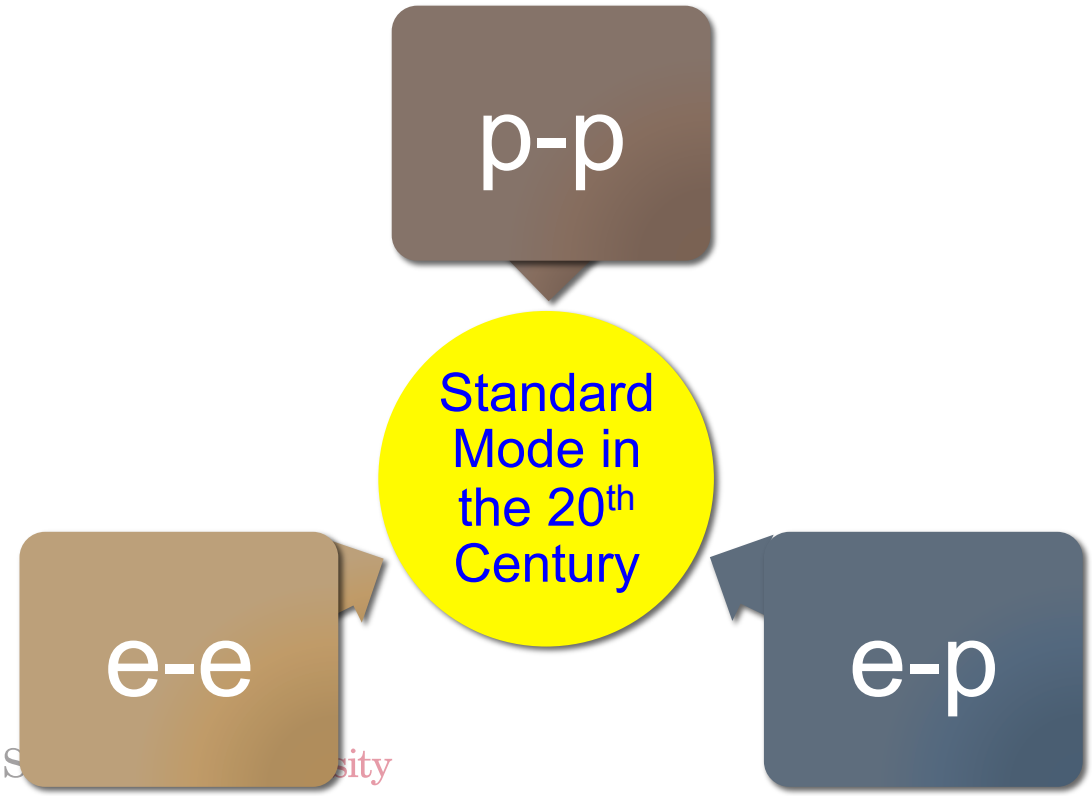
One of my many favorite Italian Physicists Guido Altarelli,

(1941-2015)

used to emphasize : complementary and essential nature of different techniques… in the development of the Standard Model:



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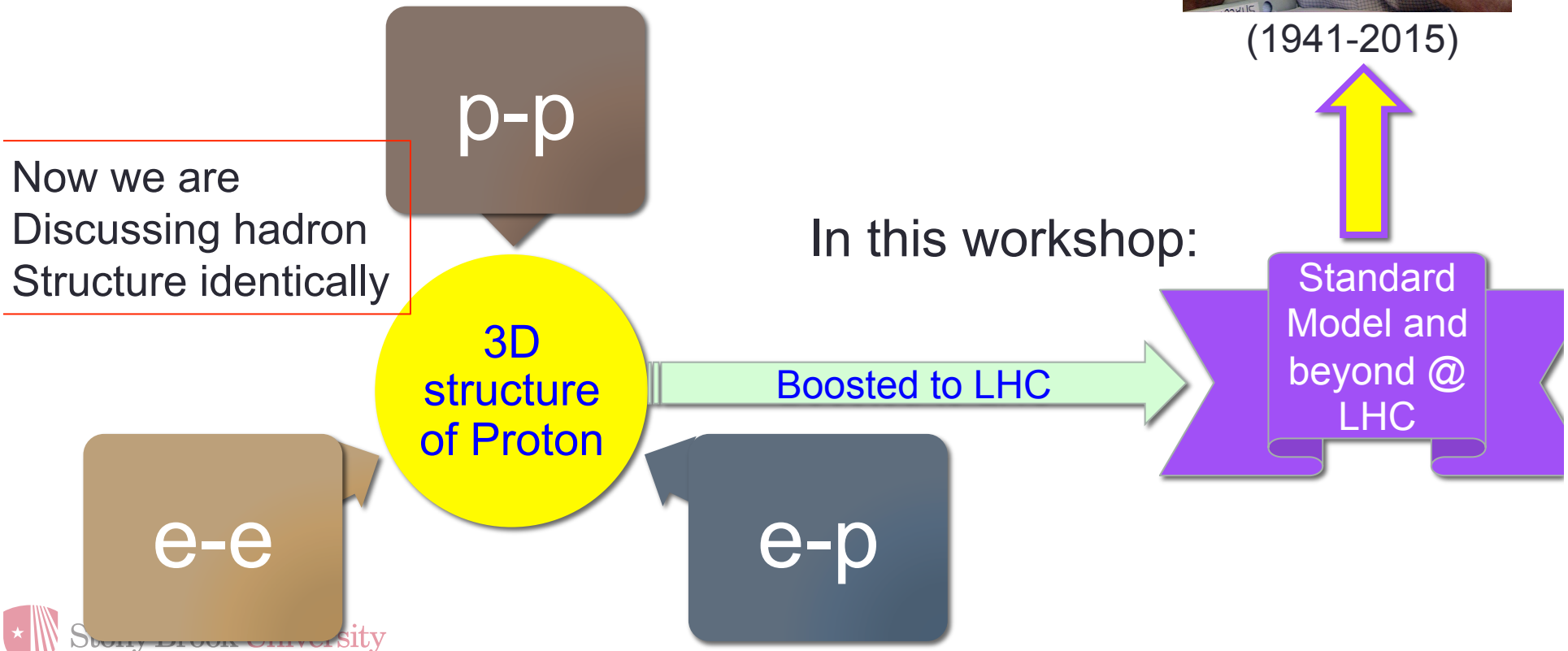
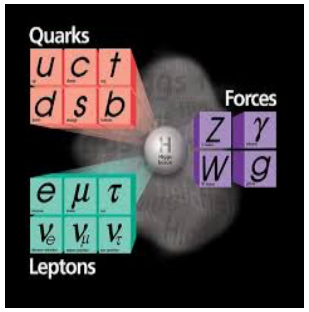
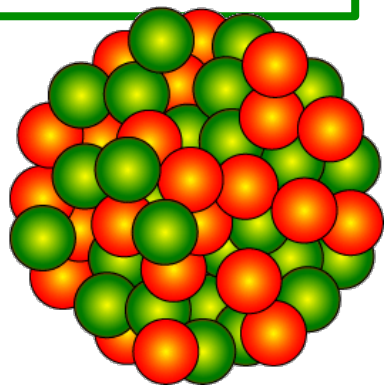


Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

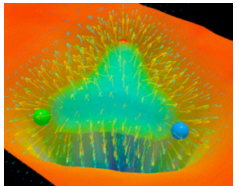
Why the EIC?
To understand the role of gluons in binding quarks & gluons into Nucleons and Nuclei





Role of gluons in hadron & nuclear structure

Dynamical generation of hadron masses & nuclear binding



- Massless gluons & almost massless quarks, *through their interactions,* generate more than 95% of the mass of the nucleons:

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

- Gluons carry ~50% the proton's momentum, **?%** of the nucleon's spin, and are responsible for the transverse momentum of quarks

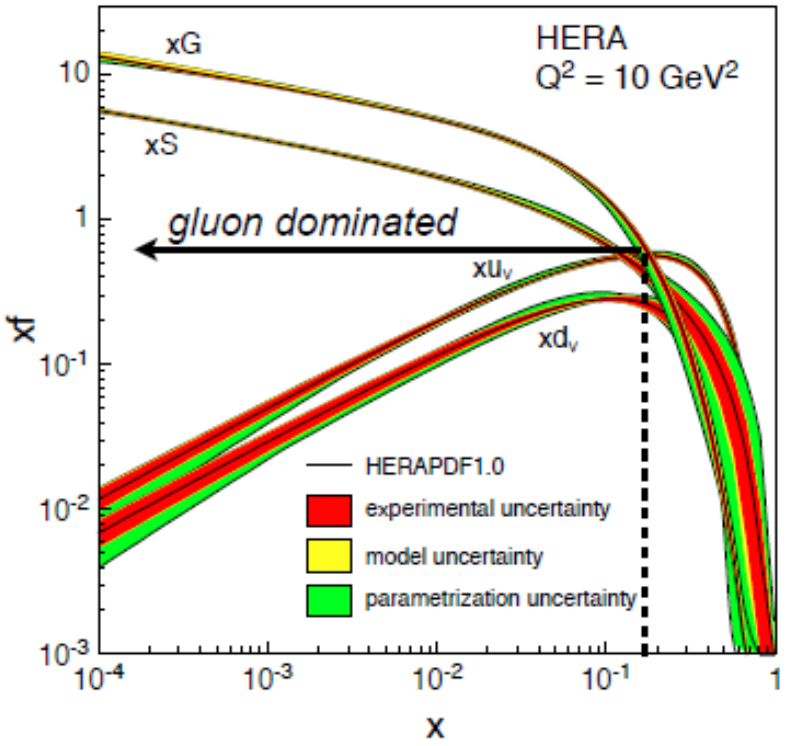
- The quark-gluon origin of the nucleon-nucleon forces in nuclei not quite known

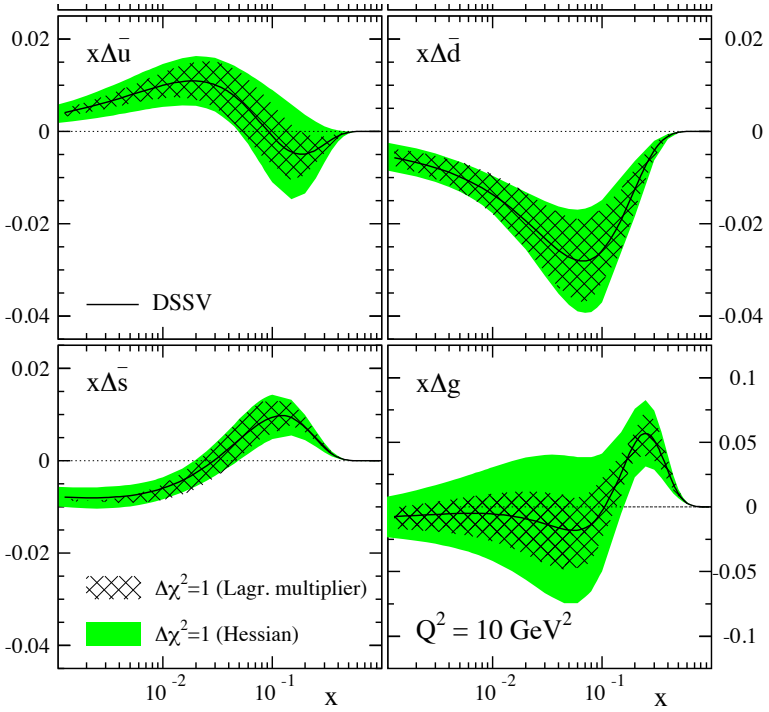
- Lattice QCD can't presently address dynamical properties on the light cone

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

CONFINEMENT!

What does a proton look like?
Unpolarized & polarized parton distribution functions





Need to go beyond 1-dimension!

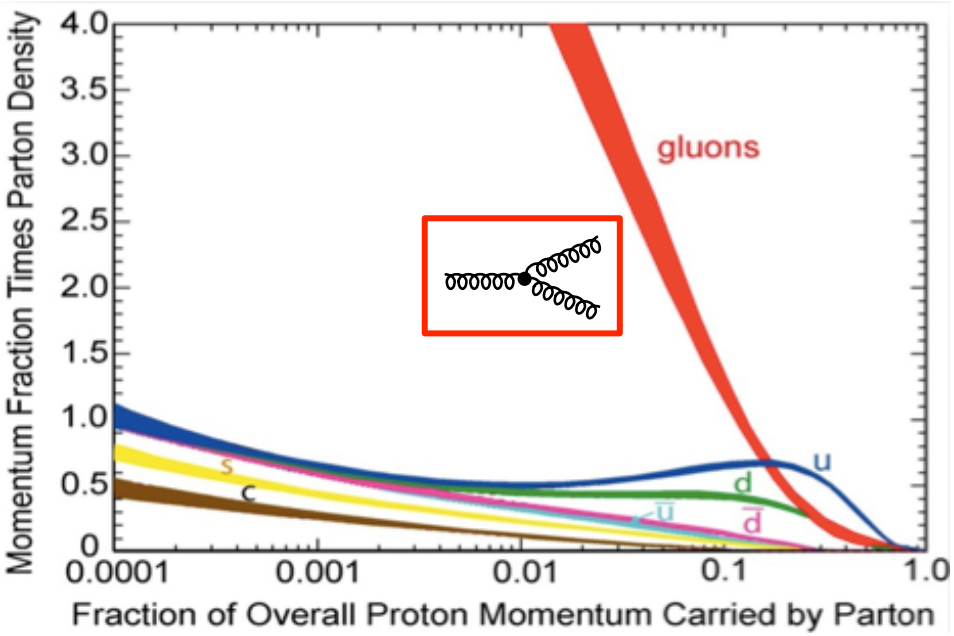
Need 3D Images of nucleons in Momentum & Position space

Could they give us clues on orbital motion of partons?

Understanding the nucleon spin

Gluon and the consequences of its interesting properties:

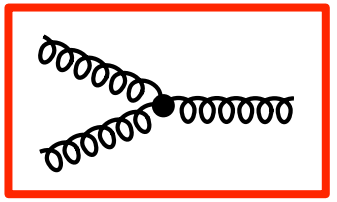
Gluons carry color charge ➔ Can interact with other gluons!



Apparent "indefinite rise" in gluon distribution in proton!

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

recombination

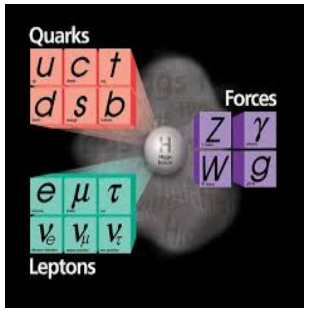


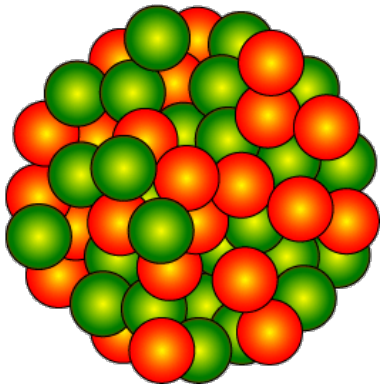
Where? No one has unambiguously seen this before!

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

Why an Electron Ion Collider?

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





The Electron Ion Collider

Two options of realization!

For e-N collisions at the EIC:

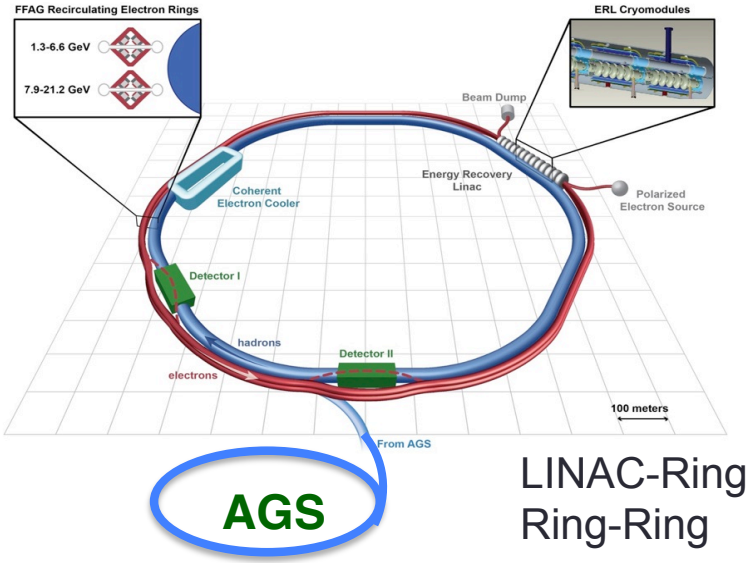
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

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

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

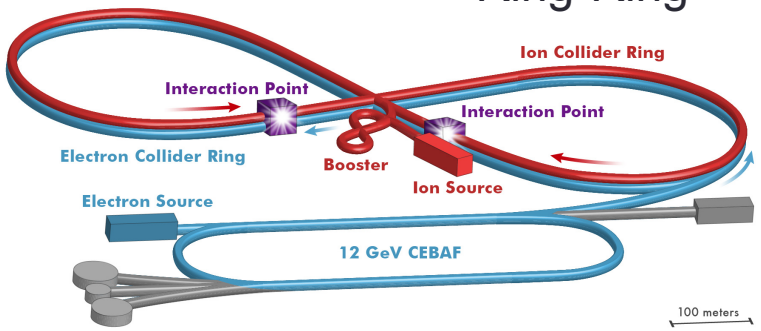
Both designs use DOE's significant investments in infrastructure



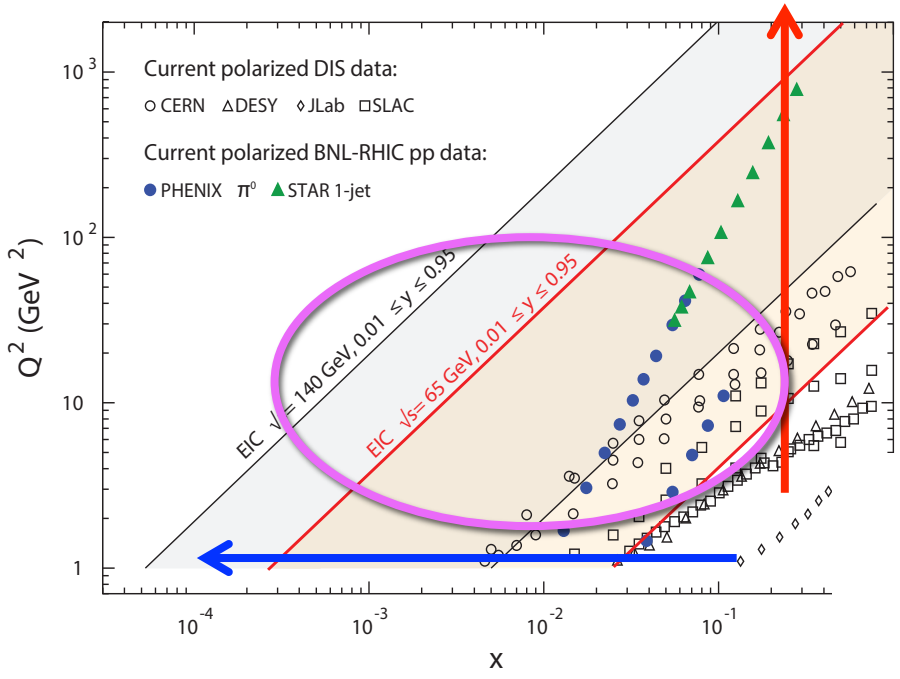
LINAC-Ring
Ring-Ring

Not to scale

Ring-Ring



EIC: Kinematic reach & properties

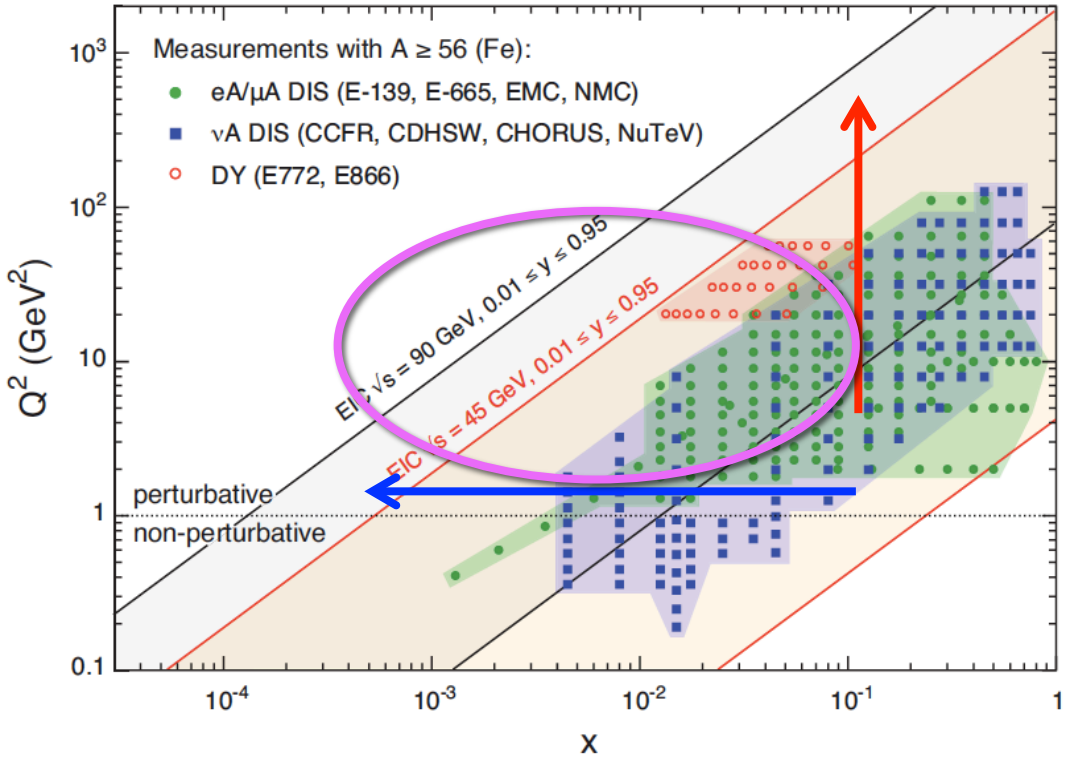


For e-N collisions at the EIC:

- ✓ **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

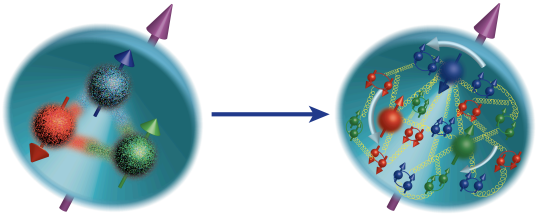
For e-A collisions at the EIC:

- ✓ **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)



Proton as a laboratory for QCD

3D structure of hadrons in momentum and position space….

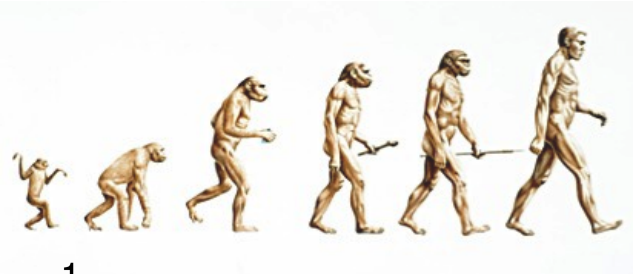


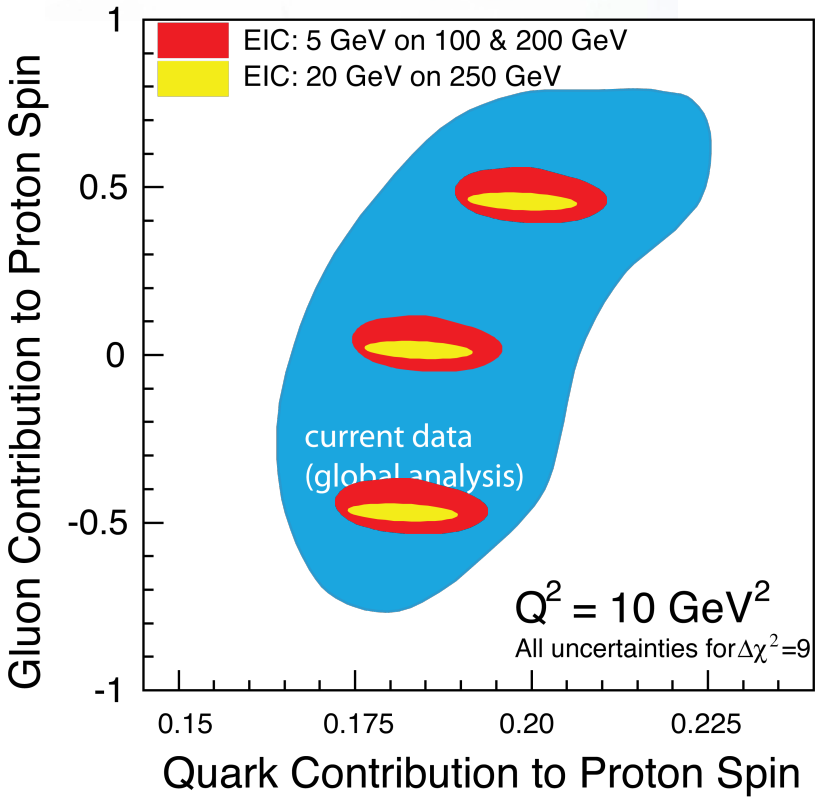
Our Understanding of Nucleon Spin

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

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

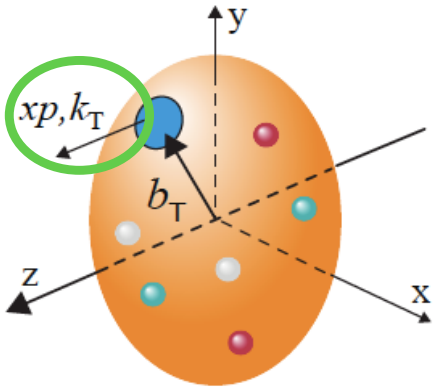
Precision in $\Delta\Sigma$ and Δg ➔ A clear idea Of the magnitude of L_Q+L_G

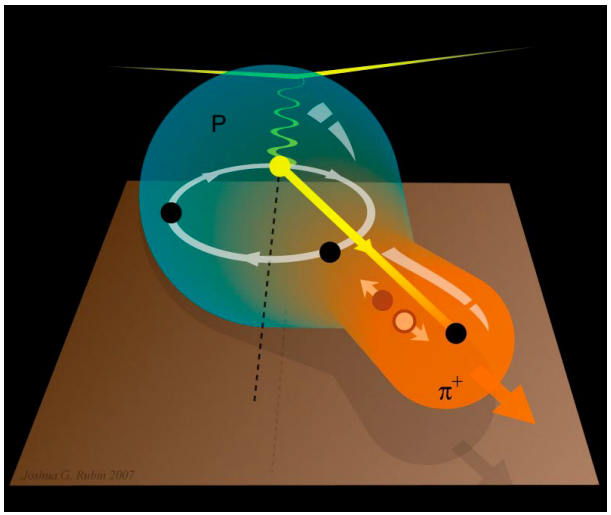


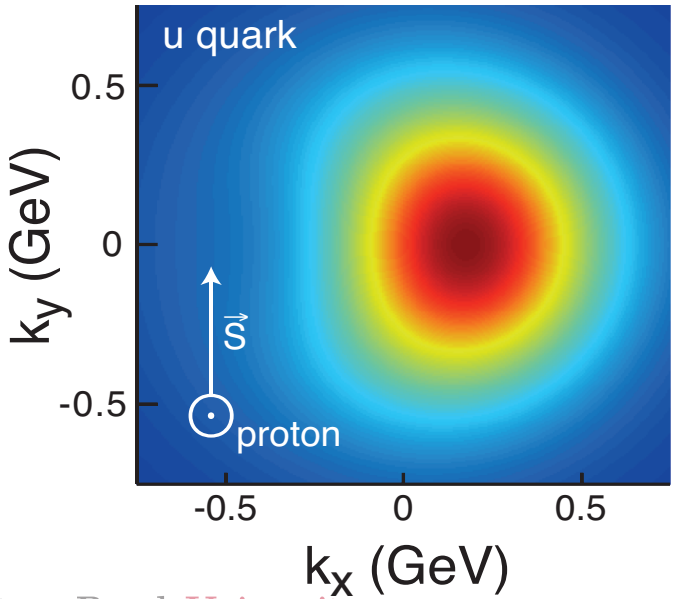


Measurement of Transverse Momentum Distribution

Semi-Inclusive Deep Inelastic Scattering

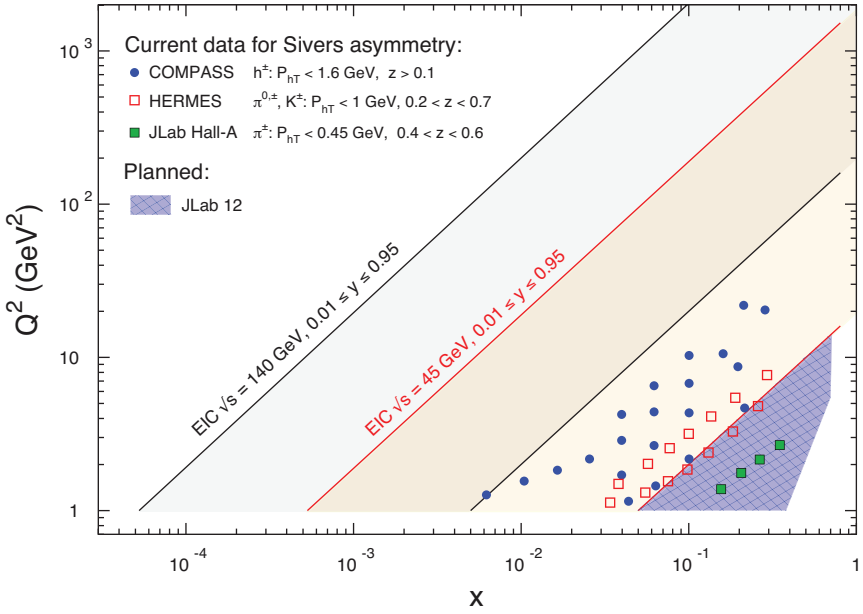






- Naturally, two scales:
  - high Q – localized probe
    To "see" quarks and gluons
  - Low p_T – sensitive to confining scale
    To "see" their confined motion
  - *Theory – QCD TMD factorization*

Scope & possible impact of EIC on Sivers Function measurements.... Quark TMDs



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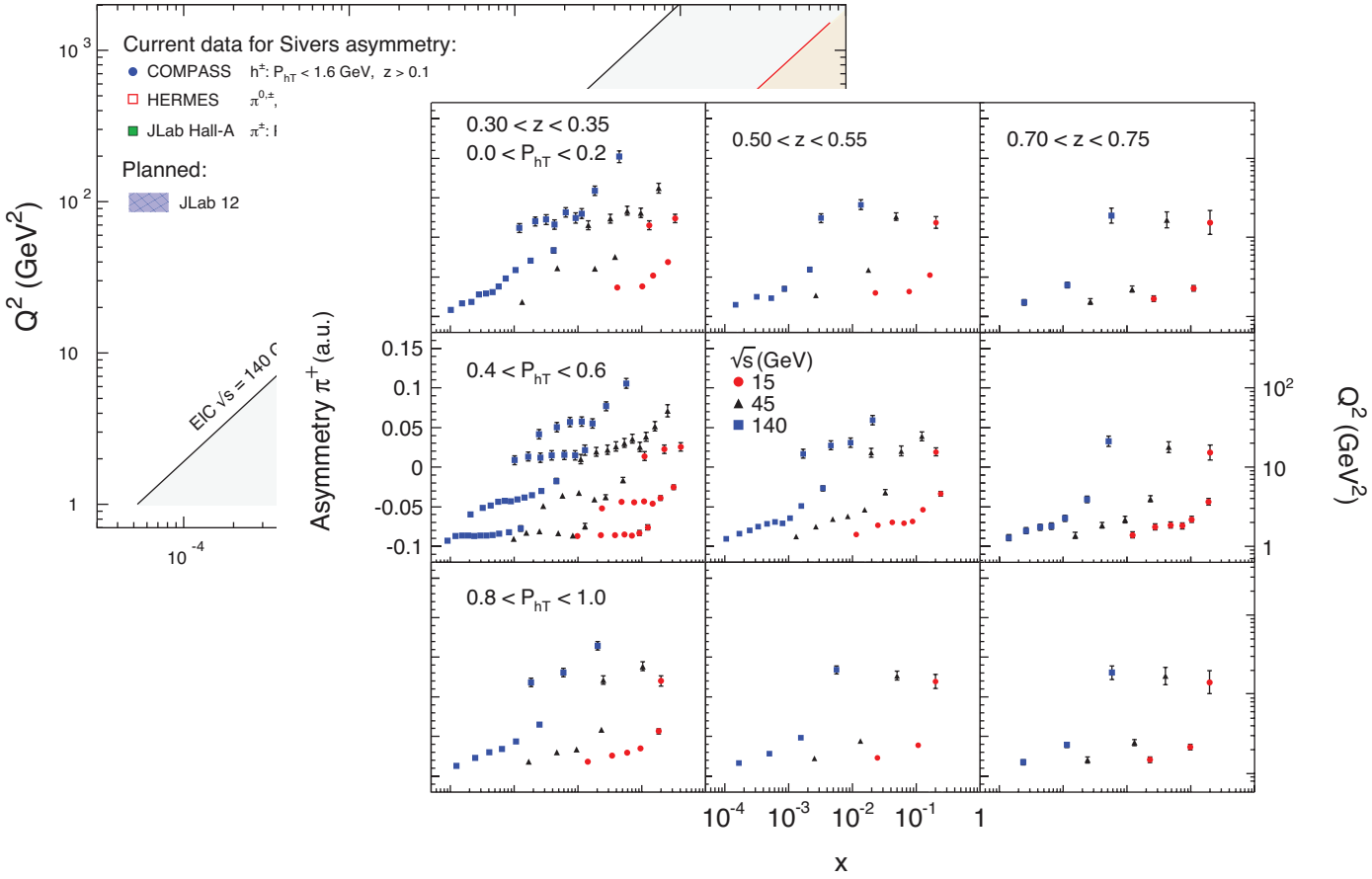
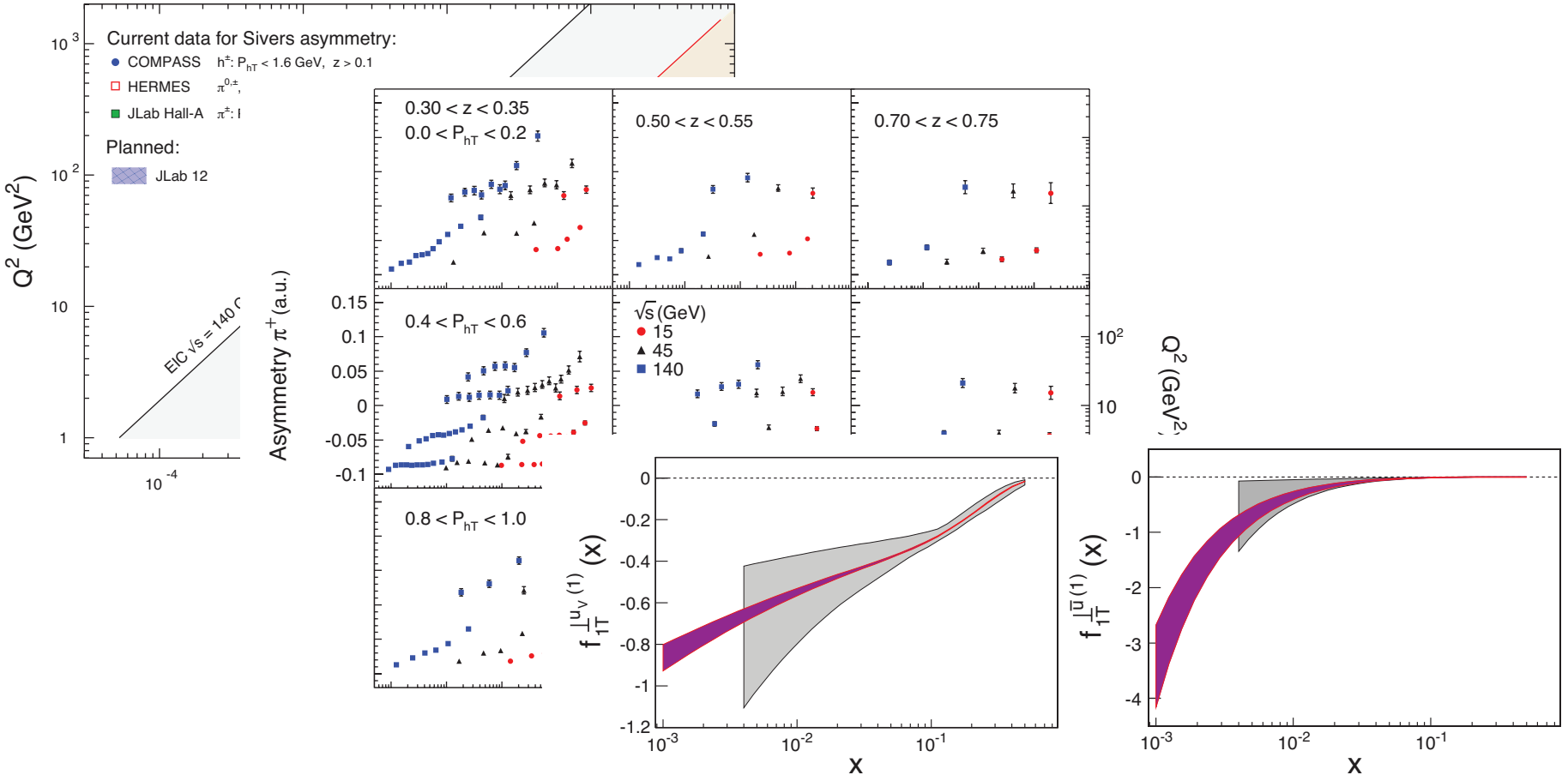


All for 10 fb^{-1} luminosity.....

Scope & possible impact of EIC on Sivers Function measurements.... Quark TMDs



Stony Brook University

All for 10 fb^{-1} luminosity.....

Gluon TMDs just as important, but no measurements yet!

Possible to measure them at the EIC with the following possible measurement campaigns:

- Di-Jet or Di-hadron production through photon-gluon-fusion process
- Heavy quark production
- Quarkonium production

--- All with *transversely polarized* hadrons in e-p, e-A_{light}

These measurements were thought of but not fully wetted for prime-time simulations studies (other than di-meson production) before the EIC-White Paper. Now these studies are timely.

Gluon TMDs just as important, but no measurements yet!

Possible to measure them at the EIC with the following possible measurement campaigns:

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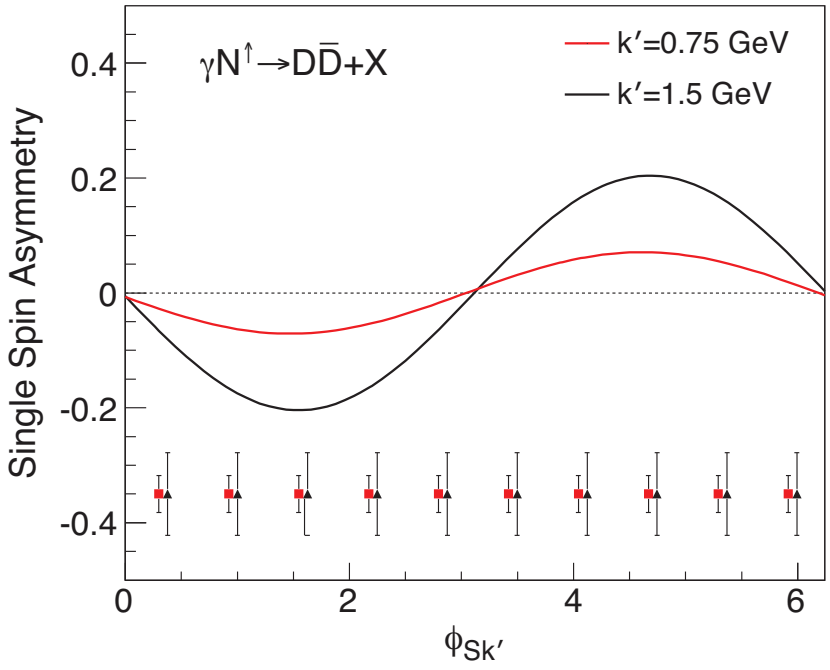
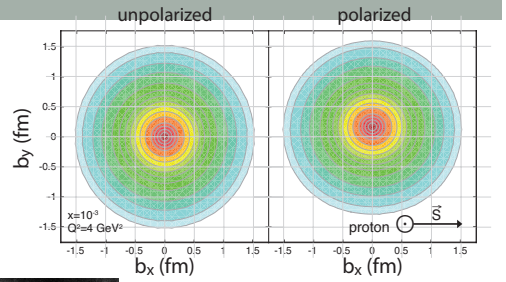


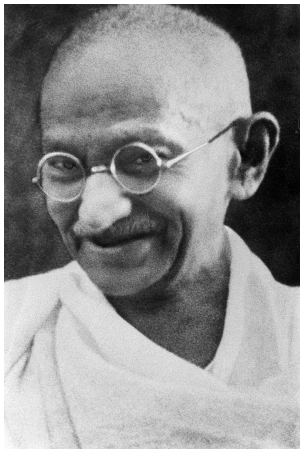
Spatial Imaging of quarks & gluons

Generalized Parton Distributions

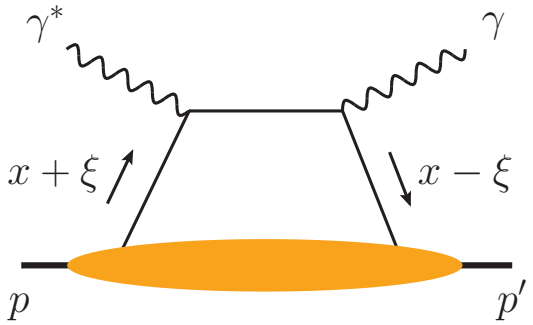


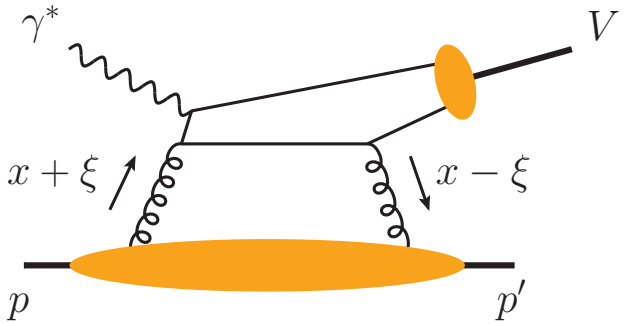
Historically, investigations of nucleon structure and dynamics involved breaking the nucleon…. (exploration of internal structure!)

To get to the **orbital motion** of quarks and gluons we need **non-violent collisions**



Quarks Motion





Gluons: Only @ Collider

Deeply Virtual Compton Scattering
Measure all three final states
e + **p** → e'+ **p'**+ γ

Fourier transform of momentum transferred=(p-p') → Spatial distribution

Stony Brook

Exclusive measurements → measure "everything"

3-Dimensional Imaging Quarks and Gluons

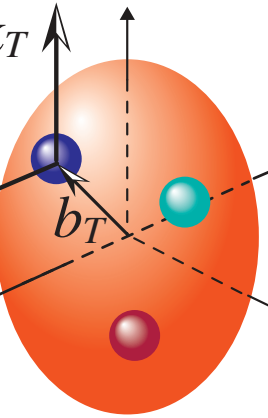
Momentum space

$W(x,b_T,k_T)$

$\int d^2b_T$

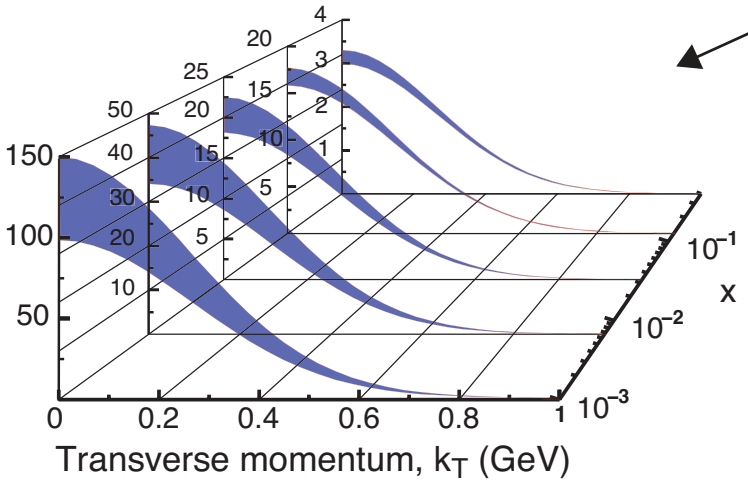
$\int d^2k_T$

Coordinate space



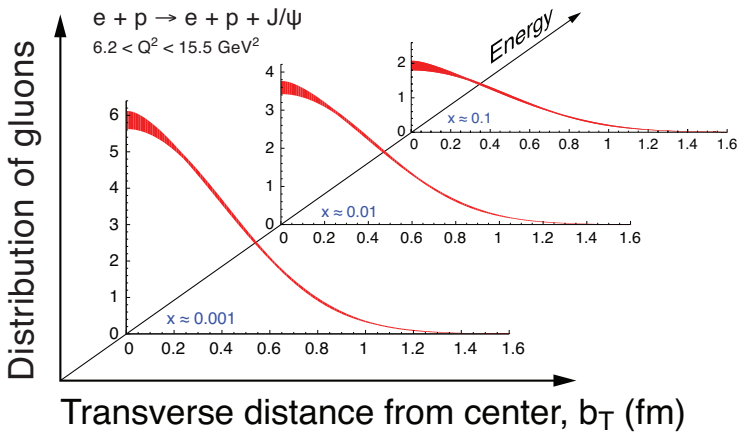
Quarks

$f(x,k_T)$



$f(x,b_T)$

Gluons



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

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

3-Dimensional Imaging Quarks and Gluons

Momentum space

Coordinate space

$W(x,b_T,k_T)$

$\int d^2b_T$

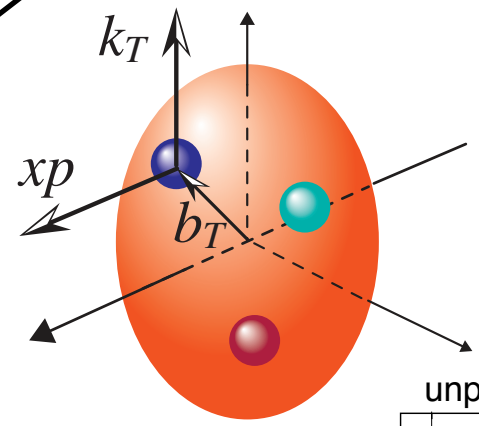
$\int d^2k_T$

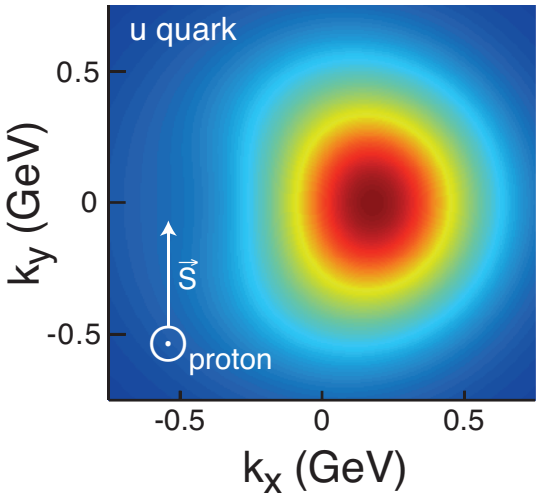
$f(x,k_T)$

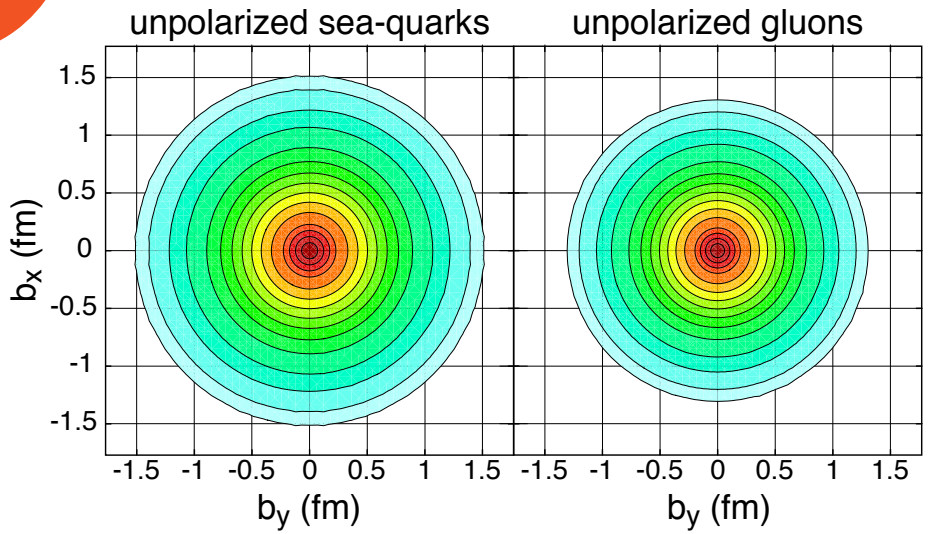
$f(x,b_T)$

Quarks

Gluons



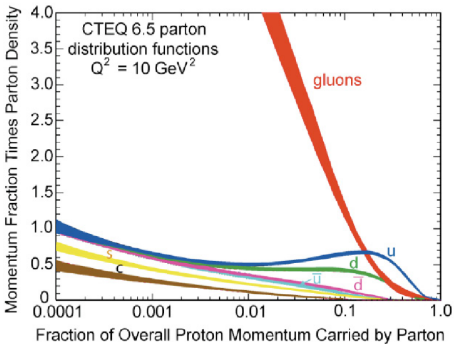




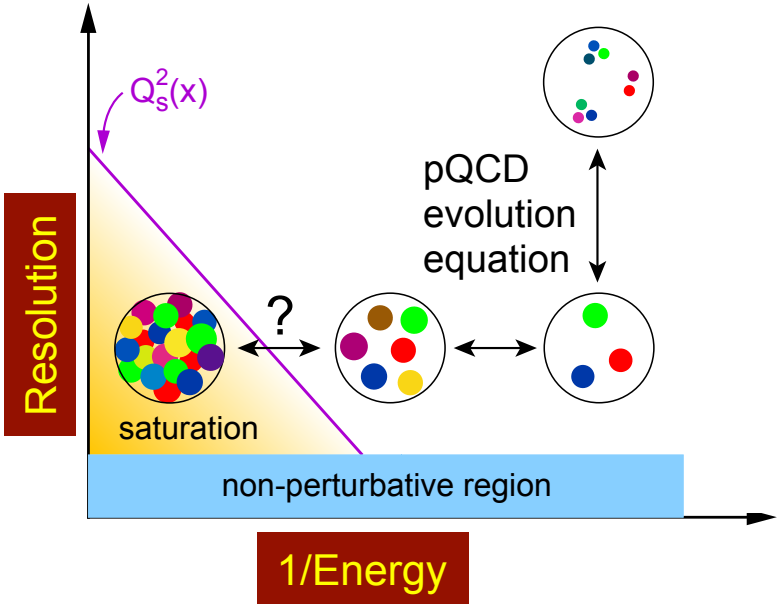
Position r X Momentum p → Orbital Motion of Partons

➔ *Directly comparable with Lattice QCD Calculations*

Stony Brook



What do we learn from low-x studies?



What tames the low-x rise?

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

gluon emission = gluon recombination

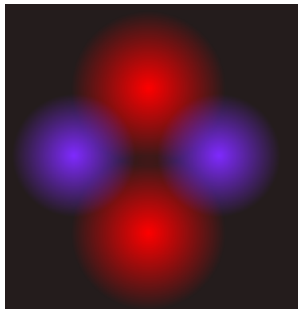
At Q_S

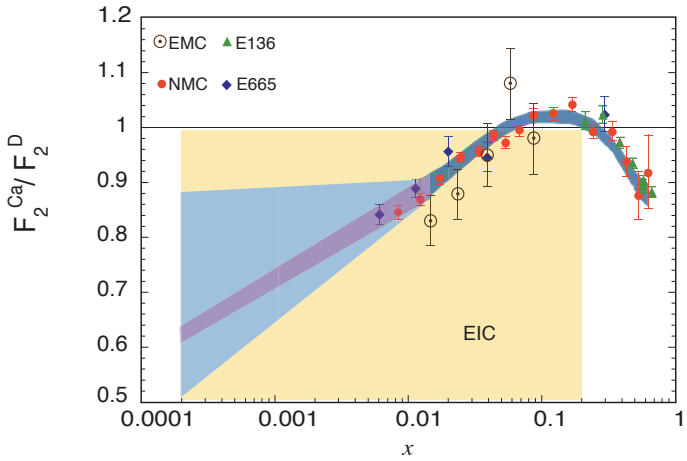
First observation of gluon recombination effects in nuclei:
➔leading to a *collective* gluonic system!
First observation of g-g recombination in *different* nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

Puzzles and challenges….

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

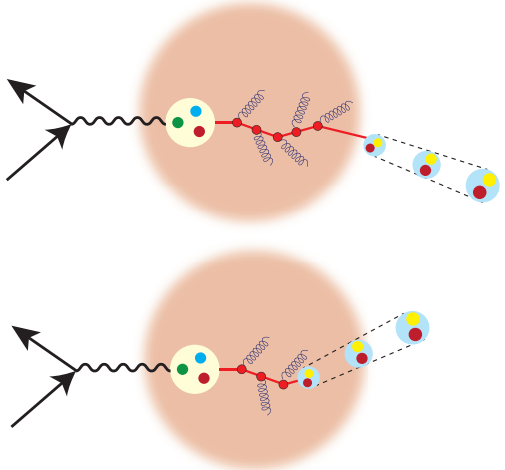
Are gluons distributions broader than quark distributions in nuclei?





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

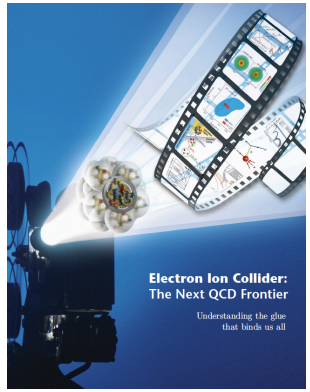
Color correlations within nuclei



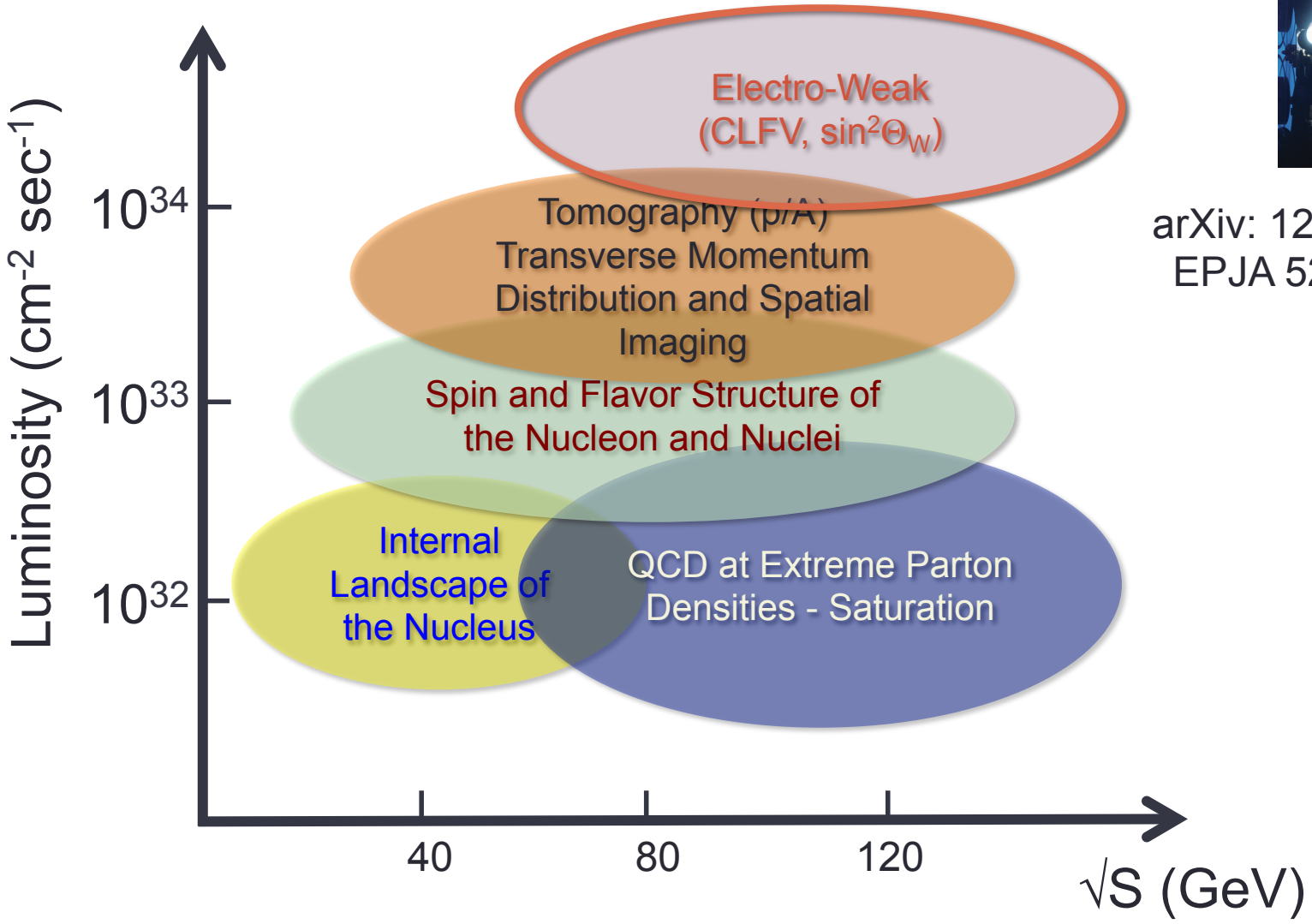
How does nuclear matter respond to fast moving color charge passing through it? (hadronization…. confinment?)

➔ How does a jet propagate through a nucleus (new?)

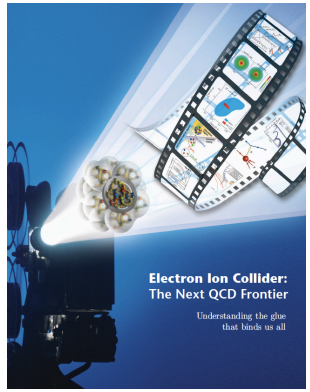
Physics vs. Luminosity & Energy



arXiv: 1212.1701.v3
EPJA 52, 9 (2016)



Physics vs. Luminosity & Energy



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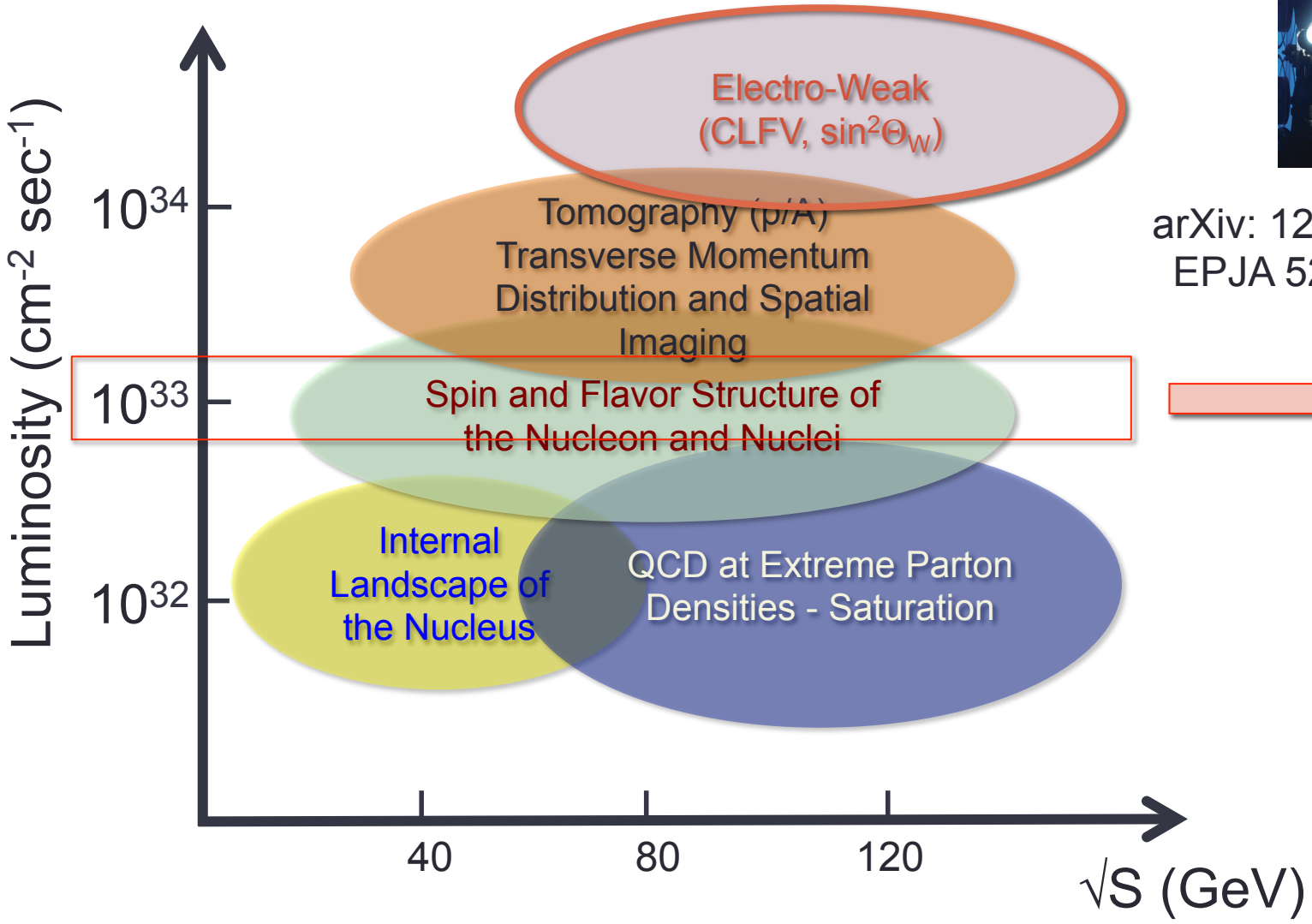


Uncharted physics terrains for EIC:

- Impact of super-precise PDFs in $x > 0.0$, $1 < Q^2 < 100$ GeV^2 for future Higgs studies (some insight through LHeC studies, but serious effort on EIC beginning now).
- What role would transverse W production in e-p play? (Transverse W-Production at LHC) – (this WS)

- Heavy quark and quarkonia (c, b quarks) studies beyond HERA, with 100-1000 times luminosities (??)
- What if the hadrons are transversely polarized? (this WS)

- Internal structure of jets with variability of CM 50-140 GeV^2, in comparison with HERA, Tevatron & LHC energies, and with controlled electron & proton polarizations (jet fragmentation studies) aided by knowledge from e+e- physics at BaBar/Belle & in future Super-Belle ("Collins Functions")
- Jet propagation in nuclei… a topic interest (this WS)

- Other low x studies with nuclei….. Gluon TMDs at low-x! (this WS)

REALIZATION….

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

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

RECOMMENDATION:

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

Initiatives:

Theory
Detector & Accelerator R&D

NEW Money for EIC Accelerator R&D already assigned $7m/yr

Detector R&D money ~1.3M/yr
Needs significant increase

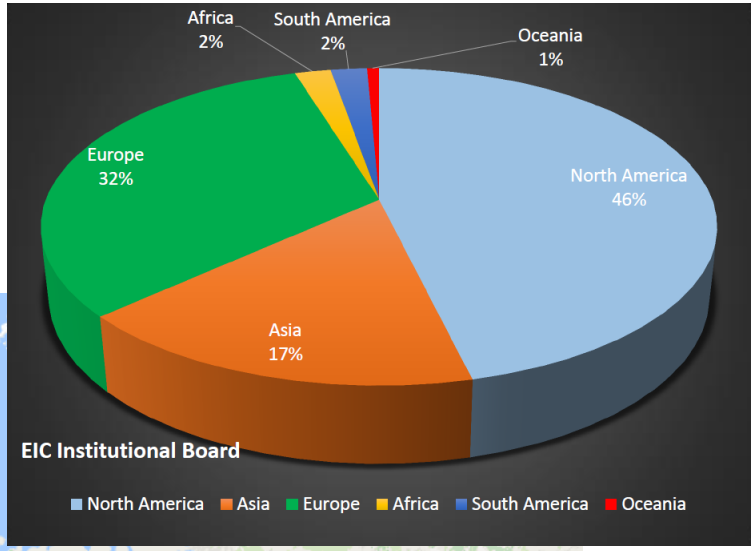
The EIC Users Group: EICUG.ORG

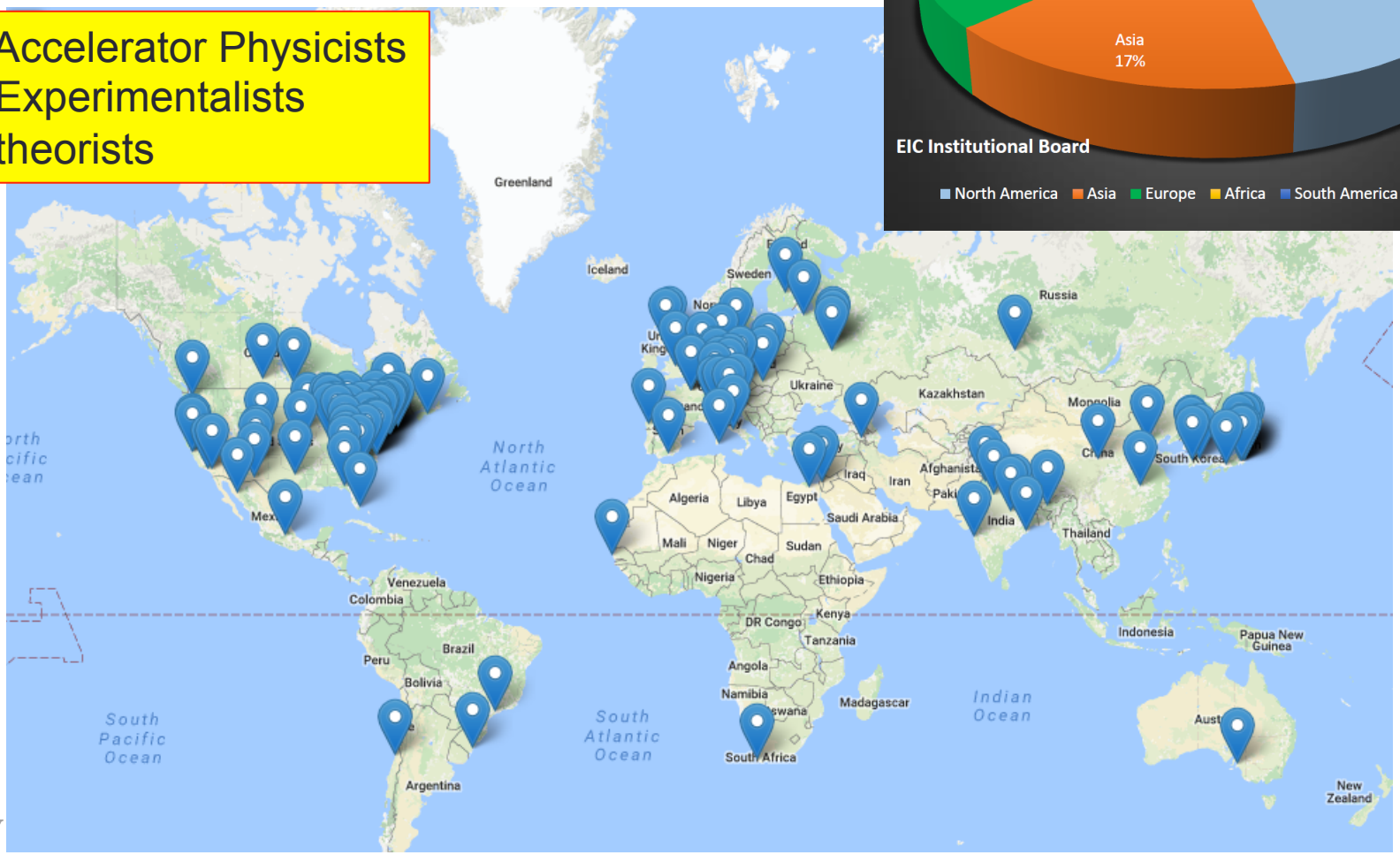
(no students included as of yet)

663 collaborators, 28 countries, 147 institutions... (October 09, 2016)

Map of institution's locations

~141 Accelerator Physicists
~391 Experimentalists
~131 theorists





Stony

Community/Collaboration building:

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

The EIC Users Meeting at Stony Brook, June 2014:

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

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

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

Recent EICUG Argonne National Laboratory July 7-10, 2016

http://eic2016.phy.anl.gov

Next two meetings:

January 2017 (BlueJeans)

July 18-22, 2017 Trieste, Italy

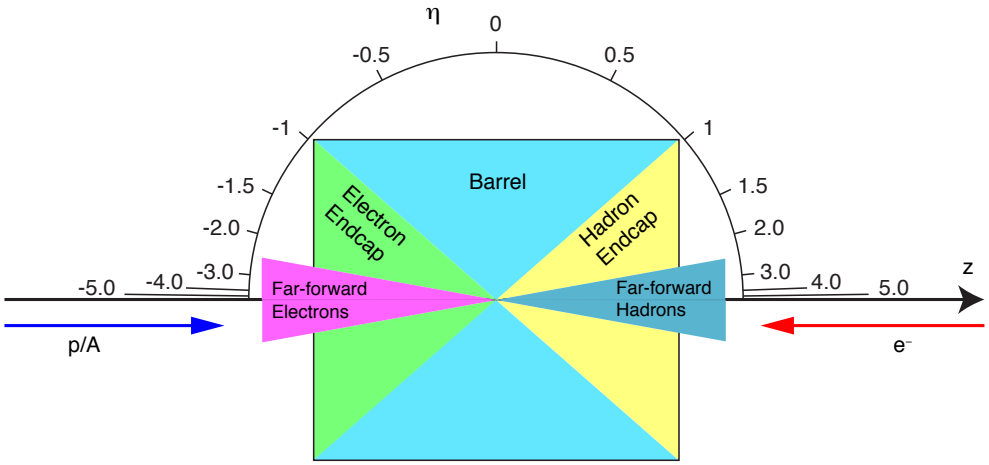
Ample opportunities for contributions & participation!

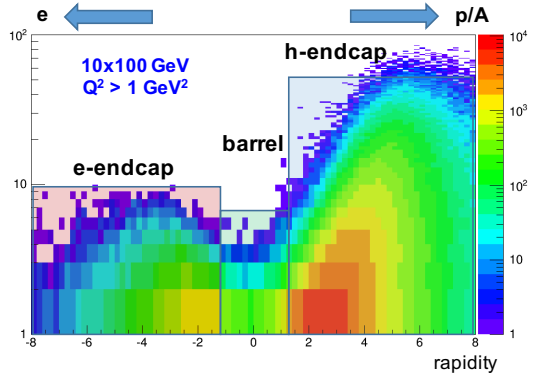
EIC Detector Concepts

Requirement are mostly site-independent with some slight differences in the forward region (IR integration)

In Short:

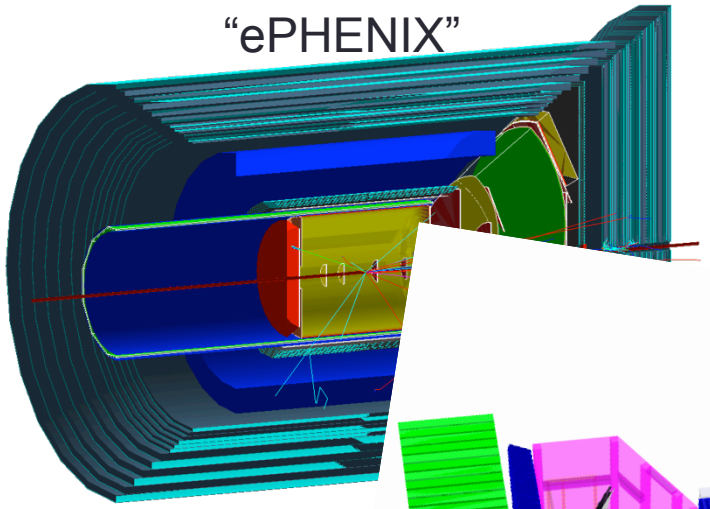
- Hermetic detector, low mass inner tracking, good PID (e and π/K/p) in wide range, calorimetry
- Moderate radiation hardness requirements, low pile-up, low multiplicity

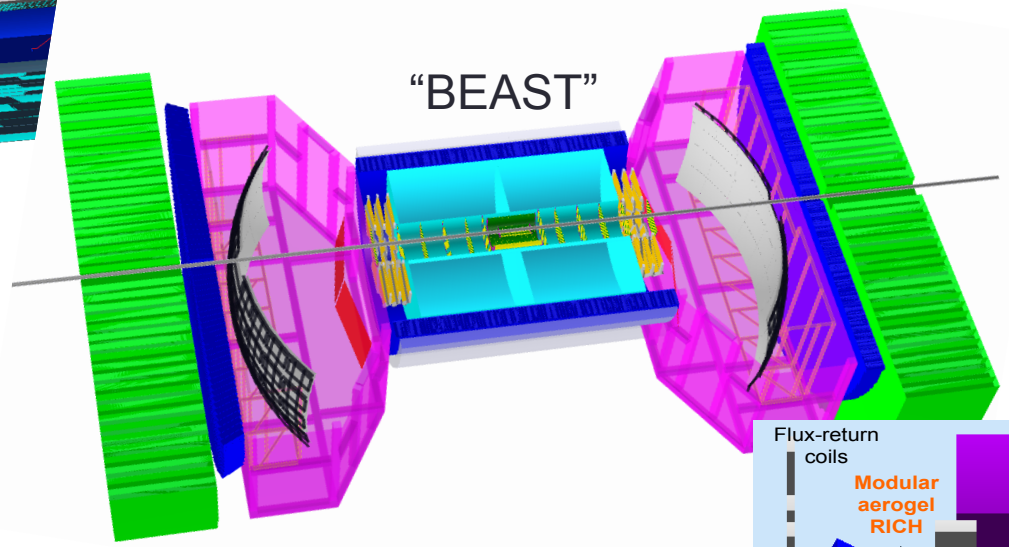




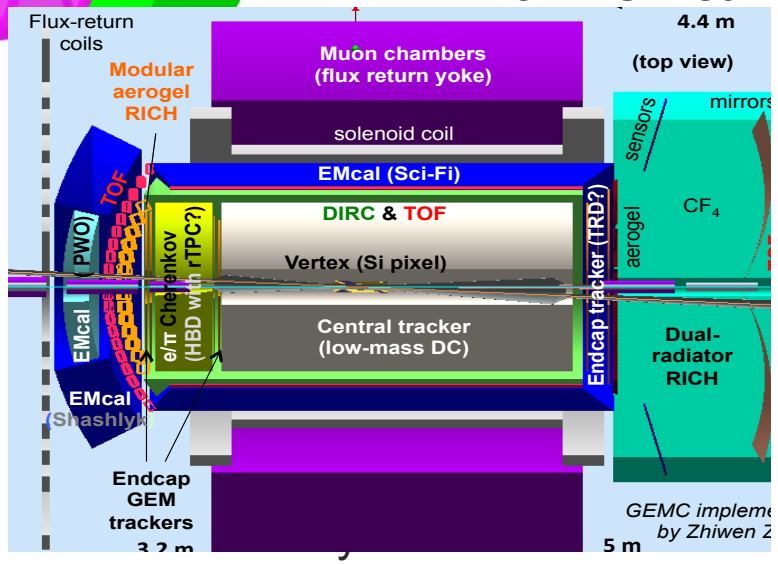
Curtsey of Thomas Ullrich

EIC Detector Concepts





JLEIC Det



Path forward for the EIC:

- Science Review by National Academy of Science (& Engineering & Arts) (National Research Council)
  - Committee being formed now, expect report by September 2017

- Positive NAS review will trigger the DOE's CD process
  - CD0 (acceptance of the critical need for science by DOE) FY18
  - EIC-Proposal's Technical & Cost review → FY19 (site selection)
  - CD2 requires site selection
  - **Major Construction funds ("CD3") by 2022/23"**
    - Assuming 1.6% sustained increase over inflation of the next several years (Long Range Plan)
    - Consistent with the past 10 years of NP funding increases in the US

Explore in this workshop on TMDs…

While EIC will do nothing directly to compete with measure things at the LHC energies ….

It will measure things in QCD: precisely and enhance our understanding of QCD….

Such that measurements made at LHC would be clearly interpreted as signals within or outside of the Standard Model….

Explore in this workshop on TMDs…

While EIC will do nothing directly to compete with measure things at the LHC energies ….

It will measure things in QCD: precisely and enhance our understanding of QCD….

Such that measurements made at LHC would be clearly interpreted as signals within or outside of the Standard Model….

In this sense,

EIC will contribute in such a way as to make LHC worth its cost… both in money and its gigantic effort!

--Perhaps too provocative a statement…. But may be…

Summary:

The EIC (with its precision and control) will profoundly impact our understanding of **the many body structure of nucleons and nuclei in terms of sea quarks & gluons** → ***The bridge between sea quark/gluons to Nuclei***

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

→ ***High potential for discovery***

New physics opportunities are now being explored… connections to science of LHC are manifesting themselves and proving to be important:

- **Uncertainties in the Higgs production in LHC-II era**
- **Transverse momentum distributions and their consequences to LHC observables (p_T of W's at LHC for example)**
- **Gluon TMDs…..**

All being explored in this workshop…

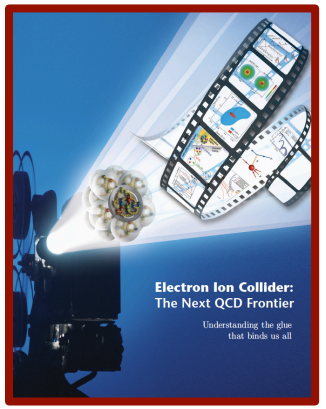
Future QCD studies, (even at LHC(?)) demands an Electron Ion Collider

NSAC agrees and we are moving forward!

THANK YOU

Thanks to many of my EIC Collaborators and Enthusiasts who led many of the studies presented in this talk
See: arXiv:1108.1713, D. Boer et al.

Without the EIC White Paper Writing Group the EIC White Paper would not have existed.
Special thanks to Dr. Jianwei Qiu and Prof. Zein-Eddine Meziani, my Co-Editors for the EIC White Paper
See: arXiv:1212.1701.v3 , A. Accardi et al.
Eur. Phy. J. A 52, 9 (2016)



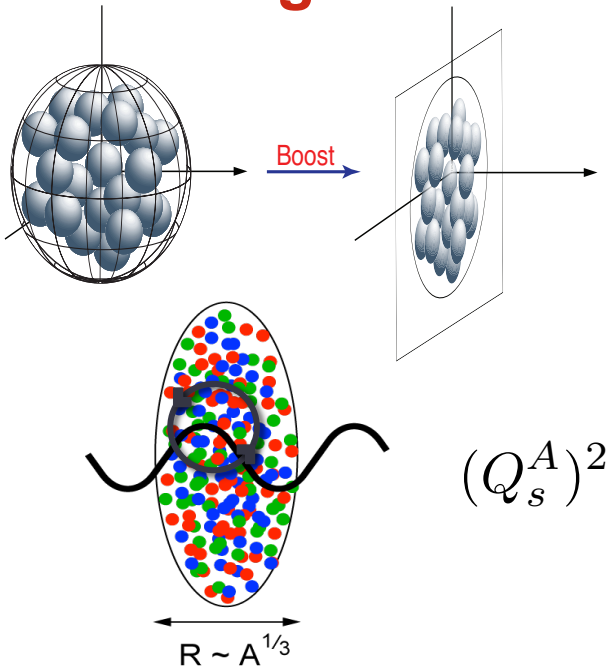
The eRHIC and JLEIC machine design teams

Also gratefully acknowledge recent input from: M. Diefenthaler, R. Ent, R. Milner, R. Yoshida

How to explore/study this new phase of matter?

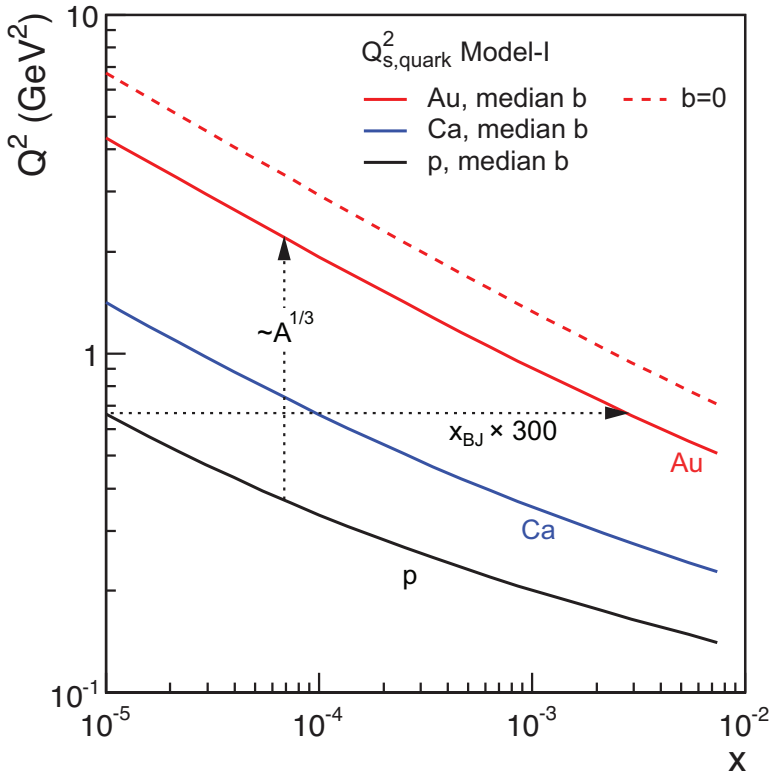
(multi-TeV) e-p collider OR **a (multi-10s GeV) e-A collider**

Advantage of nucleus →



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

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



Enhancement of Q_S with A:
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

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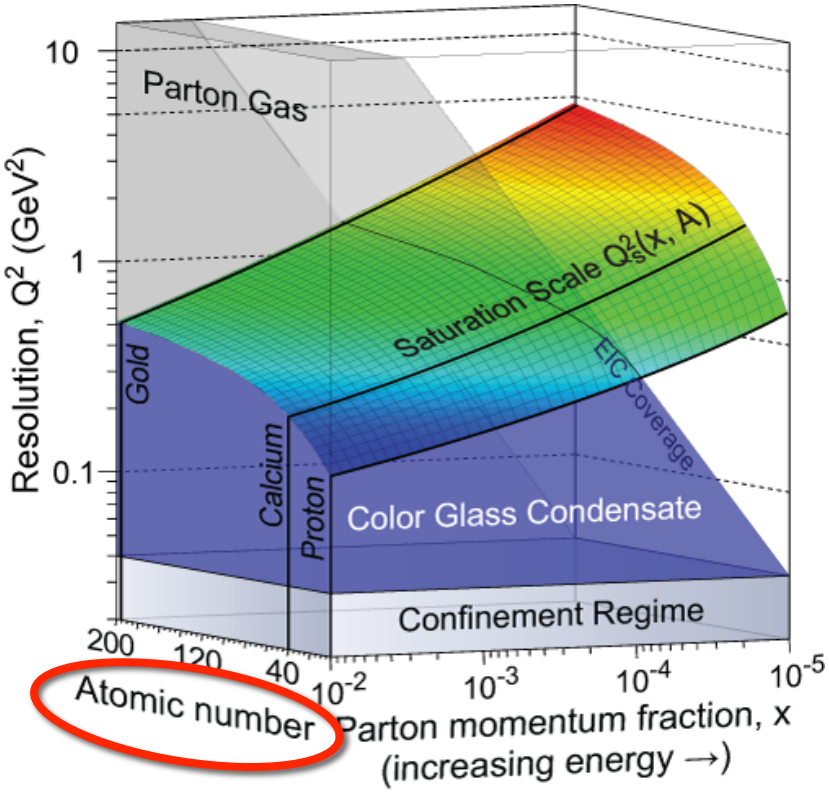
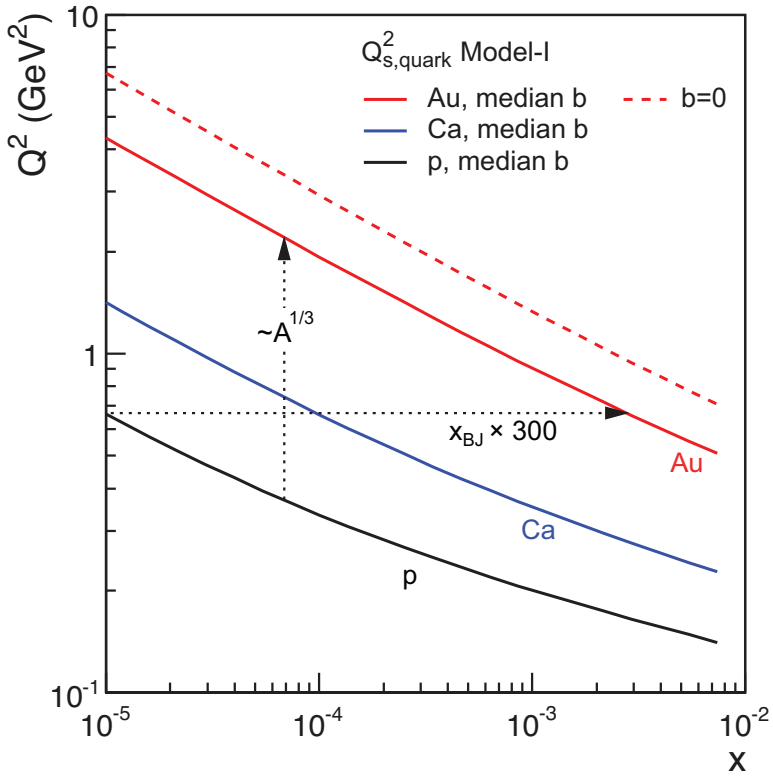




Enhancement of Q_S with A:
Saturation regime reached at significantly lower energy (read: "cost") in nuclei

Charge to the National Academy for the review of EIC (2016) (my rendition of the charge to fit on 1 slide)

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility

In particular, the committee will address the following questions:

- What is the merit and significance of the science? What is its importance in the overall context of research in nuclear physics and the physical sciences in general?
- Capabilities of other facilities, existing and planned, domestic and abroad? What would be the unique scientific role of the US EIC complementary to existing and planned facilities?
- What are the benefits to (US) leadership in nuclear physics?
- What are the benefits to other fields of science and to society?

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

The 2015 Long Range Plan for Nuclear Science

Not much time!

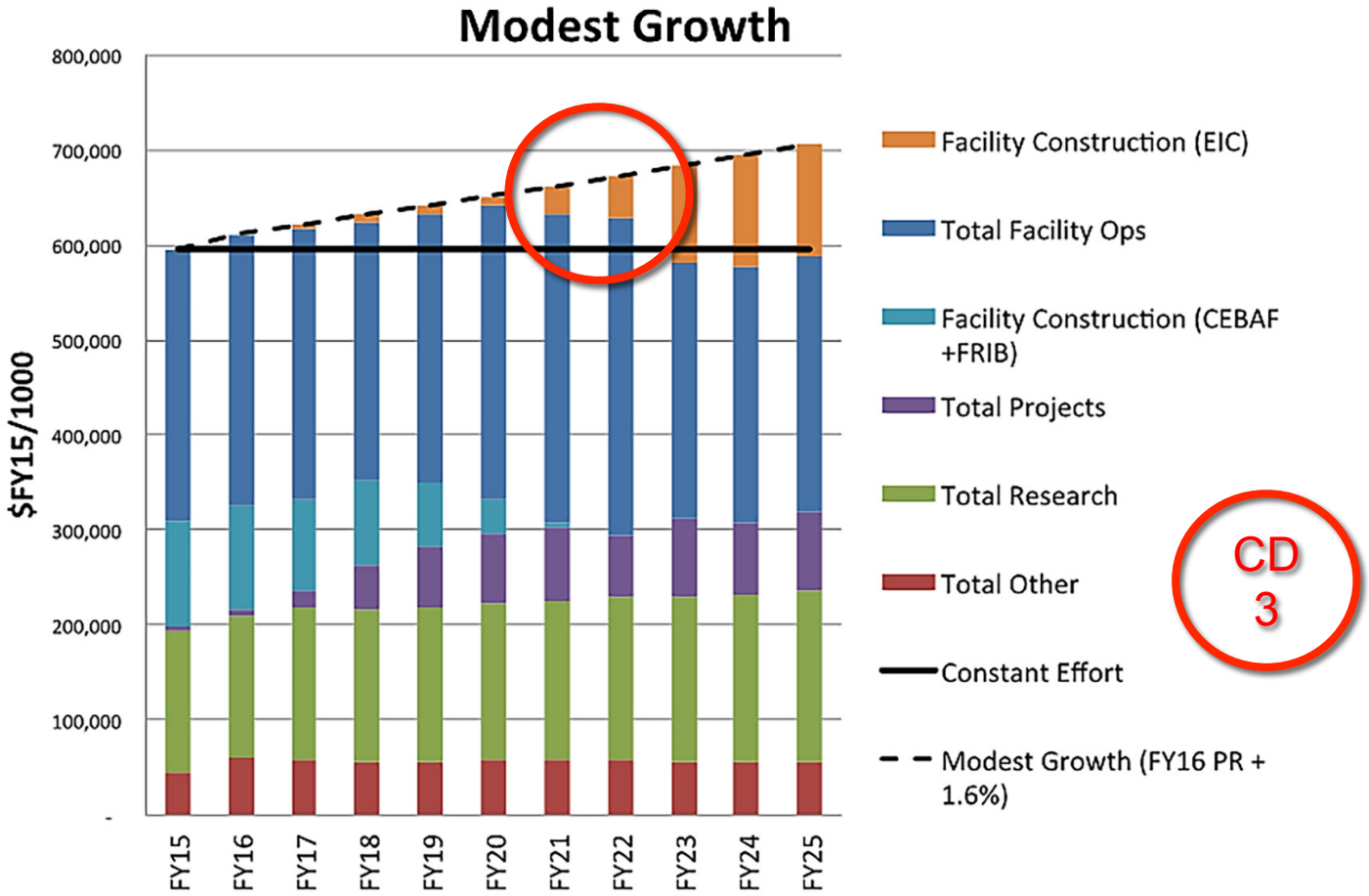
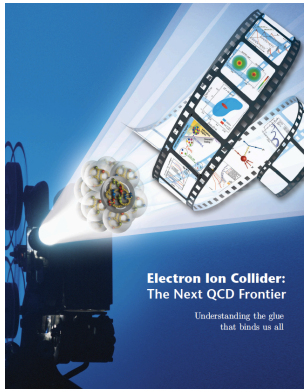
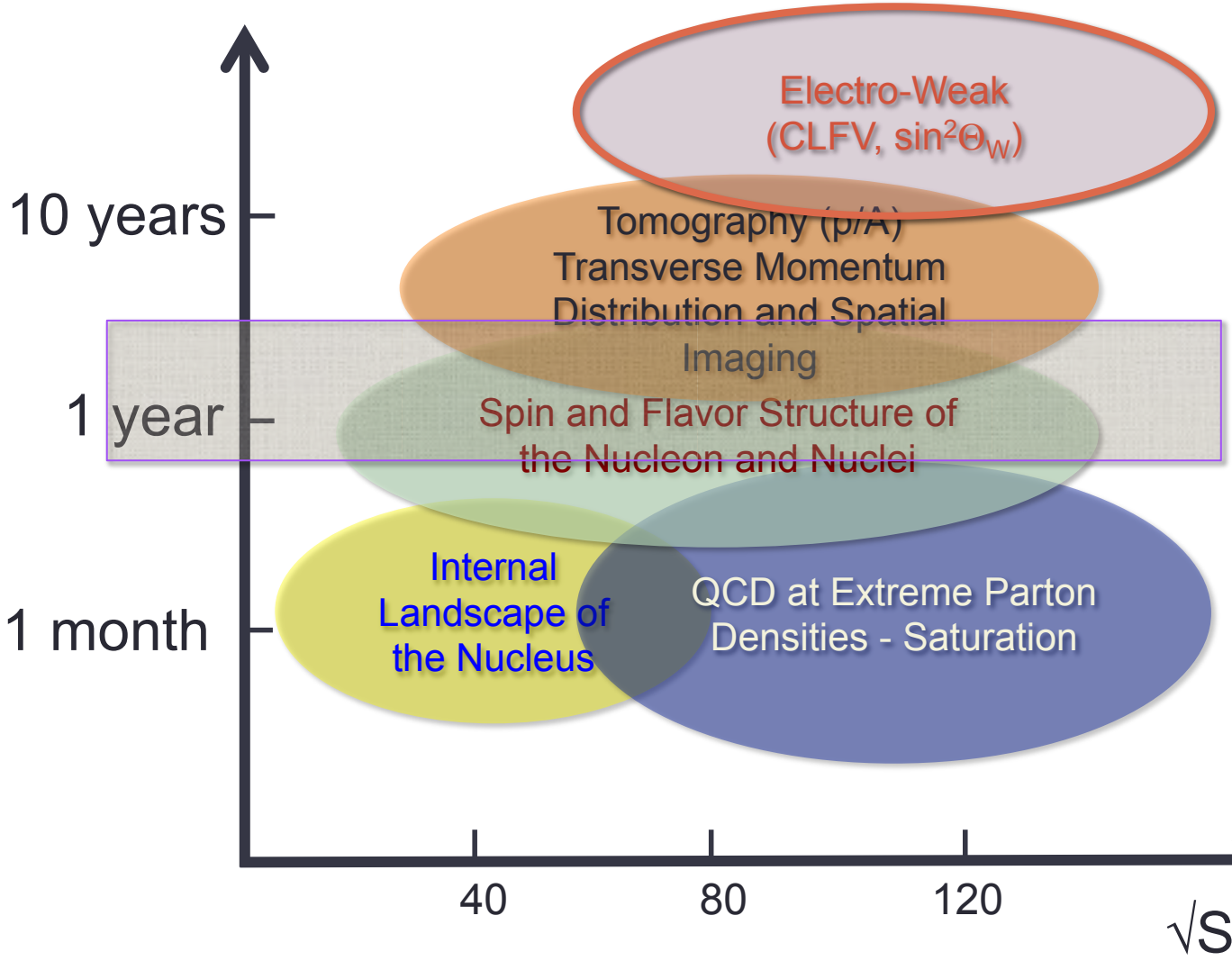


Figure 10.4: *DOE budget in FY 2015 dollars for the Modest Growth scenario.*

Physics vs. Luminosity & Energy





arXiv: 1212.1701.v3
EPJA 52, 9 (2016)

White Paper
Science Possible
With ~5-10** years
Of operation
At 10^{33} $cm^{-2}sec^{-1}$
luminosity

Stony Brook University

** Assuming realistic rise in EIC luminosity rise in time

Community/Collaboration building:

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