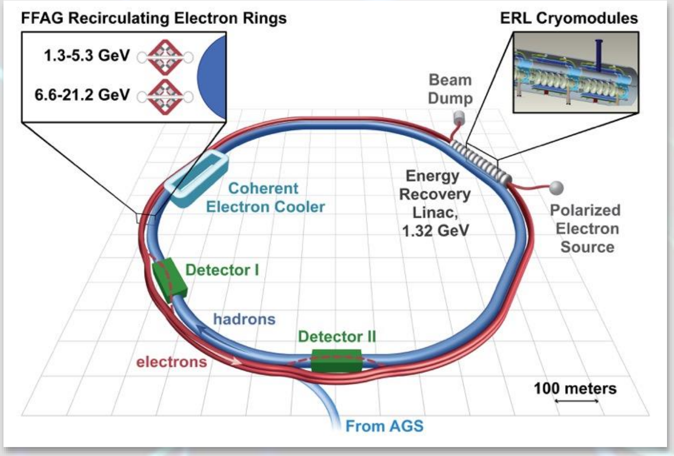
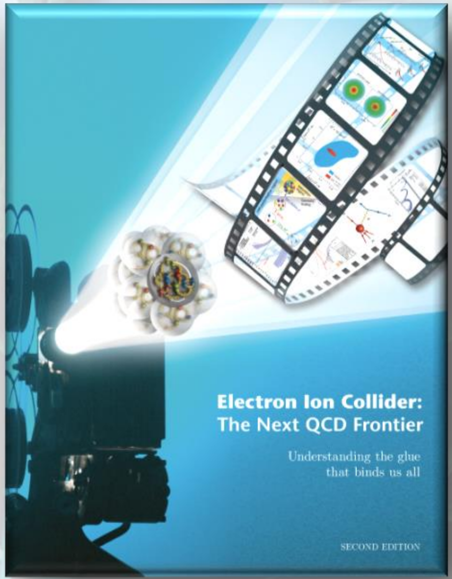
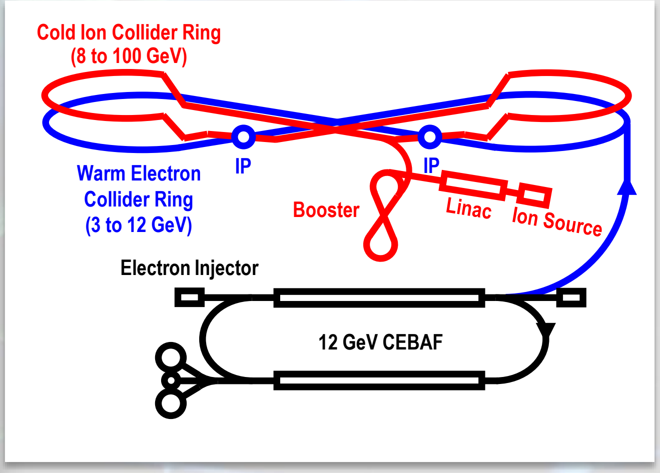
The US-based Electron-Ion Collider: Imaging the Gluons and Quark Sea of Nucleons and Nuclei







Rolf Ent
Jefferson Lab

The US-based Electron-Ion Collider

- EIC: Introduction
- The requirements and conceptualizations of the EIC
- The Science of the EIC White Paper
  Imaging the Gluons and Quark Sea of Nucleons and Nuclei
- The NSAC Long-Range Planning process in the US – status
  (NSAC = Nuclear Science Advisory Committee)
- Next steps

The Structure of the Proton

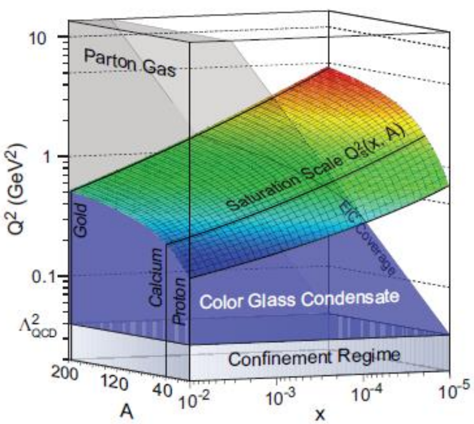
Naïve Quark Model: proton = uud (valence quarks)

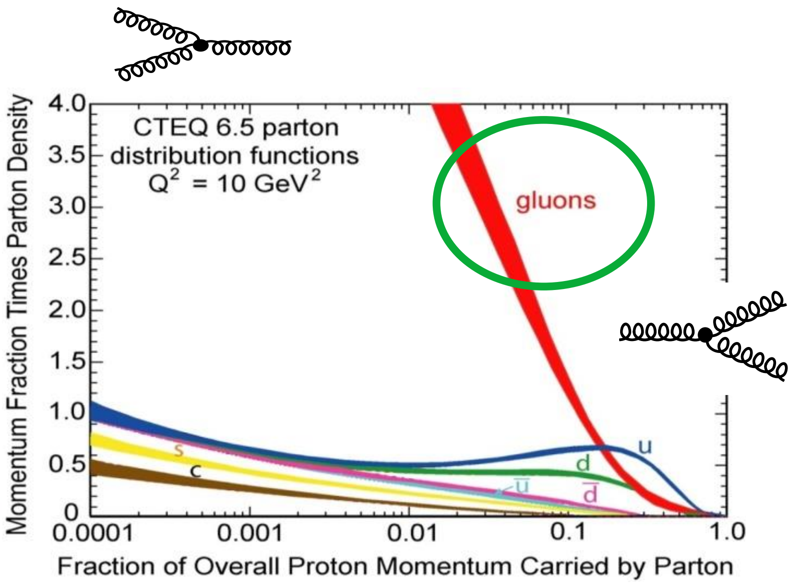
QCD: proton = uud + $u\bar{u}$ + $d\bar{d}$ + $s\bar{s}$ + …

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

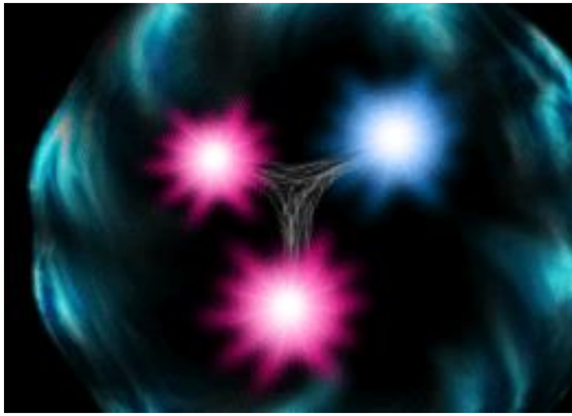
& gluons are abundant

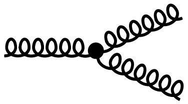
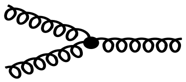
gluon dynamics





Non-trivial sea structure

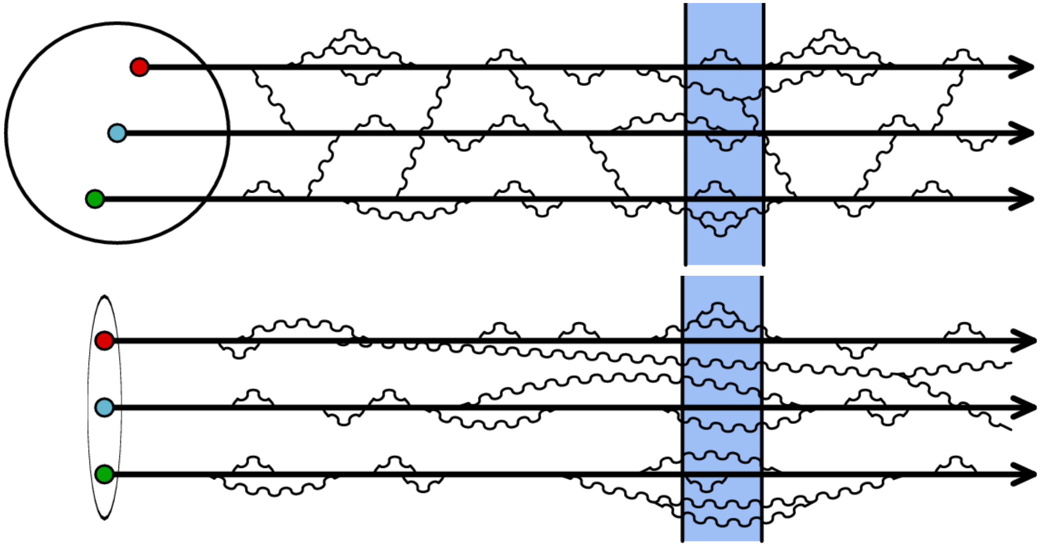


- The proton is **far more** than just its up + up + down (valence) quark structure
- Gluon ≠ photon: Radiates  and recombines: 

Proton at Low and High Energy

Low energy
High x
Regime of JLab

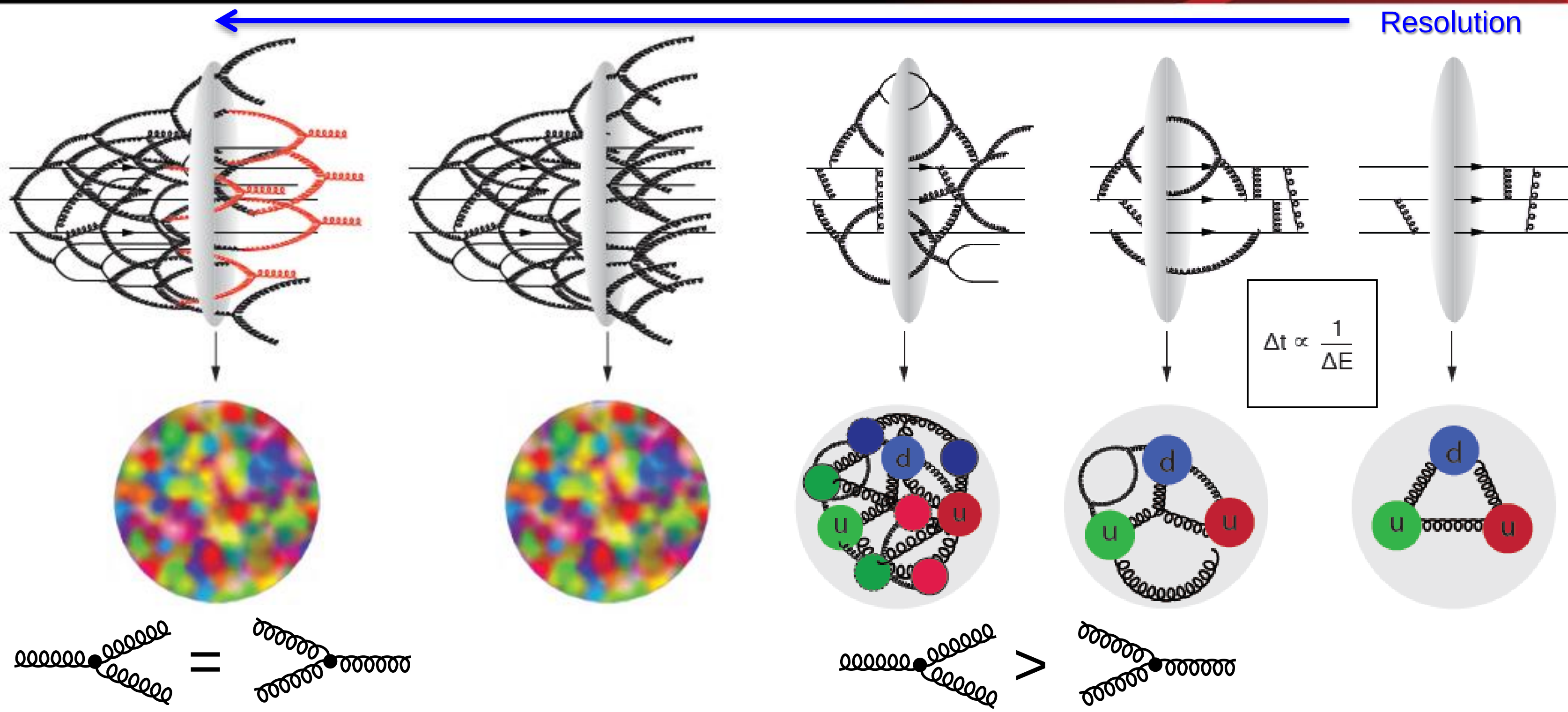
High energy
Low- x
Regime of a Collider

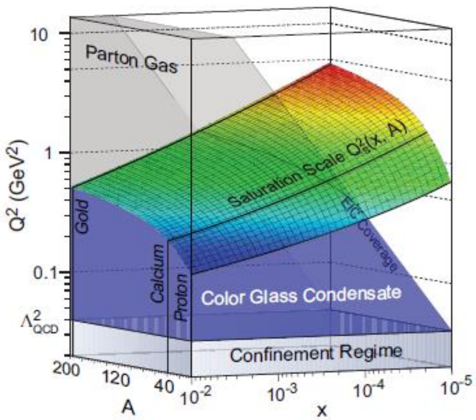


At high energy:

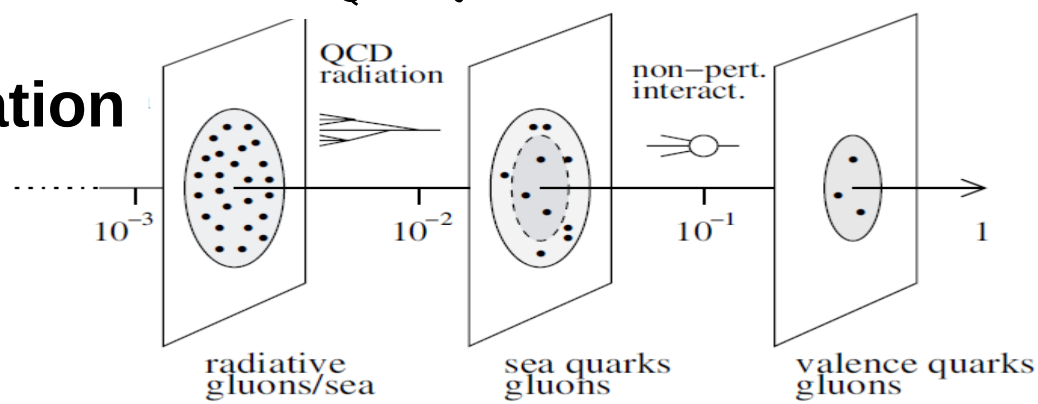
- Wee partons fluctuations time dilated in strong interaction time scales
- Long lived gluons can radiate further smaller x gluons ➔ **runaway growth?**

The Evolution of a Proton – Deep into the Sea

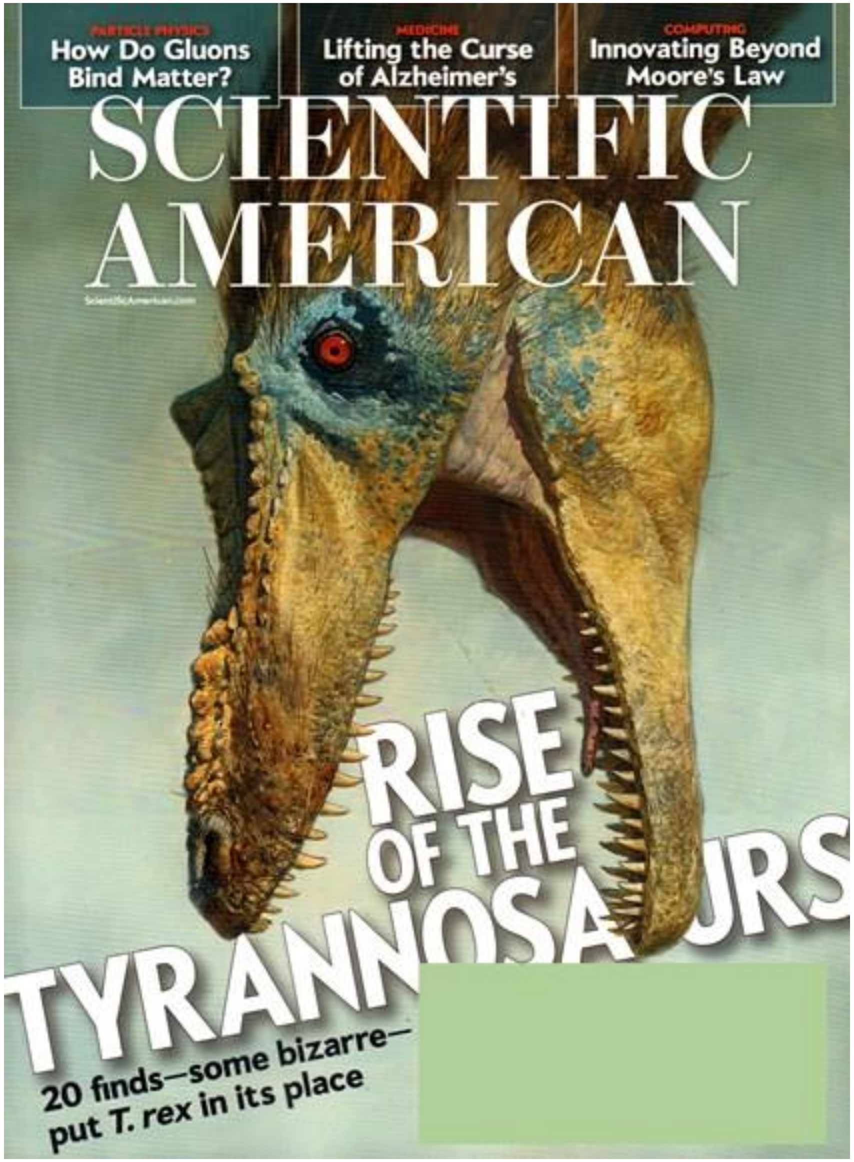




Saturation



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

Illustration by Maria Corte

Gluons and the EIC – France Coverage

Pour La Science - September 2015

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PUBLICITÉ France
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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.

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OJD PRESSE PAYANTE Diffusion Certifiée 2014

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

The Electron Ion Collider

For e-N collisions at the EIC:

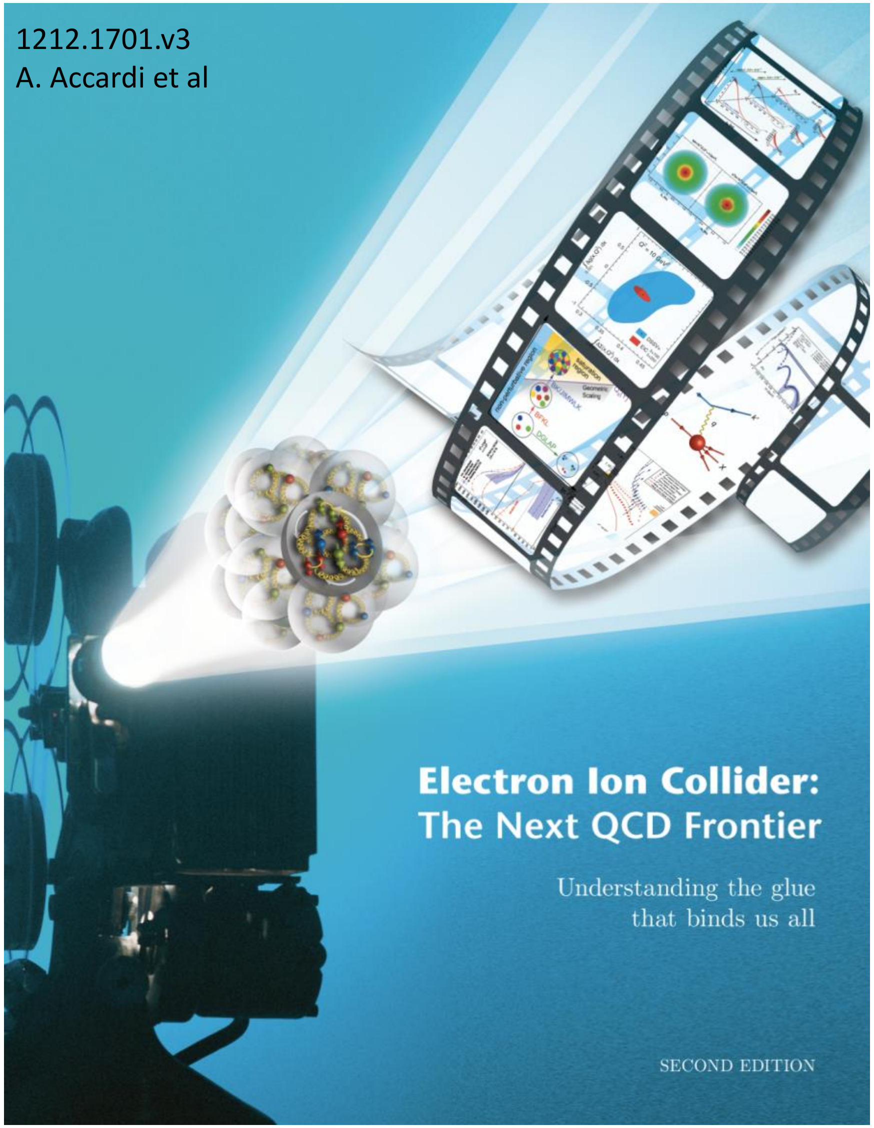
✓ Polarized beams: e, p, d/^{3}He
✓ e beam 3-10(20) GeV
✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
100-1000 times HERA
✓ 20-~100 (140) GeV Variable CoM

For e-A collisions at the EIC:

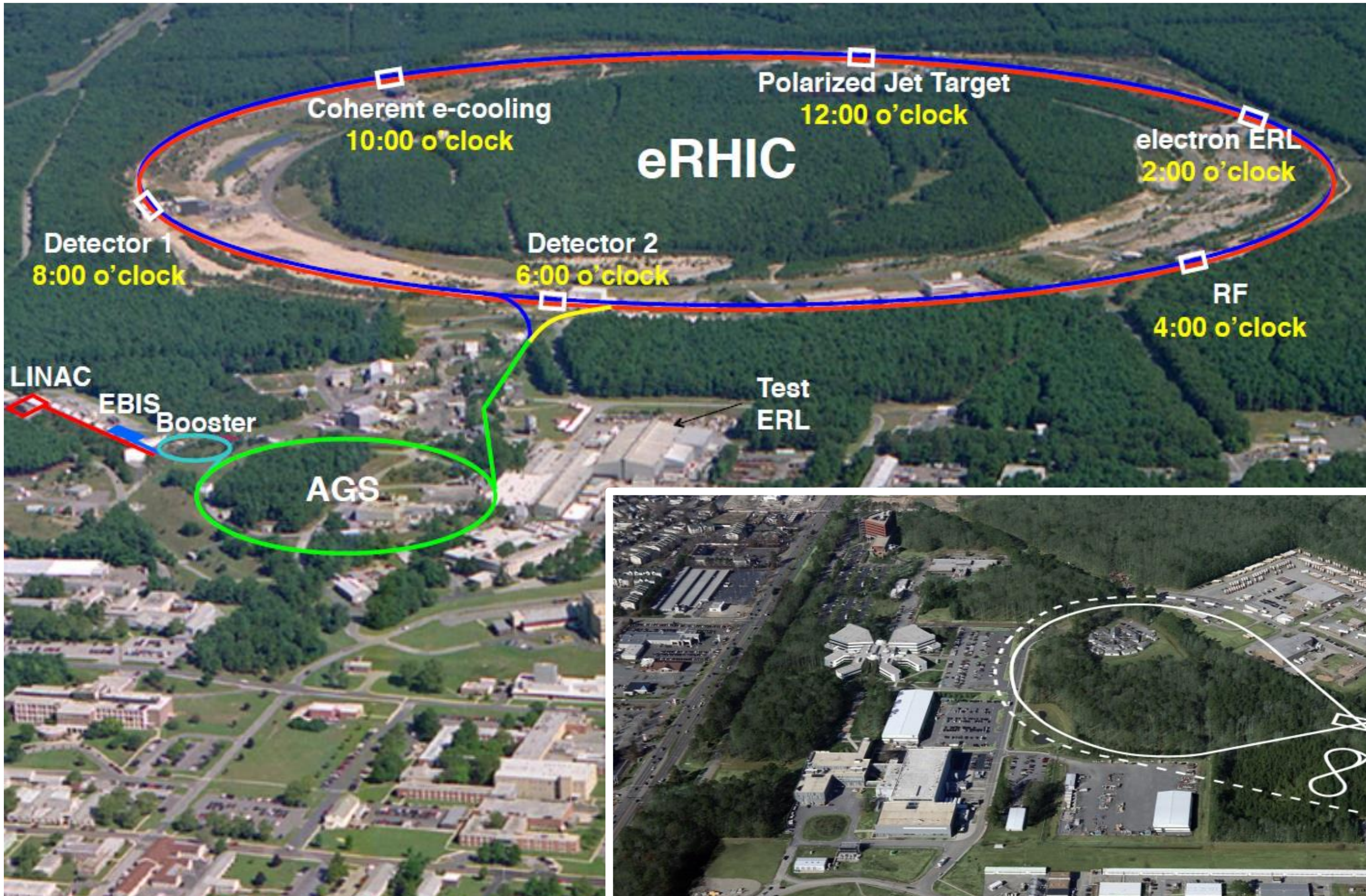
✓ **Wide range in nuclei**
✓ Luminosity per nucleon same as e-p
✓ Variable center of mass energy

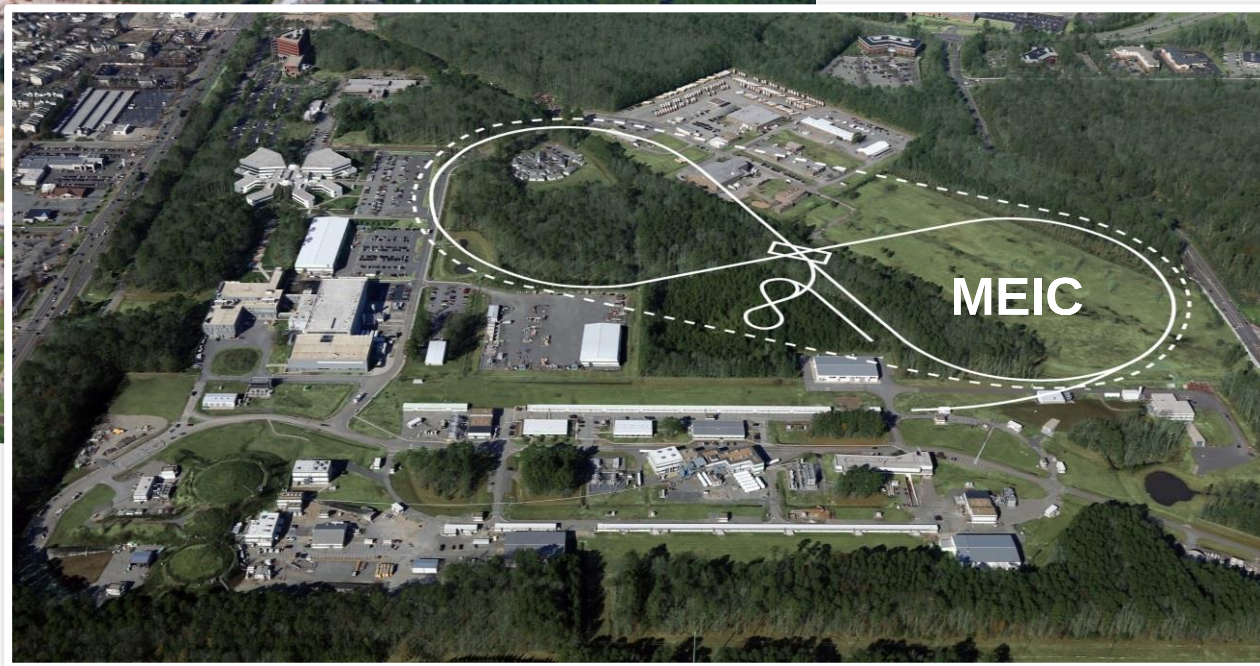
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

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



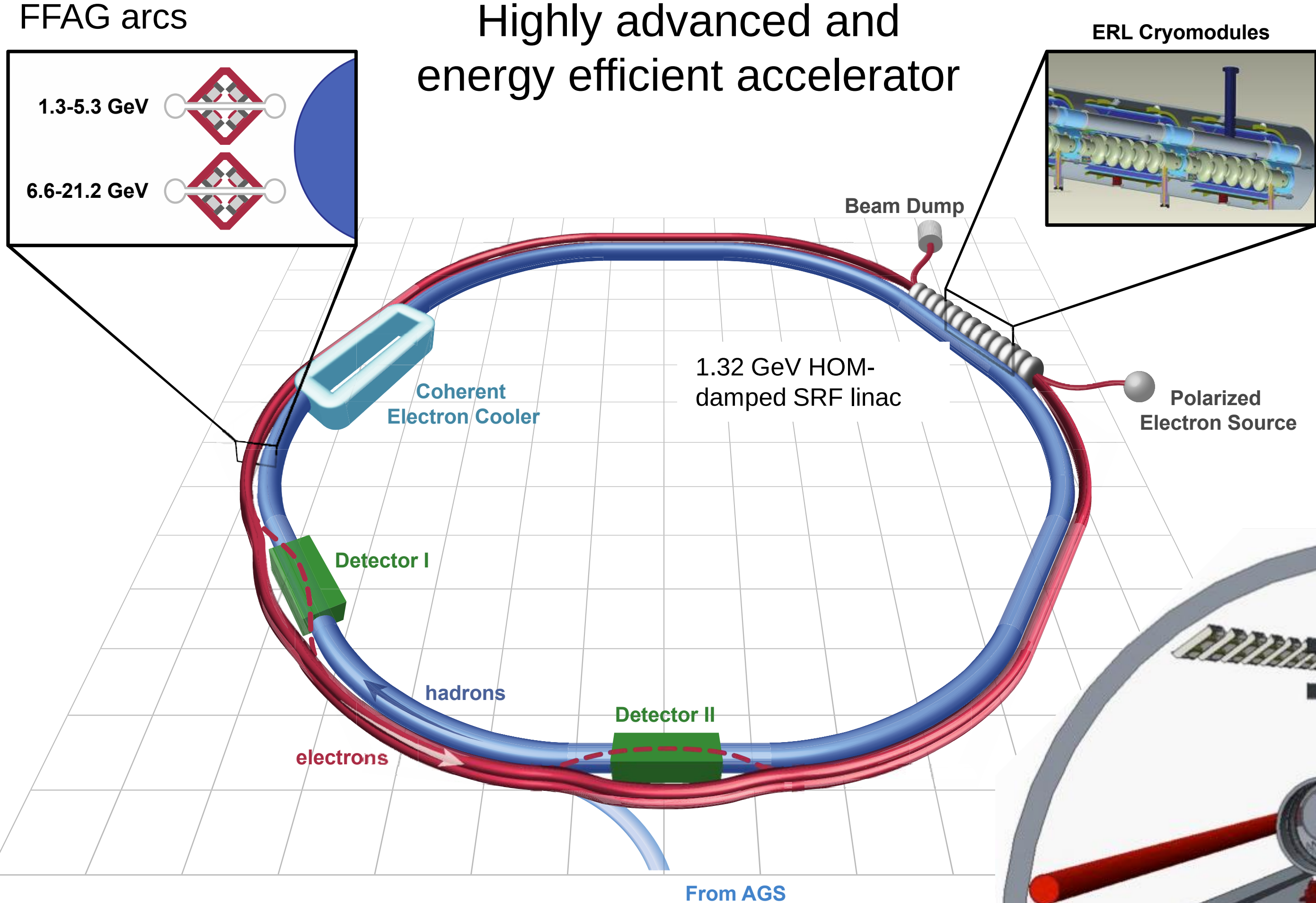
US-Based EICs

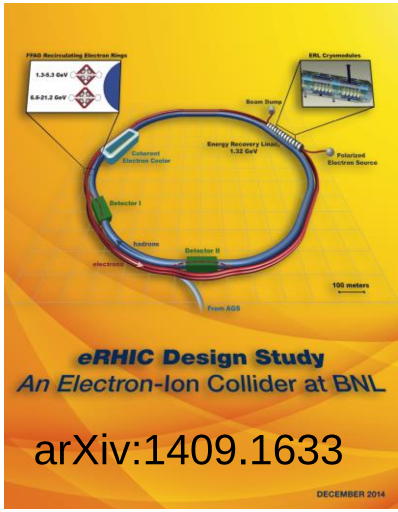


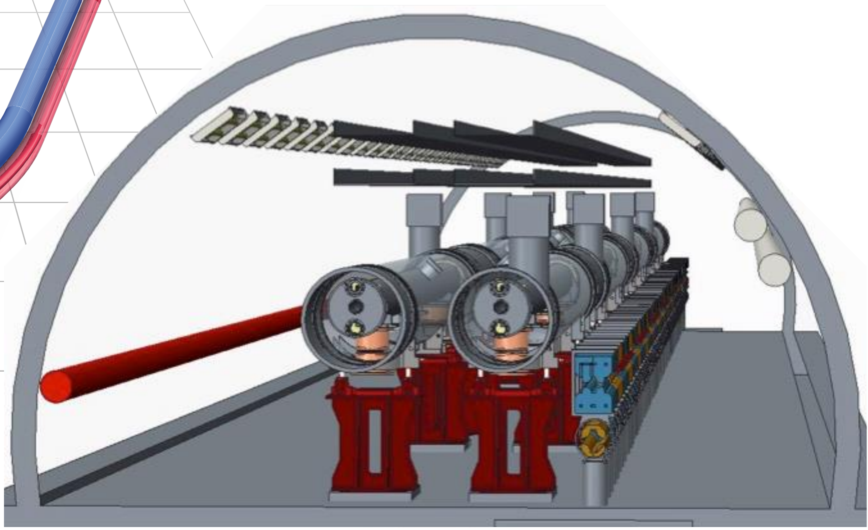


eRHIC Baseline Design

Highly advanced and energy efficient accelerator







- 4.1×10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 126 GeV (15.9 GeV e↑on 250 GeV p↑)

MEIC Baseline Design

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

Features:

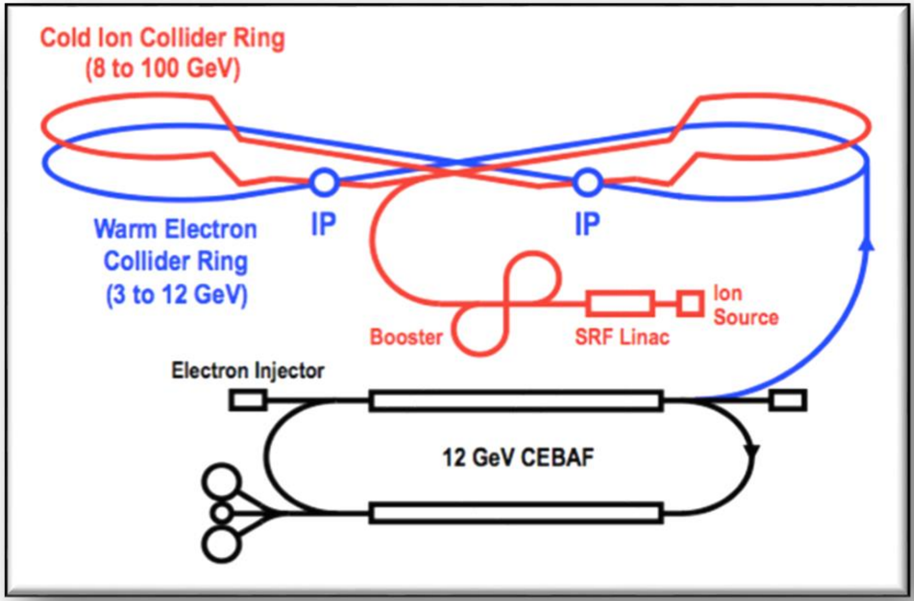
- Collider ring circumference: ~2100 m
- Electron collider ring and transfer lines : PEP-II magnets, RF (476 MHz) and vacuum chambers
- Ion collider ring: super-ferric magnets
- Booster ring: super-ferric magnets
- SRF ion linac

Goals:

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

Collaborators:

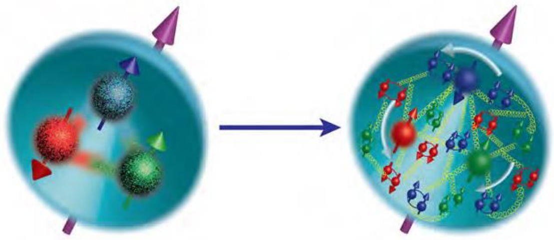
ANL, Fermilab, SLAC
Texas A&M



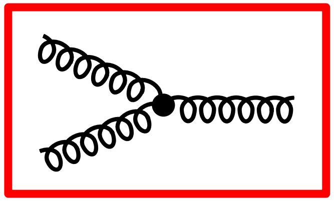
QCD Science Questions

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

Role of Orbital angular momentum?



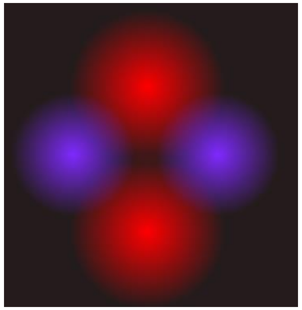
What happens to the gluon density in nuclei at high energy? Does it saturate, into a gluonic form of matter of universal properties?

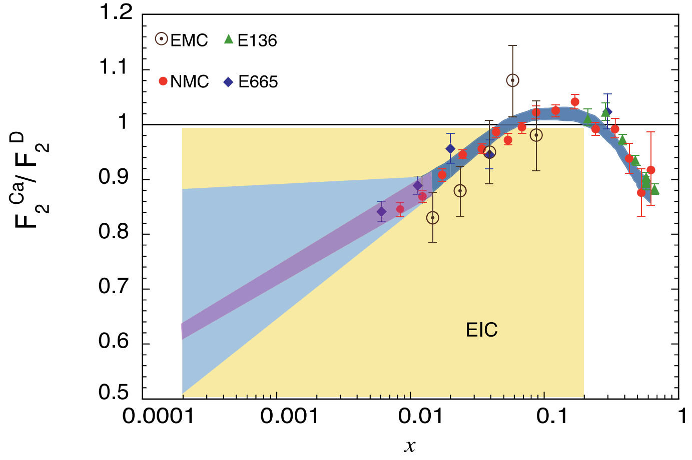


?

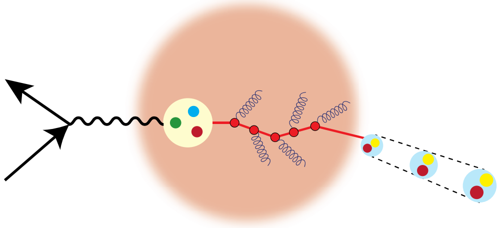
QCD Science Questions – cont.

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

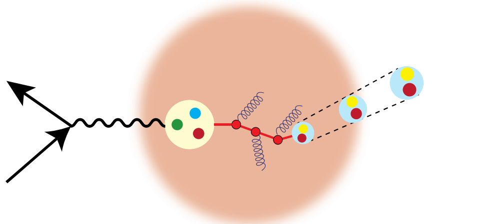




How does the nuclear environment affect the distributions of quarks and gluons and their interactions inside nuclei?

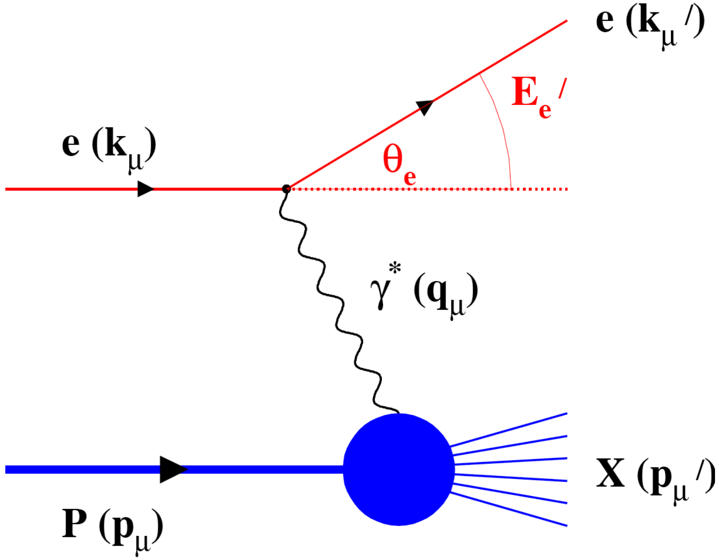


How does nuclear matter respond to a fast moving color charge passing through it?



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

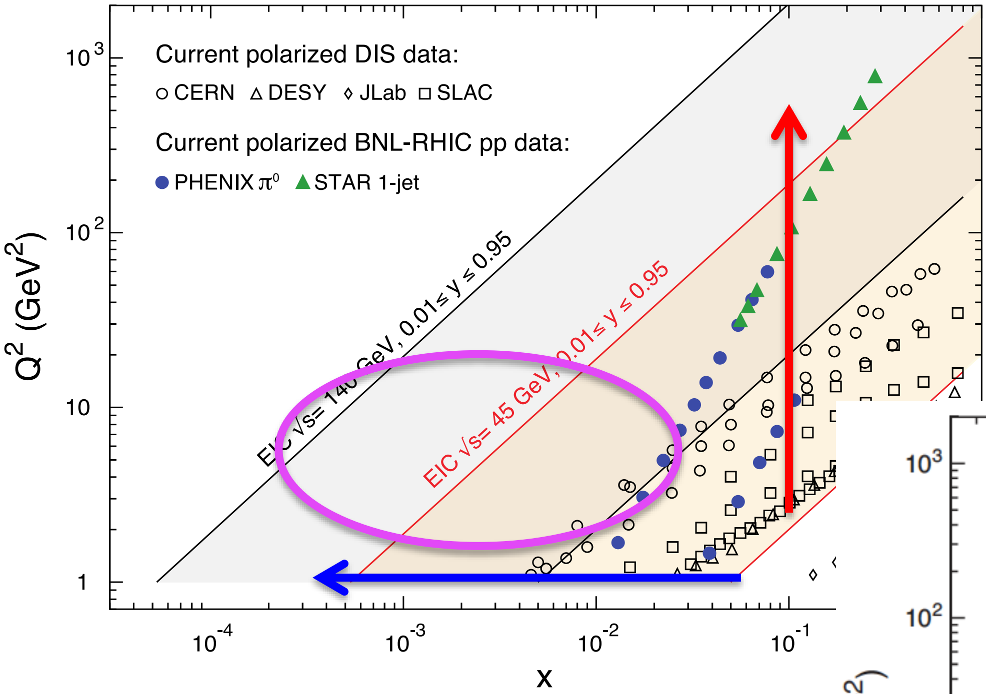
$Q^2 = S\, x\, y$

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

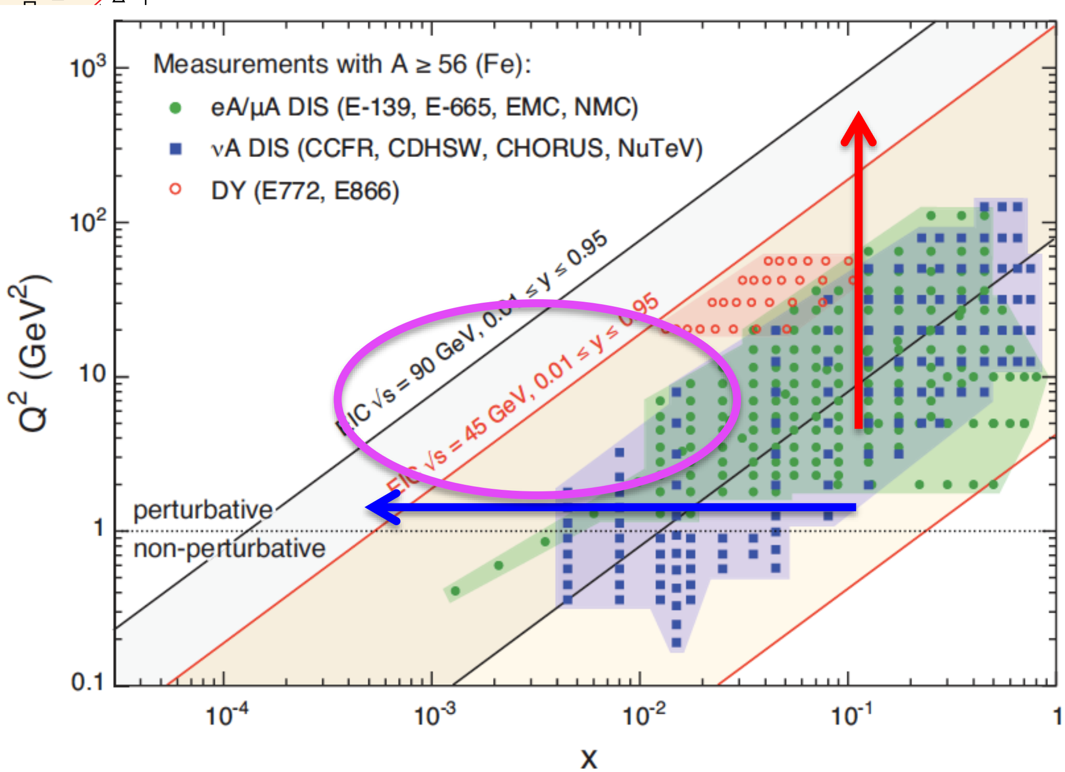
Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)
Detect every things including scattered proton/nucleus (or its fragments)

US EIC: Kinematic reach & properties



For e-N collisions at the EIC:

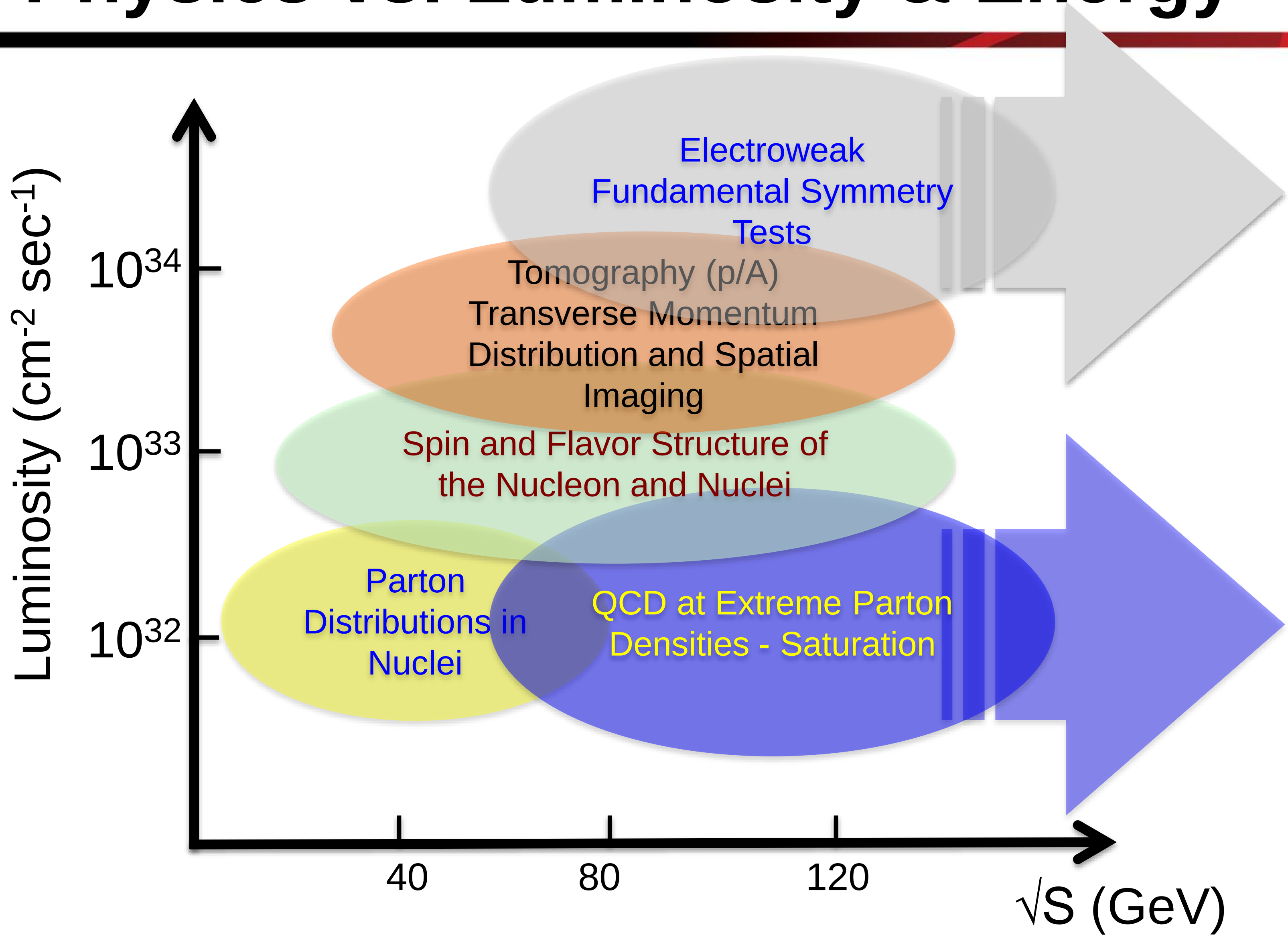
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics



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)

Physics vs. Luminosity & Energy

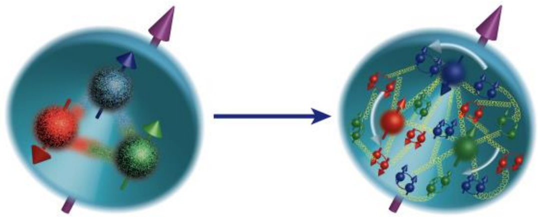


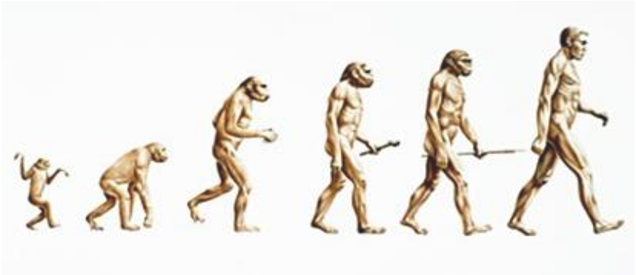
EIC – World's First Polarized eN Collider

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?

Our Understanding of Nucleon Spin

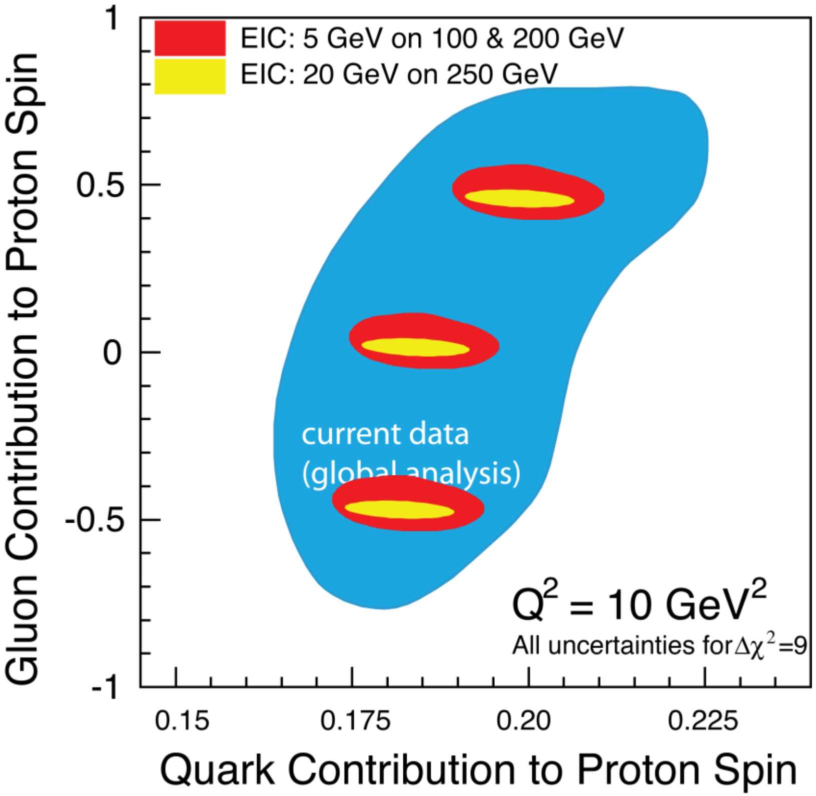




$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = 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



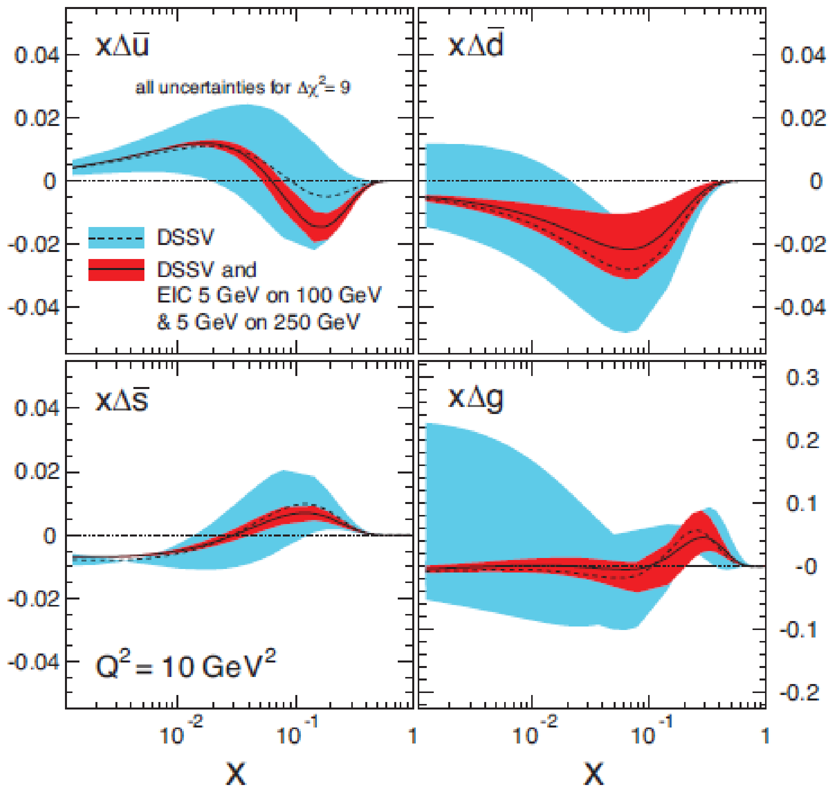
Helicity PDFs at an EIC

A Polarized EIC:

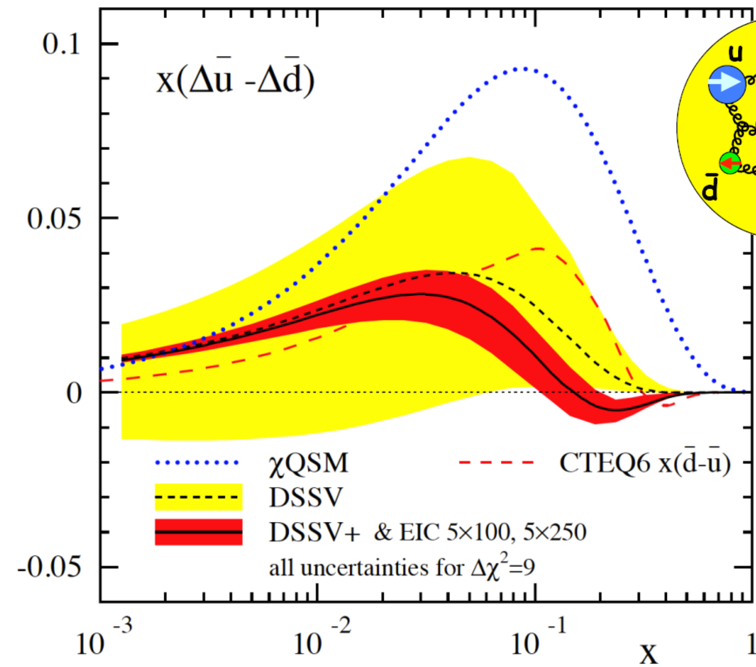
- Tremendous improvement on $x\Delta g(x)$
- Good improvement in $\Delta\Sigma$
- Spin Flavor decomposition of the Light Quark Sea

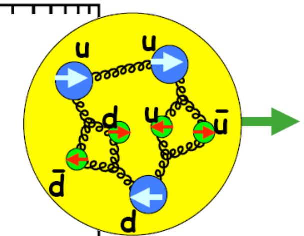
Many models predict $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$

Needs range of √s, here from ~ 45 to ~ 70



Needs range of √s ~ 30-70 (and good luminosity)





3D Imaging of Quarks and Gluons

$W(x, b_T, k_T)$

Momentum space

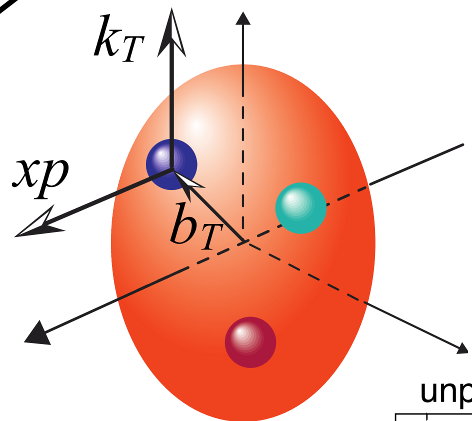
$\int d^2 b_T$

$f(x, k_T)$

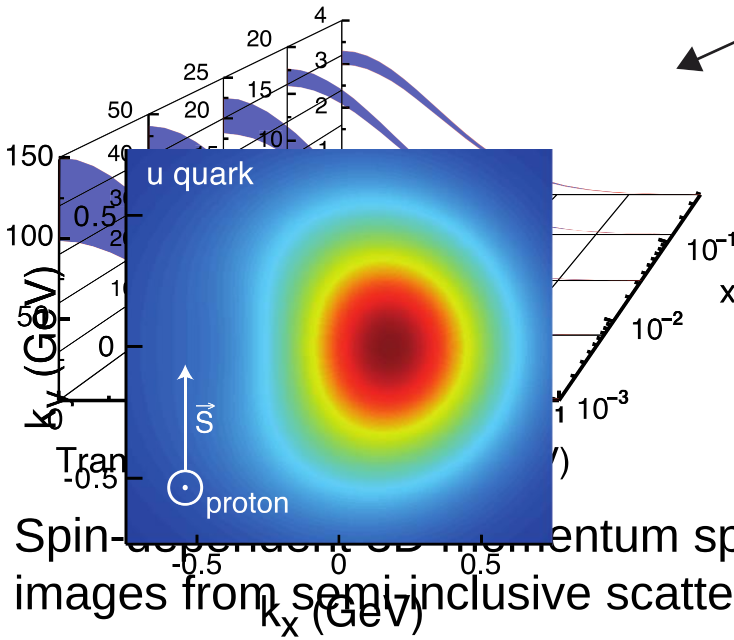
Coordinate space

$\int d^2 k_T$

$f(x, b_T)$

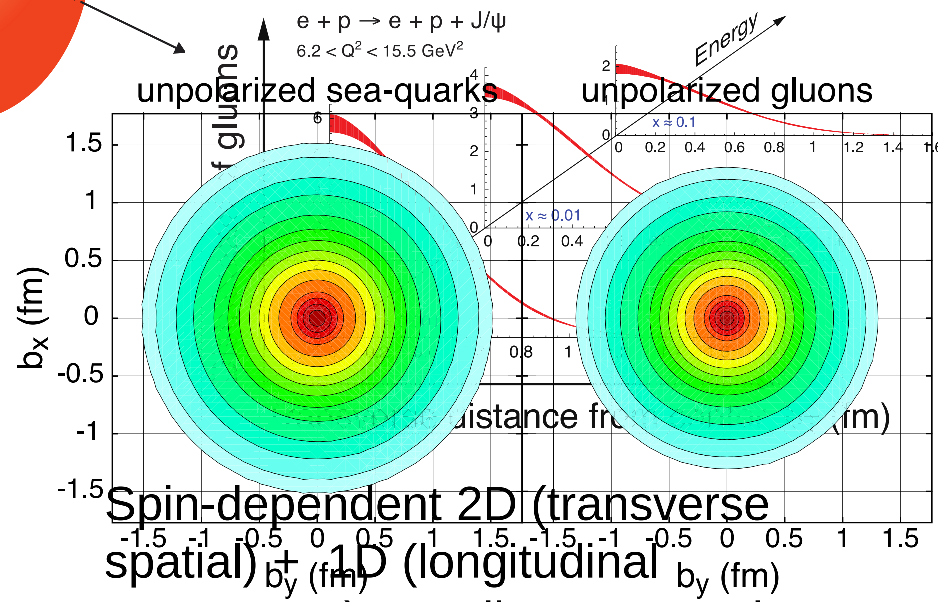


Quarks



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

Gluons

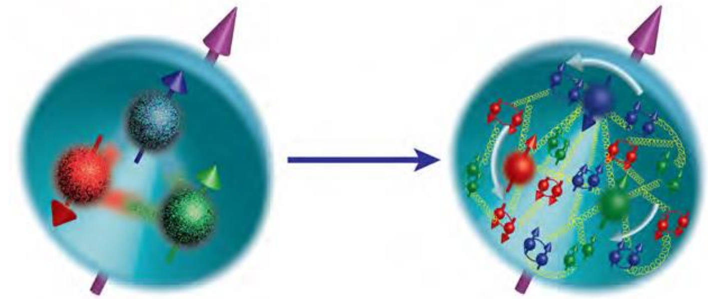


Spin-dependent 2D (transverse spatial) + 1D (longitudinal momentum) coordinate space images

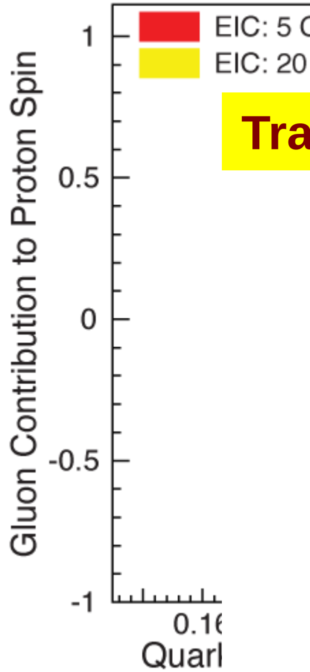
Position *r* X Momentum *p* → Orbital Motion of Partons

2+1 D partonic image of the proton

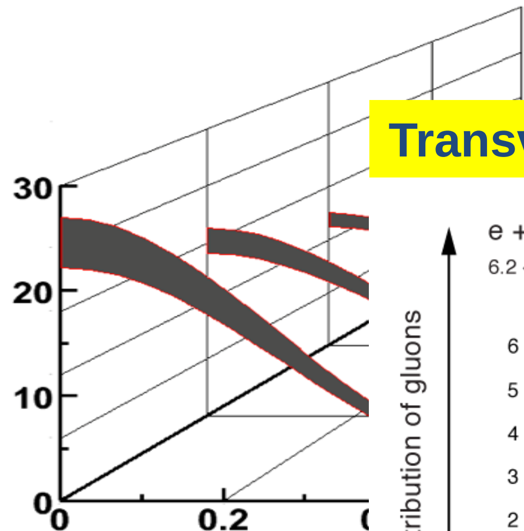
Spatial distance from origin X Transverse Momentum
→ Orbital Angular Momentum



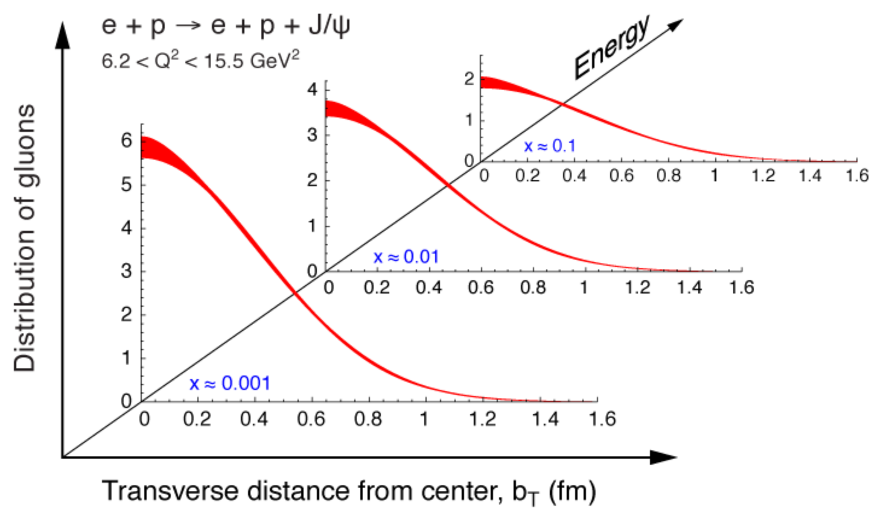
Helicity Distributions: ΔG and ΔΣ

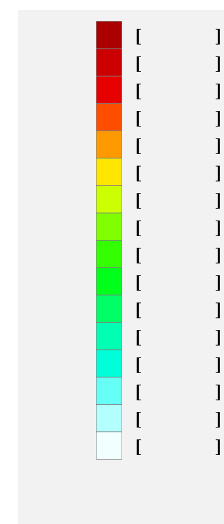


Transverse Momentum Distributions

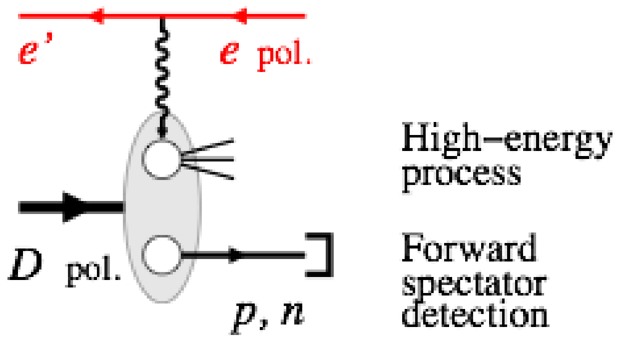


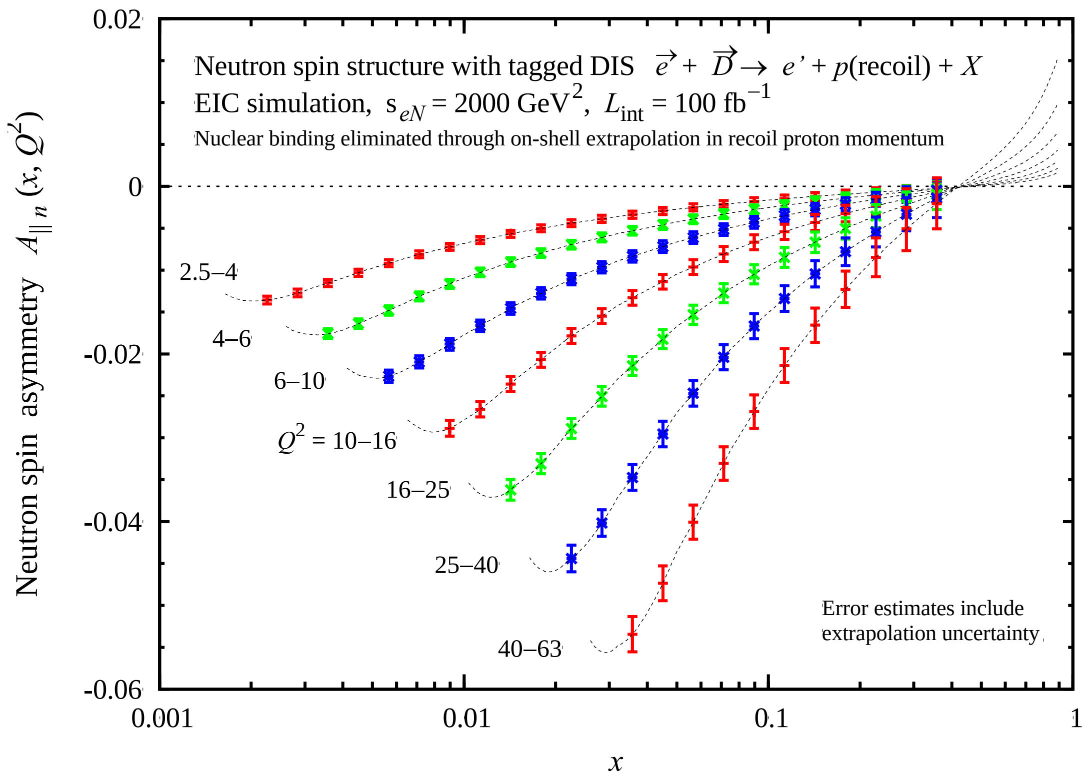
Transverse Position Distributions





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

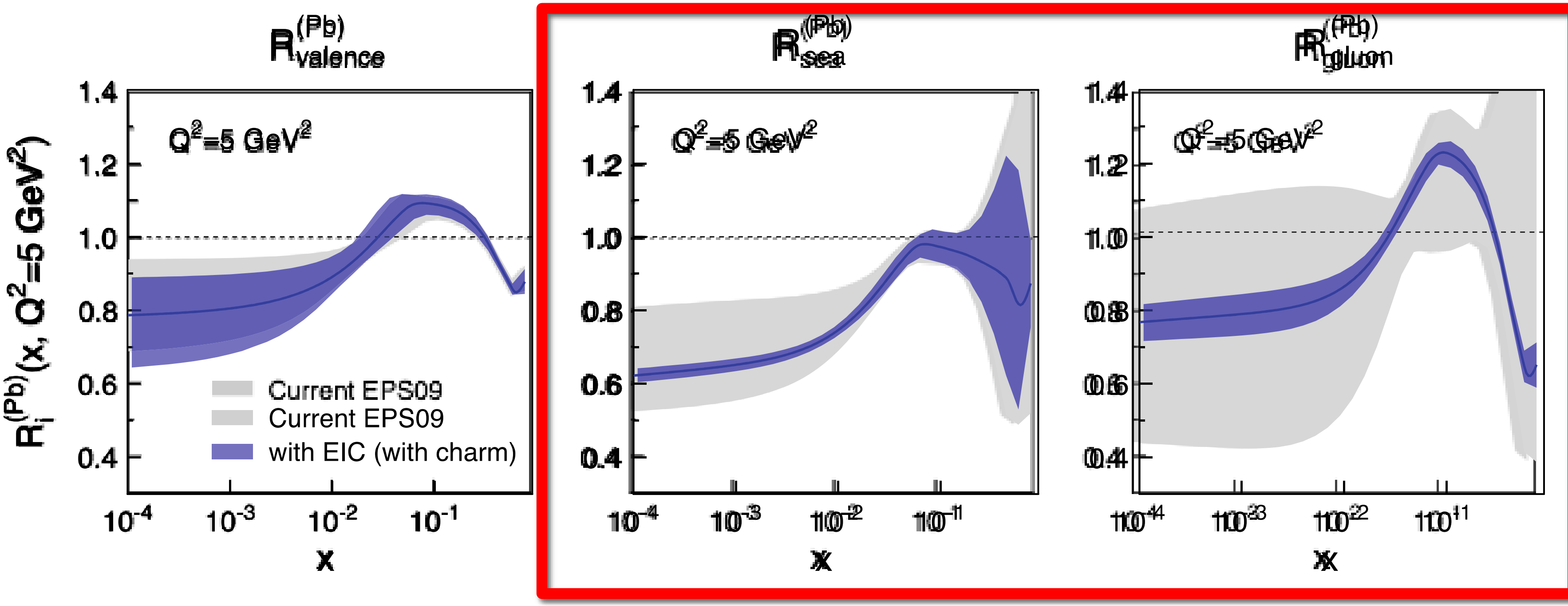
EIC – World's First eA Collider

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!

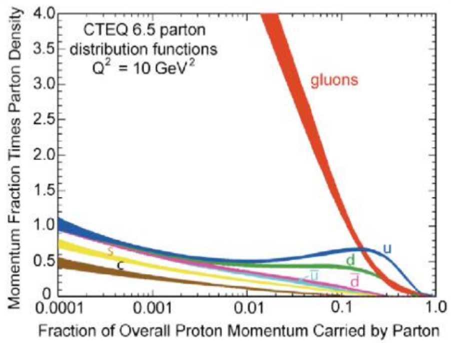


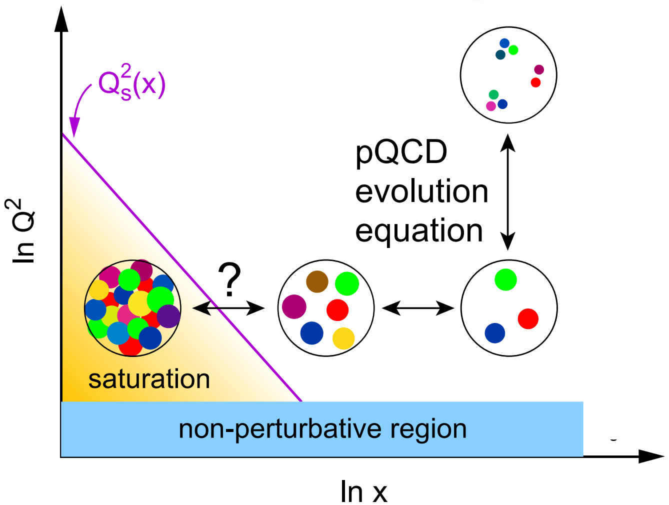
Ratio of Parton Distribution Functions of Pb over Proton:

- 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

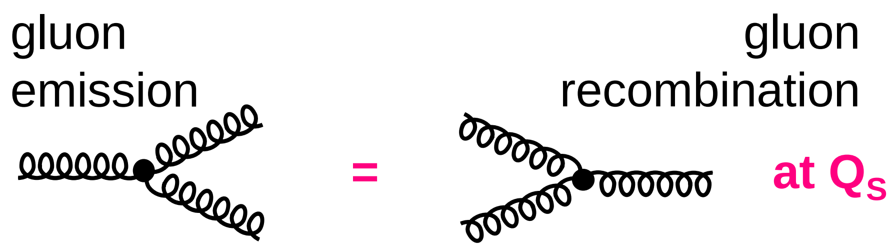
What do we learn from low-x studies?





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!

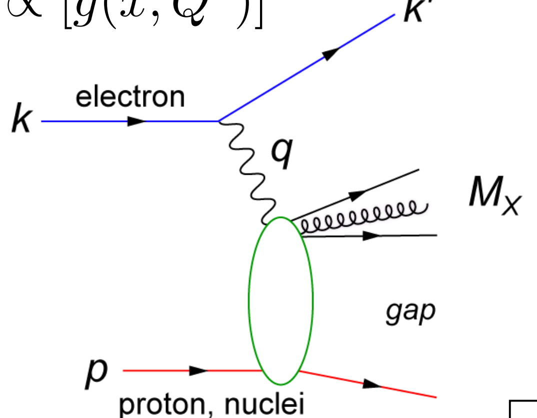
First observation of g-g recombination in different nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate an appropriate effective theory?

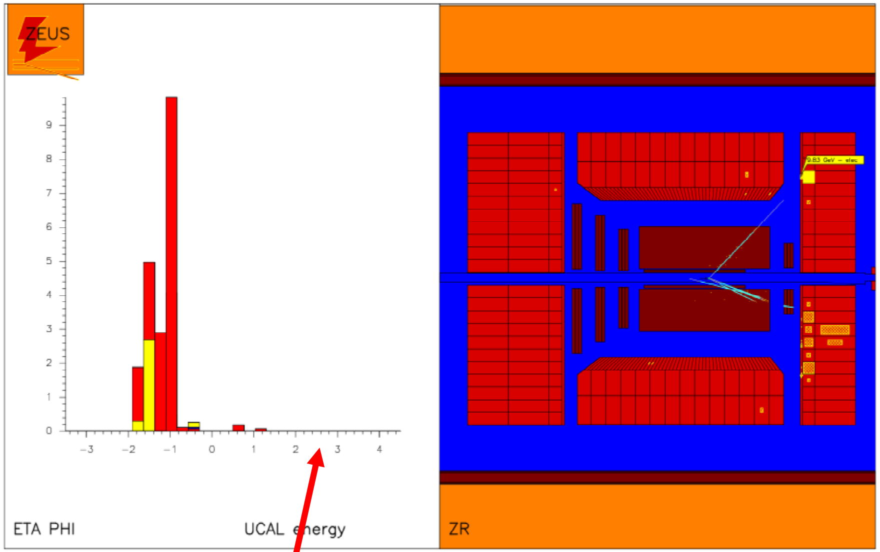
Saturation/CGC – what to measure?

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

Diffractive event

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



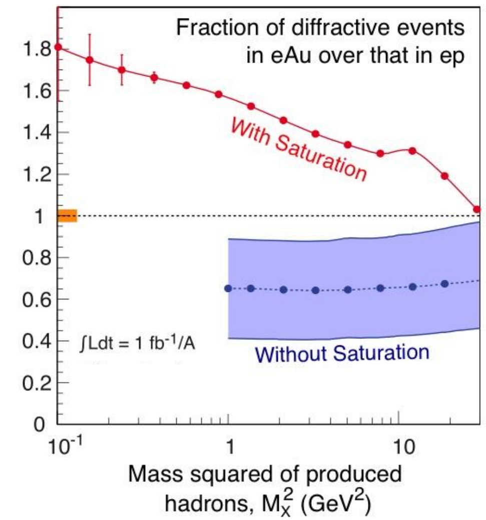


No activity in proton direction

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)

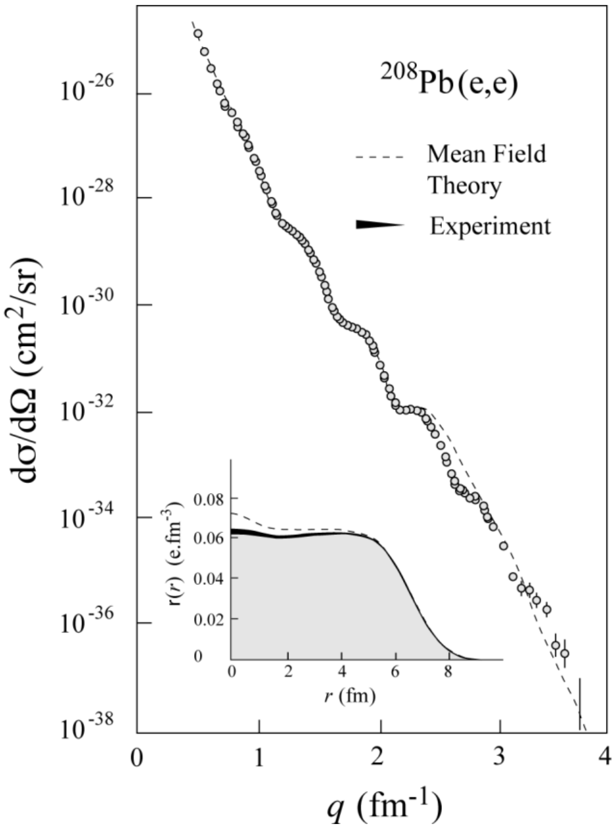


Exposing different layers of the nuclear landscape with electron scattering

History:

Electromagnetic

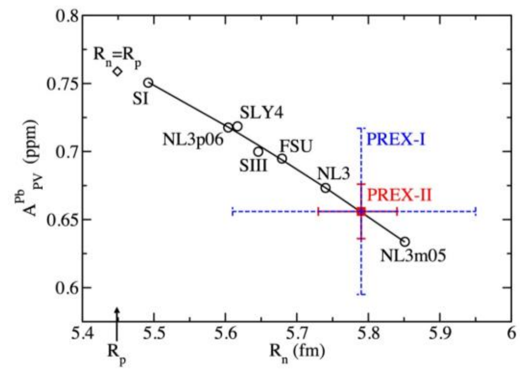
Elastic electron-nucleus scattering → charge distribution of nuclei

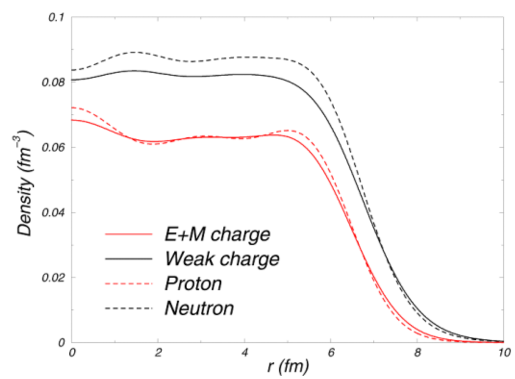


Present/Near-future:

Electroweak

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

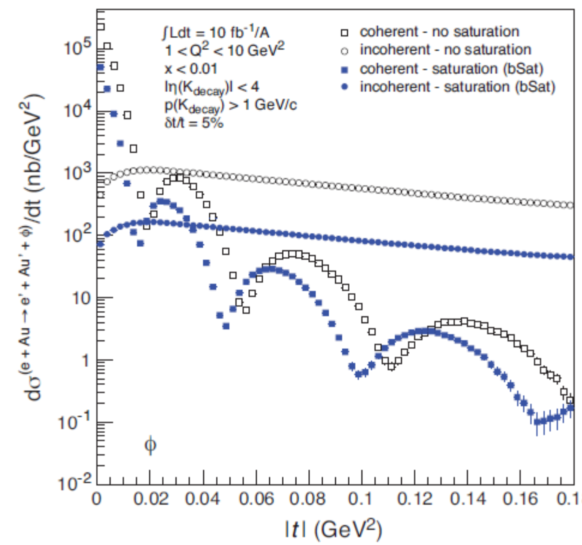




Future:

Color dipole

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



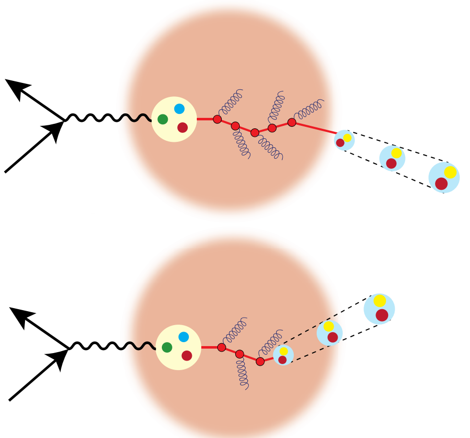
Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

Emergence of hadrons from partons

Nucleus as a Femtometer sized filter

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

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

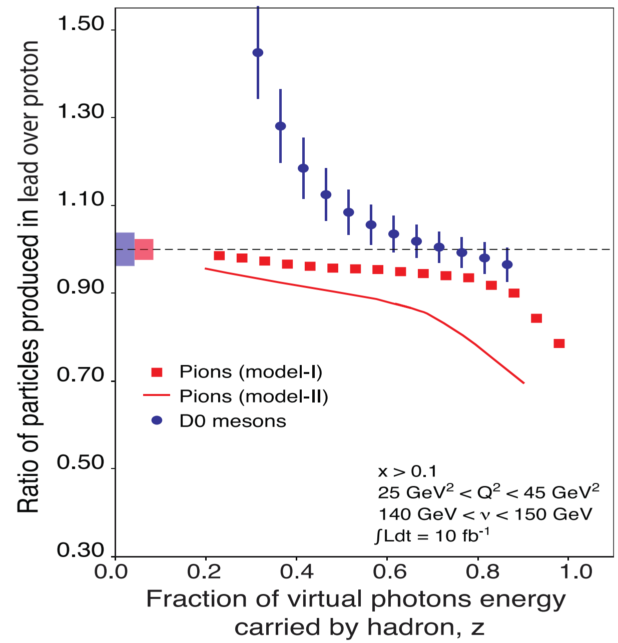


Control of ν by selecting kinematics;

Control the medium by selecting ions

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

Energy loss by light vs. heavy quarks:



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

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

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

Budget Assumptions

"Discussion of Budgets in light of priorities and recommendations"

Charge to NSAC to Develop a New Long Range Plan

The new NSAC Long Range Plan (LRP) should articulate the scope and the scientific challenges of nuclear physics today, what progress has been made since the last LRP, and the impacts of these accomplishments both within and outside of the field. It should identify and prioritize the most compelling scientific opportunities for the U.S. program to pursue over the next decade and articulate their scientific impact. A national coordinated strategy for the use of existing and planned capabilities, both domestic and international, and the rationale for new investments should be articulated. To be most helpful, the LRP should indicate what resources and funding levels would be required (including construction of new facilities, mid-scale instrumentation, and Major Items of Equipment) to maintain a world-leadership position in nuclear physics research and what the impacts are and priorities should be if the funding available provides for constant level of effort from the FY 2015 President's Budget Request into the out-years (FY 2016-2025), with constant level of effort defined using the published OMB inflators for FY 2016 through FY 2025. A key element of the new NSAC LRP should be the Program's sustainability under the budget scenarios considered.

DNP Town Meetings – Programs

Town Meeting on Computational Nuclear Physics
SURA, Washington DC, 14-15 July, 2014
https://www.jlab.org/conferences/cnp2014/

Town Meeting on Education and Innovation
Michigan State University, East Lansing, 7-8 August 2014
http://meetings.nscl.msu.edu/Education-Innovation-2014/program.htm

Town Meeting on Nuclear Structure and Nuclear Astrophysics
Texas A&M University, College Station, 21-23 August 2014
http://www.lecmeeting.org/program.htm

Town Meeting on QCD and Hadronic Physics
Town Meeting on Phases of QCD Matter
(One Day Joint)
Temple University, Philadelphia, 13-15 September 2014
https://indico.bnl.gov/conferenceTimeTable.py/pdf?view=standard&confId=857

Town Meeting on Fundamental Symmetries and Neutrinos
Chicago, 28-29 September 2014
https://fsnutown.phy.ornl.gov/fsnuweb/

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 this Summer
- ✓ DNP Town Meetings in the July/September time frame
- ✓ Joint APS-DNP-JPS Meeting Oct. 7-11, 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 to have greatest impact
- ✓ Cost review of EIC by February
- ✓ Most of text of report assembled by April 10
- ✓ Resolution meeting of Long Range Plan working group April 16-20, 2015
- ✓ Draft report reviewed by external wise women and men
- LRP final report due October 2015

  (Formally voted upon and accepted at NSAC meeting mid October)

Ongoing and next steps

Ongoing: Generic EIC-related detector R&D

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

~140 physicists, 31 institutes (5 Labs, 22 Universities, 9 Non-US Institutions) 15+ detector consortia exploring novel technologies for tracking, particle ID, calorimetry at the EIC:

→ *Weekly meetings, workshops and test beam activities already underway*

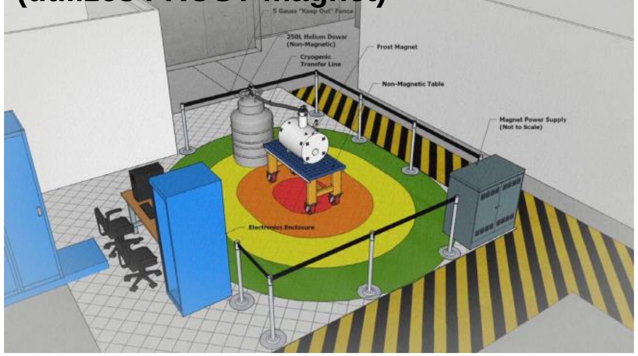
→ Many R&D proposals are collaborative (BNL/JLab/users)

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

JLab active partner to provide support for staff and users in this Generic EIC Detector R&D program

- Provide organization for users
- Assist in proposal preparation
- Provide infrastructure for R&D topics, e.g. 5T sensor test facility re-using existing magnets
- Often synergy with 12-GeV related work (like SiPMs, DIRC, PbWO4 crystals)

High-B-field sensor test facility at JLab (utilizes FROST magnet)



Some EIC Events (since ~ May 2014)

Event	Date
Presentation on EIC & LHeC to INFN Long-Term Strategy Meeting	May 2014
EIC users meeting – about 180 participants	Jun. 2014
POETIC V @ Yale	Sep. 2014
Joint DNP/JPS Workshop on Future Directions in High-Energy QCD	Oct. 2014
Revision of EIC White Paper – v2 & v3	Dec. 2014
NSAC cost review	Jan. 2015
Joint (w. users, BNL) preparation of EIC talk for the LRP process	Jan.-Mar.15
Joint (w. users, BNL) Meeting at SURA to prepare for LRP	Mar. 2015
Letter from Asia (China, India, Japan, Korea) showing interest in EIC to NSAC chair	Apr. 2015
NSAC LRP Working Group	Apr. 2015
Scientific American article on Gluons	May 2015
Participation in LHeC meeting	June 2015
Presentation on EIC at U Torino and at INFN Headquarters	June 2015
Discussion with Orsay & Saclay on French involvement in EIC	July 2015
POETIC VI @ Palaiseau	Sep. 2015
NSAC meeting to formally approve 2015 LRP document	Oct. 2015

What's next: EIC Users Meeting

Dear Friends and Colleagues,

We are happy to announce that the next meeting of the EIC collaborators and enthusiasts will be held at U. of California at Berkeley (UCB). The dates of the meeting are: January 6-9, 2016. — Please mark your calendars. Web pages with information about logistical and scientific planning are being setup. Please stay tuned.

We look forward to seeing you at UCB.

Sincerely,
Abhay Deshpande, also for:
Elke Aschenauer, Rolf Ent, Barbara Jacak, Robert McKeown,
Richard Milner, Berndt Mueller & Thomas Ullrich

What's next: EIC User Organization

Mail from Abhay Deshpande, Rolf Ent, Richard Milner and Thomas Ullrich, in collaboration with BNL and JLab management, recently sent to mailing list of potential EIC-interested institutions, and also to the general RHIC and CEBAF user mailing lists.

Dear X,

In the 2015 long range planning (LRP) activity of the US Nuclear Science Community **the joint Town Meetings on QCD unanimously and enthusiastically endorsed the Electron-Ion Collider (EIC) as the highest priority for new facility construction in the US.** The view of the broader US nuclear science community, to be expressed in the NSAC Long Range Plan, will be released in October of this year. We hence think it is timely for the US and the international users of a future US-based EIC to organize more formally with the goal of giving the future users community a stronger and more visible role in the process leading to the creation of an EIC.

We are writing to invite you and colleagues at your Institution to join in the international Electron-Ion Collider Users Group (EICUG) with the aim of realizing the EIC in the United States. Currently there are two designs of the US EIC under consideration, one at Brookhaven National Laboratory based on RHIC and the other at Jefferson Laboratory based on the 12-GeV CEBAF facility. The EICUG will work together, across these efforts, to …

We request all users group members to designate a representative from their home institution to be a member of the EICUG's Steering Committee (SC).

…

EIC Realization Imagined

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

- It seems unlikely that a CD0 (US Mission Need statement) will be awarded without a National Academy of Sciences study
- EIC accelerator R&D questions will not be completely answered until ~2017
- EIC construction has to start **after FRIB completion**, with FRIB construction anticipated to start ramping down near or in FY20

→ Most optimistic scenario would have EIC construction start (CD3) in FY20

→ Best guess for EIC completion assuming formal NSAC/LRP recommendation would be 2025-2030 timeframe

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 together can provide the **intellectual and technical leadership to realize the EIC**, a frontier accelerator facility.

The future of nuclear science demands an Electron Ion Collider

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.

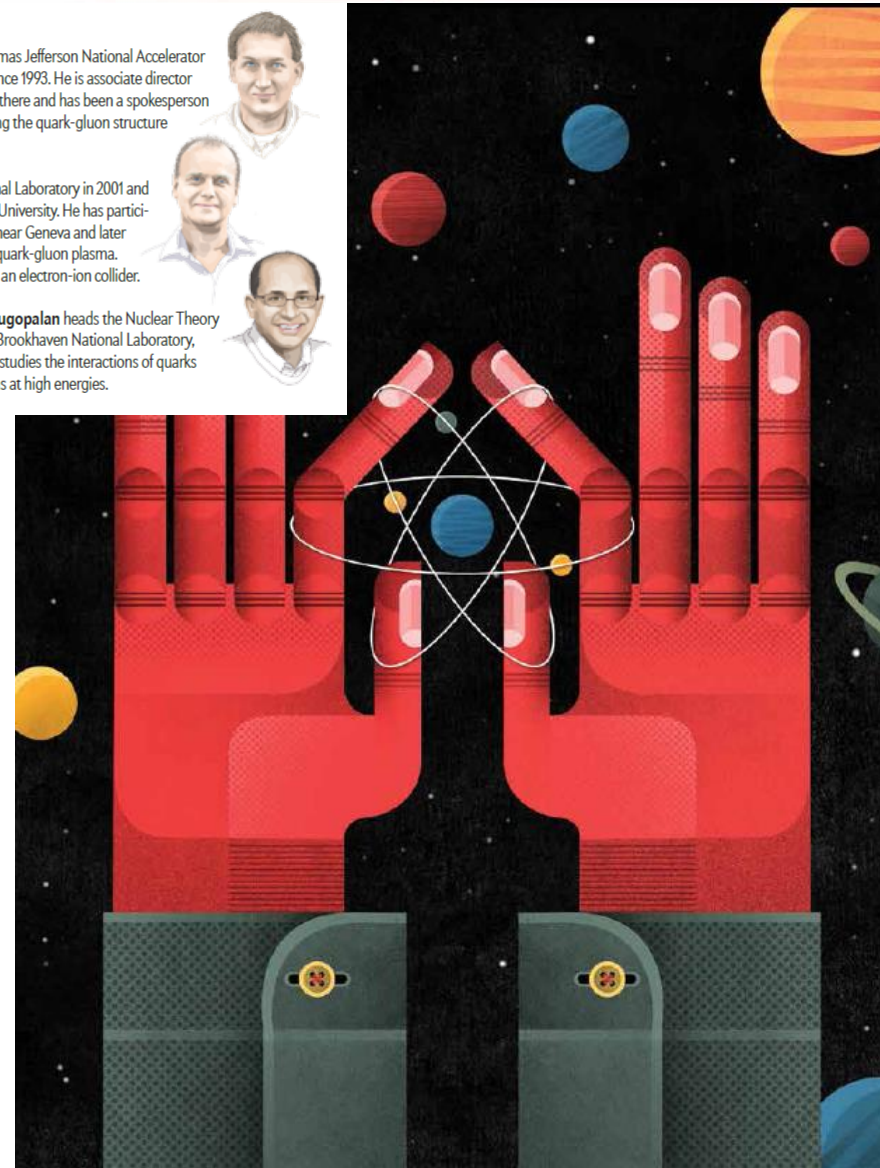


Illustration by Maria Corte

NSAC EIC Cost Review – Jan 26-28

From Ed Temple's presentation to NSAC, publicly available on the web

Guidelines

- Understanding that a detailed conceptual design has not been completed the Sub-committee is asked to provide NSAC with its best current estimate of costs of the projects that will address the physics opportunities identified in the EIC White Paper (arXiv:1212.1701v2), including R&D, construction, pre-operating and operating costs and initial experimental equipment. NSAC is aware that there are uncertainties regarding siting and other issues that limit the precision of such an estimate at this time. Nevertheless, the advice of the Sub-committee will be of great value to NSAC as it evaluates the relative merit of this and other initiatives

NSAC's Sub-Committee review of the EIC (Electron Ion Collider) Cost Estimates
L. Edward Temple, Jr., Chairman

Cost Review Presentation to NSAC

From Ed Temple's presentation to NSAC, publicly available on the web

Overall Review Committee Summary

- eRHIC incorporates certain technical advances which are beyond the state of the art; the 31% contingency is, in the opinion of the subcommittee insufficient.
- MEIC is based on largely conventional technology with fewer technical risks; the proposed 35% contingency is marginally sufficient.
- An EIC could be built for about $1.5B in FY15$.
  - This is equal to the MEIC TPC and $0.5B higher than the eRHIC TPC to account for the higher technical risk.
- The total on-project cost may potentially be reduced as technical risk is retired, by off-project funds especially for the detectors from international sources, by redirection of operating funds at the host laboratory or by reducing the design requirements.

eRHIC pre-project R&D

(Accelerator R&D, as shown at NSAC Long-Range Plan Resolution Group meeting by Berndt Mueller)

Retire the main technical performance risks by 2017/18:

Prototyping of funneling polarized electron source (BNL LDRD)

Prototype currently in test at Stony Brook; first beam from two cathodes in one gun; prototype supports full tests with 20 cathodes

Strong cooling of hadron beams (DOE NP, BNL PD)

Coherent electron Cooling Proof-of-Principle in 2016/17 using 40 GeV/n Au beams; micro-bunching technique test also possible and planned

High average current, multi-pass ERL (Navy, DOE NP, CEBAF?)

Results from test-ERL in 2015/16

We aim at developing a decision-ready, scientifically compelling EIC project with TPC *well below* $1B by 2018.

Remember:

Risk retiring R&D (stochastic cooling was deemed too risky in 2007) shaved 3 years and ~$80M off the RHIC luminosity upgrade

Overview R&D for the MEIC baseline

(Accelerator R&D, as shown at EIC cost review as part of the assigned homework)

Needed R&D	Risk level	Mitigating strategies	Mitigated risk level
Bunched beam electron cooling ERL only	MEDIUM	▪ Test of bunched beam cooling at IMP (LDRD) ▪ Experience from RHIC low energy cooling ▪ Development of a 200 mA unpolarized e- gun	LOW
Low β^* ion ring	MEDIUM	▪ Chromatic and IR nonlinear correction schemes ▪ DA tracking with errors and beam beam ▪ Operational experience at hadron colliders	LOW
Space charge dominated beams	MEDIUM	▪ Simulation ▪ DC cooling in Booster ▪ Operational experience at UMER and IOTA rings ▪ Study of space charge compensation at eRHIC	LOW
Figure 8 layout	MEDIUM	▪ Spin tracking simulations	LOW
Super ferric magnets	MEDIUM	▪ Existing prototypes (SSC, GSI) ▪ Early MEIC prototype (FY15-16) ▪ Operational experience at GSI ▪ Alternative cosθ designs	LOW
Crab cavities	MEDIUM	▪ Prototypes ▪ Operational experience at KEK-B and LHC ▪ Test of crab cavity in LERF (FEL)	LOW
SRF R&D	LOW	▪ 952 MHz RF development	LOW

Charge to NSAC to Develop a New Long Range Plan

U.S. Department of Energy
and the
National Science Foundation

Dr. Donald Geesaman
Chair
DOE/NSF Nuclear Science Advisory Committee
Argonne National Laboratory
9800 South Cass Avenue
Argonne, Illinois 60439

Dear Dr. Geesaman:

This letter requests that the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) conduct a new study of the opportunities and priorities for United States nuclear physics research and recommend a long range plan that will provide a framework for coordinated advancement of the Nation's nuclear science research programs over the next decade. This exercise should exclude the DOE Isotope Program managed by the DOE Office of Science's Office of Nuclear Physics, for which a dedicated strategic planning exercise will be convened.

Charge to NSAC to Develop a New Long Range Plan

The new NSAC Long Range Plan (LRP) should articulate the scope and the scientific challenges of nuclear physics today, what progress has been made since the last LRP, and the impacts of these accomplishments both within and outside of the field. It should identify and prioritize the most compelling scientific opportunities for the U.S. program to pursue over the next decade and articulate their scientific impact. A national coordinated strategy for the use of existing and planned capabilities, both domestic and international, and the rationale for new investments should be articulated. To be most helpful, the LRP should indicate what resources and funding levels would be required (including construction of new facilities, mid-scale instrumentation, and Major Items of Equipment) to maintain a world-leadership position in nuclear physics research and what the impacts are and priorities should be if the funding available provides for constant level of effort from the FY 2015 President's Budget Request into the out-years (FY 2016-2025), with constant level of effort defined using the published OMB inflators for FY 2016 through FY 2025. A key element of the new NSAC LRP should be the Program's sustainability under the budget scenarios considered.

The extent, benefits, impacts and opportunities of international coordination and collaborations afforded by current and planned major facilities and experiments in the U.S. and other countries, and of interagency coordination and collaboration in cross-cutting scientific opportunities identified in studies involving different scientific disciplines should be specifically addressed and articulated in the report. The scientific

Charge to NSAC to Develop a New Long Range Plan

impacts of synergies with neighboring research disciplines and further opportunities for mutually beneficial interactions with outside disciplines, should be discussed.

In the development of previous LRP's, the Division of Nuclear Physics of the American Physical Society (DNP/APS) was instrumental in obtaining broad community input by organizing town meetings of different nuclear physics sub-disciplines. The Division of Nuclear Chemistry and Technology of the American Chemical Society (DNC&T/ACS) was also involved. We encourage NSAC to exploit this method of obtaining widespread input again, and to further engage both the DNP/APS and DNC&T/ACS in laying out the broader issues of contributions of nuclear science research to society.

Please submit your report to DOE and NSF by October 2015. The agencies very much appreciate NSAC's willingness to undertake this task. NSAC's previous LRP's have played a critical role in shaping the Nation's nuclear science research effort. Based on NSAC's laudable efforts in the past, we look forward to a new plan that can be used to chart a vital and forefront scientific program into the next decade.

Sincerely,

Patricia M. Dehmer
Acting Director
Office of Science

F. Fleming Crim
Assistant Director
Directorate for Mathematical
and Physical Sciences

Electron Ion Collider

NSAC 2007 Long-Range Plan:

"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."

NSAC 2015 Long-Range Plan:

- EIC remains next QCD frontier
- Unanimously endorsed by QCD Town Meetings
- Community has reached consensus on parameters

EIC Community White Paper arXiv:1212.1701v3

- Highly polarized ($\sim$ 70%) electron and nucleon beams
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from $\sim 20 - \sim 100$ GeV, upgradable to ~ 140 GeV
- High collision luminosity $\sim 10^{33-34}$ cm^{-2}s^{-1}
- Possibilities of having more than one interaction region

QCD and Hadron Physics – Cool QCD

1. With highest priority, we recommend both completion of construction and full operation of the 12 GeV CEBAF at the Thomas Jefferson National Accelerator Facility, along with targeted instrumentation investments such as the MOLLER and SoLID projects.

2. A high luminosity, high-energy polarized Electron Ion Collider (EIC) is the highest priority of the U.S. NP QCD community for future new construction after FRIB. *(voted jointly with Phases of QCD community)*

3. We recommend strong support for other existing facilities, such as the polarized proton facility at RHIC, university-based laboratories, and the scientists involved in these efforts. …

4. We recommend that support for the theory program be increased, in a balanced manner and in proportion to new and continuing investment in experiment. …

Phases of QCD Matter – Hot QCD

1. As our highest priority we recommend a program to complete the search for the critical point in the QCD phase diagram and to exploit the newly realized potential of exploring the QGP's structure at multiple length scales with jets at RHIC and LHC energies. This requires implementation of new capabilities of the RHIC facility (a state-of-the-art jet detector such as sPHENIX and luminosity upgrades for running at low energies) needed to complete its scientific mission, continued strong U.S. participation in the LHC heavy-ion program, and strong investment in a broad range of theoretical efforts employing various analytical and computational methods.

2. A high luminosity, high-energy polarized Electron Ion Collider (EIC) is the U.S. QCD Community's highest priority for future new construction after FRIB.

3. We endorse the new initiatives and investments proposed in the Recommendation and Request received from the Computational Nuclear Physics Town Meeting, at a level to be determined by the requested NSAC subcommittee. In addition, we recommend new funding to expand the successful "Topical Collaborations in Nuclear Theory" program initiated in the last Long Range Plan of 2007, to a level of at least one new Topical Collaboration per year

Helicity PDFs at an EIC

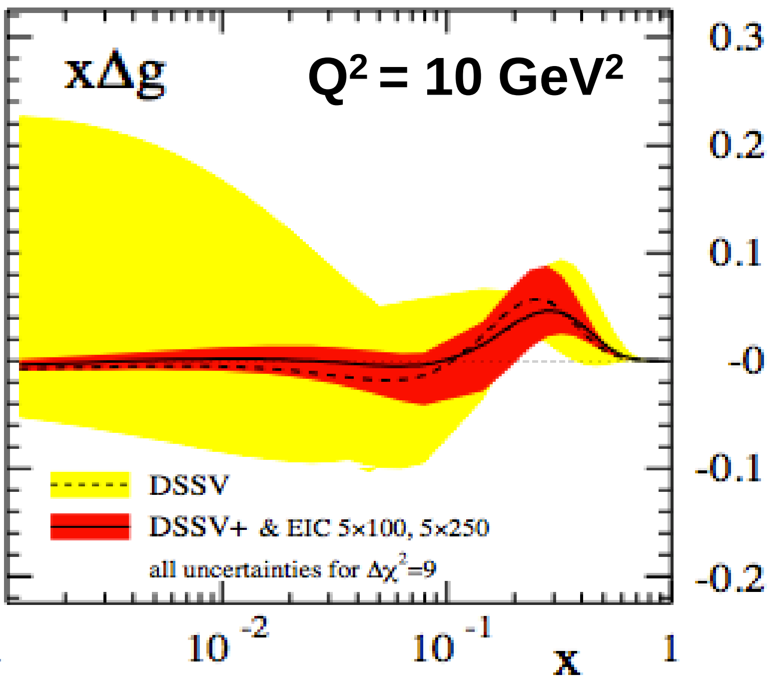
A Polarized EIC:

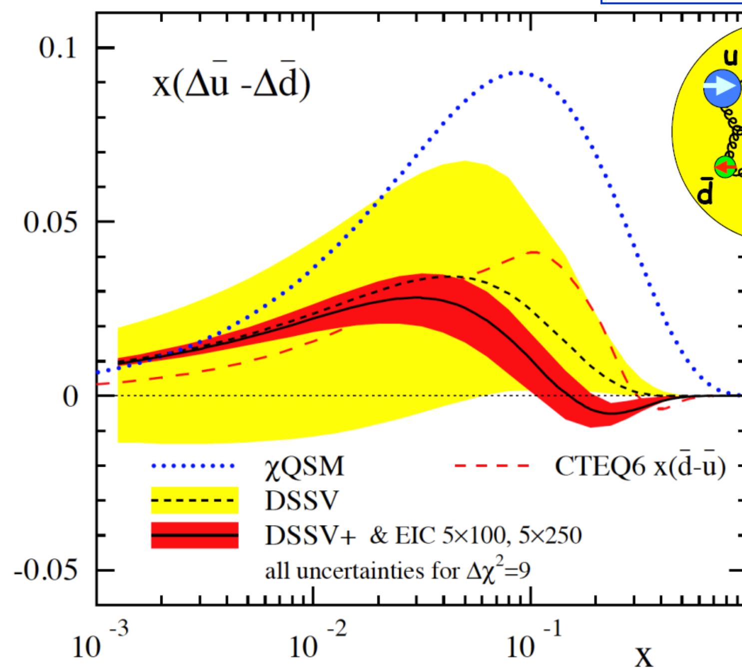
- Tremendous improvement on $x\Delta g(x)$
- Good improvement in $\Delta\Sigma$
- Spin Flavor decomposition of the Light Quark Sea

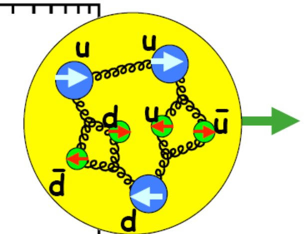
Needs range of $\sqrt{s}$, here from ~ 45 to ~ 70

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

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



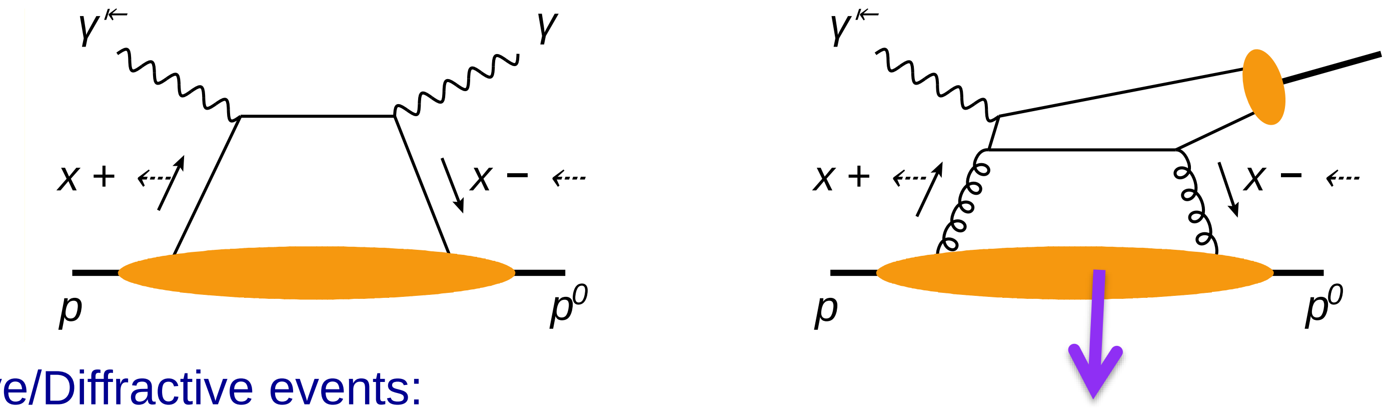




Spatial Imaging of Quarks and Gluons

Access to Generalized Parton Distributions

Quarks:
At fixed
Target



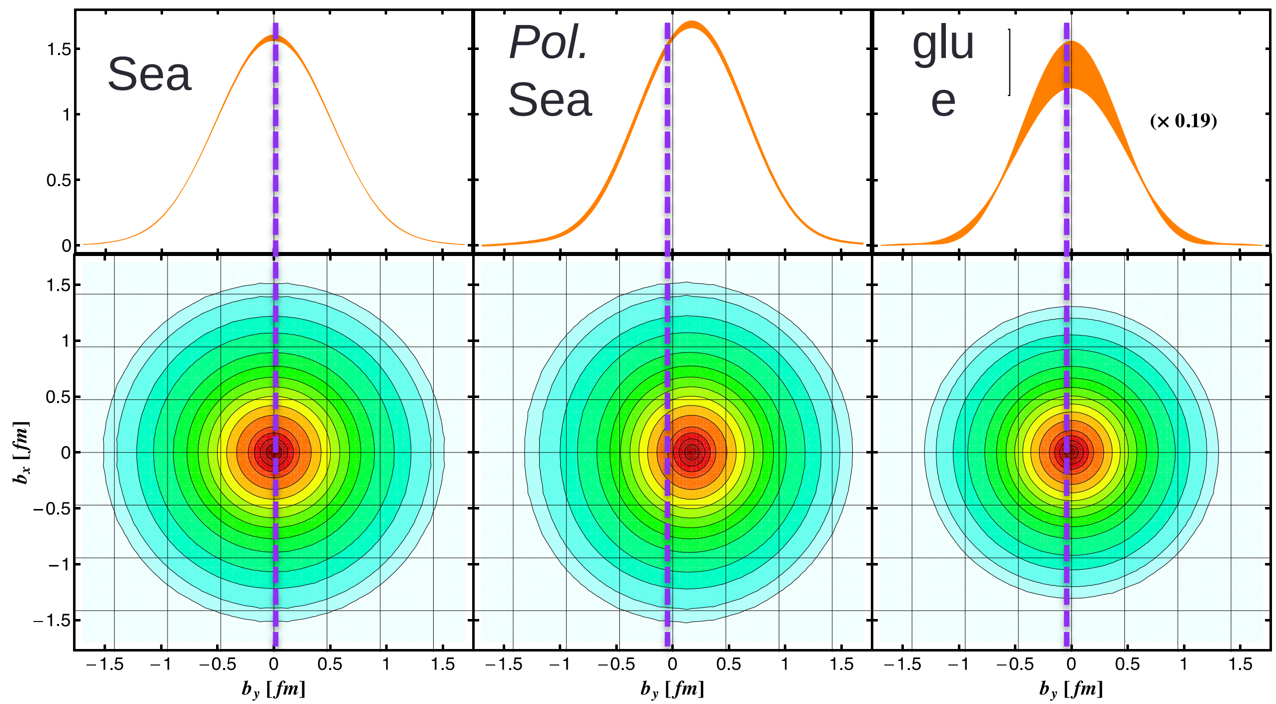
Sea quarks,
Gluons:
Only @ the
Collider

Exclusive/Diffractive events:

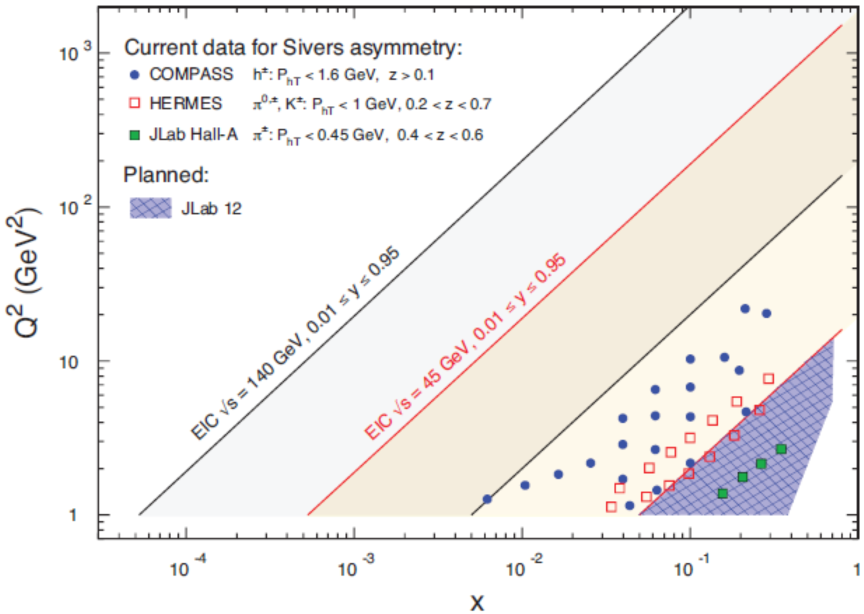
e + **p** → e'+ **p'**+ J/ψ

Fourier transform of
t=(p-p') →
Spatial distribution

Images of sea Quarks
& Gluon's spatial dist.
Via J/Ψ production
With the EIC



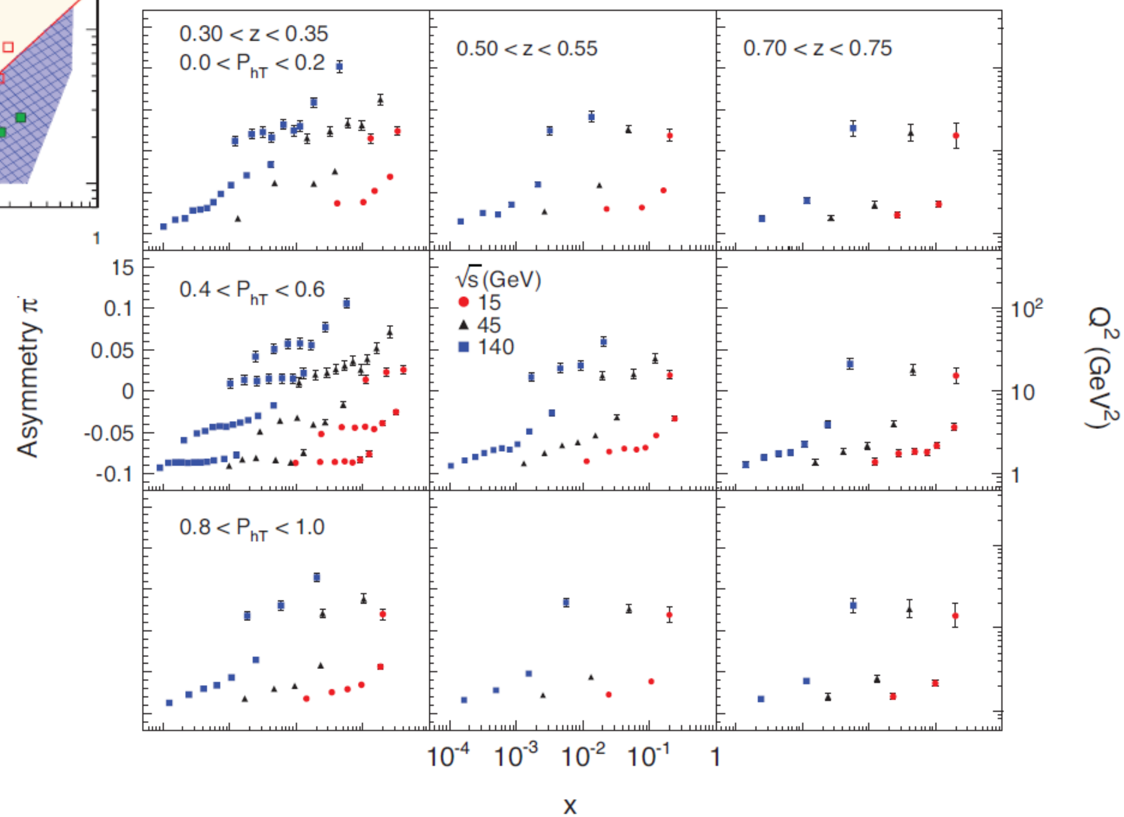
TMD Landscape at an EIC: Sivers as example



● √s ~ 15 GeV

▲ √s ~ 45 GeV

(■ √s ~ 140 GeV) upgraded EIC



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}

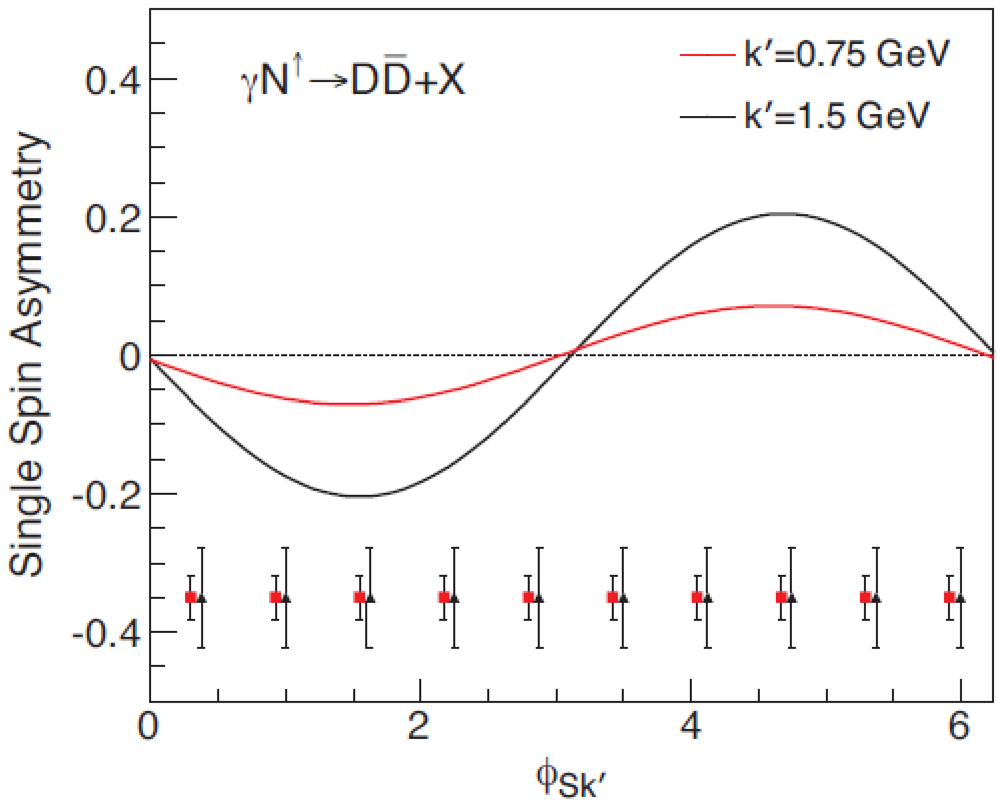
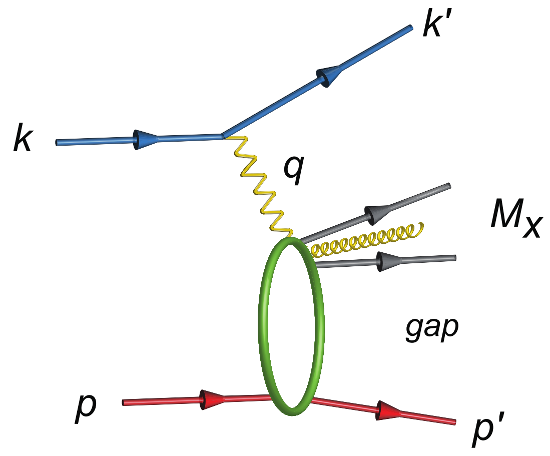


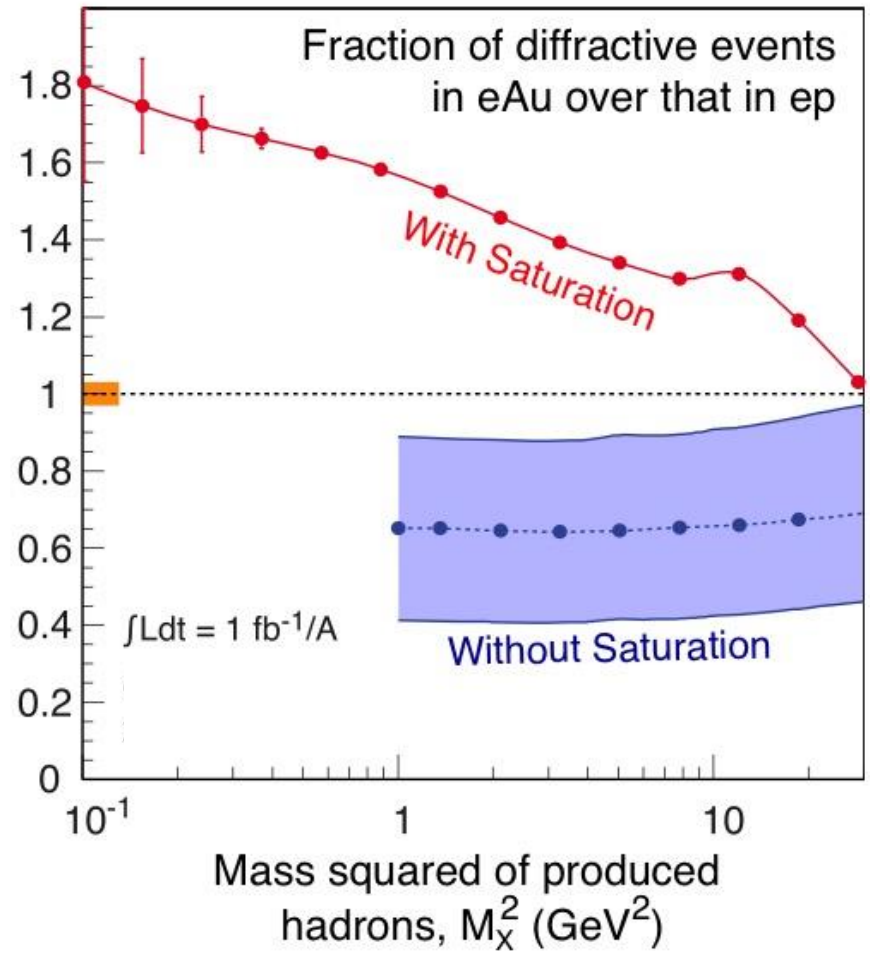
Figure 2.17: The single transverse spin asymmetry for $\gamma^* N^\uparrow \to D^0 \bar{D}^0 + X$, where ϕ is the azimuthal angle between the total transverse momentum $k'_\perp$ of the D-$\bar{D}$ pair and the transverse polarization vector $S_\perp$ of the nucleon. The asymmetries and the experimental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

Saturation/CGC – what to measure?

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

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





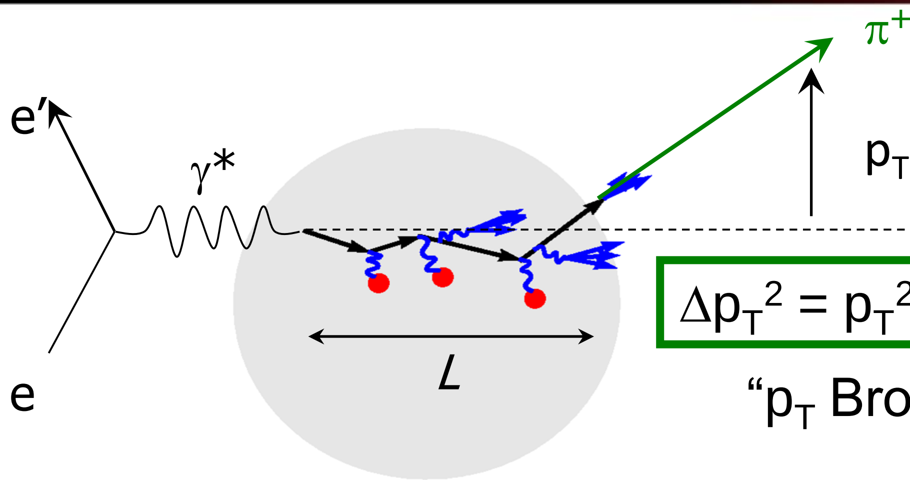
At HERA

ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

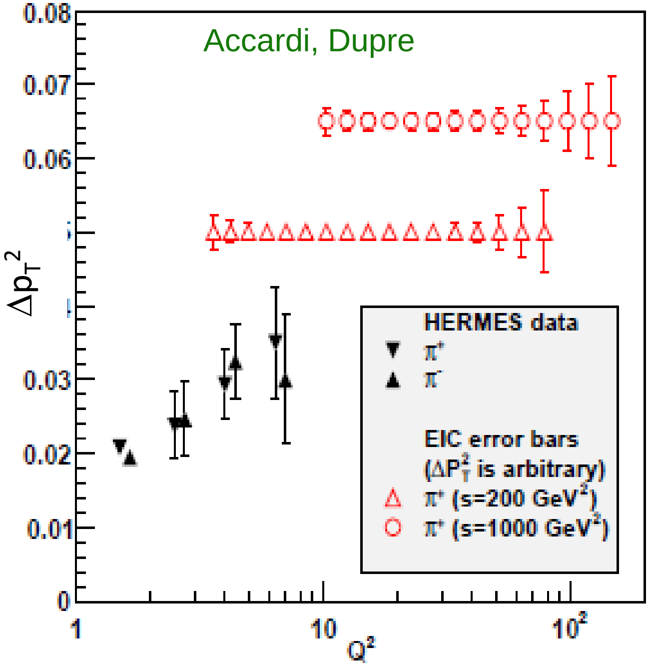
eA: 25-30% diffractive

Hadronization – parton propagation in matter



$\Delta p_T^2 = p_T^2(A) - p_T^2(^2H)$

"p_T Broadening"



Comprehensive studies possible:

- wide range of energy ν = 10-1000 GeV
- wide range of Q^2: evolution
- Hadronization of charm, bottom
- High luminosity for 3D and correlations

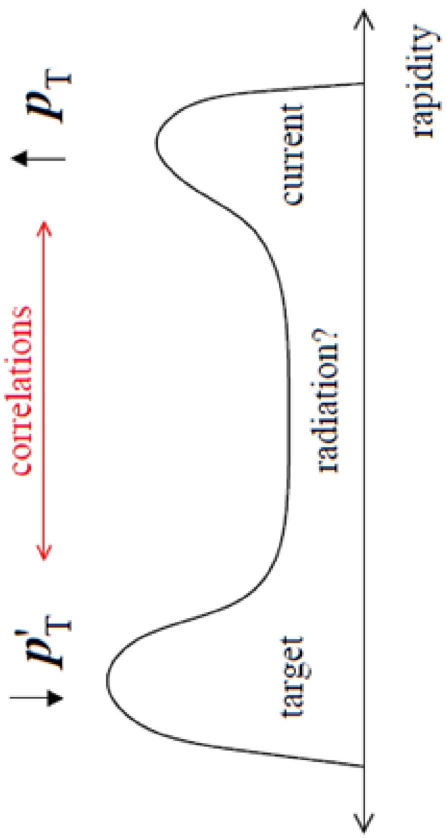
EIC: Understand the conversion of color charge to hadrons through fragmentation and breakup

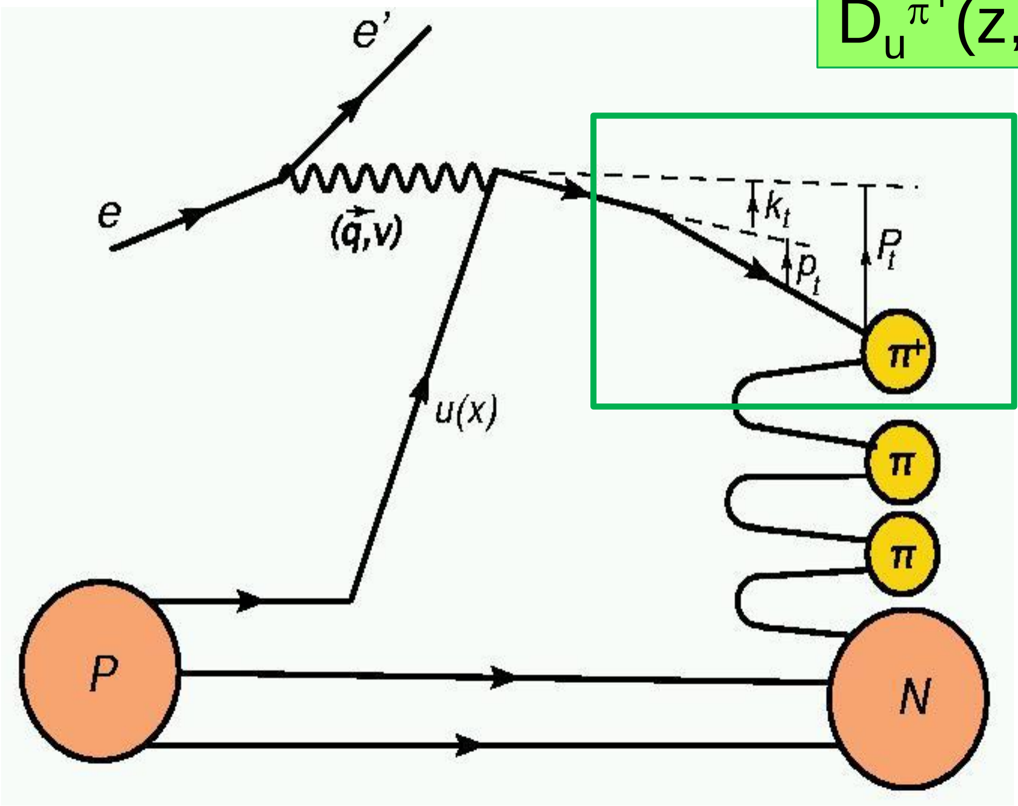
Color neutralization – it's a correlated 3D problem

Can we learn more from correlating with the target fragmentation region?

Final transverse momentum of the detected pion **P_t** arises from convolution of the struck quark transverse momentum **k_t** with the transverse momentum generated during the fragmentation **p_t**.

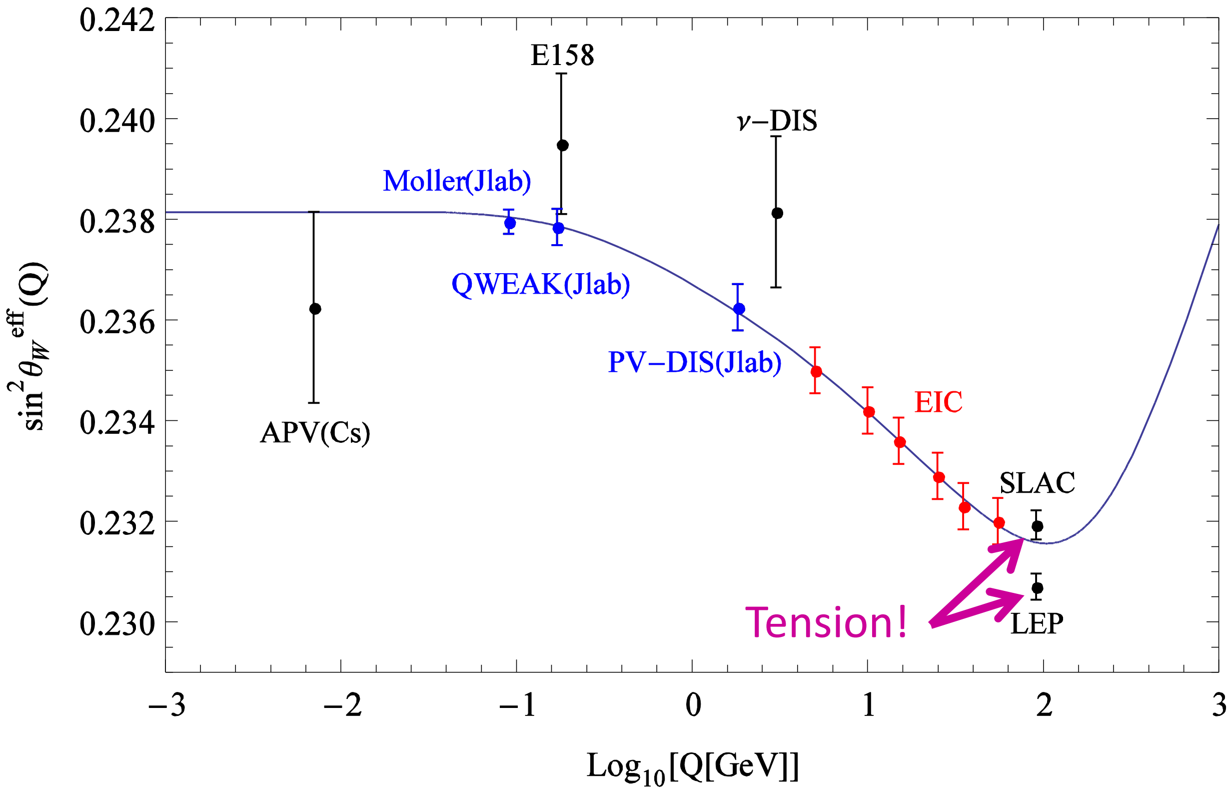
$D_u^{\pi^+}(z, p_t)$





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