Physics Case
for
an Electron-Ion Collider

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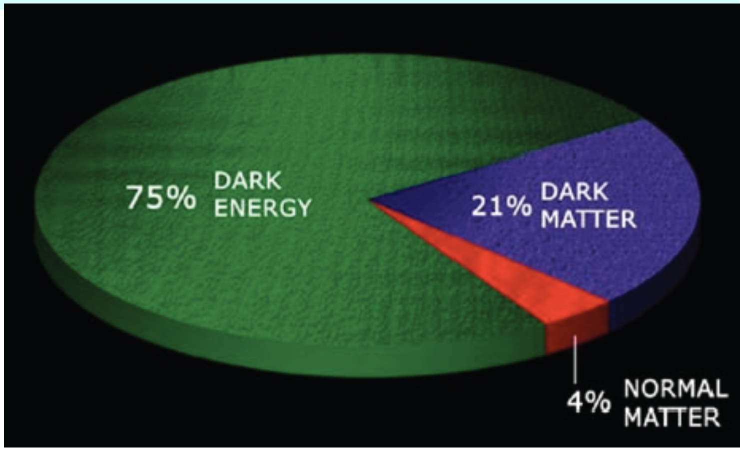
KITPC program
From nucleon structure to nuclear structure and compact astrophysical objects
KITPC, Beijing, China, June 11 – July 20, 2012

The big picture



- ❑ **The universe:**

  Dark energy, dark matter,
  and the visible world

- ❑ **Dark energy:**

  The universe's accelerating expansion requires a massive amount of dark energy (~75% of the universe's energy budget)

- ❑ **Dark matter:**

  The motion of stars and galaxies needs a lot of dark matter (~21% of the universe's energy budget)

- ❑ **The visible world:**

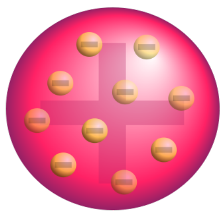
  Everything that we can see by our eyes, and telescopes
  ~ only 4% of the universe's energy budget

  Has the most impact on our life, and
  Has been mostly investigated in generations!

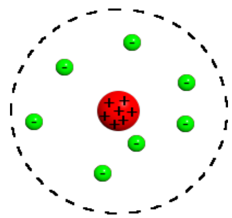
The visible world

- **What builds up the visible world?** The Atom!

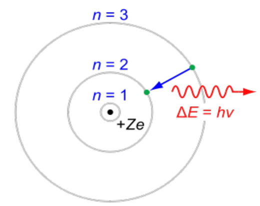
The Rutherford experiment (100 yrs ago) – evolution of our knowledge:



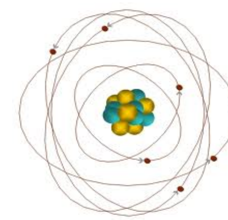
J.J. Thomson's
plum-pudding model



Rutherford's
planetary model



Bohr's model
Hydrogen atom



Modern model
Quantum orbitals

- **What makes up the mass of the atom, the visible world?**

Nuclear mass makes up 99.9% mass of atoms – localized "+" charge

But, the nucleus takes only one trillionth volume of the atom!

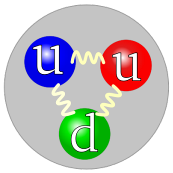
- **What determines the properties of the atom, the visible world?**

Nuclear properties determine the fundamental properties of atoms, hence of the visible world

Critical importance of nuclear science!

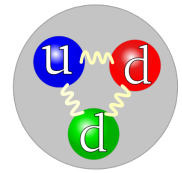
Nuclear science and QCD

❑ The nucleus – in the heart of all atoms:



Proton (1919)

Quarks: u, d, …
Gluons



Neutron (1931)

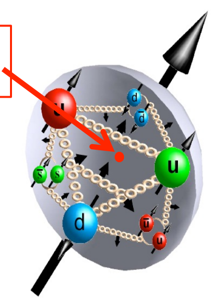
Held together by the confining color force of QCD – the strong force!

❑ Nuclear Science and QCD:

Ultimate long-term goal – the emergence of nucleon and nuclei from QCD

- ✧ Understand the quarks and gluons, and their interactions in QCD
- ✧ Understand the nucleon, its properties and structure in quarks, gluons
- ✧ Understand the role of quarks and gluons in nuclei
- ✧ …

< 1/10 fm

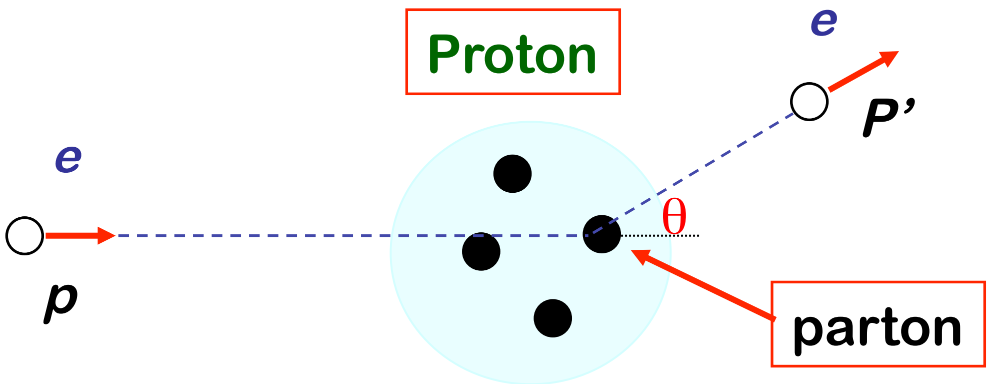


❑ What do we need?

- ✧ Sharp, sub-femtometer probes to see quarks and gluons – “snapshot”
- ✧ Cat-scan nucleon and nucleus with the sub-femtometer resolution

We believe QCD

- SLAC's "Rutherford" experiment (60 years later – 1969):



Electron-proton Deep Inelastic Scattering (DIS)

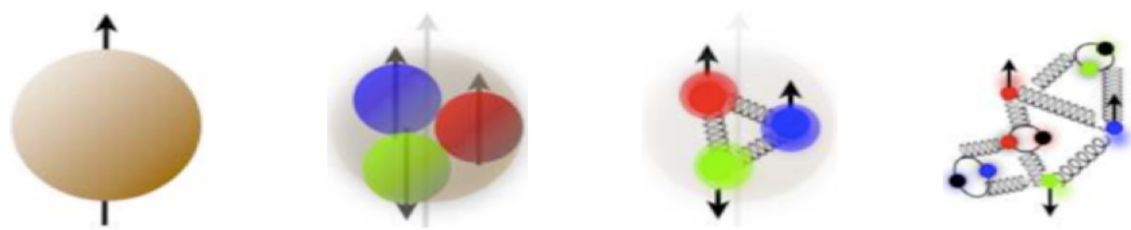
- ✧ Two variables: x_B, Q^2
- ✧ Localized probe:

$$Q^2 = -(p - p')^2 \gg 1\ \text{fm}^{-2}$$

$$\Rightarrow \frac{1}{Q} \ll 1\ \text{fm}$$

- Evolution of our knowledge:

Nucleon:



Resolution →

We believe QCD

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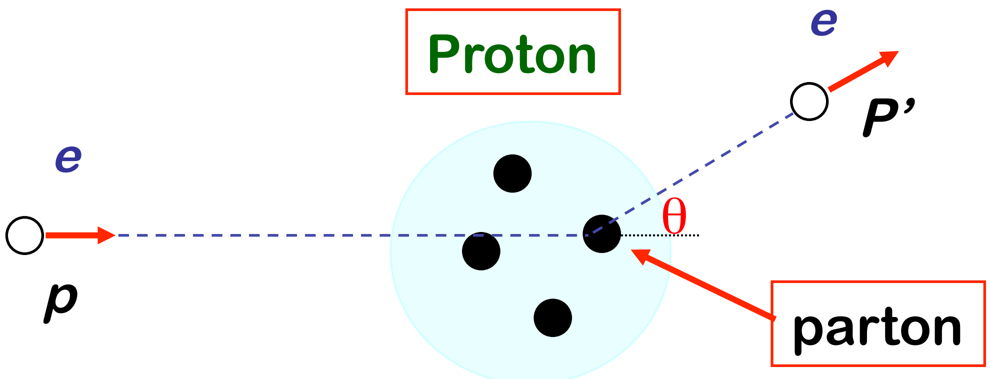

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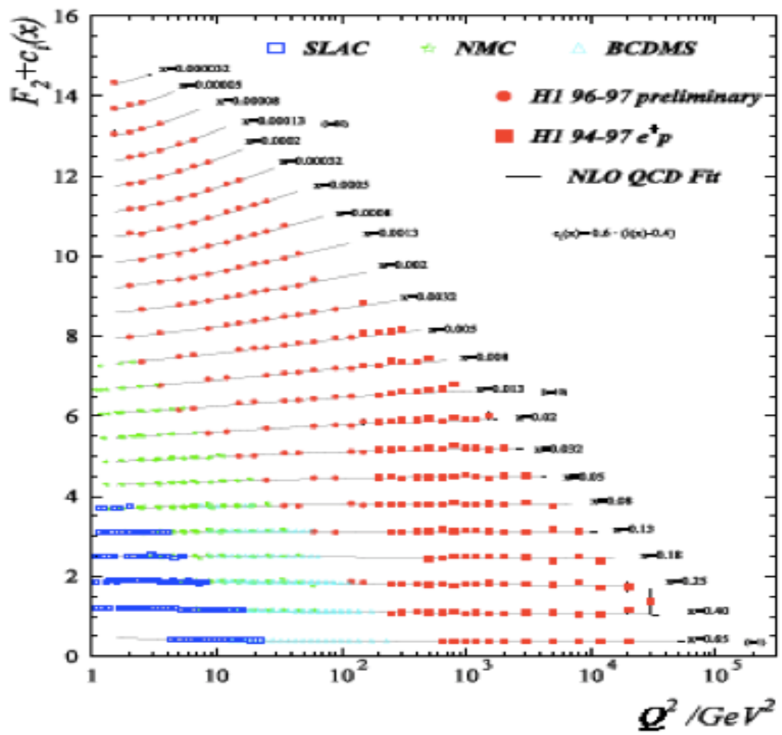
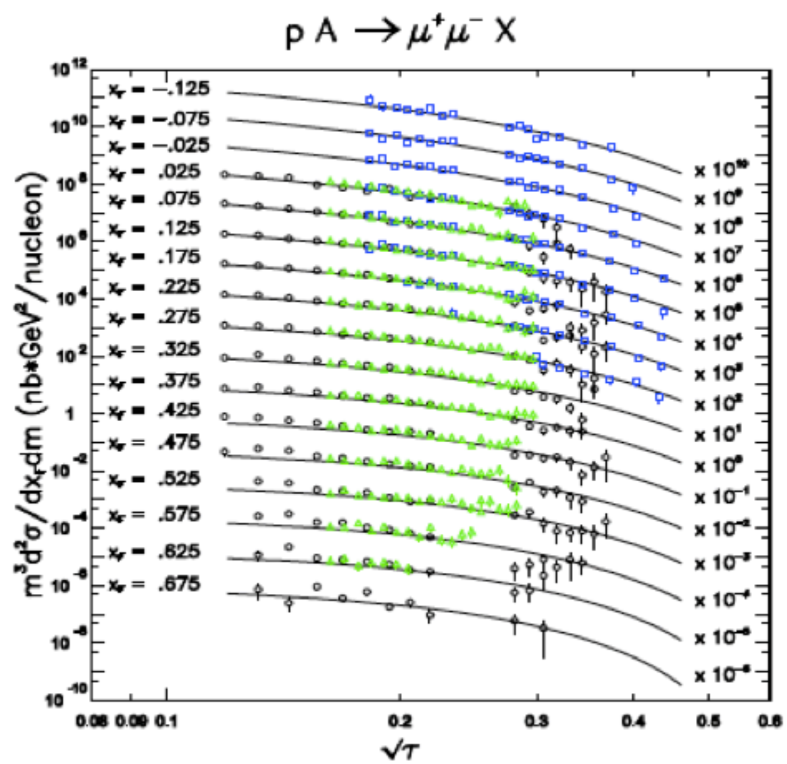
- Evolution of our knowledge:

The probe:

< 0.1 fm





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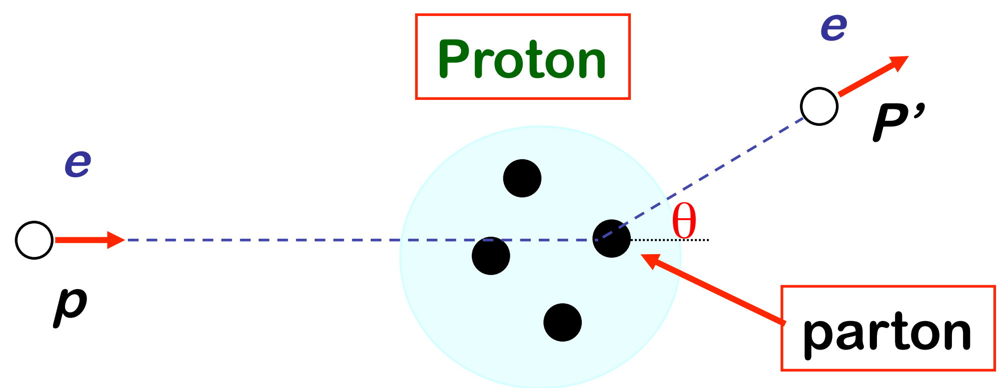


Electron-proton Deep Inelastic Scattering (DIS)

✧ Two variables: x_B, Q^2

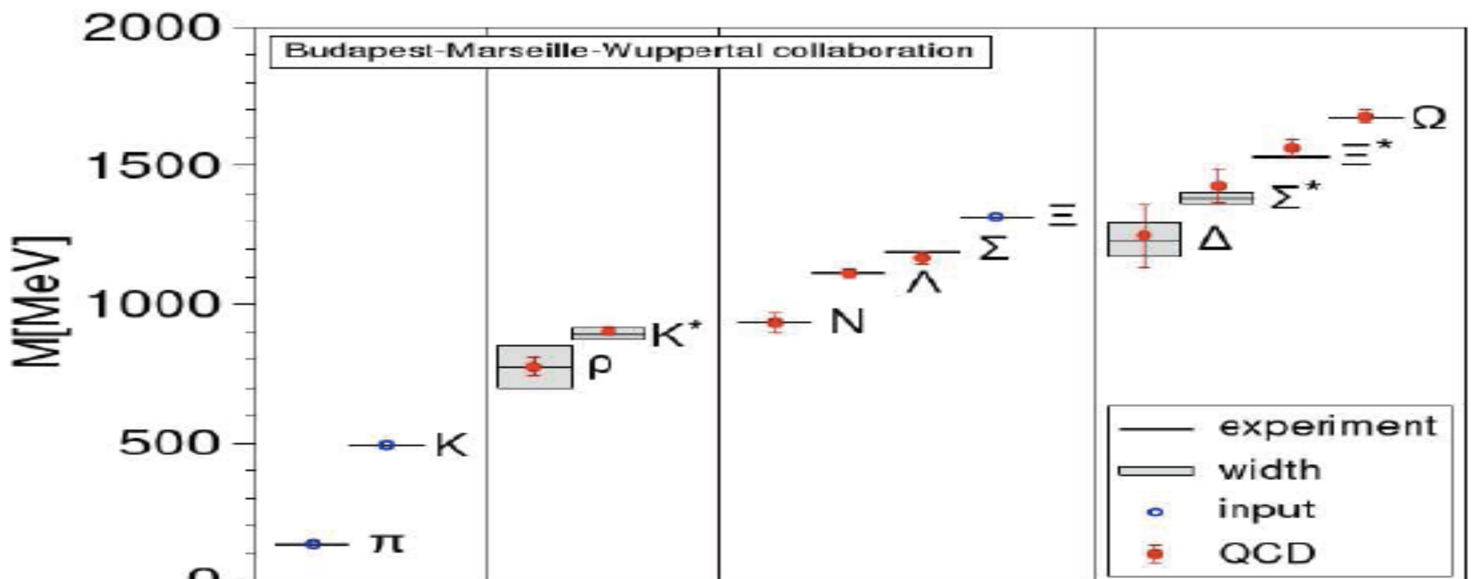
✧ Localized probe:

$$Q^2 = -(p-p')^2 \gg 1\ \mathrm{fm}^{-2}$$

$$\Rightarrow \frac{1}{Q} \ll 1\ \mathrm{fm}$$

- Evolution of our knowledge:

Hadron mass:
Lattice

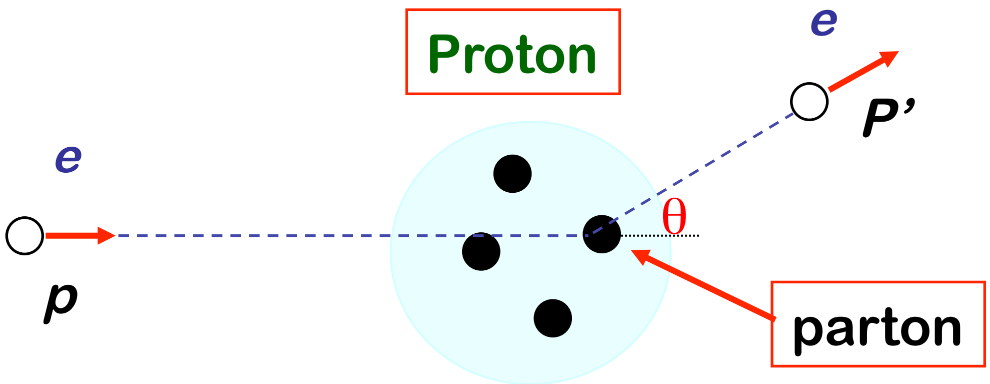


But,

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

We believe QCD

❑ SLAC's "Rutherford" experiment (60 years later – 1969):



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$$Q^2 = -(p-p')^2 \gg 1\ \mathrm{fm}^{-2}$$

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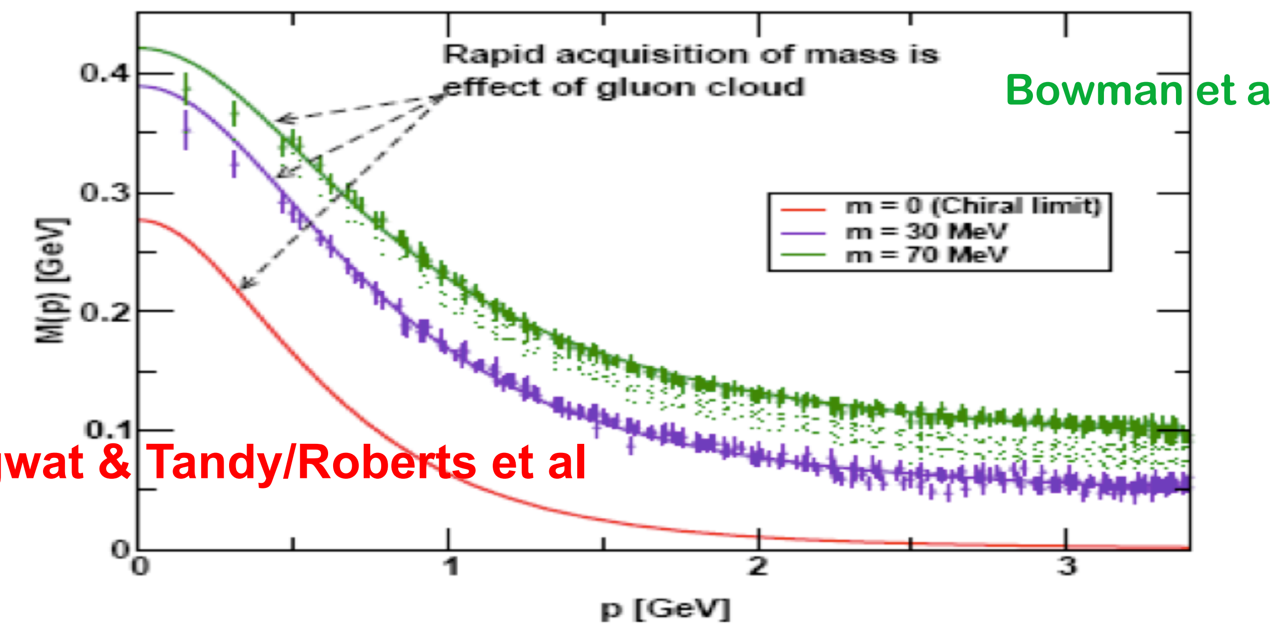
❑ Evolution of our knowledge:

Quark mass:

Lattice

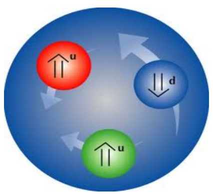


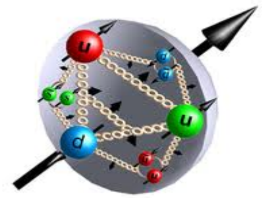
Mystery:

"Mass without mass!"

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

Gluons and sea quarks in the proton





❑ **The challenging intellectual questions:**

✧ How to reconcile the two very different pictures of the proton:
the QM's three quarks vs the picture of many quarks and gluons?

The role of the gluon and sea in determining the hadron structure?

✧ How does the proton spin originate at the level of quarks and gluons?

Polarization + motion { Quark polarization ~ 30%
Quark motion (lattice) ~ 0 → Role of gluons?

✧ How does confinement manifest itself in the structure of hadrons?

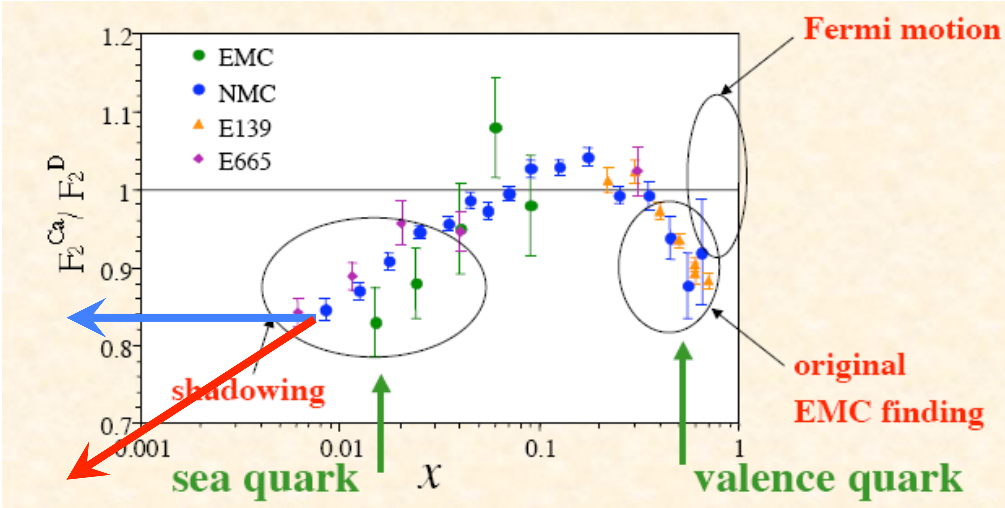
Confined spatial + momentum distribution ~ 1 fm or 200 MeV

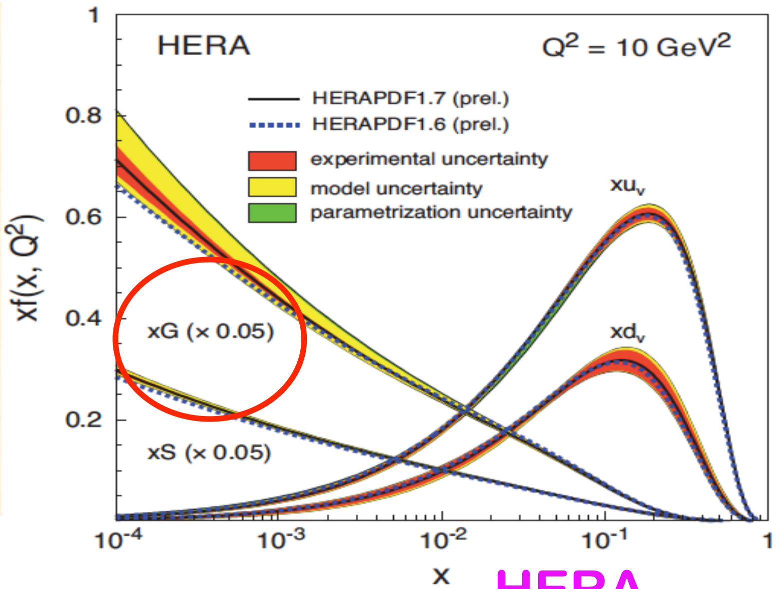
Where and how gluons and sea quarks distribute inside the hadron?

→ hints to confinement mechanism?

Nucleus, a laboratory for QCD

EMC discovery





HERA discovery

❑ The challenging intellectual questions:

✧ **What is the nuclear landscape of see quarks and gluons?**

Lump around the "nucleons"? — QED: molecule/crystal

A property of whole nucleus?

✧ **What governs the transition from quarks and gluons to hadrons?**

Hadronization, nuclear matter at a filter? color tomography?

✧ **Does the density of soft gluons saturate, producing the matter of universal properties in all hadrons and nuclei?**

Gluon saturation? Dynamical scale – Q_s? Color glass condensate?

The question

How to meet these challenges in QCD?
the nature of visible matter?

Future "Rutherford" experiments
at
An Electron-Ion Collider (EIC)

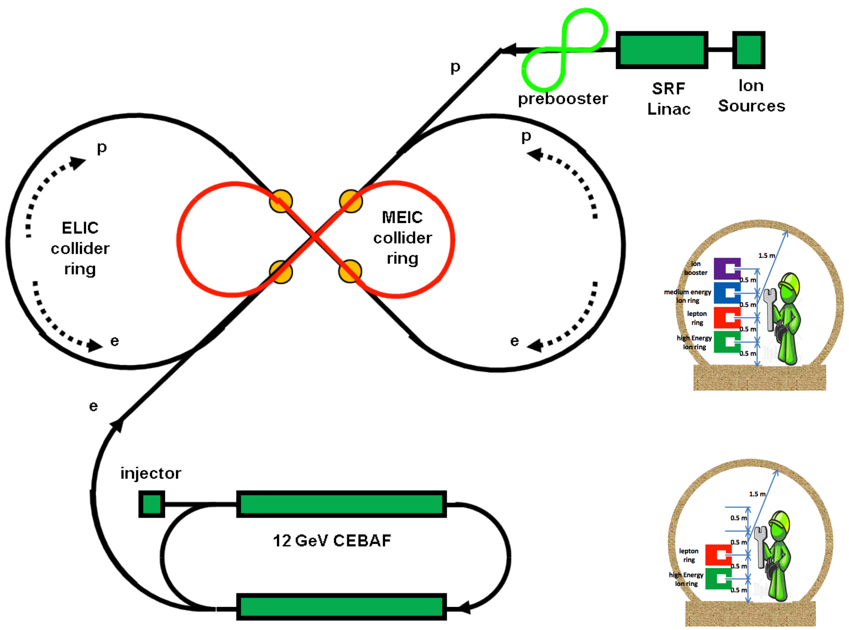
Explore the role of gluons and sea quarks in QCD

Next frontier of QCD and strong interaction!

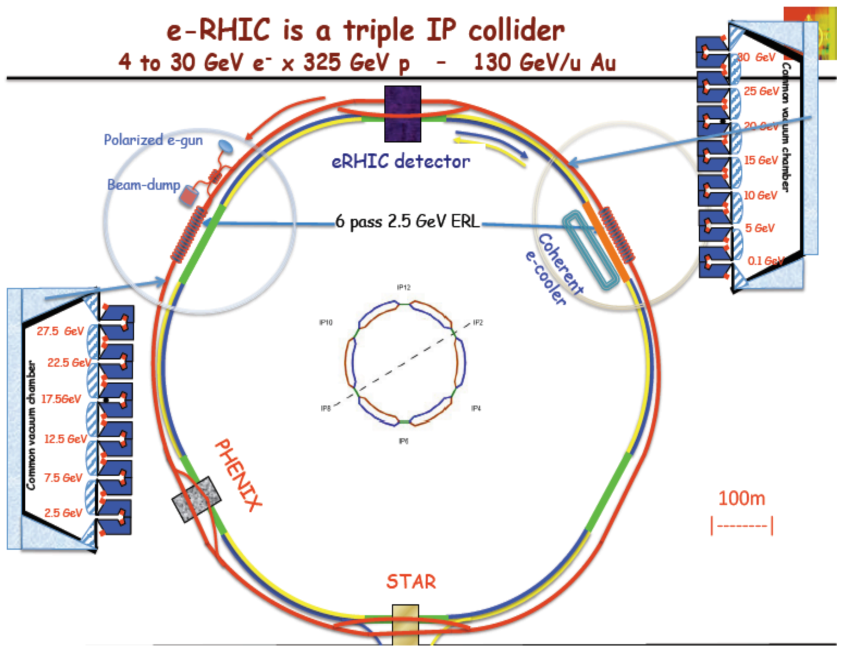
Electron-Ion Collider (EIC)

- ❑ Electro-Ion Collider (8-10 years later?):
  - ✧ First (might be the only) polarized electron-proton collider in the world
  - ✧ First electron-nucleus (various species) collider in the world
- ❑ Two possible options:

ELIC (Jlab)



eRHIC (BNL)



The intensity and the versatility frontier, allowing all six questions to be addressed or explored in one facility

at least 100 times higher in luminosity than HERA

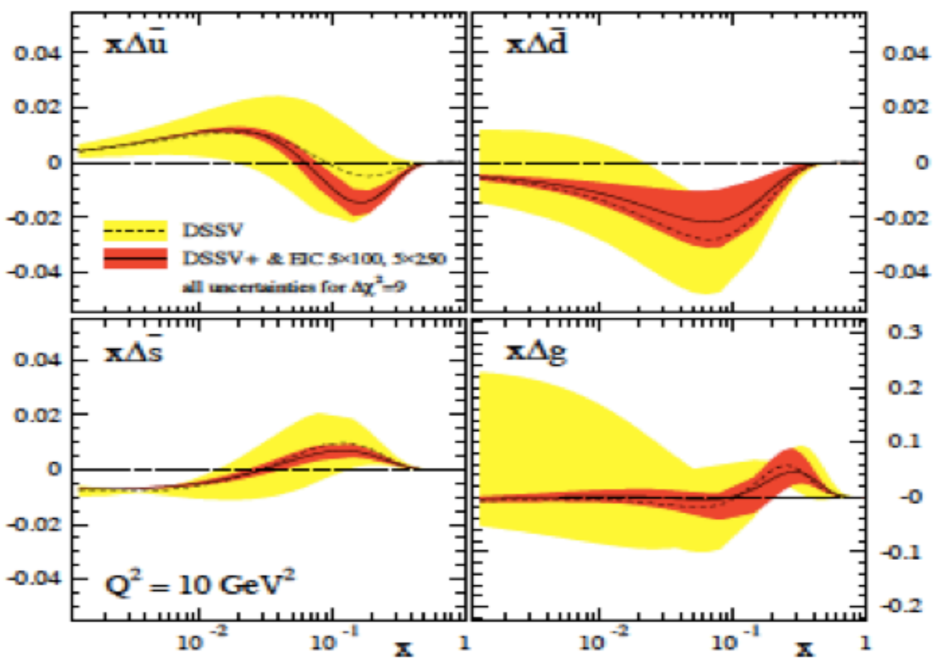
Golden measurements

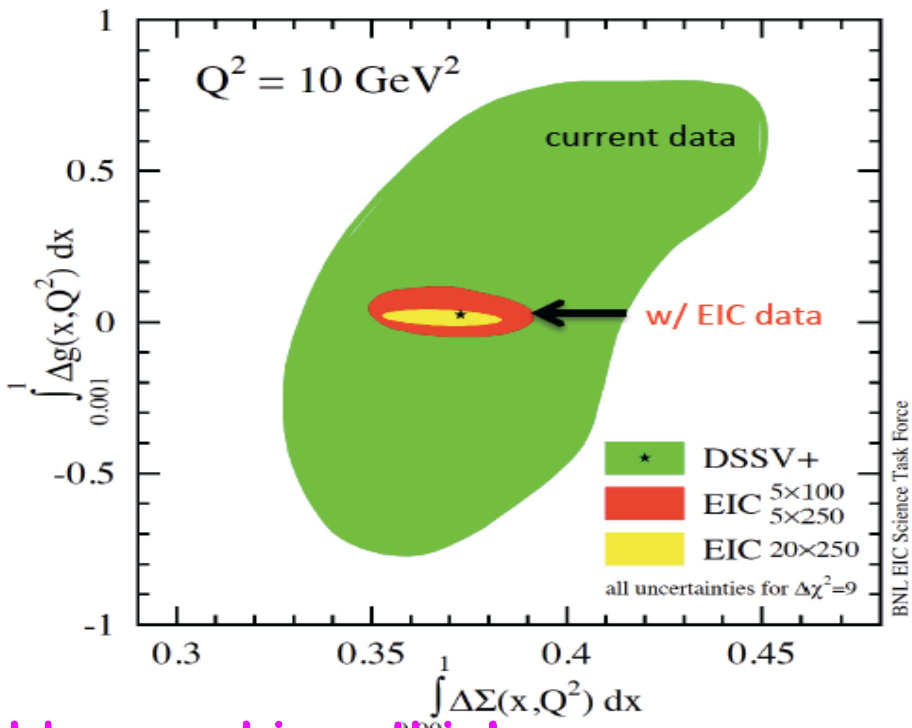
The spin and flavor structure of the nucleon

- Proton – composite particle of quarks and gluons:

  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!

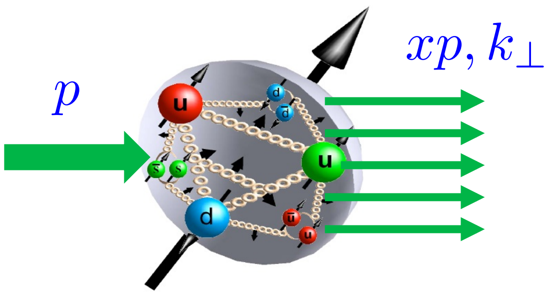
- The proton spin:

  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

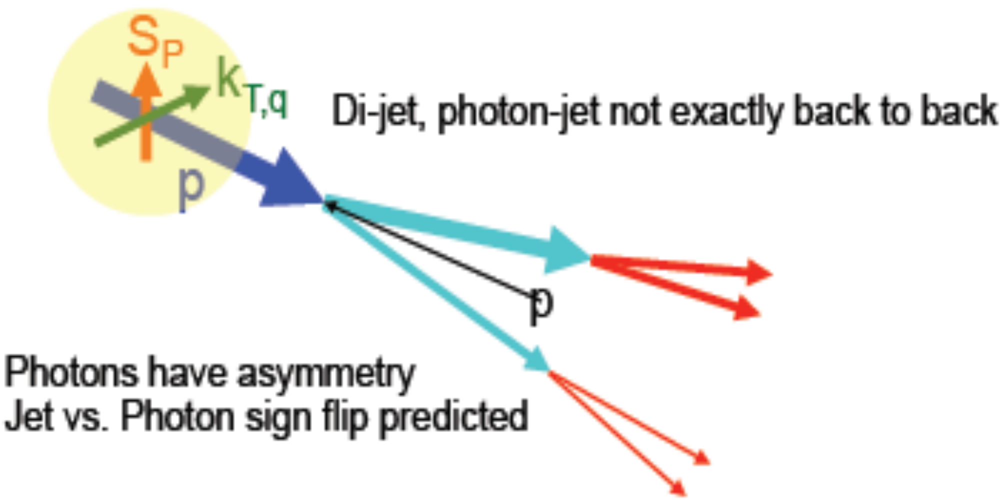
1+2D confined motion in a nucleon

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



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

- ❑ **Quantum correlation between hadron spin and parton motion:**



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

1+2D confined motion in a nucleon

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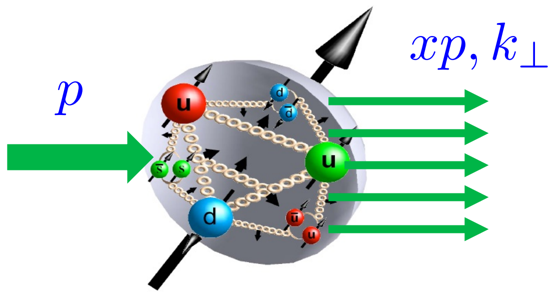

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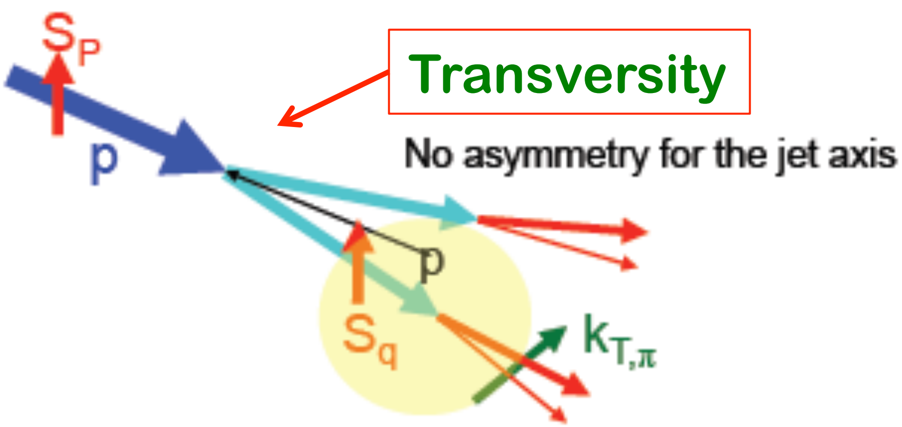


Collins effect – Collins function

Parton's transverse spin influence its hadronization

- ❑ **Single-spin asymmetry:**

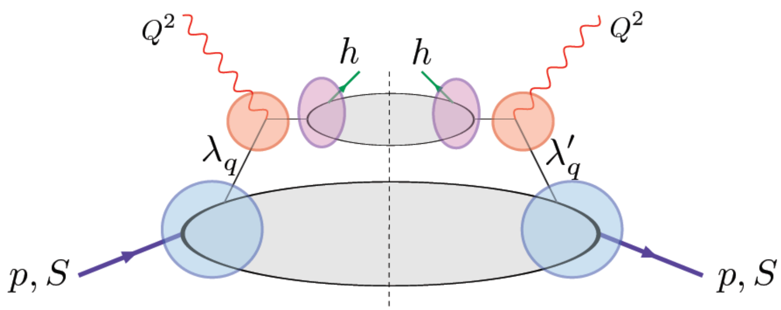
$$A(\ell,\vec{s}) \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$

Enhance the role of transverse motion – confined motion!

Only EIC can cover the sea and gluon. Limitation on proton-proton machine

EIC is ideal for probing TMDs

❑ Two scales – SIDIS has the natural kinematics:



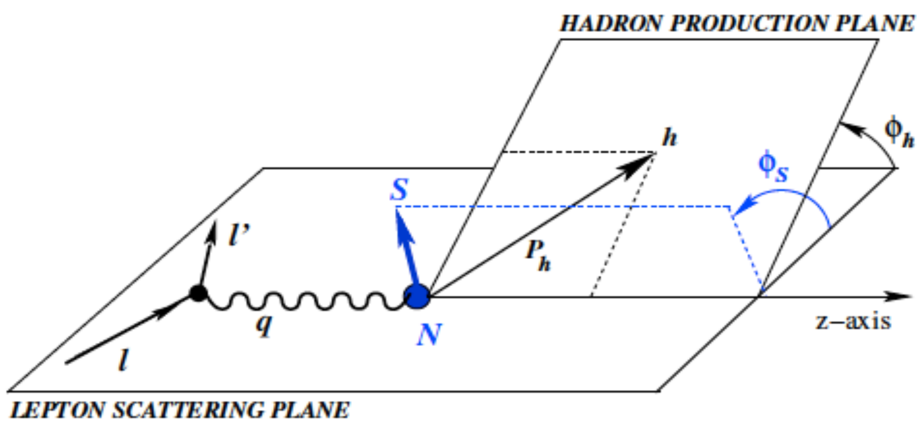
$$\ell(s_e) + p(s_p) \to \ell + h(s_h) + X$$

Natural event structure:

high Q - localized probe

Low p_T - sensitive to confining scale

❑ Two scattering plans – Separation of various TMDs:



Two scattering plans:

leptonic, and hadronic

Angular modulation to separate Collins effect from Sivers effect

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

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

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

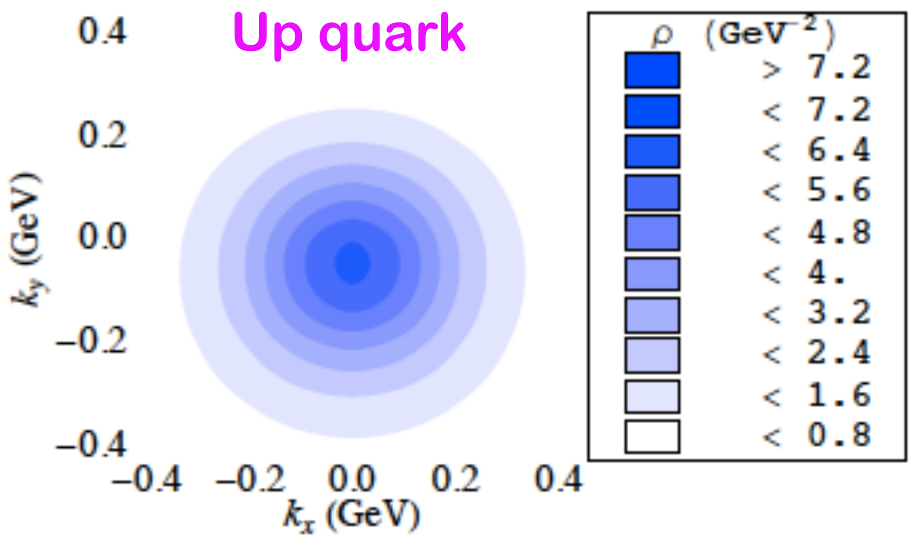
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

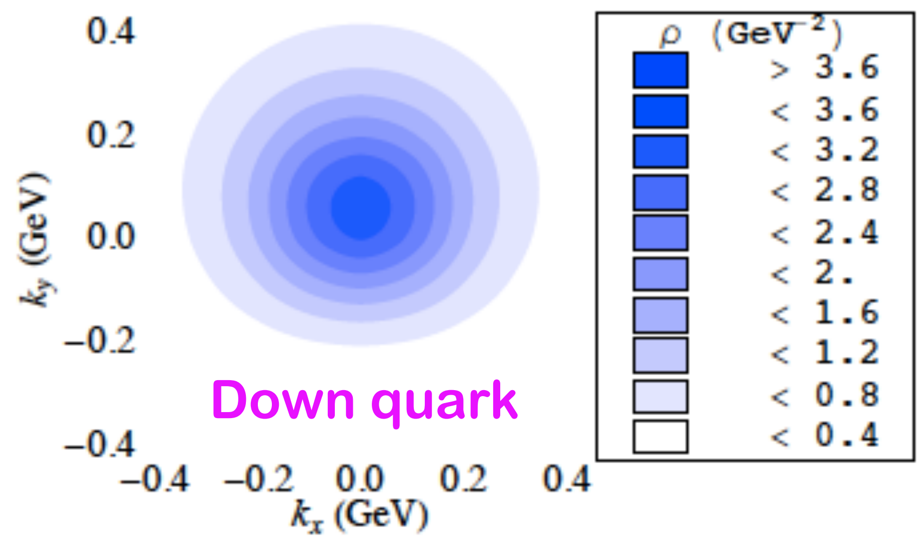
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

What EIC can do to Sivers function?

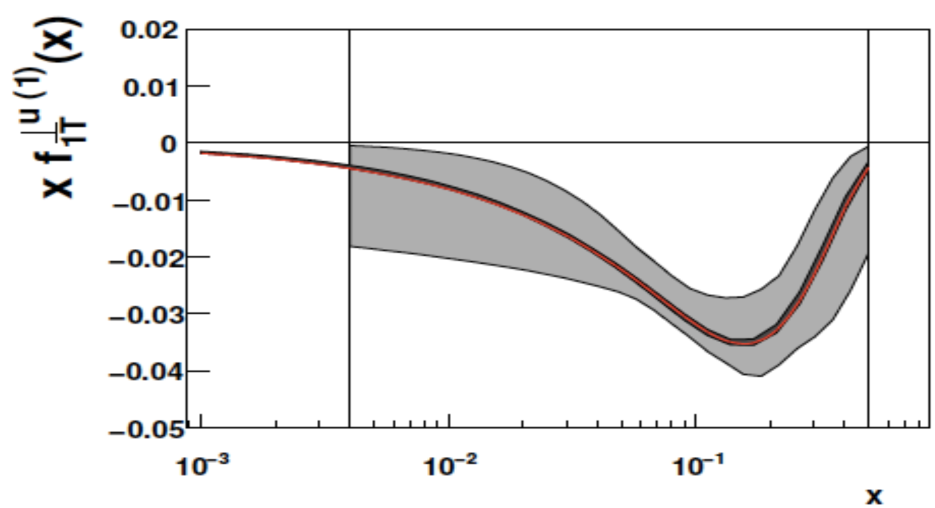
❑ Unpolarized quark inside a transversely polarized proton:

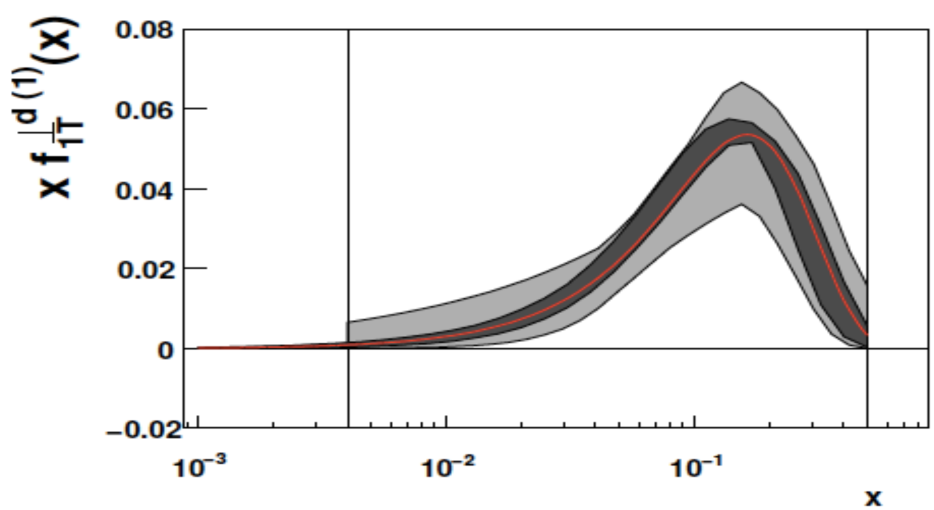




Color confined radius at different x?

❑ Role of momentum fraction – x:





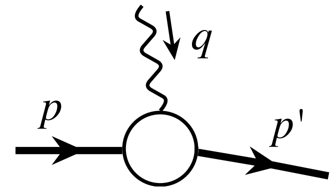
1+2D spatial imaging of color?

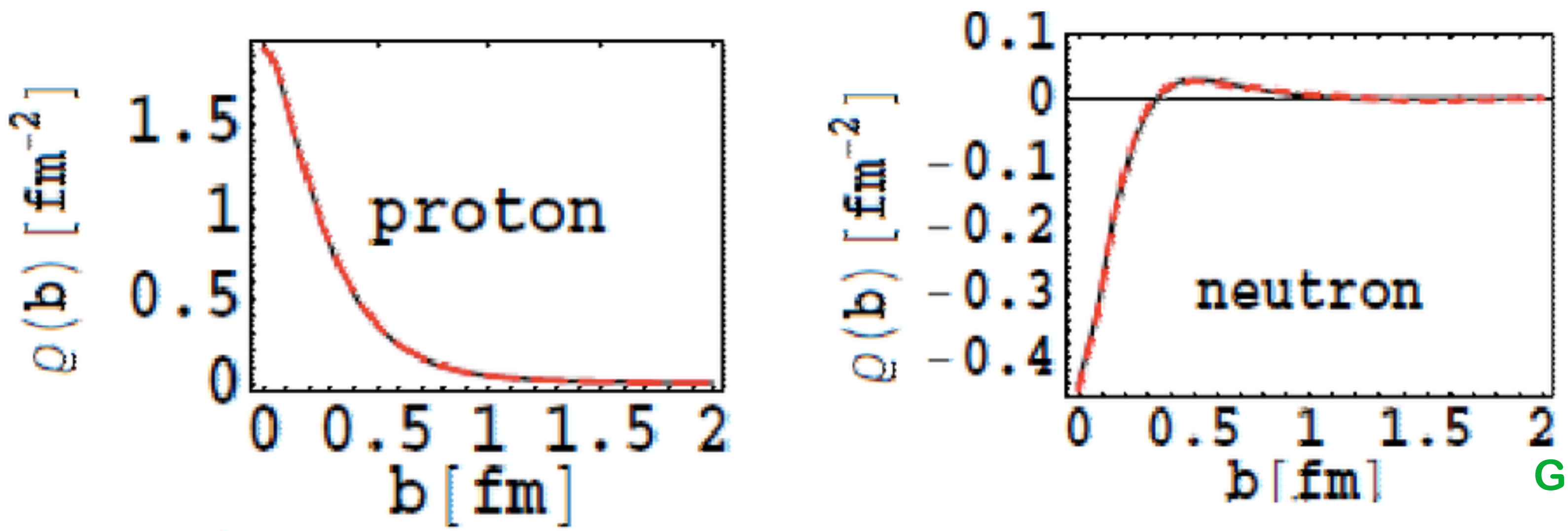
- The "big" question:

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

- Electric charge distribution:

  Elastic electric form factor ➡ Charge distributions

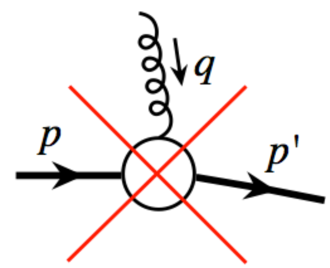




G.A. Miller (2007)

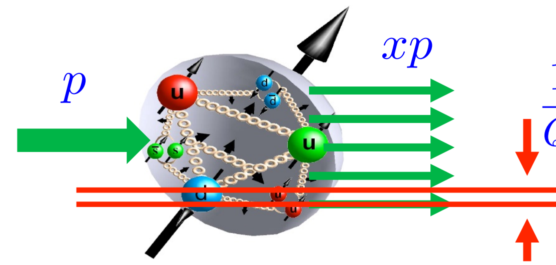
- But, NO color elastic nucleon form factor!

  Hadron is colorless and gluon carries color

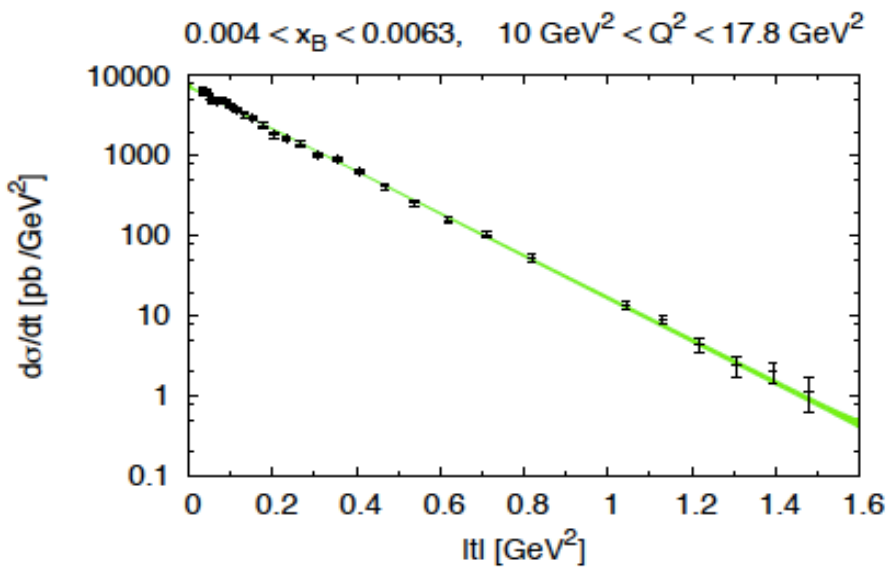


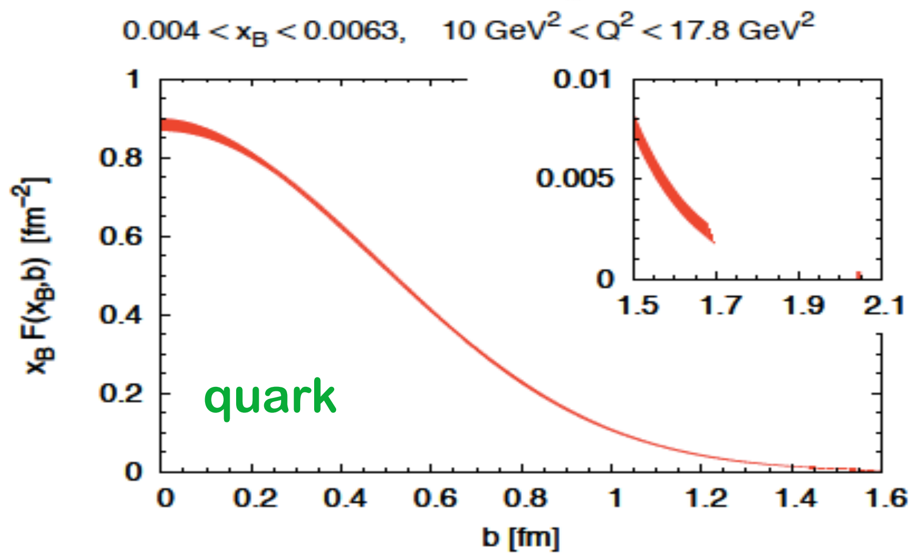
1+2D spatial imaging of parton density

❑ 2D Fourier transformation:



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





❑ Total quark's orbital contribution to proton's spin:

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

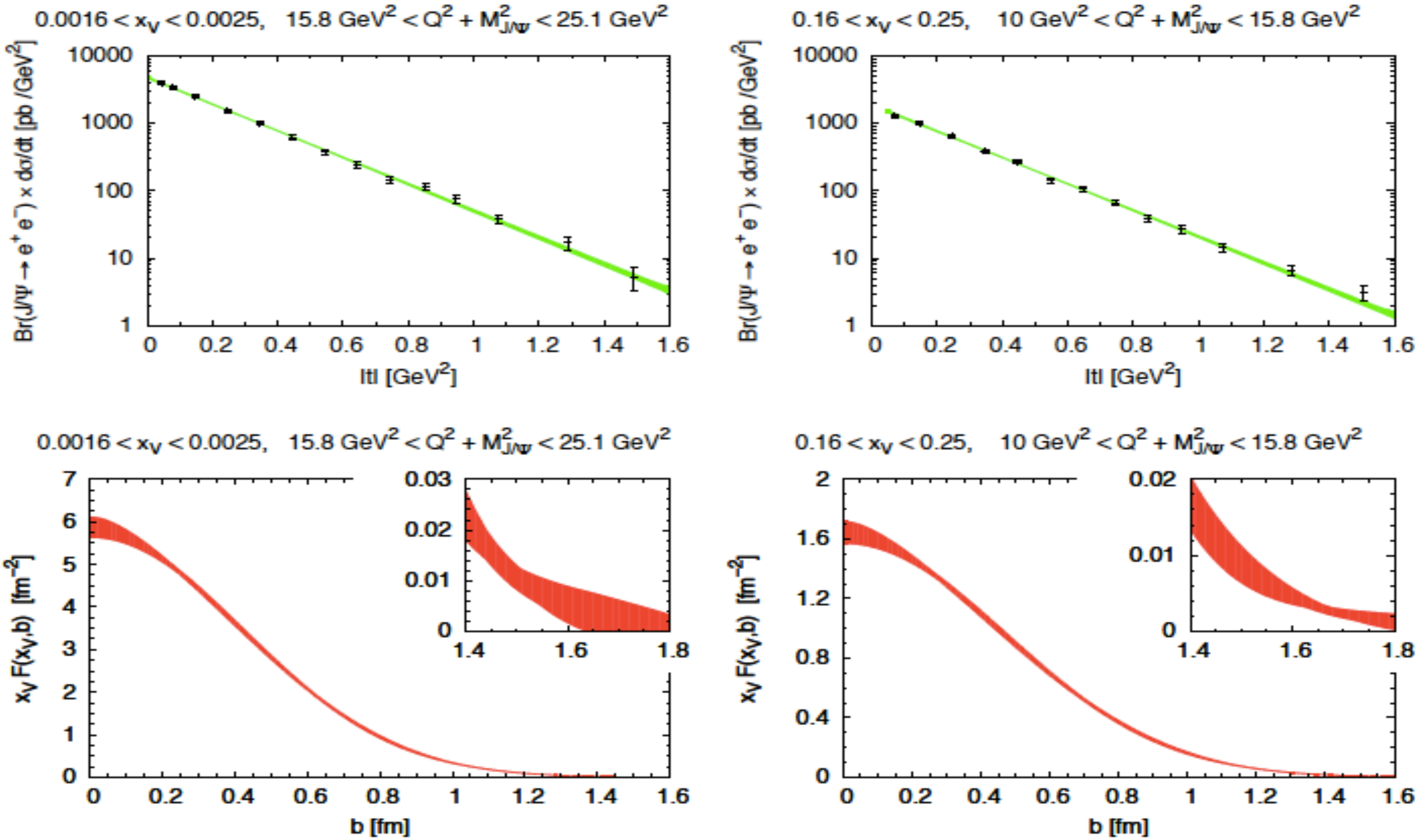
The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab 12

Should this be consistent with Lattice QCD?

Imaging of gluons

- ❑ **J/ψ production @ EIC:**

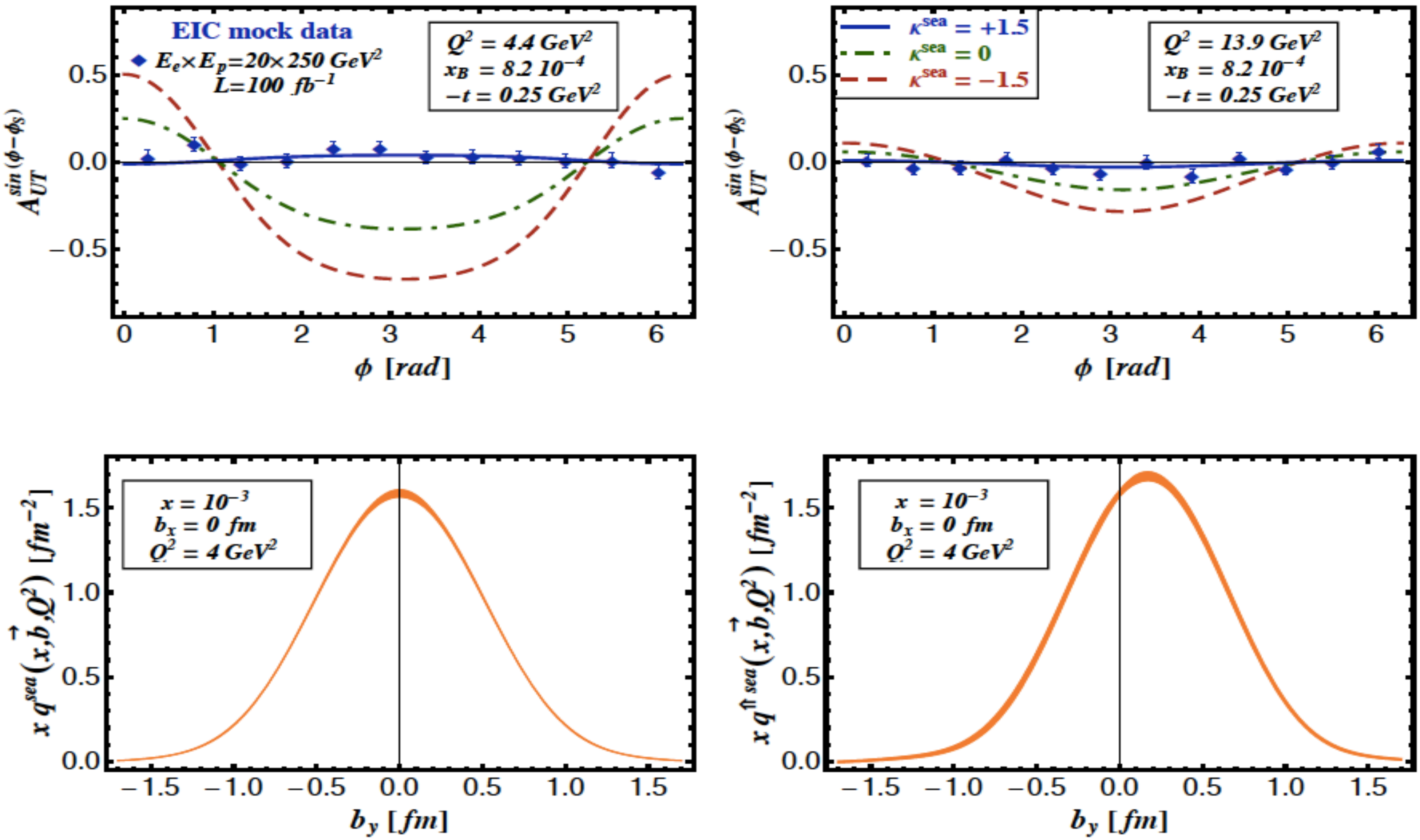
$10\,\mathrm{fb}^{-1}$ at $20 \times 250\,\mathrm{GeV}$ | $10\,\mathrm{fb}^{-1}$ at $5 \times 100\,\mathrm{GeV}$



Spin effect

M. Diehl, DIS2012

❑ Transverse-spin @ EIC:



No other machine in the world can do this!

Nucleus, a Laboratory for QCD

- **The nucleus:**

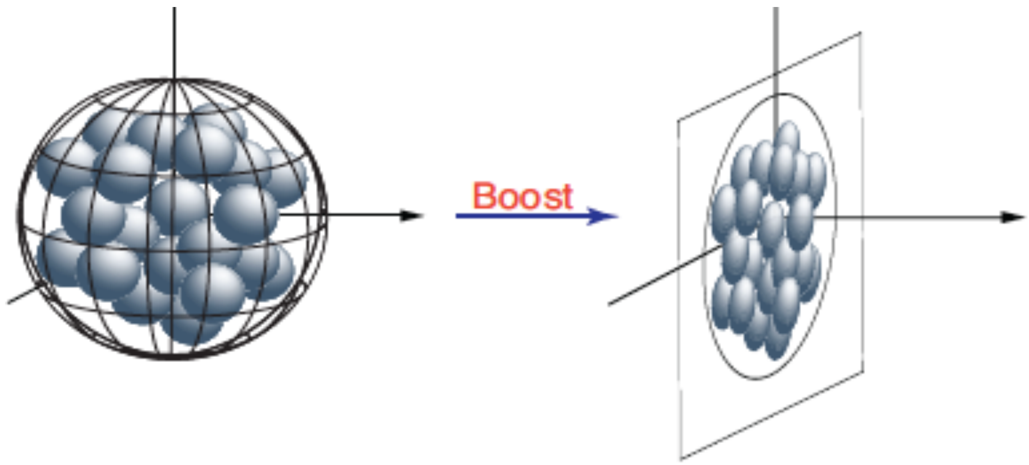
  Binding energy/nucleon ~ 8 MeV << Q < a few GeV

  ➡ 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**



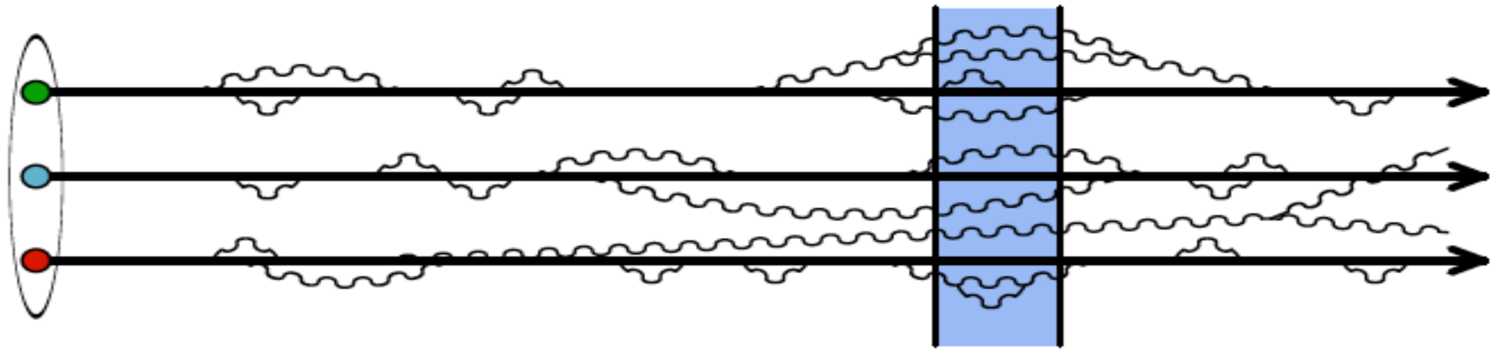
Probe size: transverse - $\frac{1}{Q} \ll 1 \text{ fm}$, longitudinal size - $\frac{1}{xp} \sim \frac{1}{Q} \ll 1 \text{ fm}$

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

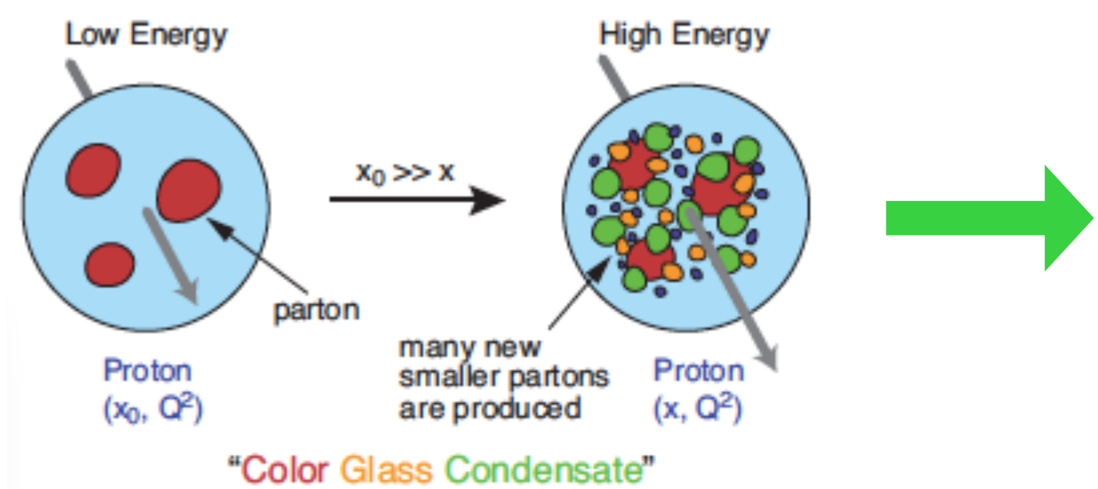
$$x < x_c = \frac{1}{2mR} \sim 0.1$$

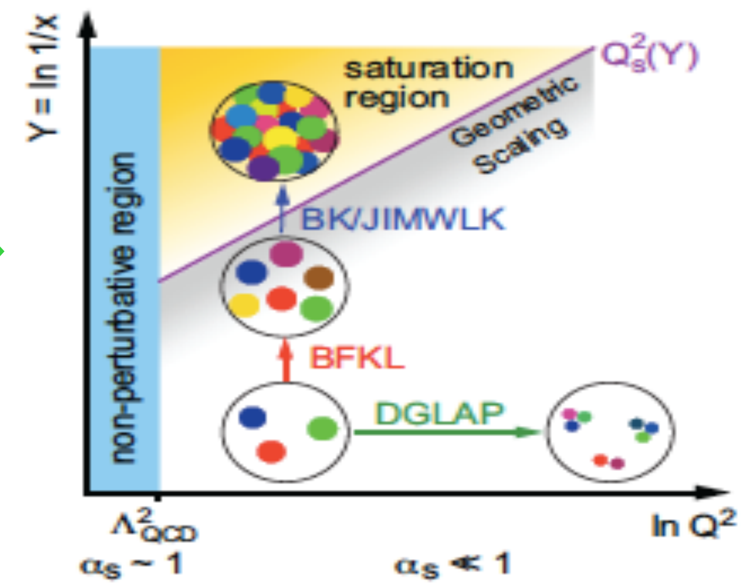
Soft gluons at small-x

- Gluon recombination and saturation ought to be there:



- QCD at high gluon density – new regime – universal feature:





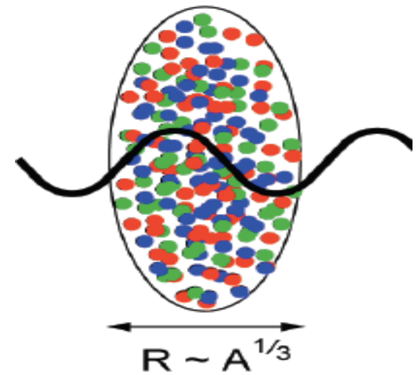
- Universal scale – saturation scale:

$$Q_s^2 \propto \frac{1}{x^\lambda} \frac{A^{1/3}}{R^2}$$

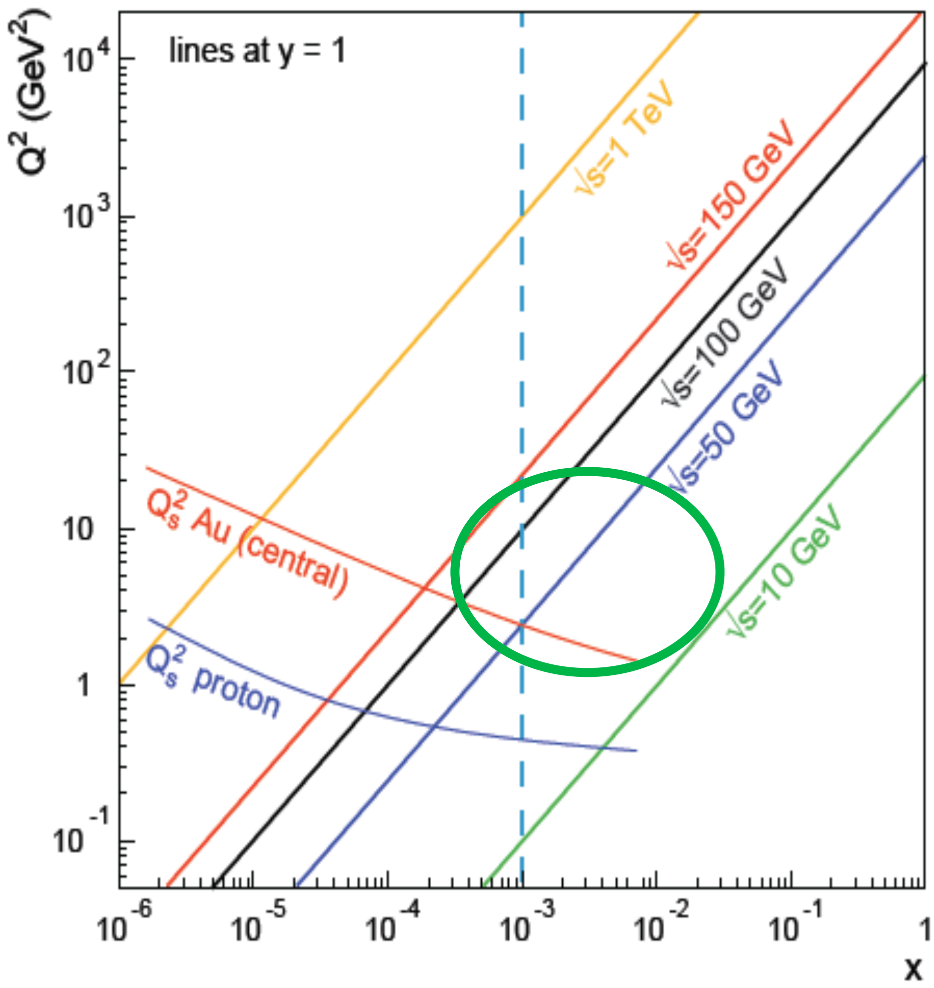
Boundary between CGC and pQCD parton gas?

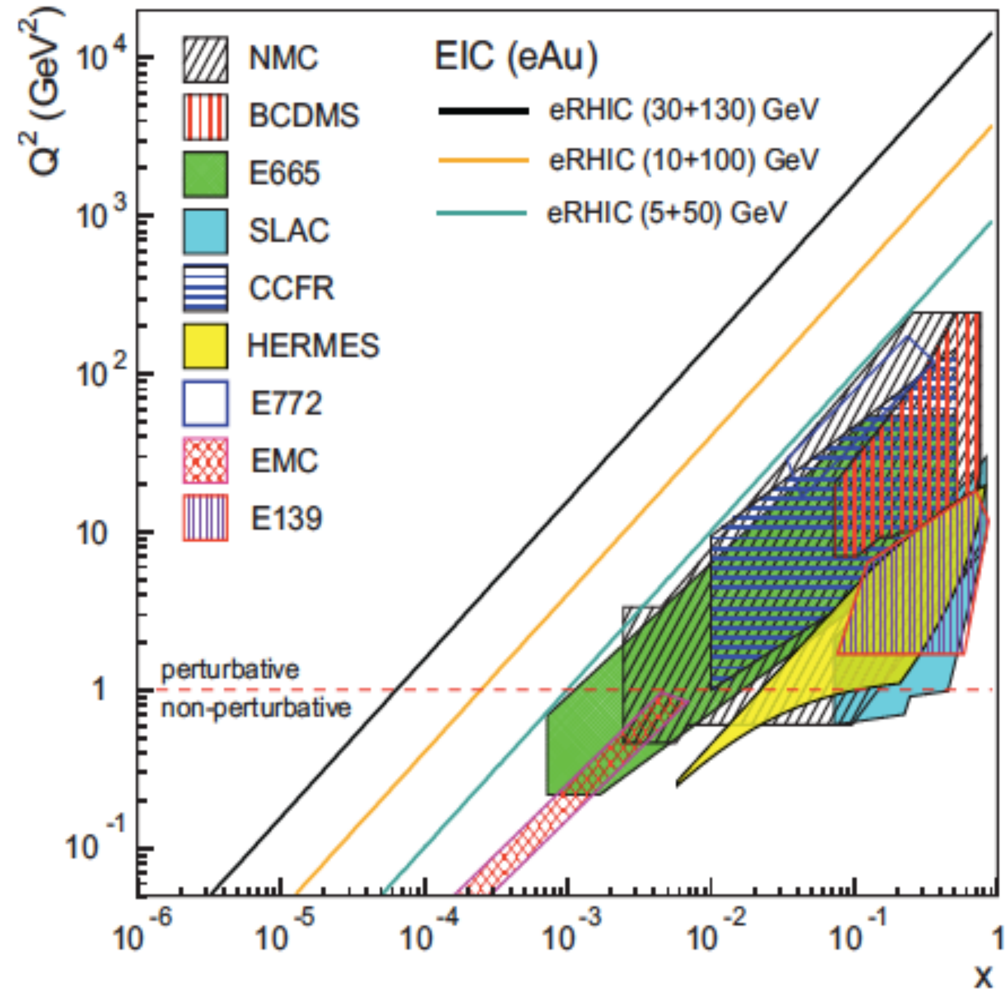
Reaching the saturation with eA

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



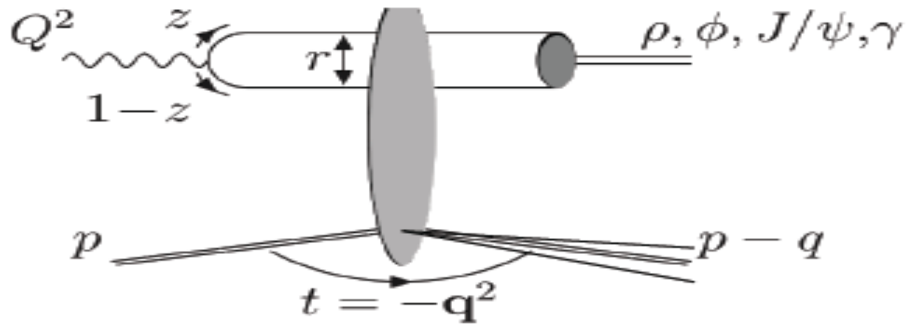
$$Q_s^2(eA) \propto Q_s^2(ep)\ A^{1/3}$$





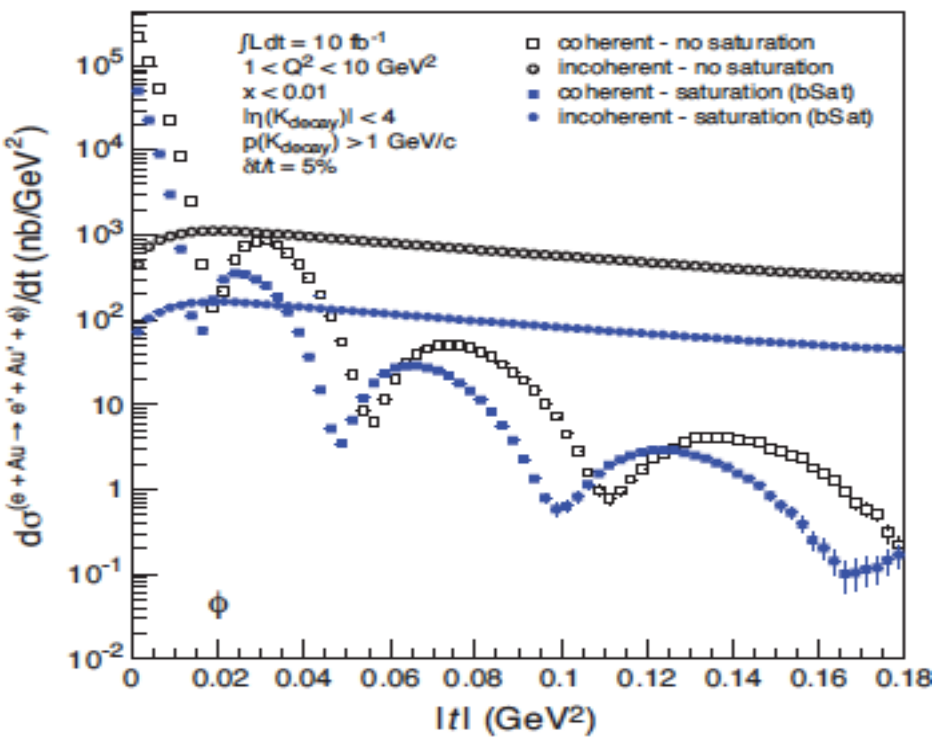
Discover the saturation

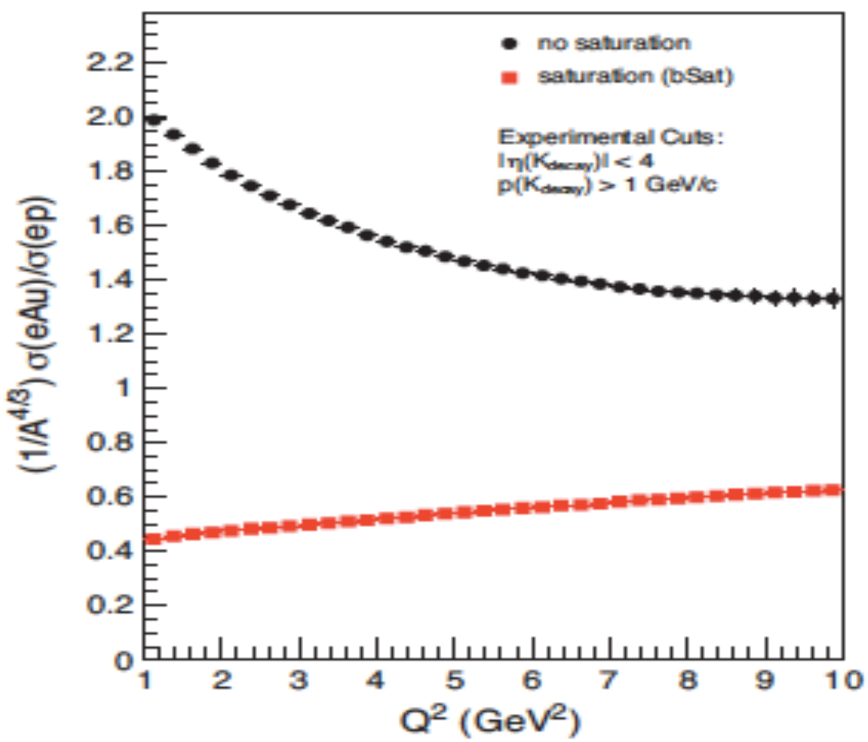
- **Diffractive vector mesion (Φ, J/ψ, ..) production:**



- as a function of t

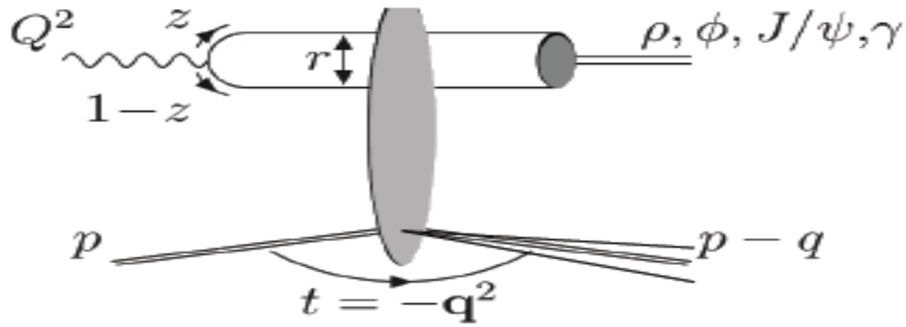
- **Φ–production:**





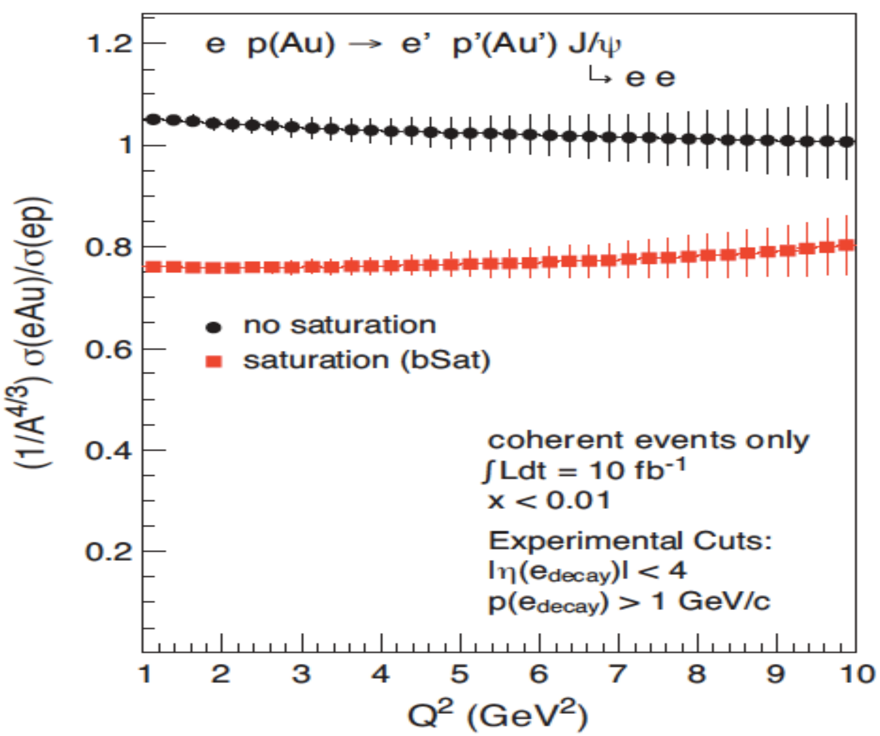
Discover the saturation

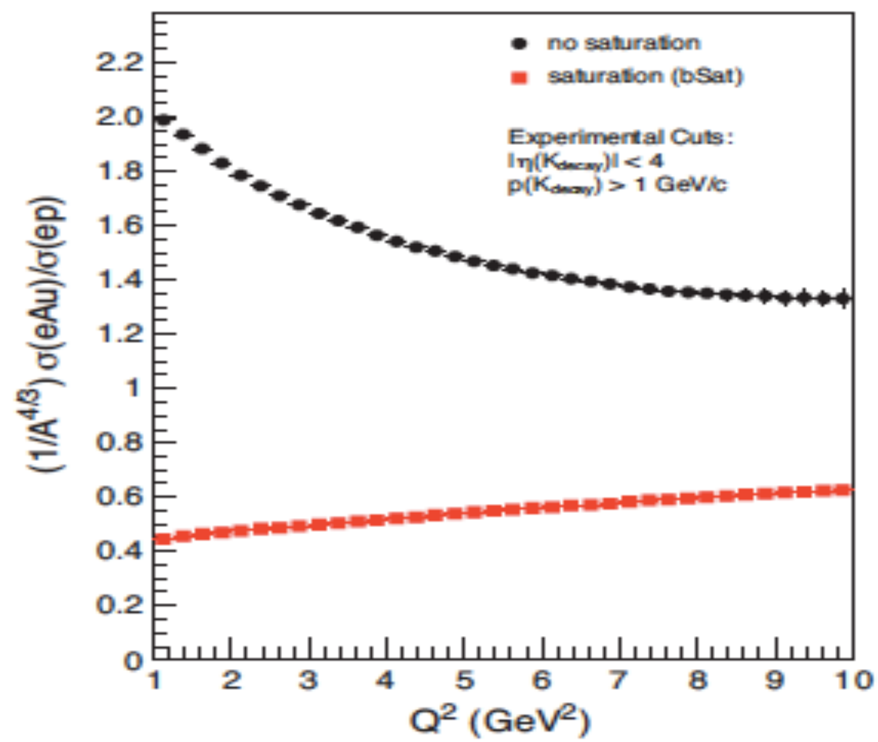
- Diffractive vector mesion (Φ, J/ψ, ..) production:



- as a function of t

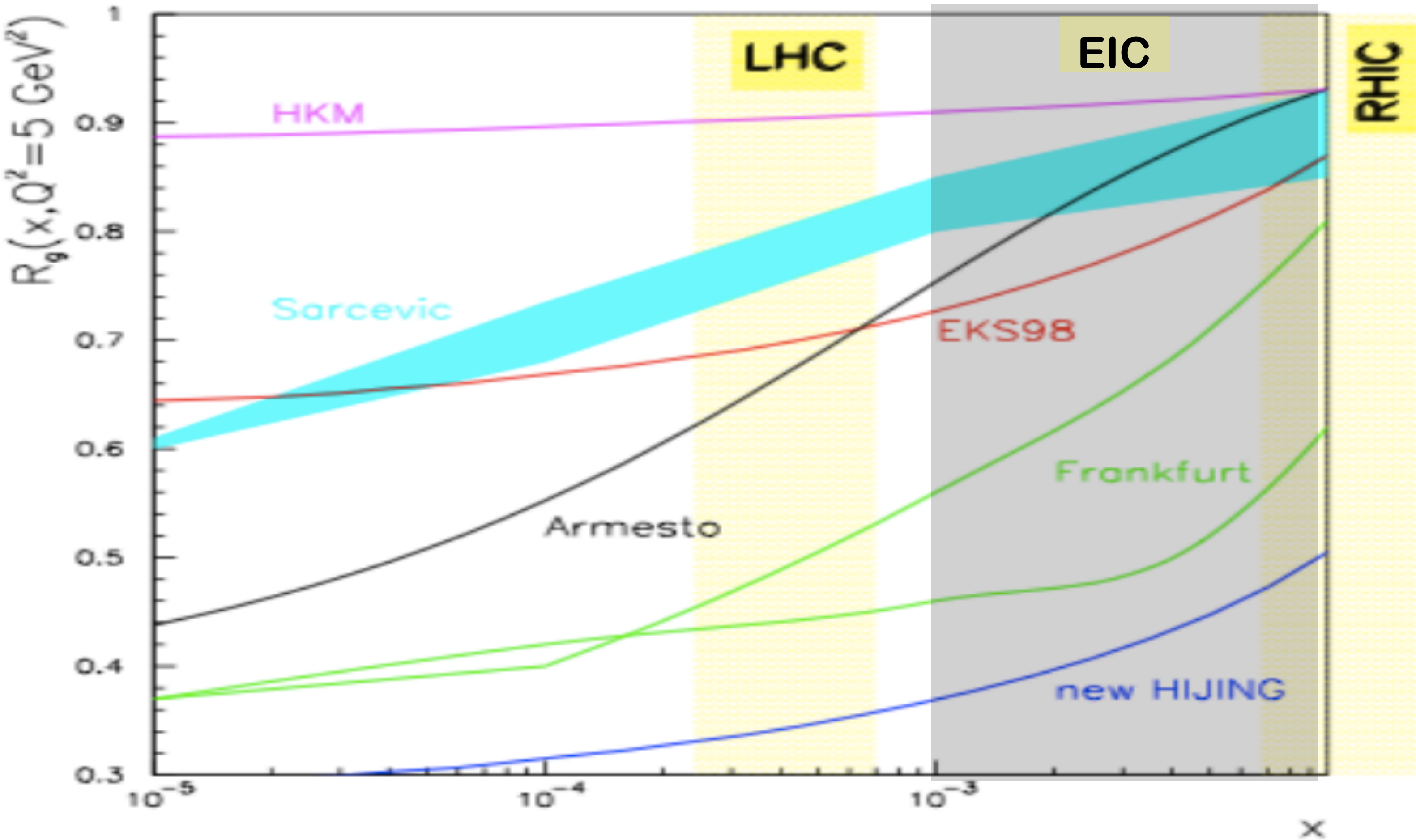
- J/ψ–production:





The quark-gluon landscape of nucleus

❑ **Nuclear gluon distribution:**



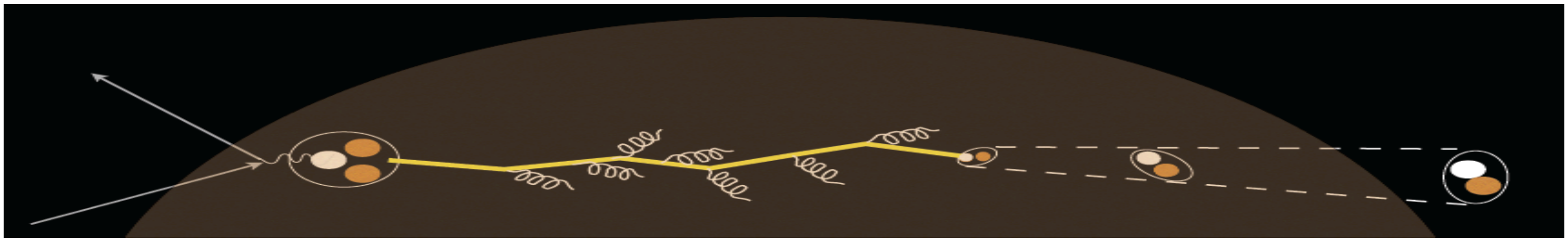
Never really be measured!

❑ **Quantum fluctuation of gluon distribution in a nucleus:**

Much needed initial condition of Relativistic Heavy Ion Collisions!

Hadronization – medium effect

❑ Unprecedented range of photon energy ν at EIC: $\nu = \frac{Q^2}{2mx}$



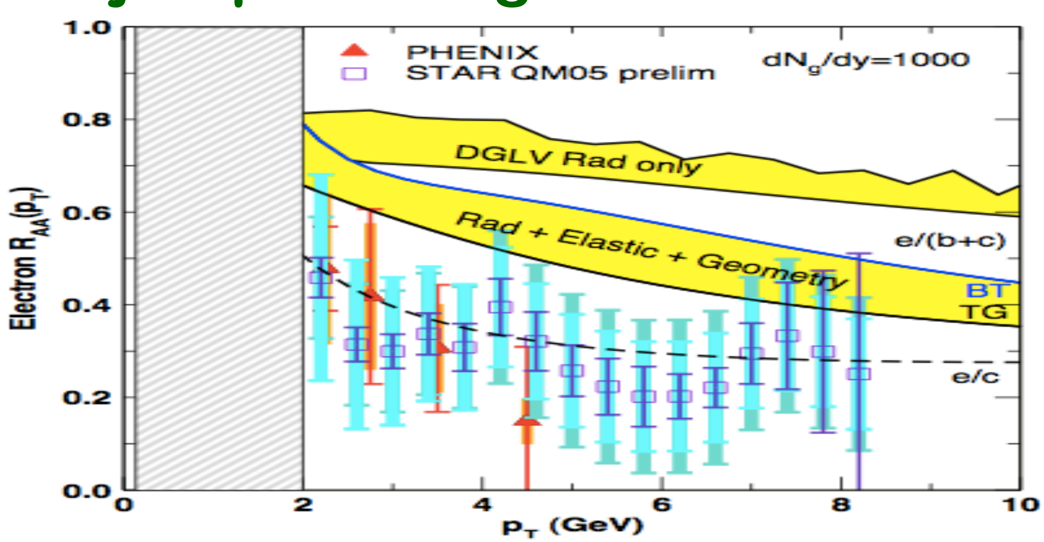
✧ Small ν - in medium hadronization:

Stages of hadronization: parton, pre-hadron, hadron

✧ Large ν - parton multiple scattering:

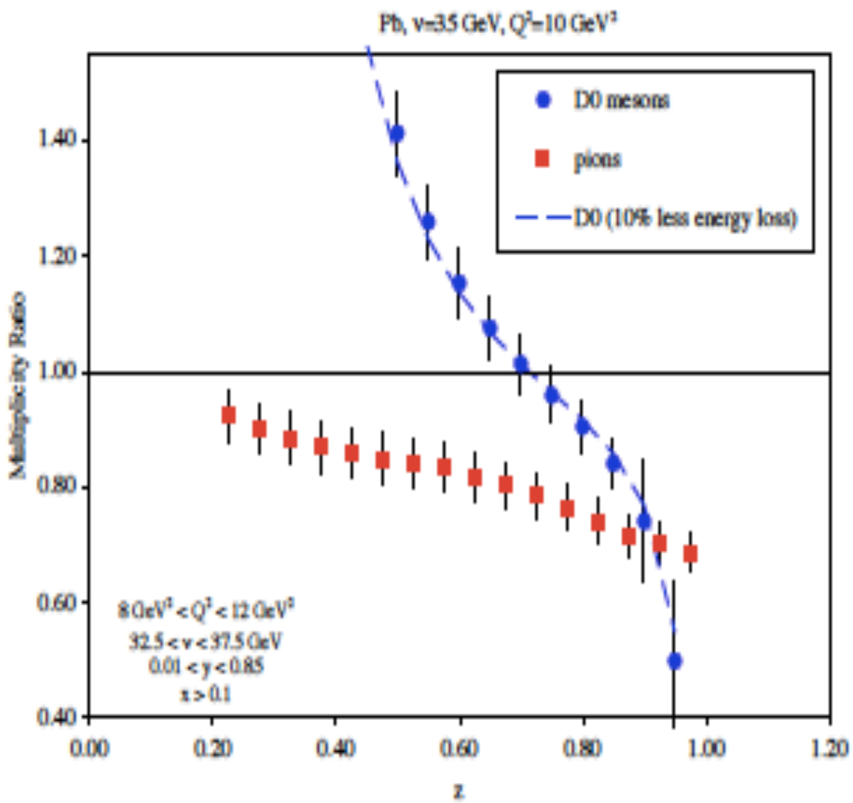
Parton energy loss – cold nuclear matter $\hat{q}$

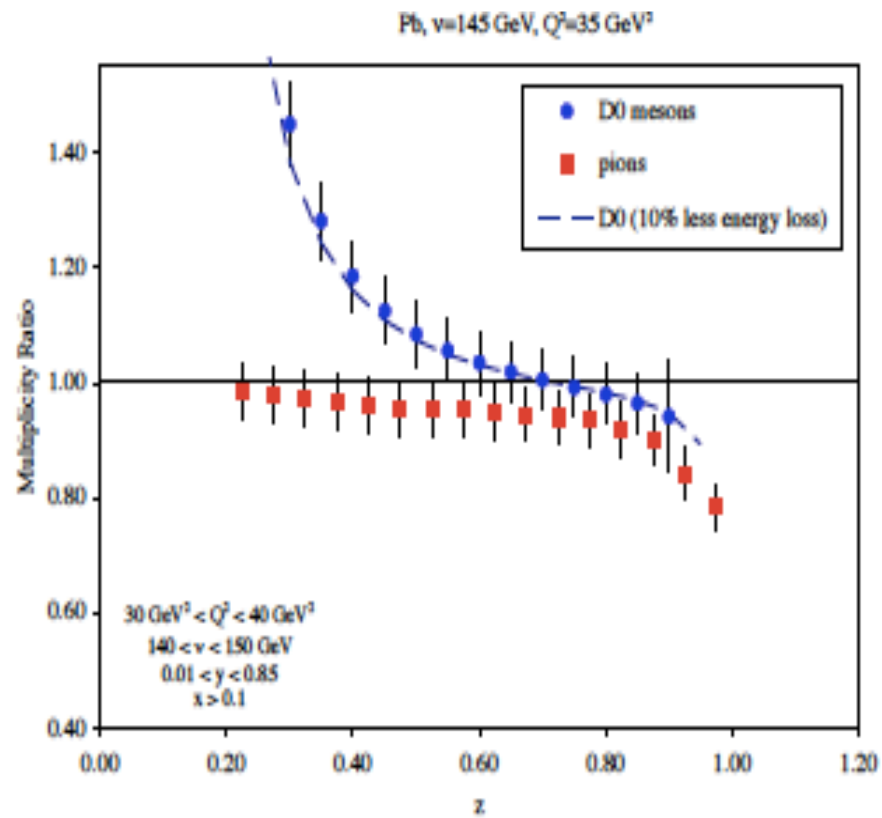
❑ Mass effect of jet quenching at RHIC:



QCD medium effect – energy loss

❑ Clean test of quark mass effect at EIC:





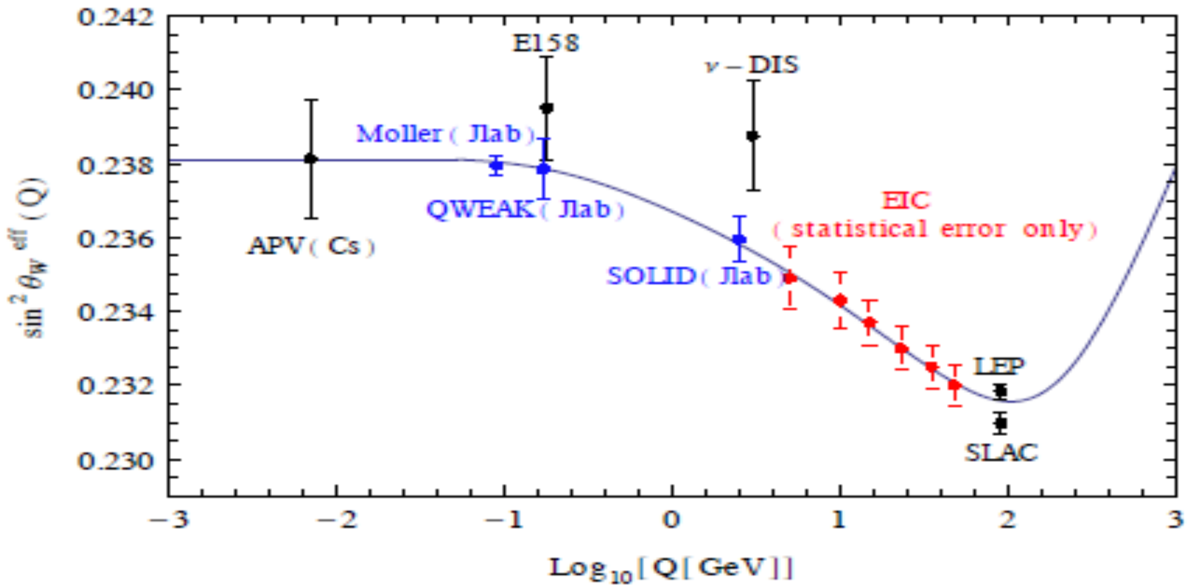
Immediate consequence of the difference between the light and heavy quark fragmentation functions

❑ The EIC:

- ✧ Shed light on the hadronization process – quark mass effect?
- ✧ What governs the transition from quarks and gluons to hadrons?

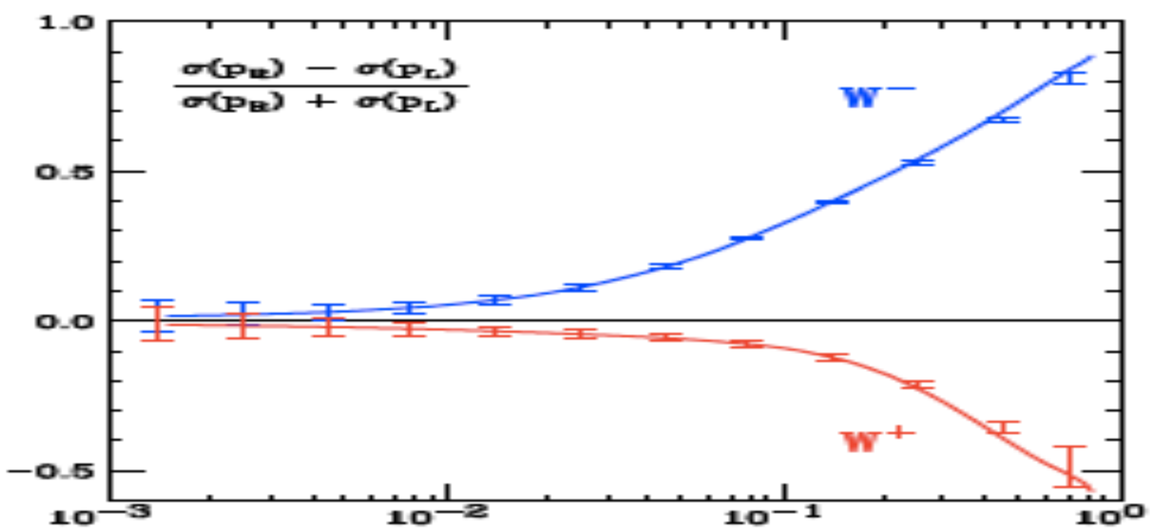
Opportunities at the luminosity frontier

- Mixing angle of weak interaction – high luminosity:



Fill the region never be measured

- Parity-violating single longitudinal asymmetries:



Flavor separation of helicity distributions

The three important goals of EIC

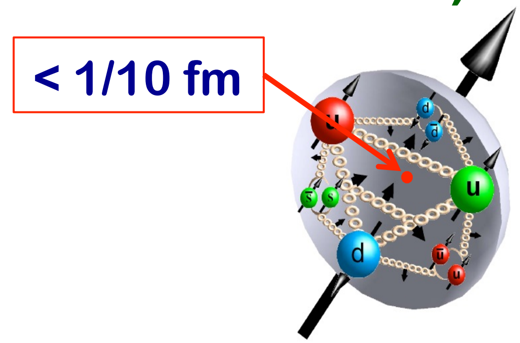
- ❑ Extract the confined motion of quarks and gluons in a nucleon with and without polarization, and in a nucleus – STAGE ONE
  - ✧ Possible clue for color confinement, hadron – parton correlations, …
  - ✧ Ultimate solution of proton spin – hadron property in QCD
  - ✧ Naturally measured at EIC, not easy, if not impossible, at other machines
- ❑ Measure the confined spatial distribution of quarks and gluons in a nucleon with and without polarization, and in a nucleus
  - ✧ Complementary to the measurement on the confined motion
  - ✧ Sum rule for proton spin – hadron property in QCD
  - ✧ EIC has the "sufficient" kinematic reach for reliable imaging
- ❑ Discover clear evidences of QCD's manybody non-linear dynamics and the range of color coherence – STAGE ONE
  - ✧ Saturation scale – consequence of QCD non-linear dynamics
  - ✧ Range of color coherence – nuclear property in QCD
  - ✧ EIC, like RHIC for heavy ion, can pioneer the search of non-linear dynamics

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

- EIC with polarization provides a new program to explore new frontier research of QCD dynamics – key to the visible matter

Rutherford exp’t	SLAC “Rutherford”	Future “Rutherford”
1911	1969	2020?
Nucleus Atomic structure	Parton Collinear PDFs	Manybody non-linear dynamics Confined partonic structure

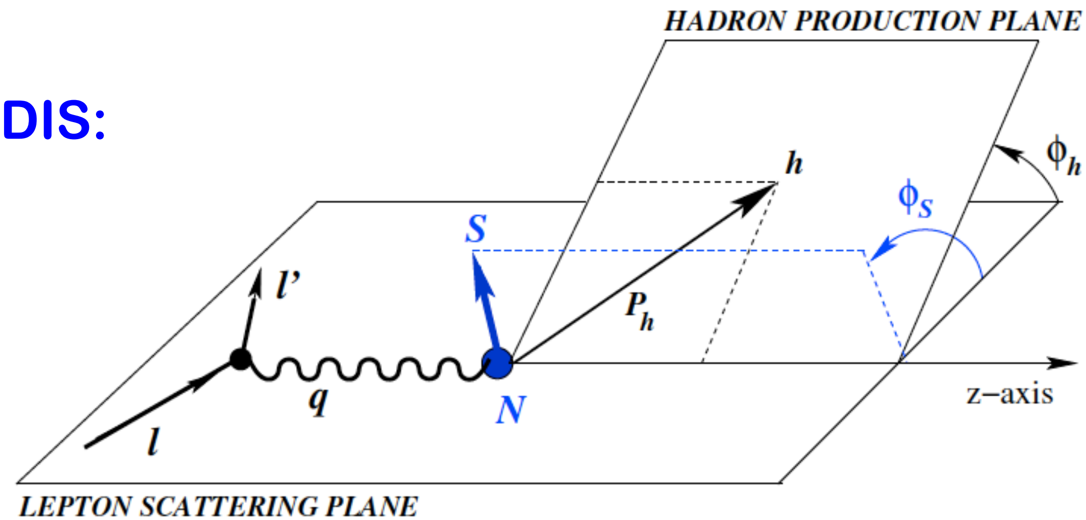
Thank you!

1+2D confined motion in a nucleon

- **Going beyond the PDFs – 3D motion of quarks and gluons:**

High resolution scattering, but, still sensitive to parton's transverse motion

Semi-inclusive DIS:



$Q >> P_T$

3D confined motion in a nucleon

- Going beyond the PDFs – 3D motion of quarks and gluons:

  High resolution scattering, but, still sensitive to parton's transverse motion

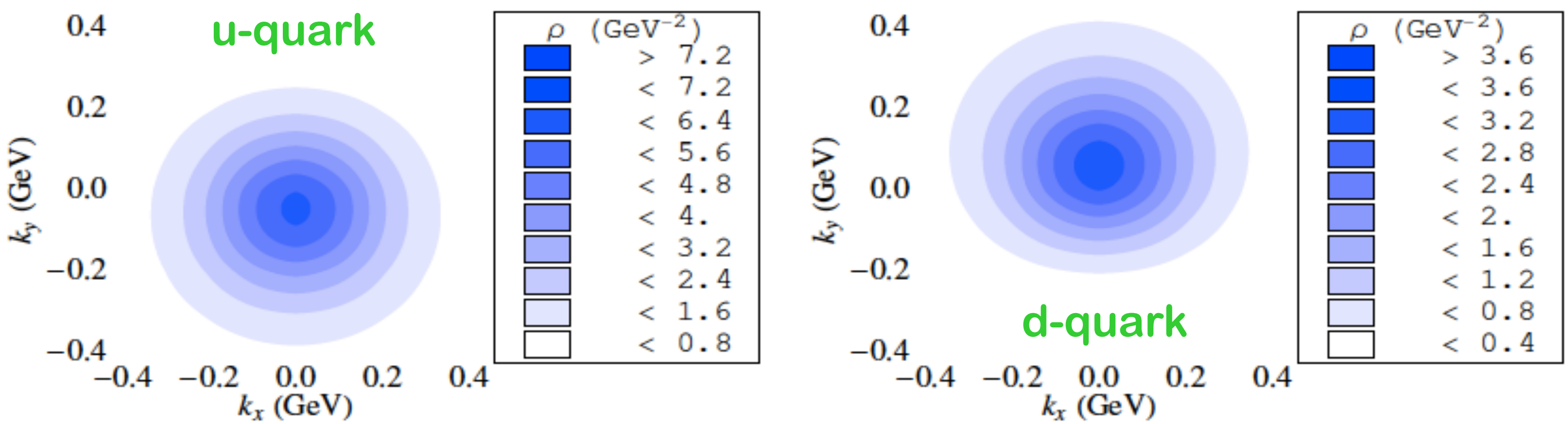
- QCD quantum correlations between spin and motion:

  Sivers effect – correlations of hadron spin and parton transverse motion

  Collins effect – influence of parton spin on direction of produced hadrons

  …

- Momentum tomography – wide range of x and Q^2:



In a fast moving nucleon in z-direction while polarized in x-direction

- The EIC – initiate the program on sea quarks and gluons:

  Complementary to Jlab 12 (Valence) – not achievable by other machines