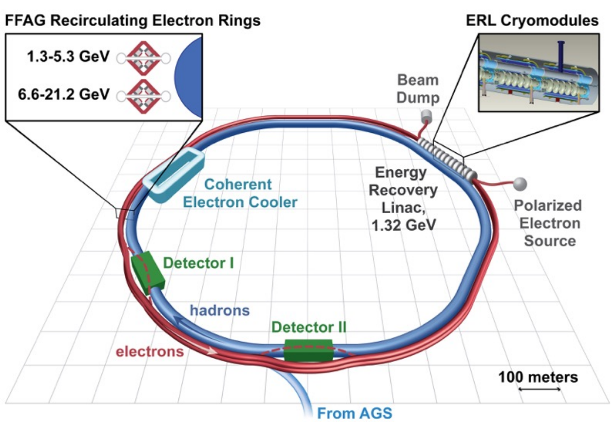
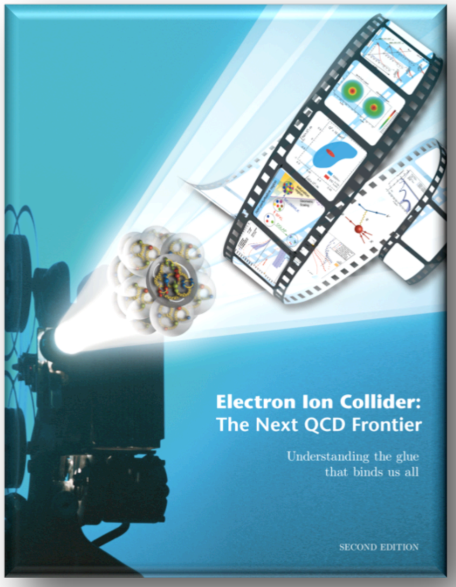
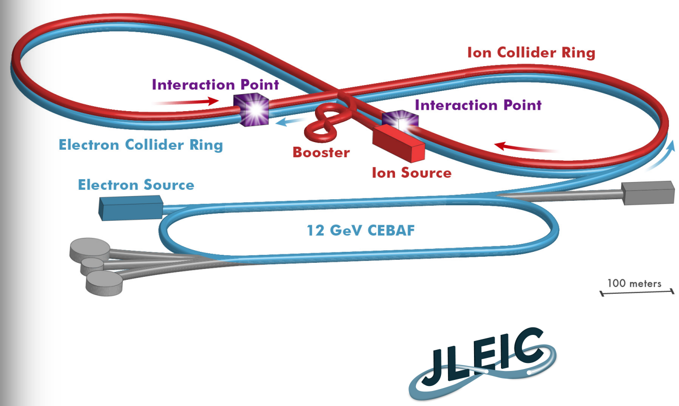
Electron-Ion Collider: Physics, Machine and Outlook







Rik Yoshida
Jefferson Lab

MENU 2016
June 25-29, Kyoto Japan

Jefferson Lab
Thomas Jefferson National Accelerator Facility

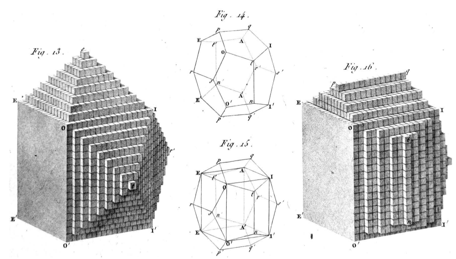
OUTLINE

- Physics of Electron-Ion Collider
  - New Probes and New Sciences
  - EIC Physics program
    - Nucleon structure
    - Nuclear structure
    - Beyond nuclear structure
- US Proposals for EIC
  - eRHIC and JLEIC
- US Nuclear Physics Long Range Planning Process
- The Next Steps in the US

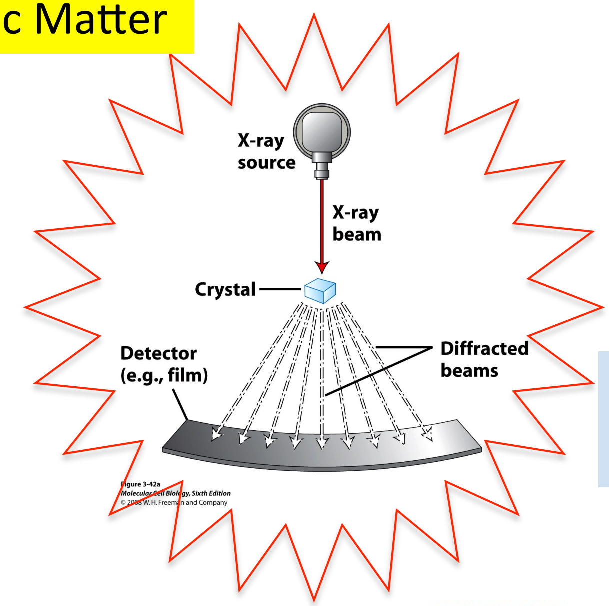
Physics of the Electron-Ion Collider

New Probes and New Science

Example: Structure of Atomic Matter

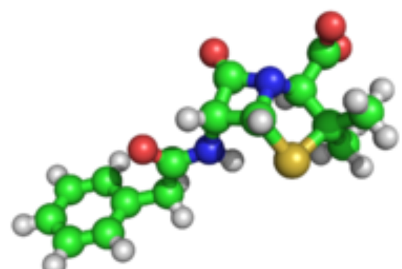


Crystal Structure: 1801

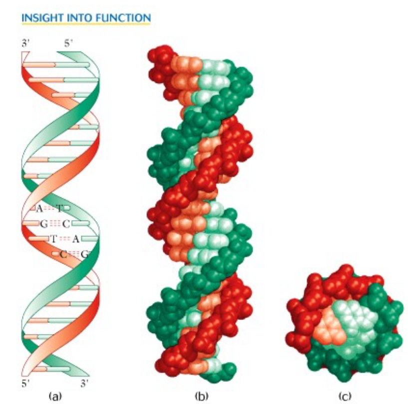


Advent of X-ray Diff. 1912

Probe with the right scale!



3D structure of penicillin: 1945

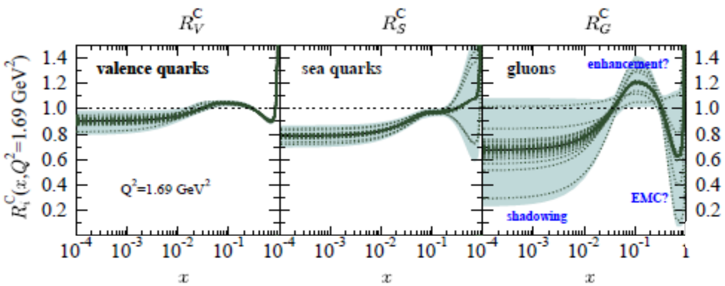


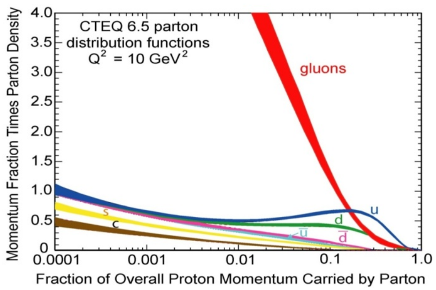
Double Helix: 1953

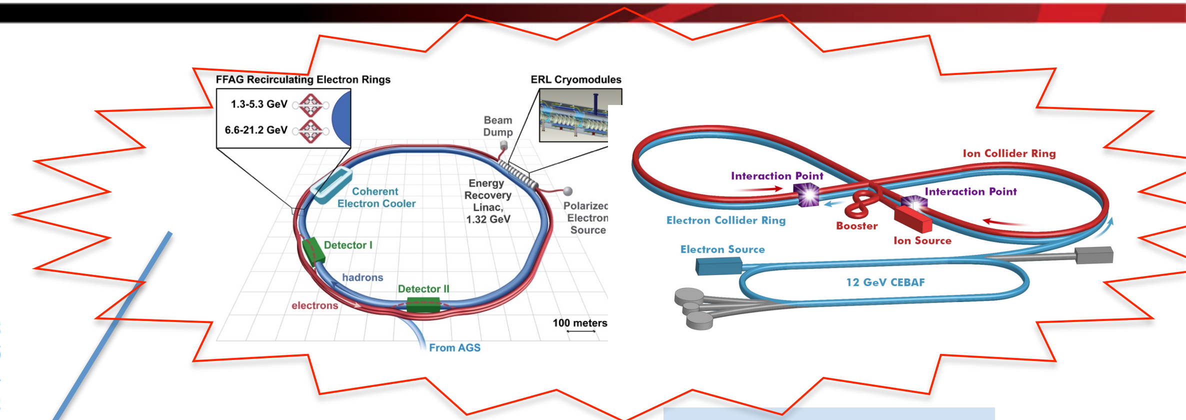
Precise understanding of structure leads to rich new sciences

New Probe for Nuclear Science

2016

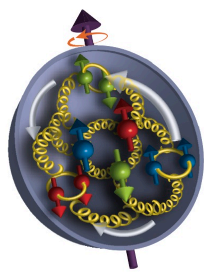


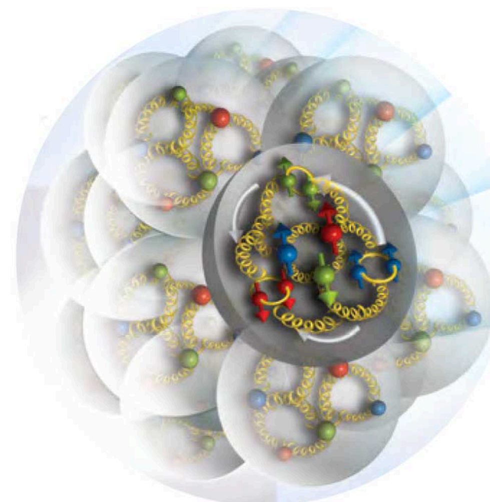




Advent of EIC: ~2027

Probe with the right scale!



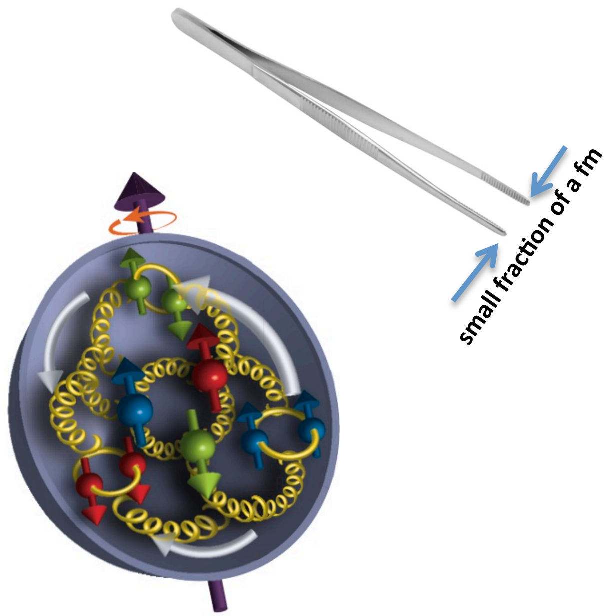


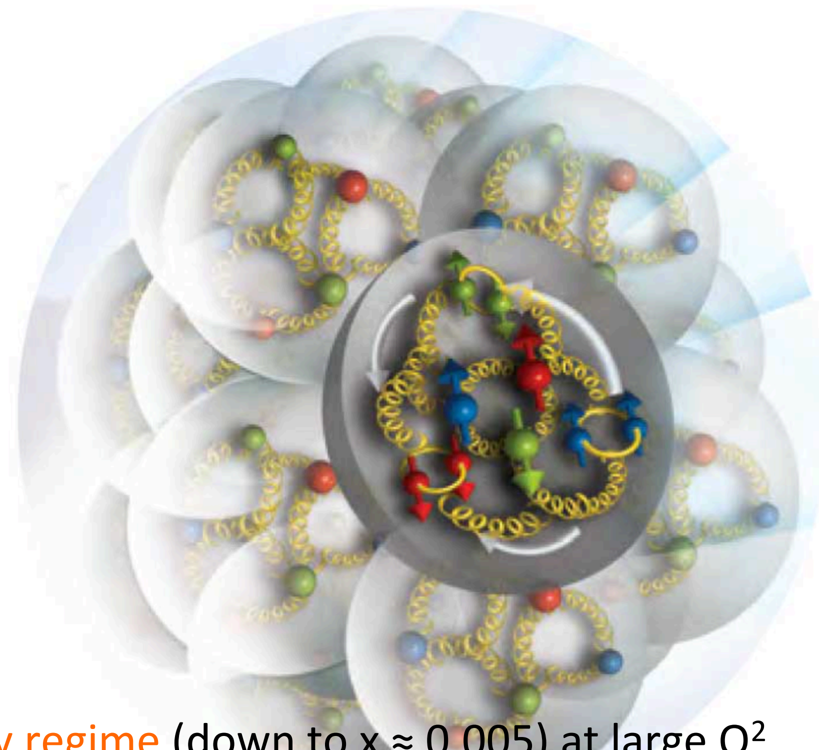
Precise understanding of structure and dynamics: dawn of new science

Jefferson Lab

EIC Physics Program

Program aim: Revolutionize the understanding of nucleon and nuclear structure and associated dynamics. Explore new states of QCD.



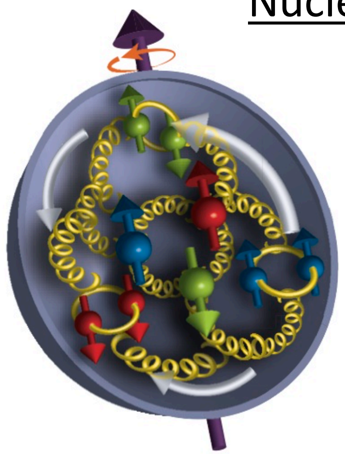


Program

- Probe the nucleon in the many-body regime (down to $x \approx 0.005$) at large Q^2
- Probe the nuclei in the N-N and multi-N interaction regime at large Q^2
- Extend our understanding of QCD (saturation, jets in cold nuclear matter)

Boring? Sounds like you've heard this for 30 years? No! Not Really!

Understanding the Nucleon at the Next Level



Nucleon: A many-body system with challenging characteristics

Relativistic ($M_{proton} >> M_{quark}$)

Strongly Coupled (QCD)

Quantum Mechanical (Superposition of configurations)

Measure in the Multi-Body regime:
- Region of quantum fluctuation + non-perturbative effects → dynamical origin of mass, spin.

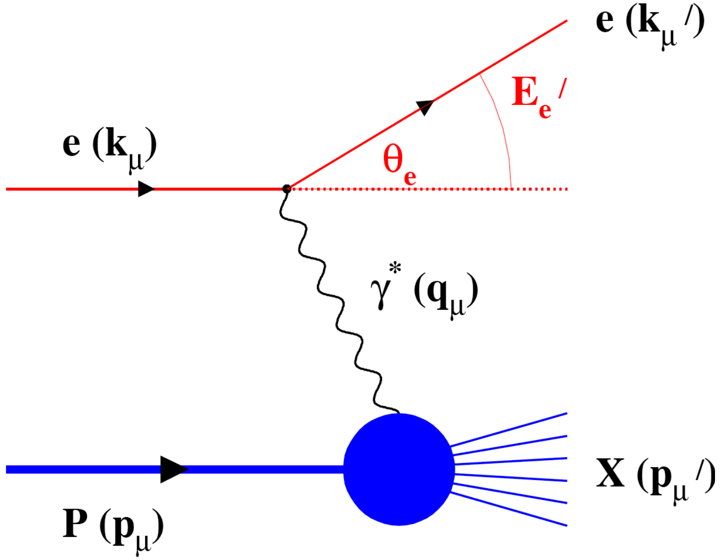
For the first time, get (almost?) all relevant information about quark-gluon structure of the nucleon

Designing EIC → Designing the right probe

- Resolution appropriate for quarks and gluons
- Ability to project out relevant Q.M. configurations

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

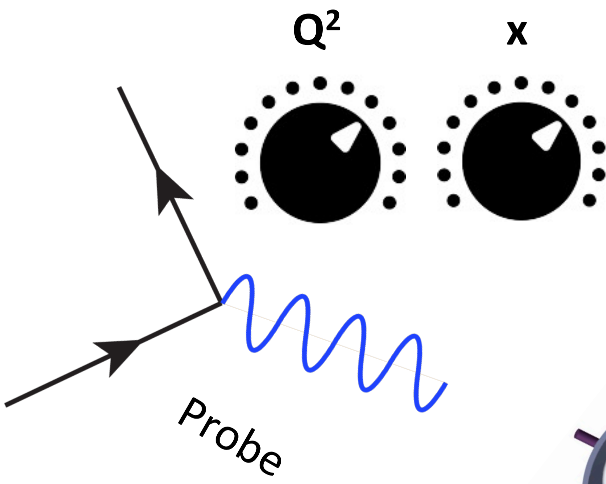
$$Q^2 = S\ x\ y$$

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

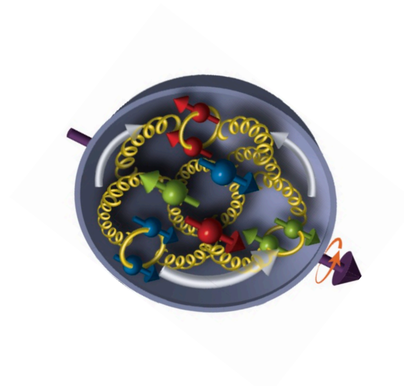
Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X
Detect the scattered lepton in coincidence with identified hadrons/jets in the detector

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

Parameters of the Probe

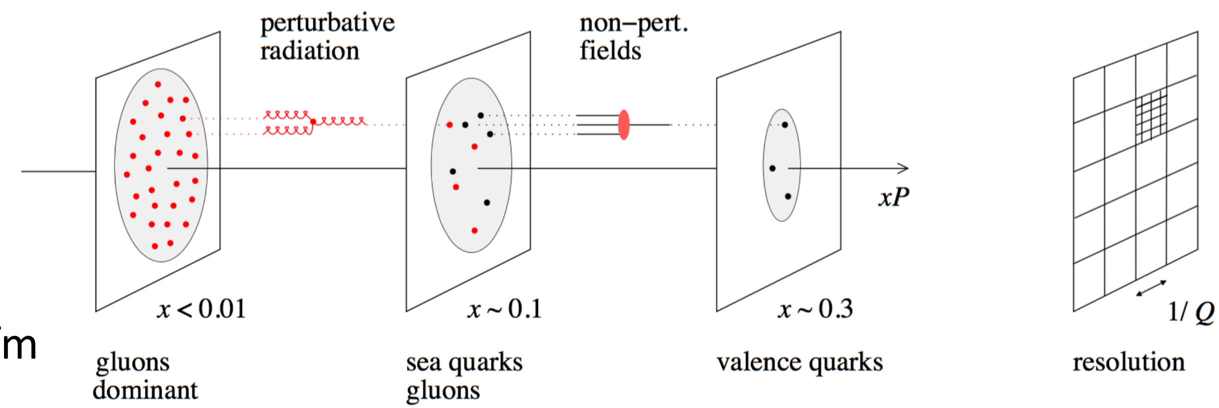


Ability to change **x** projects out different configurations where different dynamics dominate



Ability to change **Q^2** changes the resolution scale

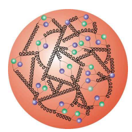
$Q^2 = 400\ \text{GeV}^2 \Rightarrow 1/Q = .01\ \text{fm}$



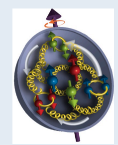
Where EIC Needs to be in x (nucleon)

Saturation Regime: Needs to be Accessed via Ions (see later)

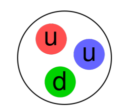
Collective Regime



Many-body Regime



Few-body Regime



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

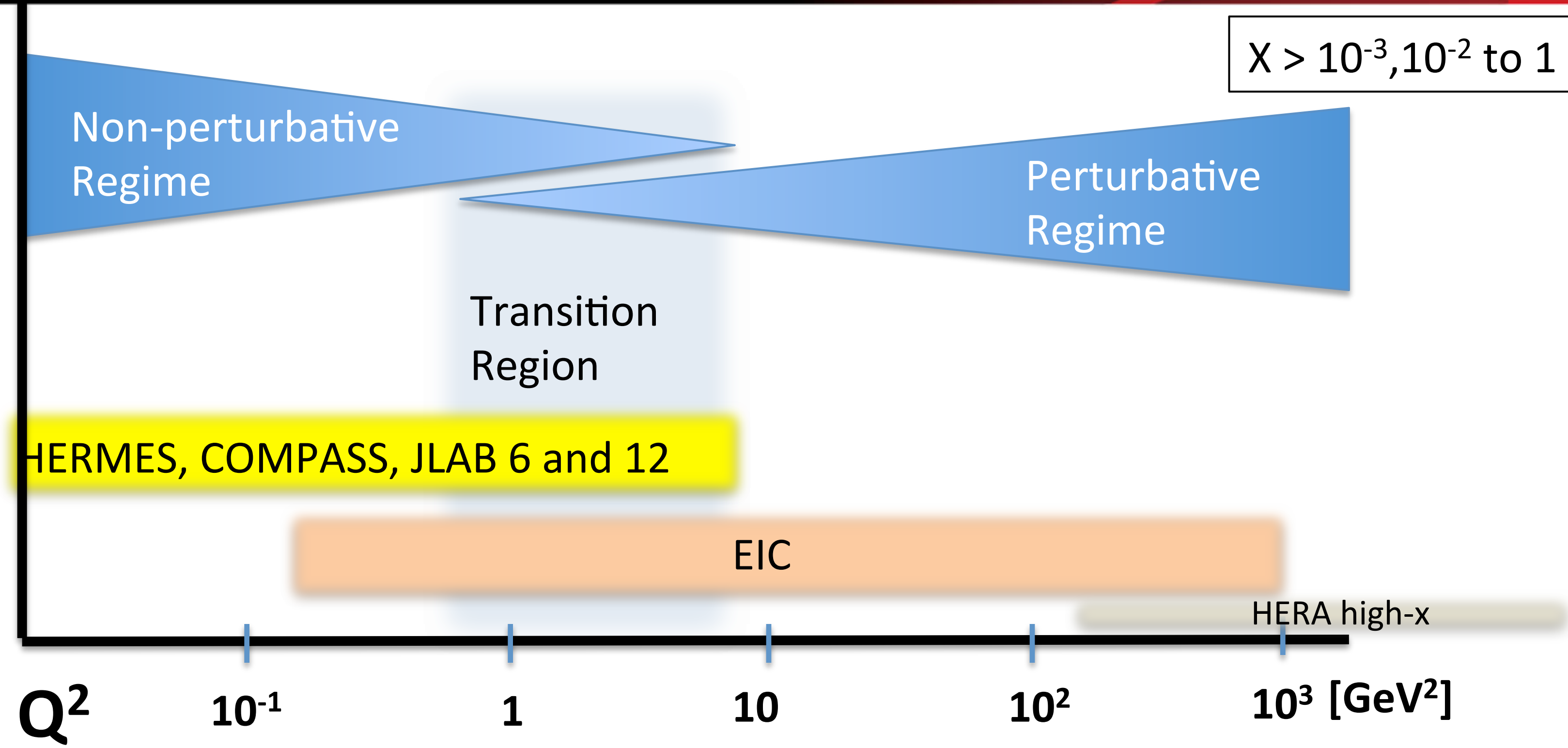
QCD Radiation Dominated (Studied at HERA)

Hadron Structure Dominated

Main interest for EIC Nucleon/Nuclear Program

Spin,TMD, GPD…

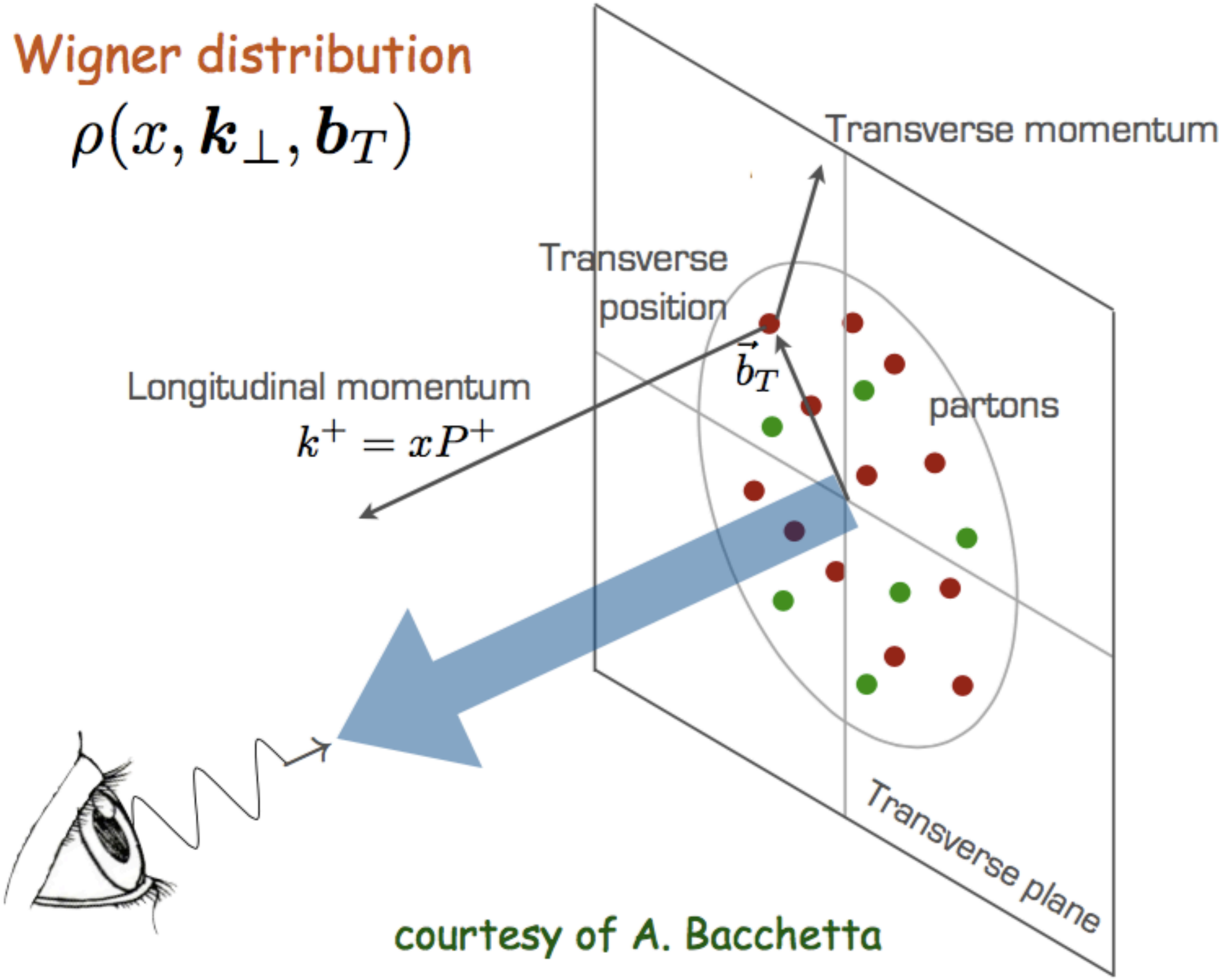
Where EIC needs to be in Q^2



- 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

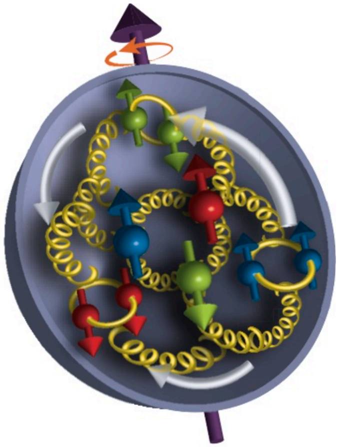
Disentangle Pert./Non-pert., Leading Twist/Higher Twist

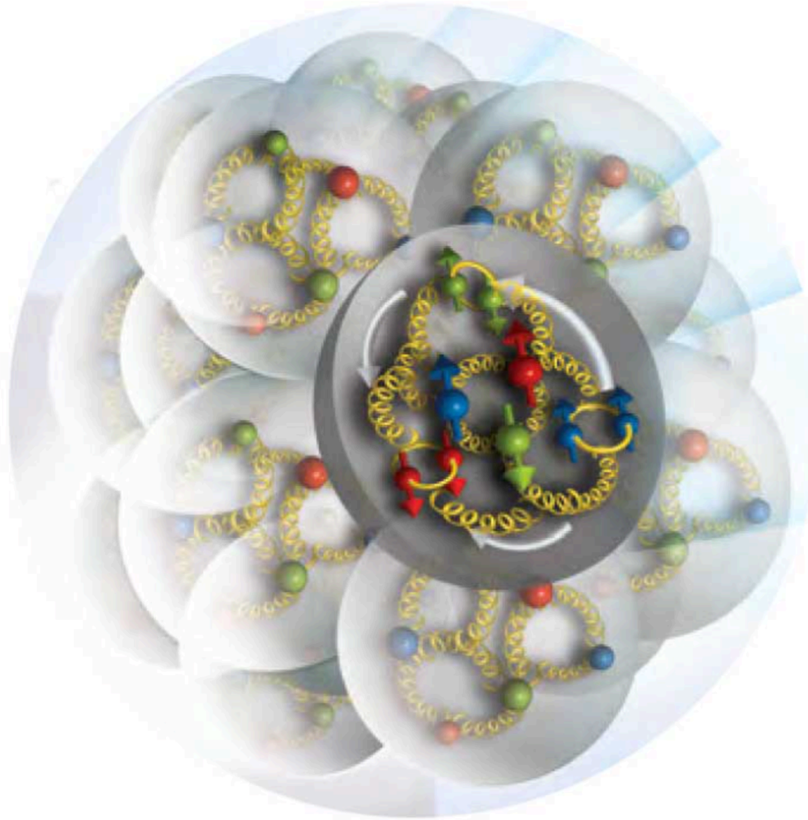
Theoretical Framework



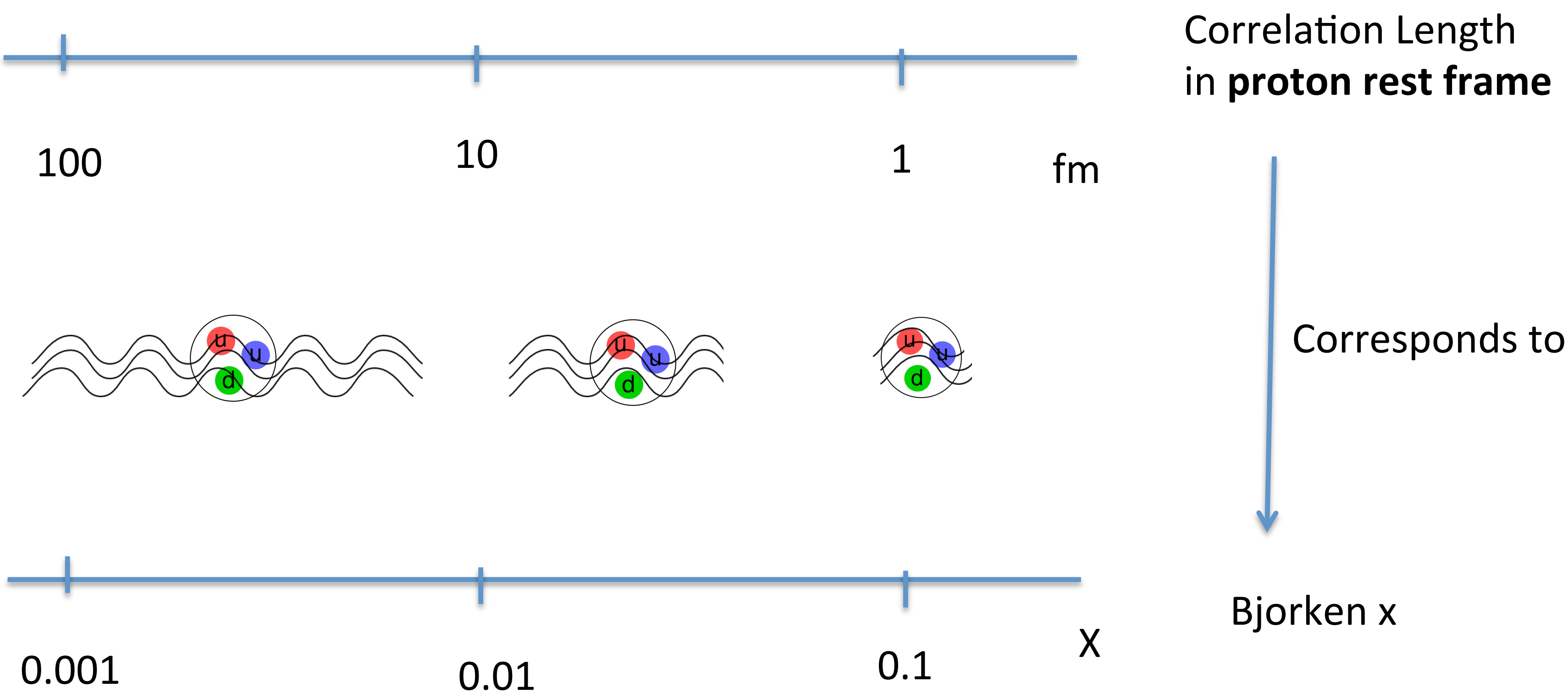
Theoretical progress in the past decades: Ready for the EIC physics program!

Understanding the Nuclei at the Next Level



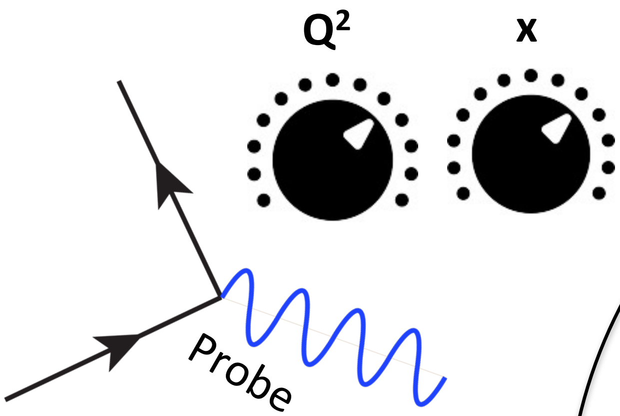


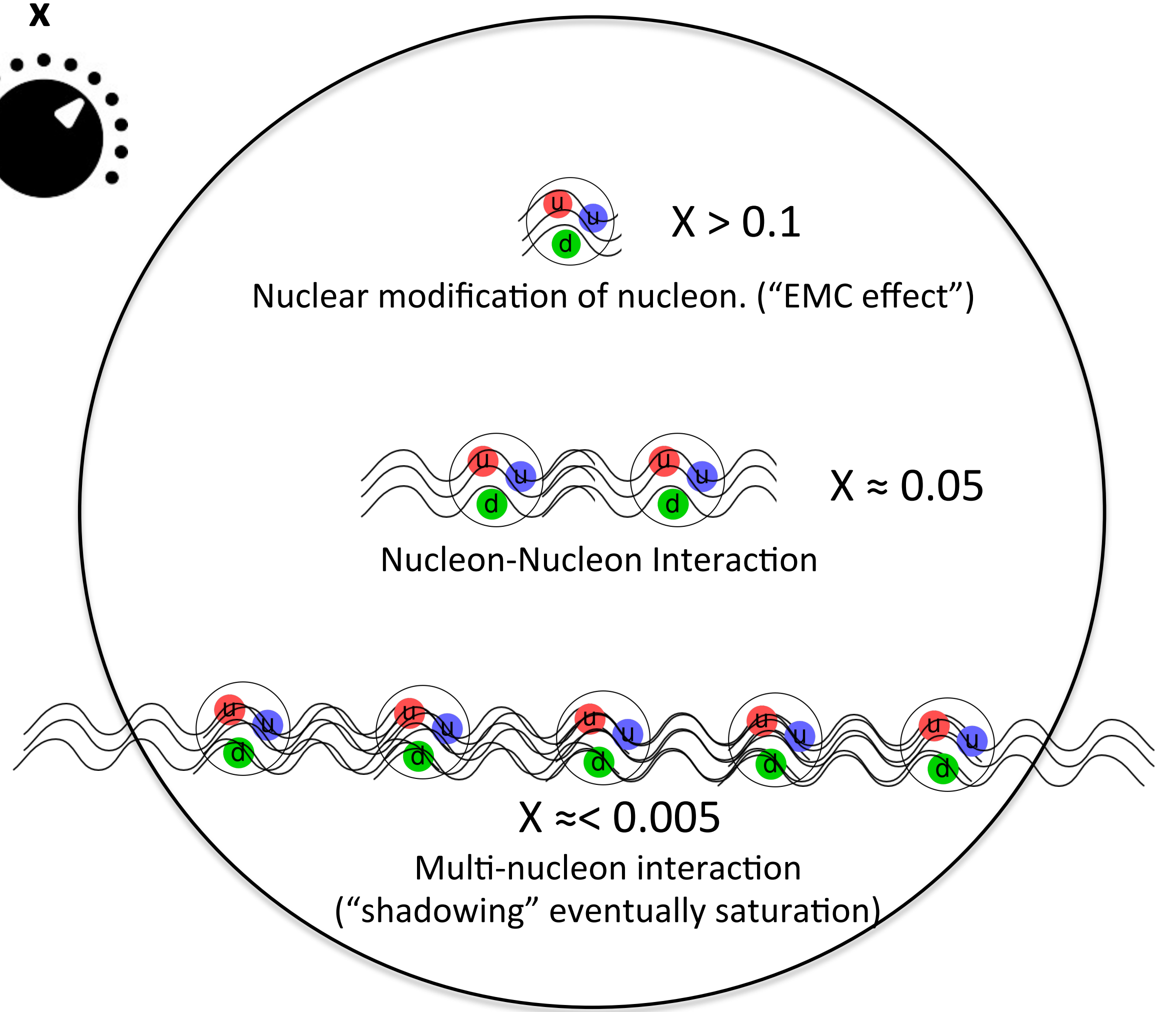
Bjorken x and length scale



In the proton rest frame, QCD field (x < 0.1) extends far beyond the proton charge radius

Parameters of the Probe (Nuclei)



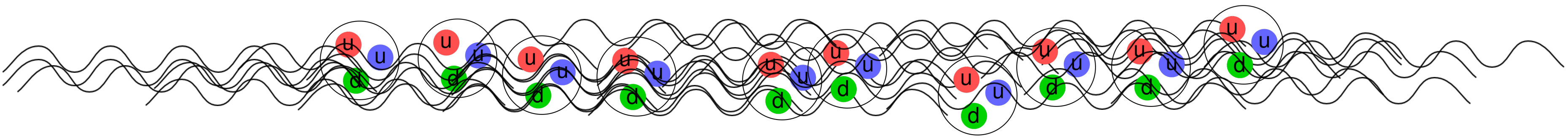


Probing the nucleon interaction in the nuclei (note this is different from correlation measurements)

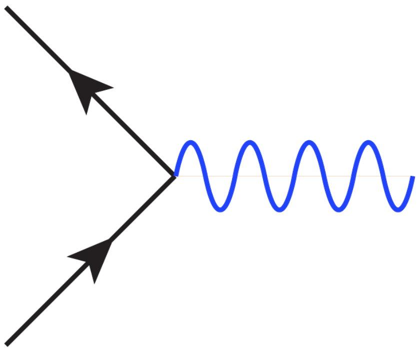
Note: the x range for nuclear exploration is similar to the nucleon exploration

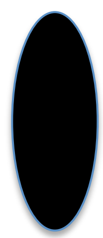
Beyond Nuclear Structure

Saturation



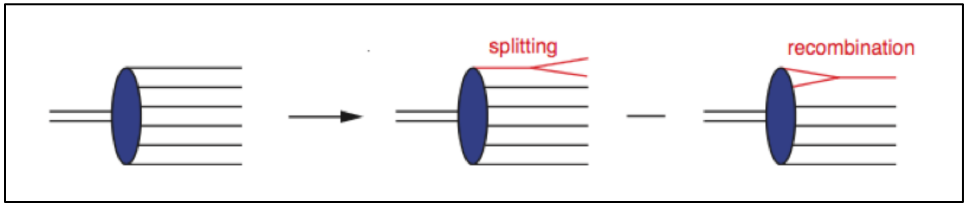
Eventually at low enough x





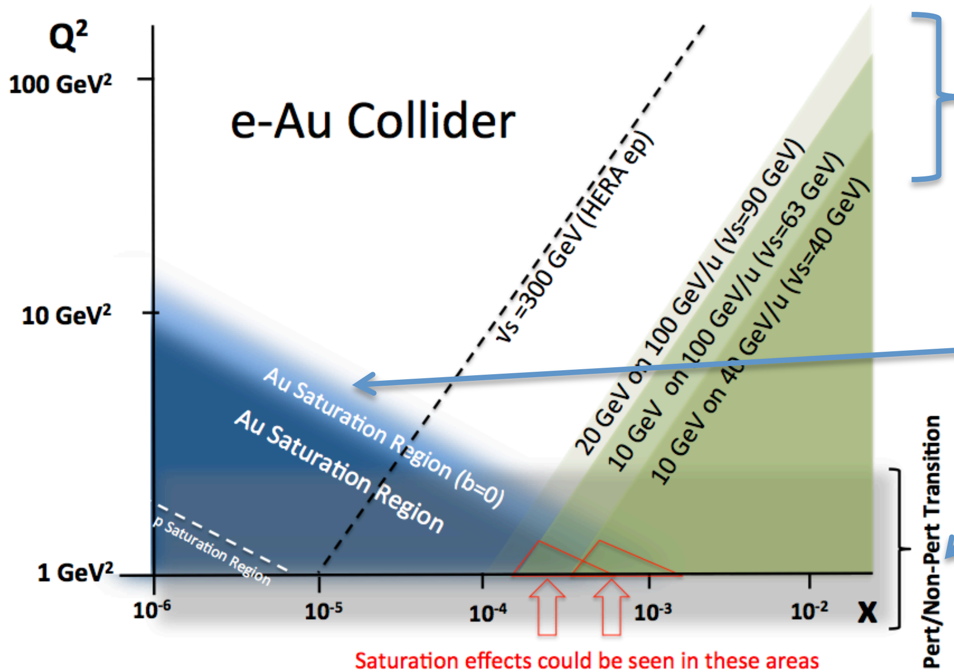
Cross-section will saturate

Equivalent to →



Can we see it at EIC?

Saturation Regime and EIC



EIC kinematic reach for various scenarios

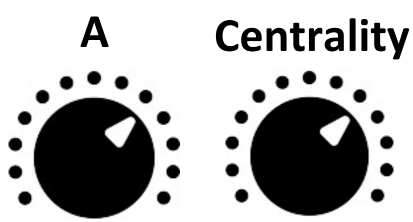
Two competing scales

$Q_s(x)$: Saturation Scale

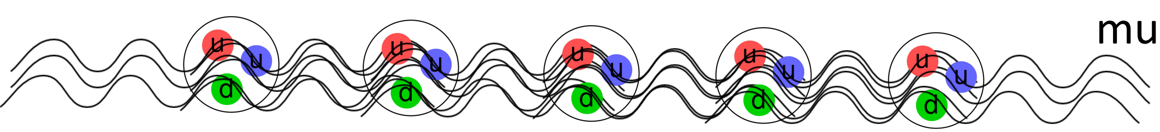
Q_0 : Perturtative when $Q > Q_0$

Ideally, x such that $Q_s >> Q_0$

EIC has two knobs to turn

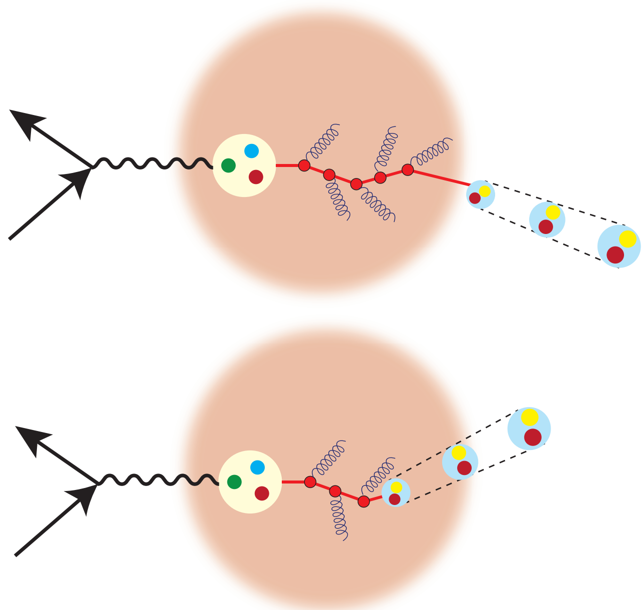


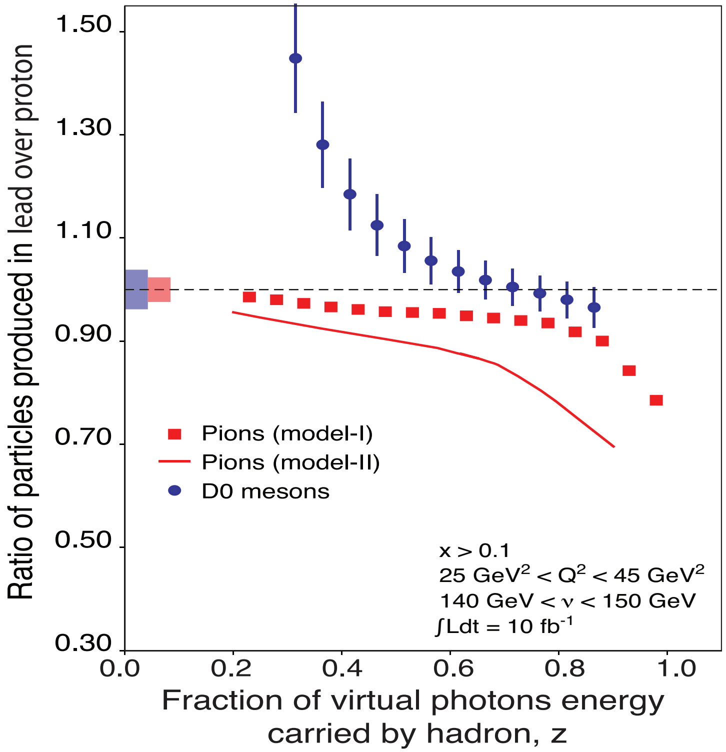
Investigate the on-set of saturation



multi-nucleon coherence → saturation

Jets, Hadronization



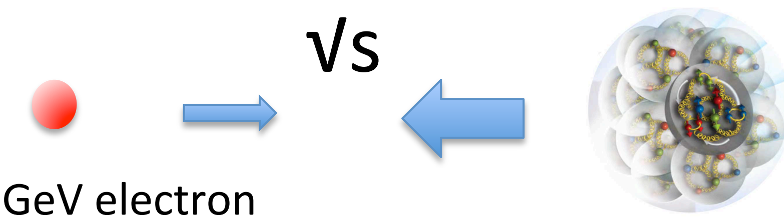


ν = E-E' = 100-200 GeV to keep jet within nucleus

√s = 32-45 GeV for y=0.1 (keeping jet in the central region of the detector)

Designing The Right Probe: $\sqrt{s}$

What are the right parameters for the collider for the EIC science program?

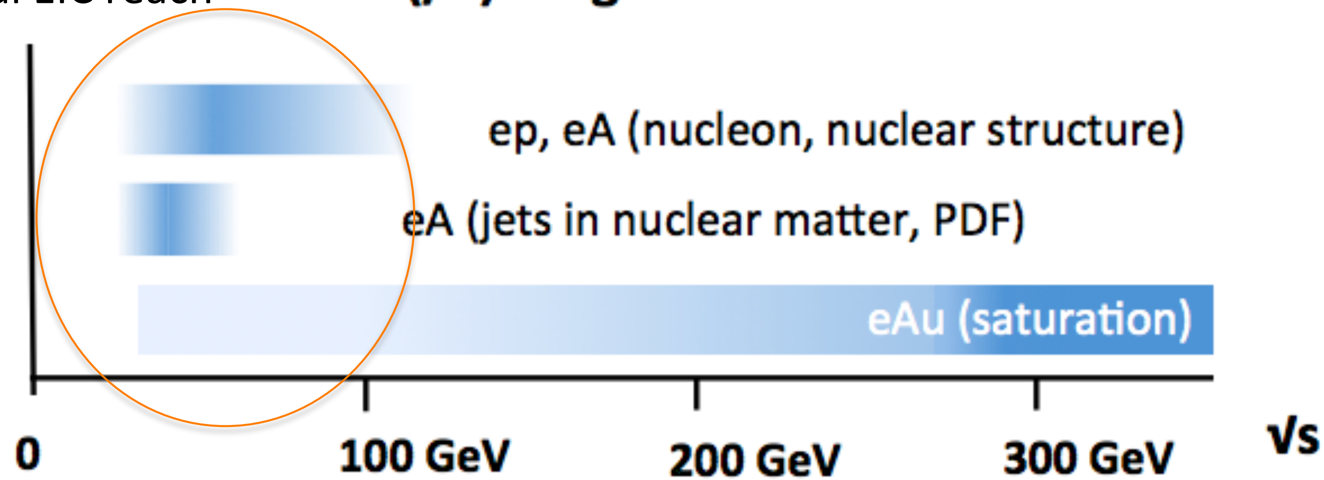


~10 GeV electron realizable

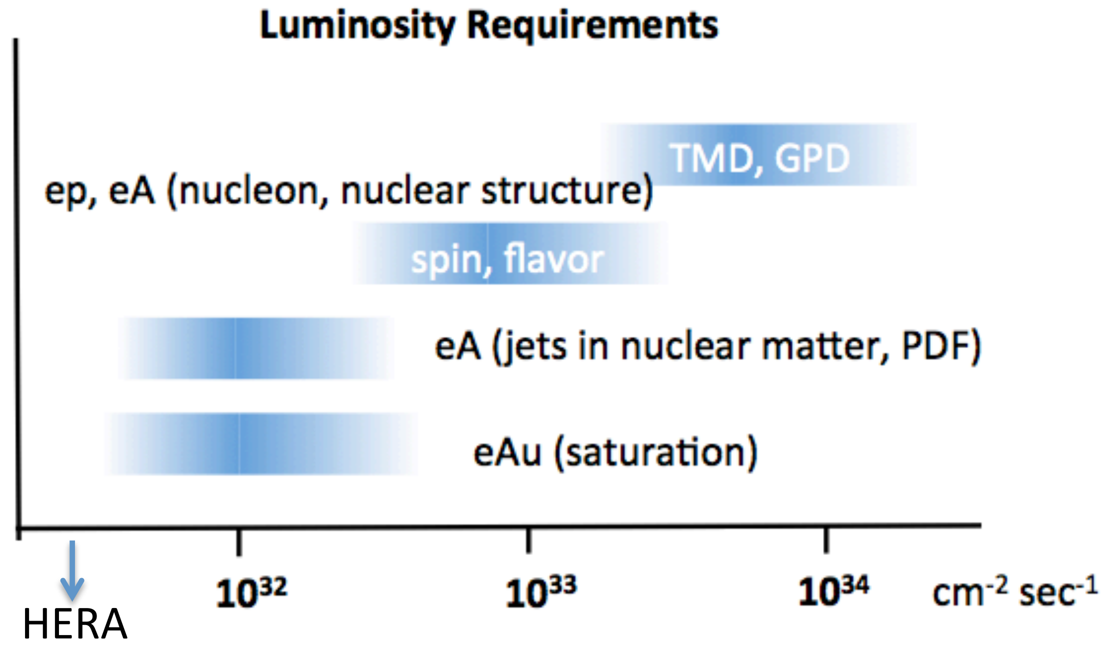
~100 GeV/u ion realizable

Practical EIC reach

√s(/u) range of interest



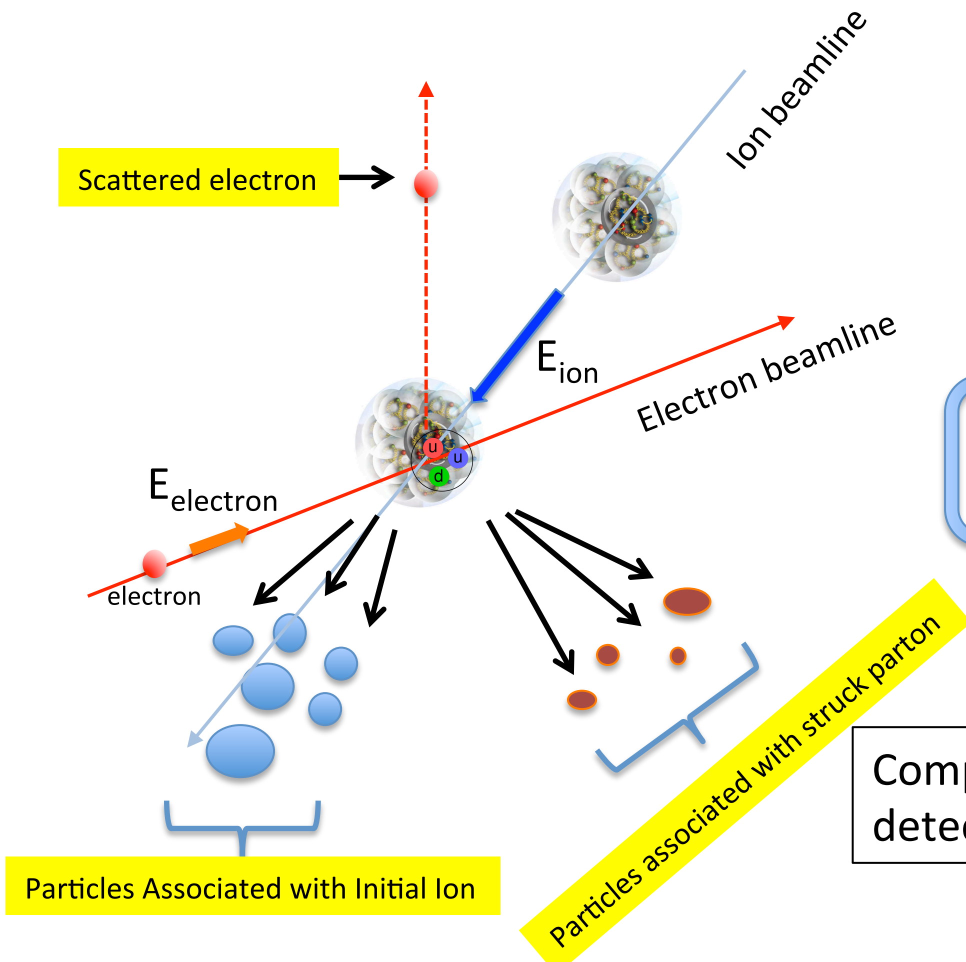
Luminosity Needed for Topics



Central mission of EIC (nuclear and nucleon structure) requires high luminosity.

See Abhay Deshpande's talk Friday afternoon for EW and BSM opportunities at EIC

E_{ion} and $E_{ion}/E_{electron}$



EIC needs to detect all three types of particles

- Scattered electron
- Particles Associated with Initial Ion
- Particles associated with struck parton

These become more forward boosted and harder to measure with increasing E_{ion} and $E_{ion}/E_{electron}$

Complicated dependence on beam energies, detector capability and physics goals.

This optimization is on-going: depends on the physics program!

The Electron Ion Collider

For e-N collisions at the EIC:

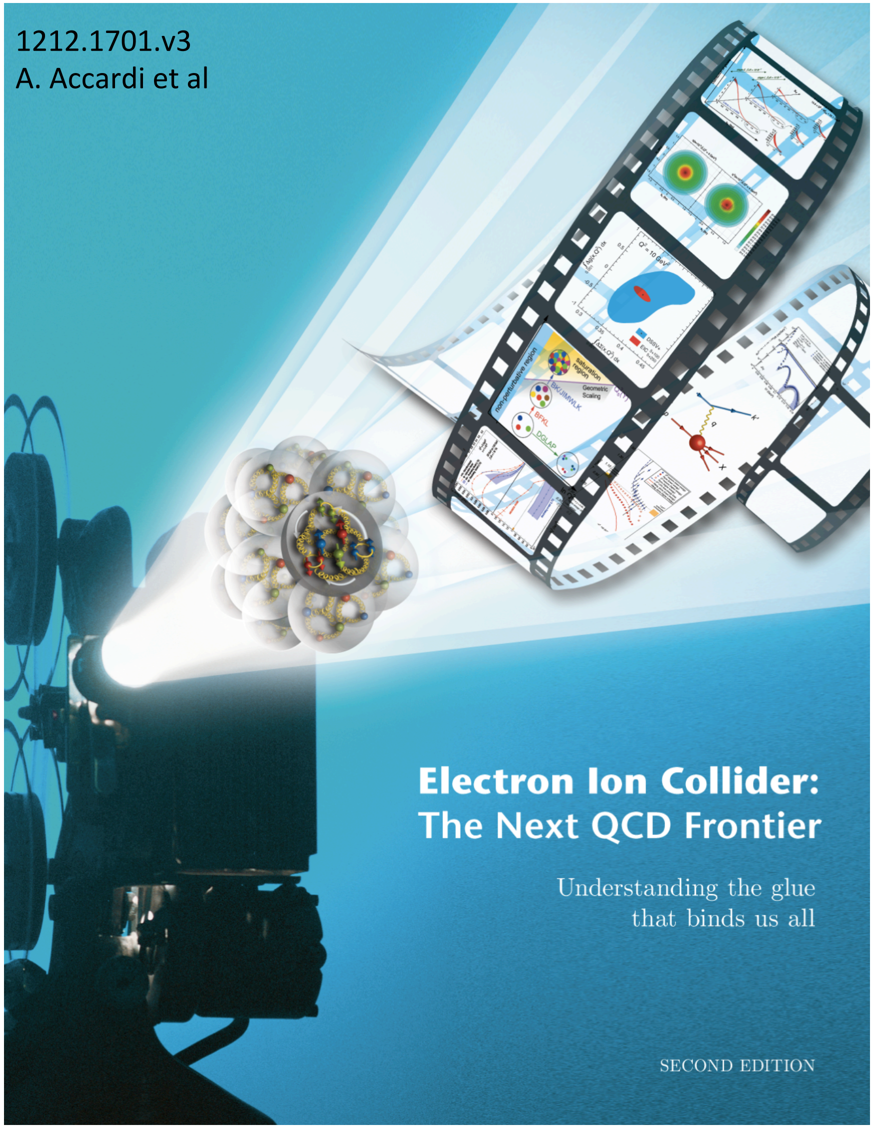
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 3-10(20) GeV
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$
  100-1000 times HERA
- ✓ 20-~100 (140) GeV Variable CoM

For e-A collisions at the EIC:

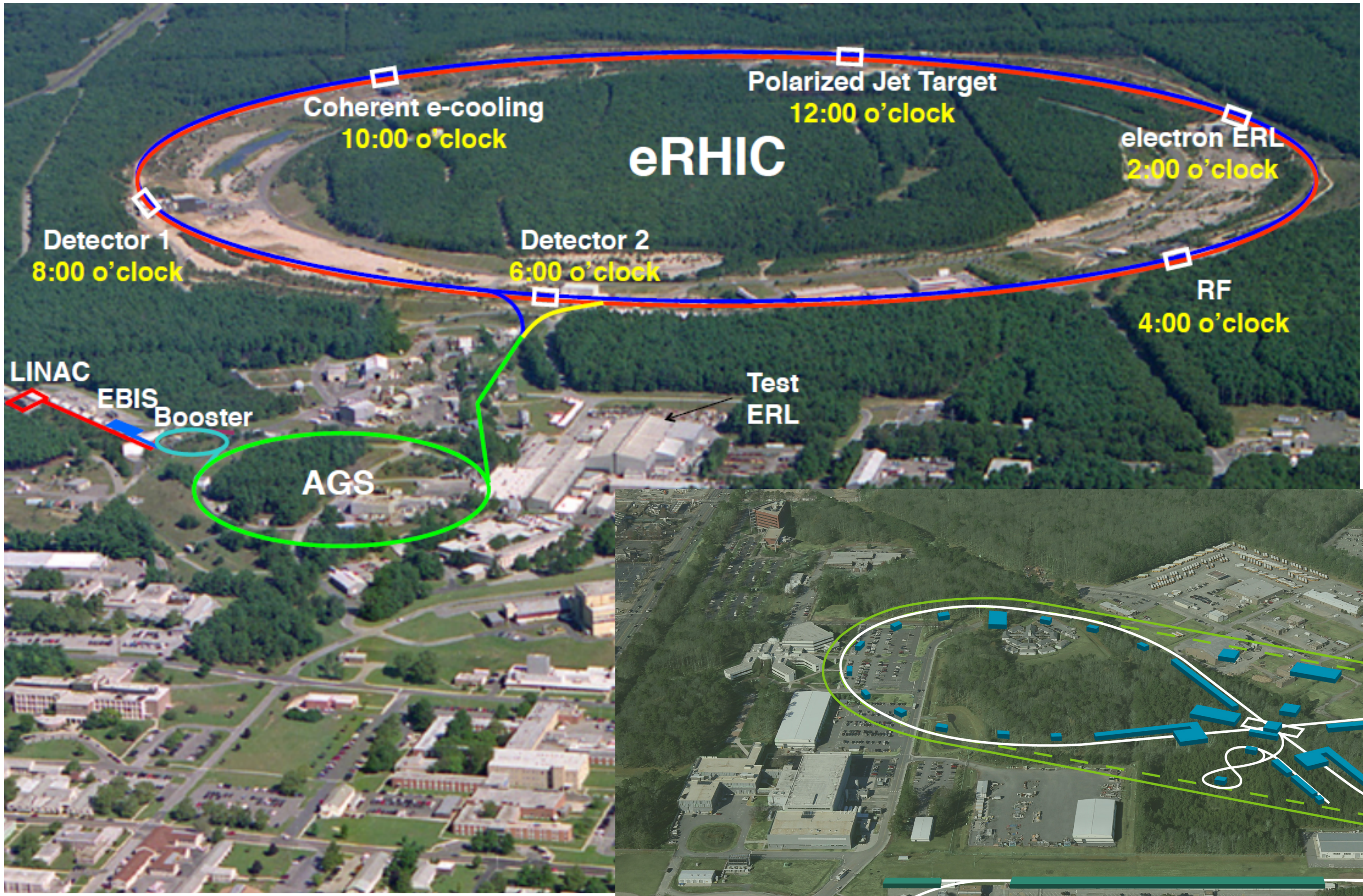
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

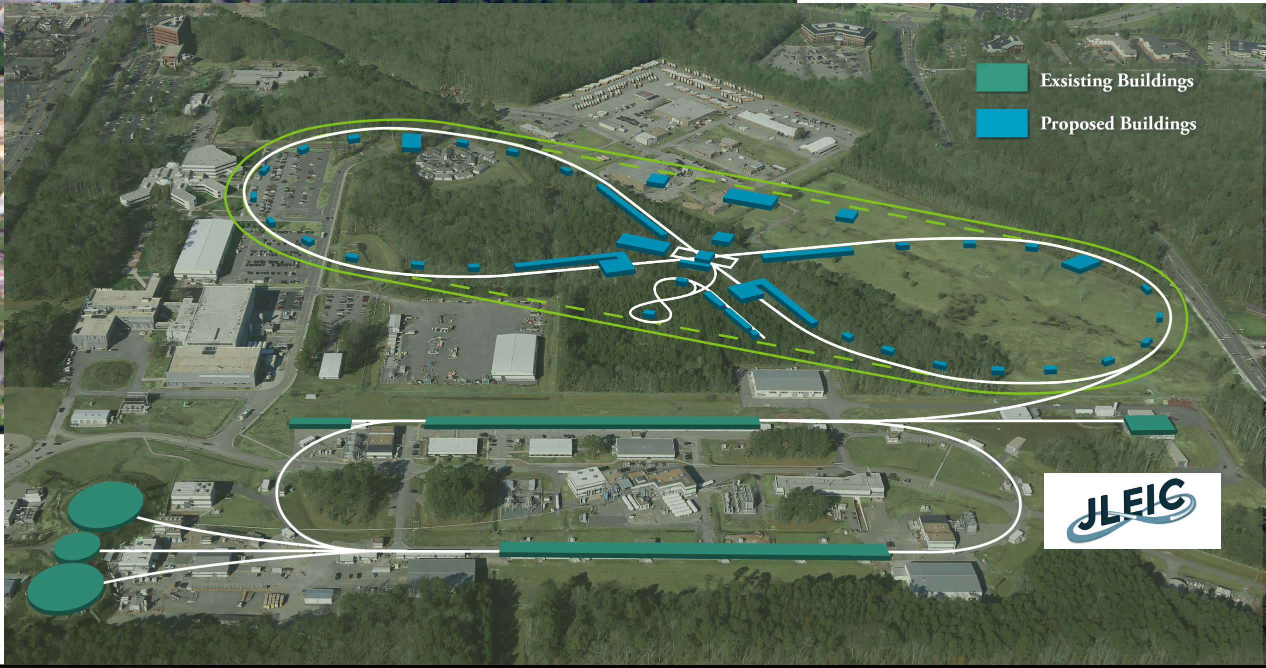
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

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



US-Based EIC Proposals

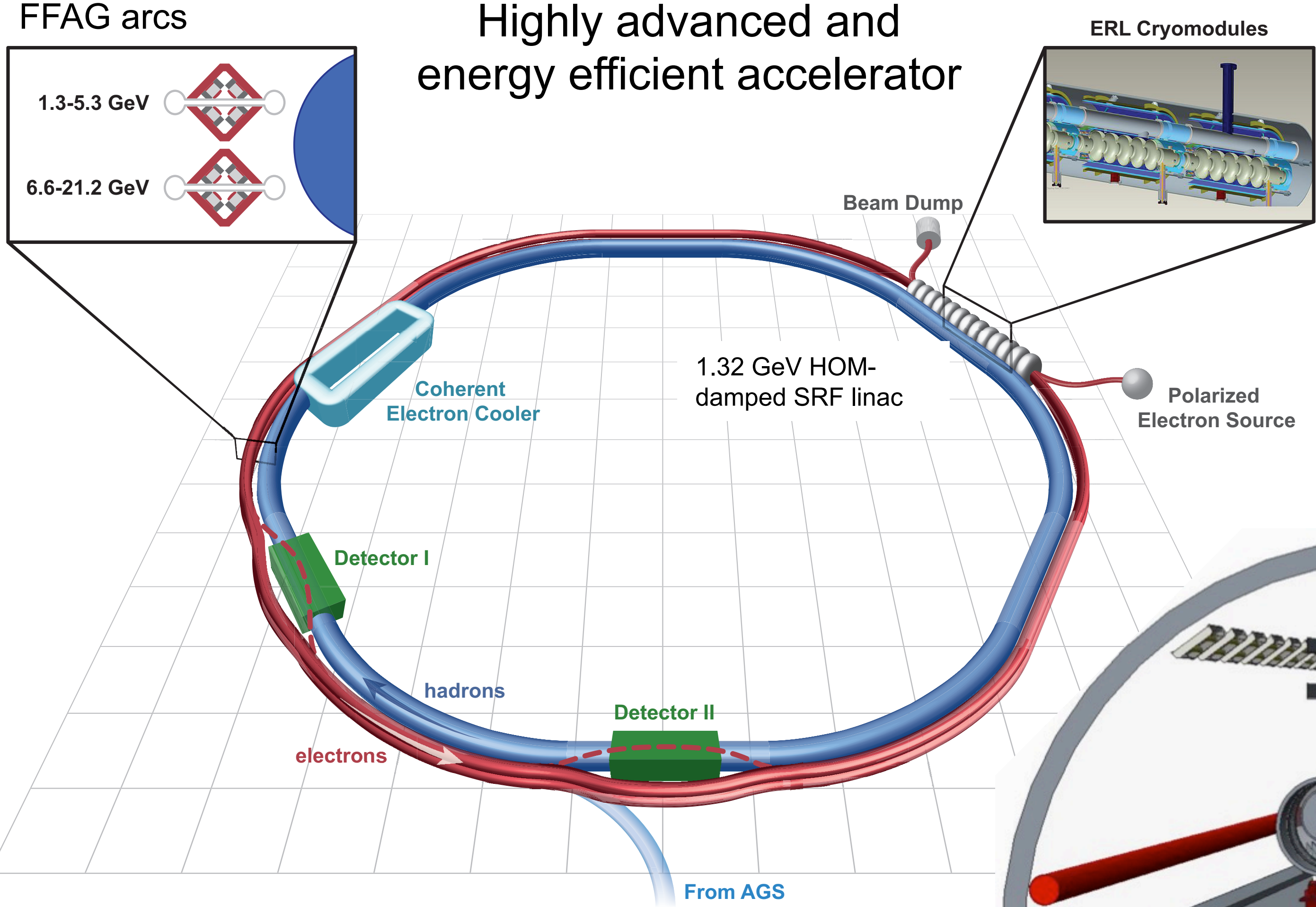


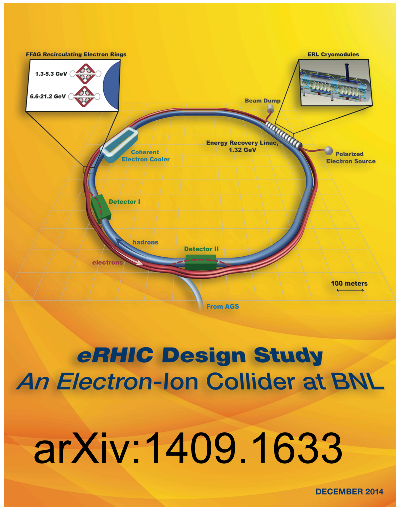


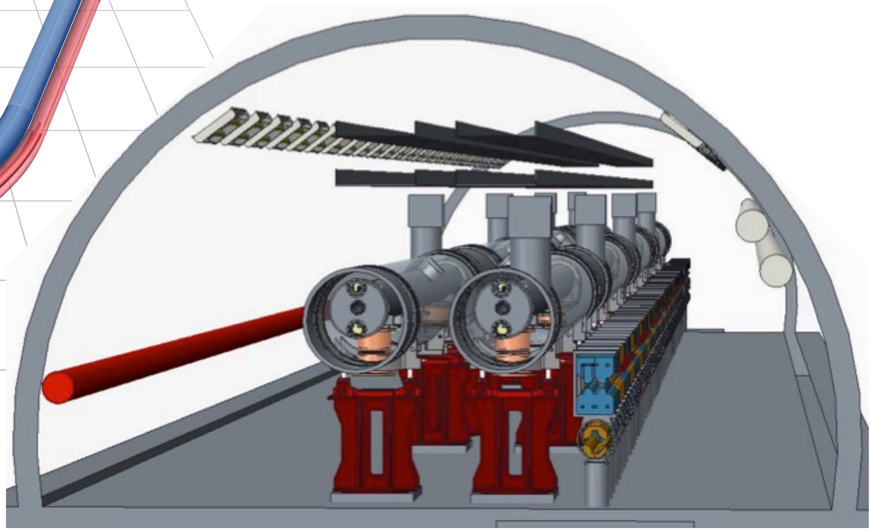
Jefferson Lab

eRHIC Baseline Design

Highly advanced and energy efficient accelerator





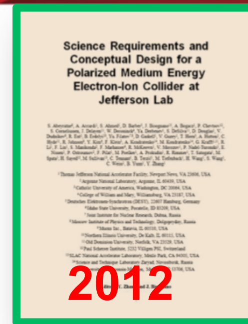


- Peak luminosity 2×10^{34} cm^{-2} s^{-1} for $\sqrt{s}$ ~ 70-105 GeV (250 GeV p↑)
- Low-risk luminosity ~ 5-9 $\times 10^{32}$ cm^{-2} s^{-1}

JLEIC Baseline Design

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


Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

arXiv:1209.0757


MEIC Design Summary

January 20, 2015

Author List

arXiv:1504.0796

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

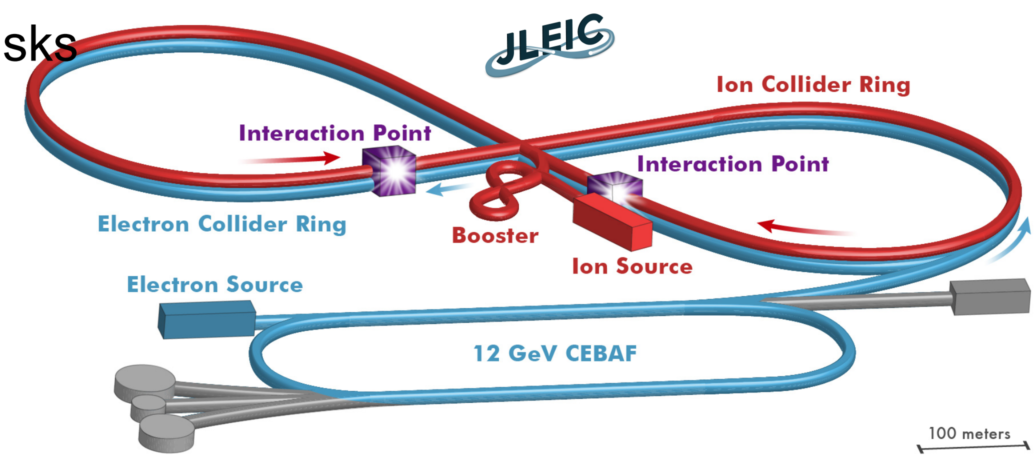
Goals:

- 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



The US Nuclear Science Long-Range Planning Process

US 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, JLab 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

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

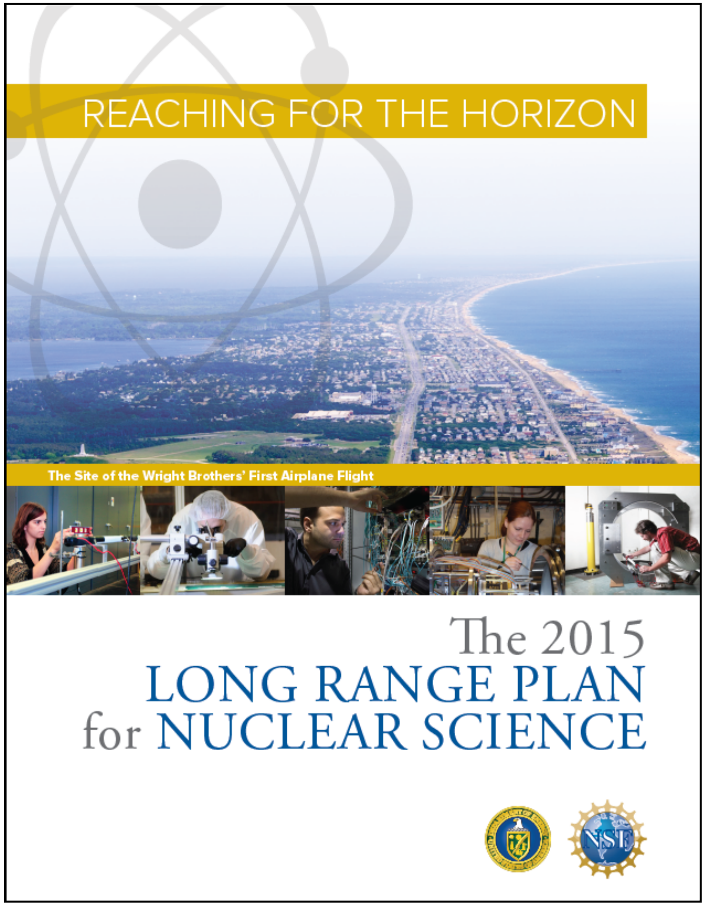
Town Meeting on Fundamental Symmetries and Neutrinos
Chicago, 28-29 September 2014
https://fsnutown.phy.ornl.gov/fsnuweb/

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 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)



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.**

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.**

Ongoing and next steps

EIC Realization Imagined

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

- A National Academy of Sciences study has been initiated and the committee is being formed. Charge: "assess the scientific justification for a U.S. domestic electron ion collider facility, " (Wider Science Community) Likely to take ~12-18 months. Our next challenge.

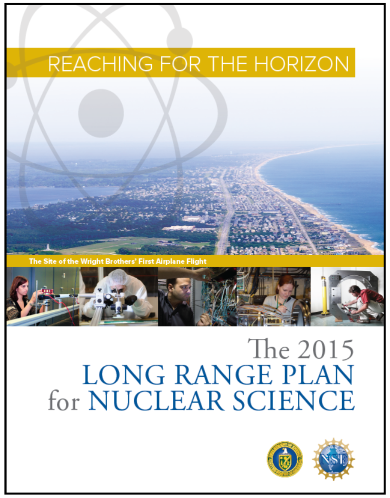
- DOE project "CD0" (Establish Mission need established) will be after the NAS study: i.e end 2017, early 2018.

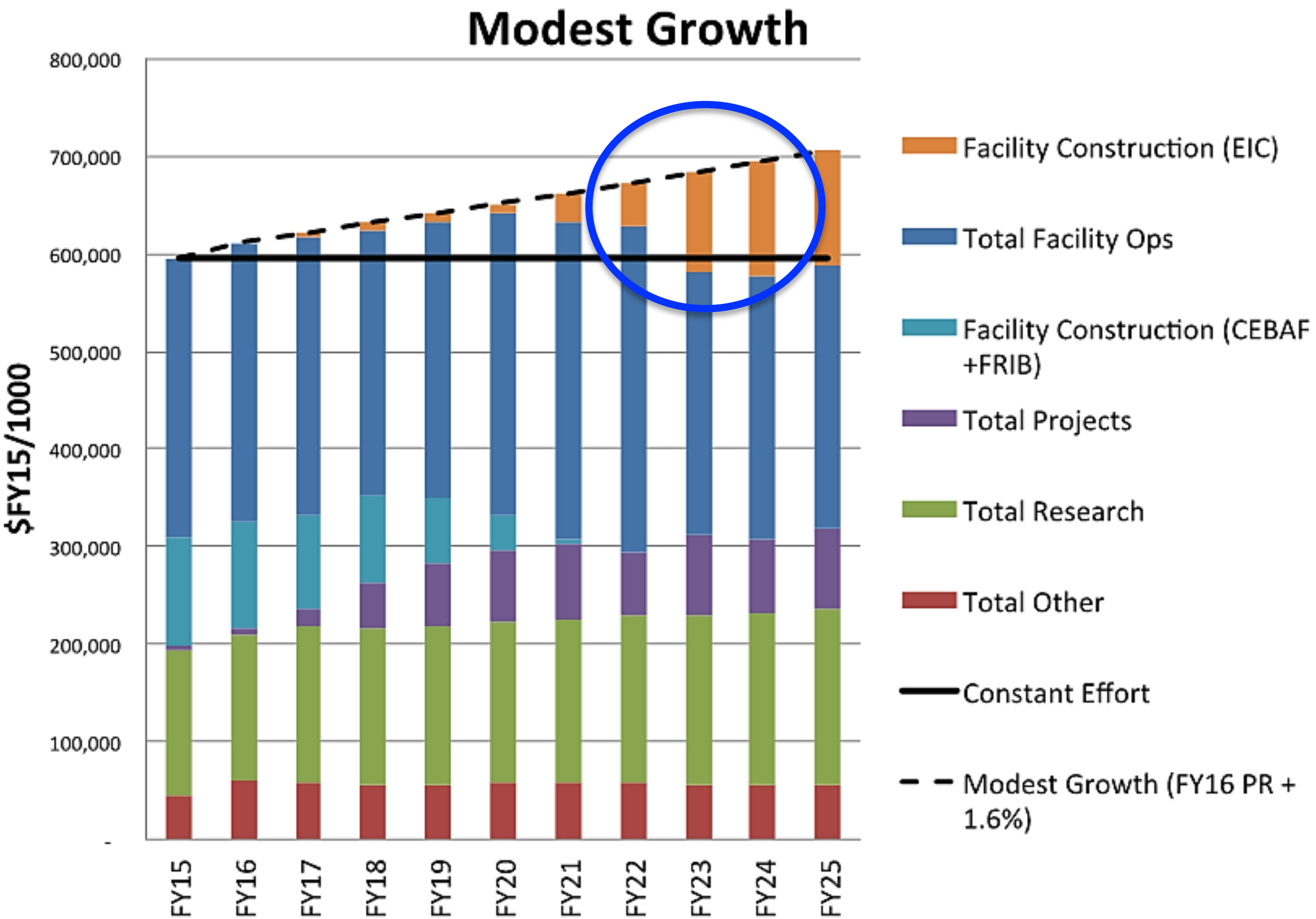
- EIC construction has to start **after FRIB completion**, with FRIB construction anticipated to start ramping down near or in FY20

→ <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 formal NSAC/LRP recommendation would be 2025-2030 timeframe

DOE budget in FY 2015 dollars for Modest Growth scenario





Note:
Separate budget from DOE HEP

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*

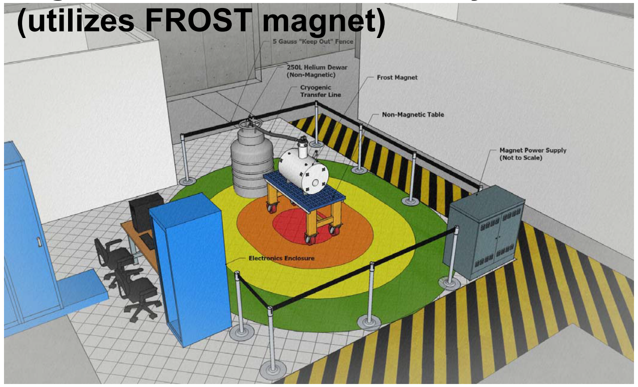
→ Many R&D proposals are collaborative (BNL/JLab/users)

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

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

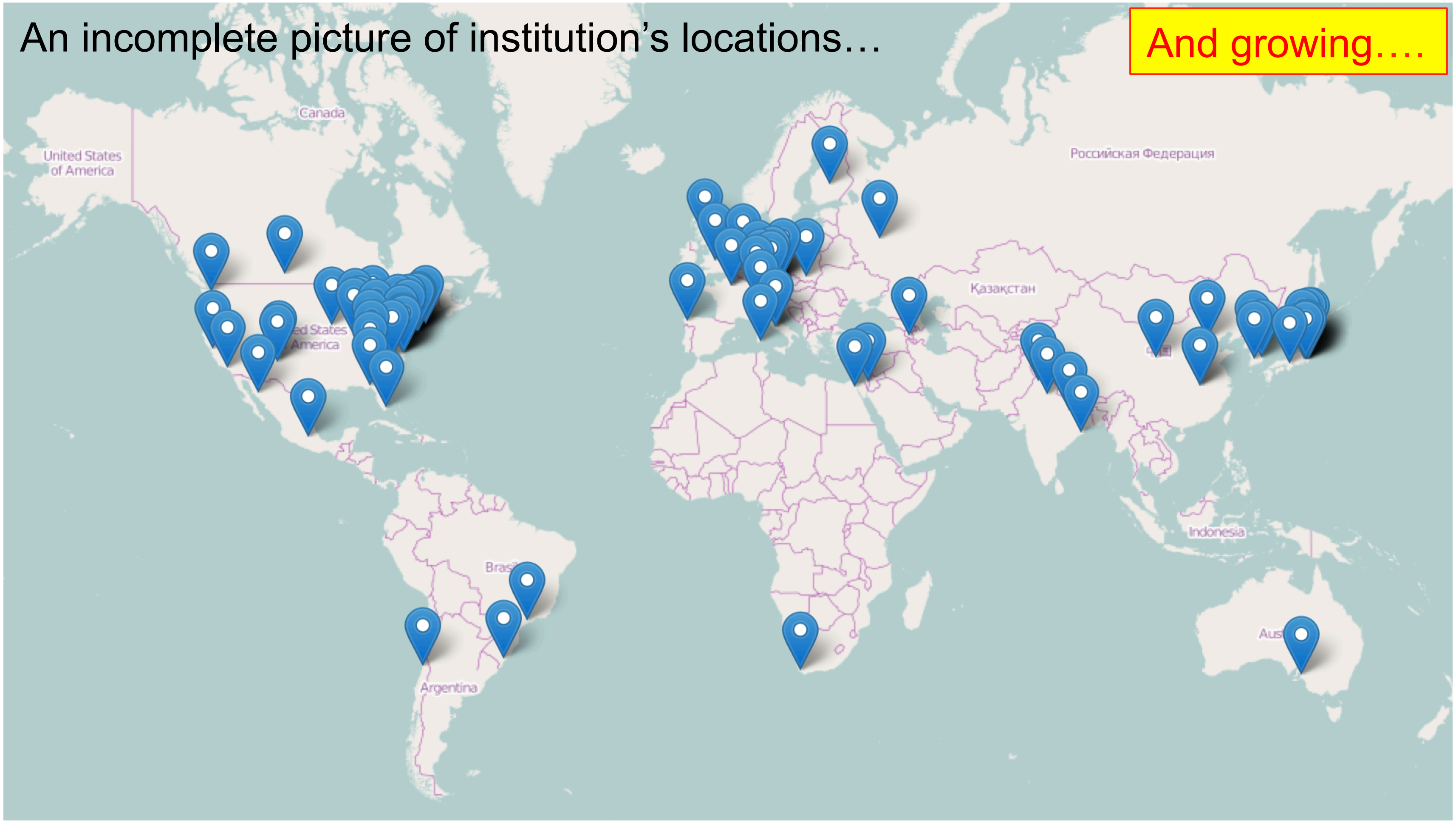
- Provide organization for users
- Assist in proposal preparation
- Provide infrastructure for R&D topics, e.g. 5T sensor test facility re-using existing magnets
- Often synergy with existing program

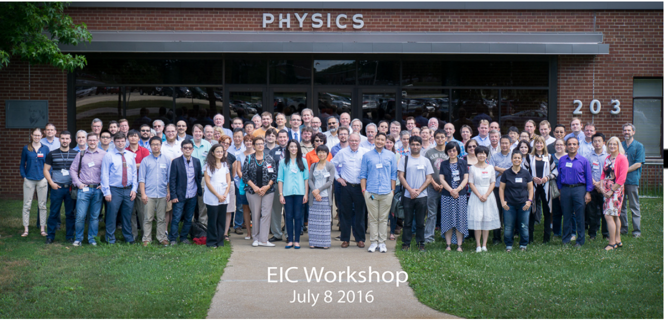
High-B-field sensor test facility at JLab (utilizes FROST magnet)



The EIC Users Group: EICUG.ORG

651 collaborators, 27 countries, 142 institutions.





What's next

Just had generic detector R&D with EIC UG meeting

July 6-7, 2016 Generic EIC-related detector R&D meeting at Argonne.

July 7-9, 2016 EIC Users Group Meeting at Argonne.

http://eic2016.phy.anl.gov

- A Charter for EICUG Participation approved and now setting up Steering Committee.
- Much to prepare: case for the NAS committee, setting up working groups, plan the EIC physics program… (Come join us! eicug.org)
- Very first EIC User Group Satellite Meeting at INPC in Adelaide
  Monday September 12, from 5:45 to 7:00 pm
- Another EICUG meeting early 2017.
- EICUG meeting at Trieste, July 18-22, 2017, (INFN Trieste)

Conclusion

- EIC Program aim: Revolutionize the understanding of nucleon and nuclear structure and associated dynamics. Explore new states of QCD.

- For the first time, EIC will enable us to study the nucleon and the nucleus at the scale of quarks and gluons, over (arguably) all of the kinematic range that are relevant for exploring the nuclear and nucleon structure and the associated QCD dynamics.

- 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. Now we must turn this into real participation!

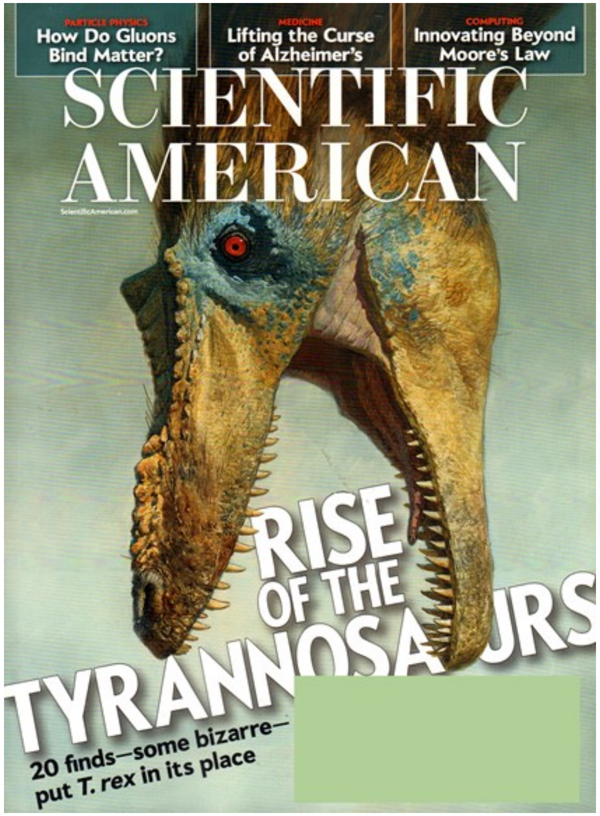
- In the next decades, with the advent of EIC, nuclear science will grow and become more central to the sciences. We're just getting started!

The future of science demands an Electron Ion Collider

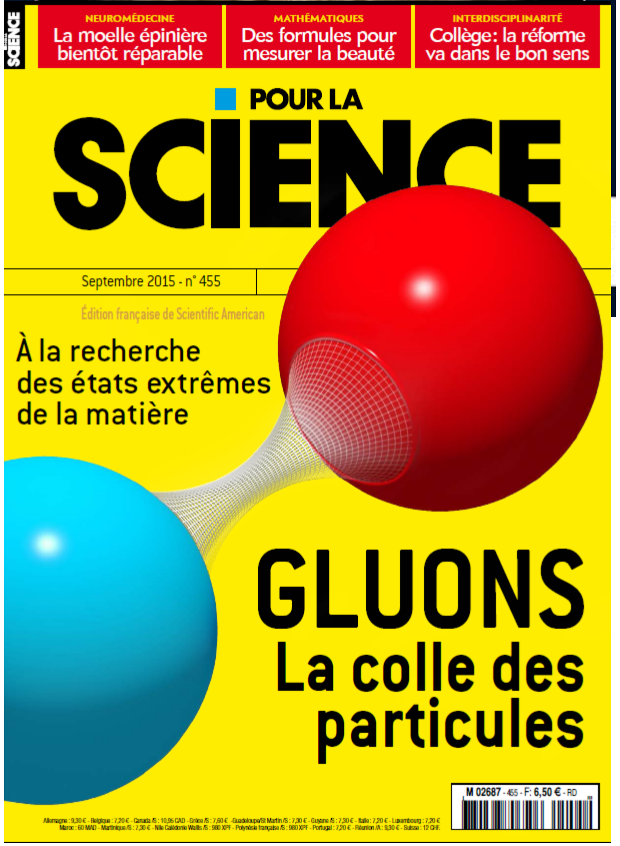

PARTICLE PHYSICS
the glue that binds us


Le cause della crisi dell'olivo in Italia
Luglio 2015
€ 4,50
Le Scienze
www.lescienze.it
edizione italiana di Scientific American
Settant'anni con l'atomica
16 luglio 1945: nel deserto del New Mexico esplode il primo ordigno nucleare. Dando il via a una corsa agli armamenti che non si è ancora fermata


Spektrum
DER WISSENSCHAFT
GRIPPEVIREN
Ein mathematisches Modell lüftet ihr Geheimnis
GLUONEN
Der Klebstoff, der die Welt zusammenhält
BÄUME
Wie wir Wälder für den Klimawandel wappnen
RELATIVITÄT
Den Gravitationswellen auf der Spur
Der Ursprung der
MYTHEN
Am Anfang der Menschheitsgeschichte stehen drei Erzählungen

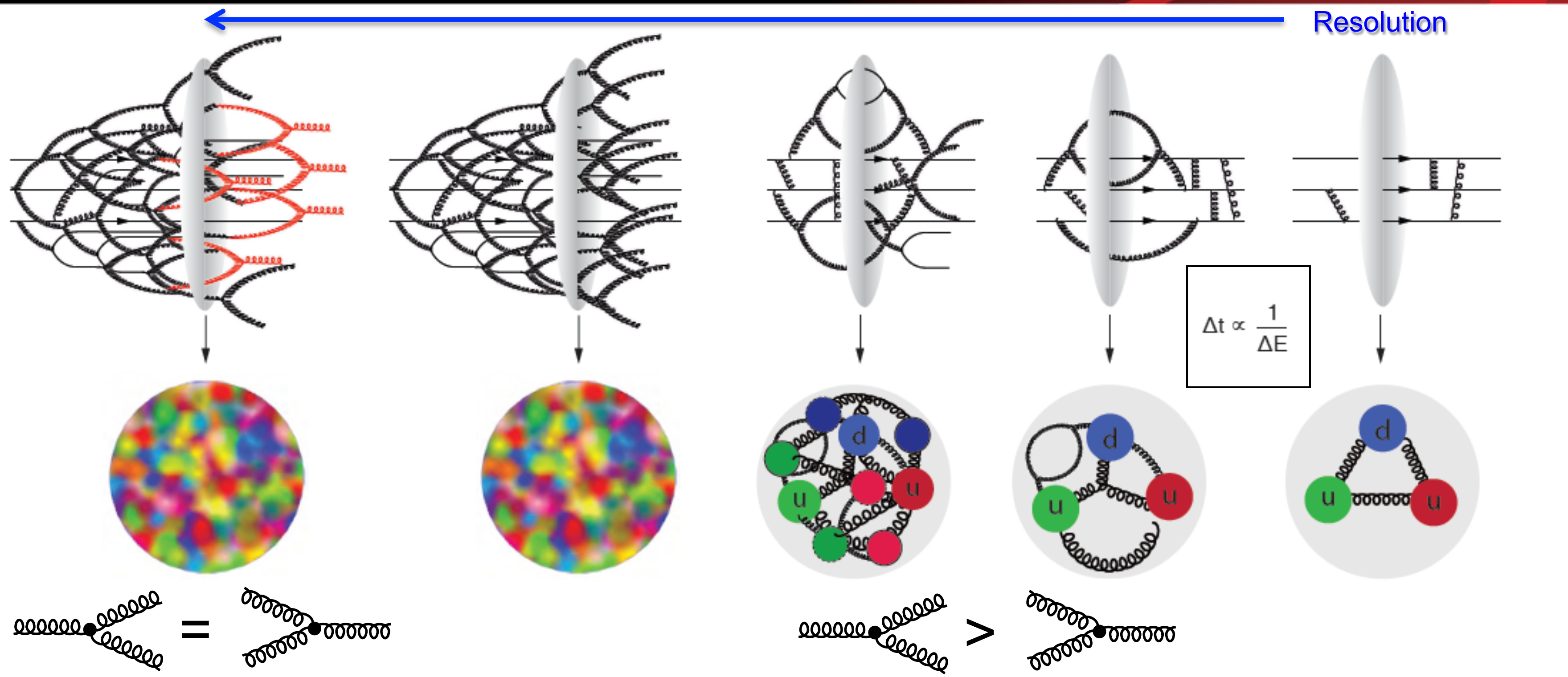

PARTICLE PHYSICS
How Do Gluons Bind Matter?
MEDICINE
Lifting the Curse of Alzheimer's
COMPUTING
Innovating Beyond Moore's Law
SCIENTIFIC AMERICAN
RISE OF THE TYRANNOSAURS
20 finds—some bizarre—put T. rex in its place

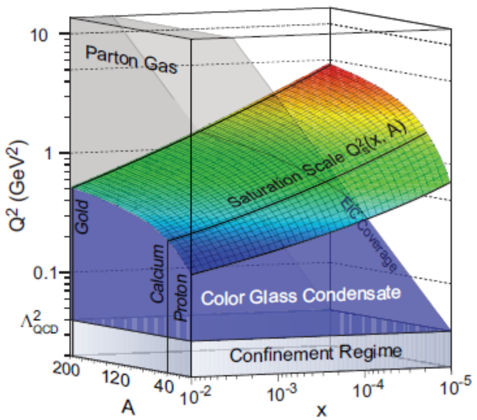

SCIENTIFIC AMERICAN
BRASIL
MEDICINA
Mutação rara traz pistas para cura do Alzheimer
FÍSICA
Novas pesquisas sobre as partículas que mantêm o Universo unido
COMPUTAÇÃO
Fabricantes de chips buscam material para substituir o silício
DEVASTAÇÃO volta a crescer na AMAZÔNIA
Após quatro anos sucessivos de queda, números do desmatamento da grande floresta tropical brasileira retomam tendência de aumento


NEUROMÉDECINE
La moelle épinière bientôt réparable
MATHÉMATIQUES
Des formules pour mesurer la beauté
INTERDISCIPLINARITÉ
Collège: la réforme va dans le bon sens
POUR LA SCIENCE
Septembre 2015 - n° 455
Édition française de Scientific American
À la recherche des états extrêmes de la matière
GLUONS
La colle des particules

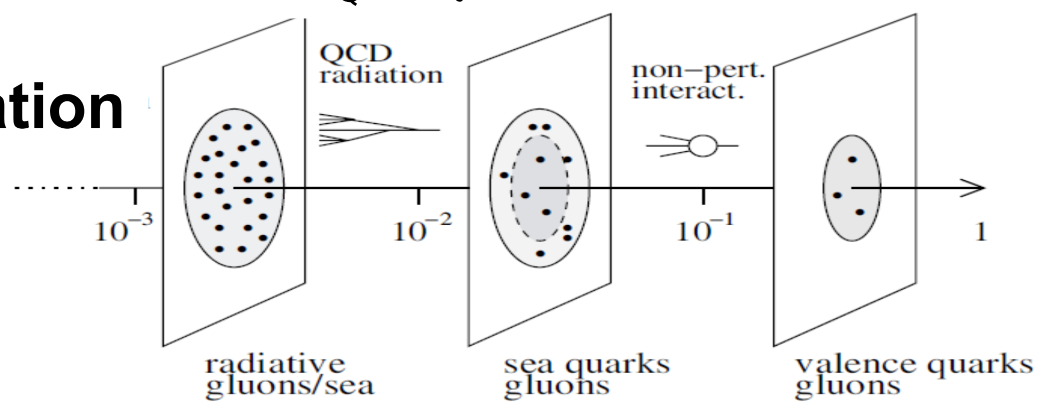
BACKUP

The Evolution of a Proton – Deep into the Sea

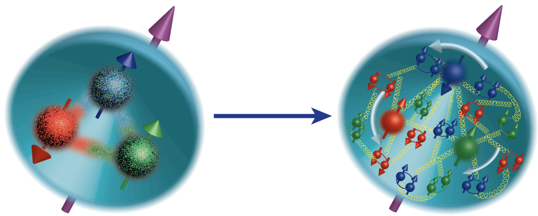


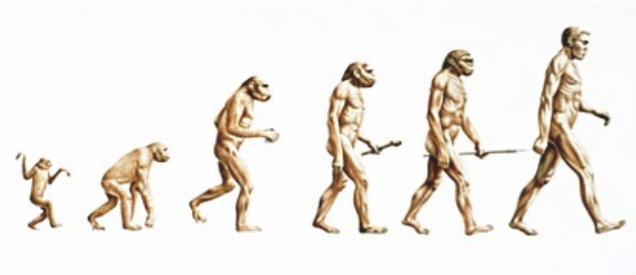


Saturation



Our Understanding of Nucleon Spin

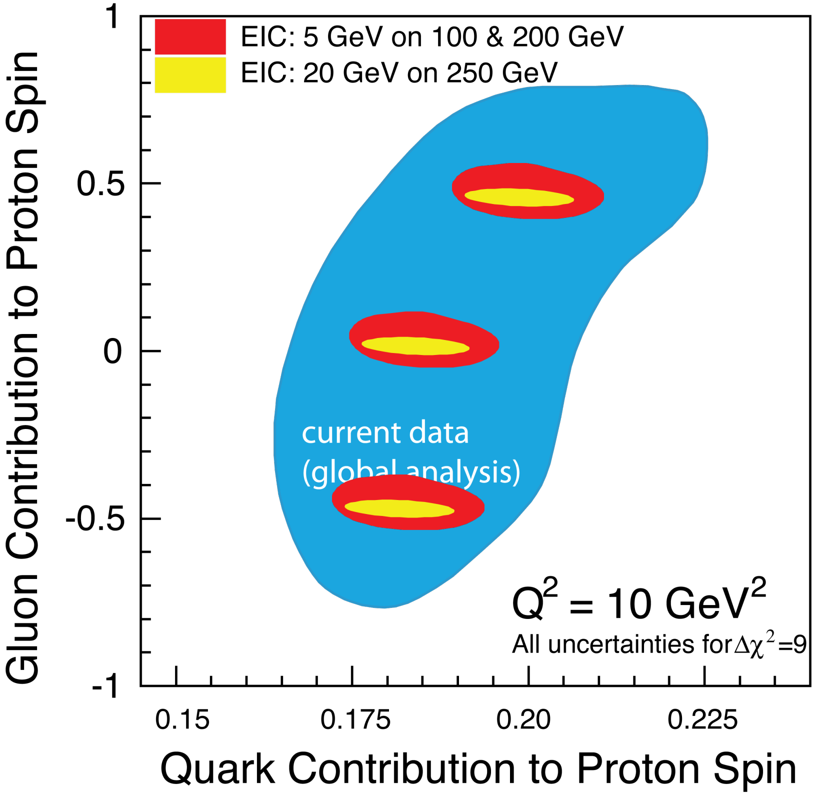




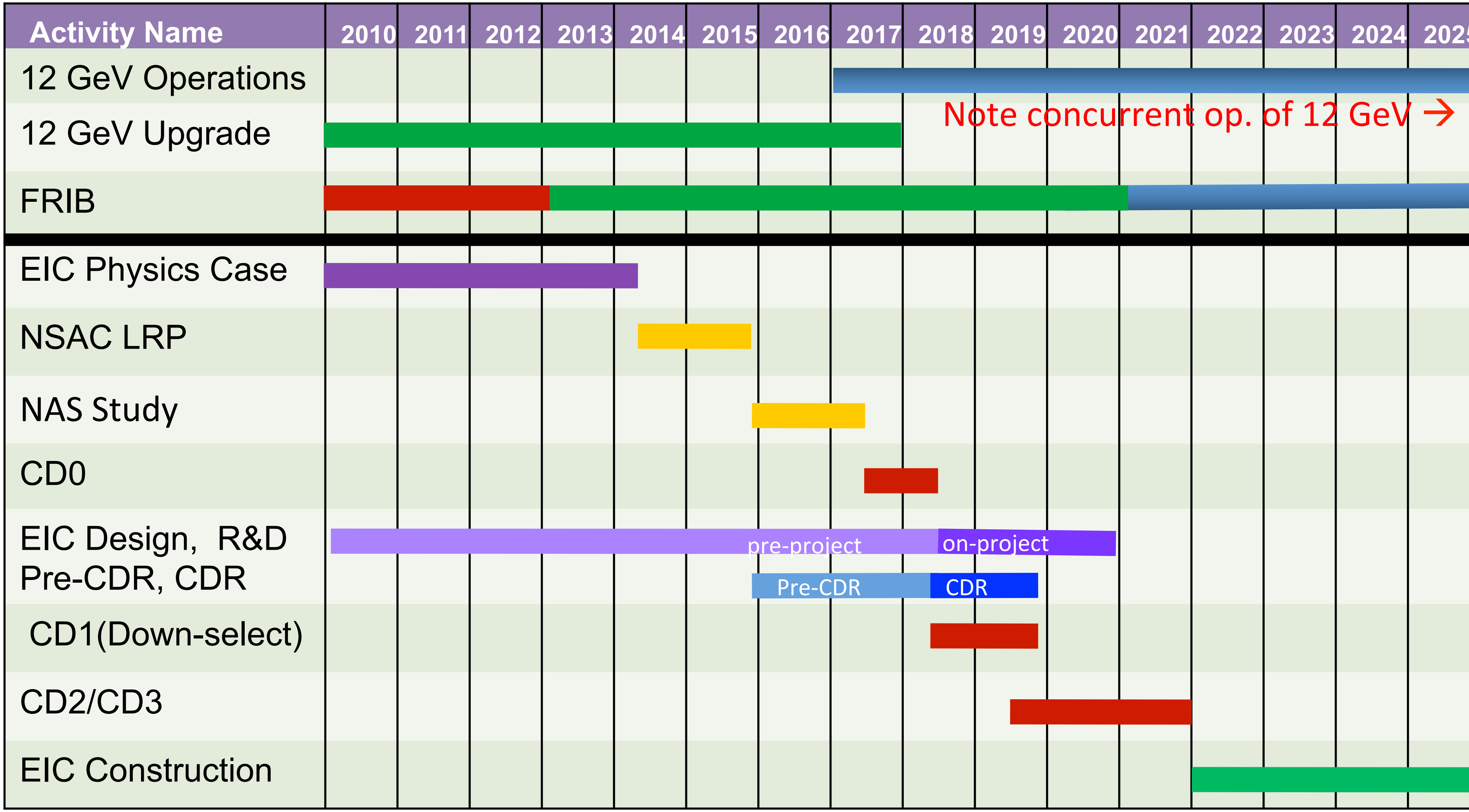
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = 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

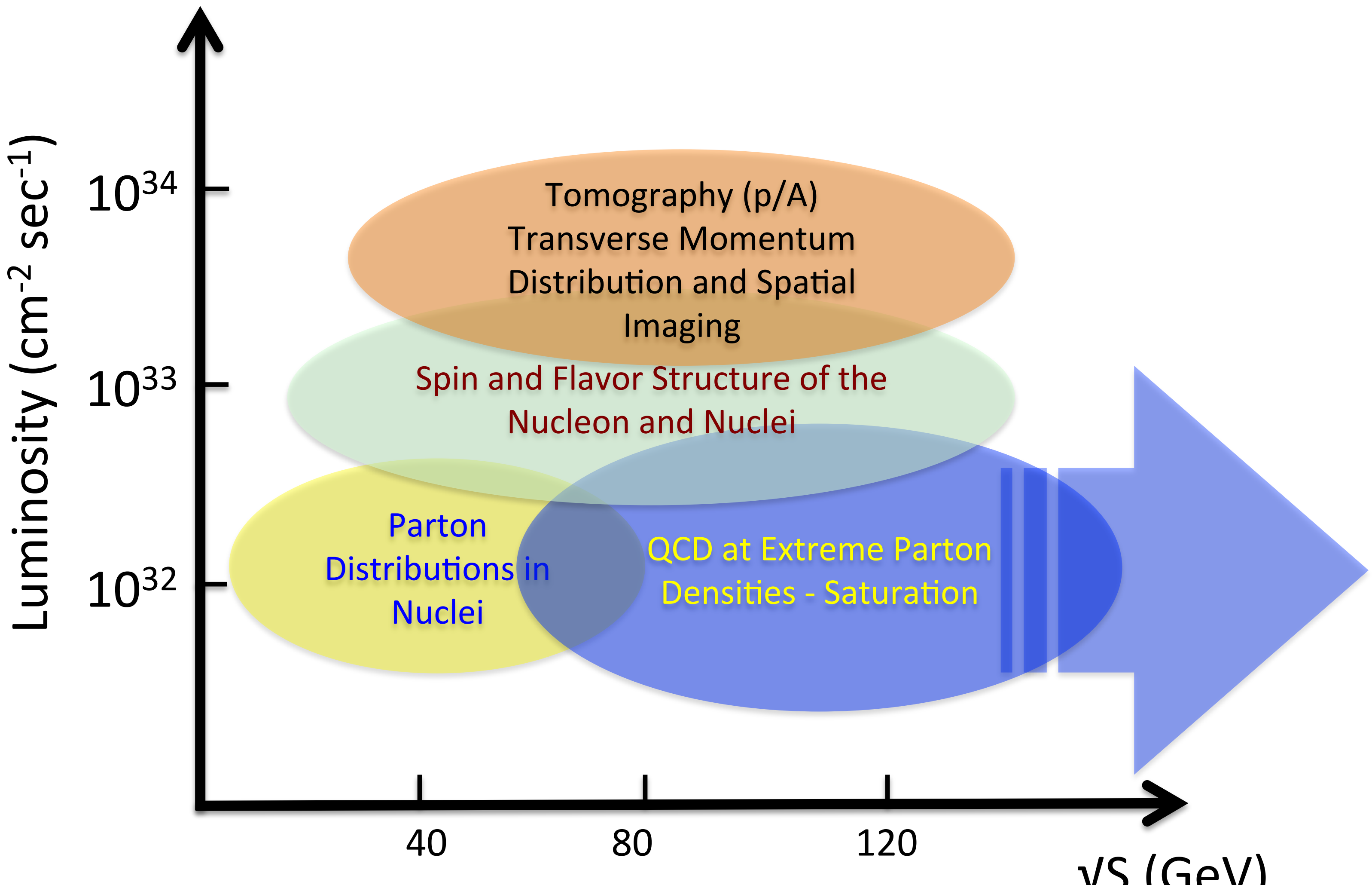


EIC Timeline (for JLEIC planning)

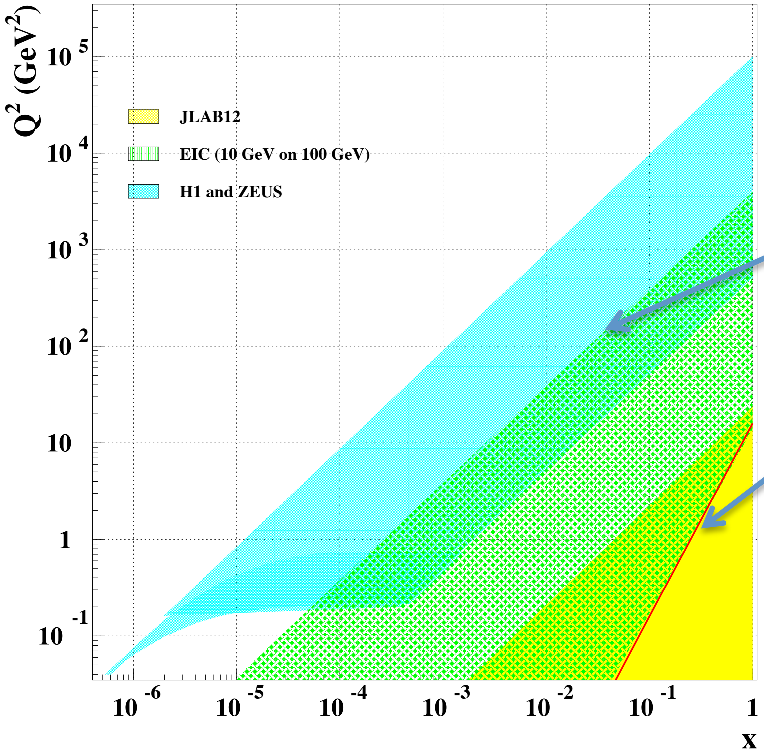


CD0 = DOE "Mission Need" statement; **CD1** = design choice and site selection (VA/NY)
CD2/CD3 = establish project baseline cost and schedule

Physics vs. Luminosity & Energy



JLEIC parameters (nucleon)



Cross section decreases rapidly with higher X

This edge determined by √s:
√s = 65 GeV

This edge determined by proton beam energy:
E_{proton} < 100 GeV -> $E_{electron}$ = 10 GeV^2

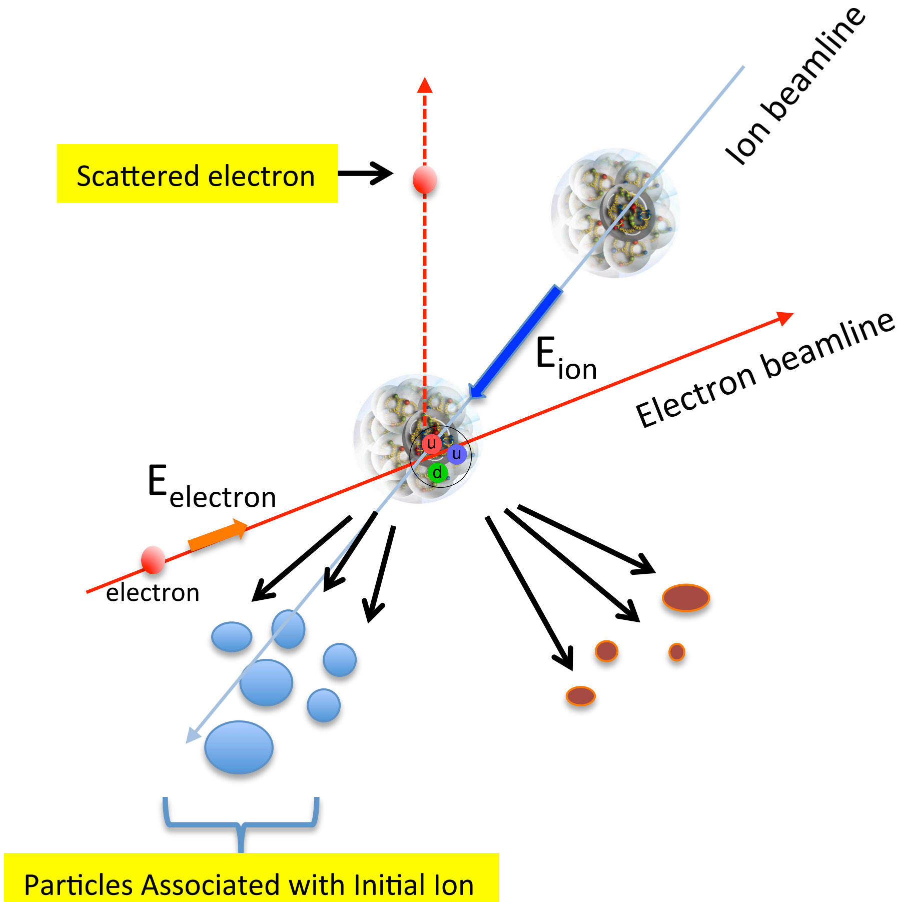
Measure at x of 10^{-3} to 1, exclusive processes
Luminosity: x 10 to 100 that of HERA

Understanding hadron structure cannot be done without understanding spin:
Polarized proton and electron beams

Sets some of the basic parameters of the JLEIC design

Jefferson Lab

Detector and IR Design



Many R&D and development in the Detector and Interaction Region (IR) design.
→ can't cover all topics here

One example of Detector/IR/Accelerator optimization

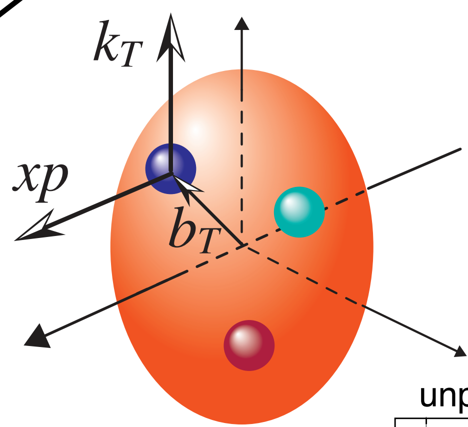
Usually not a priority at colliders. Very important for EIC physics

Want to have a 100% acceptance for these particles

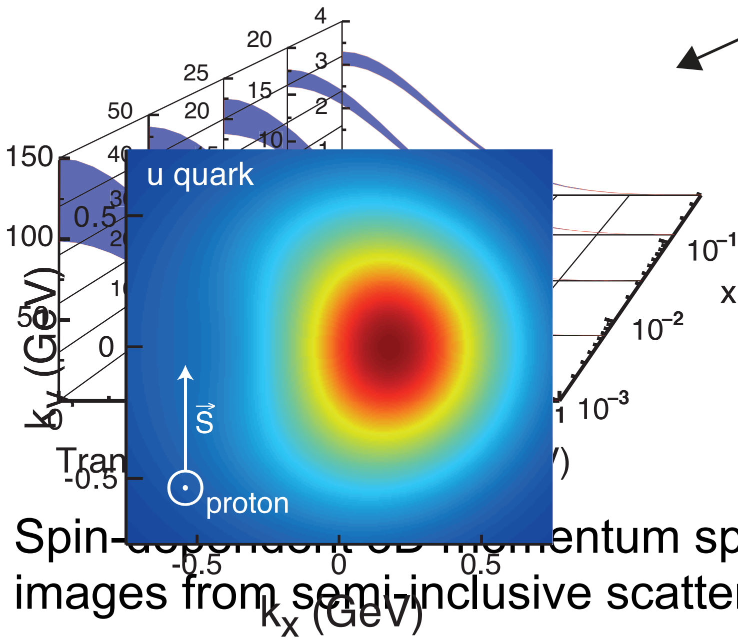
3D Imaging of Quarks and Gluons

$W(x,b_T,k_T)$

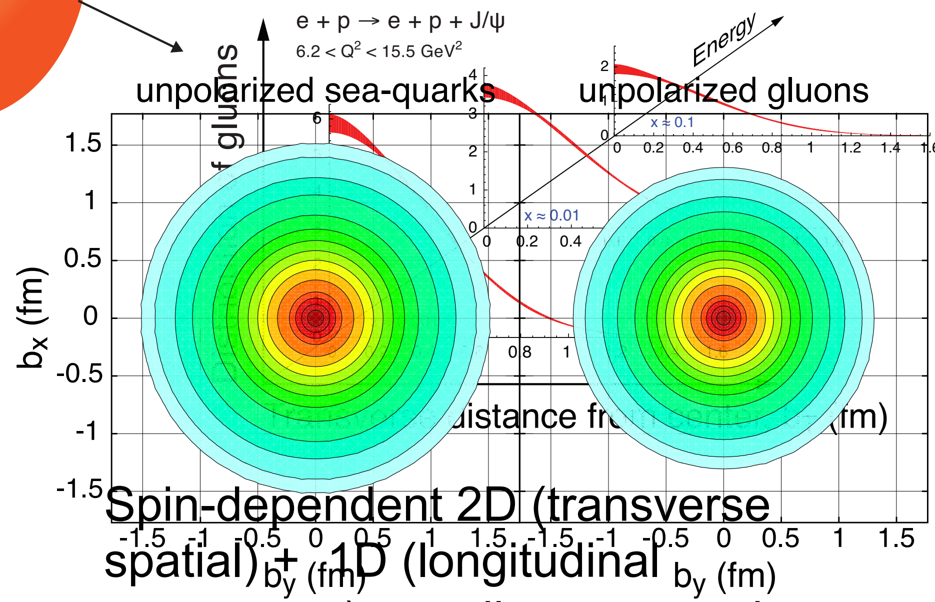
Momentum space $\int d^2b_T$ $\int d^2k_T$ *Coordinate space*



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



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

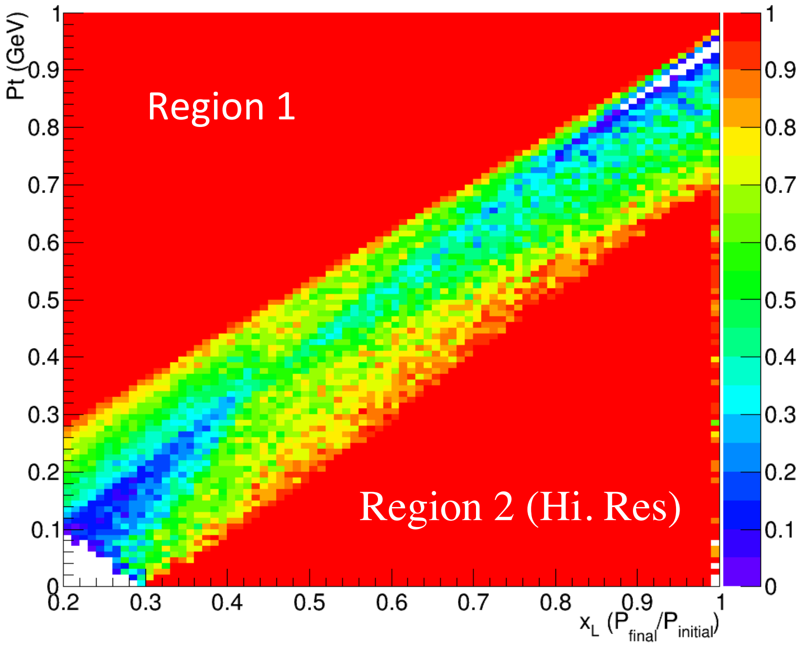


Spin-dependent 2D (transverse spatial) + 1D (longitudinal momentum) coordinate space images

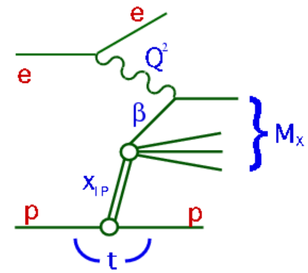
Position *r* X Momentum *p* → Orbital Motion of Partons

Acceptance for p’ in ep->e’Xp’

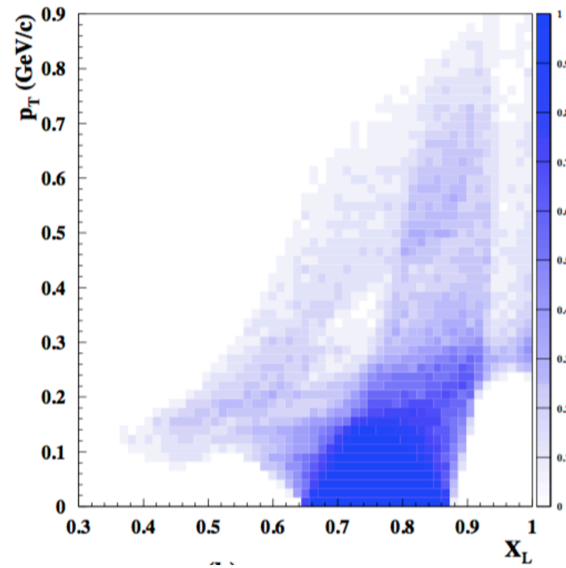
acceptance



Zhiwen Zhao



ZEUS
Leading Proton Spectrometer



$X_L = E_{p'}/E_p$

Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

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

Jefferson Lab

National Science Academy: 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?

Substantially the same as the RISAC charge