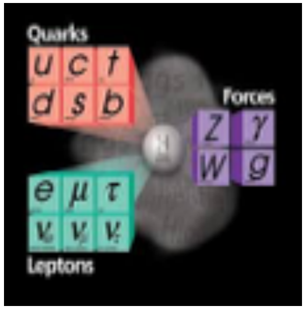
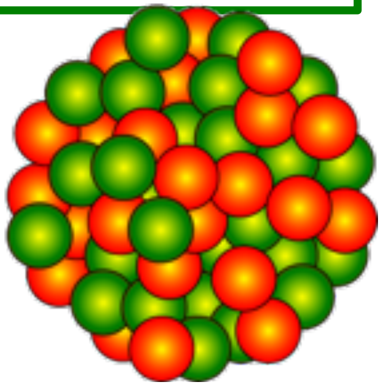
Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

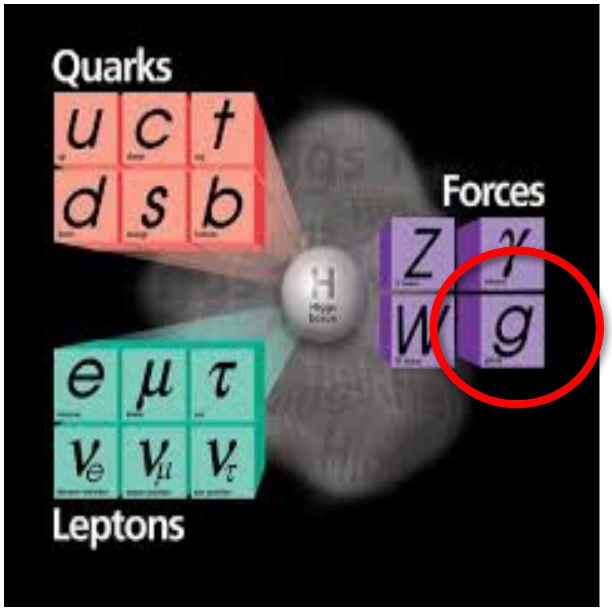
Why the EIC?

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





Gluon in the Standard Model of Physics



Gluon: carrier of strong force (QCD)

Chargeless, massless, but carries color-charge

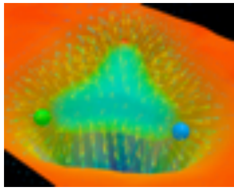
Binds the quarks and gluons inside the hadrons with tremendous force! (Strong force)

At the heart of many un/(ill)-understood phenomena:

Color Confinement, composition of nucleon spin, quark-gluon plasma at RHIC & LHC…

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 95% of the mass of the nucleons:

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

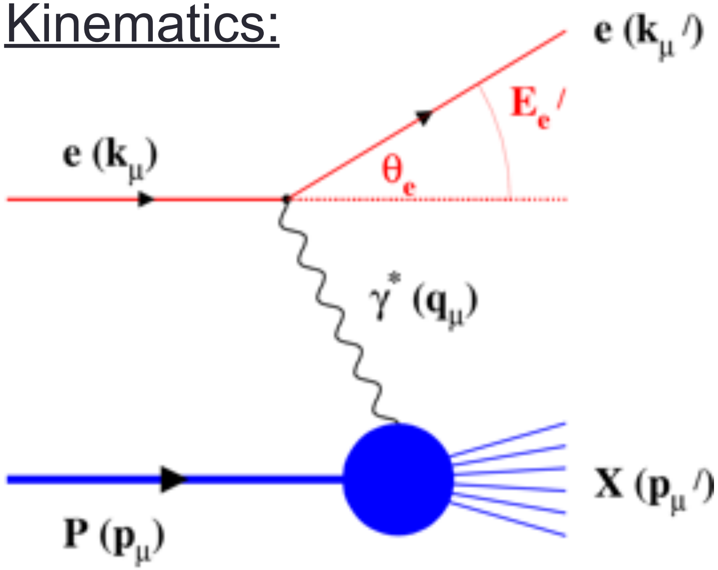
- Gluons carry ~50% the proton's momentum, **?%** of the nucleon's spin, and are responsible for the transverse momentum of quarks
- The quark-gluon origin of the nucleon-nucleon forces in nuclei not quite known
- Lattice QCD can't presently address dynamical properties on the light cone

Experimental insight and guidance crucial for complete understanding of *how* hadron & nuclei emerge from quarks and gluons

CONFINEMENT!

Deep Inelastic Scattering brings Precision

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

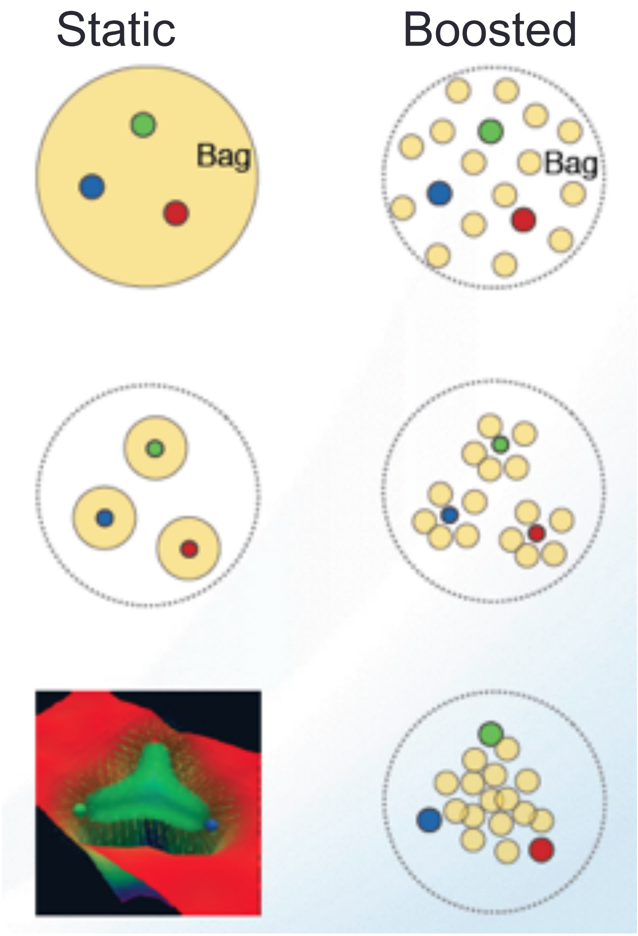
Detect the scattered lepton in coincidence with identified hadrons/jets

Exclusive measurements:

e+p/A → e'+h(π,K,p,jet)+p'/A'

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

What does a proton look like?



Bag Model: Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

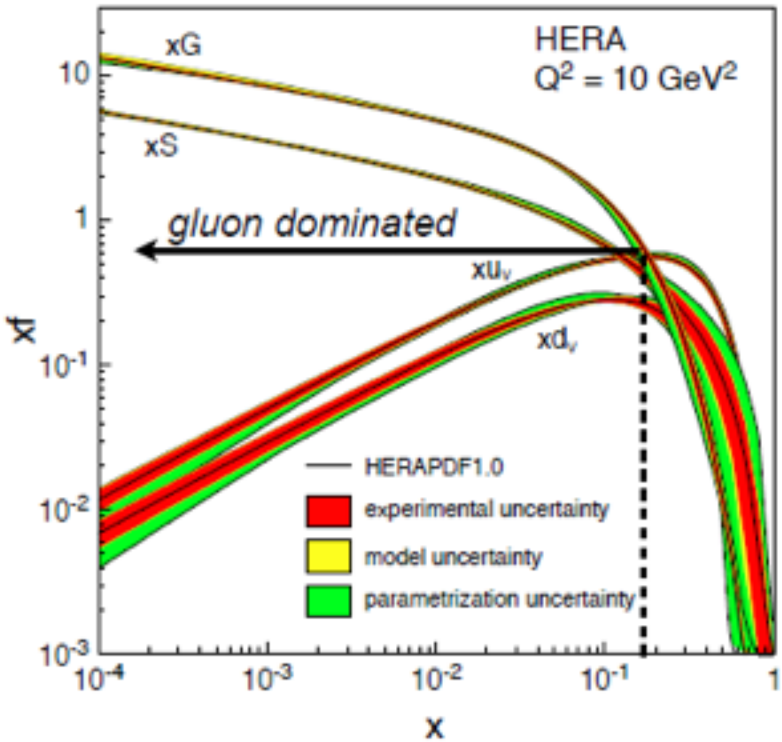
Constituent Quark Model: Gluons and sea quarks hide inside massive quarks.
Gluon radius ~ Charge Radius

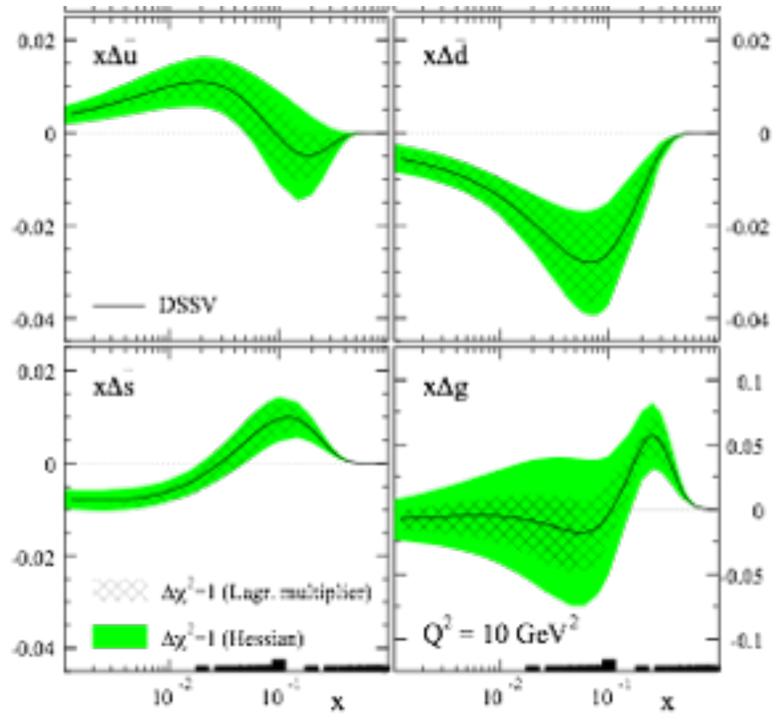
Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks: Gluon radius < Charge Radius

Need transverse images of the quarks *and gluons* in protons

What does a proton look like? Unpolarized & polarized

We only *have a 1-dimensional picture!*





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 does a proton look like?
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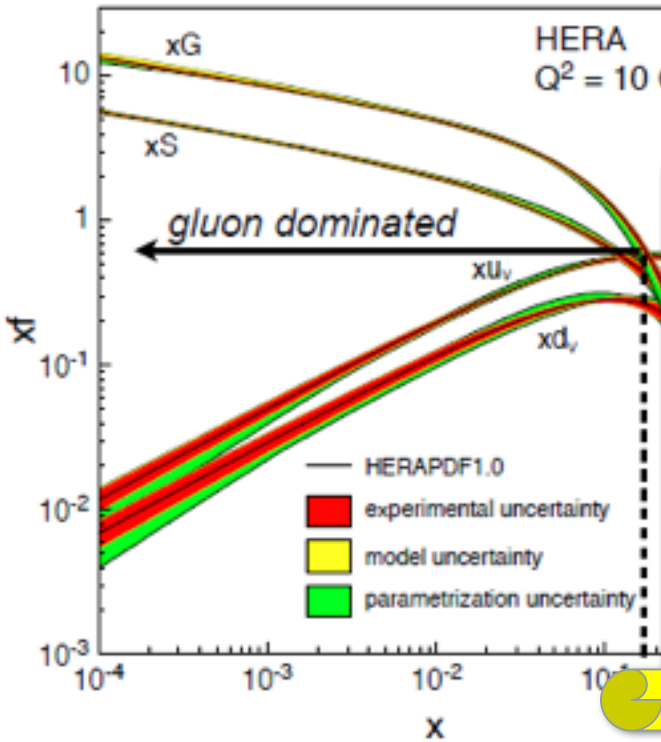
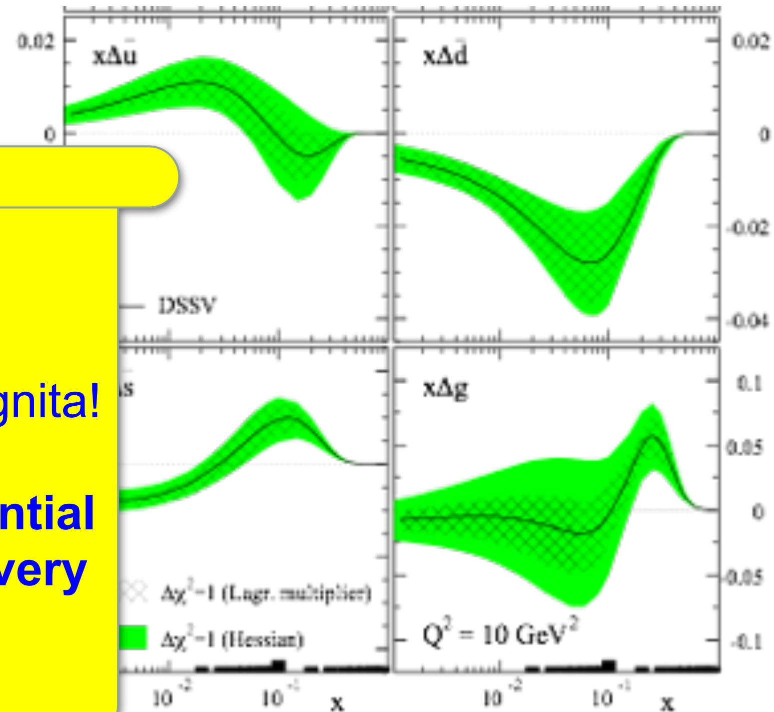


QCD
Terra-incognita!

High Potential for Discovery



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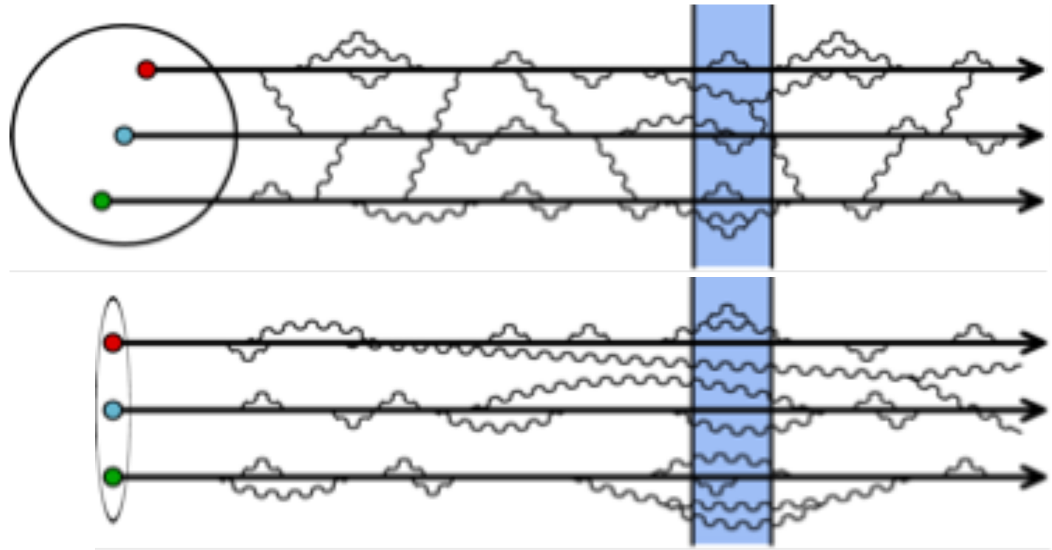
Could they give us clues on orbital motion of partons?

How does a Proton look at low and high energy?

Low energy
High x
Regime of fixed target exp.

High energy
Low- x
Regime of a Collider



At high energy:

- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate further smaller x gluons ➔ which intern radiate more……. Leading to a **runaway growth?**

Gluon and the consequences of its interesting properties:

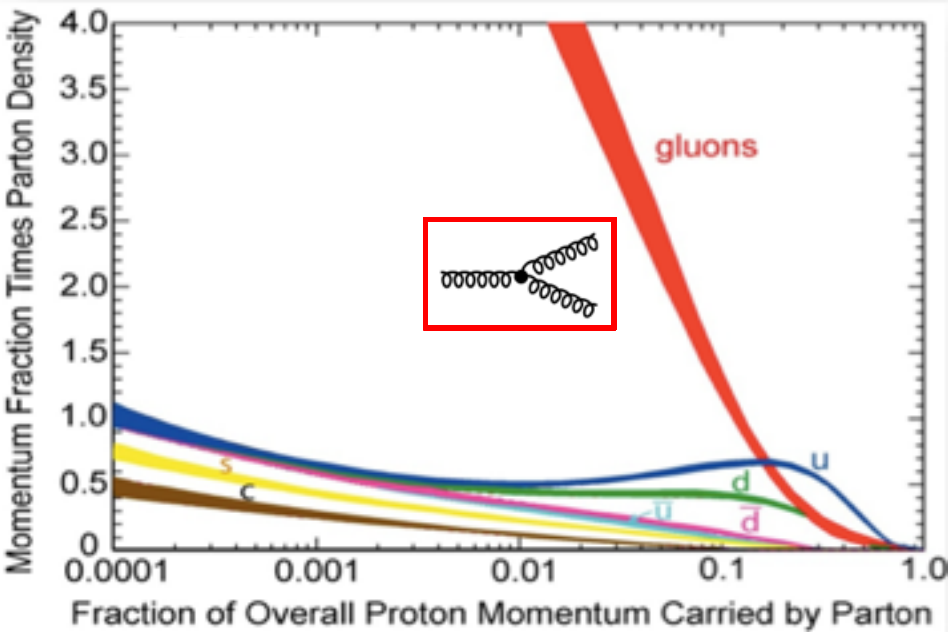
Gluons carry color charge ➔ Can interact with other gluons!

"…The result is a self catalyzing enhancement that leads to a runaway growth.
A small color charge in isolation builds up a big color thundercloud…."

F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004

Gluon and the consequences of its interesting properties:

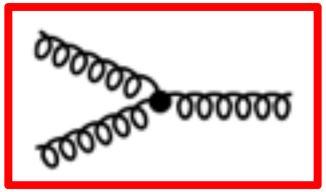
Gluons carry color charge → Can interact with other gluons!



Apparent "indefinite rise" in gluon distribution in proton!

What could **limit this indefinite rise?** → saturation of soft gluon densities via gg→g recombination must be responsible.

recombination



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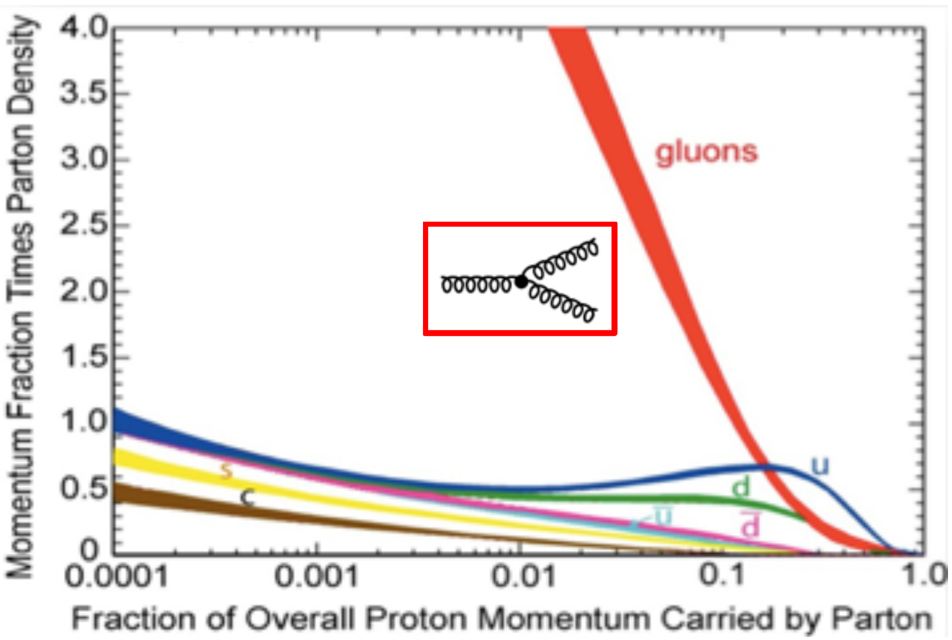

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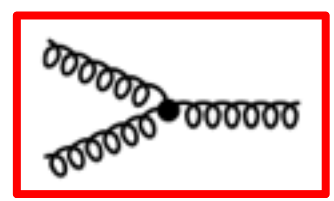
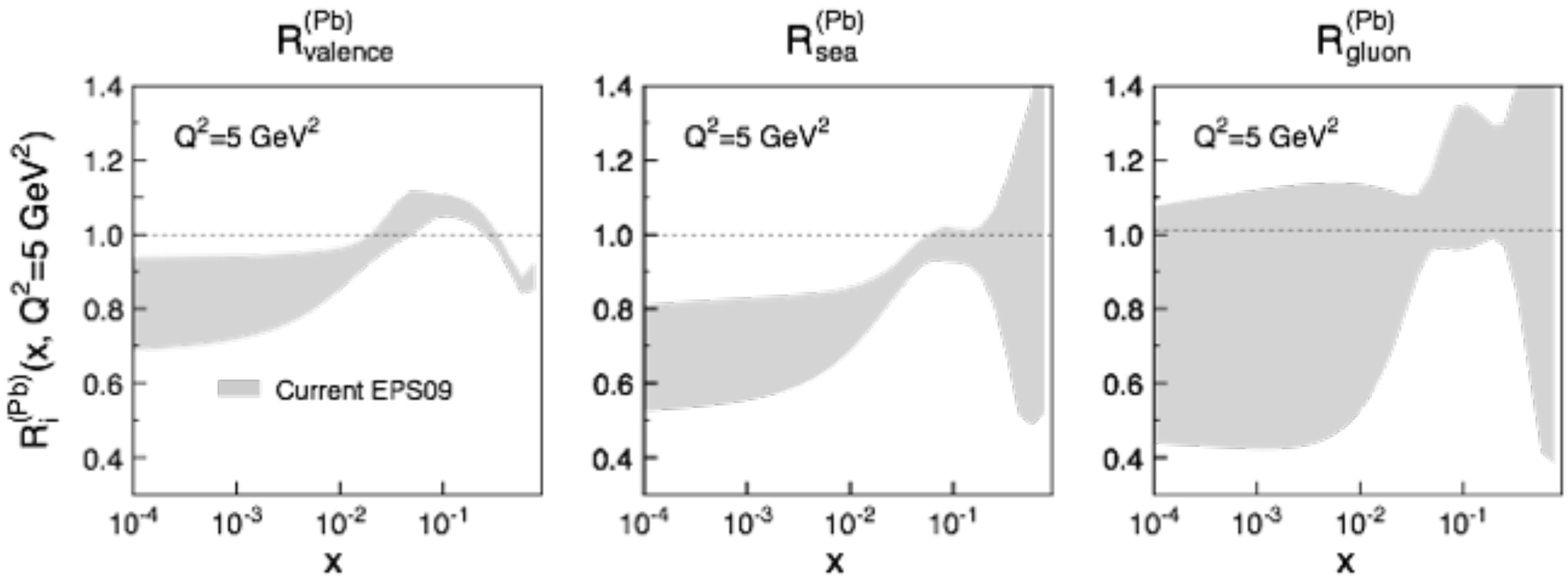


Where? No one has unambiguously seen this before!

If true, effective theory of this →"Color Glass Condensate"

McLerran & Venugopalan et al

What does a nucleus look like?



Large uncertainties & only 1-D information!
Need to reduce uncertainties & ***go beyond the 1-dimensions***
Need (2+1)D partonic images of nuclei*.*

Fully understand: emergence of hadrons in Cold QCD matter &
initial state ←→ properties of QGP formed in AA collisions

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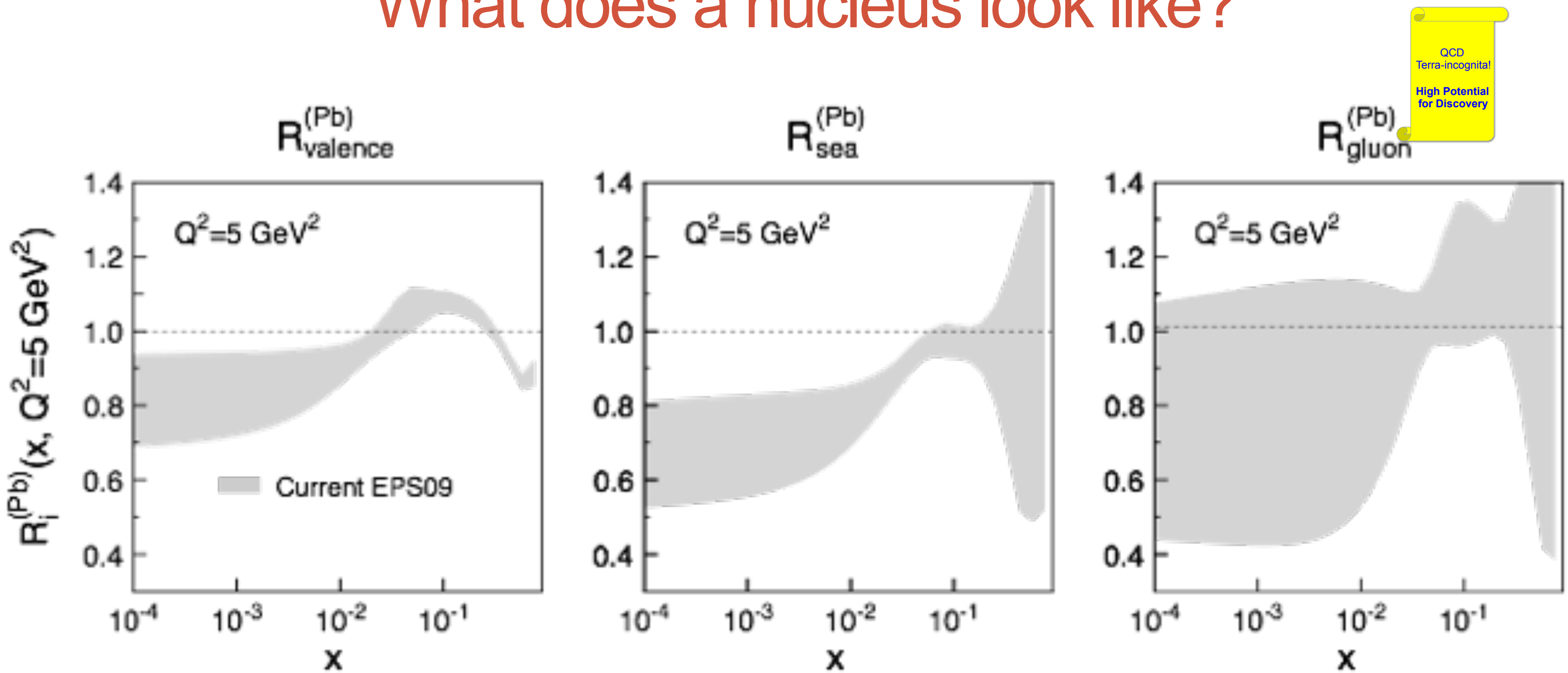

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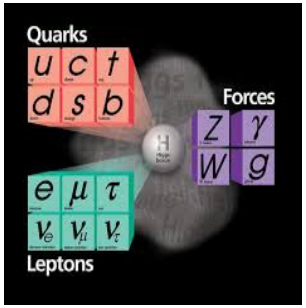
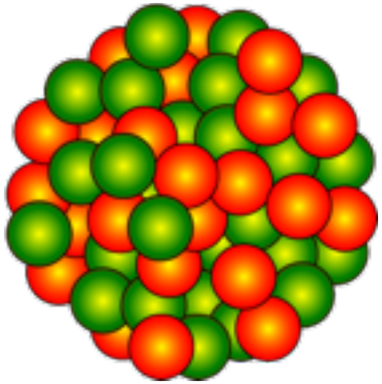
Why an Electron Ion Collider?

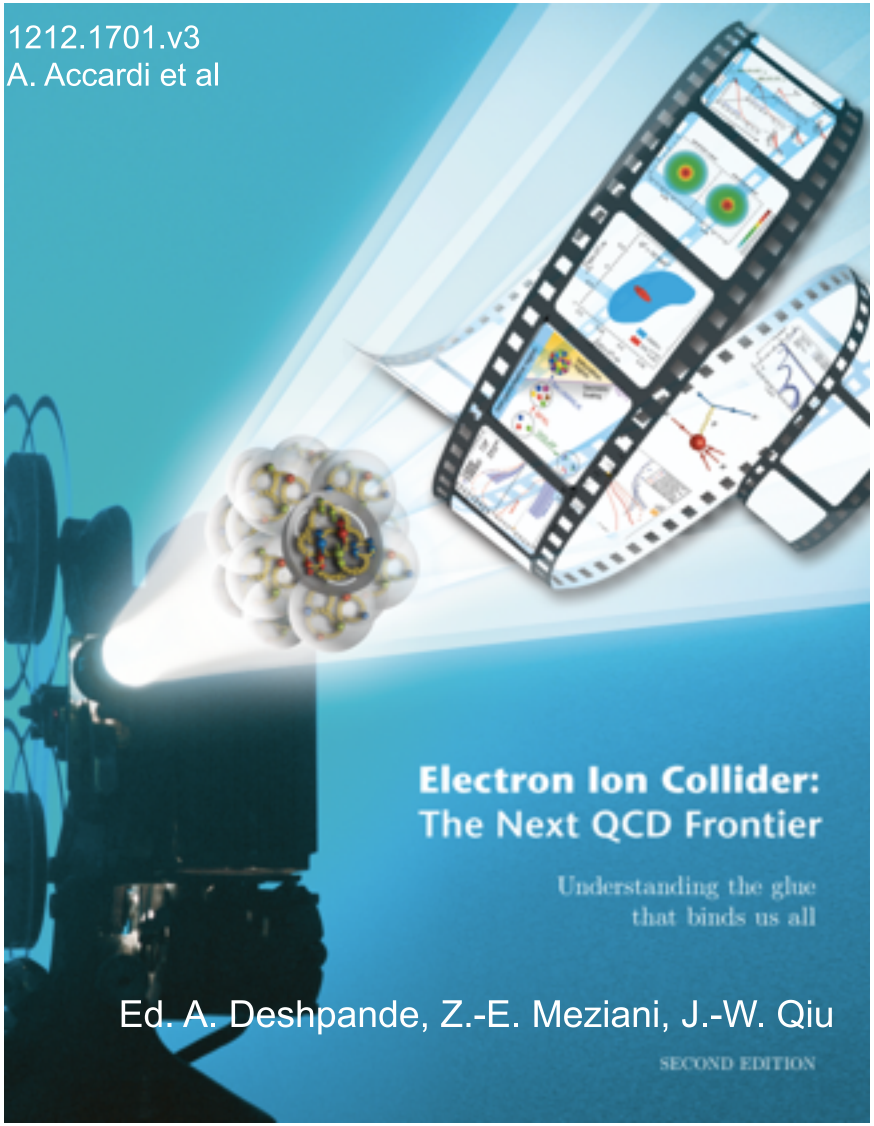
A new facility, EIC, with a versatile range of kinematics, beam polarizations, high luminosity and beam species, is required to ***precisely image*** *the sea quarks and gluons in nucleons and nuclei*, to explore the new QCD frontier of strong color fields in nuclei, and to resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD

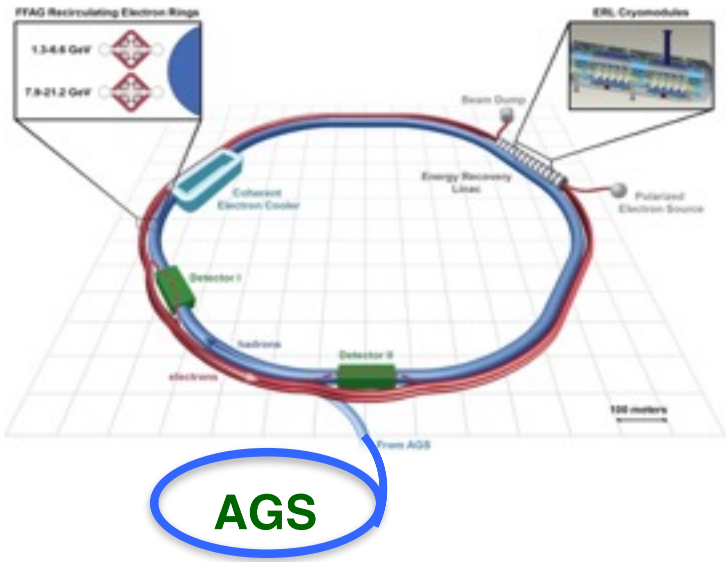


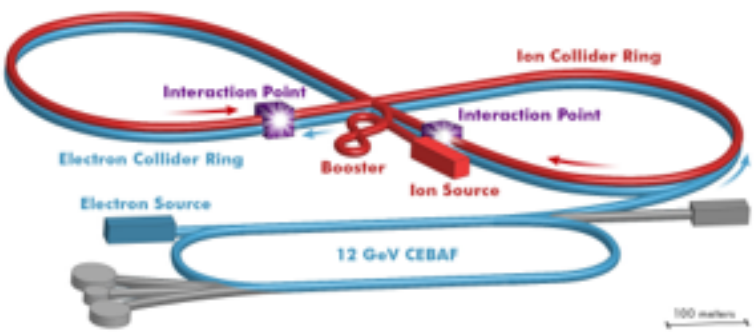



The Electron Ion Collider

Two options of realization!





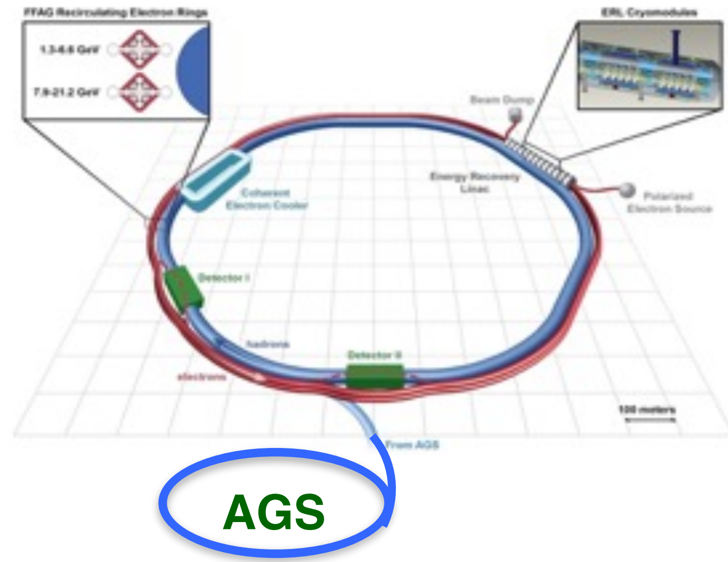


The Electron Ion Collider

Two options of realization!

For e-N collisions at the EIC:

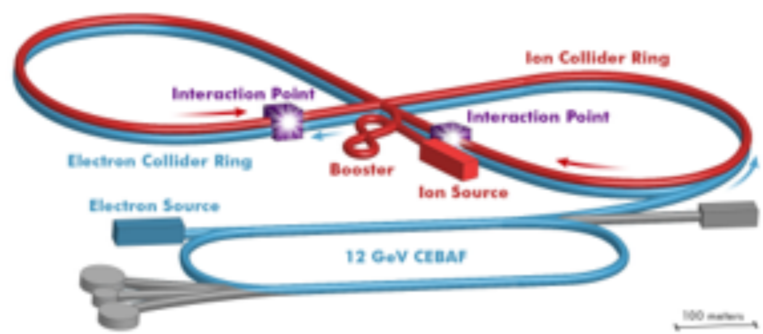
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM



For e-A collisions at the EIC:

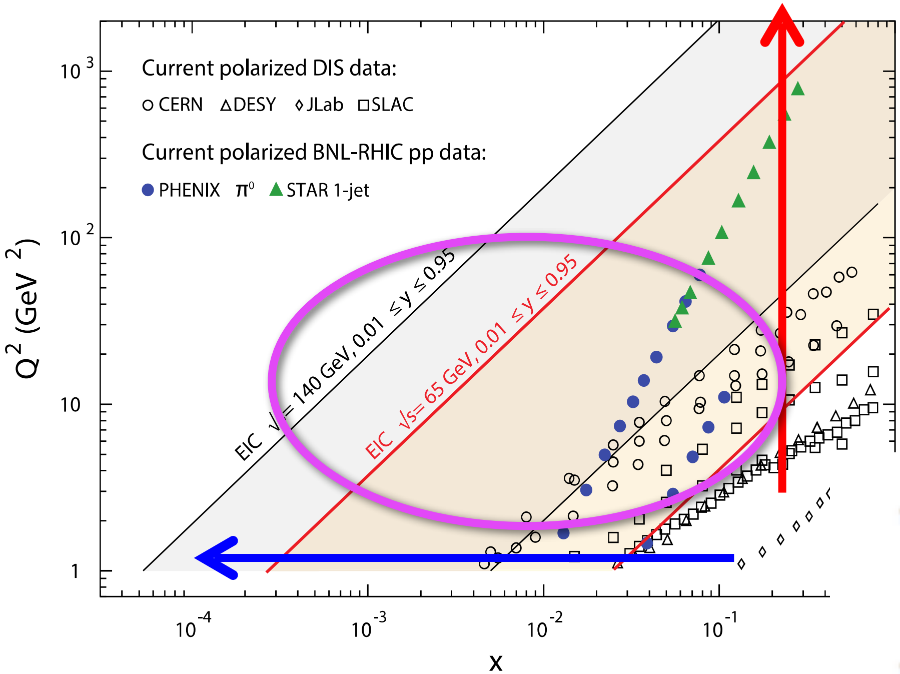
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

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

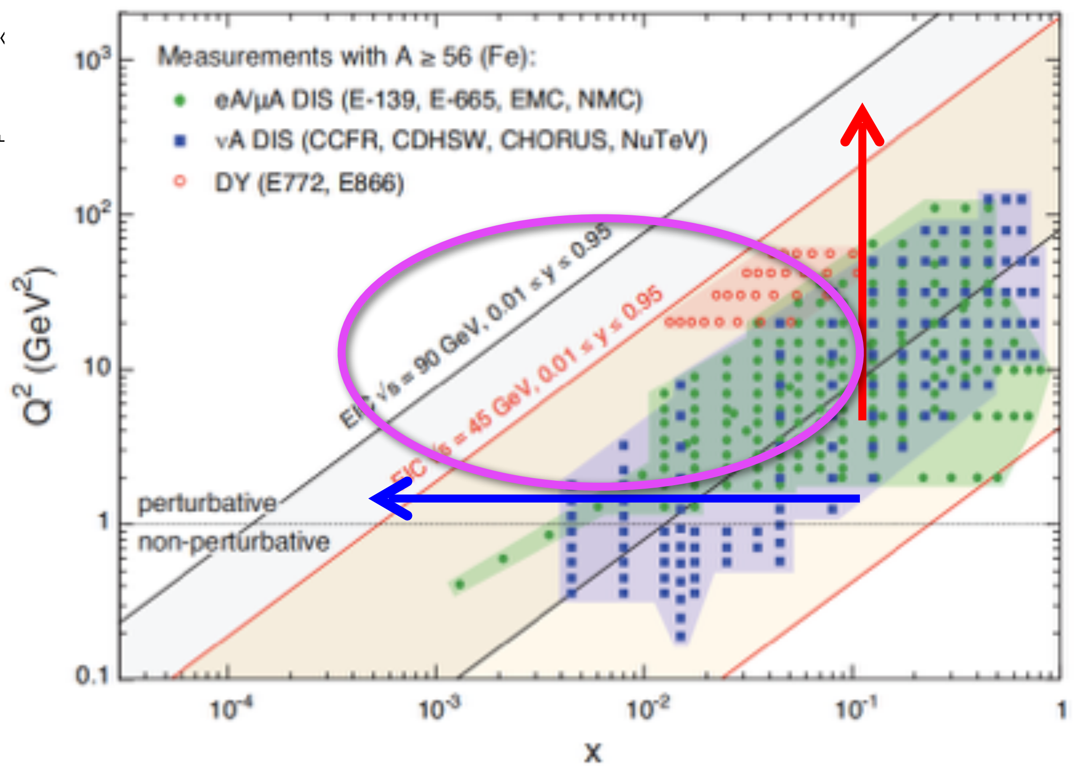


For e-N collisions at the EIC:

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

For e-A collisions at the EIC:

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



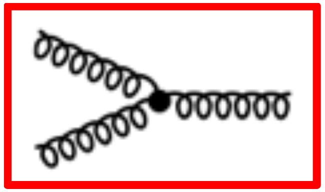
Puzzles and challenges in understanding these QCD many body emergent dynamics

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?

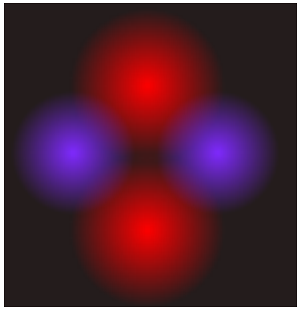
What happens to the gluon density in nuclei at high energy? Does it saturate in to a gluonic form of matter of universal properties?

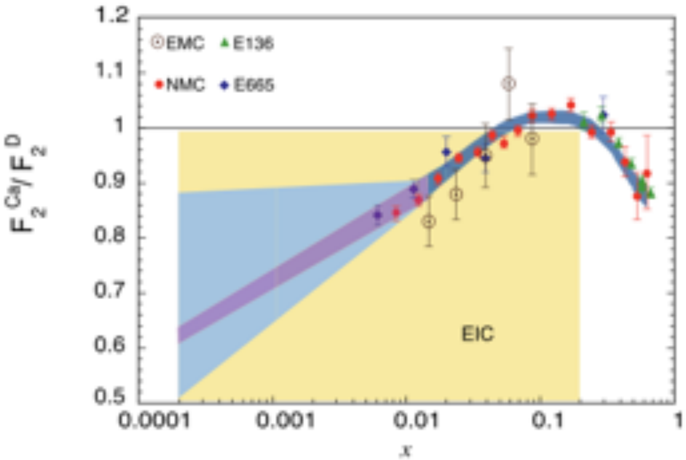


?

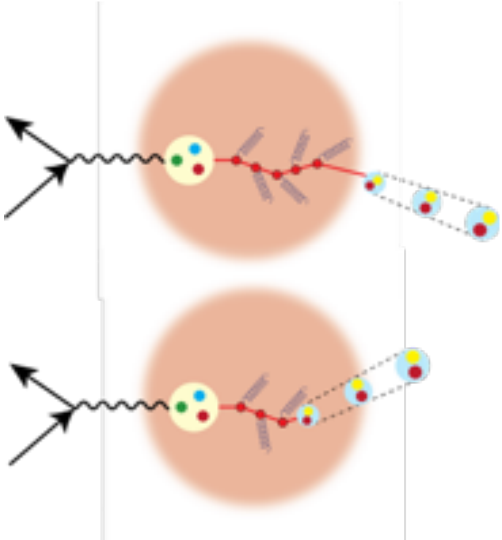
Puzzles and challenges….

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





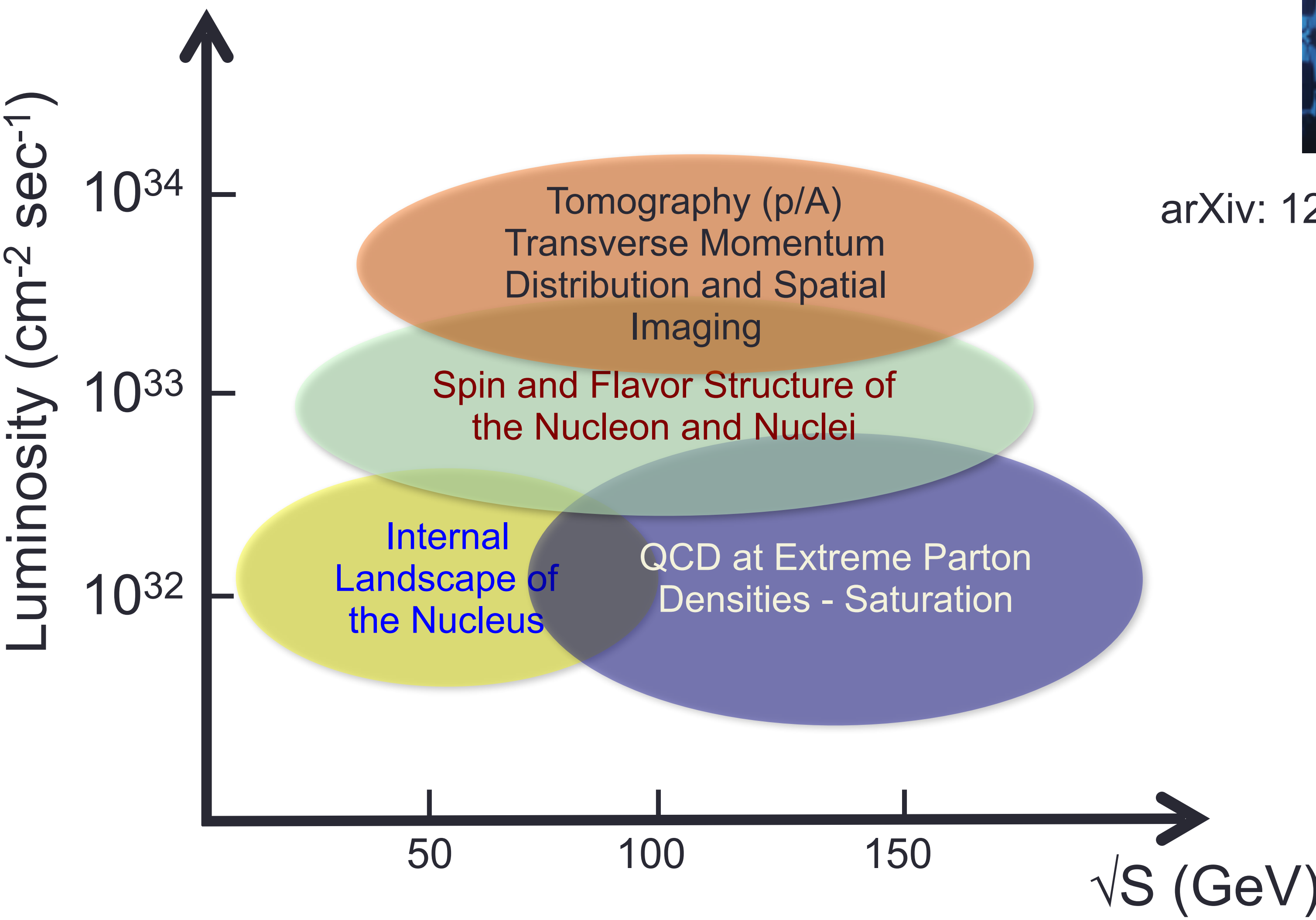
How does the nuclear environment affect the distributions of quarks and gluons and their interactions inside nuclei?



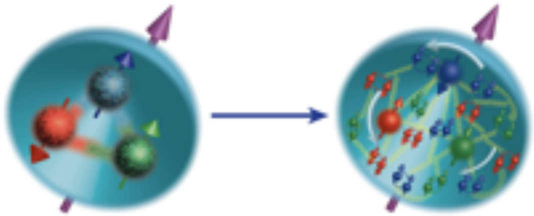
How does nuclear matter respond to fast moving color charge passing through it? (hadronization…. confinment?)

Physics vs. Luminosity & Energy

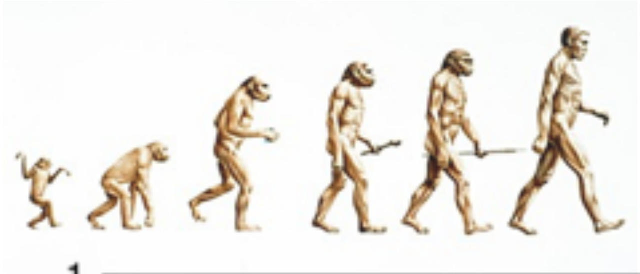
arXiv: 1212.1701.v3

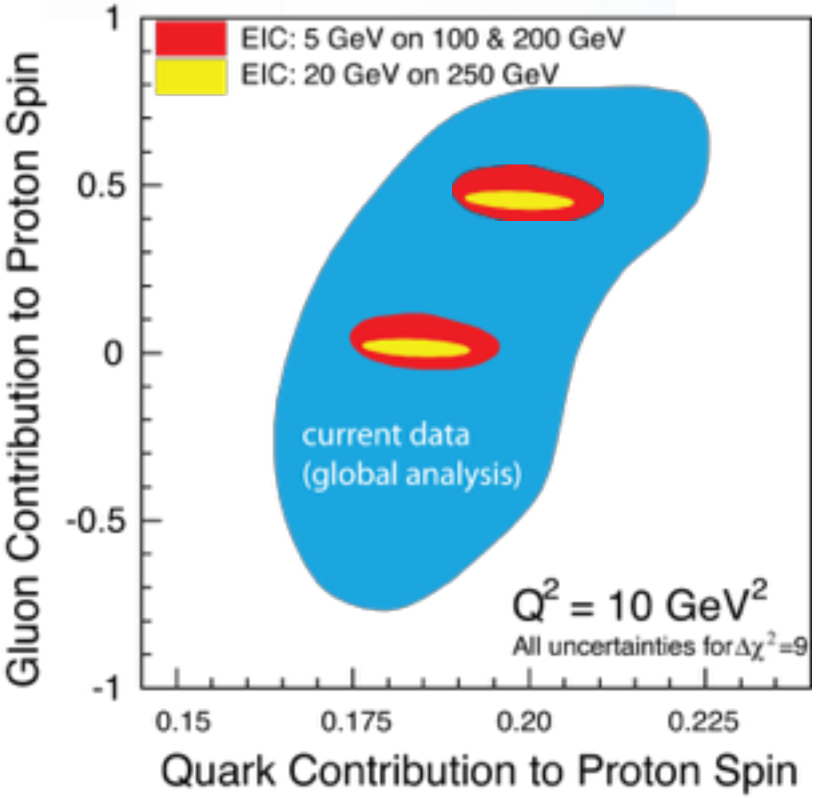


Our Understanding of Nucleon Spin



$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$





$\Delta\Sigma/2$ = Quark contribution to Proton Spin

L_Q = Quark Orbital Ang. Mom

Δg = Gluon contribution to Proton Spin

L_G = Gluon Orbital Ang. Mom

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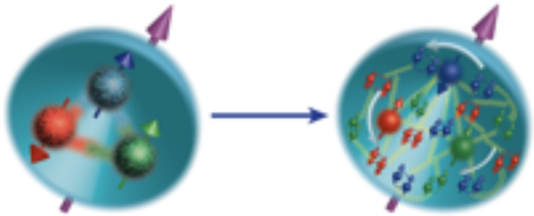

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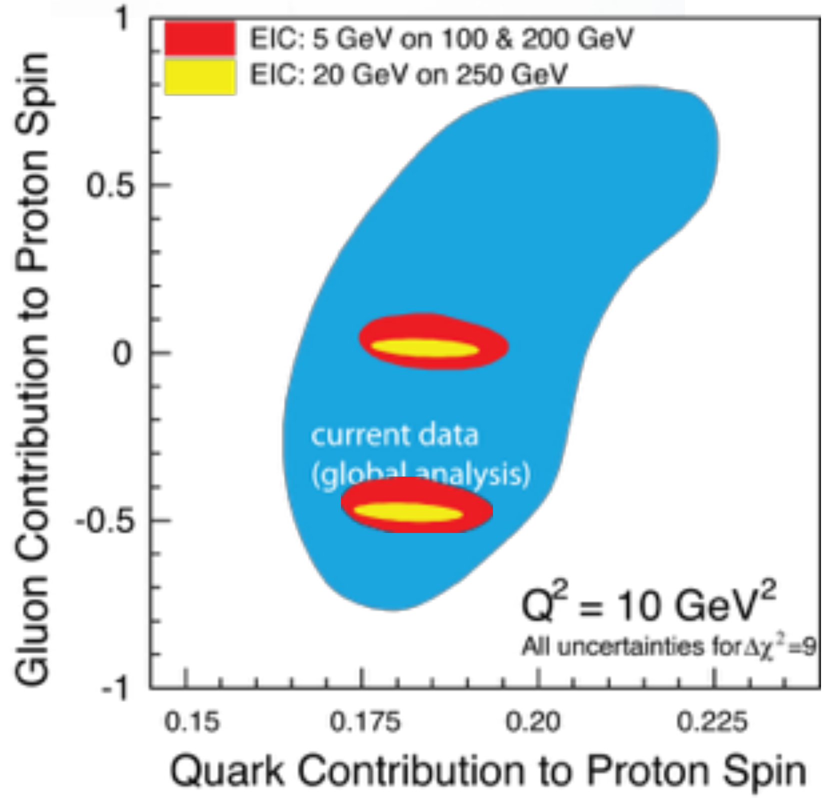

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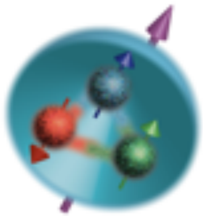

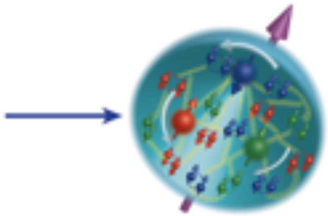

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L_Q = Quark Orbital Ang. Mom
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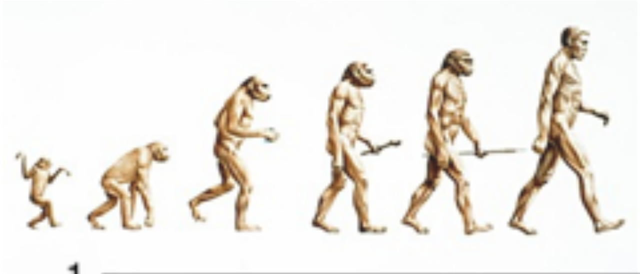
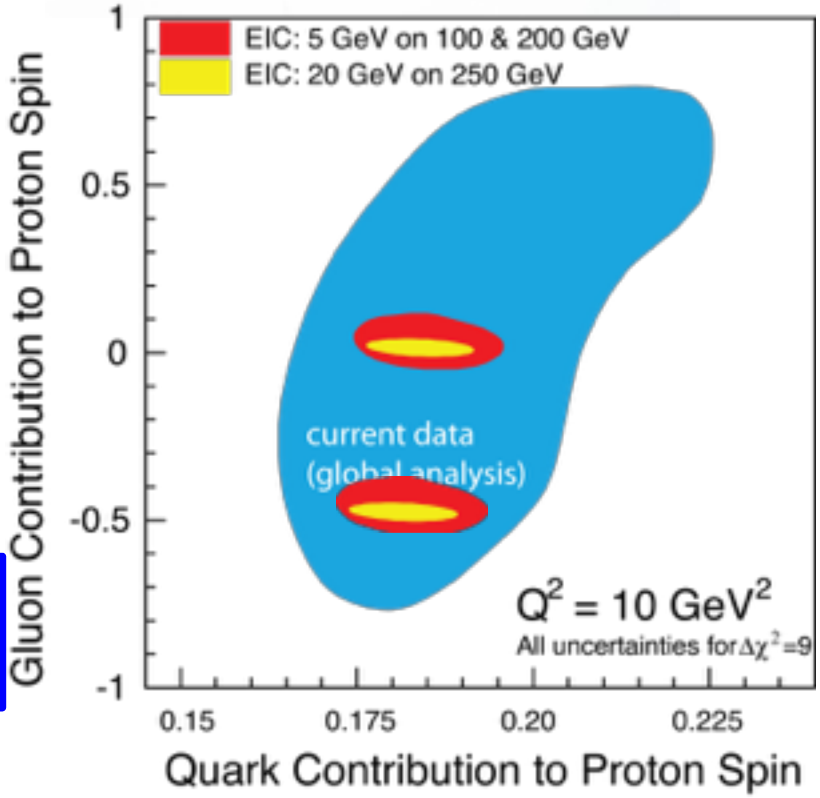
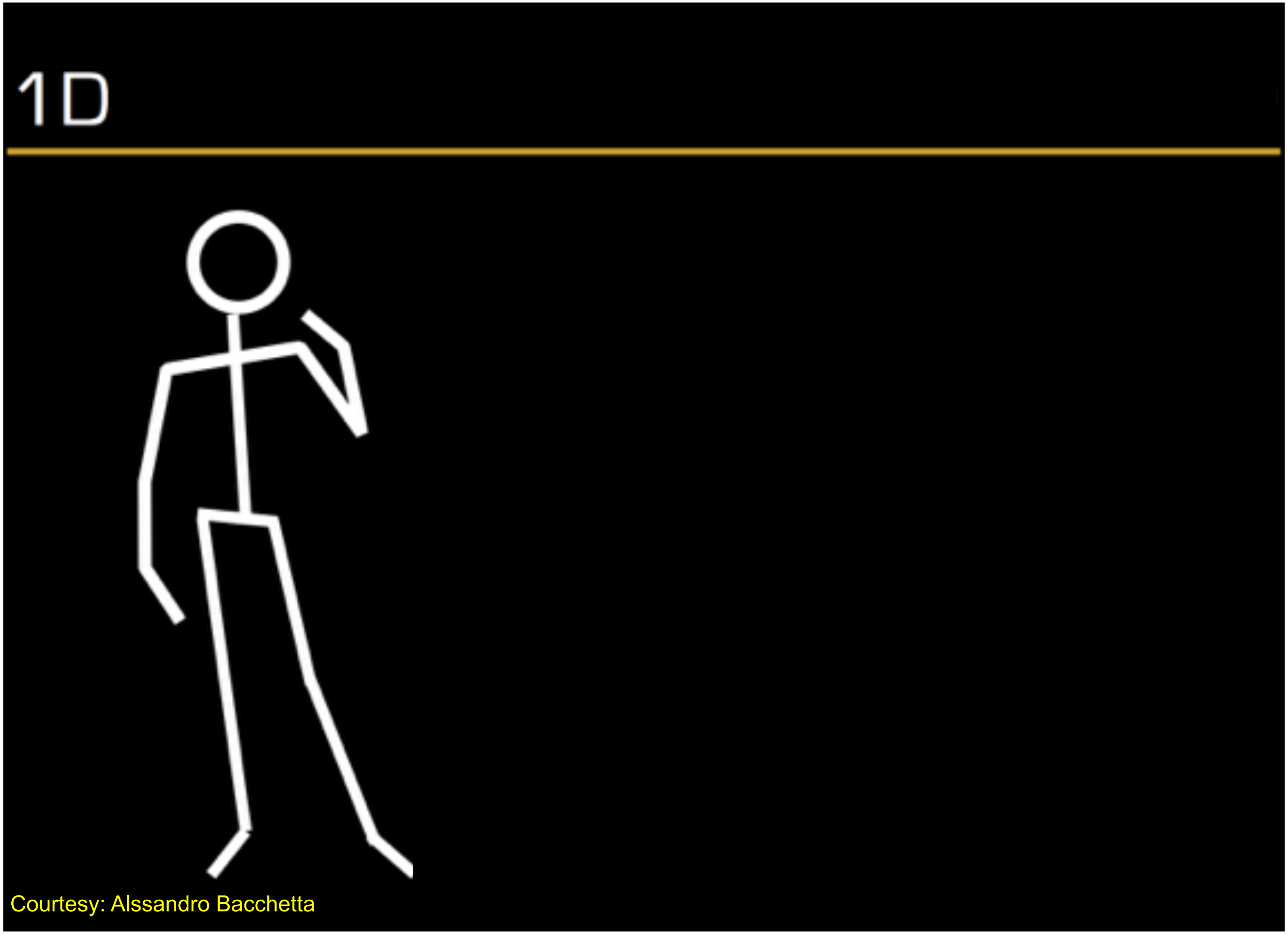
L_G = Gluon Orbital Ang. Mom

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





What do we look like?



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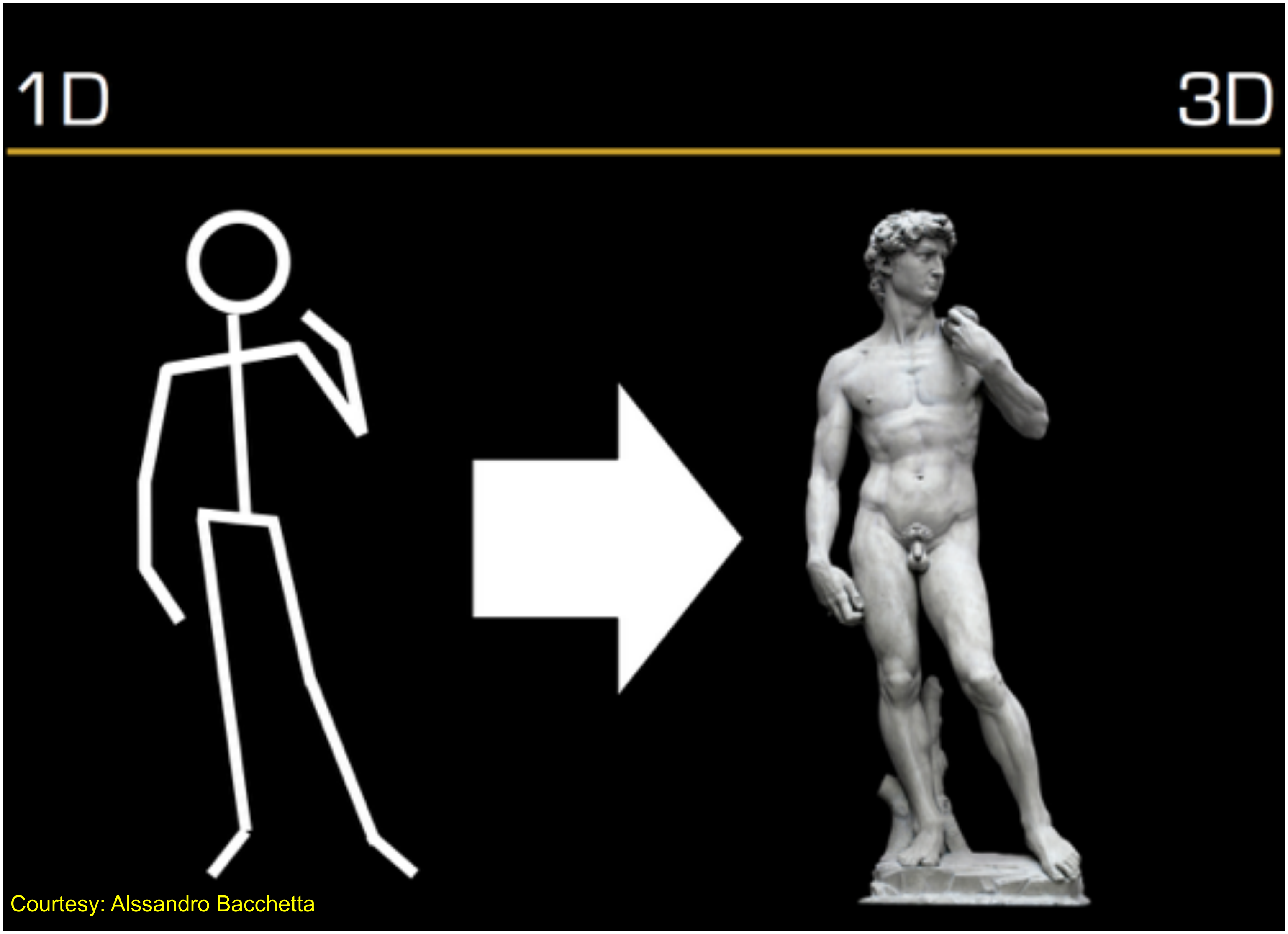

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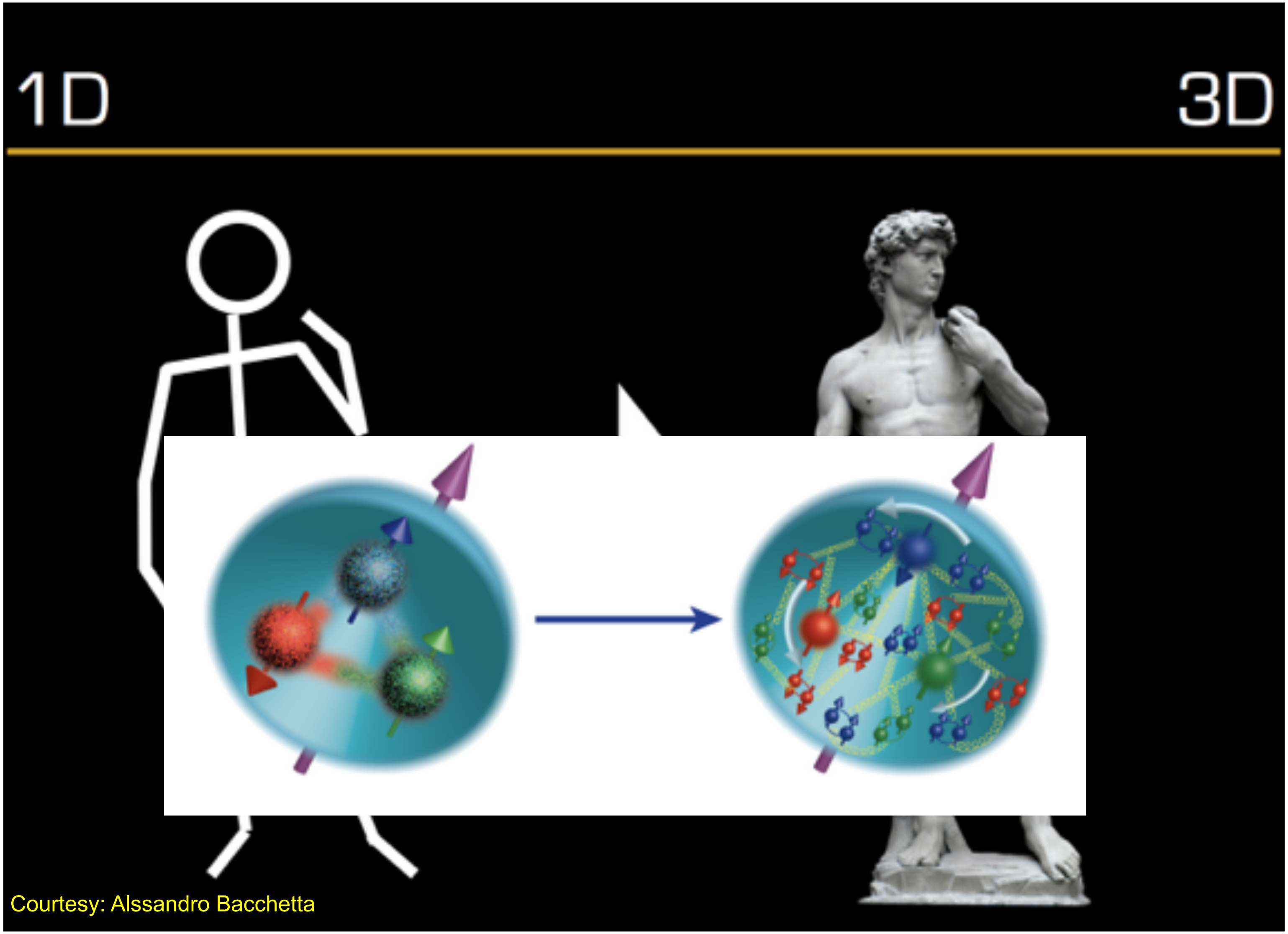


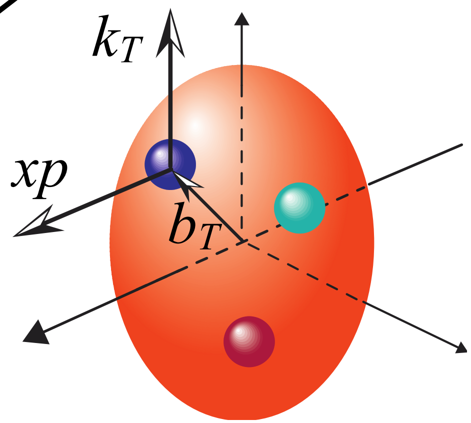
3-Dimensional Imaging Quarks and Gluons

Momentum space

$W(x,b_T,k_T)$

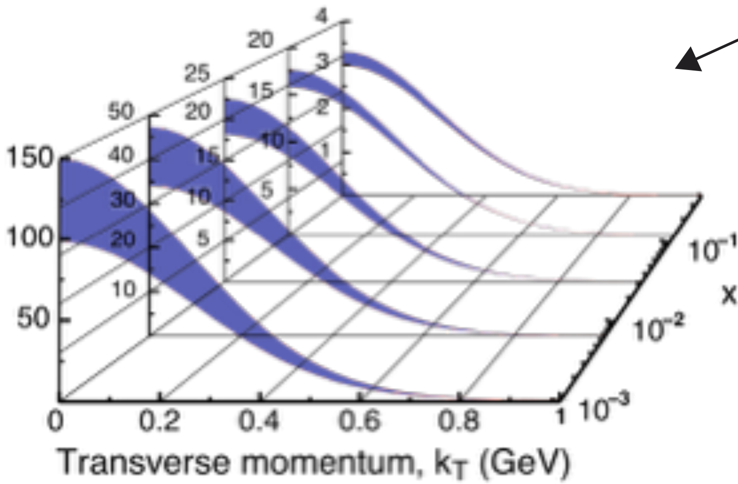
Coordinate space

$\int d^2b_T$ $\int d^2k_T$



$f(x,k_T)$ $f(x,b_T)$

Quarks



Spin-dependent 3D momentum space images from semi-inclusive scattering

3-Dimensional Imaging Quarks and Gluons

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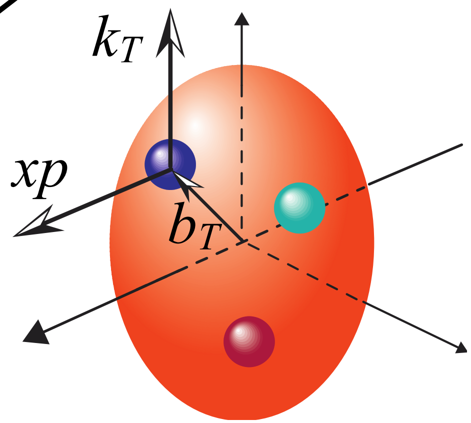
Momentum space

$\int d^2b_T$

$\int d^2k_T$

Coordinate space

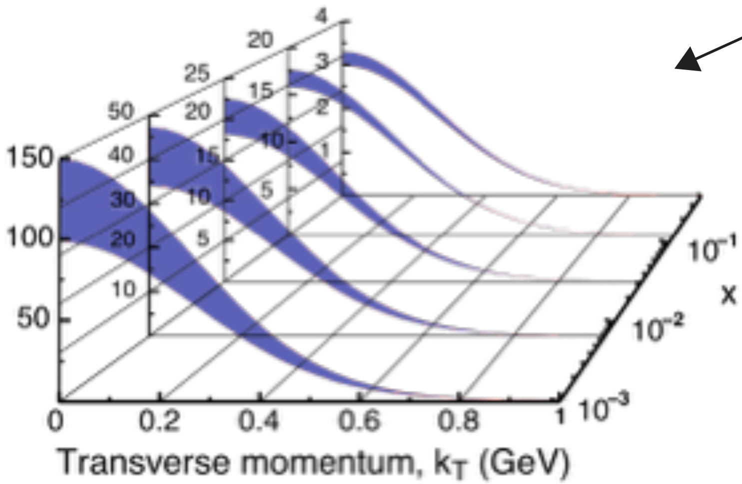


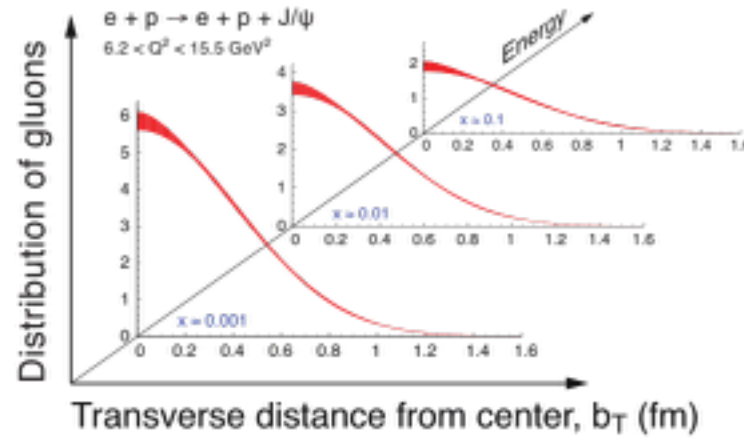
Quarks

$f(x,k_T)$

$f(x,b_T)$

Gluons



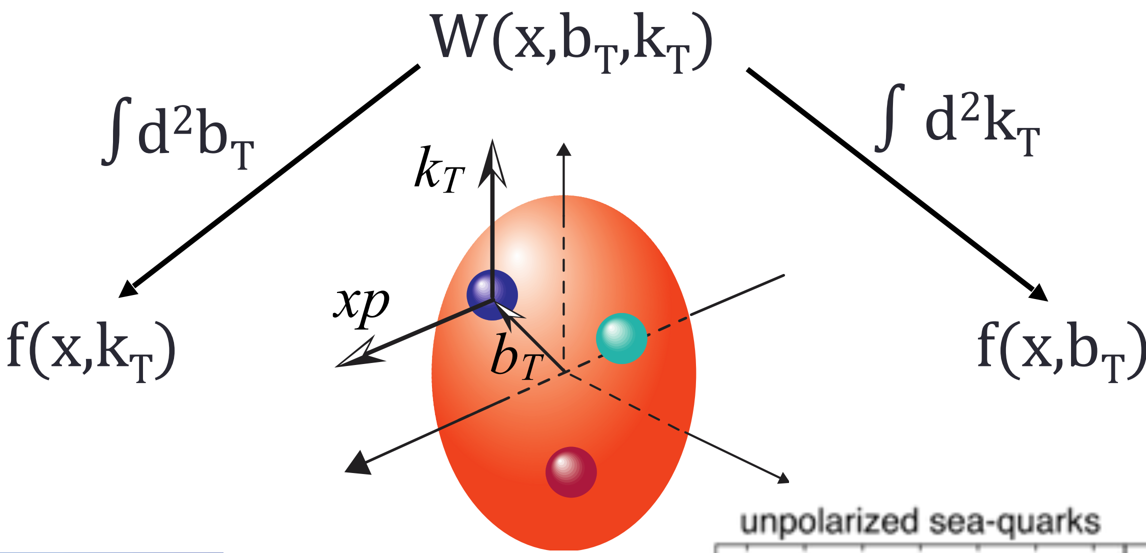


Spin-dependent 3D momentum space images from semi-inclusive scattering

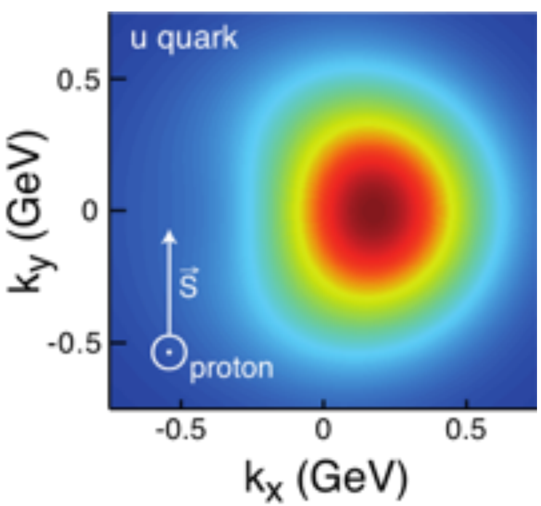
Spin-dependent 2D (transverse spatial) + 1D (longitudinal momentum) coordinate space images from exclusive scattering

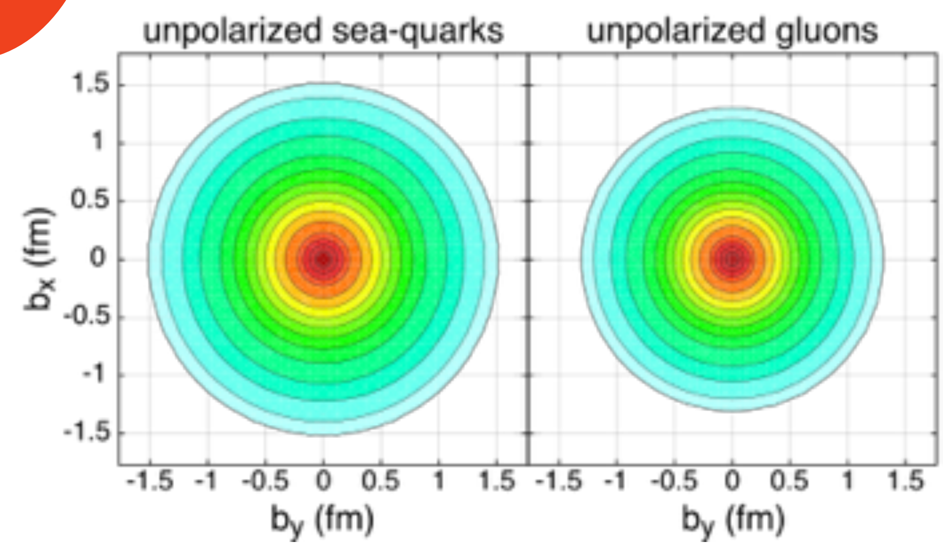
3-Dimensional Imaging Quarks and Gluons

Momentum space



Coordinate space





3-Dimensional Imaging Quarks and Gluons

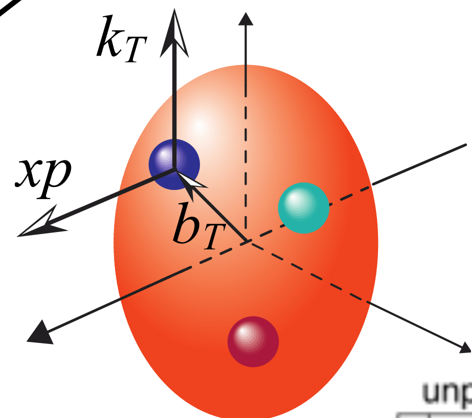
$W(x,b_T,k_T)$

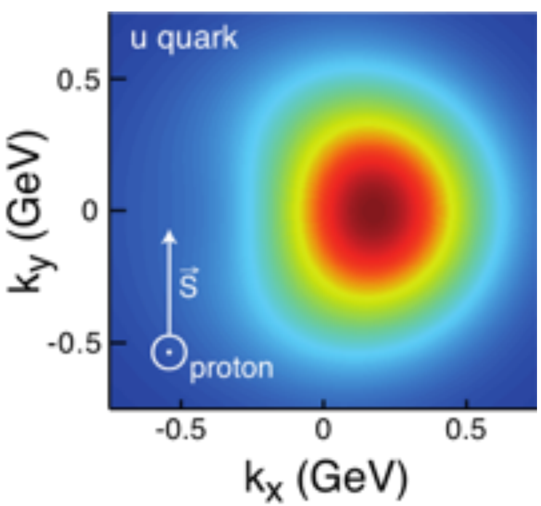
Momentum space

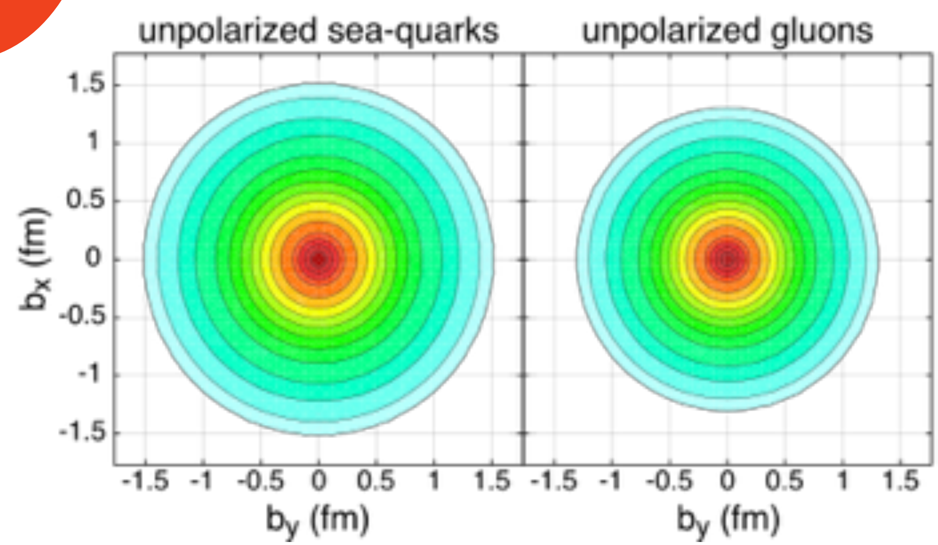
$\int d^2b_T$ → $f(x,k_T)$

Coordinate space

$\int d^2k_T$ → $f(x,b_T)$

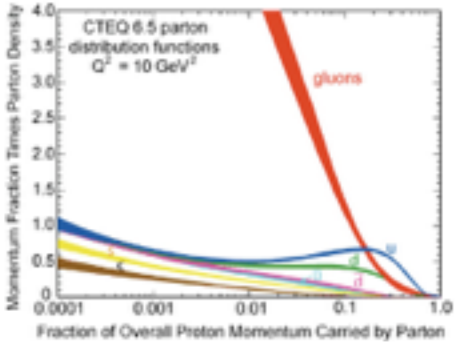




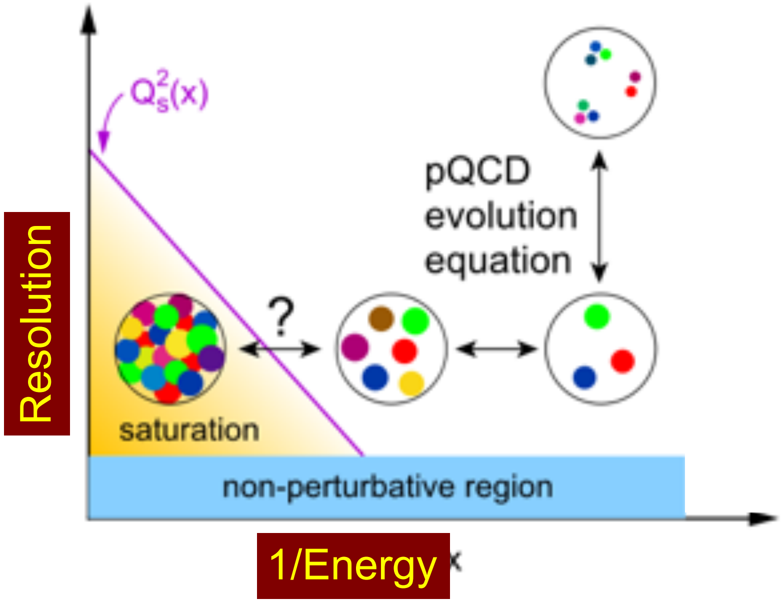


Position r X Momentum p → Orbital Motion of Partons

→ *Directly comparable with Lattice QCD Calculations*



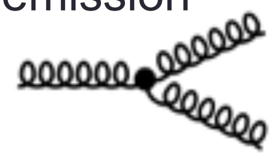
What do we learn from low-x studies?



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



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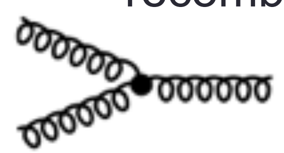
gluon recombination



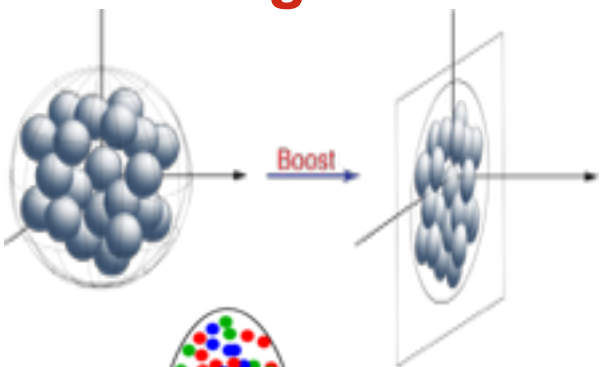
At Q_S

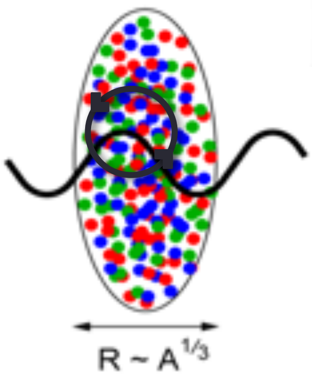
First observation of gluon recombination effects in nuclei:
→leading to a *collective* gluonic system!
First observation of g-g recombination in *different* nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

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 →





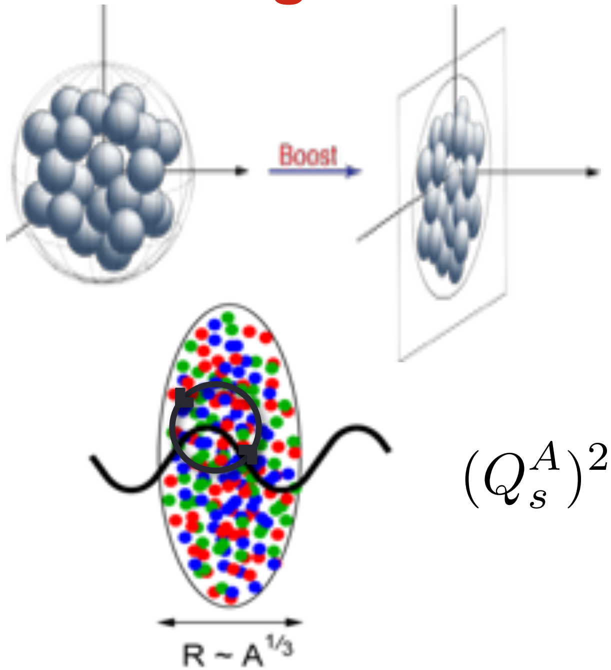
$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

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

How to explore/study this new phase of matter?

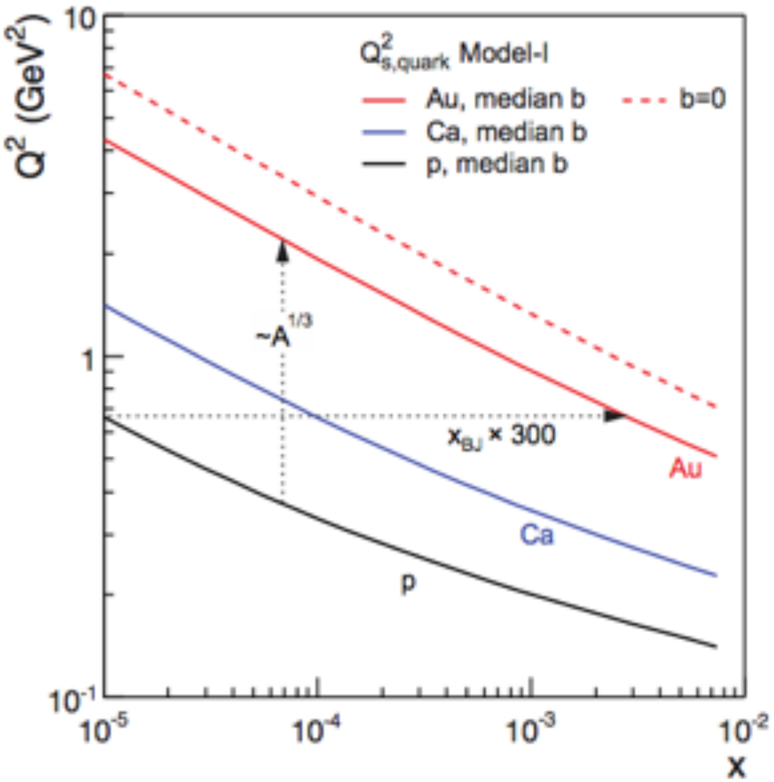
(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**

Advantage of nucleus →



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

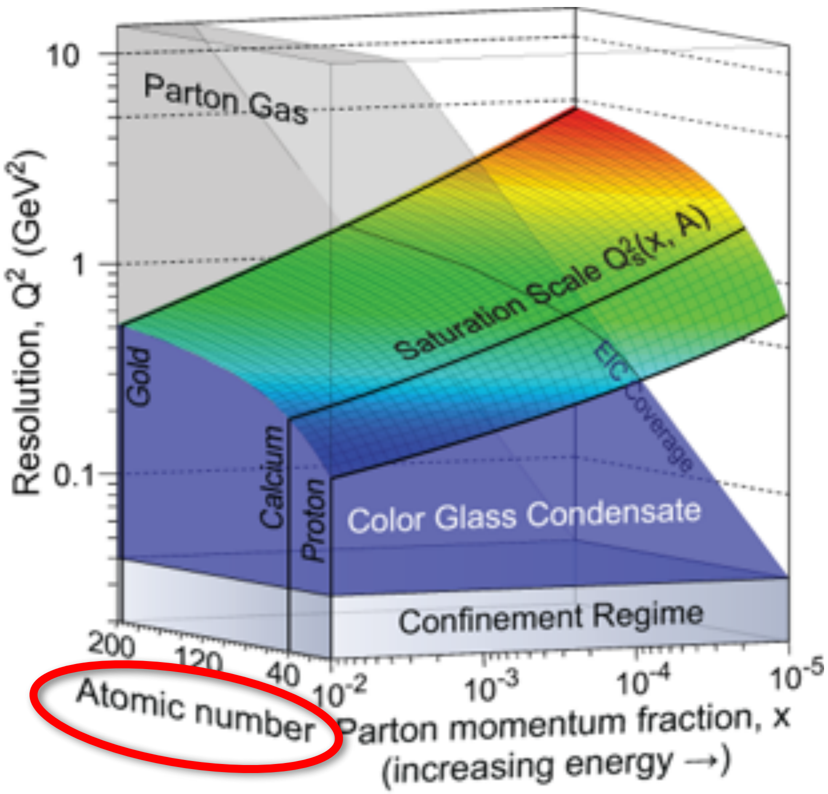
$L \sim (2m_N x)^{-1} > 2\,R_A \sim A^{1/3}$

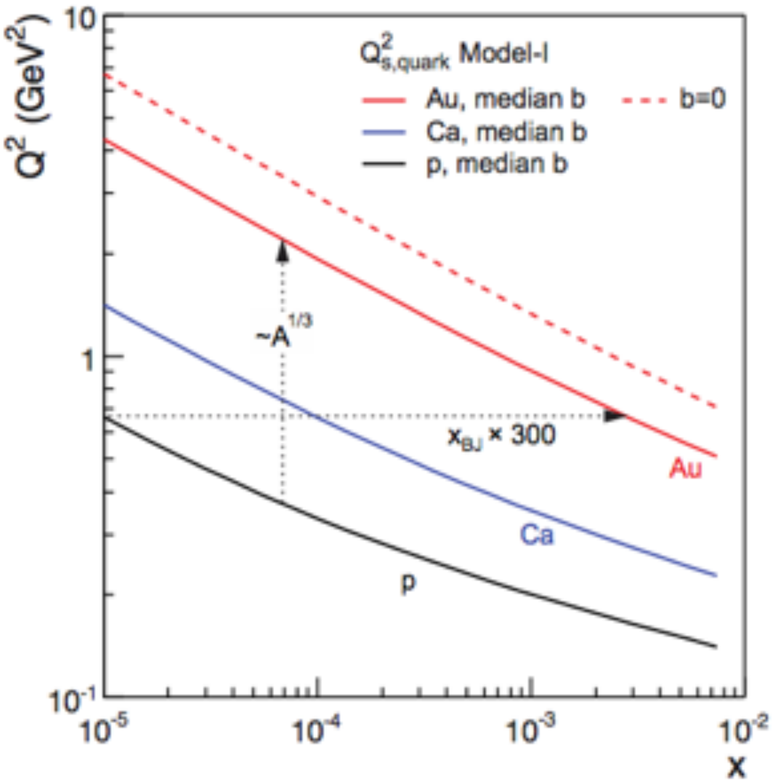


How to explore/study this new phase of matter?

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

Advantage of nucleus →





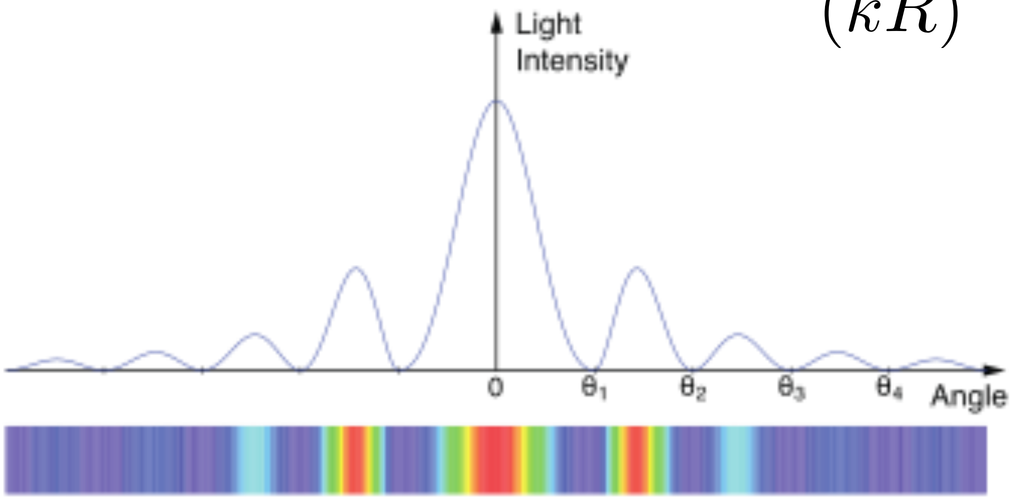
Enhancement of Q_S with A:

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

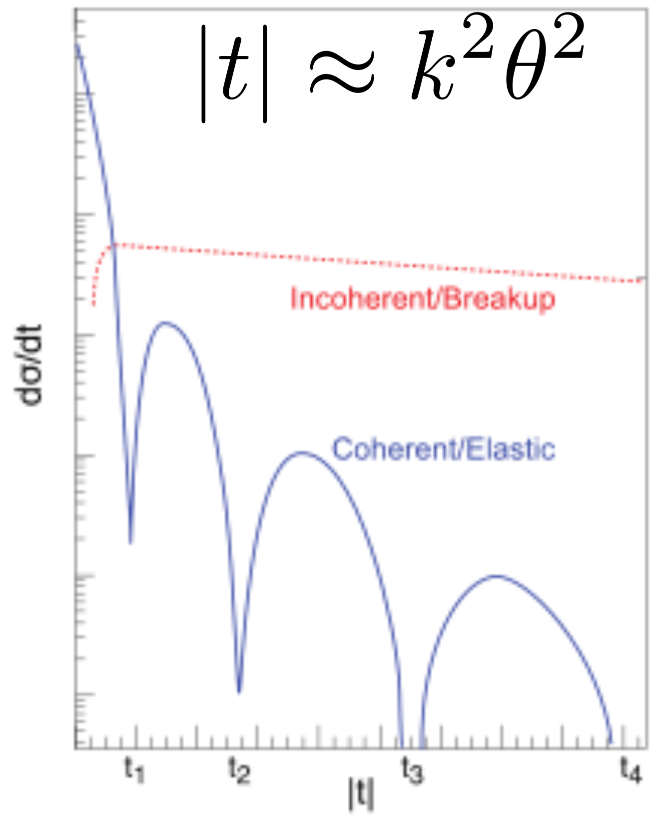
Best signal for CGC? → Diffraction!

Light with wavelength λ obstructed by an opaque disk of radius R suffers diffraction: *k* → wave number

$$\theta_i \sim \frac{1}{(kR)}$$

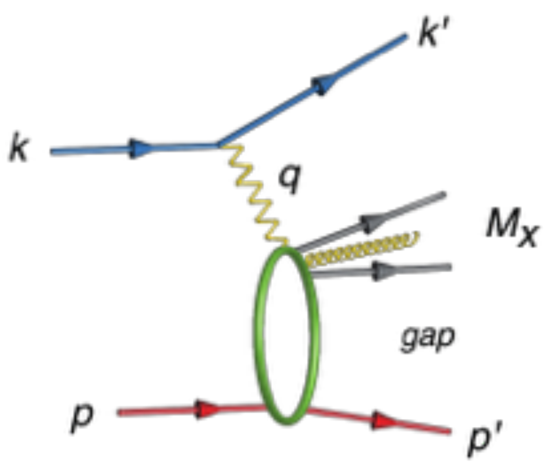


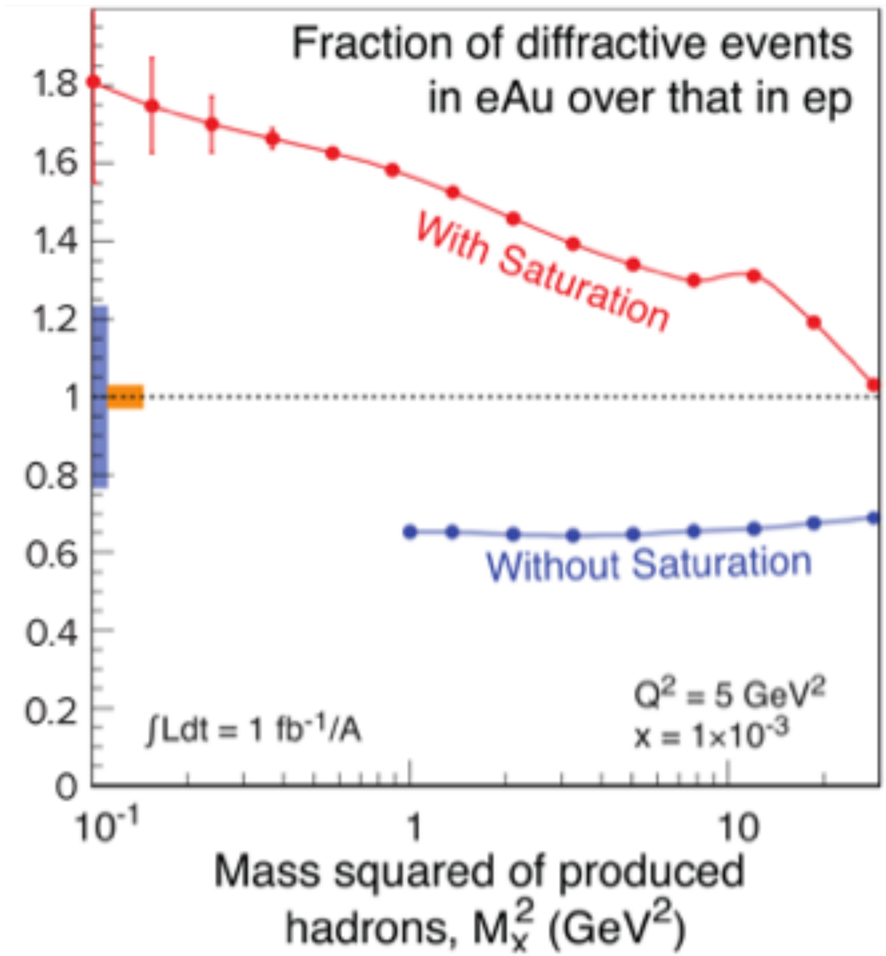
$$|t| \approx k^2\theta^2$$



Best signal for CGC? → Diffraction!

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

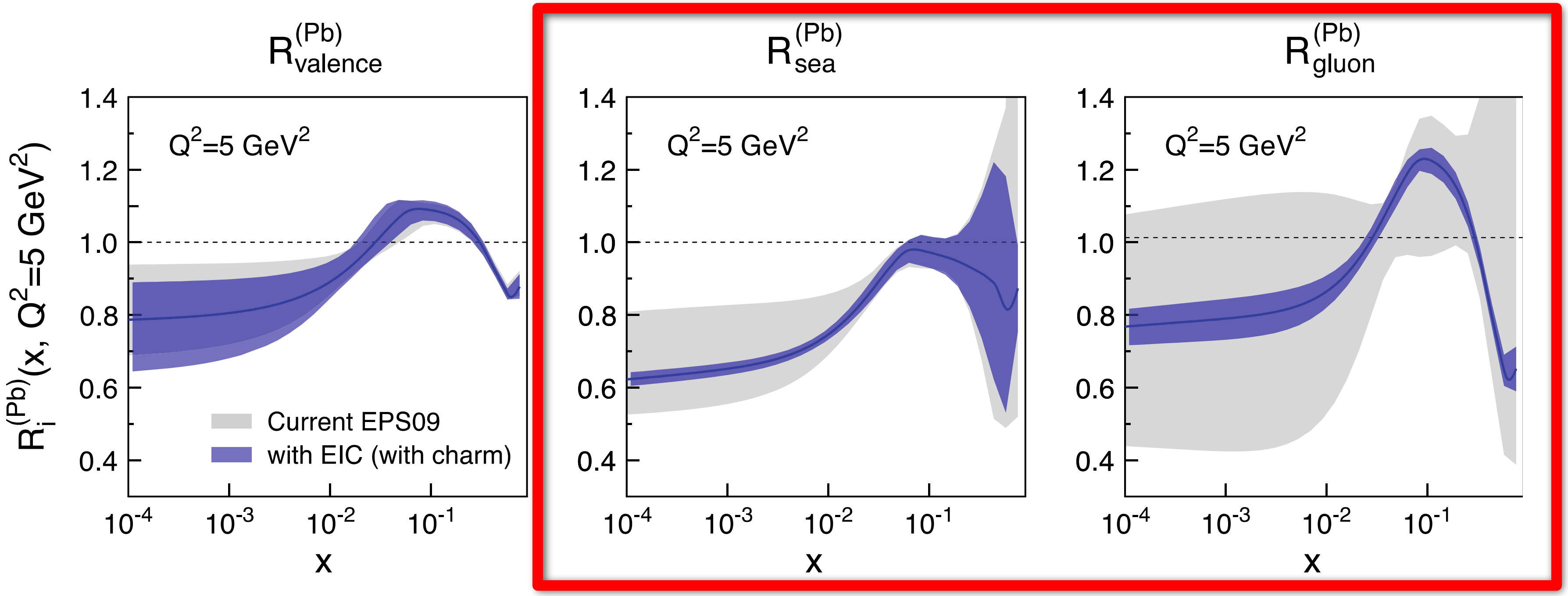




At HERA ep: 10-15% diffractive

At EIC eA, if Saturation/CGC
eA: 25-30% diffractive

EIC: impact on the knowledge of nPDFs

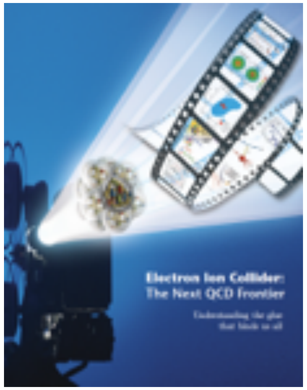


Ratio of Parton Distribution Functions of Pb over Proton:

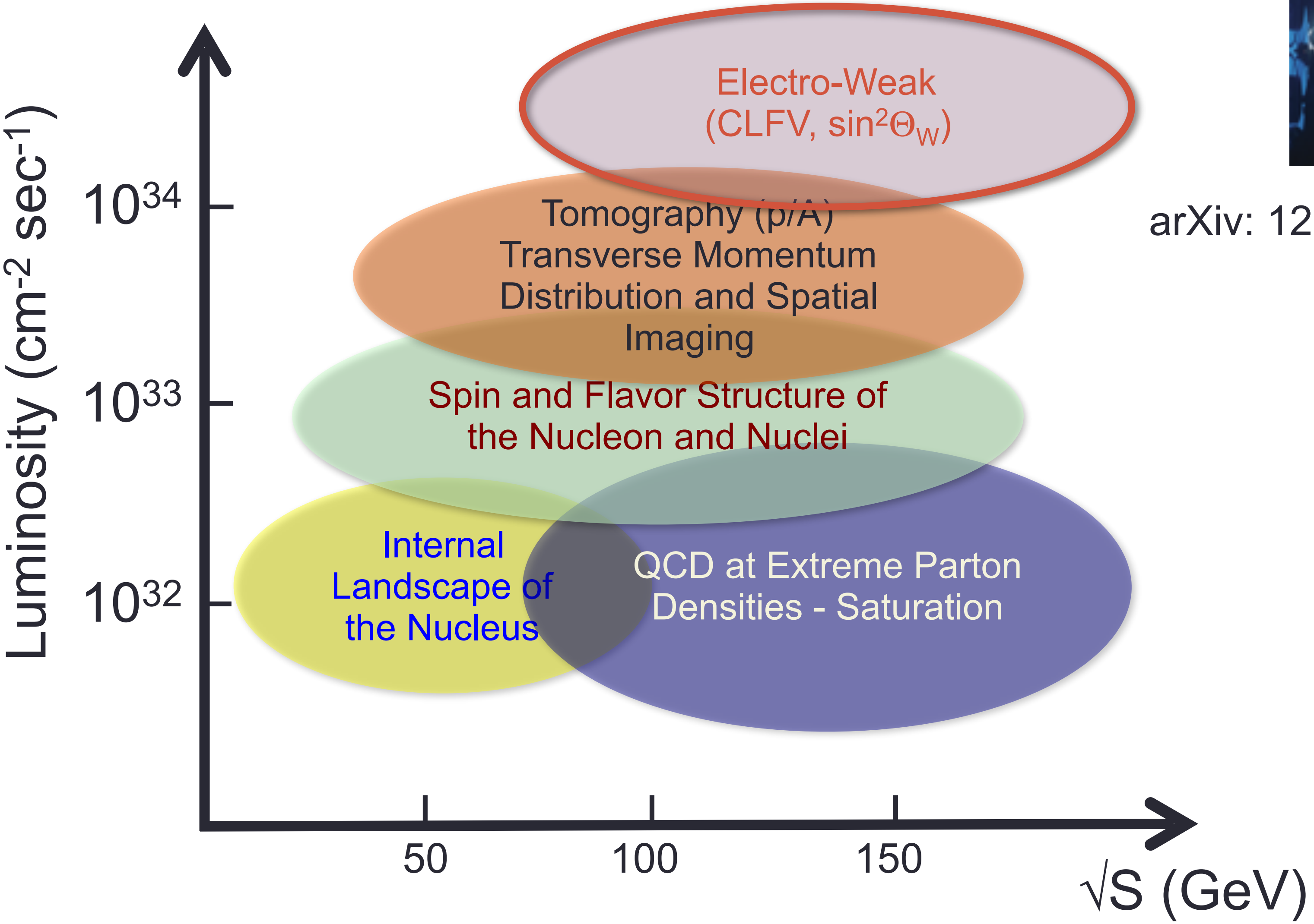
- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
- With EIC significantly reduces uncertainties

- Impossible for current and future pA data at RHIC & LHC data to achieve

Physics vs. Luminosity & Energy

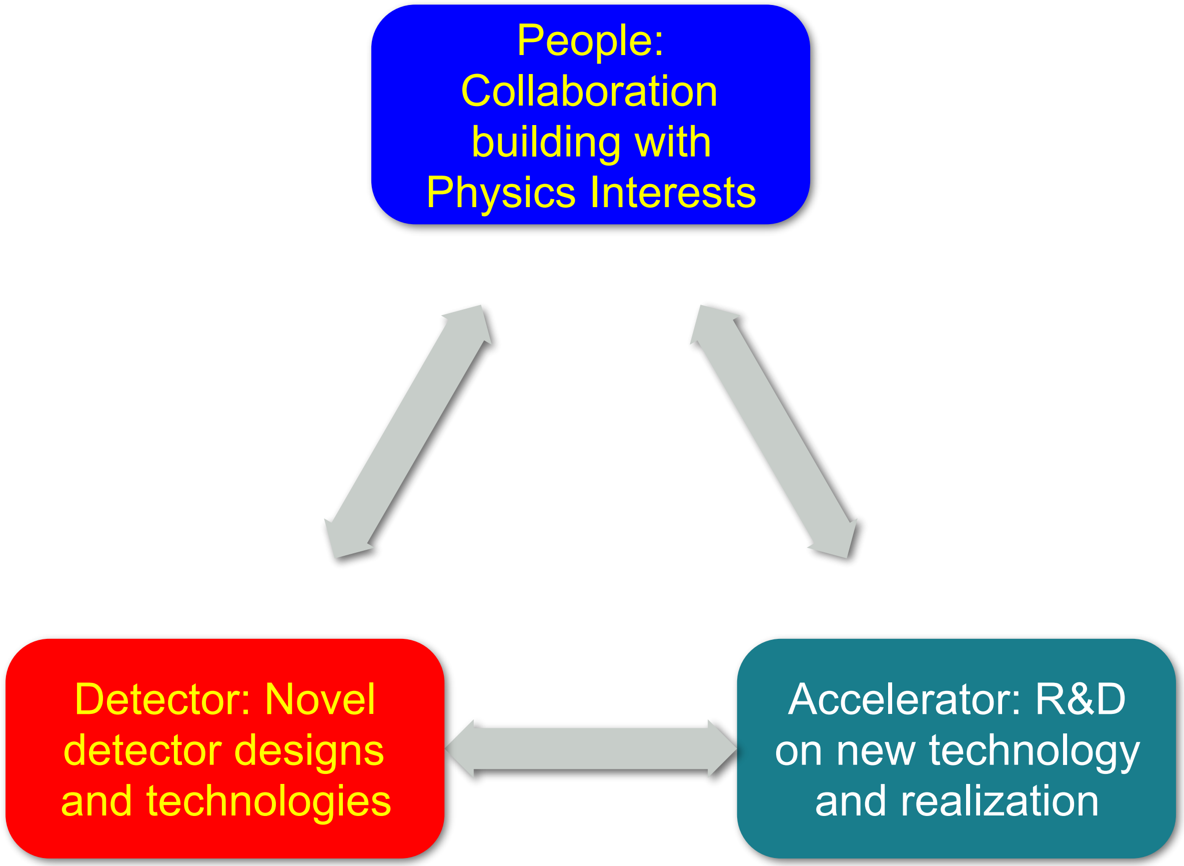


arXiv: 1212.1701.v3



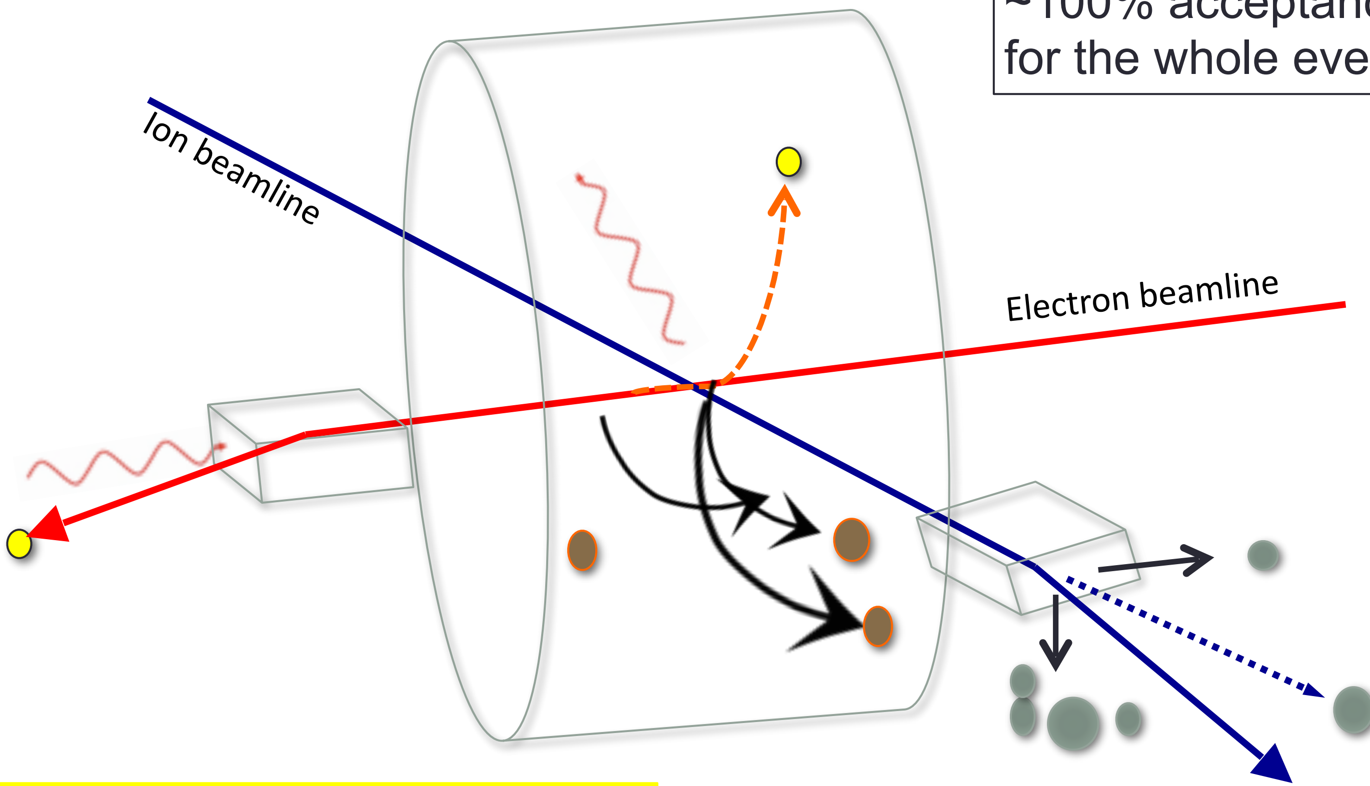
Realization And Project Status

Realization requires:



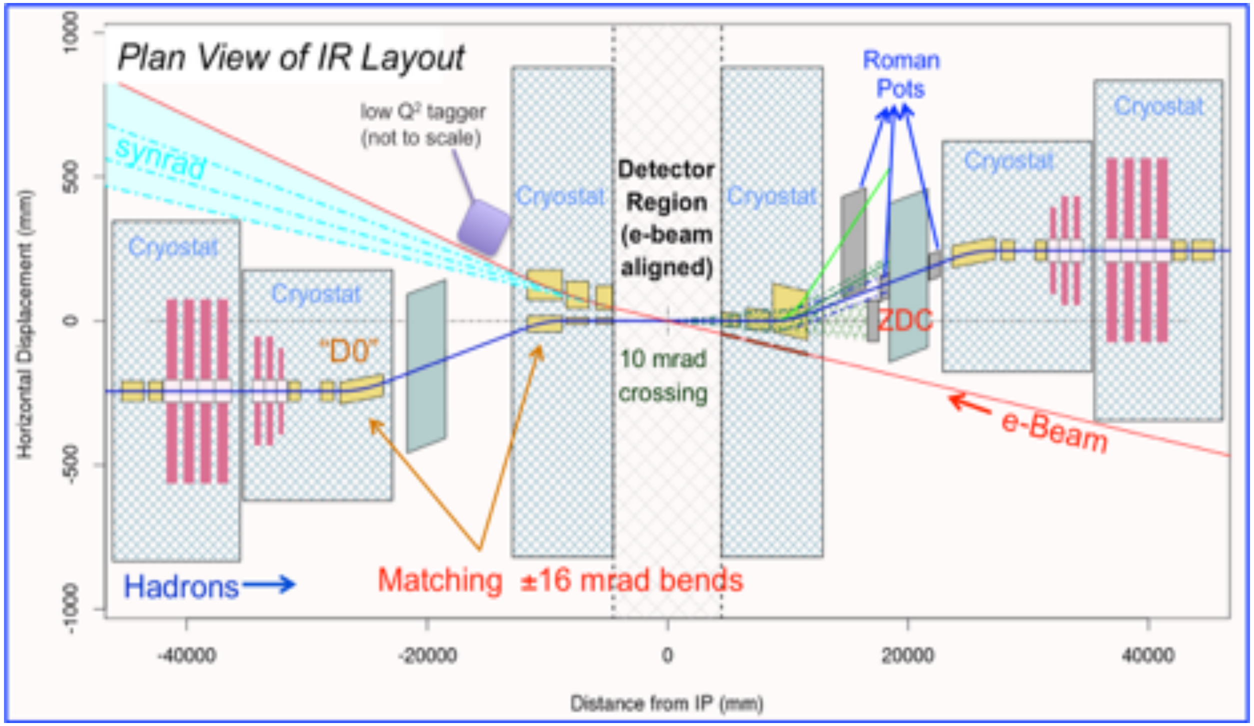
Interaction Region Concept

Possible to get ~100% acceptance for the whole event



Total acceptance detector (and IR)

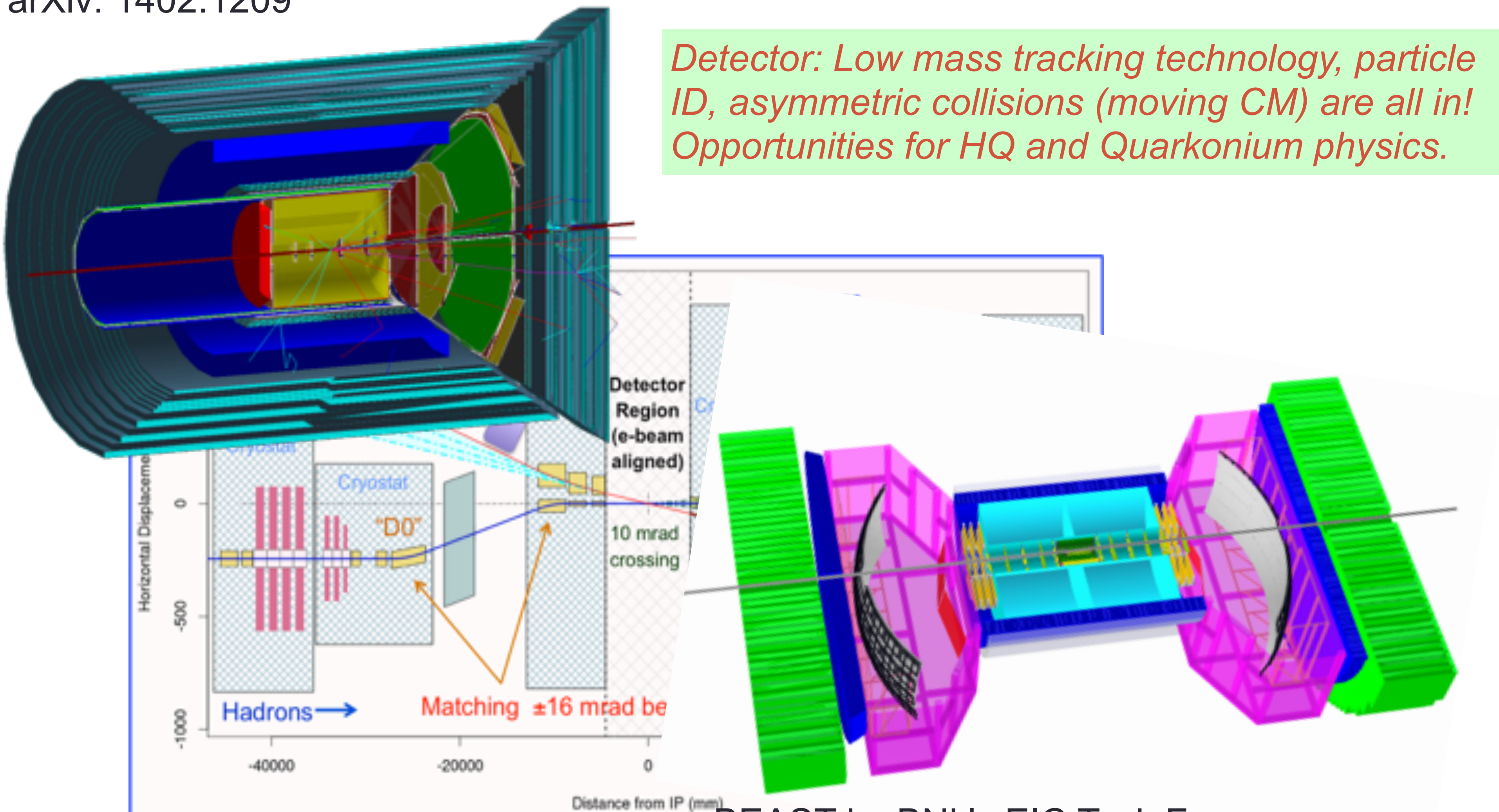
EIC IR & Detector Plan both at eRHIC & JLEIC



EIC IR & Detector Plan both at eRHIC & JLEIC

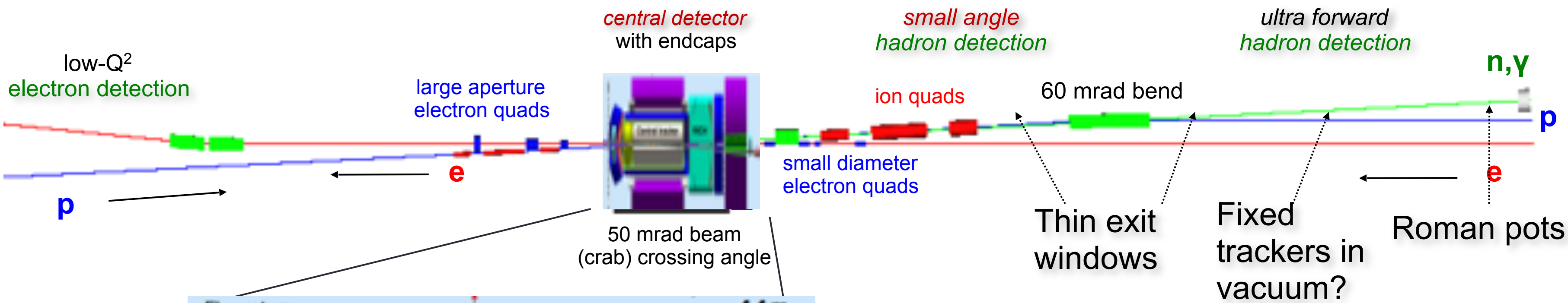
Day-1 Detector: CELESTE
A.K.A. "ePHENIX" with BaBar Solenoid
arXiv: 1402.1209

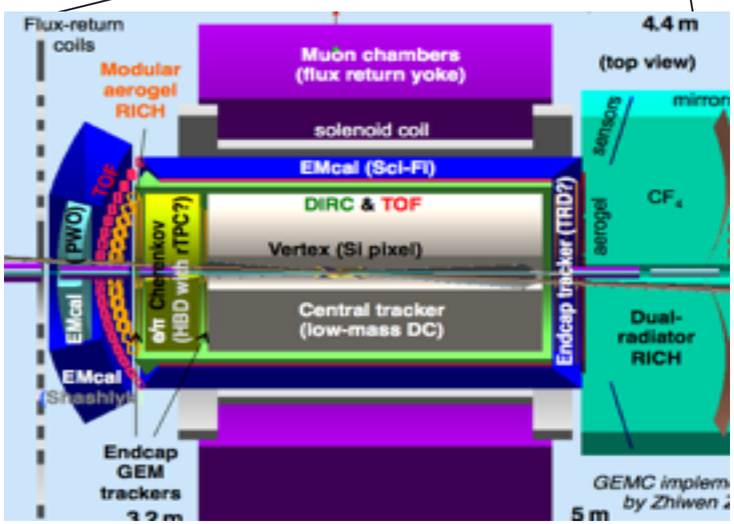
Detector: Low mass tracking technology, particle ID, asymmetric collisions (moving CM) are all in! Opportunities for HQ and Quarkonium physics.



BEAST by BNL's EIC Task Force
arXiv: 1409.1633

EIC at JLab: Integrated IR & Detector

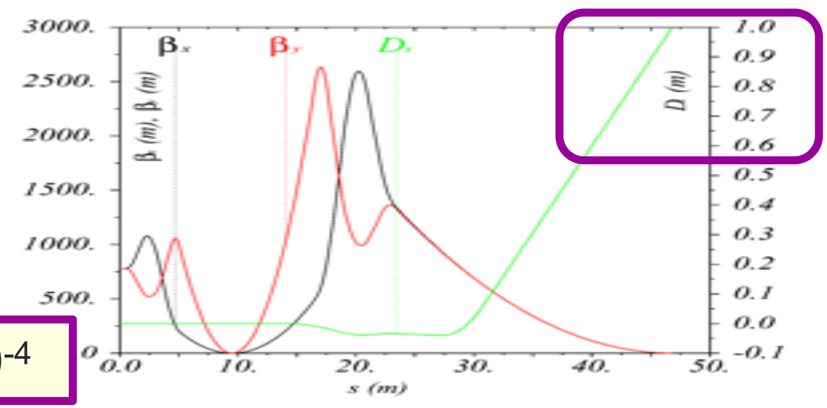




Hadron/Ion detection in 3 stages

- ❑ Endcap with 50 mrad crossing angle
- ❑ Small dipole covering angles to a few degrees
- ❑ Ultra-forward up to one degree, for particles passing accelerator quads

Cartoon of central detector based on dual solenoid a la ILC4 detector, but using the previous iteration interaction region design.



Beamline functions as spectrometer: $dp/p < 3 \times 10^{-4}$

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….

Community/Collaboration building:

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

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Recent EICUG Argonne National Laboratory July 7-10, 2016

http://eic2016.phy.anl.gov

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Recent EICUG Argonne National Laboratory July 7-10, 2016

http://eic2016.phy.anl.gov

Next two meetings:

January 2017 (BlueJeans)

July 18-22, 2017 Trieste, Italy

Ample opportunities for contributions & participation!

EICUG Today: 656 Users, 137 Institutes, 27 Countries

355 experimentalists, 111 theorists, 141 accelerator-physicists, 43 unknowns

Detector R&D

An active Generic Detector R&D Program for EIC underway, (supported by DOE, administered by BNL, T. Ullrich):

- An external committee of 8 peple reviews all proposals
- ~140 physicists, 31 institutes (5 Labs, 22 Universities, 9 Non-US Institutions) 15+ detector consortia exploring novel technologies for tracking, particle ID, calorimetry
- → *Weekly meetings, workshops and test beam activities already underway*
- → *https://wiki.bnl.gov/conferences/index.php/EIC_R%25D*
- → *MUCH TO BE DONE… despite many successes….*

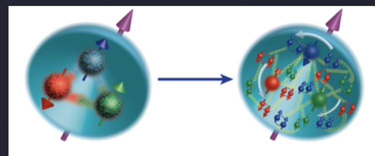
Currently the program receives ~$1.3M annually. Intent is to increase it to at least two or three times this in near future.

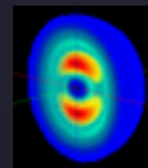
Opportunity for non-US Sources to make an impact!

Path forward for the EIC:

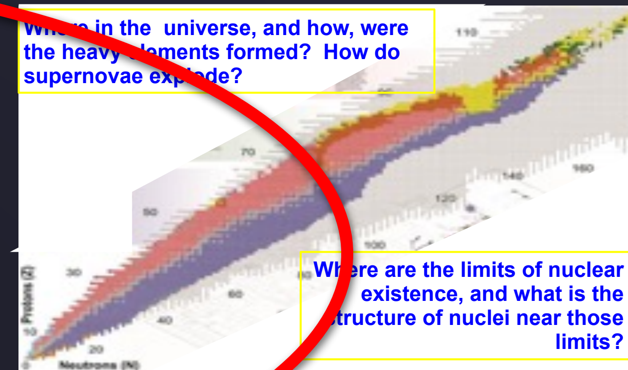
- Science Review by National Academy of Science (& Engineering & Arts) (National Research Council)
- Positive NAS review will trigger the DOE's CD process
  - CD0 (acceptance of the critical need for science by DOE) FY18
  - EIC-Proposal's Technical & Cost review → FY19 (site selection)
  - CD2 requires site selection
  - Major Construction funds ("CD3") by 2022/23"
  - Assuming 1.6% sustained increase over inflation of the next several years (Long Range Plan)

21st Century Nuclear Science: Probing nuclear matter in all its forms & exploring their potential for applications



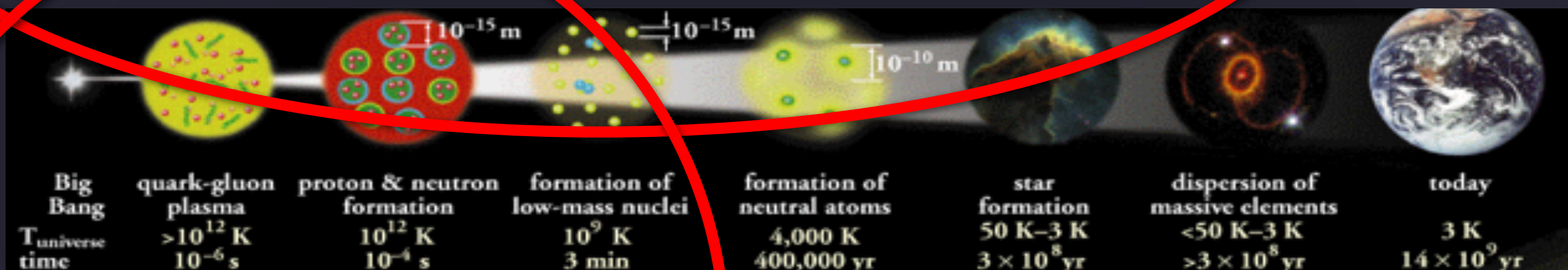


How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?

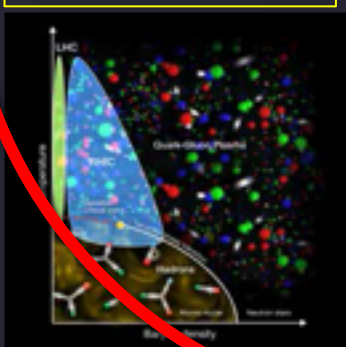


Where in the universe, and how, were the heavy elements formed? How do supernovae explode?

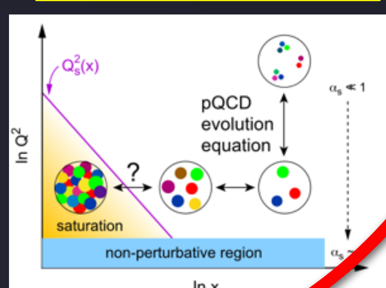
Where are the limits of nuclear existence, and what is the structure of nuclei near those limits?



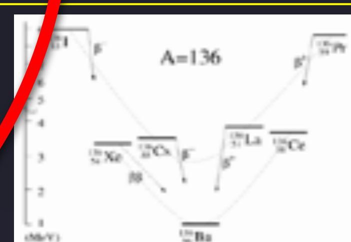
What is the nature of the different phases of nuclear matter through which the universe has evolved?



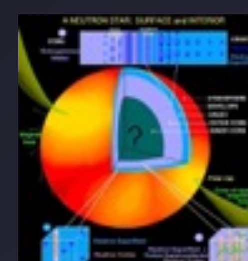
Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?



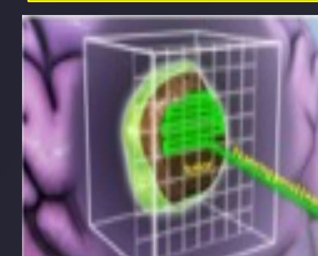
How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?



How are the nuclear building blocks manifested in the internal structure of compact stellar objects, like neutron stars?



How can technologies developed for basic nuclear physics research be adapted to address society's needs?



Summary:

The EIC (with its precision and control) will profoundly impact our understanding of the **structure of nucleons and nuclei in terms of sea quarks & gluons**

→ ***The bridge between sea quark/gluons to Nuclei***

The EIC will enable **IMAGES** of **yet unexplored regions of phase spaces in QCD** with its high luminosity/energy, nuclei & beam polarization

→ ***High potential for discovery***

Outstanding questions raised by world wide experiments at CERN, BNL and Jeff Lab, have **naturally led us to the science and design parameters of the EIC:** **World wide interest and opportunity** in collaborating on the EIC

Accelerator scientists at RHIC, Jlab in collaboration with **many from outside accelerator experts** will provide the **intellectual and technical leadership for to realize the EIC** -- *a frontier accelerator facility.*

Future QCD studies, particularly for Gluons, demands an Electron Ion Collider

NSAC agrees and we are moving forward!

Electroweak & beyond….(?)

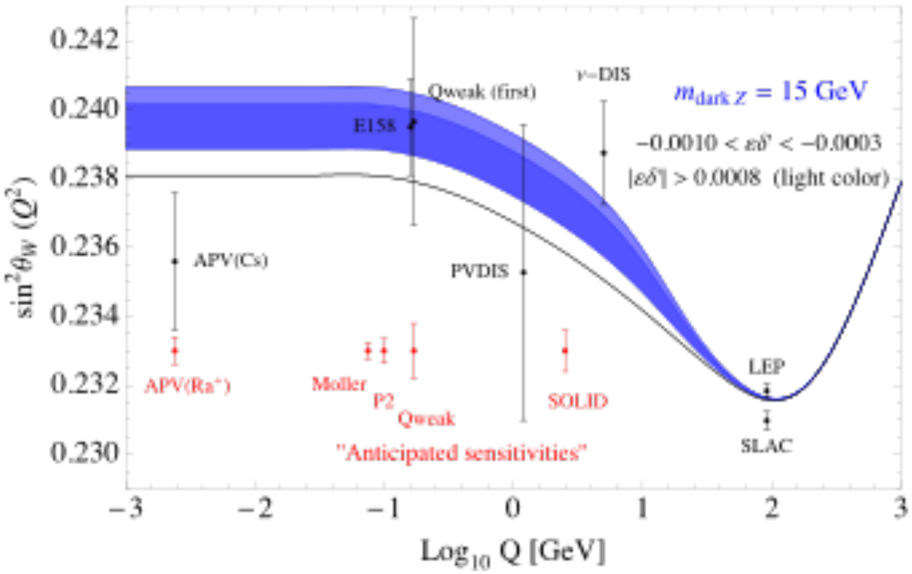
BNL LDRD: Deshpande, Marciano, Kumar & Vogelsang

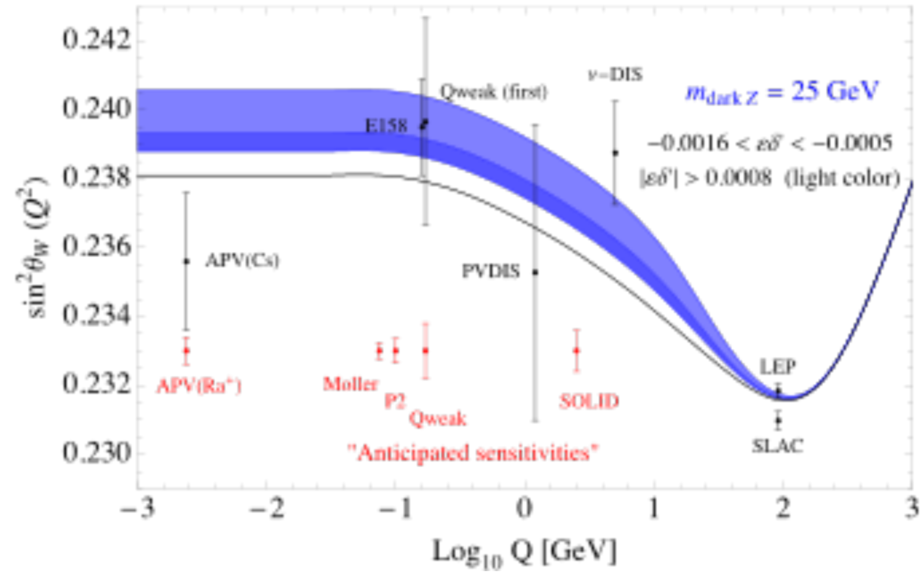
- Electro-weak deep inelastic scattering
  - Electroweak structure functions (including spin)
  - Significant contributions from W and Z bosons which have different couplings with *quarks and anti-quarks*

- Parity violating DIS: a probe of beyond TeV scale physics
  - Measurements at higher Q^2 than the PV DIS 12 GeV at Jlab
  - Precision measurement of $\mathrm{Sin}^2\Theta_W$

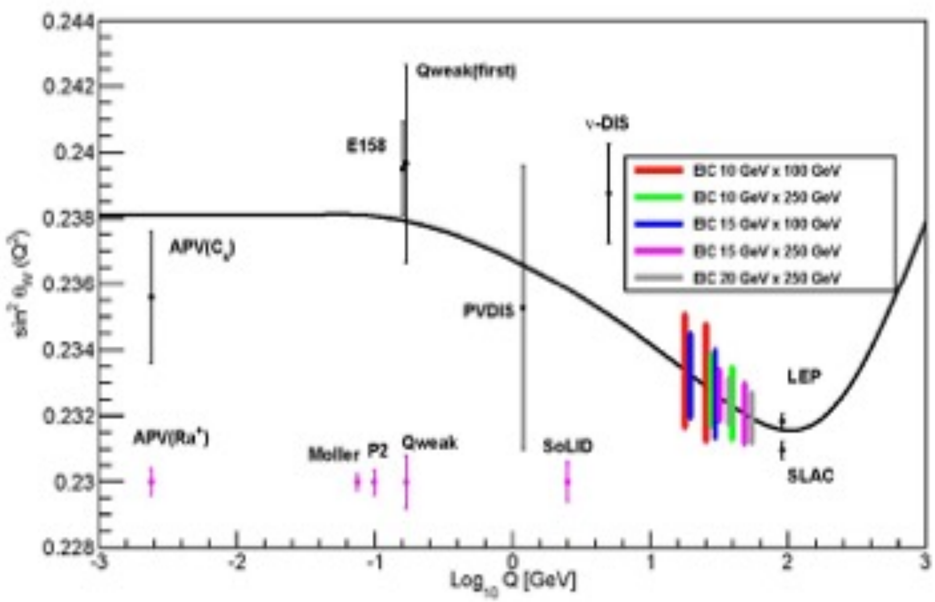
- New window for physics beyond SM through LFV search M. Gonderinger & M. Ramsey-Musolf, JHEP 1011 (045) (2010); arXive: 1006.5063 [hep-ph]

$$e^- + p \rightarrow \tau^- + X$$





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



and William J. Marciano[1]

Dark Z Study: arXiv:1507.00352

EIC Study .

Y. Zhao, *A. Deshpande & K. Kumar et al.*

Innovative Accelerator Science

On going R&D on accelerator concepts and technologies:

- High current polarized electron gun
- High current Energy Recovery Linac (ERL)
- Coherent electron cooling
- Fixed Field Acceleration Gradient beam transport
- High gradient crab cavities
- Super-ferric magnets
- Figure-8 shaped e/h rings to aid polarization of beams

eRHIC R&D (first five items)

JLEIC R&D (last three items)

Most of these are of global interest!

Realizing these for the US EIC requires *cutting edge accelerator science*

T. Hallman, Office of NP at the NSAC meeting March 23, 2016

Seeding the Possibility of a Future Electron Ion Collider

NP Planning for EIC Accelerator R&D

In view of Recommendation III in the 2015 LRP report on the realization of an EIC, NP is fomenting a plan in discussion with EIC stakeholders:

18 months NAS study:	US-BASED ELECTRON ION COLLIDER SCIENCE ASSESSMENT
March - July 2016:	Competitive FOA published this month, proposals due May 2 to select and fund accelerator R&D for Next Generation NP Facilities for 1 year only.
Summer 2016	Conduct an NP community EIC R&D panel (EIC-R&D) Review charged with generating a report as basis for FY17-FY20+ EIC accelerator R&D funding. <u>NP to appoint Chair of the panel</u>
Late Fall 2016:	Use the EIC panel report from the panel to publish a new Accelerator R&D FOA for FY2017 funding.

Funding amount and source for EIC accelerator R&D in FY17 and beyond:

Funding level:	Aiming for $7M, exact amount to be guided by EIC-R&D Review's report
Funding sources:	~$1.9M from NP competitive pot, the rest generated by percentage tax to RHIC and CEBAF Accelerator Operations budgets (~2.6% FY17 president request for each Lab).

T. Hallman, Office of NP at the NSAC meeting March 23, 2016

Next Formal Step on the EIC Science Case

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
Division on Engineering and Physical Science
Board on Physics and Astronomy
U.S.-Based Electron Ion Collider Science Assessment

Summary

The National Academies of Sciences, Engineering, and Medicine ("National Academies") will form a committee to carry out a thorough, independent assessment of the scientific justification for a U.S. domestic electron ion collider facility. In preparing its report, the committee will address the role that such a facility would play in the future of nuclear science, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics. The need for such an accelerator will be addressed in the context of international efforts in this area. Support for the 18-month project in the amount of $540,000 is requested from the Department of Energy.

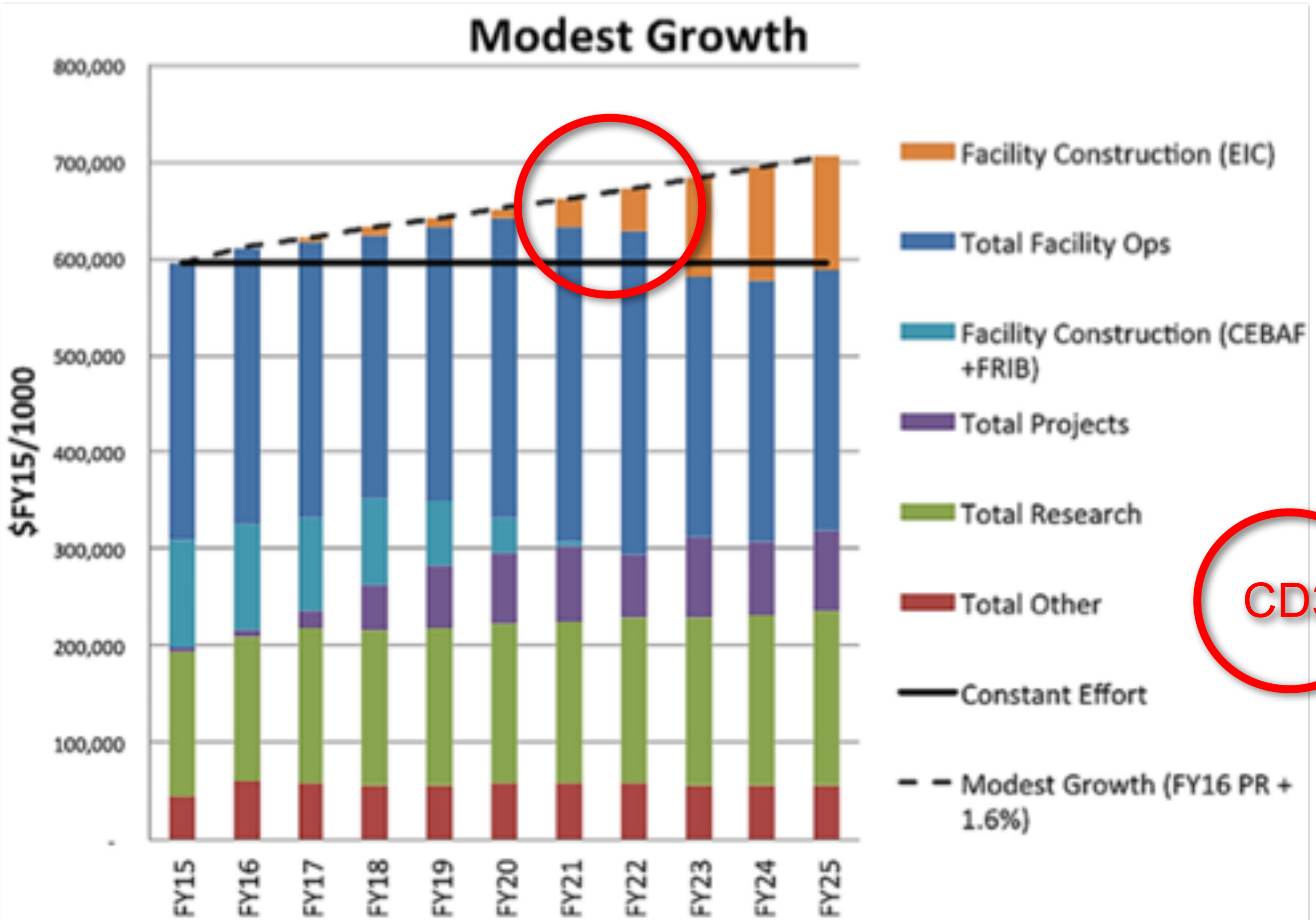
Mail reviews received; proposal approved for funding in PAMS; PR package in PAMS being processed.

Progress is also being made on a second Joint NAS study on Space Radiation Effects Testing

Assumption: "Modest Growth" → 1.6% growth/year above constant effort

The 2015 Long Range Plan for Nuclear Science

Not much time!



CD3

Figure 10.4: DOE budget in FY 2015 dollars for the Modest Growth scenario.