ANNIVERSARY SYMPOSIUM

C.N. YANG INSTITUTE FOR THEORETICAL PHYSICS

SCGP: Small Auditorium Rm 102, October 9-10, 2016

Future facilities: Electron Ion Colliders

The next QCD frontier

Understanding the glue that binds us all

Jianwei Qiu

Theory Center, Jefferson Lab

(YITP postdoc 1989-1991, BNL Prof. 2010-2016)

Theory Center

Jefferson Lab

EXPLORING THE NATURE OF MATTER

Road to YITP …

❑ Before coming to YITP:

1987: Ph.D. Columbia University
1987-89: Postdoc, Argonne National Lab
1989-91: Postdoc, YITP, Stony Brook University

❑ At YITP:

Collaborated with George Sterman on many topics:
- QCD factorization, power correction
- Spin physics
- Heavy quarkonium, …

Continue collaboration ever since, …

❑ After YITP:

1991-2010: Faculty at Iowa State University

❑ Coming back to YITP:

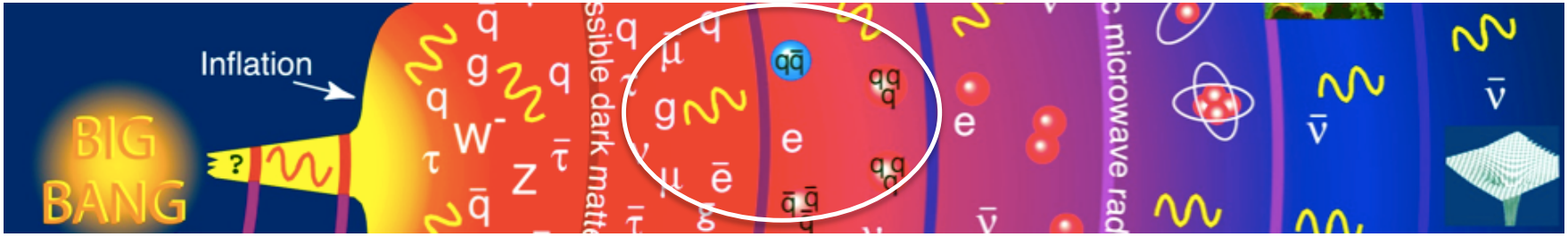
2010-16: Brookhaven Professor, joint with BNL

❑ New Challenge:

Associate Director for theory and computational physics, and Director for the Theory Center, Jefferson Lab

21st Century Nuclear Science

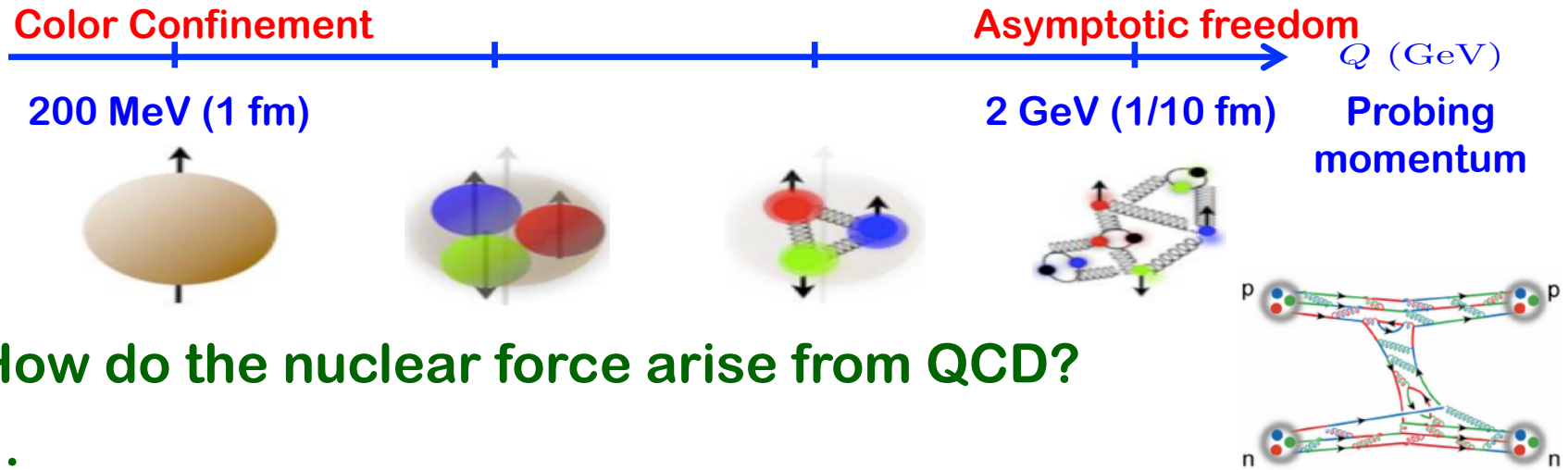
- What is the role of QCD in the evolution of the universe?



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

  Their mass, spin, magnetic moment, …

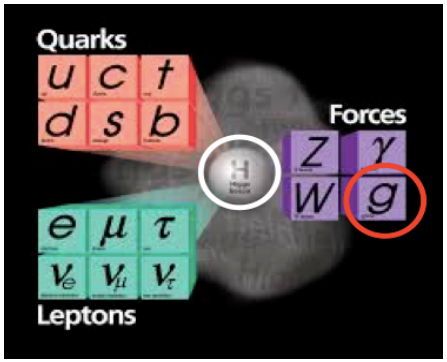
- What is the QCD landscape of nucleon and nuclei?

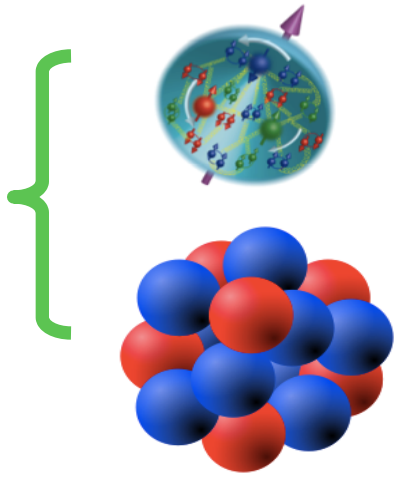


- How do the nuclear force arise from QCD?
- …

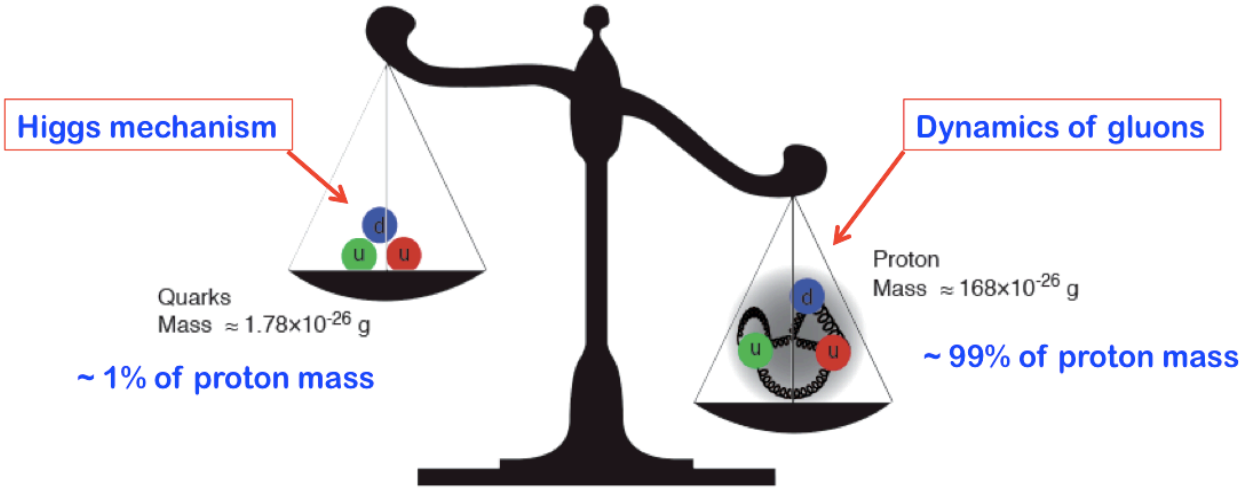
The next QCD frontier

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

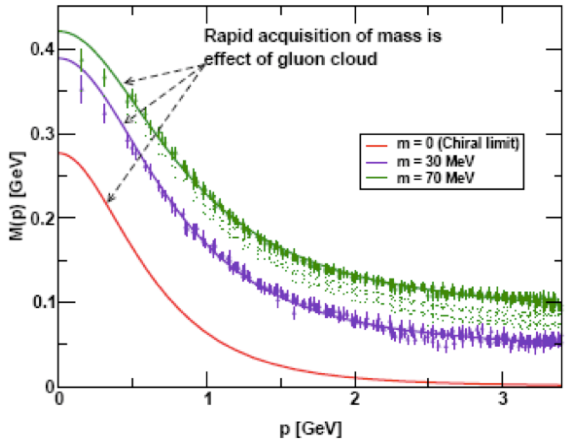




- Gluons are weird particles!
  - ✧ Massless, yet, responsible for nearly all visible mass



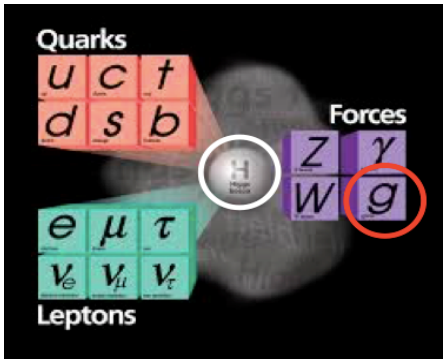
"Mass without mass!"

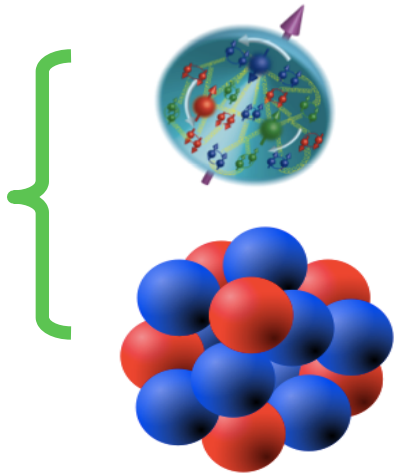


Bhagwat & Tandy/Roberts et al

The next QCD frontier

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





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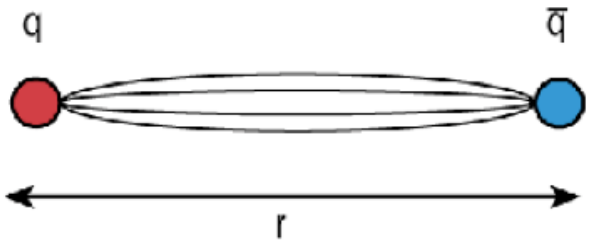
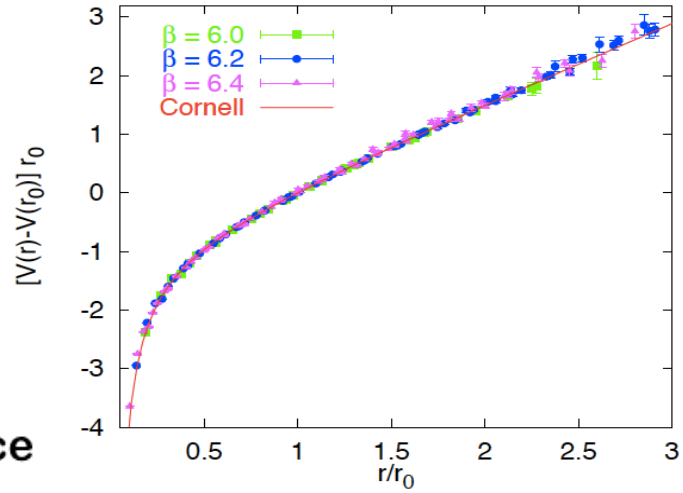
  - ✧ Carry color charge, responsible for color confinement and strong force

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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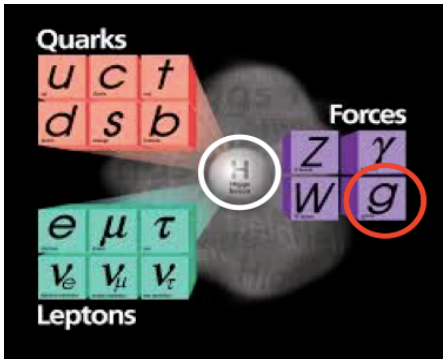

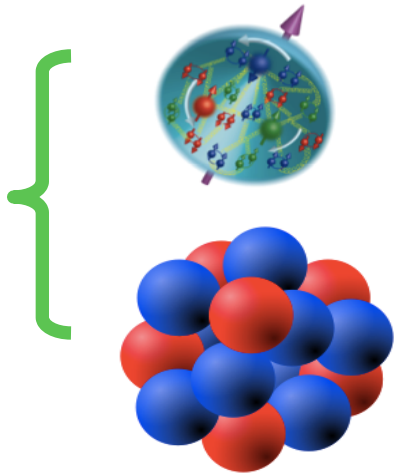

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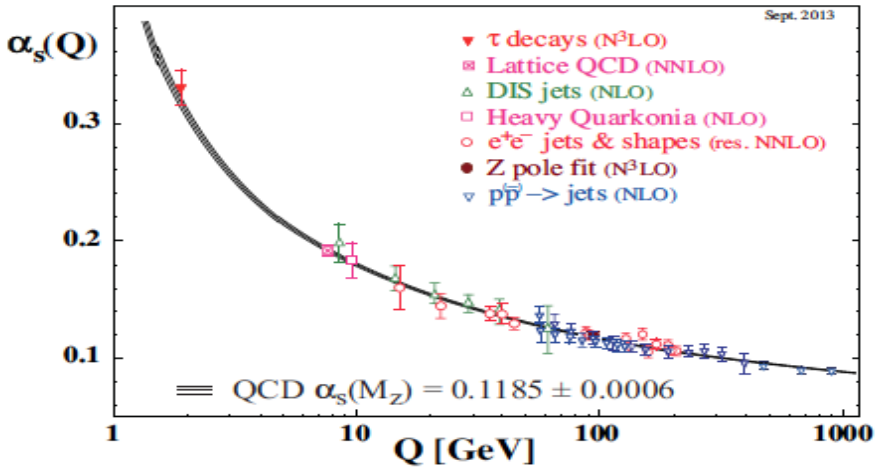
    but, also for asymptotic freedom

Nobel Prize, 2004

→ QCD perturbation theory



The next QCD frontier

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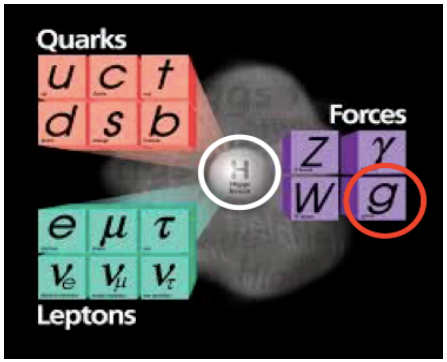

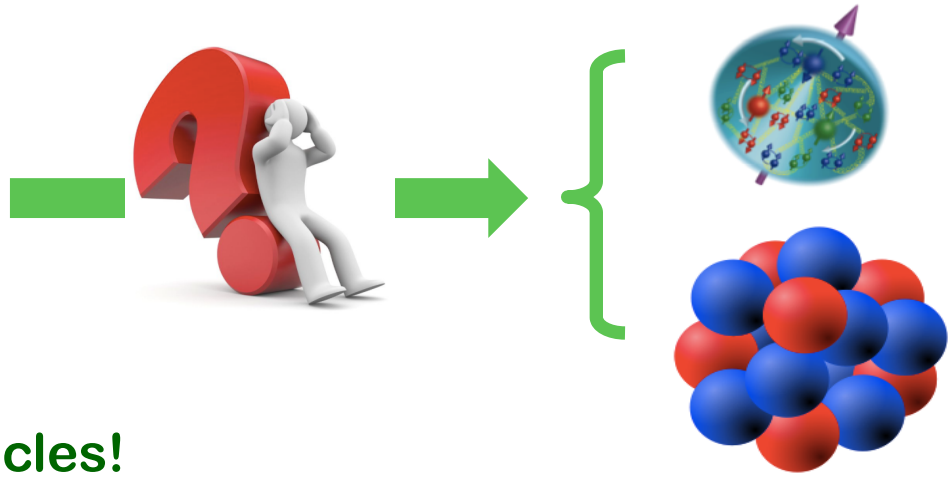

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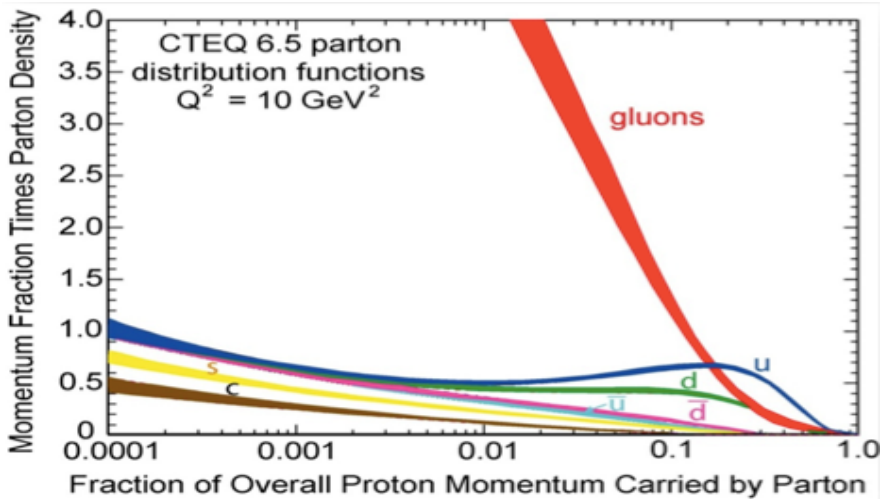

The next QCD frontier

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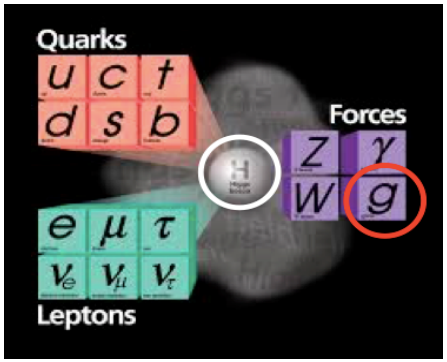

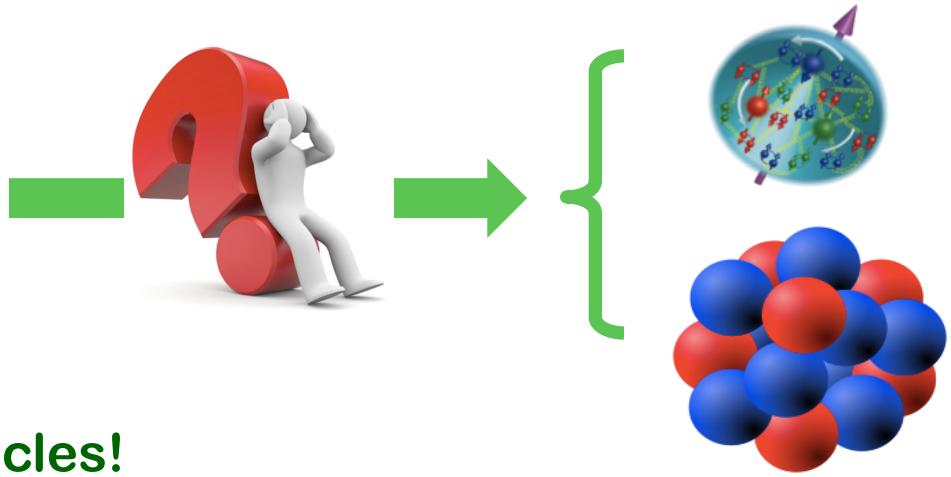

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but, also for asymptotic freedom,

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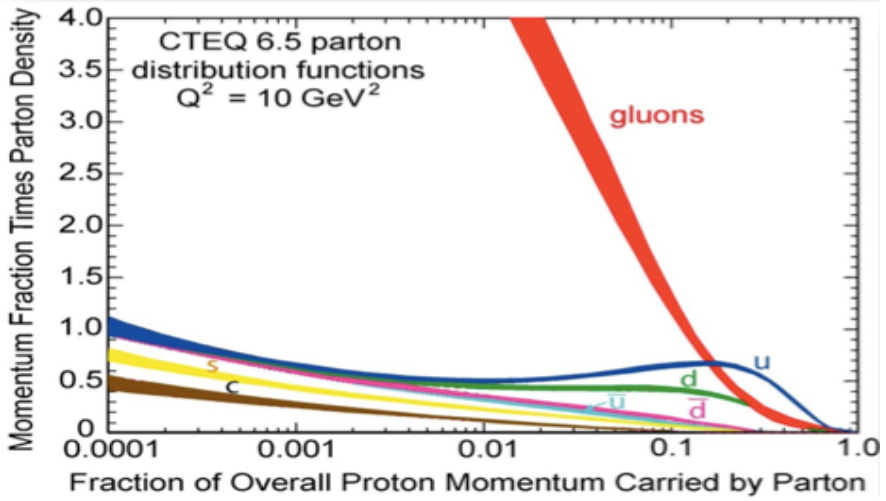
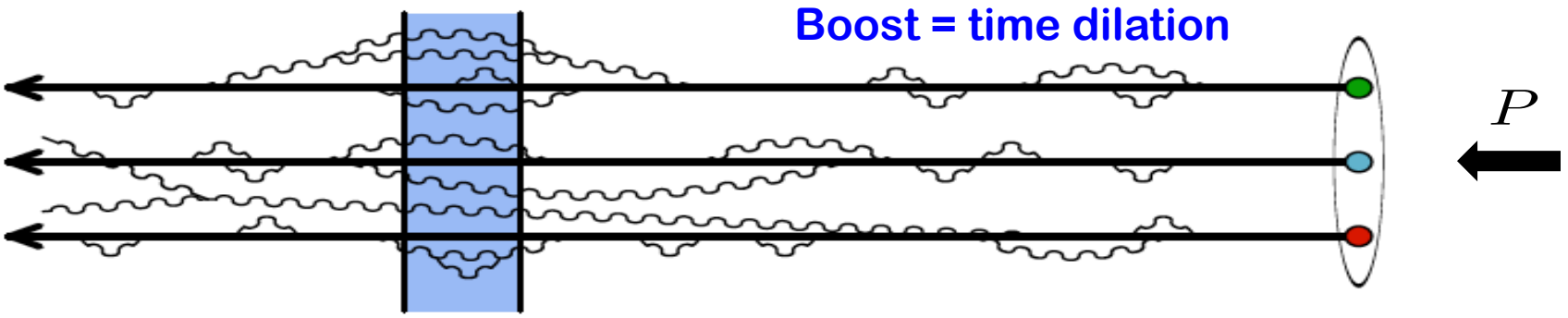
Without gluons, there would be NO nucleons, NO atomic nuclei… NO visible world!

See also A. Deshpande's talk



How to "see" the hadron's partonic structure?

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



Hard probe (t ~ 1/Q < fm): *Catches the quantum fluctuation!*

- ✧ Longitudinal momentum fraction – *x* : $xP \sim Q$
- ✧ Transverse momentum – confined motion: $1/R \sim \Lambda_{\rm QCD} \ll Q$

- Challenge:

  No modern detector can see quarks and gluons in isolation!

- Question:

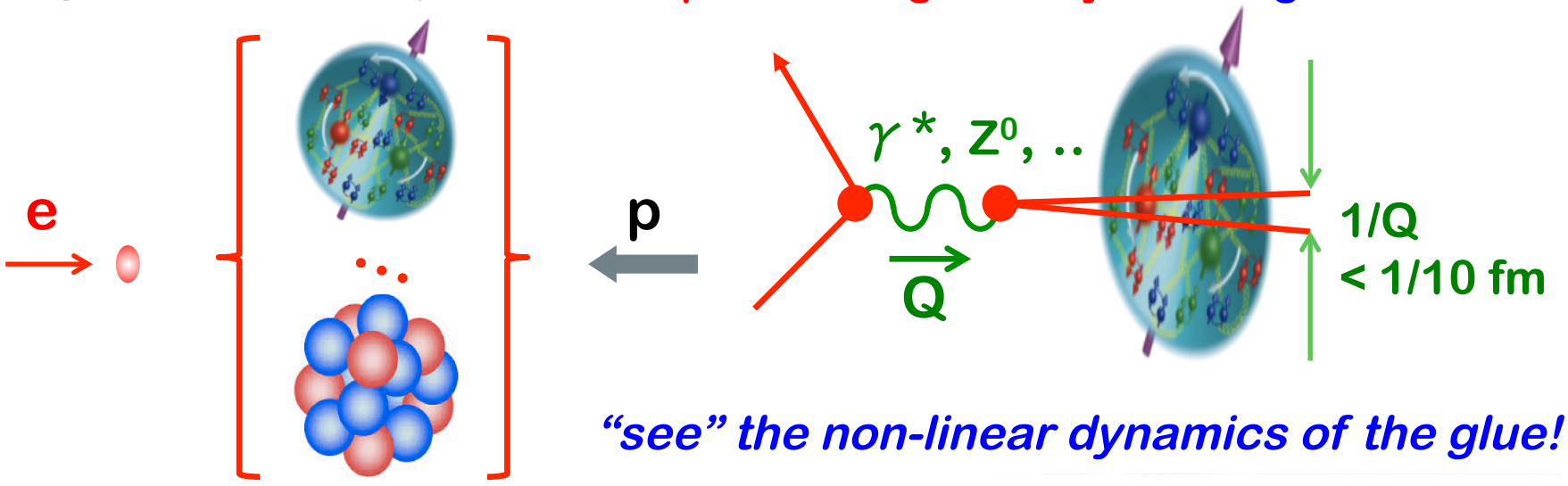
  How to quantify the hadron structure if we cannot see quarks and gluons? *We need the probe!*

- Answer:

  QCD factorization! *Not exact, but, controllable approximation!*

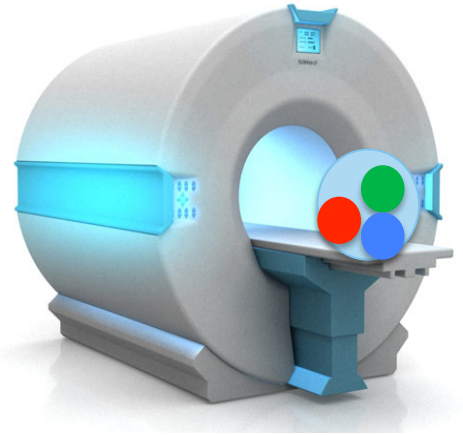
Electron-Ion Collider (EIC)

- 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

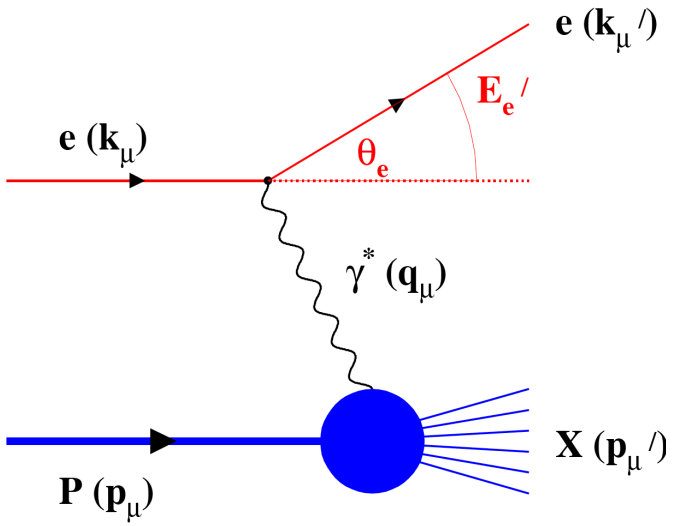
- Why now?

  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

$Q^2 = S \times y$

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)

EIC: the World Wide Interest

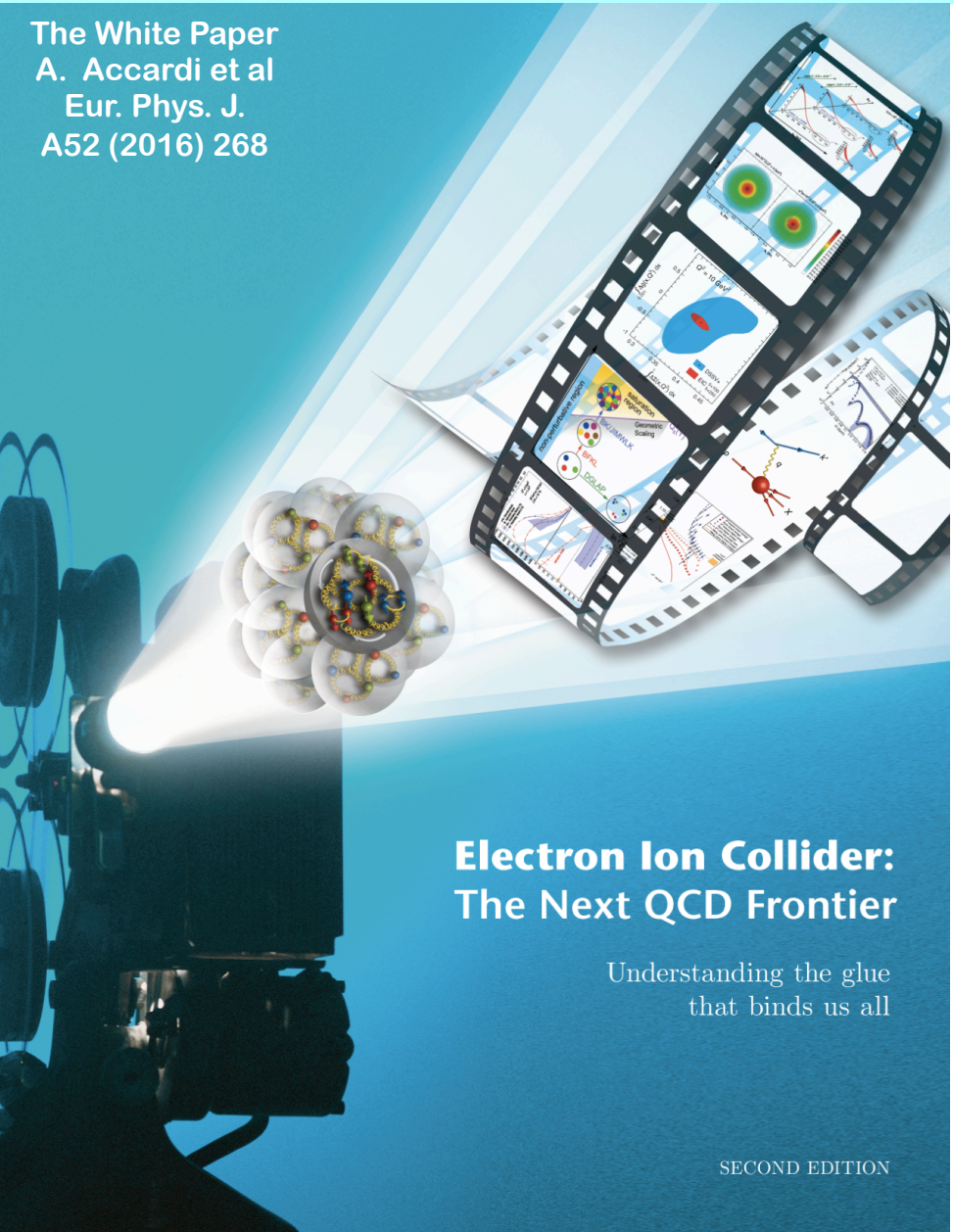
	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)	p, d, ^{3}He	p,d
L [$cm^{-2}\ s^{-1}$]	2×10^{31}	10^{33}	10^{33-34}	10^{33-34}	$10^{32-33} \rightarrow 10^{35}$	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2022 (?)	2022	Post-12 GeV	2019 → 2030	upgrade to FAIR

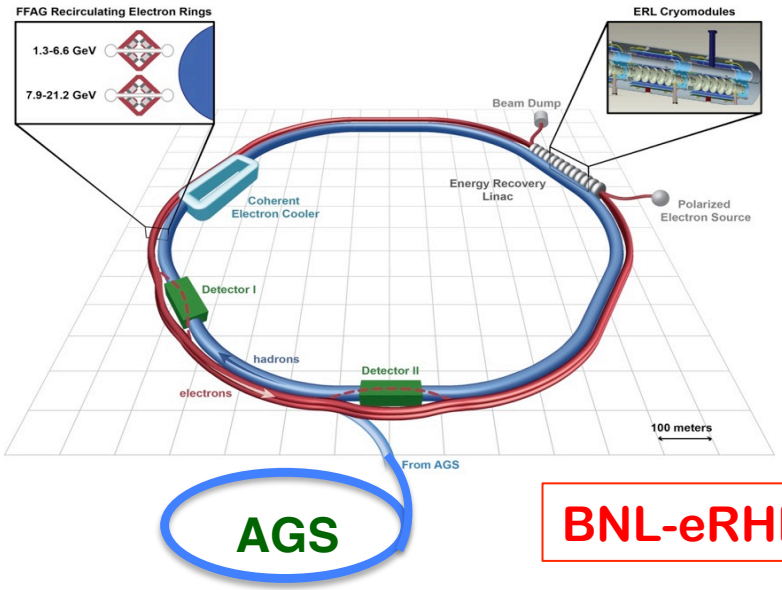
The past

Possible future

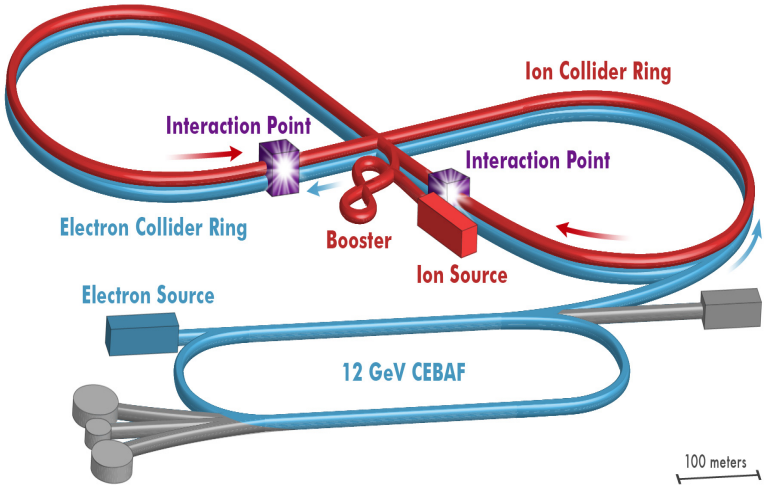
US EIC – two options of realization

The White Paper
A. Accardi et al
Eur. Phys. J.
A52 (2016) 268



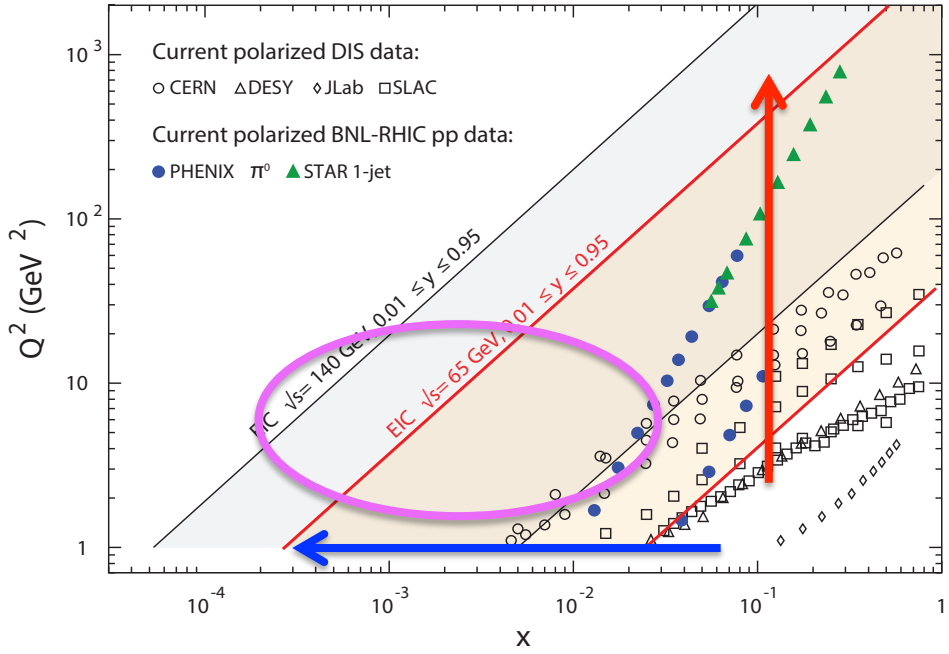


BNL-eRHIC



JLab-JLEIC

US EIC – Kinematic reach & properties

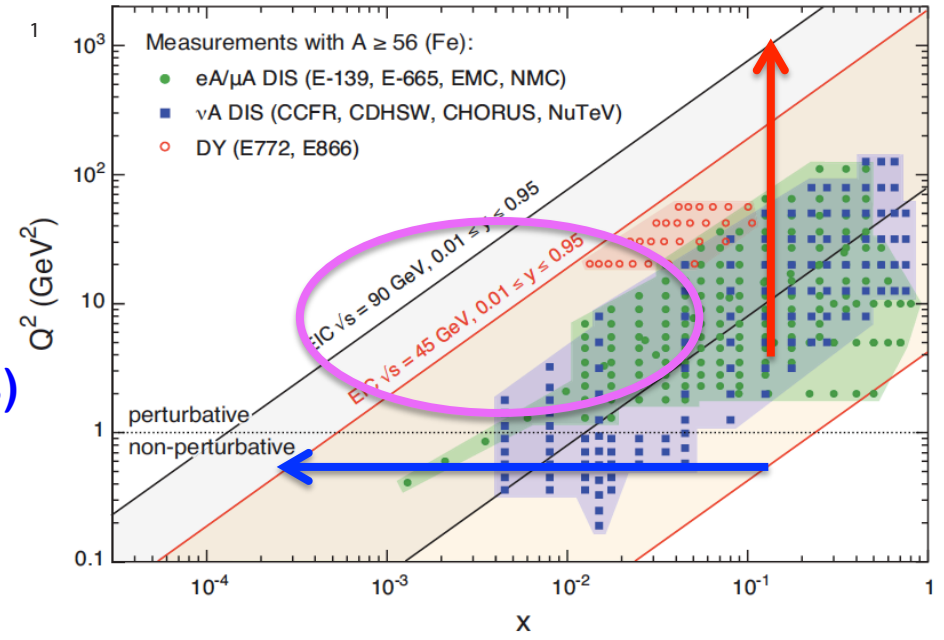


For e-N collisions at the EIC:

- ✓ 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)



"Big" questions to be answered, …

- **How does QCD generate the nucleon mass?** ➡ Success of Lattice QCD

  "… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

  REACHING FOR THE HORIZON

  The 2015 Long Range Plan for Nuclear Science

- **Role of quarks and gluons?**
  - Trace of the QCD energy-momentum tensor:

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

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

  - Mass, trace anomaly, chiral symmetry break, and …

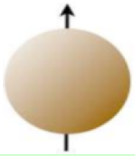
$$m^2 \propto \langle p|T^{\alpha}_{\ \alpha}|p\rangle \quad \Rightarrow \quad \frac{\beta(g)}{2g} \langle p|F^2|p\rangle$$

  ➡ quarkonium production near the threshold, from JLab12 to EIC

Workshop: https://phys.cst.temple.edu/meziani/proton-mass-workshop-2016/

“Big” questions to be answered, …

- How does QCD generate the nucleon’s spin?



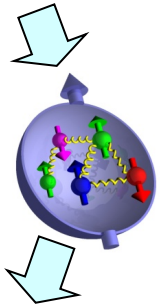
Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g) = \sum \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle$$

Quark helicity
Best known

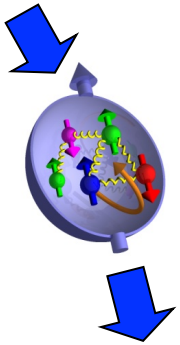
$$\frac{1}{2}\int dx\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$
$$\sim 30\%$$

Spin “puzzle”



Gluon helicity
Start to know

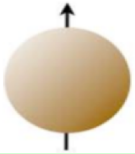
$$\Delta G = \int dx \Delta g(x)$$
$$\sim 20\% (\text{with RHIC data})$$



Orbital Angular Momentum of quarks and gluons
Little known

“Big” questions to be answered, …

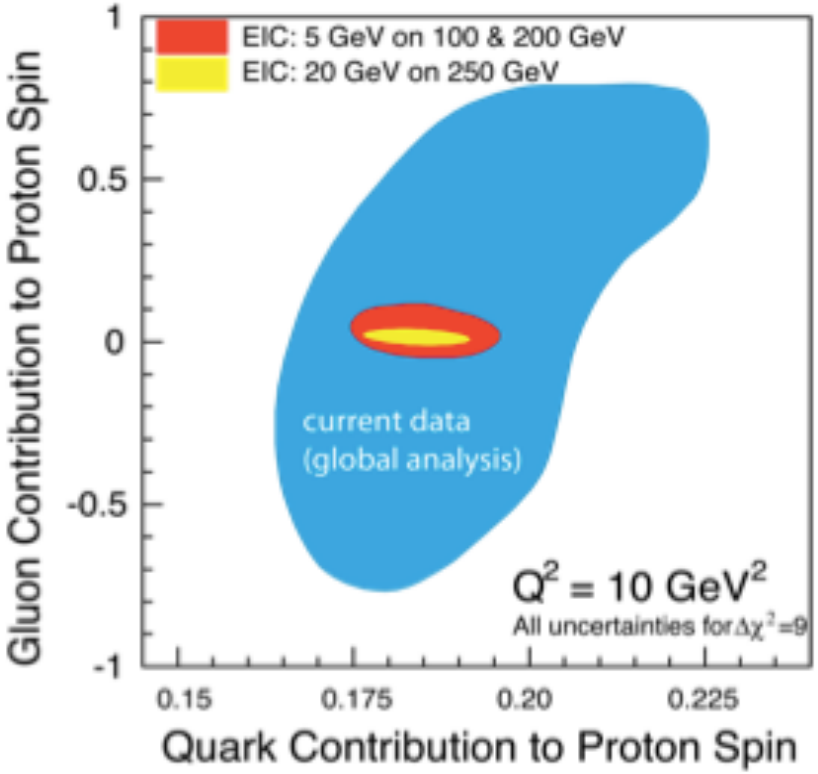
- How does QCD generate the nucleon’s spin?



Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g) = \sum \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle$$

- What can EIC do?



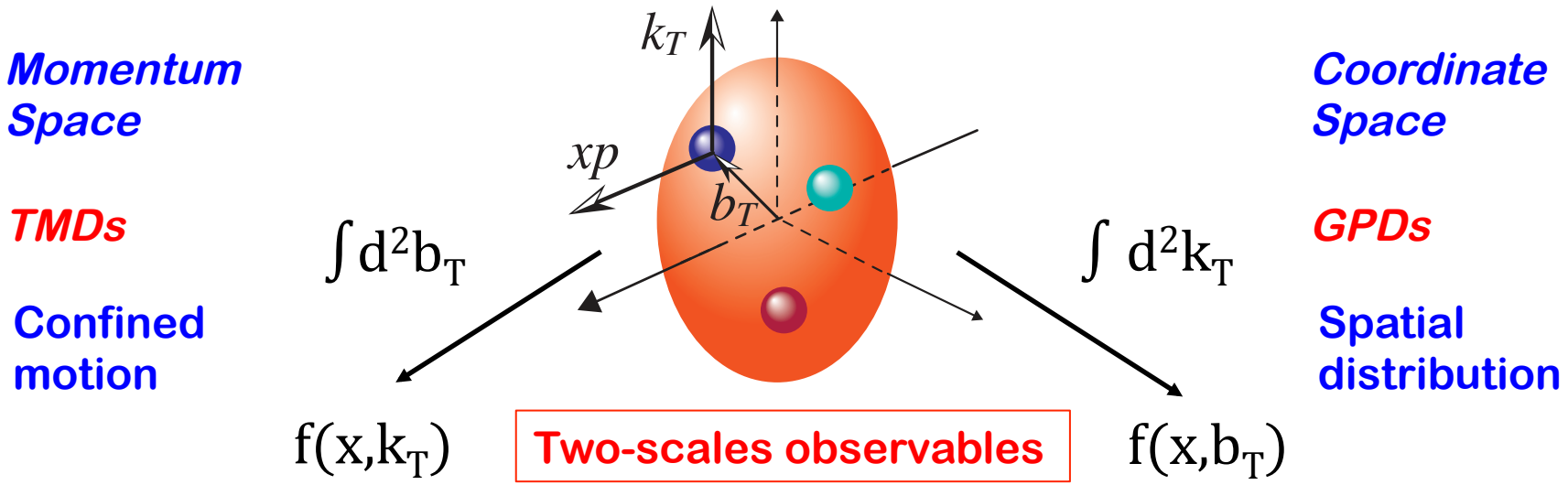
To understand the proton spin, fully, we need to understand the confined motion of quarks and guons in QCD

➡ **TMDs, GTMDs, …**

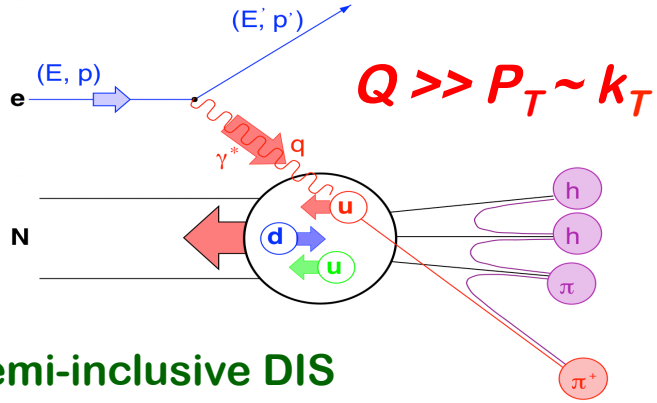
Need QCD factorization Ror two-scale observables!

“Big” questions to be answered, …

- 3D boosted partonic structure:

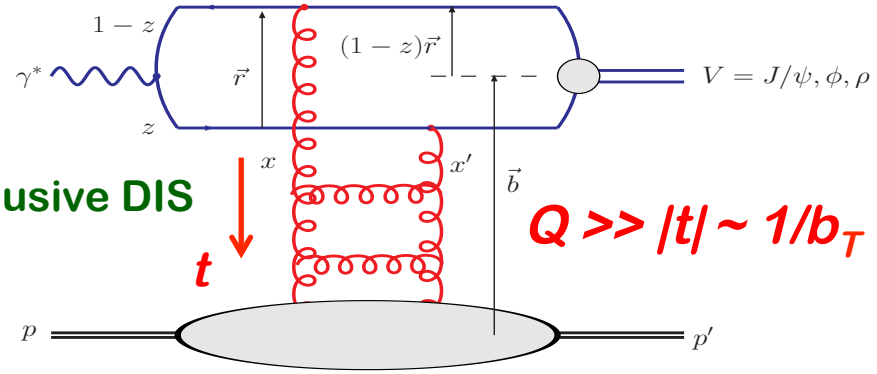


3D momentum space images



Semi-inclusive DIS

2+1D coordinate space images



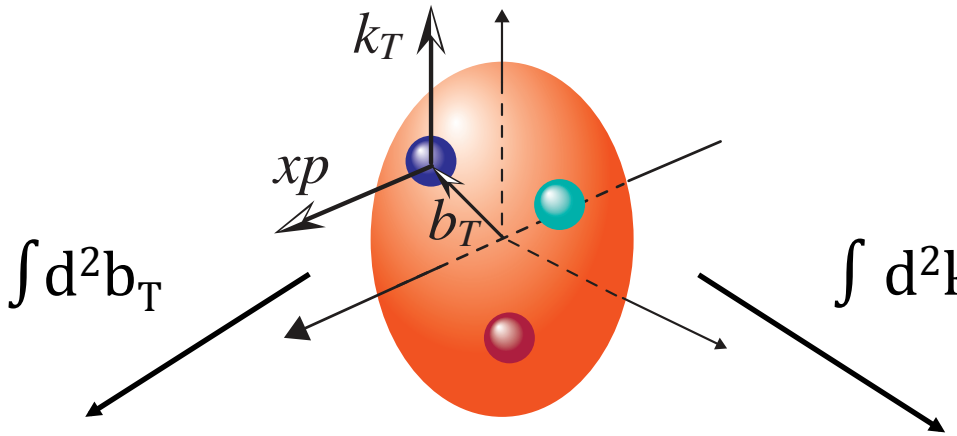
JLab12 – valence quarks, EIC – sea quarks and gluons

“Big” questions to be answered, …

- **3D boosted partonic structure:**

Momentum Space

TMDs

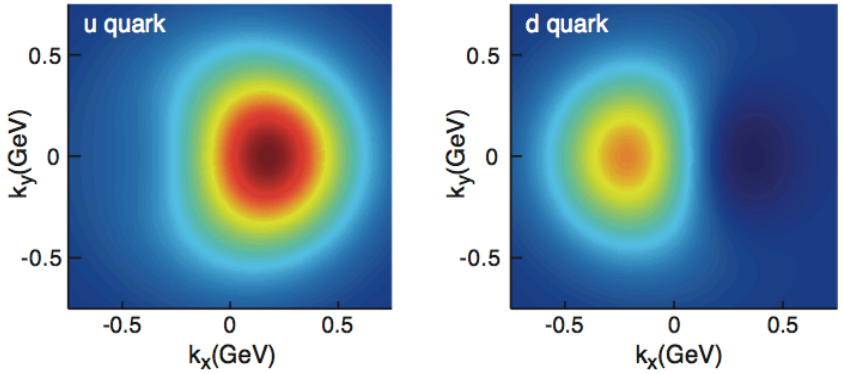


Coordinate Space

GPDs

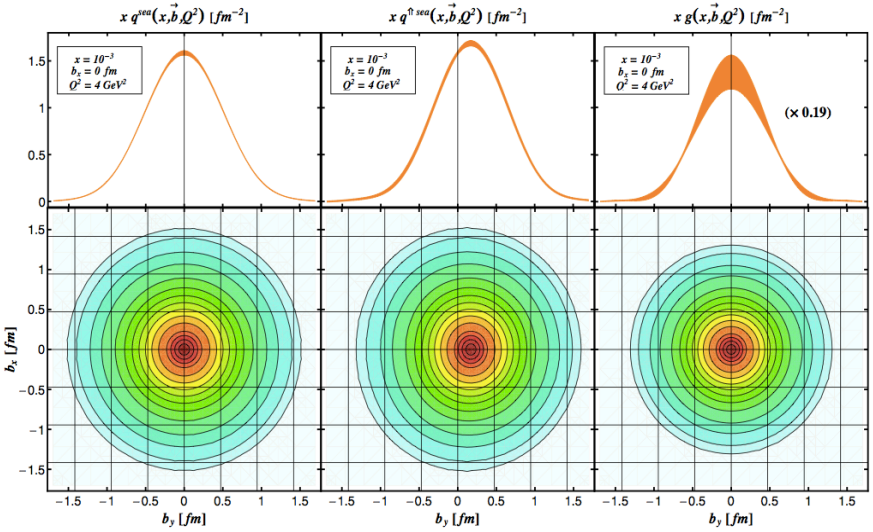
$f(x,k_T)$ **EIC white paper: arXiv:1212.1701** $f(x,b_T)$

Sivers Function



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

Imaging



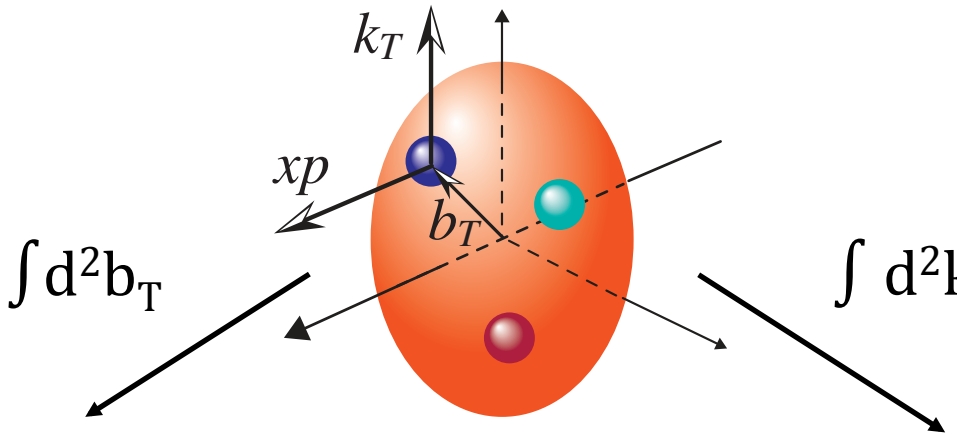
Spatial density distributions – “radius”

“Big” questions to be answered, …

- High energy probes “see” the boosted partonic structure:

Momentum Space

TMDs

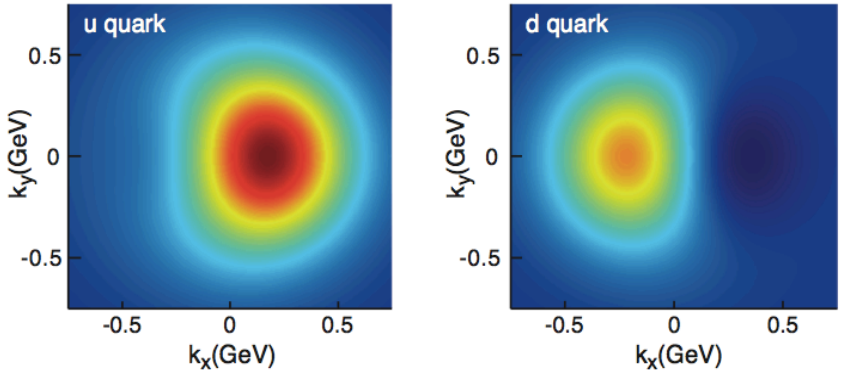


Coordinate Space

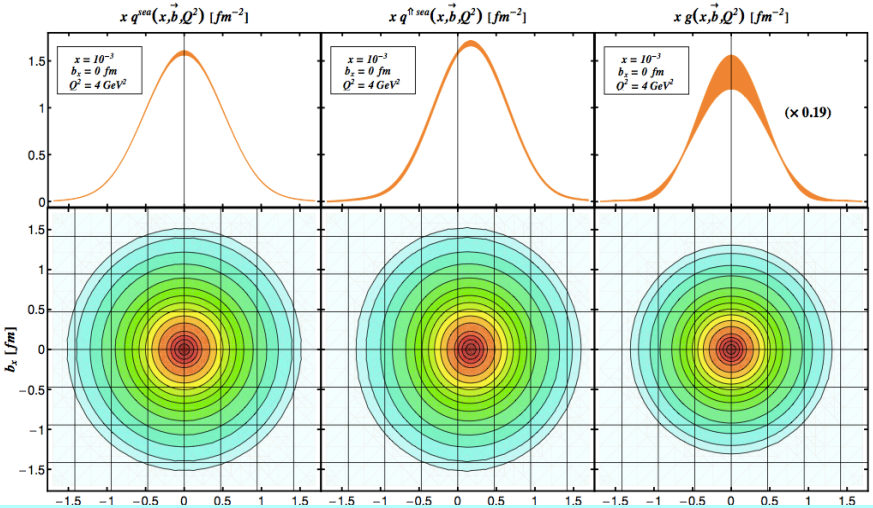
GPDs

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

Sivers Function



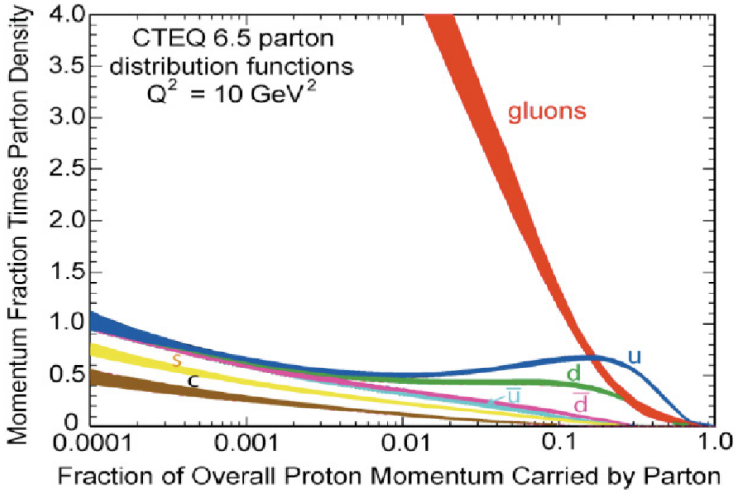
Imaging



Position *r* x Momentum *p* → Orbital Motion of Partons

“Big” questions to be answered, …

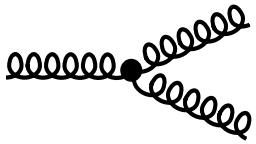
❑ Run away gluon density at small x?



What causes the low-x rise?

gluon radiation

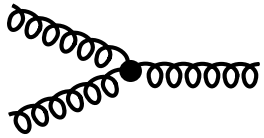
– non-linear gluon interaction



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:

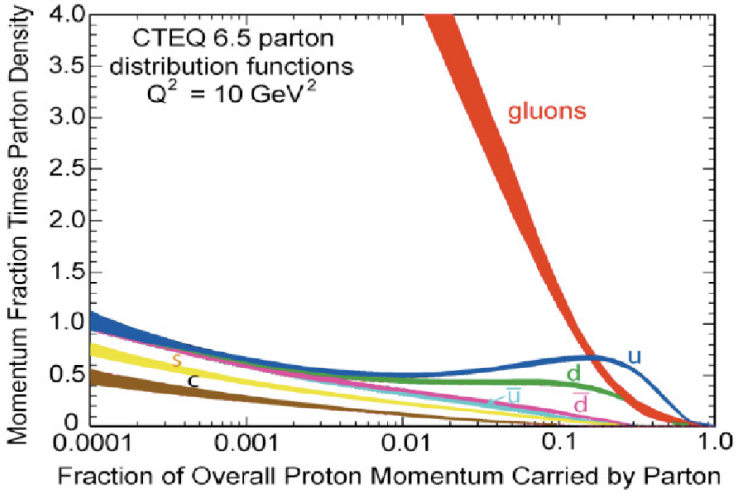
$$Q^2 \frac{d}{dQ^2} x\phi_\gamma(x,Q^2) \approx \frac{\alpha_{em}}{\pi} \left[-\frac{2}{3} x\phi_\gamma(x,Q^2) + \int_x^1 \frac{dx'}{x'} x' [\phi_{e+}(x',Q^2) + \phi_{e-}(x',Q^2)] \right]$$

✧ At very small-x, proton is “black”, positronium is still transparent!

✧ Recombination of large numbers of glue could lead to saturation phenomena

“Big” questions to be answered, …

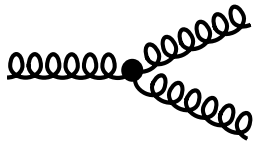
❑ Run away gluon density at small x?



What causes the low-x rise?

gluon radiation

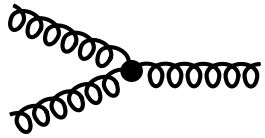
– non-linear gluon interaction



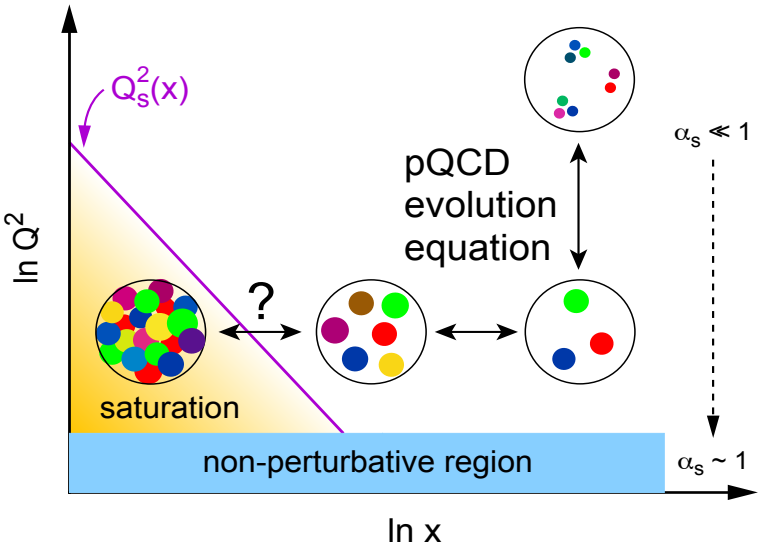
What tames the low-x rise?

gluon recombination

– non-linear gluon interaction

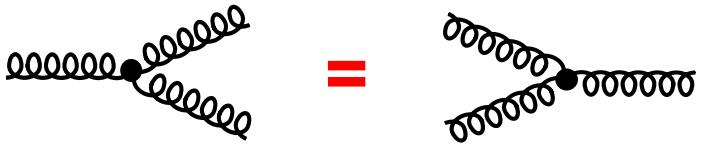


❑ Particle vs. wave feature:



Gluon saturation – Color Glass Condensate

Radiation = Recombination



at Q_s

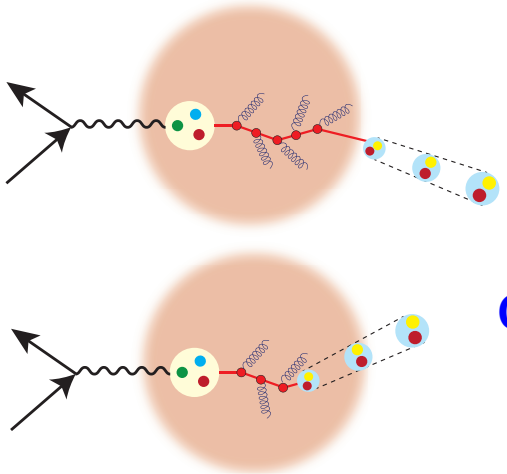
Leading to a collective gluonic system?

with a universal property of QCD?

new effective theory QCD – CGC?

“Big” questions to be answered, …

❑ Emergence of a hadron?

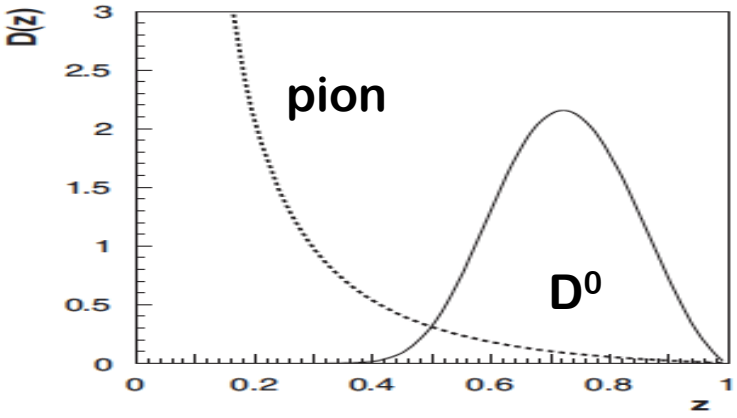


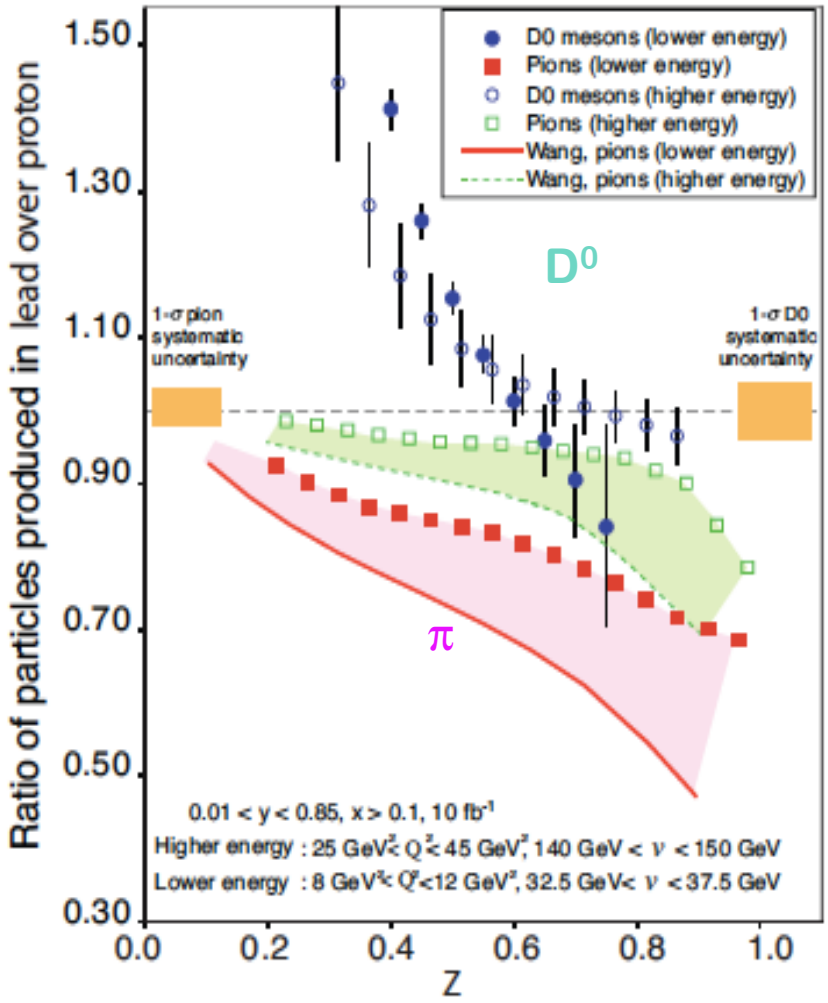
$$\nu = \frac{Q^2}{2mx}$$

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

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!