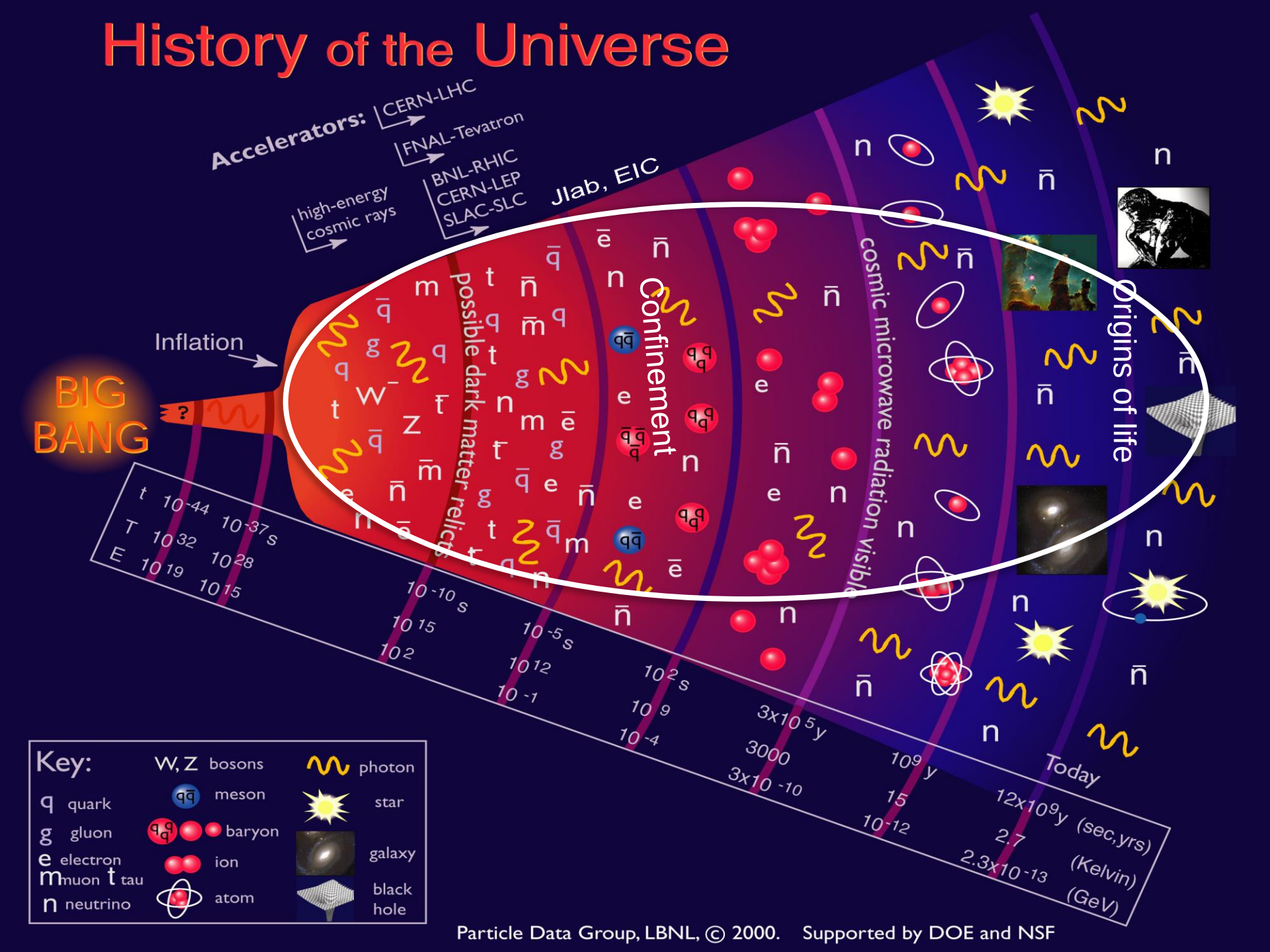
Electron Ion Collider Physics
The glue that binds us all: Next QCD frontier!

Zein-Eddine Meziani
Temple University

"It is difficult and often impossible to judge the value of a problem correctly in advance; for the final award depends upon the gain which science obtains from the problem."

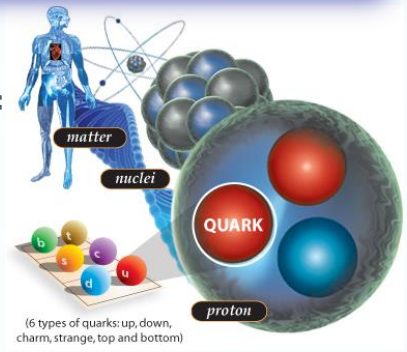
David Hilbert, 1900 Paris

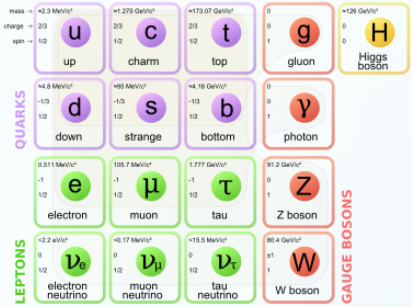
History of the Universe



Nuclear Science and QCD

- Nuclear Science
  - **To discover, explore and understand all forms of nuclear matter**
- Nuclear Matter
  - Quarks + Gluons + Interactions →Nucleons →Nuclei
  - At the heart of the visible universe, accounting for essentially all its mass
- Among the Experimental Tools:
  - Giant electron microscopes opened the gateway to nucleon structure at Stanford and at SLAC using electron proton scattering.
  - Modern microscopes are pushing the frontiers of resolution, brightness and polarization combined.
- Theory Tools: Quantum Chromodynamics (QCD)
  - A fundamental theory of quarks and gluons
  - Describes the formation of all forms of nuclear matter





Understanding of QCD is a fundamental and compelling goal of Nuclear Science

The Science Problem ?

- The structure of all nuclear matter in Quantum Chromodynamics (QCD) and ultimately confinement

What do we know?

- QCD successes in the perturbative regime are impressive, many experimental tests led to this conclusion

But

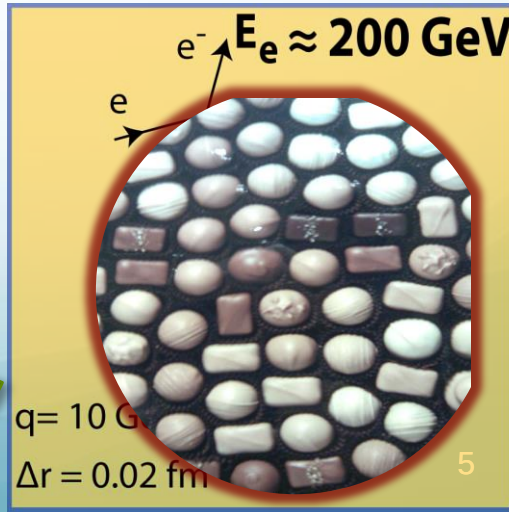
- Many non-perturbative aspects of QCD including confinement are still puzzling. Confinement has been identified as one of the top millenium problems in Physics (Gross, Witten,…) Many conferences have been devoted to this problem

Probing deeper for the fundamental degrees of freedom, quarks and gluons

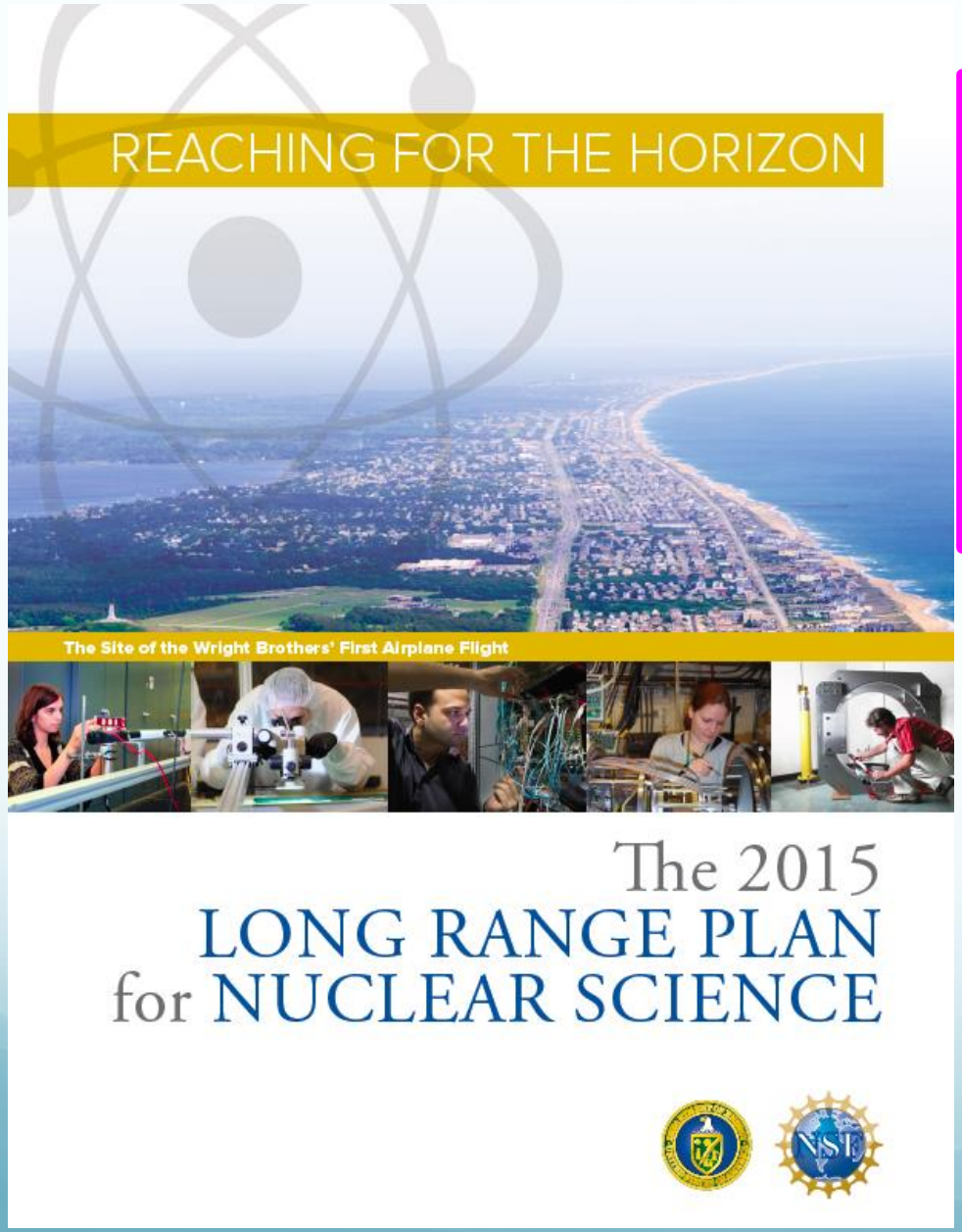
Can we develop analytical tools to connect hadron structure and properties at low energy to their parton descriptions at high energy?

Quarks & Gluons

Emergent Phenomenon



The NSAC Long Range Plan and The EIC



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 Users Group Meetings:

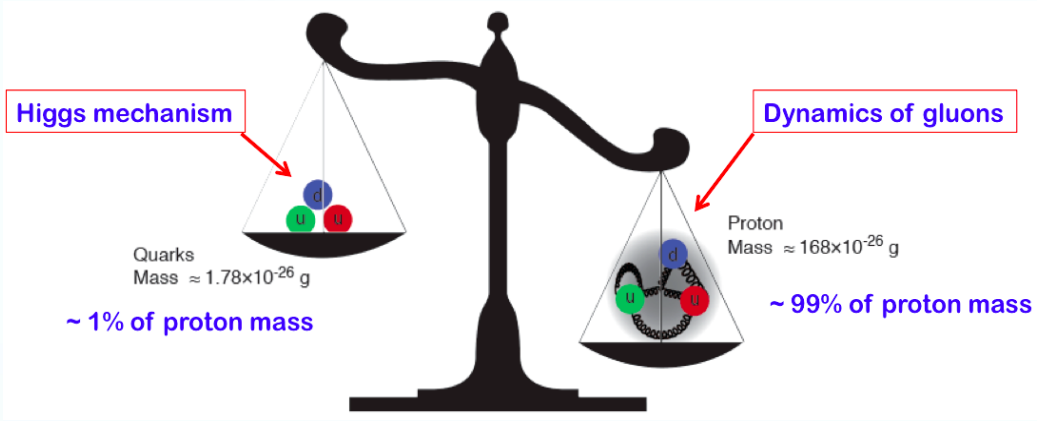
- Stony Brook University, NY
  June 24-27, 2014
- UC at Berkeley, CA
  January 6-9, 2016
- **Argonne National Lab, IL**
  July 7-9, 2016

http://eic2016.phy.anl.gov/

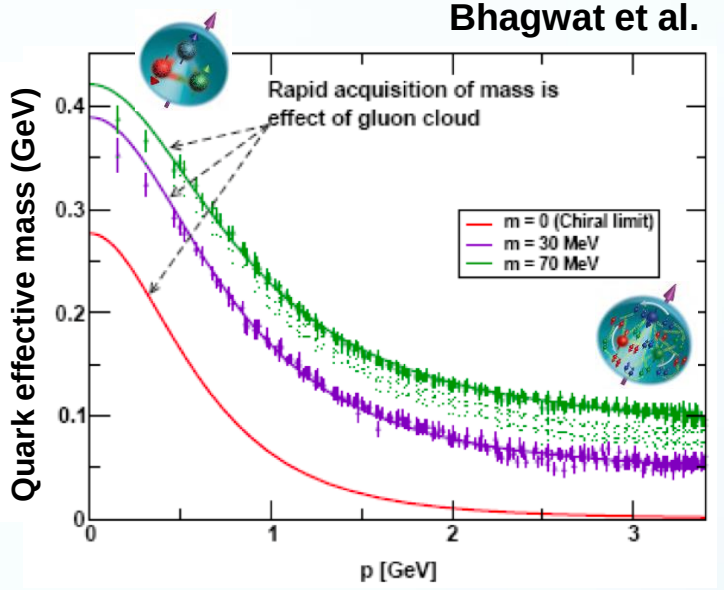
http://www.eicug.org/web/

Gluons play a special role in QCD

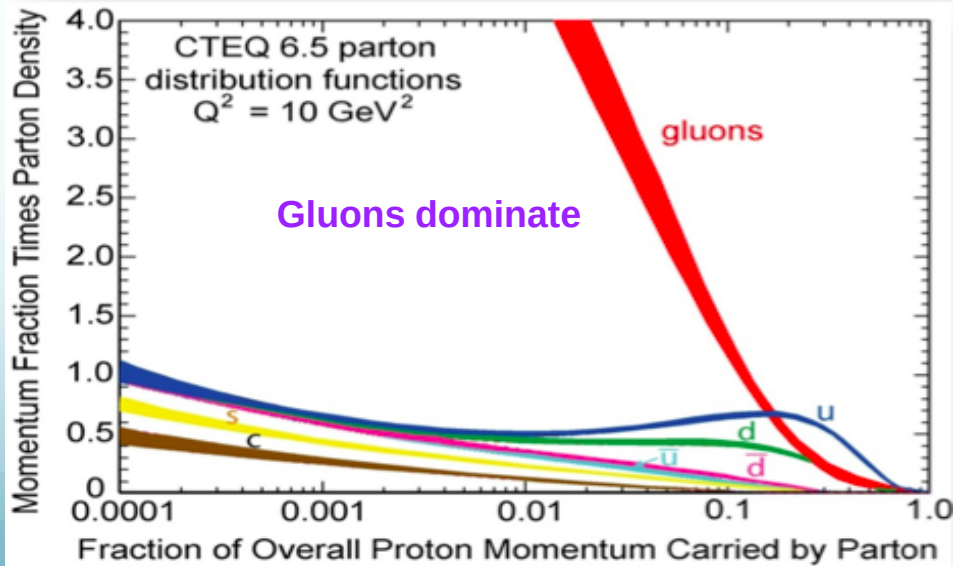
- Gluons are massless, yet, responsible for nearly all visible mass



Bhagwat et al.



- **Gluons carry color charge and are responsible for color confinement and strong force, but also for asymptotic freedom**
- **Without gluons, there would be no nucleons, no atomic nuclei … and therefore no visible world!**

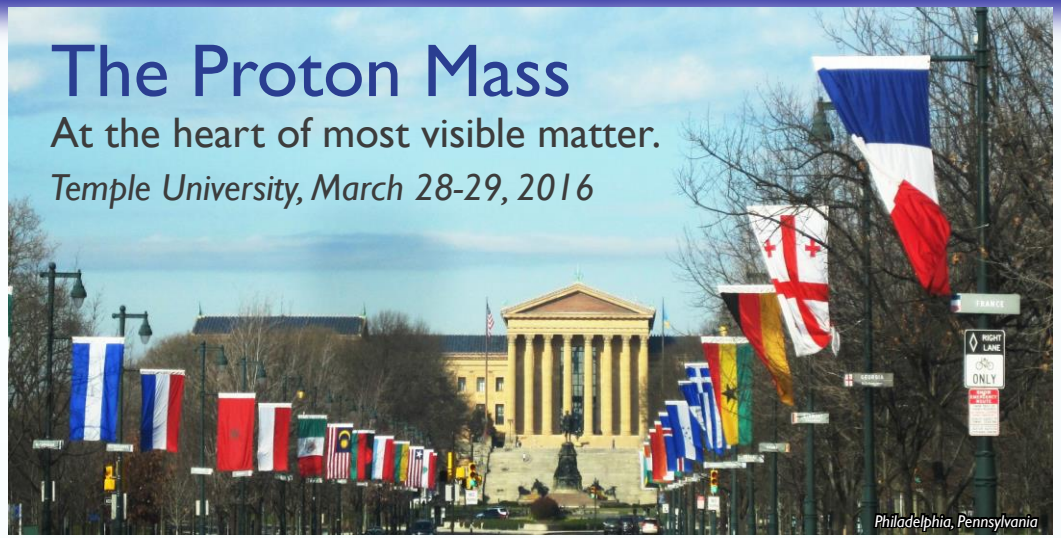


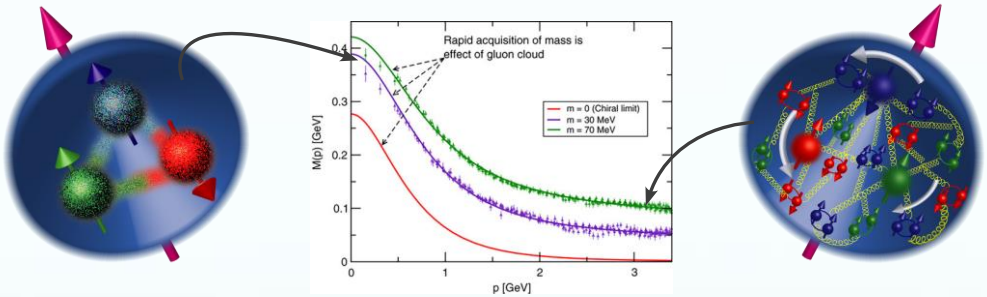
https://phys.cst.temple.edu/~meziani/proton-mass-workshop-2016

The Proton Mass

At the heart of most visible matter.

Temple University, March 28-29, 2016





$M_p = 2m_u^{\text{eff}} + m_d^{\text{eff}}$

$$H_{QCD} = H_q + H_m + H_g + H_a$$

Quark kinetic and potential energy $H_q = \int d^3x \psi^\dagger(-i\mathrm{D}\cdot\alpha)\psi$

Quark masses $H_m = \int d^3x \bar{\psi} m \psi$

Gluon kinetic and potential energy $H_g = \int d^3x \frac{1}{2}(\mathrm{E}^2 + \mathrm{B}^2)$

Trace anomaly $H_a = \int d^3x \frac{9\alpha_s}{16\pi}(\mathrm{E}^2 - \mathrm{B}^2)$

Speakers

Stan Brodsky (SLAC)
Xiandong Ji (Maryland)
Dima Kharzeev (Stony Brook & BNL)
Keh-Fei Liu (University of Kentucky)
David Richards (JLab)
Craig Roberts (ANL)
Martin Savage (University of Washington)
Stepan Stepanyan (JLab)
George Sterman (Stony Brook)

Moderator

Alfred Mueller (Columbia)

Local Organizers

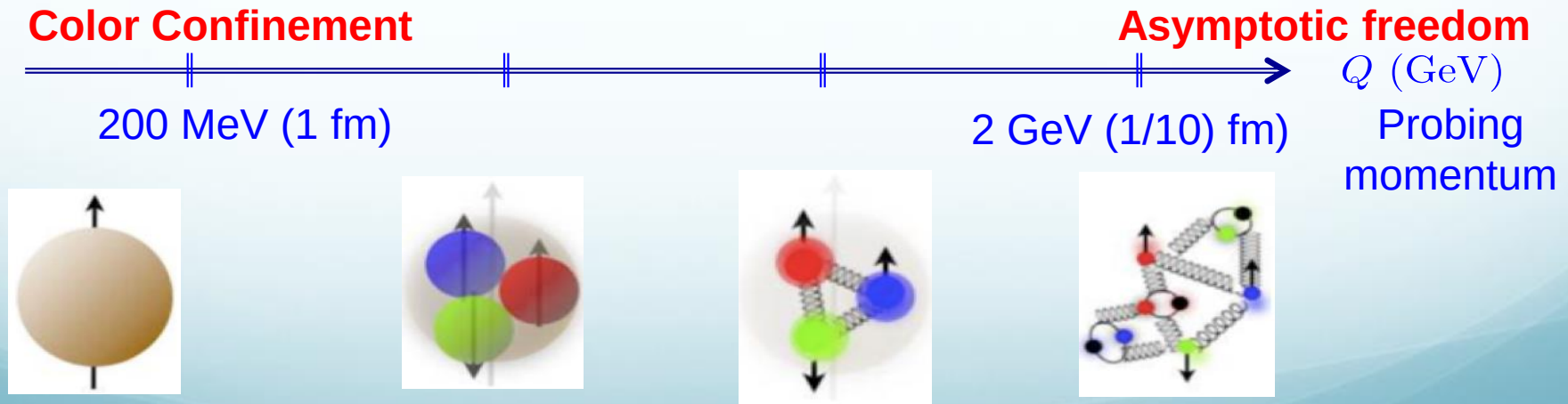
Zein-Eddine Meziani (Temple U.)
Jianwei Qiu (Brookhaven National Lab)

Workshop Topics

- Hadron Mass Calculation: Lattice QCD and Other Methods
- Hadron Mass Decomposition

TEMPLE UNIVERSITY

Present Theoretical Tools



Experimental Tools: Scattering

- Inclusive scattering
  - Detect the scattered lepton only

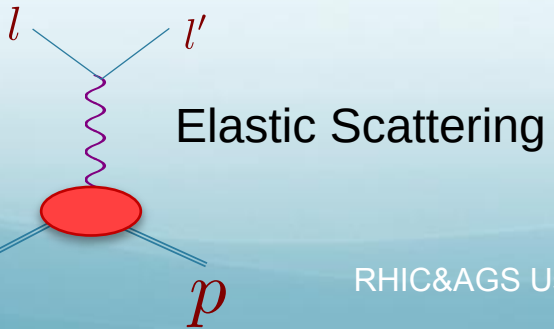
$$e + p/A \rightarrow e' + X$$

- Semi-Inclusive scattering
  - Detect the scattered lepton in coincidence with identified hadrons/jets

$$e + p/A \rightarrow e' + h(\pi, K, jet) + X$$

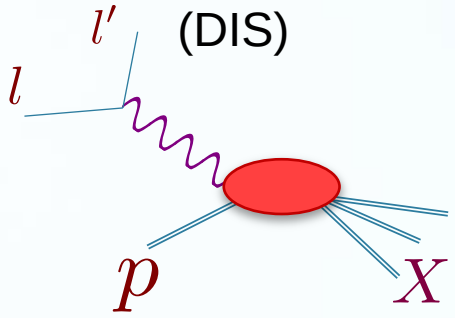
- Exclusive scattering
  - Detect all particles in final state

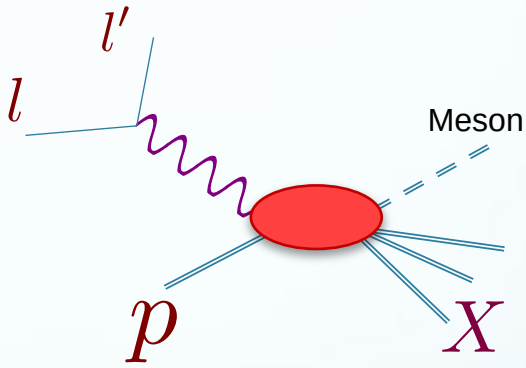
$$e + p/A \rightarrow e' + p'/A' + \gamma, h(\pi, K, J/\psi)$$



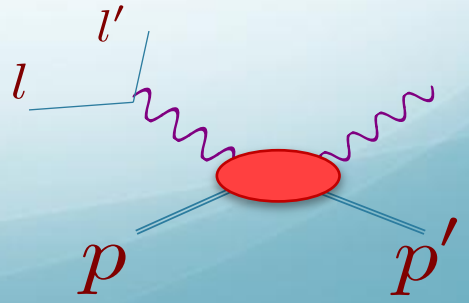
Elastic Scattering

Deep Inelastic Scattering (DIS)





Deep Virtual Compton Scattering



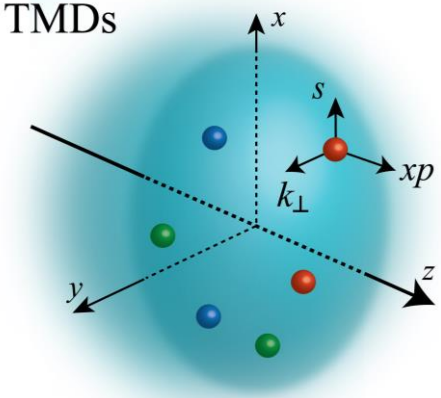
Unified View of Nucleon Structure

$W_p^u(x,k_T,r_T)$ *Wigner distributions*

5D Dist.

Transverse Momentum Dep. Dist.

TMDs

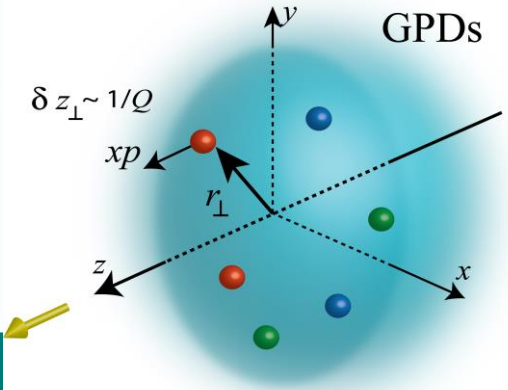


dr_T

d^2k_T

Generalized Parton Dist.

GPDs



TMD $f_1^u(x,k_T)$, $h_1^u(x,k_T)$

GPD

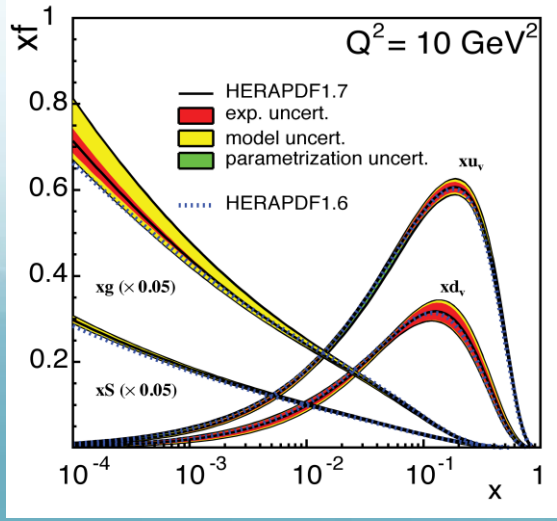
"3D" imaging

d^2k_T

d^2r_T

dx &Fourier Transformation

Parton Distribution Functions

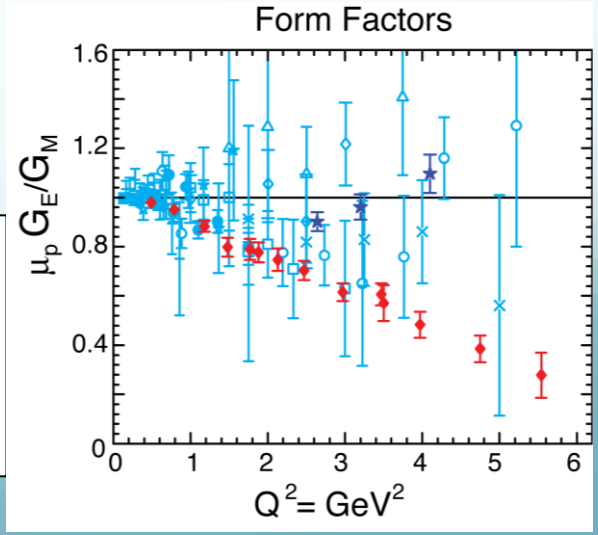


PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

1D

Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$

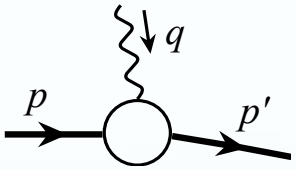
Form Factors

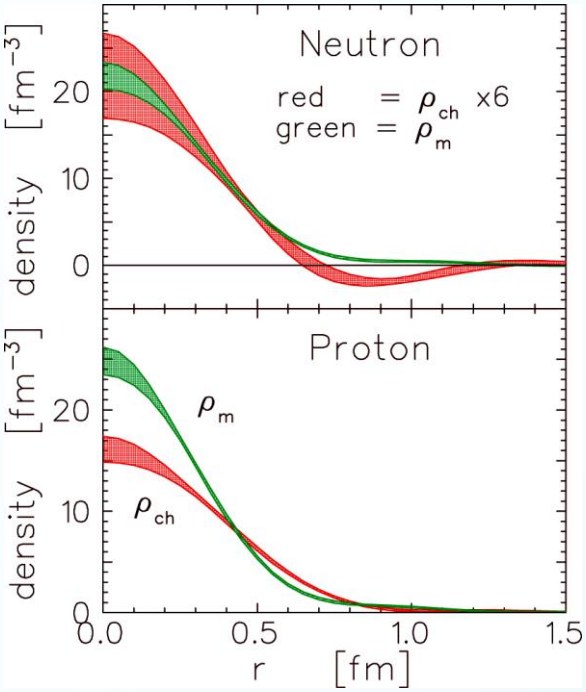


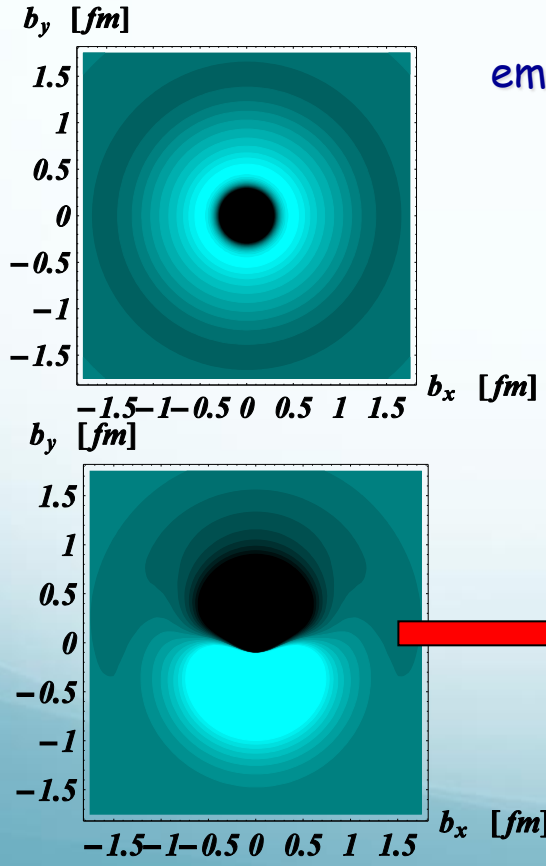
Elastic scattering and the charge inside the proton?

➢ Electric charge distribution:

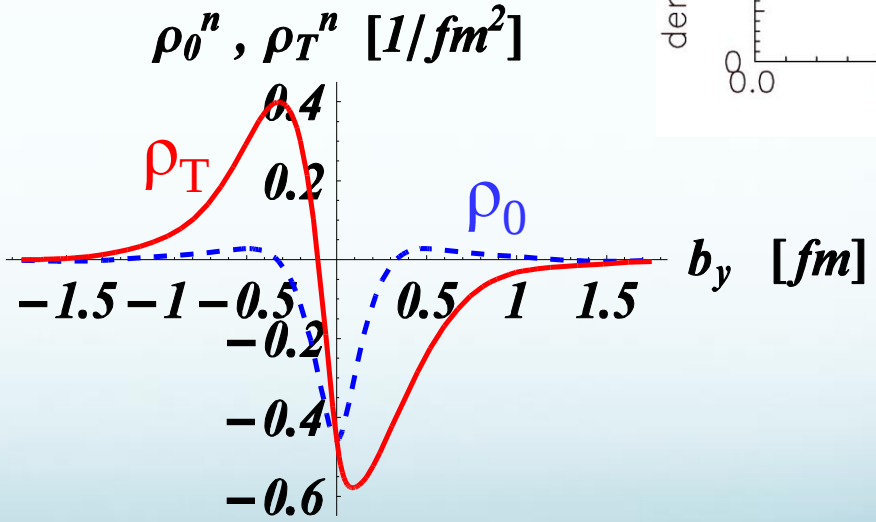
Elastic electric form factor
➡ Charge distributions







empirical quark transverse densities in Neutron



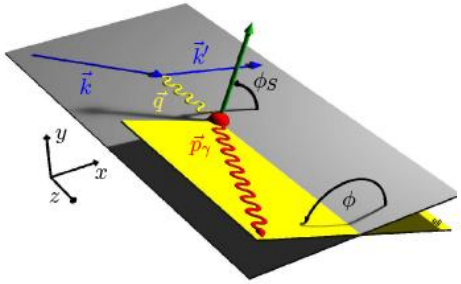
densities : Miller (2007); Carlson, Vanderhaeghen 2007)

induced EDM : $d_y = F_{2n}(0) \cdot e / (2 M_N)$

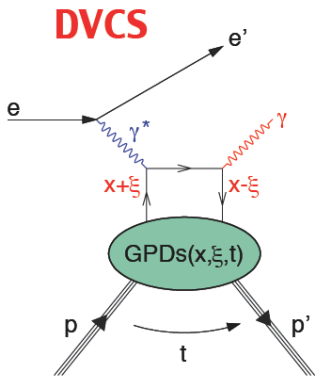
Deep Virtual Compton Scattering

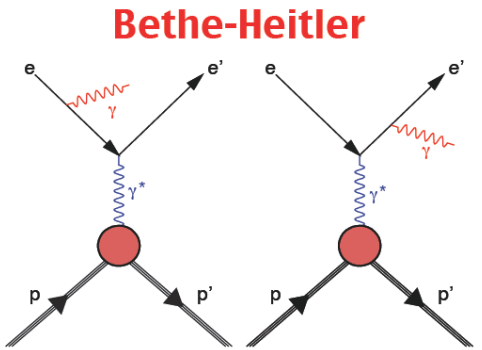
Information on the real and imaginary part of the QCD scattering amplitude

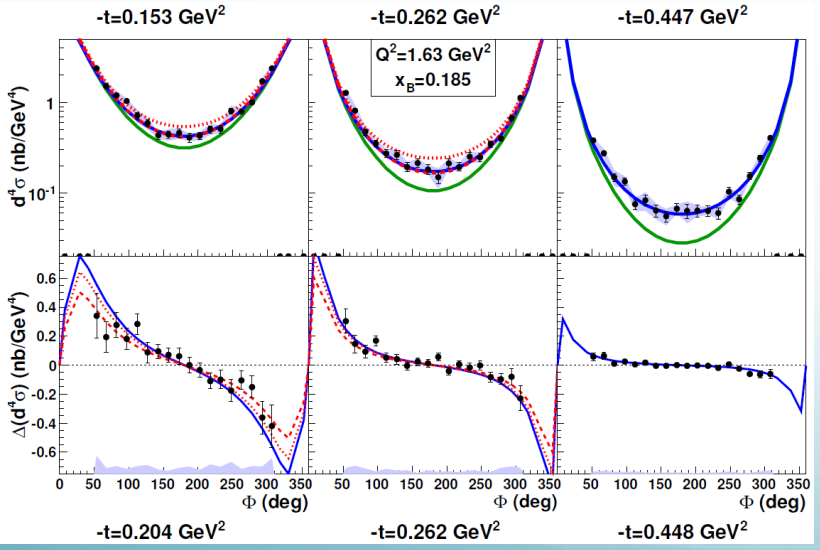
$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} \propto \left(|\mathcal{T}_{DVCS}|^2 + |\mathcal{T}_{BH}|^2 + \mathcal{I}\right)$$

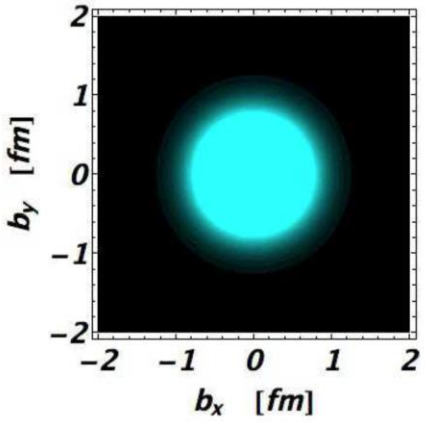


BH only
VGG (H only)
KM10 (Kumericki, Mueller)
KM10a

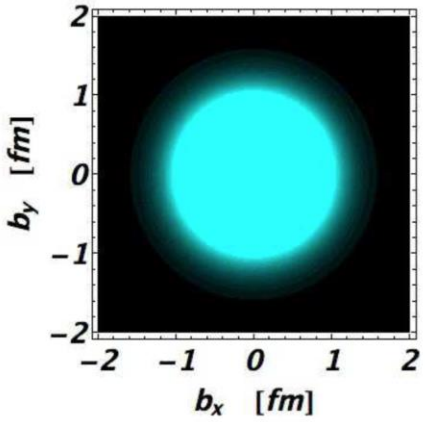








x=0.25

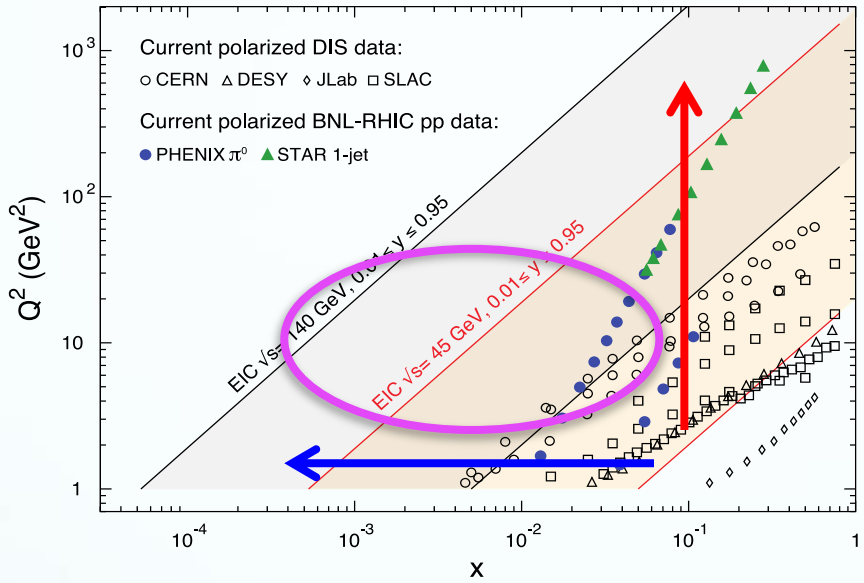


x=0.09

H. S. Jo et. al. [arXiv: 1504.02009]

M. Guidal et. al. [arXiv:1303.6600] hep-ph

EIC-Kinematic reach & Machine properties

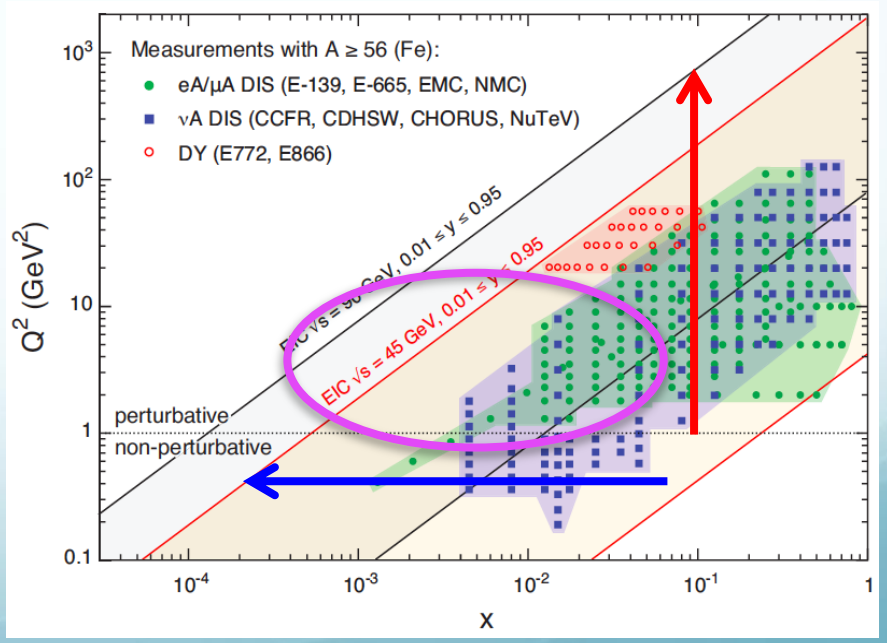


e-N collisions:

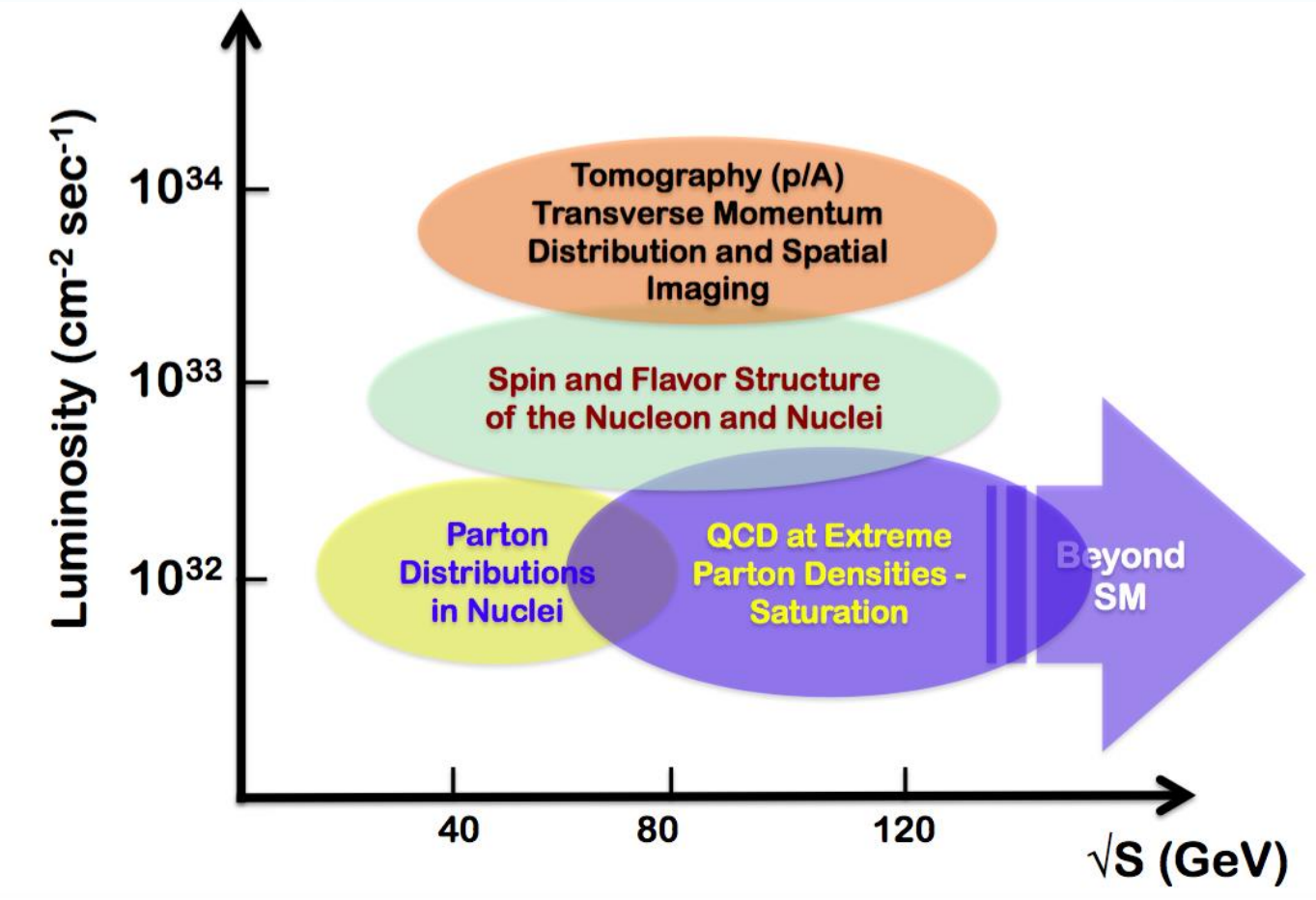
- ✓ First polarized e-p collider
- ✓ Collision energy: 20 – 150 GeV
- ✓ Luminosity ~ $10^{33\text{-}34}$ cm^{-2} s^{-1}
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range – evolution
- ✓ Wide x range – spanning from valence to low-x physics

e-A collisions:

- ✓ First e-A collider
- ✓ Polarized beams, p, d/^{3}He
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range - evolution
- ✓ Wide x region (high gluon densities)

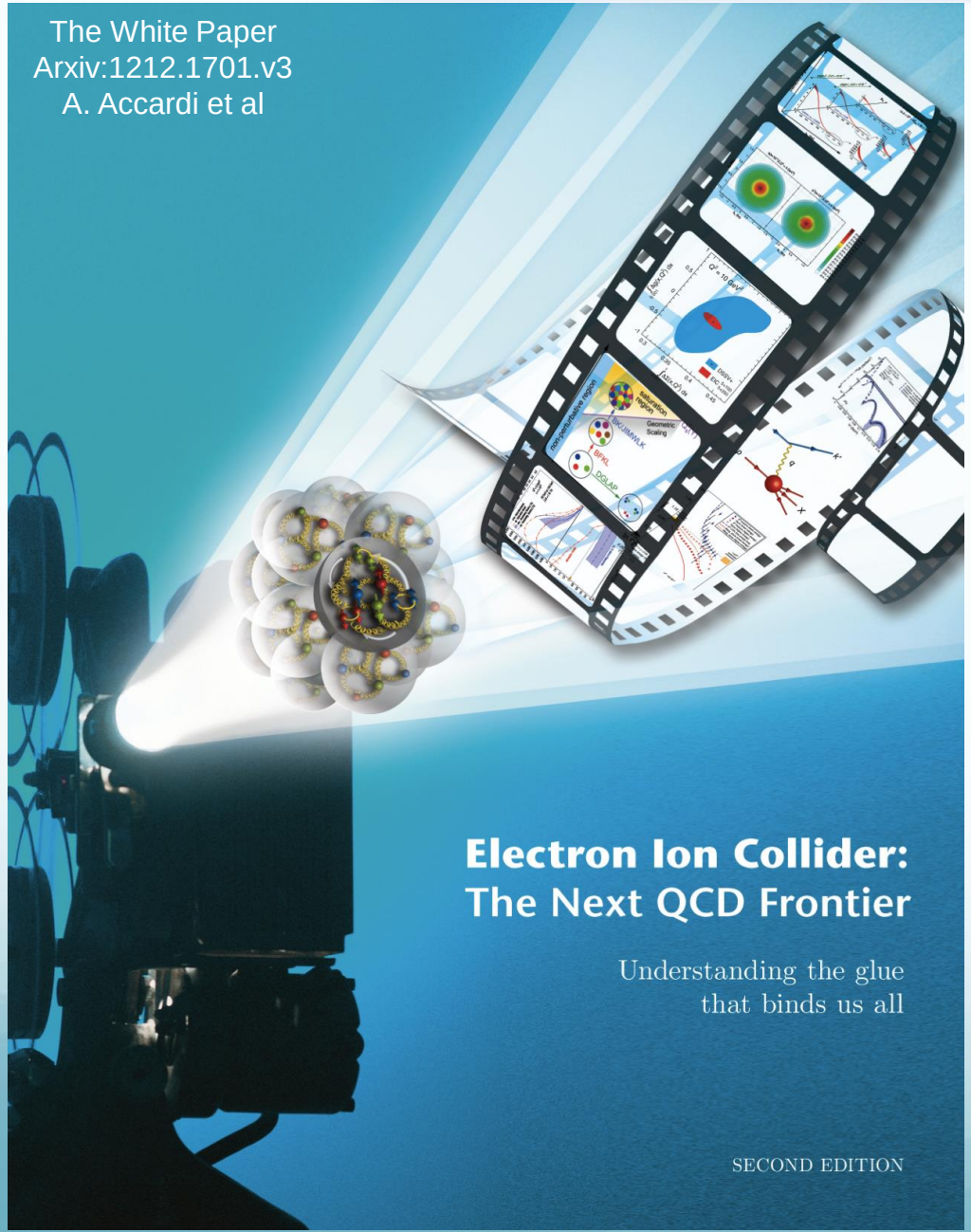


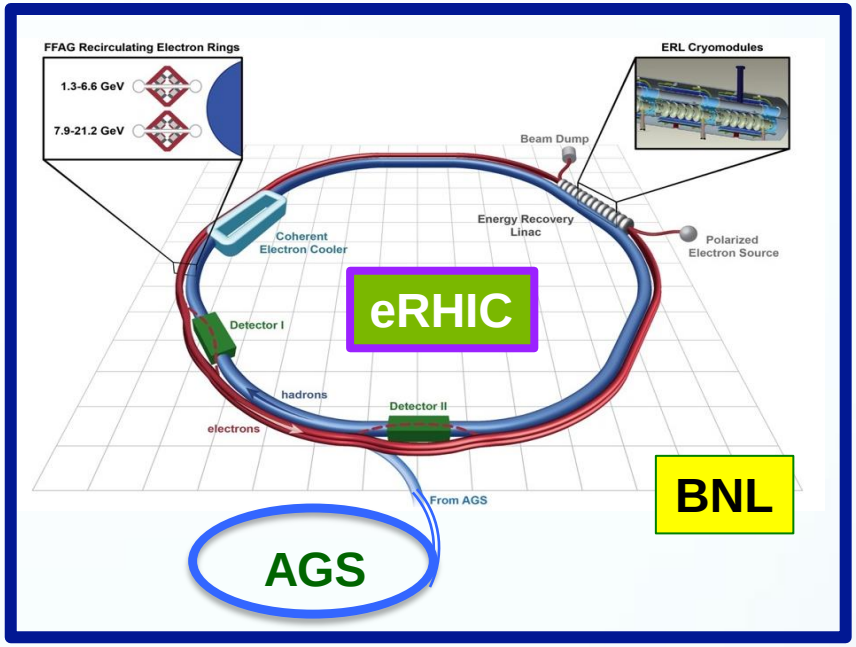
Electron-Ion Collider

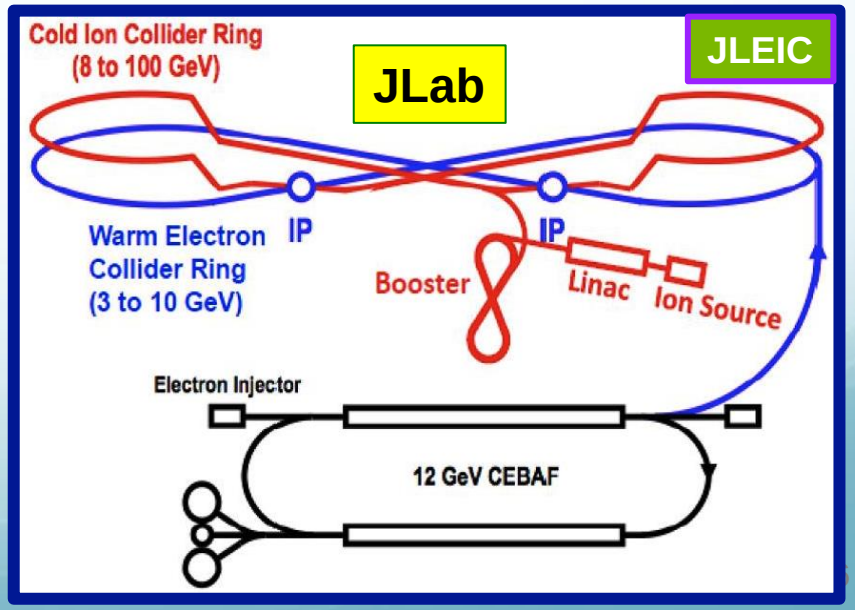


EIC: Two Options of Realization

The White Paper
Arxiv:1212.1701.v3
A. Accardi et al







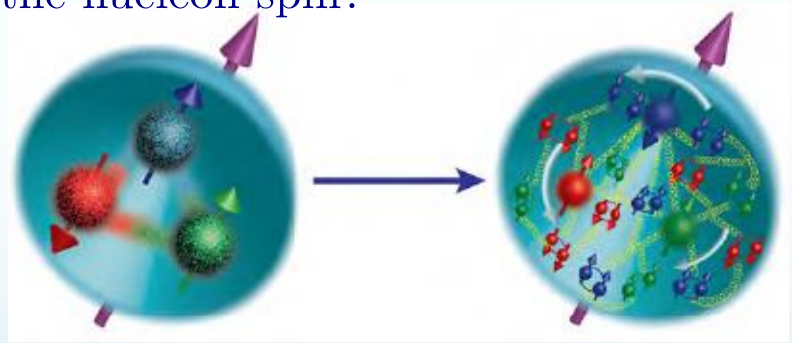
Fundamental QCD Question

How do quarks and gluons confine themselves into a proton?

The color confinement

"Hints" from knowing hadron structure

- **Hadron structure:**
  - **How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?** How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?



- **Proton spin:**

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

It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons

Need a polarized proton beam!

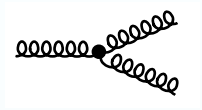
Fundamental QCD question - II

How do gluons saturate themselves into a new form of matter?

Color Glass Condensate

- **Gluon, unlike photon:**

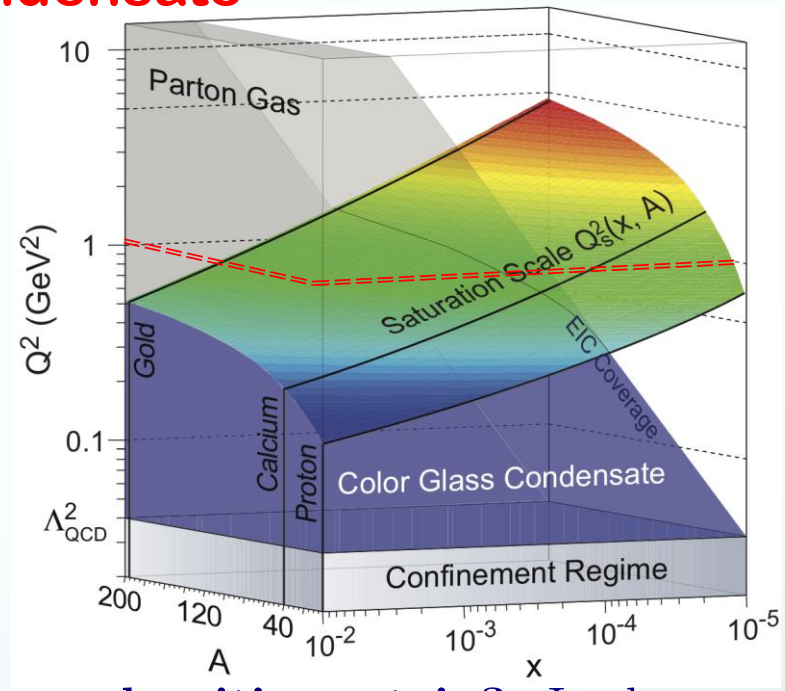
  Radiate:

  Recombine:

  - ✧ **Dynamical scale Q_s from the balance**
  - ✧ **New mathematical framework**
  - ✧ **Universal properties (CGC)**



From the EIC White Paper

- **Where does the saturation of gluon densities set in?** Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

Need a heavy ion beam!

Electron-Ion Collider

- **An ultimate machine to provide answers to QCD questions**
  - ✧ A collider to provide kinematic reach well into the gluon-dominated regime
  - ✧ An electron beam to bring to bear the unmatched precision of the electromagnetic interaction as a probe
  - ✧ Polarized nucleon beams to determine the distributions and correlations of sea quark and gluon distributions with the nucleon spin
- **A machine at the frontier of polarized luminosity, combined with versatile kinematics and beam species**

Answers all above QCD questions at a single facility

EIC: Goals and deliverables

The key measurements

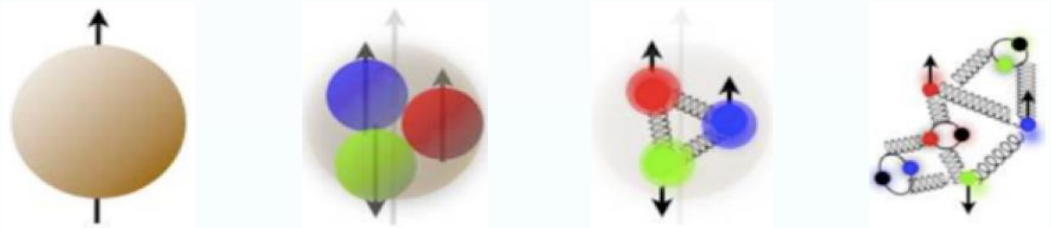
Why is it a unique facility with capabilities unmatched by existing and planned facilities?

Proton spin and hadron structure?
Beyond a one dimensional view

- **Proton – composite particle of quarks and gluons:**

  Mass = intrinsic (quark masses) + quarks motion (kinetic + potential)
  + gluon motion (kinetic + potential) + trace anomaly

  Spin = intrinsic (partons spin) + motion (orbital angular momentum)

$S(\mu) = \frac{1}{2}$  $\mu \Rightarrow \infty$

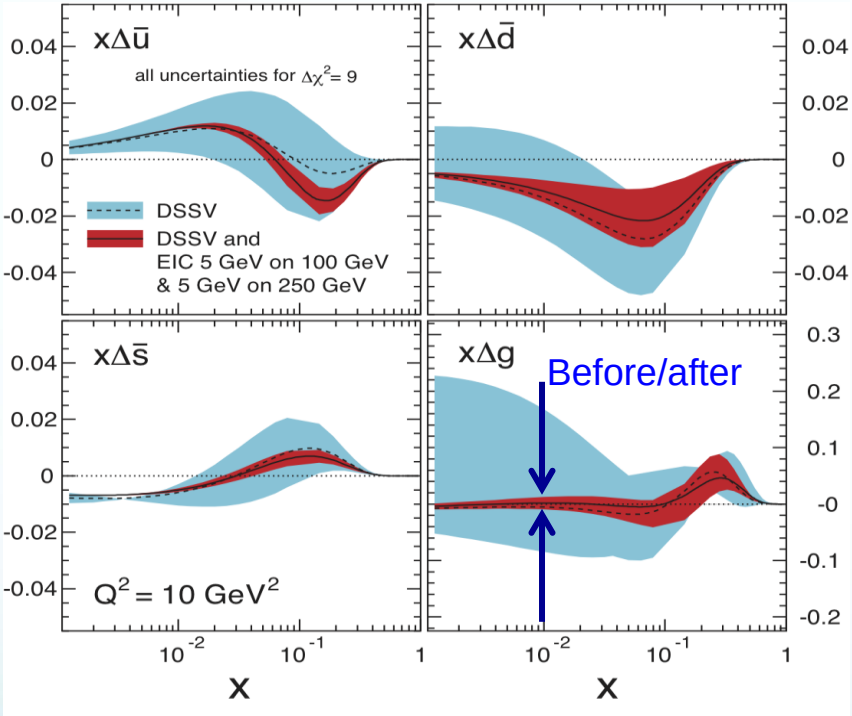
- **Over 20 years effort (following EMC discovery)**
  - ✧ Quark (valence + sea) helicity: $\sim 30\%$ of proton spin
  - ✧ Gluon helicity: positive with large uncertainty from limited x range

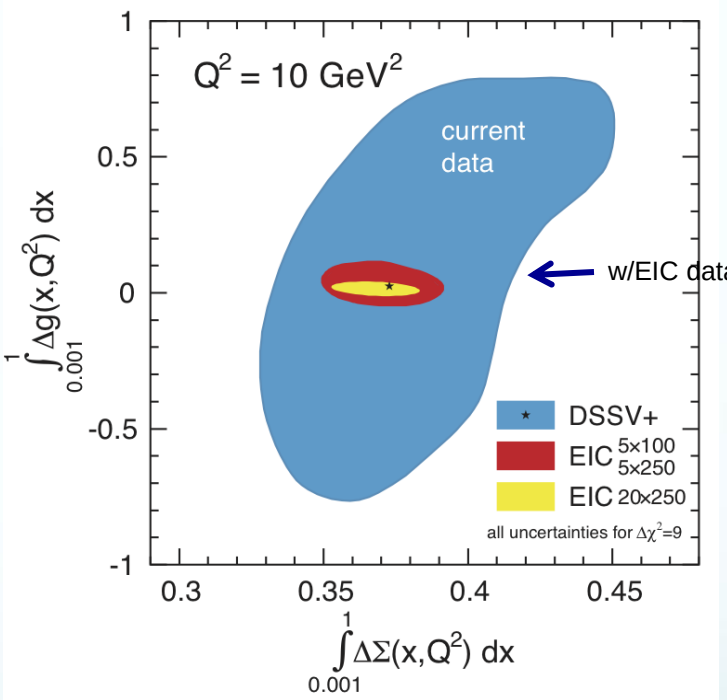
How to explore the "full" gluon and sea quark contribution?
How to quantify the role of orbital motion?

Proton spin and hadron structure?

- **The EIC – the decisive measurement** (1st year of running):

(Wide Q^2, x including low x range at EIC)

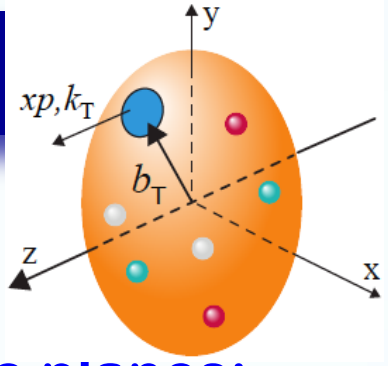




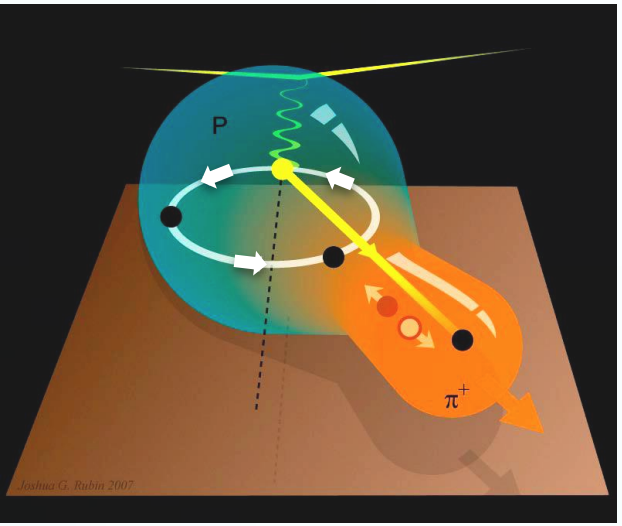
No other machine in the world can achieve this!

- **Solution to the proton spin puzzle:**
  - ✧ ***Precision measurement of ΔG – extends to smaller x regime***
  - ✧ ***Orbital angular momentum – motion transverse to proton's momentum***

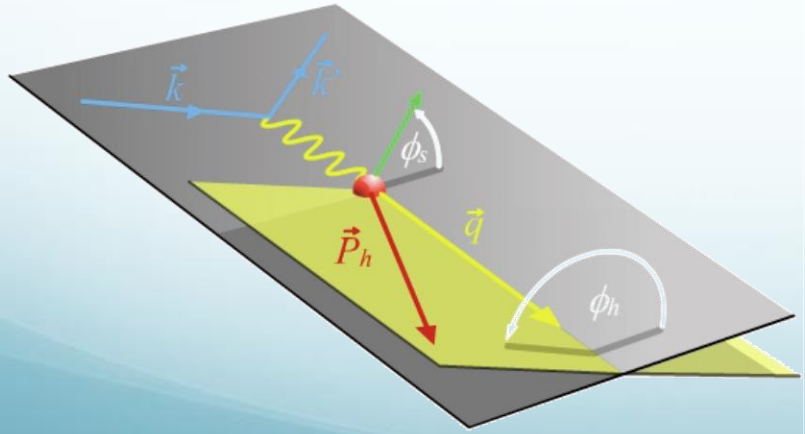
EIC is the best for probing TMDs



- **TMDs - rich quantum correlations:**



- **Naturally, two scales and two planes:**
  - Two scales (theory-QCD TMD factorization):
    high Q - localized probe
    Low p_T - sensitive to confining scale
  - Two planes:
    angular modulation to separate TMDs



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

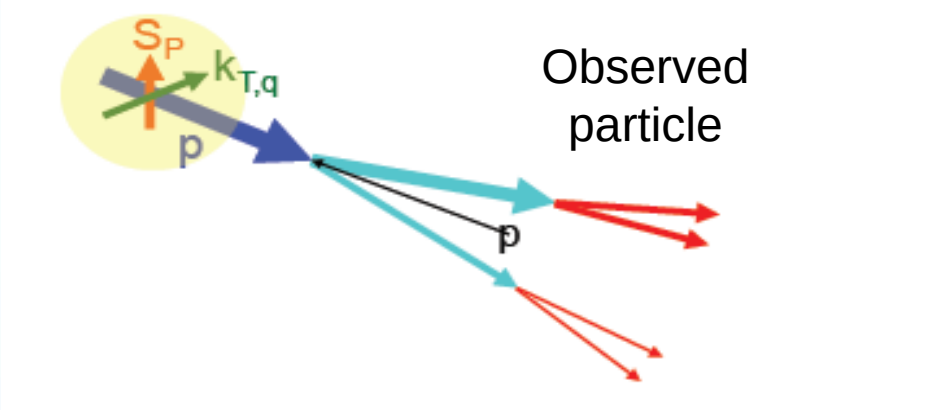
$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

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

Hard to separate TMDs in hadronic collisions

Confined motion in a polarized nucleon

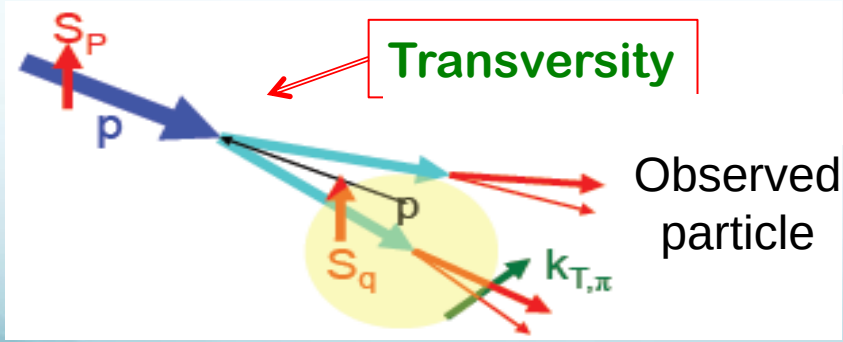
- **Quantum correlation between hadron spin and parton motion:**



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

- **Quantum correlation between parton spin and hadronization:**



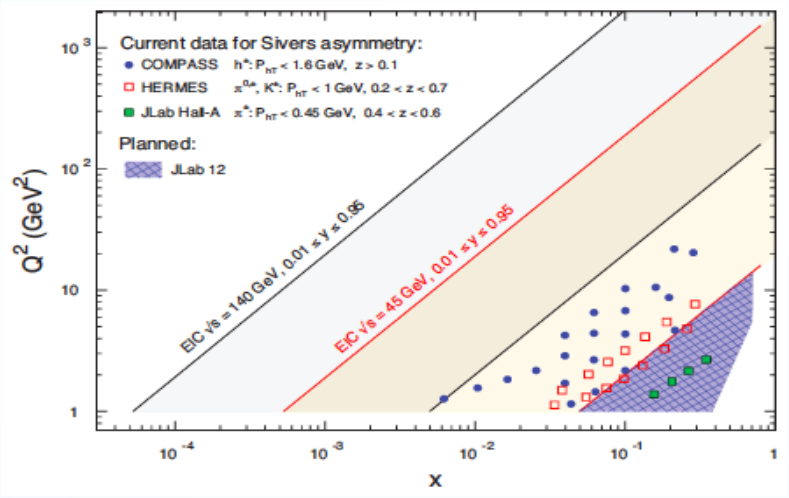
Collins effect – Collins function

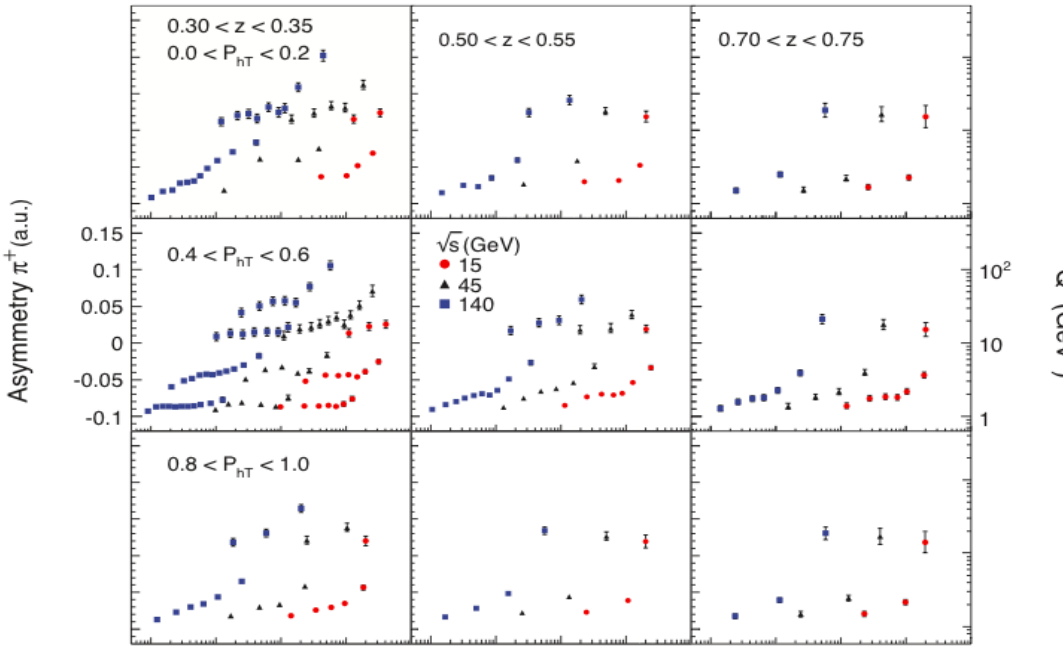
Parton's transverse spin influence its hadronization

JLab12 and COMPASS for valence, EIC covers the sea and gluon!

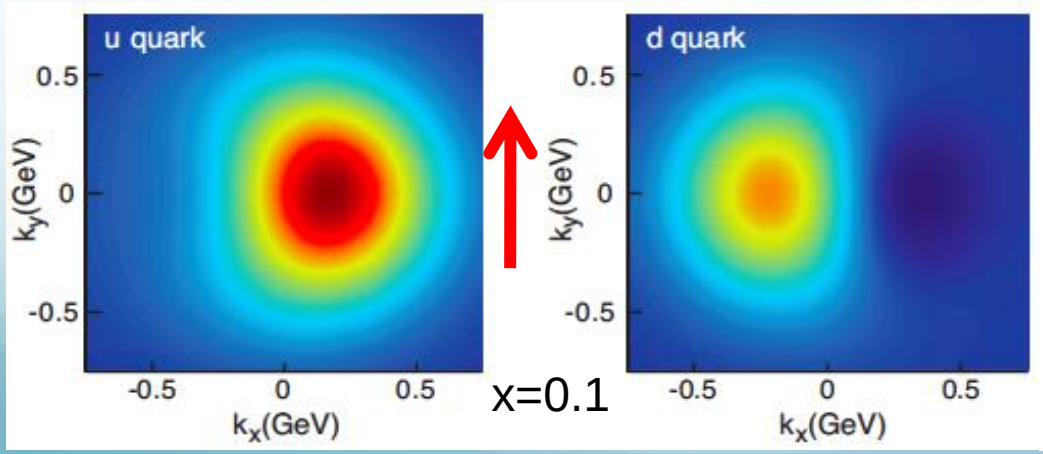
What can EIC do for the Sivers function?

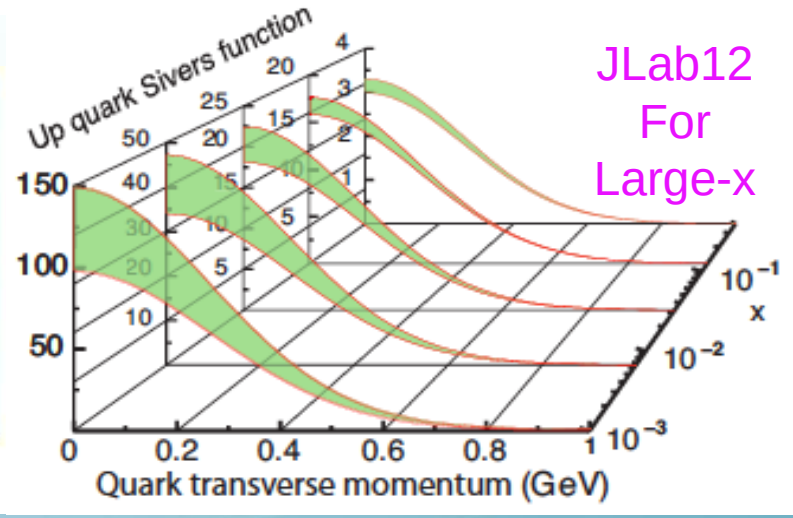
- Coverage and Simulation:





- Unpolarized quark inside a transversely polarized proton:



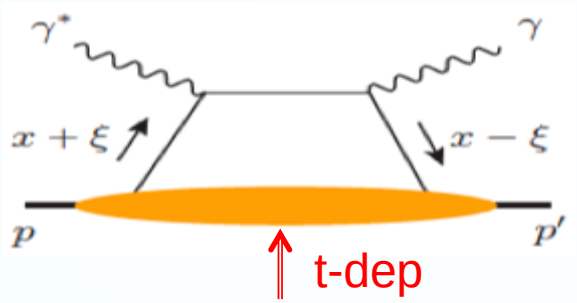


No other machine in the world can do this!

Spatial imaging of sea quarks

EIC: Sea quarks

- **Exclusive processes - DVCS**:



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

$$t = (p' - p)^2$$

$$\xi = (P' - P) \cdot n/2$$

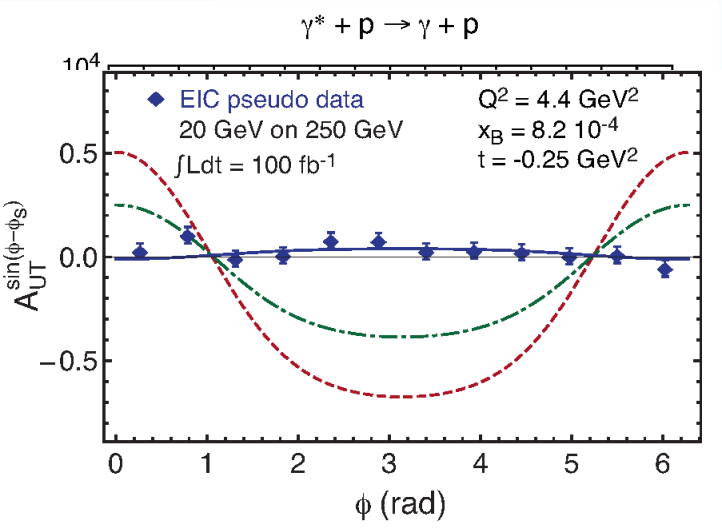
CFFs→GPDs

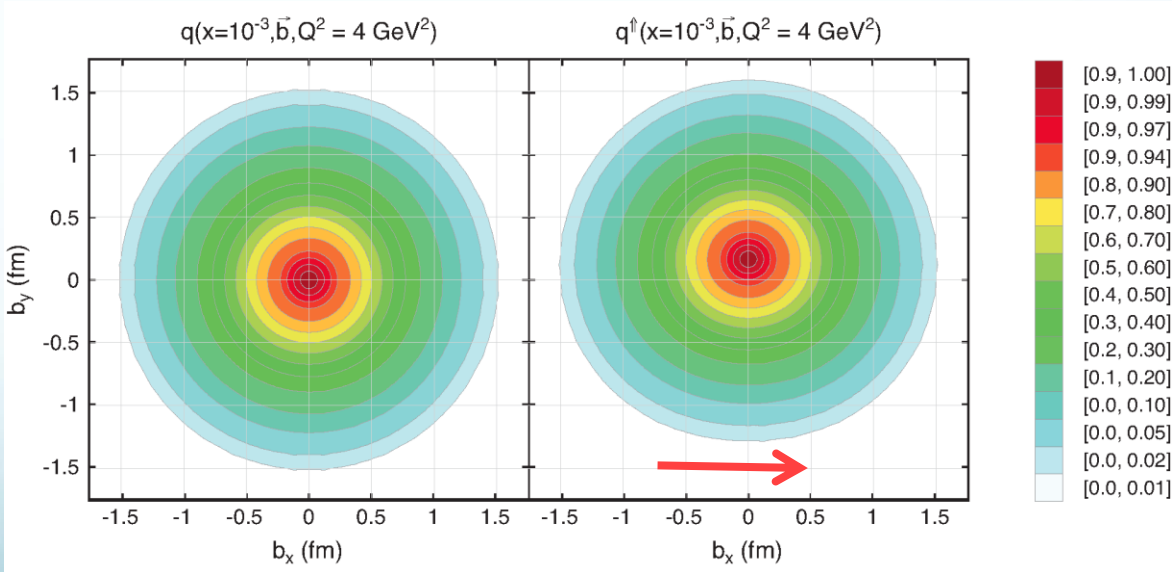
$$H_q(x,\xi,t,Q), E_q(x,\xi,t,Q), \ldots$$

F.T. of t-dep → Spatial distributions

JLab 12: Valence quarks

EIC: Sea quarks



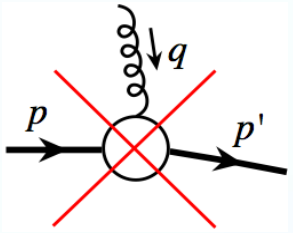


How about the glue?

An Important question!

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

- **Unfortunately NO color elastic nucleon form factor!**

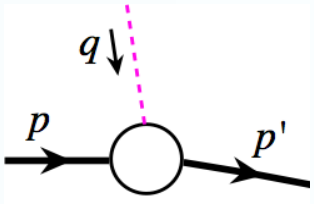


Hadron is colorless and gluon carries color

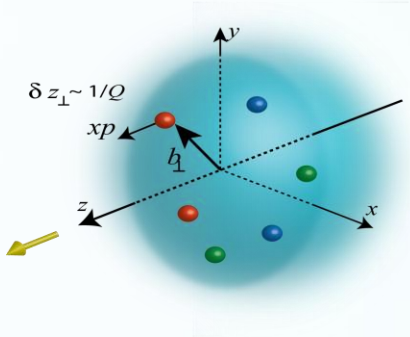
What to do?

Spatial imaging of gluons

➢ **Need Form Factor of density operator**:

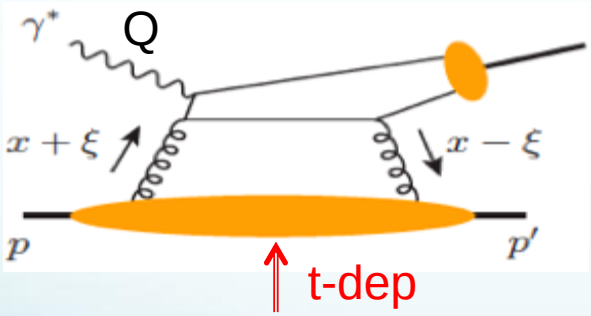


- ✧ Exchange of a colorless “object”
- ✧ “Localized” probe
- ✧ Control of exchanged momentum



➢ **Exclusive vector meson production:**

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

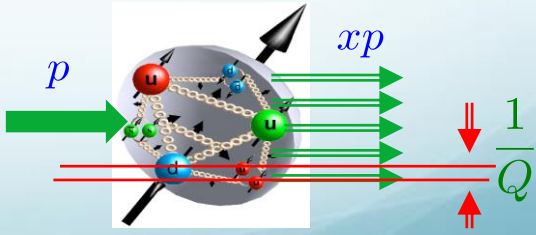


J/Ψ, Φ, …

- ✧ Fourier transform of the t-dep

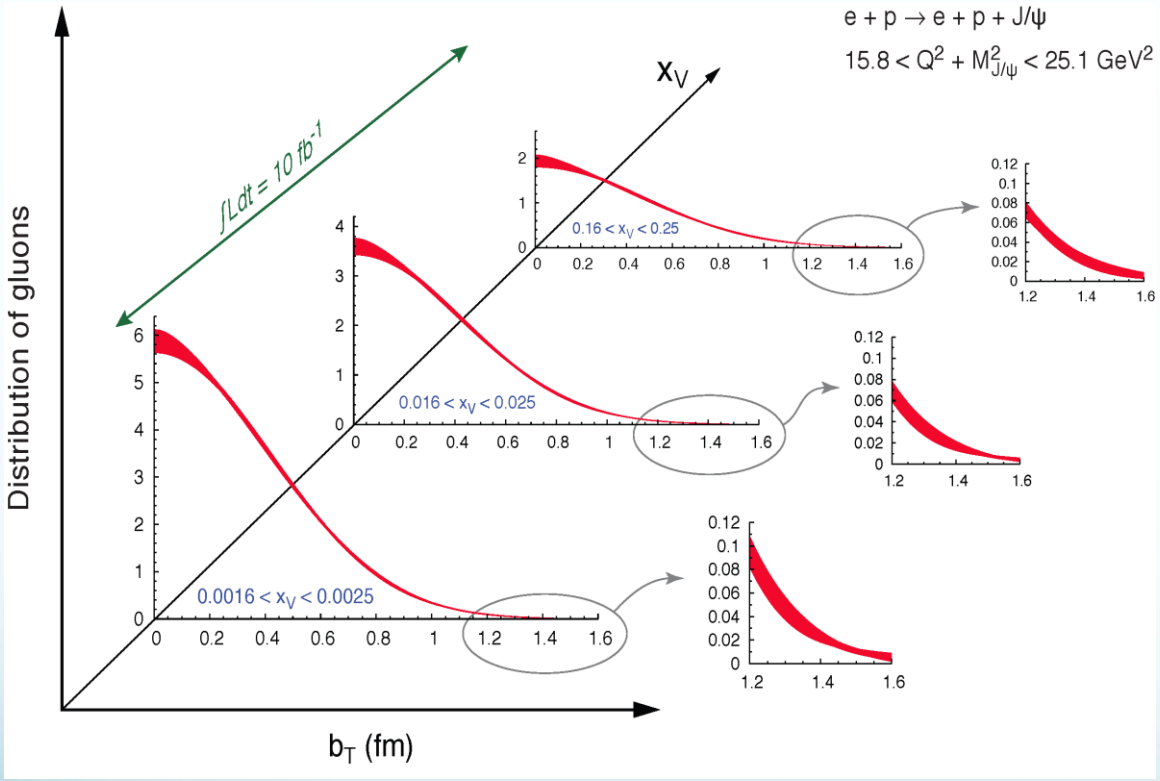
➡ Spatial imaging of glue density

- ✧ Resolution ~ 1/Q or 1/M_Q



Spatial imaging of gluon density

- **Gluon imaging from simulation:**



$$x_V = \frac{M^2_{J/\psi} + Q^2}{W^2 + Q^2 - M^2_N}$$

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

Images of gluons from exclusive J/ψ production

Only possible at the EIC: From the valence quark region deep into the sea quark region

A direct consequence!

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

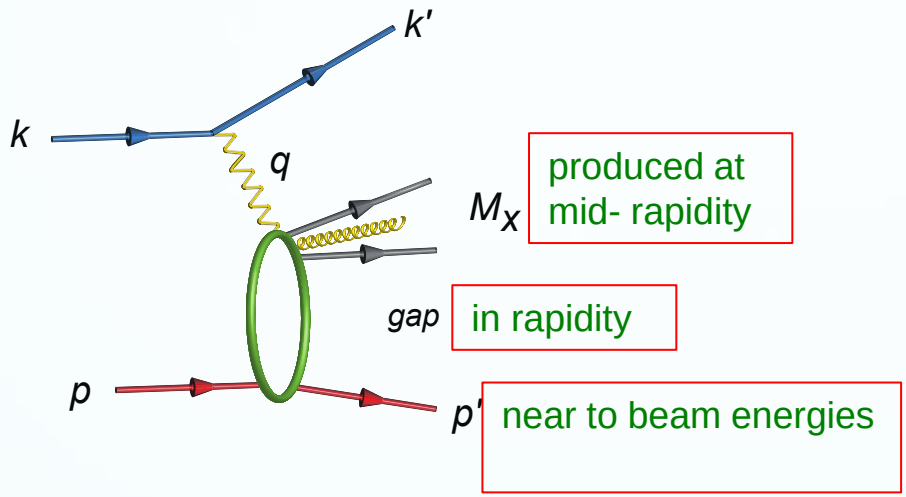
$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\,[H_q(x,\xi,t) + E_q(x,\xi,t)] = \frac{1}{2}\Delta q + L_q$$

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

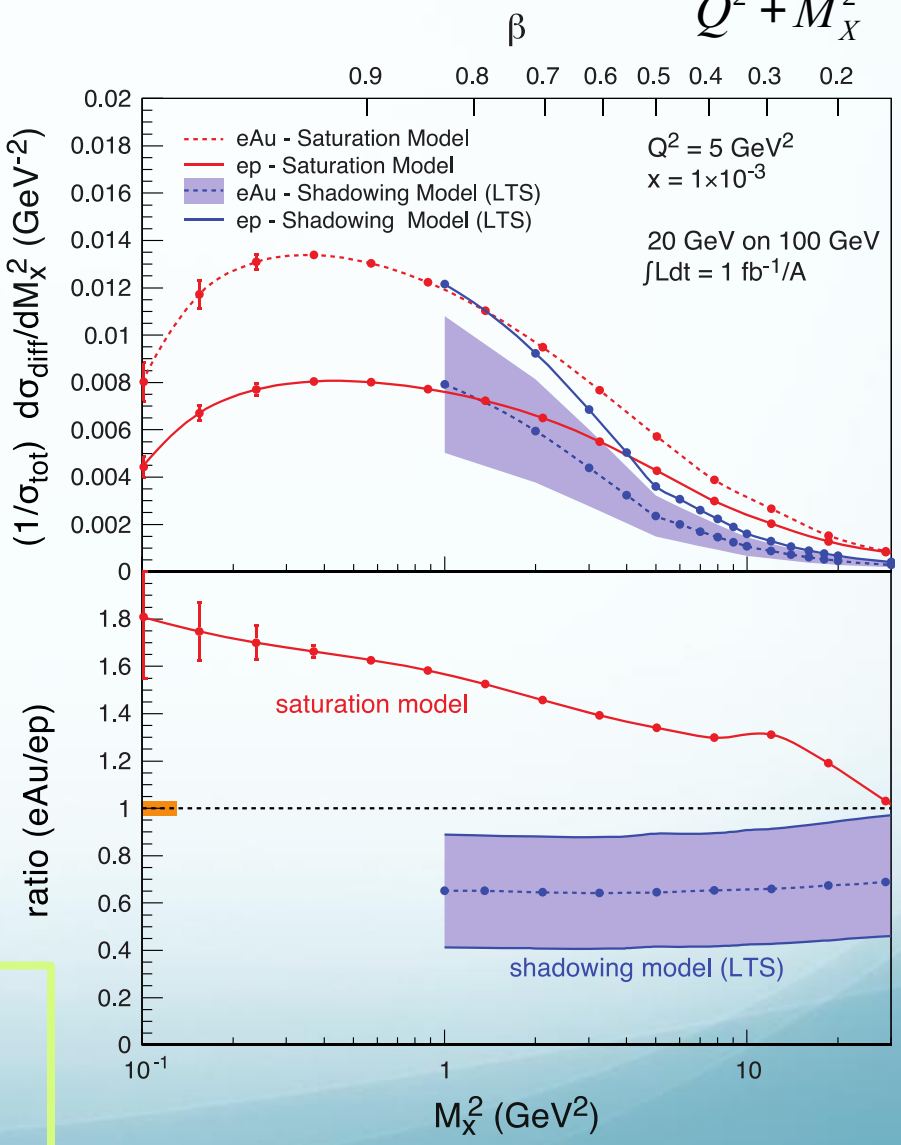
The Best Signature for Gluon Saturation

Diffractive cross section

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



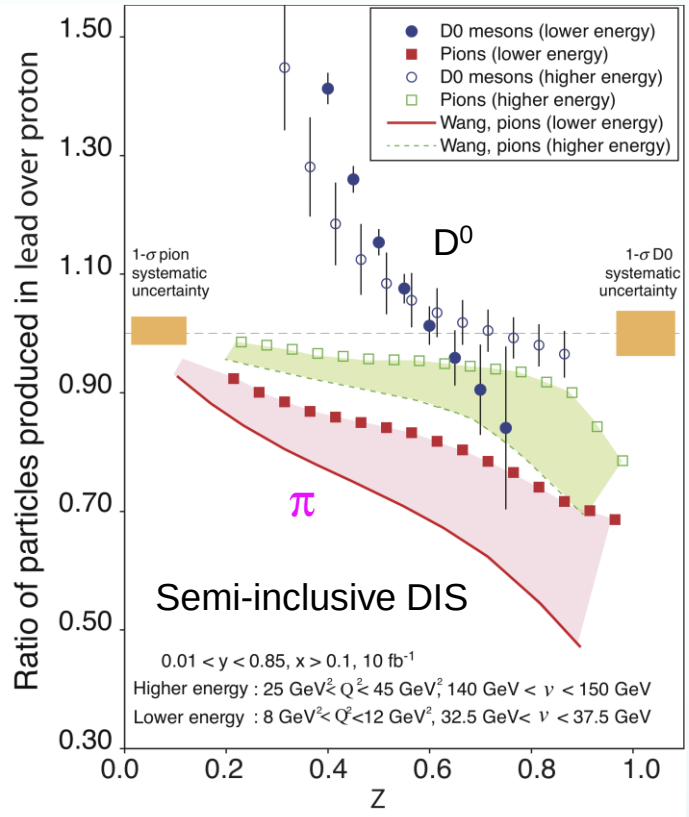
$$b \gg \frac{Q^2}{Q^2 + M_X^2}$$



- Color singlet exchange, Strong non-linear effect
- Factorization for diffractive process works in DIS, not in pp, pA or AA

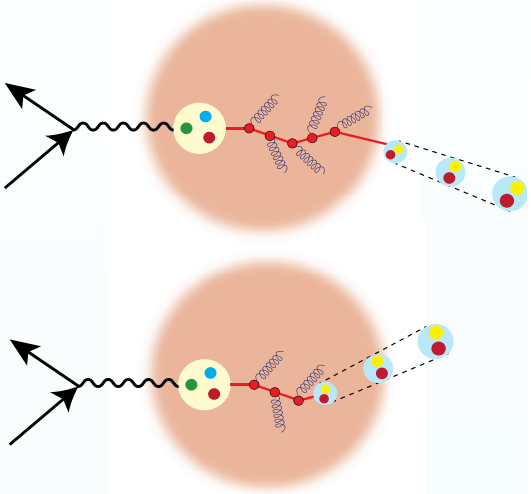
At HERA: 15% of DIS are hard diffractive events!
At EIC: **Saturation (CGC model) 25% of DIS are expected to be hard diffractive events?**

How do Hadrons Emerge from Created Partons?



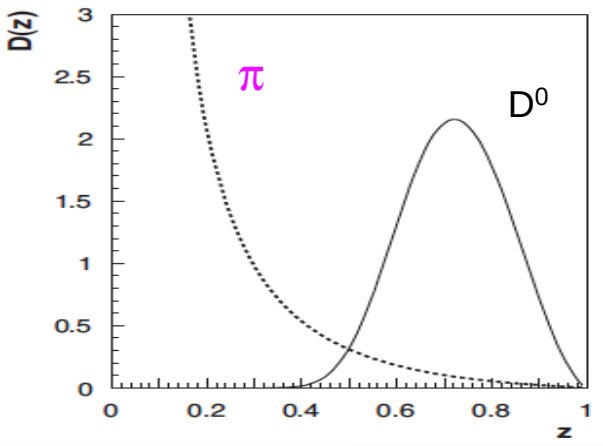
(z) **Fraction of the photon energy v carried by the hadron**

Hadronization outside



Hadronization inside

Mass dependence of fragmentation function



- At the EIC, we will have unprecedented range in photon energies
- We can control parton kinematics
- We will use nuclei as femtometer detector to study space-time dynamics of hadronization

The many fronts of experimental studies in an EIC

Inclusive

Generalized Parton Distributions

Since 1998

Exclusive reactions In nucleons and nuclei

Elastic form factors
Deep Virtual Compton Scattering
Deep Virtual Meson Production

Transverse Momentum Dependent D.

Since 2002

Semi-Inclusive DIS In nucleons and nuclei

Distributions and Fragmentation functions

Parton distributions
Sum rules and polarizabilities

Saturation in Nucleon and Nuclei
Inclusive, Semi-Inclusive and Exclusive reactions in Nucleon and Nuclei
Structure functions, hadron correlations and diffractive scattering

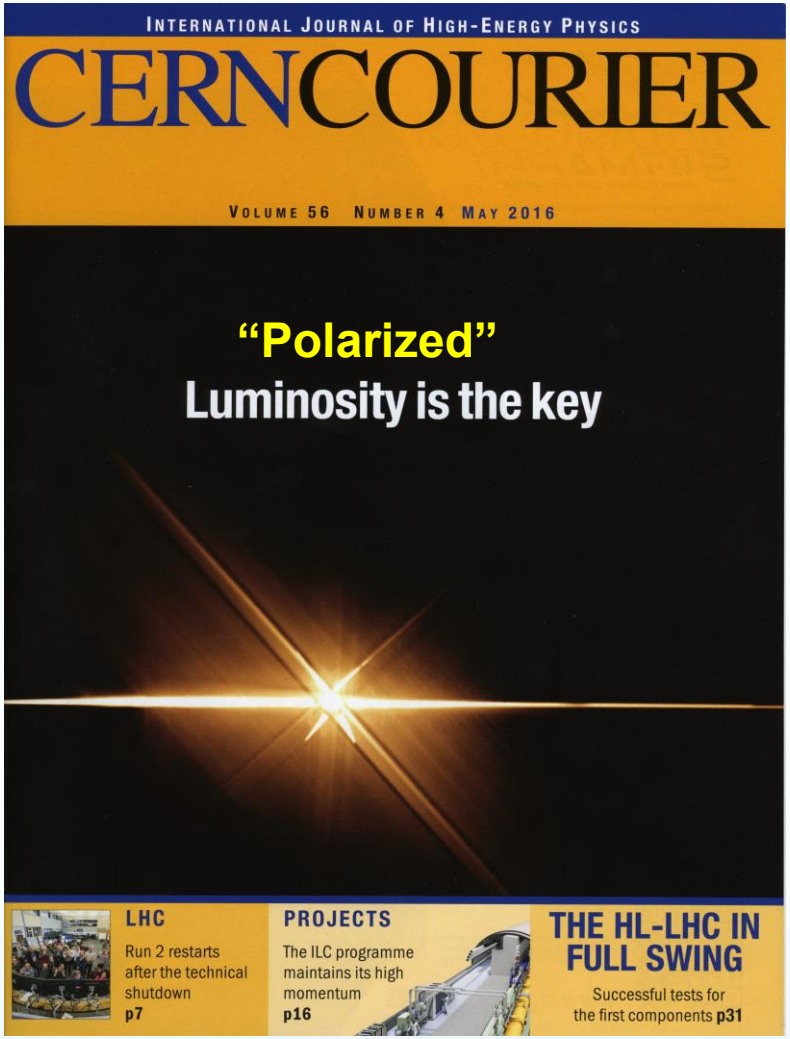
Electroweak probe to hadronic systems

Precision electroweak/Beyond the standard Model

Summary

- EIC is “the” machine to understand the glue that bind us all
- It is “the” brightest sub-femtometer scope to ANSWER fundamental questions in QCD in ways that no other facility in the world can
- Extends the QCD programs developed at BNL and JLab in dramatic and fundamentally important ways
- EIC would benefit fundamental nuclear science and accelerator / detector technology

Thank you!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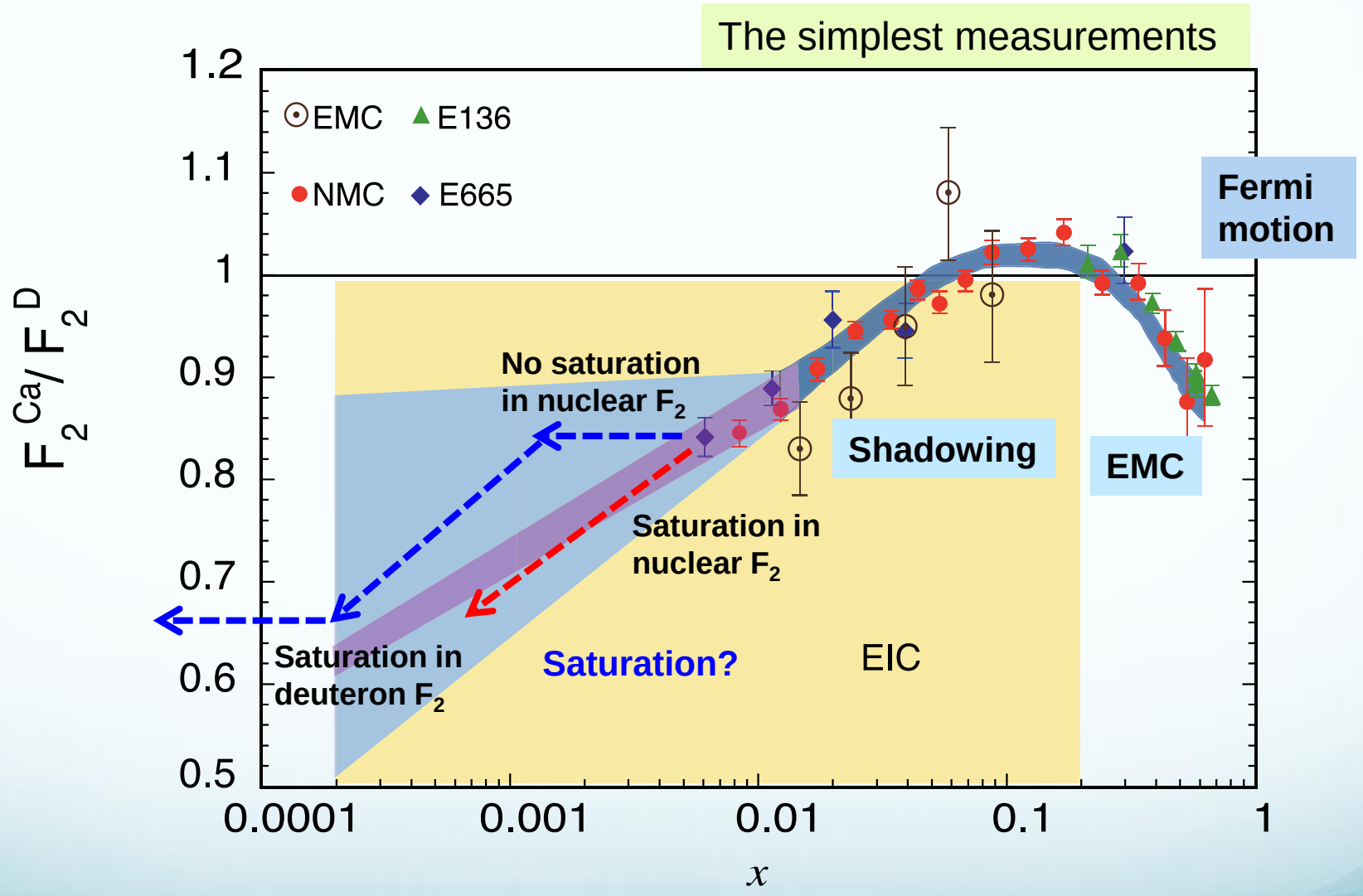
CERNCOURIER
VOLUME 56 NUMBER 4 MAY 2016
"Polarized"
Luminosity is the key
LHC
Run 2 restarts after the technical shutdown p7
PROJECTS
The ILC programme maintains its high momentum p16
THE HL-LHC IN FULL SWING
Successful tests for the first components p31

Probing Gluon Saturation



- Could a nucleus behave like a large proton at small x ?
- What is the A dependence of saturation scale?

Physics opportunities at EIC

➢ Machine parameters

- ✧ Collision energy: $\sqrt{s} \sim 20 - 100$ GeV Upgradable to ~ 150 GeV
- ✧ Luminosity: **$10^{33\text{-}34}$ cm^{-2} s^{-1}** (compare to **HERA luminosity ~** 5x10^{31} **cm^{-2} s^{-1}**)
- ✧ Polarized proton and various nuclei

➢ Key Deliverables

Deliverables	Observables	What we learn
Sea/gluon x~10^{-2} -10^{-4} S.F.	Inclusive DIS at low-x, in e-p	**Sea/gluon contrib. to proton spin, flavor separation**
Polarized and unpolarized TMDs	SIDIS e-p, single hadron, Dihadron and heavy flavors	**3D momentum images of quarks and gluons**
Sea quarks and gluon GPDs	DVCS, Exclusive J/Ψ, ρ,φ production	**Spatial images of sea and gluon, angular mom. J_q , J_g**
Weak mixing angle	PV asymmetries in DIS	**EW symmetry breaking, BSM**