J-PARC

Electron-Ion Collider: Taking us to the next QCD Frontier

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August 3, 2016

Acknowledgement: Much of the physics presented here are based on the work of EIC White Paper Writing Committee put together by BNL and JLab managements, …

U.S. - based EIC

❑ NSAC 2007 Long-Range Plan:

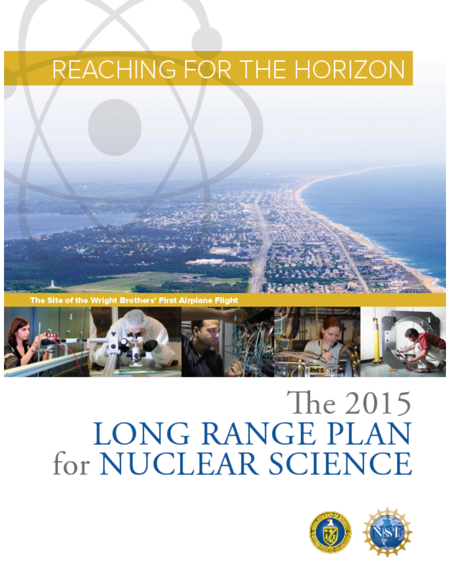
"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**."

❑ NSAC Facilities Subcommittee (2013):

"The Subcommittee ranks an EIC as **Absolutely Central** in its ability to contribute to world-leading science in the next decade."

❑ NSAC 2015 Long-Range Plan:

"We recommend a **high-energy high-luminosity polarized EIC** as **the highest priority for new facility construction** following the completion of FRIB."



❑ EIC User Group Meetings:

Stony Brook University, NY – June 24-27, 2014
UC at Berkeley, CA – January 6-9, 2016
Argonne National Lab, IL – July 7-9, 2016

Why the EIC?

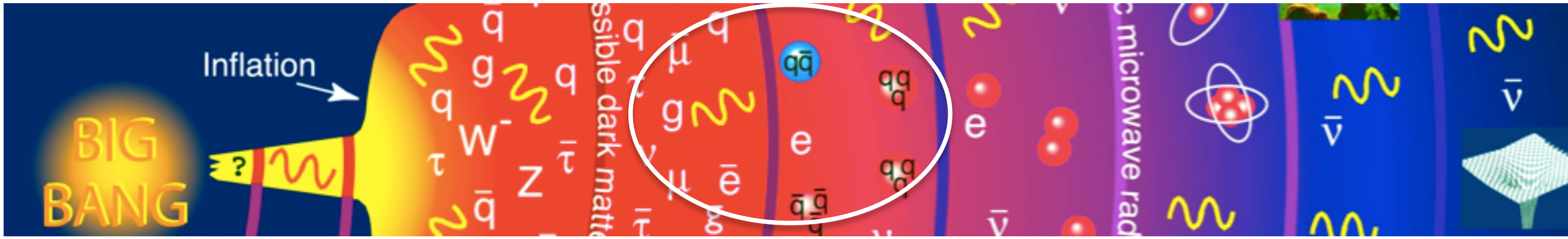
To understand the role of gluons in binding Quarks and Gluons into Nucleons and Nuclei

Outline of the rest of my talk

- 21st Century Nuclear Science
- The next QCD frontier
- The Electron-Ion Collider
- Key deliverables & opportunities, …
- Summary

21st Century Nuclear Science

- ❑ What is the role of QCD in the evolution of the universe?



- ❑ How hadrons are emerged from quarks and gluons?
- ❑ How does QCD make up the properties of hadrons?

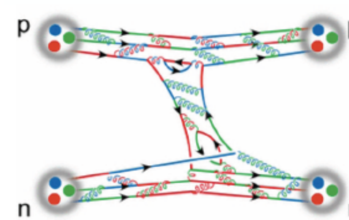
  Their mass, spin, magnetic moment, …

- ❑ What is the QCD landscape of nucleon and nuclei?

Color Confinement — Asymptotic freedom

Q (GeV)

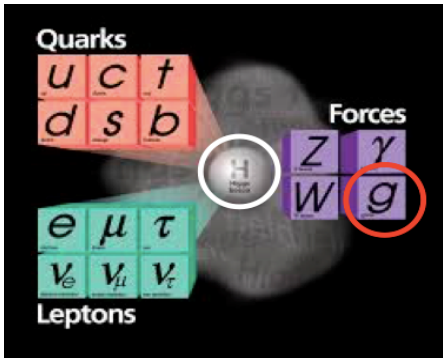
200 MeV (1 fm) — 2 GeV (1/10 fm) — Probing momentum

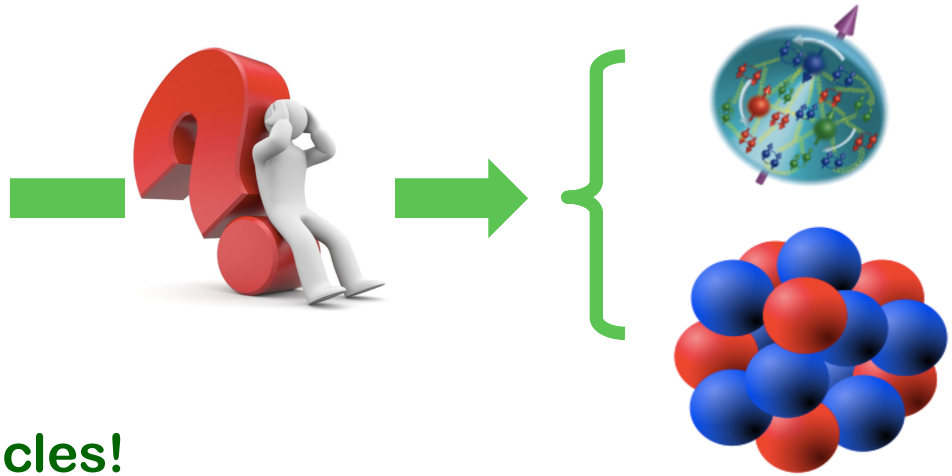


- ❑ How do the nuclear force arise from QCD?
- ❑ …

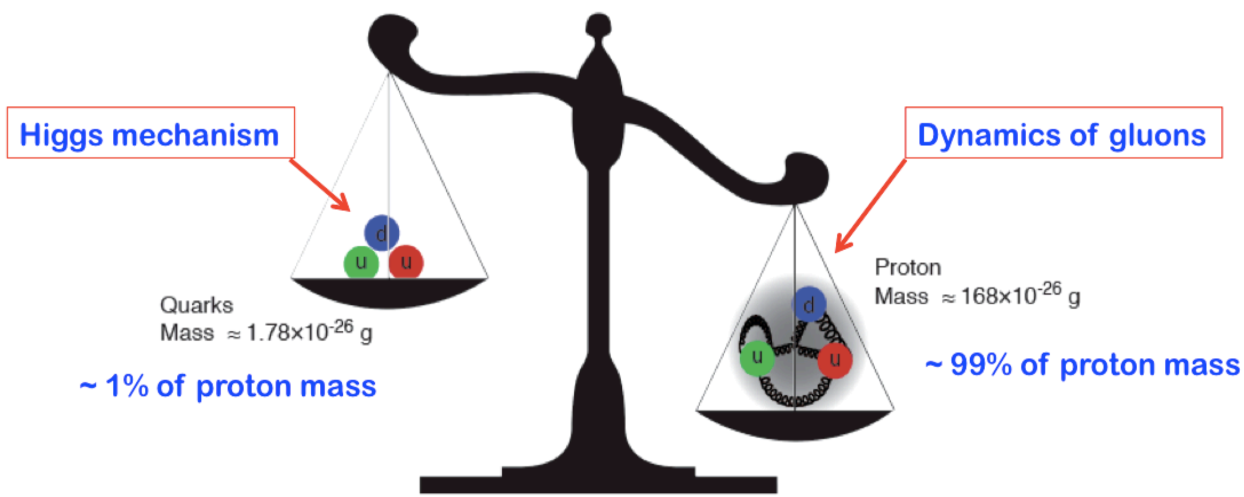
The next QCD frontier

- ❑ **Understanding the glue that binds us all – the Next QCD Frontier!**

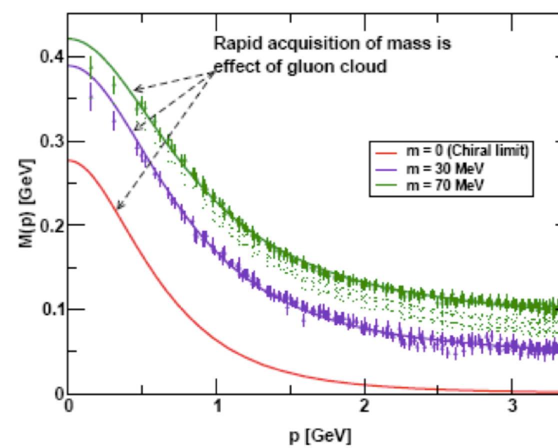




- ❑ **Gluons are weird particles!**
  - ✧ **Massless, yet, responsible for nearly all visible mass**



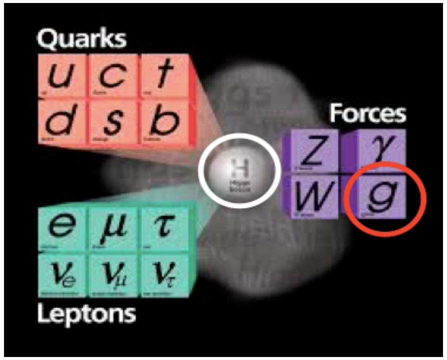
"Mass without mass!"

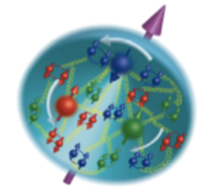


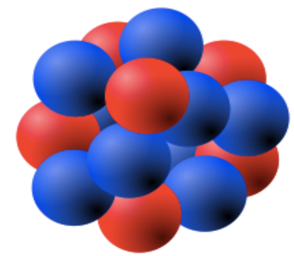
Bhagwat & Tandy/Roberts et al

The next QCD frontier

- Understanding the glue that binds us all – the Next QCD Frontier!







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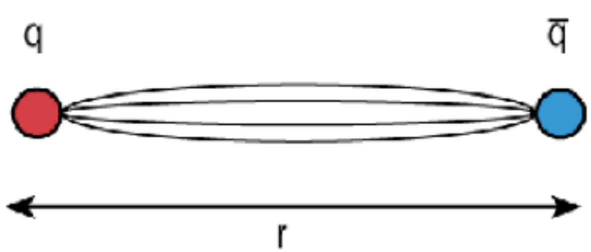
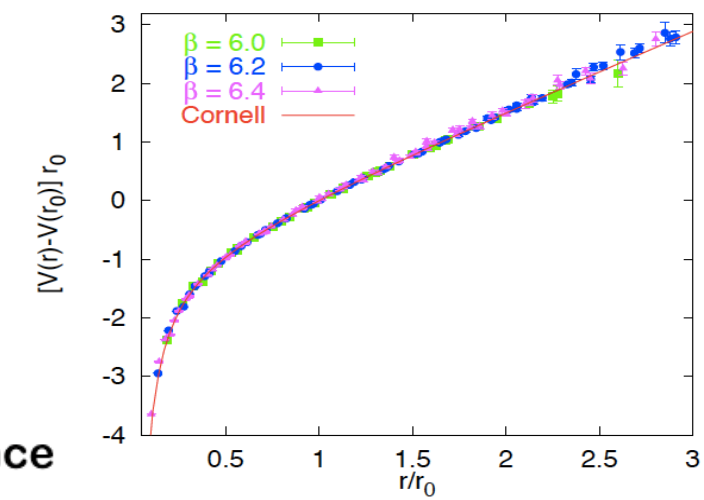
  - ✧ Massless, yet, responsible for nearly all visible mass
  - ✧ Carry color charge, responsible for color confinement and strong force

Force between a heavy quark pair



Heavy quarks experience a force of ~16 tons at ~1 Fermi (10^{-15} m) distance



The next QCD frontier

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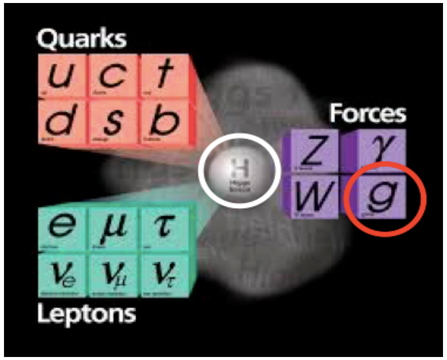

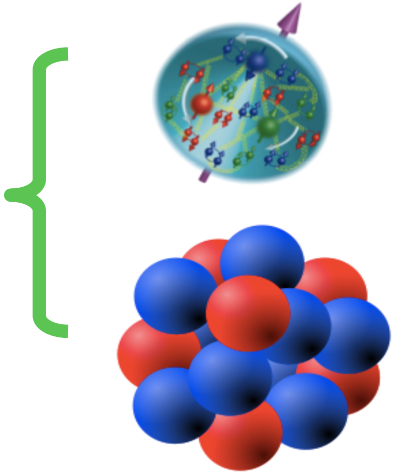

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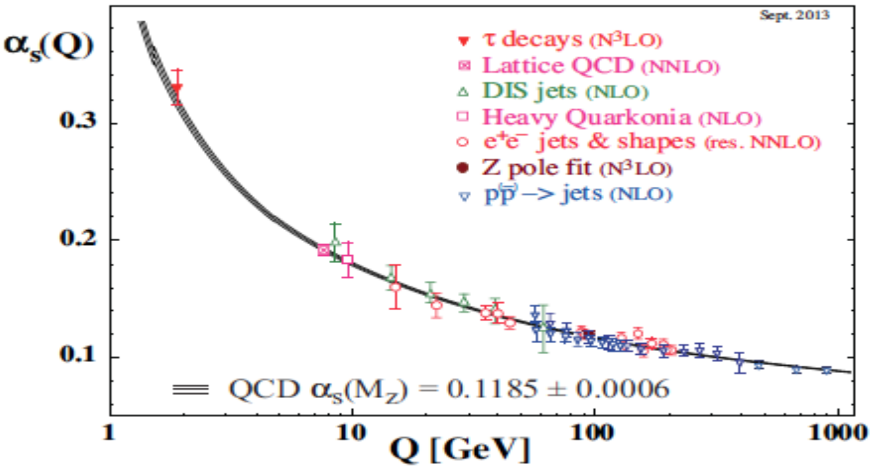
but, also for asymptotic freedom

Nobel Prize, 2004



→ QCD perturbation theory

The next QCD frontier

❑ Understanding the glue that binds us all – the Next QCD Frontier!

❑ Gluons are weird particles!

✧ Massless, yet, responsible for nearly all visible mass

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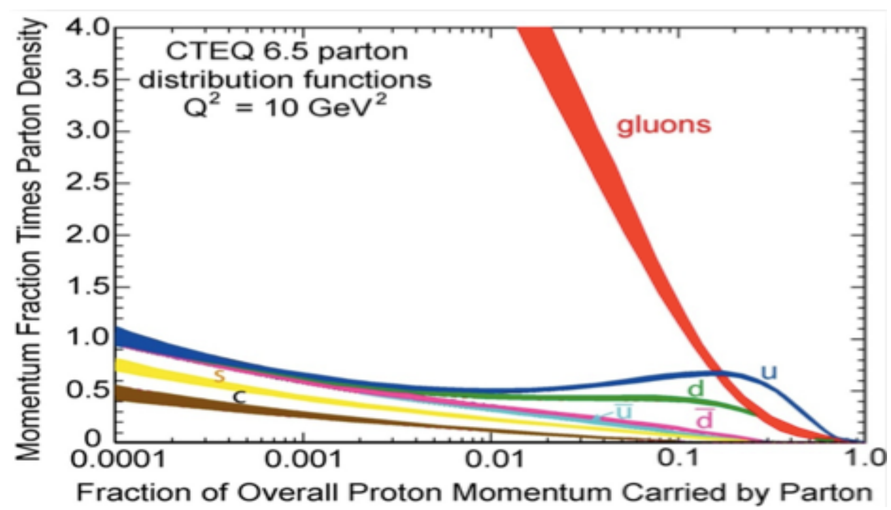
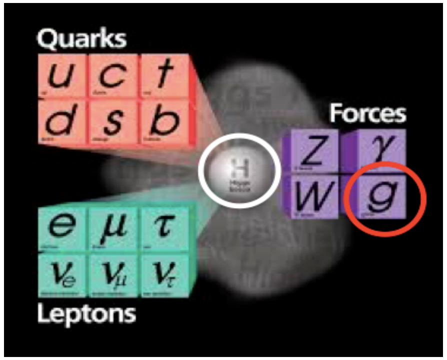
but, also for asymptotic freedom,

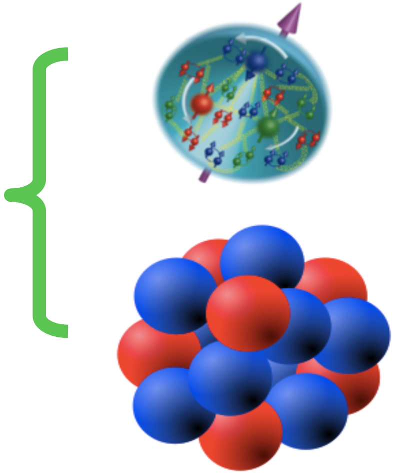
as well as the abundance of glue



The next QCD frontier

- ❑ **Understanding the glue that binds us all – the Next QCD Frontier!**





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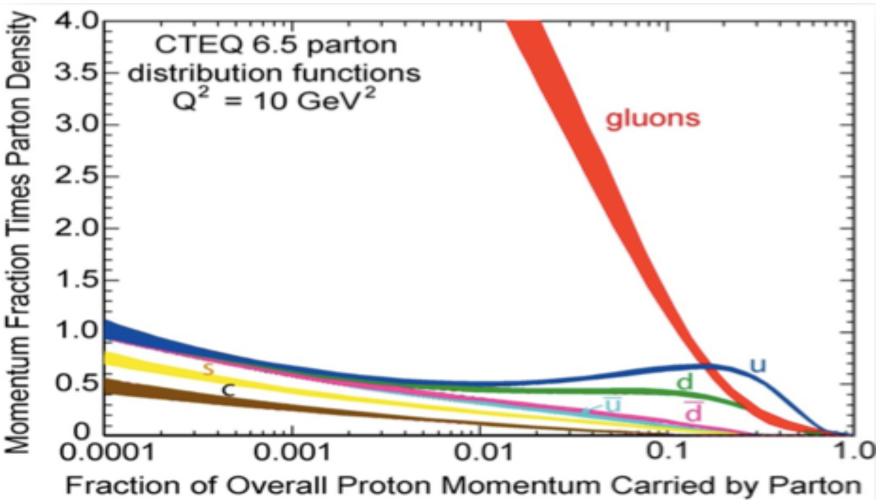
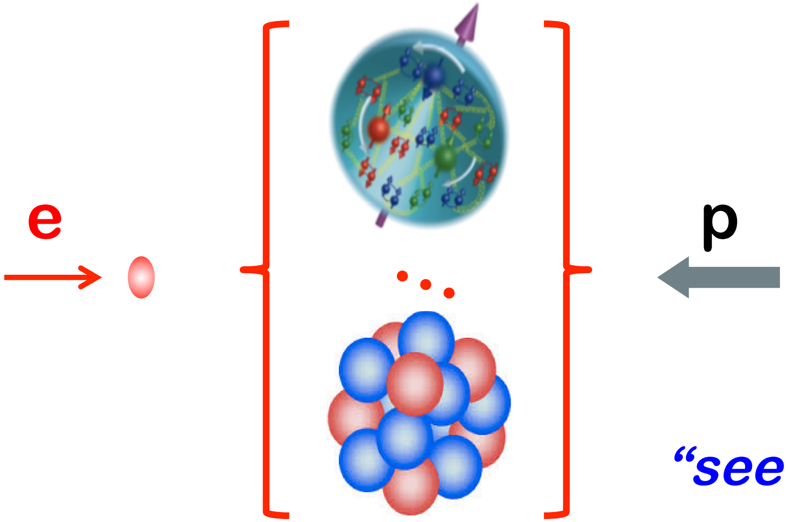


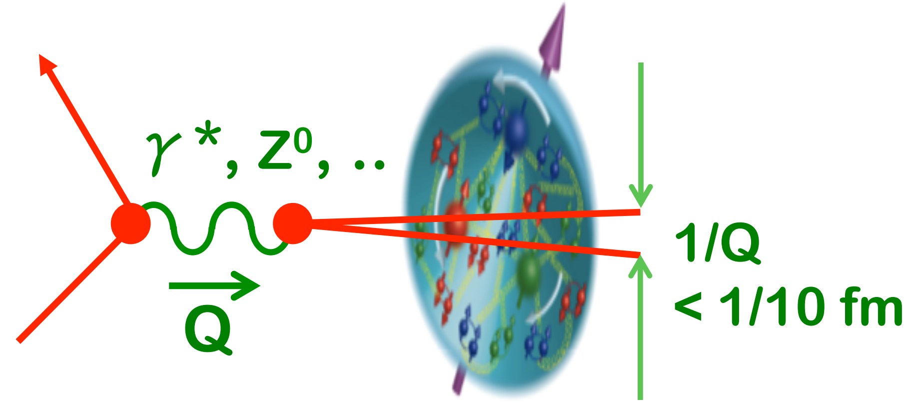
Without gluons, there would be NO nucleons, NO atomic nuclei… NO visible world!

See also A. Deshpande's talk

Electron-Ion Collider (EIC)

- A giant "Microscope" – "see" quarks and gluons by breaking the hadron





"see" the non-linear dynamics of the glue!

- A sharpest "CT" – "imagine" quark/gluon without breaking the hadron
  - "cat-scan" the nucleon and nuclei with better than 1/10 fm resolution
  - "see" the proton "radius" of gluon density

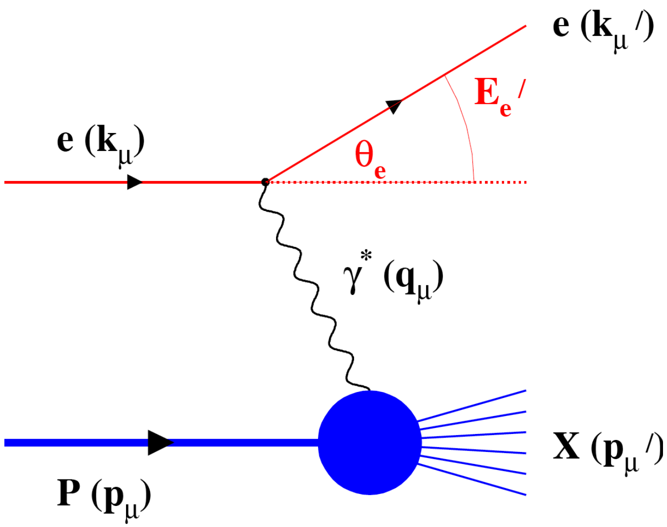
- Why now?

  Exp: advances in luminosity, energy reach, detection capability, …

  Thy: breakthrough in factorization – "see" confined quarks and gluons, …

Many complementary probes at one facility

- Lepton-hadron facility – "see" glue via quarks:



Q^2 → Measure of resolution

y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton

$Q^2 = S\, x\, y$

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

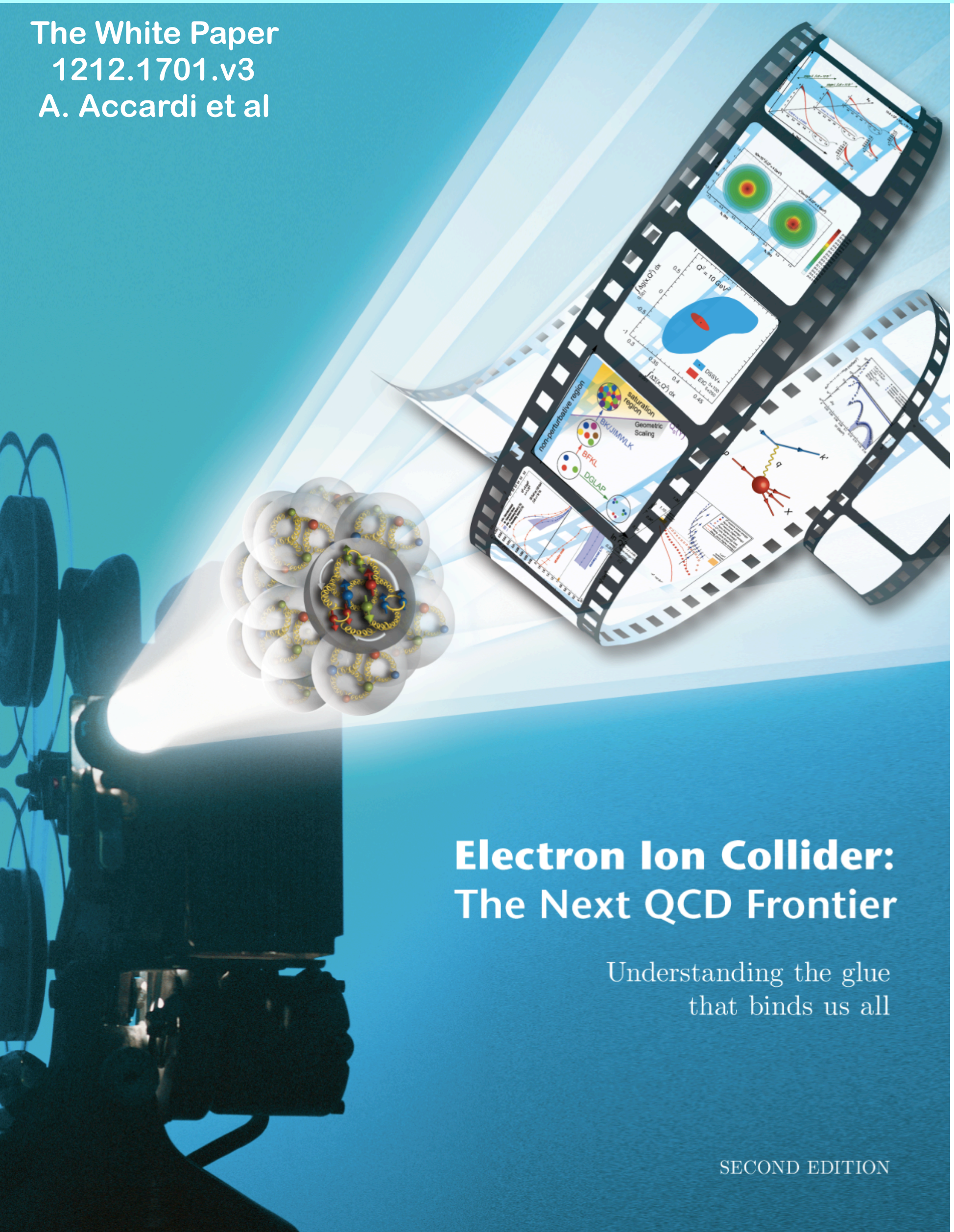
Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X

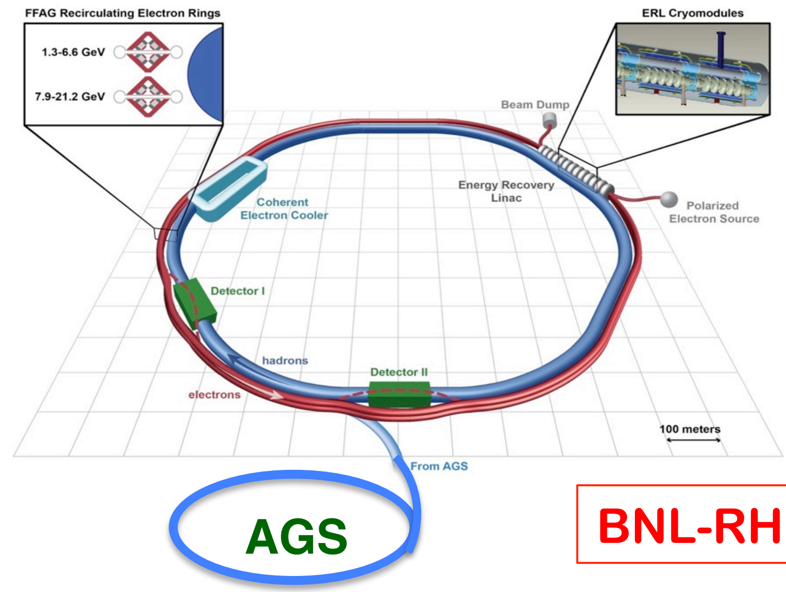
Detect the scattered lepton in coincidence with identified hadrons/jets

Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)

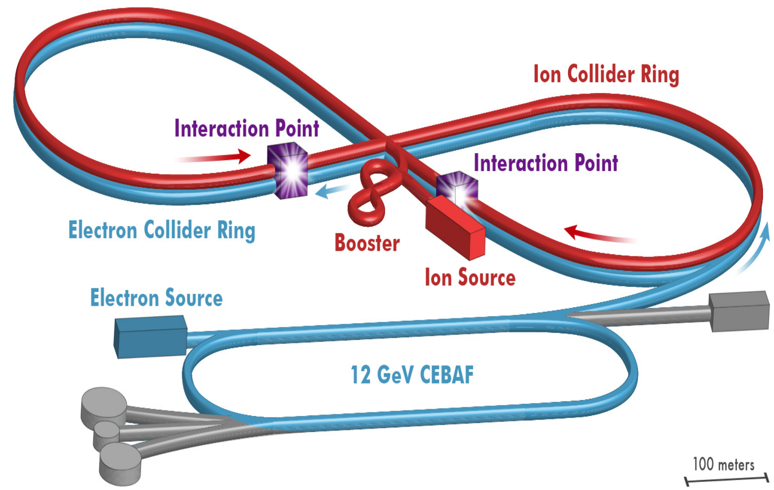
Detect every things including scattered proton/nucleus (or its fragments)

US EIC – two options of realization



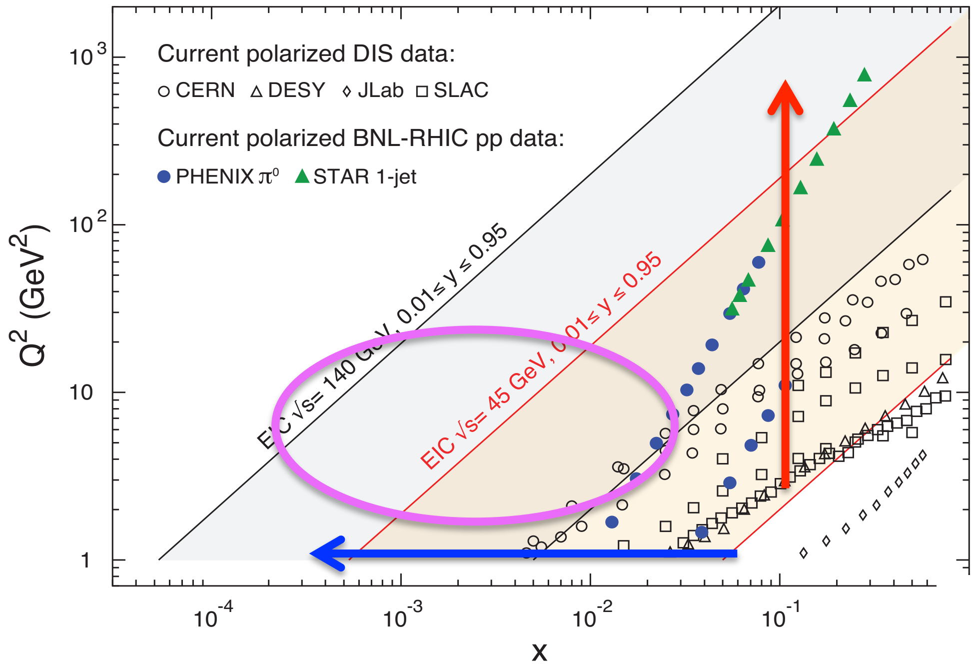


BNL-RHIC



JLab-CEBAF

US EIC – Kinematic reach & properties

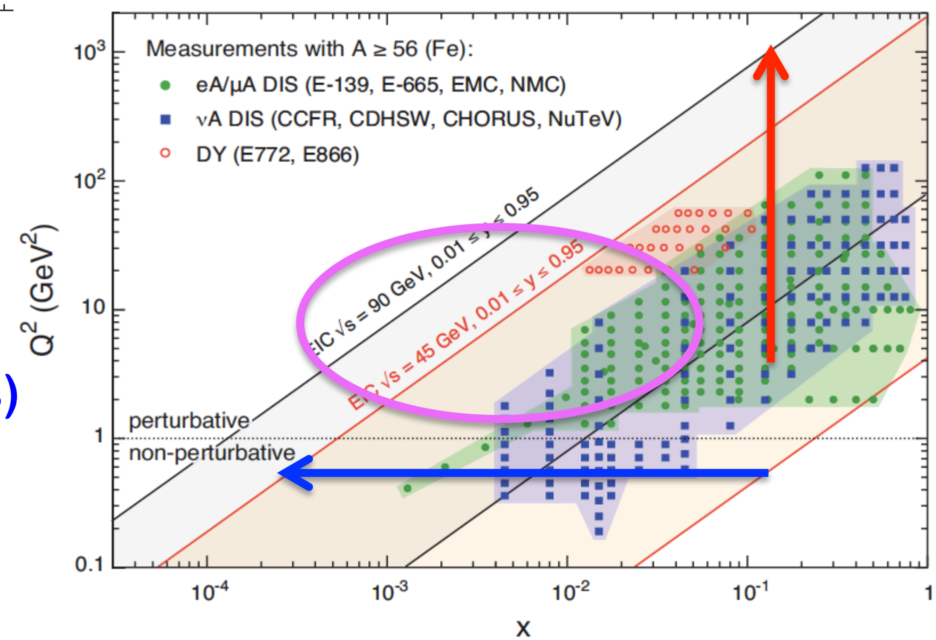


For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning from valence to low-x physics
- ✓ 100-1K times of HERA Luminosity

For e-A collisions at the EIC:

- ✓ Wide range in nuclei
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range (evolution)
- ✓ Wide x region (high gluon densities)



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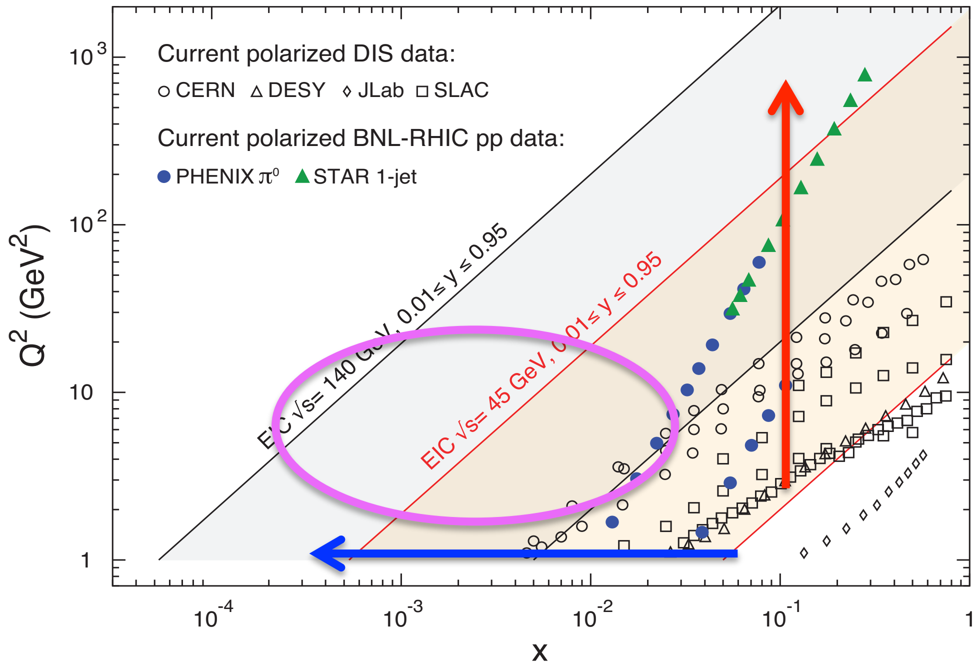

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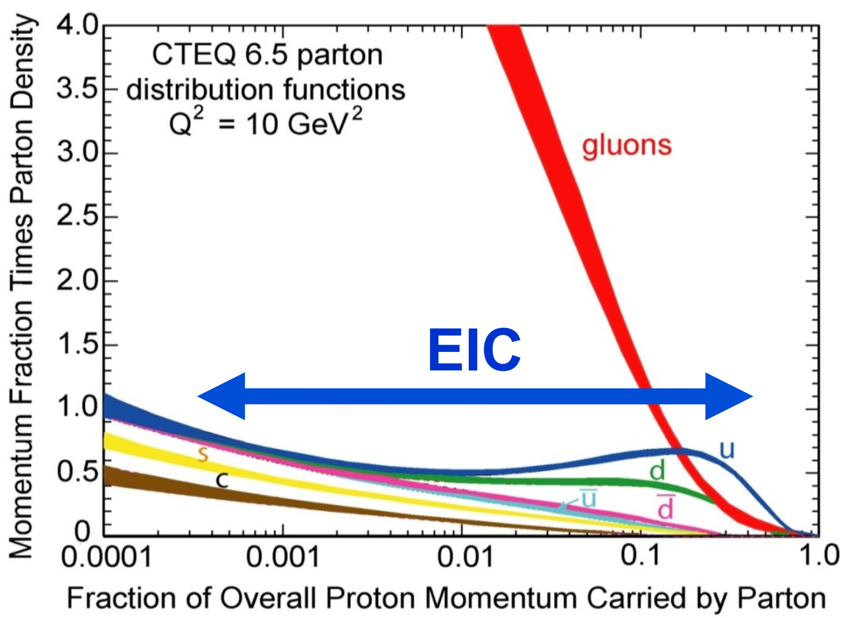


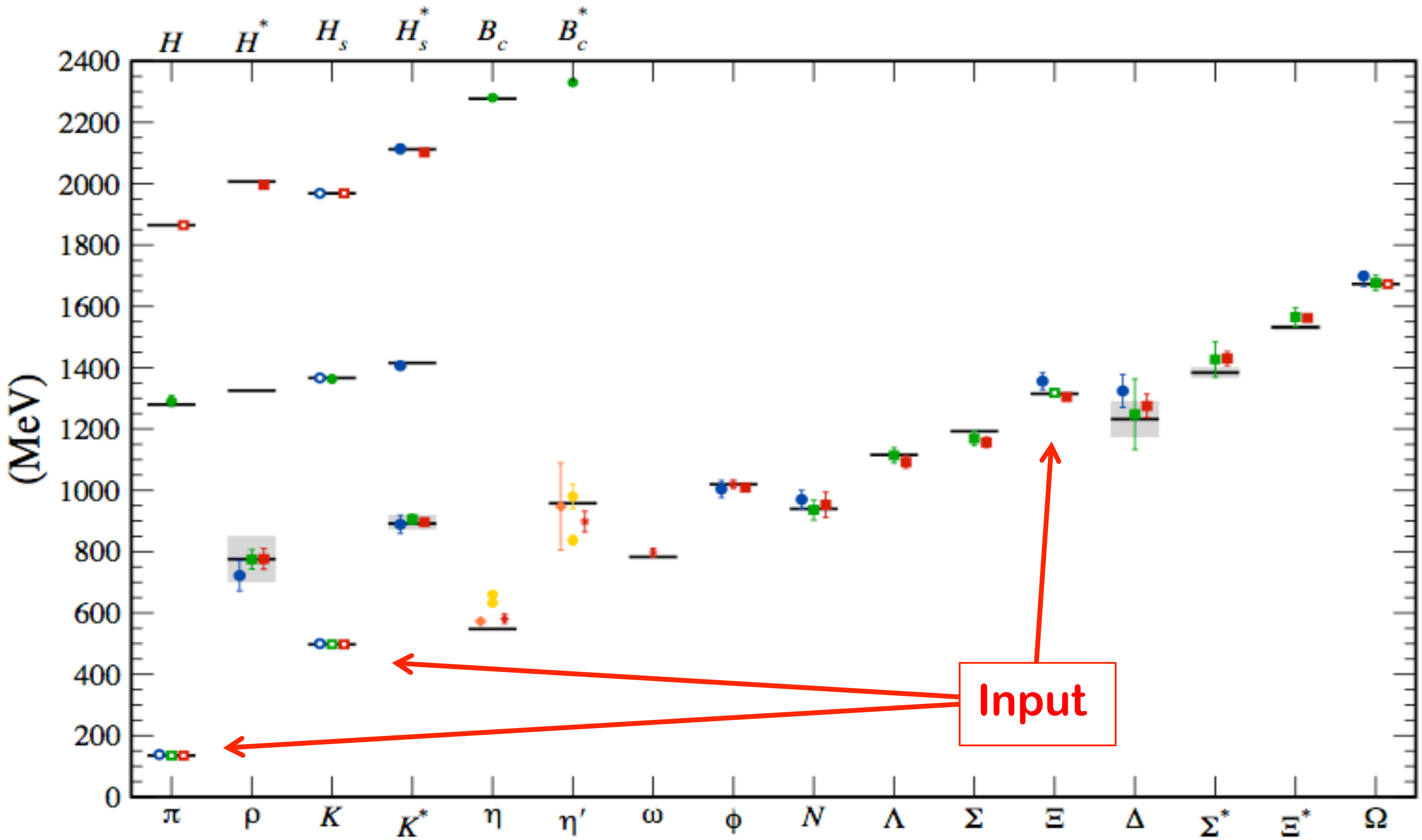
EIC explores the "sea" and the "glue", the "valence" with a huge level arm

The key deliverables & opportunities

Why existing facilities, even with upgrades, cannot do the same?

QCD and hadron properties: mass, spin, …

- Hadron mass from Lattice QCD calculation:



A major success of QCD – is the right theory for the Strong Interaction!

How does QCD generate this? The role of quarks vs that of gluons?

Mass vs. Spin

❑ Mass – intrinsic to a particle:

= Energy of the particle when it is at the rest

✧ QCD energy-momentum tensor in terms of quarks and gluons

$$T^{\mu\nu} = \frac{1}{2}\,\overline{\psi} i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi + \frac{1}{4}\,g^{\mu\nu}F^2 - F^{\mu\alpha}F^{\nu}{}_{\alpha}$$

✧ Proton mass:

$$m = \frac{\langle p|\int d^3x\, T^{00}\,|p\rangle}{\langle p|p\rangle} \sim \text{GeV}$$

p at rest

X. Ji, PRL (1995)

❑ Spin – intrinsic to a particle:

= Angular momentum of the particle when it is at the rest

✧ QCD angular momentum density in terms of energy-momentum tensor

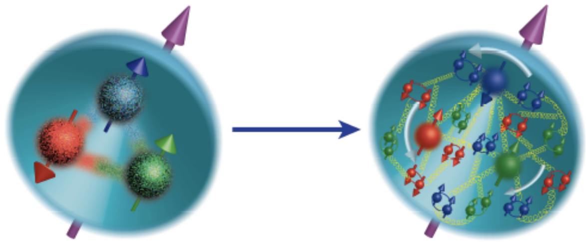
$$M^{\alpha\mu\nu} = T^{\alpha\nu}x^{\mu} - T^{\alpha\mu}x^{\nu} \qquad J^i = \frac{1}{2}\epsilon^{ijk}\int d^3x M^{0jk}$$

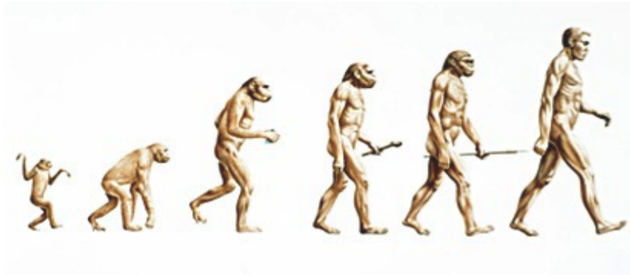
✧ Proton spin:

$$S(\mu) = \sum_f \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2}$$

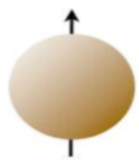
Proton spin

❑ **Proton's spin:**



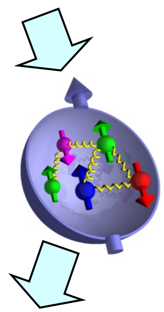


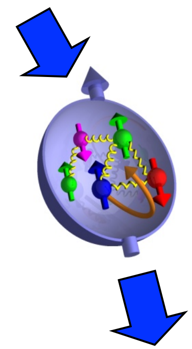
❑ **Current understanding:**



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Proton Spin





Quark helicity
Best known

$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

Spin "puzzle"

Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

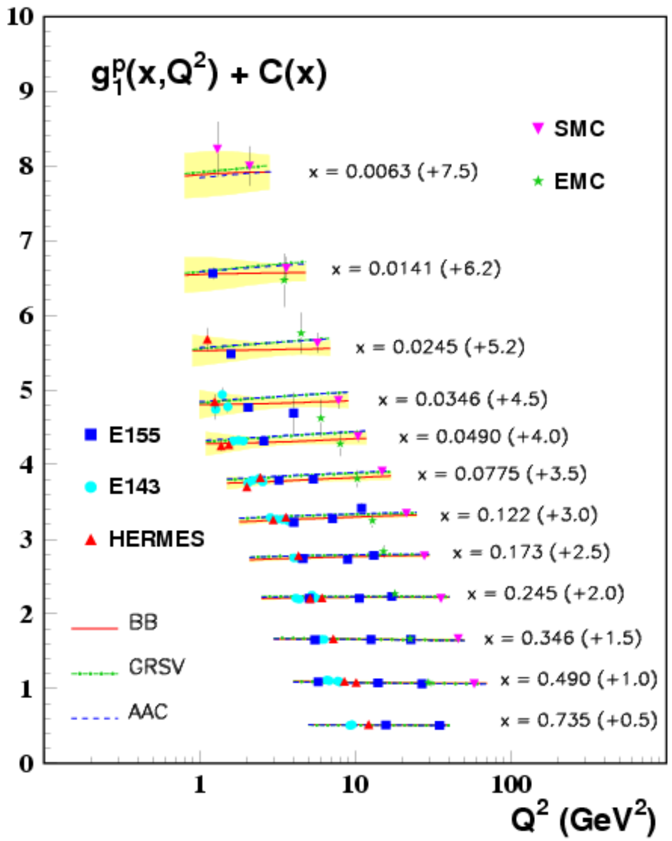
$$\sim 20\% (\text{with RHIC data})$$

Orbital Angular Momentum of quarks and gluons
Little known

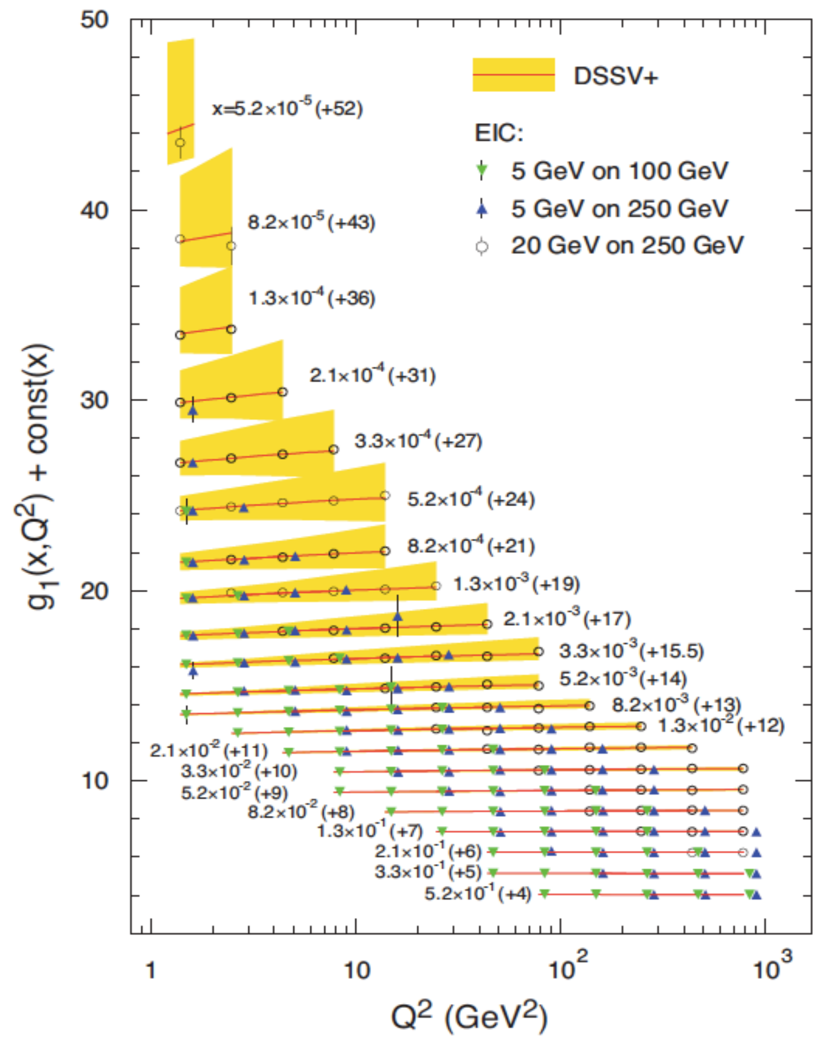
If we do not understand proton spin, we do not understand QCD

The power and precision of EIC

❑ Polarized x-section at EIC:



at EIC



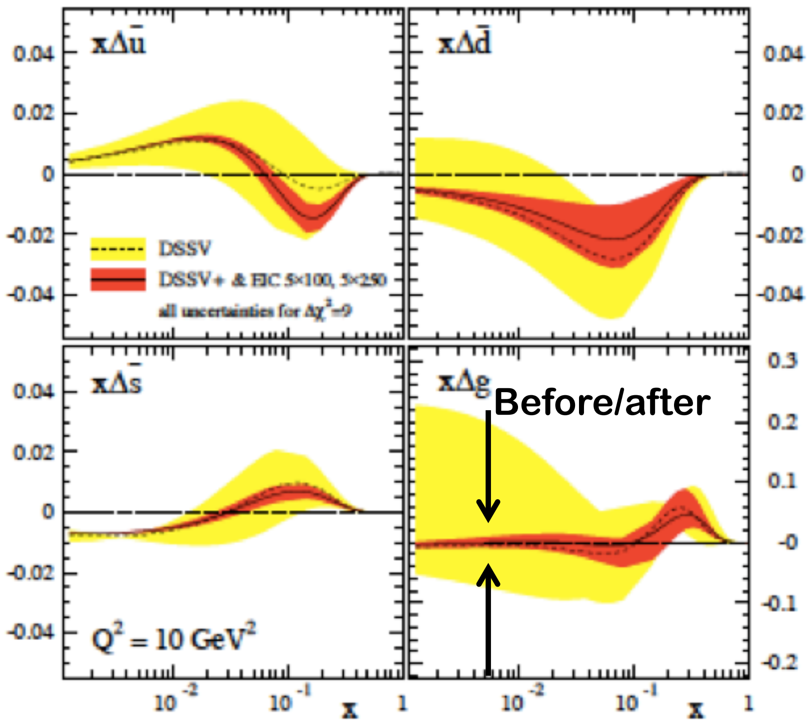
❑ Reach out the glue:

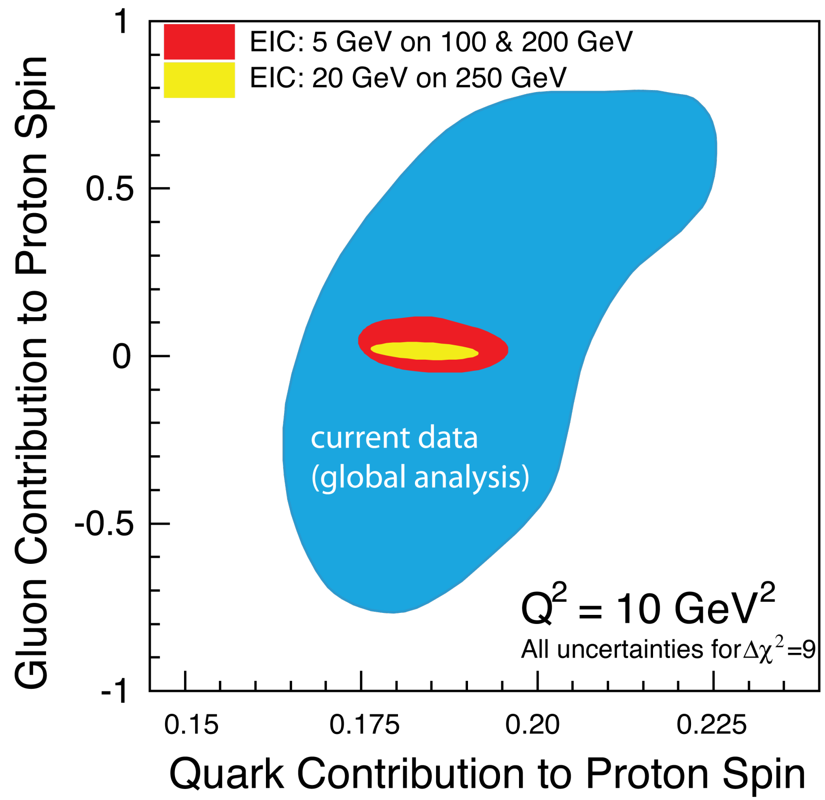
$$\frac{dg_1(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x,Q^2) + \cdots$$

Our understanding of proton spin

- **The decisive measurement (1st year of running at US EIC):**

(Low x and wide x range at EIC)





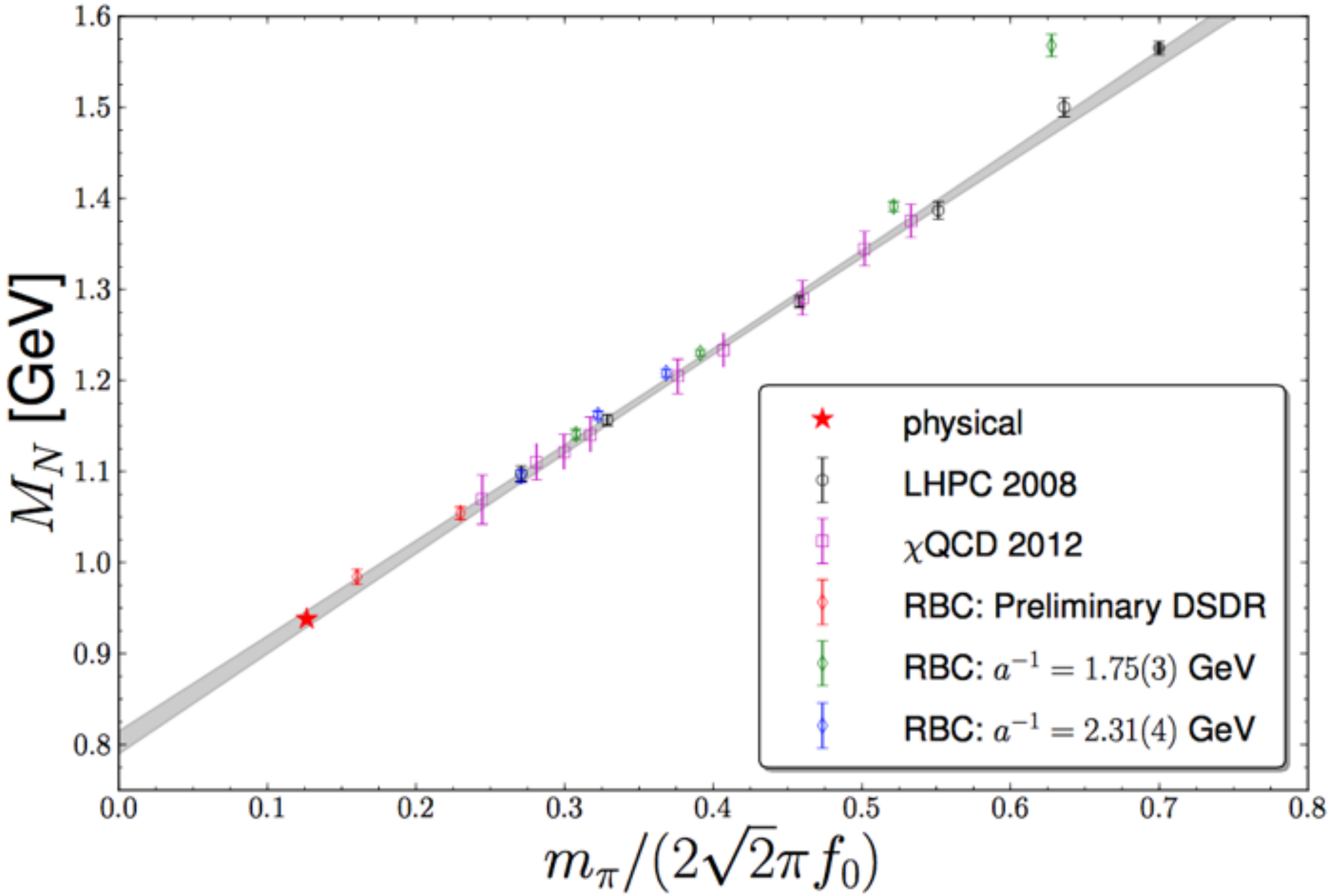
Precision in $\Delta\Sigma$ and Δg → A clear idea of the magnitude of L_Q+L_G

No other machine in the world can achieve this!

Nucleon mass

- ❑ **Lattice QCD calculation:**

Martin Savage (U of Washington
David Richards (Jlab)



$$M_N = 800\ \text{MeV} + m_\pi$$

Unexpected behavior !! Why?

Nucleon mass

- How do quarks and gluons contribute to the nucleon mass?
  - QCD energy-momentum tensor in terms of quarks and gluons

$$T^{\mu\nu} = \frac{1}{2}\,\overline{\psi}\, i\overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi + \frac{1}{4}\, g^{\mu\nu}F^2 - F^{\mu\alpha}F^{\nu}{}_{\alpha}$$

  - Its hadronic matrix element with zero momentum transfer:

$$\langle p|\, T^{\mu\nu}\, |p\rangle \propto p^\mu p^\nu \quad \Rightarrow \quad \langle p|\, T^{\mu\nu}\, |p\rangle (g_{\mu\nu}) \propto p^\mu p^\nu (g_{\mu\nu}) = m^2$$

  - Invariant hadron mass (in any frame):

$$m^2 \propto \langle p| T^{\alpha}{}_{\alpha}\, |p\rangle$$

with

$$T^{\alpha}_{\alpha} = \frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu} + \sum_{q=u,d,s} m_q (1+\gamma_m)\overline{\psi}_q \psi_q$$

QCD trace anomaly

$$\beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$$

➡ At the chiral limit, the entire mass is from gluons!

Kharzeev @ Temple workshop

  - Heavy quarkonium production near threshold at JLab12 & EIC

New opportunities and activities for EIC!

Meziani @ Temple workshop

Nucleon mass

Xiangdong Ji (Maryland)
Dima Kharzeev (Stony Brook
Keh-Fei Liu (Kentucky)

❑ Decomposition – sum rules:

✧ Hadron state:

$|P\rangle$ **With the normalization:** $\langle P|P\rangle = (E/M)(2\pi)^3\delta^3(\mathbf{0})$

✧ Hamiltonian:

$$\langle P|H|P\rangle = (E^2/M)(2\pi)^3\delta^3(\mathbf{0}) \qquad \text{with} \quad H_{\mathrm{QCD}} = \int d^3\vec{x}\, T^{00}(0,\vec{x})$$

✧ Hadron mass:

X. Ji, PRL (1995)

$$M = \frac{\langle P|H_{\mathrm{QCD}}|P\rangle}{\langle P|P\rangle}\Big|_{\text{rest frame}} \quad = H_q + H_m + H_g + H_a$$

Mass type	H_i	M_i	$m_s \to 0$ (MeV)	$m_s \to \infty$ (MeV)
Quark energy	$\psi^\dagger(-i\mathbf{D}\cdot\boldsymbol{\alpha})\psi$	$3(a-b)/4$	270	300
Quark mass	$\bar{\psi}m\psi$	b	160	110
Gluon energy	$\frac{1}{2}(\mathbf{E}^2+\mathbf{B}^2)$	$3(1-a)/4$	320	320
Trace anomaly	$\frac{9\alpha_s}{16\pi}(\mathbf{E}^2-\mathbf{B}^2)$	$(1-b)/4$	190	210

$$a(\mu^2) = \sum_f \int_0^1 x[q_f(x,\mu^2) + \bar{q}_f(x,\mu^2)]dx$$

$$bM = \langle P|m_u\bar{u}u + m_d\bar{d}d|P\rangle + \langle P|m_s\bar{s}s|P\rangle$$

Nucleon mass

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  $|P\rangle$ **With the normalization:** $\langle P|P\rangle = (E/M)(2\pi)^3\delta^3(0)$

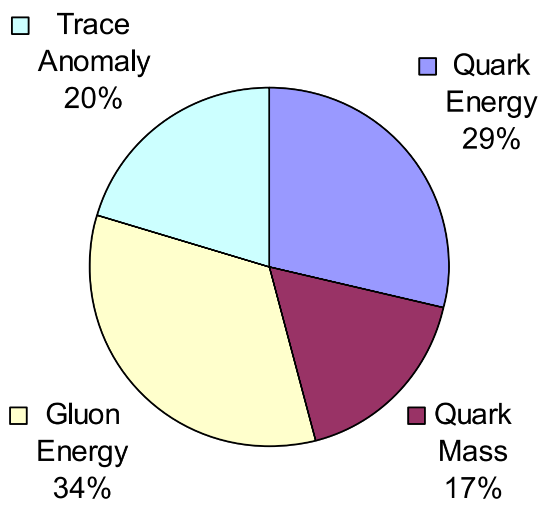
- ✧ **Hamiltonian:**

  $$\langle P|H|P\rangle = (E^2/M)(2\pi)^3\delta^3(0) \qquad \textbf{with} \qquad H_{\rm QCD} = \int d^3\vec{x}\, T^{00}(0,\vec{x})$$

- ✧ **Hadron mass:**

X. Ji, PRL (1995)

$$M = \frac{\langle P|H_{\rm QCD}|P\rangle}{\langle P|P\rangle}\Big|_{\rm rest\ frame} = H_q + H_m + H_g + H_a$$



Update on lattice effort K.-F. Liu

New opportunities and activities for EIC!

Boosted 3D nucleon structure

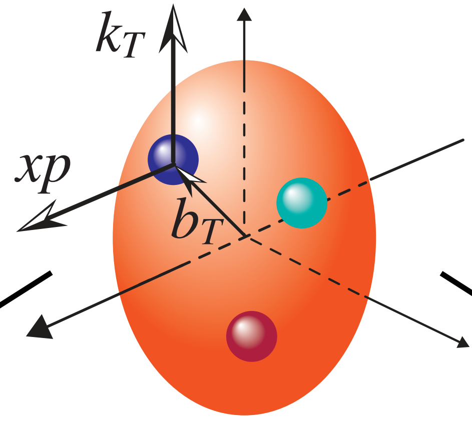
- High energy probes "see" the boosted partonic structure:

Momentum Space

TMDs

Confined motion

$\int d^2 b_T$



$\int d^2 k_T$

Coordinate Space

GPDs

Spatial distribution

$f(x,k_T)$ **Two-scales observables** $f(x,b_T)$

3D momentum space images

2+1D coordinate space images

- Need x-sections with two-momentum scales observed:

$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\mathrm{QCD}}$$

✧ Hard scale: Q_1 localizes the probe to see the quark or gluon d.o.f.

✧ "Soft" scale: Q_2 could be more sensitive to hadron structure, e.g., confined motion

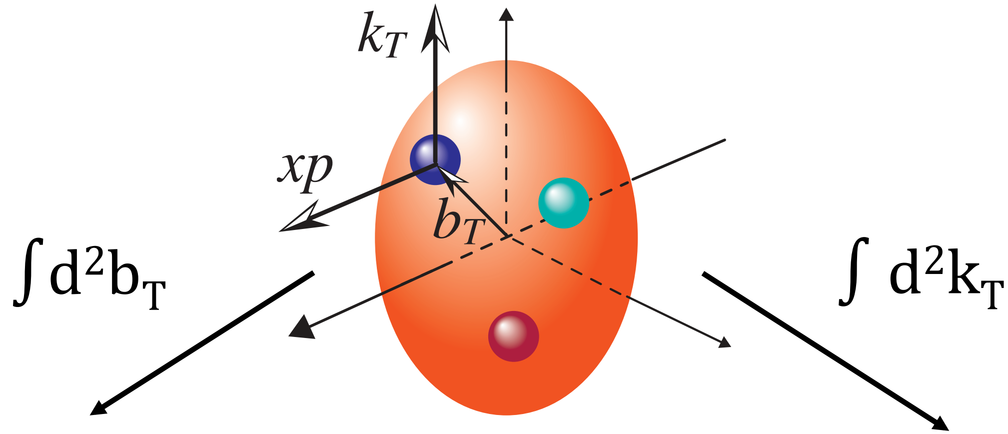
Boosted 3D nucleon structure

❑ **High energy probes "see" the boosted partonic structure:**

Momentum Space

TMDs

Confined motion



Coordinate Space

GPDs

Spatial distribution

$f(x,k_T)$ **Two-scales observables** $f(x,b_T)$

3D momentum space images

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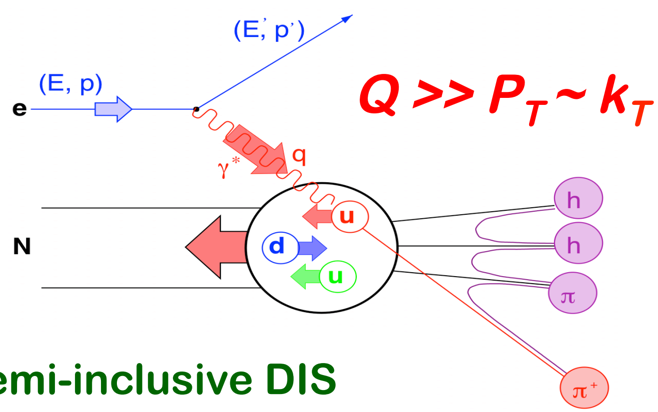
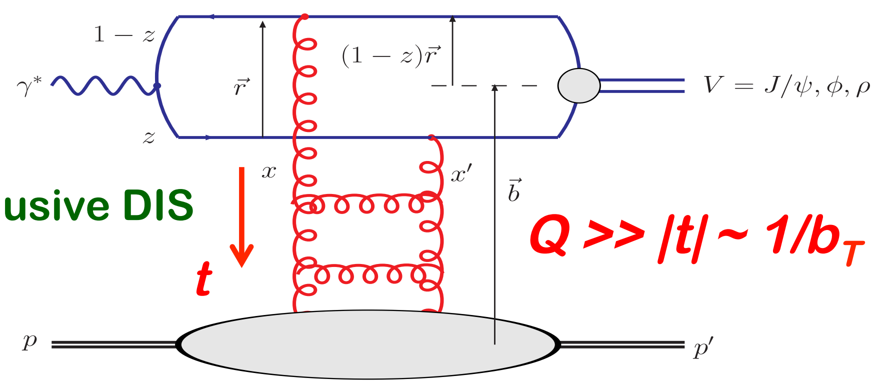


Semi-inclusive DIS



Exclusive DIS

JLab12 – valence quarks, EIC – sea quarks and gluons

Boosted 3D nucleon structure

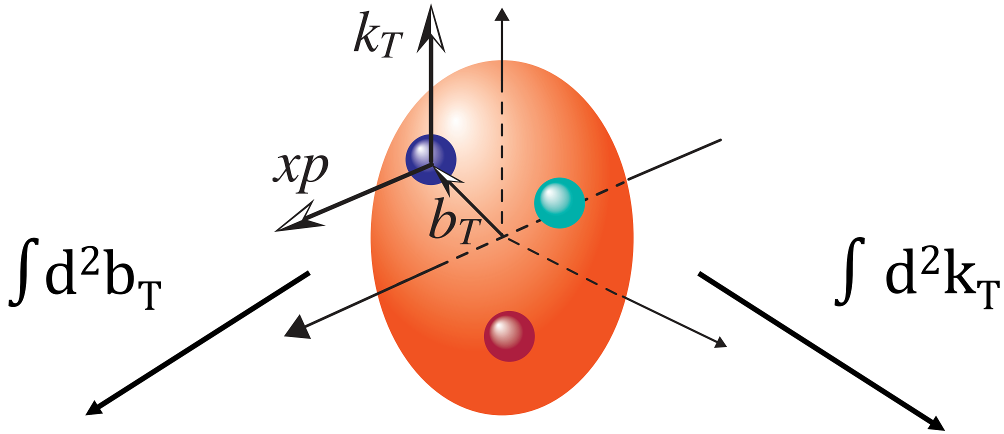
- High energy probes "see" the boosted partonic structure:

Momentum Space

TMDs

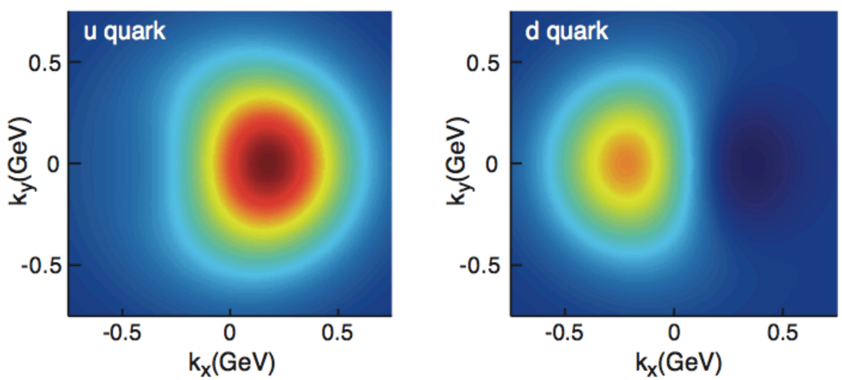
Coordinate Space

GPDs



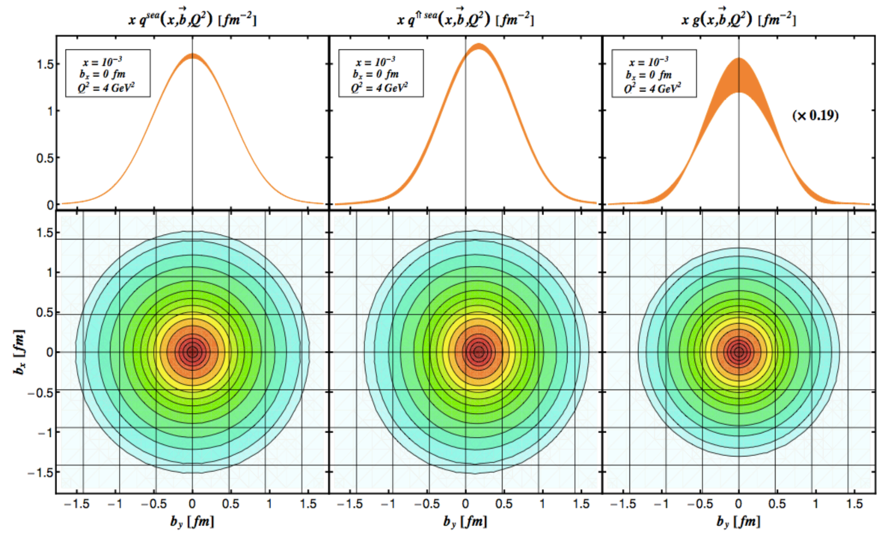
$f(x,k_T)$ **EIC white paper: arXiv:1212.1701** $f(x,b_T)$

Sivers Function



Density distribution of an unpolarized quark in a proton moving in z direction and polarized in y-direction

Imaging



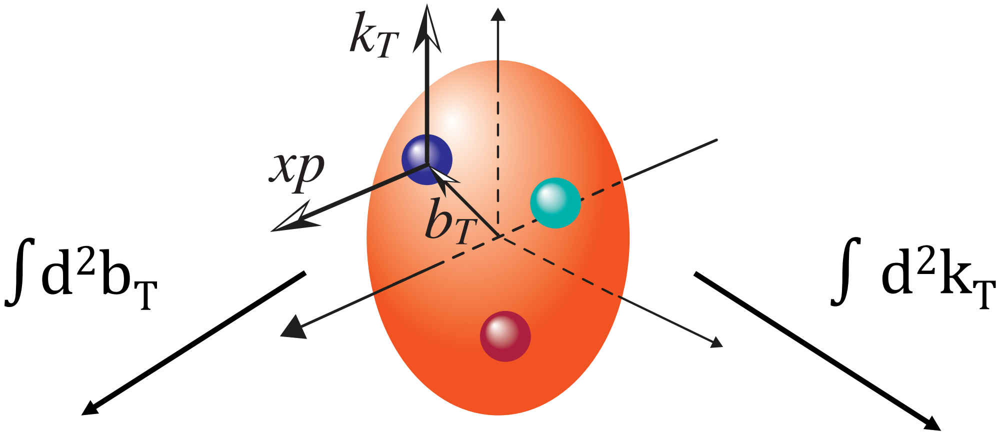
Spatial density distributions – "radius"

Boosted 3D nucleon structure

- High energy probes "see" the boosted partonic structure:

Momentum Space

TMDs

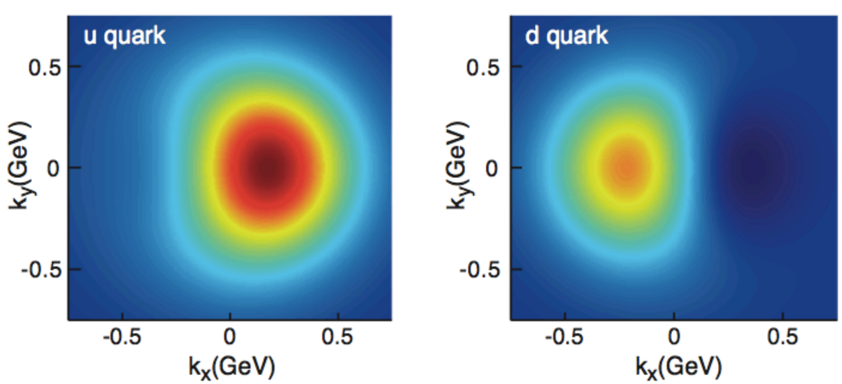


Coordinate Space

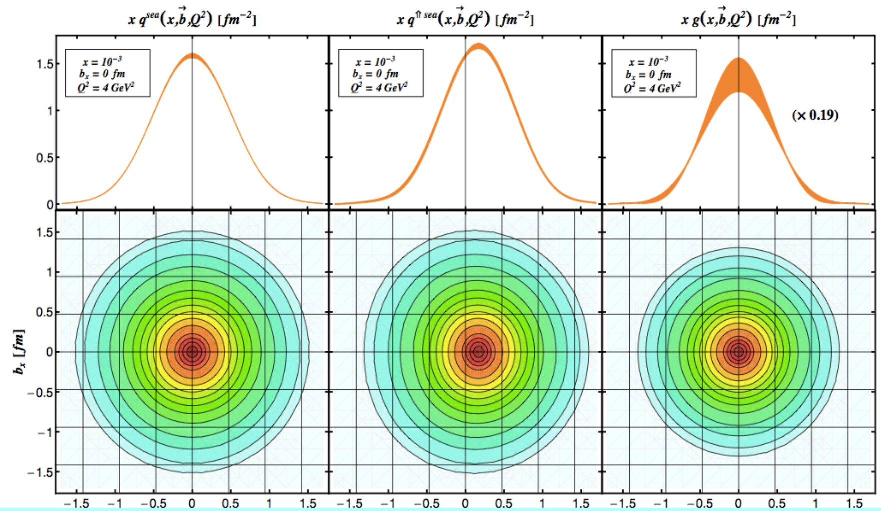
GPDs

$f(x,k_T)$ EIC white paper: arXiv:1212.1701 $f(x,b_T)$

Sivers Function



Imaging



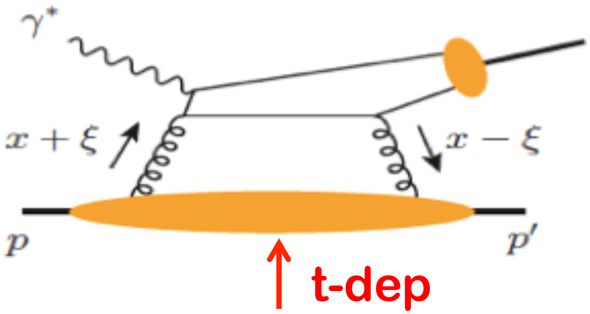
Position r x Momentum p → Orbital Motion of Partons

Spatial distribution of gluons

❑ **Exclusive vector meson production:**

$$\frac{d\sigma}{dx_B dQ^2 dt}$$

EIC-WhitePaper



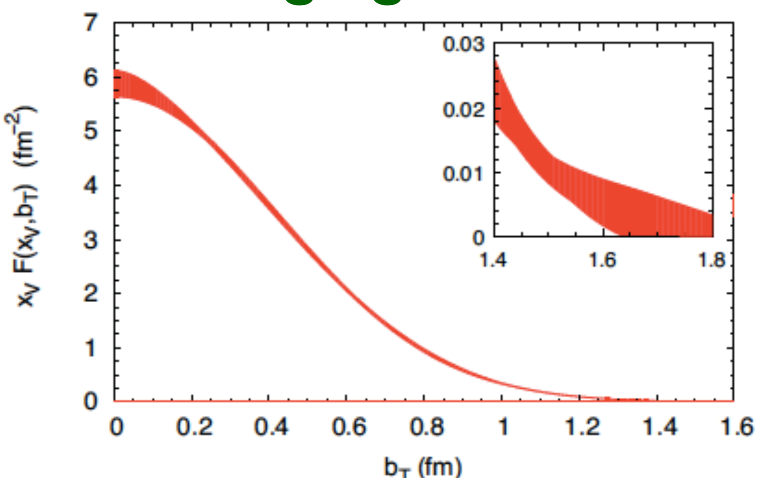
J/Ψ, Φ, …

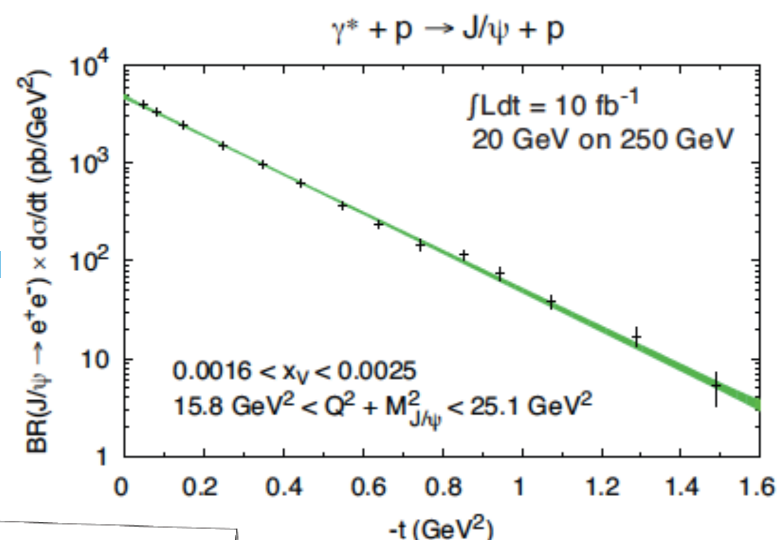
✧ Fourier transform of the t-dep

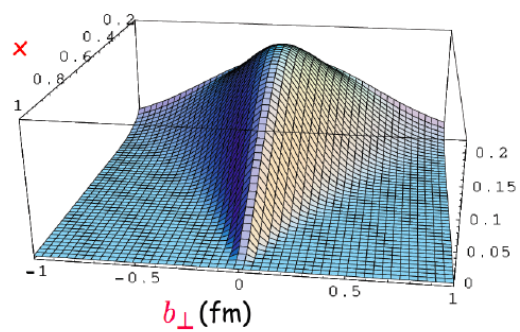
➡ Spatial imaging of glue density

✧ Resolution ~ 1/Q or $1/M_Q$

❑ **Gluon imaging from simulation:**







Only possible at the EIC

Proton radius of gluon density

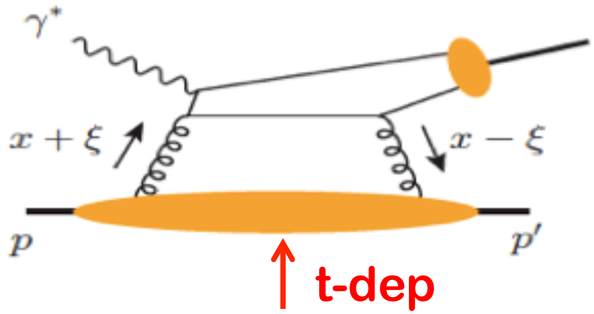
"Gluon radius (x)"

Why the "radius" is very interesting?

Spatial distribution of gluons

❑ **Exclusive vector meson production:**

$$\frac{d\sigma}{dx_B dQ^2 dt}$$ EIC-WhitePaper



J/Ψ , Φ, …

✧ Fourier transform of the t-dep

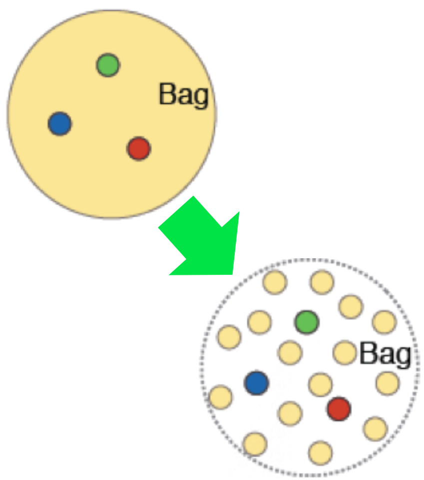
➡ Spatial imaging of glue density

✧ Resolution ~ 1/Q or 1/M_Q

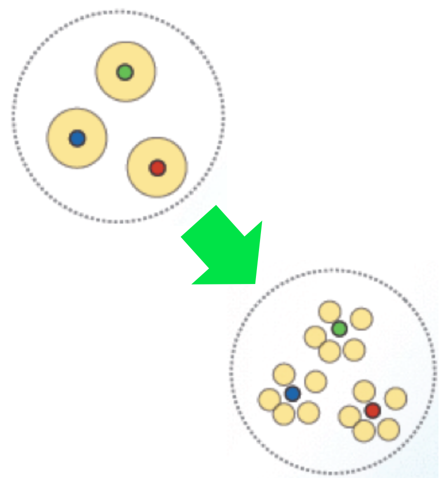
❑ **What does the proton look like?**

Static:

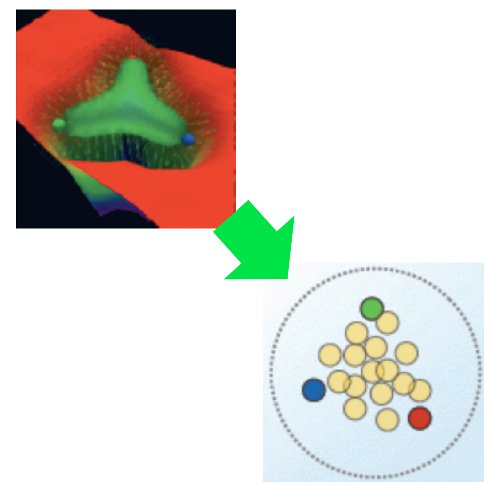
Hard probe:



Bag Model



Quark Model

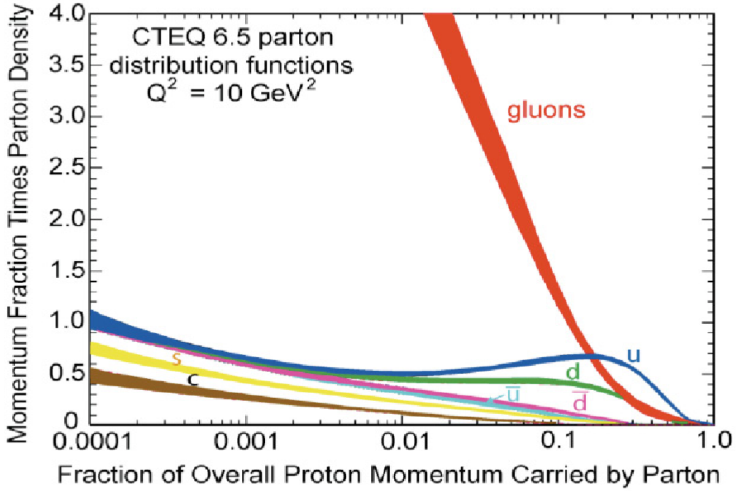


Lattice

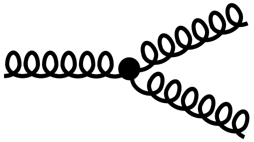
Proton "radius" of gluon density is extremely sensitive to the color confinement mechanism, in particular, its "x"-dependence !

Run away gluon density at small x?

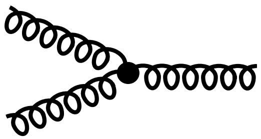
❑ HERA discovery:



What causes the low-x rise?
gluon radiation
– non-linear gluon interaction



What tames the low-x rise?
gluon recombination
– non-linear gluon interaction



❑ QCD vs. QED:

QCD – gluon in a proton:

$$Q^2 \frac{d}{dQ^2} xG(x,Q^2) \approx \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dx'}{x'} x' G(x',Q^2)$$

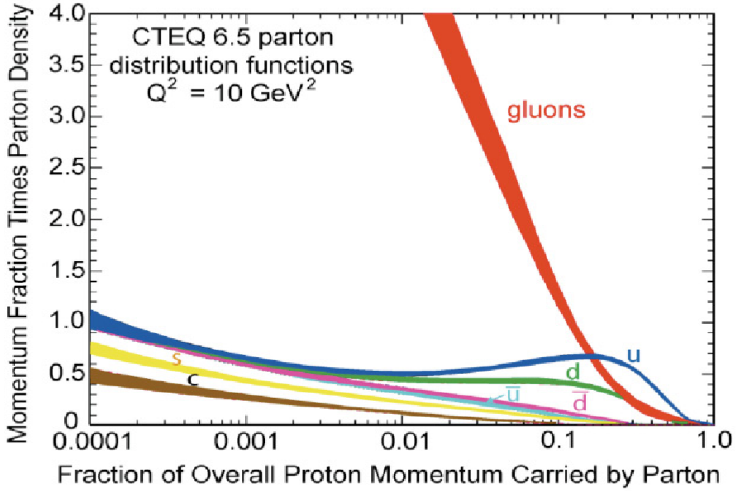
QED – photon in a positronium:

$$Q^2 \frac{d}{dQ^2} x\phi_\gamma(x,Q^2) \approx \frac{\alpha_{em}}{\pi} \left[-\frac{2}{3} x\phi_\gamma(x,Q^2) + \int_x^1 \frac{dx'}{x'} x' [\phi_{e^+}(x',Q^2) + \phi_{e^-}(x',Q^2)] \right]$$

- ✧ At very small-x, proton is **"black"**, positronium is still **transparent!**
- ✧ Recombination of large numbers of glue could lead to **saturation phenomena**
- ✧ Universal property of QCD!

Run away gluon density at small x?

❑ HERA discovery:



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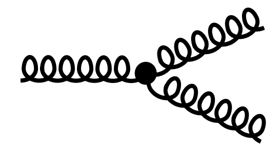

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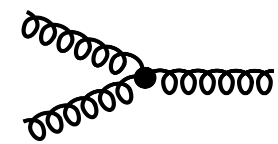
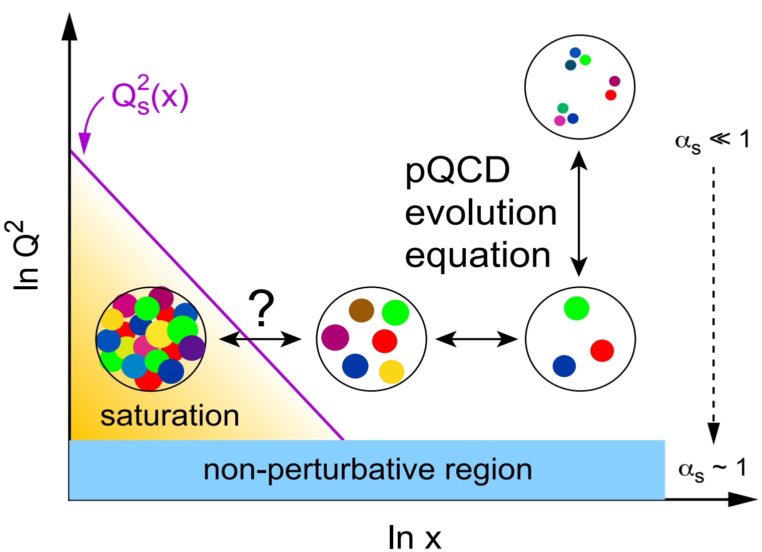
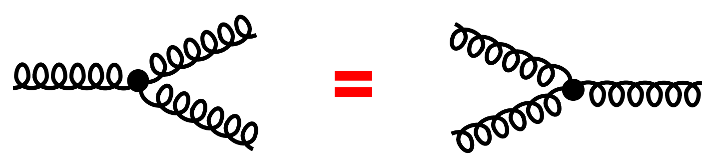


❑ Particle vs. wave feature:



Gluon saturation – Color Glass Condensate

Radiation = Recombination



at Q_s

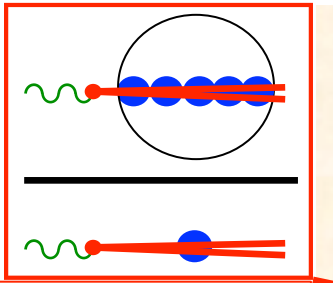
Leading to a collective gluonic system?

with a universal property?

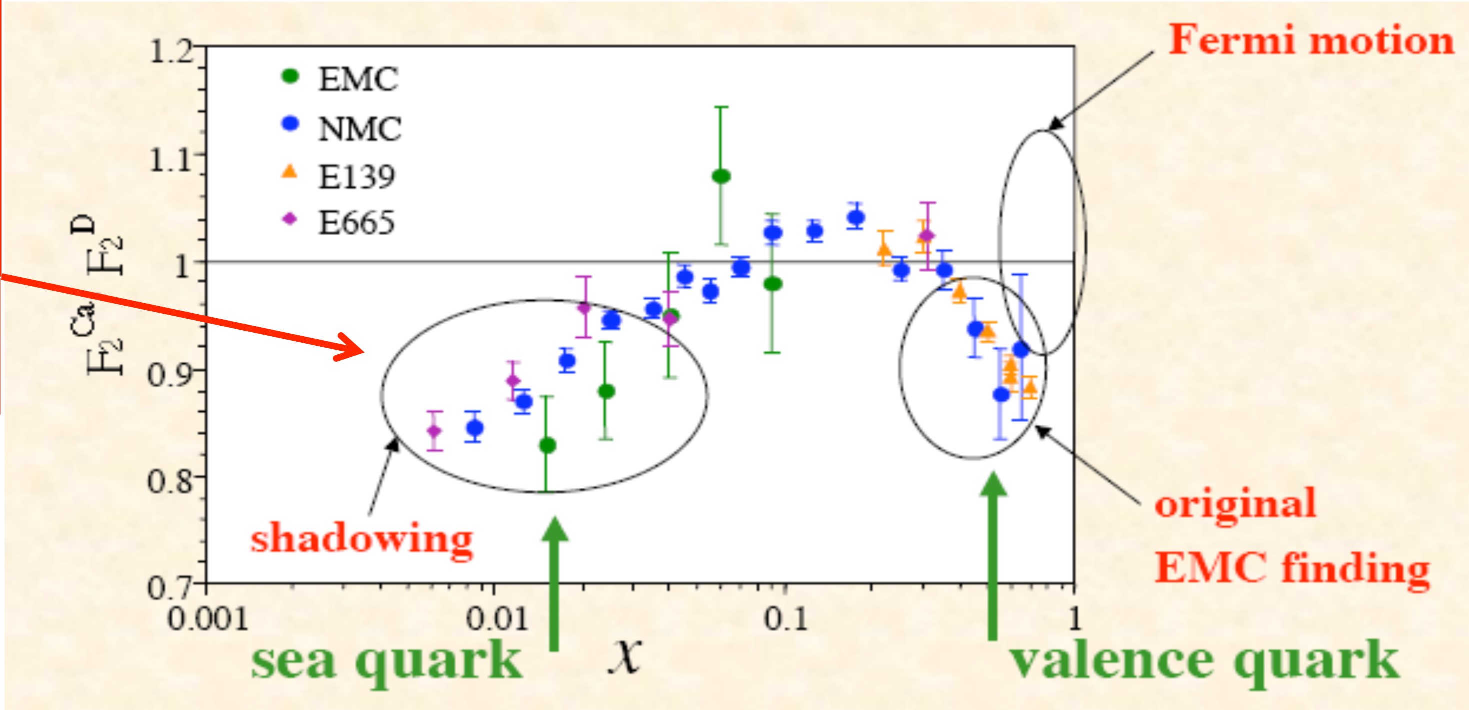
new effective theory QCD – CGC?

An "easiest" measurement at EIC

❑ Ratio of F_2: EMC effect, Shadowing and Saturation:



Color localized inside nucleons



An “easiest” measurement at EIC

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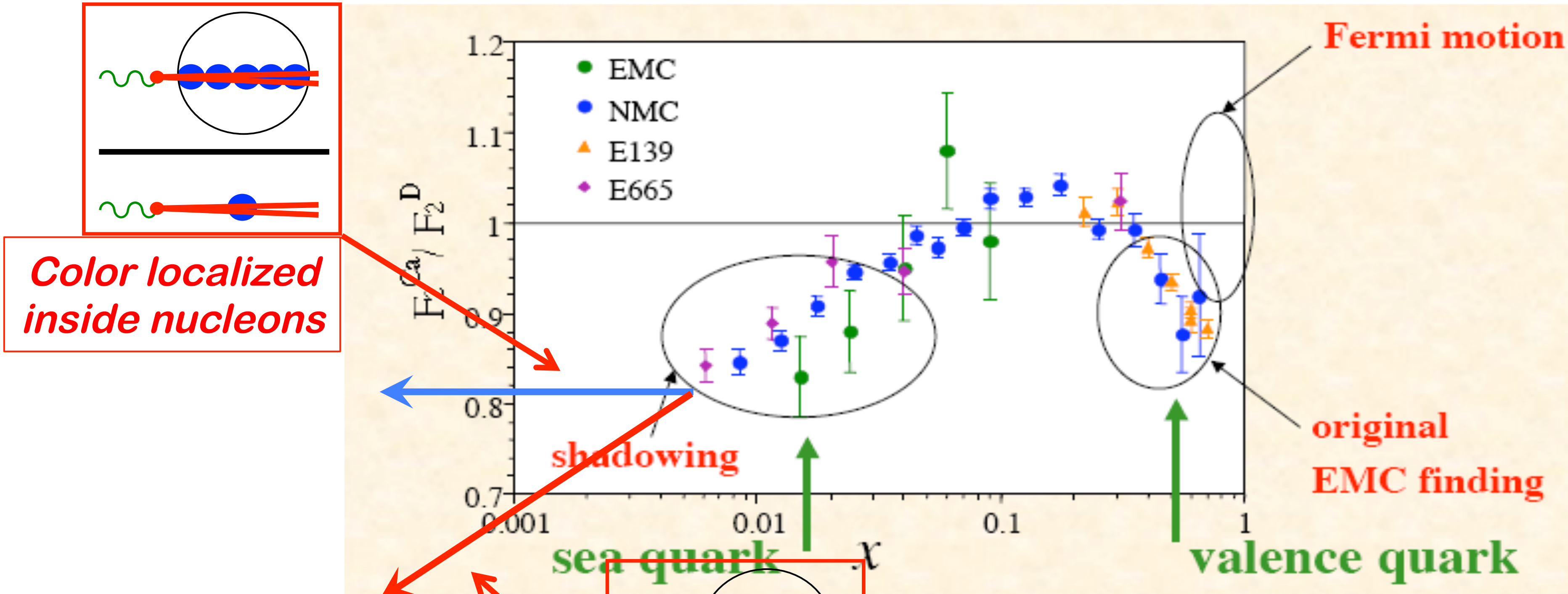


- Questions:

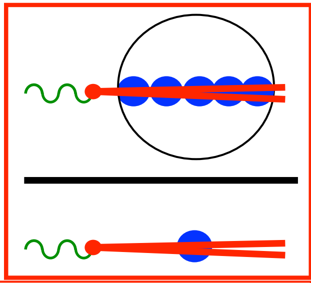
Will the suppression/shadowing continue fall as x decreases?

Could nucleus behaves as a large proton at small-x?

Range of color correlation – could impact the center of neutron stars!

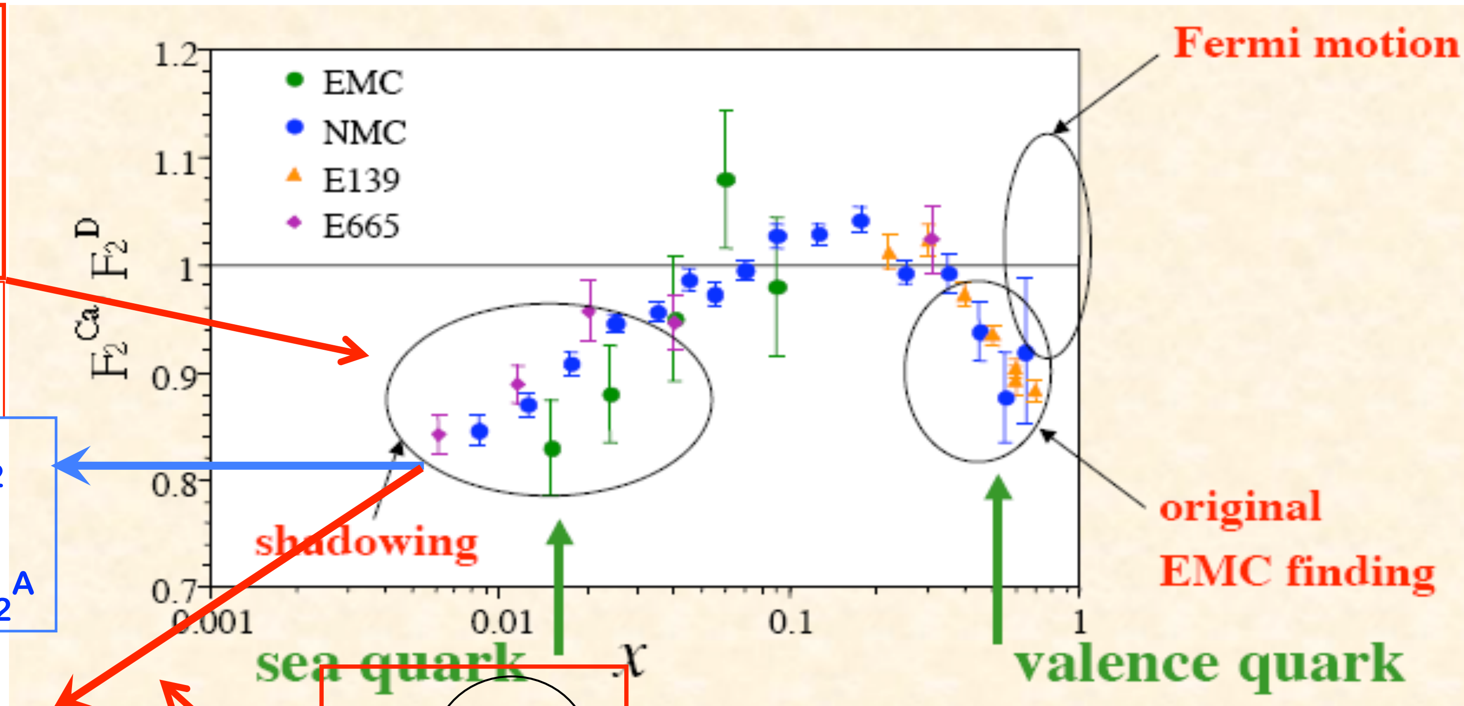
An "easiest" measurement at EIC

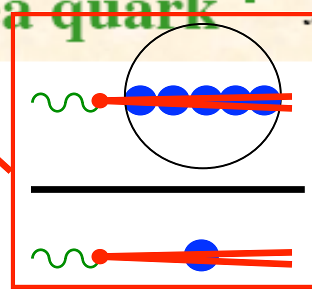
- Ratio of F_2: EMC effect, Shadowing and Saturation:



Color localized inside nucleons

Saturation in RF_2
=
No saturation in F_2^A





Color leaks outside nucleons

- Questions:

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An “easiest” measurement at EIC

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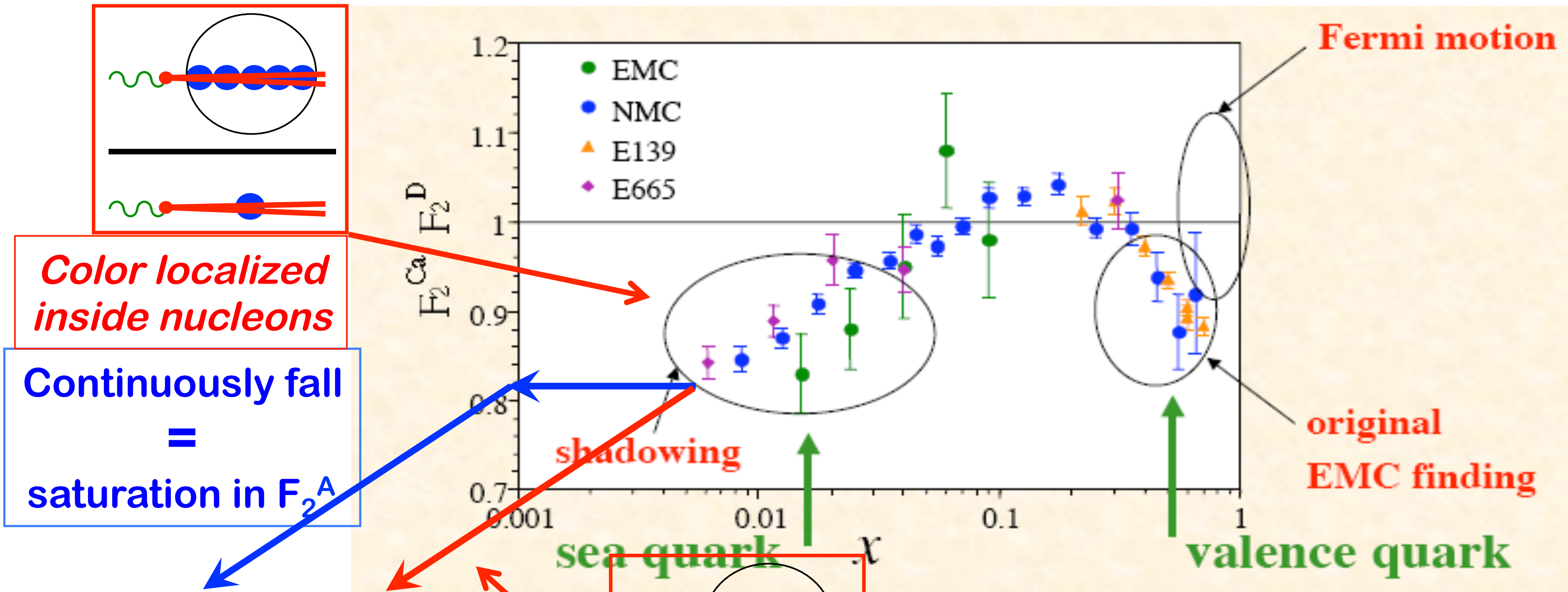

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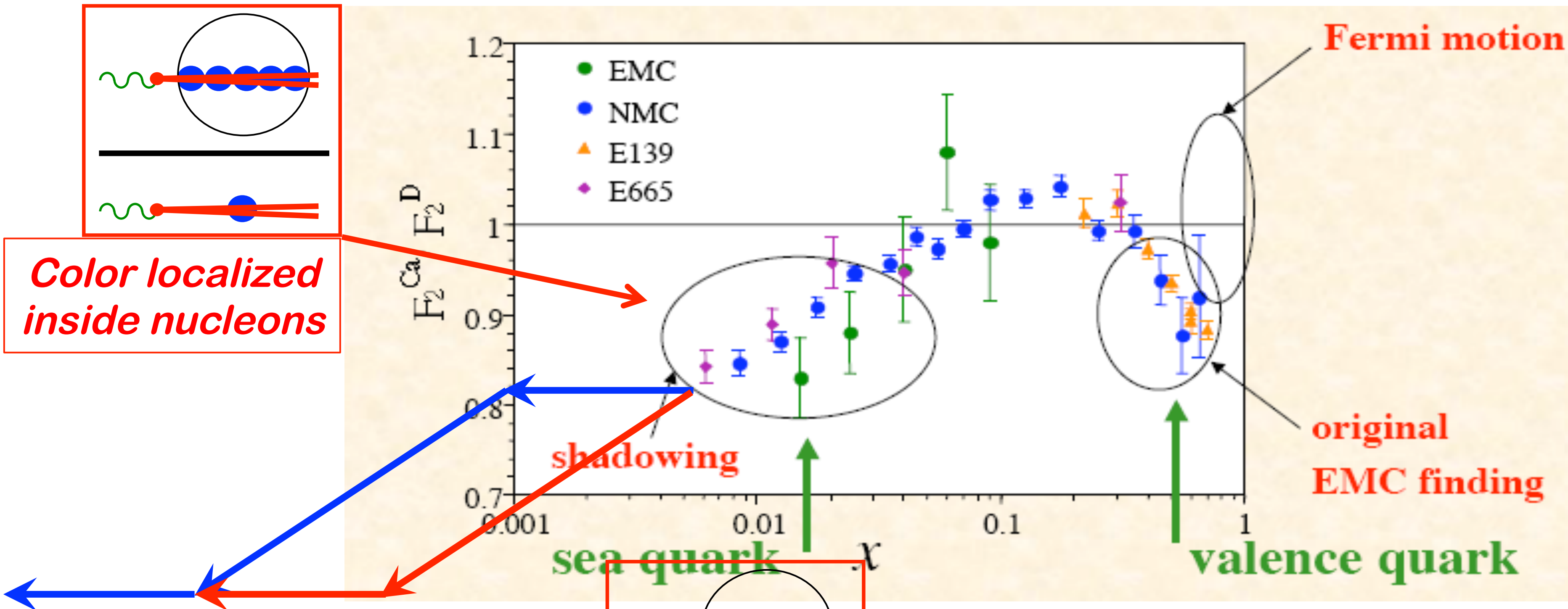
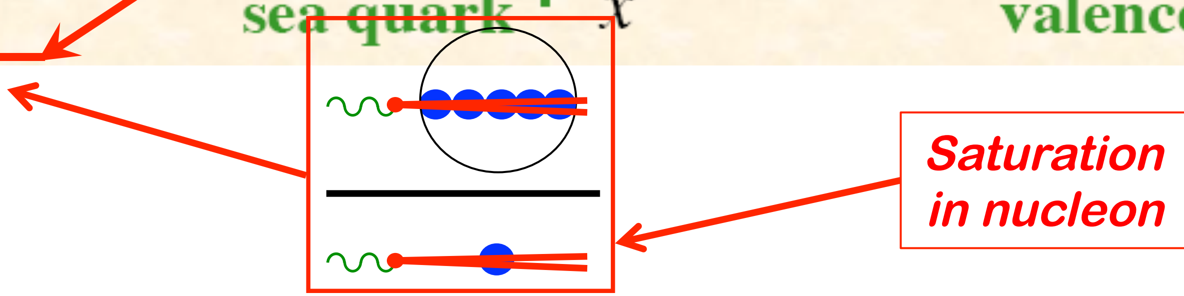




❑ Questions:

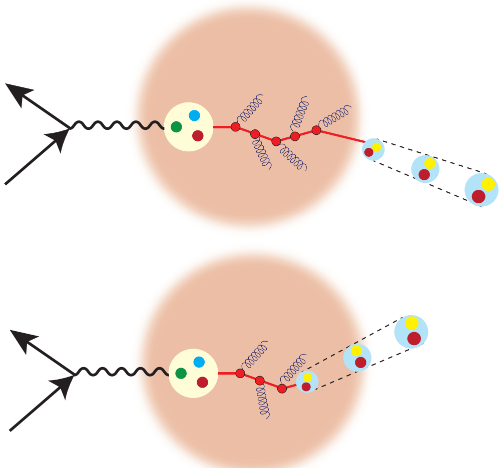
Will the suppression/shadowing continue fall as x decreases?

Could nucleus behaves as a large proton at small-x?

Range of color correlation – could impact the center of neutron stars!

Emergence of hadron at EIC

❑ Fermi-side detectors – nuclei:

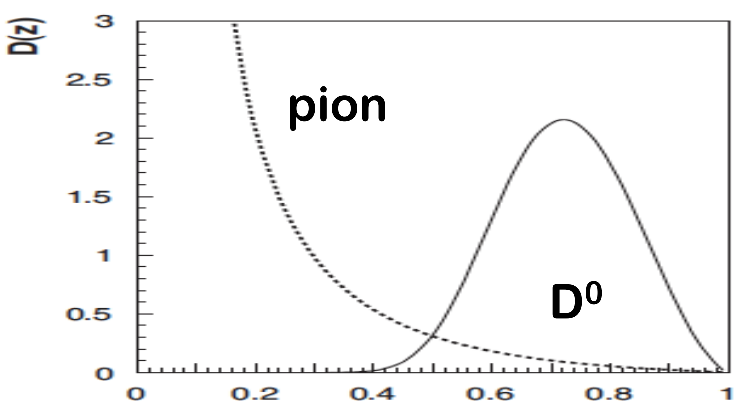


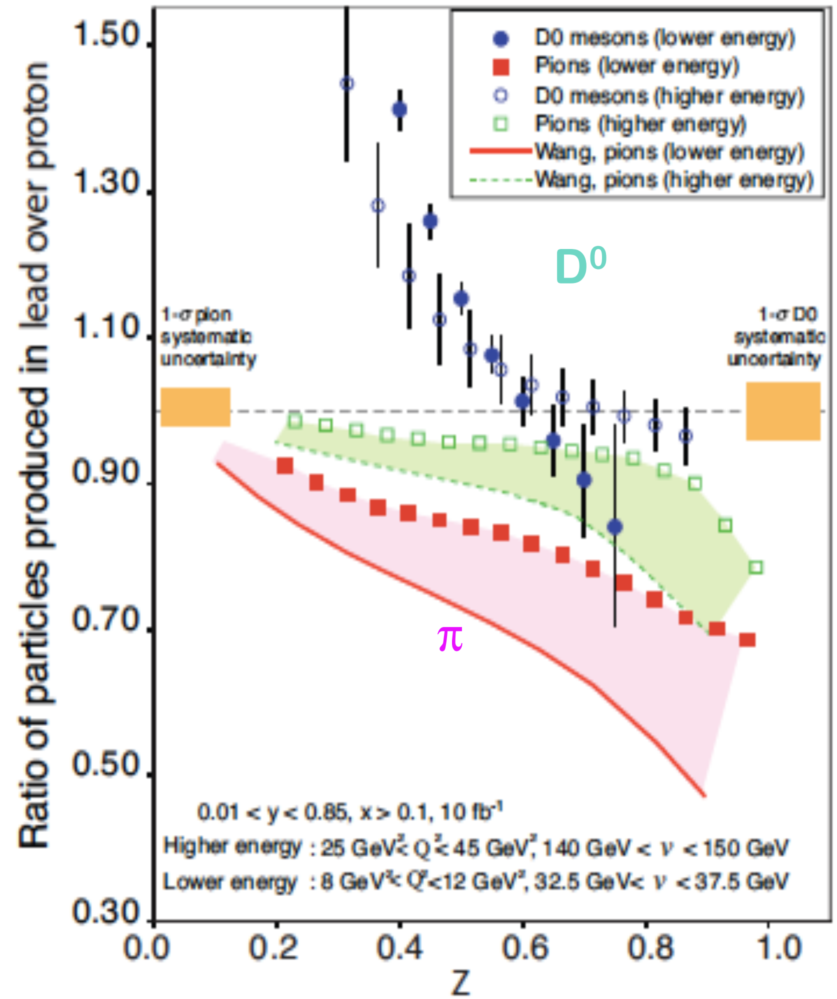
$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

❑ Heavy quark energy loss:

– Mass dependence of fragmentation



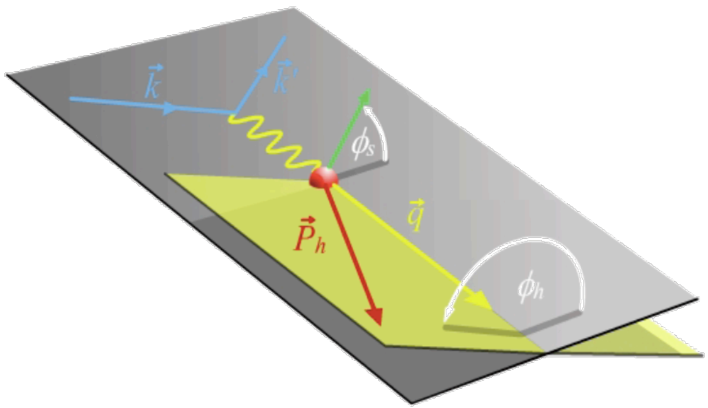


Need the collider energy of EIC and its control on parton kinematics

Color fluctuation – azimuthal asymmetry at EIC

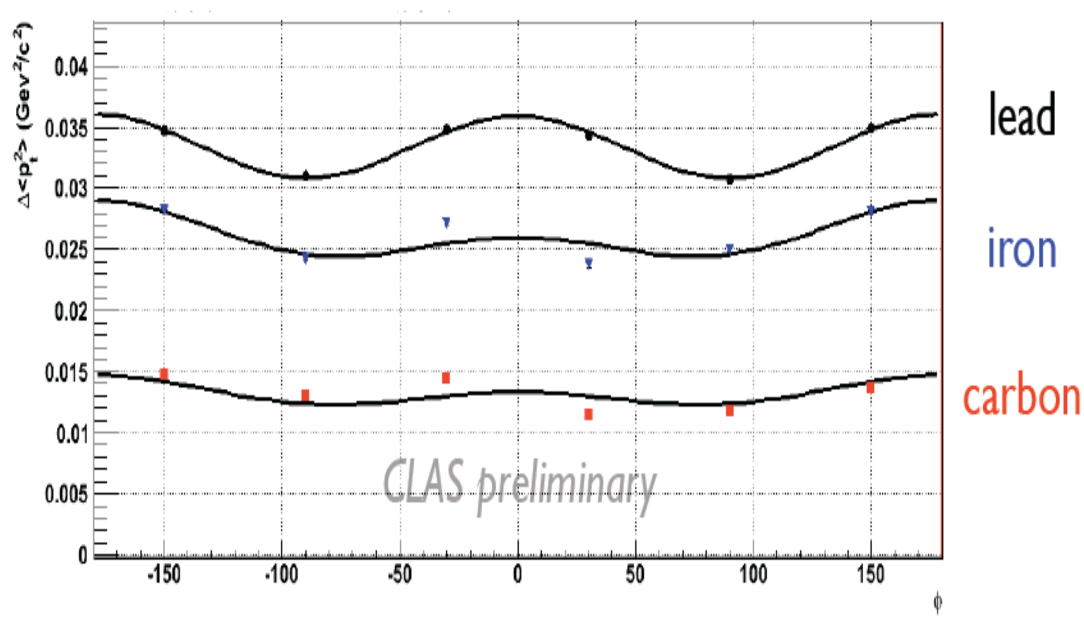
Hicks, KEK-JPAC2013

❑ Preliminary low energy data:



$$\langle p_T^2(\phi_{pq})\rangle_A = \int dp_T^2\, p_T^2 \frac{d\sigma_{eA}}{dx_B dQ^2 dp_T^2 d\phi} \Big/ \frac{d\sigma_{eA}}{dx_B dQ^2}$$

$$\langle \Delta p_T^2(\phi)\rangle_{AN} \equiv \langle p_T^2(\phi)\rangle_A - \langle p_T^2(\phi)\rangle_N$$



Contain terms in cos(ϕ_{pq}) and cos(2ϕ_{pq})
only statistical uncertainties shown

❑ Classical expectation:

Any distribution seen in Carbon should be washed out in heavier nuclei

❑ Surprise:

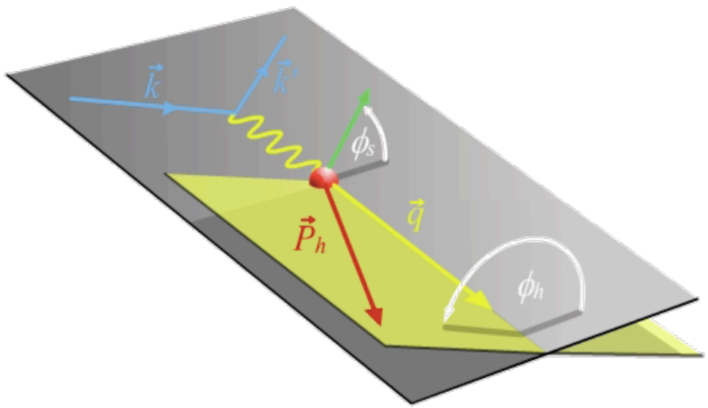
Azimuthal asymmetry in transverse momentum broadening

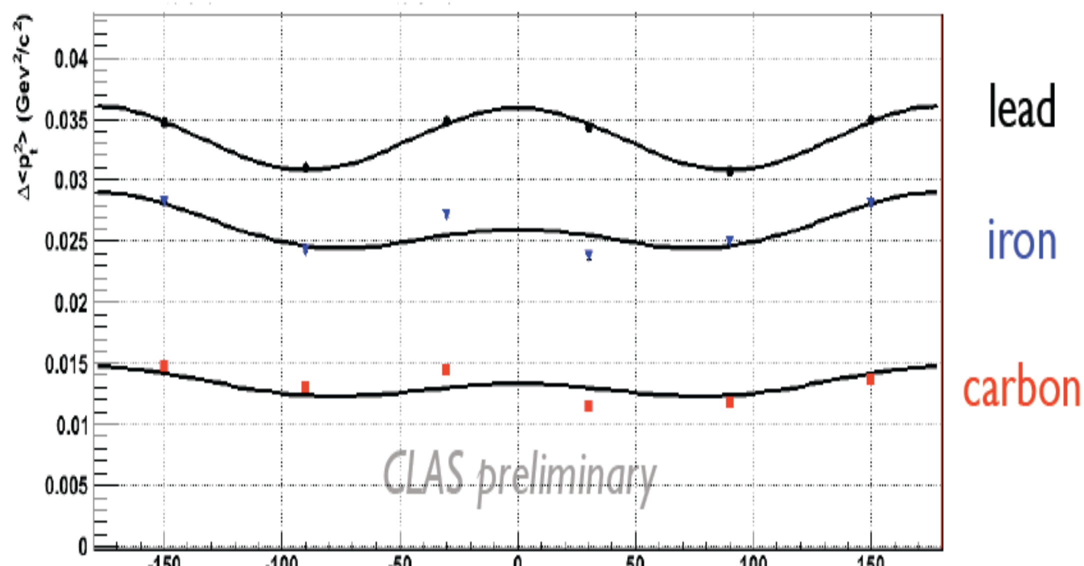
➡ ***Fluctuation and v_n at EIC!***

Color fluctuation – azimuthal asymmetry at EIC

Hicks, KEK-JPAC2013

- ❑ **Preliminary low energy data:**





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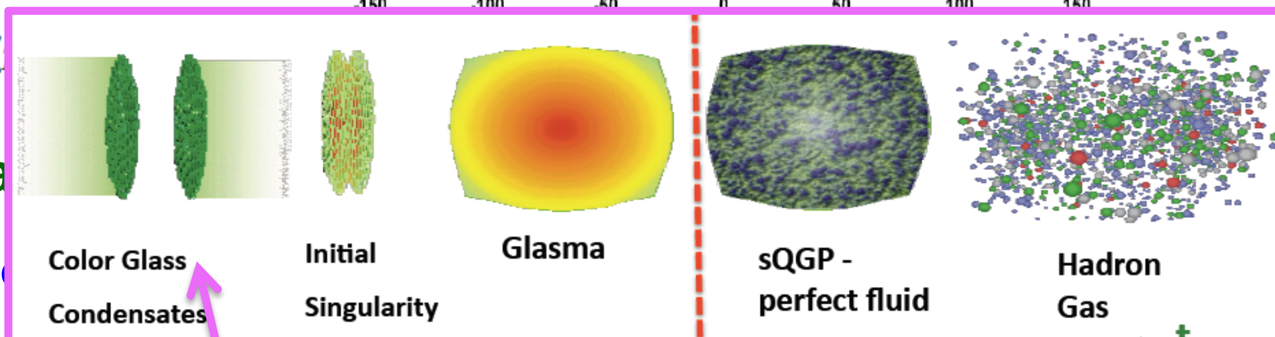
$$\langle \Delta p_T^2(\phi)\rangle_{AN} \equiv \langle p_T^2(\phi)\rangle_A - \langle$$

- ❑ **Classical expecta**

  Any distribution se

- ❑ **Surprise:**

  Azimuthal asymmet



Provide important information for the initial conditions in Nucleus-Nucleus Collisions

➡ ***Fluctuation and v_n at EIC!***

Summary

- EIC is a ultimate QCD machine:
  1) to discover and explore the quark/gluon structure and properties of hadrons and nuclei,
  2) to search for hints and clues of color confinement, and
  3) to measure the color fluctuation and color neutralization

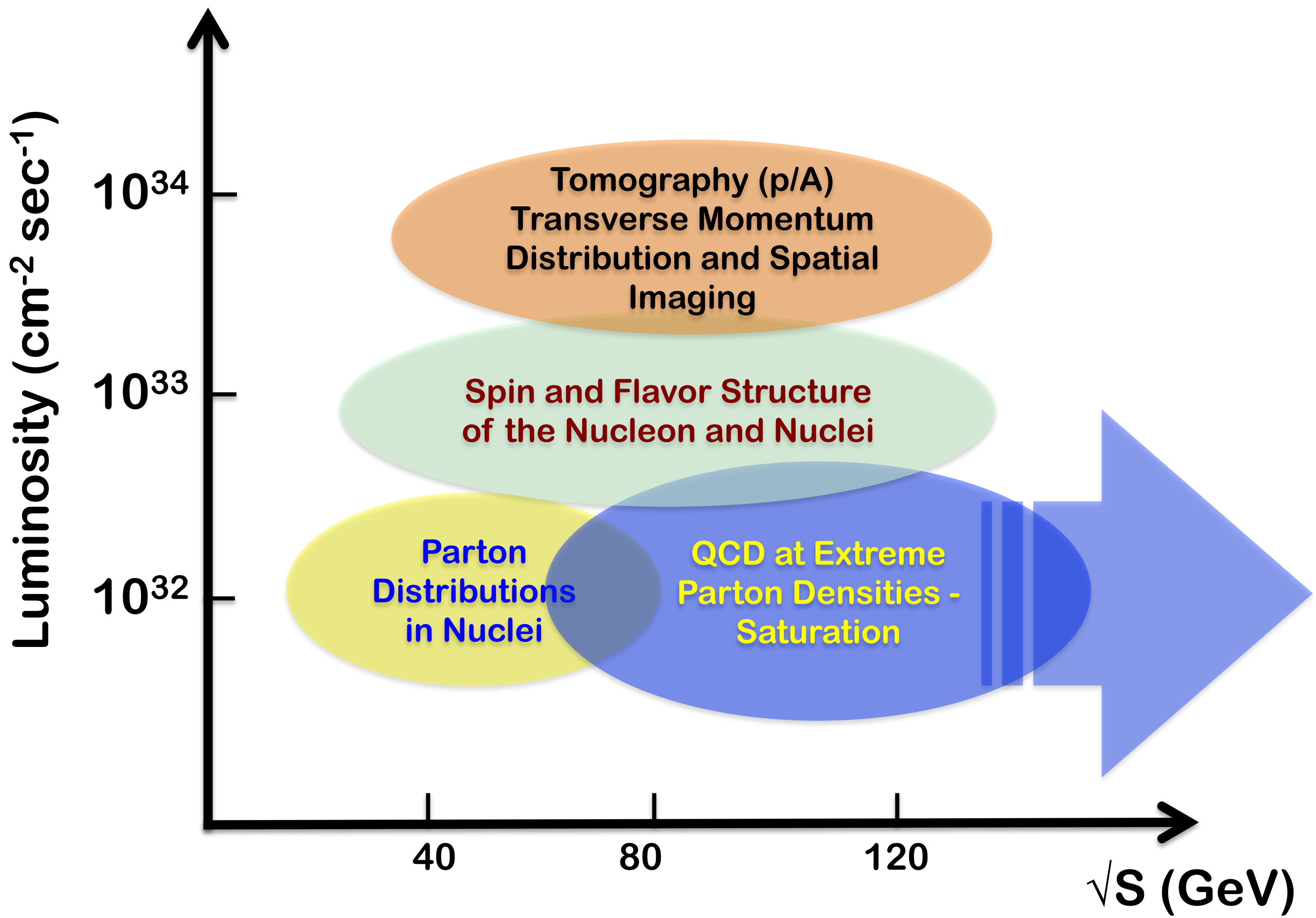
- EIC is a tomographic machine for nucleons and nuclei with a resolution better than 1/10 fm

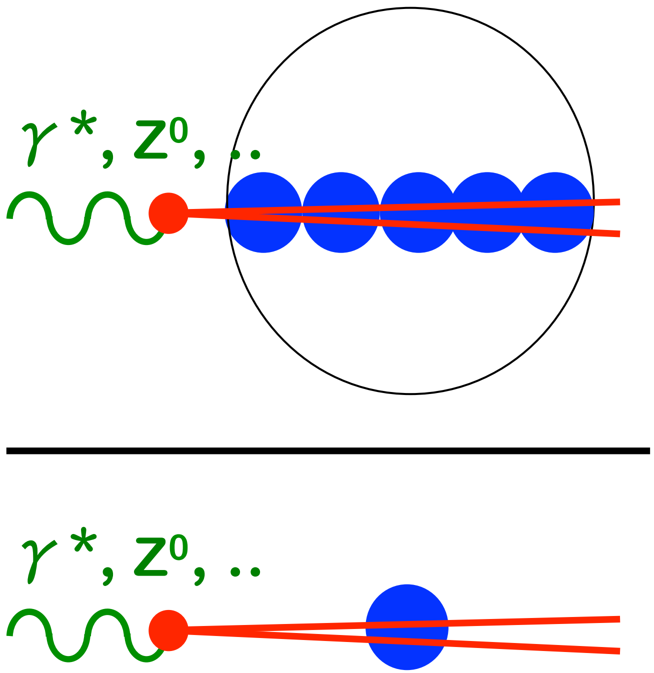
- EIC designs explore the polarization and intensity frontier, as well as the frontier of new accelerator/detector technology

- EIC@US is sitting at a sweet spot for rich QCD dynamics – capable of taking us to the next QCD frontier

Thanks!

US EIC – Physics vs. Luminosity & Energies




γ*, Z0, ..
γ*, Z0, ..