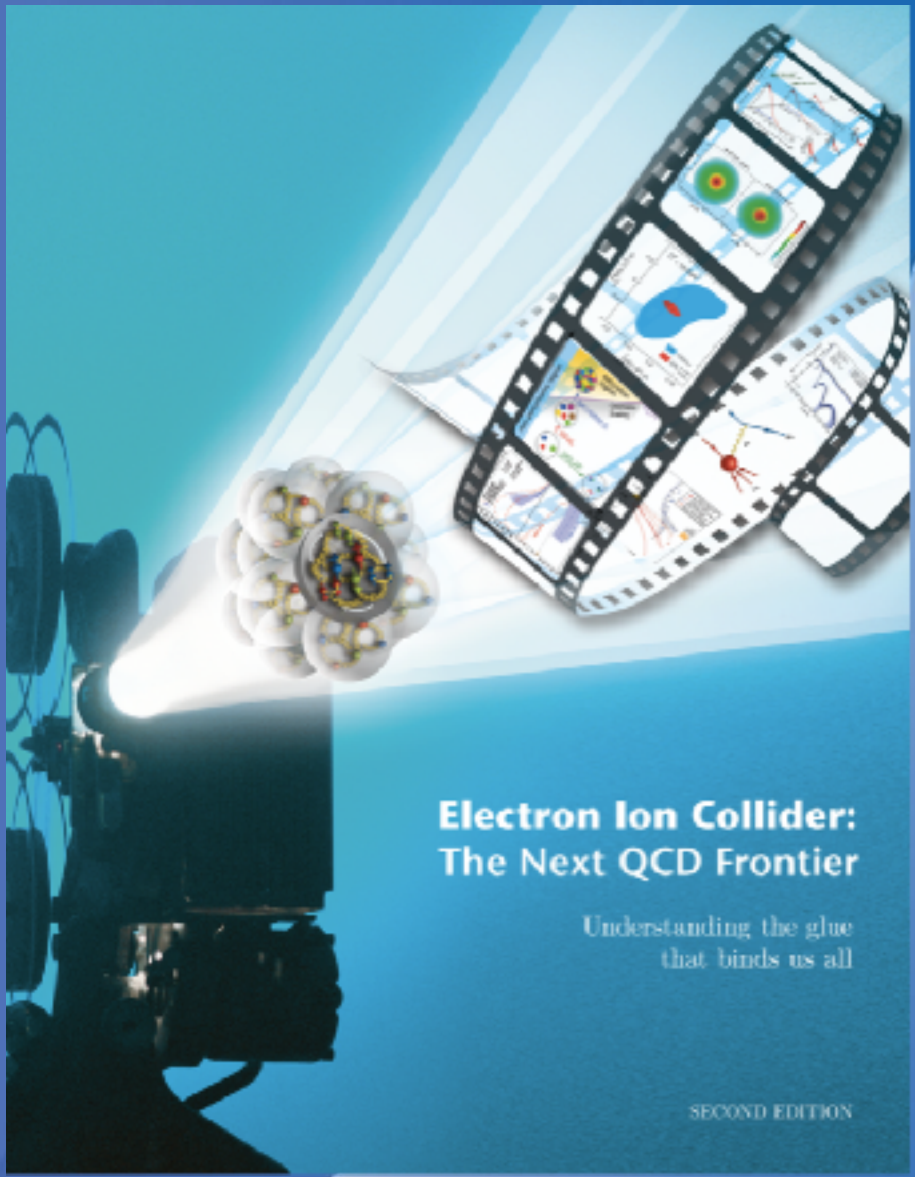
eRHIC

An Electron Ion Collider at BNL



Berndt Mueller

POETIC 7
November 15, 2016

Overview

- Why we need to build an EIC
- Requirements for an EIC
- eRHIC: An EIC at BNL
  - Physics Reach
  - Technical realization
- eRHIC R&D
- eRHIC Schdule
- Summary

EIC Objectives

- Together with FRIB, the EIC ensures a world-leading accelerator based nuclear science program in the U.S. beyond 2025 when the RHIC II and J-Lab 12 GeV programs will have reached their goals.
- The EIC will close the last glaring gap in our understanding of the visible world around us: *It will reveal how gluons bind quarks into nucleons and complex nuclei.*
- Pushing into kinematic domains that have never been explored before, the EIC will have ample discovery potential, in addition to being a precision imaging device. *Large energy range is important for this.*
- The EIC physics program will bring together both, the J-Lab and RHIC user communities, and attract a world-wide user community to the U.S.
- The EIC should be a facility at the technological forefront - it will be the only U.S. based particle collider in the foreseeable future - we need to find the right balance between technical risk and innovation.
- The EIC will be the world's leading *QCD Laboratory* - a centerpiece amongst nuclear physics facilities around the world.

Proton structure, mass, and spin

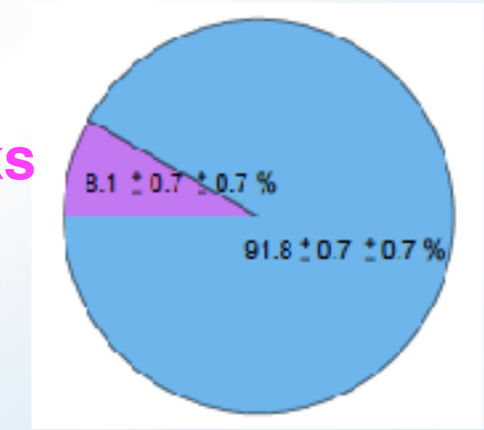
Over the course of the past century we have explored the structure and composition of the matter around us from the macroscopic to the atomic scale. We now know in great detail how matter is built up from from its elementary constituents, at the molecular, atomic, even subatomic scale.
But we do not know how the most elementary of atomic nuclei, the proton, which constitutes approximately half of the mass of our own bodies, is built up from its constituents - quarks and gluons.
Understanding the structure of the proton and its sister particle, the neutron, is the final frontier of the science of the things in and around us.

Only an electron-ion collider can do this!

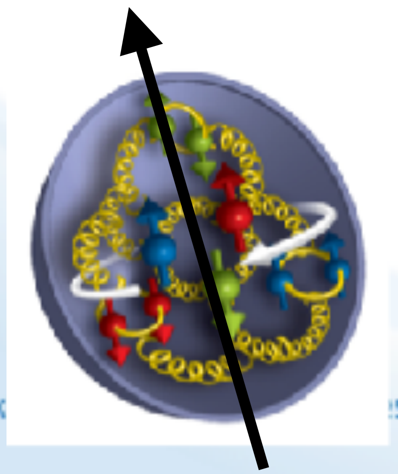
The proton mass puzzle:

Quarks carry less than 10% of the proton's mass
How do gluons generate the energy for the nucleon mass?

Proton mass balance



Spin



The proton spin puzzle:

Quarks carry only ~30% of the proton's spin
How do quark and gluon dynamics generate the remainder of the proton's spin?

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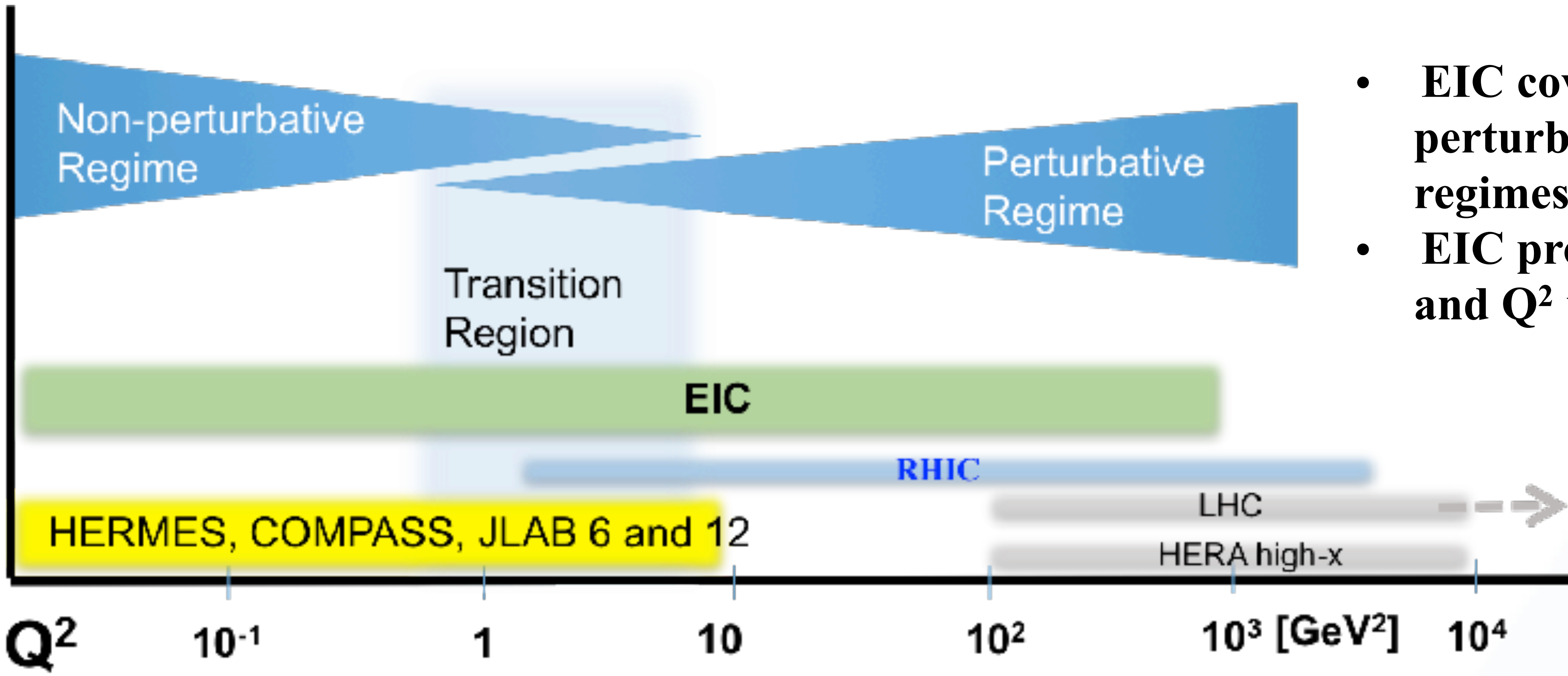
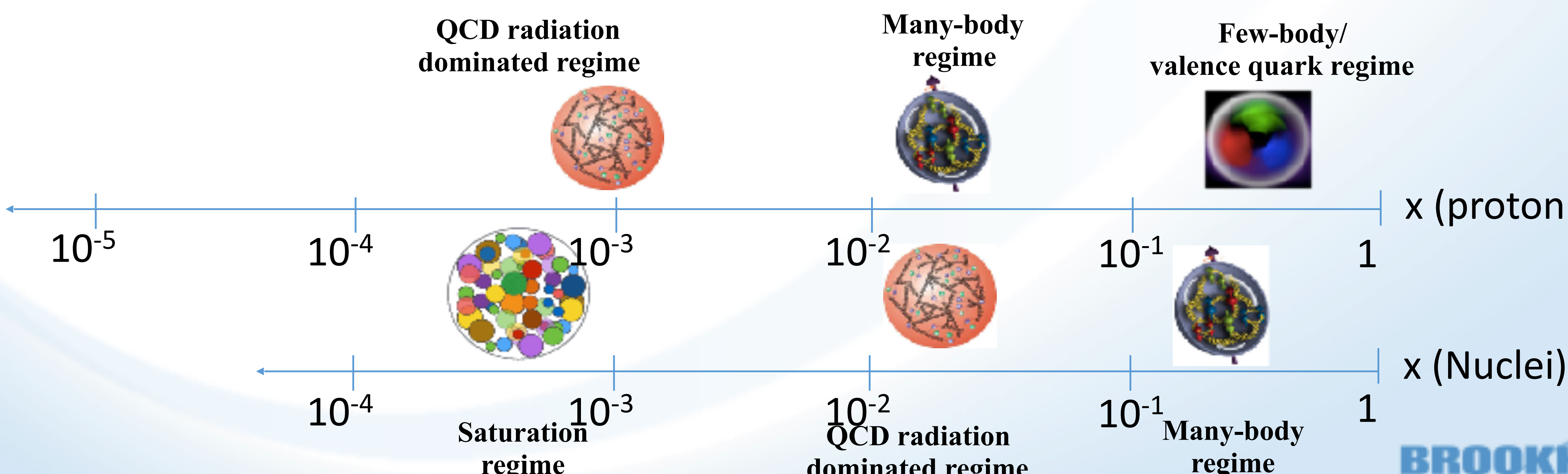
Why large x-Q^2 coverage is important

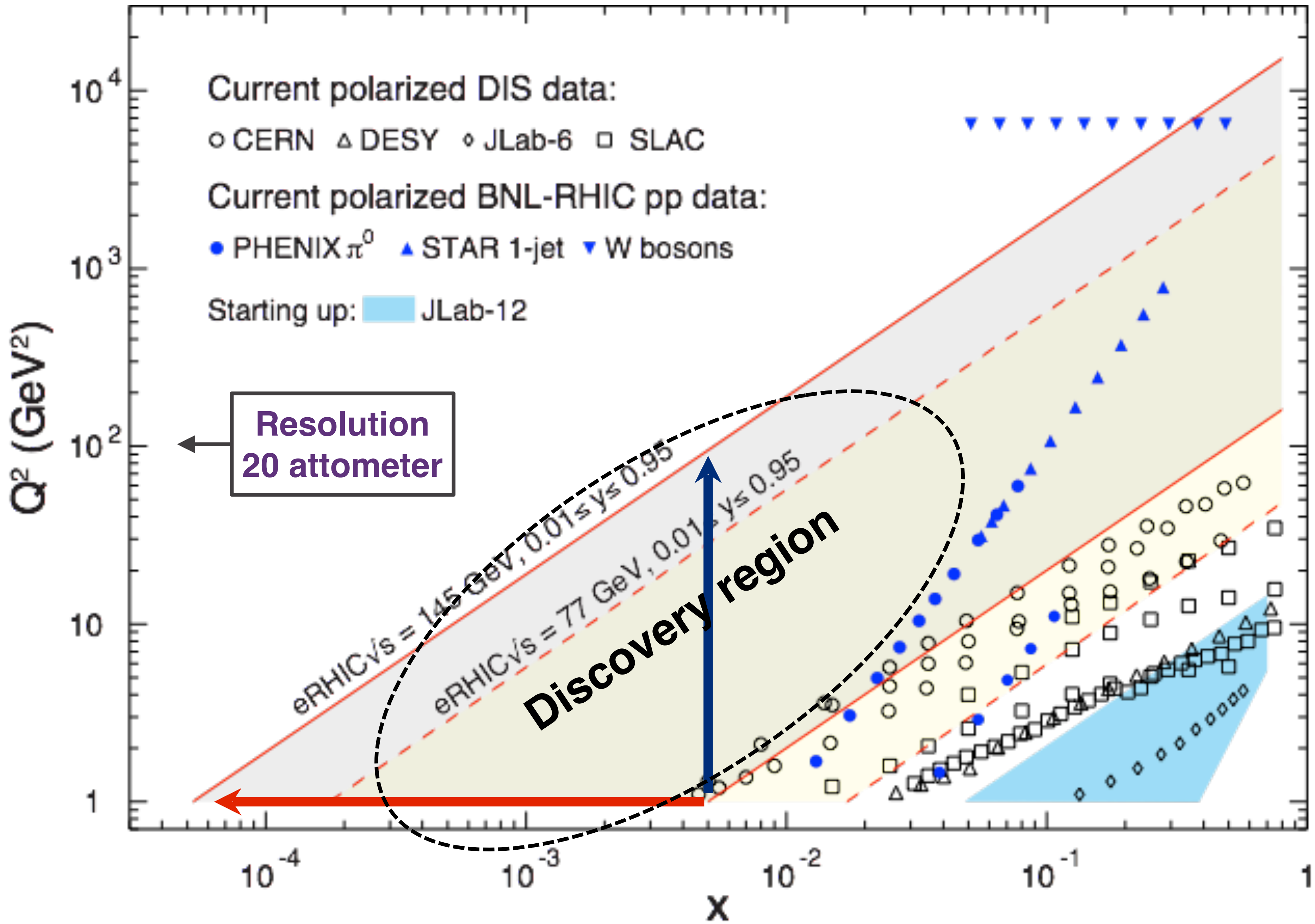


- EIC covers non-perturbative, perturbative and transition regimes
- EIC provides long evolution range and Q^2 up to ~1000 GeV^2 (0.01 fm)

Going from large to small x nucleons and nuclei reveal their full structure



Requirements: √s and Polarization



polarized
ep*, μ*p*, *pp

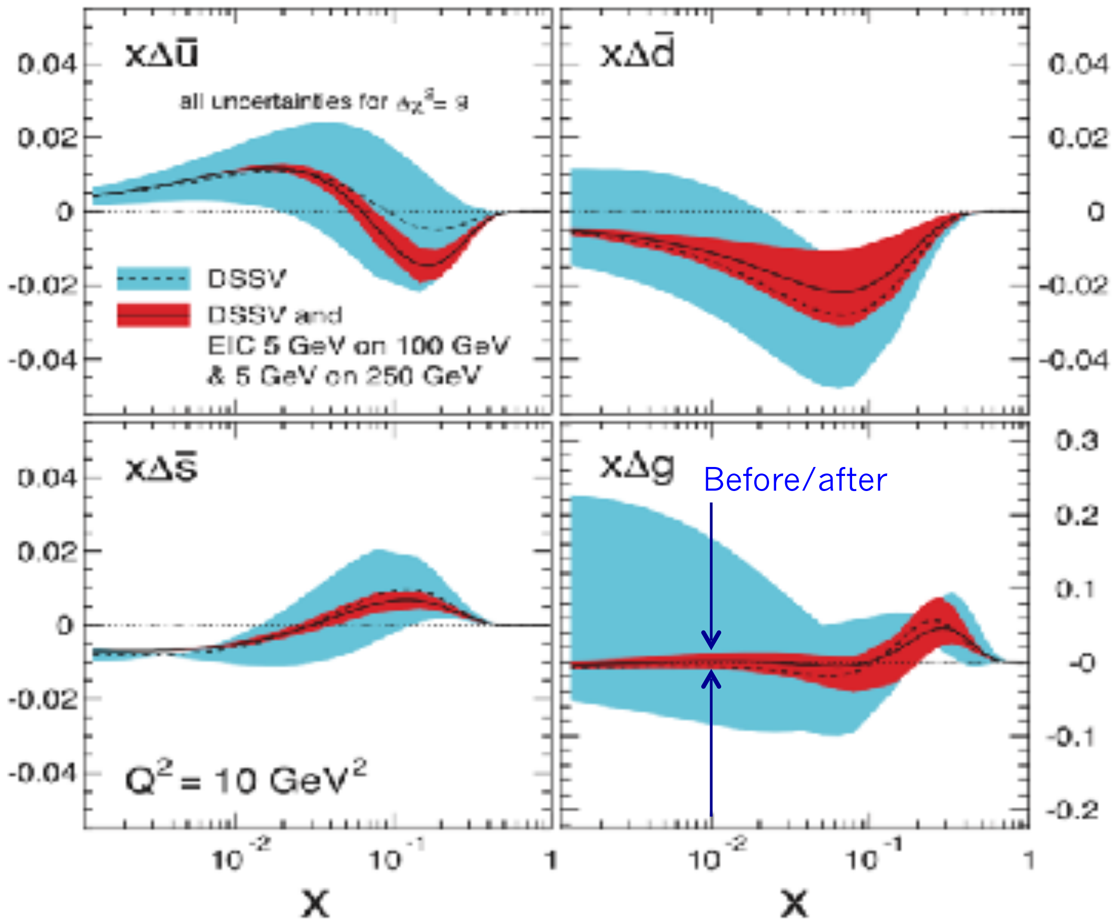
$$Q^2 \approx s \cdot x \cdot y$$

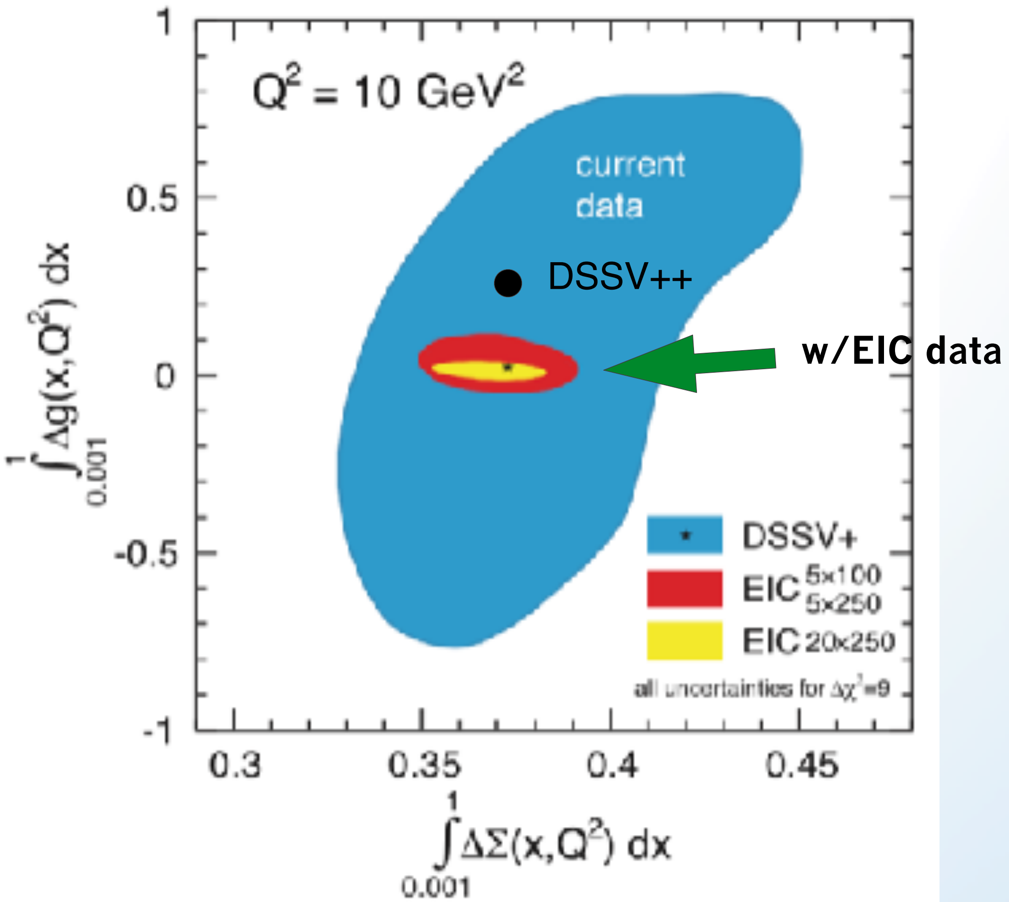
- ✳ Need to reach low-x where gluons dominate (ΔG, ΔΣ range!)
- ✳ Flexible energies (see also structure functions later)
- ✳ Need sufficient lever arm in Q^2 at **fixed** x (evolution along Q^2 or x)
- ✳ Electrons and protons/light nuclei (p, ^{3}He, d) highly polarized (70%)

Solving the spin puzzle

The EIC – the decisive measurement (in the 1st year of running)**:**

(Utilizing the wide Q^2, x range accessible at the EIC)





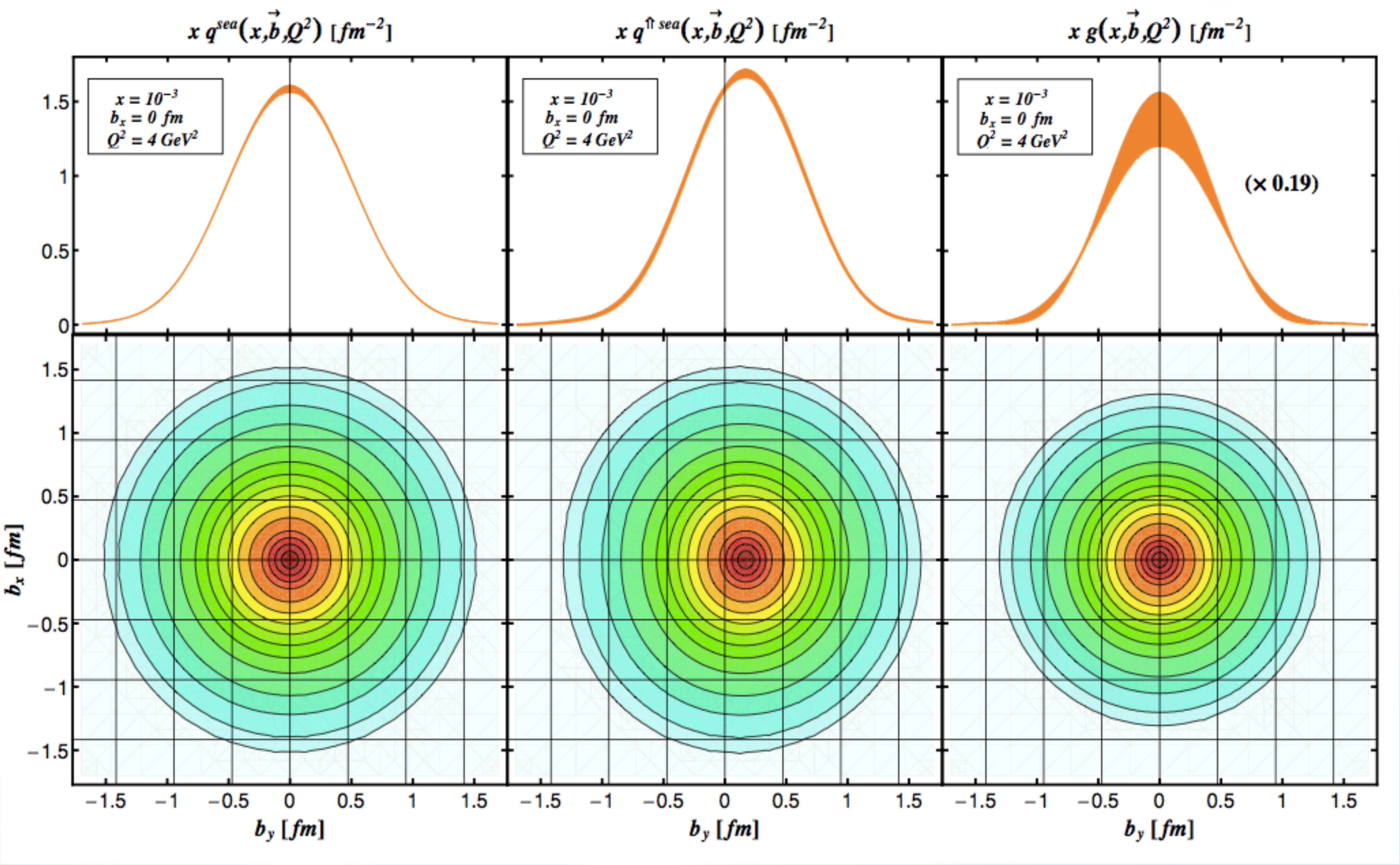
No other machine in the world can perform this measurement!

Solution to the proton spin puzzle:

- ◇ ***Precision measurement of ΔG – extends to smaller x regime***
- ◇ ***Orbital angular momentum – motion transverse to proton's momentum***

Imaging quarks and gluons

using Generalized Parton Distributions (GPD's):



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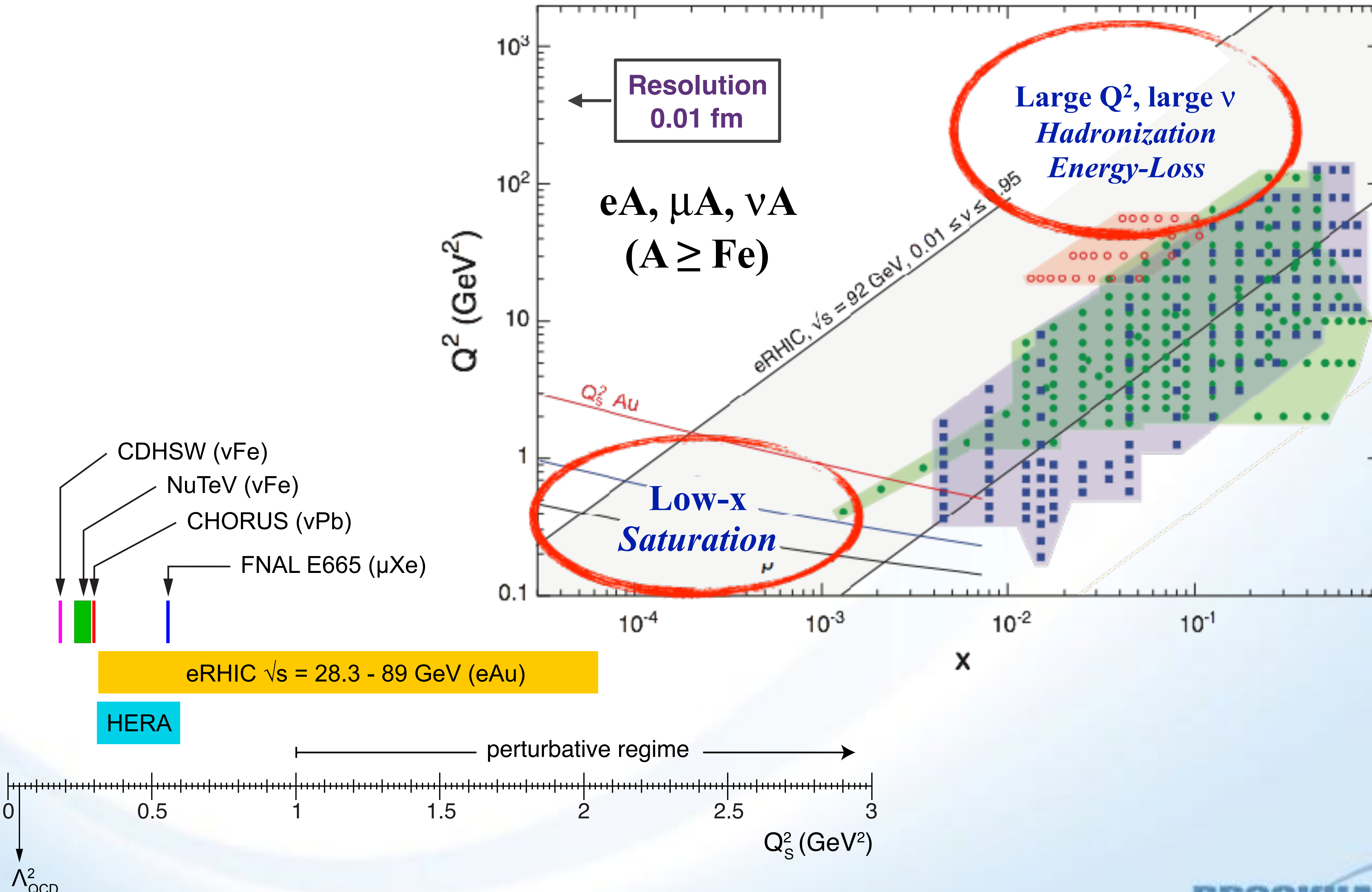
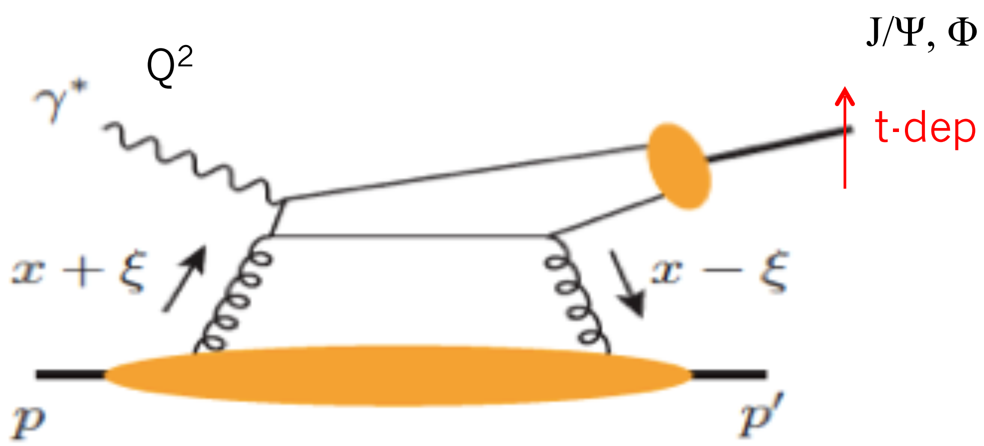
Requirements: √s and Beam Masses



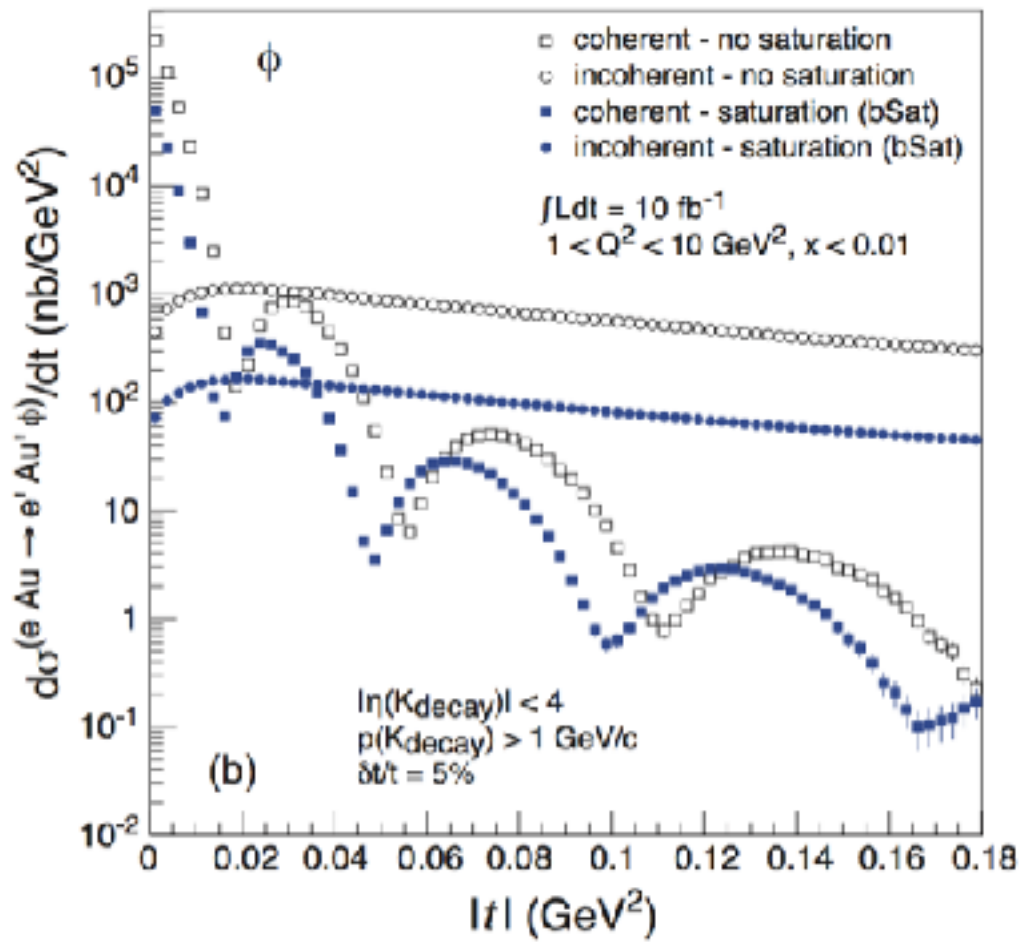
Gluons at high density

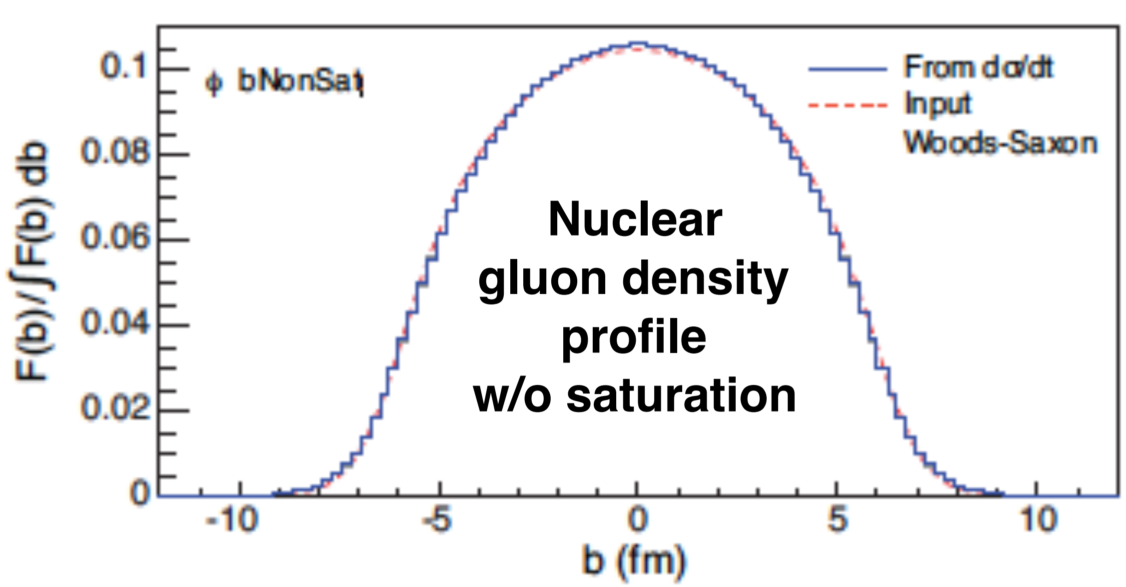
Exclusive vector meson production

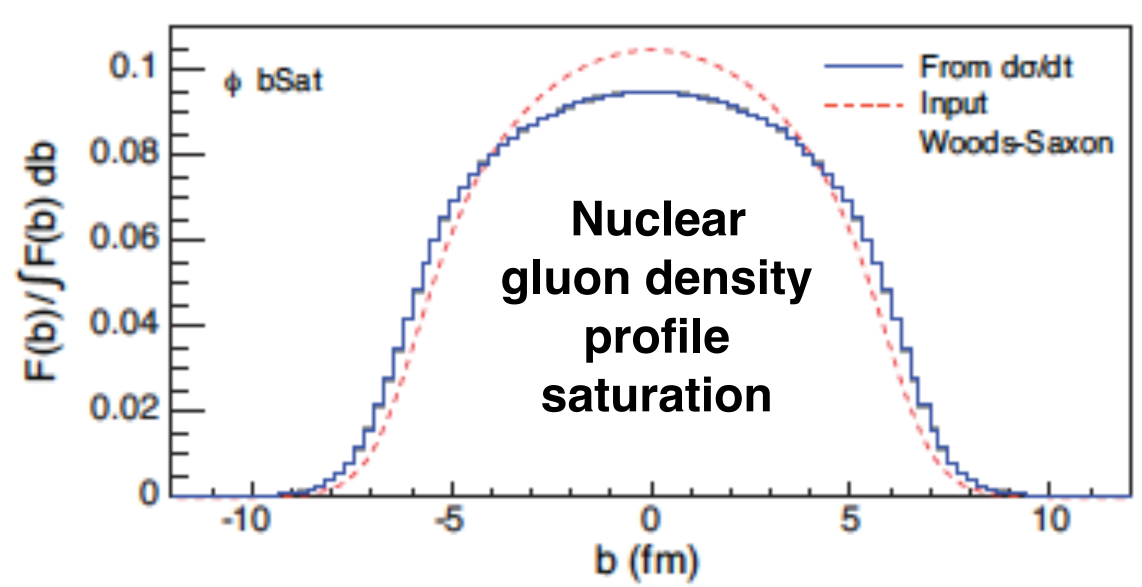


Fourier transform the differential cross section

➡ Spatial imaging of glue density

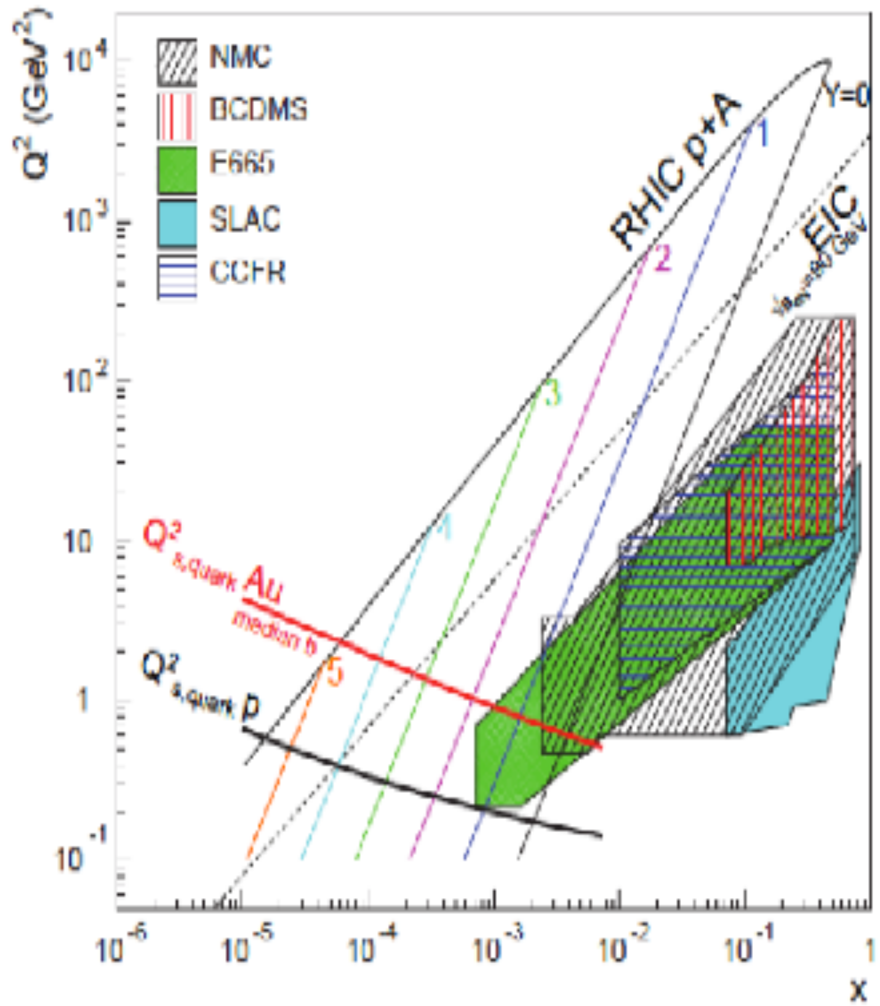


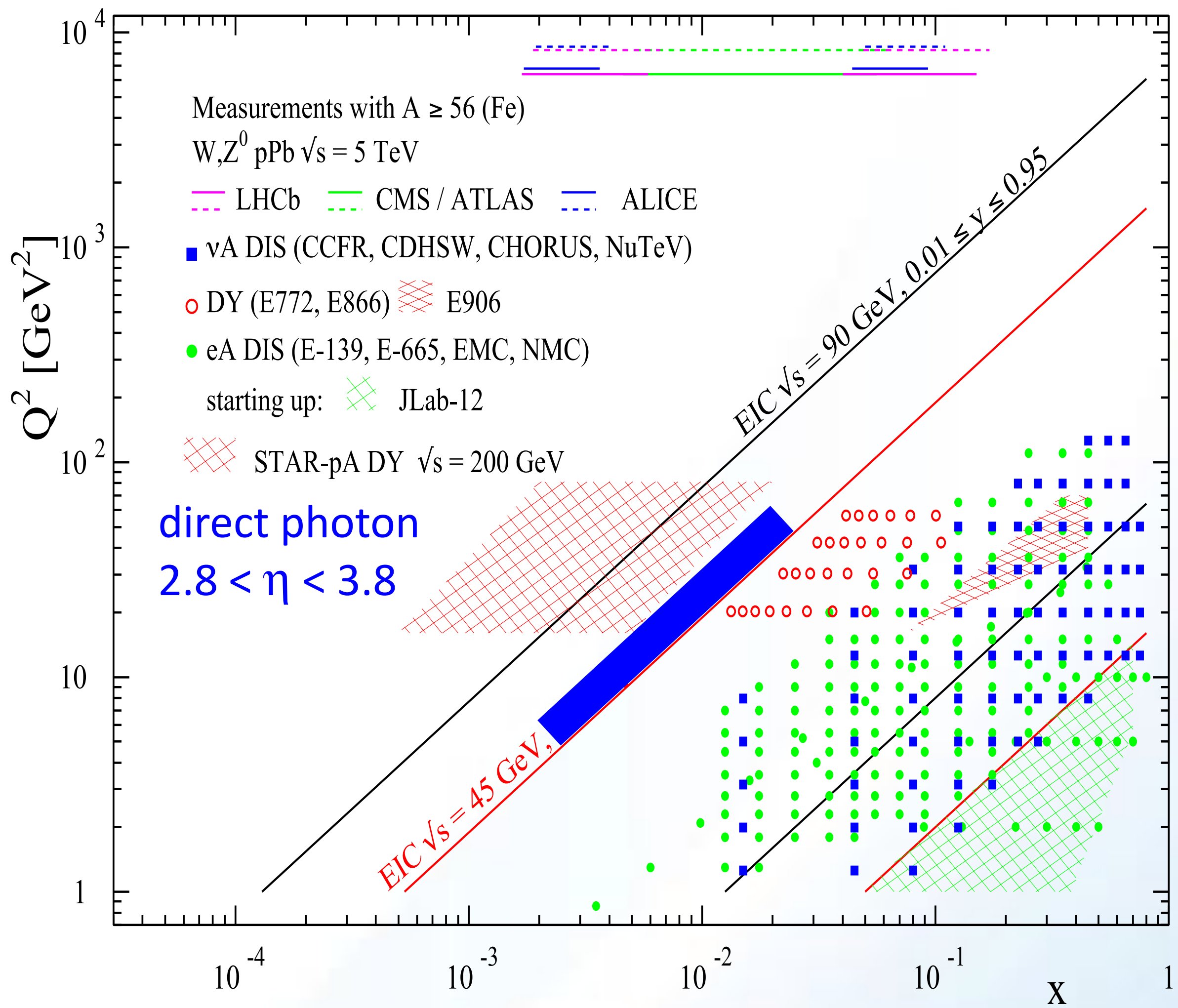




Milestones on the path to EIC: p+A

SATURATION | **NUCLEAR PDFs**

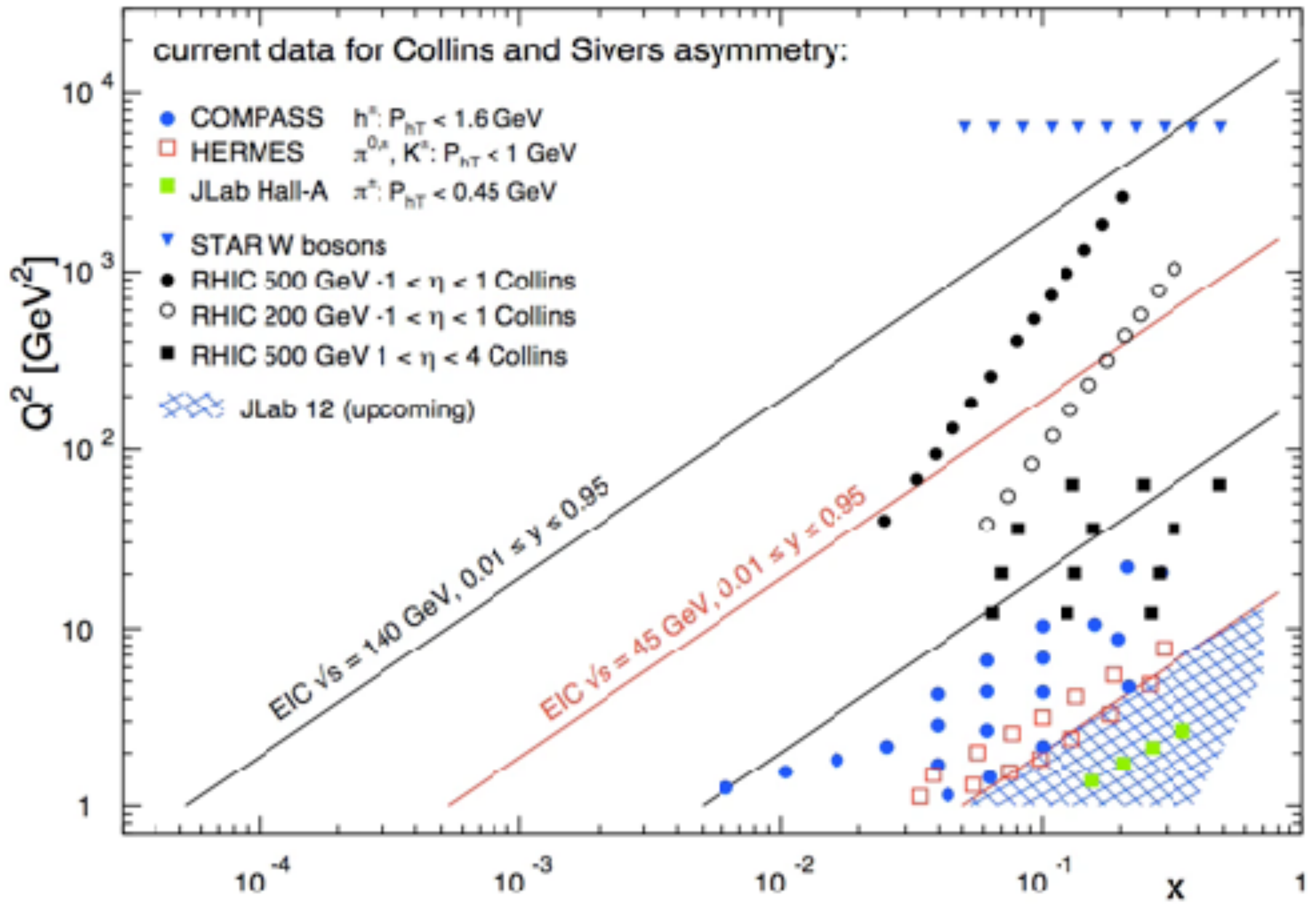




- RHIC & EIC cover similar kinematic regions: **RHIC will need to go FORWARD**
- RHIC accesses the same physics but with different probes: **ESSENTIAL to confirm mechanism**
- LHC has limited sensitivity due to high Q^2, but **only RHIC can vary A**
- At RHIC **saturation signals** include forward γ+jet and di-hadrons.
- At RHIC **gluon and sea-quark nPDFs** can be measured by Drell-Yan and direct photons.

Milestones on the path to EIC: p+p

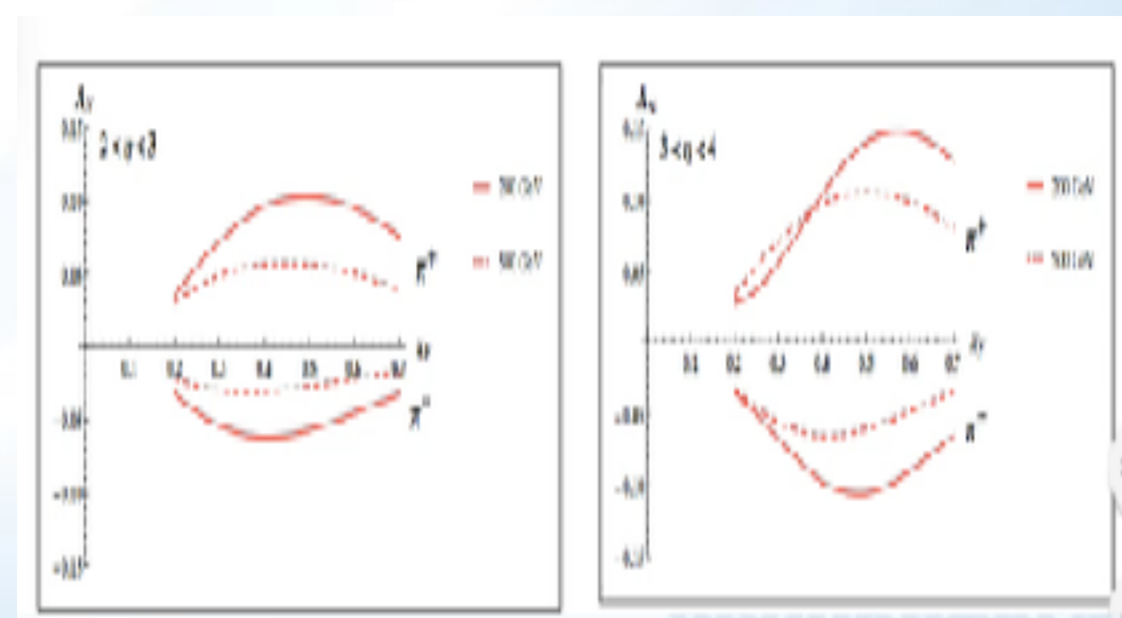
TMD Evolution



- RHIC & EIC cover similar kinematic regions
- All existing data lives at low Q^2 - RHIC data covers wide range of Q^2 and can study TMD evolution effects in preparation for EIC
- RHIC accesses the same signals as EIC but with different probes - ESSENTIAL to understand underlying mechanisms
- Only RHIC has polarized beams and tunable √s for evolution studies and the predicted non-universality of TMDs, i.e. Sivers function

Origin of Large Forward SSA

- New work suggests that quark-gluon-quark correlations (twist-3 FF) could explain large forward π^0 A_N. Measurements for charged hadrons at RHIC at both 200 and 500 GeV in the forward region would help confirm the validity of these predictions.



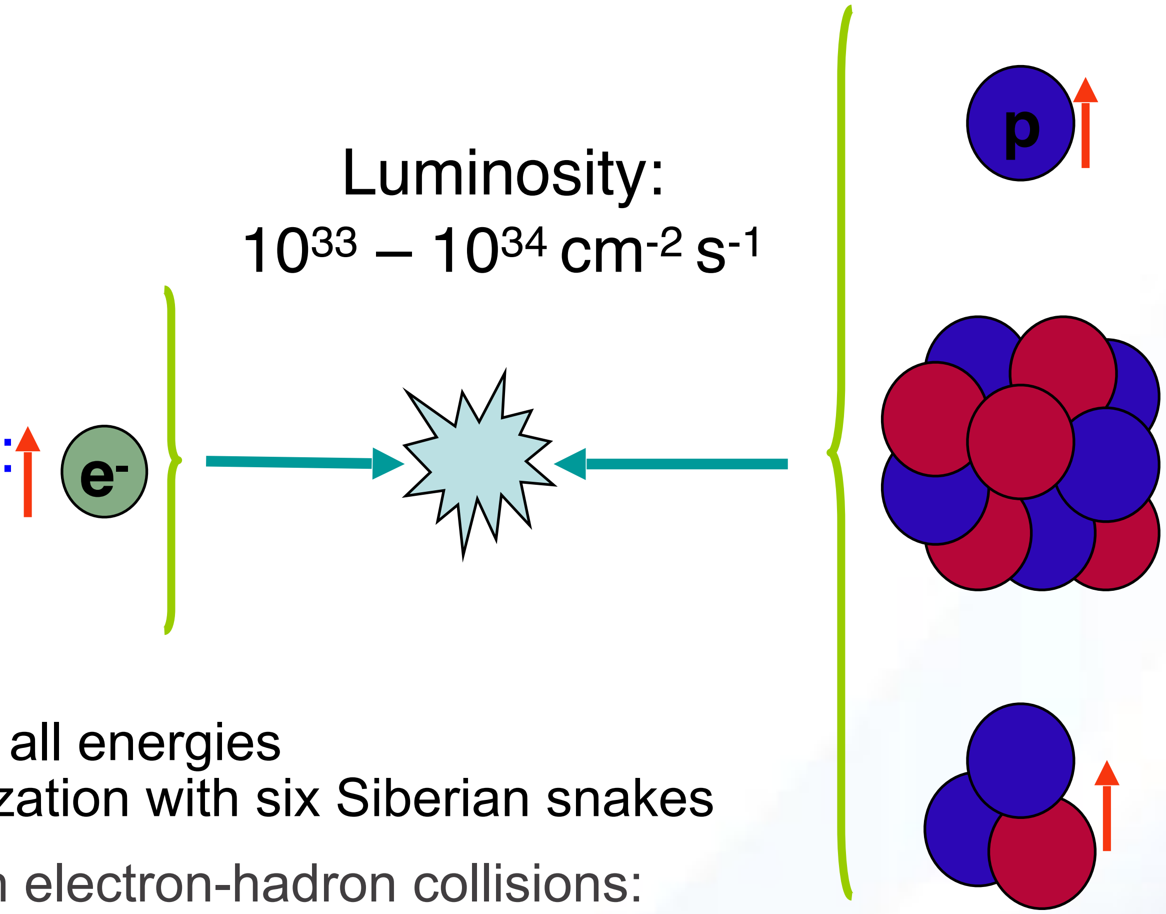
eRHIC: An Electron Ion Collider at BNL

Concept: Add an electron accelerator to the $2.5B RHIC/AGS complex including existing RHIC tunnel, detector buildings and cryo facility

Center-of-mass energy range: 20 – 140 GeV

Luminosity:
$10^{33} - 10^{34}$ cm^{-2} s^{-1}

80% polarized electrons:
3 – 18 GeV

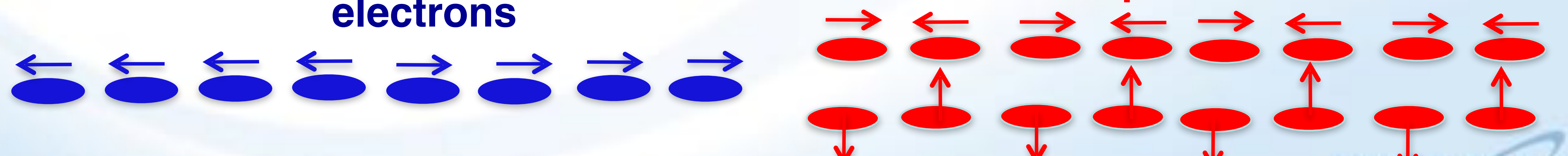


70% polarized protons
25 – 275 GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 – 110 GeV/u

Pol. light ions (^{3}He)
17 – 184 GeV/u

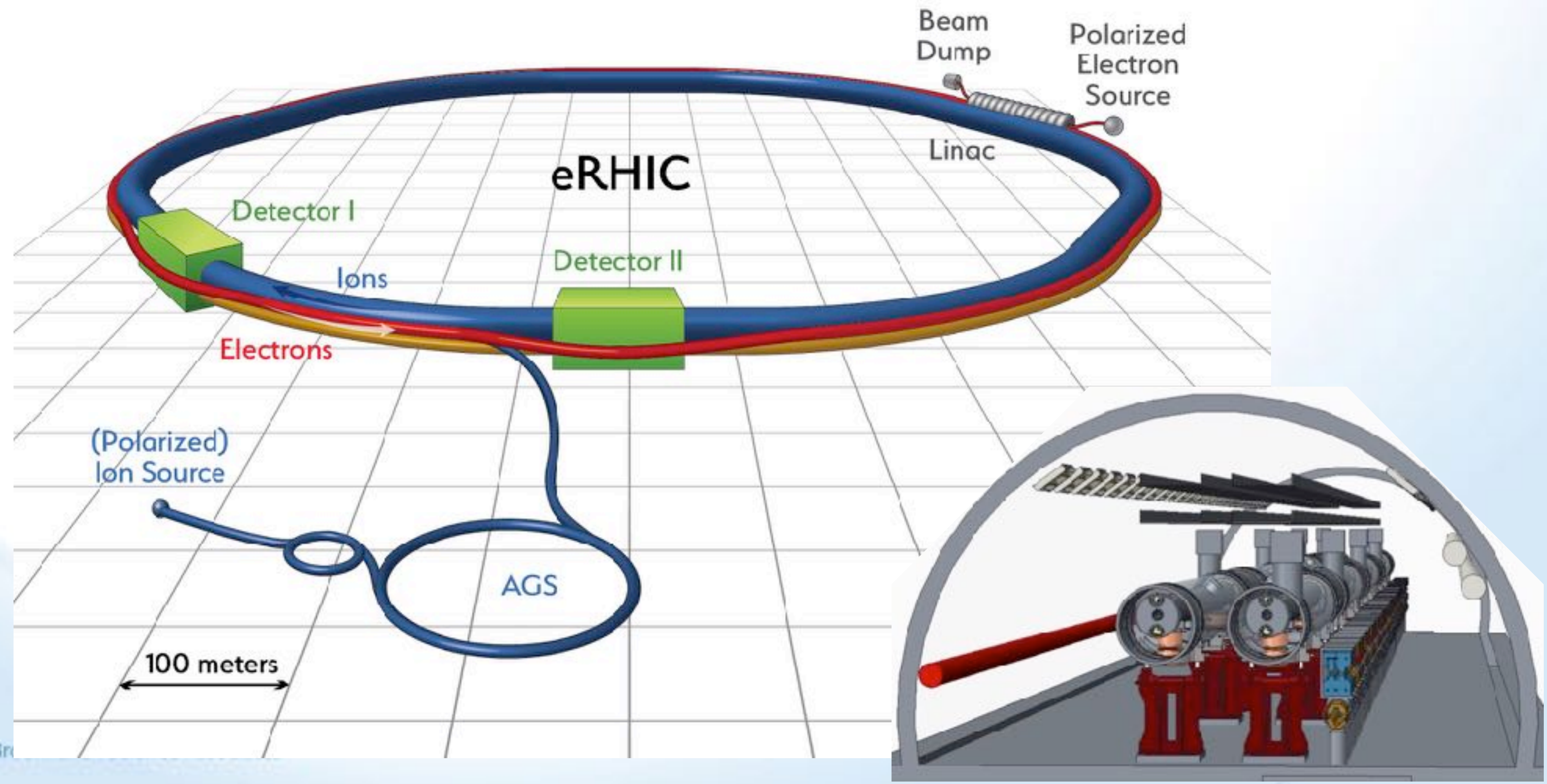
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:



* It is possible to increase the RHIC ring energy by 10%

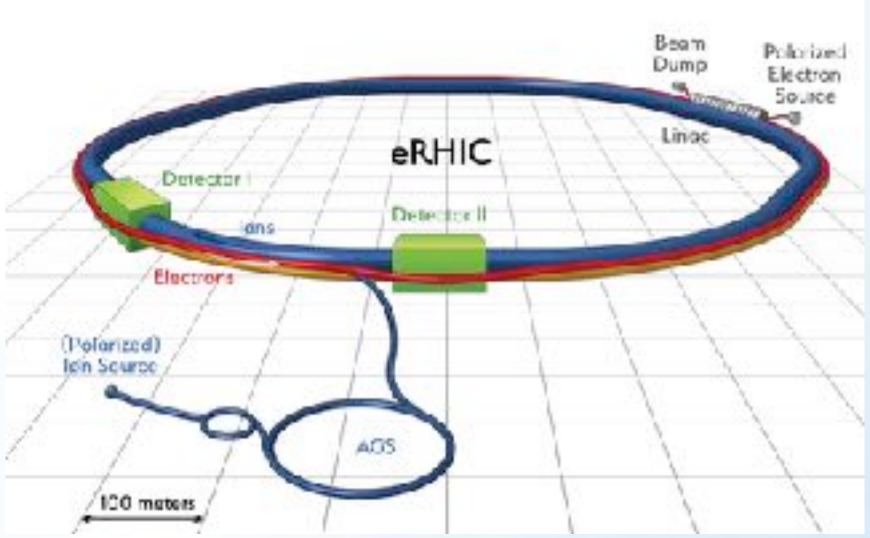
“Ultimate” eRHIC design

- Peak luminosity: 2×10^{34} cm^{-2} s^{-1}
- ERL and permanent magnet arcs reduce power consumption to about 15 MW



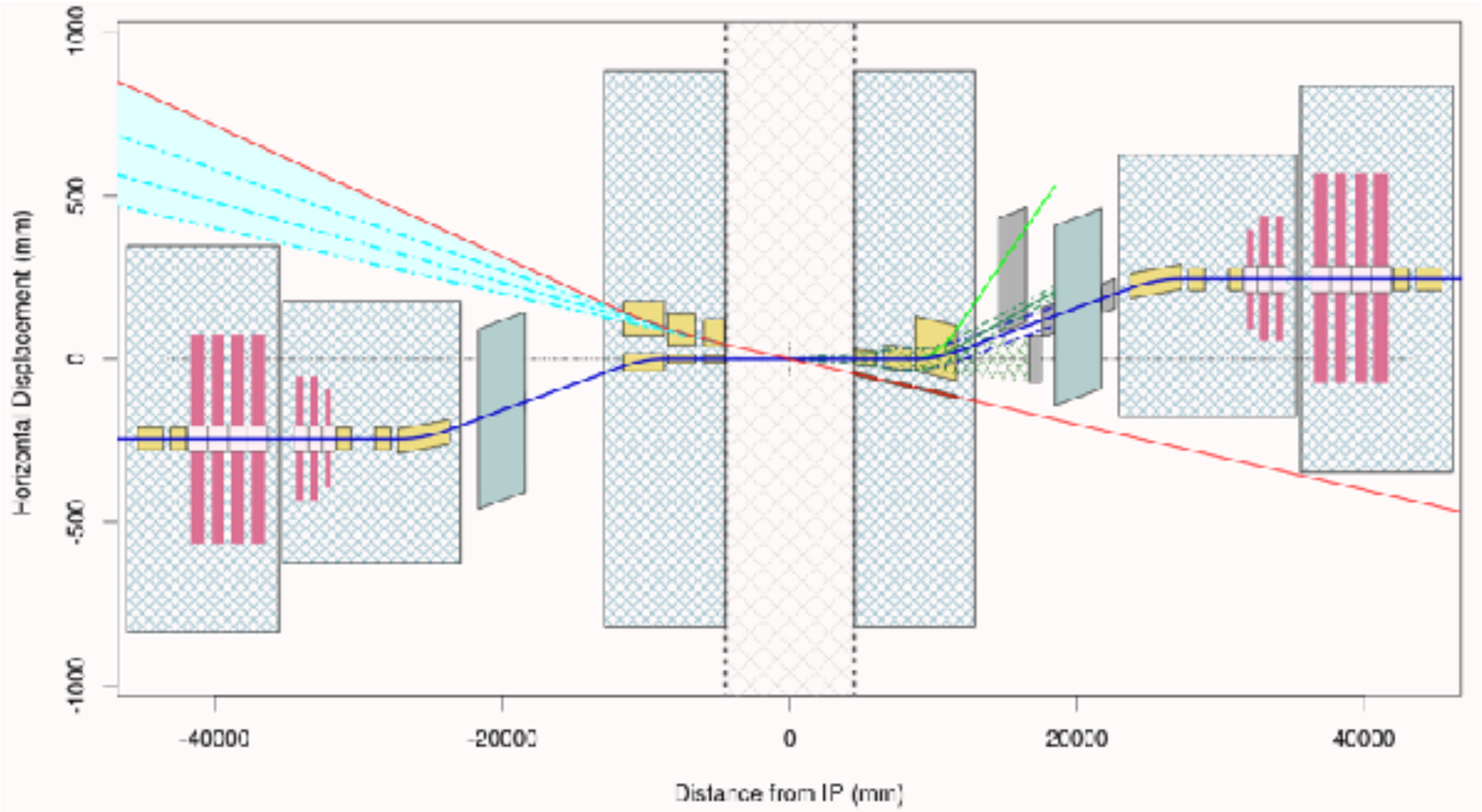
Initial eRHIC design

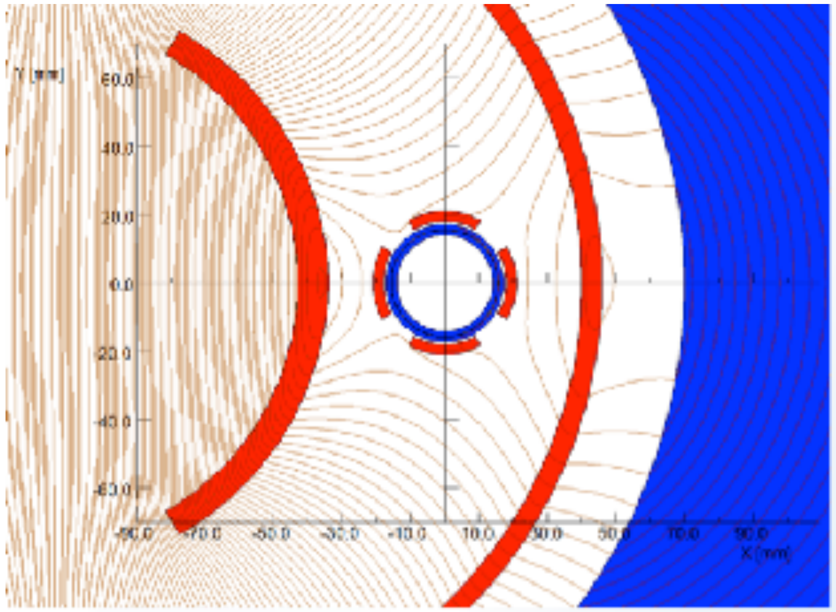
- **Minimize cost and technical risk:**
  - Center-of-mass energy reach of 140 GeV to cover the whole EIC science case
  - The initial luminosity will be 10^{32-33} cm^{-2} s^{-1} and will later be increased with the installation of hadron cooling, as was done for RHIC
- **Low risk ERL-Ring**:
  - Expected to have lower cost, especially if cost reduction R&D is successful
  - ERL: 3 GeV, 650 MHz linac with 6 recirculation loops similar to CEBAF
  - High luminosity from colliding bright electron bunches only once with RHIC proton bunches



- **Low risk Ring-Ring**:
  - Based on existing technology
  - Full energy polarized injector using 6 GeV SRF Linac with 3 recirculation loops
  - High intensity electron storage ring similar to PEP II or KEK-B
- Both designs can be upgraded to the ultimate eRHIC ERL-Ring design with the addition of fast electron cooling of proton beams.

High-luminosity, full-acceptance IR

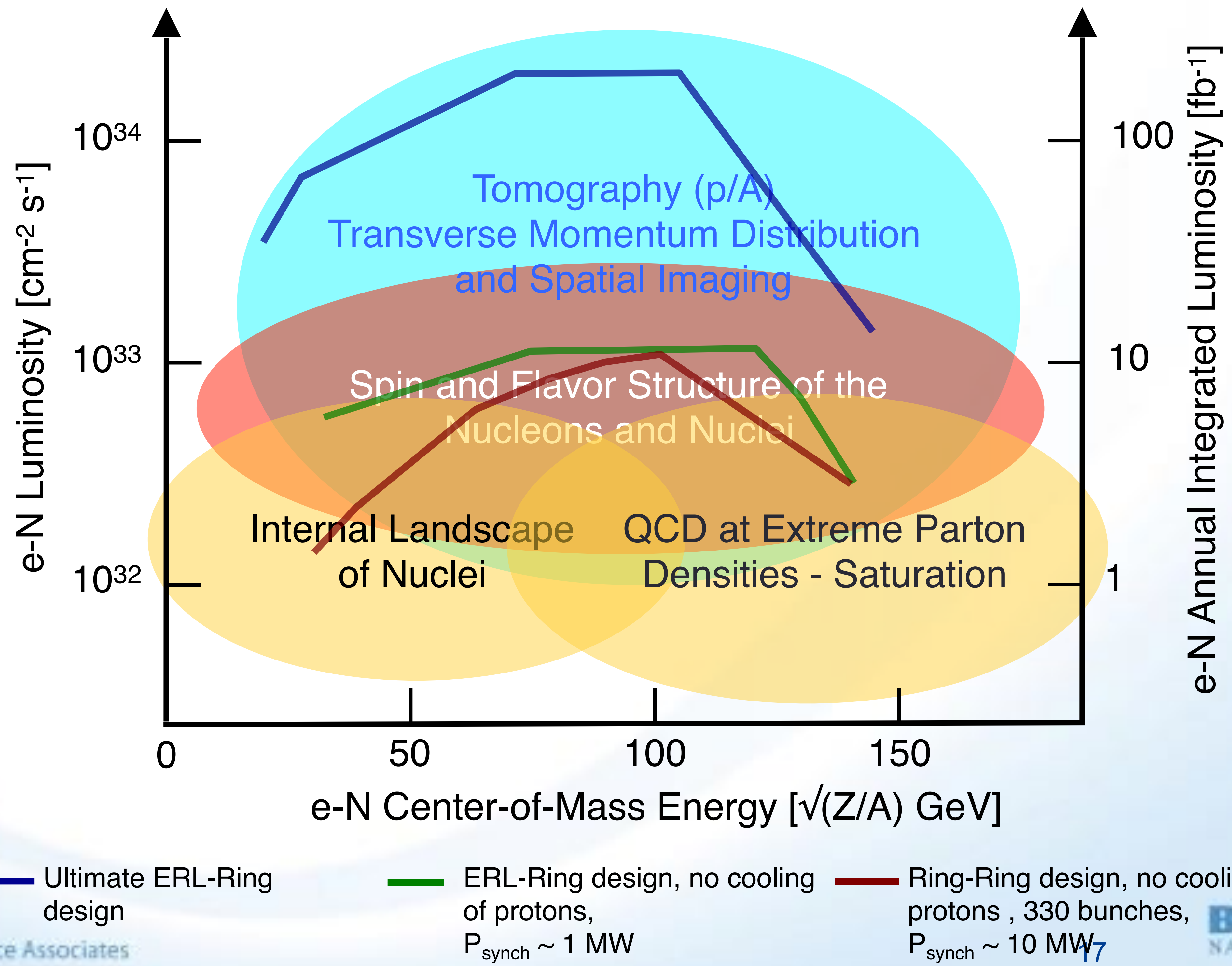




- ✦ 14 mrad crossing angle and crab-crossing
- ✦ Reaches β* of 5-10 cm with good dynamic aperture
- ✦ Final focus doublet and dipole with large aperture for forward collision products and with field-free passage for electron beam
- ✦ Only soft bends of electron beam within 60 m upstream of IP to avoid synchrotron radiation background in detector

eRHIC Peak Luminosity vs. CM Energy

Science case areas indicate the range of peak luminosities with which a statistically significant result can be achieved in about one year (10^7 sec) of running.

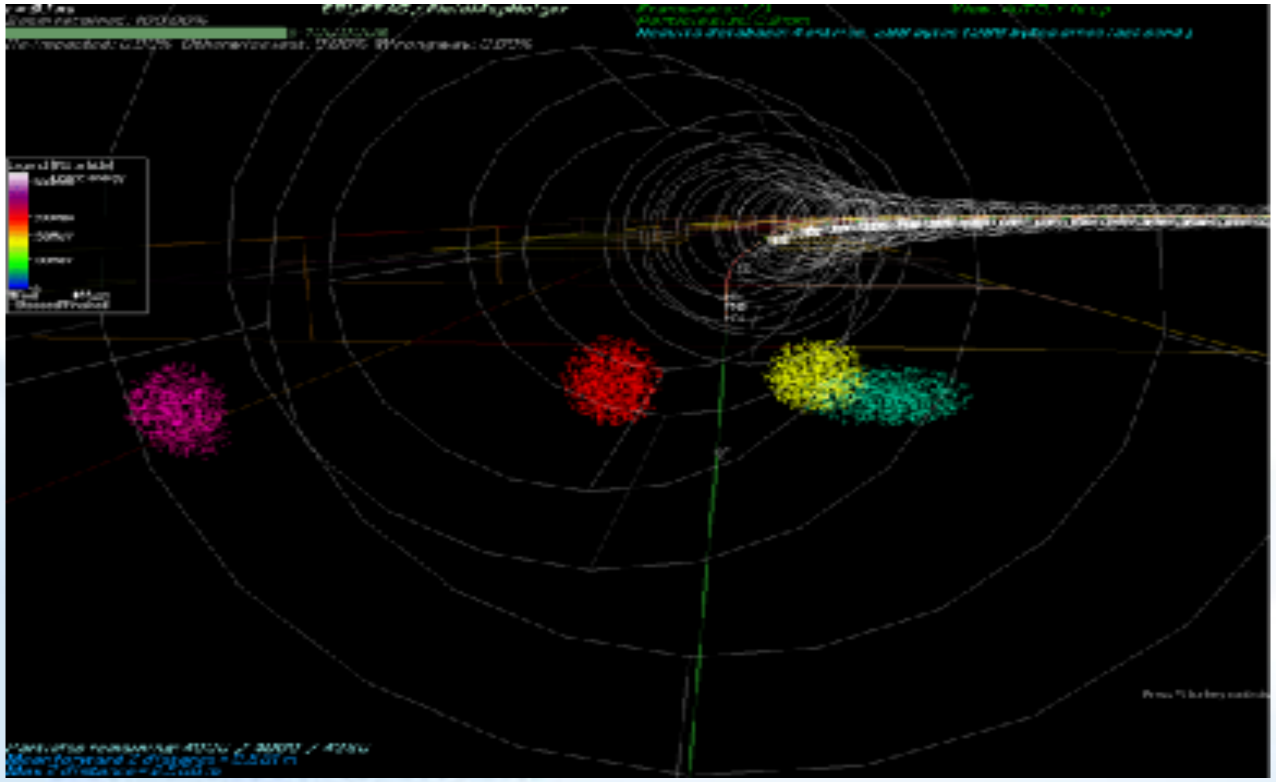


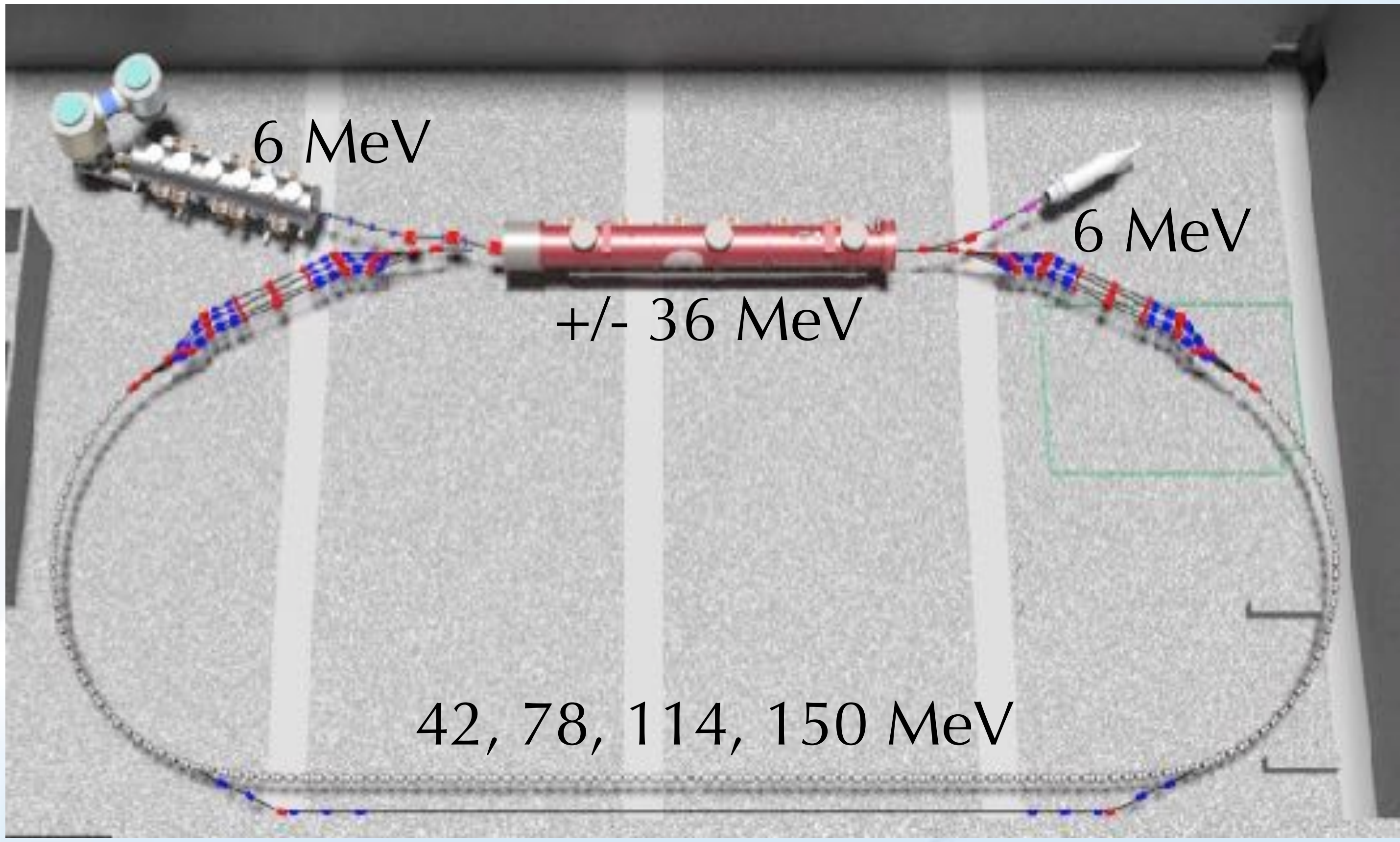
eRHIC R&D

- Ferdinand Willeke appointed as Director of eRHIC R&D and Design
  - FW leads two design teams (LR and RR)
  - Down-select planned for early 2017
- Four high priority eRHIC R&D items are to be completed in 2 – 3 years for cost reduction and performance upgrade:
  - **High intensity polarized electron source (with SBU and MIT)**
  - **ERL acceleration cavity with full Higher Order Modes (HOM) damping using waveguide dampers**
  - **Coherent electron Cooling Proof-of-Principle (PoP) test at RHIC (2017-18)**
  - **High intensity, four-pass test-ERL with strong focusing recirculation loop using the Cornell high intensity electron injector and CW SRF Linac (Project C-Beta)**
- Expect $200–300M of possible project cost savings from this R&D

C-Beta test-ERL – an eRHIC prototype

- Uses existing 6 MeV high-current injector and 36 MeV CW SRF Linac
- **ERL with single four-pass recirculation arc with x4 momentum range**
- Recirculation arc with permanent magnets
- **Adiabatic transitions from curved to straight sections**
- Test of spreader/combiner beam lines
- **Beam test of eRHIC cavities and cryostats possible**
- $25M NY State funding approved by NYSERDA board in October 2016

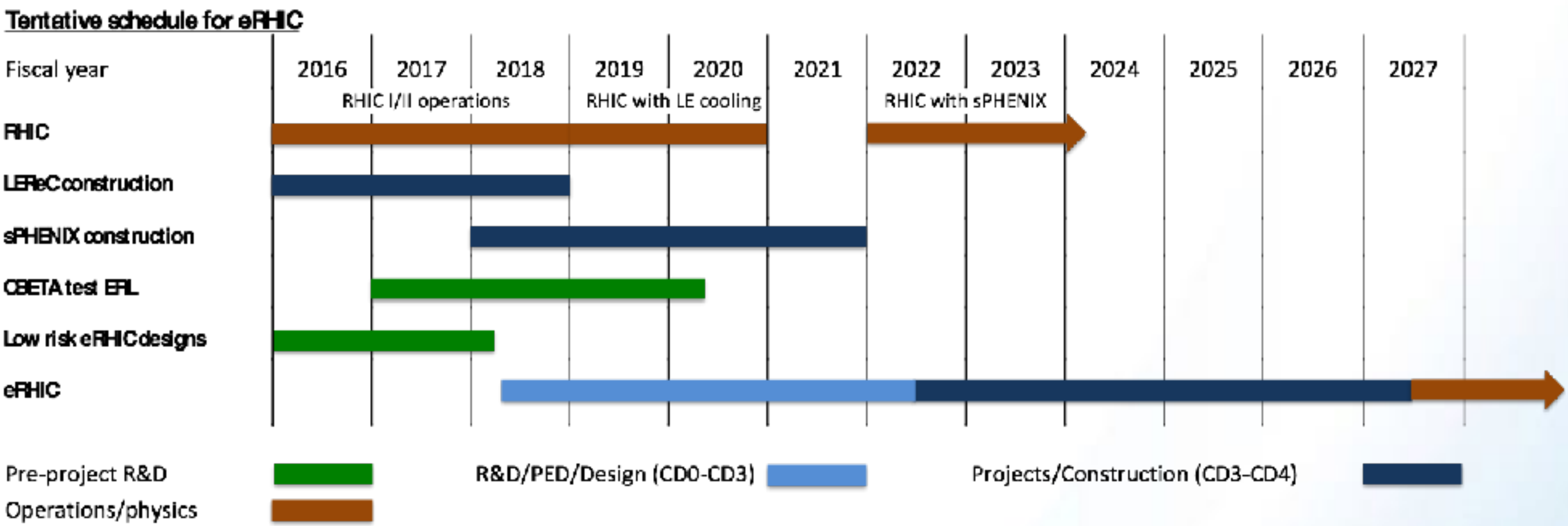




Coherent electron Cooling (CeC) Proof-of-Principle experiment

- DOE NP R&D project aiming for demonstration of CeC technique is in progress since 2012
- **Equipment and most infrastructure is installed into RHIC IP2**
- First beam from SRF gun (3 nC/bunch, 1.7 MeV) in 2015
- 20 MeV SRF linac and helical wigglers for FEL amplifier are installed, 8 MeV beam transported to beam dump in June 2016
- Proof-of-principle demonstration with 40 GeV/n Au beam scheduled during next RHIC Run (June 2017)
- **Micro-bunching test also planned with the same set-up**

Notional schedule for RHIC and eRHIC



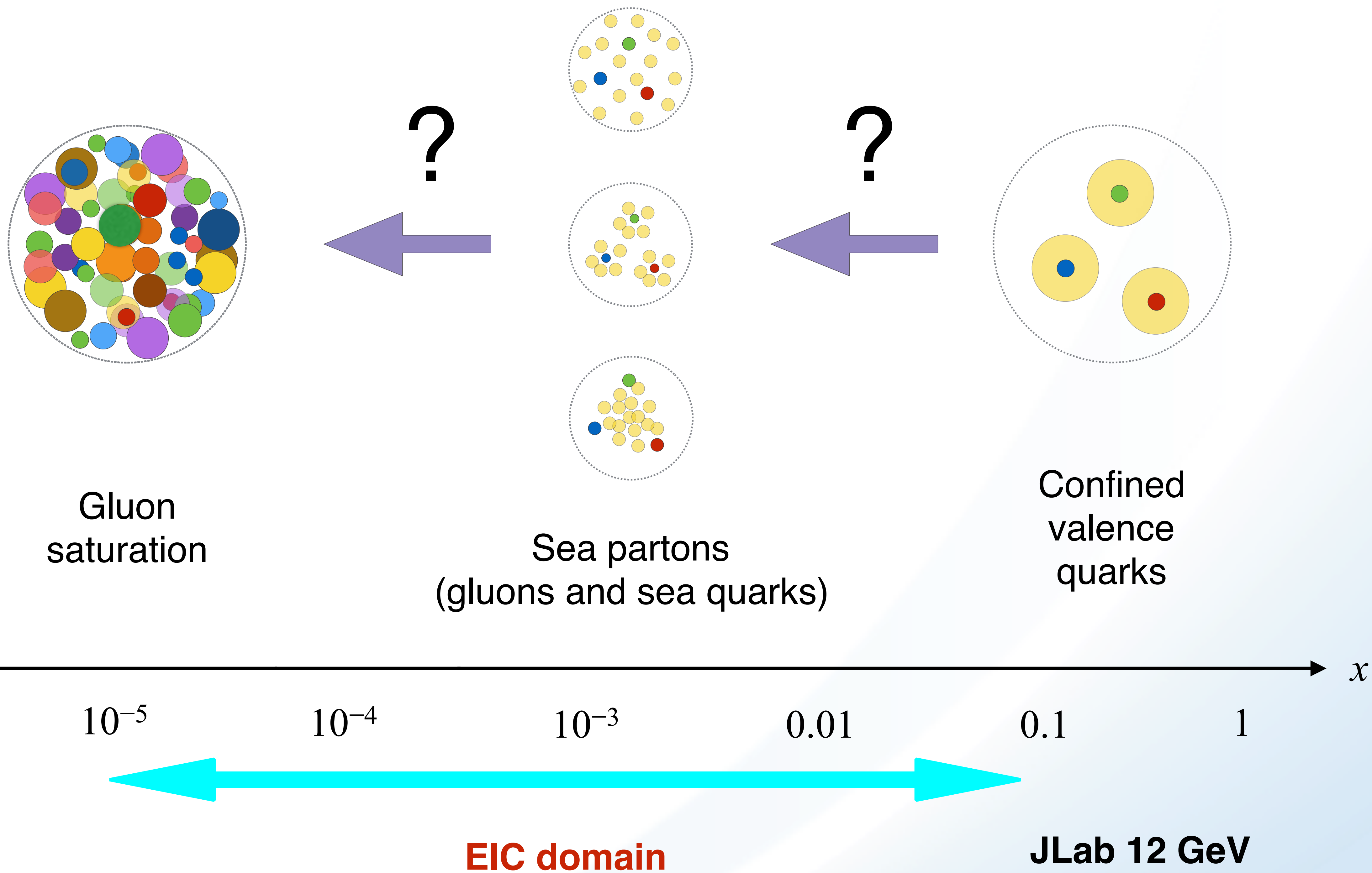
- Low Energy RHIC electron Cooling installation in 2018 for RHIC Beam Energy Scan II
- sPHENIX construction complete in 2021
- Low risk design (pCDR) complete by 2018
- High priority eRHIC R&D items complete by 2019
- eRHIC: Mission need (CD-0 in 2018?), alternative selection (CD-1 in 2019?), project baseline (CD-2 in 2020?), construction start (CD-3 in 2022?), installation (2024 – 2026?) and start of operation (CD-4 in 2027?)

eRHIC Objectives

- BNL is committed to design the best and most versatile EIC technology in reach permits and the NP community can afford.
- eRHIC will ensure a world-leading accelerator based nuclear science program in the U.S. beyond 2025.
- eRHIC will close a glaring gap in our understanding of the visible world around us: *It will reveal how gluons bind quarks into nucleons and complex nuclei.*
- Its large kinematic domain will give eRHIC ample discovery potential, providing first access to perturbative gluon saturation, in addition to being a precision imaging device.
- Its upgradability to luminosity $>10^{34}\ \mathrm{cm}^{2}\mathrm{s}^{-1}$ enables eRHIC to cover the entire range of EIC White Paper physics.
- eRHIC be a facility at the technological forefront of accelerator S&T.
- eRHIC will be the world's leading *QCD Laboratory* - a centerpiece amongst nuclear physics facilities around the world.

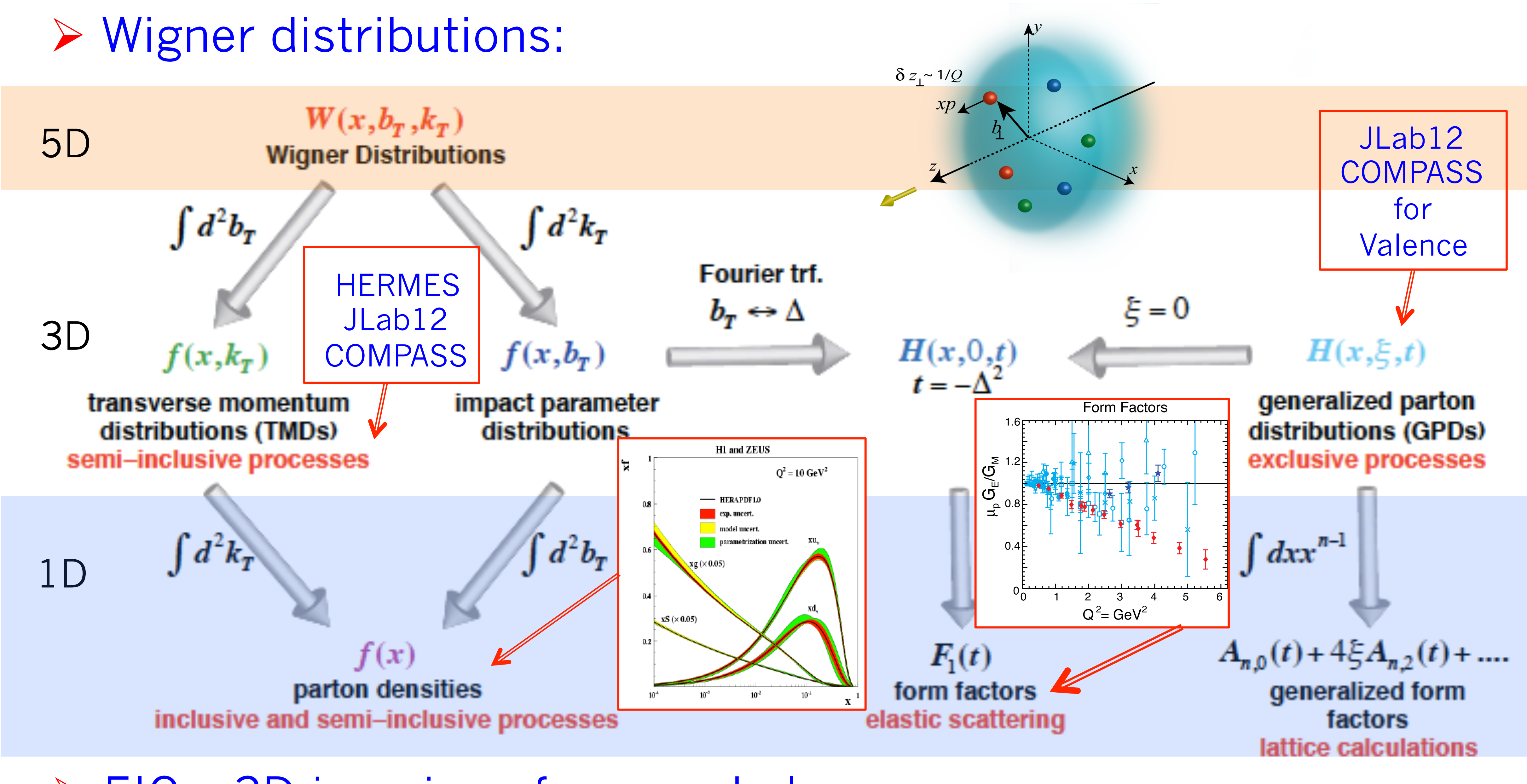
Back-up Slides

Parton structure of the proton



QCD Formalism

- Wigner distributions:



- EIC – 3D imaging of sea and gluons:
  - **TMDs – confined motion in a nucleon (semi-inclusive DIS)**
  - **GPDs – Spatial imaging of quarks and gluons (exclusive DIS)**

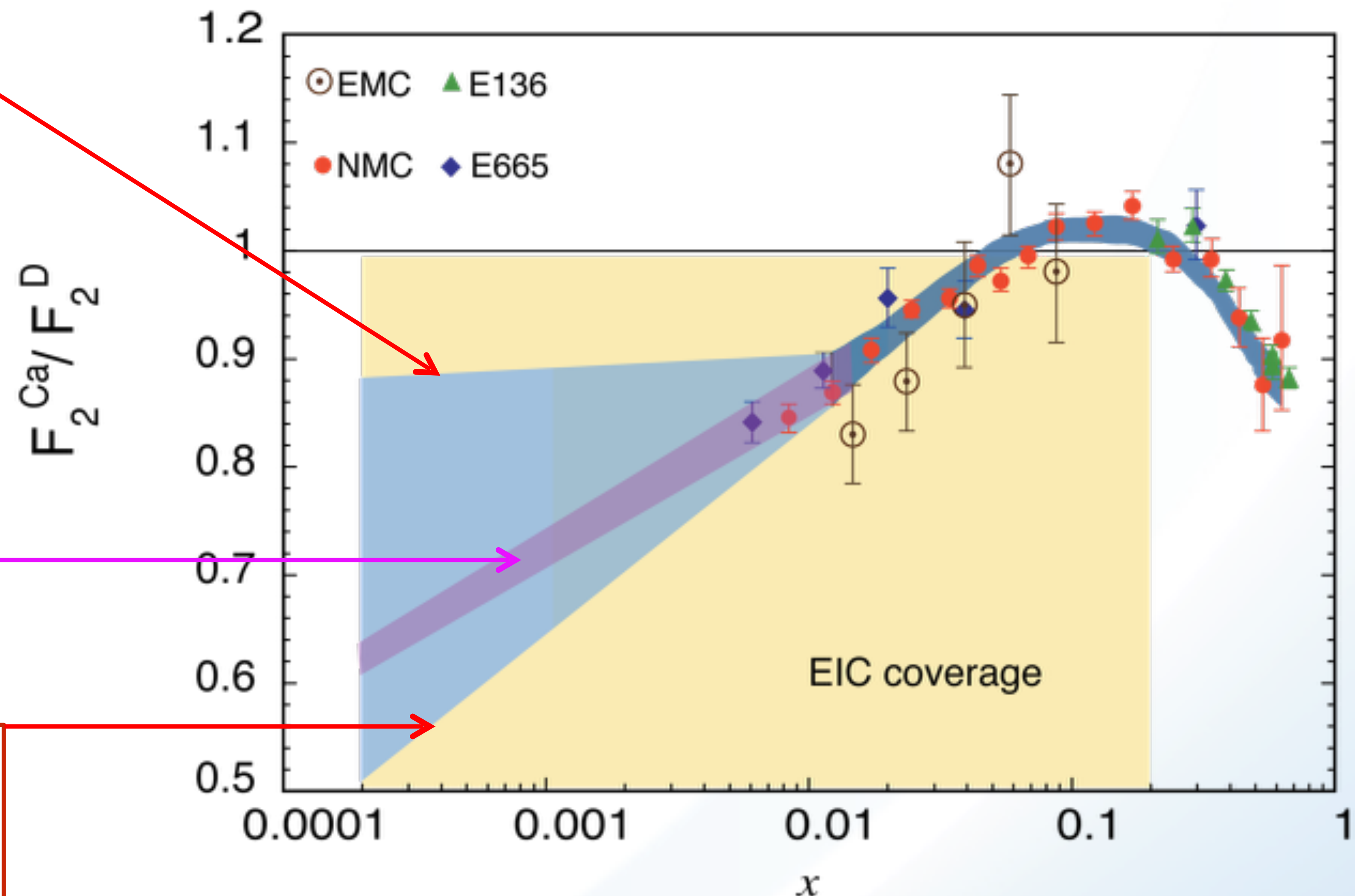
Color force range in a nucleus

➢ Ratio (F_2^A/F_2^D) of DIS structure functions:

Longitudinal color force range ~ size of nucleon

Systematic error

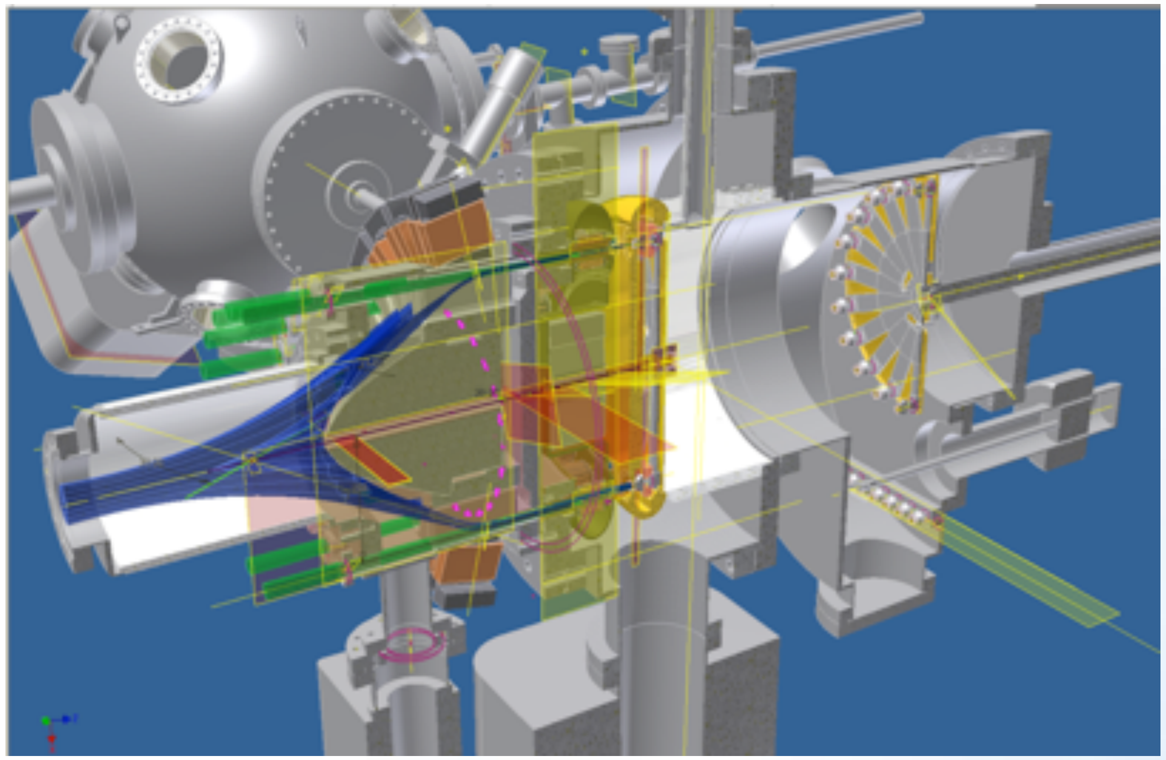
Longitudinal color force range ~ size of nucleus (assumed in CGC saturation models)

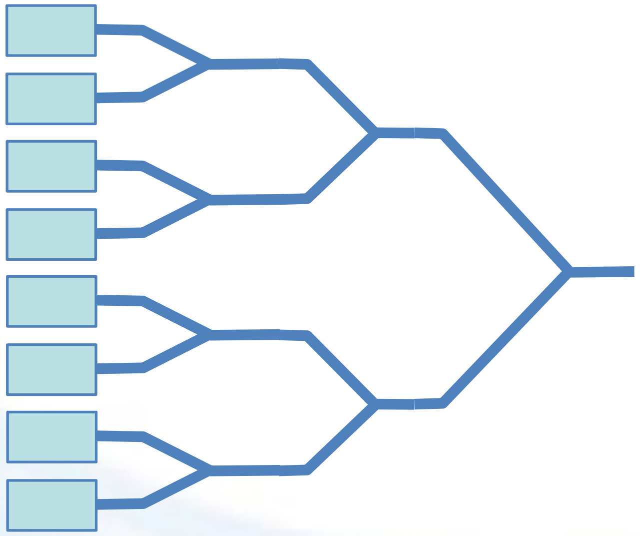


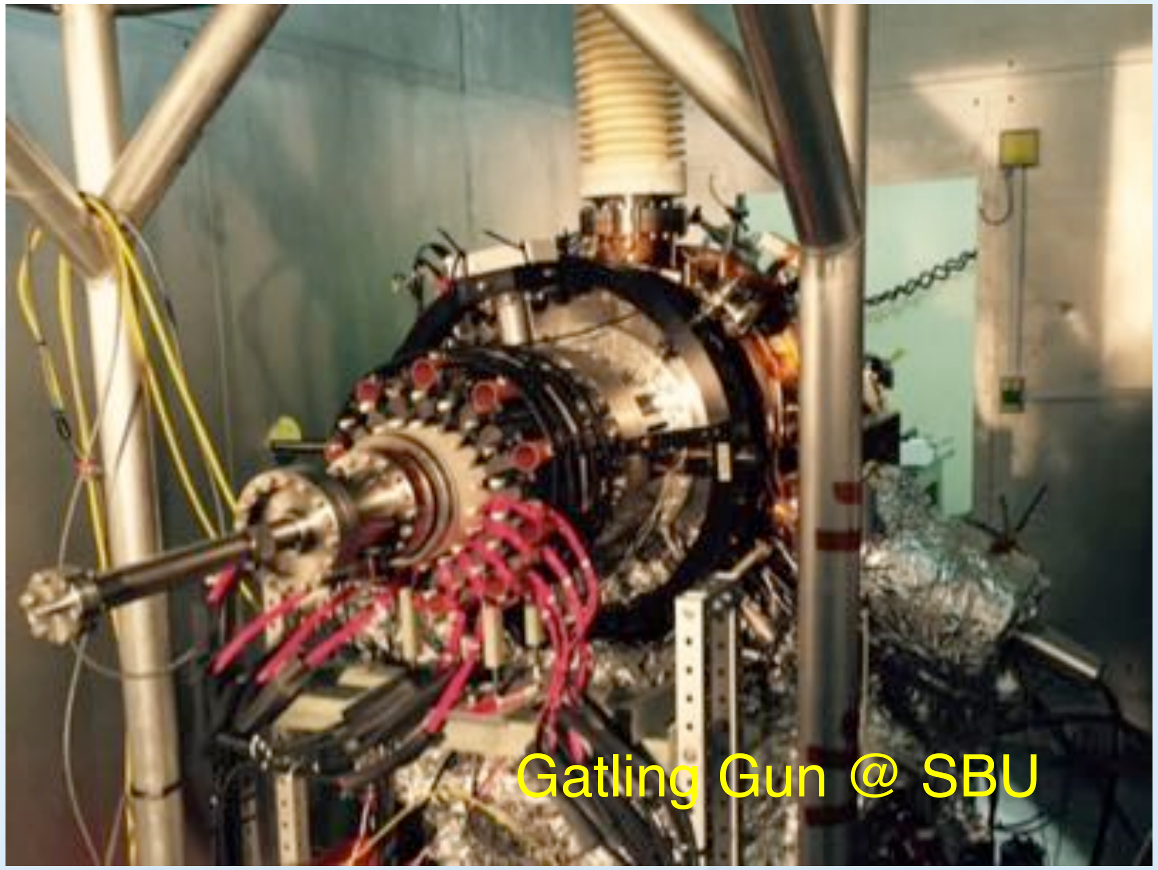
A clean measurement is only possible at the EIC !

High CW current polarized electron gun

- Gatling gun principle: multiple guns/ cathodes with same charge lifetime
  - Requires fast switching between guns/ cathodes
- Gatling Gun test-stand at SBU:
  - Tests with two cathodes started
- Low risk implementation of high current gun: fast switching between eight 6.25 mA guns







Linac cavity with HOM damping

- 650 MHz frequency of main linac accelerating cavities is benefitting from the SRF development program for the Fermilab PIP II project.
- 6 passes each of accelerating and decelerating 50 mA beam results in 600 mA total beam current in the Linac.
- This is similar to circulating beam in storage rings at KEKB and Cornell where ~10 kW of HOM power is absorbed with Ferrite or SiC beam-line dampers
- Develop waveguide dampers for more compact construction