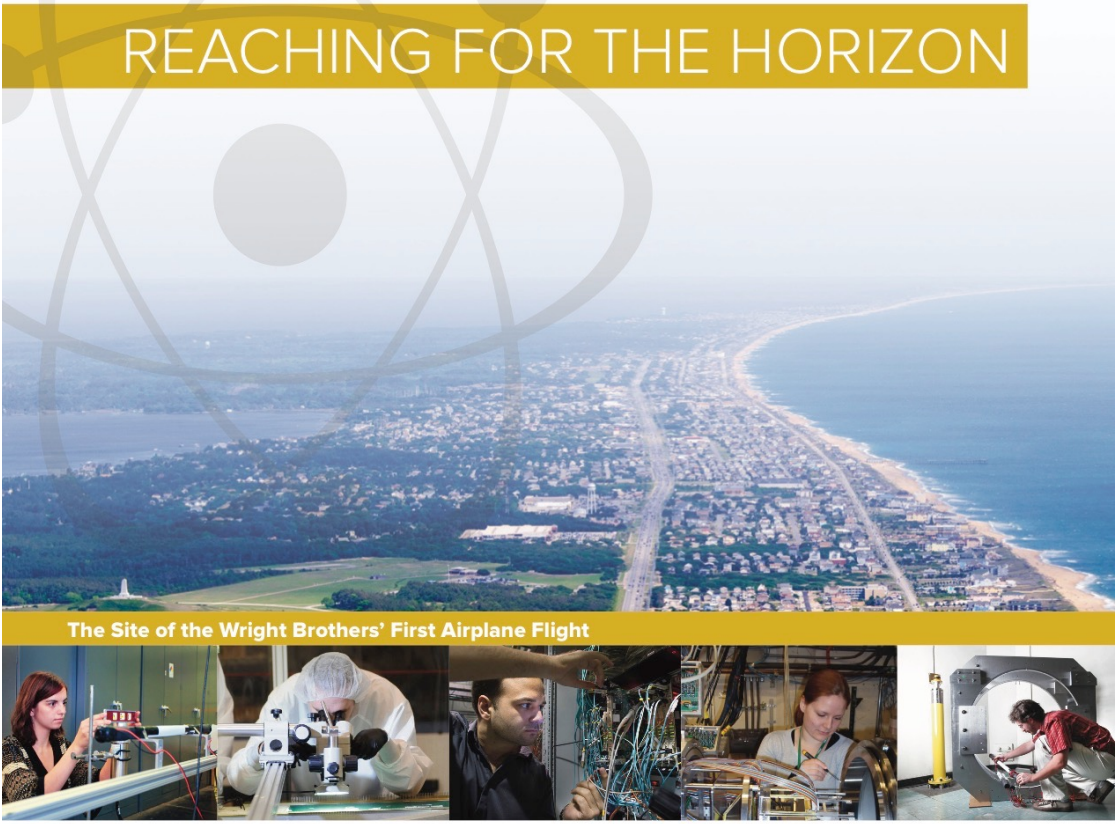


The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

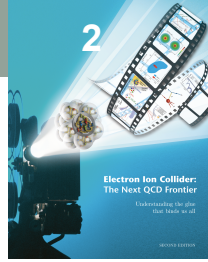
http://science.energy.gov/np/reports

RECOMMENDATION:

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

Initiatives:

Theory
Detector & Accelerator R&D



Electron Ion Collider: The next QCD frontier

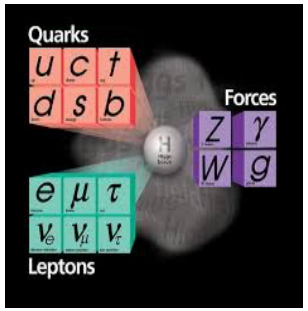
Understanding the Glue that Binds Us All

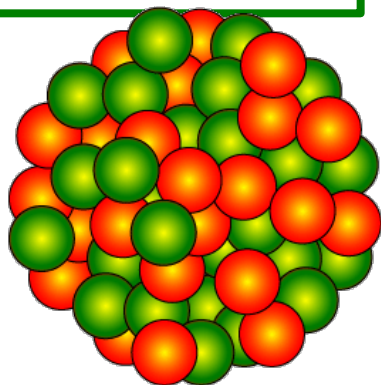
Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

Why the EIC?

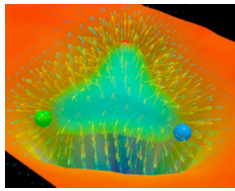
To understand the role of gluons in binding quarks & gluons into Nucleons and Nuclei





Role of gluons in hadron & nuclear structure

Dynamical generation of hadron masses & nuclear binding



- Massless gluons & almost massless quarks, *through their interactions,* generate more than 98% of the mass of the nucleons:

Without gluons, there would be no nucleons,

no atomic nuclei… no visible world!

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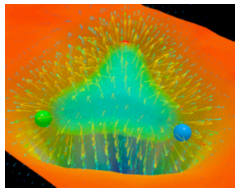

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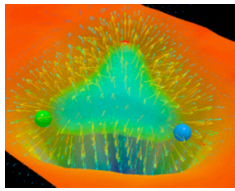

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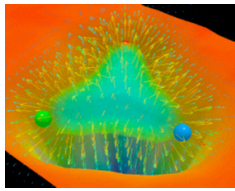

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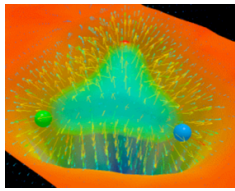

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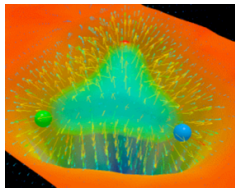

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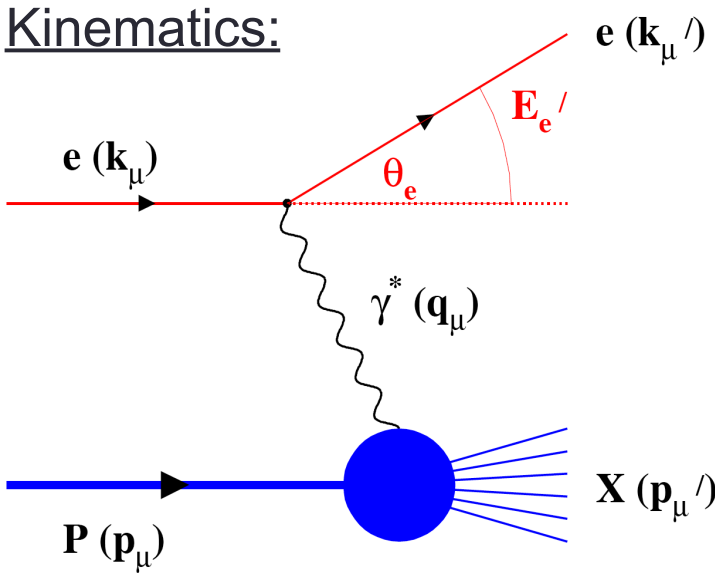
CONFINEMENT!

Deep Inelastic Scattering

Kinematics:



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

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

Measure of resolution power

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

Measure of inelasticity

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

Measure of momentum fraction of struck quark

Hadron :

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

Inclusive measurements:

e+p/A → e'+X

Detect only the scattered lepton in the detector

Semi-inclusive measurements:

e+p/A → e'+h(π,K,p,jet)+X

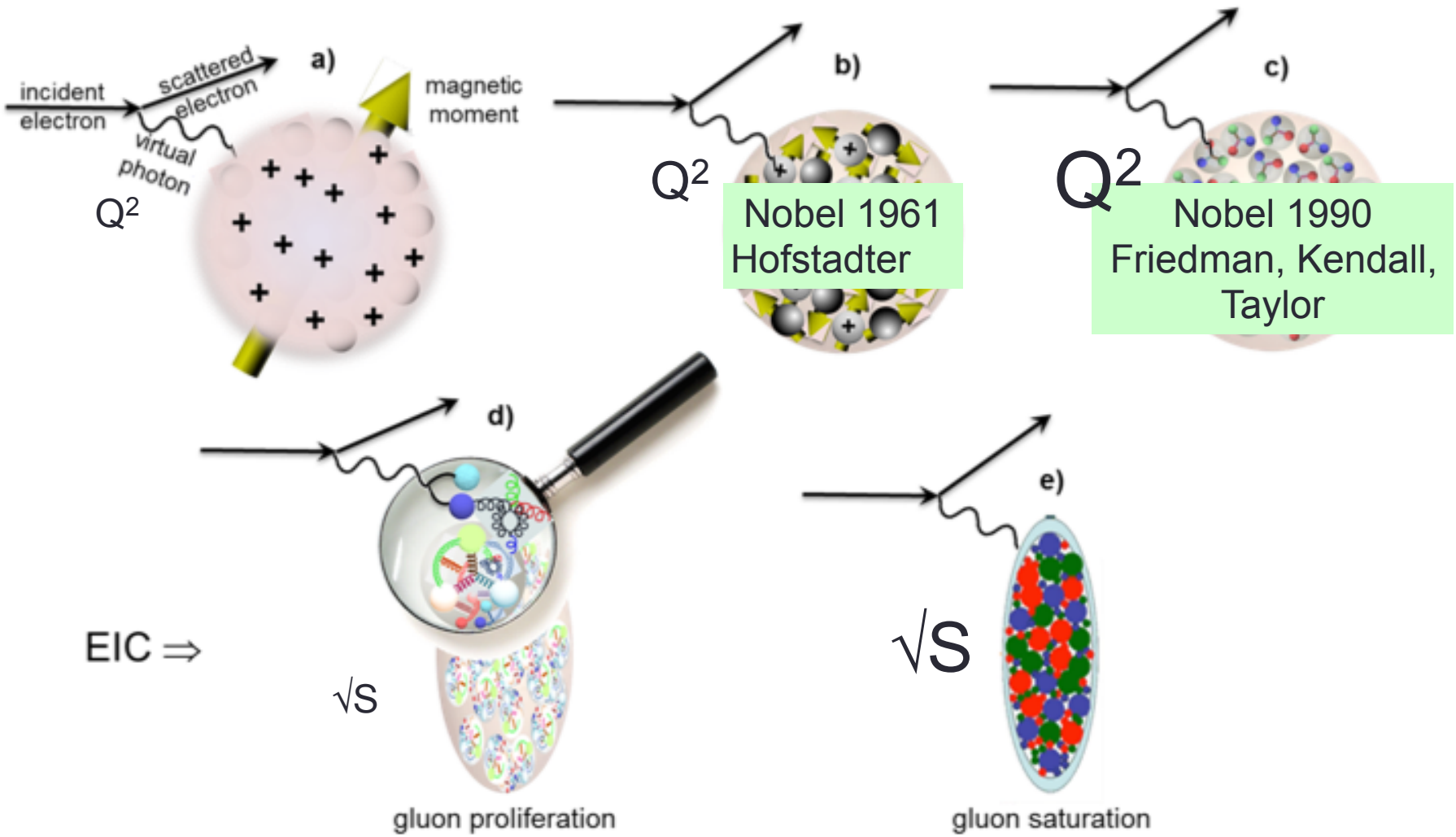
Detect the scattered lepton in coincidence with identified hadrons/jets

Exclusive measurements:

e+p/A → e'+h(π,K,p,jet)+p'/A'

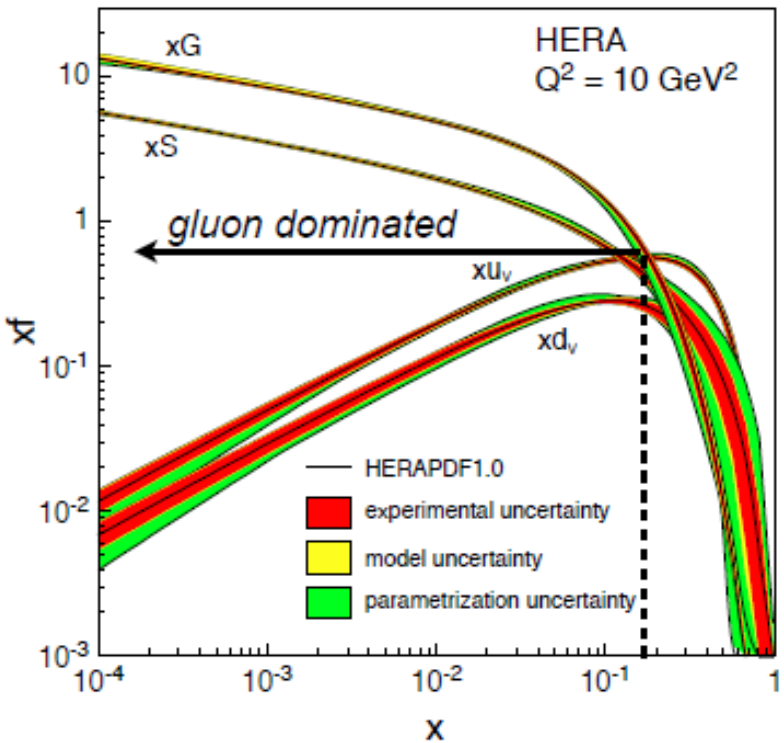
Detect scattered lepton, identify produced hadrons/jets and measure target remnants

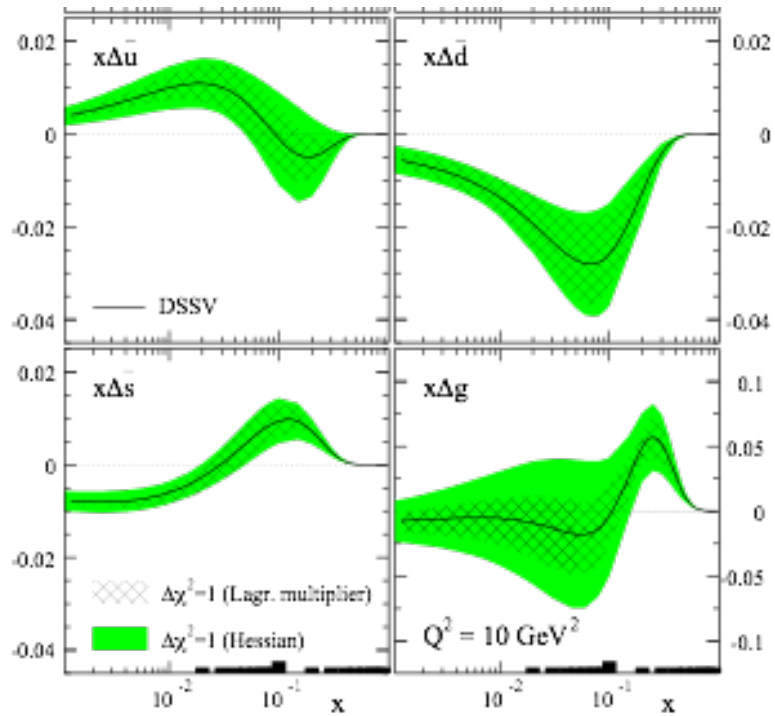
Deep Inelastic Scattering allows the Ultimate Experimental Control



What does a proton look like? Unpolarized & polarized

We only *have a 1-dimensional picture!*





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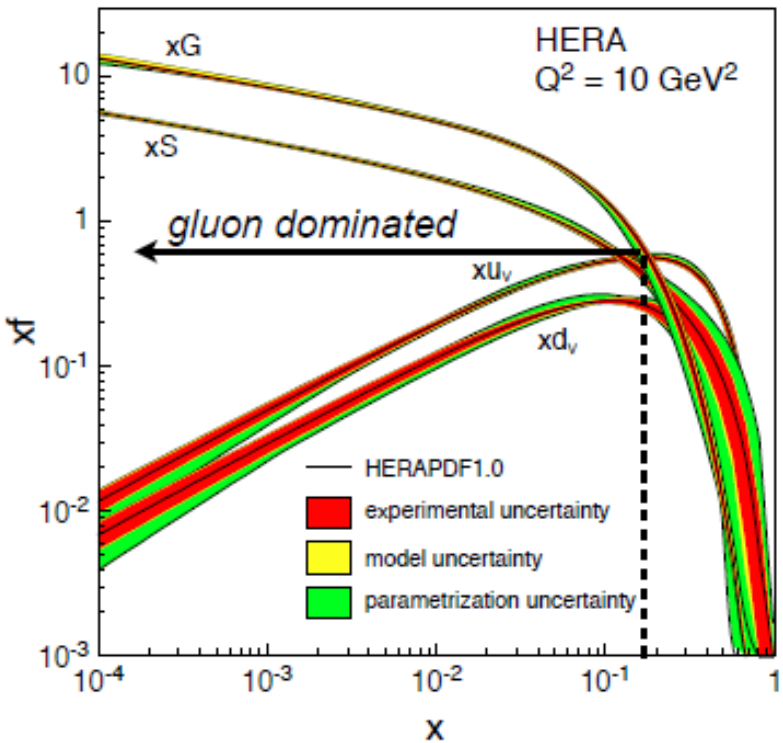
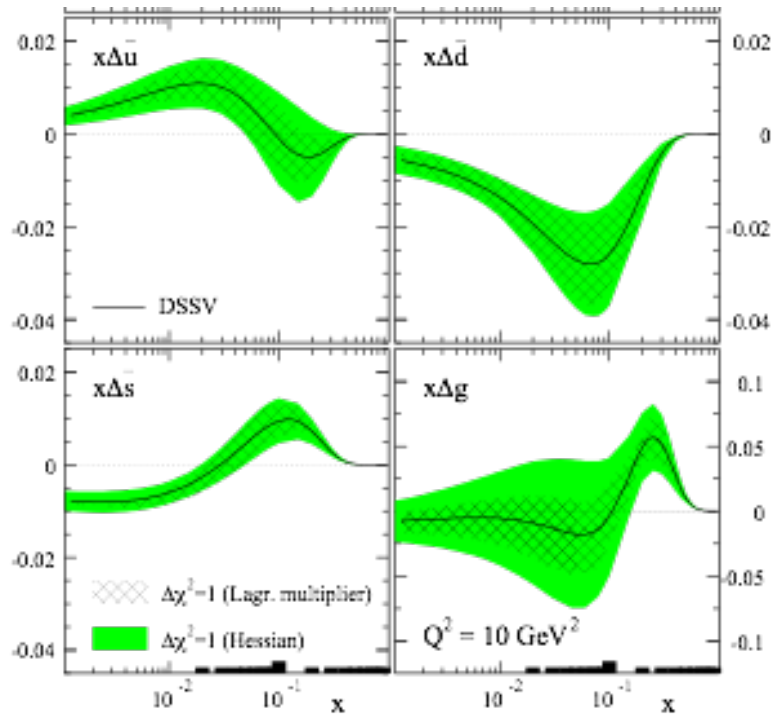
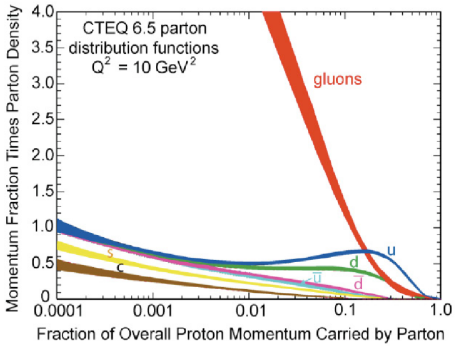




Need to go beyond 1-dimension!

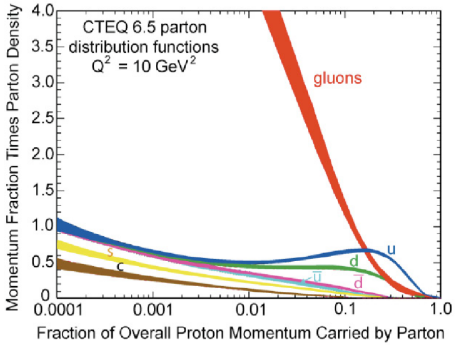
Need 3D Images of nucleons in Momentum & Position space

Could they give us clues on orbital motion of partons?



What do we learn from low-x studies?

Low-x ➔ High Energy



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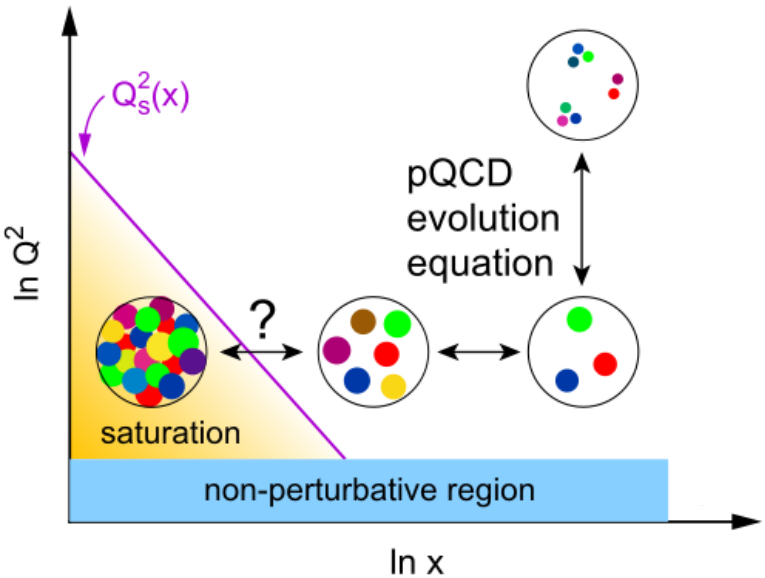

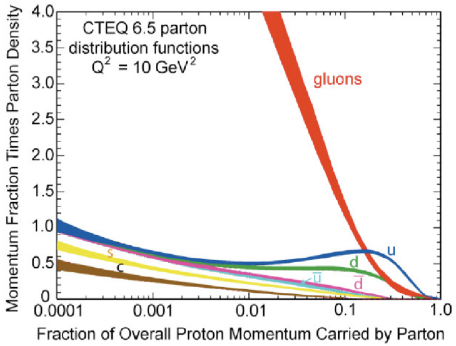

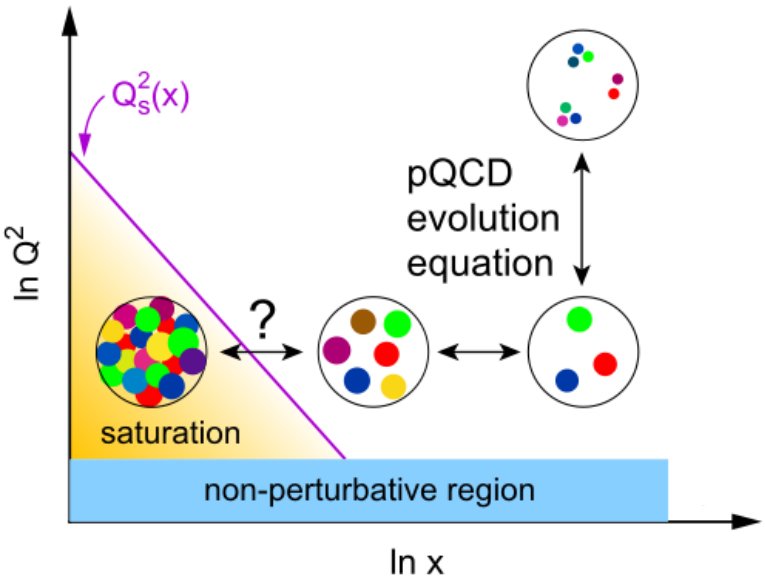

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What tames the low-x rise?

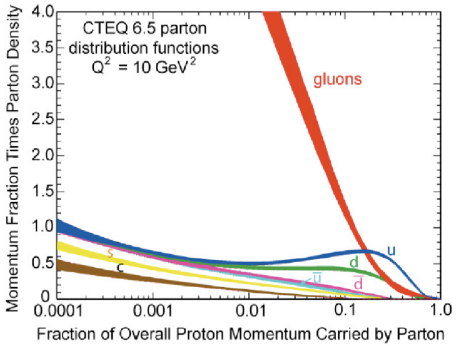
- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable

gluon emission

=

gluon recombination

At Q_S



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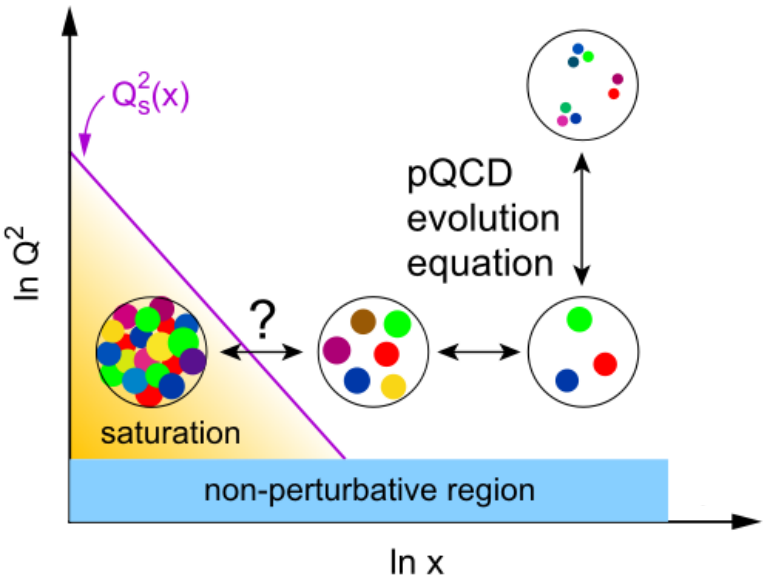

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gluon emission

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gluon recombination

At Q_S

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

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

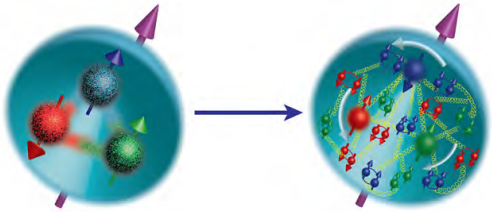
Puzzles and challenges in understanding these QCD many body emergent dynamics

How are the gluons and sea quarks, and their intrinsic spins distributed in space & momentum inside the nucleon?

Role of Orbital angular momentum?

How do they constitute the nucleon

Spin?



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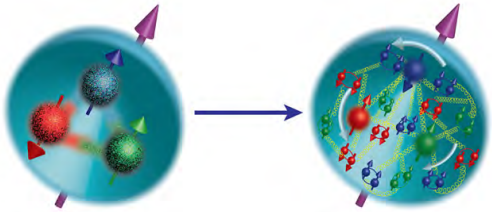
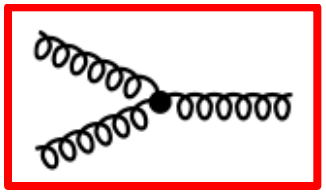


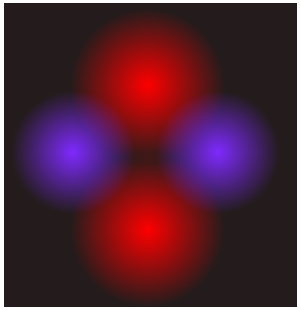
What happens to the gluon density in nuclei at high energy? Does it saturate in to a gluonic form of matter of universal properties?



?

Puzzles and challenges….

How do gluons and sea quarks contribute to the nucleon-nucleon force?



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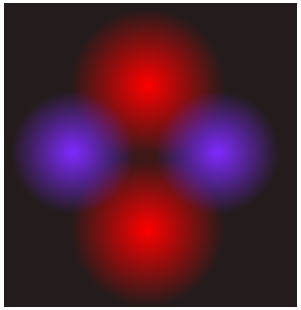

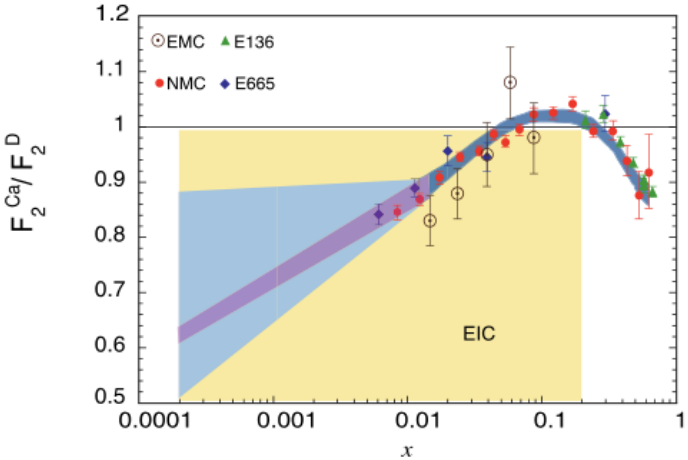

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Puzzles and challenges….

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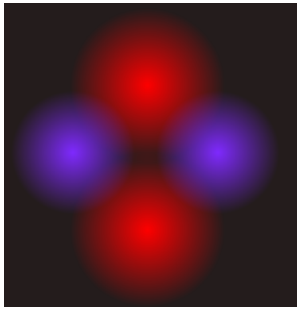

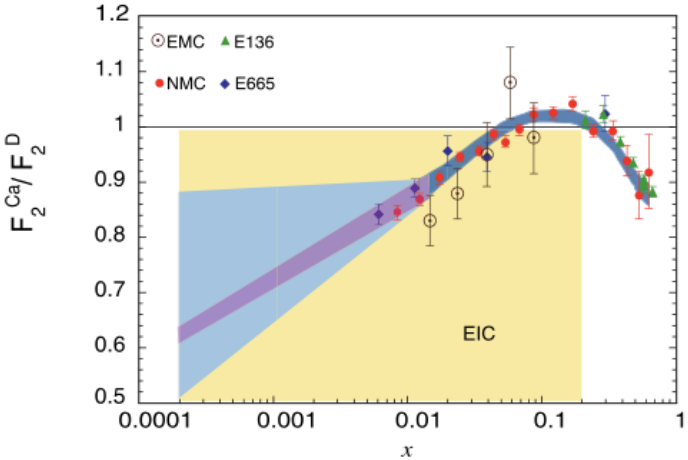

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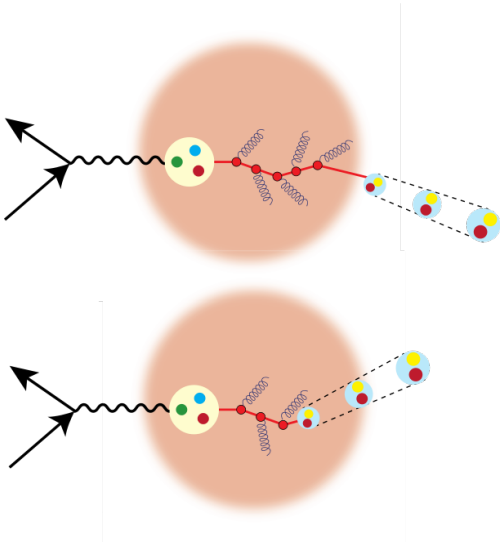
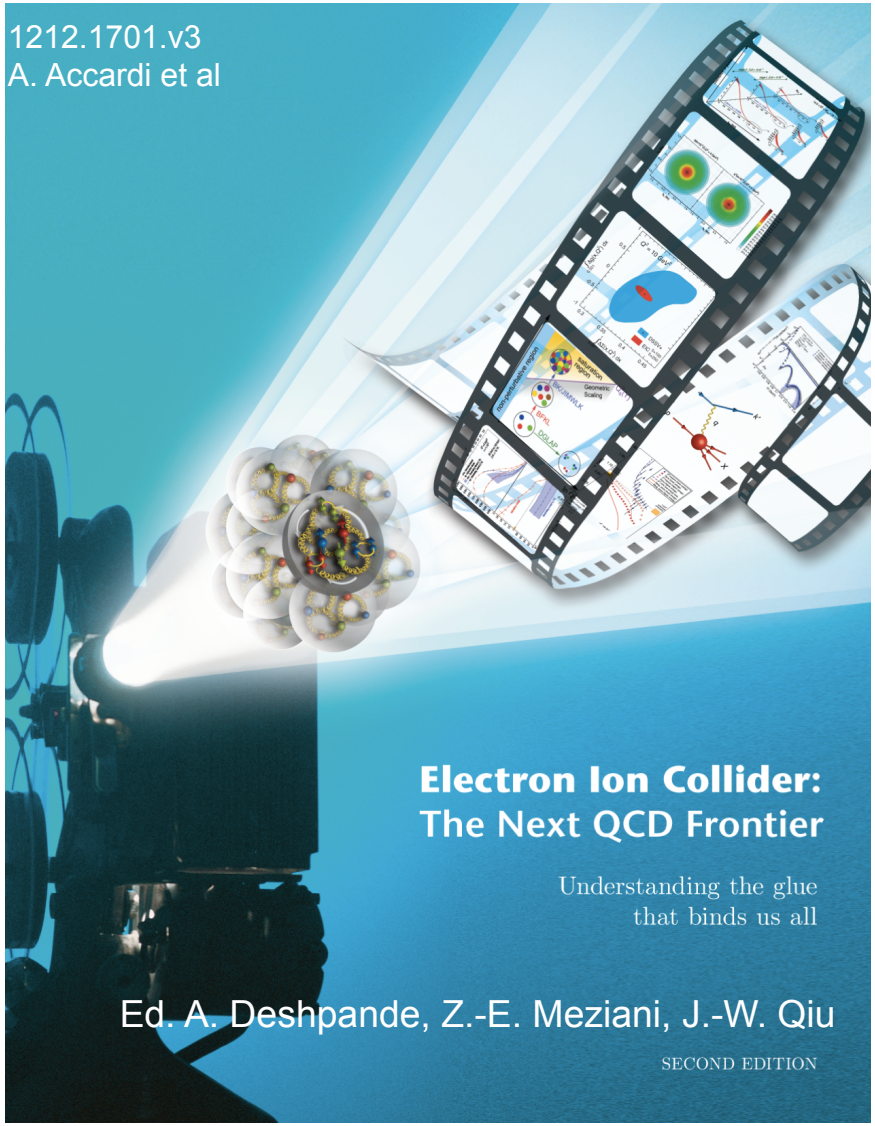
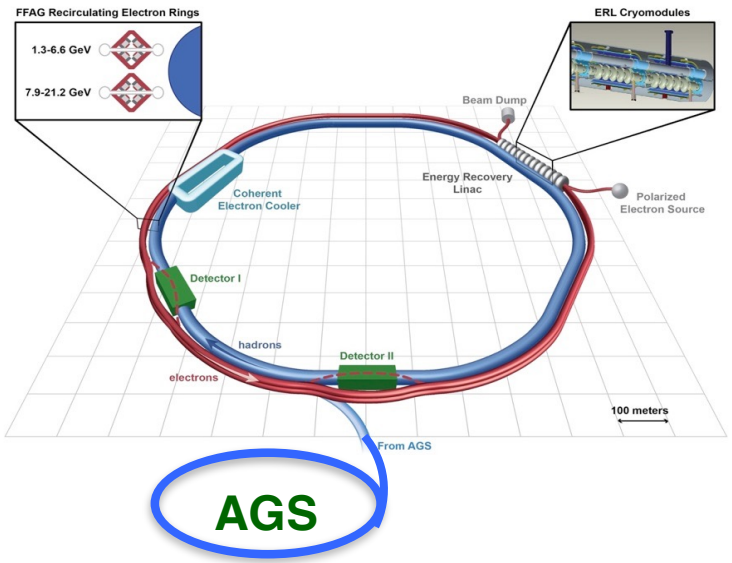
How does nuclear matter respond to fast moving color charge passing through it? (hadronization…. confinment?)

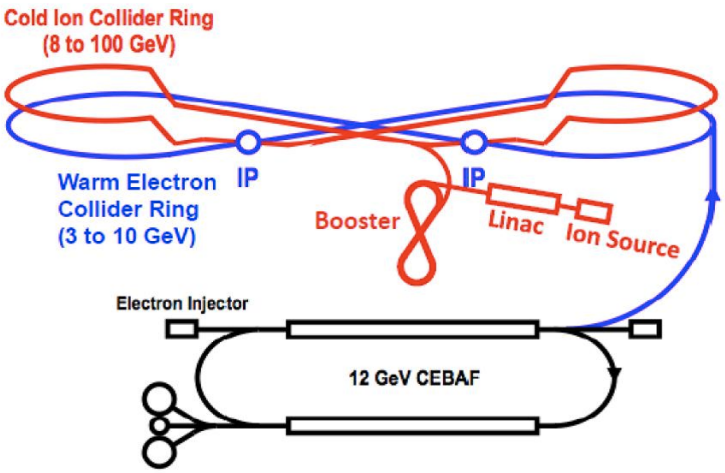


The Electron Ion Collider

Two options of realization!







The Electron Ion Collider

Two options of realization!

For e-N collisions at the EIC:

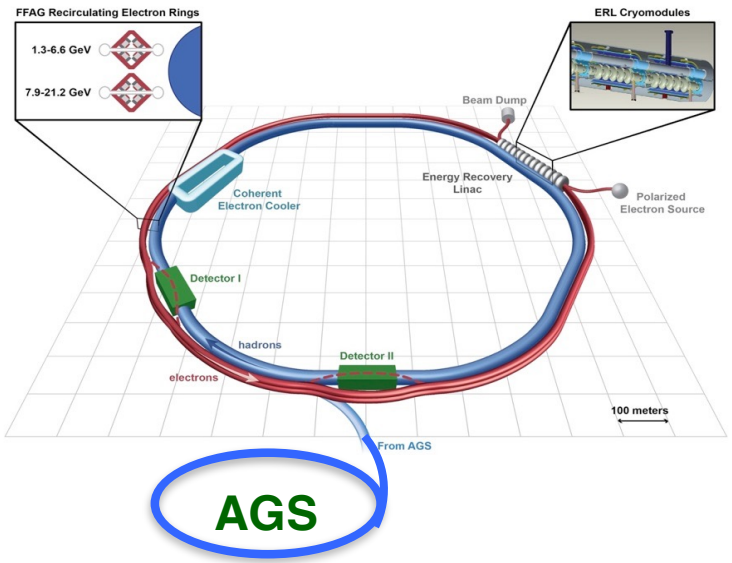
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

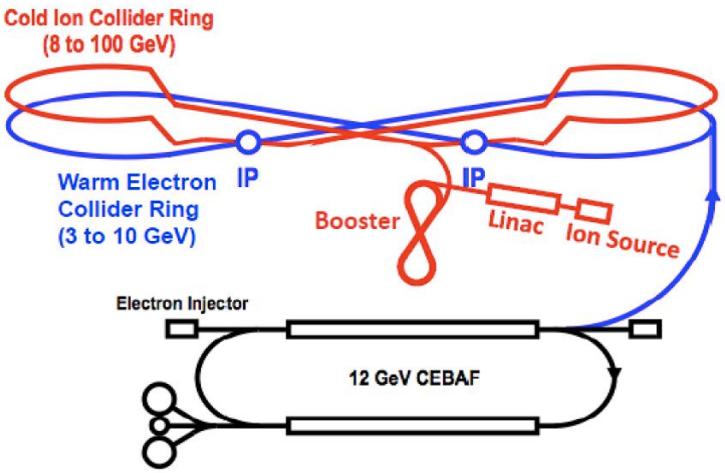
For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

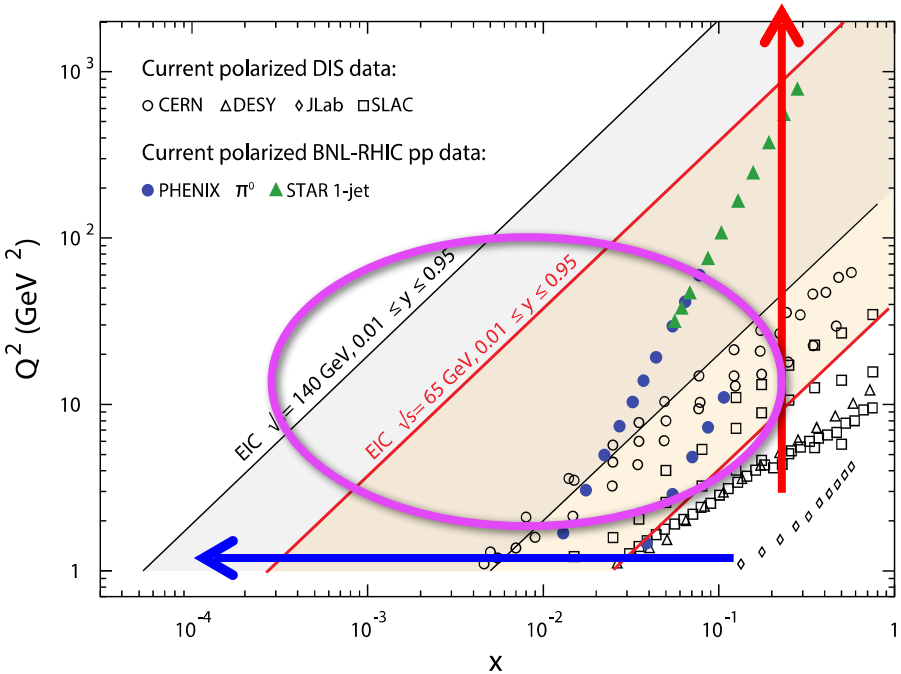
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure





EIC: Kinematic reach & properties



For e-N collisions at the EIC:

- ✓ **Polarized** beams: e, p, d/^{3}He
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- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

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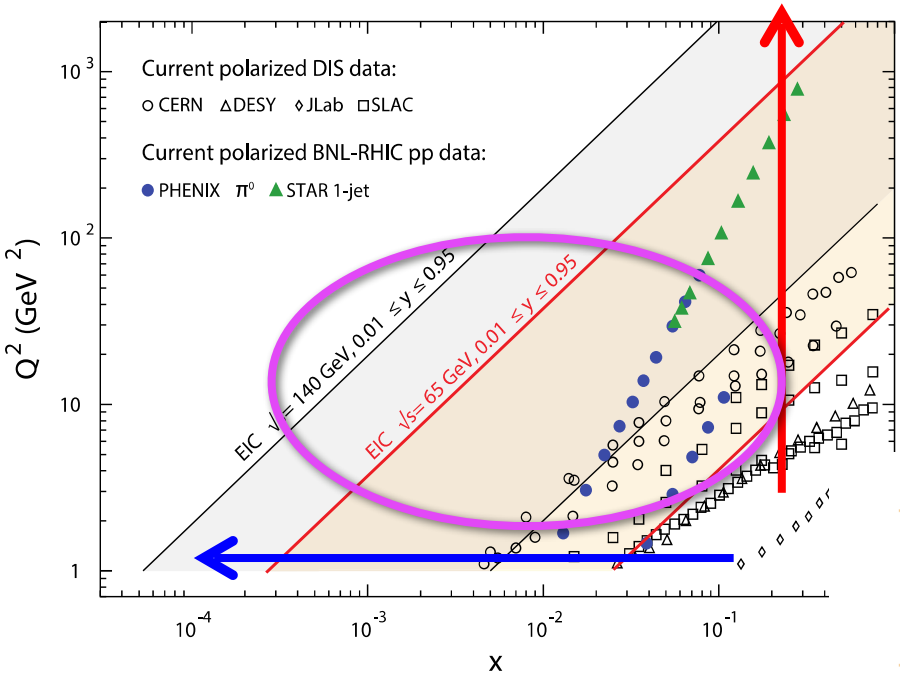

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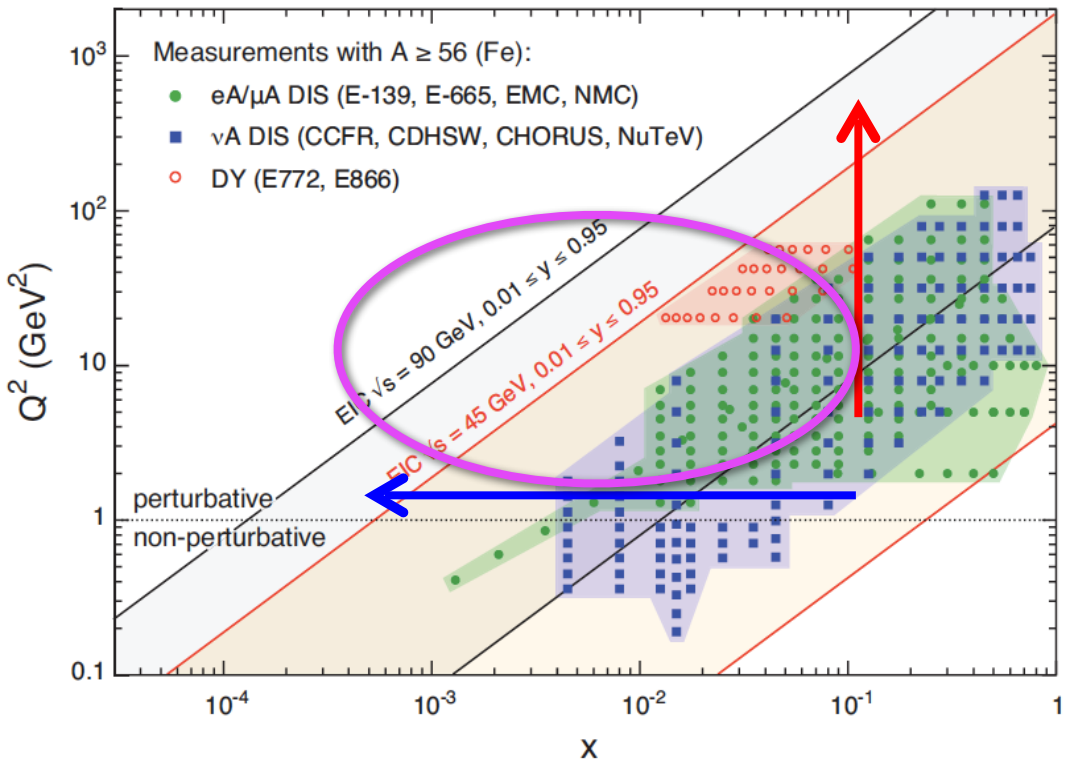
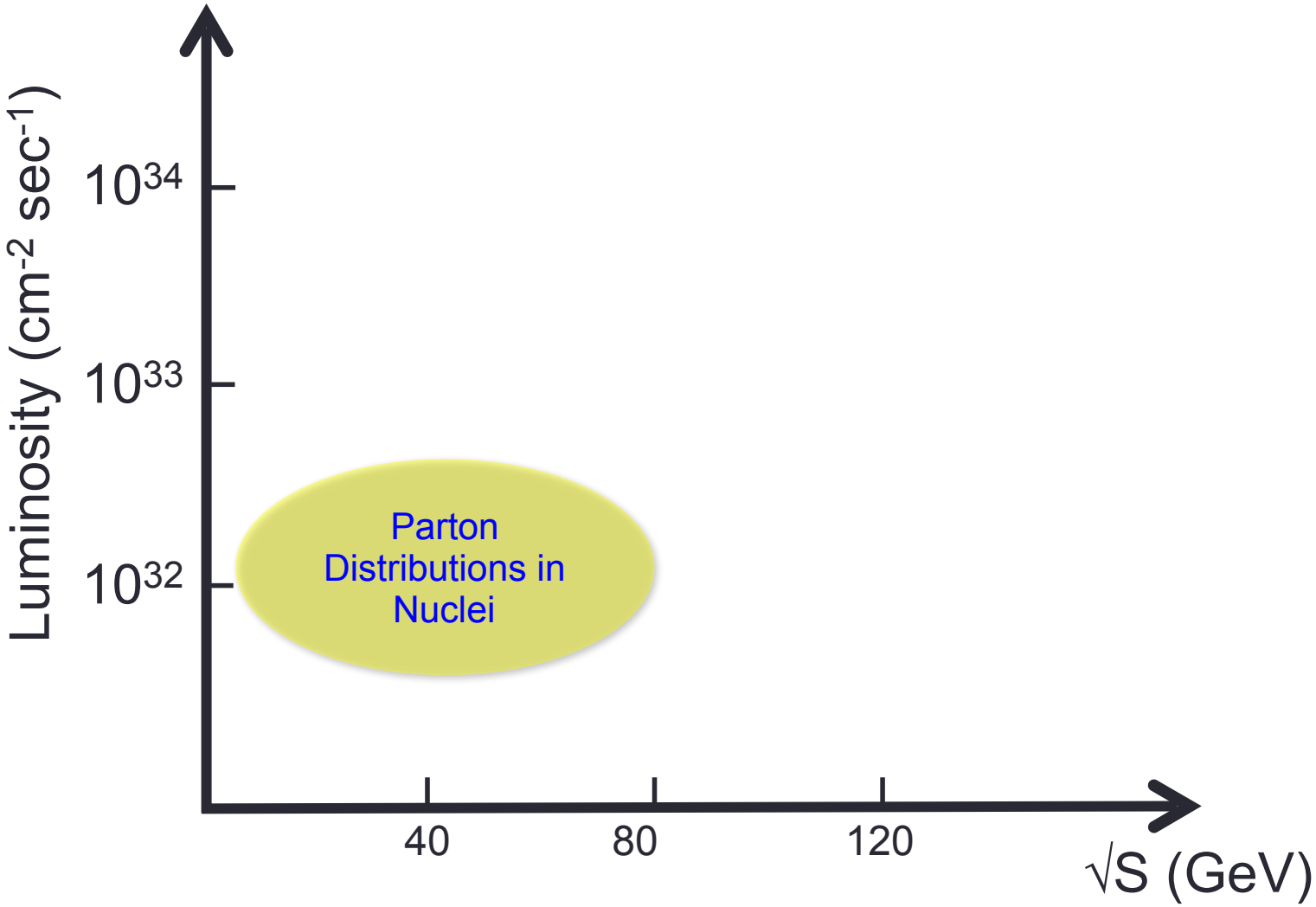
- ✓ Lum. per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)



Physics vs. Luminosity & Energy



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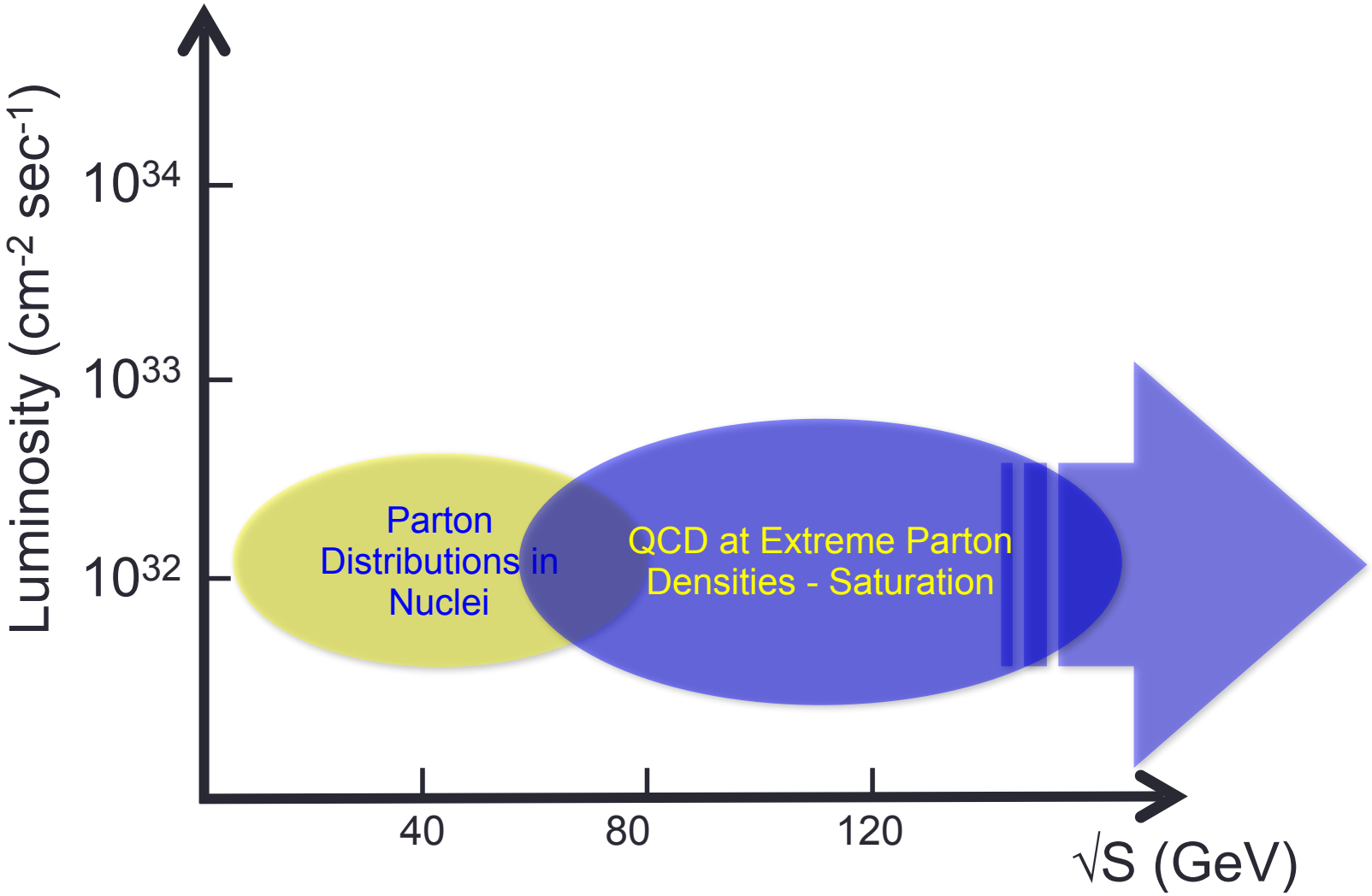

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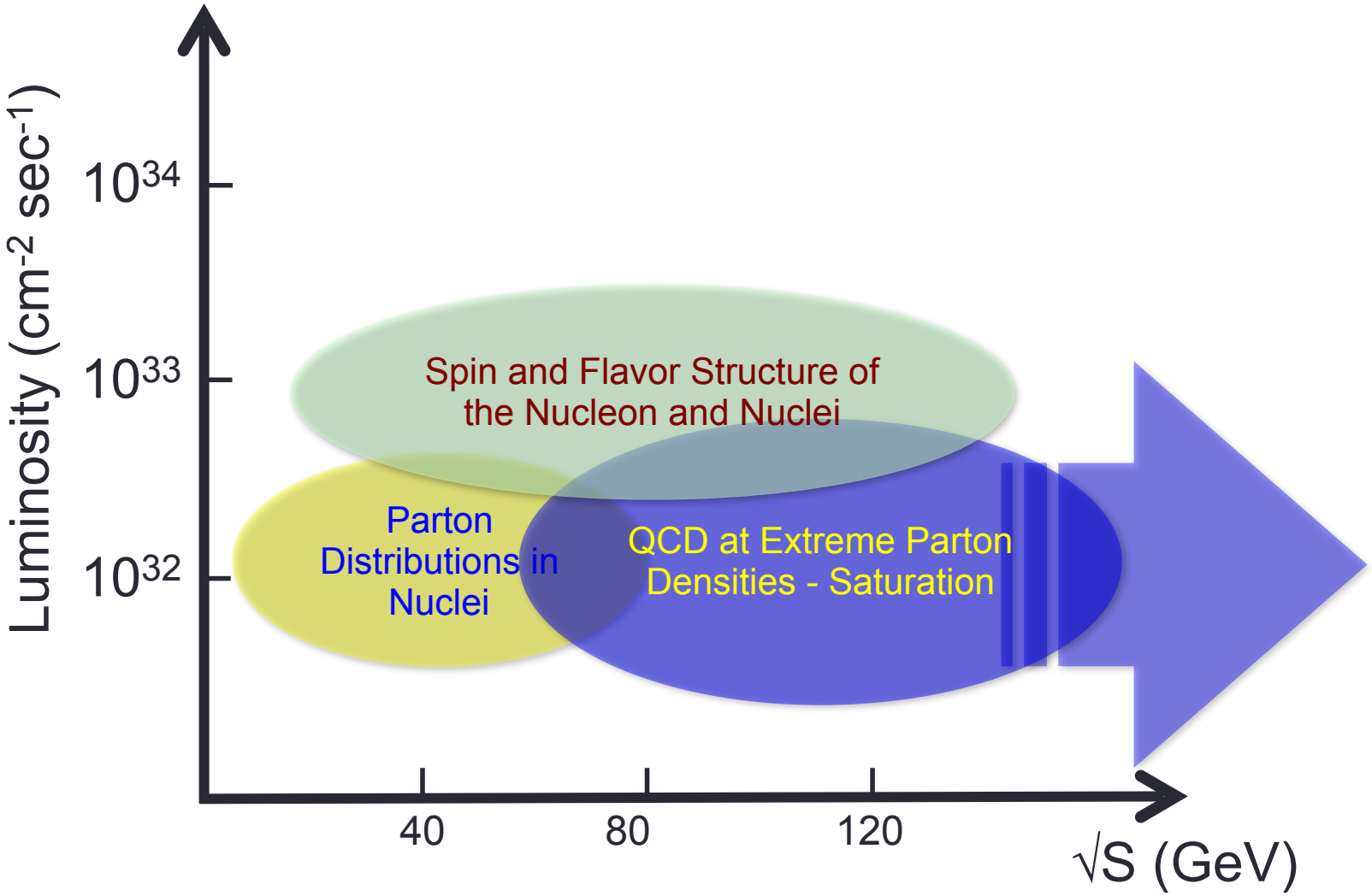

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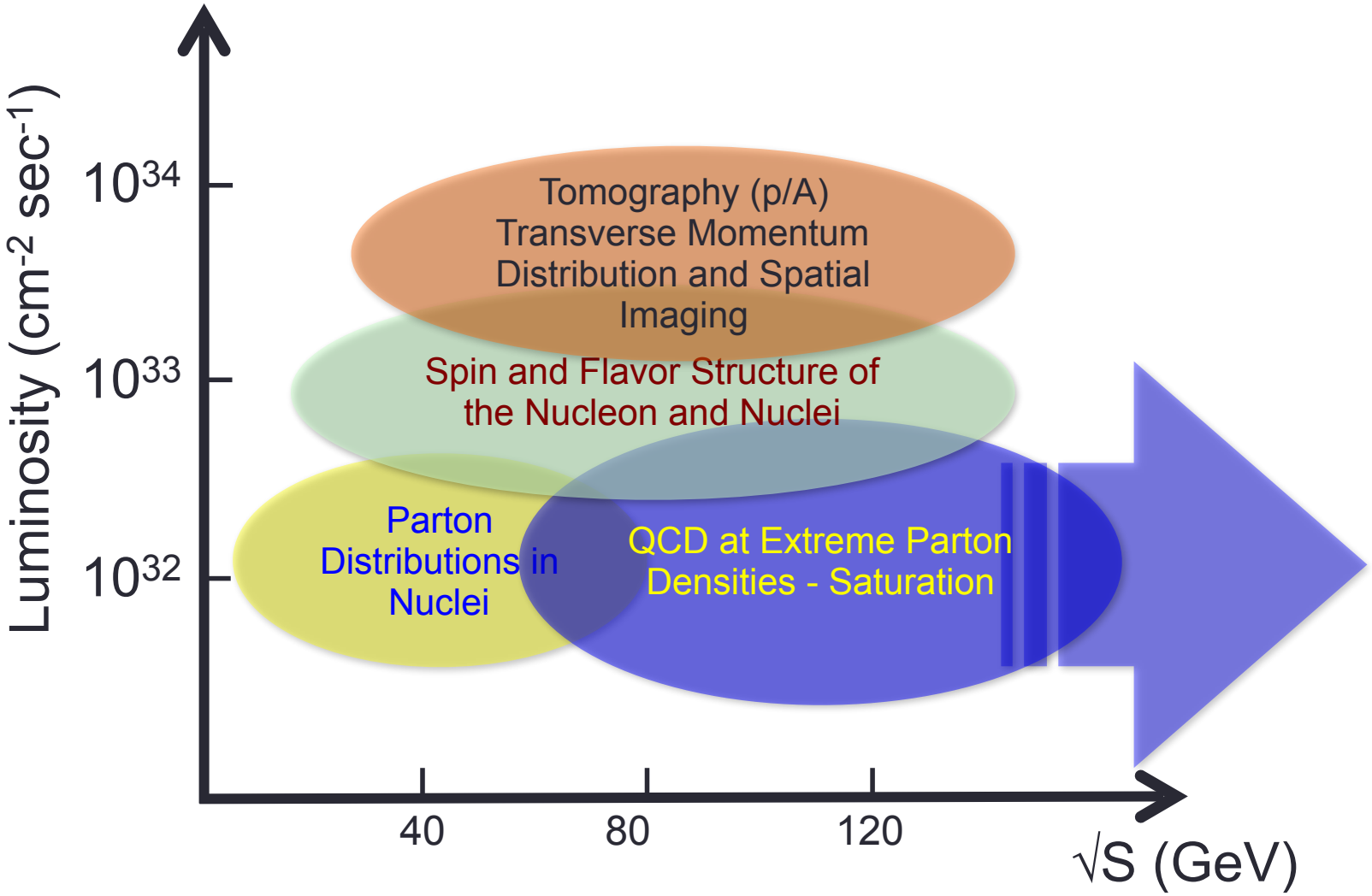
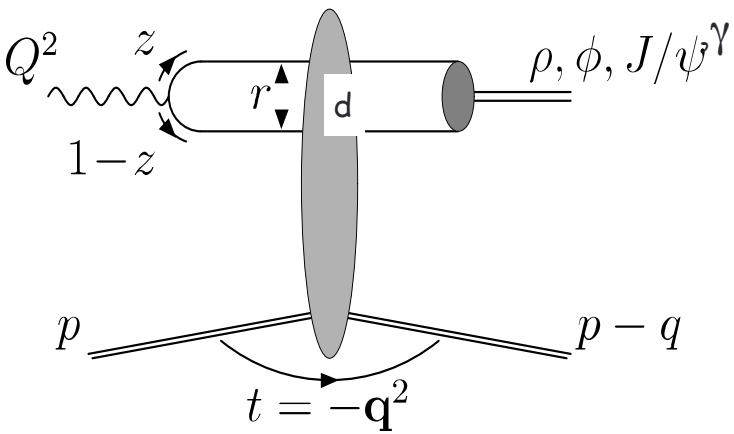


Diffractive vector meson production in eA

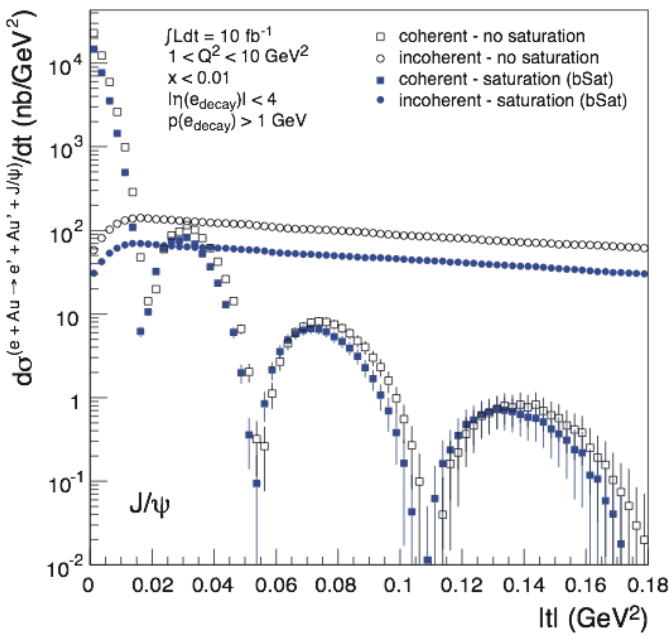


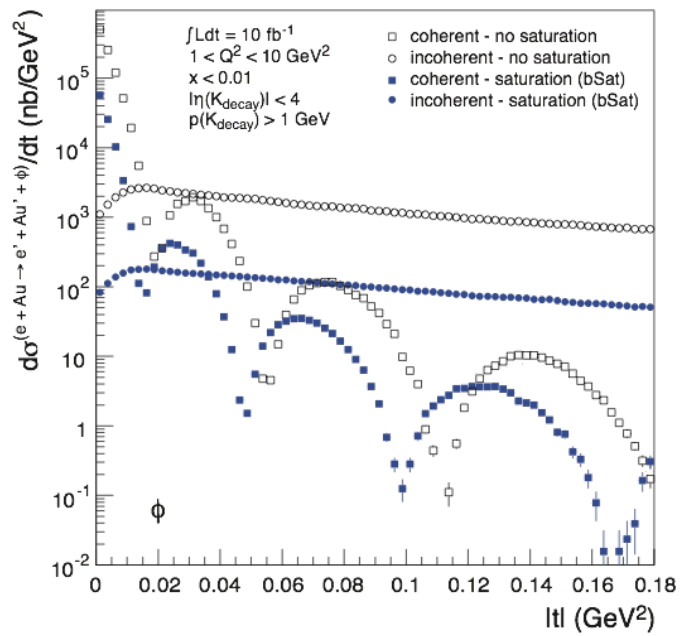
Precise transverse imaging of the gluons in protons & nuclei

→How does low x dynamics (Saturation) modify the transverse gluon distribution?

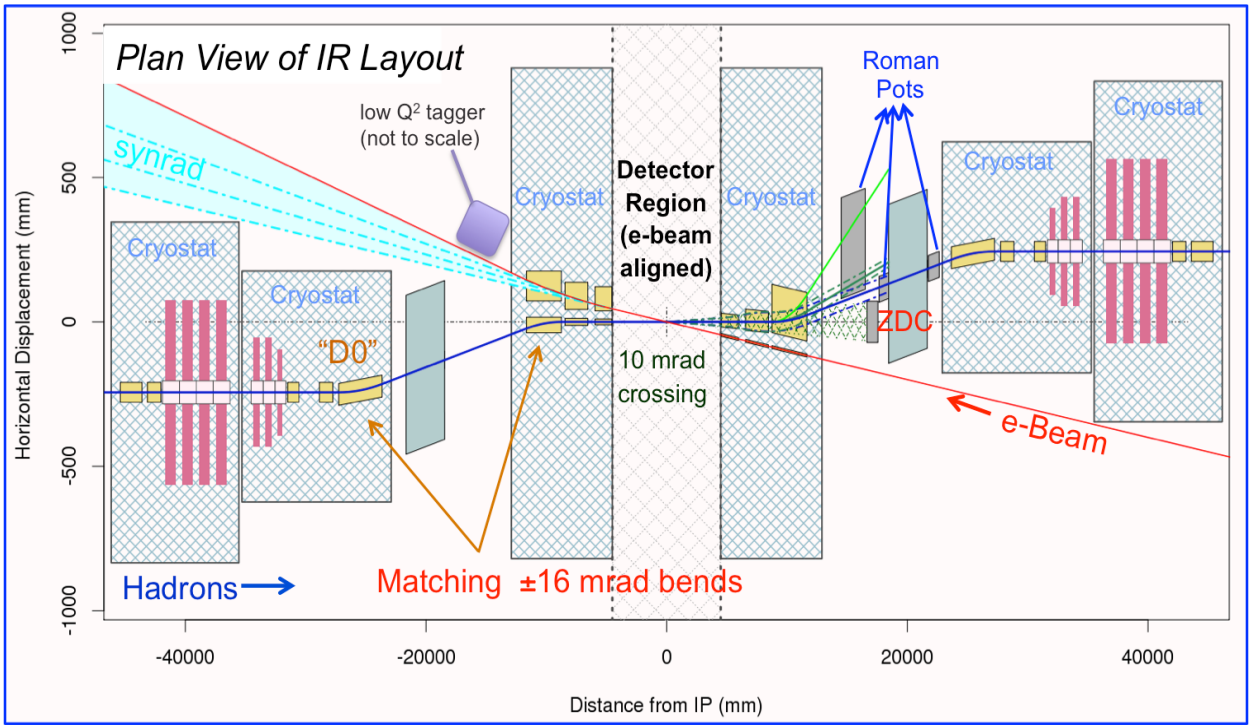
Exclusive coherent (at small t)
and incoherent (intermediate t)
Diffraction

Experimental challenges being Studied.





EIC IR & Detector Plan both at eRHIC & JLEIC



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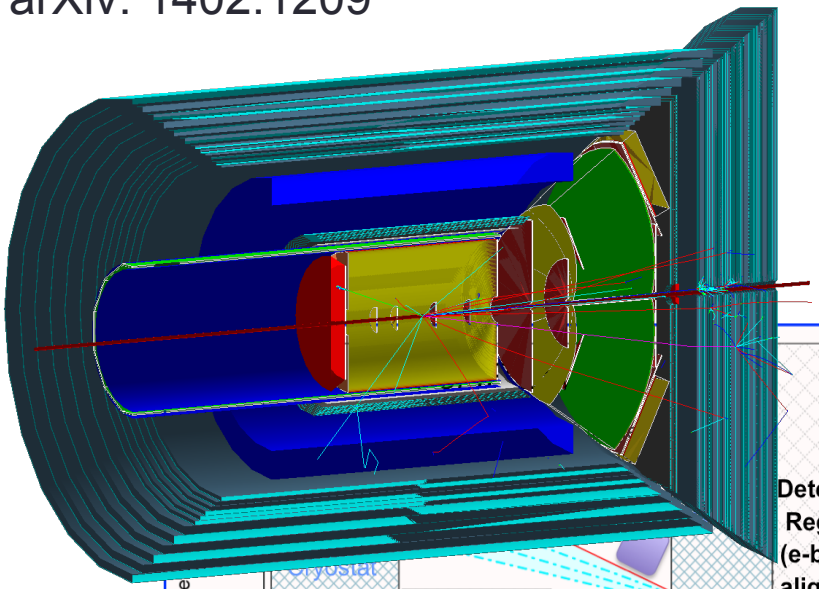
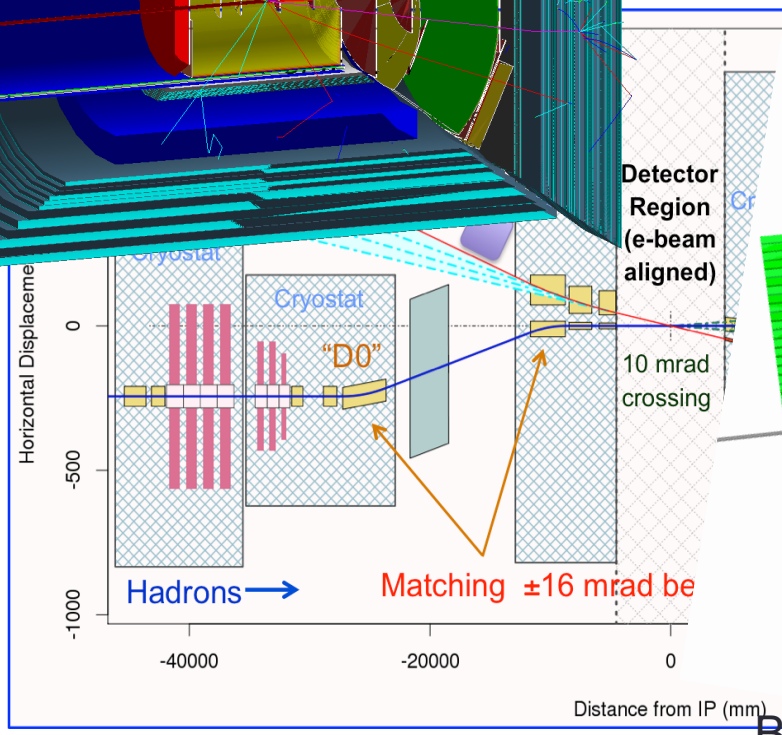
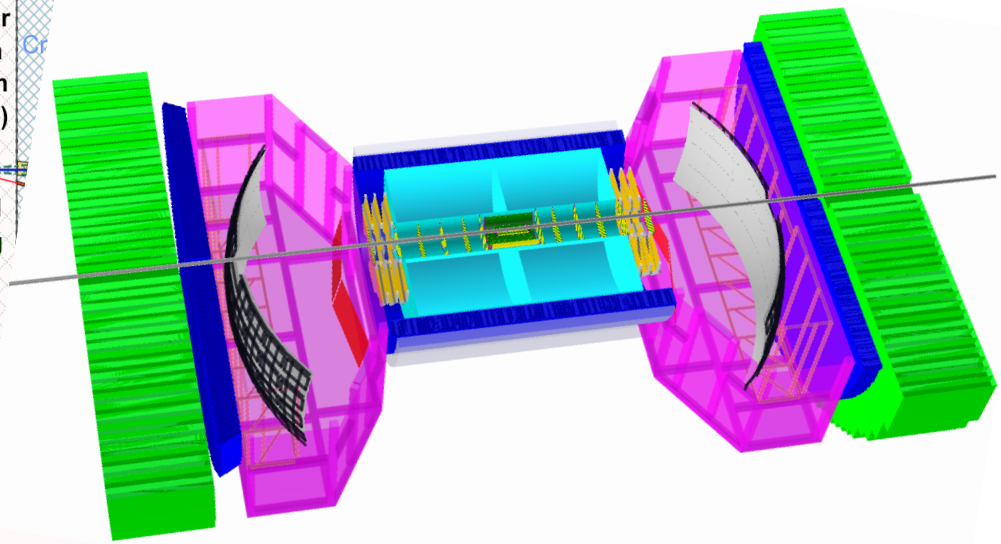
Day-1 Detector: CELESTE
A.K.A. “ePHENIX” with BaBar Solenoid
arXiv: 1402.1209







BEAST by BNL’s EIC Task Force
arXiv: 1409.1633

EIC IR & Detector Plan both at eRHIC & JLEIC

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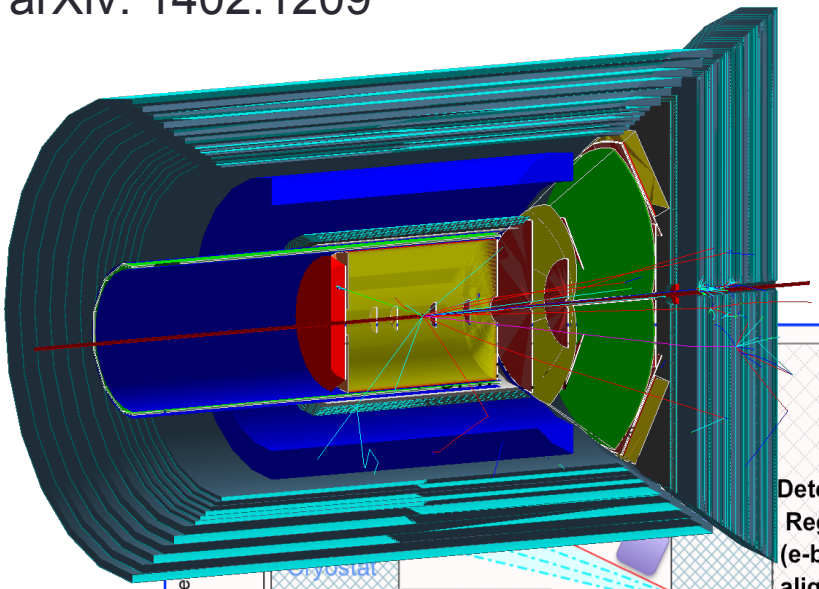
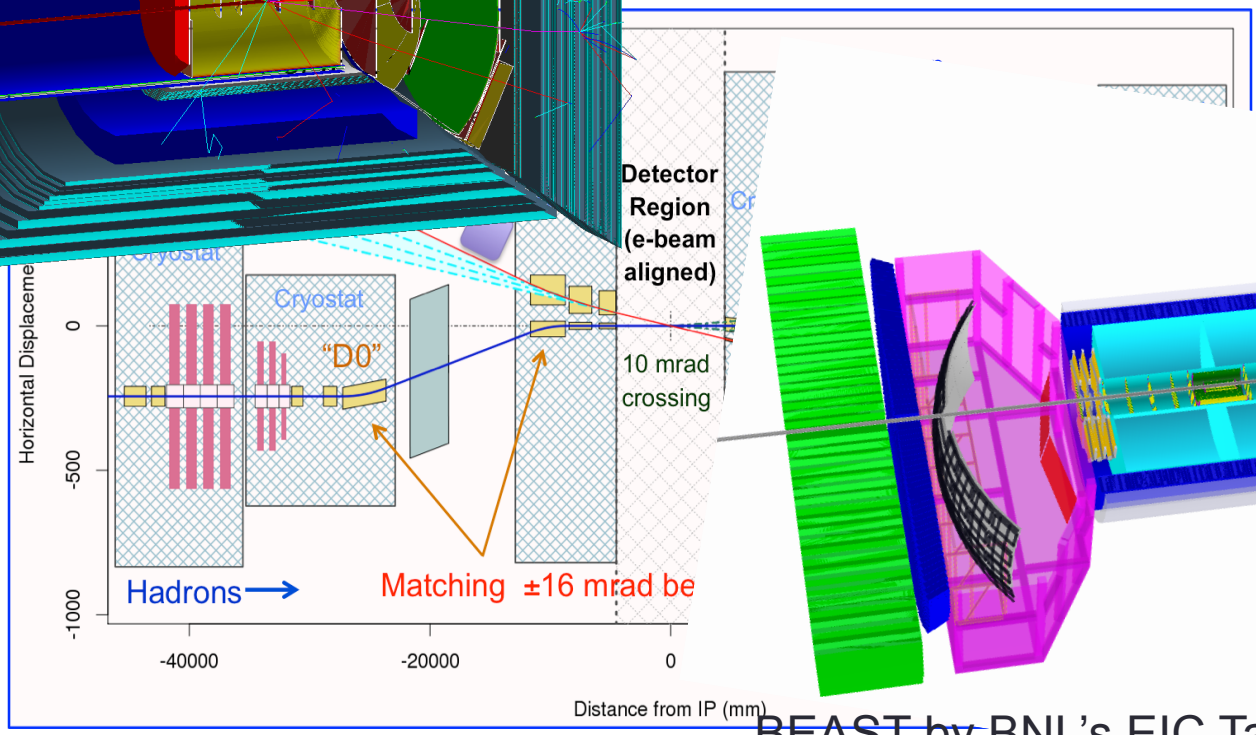
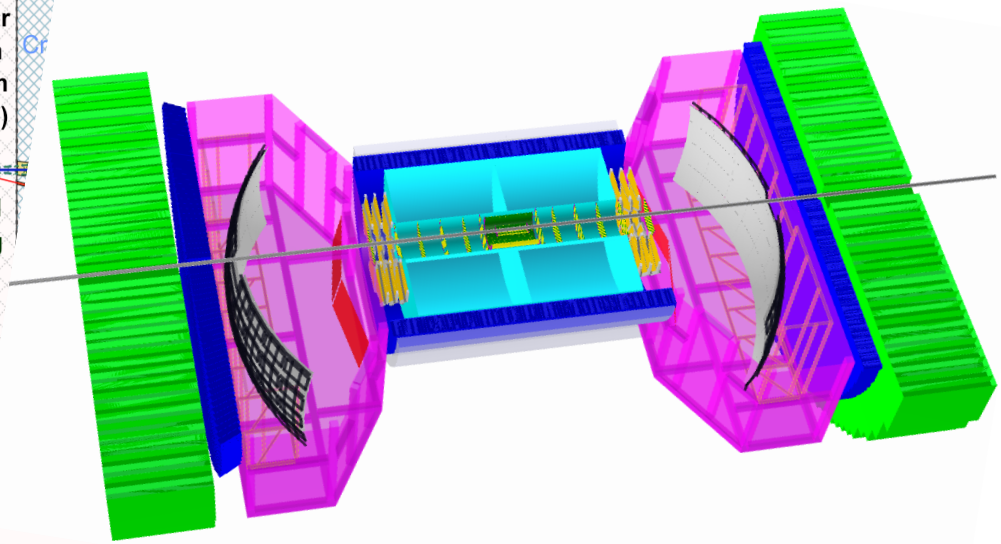
Detector: Low mass tracking technology, particle ID, asymmetric collisions (moving CM) are all in! Opportunities for HQ and Quarkonium physics.







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EIC Distinct from (the past) HERA

- Luminosity 100-1000 times that of HERA
  - **Enable 3D tomography** of gluons and sea quarks in protons
- Polarized protons and light nuclear beams
  - Critical to all spin physics related studies, including precise knowledge of gluon's & **angular momentum** contributions from partons to the nucleon's spin
- Nuclear beams of all A (p→U)
  - To study **gluon density at saturation scale** and to search for coherent effects like the color glass condensate and test its universality
- Center mass variability with minimal loss of luminosity
  - Critical to study **onset of interesting QCD** phenomena
- Detector & IR designs mindful of "Lessons learned from HERA"
  - No bends in e-beam, **maximal forward** acceptance….

Quarkonium & other bound quarks system

EIC: Need input & Studies!

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- What can the EIC add to Quarkonium physics? Studies just being considered… invitation to YOU, come join us.

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  - What can be learnt with **e-A collisions** for Quarkonium physics?
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- ***Ample opportunities for your contributions & participation!***

A new facility (EIC) is being designed and will be implemented in the next ~10 years.

Invitation to join and influence its design to extract maximum physics!

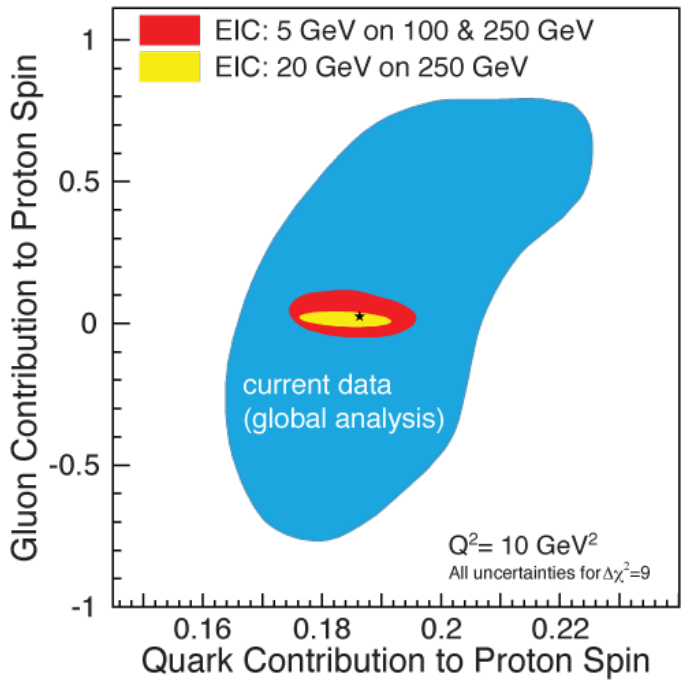
- ✓ EIC User Group → eicug.org (contact me!)
- ✓ **Next EICUG Argonne National Laboratory July 7-9, 2016 : http://eic2016.phy.anl.gov**
- ✓ Detector R&D funds for your novel proposals could be supported

Thank you!

2+1 D partonic image of the proton:

Spatial distance from origin X Transverse Momentum → Orbital Angular Momentum

Helicity Distributions: ΔG and ΔΣ



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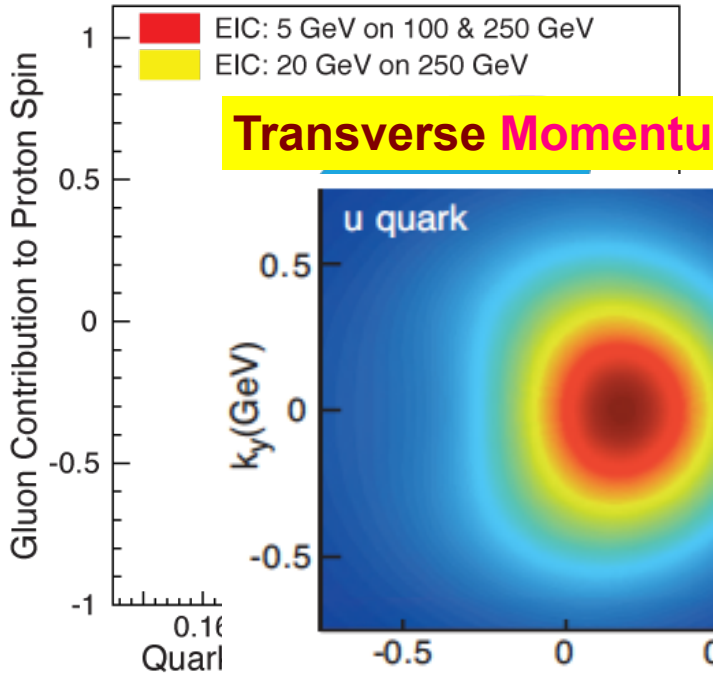
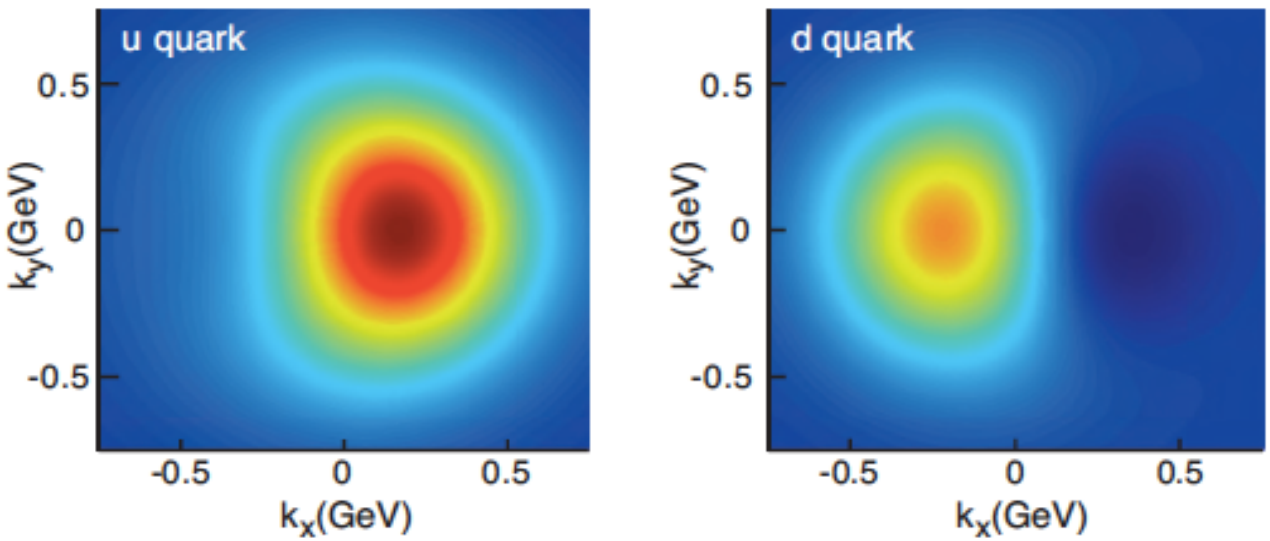


Transverse Momentum Distributions



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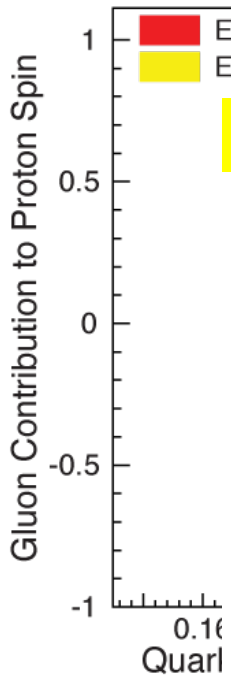

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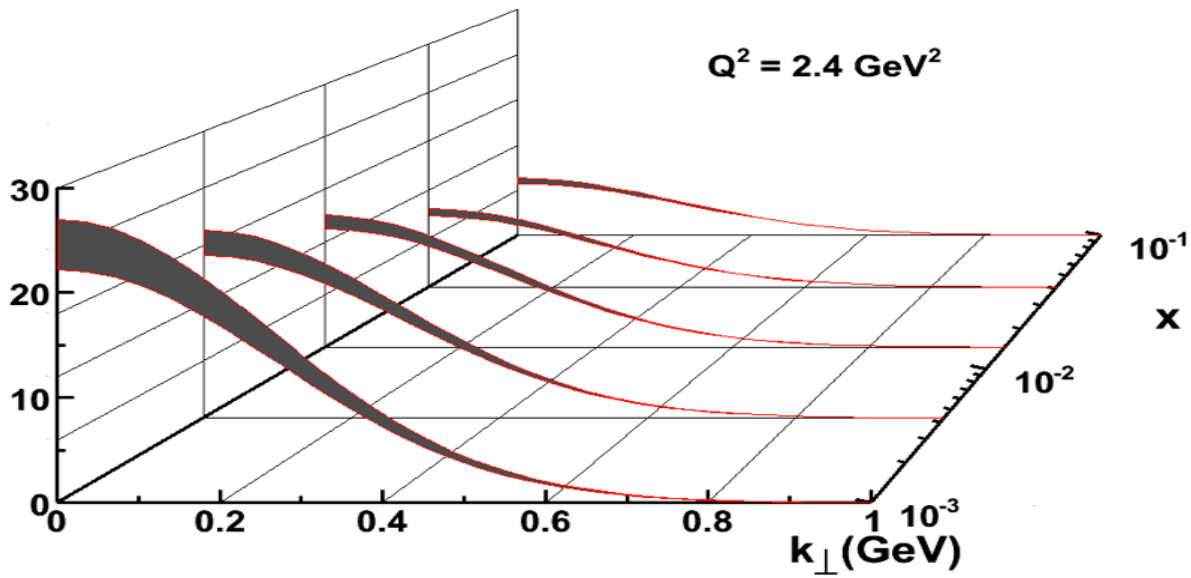

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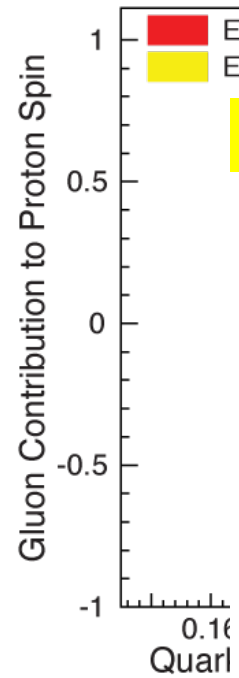

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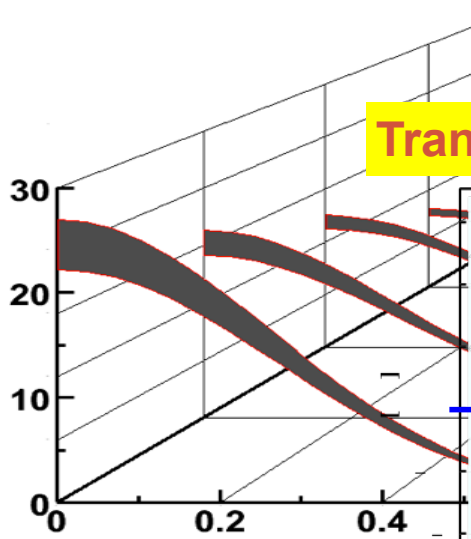
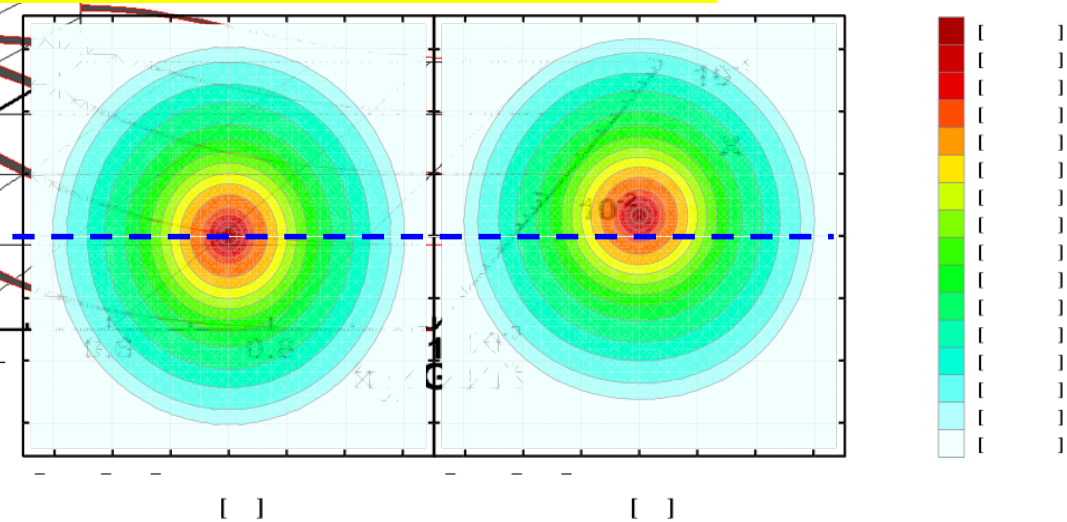


Transverse Position Distributions



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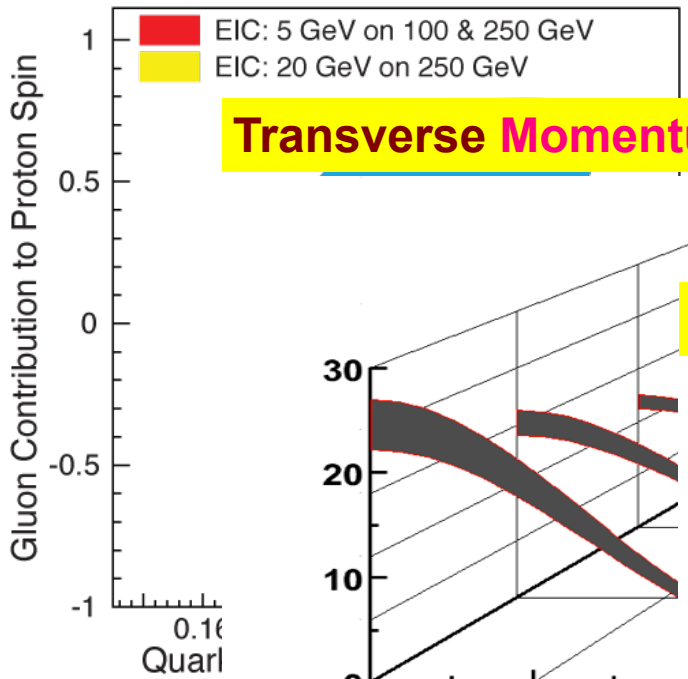
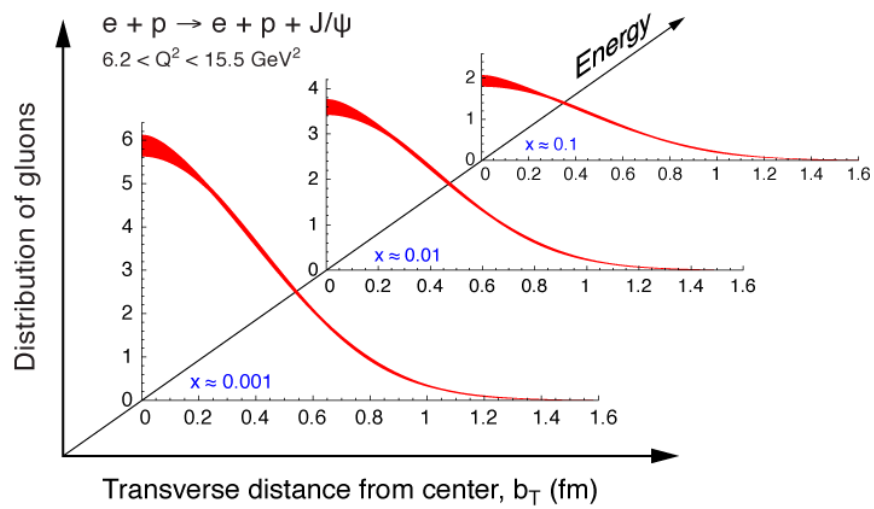
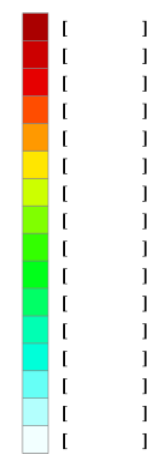


Transverse Momentum Distributions

$Q^2 = 2.4\ GeV^2$

Transverse Position Distributions





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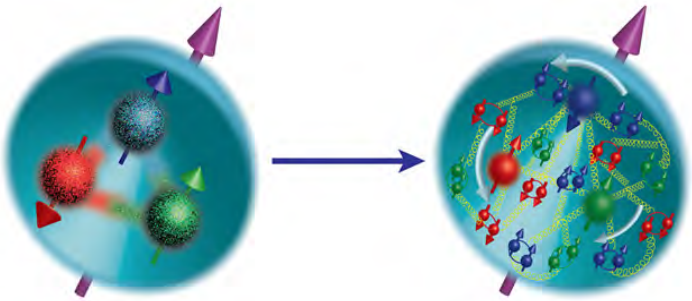

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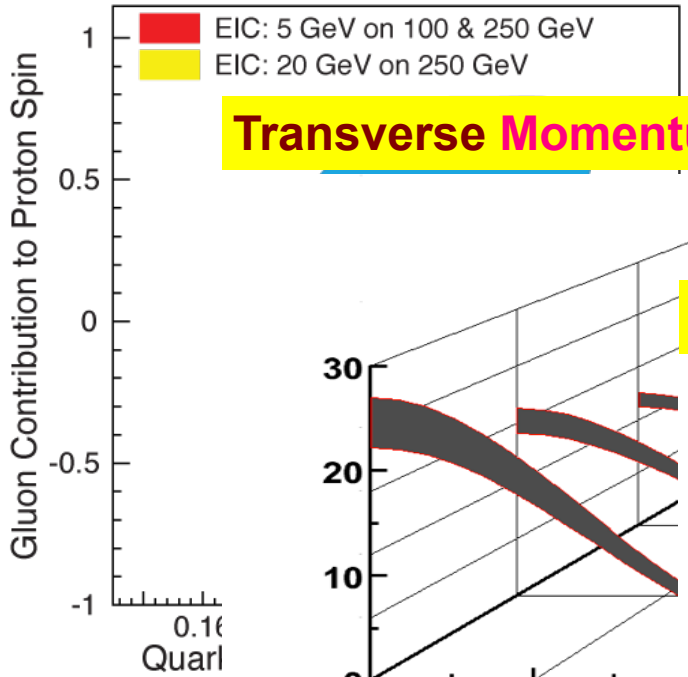

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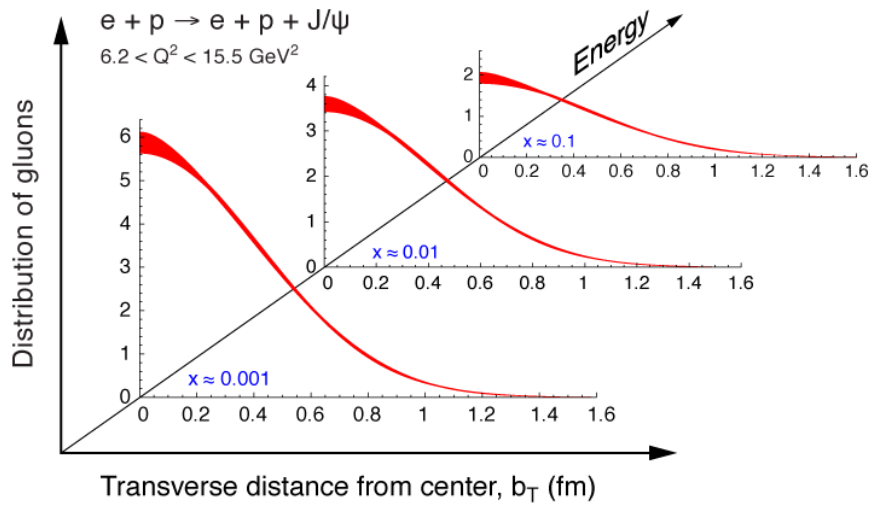
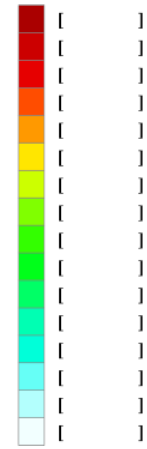




Prospect of direct comparison with lattice QCD

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

$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x \quad \text{(General. Parton Dist.s H,E)} \quad = \frac{1}{2}\Delta q + L_q$$

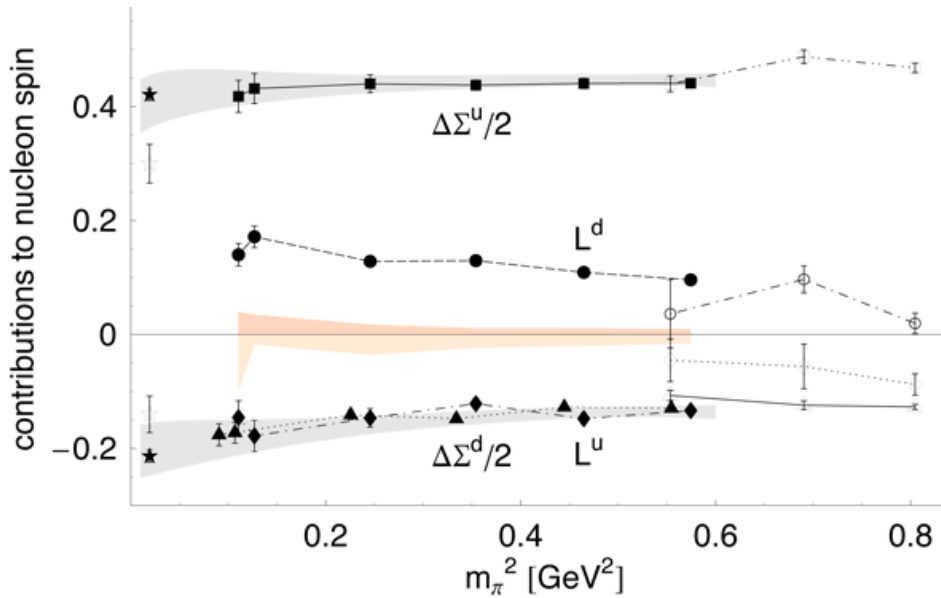
The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab12/COMPASS

J_q, calculated on Lattice QCD:

Future:

New developments on LQCD calculating parton distributions including gluon distributions:

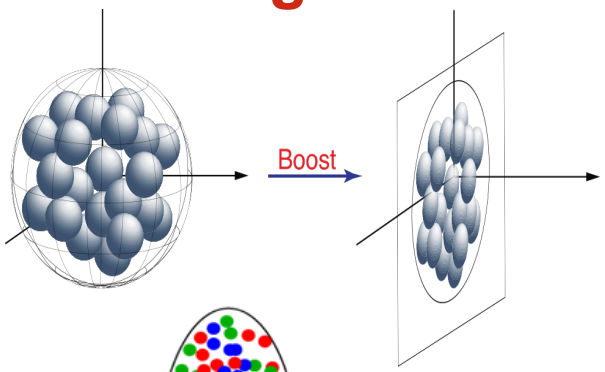
X. Ji et al. PRL 111 (2013) 112002
Y. Hatta, PRD89 (2014) 8, 085030
& Y.-Q. Ma, J.-W. Qiu 1404.6860

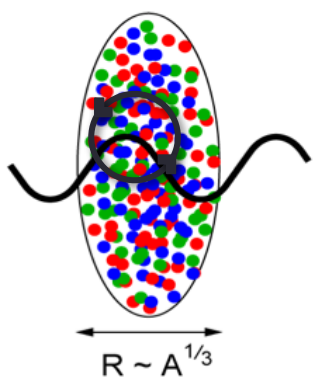


How to explore/study this new phase of matter?

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

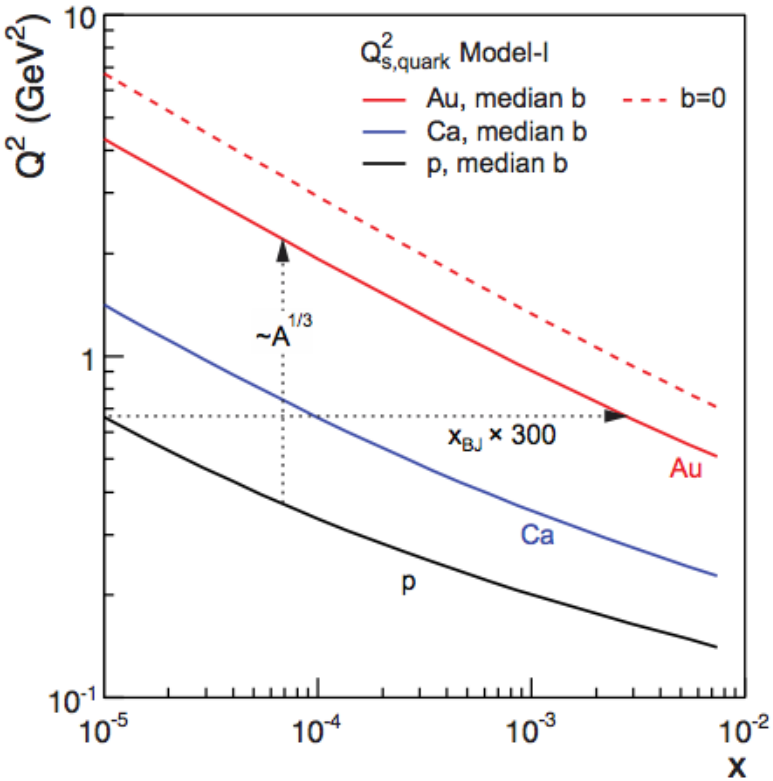
Advantage of nucleus →





$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

$L \sim (2m_N x)^{-1} > 2\ R_A \sim A^{1/3}$



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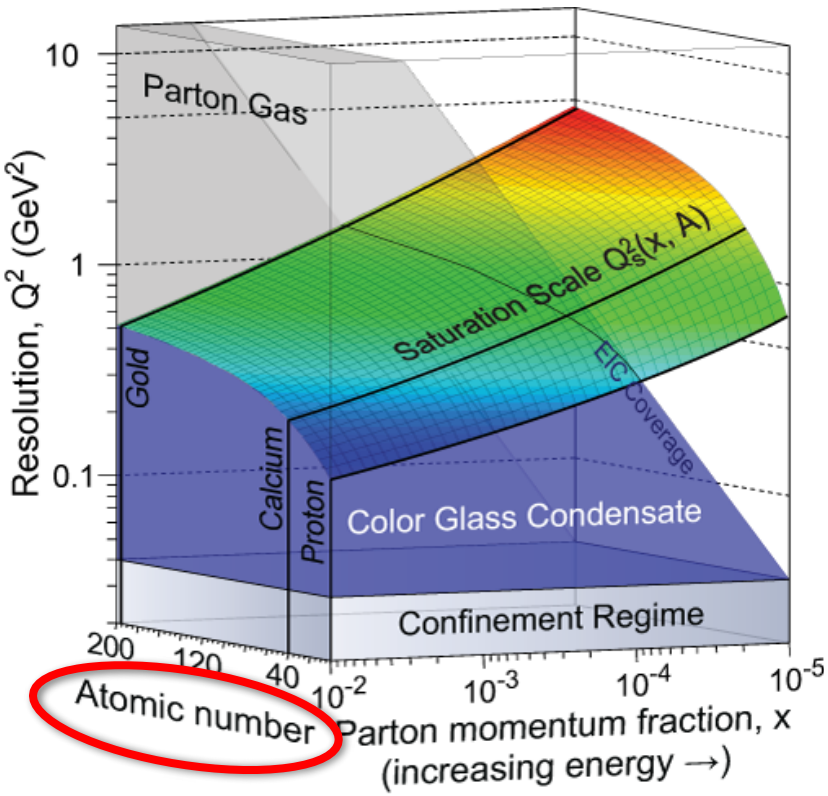
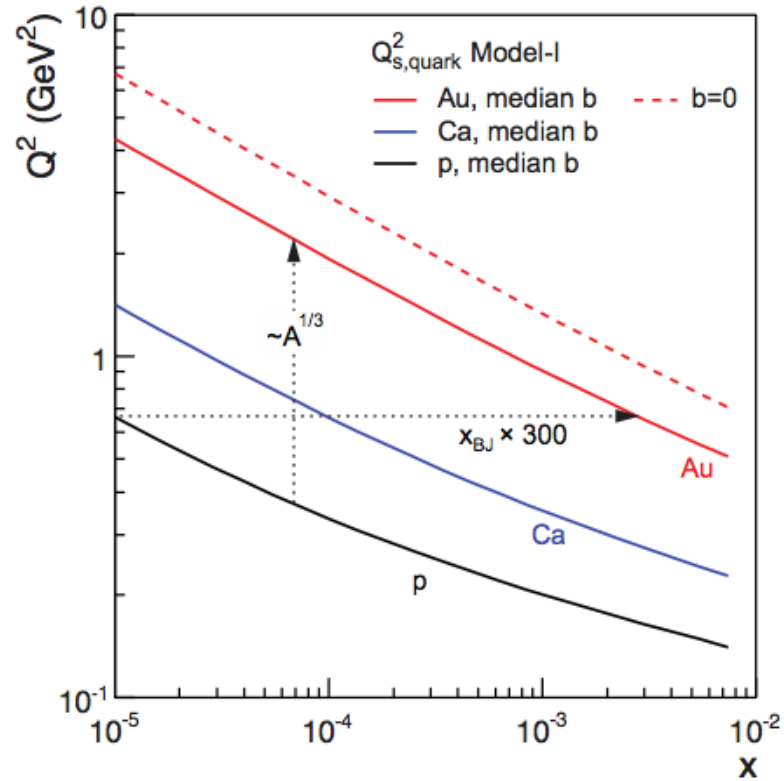




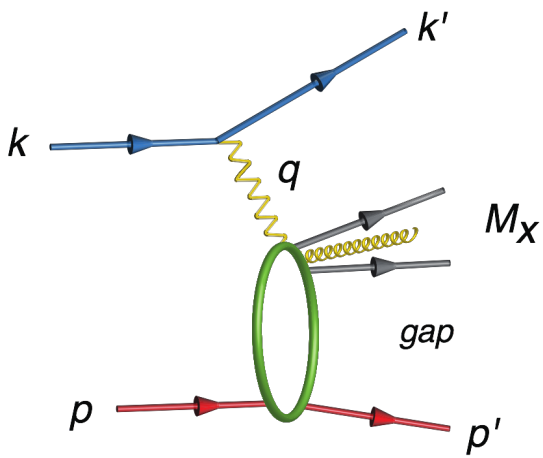
Enhancement of Q_S with A:

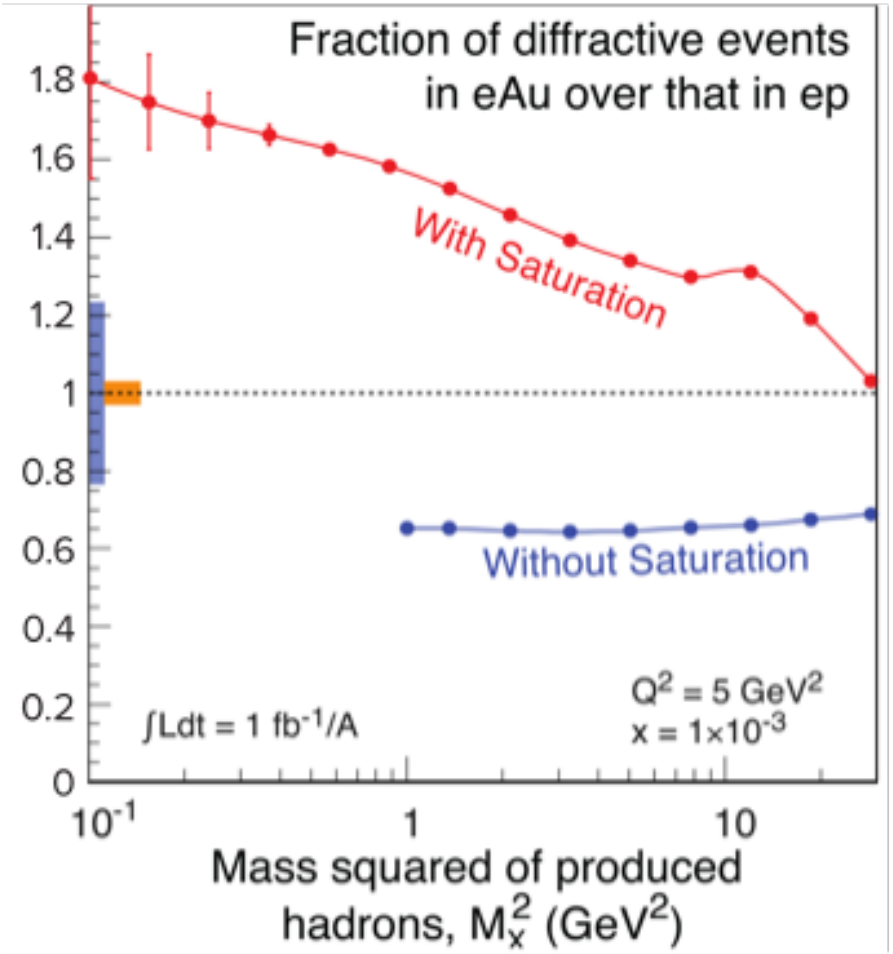
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

Saturation/CGC: What to measure?

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

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





At HERA

ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

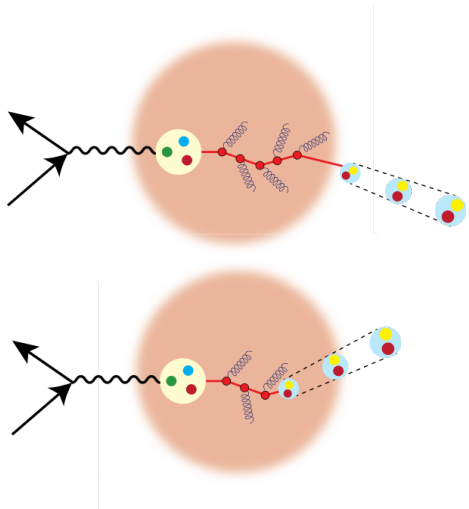
eA: 25-30% diffractive

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

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

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

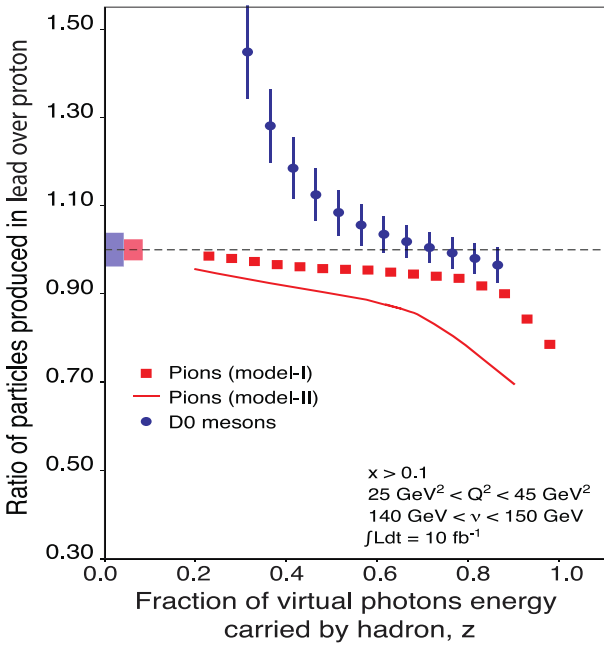


Control of ν by selecting kinematics;

Also under control the nuclear size.

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

Energy loss by light vs. heavy quarks:

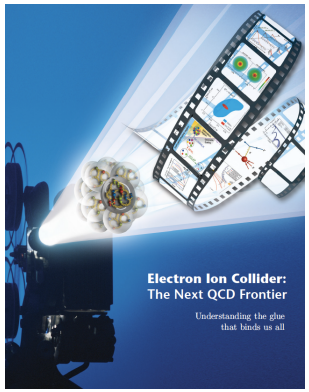


Identify π vs. D^0 **(charm)** mesons in e-A collisions: Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter:

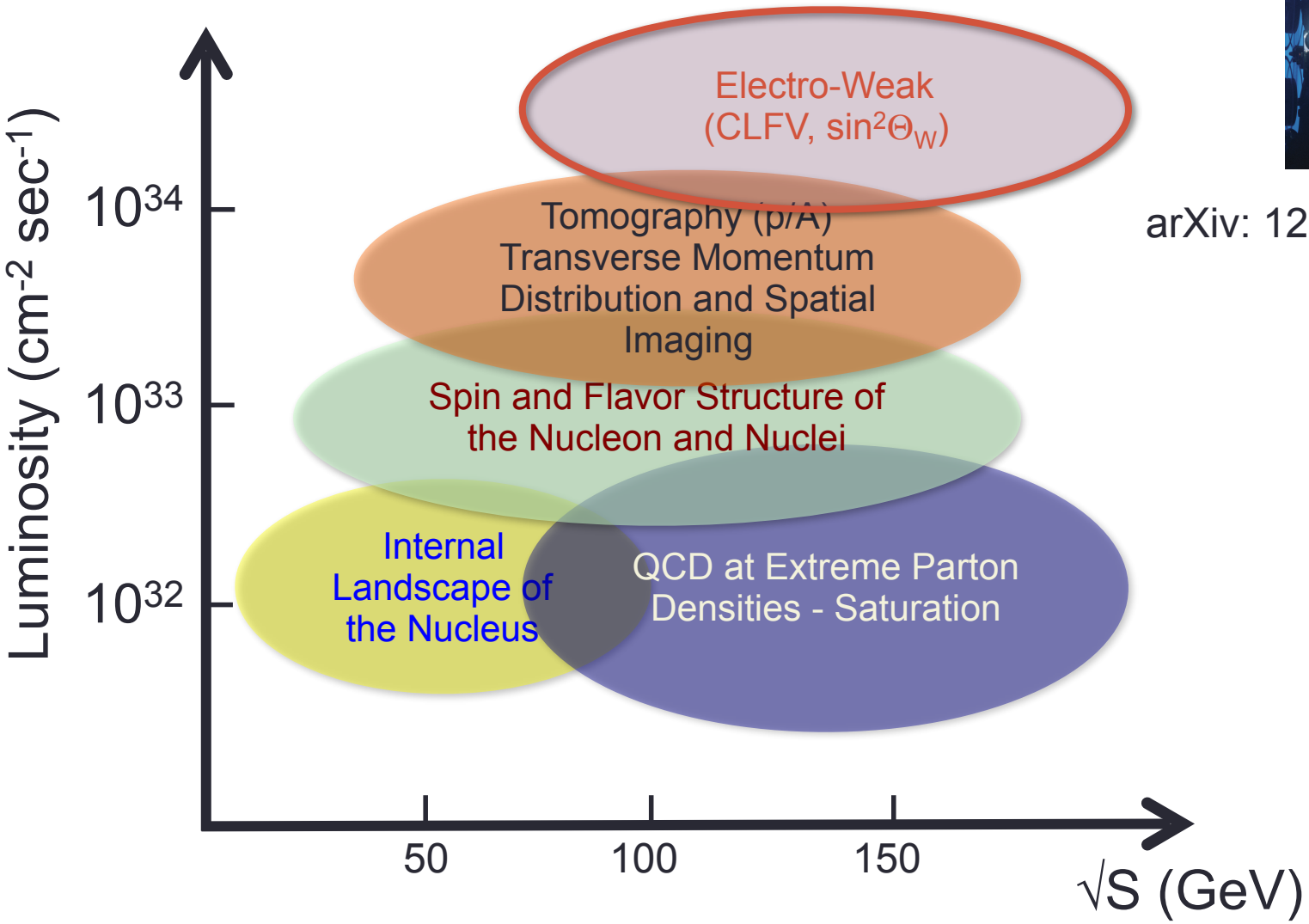
Connect to energy loss in Hot QCD

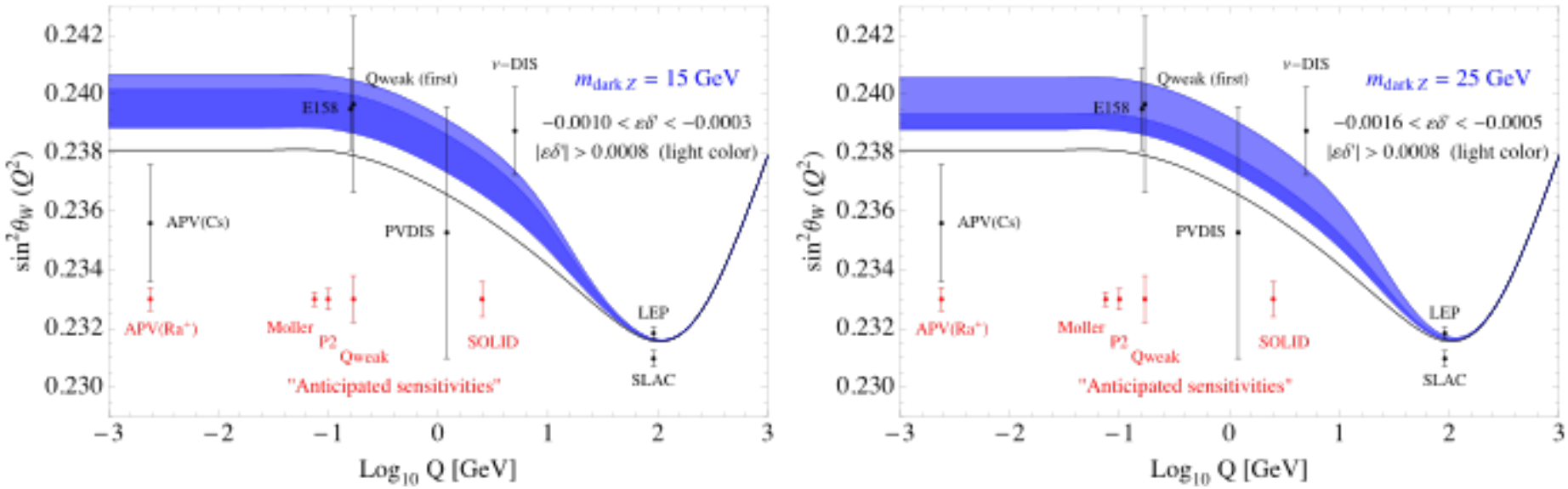
Need the collider energy of EIC and its control on parton kinematics

Physics vs. Luminosity & Energy



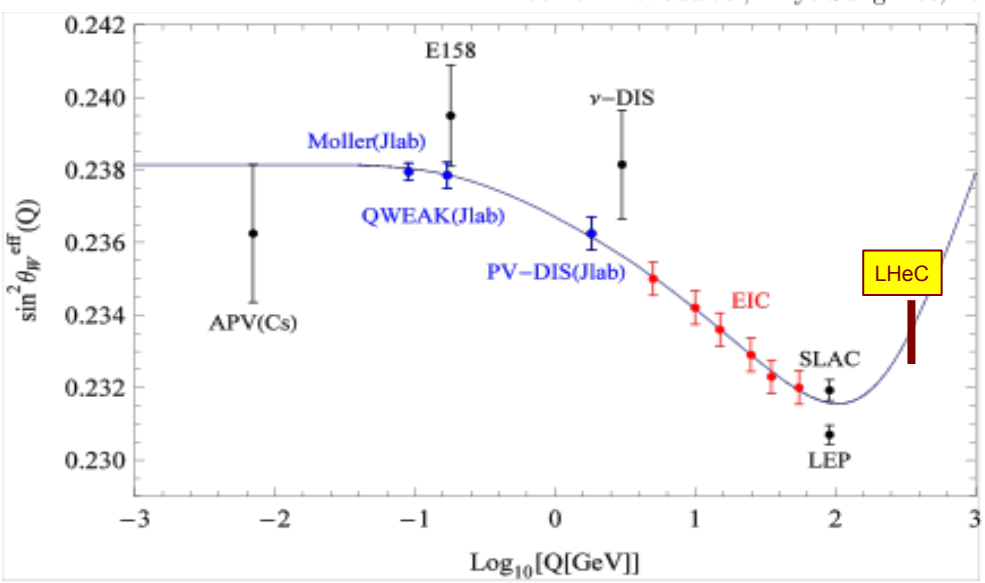
arXiv: 1212.1701.v3





Low Q^2 Weak Mixing Angle Measurements and Rare Higgs Decays

Hooman Davoudiasl,[1] Hye-Sung Lee,[2] and William J. Marciano[1]



Dark Z Study: arXiv:1507.00352

EIC Study by William Marciano et al.

A more detailed study underway:
Y. Zang, A. Deshpande & K. Kumar et al.

Community: Will **YOU** get involved?

EIC User Group → eicug.org (contact me!)

The EIC Users Meeting at Stony Brook, June 2014:

→*http://skipper.physics.sunysb.edu/~eicug/meeting1/SBU.html*

The EIC UG Meeting at University of Berkeley, January 6-9, 2016

http://skipper.physics.sunysb.edu/~eicug/meeting2/UCB2016.html

Next EICUG Argonne National Laboratory July 7-9, 2016

http://eic2016.phy.anl.gov

An active non-site-specific Generic Detector R&D Program for EIC underway, (supported by DOE, administered by BNL):

~170 physicists, 31 institutes (5 Labs, 22 Universities, 9 Non-US Institutions) 15+ detector consortia exploring novel technologies for tracking, particle ID, calorimetry

→*https://wiki.bnl.gov/conferences/index.php/EIC_R%25D*

Ample opportunities for your contributions & participation!