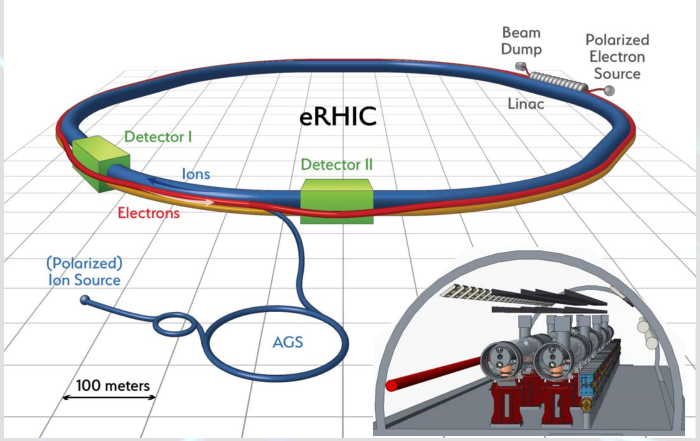
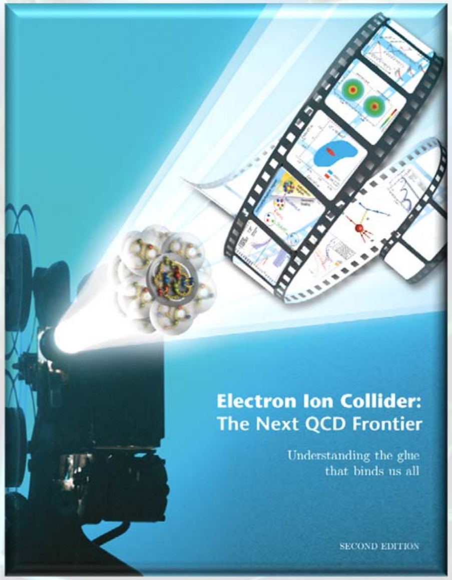
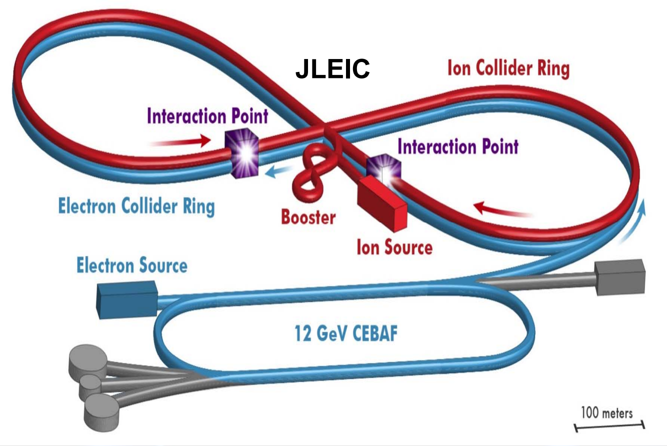
Nuclear Physics at the Electron-Ion Collider







Rolf Ent
Jefferson Lab

2016 North American Particle Accelerator Conference, Chicago, 9-14 October 2016

Jefferson Lab
Thomas Jefferson National Accelerator Facility

The US-based Electron-Ion Collider

- Electron-Ion Collider (EIC):
  - QCD@EIC Science Introduction
  - 2015 US Nuclear Science Long-Range Plan
  - The conceptualizations of the EIC

- The Science of the EIC White Paper
  Imaging the Gluons and Quark Sea of Nucleons and Nuclei

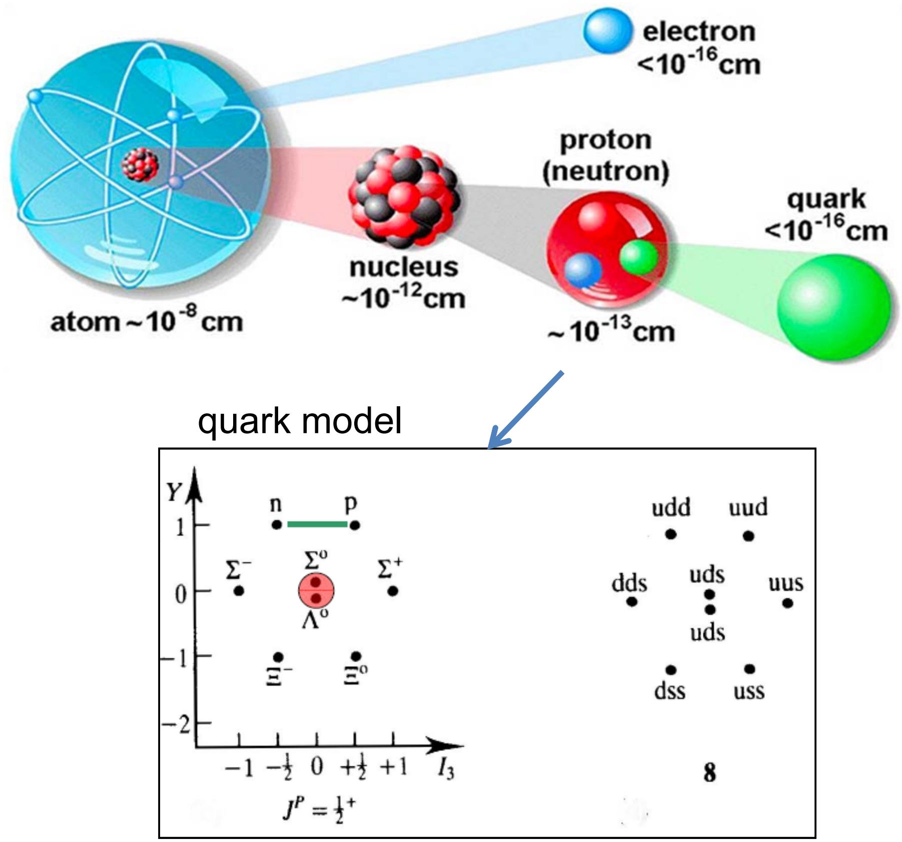
- The requirements of the EIC – unique and perhaps counterintuitive

- Next steps for the EIC

Exposing the high-energy side of nuclei

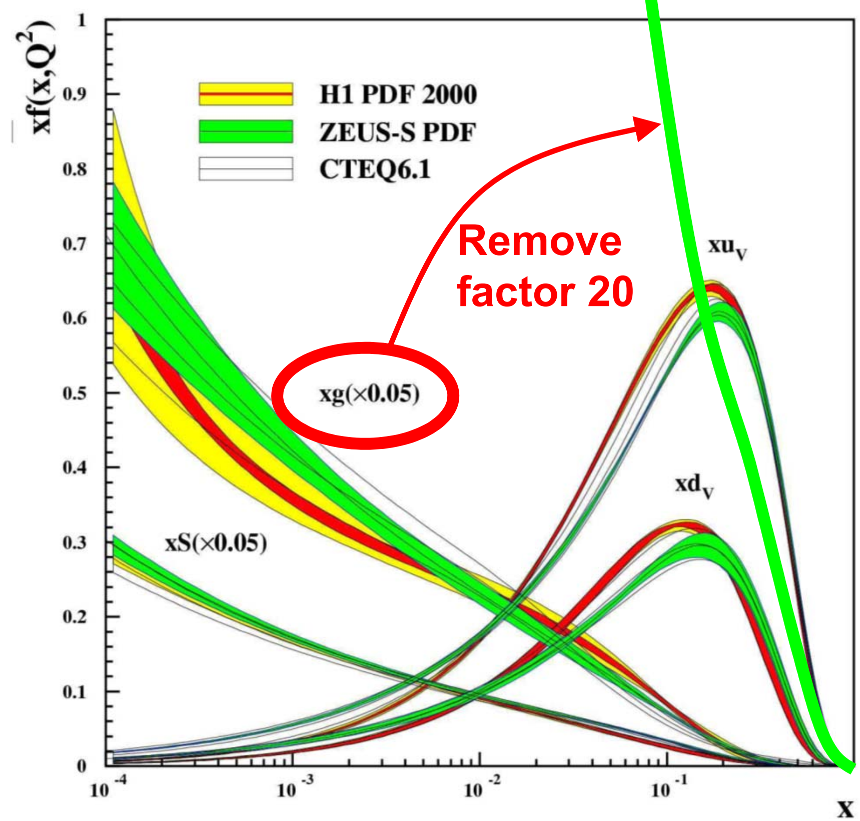
The Low Energy View of Nuclear Matter

- nucleus = protons + neutrons
- nucleon ↔ quark model
- quark model ↔ QCD



The High Energy View of Nuclear Matter

The visible Universe is generated by quarks, but dominated by gluons!
But what influence does this have on hadron structure?



The Structure of the Proton

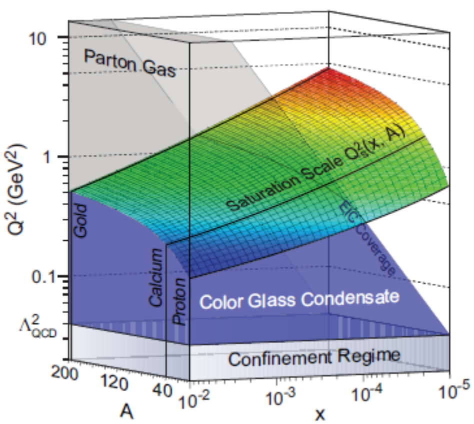
Naïve Quark Model: proton = uud (valence quarks)

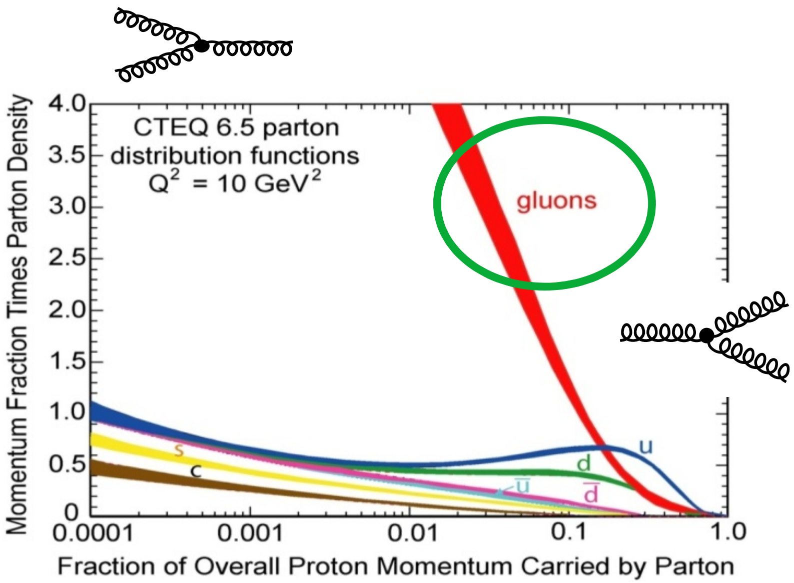
QCD: proton = uud + $u\bar{u}$ + $d\bar{d}$ + $s\bar{s}$ + …

The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$

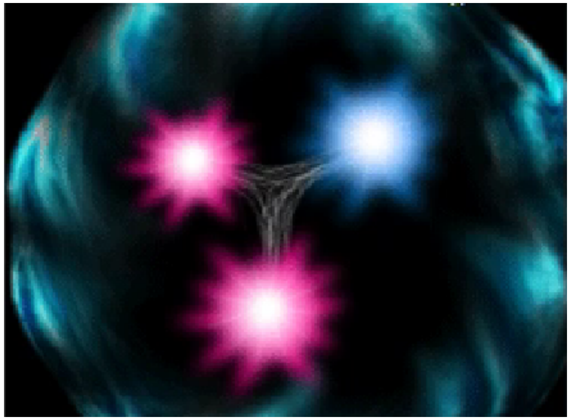
& gluons are abundant

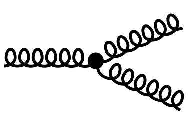
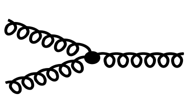
gluon dynamics





Non-trivial sea structure

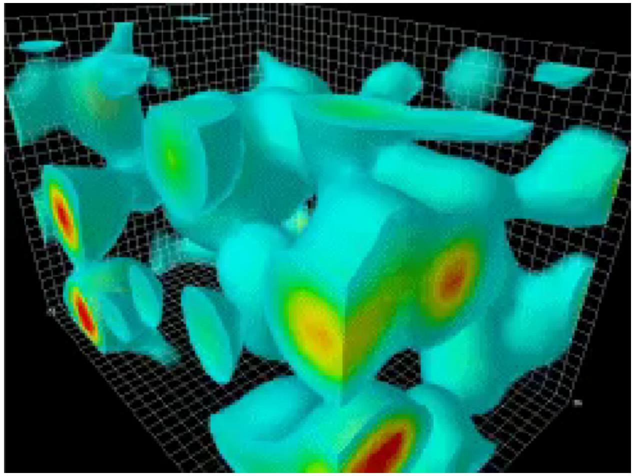


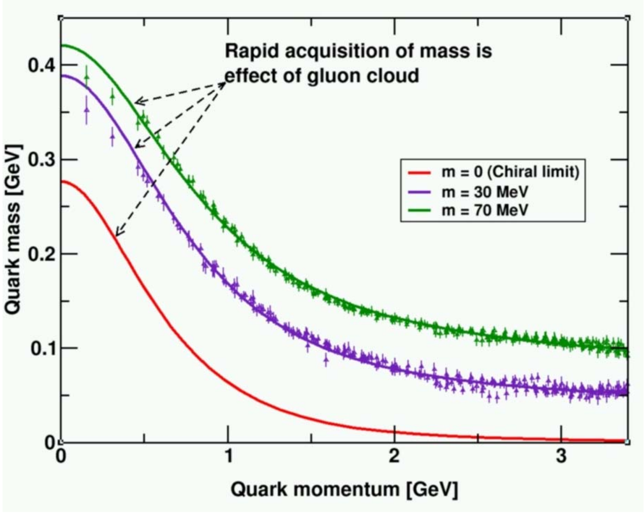
- ❑ The proton is **[far more]** than just its up + up + down (valence) quark structure
- ❑ Gluon ≠ photon: Radiates  and recombines: 

Gluons and QCD

- QCD is the fundamental theory that describes structure and interactions in nuclear matter.
- Without gluons there are no protons, no neutrons, and no atomic nuclei
- Gluons dominate the structure of the QCD vacuum

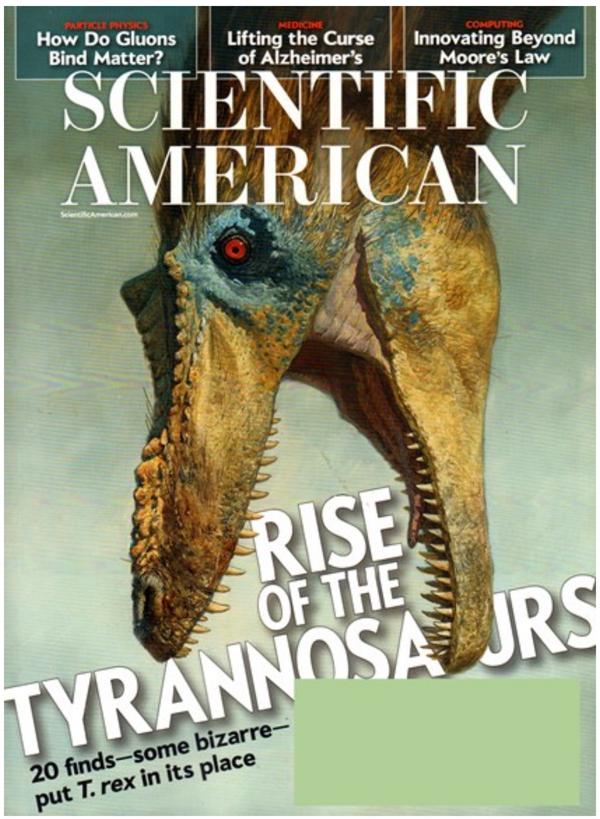
- Facts:
  - The essential features of QCD (e.g. asymptotic freedom, chiral symmetry breaking, and color confinement) are driven by gluons!
  - Unique aspect of QCD is the self interaction of the gluons
  - Mass from massless gluons and nearly massless quarks
    - Most of the mass of the visible universe emerges from quark-gluon interactions
    - The Higgs mechanism has almost no role here





PARTICLE PHYSICS

the glue that binds us



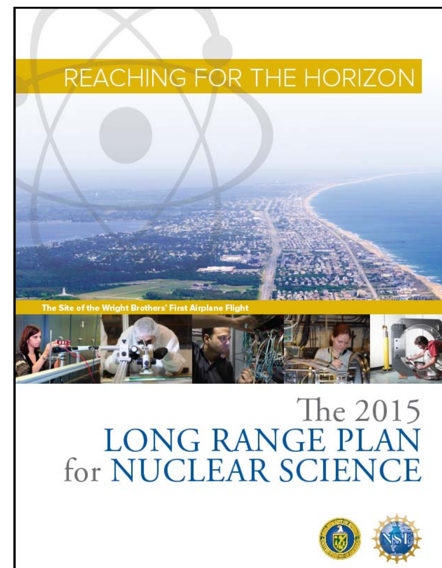
The US Nuclear Science Long-Range Planning Process

Nuclear Science Long-Range Planning

- Every 5-7 years the Nuclear Science community produces a Long-Range Planning (LRP) Document
- Previous versions:
  1979, 1983, 1989, 1996, 2002, 2007
- The final document includes a *small* set of recommendations for the field of Nuclear Science **for the next decade**
- For instance, 12 GeV construction was the highest recommendation of the 2007 plan.

How does it work:

- The Division of Nuclear Physics of the American Physical Society organizes a series of Town Meetings, where the community provides input in the form of presentations and in the form of contributed "White Papers"
- Each Town Meeting produces a set of recommendations and a summary "White Paper"
- The Nuclear Science Advisory Committee, extended to about 60 people into a Long-Range Plan Working Group, then comes together for a week and decides on a final set of recommendations and produces a LRP document



2015 NSAC LRP Recommendations - shorthand

1. **The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.**
    - **12 GeV** – unfold quark & gluon structure of hadrons and nuclei
    - **FRIB** – understanding of nuclei and their role in the cosmos
    - **Fundamental Symmetries Initiative** – physics beyond the SM
    - **RHIC** – properties and phases of quark and gluon matter

    The ordering of these four bullets follows the priority ordering of the 2007 plan

2. **We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.**

3. **We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.**

4. **We recommend increasing investment in small and mid-scale projects and initiatives that enable forefront research at universities and laboratories.**

2015 NSAC LRP Initiatives - shorthand

A number of specific initiatives are presented in the body of the report to follow. Two initiatives that support the recommendations made above and that will have significant impact on the field of nuclear science are highlighted here.

- **To meet the challenges and realize the full scientic potential of current and future experiments requires new investments in theoretical and computational nuclear physics.**
    - **Computational nuclear theory**
    - **FRIB theory alliance**
    - **Topical Collaboration expansion**

- **We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the Electron Ion Collider.**

Note: also an initiative on Workforce, Education, and Outreach to recruit and educate early career scientists, including items like REU, SULI, Summer Schools, etc.

The Conceptualizations of the EIC

The Electron Ion Collider

For e-N collisions at the EIC:

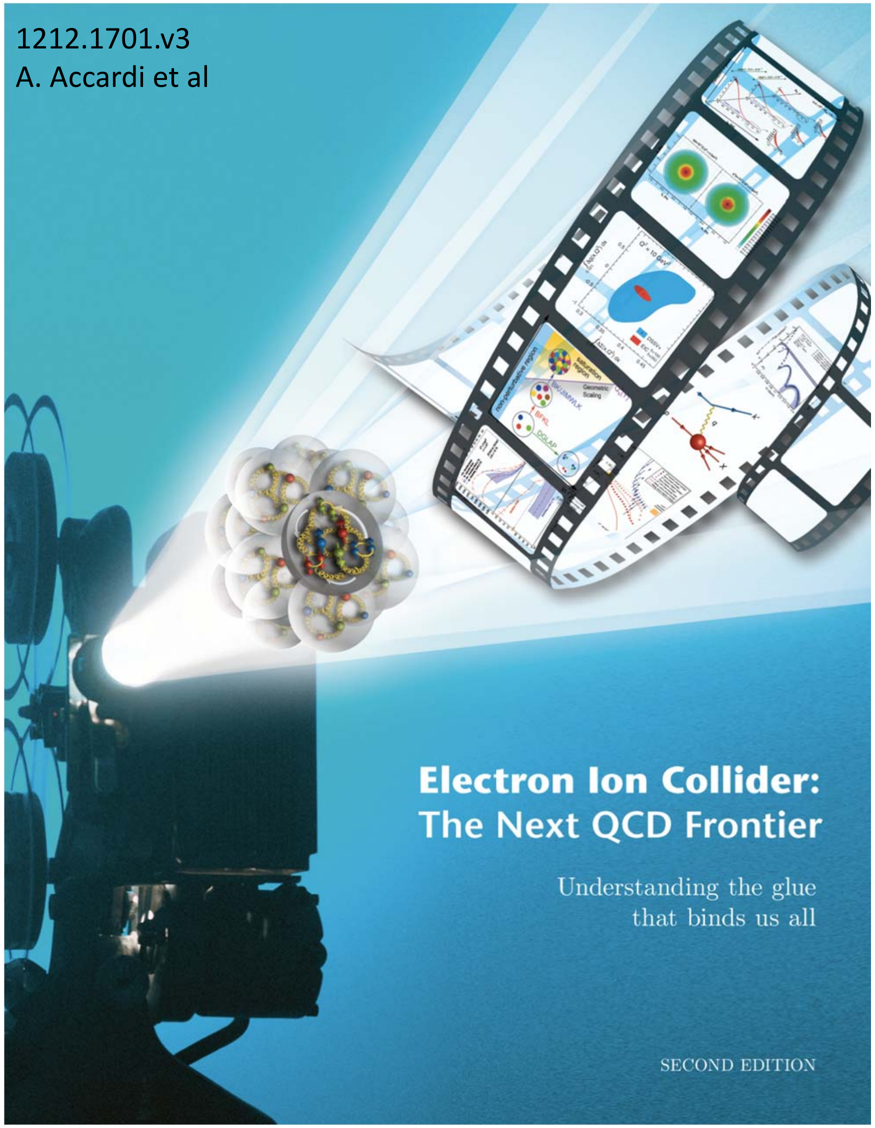
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 3-10(20) GeV
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-~100 (140) GeV Variable CoM

For e-A collisions at the EIC:

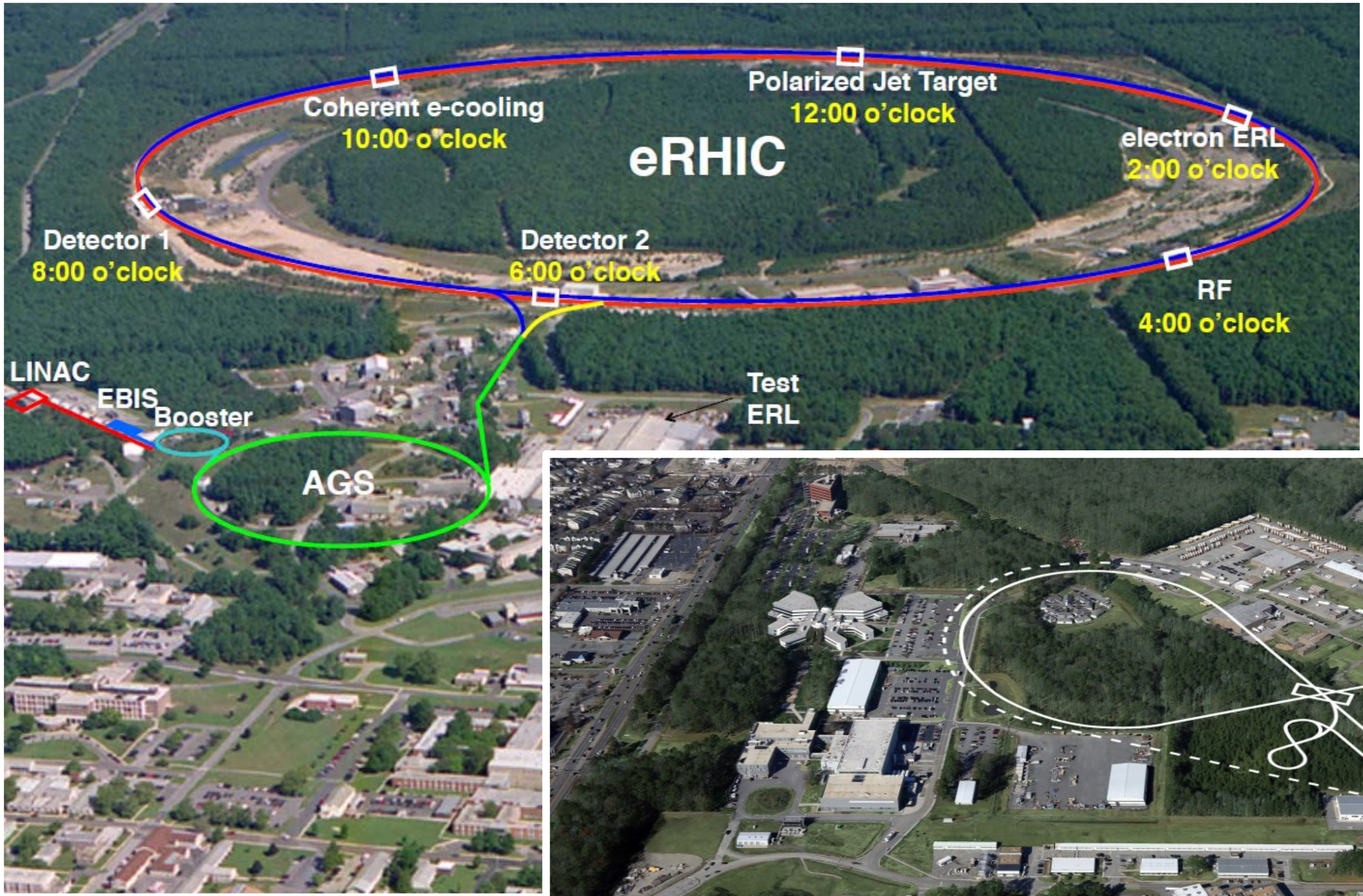
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

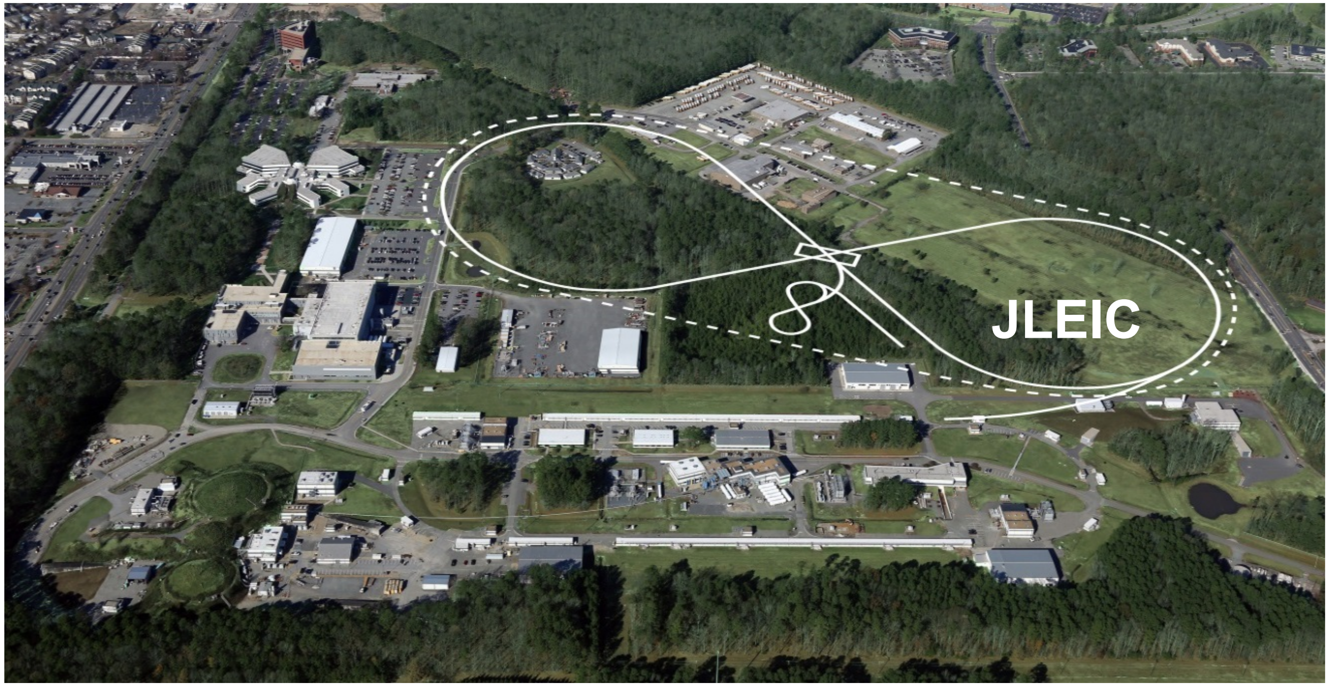
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Two proposals for realization of the science case -
both designs use DOE's significant investments in infrastructure



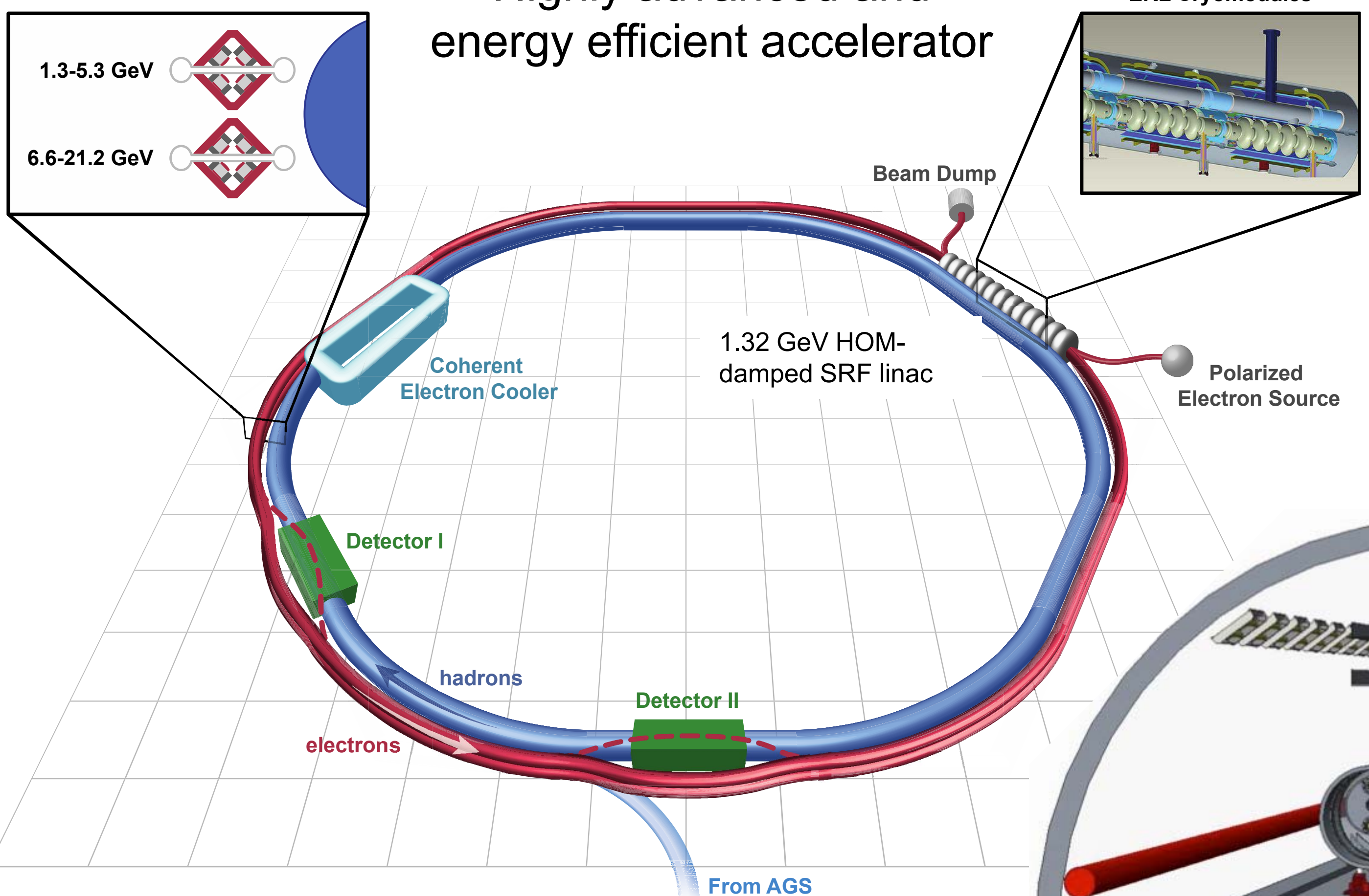
US-Based EICs

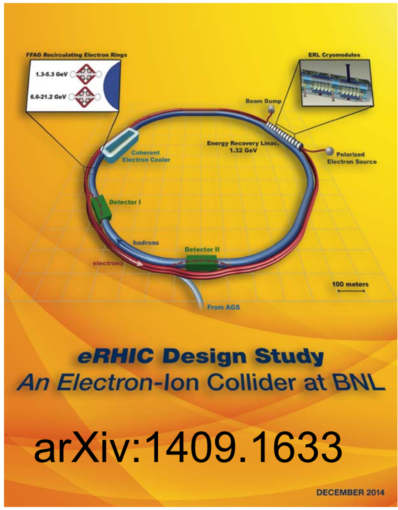


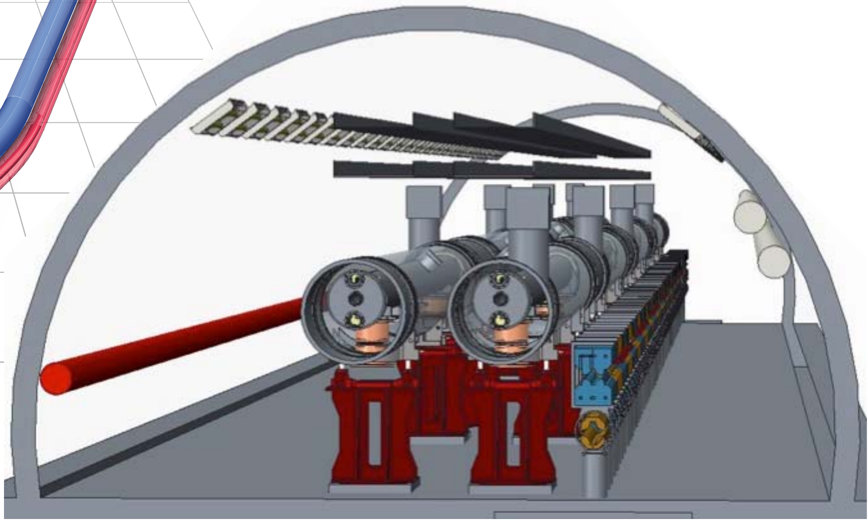


eRHIC Baseline Design – now both L-R and R-R pursued

Highly advanced and energy efficient accelerator







No civil construction

- Peak luminosity 2 × 10^{34} cm^{-2} s^{-1} for $\sqrt{s}$ ~ 70-105 GeV (250 GeV p↑)
- Low-risk luminosity ~ 5-9 × 10^{32} cm^{-2} s^{-1}

JLEIC Baseline Design

arXiv:1209.0757 (Sept. 2012)
arXiv:1504.07961 (April 2015)

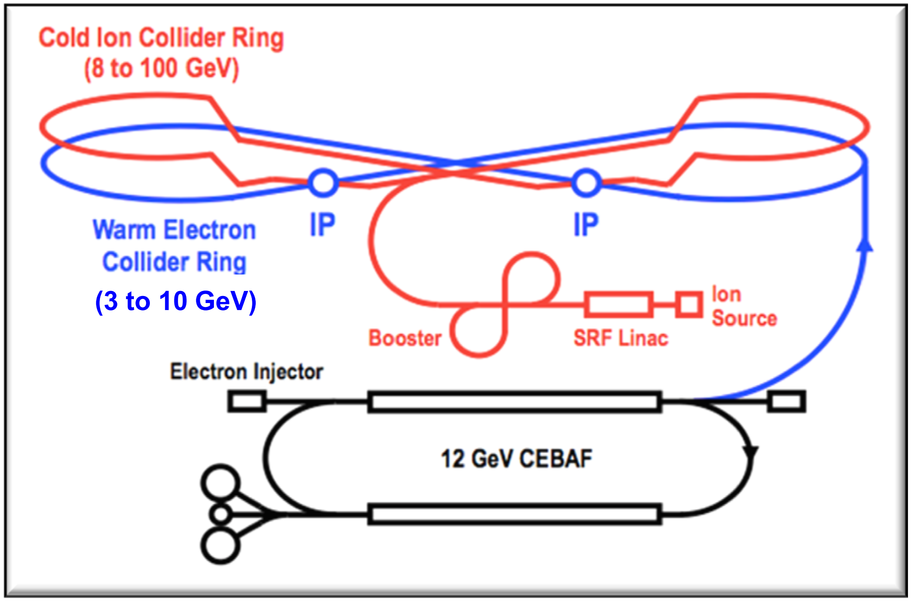
Features:

- Collider ring circumference: ~2100 m
- Electron collider ring and transfer lines : PEP-II magnets, RF (476 MHz) and vacuum chambers
- Ion collider ring: super-ferric magnets (3T)
- Booster ring: super-ferric magnets
- SRF ion linac

- Low-risk luminosity ~ 5-10 × 10^{33} cm^{-2} s^{-1}

Goals:

- Balance of civil construction versus magnet costs and risks
- Aim overall for low technical risks



Collaborators:

ANL, LBNL, Fermilab, SLAC, Texas A&M
Also DESY, Dubna

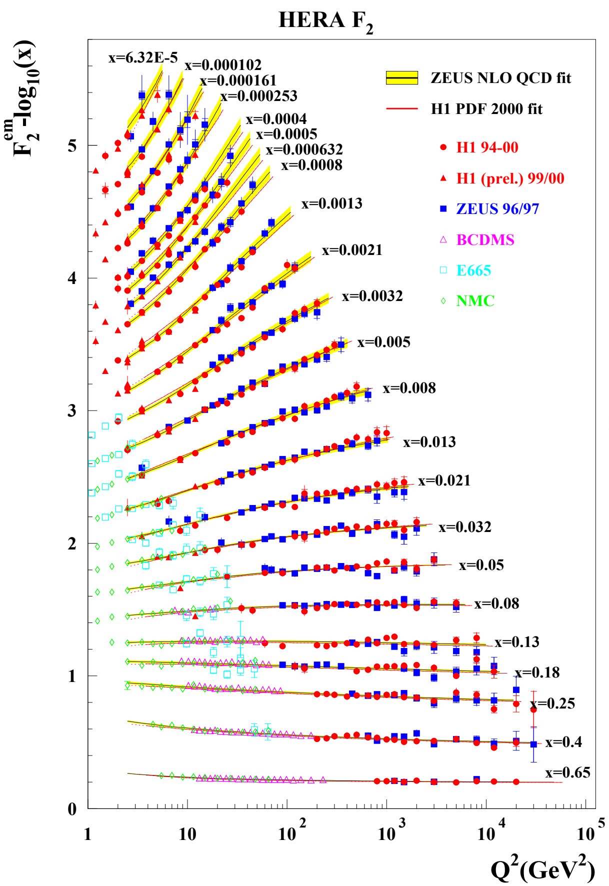
EIC – World's First Polarized eN Collider

A spin factory of polarized electrons and polarized protons/light nuclei: imaging the quarks and gluons

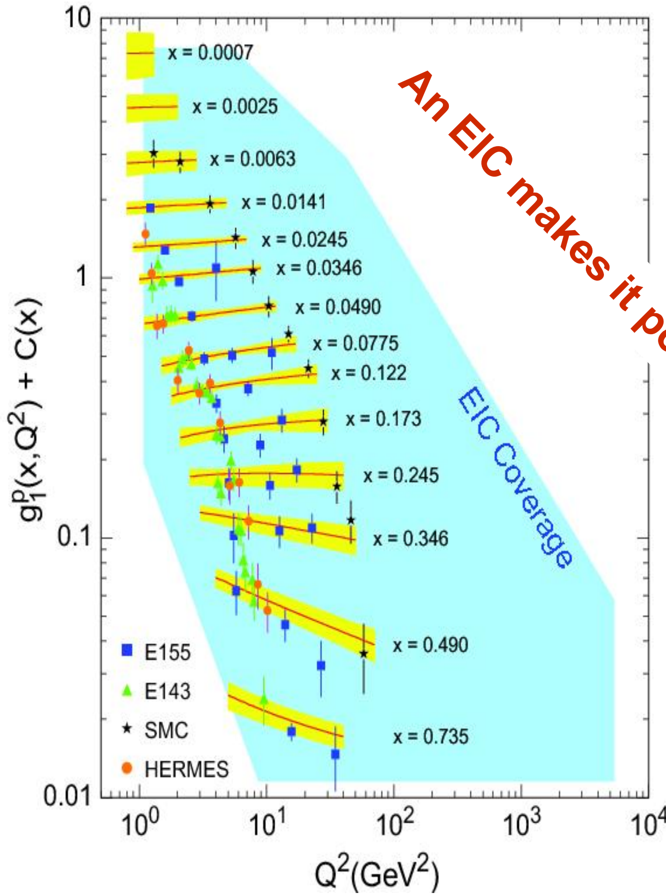
- How are the gluons and sea quarks, and their intrinsic spins distributed in space & momentum inside protons and neutrons?
- What is the role of sea quark and gluon orbital angular momentum?
- How do gluons and sea quarks contribute to the nucleon-nucleon force?

World Data on F_2^p World Data on g_1^p World Data on h_1^p

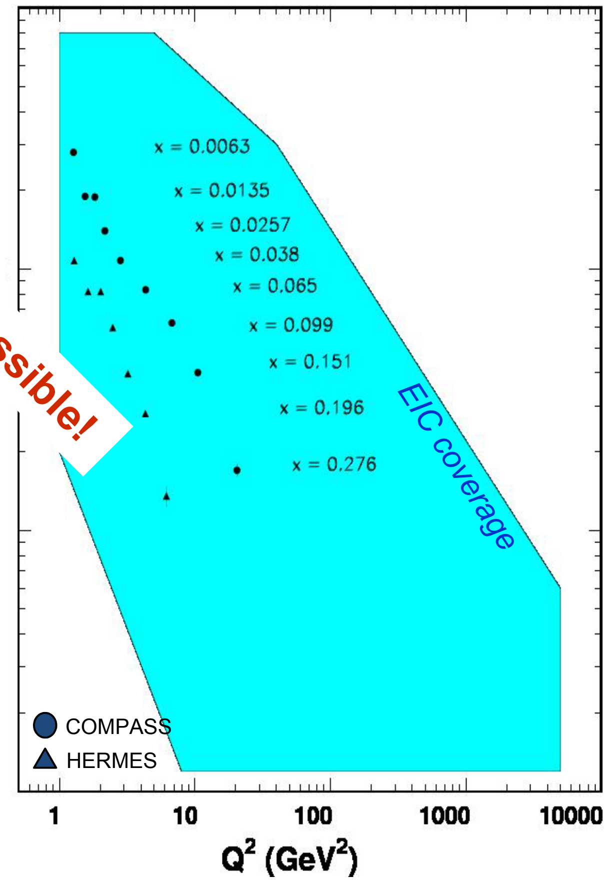
$F_{UT}^{\sin(\phi_h+\phi_s)}(x,Q^2) + C(x) \propto h_1$



momentum

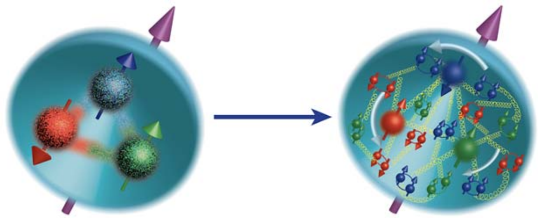


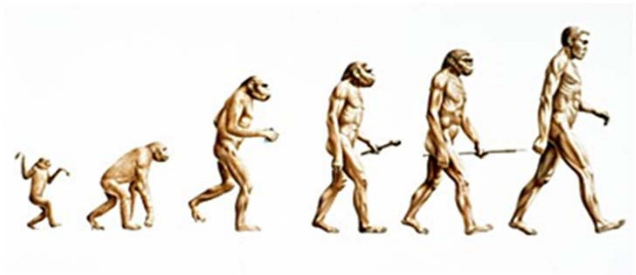
spin



transverse spin ~ angular momentum

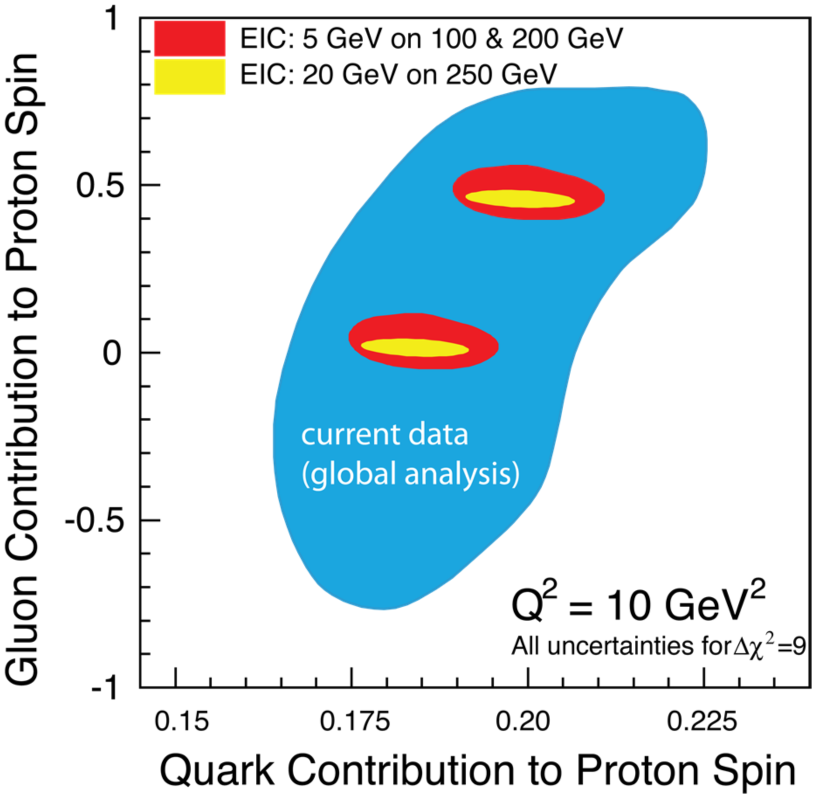
Our Understanding of Nucleon Spin



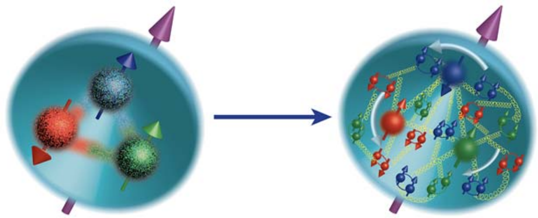


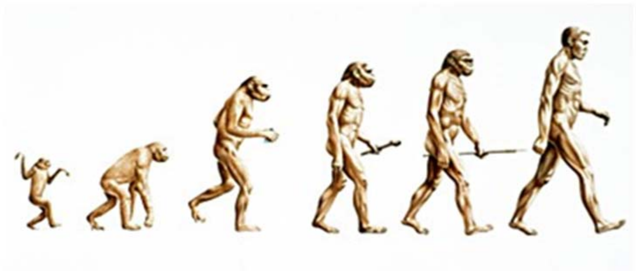
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Momentum
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Momentum

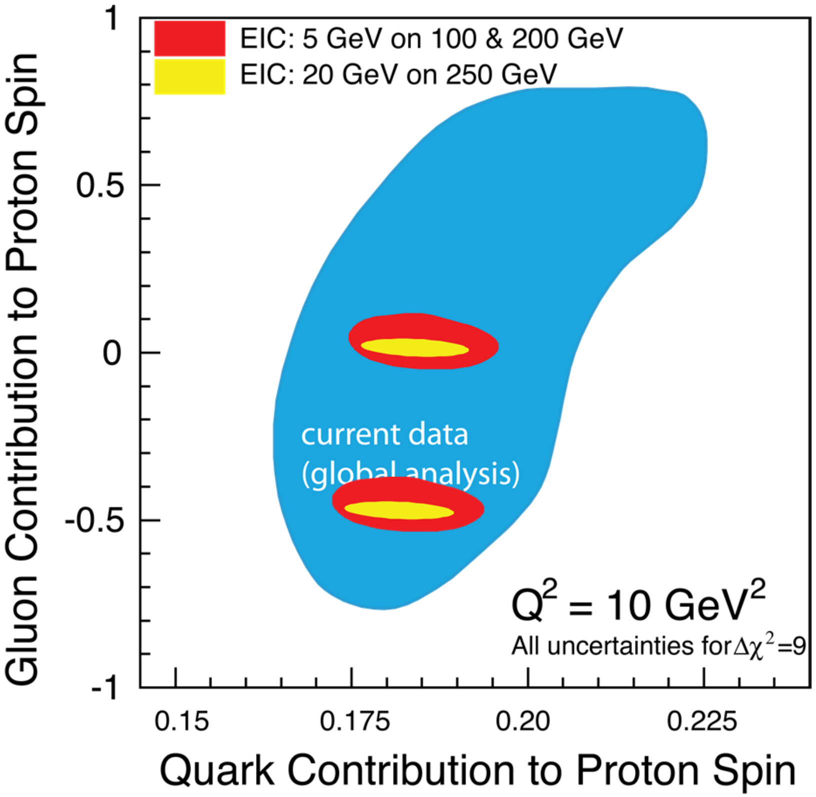


Our Understanding of Nucleon Spin





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



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

L_Q = Quark Orbital Ang. Momentum

Δg = Gluon contribution to Proton Spin

L_G = Gluon Orbital Ang. Momentum

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

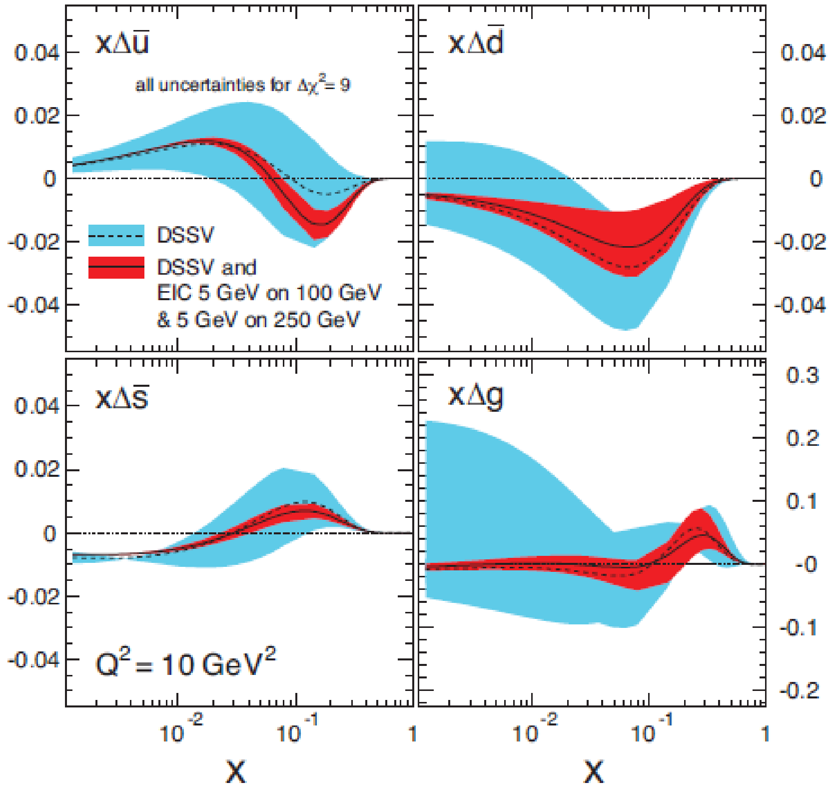
Helicity PDFs at an EIC

A Polarized EIC:

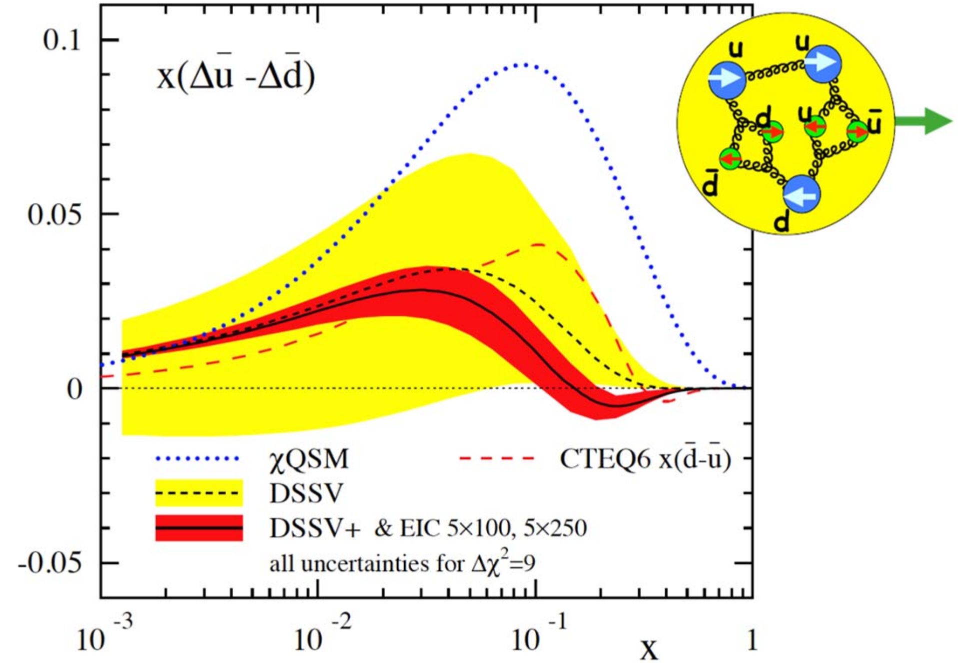
- Tremendous improvement on $x\Delta g(x)$
- Good improvement in $\Delta\Sigma$
- Spin Flavor decomposition of the Light Quark Sea

Many models predict $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$

Needs range of $\sqrt{s}$, here from ~ 45 to ~ 70



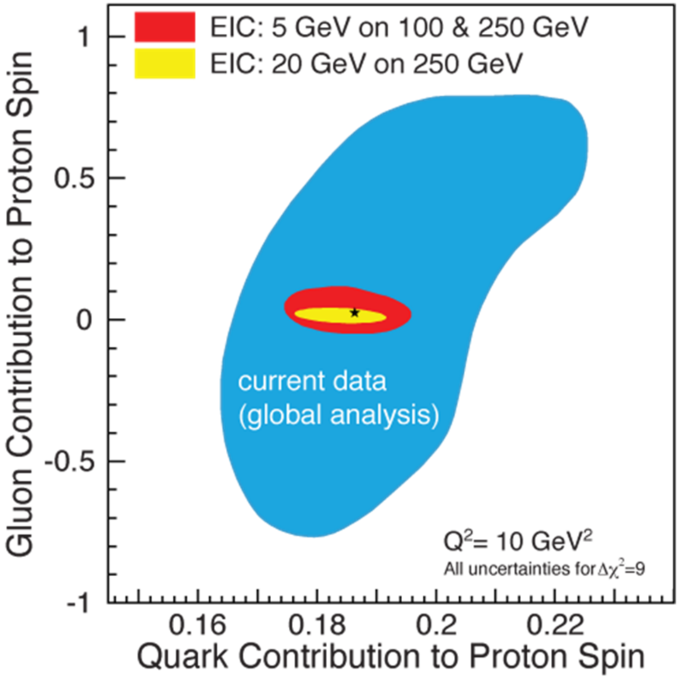
Needs range of $\sqrt{s}$ ~ 30-70 (and good luminosity)



2+1 D partonic image of the proton

Spatial distance from origin X Transverse Momentum
→ Orbital Angular Momentum

Helicity Distributions: ΔG and ΔΣ

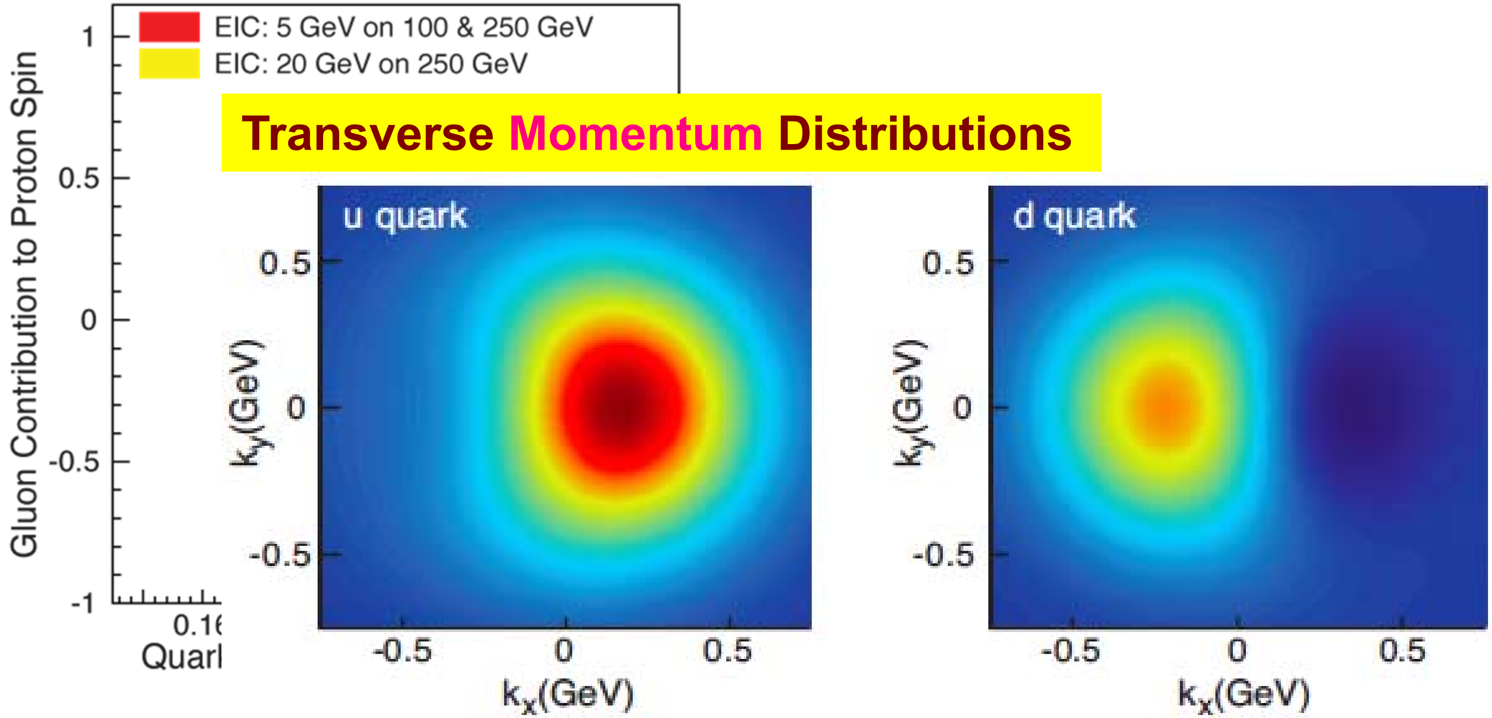


2+1 D partonic image of the proton

Spatial distance from origin X Transverse Momentum
→ Orbital Angular Momentum

Helicity Distributions: ΔG and ΔΣ

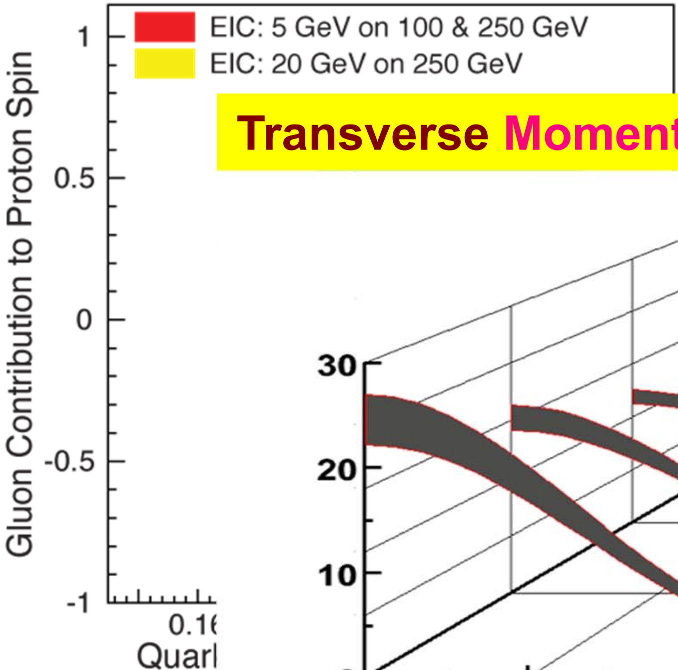
Transverse Momentum Distributions



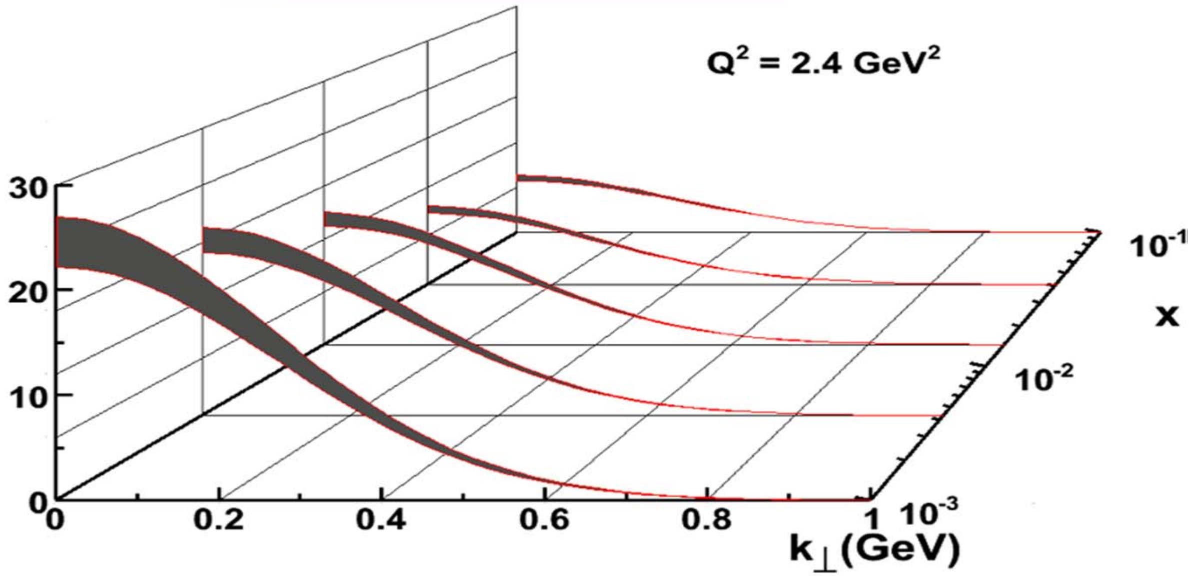
2+1 D partonic image of the proton

Spatial distance from origin X Transverse Momentum
→ Orbital Angular Momentum

Helicity Distributions: ΔG and ΔΣ

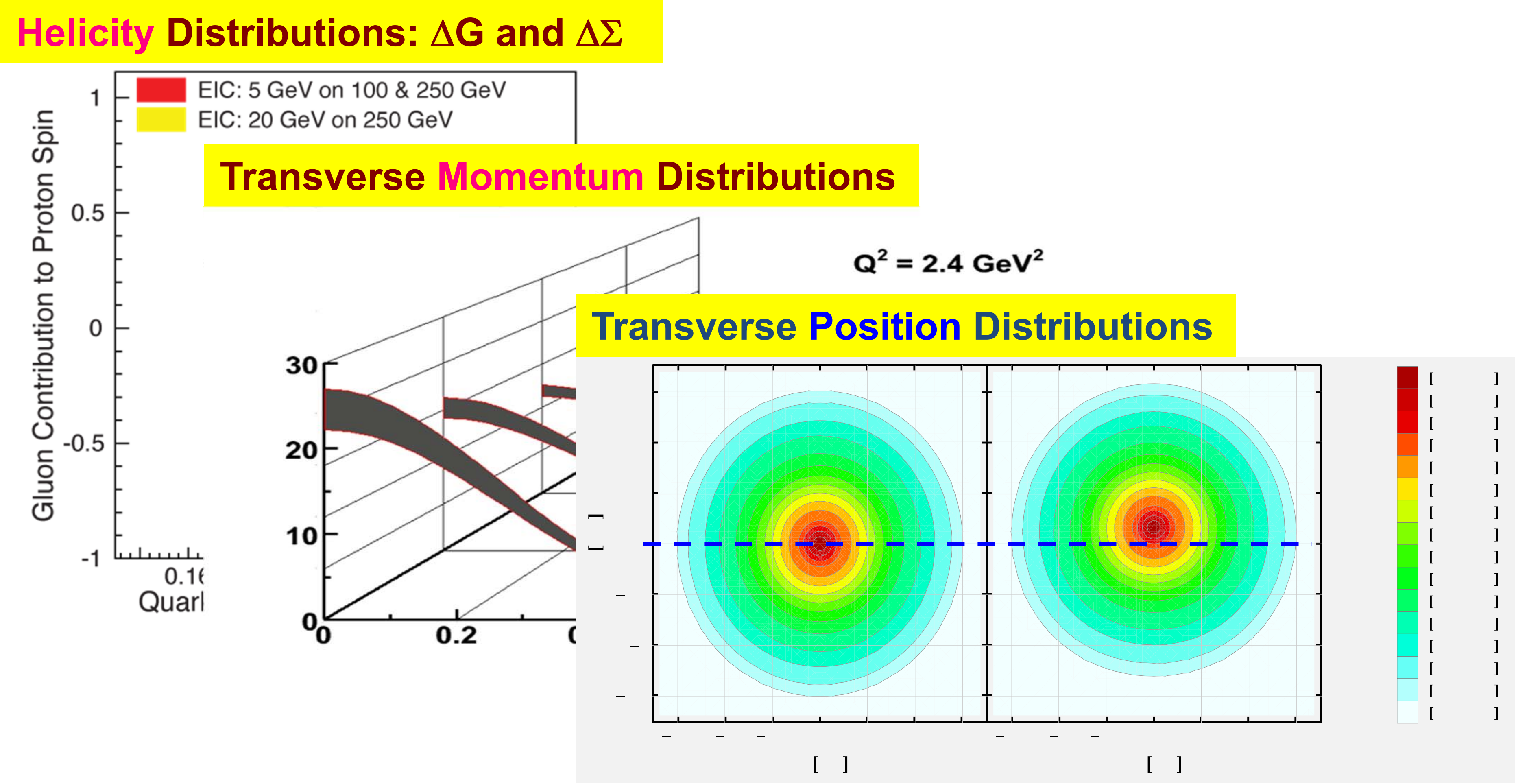


Transverse Momentum Distributions



2+1 D partonic image of the proton

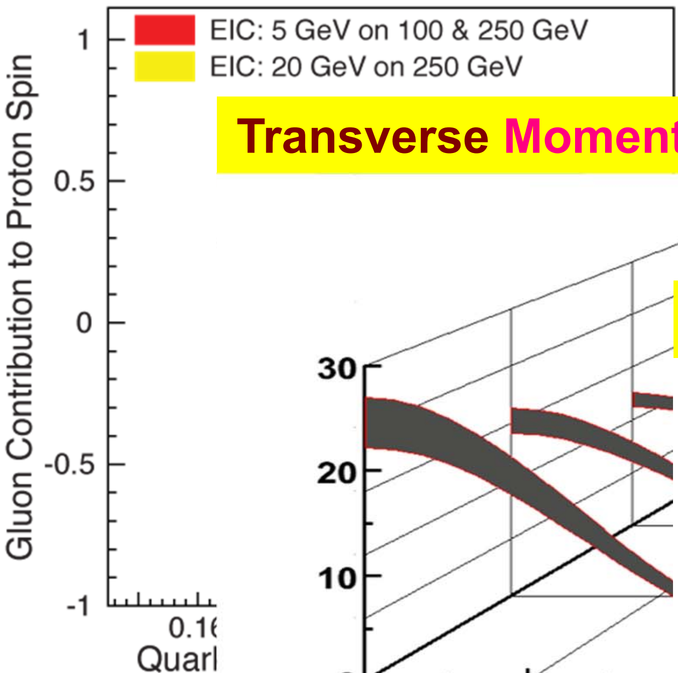
Spatial distance from origin X Transverse Momentum
→ Orbital Angular Momentum



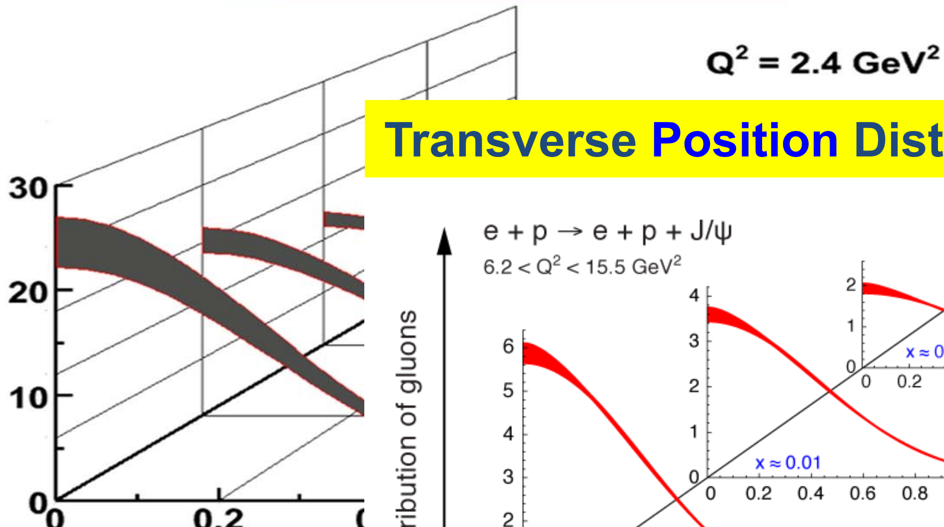
2+1 D partonic image of the proton

Spatial distance from origin X Transverse Momentum
→ Orbital Angular Momentum

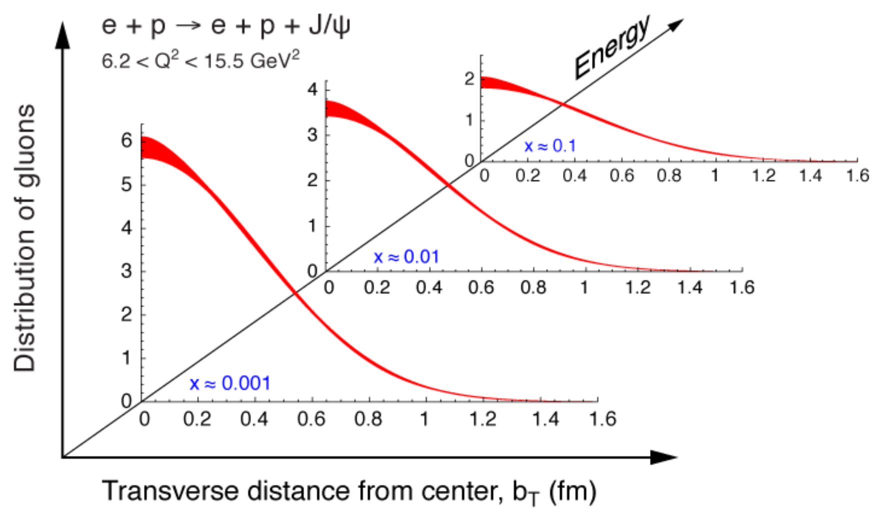
Helicity Distributions: ΔG and ΔΣ

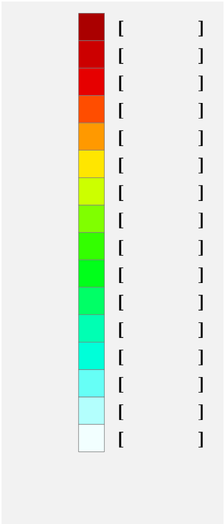


Transverse Momentum Distributions



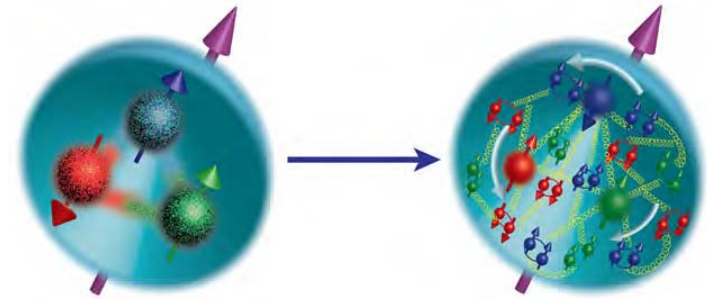
Transverse Position Distributions



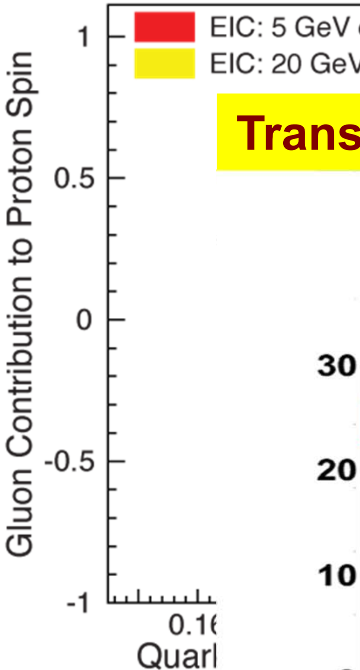


2+1 D partonic image of the proton

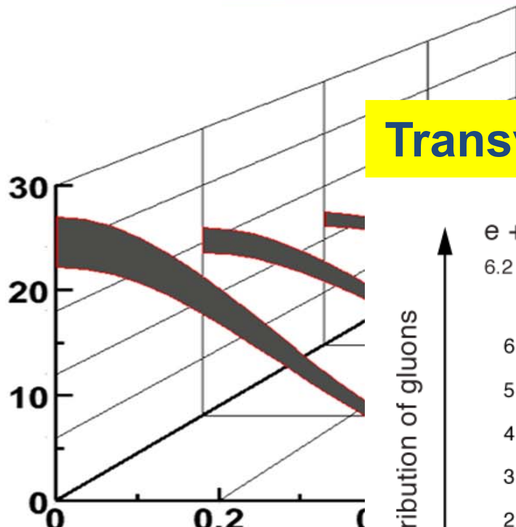
Spatial distance from origin X Transverse Momentum
→ Orbital Angular Momentum



Helicity Distributions: ΔG and ΔΣ

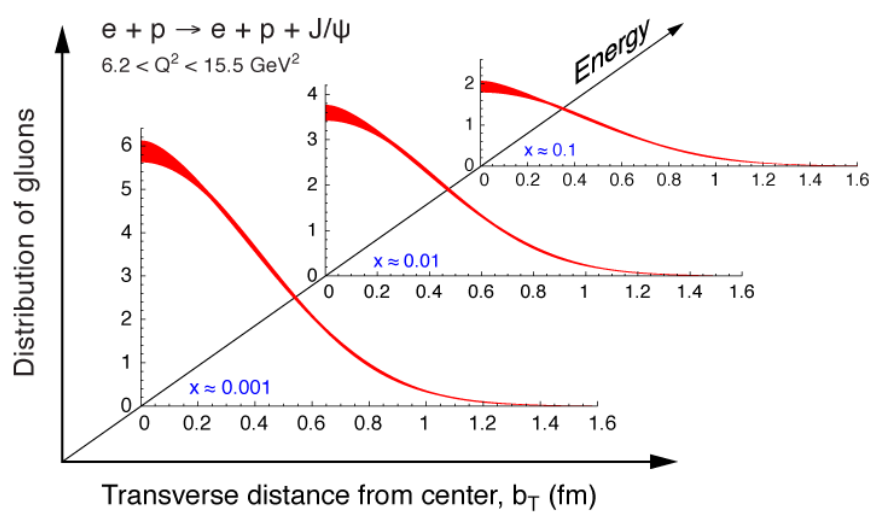


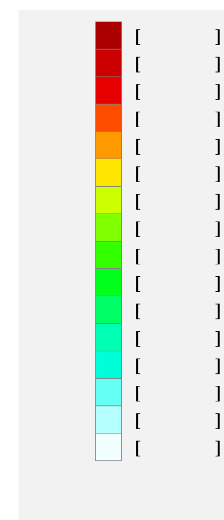
Transverse Momentum Distributions



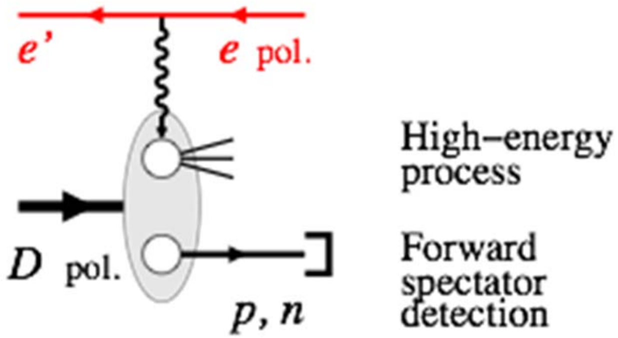
$Q^2 = 2.4\ GeV^2$

Transverse Position Distributions

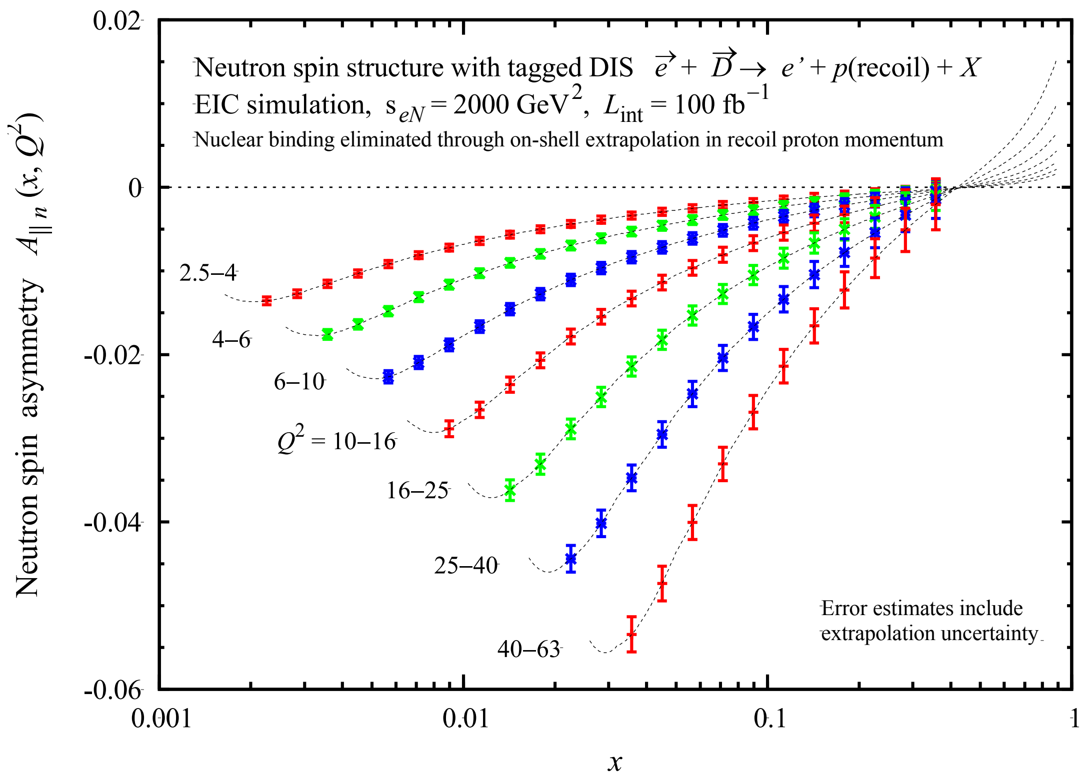




Tagging → Neutron spin structure & study of nuclear binding



Tag the recoil proton:
Study the neutron's q-g spin structure function.
Also for other few body nuclei



- Another area of interest: Measurement of the kinematics of the spectator nucleon indicator of the strength and (hence) the nature of its *binding* with the in-play nucleon(s):

→ quark-gluon origin of the nuclear binding

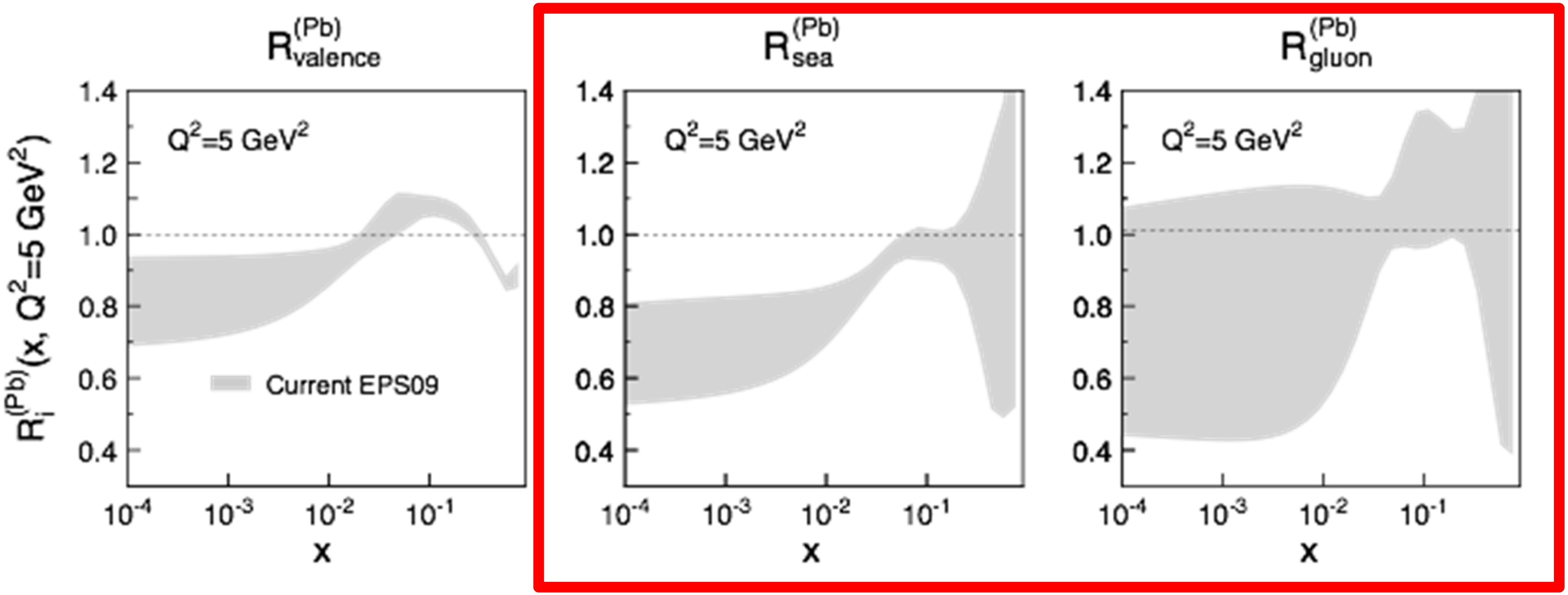
EIC – World's First eA Collider

The Nucleus: A laboratory for QCD

- What do we know about the gluons in nuclei? Very little!
- Does the gluon density saturate? Does this produce a unique and universal state of matter?
- How do color charges propagate through and interact with the nuclear medium?

EIC: sea quarks and gluons in nuclei

What do we know of gluons in nuclei? Essentially nothing!



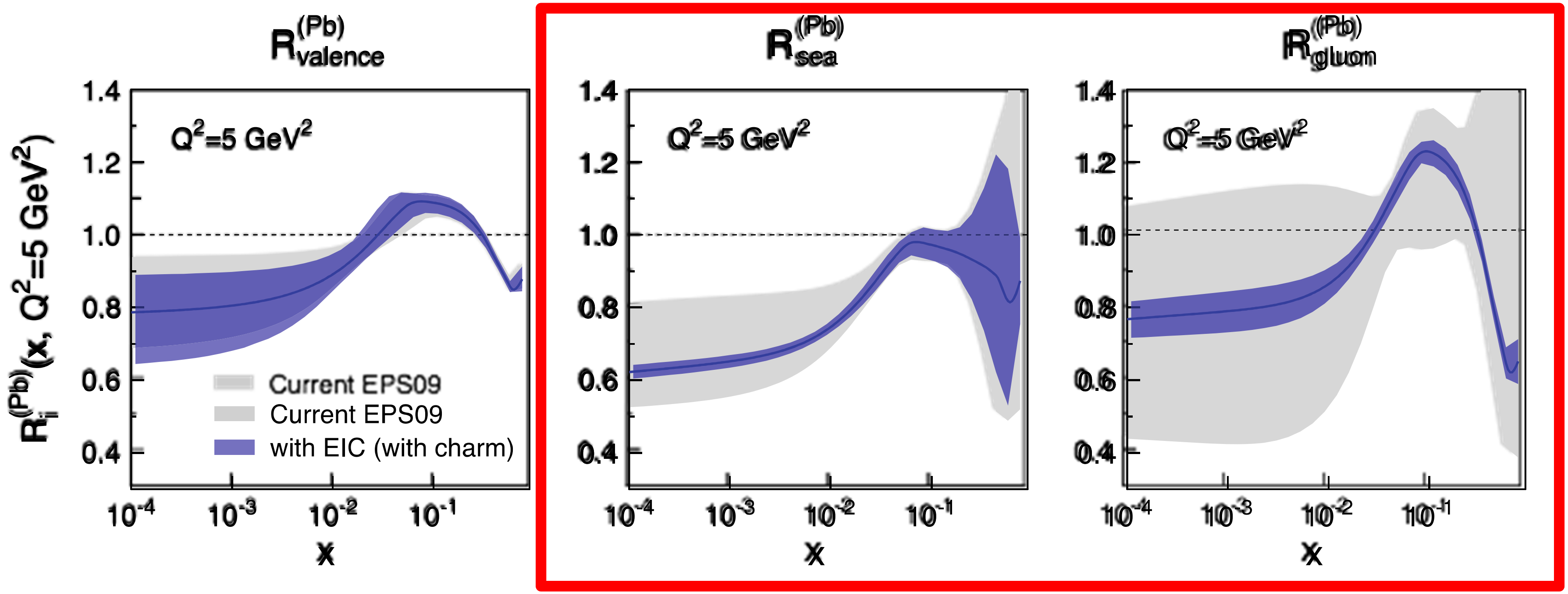
Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
- An EIC will significantly reduce uncertainties

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

EIC: sea quarks and gluons in nuclei

What do we know of gluons in nuclei? Essentially nothing!

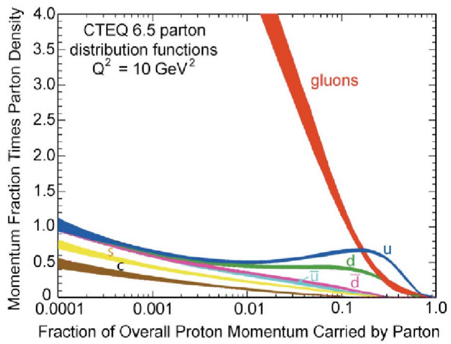


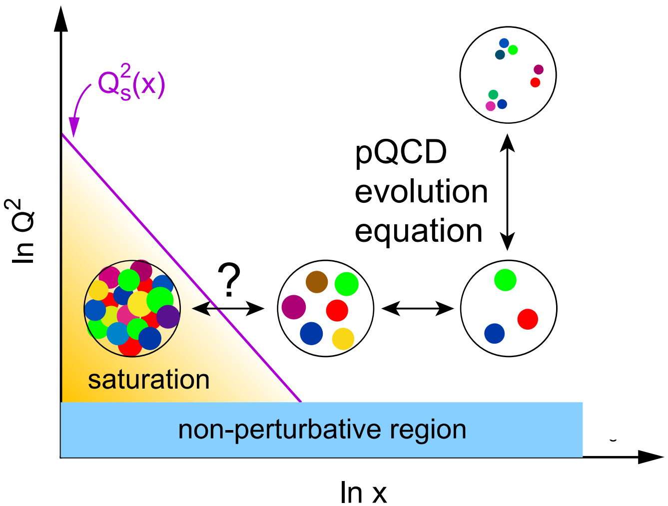
Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear sea quarks and gluons**
- An EIC will significantly reduce uncertainties

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

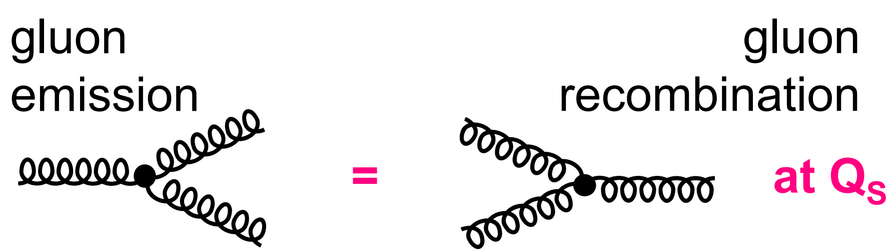
What do we learn from low-x studies?





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



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

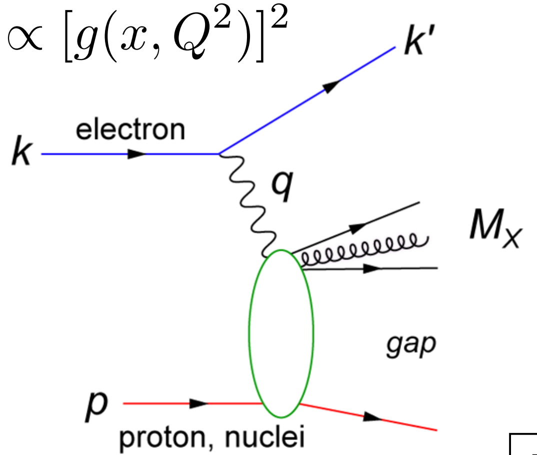
First observation of g-g recombination in different nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate an appropriate effective theory?

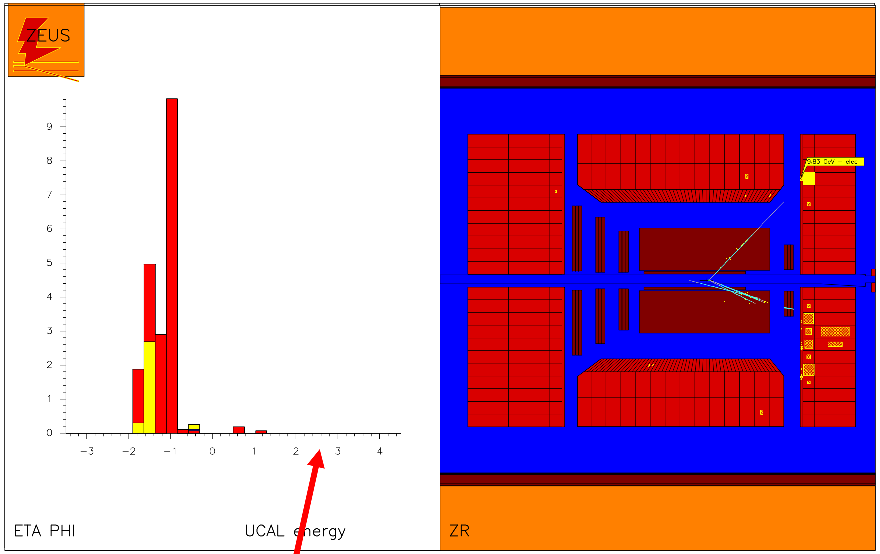
Saturation/CGC – what to measure?

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

Diffractive event

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



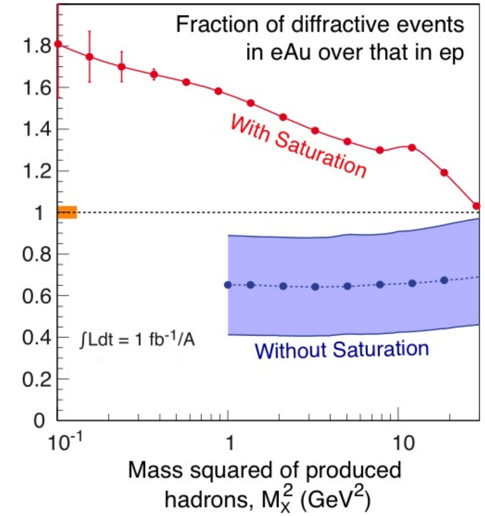


No activity in proton direction

A 7 TeV equivalent electron bombarding the proton … but nothing happens to the proton in 10-15% of cases

Predictions for eA for such hard diffractive events range up to: 25-30%... given saturation models

(EIC: utilize g ~ $A^{1/3}$ x $s^{0.3}$ to hunt for c.q. map onset of saturation)

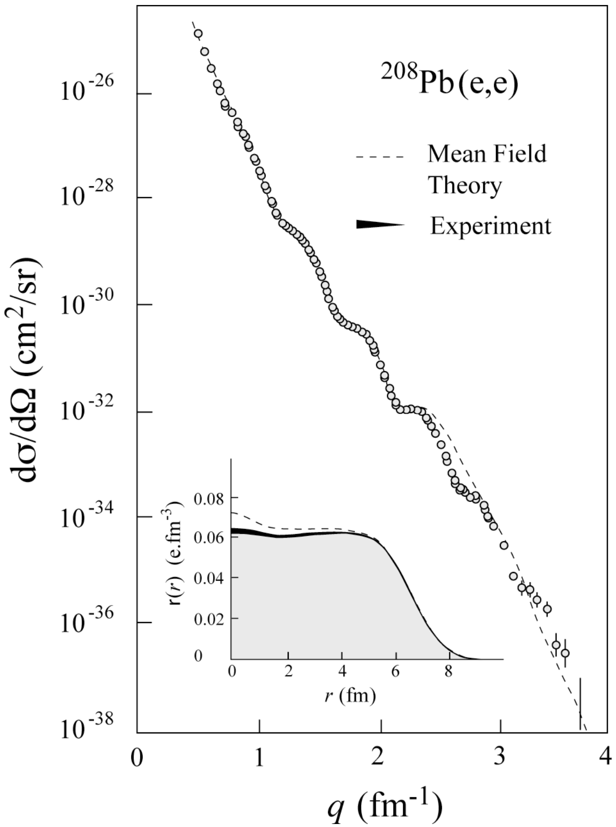


Exposing different layers of the nuclear landscape with electron scattering

History:

Electromagnetic

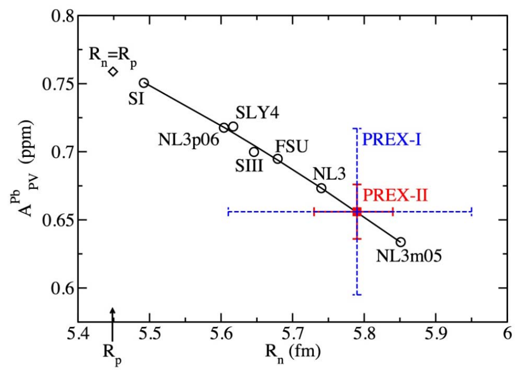
Elastic electron-nucleus scattering → charge distribution of nuclei

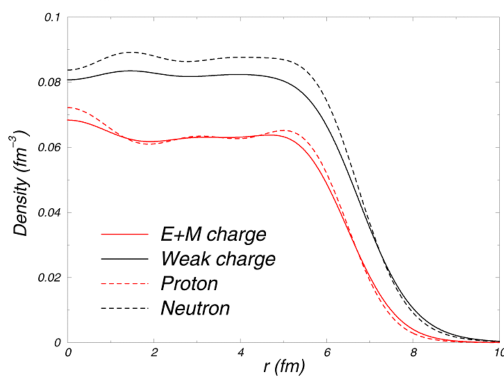


Present/Near-future:

Electroweak

Parity-violating elastic electron-nucleus scattering (or hadronic reactions *e.g.* at FRIB) → neutron skin

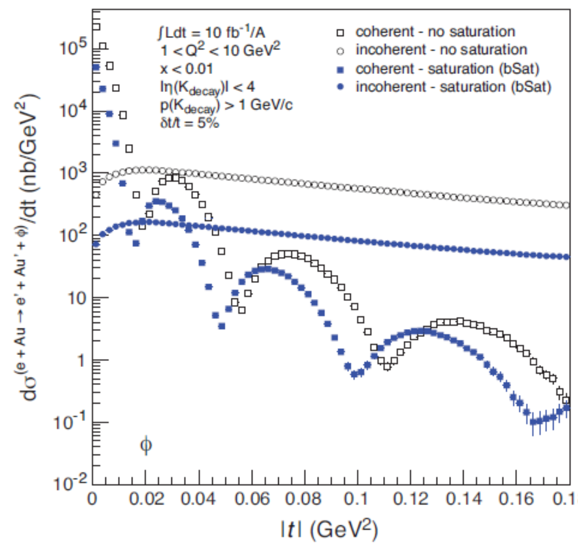




Future:

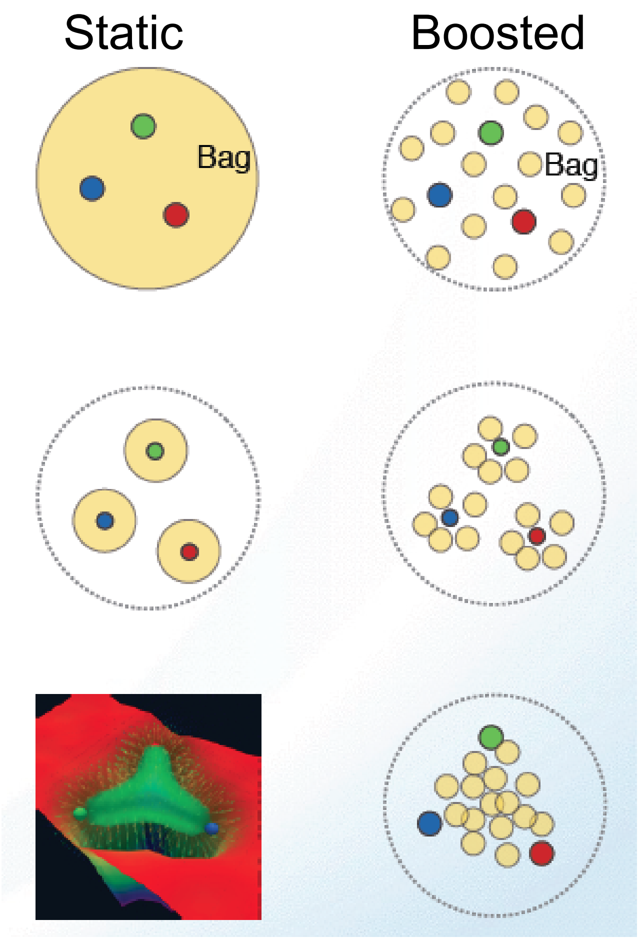
Color dipole

ϕ Production in coherent electron-nucleus scattering → gluon spatial distribution of nuclei



Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

What does a proton or (nucleus) look like?



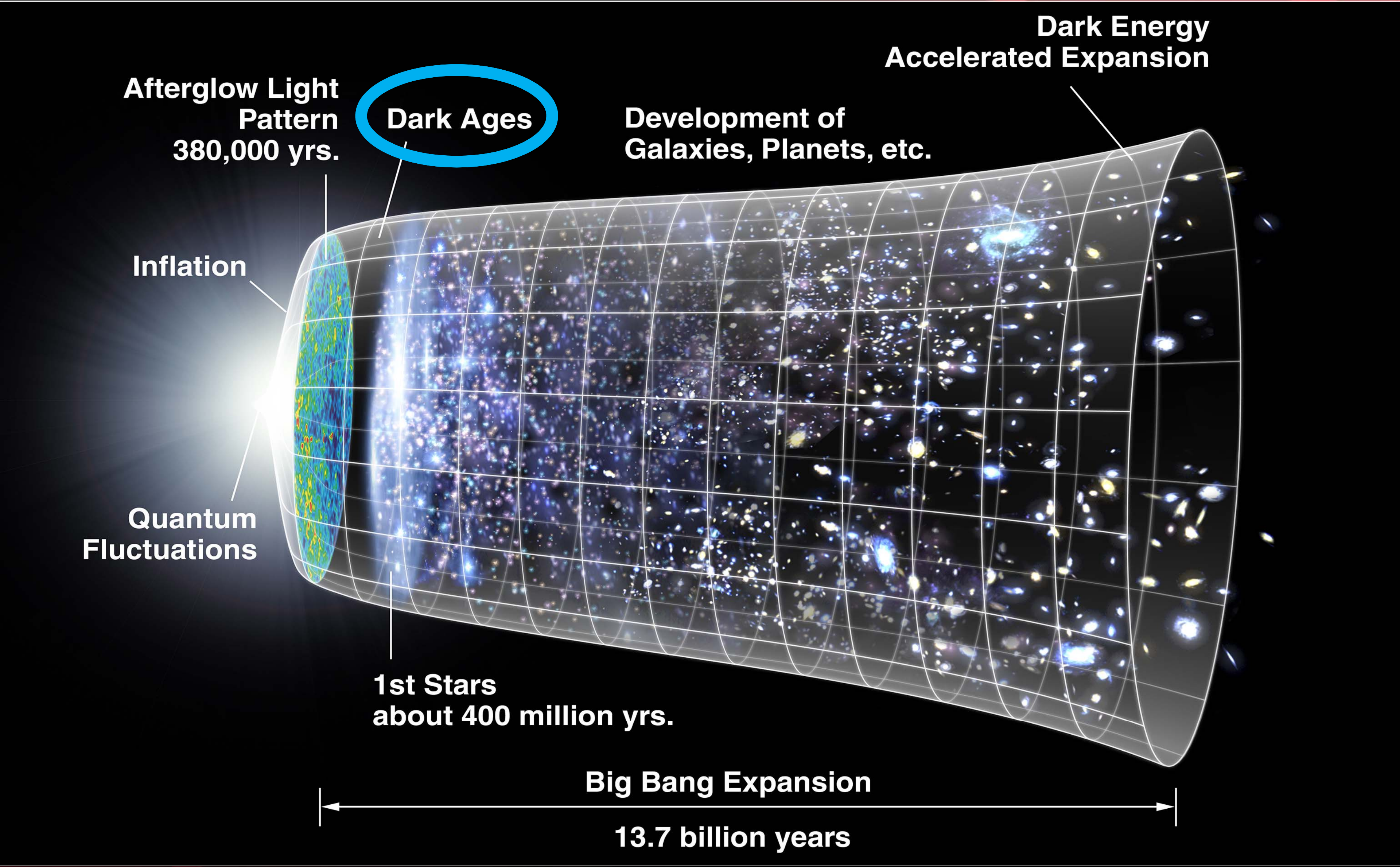
Bag Model: Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

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

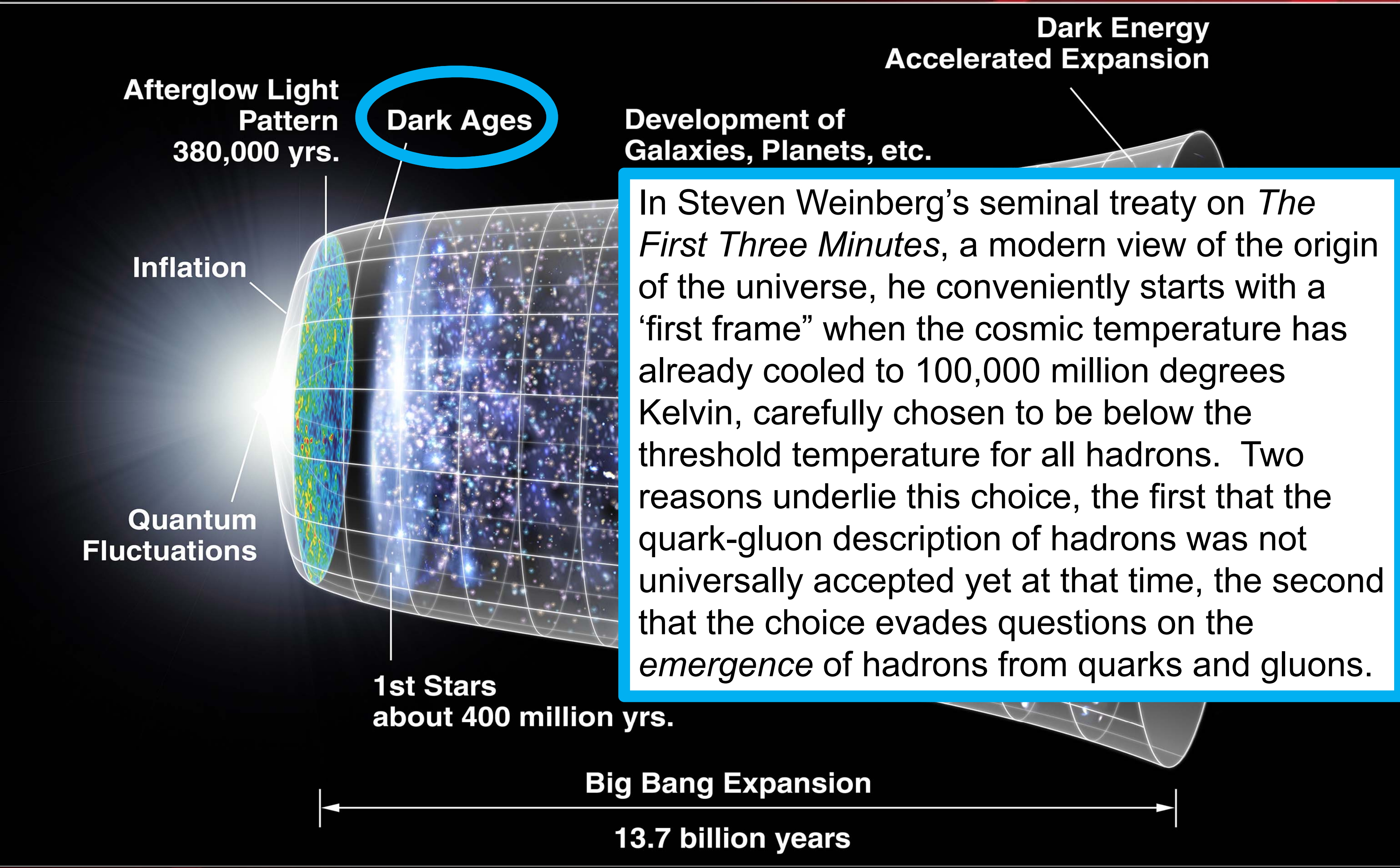
Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks:
Gluon radius < Charge Radius

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

Timeline of the Universe



Timeline of the Universe



In Steven Weinberg's seminal treaty on *The First Three Minutes*, a modern view of the origin of the universe, he conveniently starts with a 'first frame" when the cosmic temperature has already cooled to 100,000 million degrees Kelvin, carefully chosen to be below the threshold temperature for all hadrons. Two reasons underlie this choice, the first that the quark-gluon description of hadrons was not universally accepted yet at that time, the second that the choice evades questions on the *emergence* of hadrons from quarks and gluons.

Shed EIC Light on the Dark Ages

- Colored object
- Nearly massless object
- Asymptotically free object

- Colorless objects
- Massive objects
- Confined objects

EIC can measure it all

$D_a^h(z, p_t^2; Q^2)$

Understanding of the 3D structure of fragmentation into a hadron requires studies of transverse momentum, spin and hadron species dependence

From 1D to 3D fragmentation:

- Many more variables, Many more angles
- Multi-dimensional data
- Fine binnings

Color to colorless

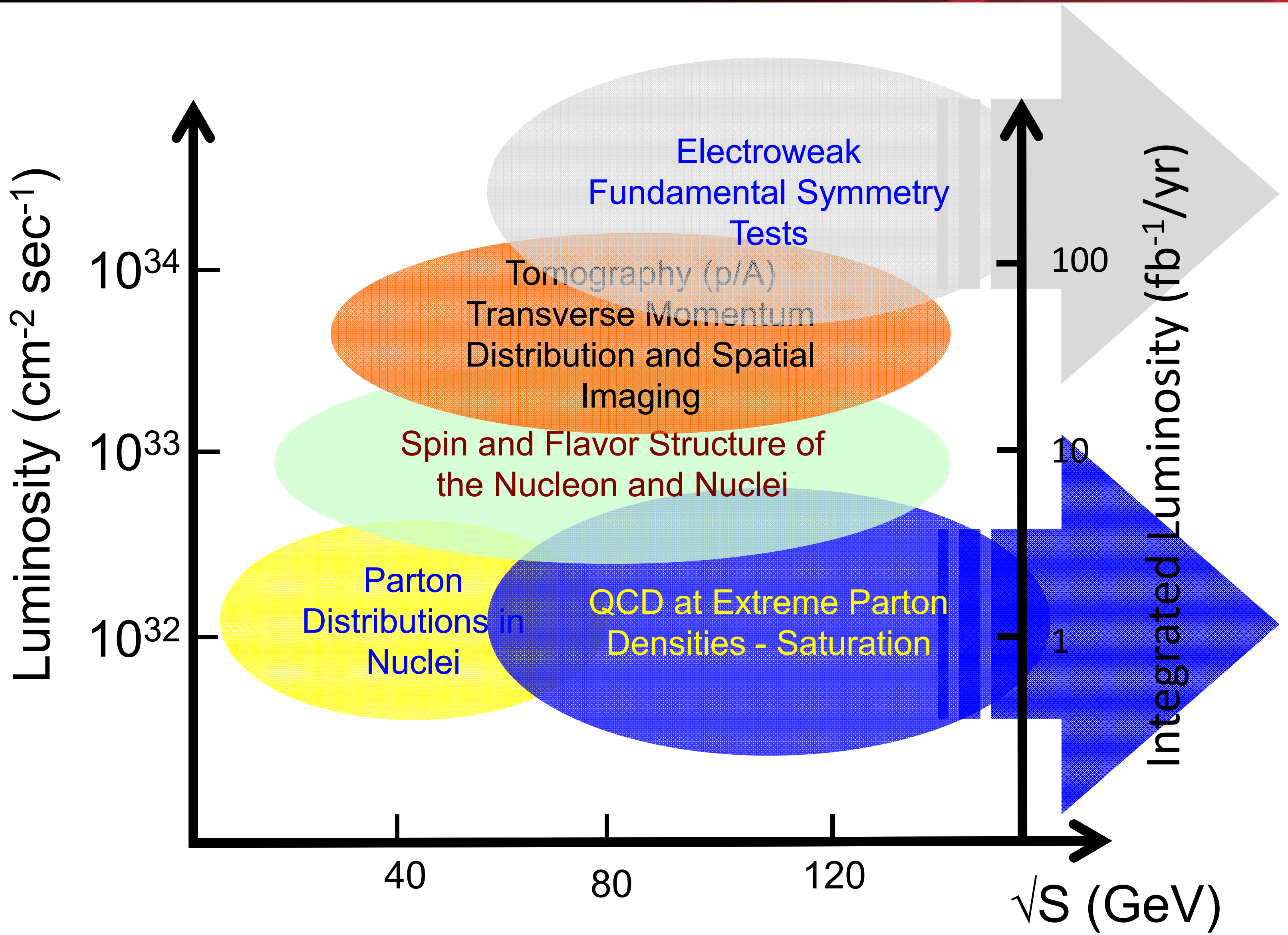
→ loss of color? No, color of first parton always was balanced by another leg.

Characteristics of fragmentation process must be influenced by

- Dynamical Chiral Symmetry Breaking
- Confinement

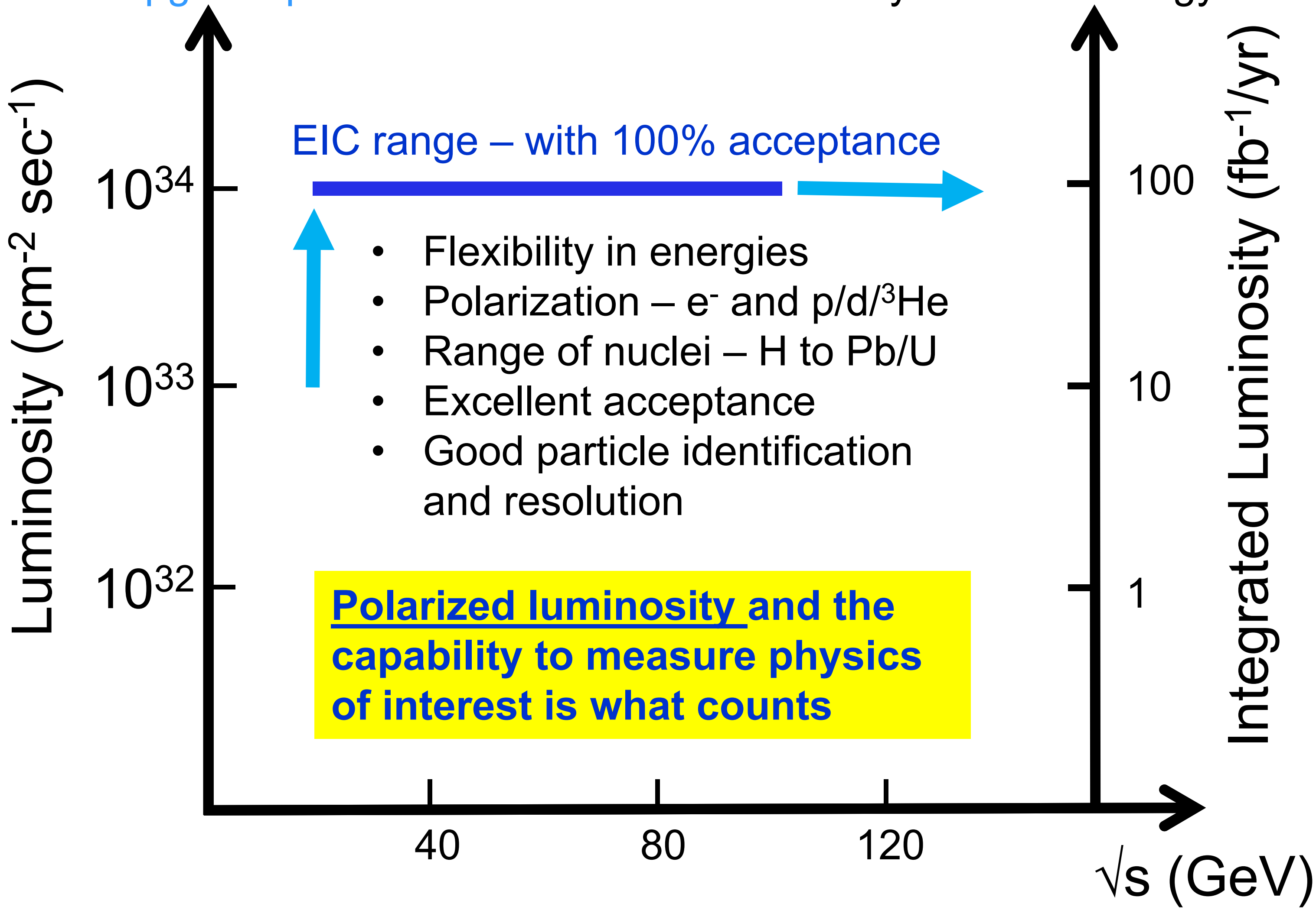
The requirements of the EIC – unique and perhaps counterintuitive

Physics vs. Luminosity & Energy

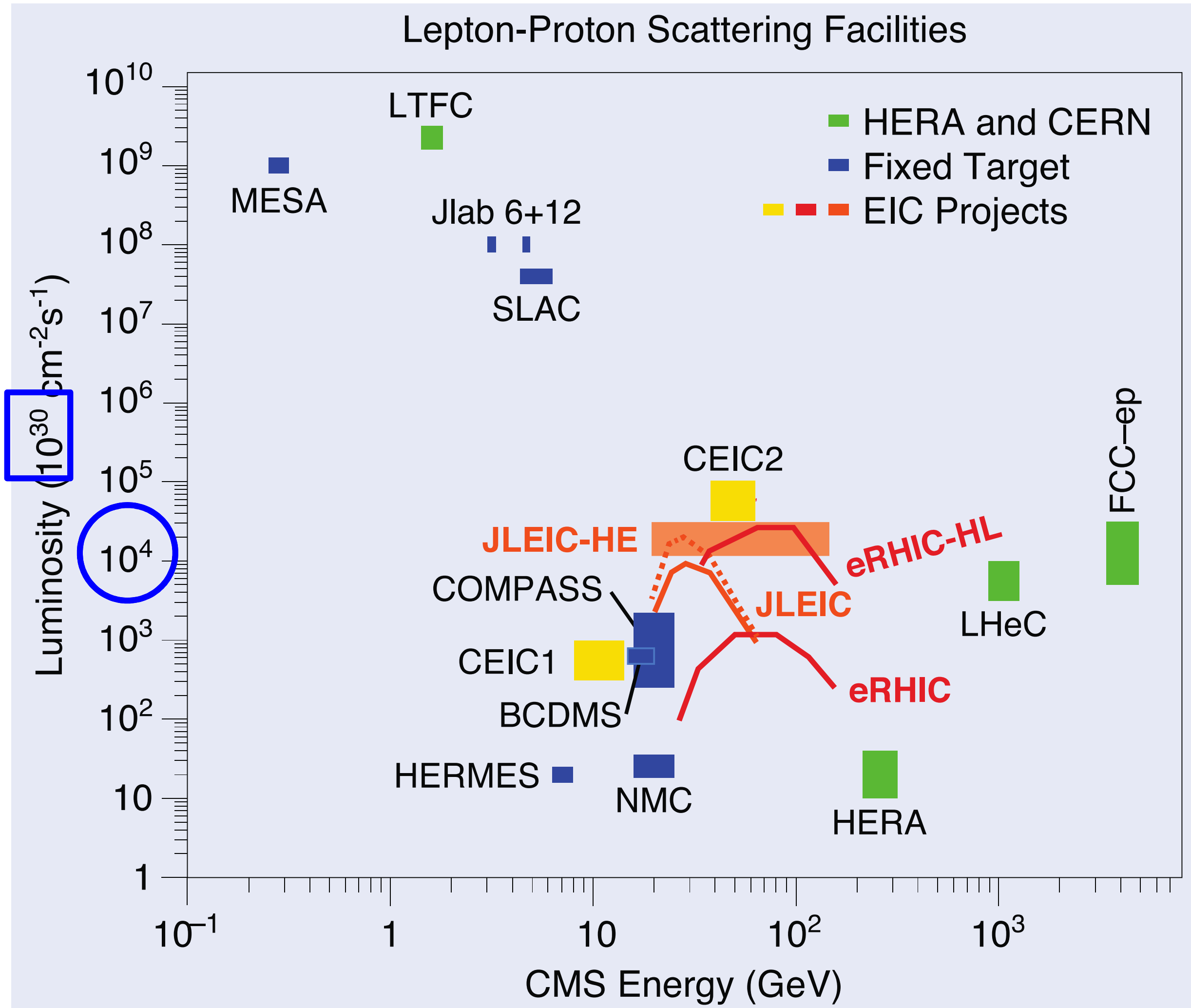


Physics vs. EIC Design Requirements

What the nuclear physicists dream off and drives the EIC designs, with upgrade paths included either in luminosity or in CM energy



Lepton-Proton Scattering Facilities



Note the upgrade paths either in luminosity or in energy reach

EIC Requirements

Requirements from Physics:

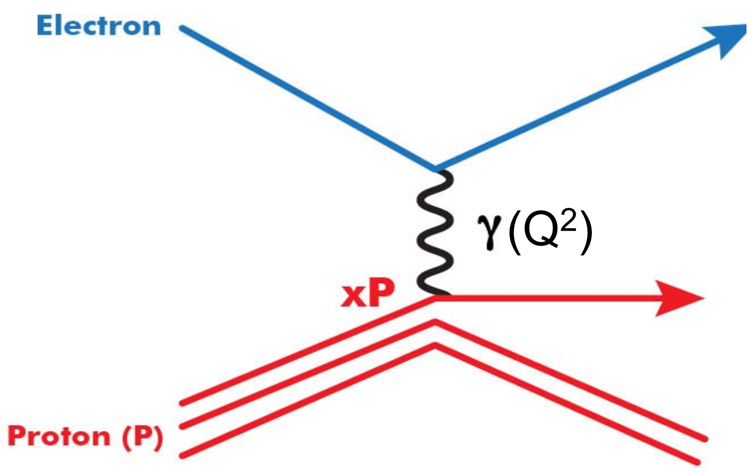
- ❑ High Luminosity > 10^{33-34} $cm^{-2}s^{-1}$ and higher → nucleon/nuclei imaging
- ❑ Flexible center of mass energy → wide kinematic reach
- ❑ Electrons (0.8) and protons/light nuclei (0.7) highly polarized → study of spin structure
- ❑ Wide range of nuclear beams (D to Pb/U) → high gluon densities
- ❑ Room for a wide acceptance detector with good PID (e/h & π, K, p) → flavor dependence
- ❑ Full (or large) acceptance for tagging, exclusivity, protons from elastic reactions, neutrons from nuclear breakup → target/nuclear fragments

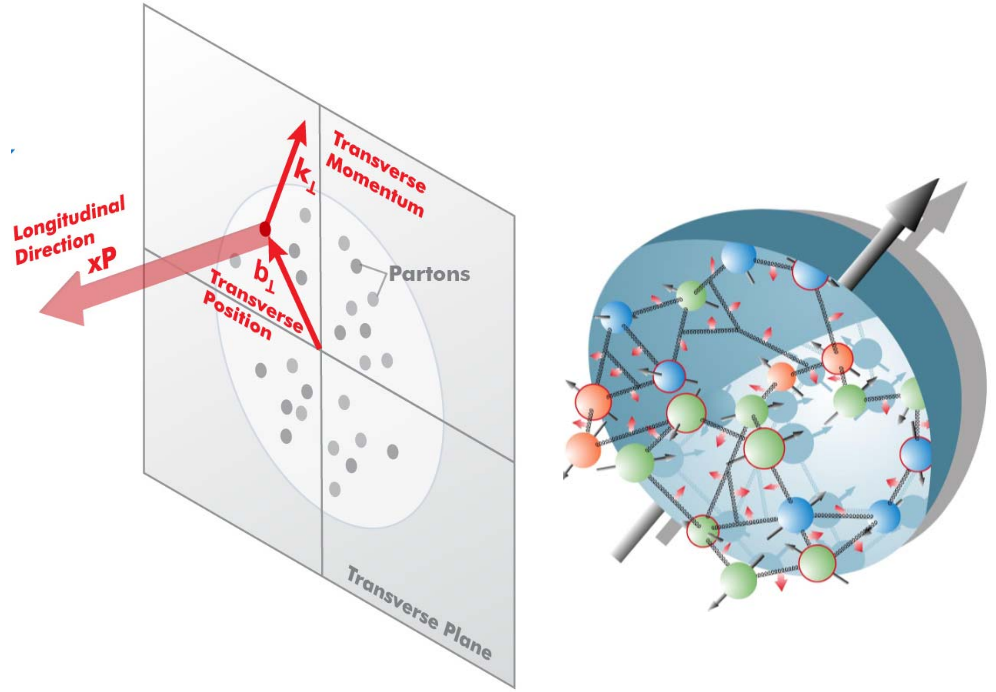
The "sweet spot" for the EIC parameters is a balance of

- High enough energies to reach high Q^2 (up to ~1000 GeV^2)
- Low enough proton energy to measure transverse scale of ~100 MeV well.
- High enough energy to explore saturation.
- High enough luminosity for the nucleon/nuclei imaging.
- IR and Detector with acceptance and performance to fully measure the relevance processes

Experimental Challenge of the EIC

$s = xyQ^2$, $s = 4E_eE_p$





On one hand: need high beam energies to resolve partons in nucleons. Q^2 needs to be up to ~1000 GeV^2

On the other hand: need to resolve quantities (k_t, b_t) of order a few hundred MeV in the proton. Limits the proton beam energy & High Lumi needed.

Electron-Ion Collider: Cannot be HERA or LHeC: proton energy too high

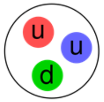
Where EIC Needs to be in x (nucleon)

Saturation Regime: Needs to be accessed via Ions

Collective Regime

Many-body Regime

Few-body Regime (JLab 12)



10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 x (for proton)

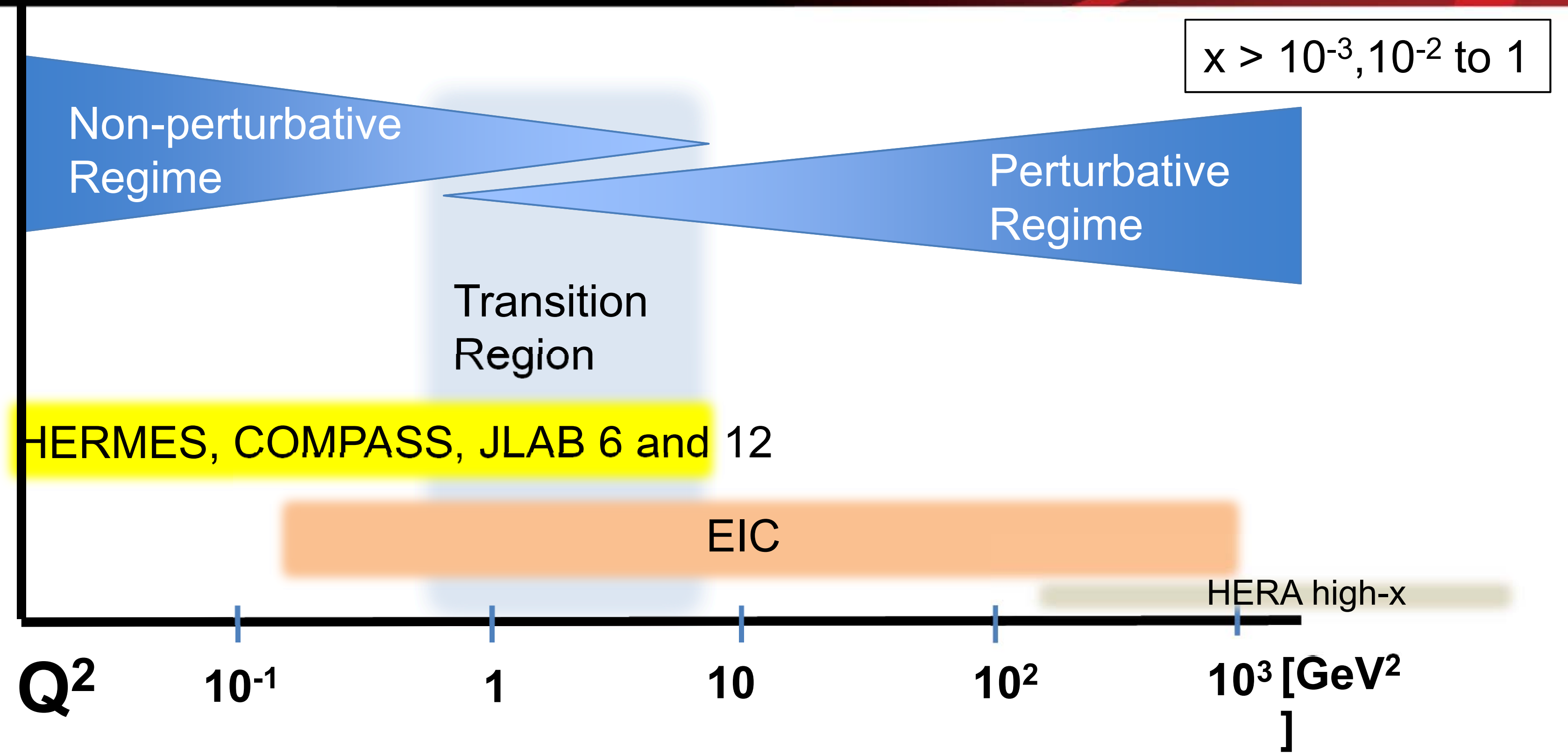
QCD Radiation Dominated (Studied at HERA)

Hadron Structure Dominated

Spin,TMD, GPD…

Main interest for EIC Nucleon/Nuclear Program

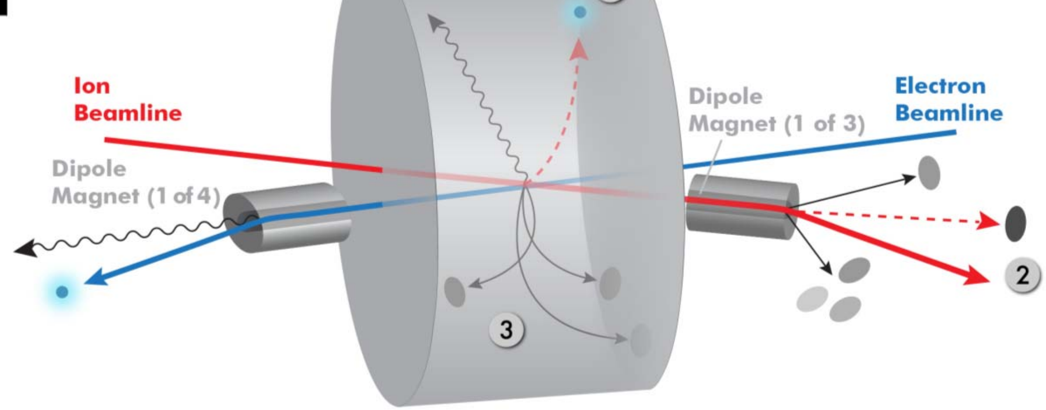
Where EIC needs to be in Q^2



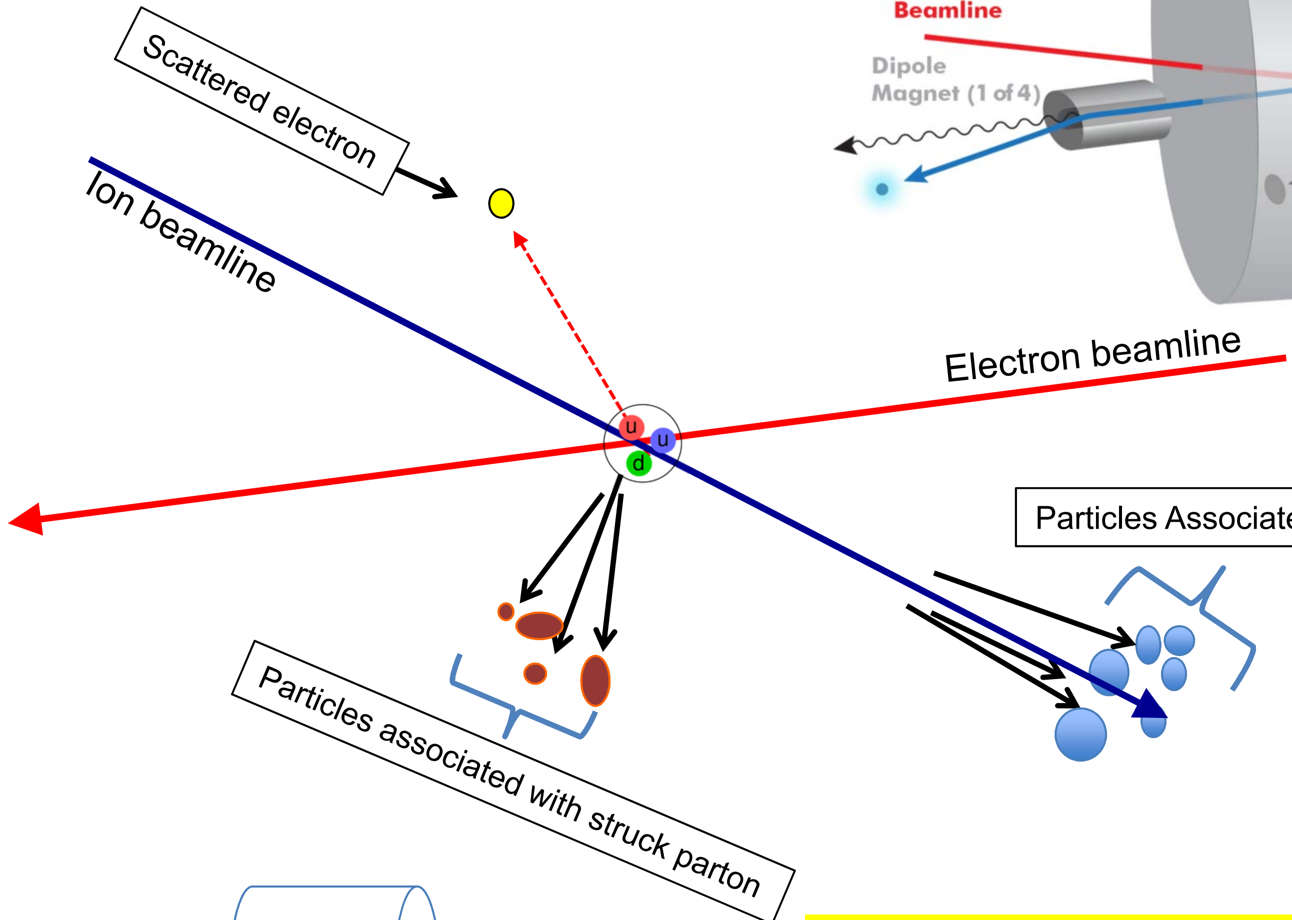
- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

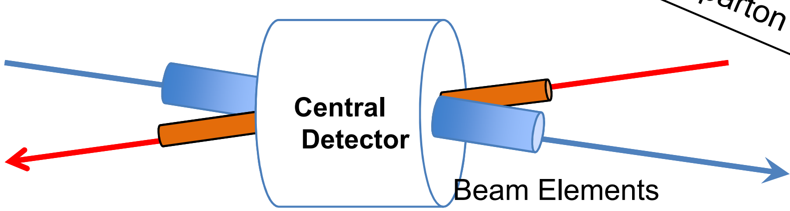
Disentangle Perturbative/Non-perturbative, Leading Twist/Higher Twist

EIC Final State Particles



Possible to get 100% acceptance for the whole event

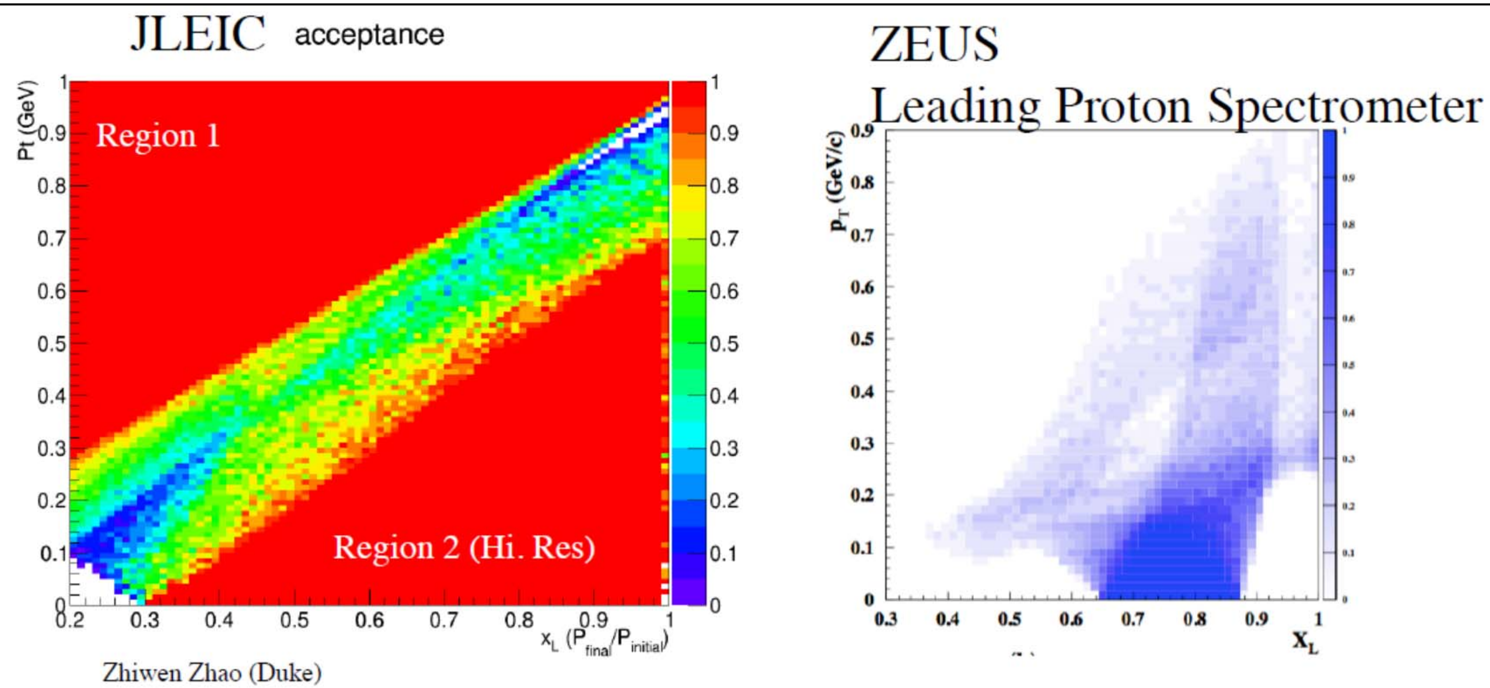




Beam elements limit forward acceptance
Central Solenoid not effective for forward

Full Acceptance for Forward Physics!

Example: acceptance for p' in e + p → e' + p' + X



Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

JLEIC: ~100% (also covers much higher X_L than ZEUS)

Huge gain in acceptance for forward tagging to measure F_2^n and diffractive physics!!!

Ongoing and next steps

EIC Realization Imagined

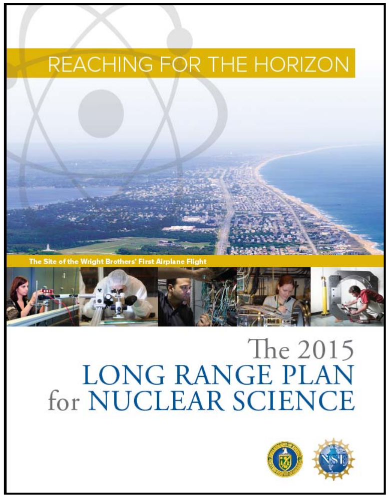
With a formal NSAC/LRP recommendation, what can we speculate about any EIC timeline?

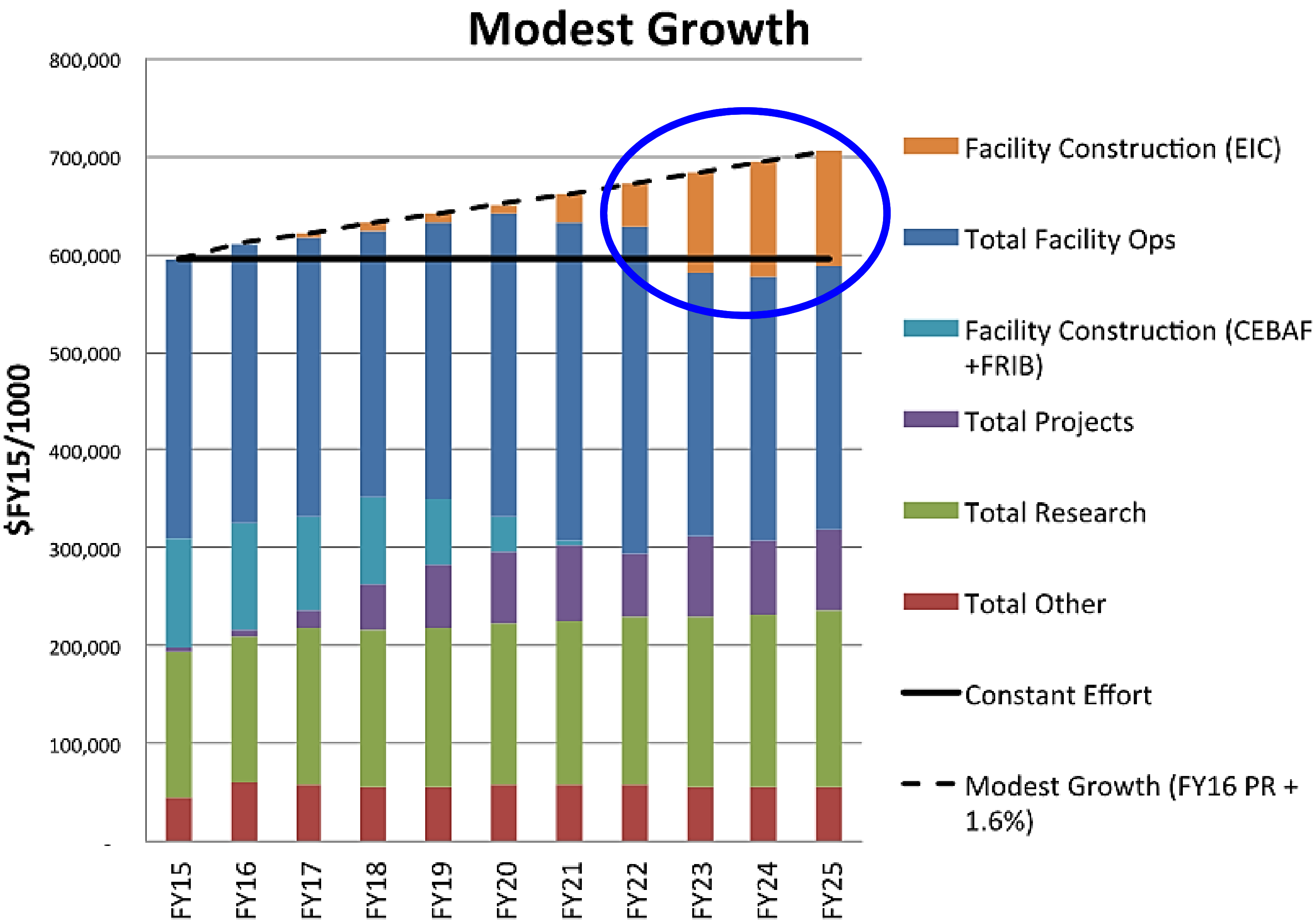
- It seems unlikely that a CD-0 (US Mission Need statement) will be awarded before completion of a National Academy of Sciences study
  - A study has been initiated and the committee is being formed
  - This would imply CD-0 Fall/Late 2017
- EIC accelerator R&D questions will not be completely answered until ~2017/18 (FOA for EIC accelerator R&D appeared, DOE/NP review planning ongoing)
- Site selection may occur at CD-1 Level, perhaps around 2019
- EIC construction has to start **after FRIB completion**, with FRIB construction anticipated to start ramping down near or in FY20

→ <u>Most optimistic</u> scenario would have EIC construction start (CD3) in FY20, perhaps more realistic FY22-23 timeframe

→ Best guess for EIC completion assuming NAS blessing would be 2025-2030 timeframe

DOE budget in FY 2015 dollars for Modest Growth scenario





The EIC Users Group: EICUG.ORG

663 collaborators, 28 countries, 147 institutions..

(no students included as of yet)

(October 09, 2016)

Keen Interest in Asia

Letter of Interest
Participation in the US Electron-Ion Collider (EIC) from Asian countries

(China, India, Japan, Korea)

Sent in the context of the US Long-Range Plan process

With this letter we want to express our interest in participating in the US EIC project. The EIC project being discussed in the Long Range Plan process of the NSAC is the most promising project in the world to be realized in a timely manner. It is a new collider which will be able to collide polarized electrons with polarized protons or nuclei. We will be able to have 100-1,000 times higher luminosity per nucleon than HERA. It promises to lead to deep understanding of high-energy QCD and the development of a novel physics field based on QCD where the gluon plays a leading role. The mass of the nucleon and the nuclei originates from gluon interactions and dynamics, and the confinement of the quarks inside the nucleon is caused by the gluons. We are keenly interested in this science, and want to strongly support the US EIC project, through a long-term collaboration for investigations of the novel gluon related physics at EIC.

What's next

- As "Town Meeting" of US Nuclear Science Long-Range Planning effort:
  June 2014 EIC Users Group Meeting at Stony Brook
  ~180 participants from all over the world
  http://skipper.physics.sunysb.edu/~eicug/meeting1/SBU.html
- After NSAC Long Range Plan, first preparatory EIC UG Meeting:
  January 2016 EIC Users Group Meeting at Un. California at Berkeley
  ~120+ participants…from all continents
  http://skipper.physics.sunysb.edu/~eicug/meeting2/UCB2016.html

- EIC UG meeting (EICUG charter accepted), joint with detector R&D meeting
  July 6-7, 2016 Generic EIC-related detector R&D meeting at ANL
  July 7-9, 2016 EIC Users Group Meeting at ANL
  http://eic2016.phy.anl.gov

- EIC User Group Satellite Meeting at INPC in Adelaide, September 12, 2016

- Preparations for National Academy of Science study ongoing

- Next EIC UG meetings: January 2017 (likely electronic) to discuss NAS study prep
  July 18-22, 2017 in Trieste, Italy ←

NAS Study - Charge to the EIC (2016)

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.

In particular, the committee will address the following questions:

- What is the merit and significance of the science that could be addressed by an electron ion collider facility and what is its importance in the overall context of research in nuclear physics and the physical sciences in general?
- What are the capabilities of other facilities, existing and planned, domestic and abroad, to address the science opportunities afforded by an electron-ion collider? What unique scientific role could be played by a domestic electron ion collider facility that is complementary to existing and planned facilities at home and elsewhere?
- What are the benefits to US leadership in nuclear physics if a domestic electron ion collider were constructed?
- What are the benefits to other fields of science and to society of establishing such a facility in the United States?

Conclusion

- The EIC will profoundly impact our understanding of the **structure of nucleons and nuclei in terms of sea quarks & gluons**.
  → **Can we provide *a bridge between sea quarks/gluons and nuclei?***
- EIC will enable **IMAGES** of **yet unexplored regions of phase spaces in QCD** with its high luminosity/energy, nuclei & beam polarization
  → ***There is high potential for discovery***
- Outstanding questions raised both by the science at RHIC/LHC and at HERMES/COMPASS/Jefferson Lab, have **naturally led to the science and design parameters of the EIC**
- There exists **world wide interest** in collaborating on the EIC
- Accelerator scientists at RHIC and JLab, in collaboration with many outside interested accelerator groups, can provide the **intellectual and technical leadership to realize the EIC**, a frontier accelerator facility.

The future of QCD-based nuclear science demands an Electron Ion Collider

QCD

Asymptotic Freedom

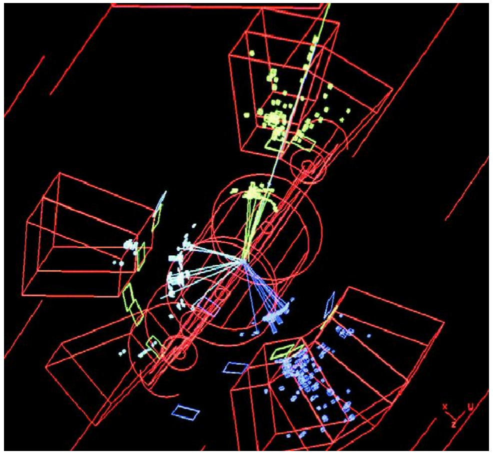
Small Distance
High Energy

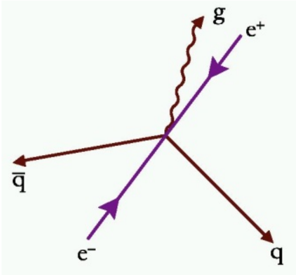
Confinement

Large Distance
Low Energy

Perturbative QCD

High Energy Scattering

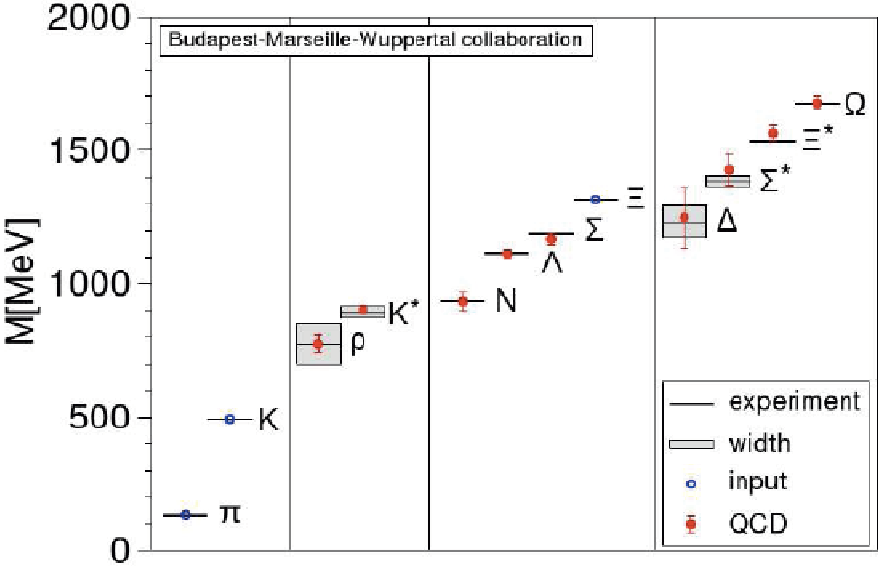




Gluon Jets Observed

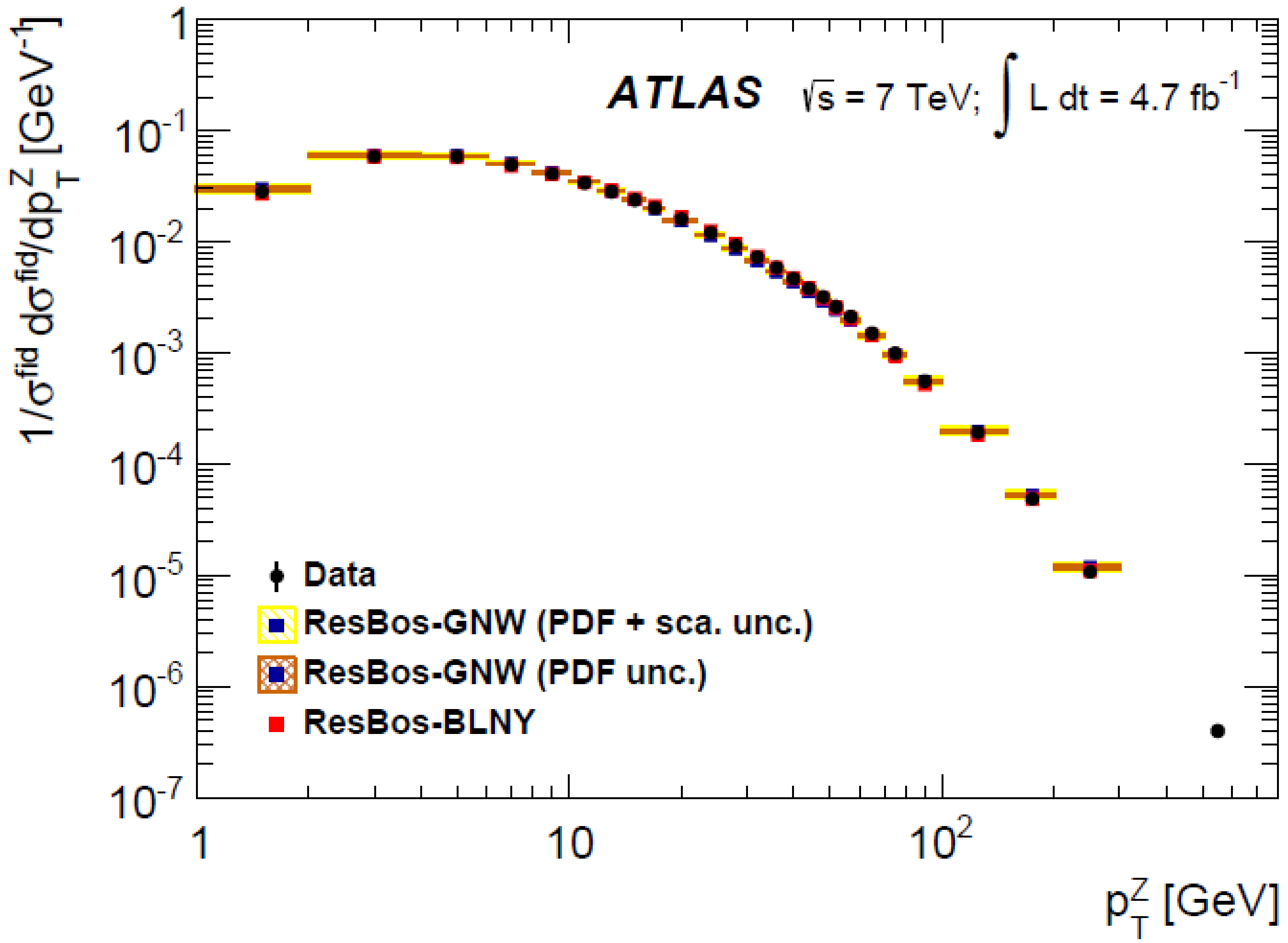
Strong QCD

Hadron Spectrum - no signature of gluons?



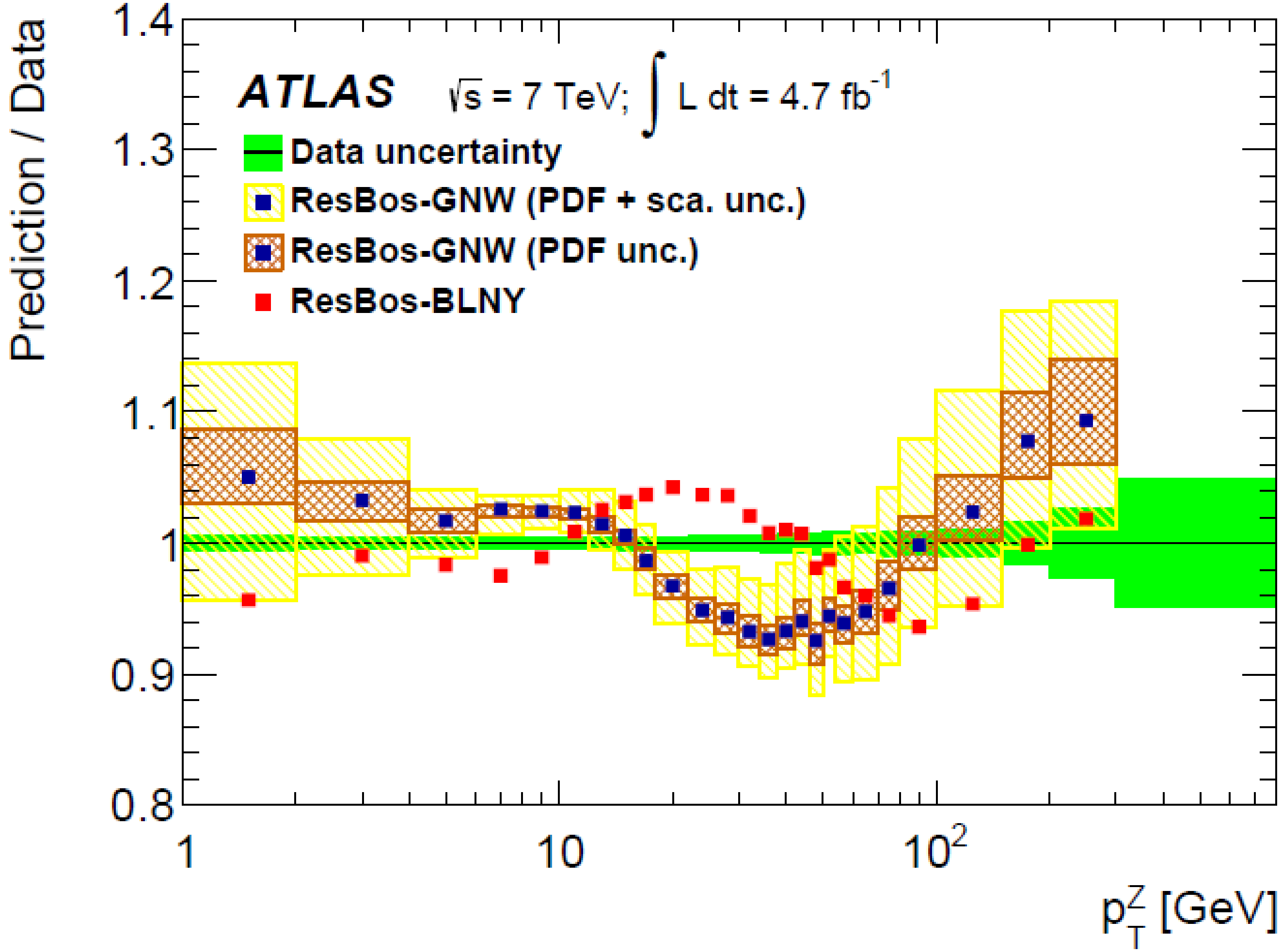
Successful perturbative predictions

Z production at the LHC



Successful perturbative predictions

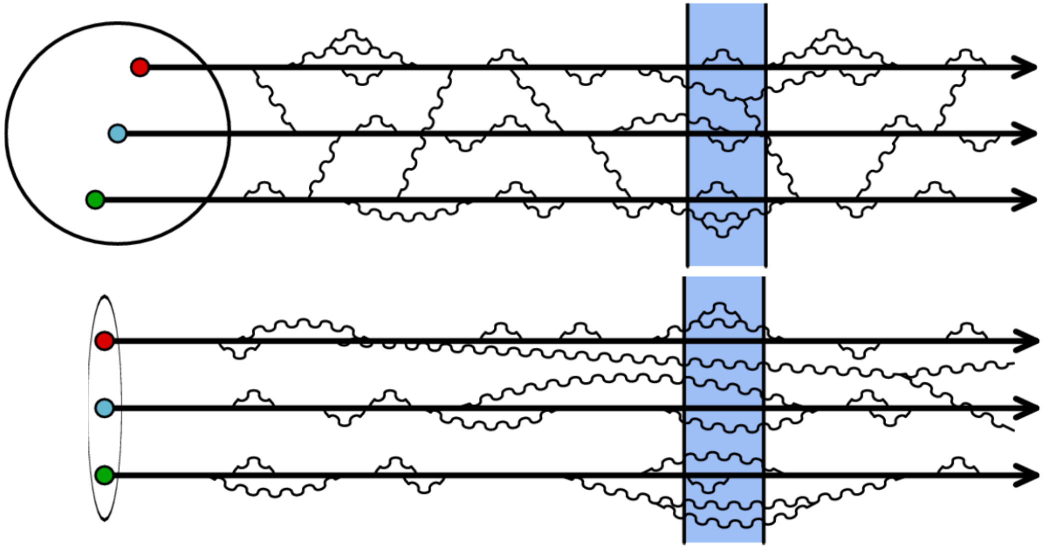
Z production at the LHC



Proton at Low and High Energy

Low energy
High x
Regime of JLab

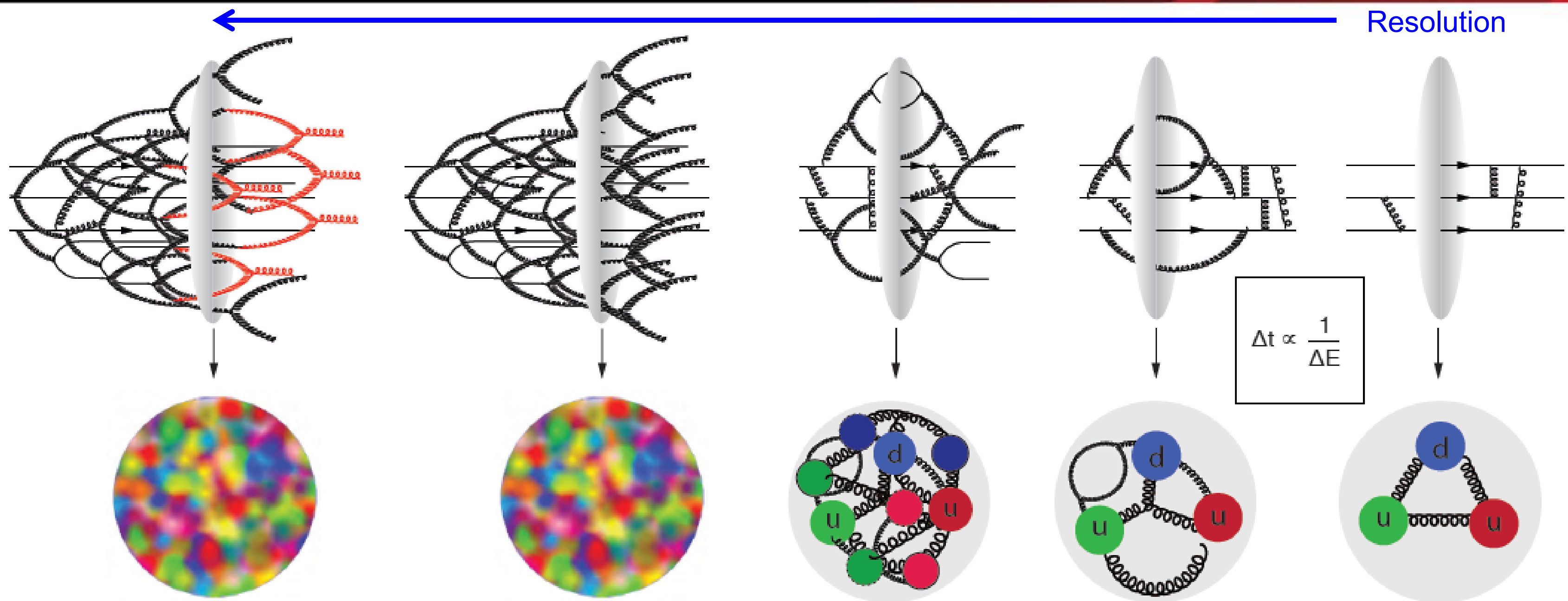
High energy
Low- x
Regime of a Collider

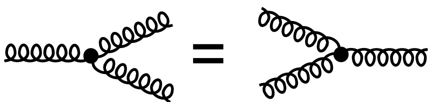


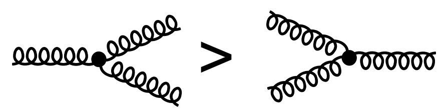
At high energy:

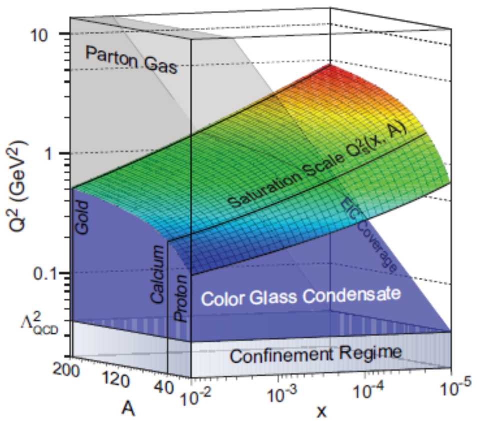
- Wee partons fluctuations time dilated in strong interaction time scales
- Long lived gluons can radiate further smaller x gluons ➔ **runaway growth?**

The Evolution of a Proton – Deep into the Sea

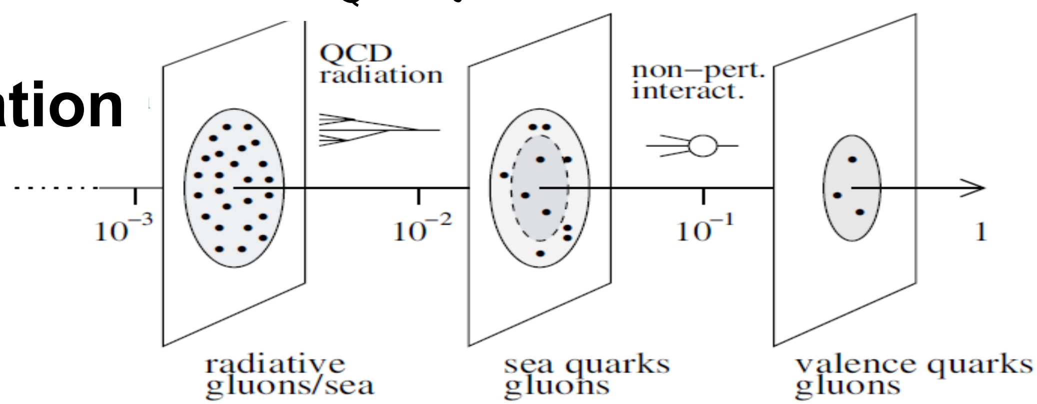






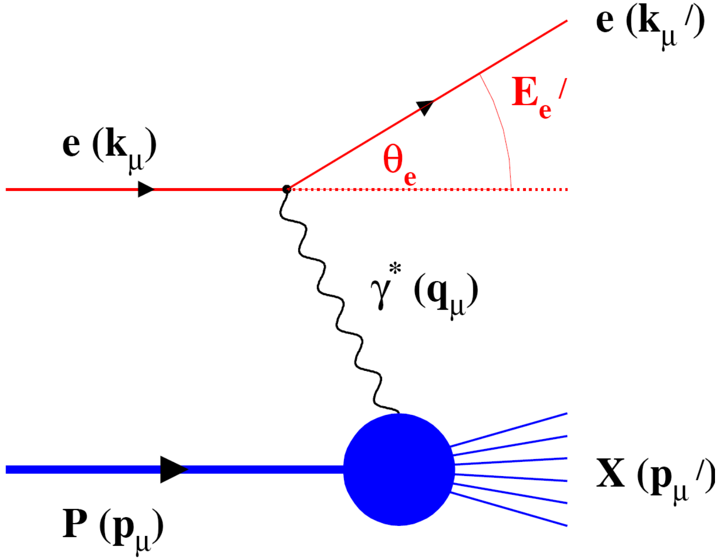


Saturation



Deep Inelastic Scattering

➔ Precision microscope with superfine control



Q^2 → Measure of resolution

y → Measure of inelasticity

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

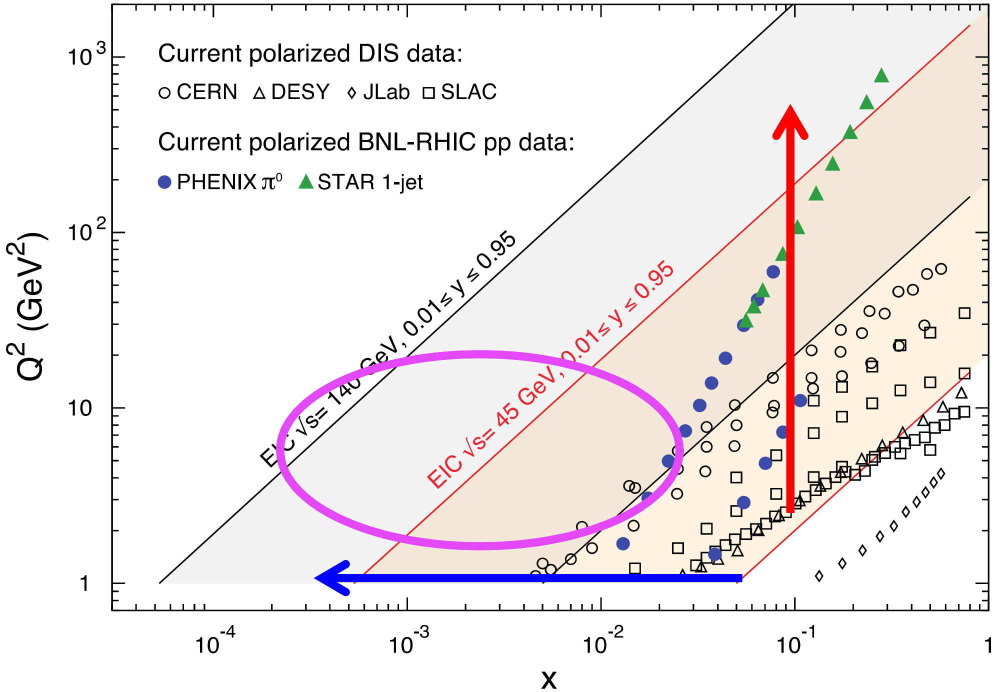
$$Q^2 = S\ x\ y$$

Inclusive events: e+p/A → e'+X
Detect only the scattered lepton in the detector

Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X
Detect the scattered lepton in coincidence with identified hadrons/jets in the detector

Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)
Detect every things including scattered proton/nucleus (or its fragments)

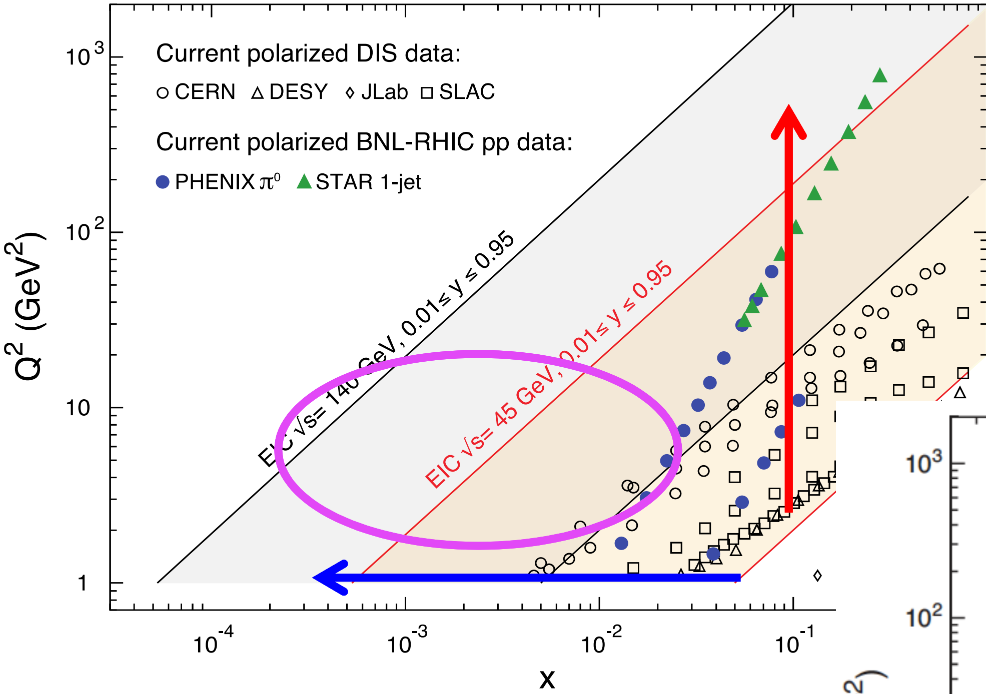
US EIC: Kinematic reach & properties



For e-N collisions at the EIC:

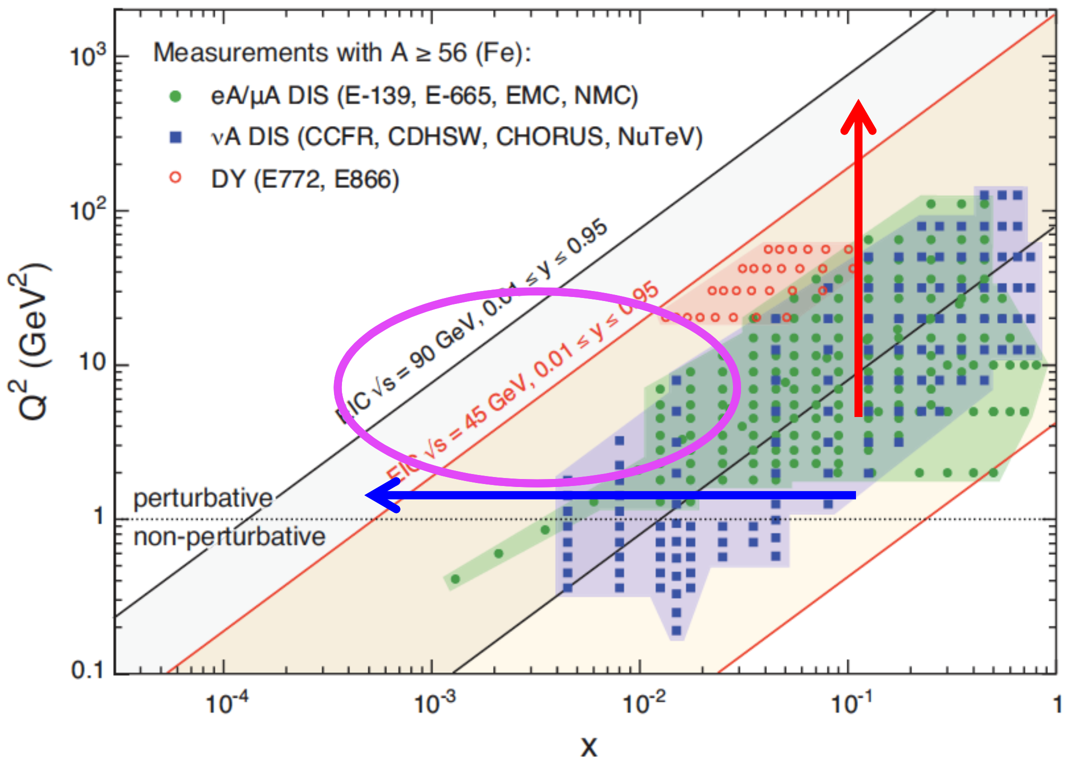
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

US EIC: Kinematic reach & properties



For e-N collisions at the EIC:

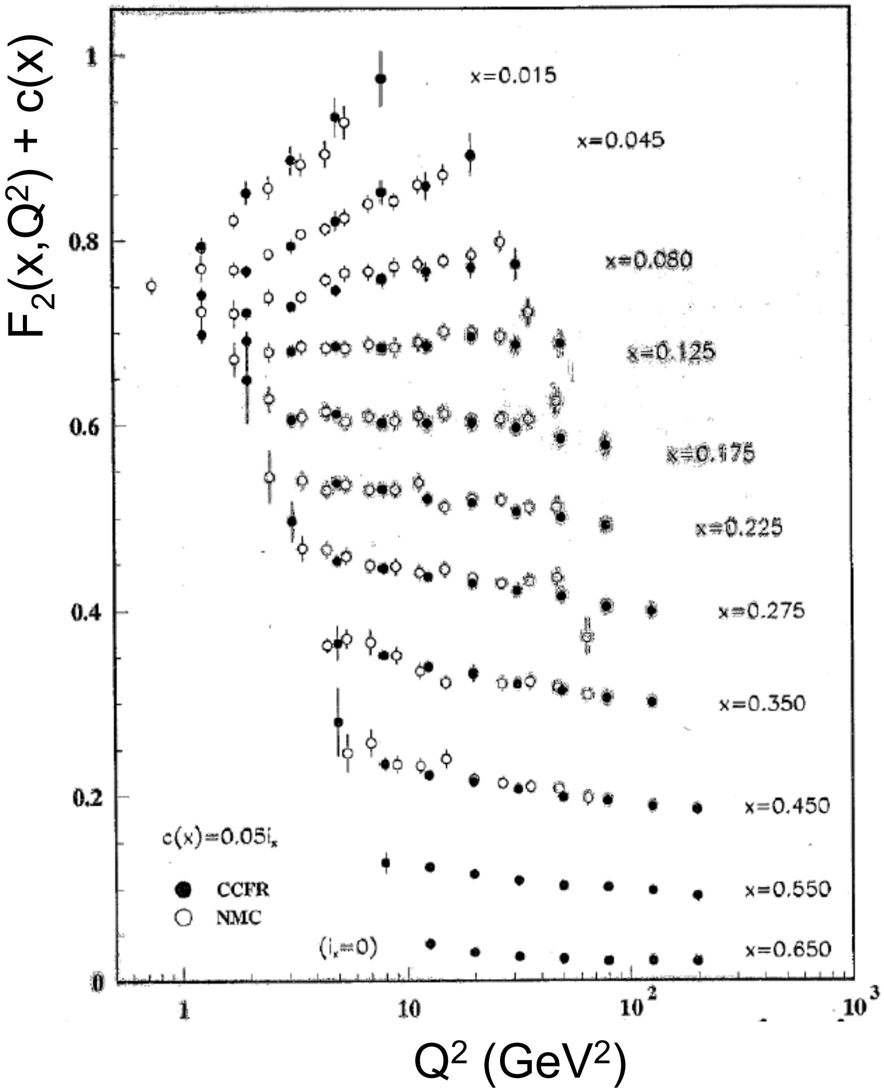
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics



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)

Structure Function by Different DIS Probes



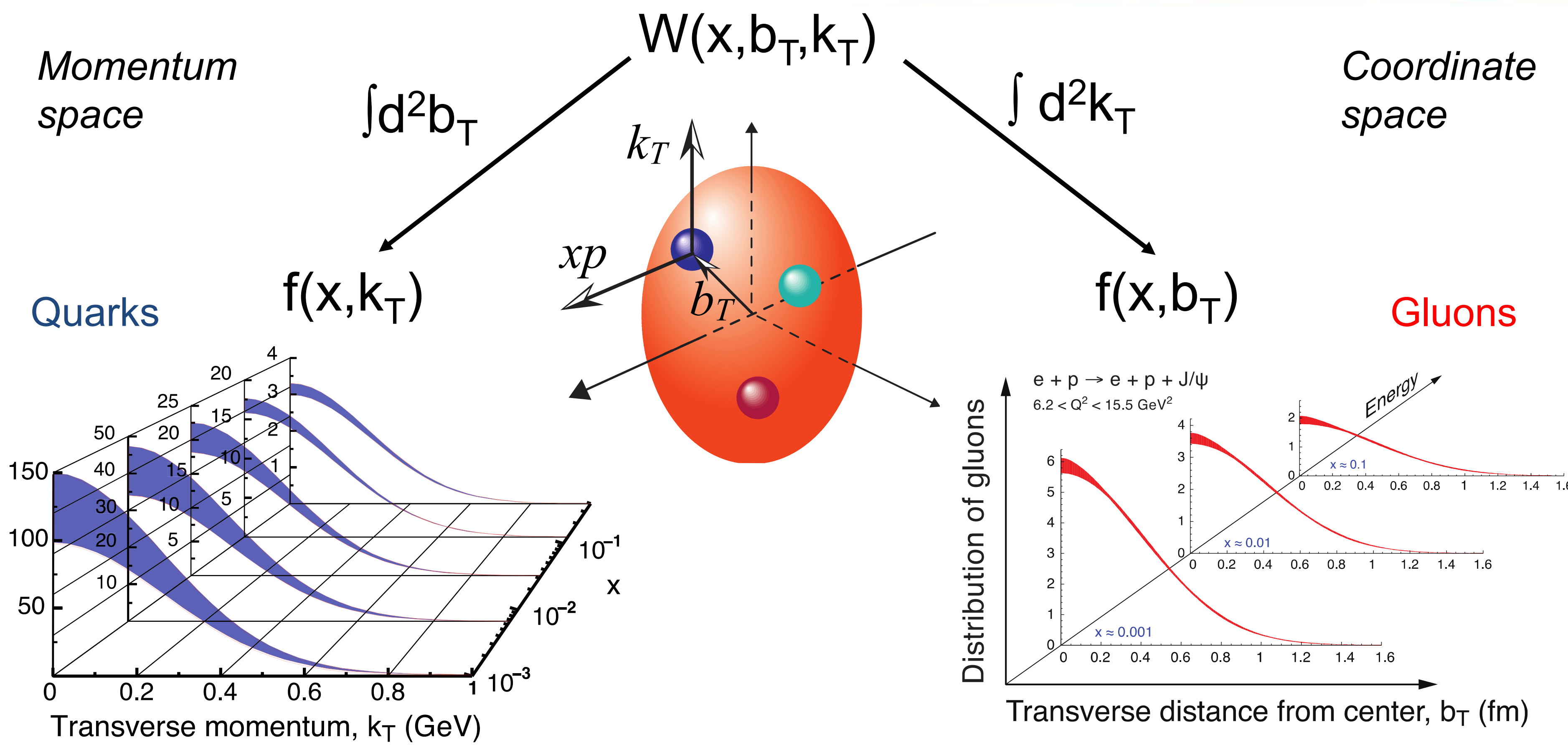
○ $F_2^{\mu D}$ μ DIS

● $F_2^{\overset{(-)}{\nu} N} \times \frac{5}{18}$ ν DIS

The Classic Example

- Extending the scaling found by the venerable SLAC (electron scattering) experiment.
- Confirming the basis of the Quark-Parton Model: the expected 5/18 charge weighting works well.
- Logarithmic Scaling Violations as anticipated from a renormalizable field theory (QCD) are clearly shown, with both muon and neutrino probes.

3D Imaging of Quarks and 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

3D Imaging of Quarks and Gluons

$W(x,b_T,k_T)$

Momentum space

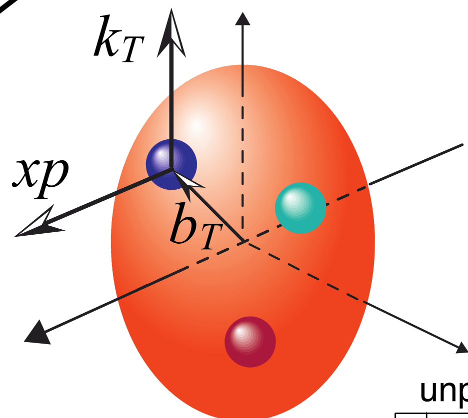
$\int d^2b_T$

$\int d^2k_T$

Coordinate space

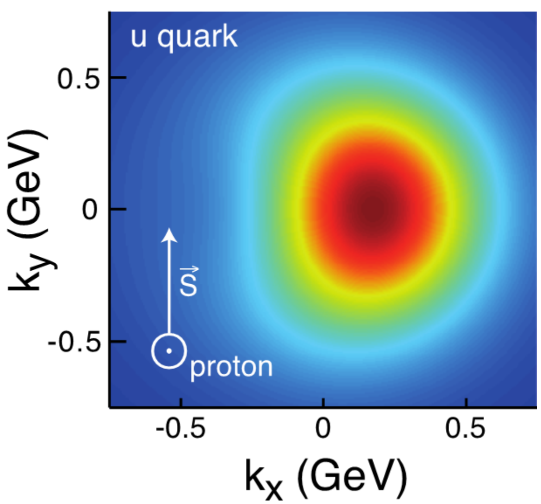
Quarks

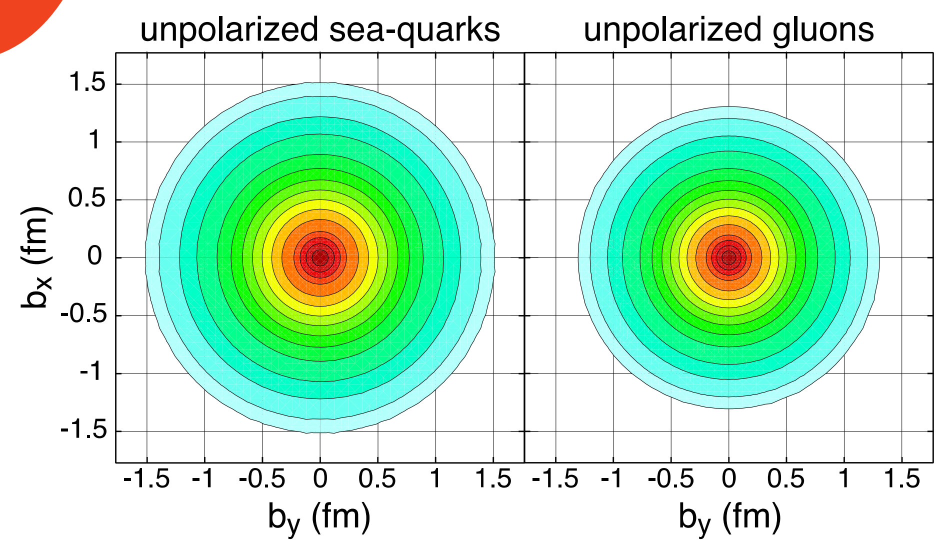
$f(x,k_T)$



$f(x,b_T)$

Gluons





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

Access to the Gluon TMDs

Access to gluon TMDs may be possible by:

- Di-jet/di-hadron production
- Heavy quark production
- Quarkonium production

Example:

$$\gamma^* N^\uparrow \to D(k_1) + \bar{D}(k_2) + X$$

where both D and $\bar{D}$ are in the current fragmentation region, with momentum k_1 and k_2, respectively, and N is a transversely polarized nucleon. Gluon Sivers will introduce an azimuthal asymmetry correlating

$k'_\perp = k_{1\perp} + k_{2\perp}$ of the $D\bar{D}$ pair

with the transvers polarization S

Integrated luminosity of 100 fb^{-1}

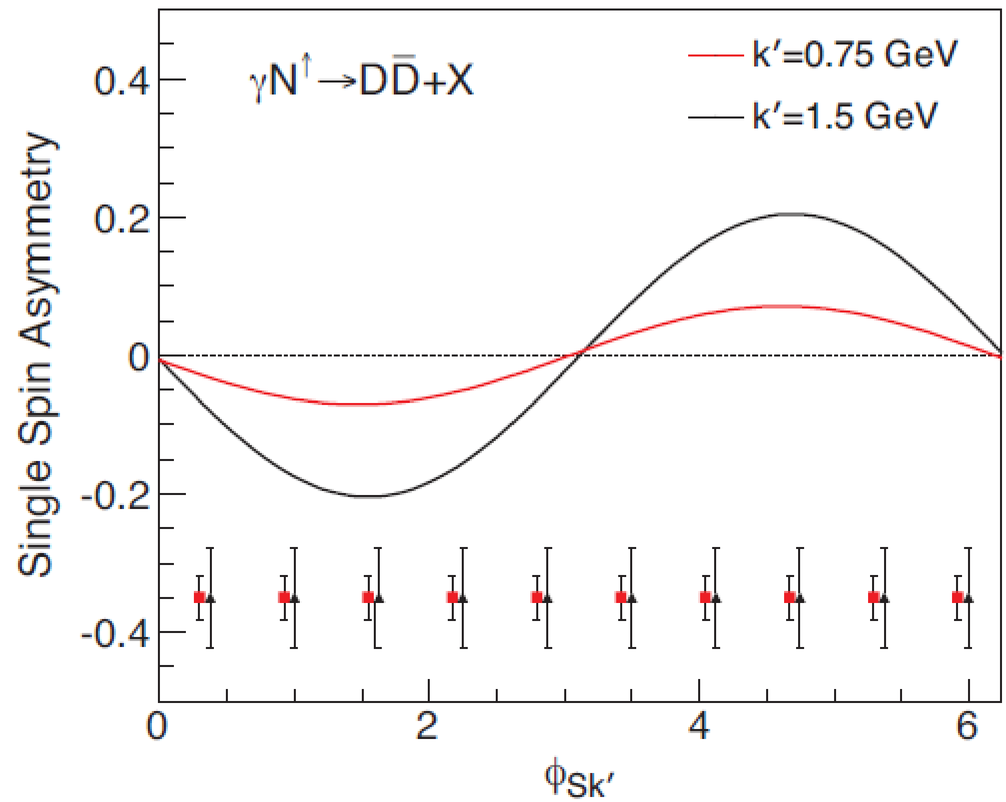
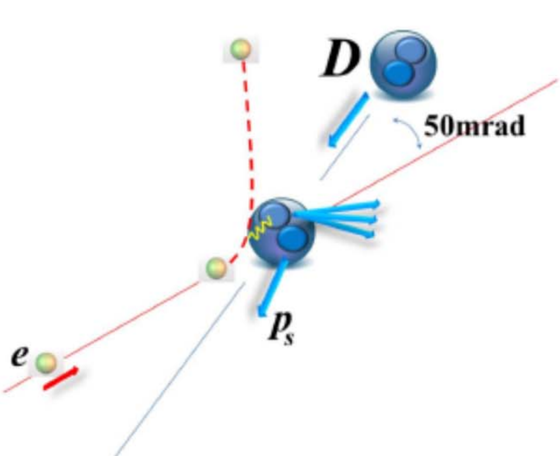
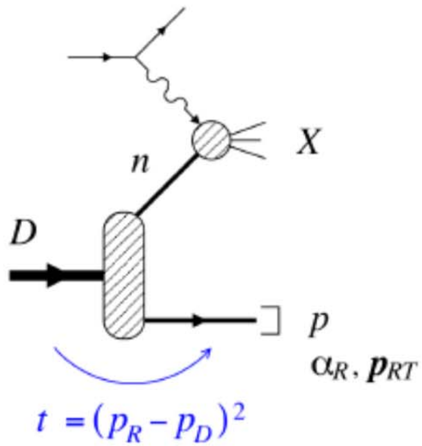
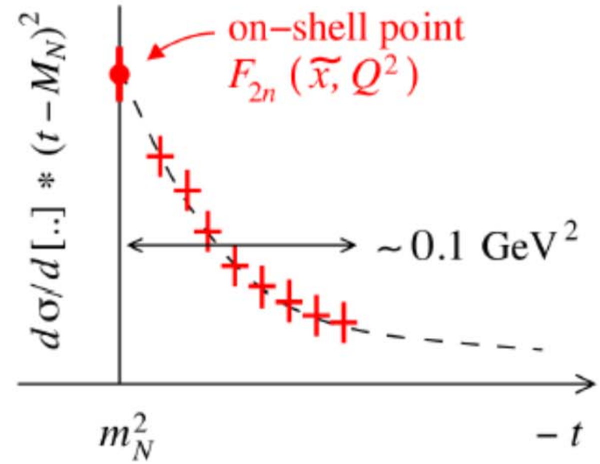


Figure 2.17: The single transverse spin asymmetry for $\gamma^* N^\uparrow \to D^0 \bar{D}^0 + X$, where ϕ is the azimuthal angle between the total transverse momentum $k'_\perp$ of the D-$\bar{D}$ pair and the transverse polarization vector $S_\perp$ of the nucleon. The asymmetries and the experimental projections are calculated for two different $k'_\perp = 0.75, 1.5\text{GeV}$ as examples. The kinematics are specified by $\langle W\rangle = 60\,\text{GeV}$, $\langle Q^2\rangle = 4\,\text{GeV}^2$.

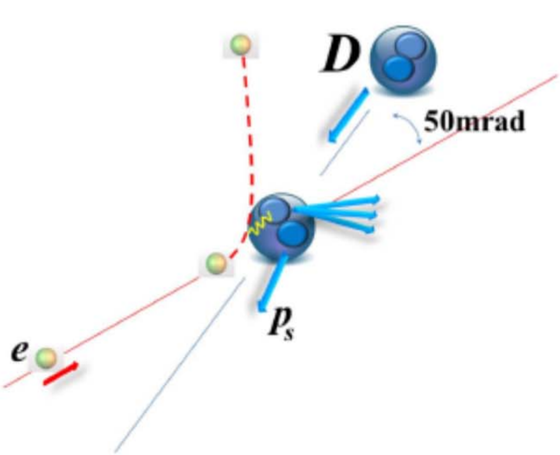
(Tagged) Neutron Structure Extrapolation in t

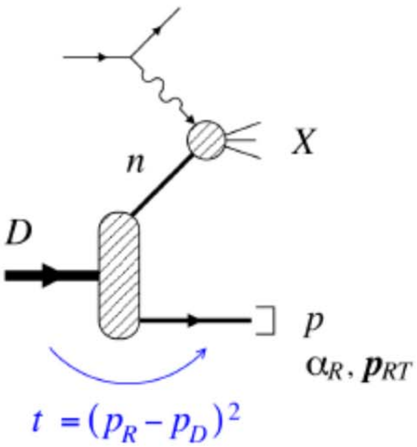


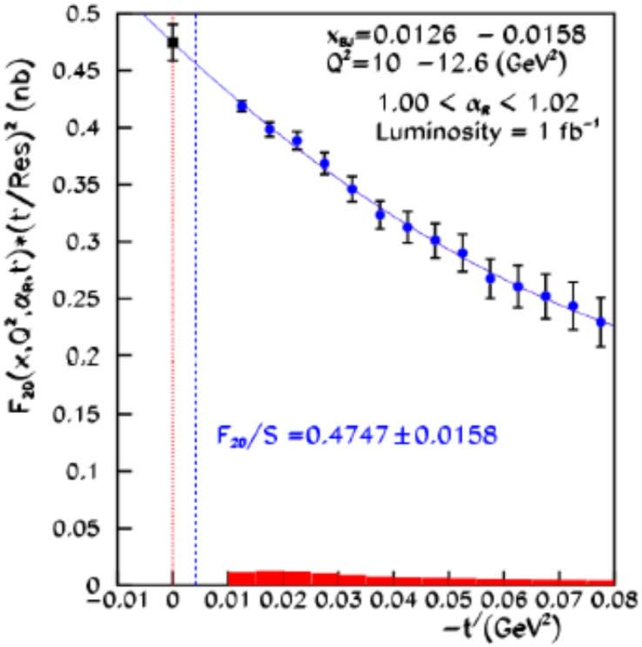




(Tagged) Neutron Structure Extrapolation in t



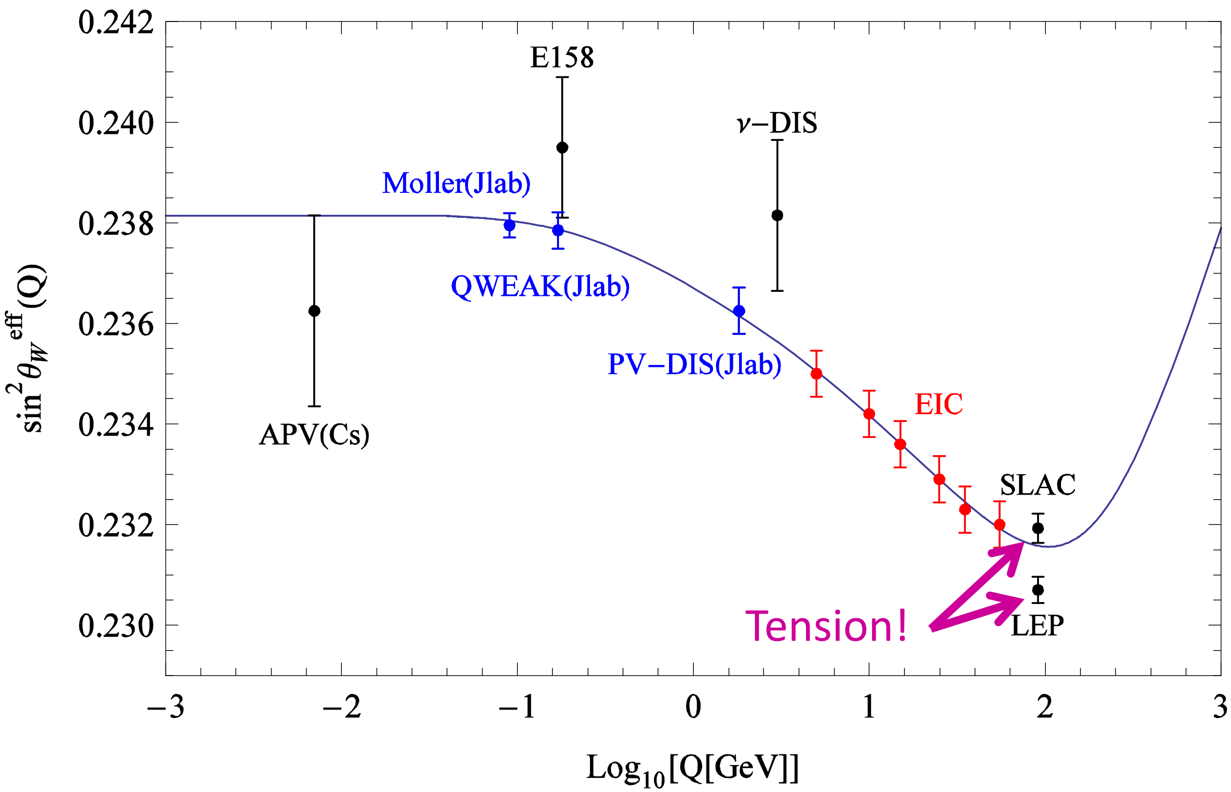




- t resolution better than 20 MeV, < fermi momentum
- Resolution limited/given by ion momentum spread
- Allow precision extraction of F_2^n neutron structure function

Completed, planned, and possible EW measurements

Scale dependence of $\sin^2\Theta_W$
"Hunting for the unseen forces of the universe"

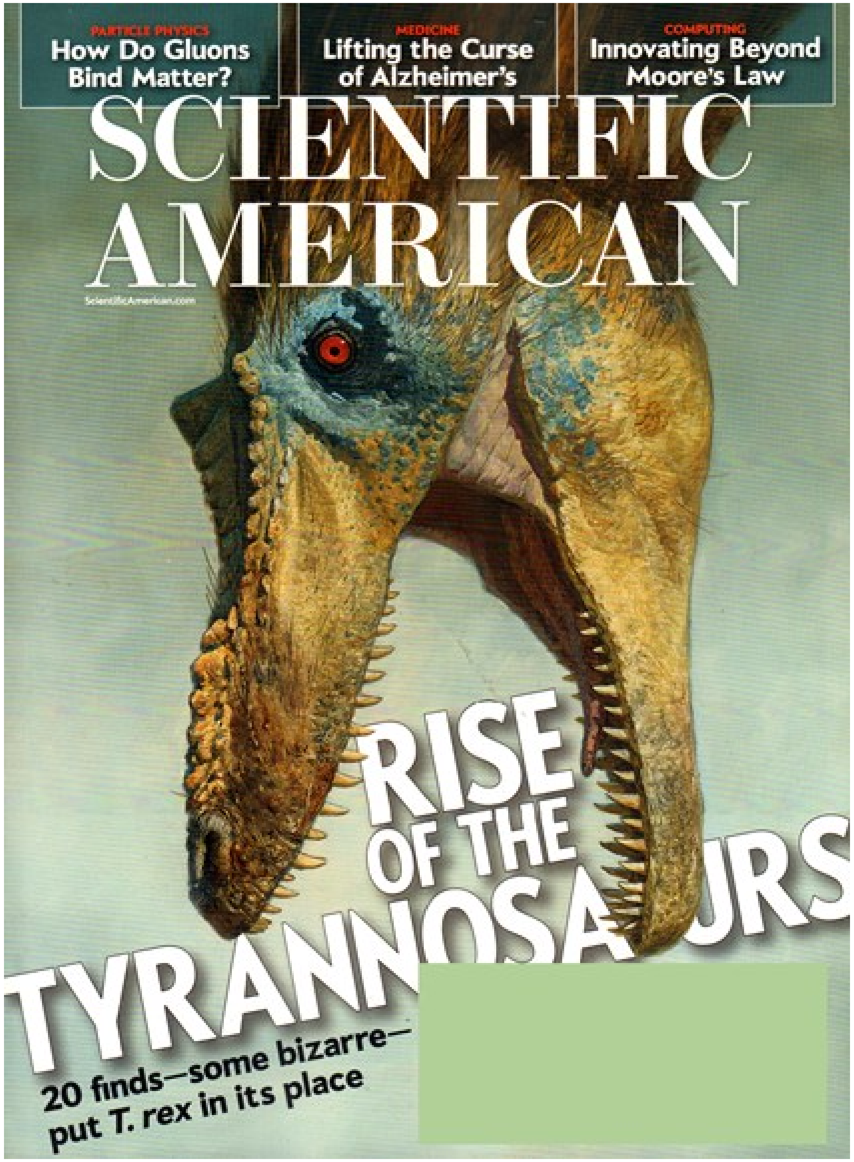


Deviation from the "curve" may be hints of BSM scenarios including: Lepto-Quarks, RPV SUSY extensions, E_6/Z' based extensions of the SM

Note: recent Tevatron point not included

→ EIC allows to probe the electro-weak mixing angle over a tremendous range of Q

Gluons and the EIC – US Coverage



Scientific American
May 2015

PARTICLE PHYSICS

the glue that binds us

Physicists have known for decades that particles called gluons keep protons and neutrons intact—and thereby hold the universe together. Yet the details of how gluons function remain surprisingly mysterious

By Rolf Ent, Thomas Ullrich and Raju Venugopalan

42 Scientific American, May 2015

Gluons and the EIC – US Coverage

Scientific American
May 2015

PARTICLE PHYSICS

the glue that binds us

Physicists have known for decades that particles called gluons keep protons and neutrons intact—and thereby hold the universe together. Yet the details of how gluons function remain surprisingly mysterious

By Rolf Ent, Thomas Ullrich and Raju Venugopalan

Rolf Ent has worked at the Thomas Jefferson National Accelerator Facility in Newport News, Va., since 1993. He is associate director of experimental nuclear physics there and has been a spokesperson for multiple experiments studying the quark-gluon structure of hadrons and atomic nuclei.

Thomas Ullrich joined Brookhaven National Laboratory in 2001 and also conducts research and teaches at Yale University. He has participated in several experiments, first at CERN near Geneva and later at Brookhaven, to search for and study the quark-gluon plasma. His recent efforts focus on the realization of an electron-ion collider.

Raju Venugopalan heads the Nuclear Theory Group at Brookhaven National Laboratory, where he studies the interactions of quarks and gluons at high energies.

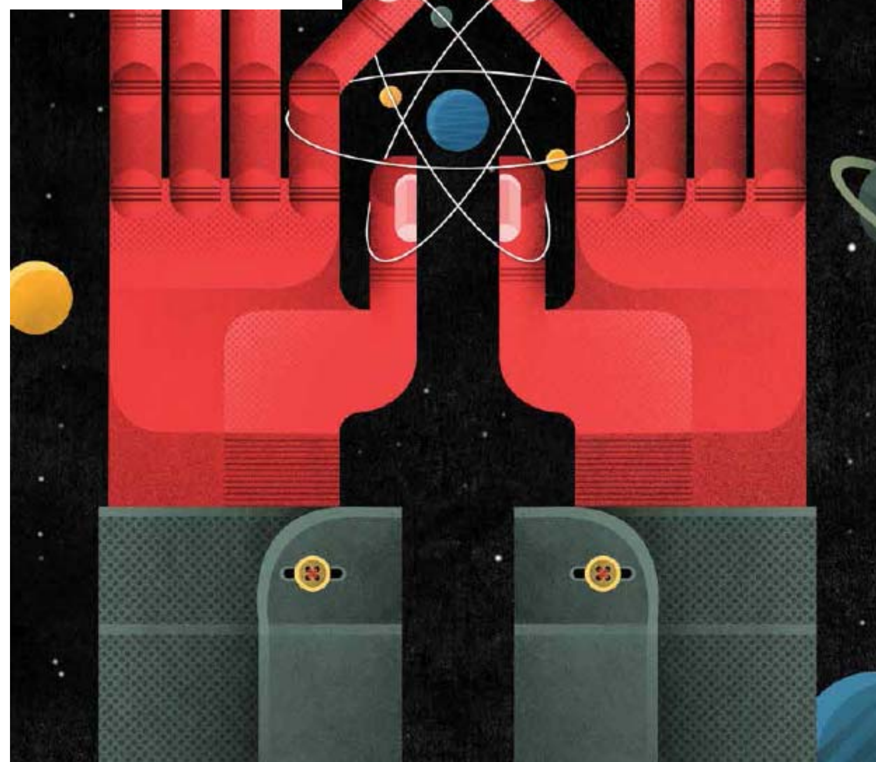


Illustration by Maria Corte

Gluons and the EIC – Brasil Coverage

Scientific American Brasil
June 2015

FÍSICA DE PARTÍCULAS – p.48

A cola que nos une

Os físicos sabem que glúons mantêm a integridade de prótons, nêutrons e do Universo. Mas ainda é um mistério como essas partículas funcionam.

Rolf Ent, Thomas Ullrich e Raju Venugopalan

FISICA
Novas pesquisas sobre as particulas que mantem o Universo unido

New inquiries on the particles that hold the universe together

Gluons and the EIC – Italy Coverage

Le Scienze
July 2015

The secrets of the particles that hold matter together

Gluons and the EIC – France Coverage

Pour La Science - September 2015

ÉDITO

POUR LA SCIENCE

www.pourlascience.fr

8 rue Férou - 75278 Paris Cedex 06

Groupe POUR LA SCIENCE
Directrice des rédactions : Cécile Lestienne

Pour la Science
Rédacteur en chef : Maurice Mashaal
Rédactrice en chef adjointe : Marie-Neige Cordonnier
Rédacteurs : François Savatier, Philippe Ribeau-Gésippe, Guillaume Jacquemont, Sean Bailly
Dossier Pour la Science
Rédacteur en chef adjoint : Loïc Mangin
Développement numérique : Philippe Ribeau-Gésippe, assisté de Dylan Beiner (stagiaire)
Directrice artistique : Céline Lapert
Maquette : Pauline Bilbault, Ingrid Leroy, Nathalie Ravier (stagiaire)
Correction et assistance administrative : Maud Bruguière
Marketing : Élise Abib et Ophélie Maillet, assistées de Héloïse Clément (stagiaire)
Direction financière et direction du personnel : Marc Laumet
Fabrication : Marianne Sigogne et Olivier Lacam
Presse et communication : Susan Mackie
Directrice de la publication et Gérante : Sylvie Marcé
Anciens directeurs de la rédaction : Françoise Pétry et Philippe Boulanger
Conseiller scientifique : Hervé This
Ont également participé à ce numéro :
François Arleo, Yves Dessaux, Denis Faure, Eitan Haddok, Christophe Pichon, Jean-Claude Rage, Stéphen Rostain, Francesca Sargolini

PUBLICITÉ France
Directeur de la publicité : Jean-François Guillotin (jf.guillotin@pourlascience.fr)
Tél. : 01 55 42 84 28 • Fax : 01 43 25 18 29
SERVICE ABONNEMENTS
Ginette Bouffaré et Nada Mellouk-Raja. Tél. : 01 55 42 84 04
Abonnement en ligne : http://www.pourlascience.fr
Courriel : abonnements@pourlascience.fr
Service des abonnements - 8 rue Férou - 75278 Paris Cedex 06
Commande de livres ou de magazines :
Pour la Science - 628 avenue du Grain d'Or 41350 Vineuil
DIFFUSION DE POUR LA SCIENCE
Contact kiosques : À Juste Titres ; Benjamin Boutonnet
Tel : 04 88 15 12 41
Information/modification de service/réassort :
Magazine disponible sur www.direct-editeurs.fr
Canada : Edipresse : 945 avenue Beaumont, Montréal, Québec, H3N 1W3 Canada.
Suisse : Servidis : Chemin des châlets, 1979 Chavannes - 2 - Bogis
Belgique : La Caravelle : 303 rue du Pré-aux-Oies - 1130 Bruxelles.
Autres pays : Éditions Belin : 8 rue Férou - 75278 Paris Cedex 06.

SCIENTIFIC AMERICAN Editor in chief : Mariette DiChristina. Executive editor : Fred Guterl. Design director : Michael Mrak. Editors : Ricky Rusting, Philip Yam, Robin Lloyd, Mark Fischetti, Seth Fletcher, Christine Gorman, Michael Moyer, Gary Stix, Kate Wong.
President : Keith McAllister. Executive Vice President : Michael Florek.

Maurice Mashaal
rédacteur en chef

Un monde coloré et cependant obscur

Depuis les années 1970, on sait que le proton et le neutron, les constituants du noyau de l'atome, ne sont pas des particules élémentaires, mais des assemblages de trois « quarks » solidement collés par des « gluons ». Ces derniers véhiculent l'interaction forte, l'une des quatre forces fondamentales de la nature, qui assure la cohésion du proton et du neutron, mais aussi du noyau atomique.

Plus largement, l'univers des quarks et des gluons fait l'objet d'une théorie cohérente et mathématisée, la chromodynamique quantique – QCD pour les intimes –, qui est l'une des colonnes maîtresses du modèle standard de la physique des particules. Pourquoi « chromo » ? Tout simplement parce que les physiciens ont dénommé « couleur » une propriété mathématique clef attachée aux quarks et aux gluons.

Des énigmes liées à des difficultés techniques ou à des failles dans la théorie ?

La chromodynamique quantique décrit ainsi un monde « coloré ». La conception de cette théorie a été un tour de force. L'analyse et la résolution de ses équations en est un autre, qui reste inachevé. De fait, certains pans de la physique de l'interaction forte sont encore mal compris. Par exemple, on ne sait pas retrouver toutes les propriétés du proton et du neutron à partir de celles de leurs constituants ; on ignore si certains états exotiques constitués uniquement de gluons existent ; ou encore, on ne sait pas bien expliquer pourquoi les particules observables sont nécessairement incolores. Pour autant, le domaine a connu plusieurs avancées récentes *(voir pages 26 à 37)*.

Les énigmes actuelles de la QCD résultent-elles seulement d'obstacles mathématiques ? C'est probable. Mais l'histoire des sciences a montré que le diable se cache parfois dans les détails : peut-être la résolution des problèmes résiduels nécessitera-t-elle de nouvelles idées, dont émergera une théorie encore meilleure. ■

© Pour la Science - n° 455 - Septembre 2015

Édito 3

Gluons and the EIC – Germany Coverage

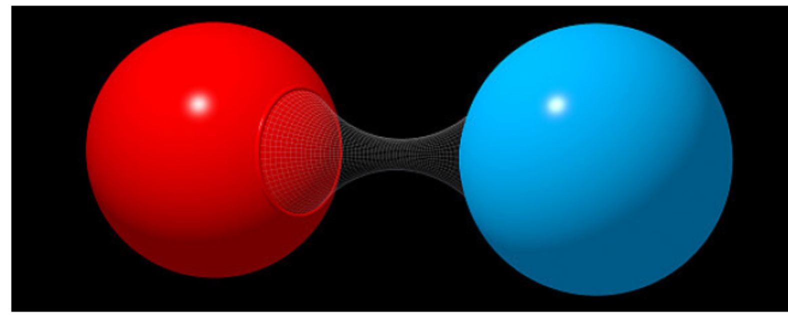
Spektrum der Wissenschaft - December 2015

TEILCHENPHYSIK

Der Klebstoff der Welt

Gluonen halten Atomkerne zusammen und erzeugen einige der fundamentalen Eigenschaften der Materie. Dabei ist vieles an diesen Teilchen rätselhaft, denn sie sind in Experimenten kaum fassbar.

Rolf Ent, Thomas Ullrich, Raju Venugopalan



© shutterstock / concept w

Anfang des 20. Jahrhunderts zeigten Physiker, dass Atome ihren Namen zu Unrecht tragen. Die nach dem griechischen Wort für "unteilbar" bezeichneten Objekte ließen sich in noch kleinere Materiebausteine spalten: Elektronen sowie Protonen und Neutronen. Später stellte sich heraus, dass die beiden Letzteren ihrerseits aus weiteren Teilchen bestehen, den Quarks. So genannte Gluonen – angelehnt an den englischen Begriff für Klebstoff – binden diese Quarks aneinander. Beide Teilchenarten sind nach heutigem Wissen nicht weiter spaltbar.

Laut Experimenten, die einen Blick in das Innere von Protonen und Neutronen

AUF EINEN BLICK

SUBATOMARE SPUKGESTALTEN

1 Die Atomkerne bestehen aus Quarks, die mittels Gluonen aneinanderhaften.

2 Die Wechselwirkung beider Teilchenarten unterliegt noch nicht vollständig verstandenen, komplizierten Regeln. Unklar ist insbesondere, wie Quarks und Gluonen die Masse und den Spin von Protonen und Neutronen erzeugen.

Nuclear Science Long-Range Planning

Adapted from Don Geesaman (ANL, NSAC Chair) presentation
See: http://science.energy.gov/np/nsac/meetings/agenda20141117/

LRP Schedule

- ✓ Charge delivered at 24 April 2014 NSAC Meeting
- ✓ LRP Working Group formed in early June of ~60 members
  - NuPECC (Europe) and ANPhA (Asia) observers included
- ✓ Community organization Summer 2014
- ✓ DNP Town Meetings in the July/September 2014 time frame
- ✓ Joint APS-DNP-JPS Meeting Oct. 7-11, 2014, Wednesday afternoon discussion
- ✓ Working Group organizational meeting Nov. 16 in Rockville, MD
- ✓ Time for more community meetings in November-January
- ✓ (Community) White Papers by end of January, 2015 to have greatest impact
- ✓ Cost review of EIC by February 2015
- ✓ Most of text of report assembled by April 10, 2015
- ✓ Resolution meeting of Long Range Plan working group April 16-20, 2015
- ✓ Draft report reviewed by external wise women and men
- ✓ LRP final report finalized October 2015
  (Unanimously accepted at NSAC meeting October 15)