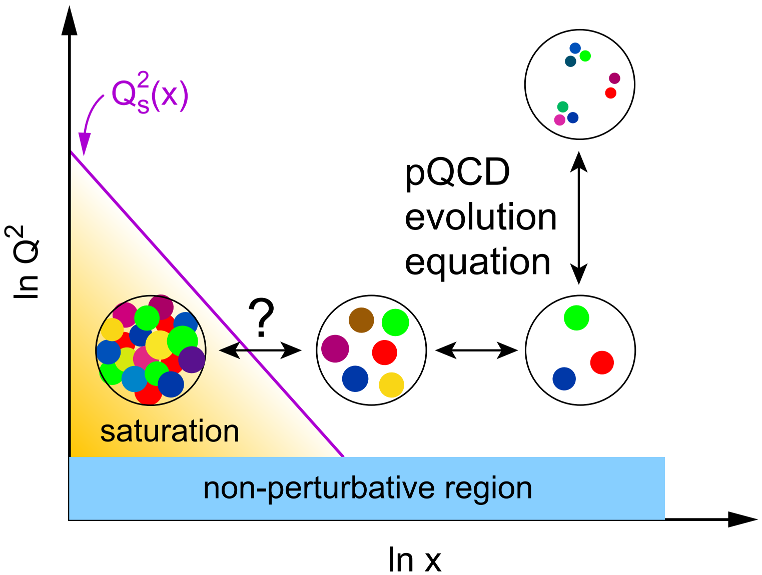
Kinematic region accessible with nuclei



What do we learn from low-x studies?

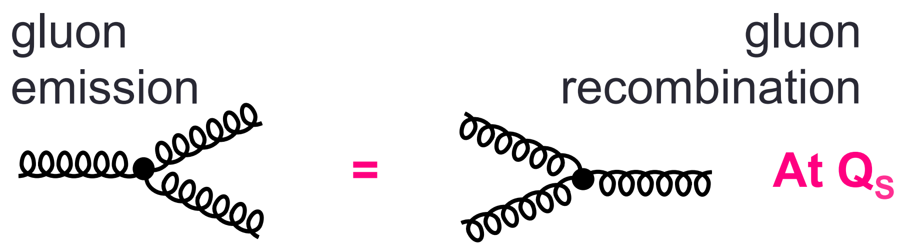
Low-x ➔ High Energy





What tames the low-x rise?

- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable



First observation of gluon recombination effects in nuclei:
➔leading to a *collective* gluonic system!

First observation of g-g recombination in *different* nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

Evolution equations…. Types & Recent advances…. (an experimentalist’s introduction)

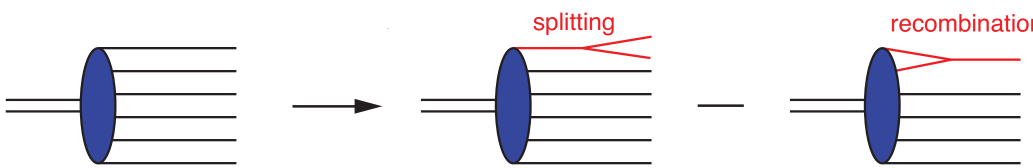
Current state of QCD theory does not allow first principle calculation of quark and gluon distributions, the evolution equations, allow one to determine these distributions at some value of (x,Q^2) if they are known at some other (initial) (x_0, Q_0^2).

- Most widely used: Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) : evolve in the Q^2 dimension
- The ones which allow you to calculate PDFs at some low-x, given those PDFs at some x_0, such that $x < x_0$ are called Balitsky-Fadin-Kuraev-Lipatov (BFKL)

$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x, r_T)$$

- Something has to modify the BFKL evolution at high energyto prevent it from becoming unphysically large

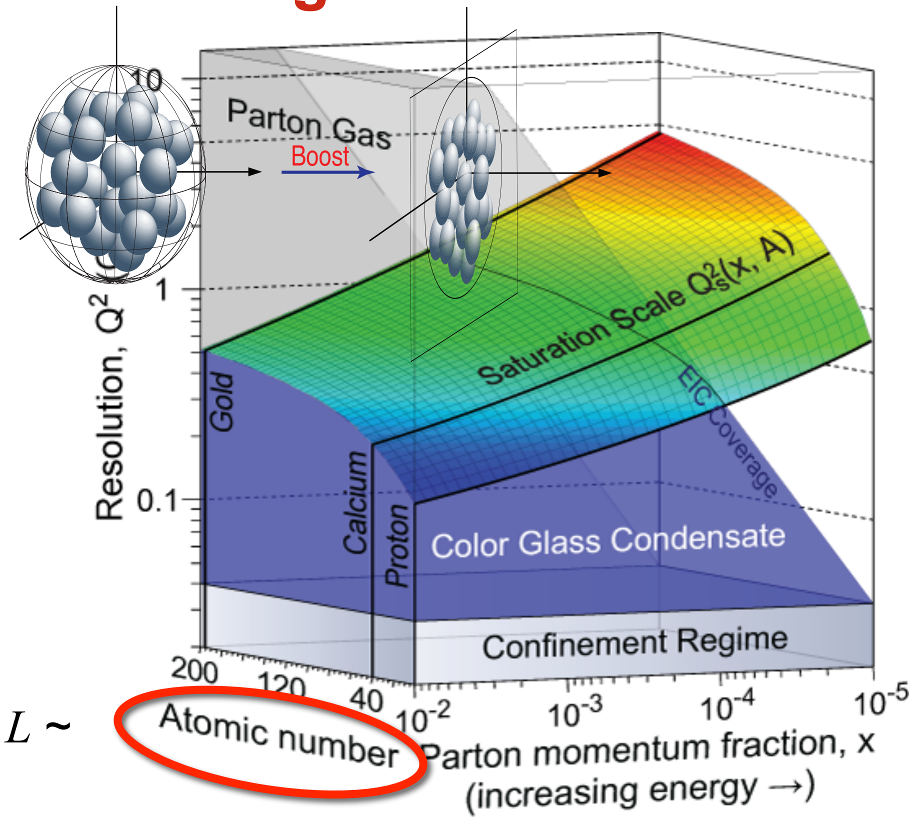
$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x, r_T) - \alpha_s [N(x, r_T)]^2$$



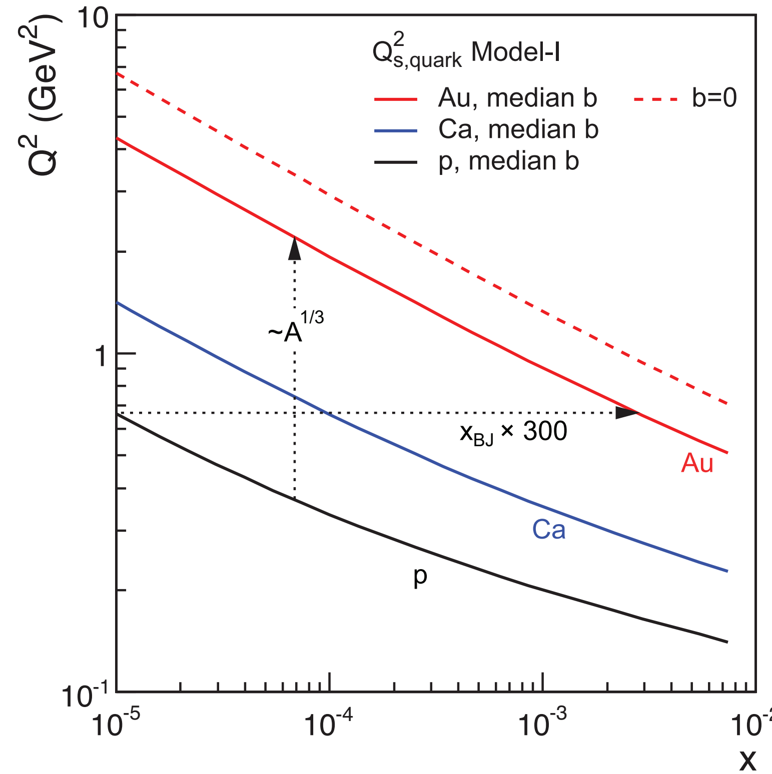
How to explore/study this new phase of matter?

(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**

Advantage of nucleus →



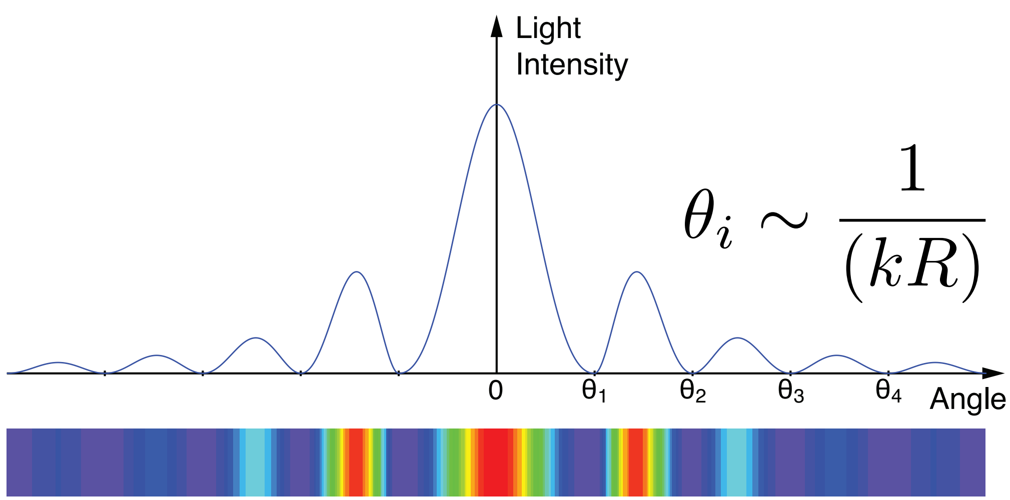
$L \sim$ $1/3$



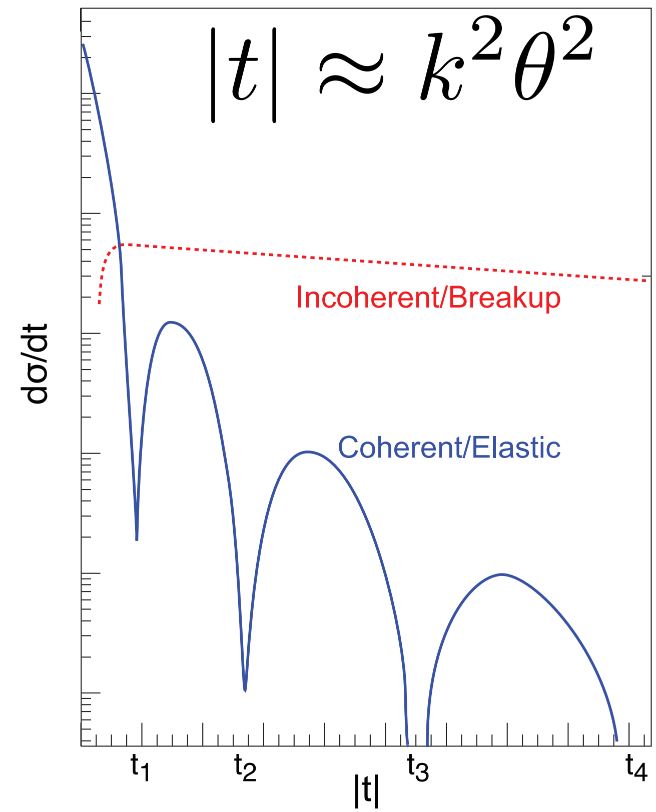
Enhancement of Q_S with A:
Saturation regime reached at significantly lower energy (read: “cost”) in nuclei

Diffraction in Optics and high energy scattering

Light with wavelength λ obstructed by an opaque disk of radius R suffers diffraction:
k → wave number

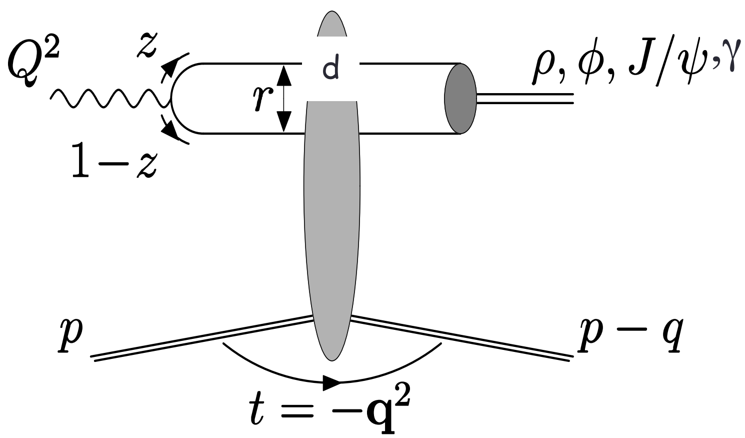


$$\theta_i \sim \frac{1}{(kR)}$$

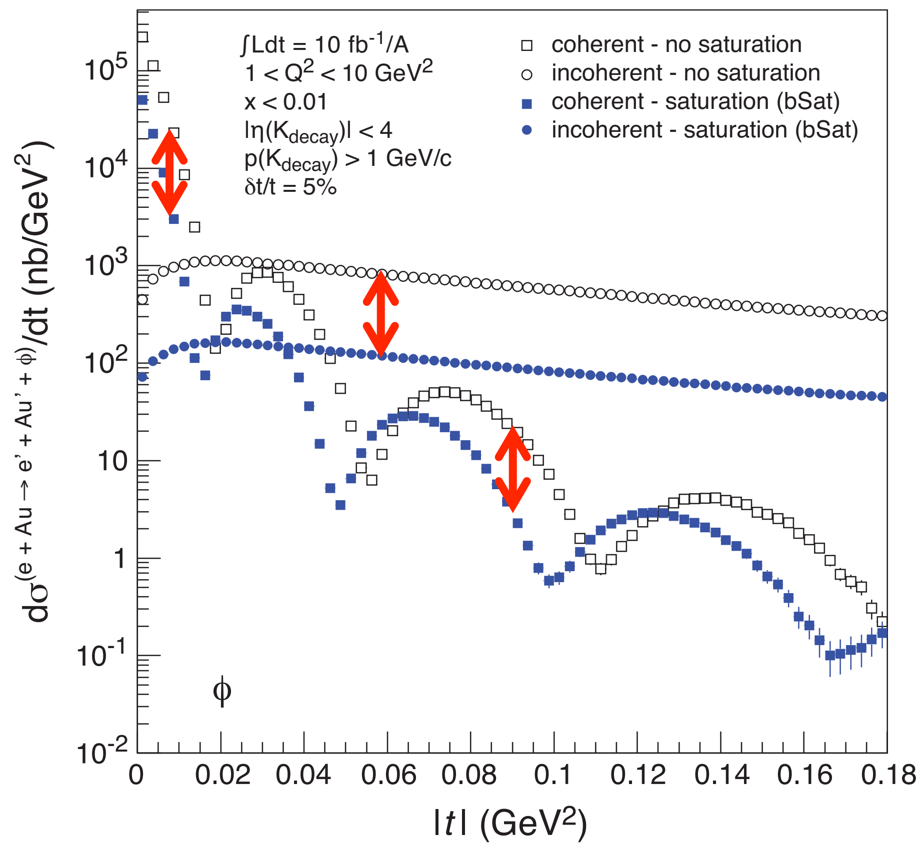


$$|t| \approx k^2\theta^2$$

Transverse imaging of the gluons nuclei



Diffractive vector meson production in **e-Au**



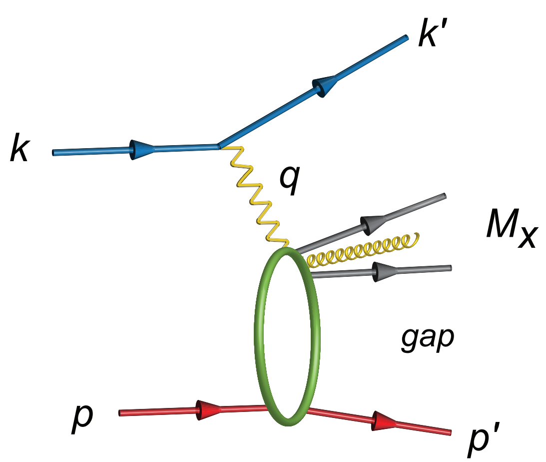
➔Does low x dynamics (Saturation) modify the transverse gluon distribution?

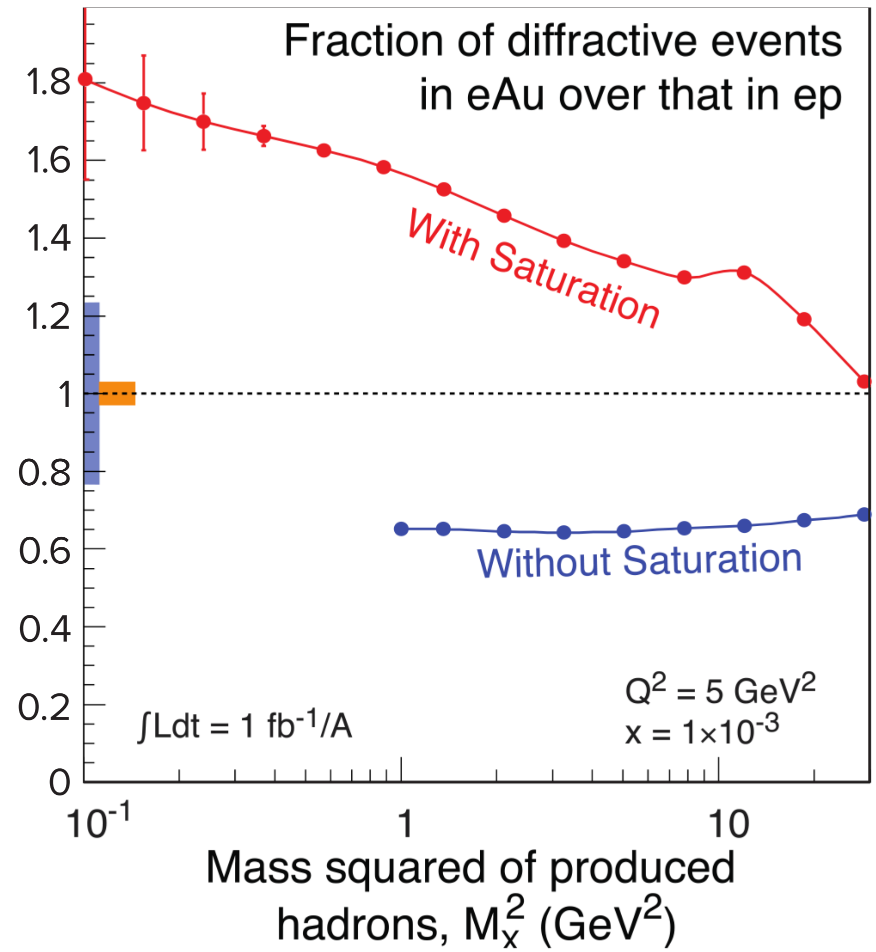
Experimental challenges being Studied.

Saturation/CGC: What to measure?

Many ways to get to gluon distribution in nuclei, but diffraction most sensitive:

$$\sigma_{\mathrm{diff}} \propto [g(x, Q^2)]^2$$





At HERA

ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

eA: 25-30% diffractive

Cross sections & PDFs (F_2, F_L, g_1)

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

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

$$\frac{1}{2}\left[\frac{d^2\sigma^{\rightleftarrows}}{dx\,dQ^2} - \frac{d^2\sigma^{\rightrightarrows}}{dx\,dQ^2}\right] \simeq \frac{4\pi\,\alpha^2}{Q^4}y\,(2-y)\,g_1(x,Q^2)$$

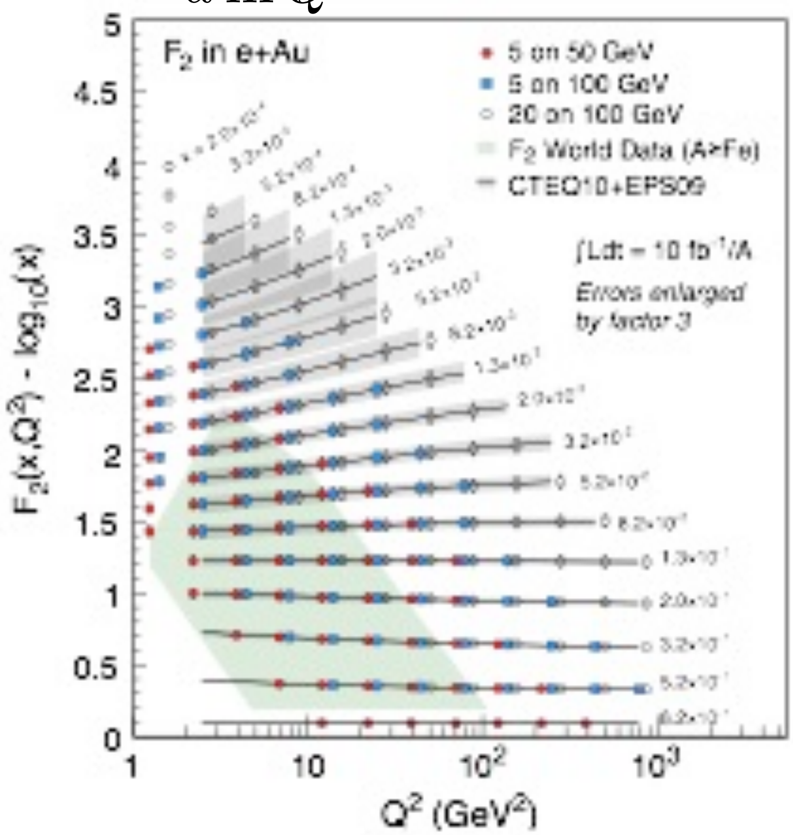
$$F_2(x,Q^2) = x\sum e_q^2\,\left[q(x,Q^2)+\bar{q}(x,Q^2)\right]\,,$$

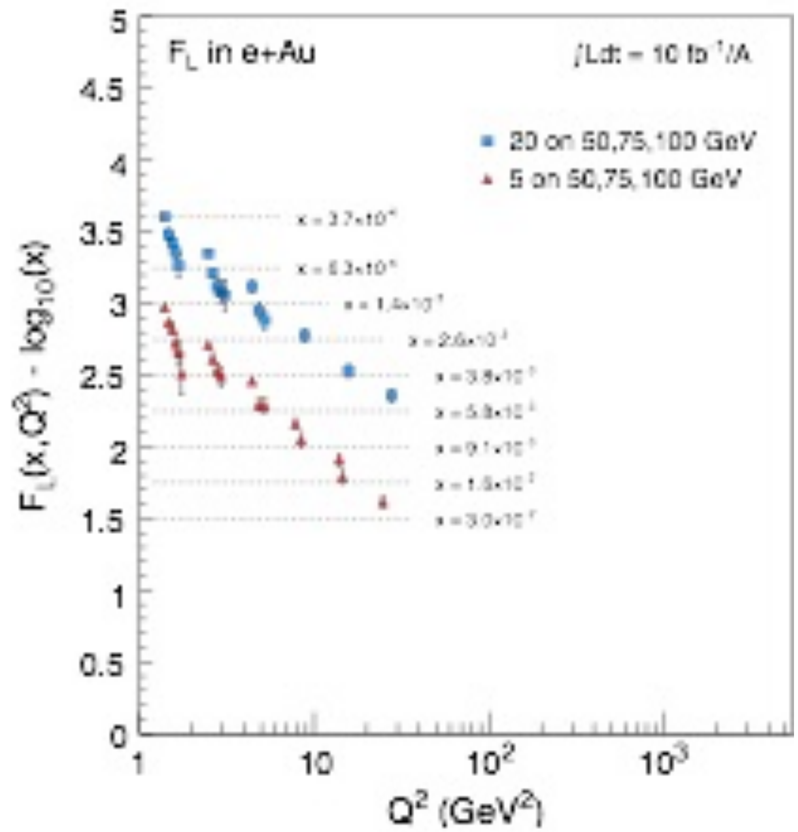
$$g_1(x,Q^2) = \frac{1}{2}\sum e_q^2\,\left[\Delta q(x,Q^2)+\Delta\bar{q}(x,Q^2)\right]\,,$$

Other clues to saturation…

$$\frac{dF_2^A(x,Q^2)}{d\ln Q^2} \propto \alpha_s G(x,Q^2)$$

$$F_L \propto \alpha_s x G(x,Q^2)$$

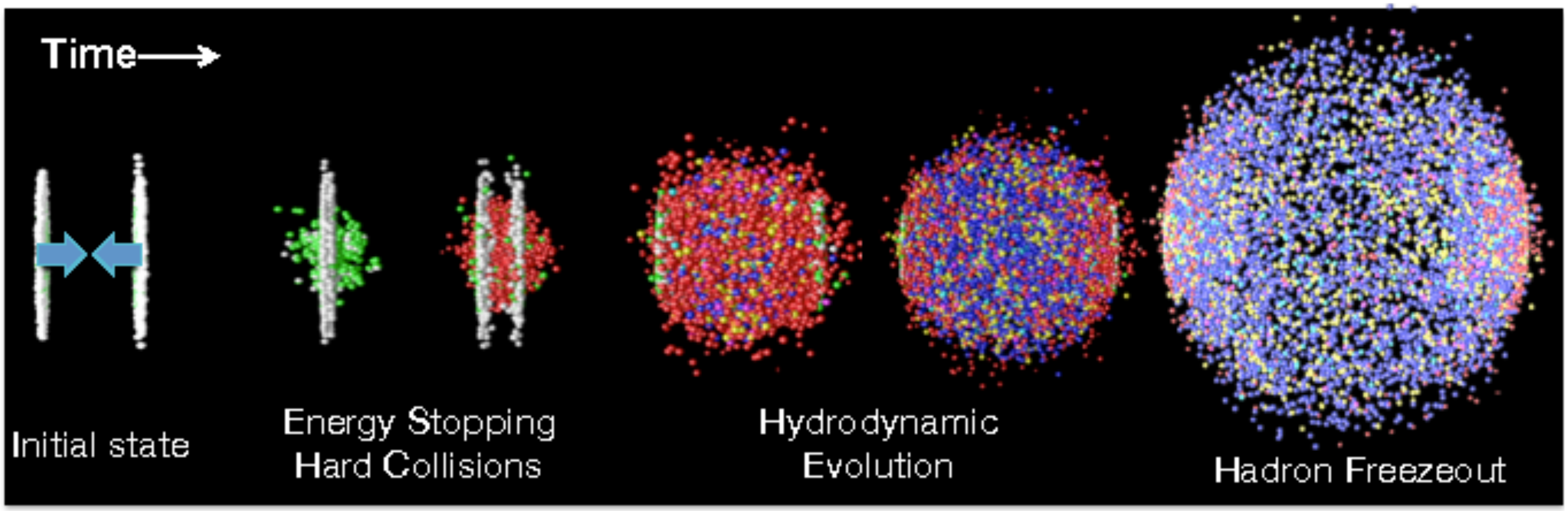


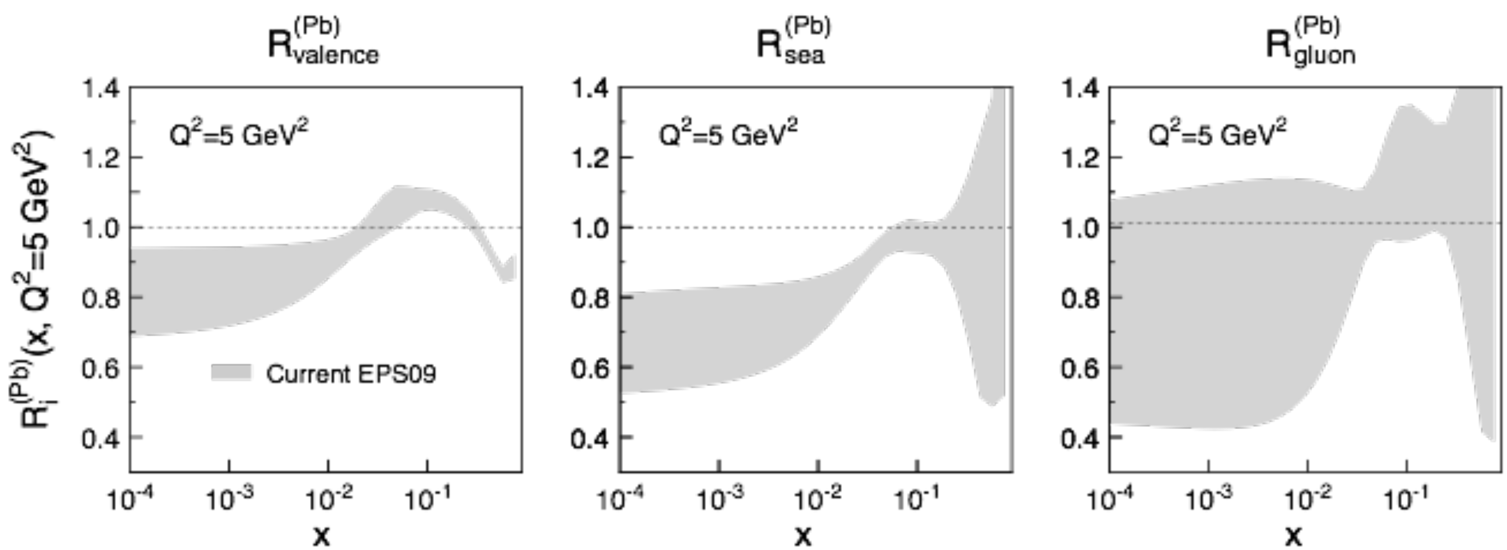


What else with nuclei?

Reduce uncertainty in parton distribution functions

Study how color propagates through nuclear medium…
another clue to "confinement"?



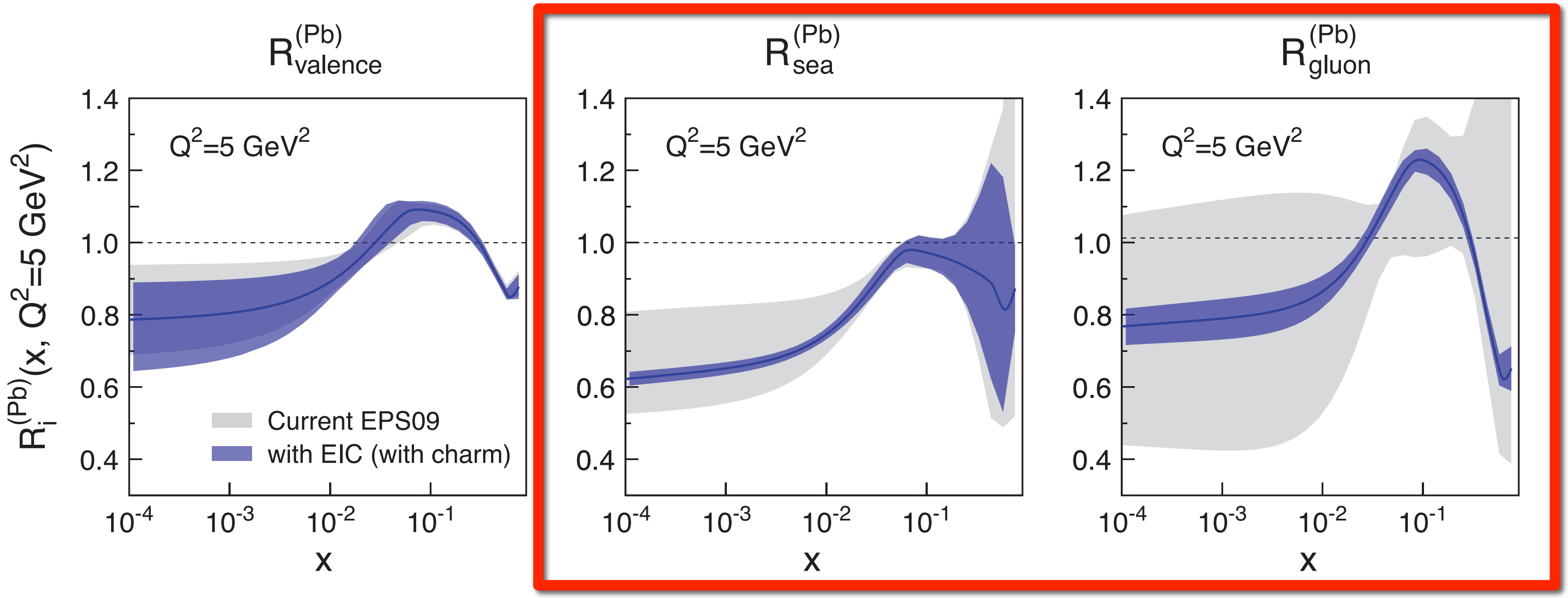


Initial State Uncertainties Unacceptably Large

Fully understand: emergence of hadrons from Hot QCD matter

initial state ←→ properties of QGP formed in AA collisions

EIC: impact on the knowledge of nPDFs



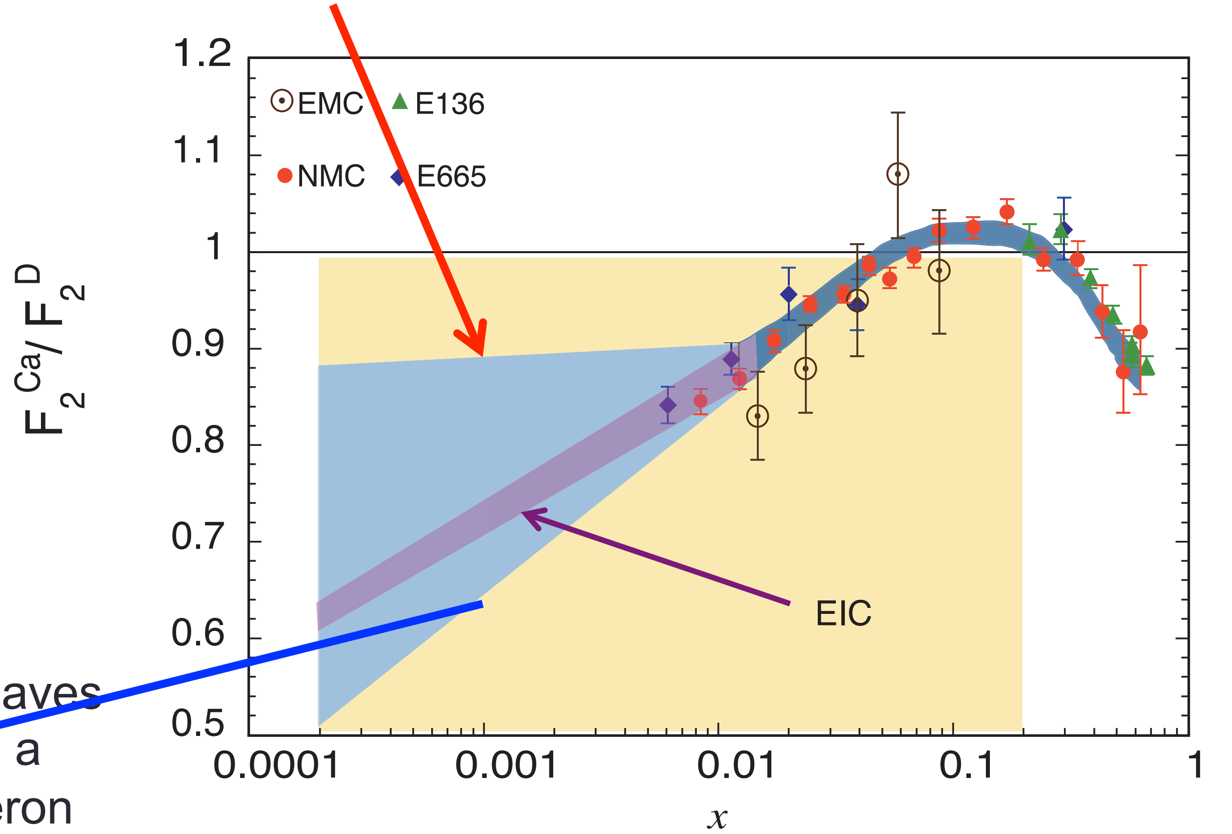
Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
- With EIC significantly reduces uncertainties

- Impossible for current and future pA data at RHIC & LHC data to achieve

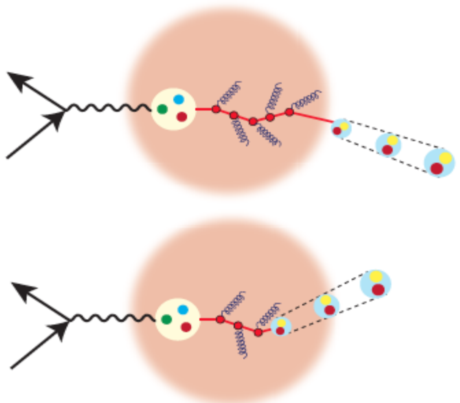
The classic EMC effect

Do the parton distributions in nuclei get modified?
Are the quarks and gluons de-confined in the nuclear medium?
Nucleus behaves **differently** than a proton/deuteron

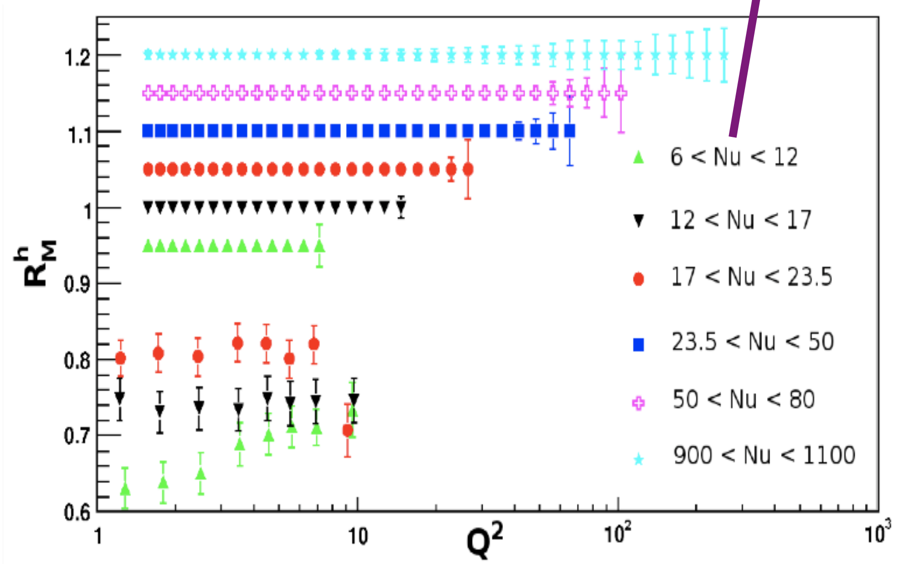


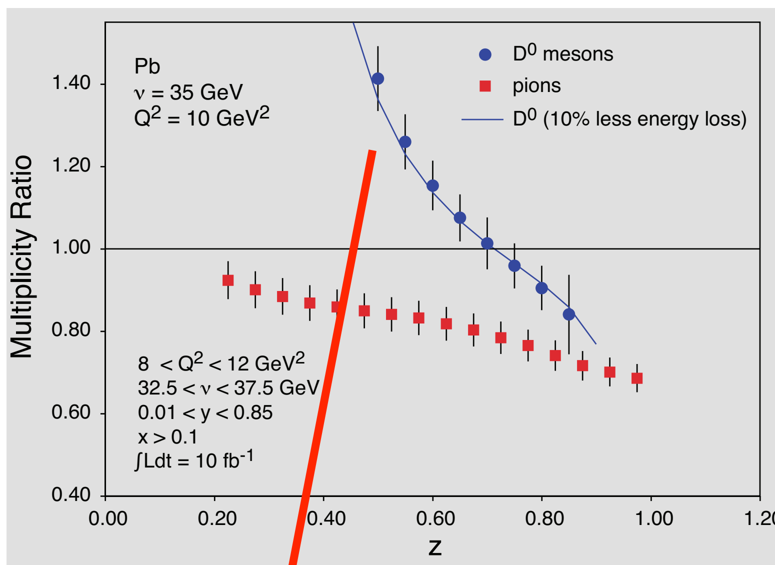
Nucleus behaves the **same** as a proton/deuteron

From Quarks and Glue into mesons and baryons



1/ν is the coherence length. Dialing it determines whether quarks (gluons) fragment in or out of nucleus





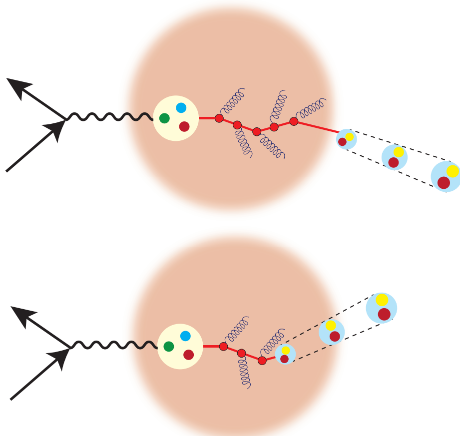
Novel sensitivity to heavy quark fragmentation

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

Unprecedented ν, the virtual photon energy range @ EIC : *precision & control*

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

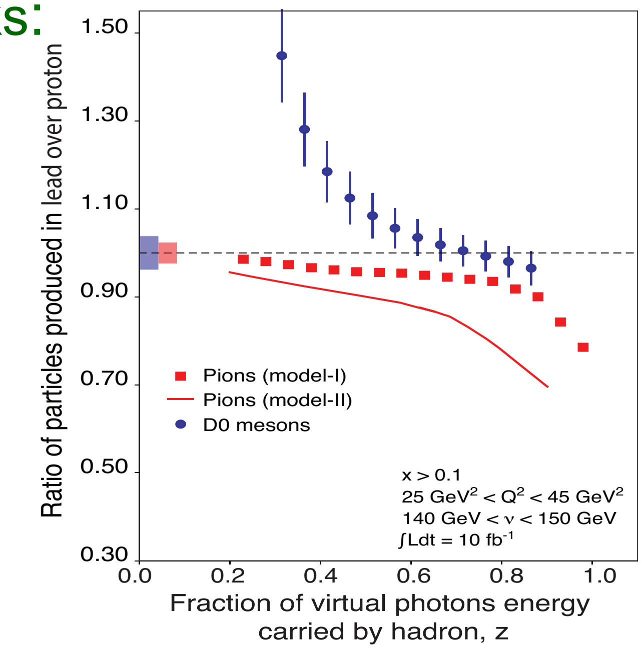


Control of ν by selecting kinematics;

Also under control the nuclear size.

Colored quark emerges as color neutral hadron ➔ What is nature telling us about confinement?

Energy loss by light vs. heavy quarks:



Identify π vs. D^0 **(charm)** mesons in e-A collisions: Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:

Connect to energy loss in Hot QCD

Need the collider energy of EIC and its control on parton kinematics

Physics vs. Luminosity & Energy