Physics Opportunity at EIC

Satoshi Yano (Hiroshima University)

10th Asian Triangle Heavy-Ion Conference - ATHIC 2025
Jun. 13-16 2025

Introduction

EIC: Energy and Intensity Frontiers

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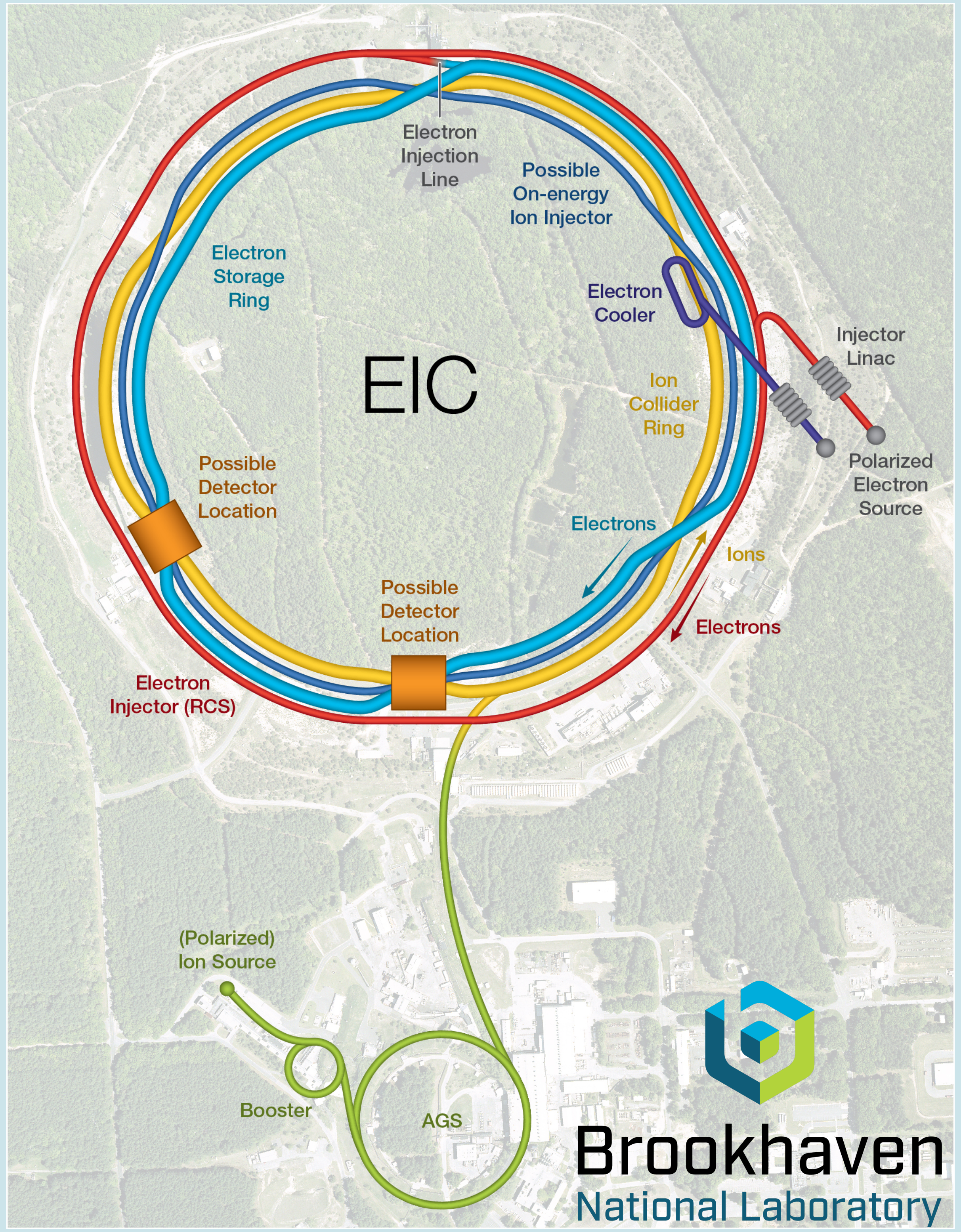

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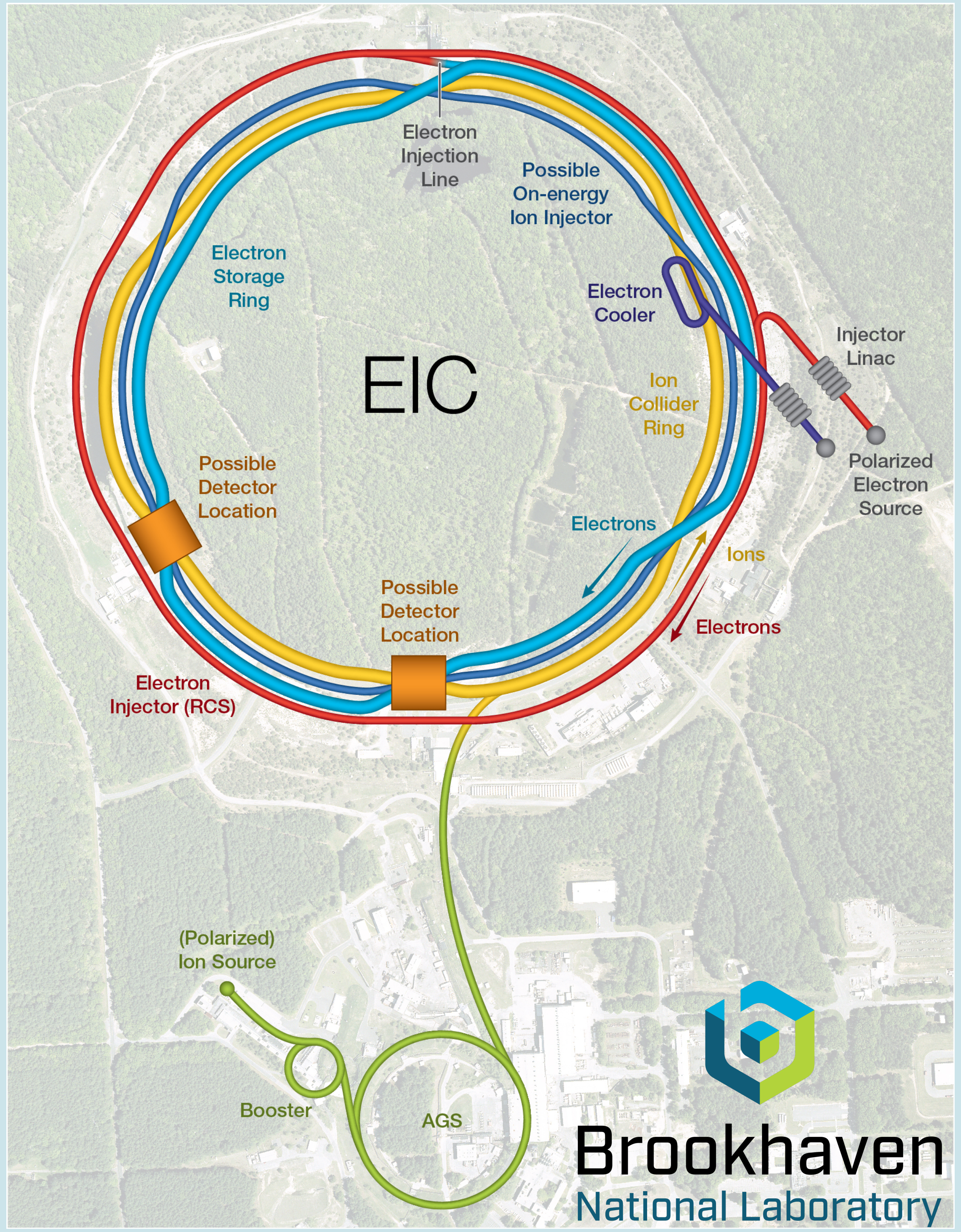

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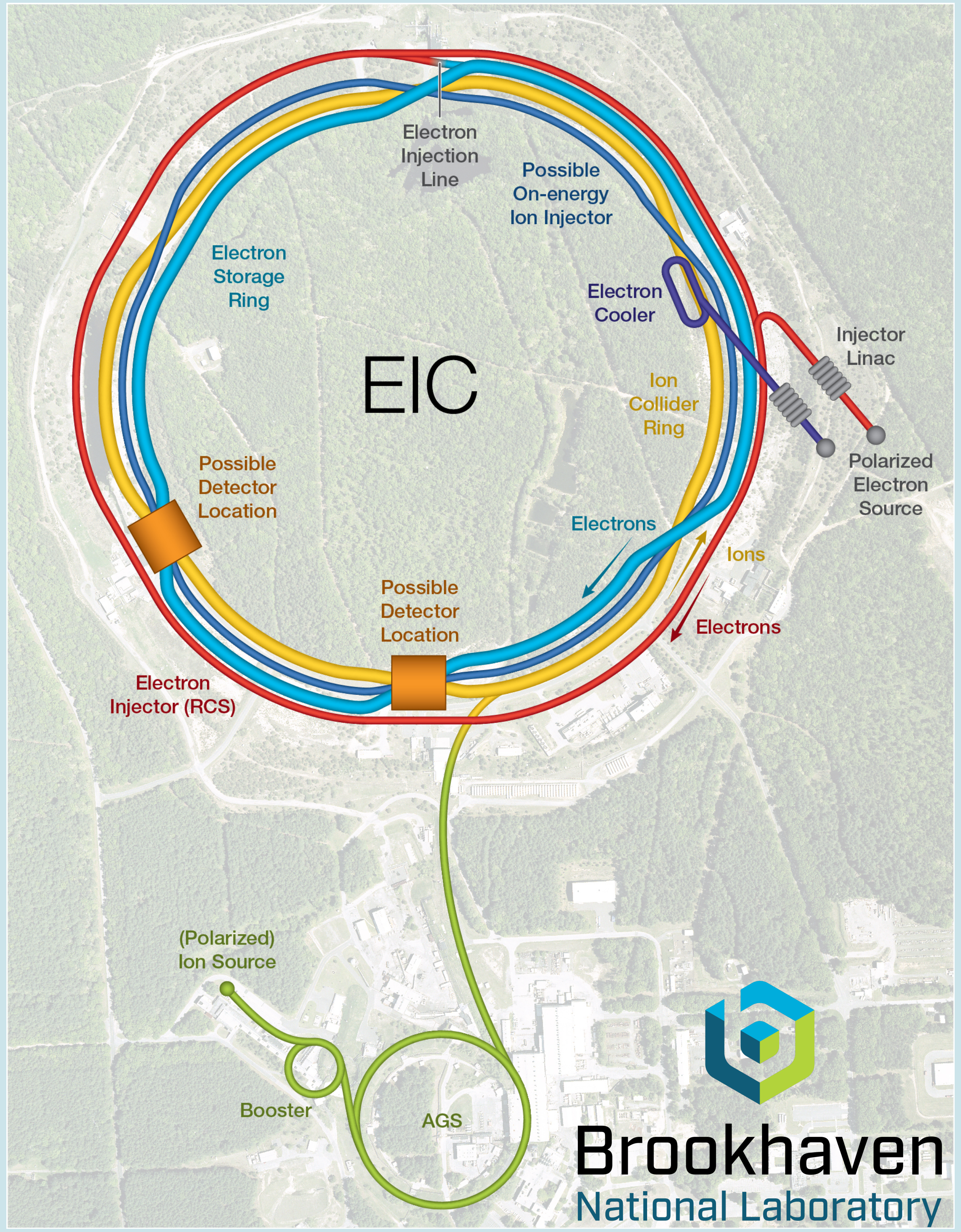

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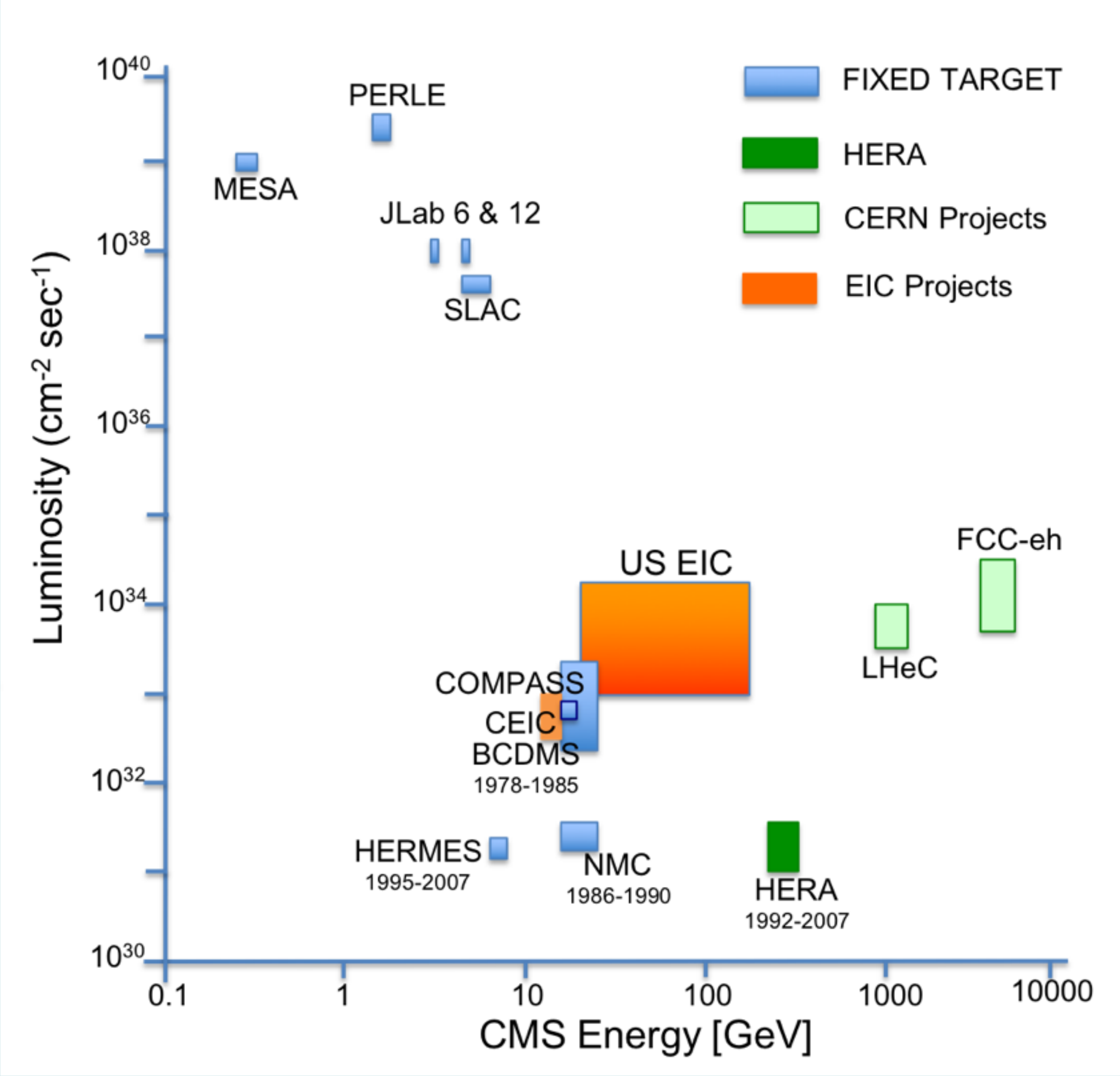

Facility performance map

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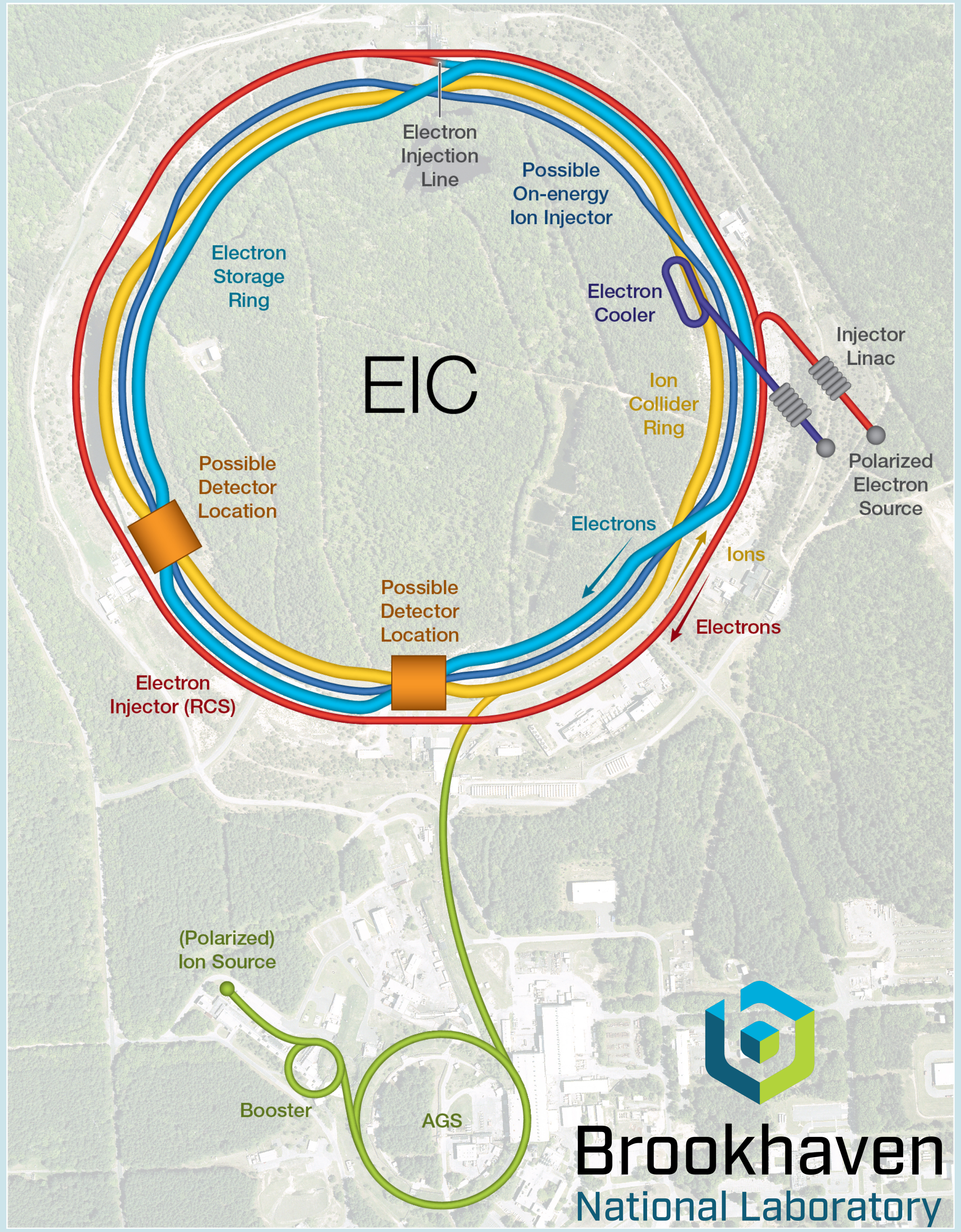

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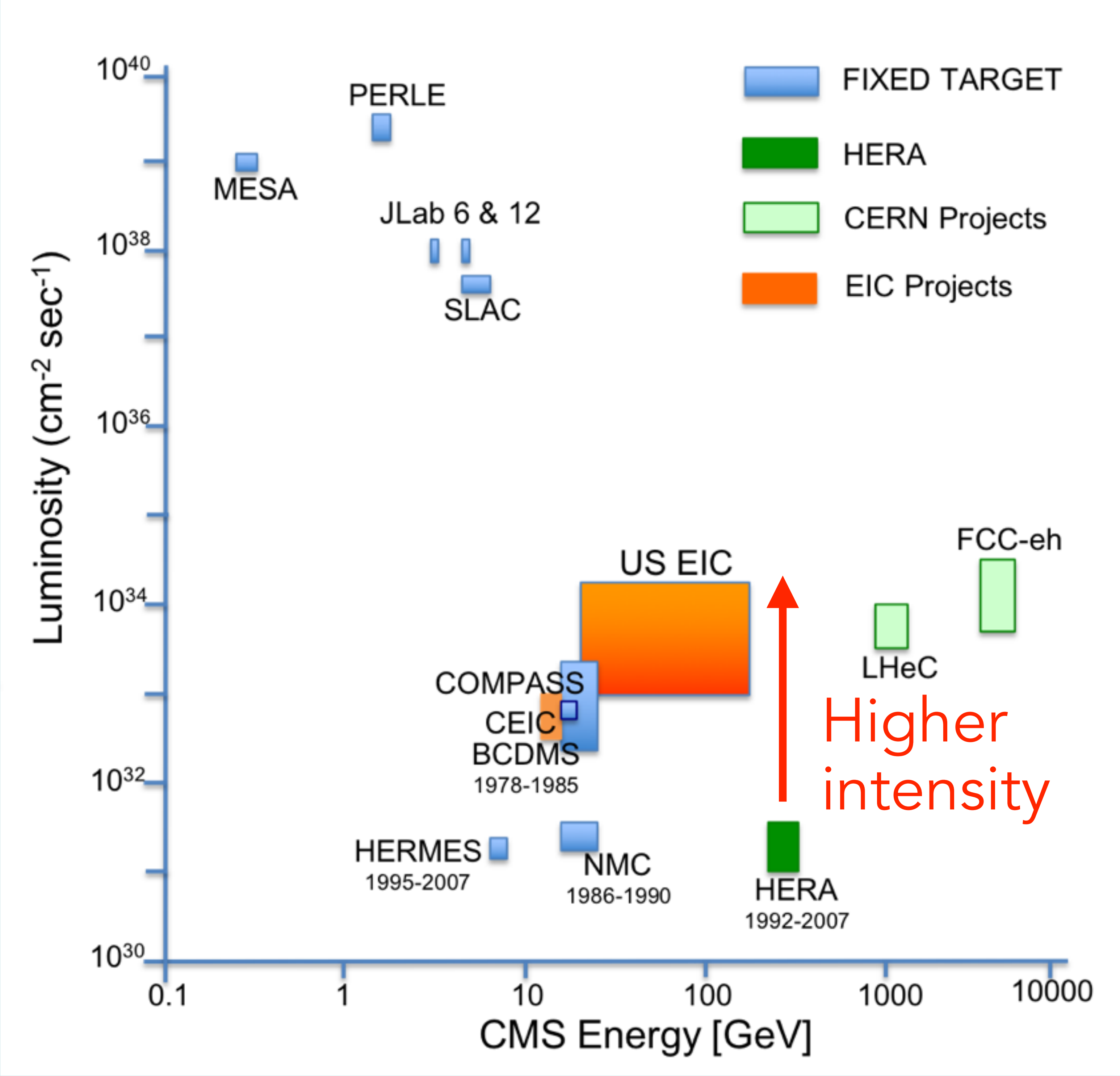

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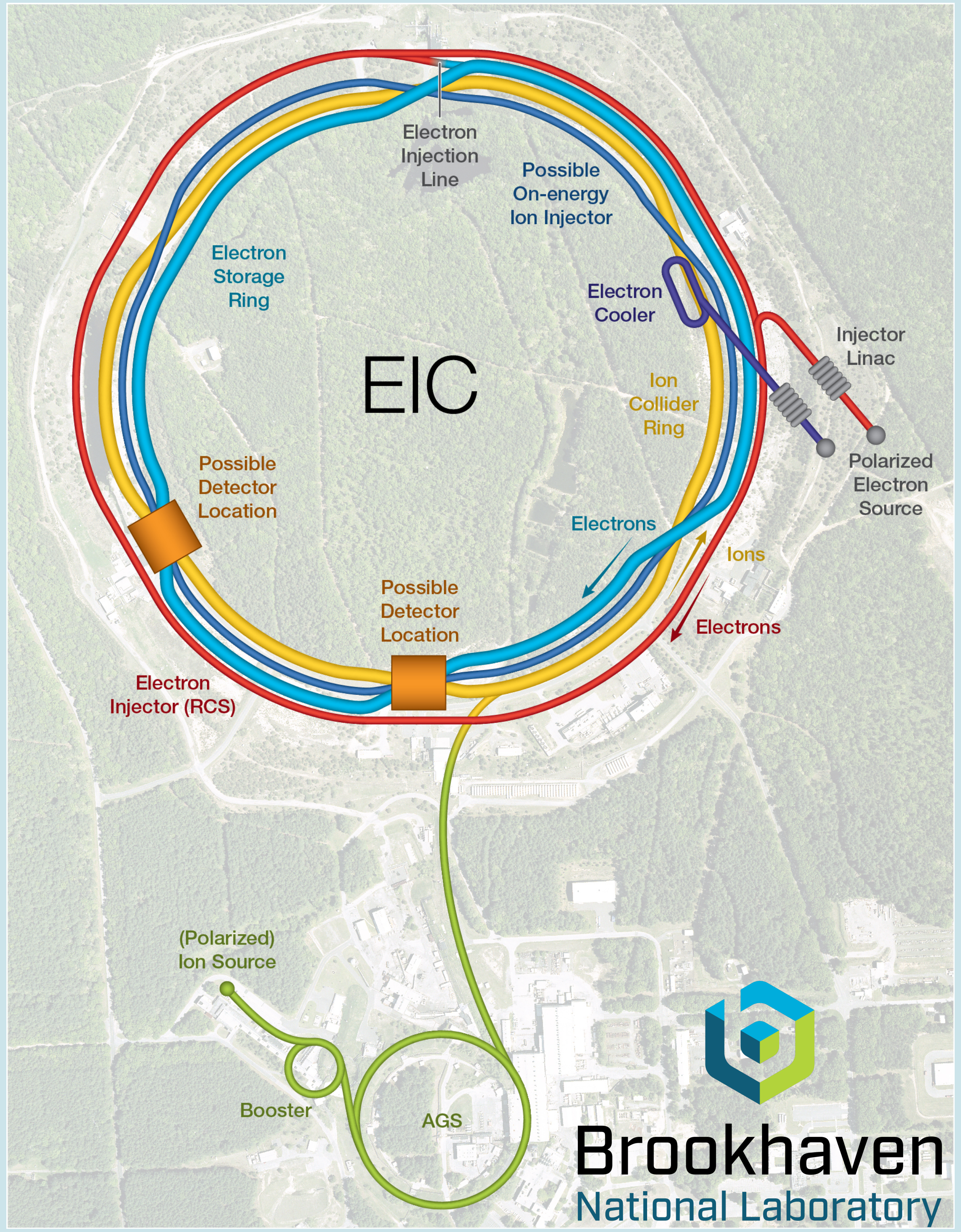

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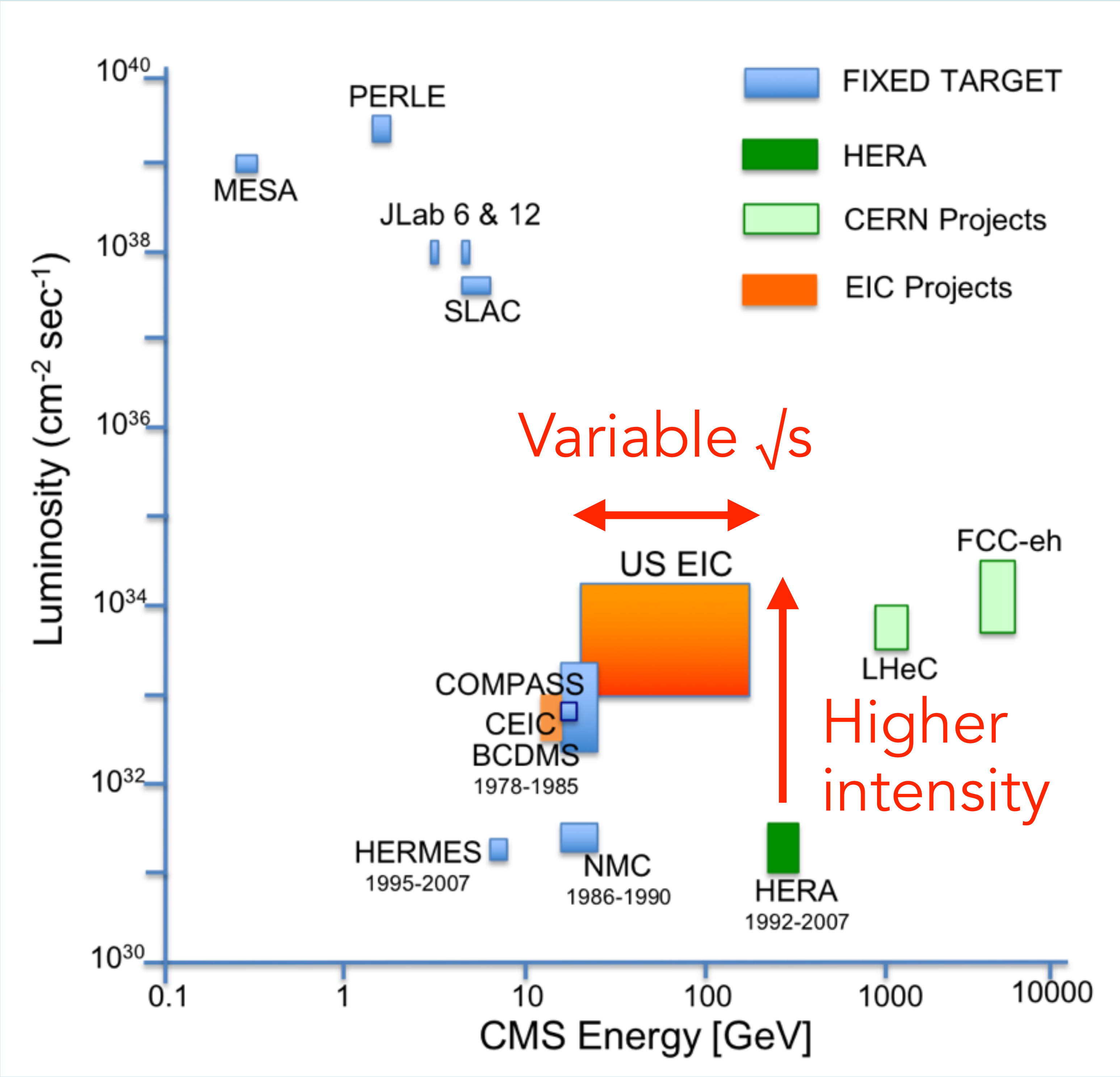
- Variable $\sqrt{s}$: HERA was 318GeV
  - 29 - 140 GeV



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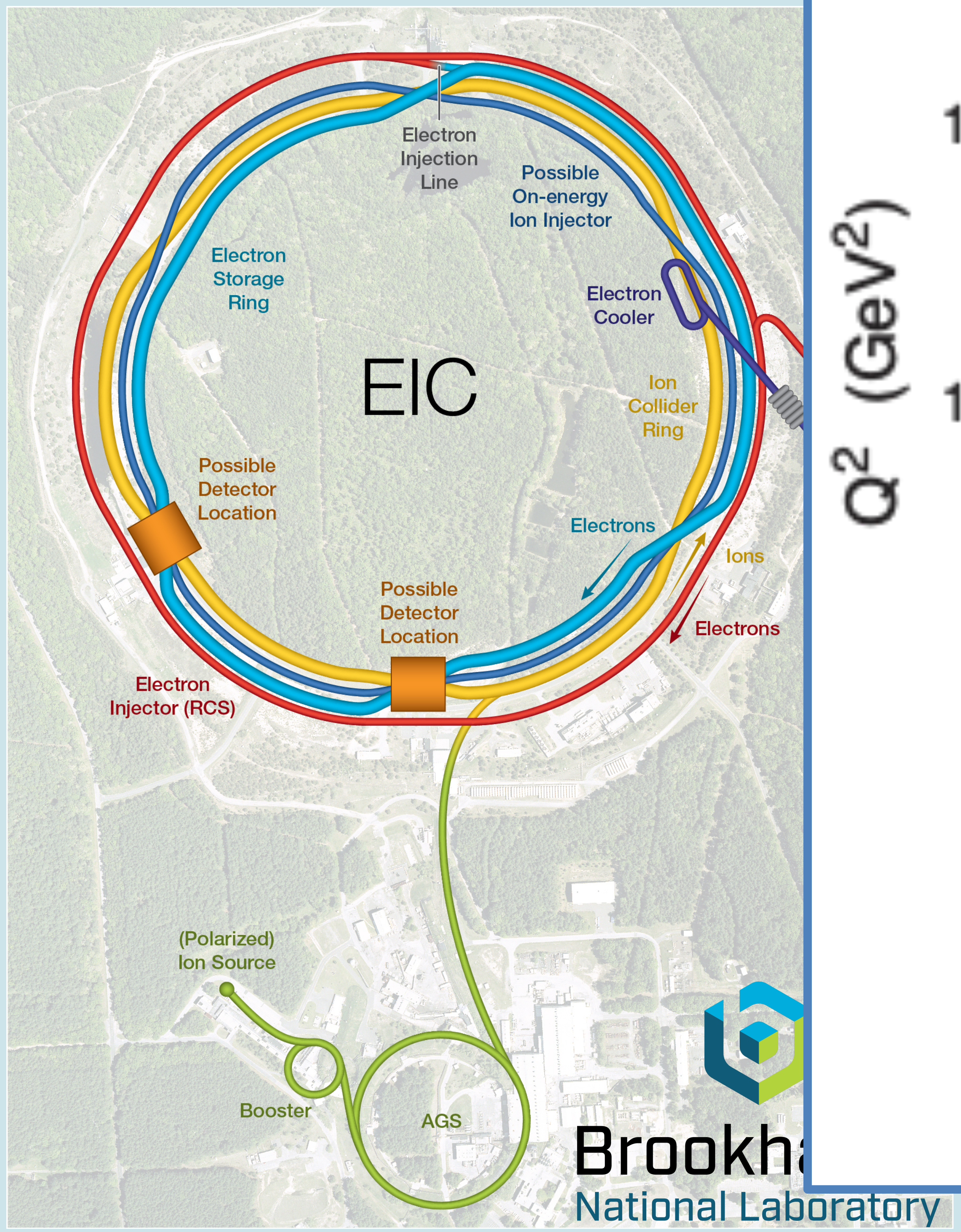
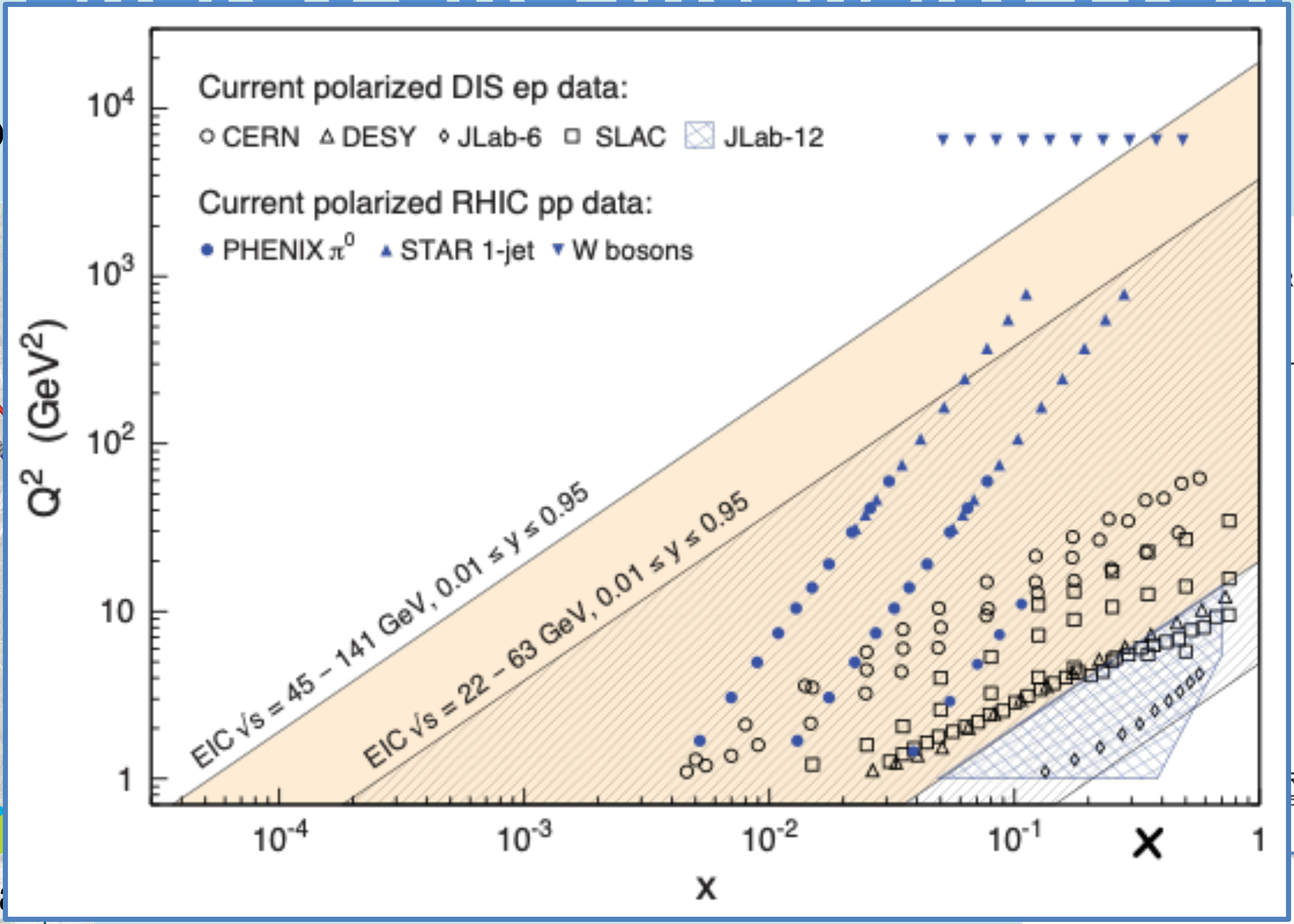
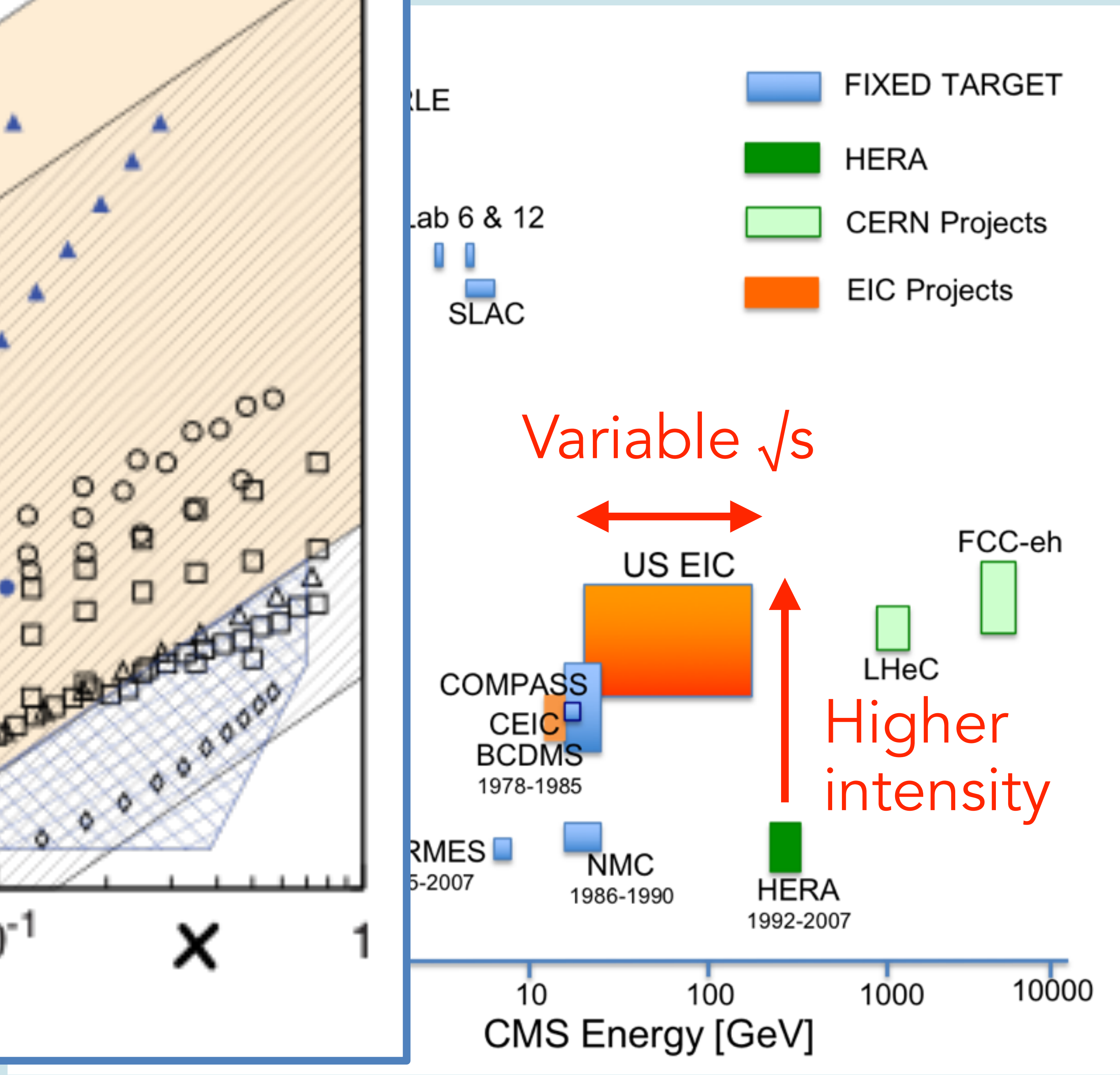
Electron-Io ... eA collider







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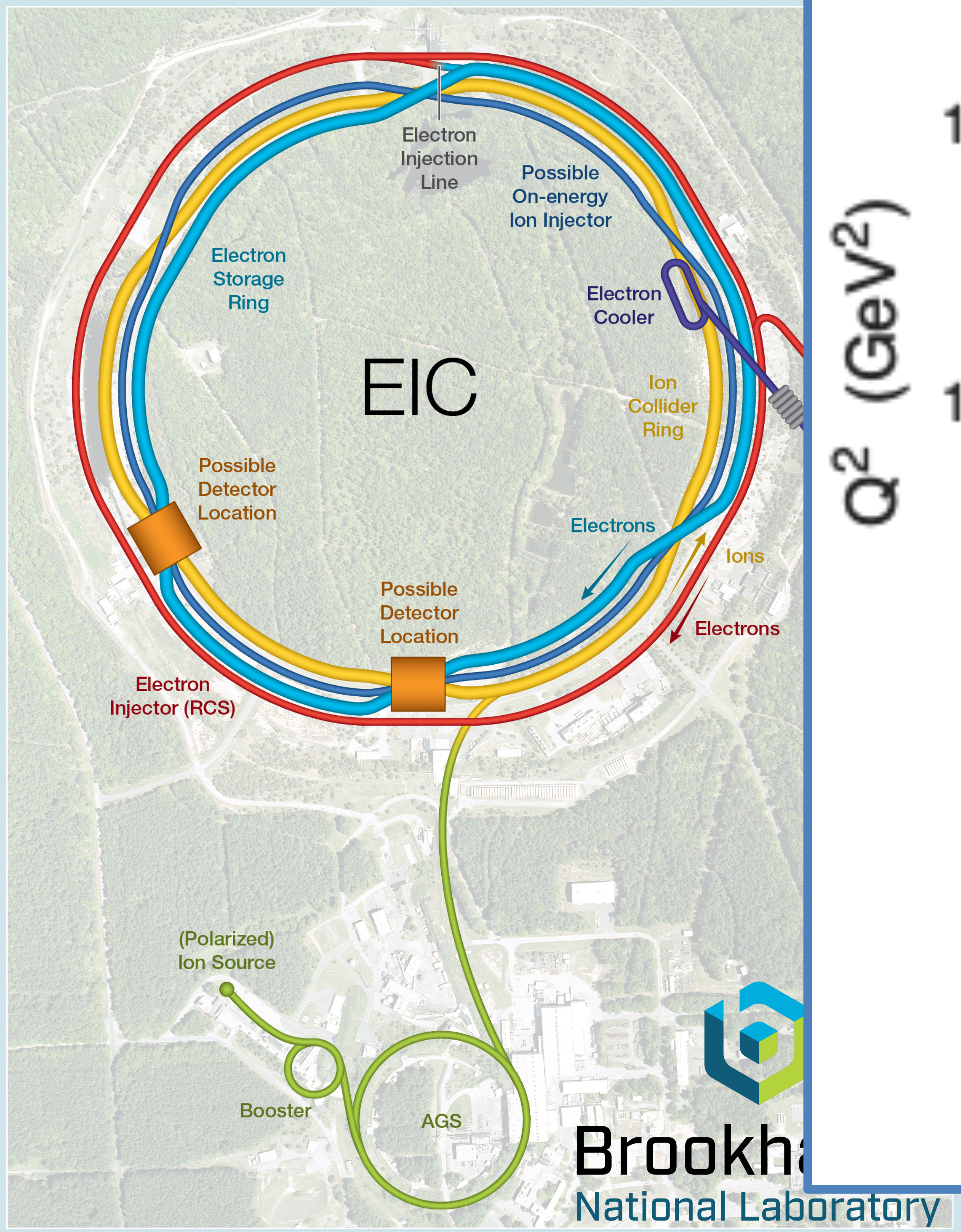

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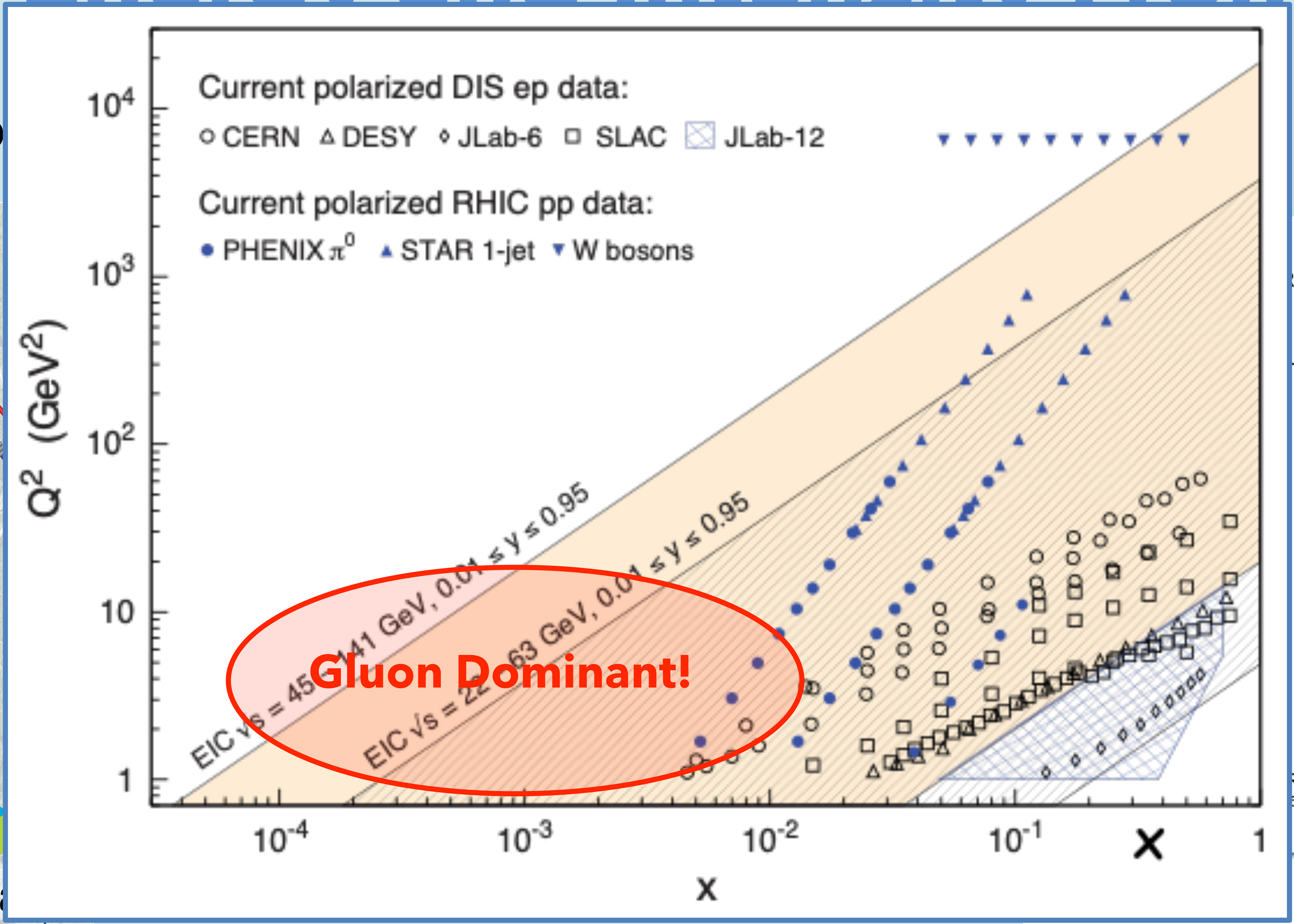

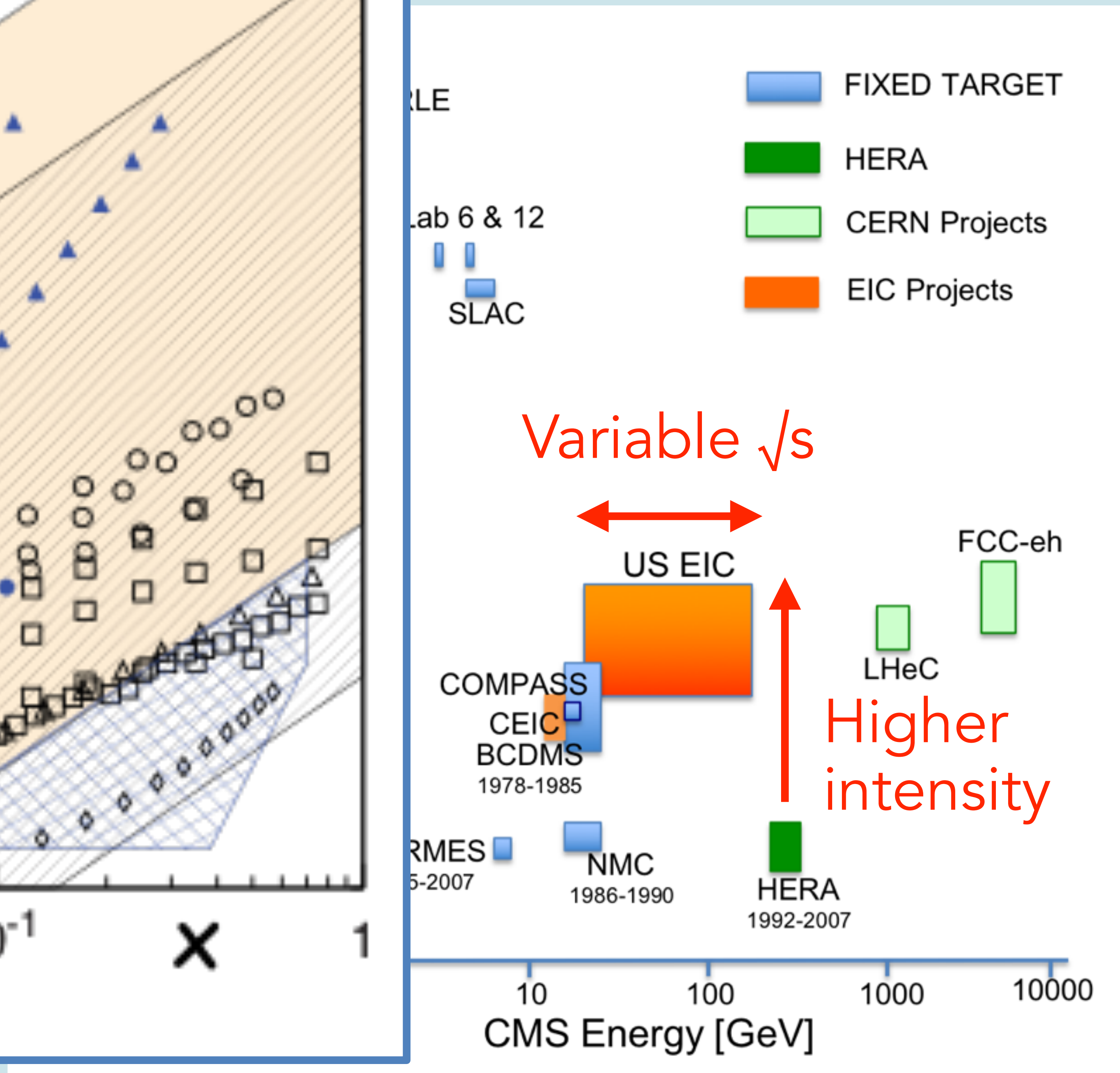

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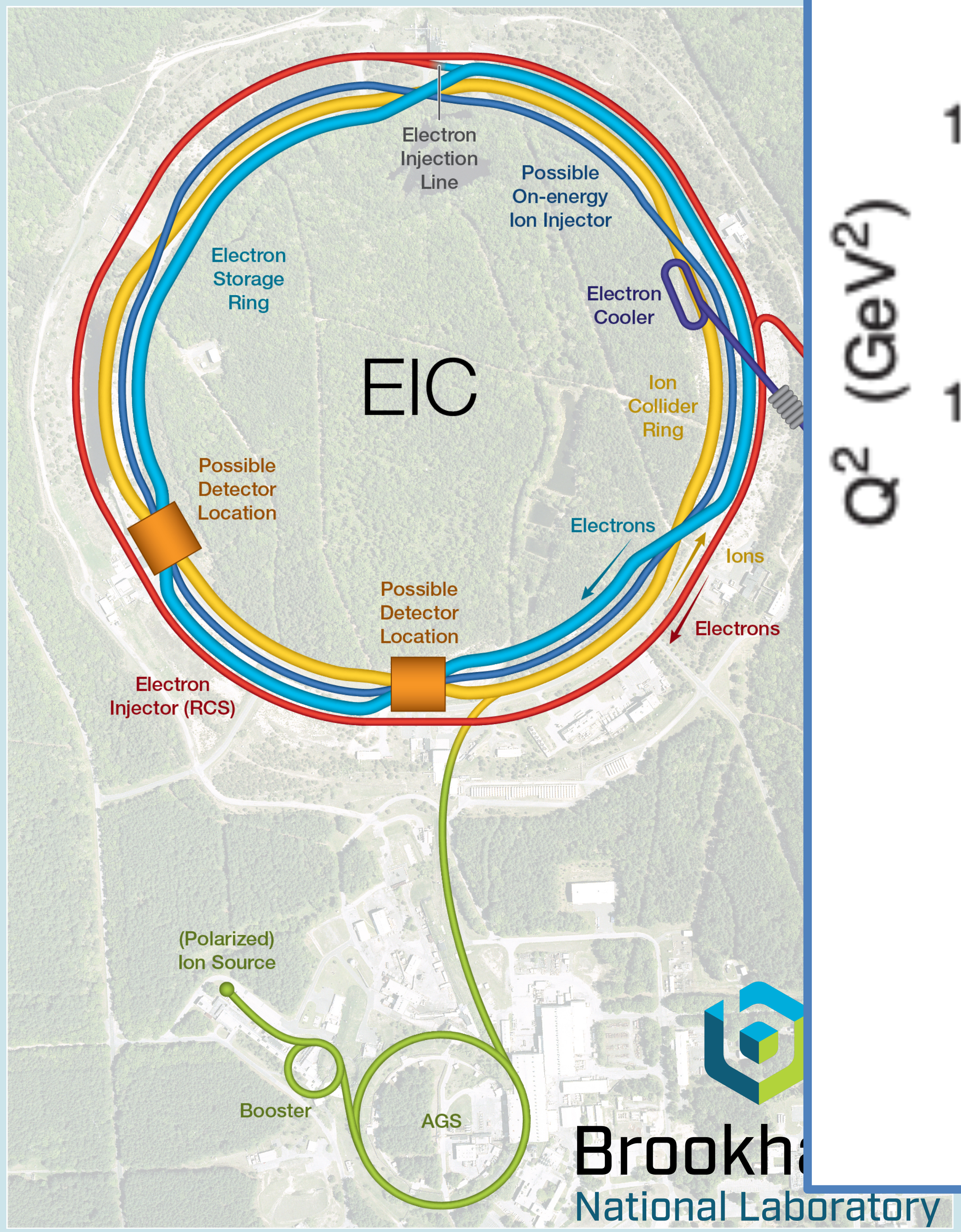

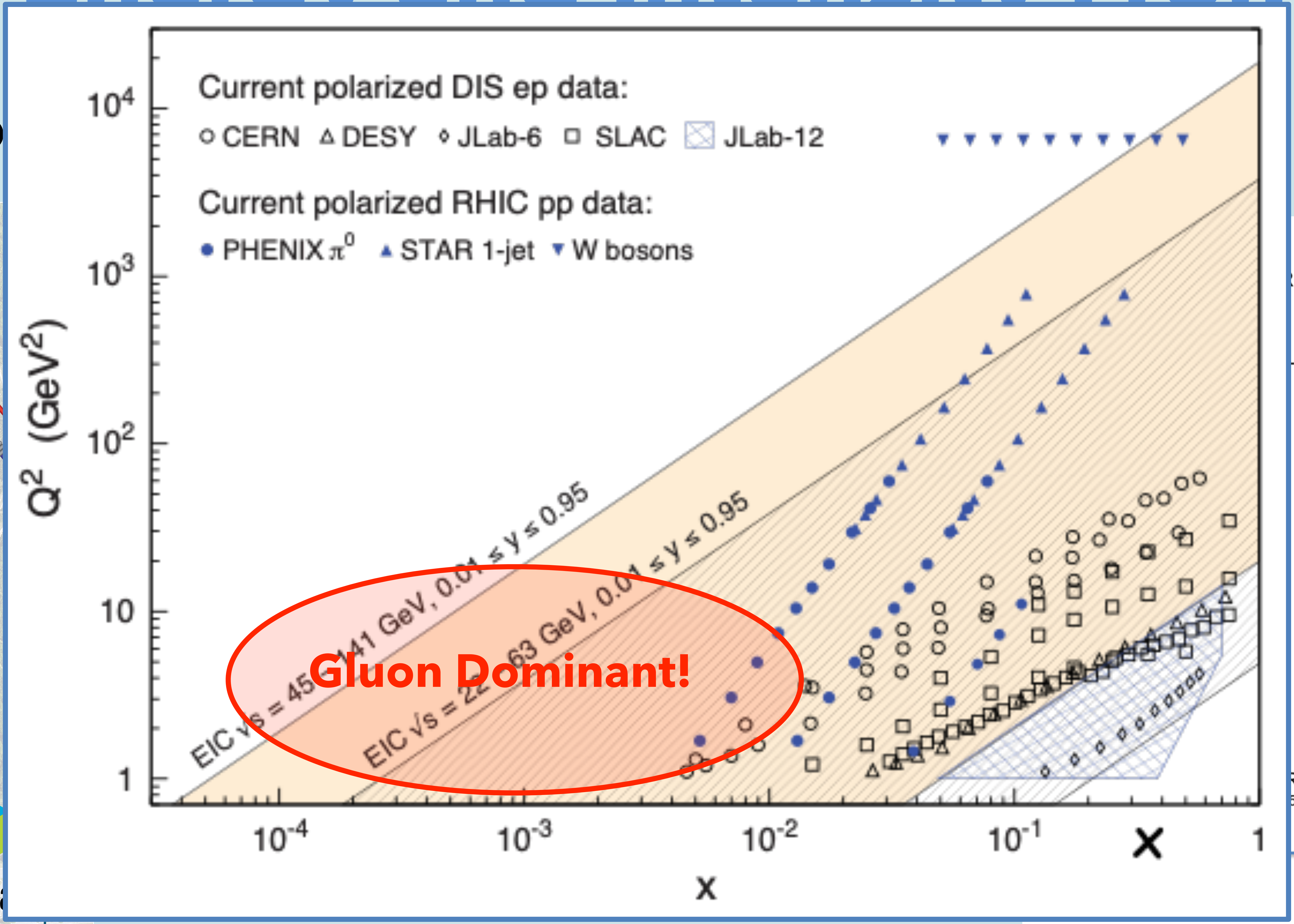

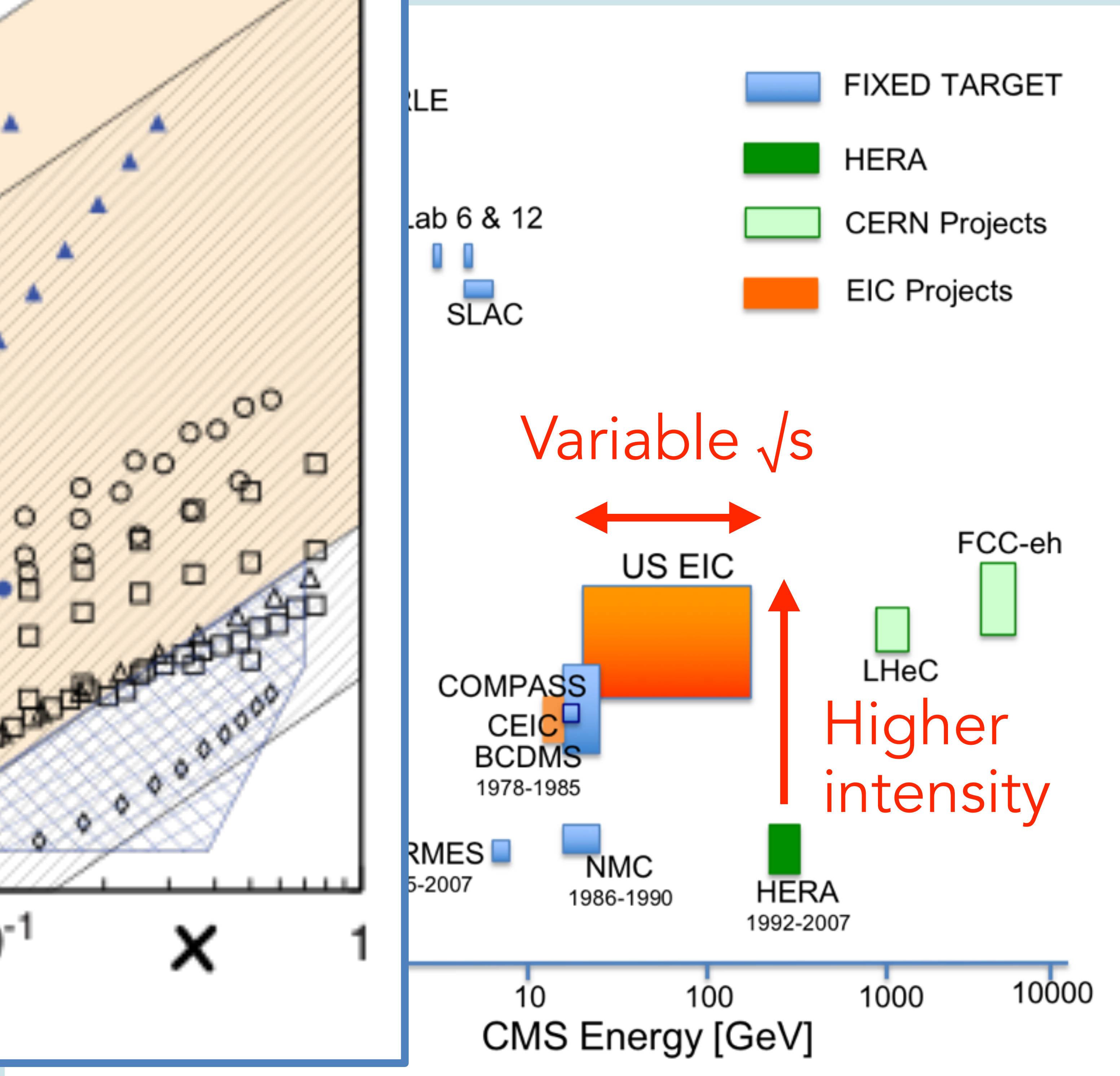

The EIC is a unique project, the only approved facility for the ultimate understanding of QCD
Most likely, the only novel high-energy collider in the next 15-20 years

Science Questions at EIC

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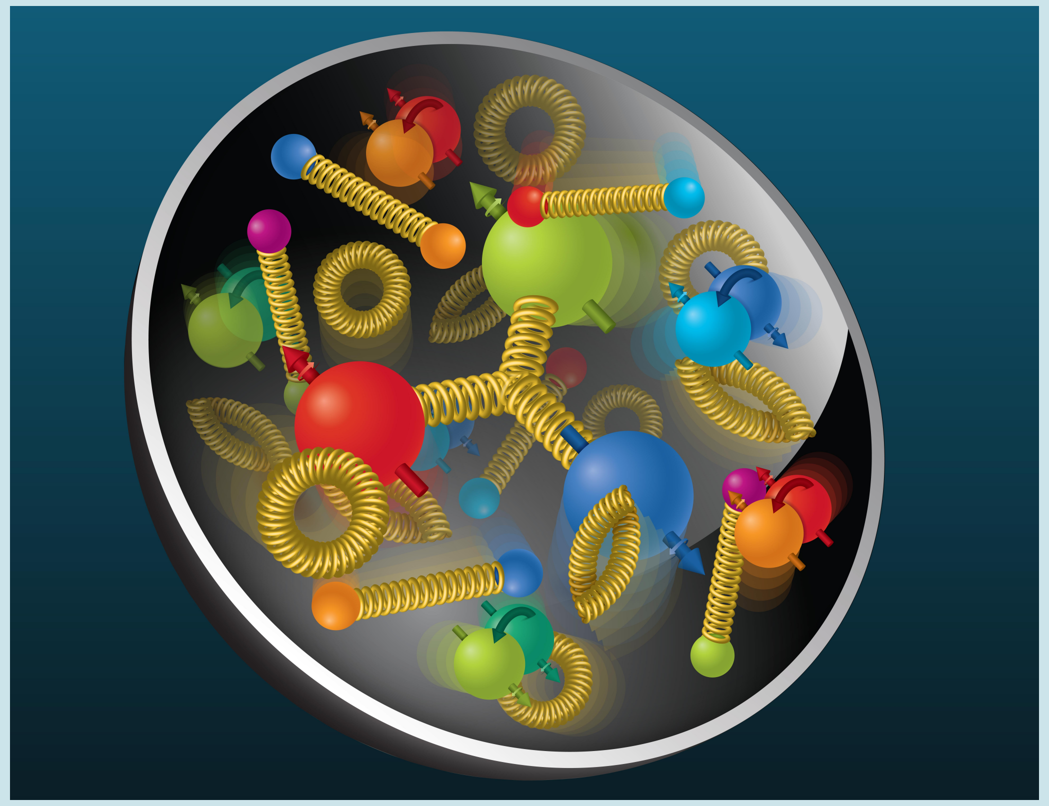
Origin of Spin and Inner Structure



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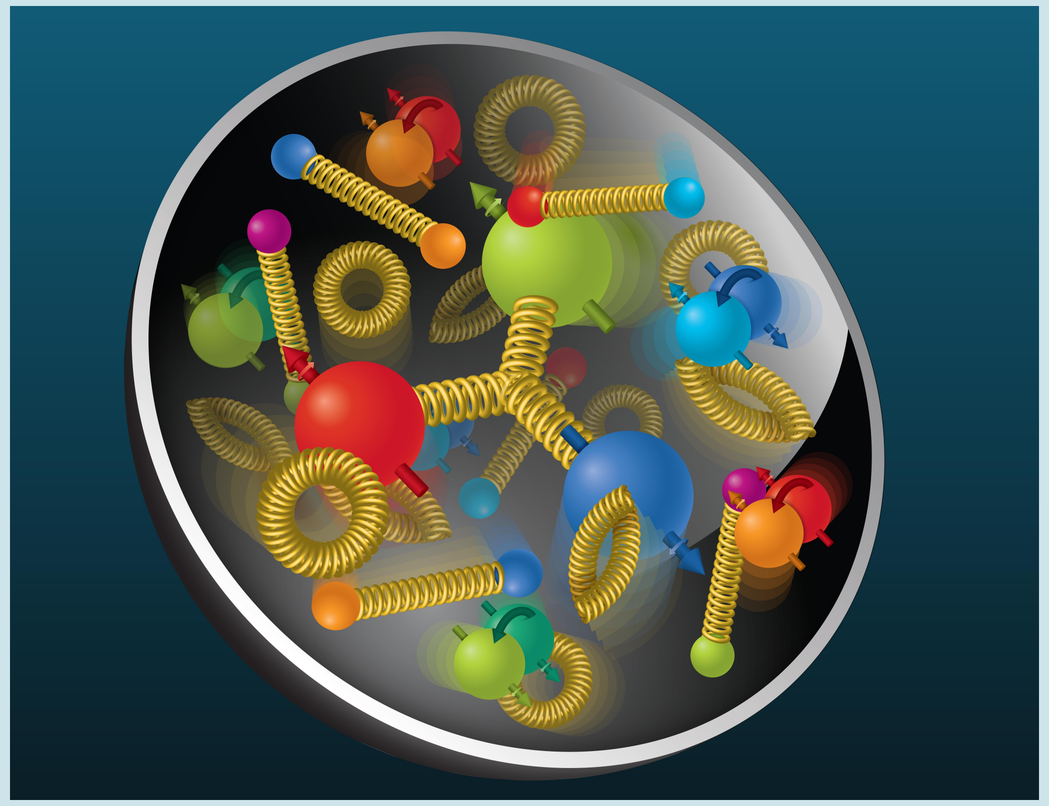

Origin of Mass

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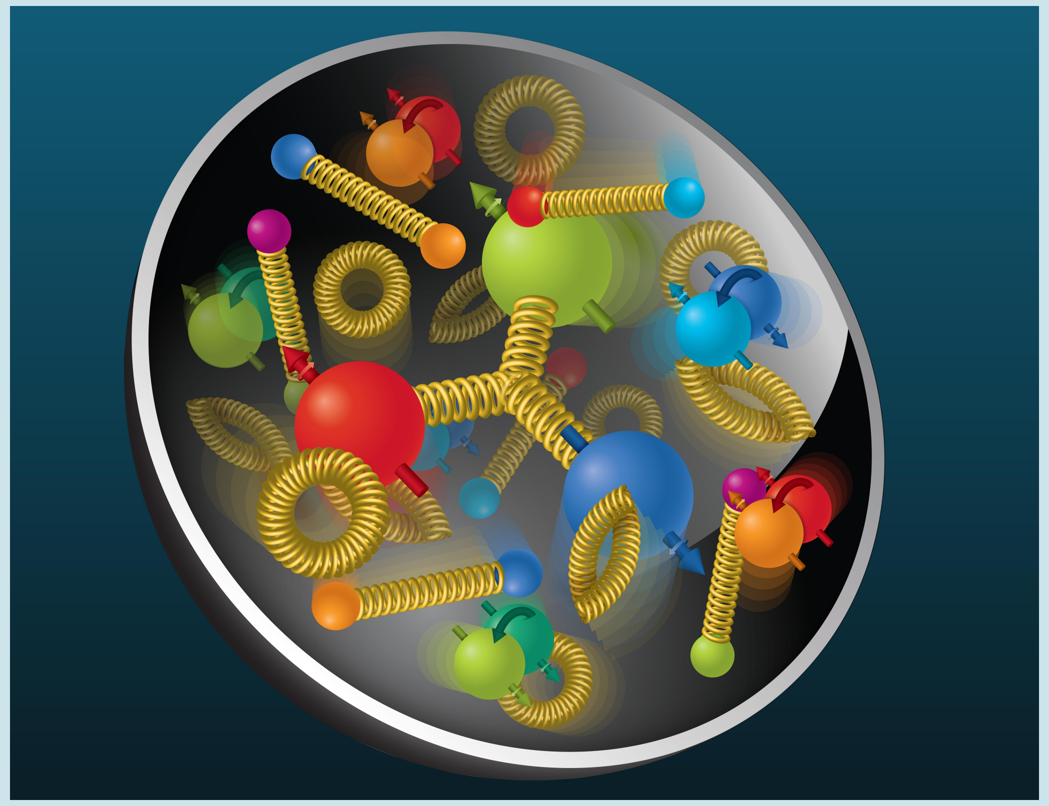

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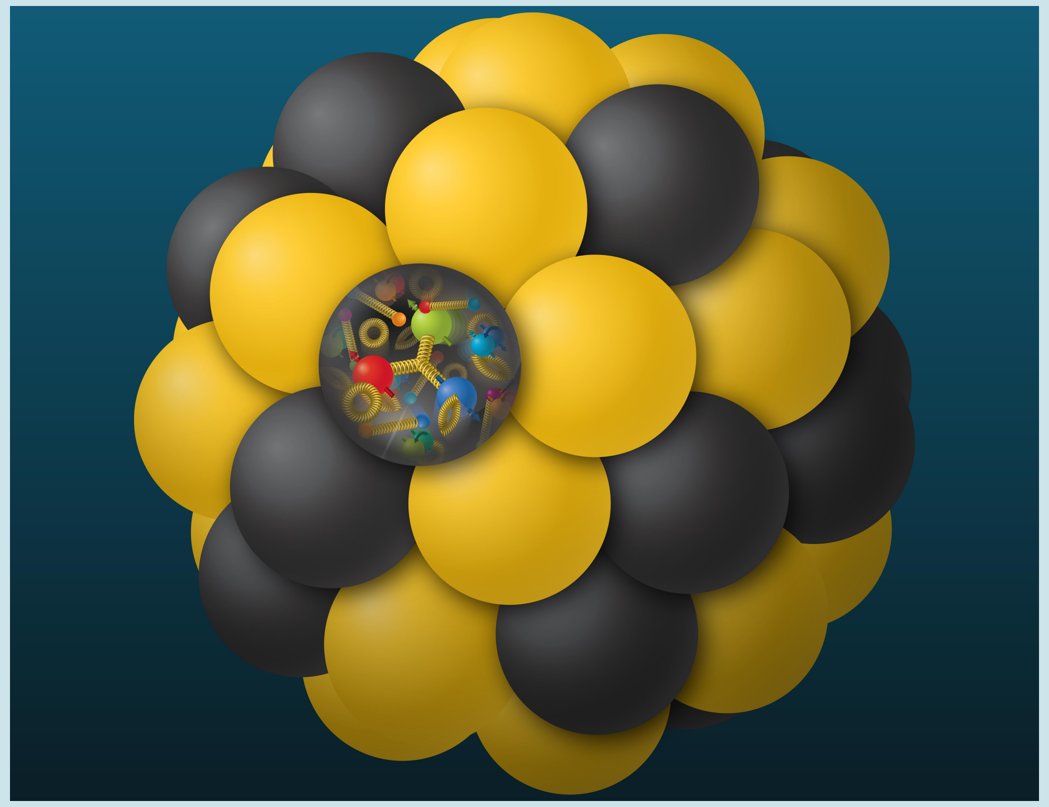
Nuclei Structure



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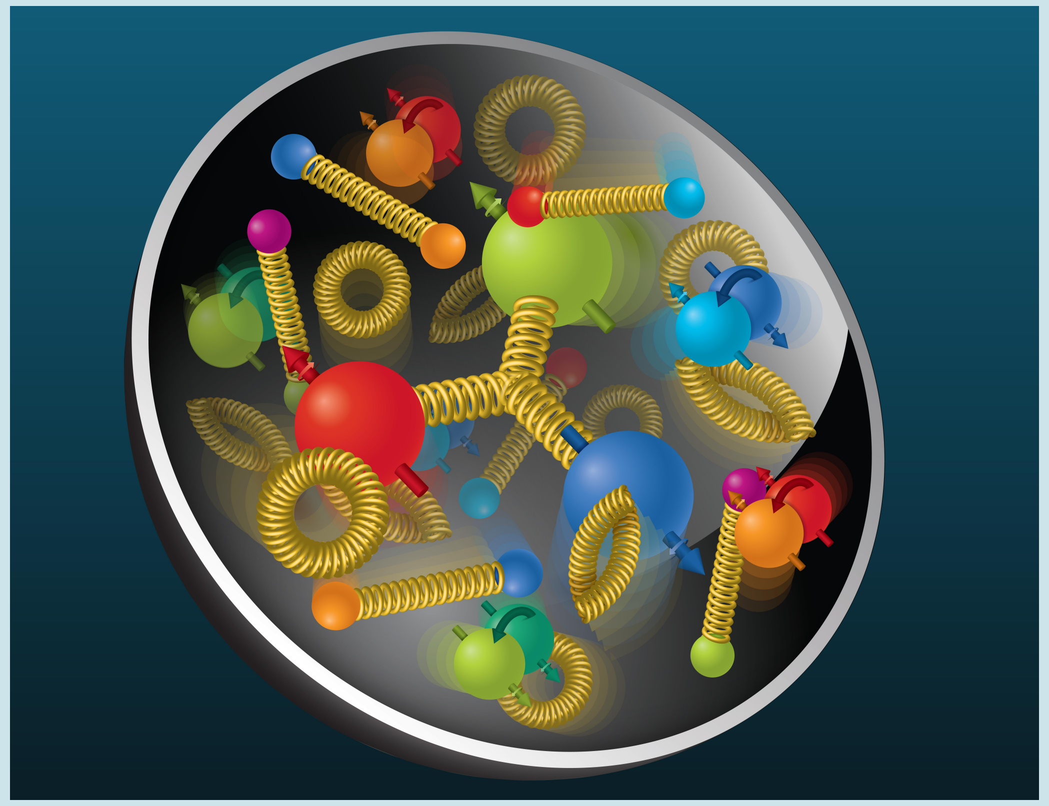

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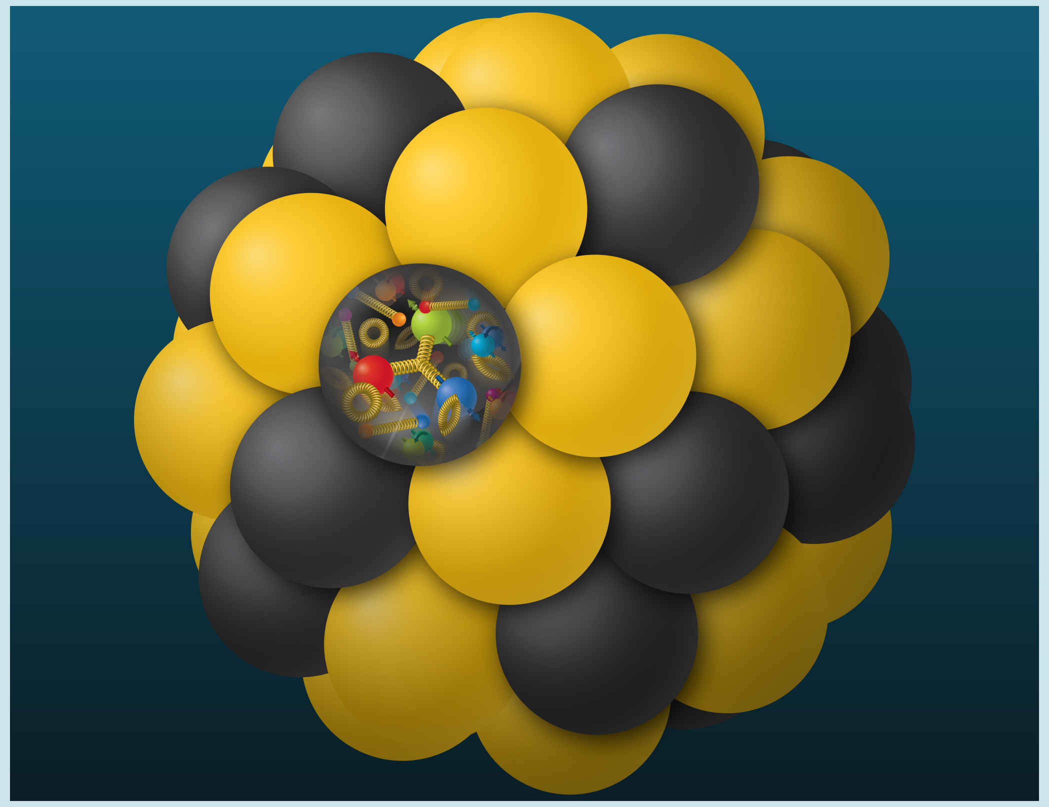
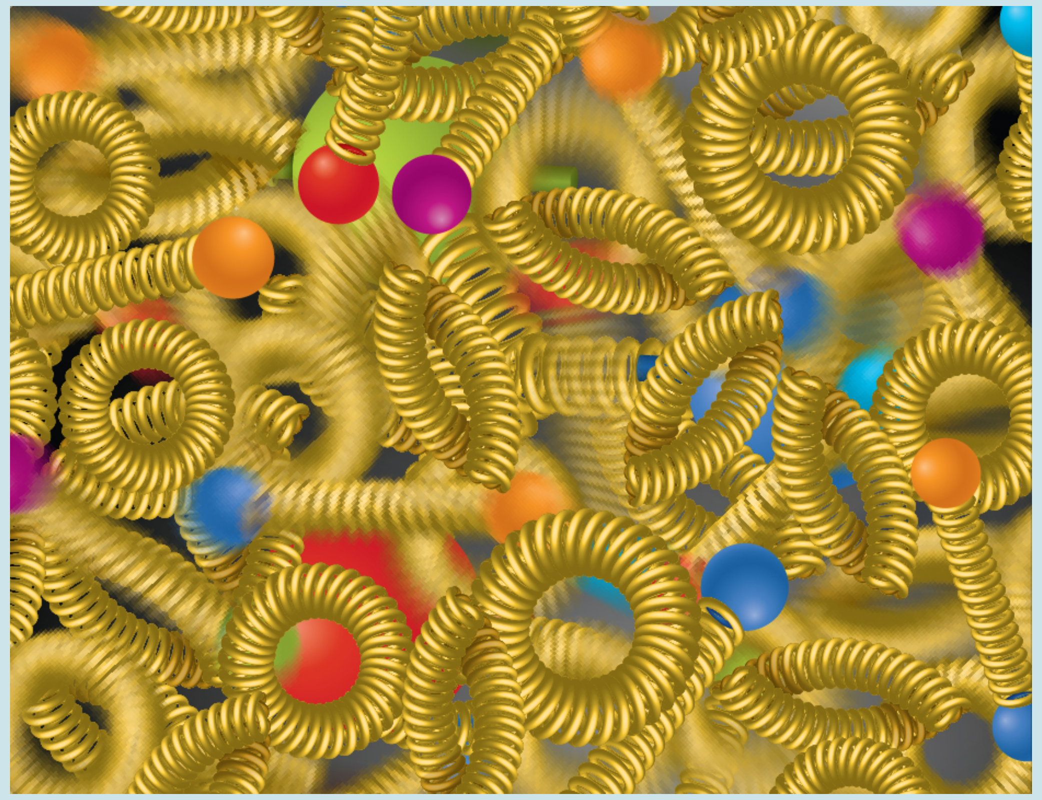


New QCD Matter



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- **New State of QCD Matter**
  - Is there CGC? Under what conditions? What properties?

Science Questions at EIC

Origin of Spin and Inner Structure | **Origin of Mass** | **Nuclei Structure** | **New QCD Matter**

In a word, to reveal gluon role in the universe!

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- **Nuclei Structure**
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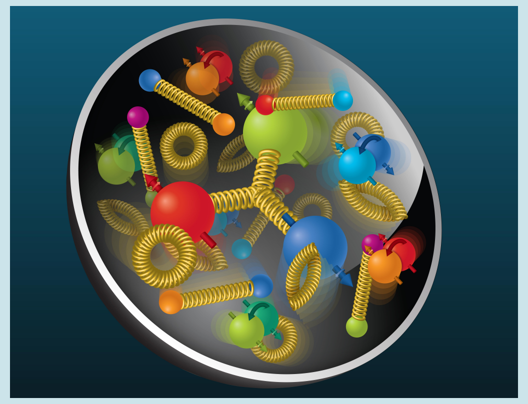
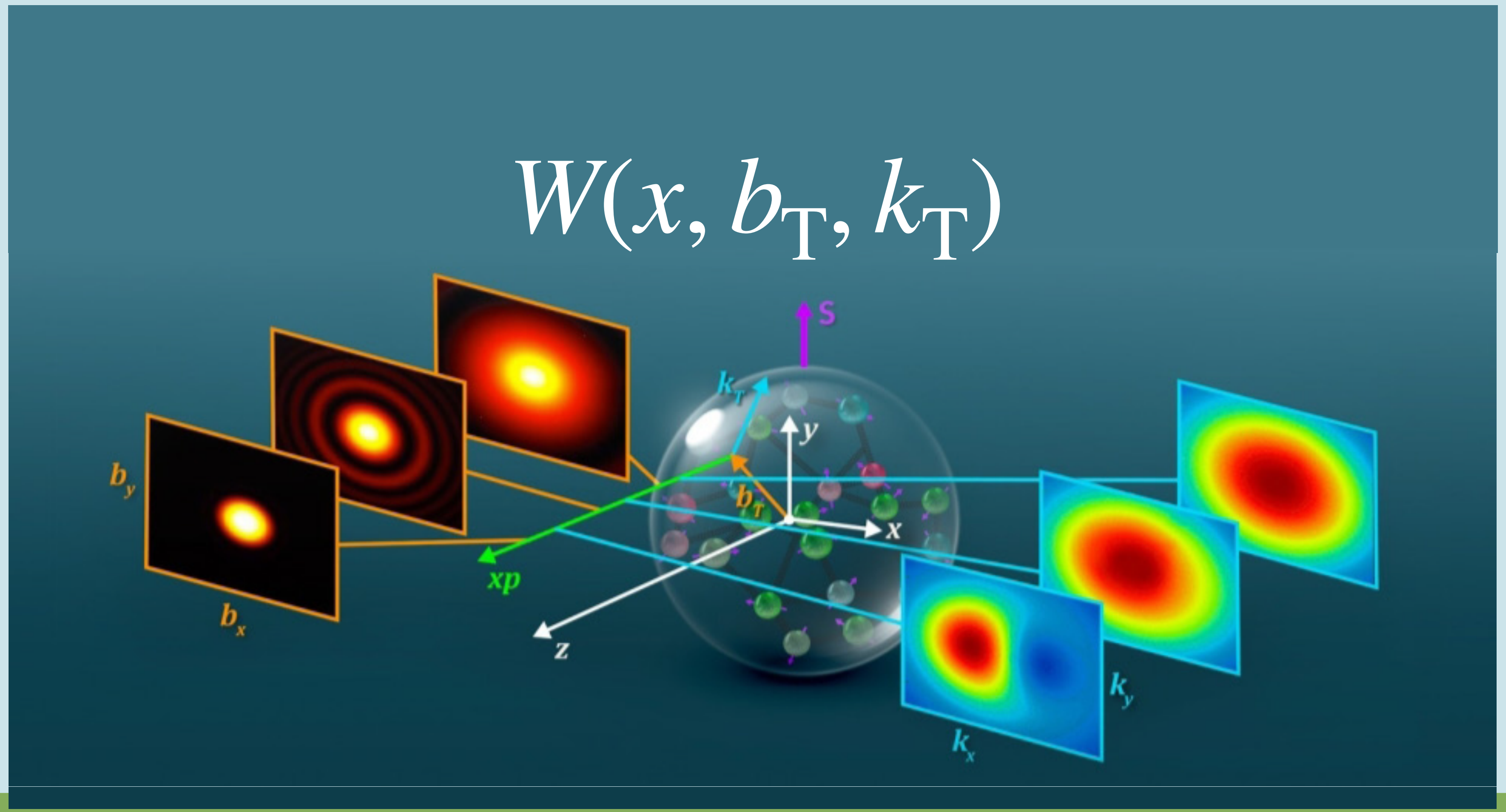
Selected Physics Highlight

Origin of Spin and Inner Structure



- The full understanding of parton distribution in spatial and momentum space is the ultimate goal of the EIC
  - Wigner function is the generating function, $W(x, b_T, k_T)$ that is impossible to determine b_T and k_T at the same time



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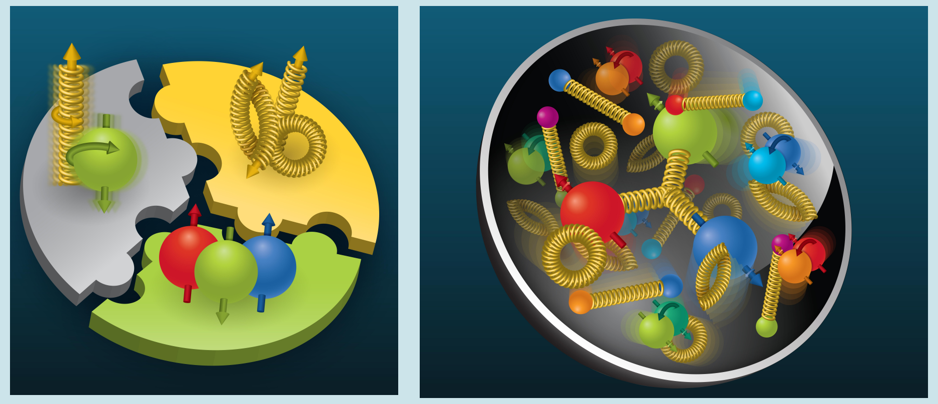

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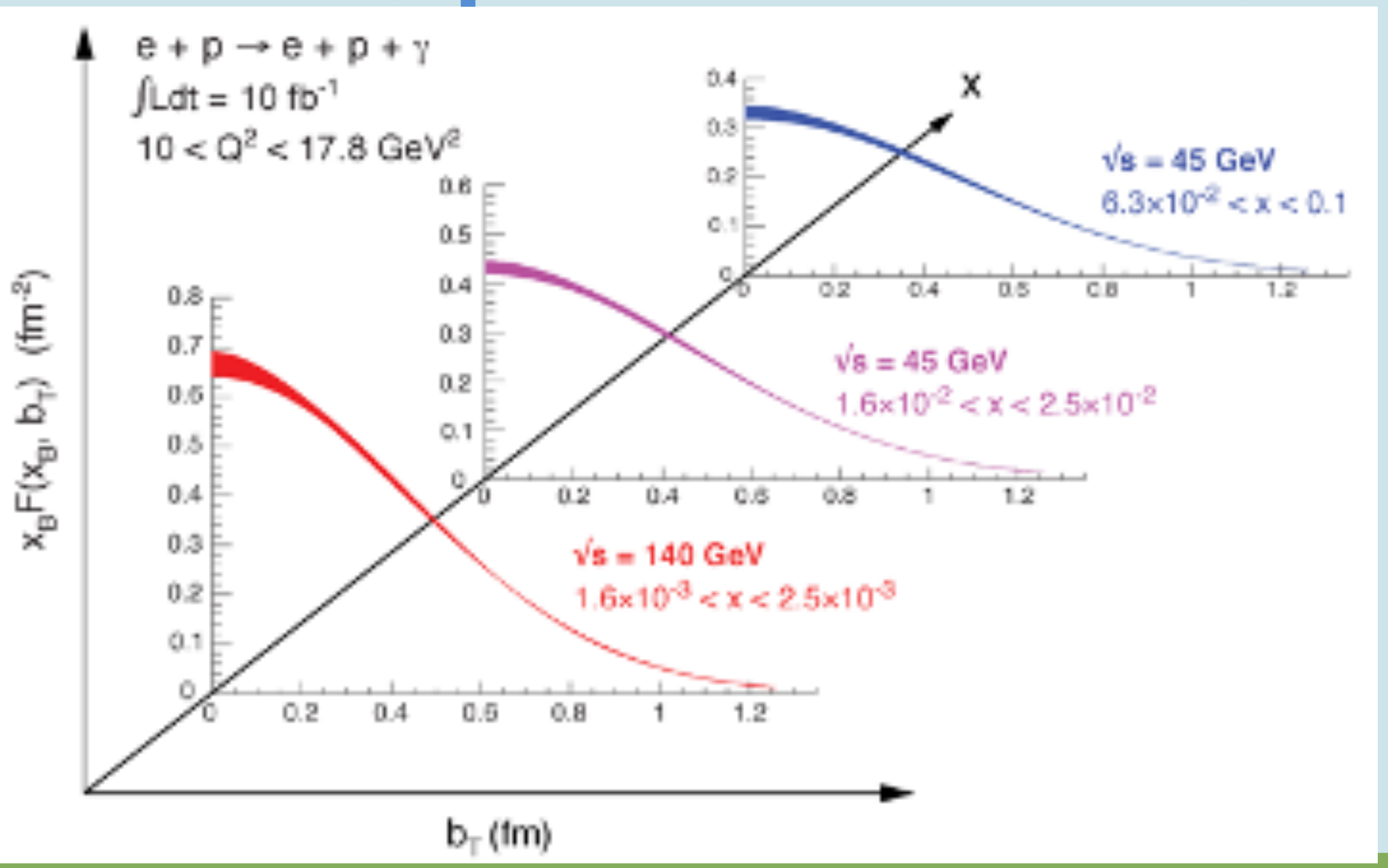
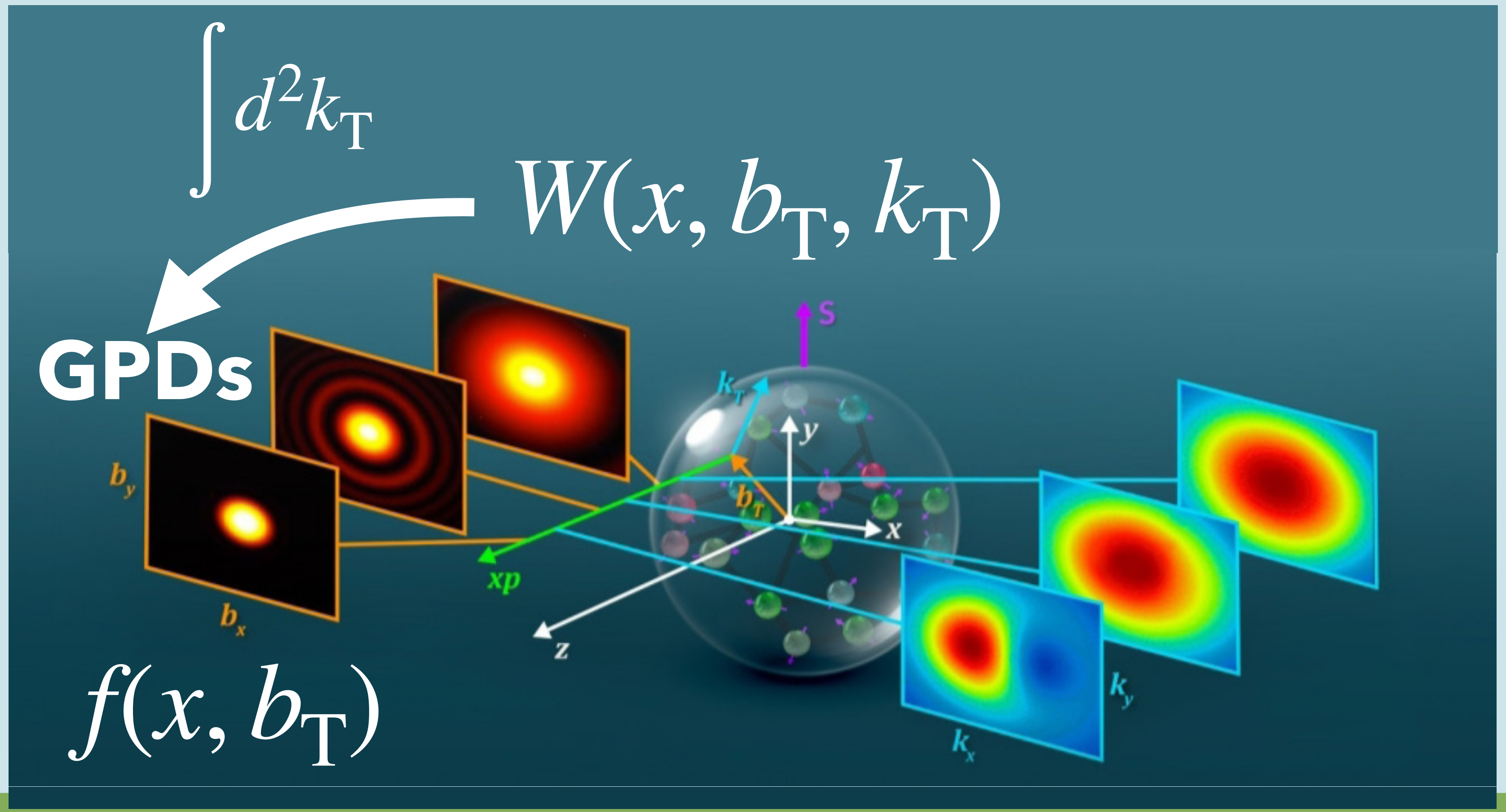
GPDs (spatial distribution)





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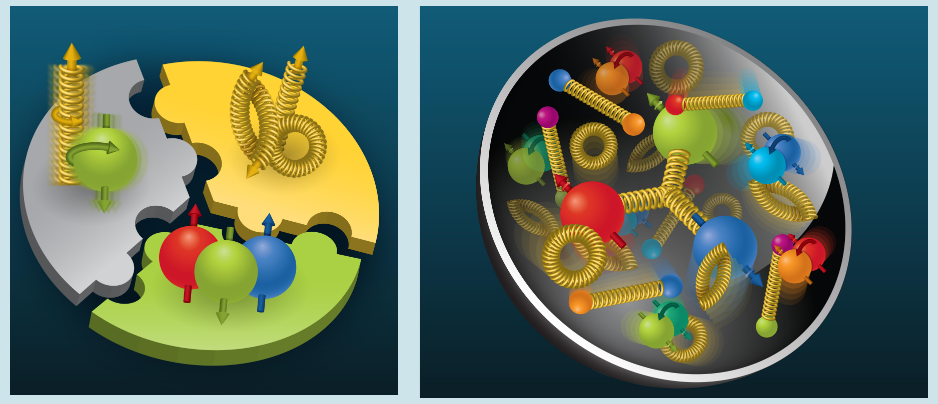

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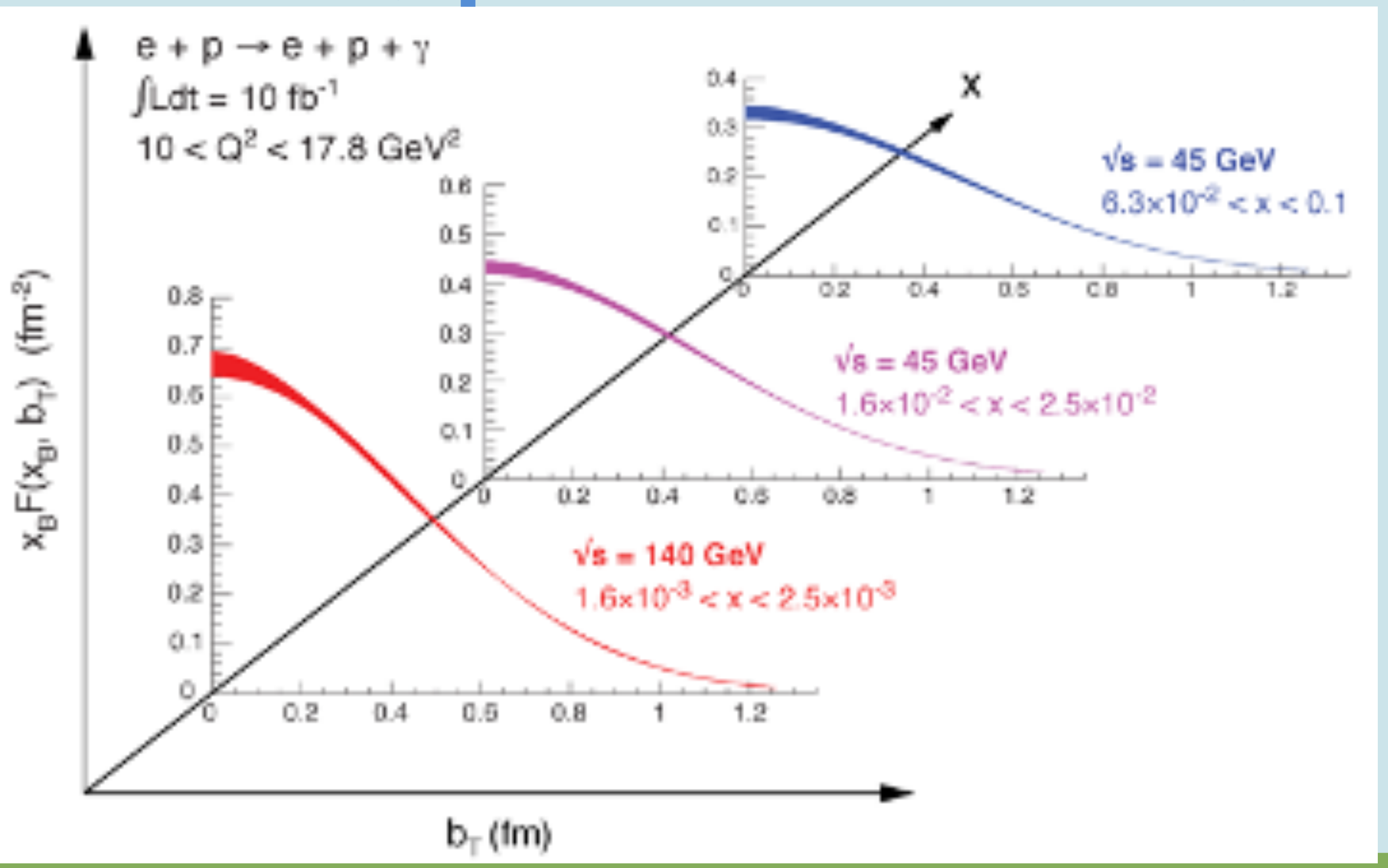
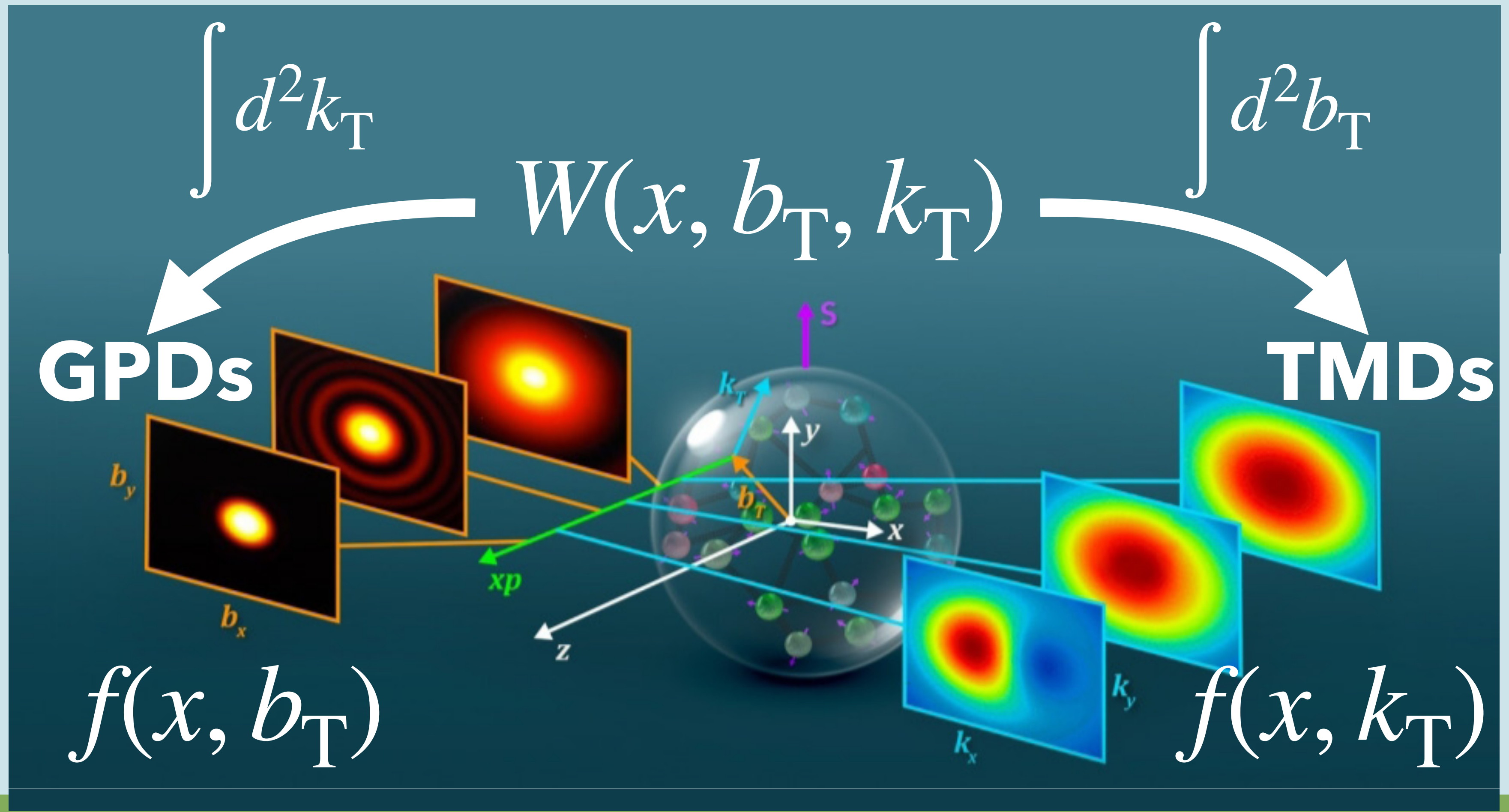
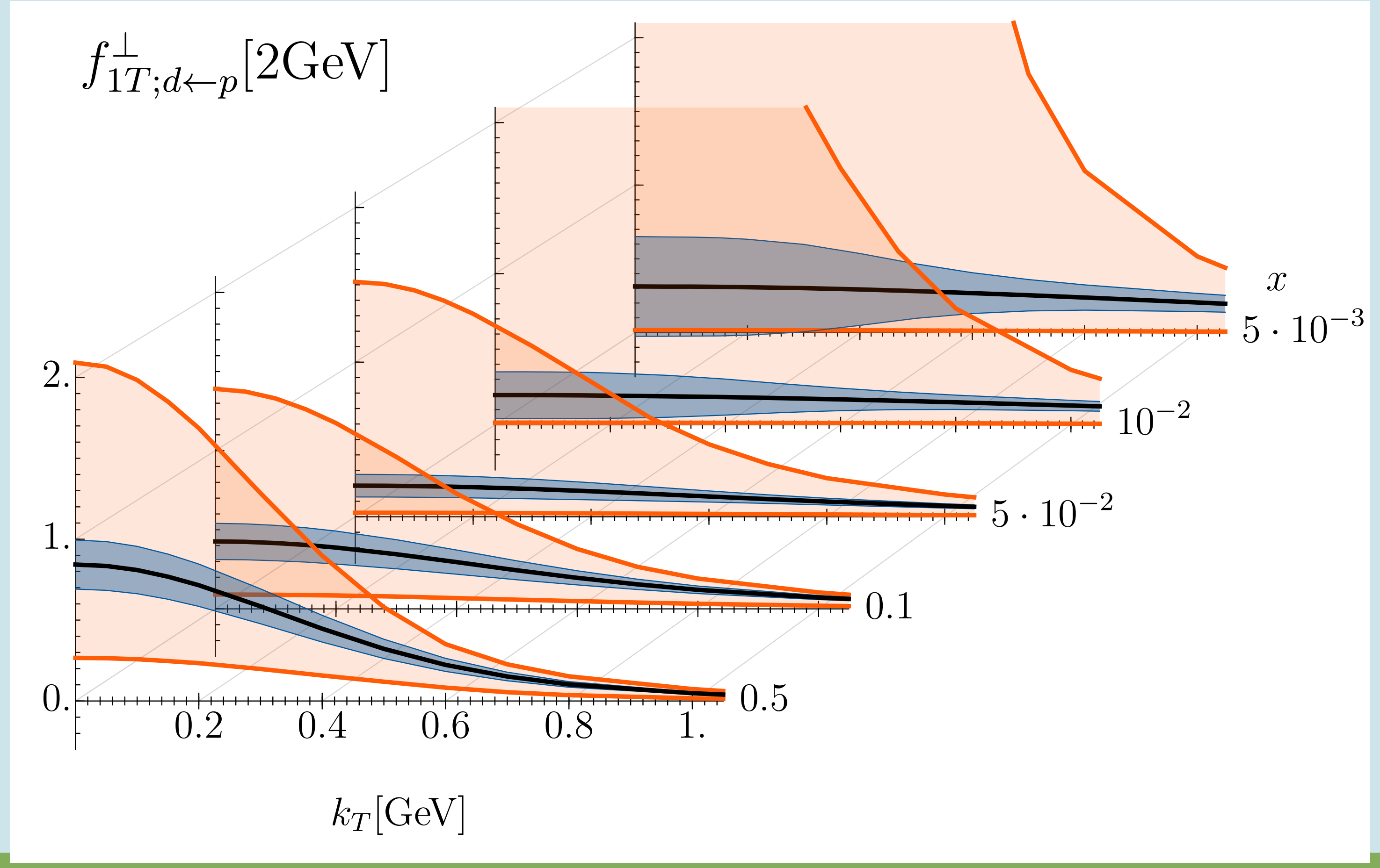
- The transverse-momentum-dependent parton distribution function (TMDs) encodes information on how the momentum of partons is correlated with the nucleon spin
  - Using polarized beams is very important!

GPDs (spatial distribution)

TMDs (momentum distribution)







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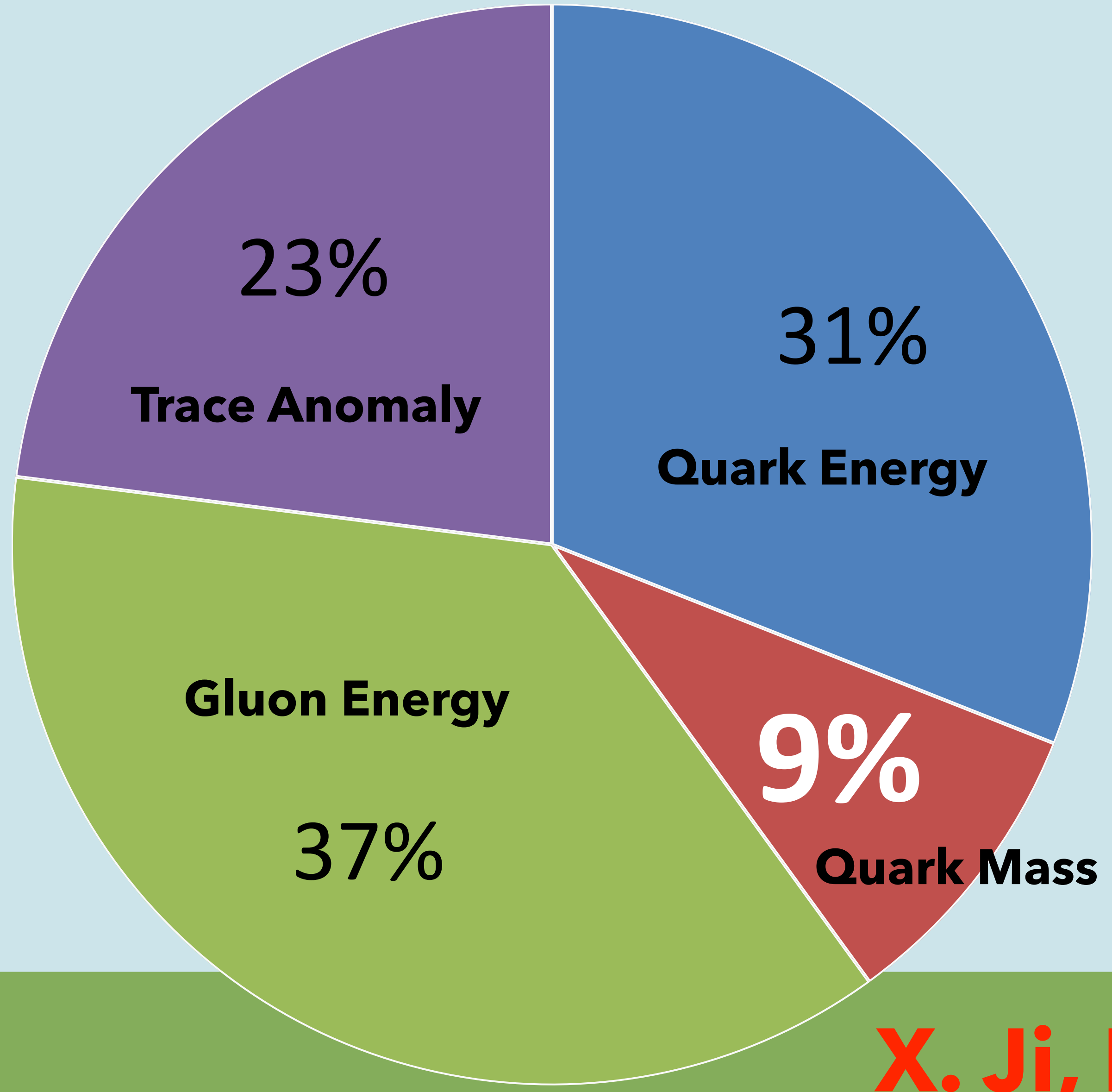

X. Ji, PRL741071(1995)

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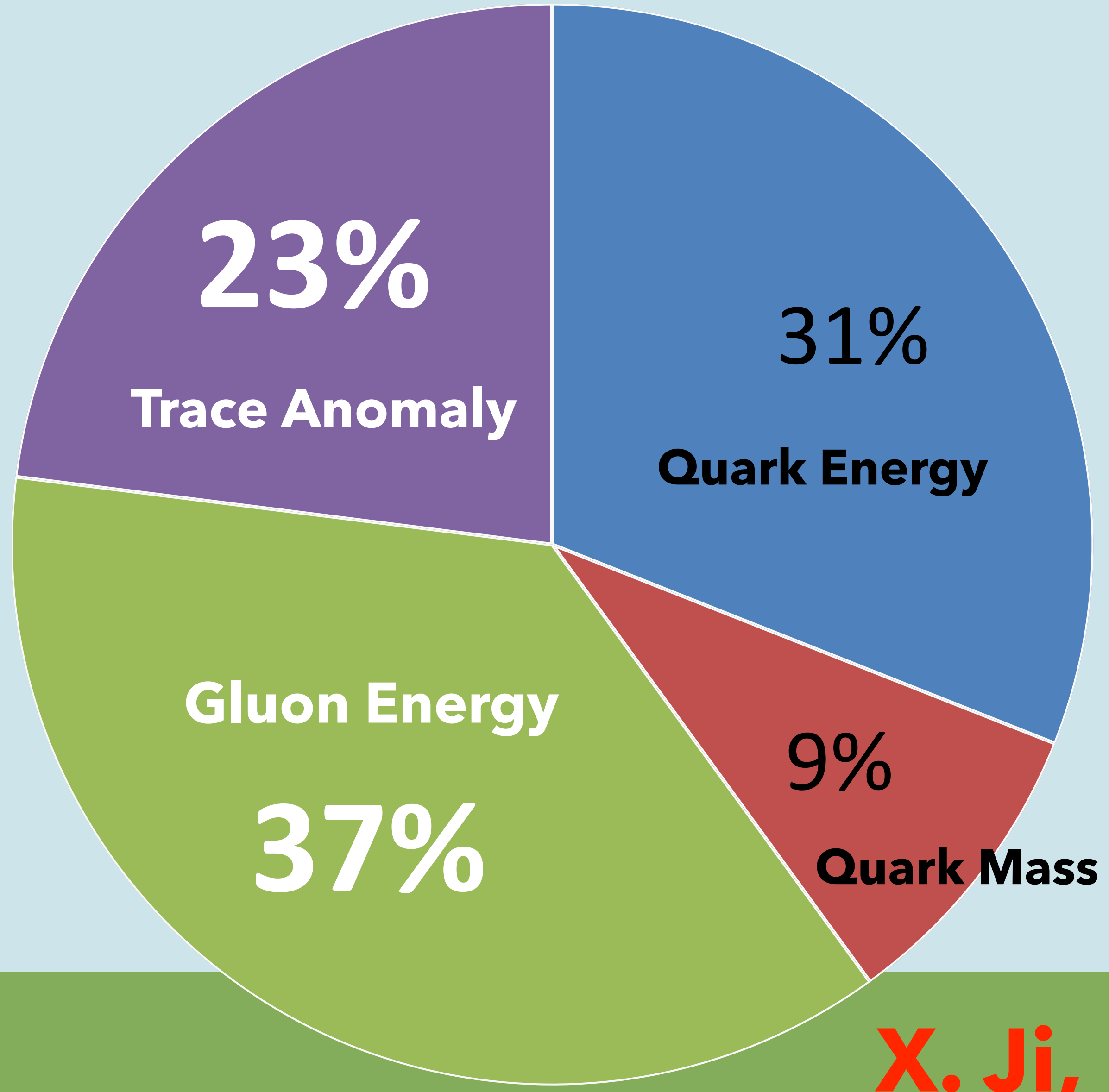

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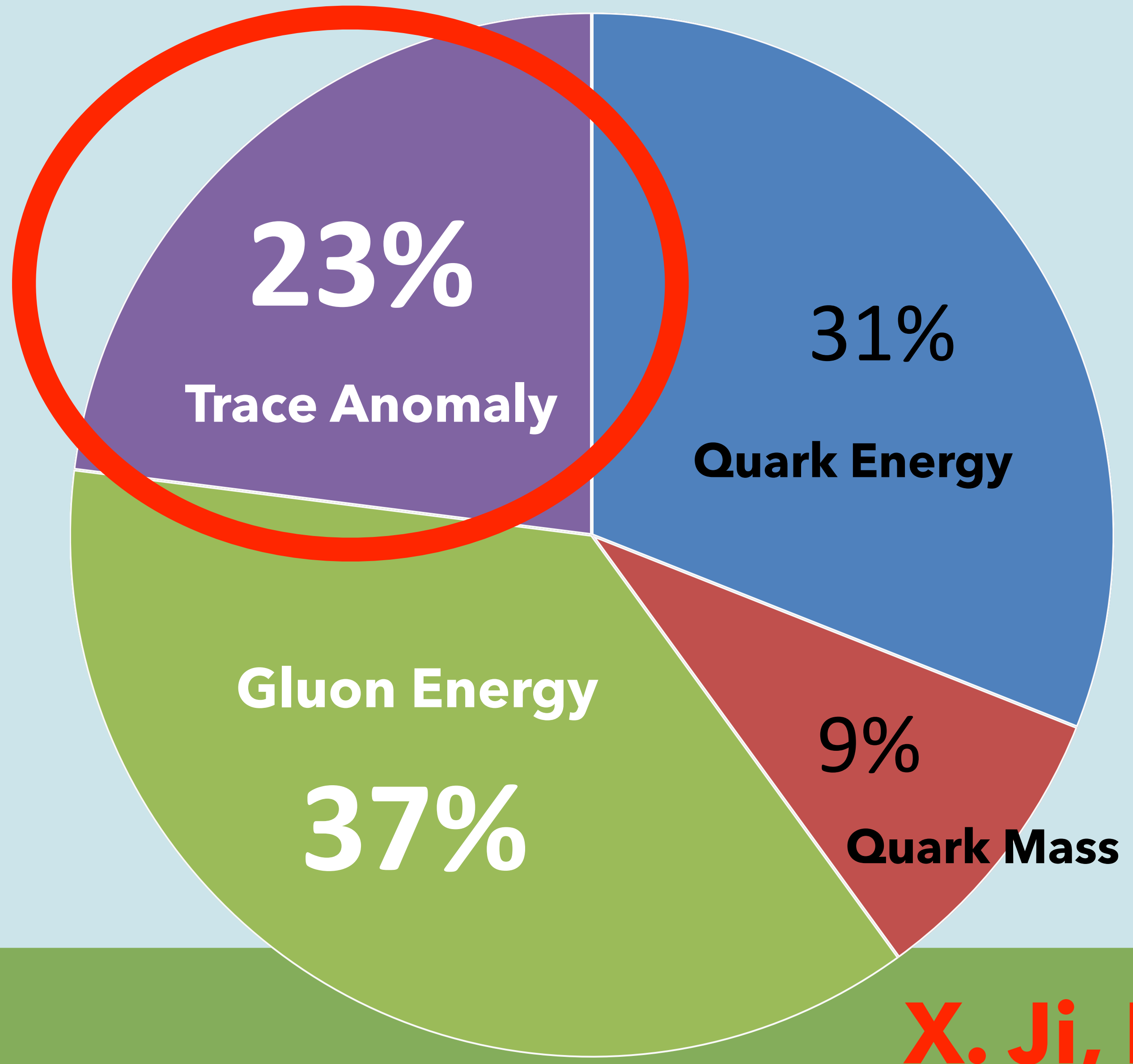

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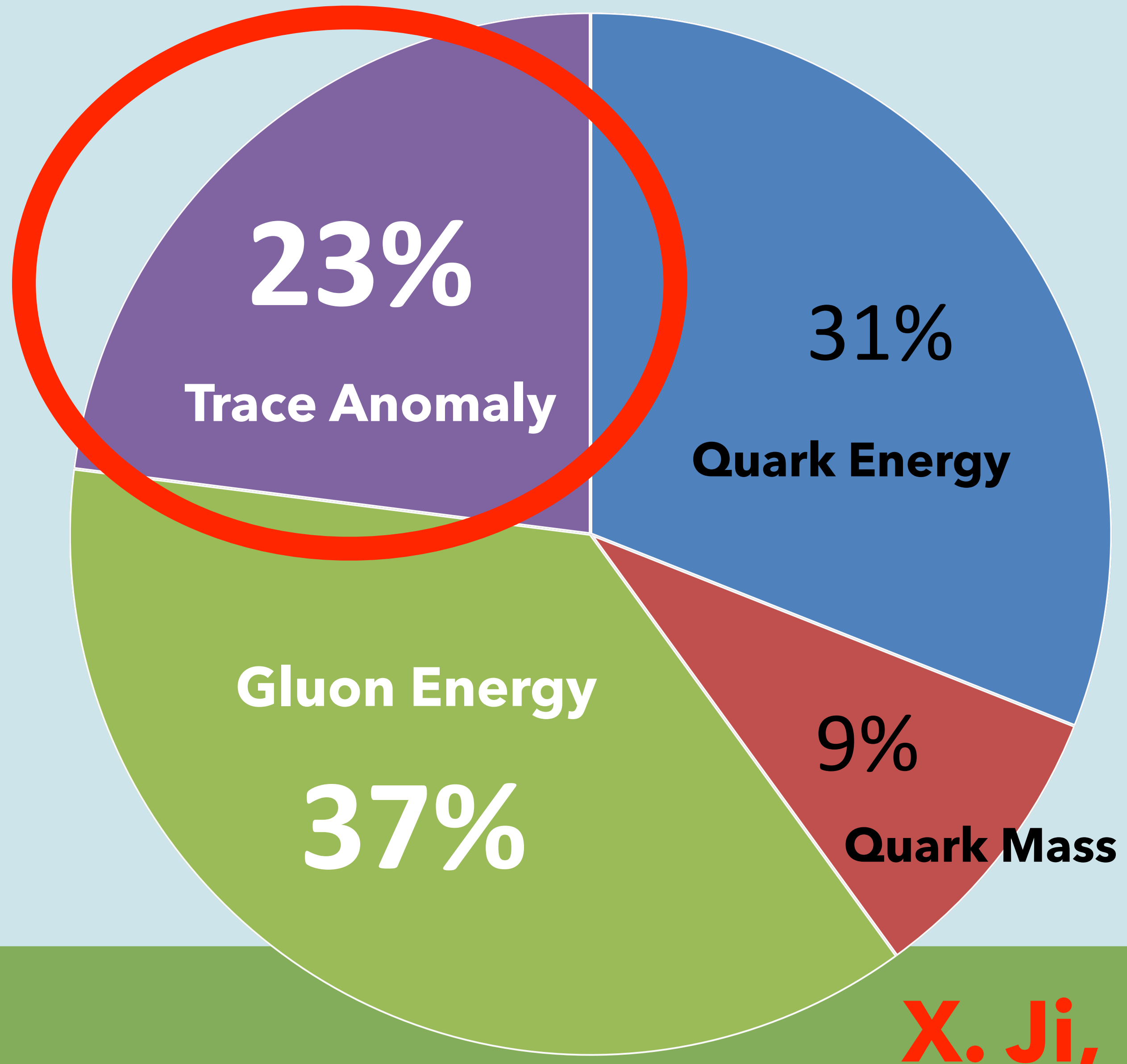
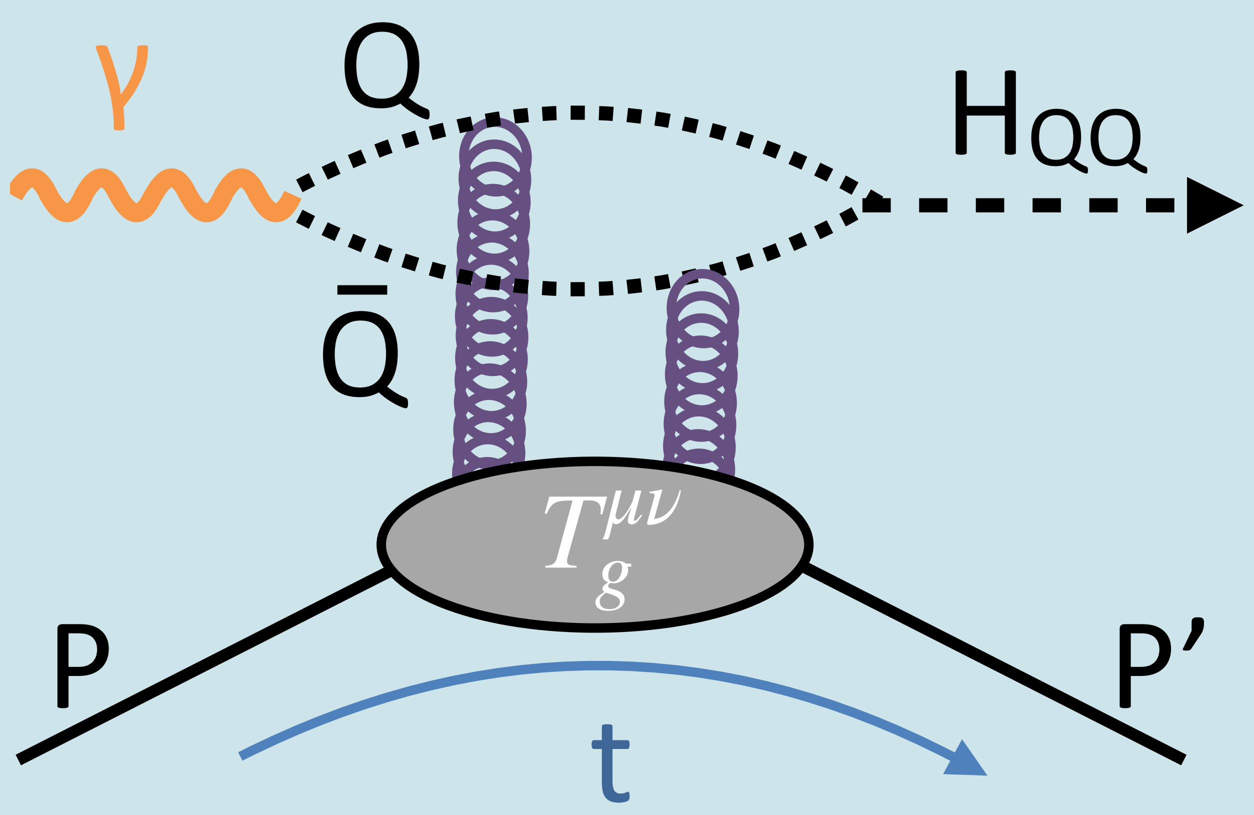


H_{QQ} = J/ψ or Υ



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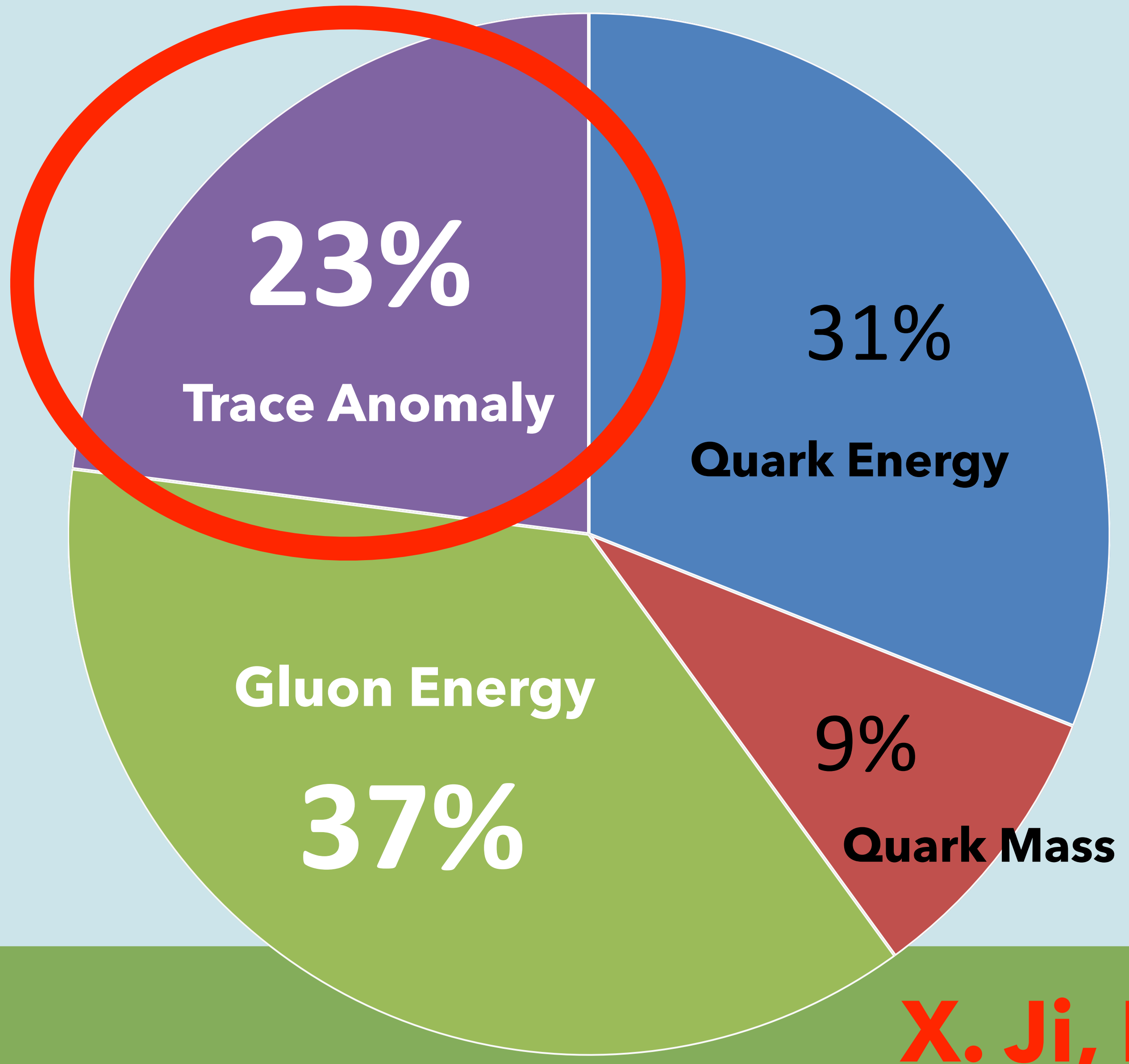

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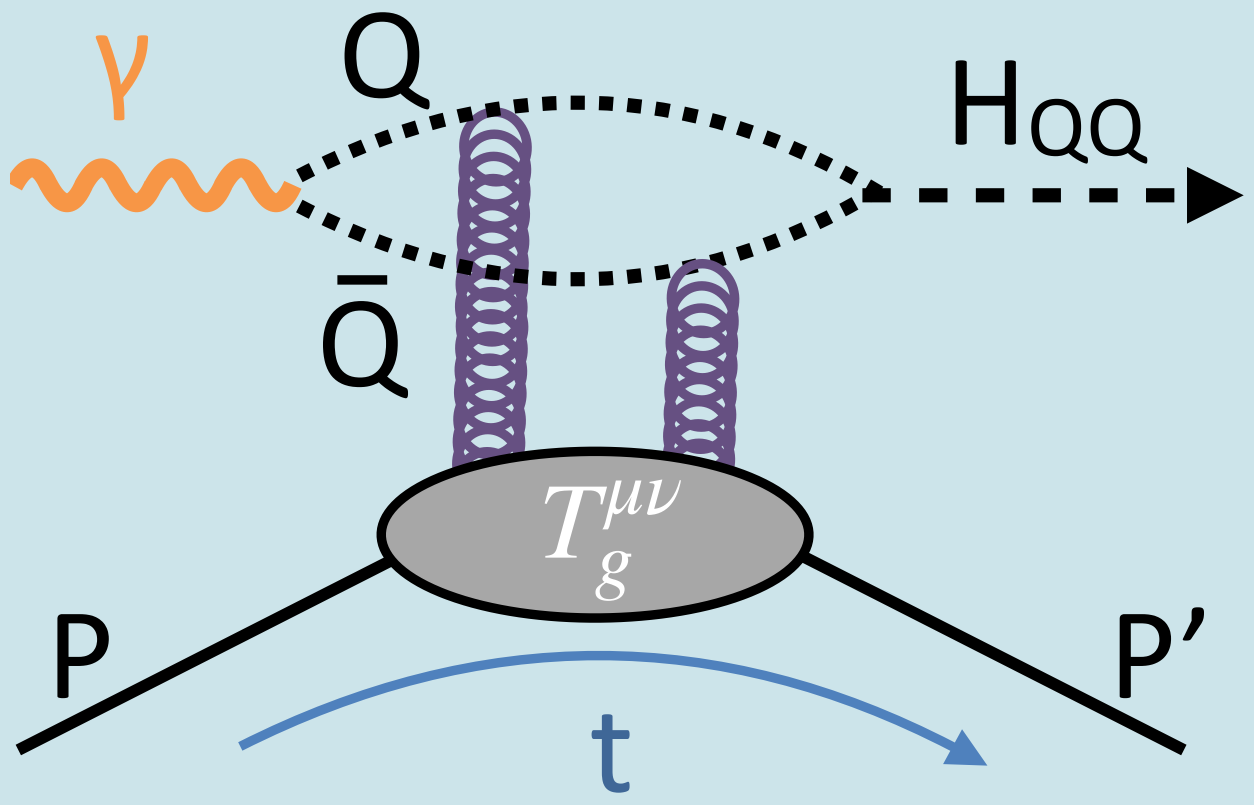

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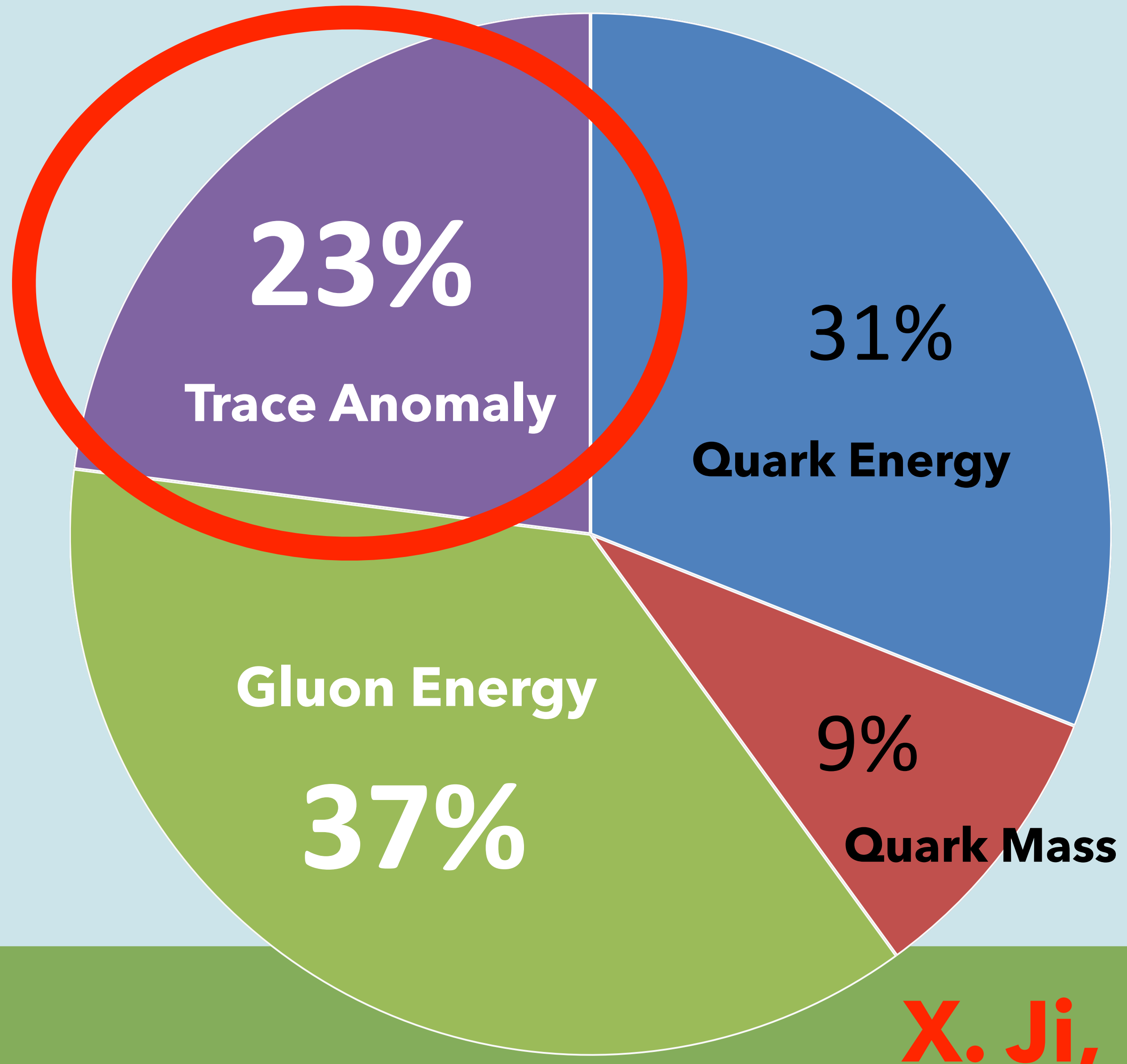

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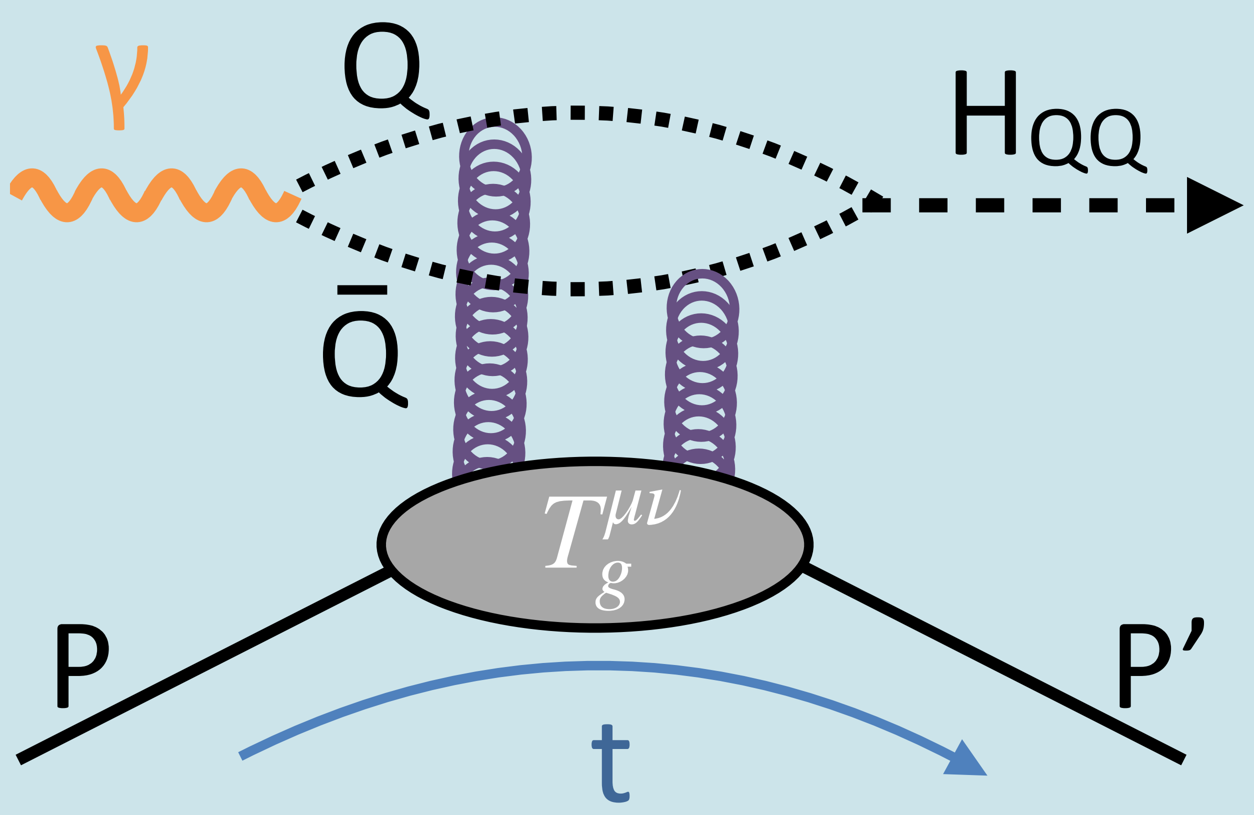
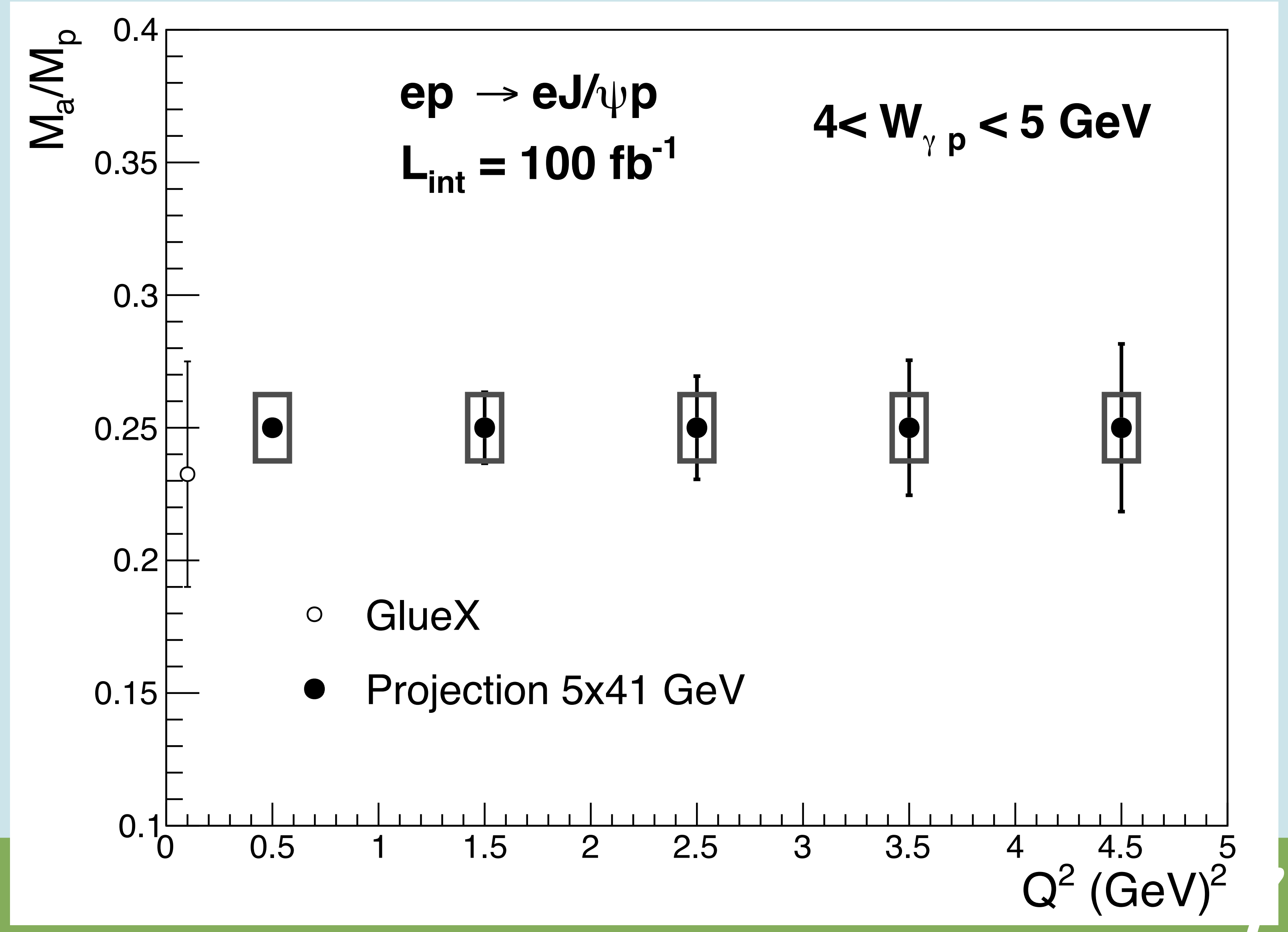
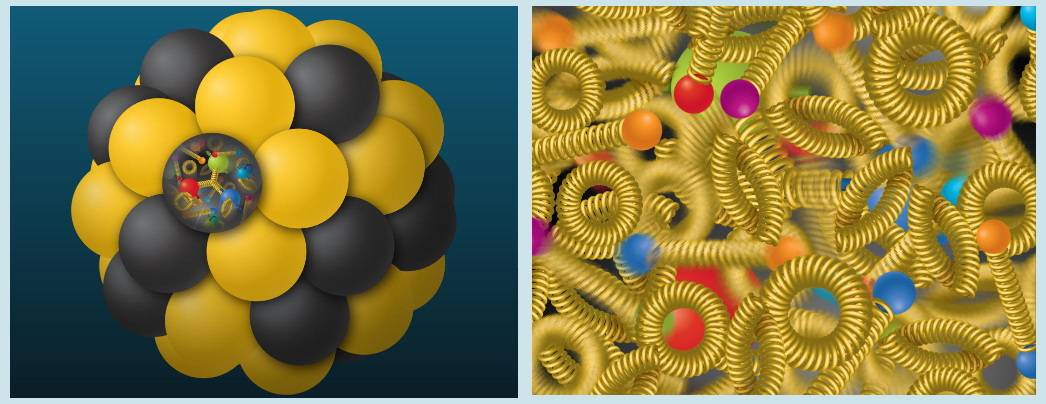




Structure of Nuclei



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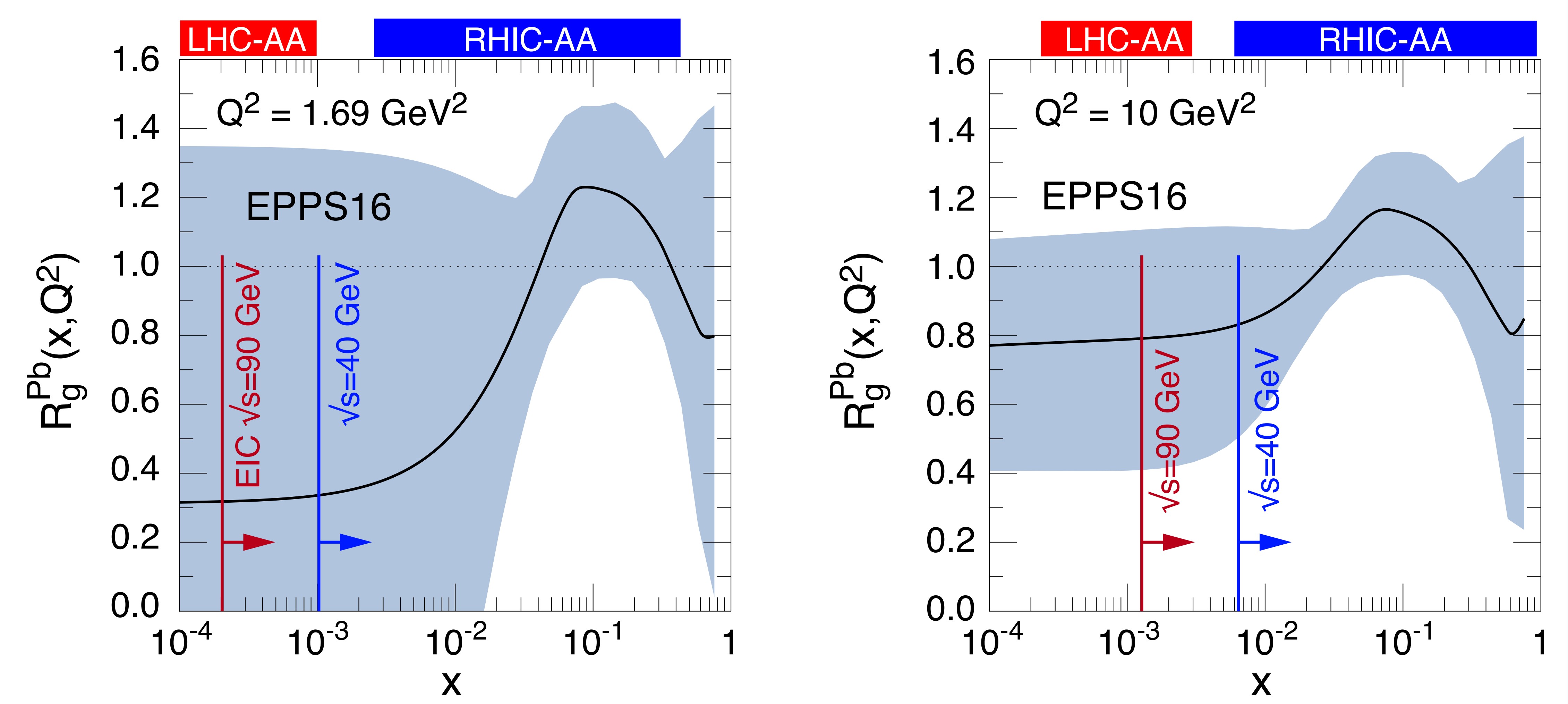

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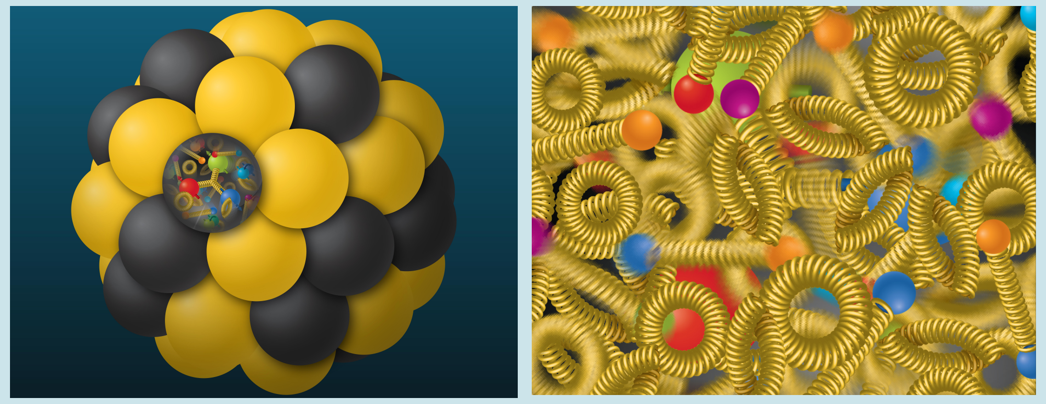

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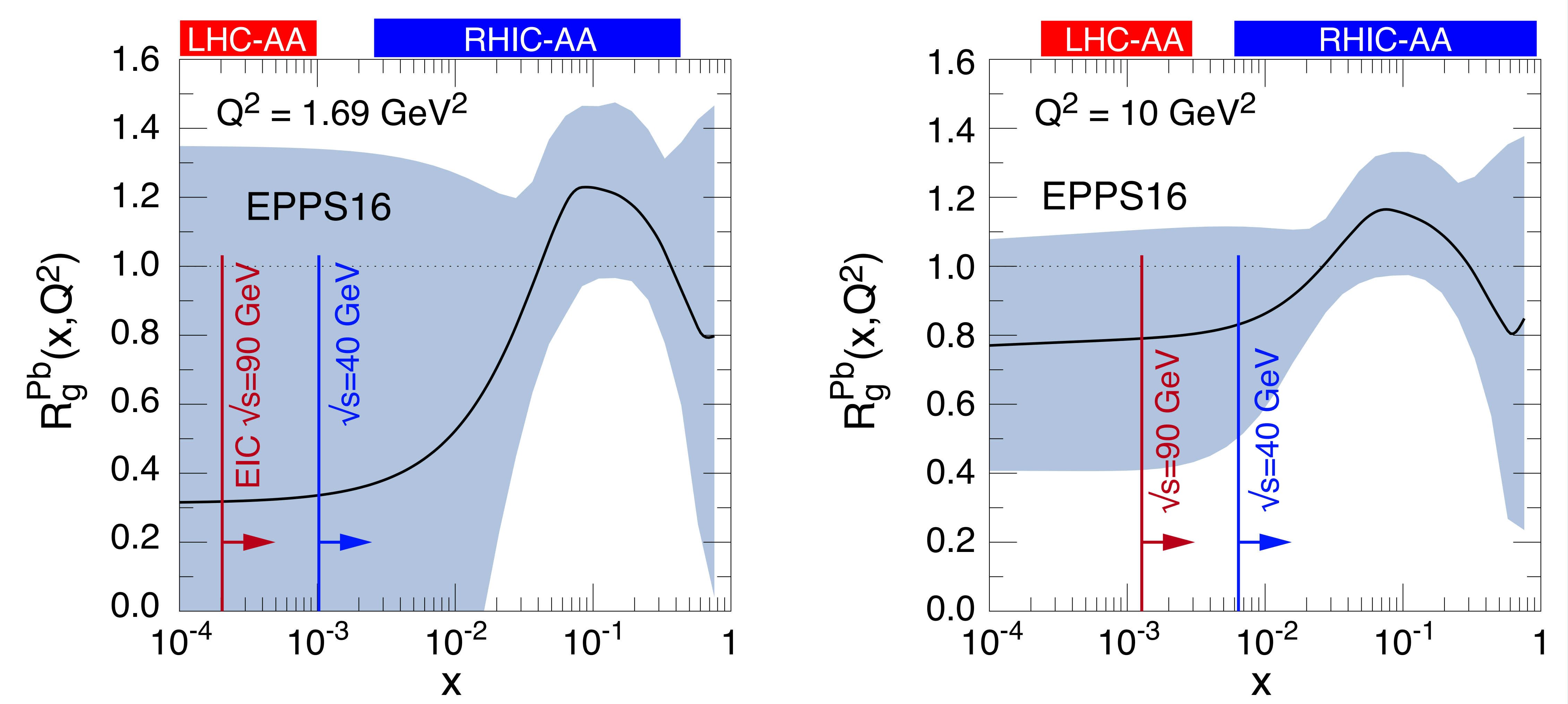

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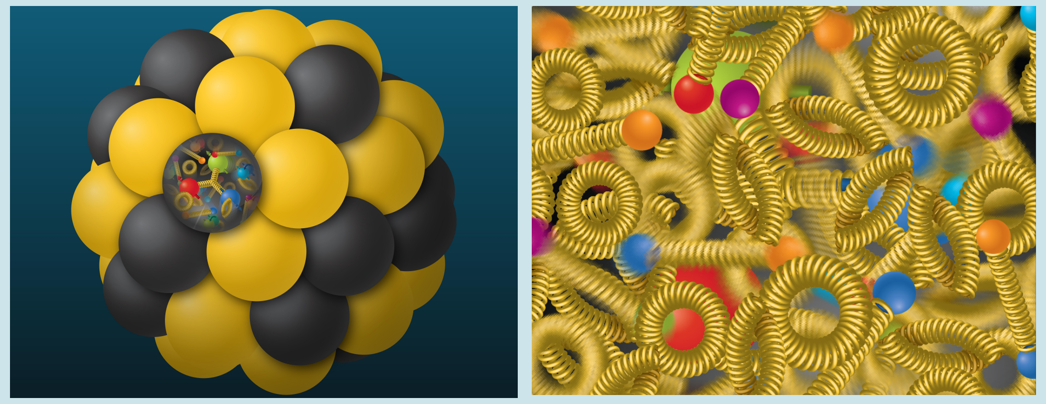

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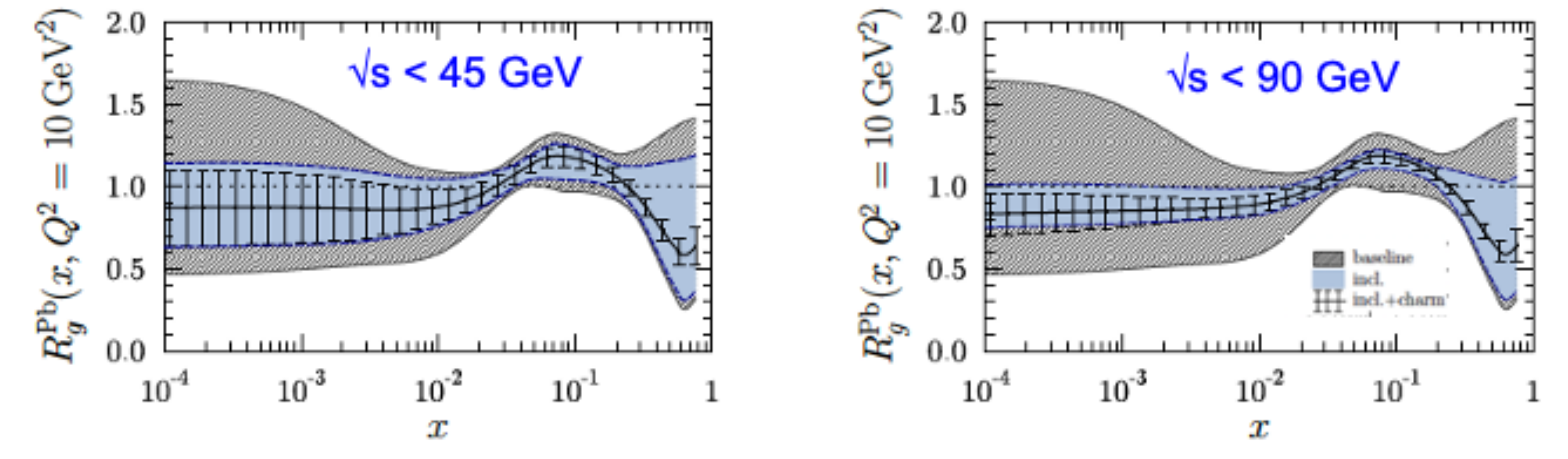

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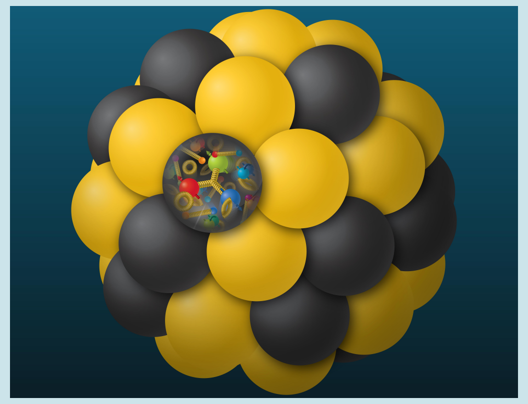

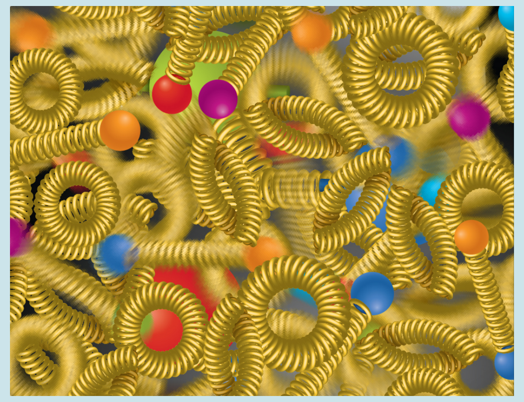

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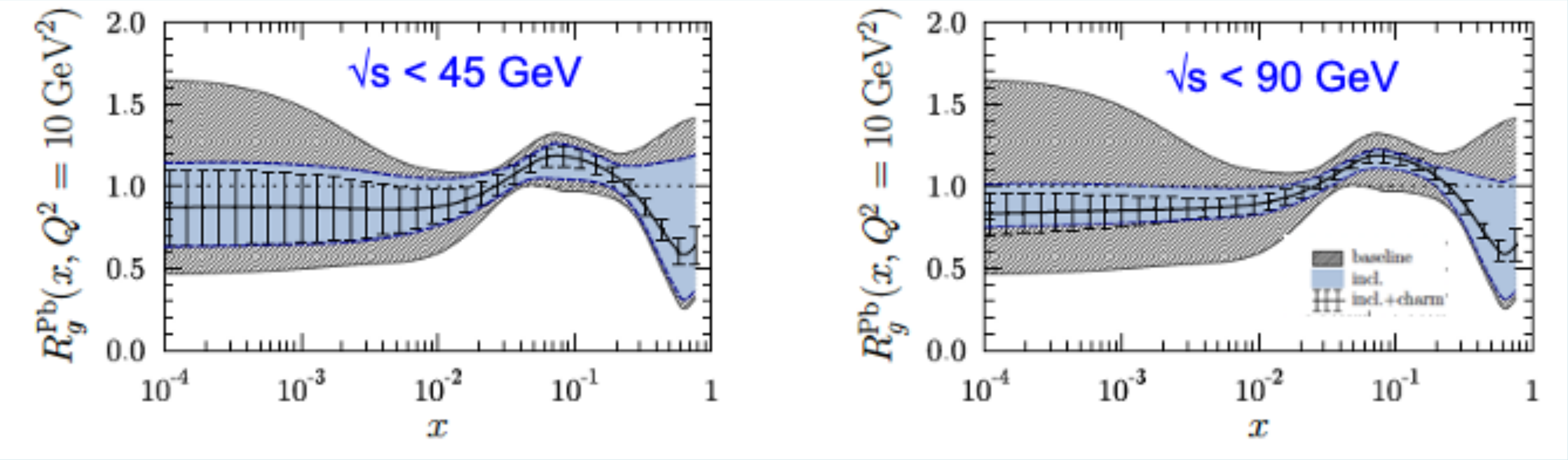

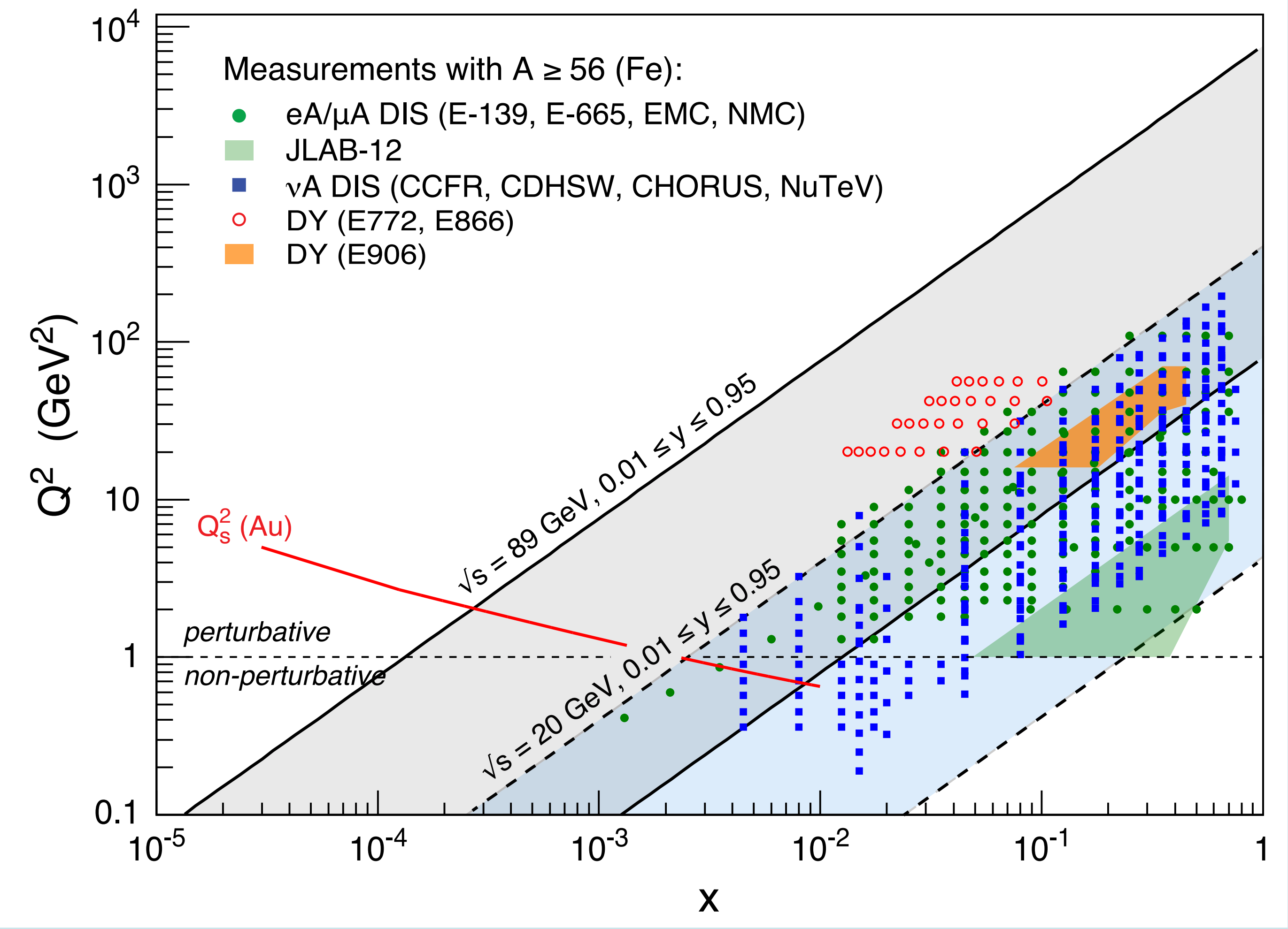

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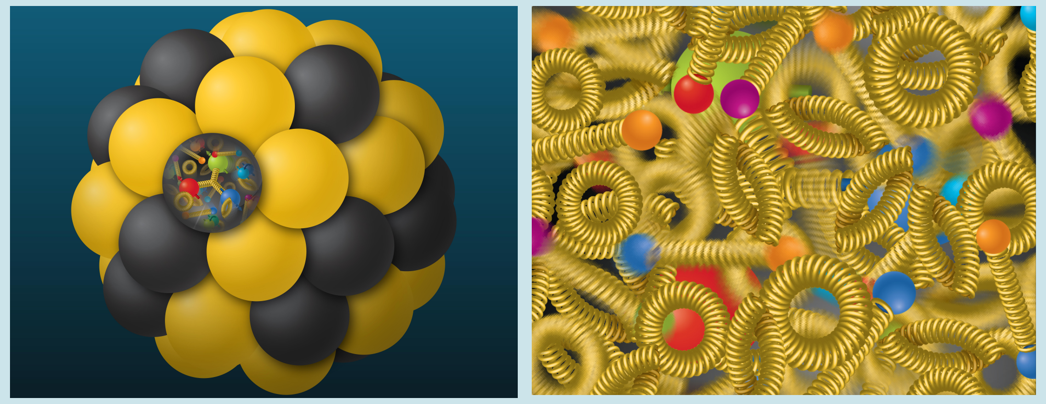

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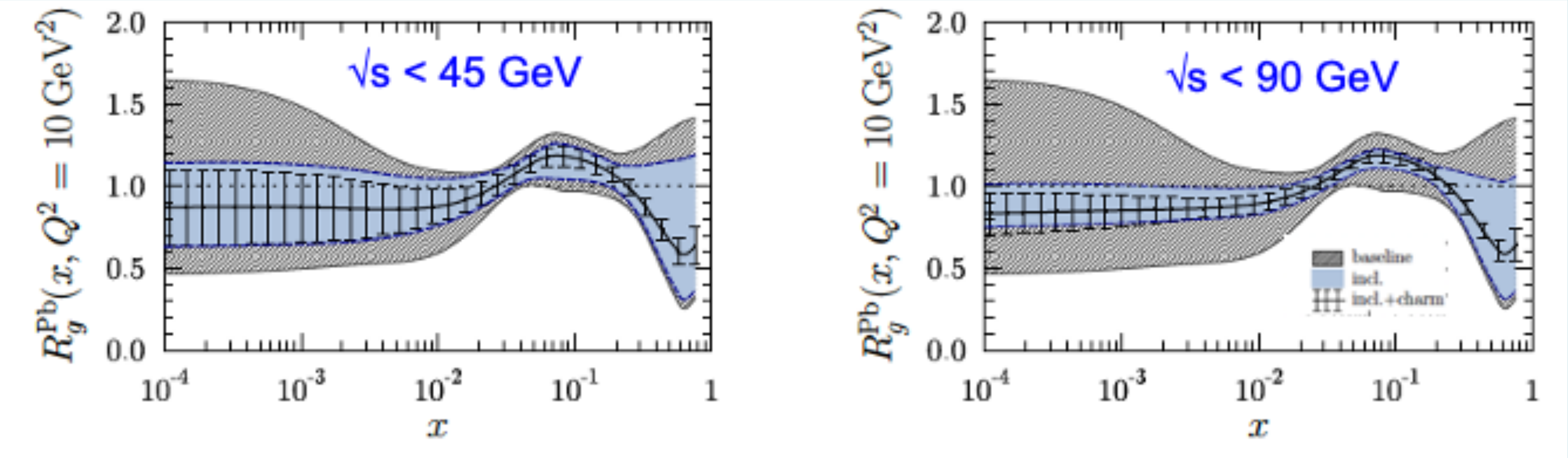
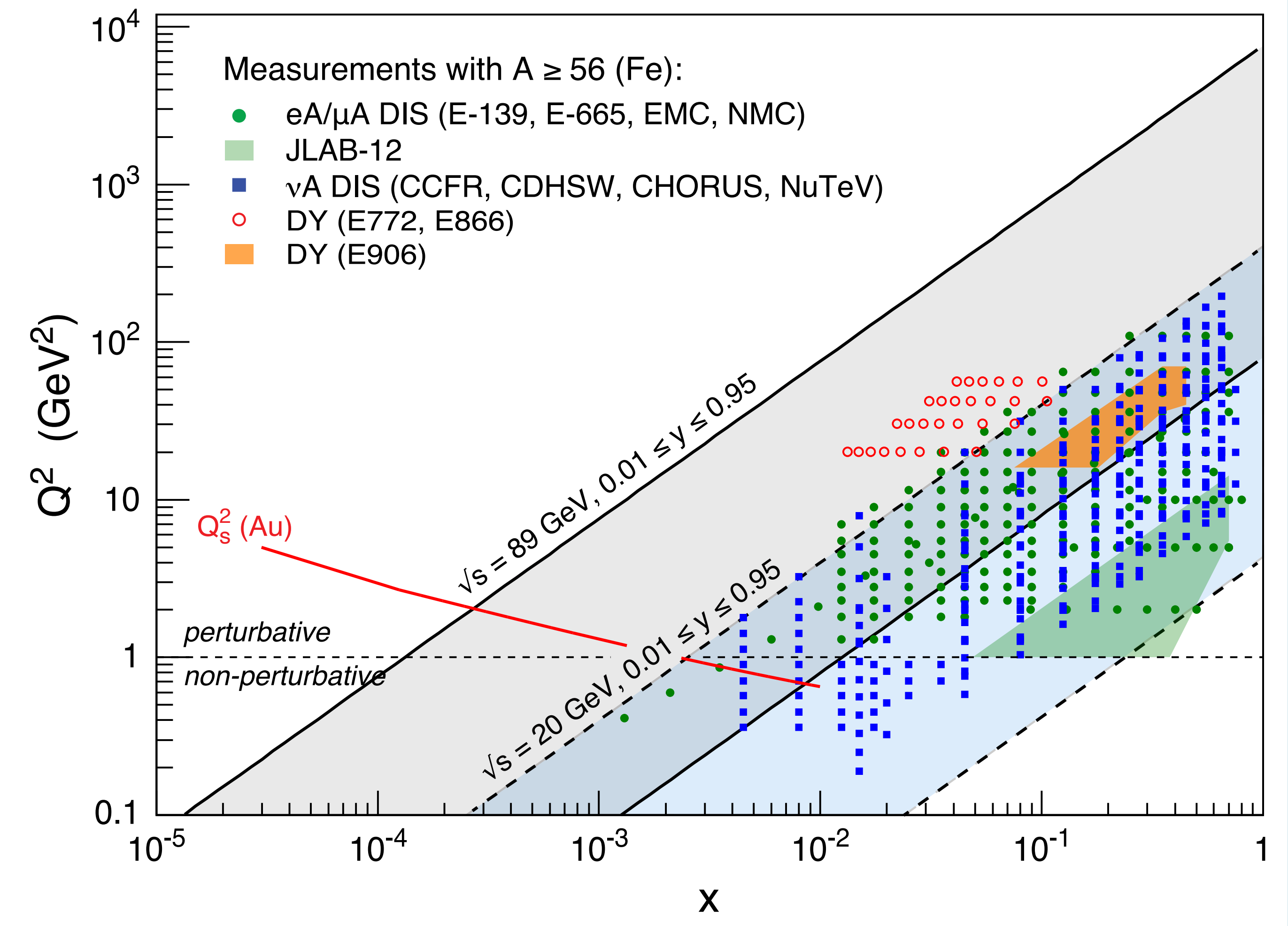
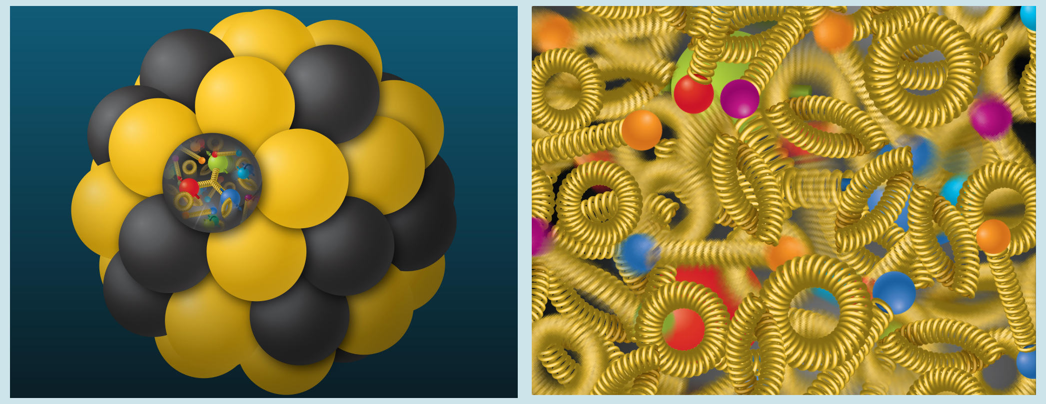
  - EIC covers a wide range of kinematic areas, across the region emerging the gluonic matter





Structure of Nuclei



- The gluon distribution in the nucleus still has large uncertainties at the LHC and RHIC region
- EIC can access the gluon distribution at the small-x regions directly
  - Thanks to enough energy and large luminosity, uncertainty can be reduced dramatically
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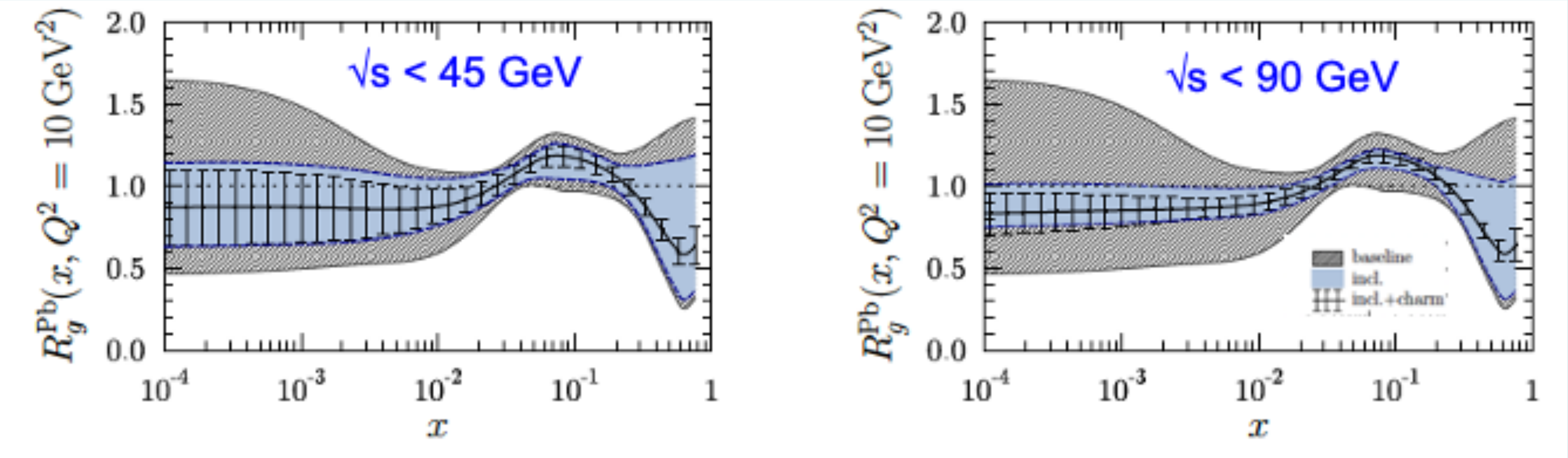
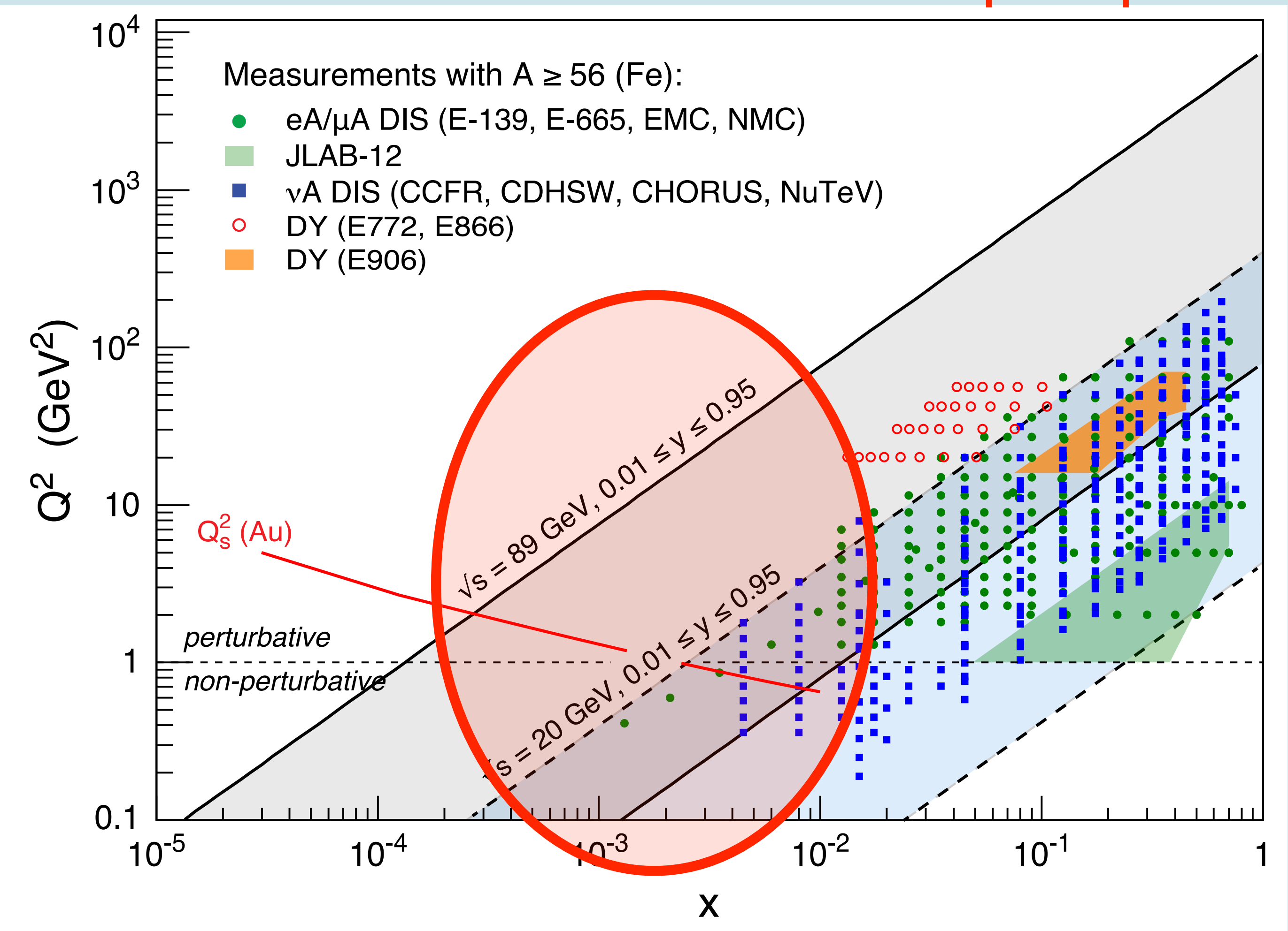


Under what conditions? What properties?



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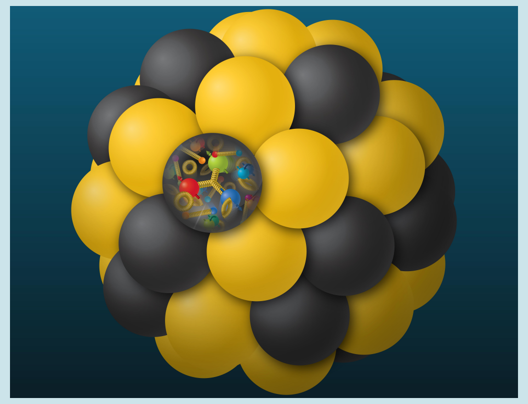

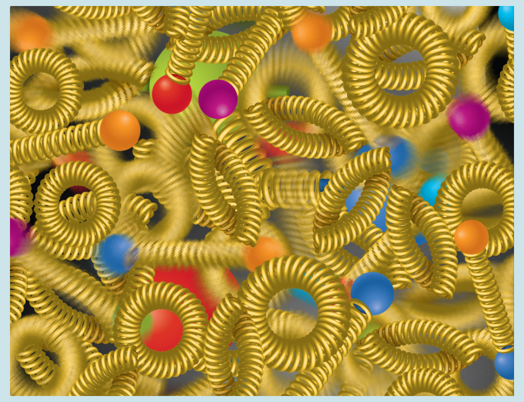

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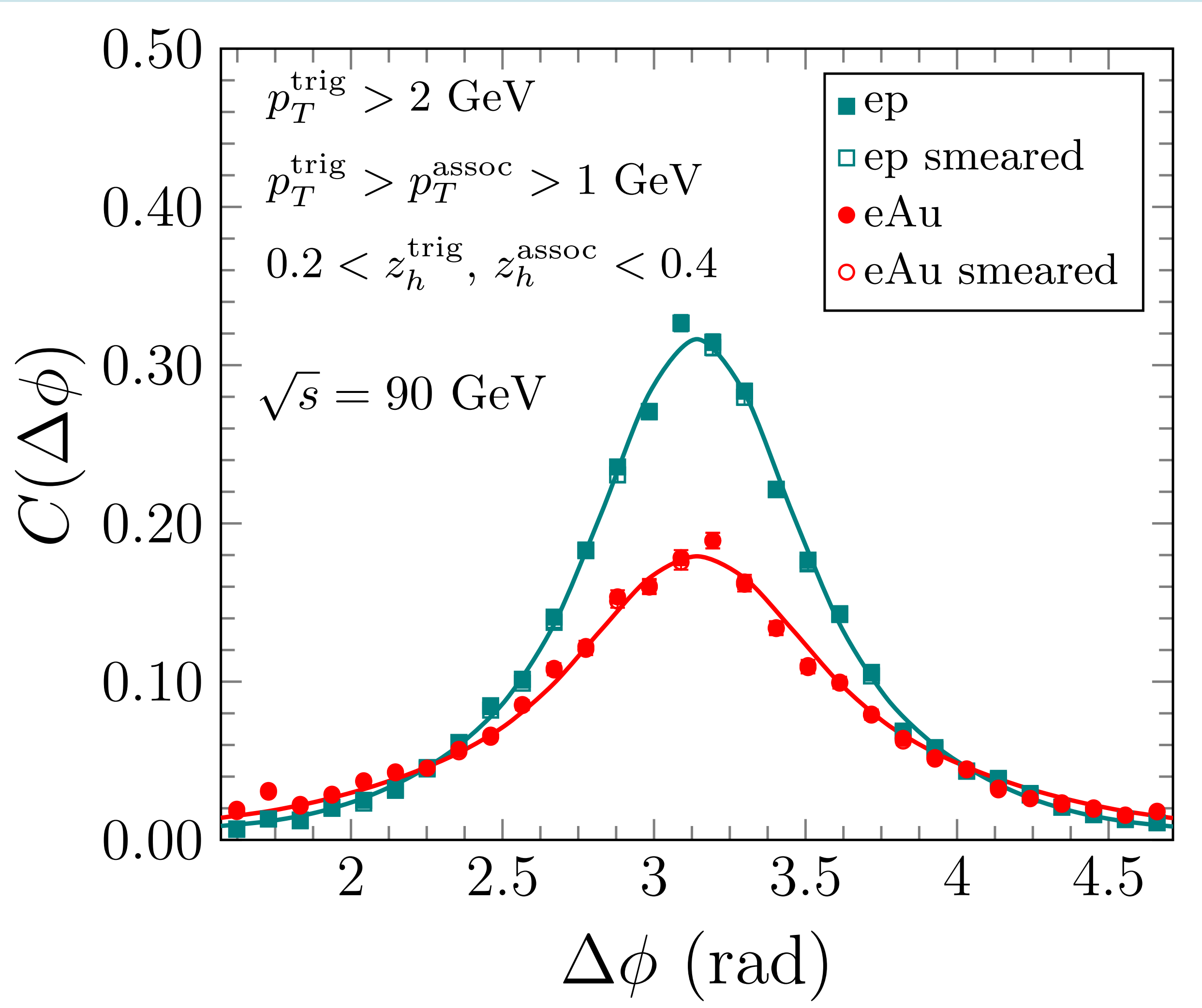
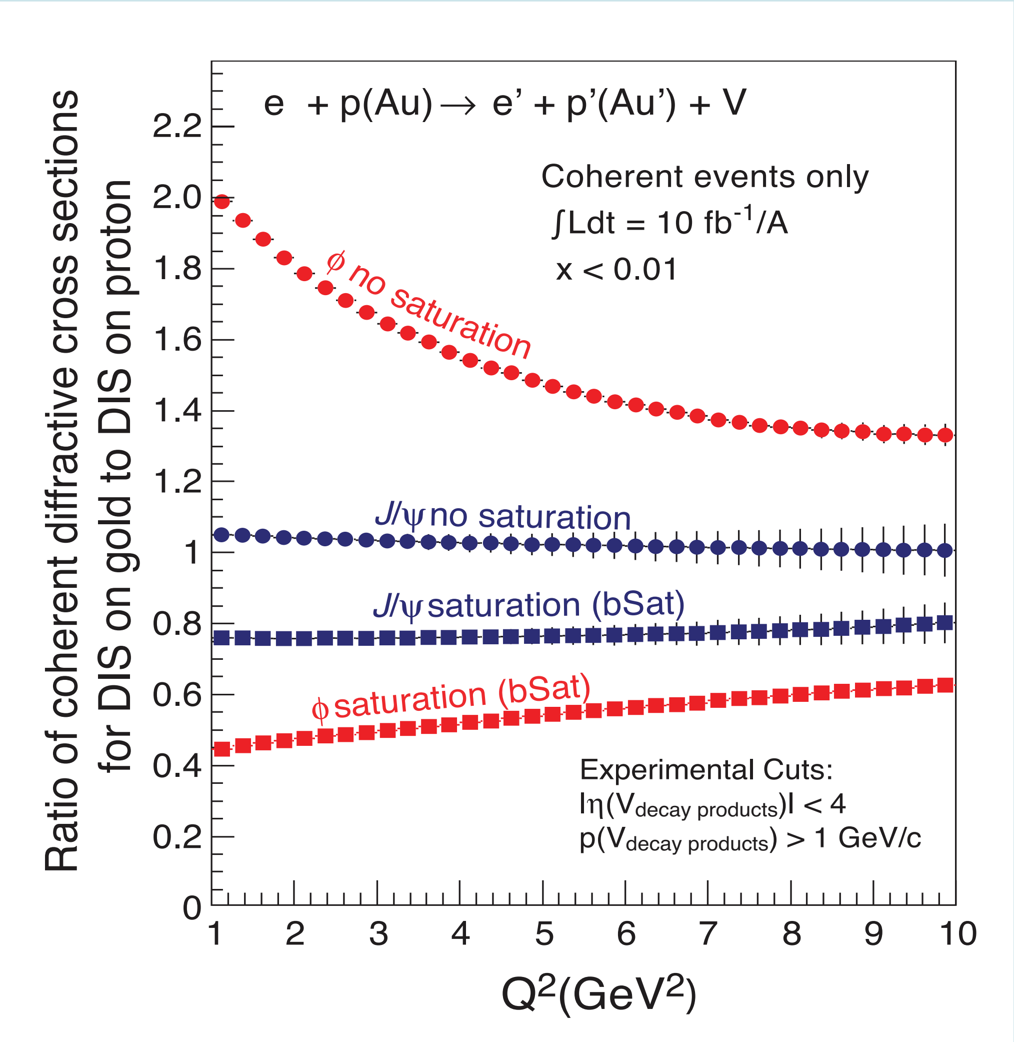
  - EIC covers a wide range of kinematic areas, across the region emerging the gluonic matter
  - No smoking gun! Global analysis combining multiple measurements is necessary





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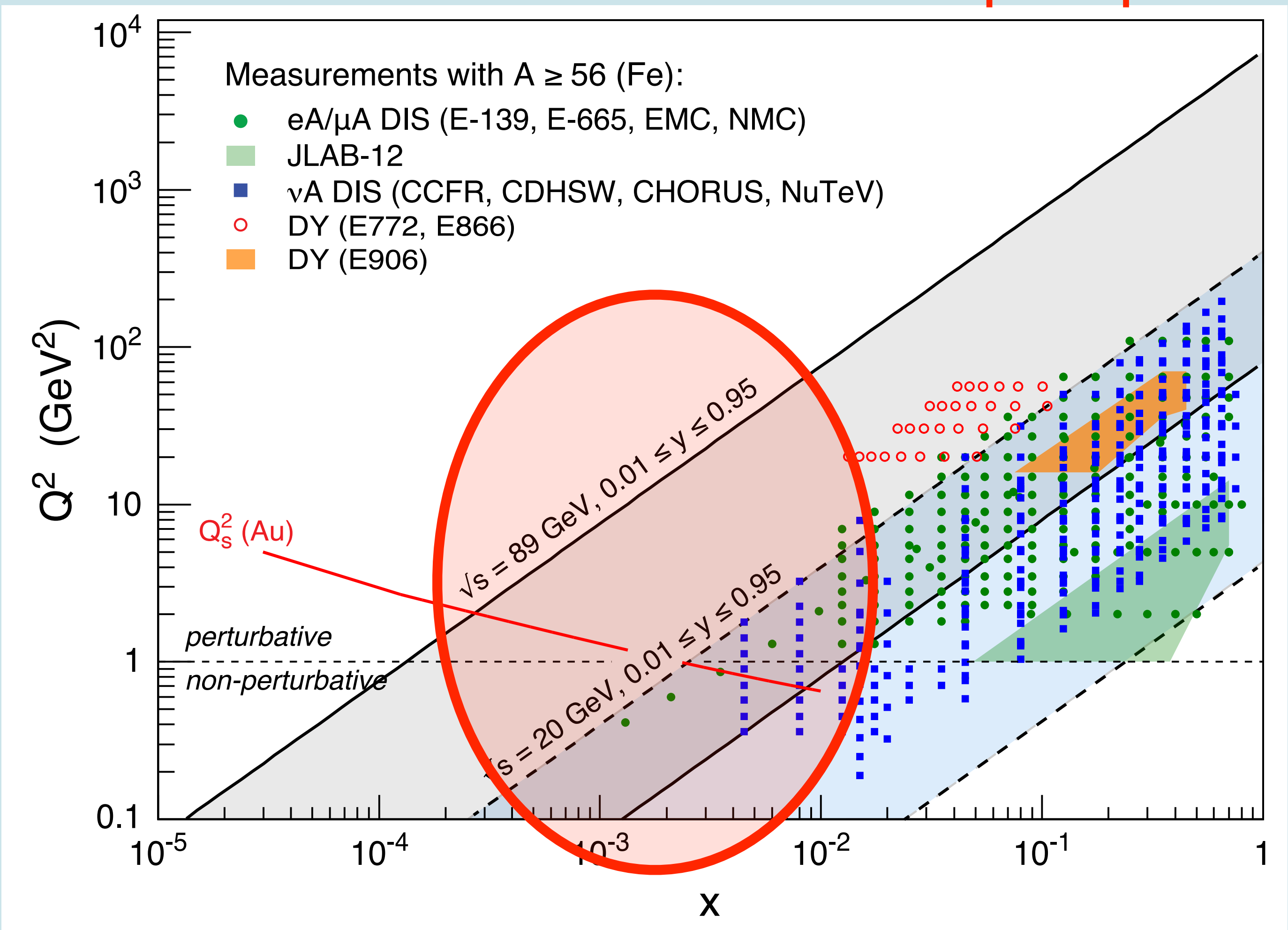
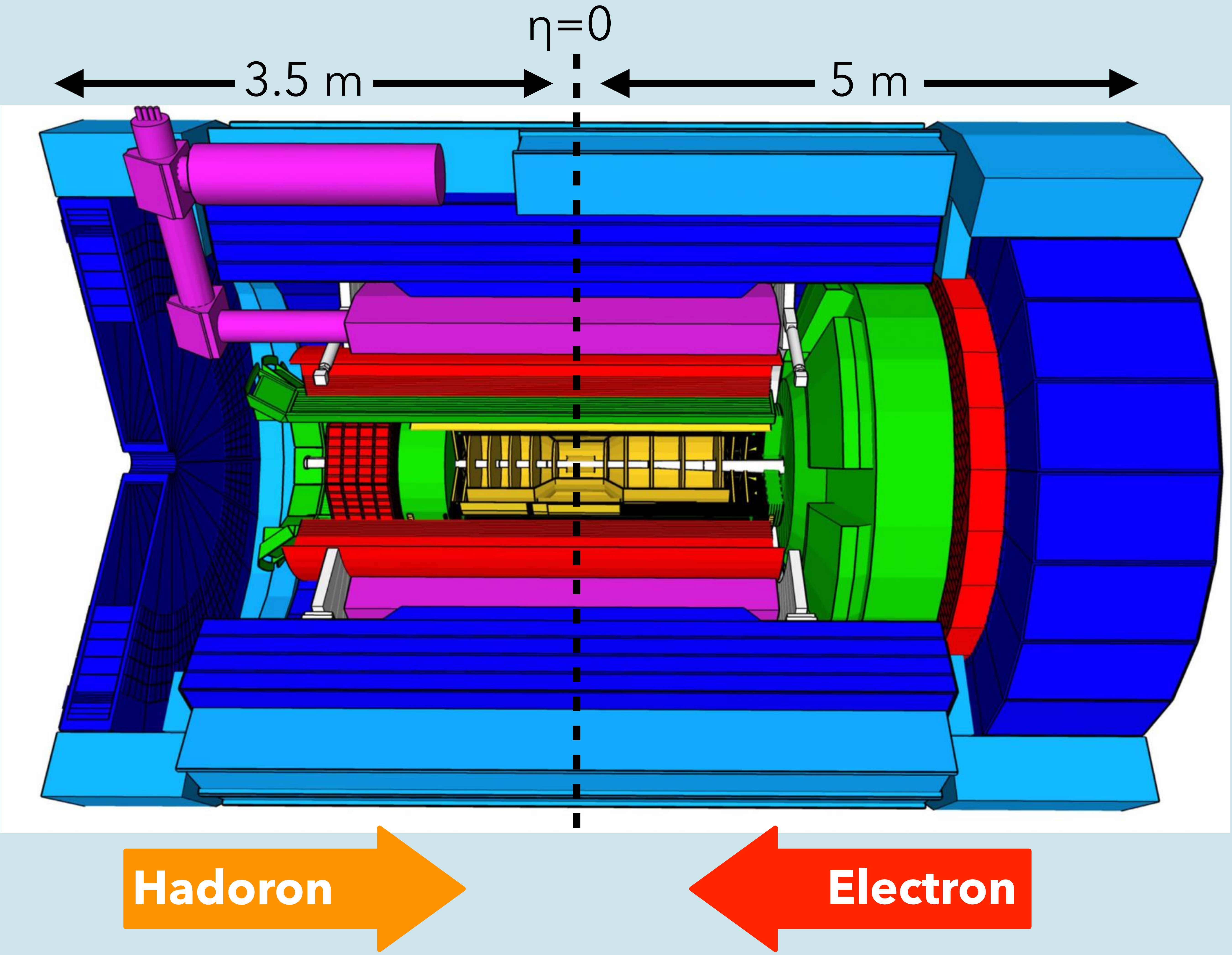


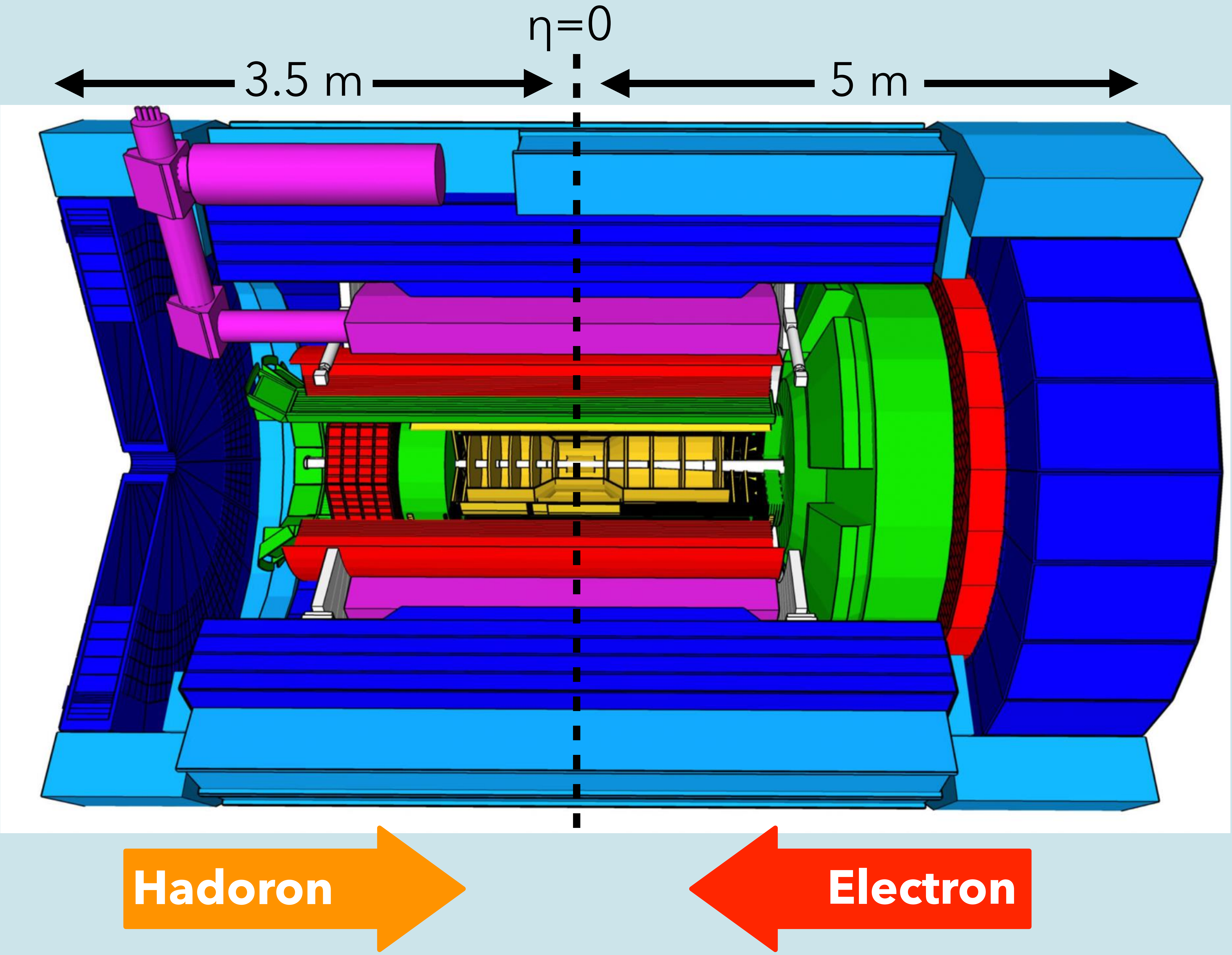
Experiment

The ePIC detector at EIC



The ePIC detector at EIC

- **Magnet**
  - New 1.7 T SC solenoid, 2.8 m bore diameter
- **Tracking**
  - Si Vertec Tracker MAPS wafer-level stiched sensor (ALICE ITS3)
  - Si Tracker MAPS barrel and disks
  - MPGDs (μRWELL, MMG) cylindrical and planr
- **Particle Identification**
  - high-performance DIRC
  - dual RICH (aerogel + gas) (forward)
  - proximity focusing RICH (backward)
  - AC-LGAD TOF (barrel + forward)
- **EM Calorimetry**
  - Imaging EMCal (Barrel)
  - W-powder/SciFi (Forward)
  - PbWO4 crystal (backward)
- **Hadron Calorimetry**
  - FeSc (Barrel, reused from sPHENIX)
  - Steel/Scint - W/Scint (backward/forward)



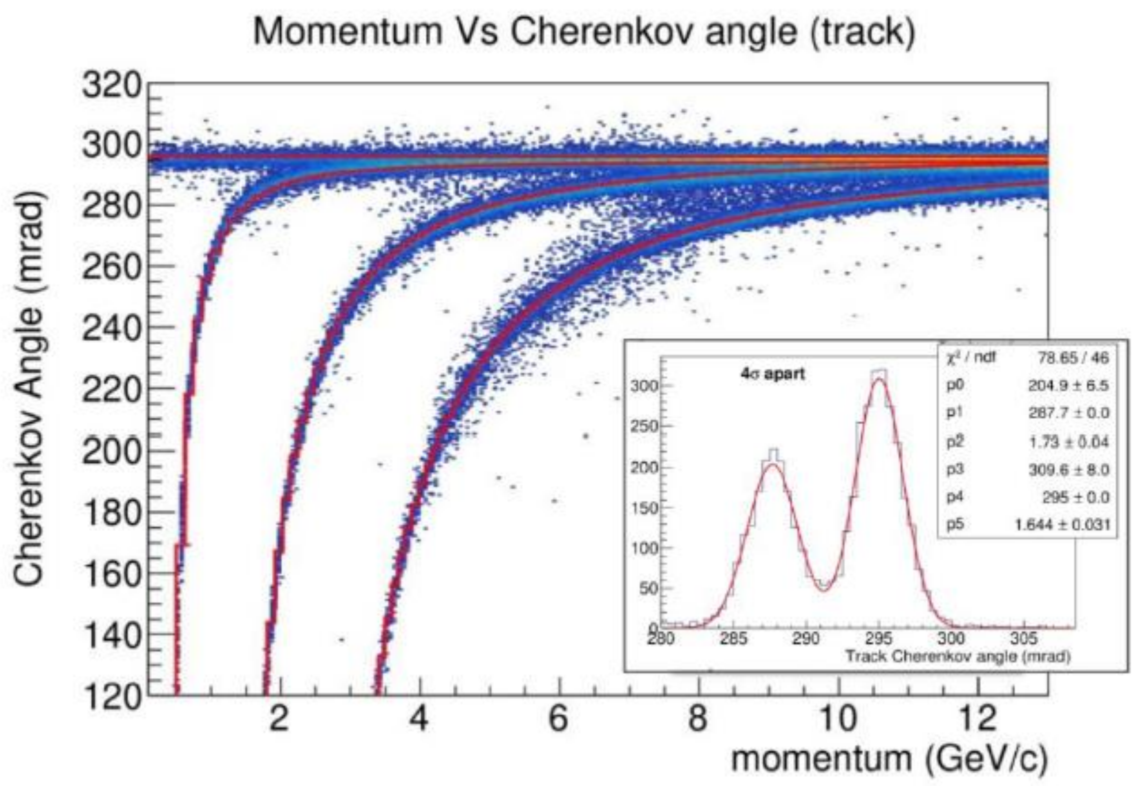
The ePIC detector at EIC

- **Magnet**

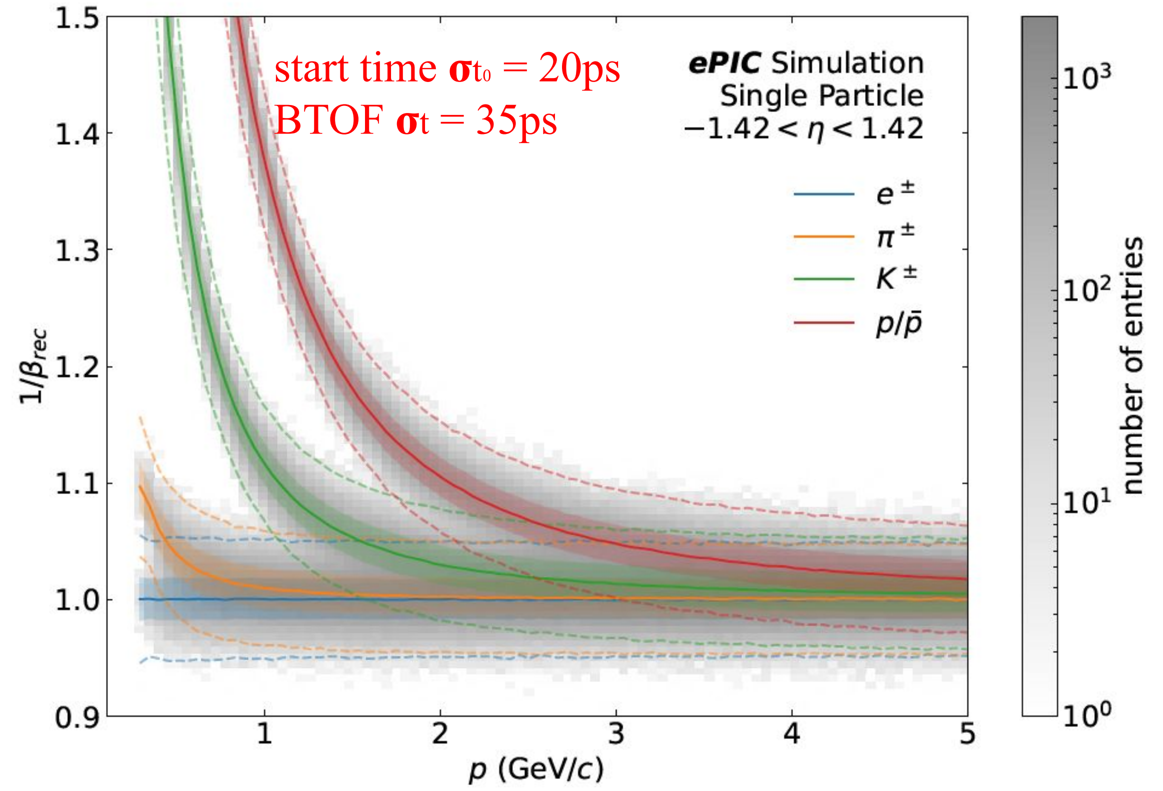
η=0

← 3.5 m → ← 5 m →

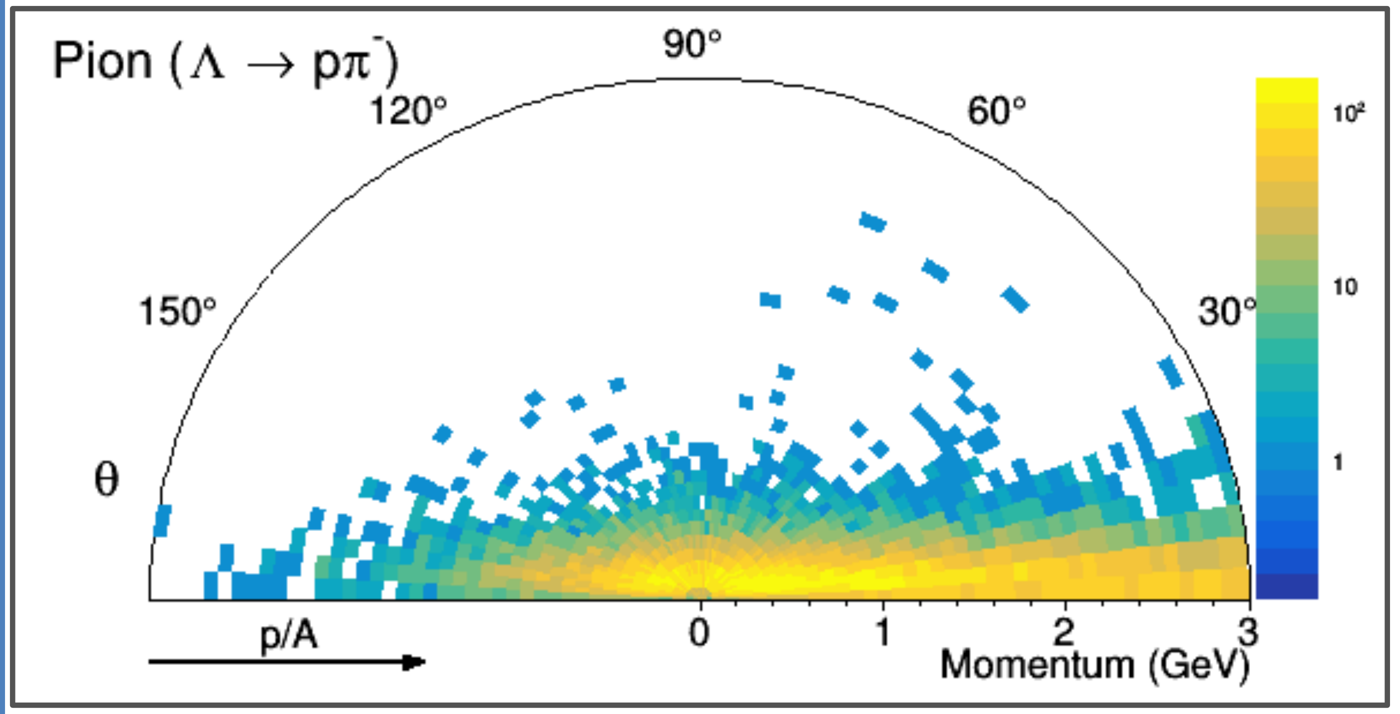
pfRICH performance



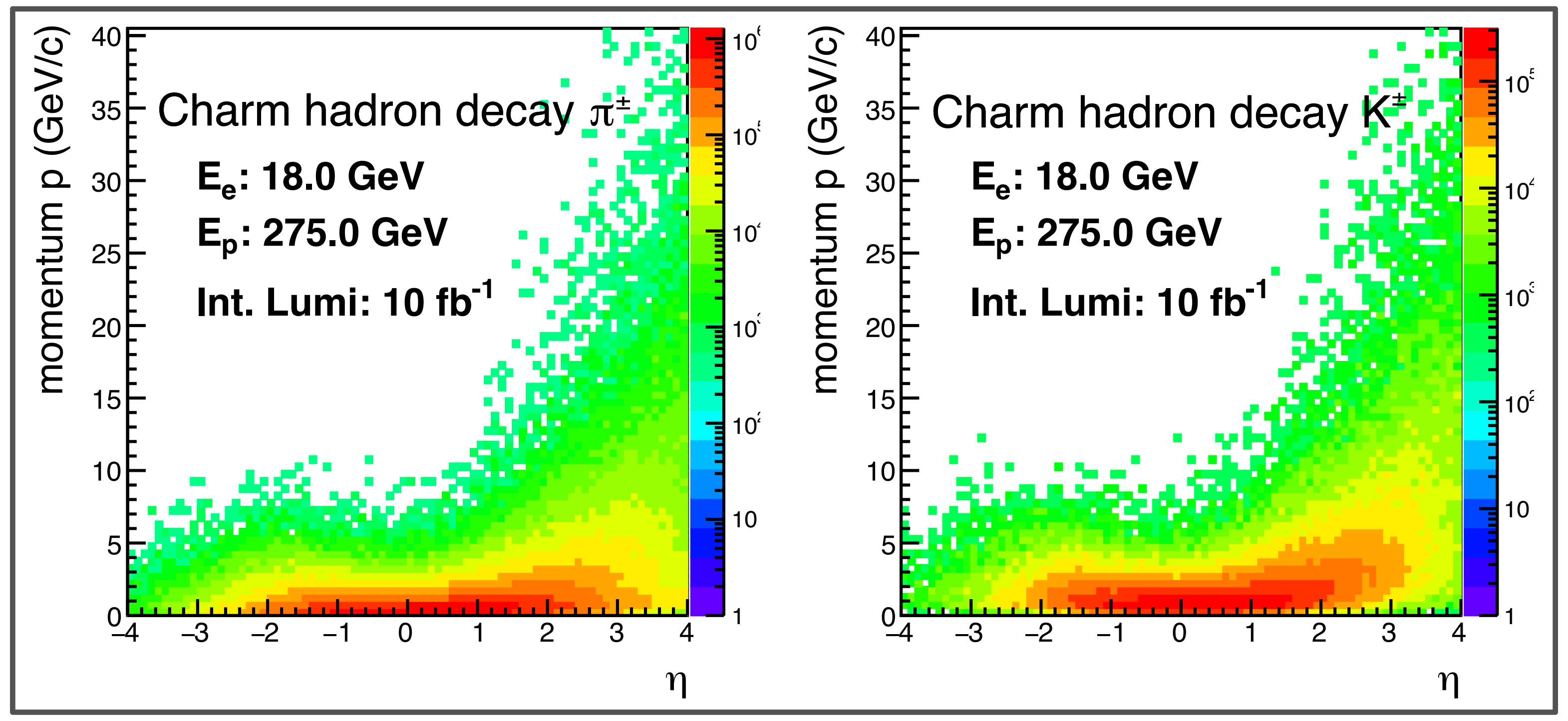
Barrel TOF performance

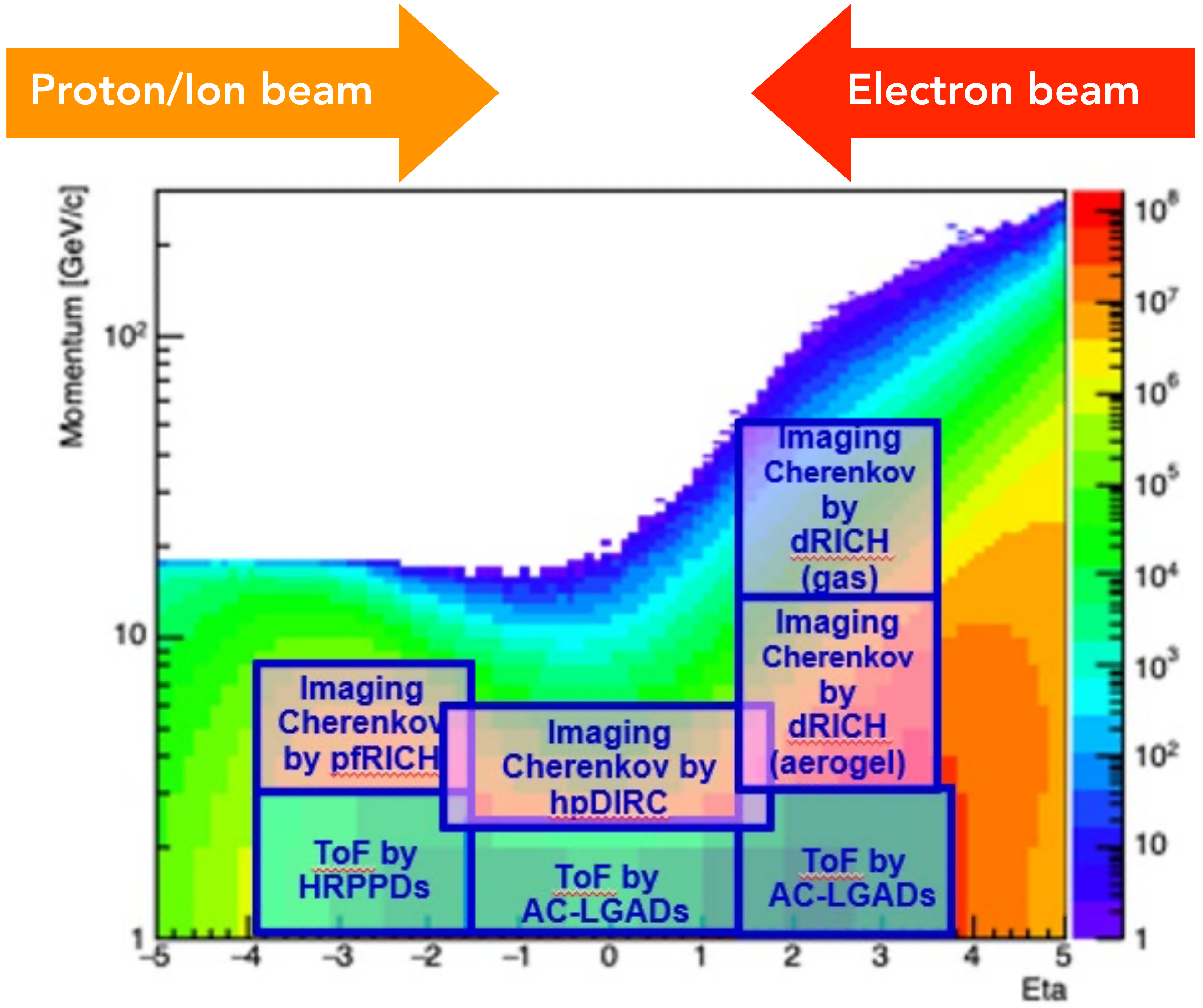


Hyperon decay hadron kinematics



Charm decay hadron kinematics

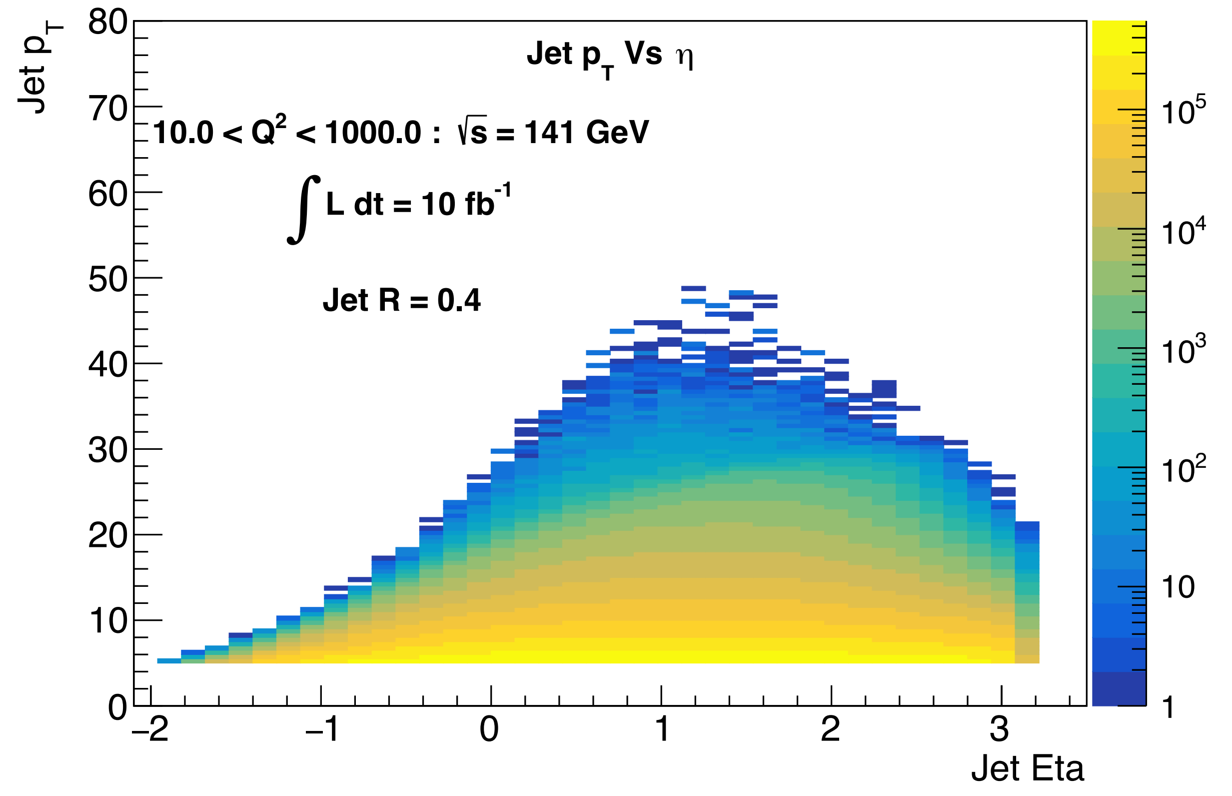




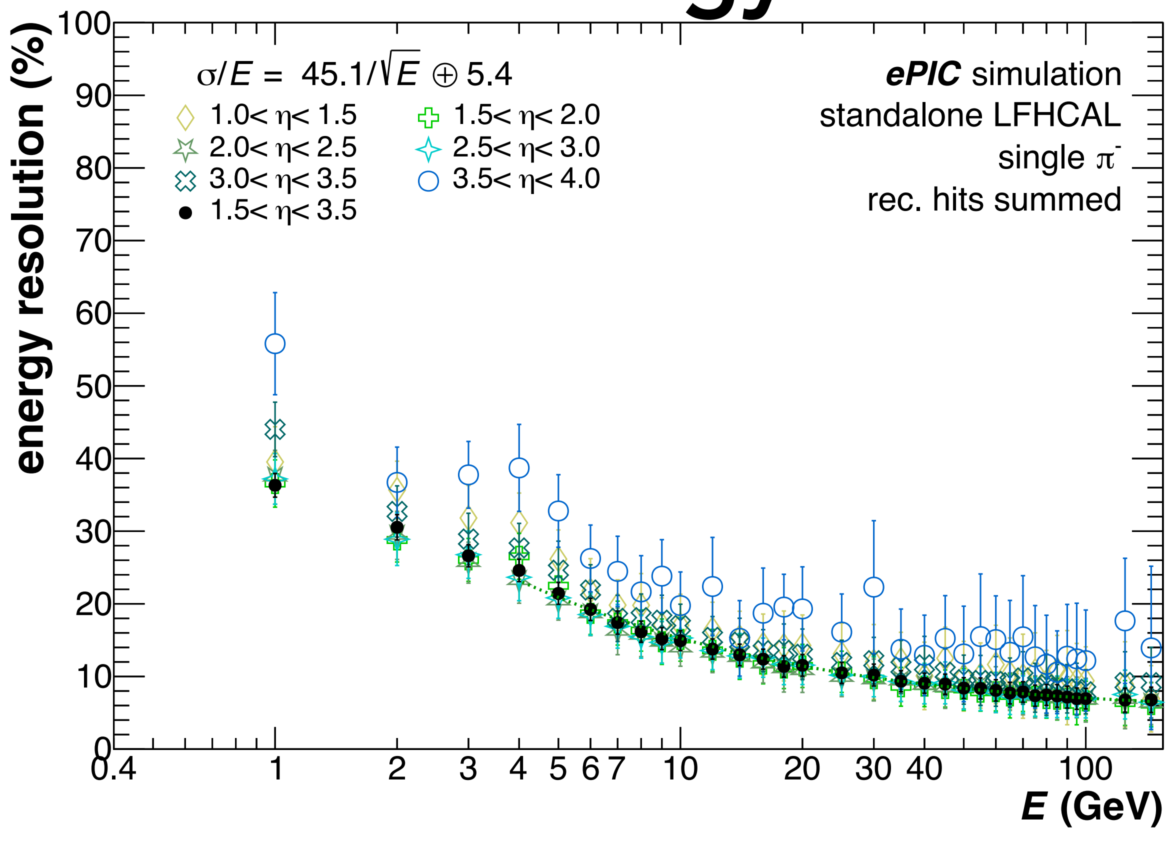
– Steel/Scint - W/Scint (backward/forward)

The ePIC detector at EIC

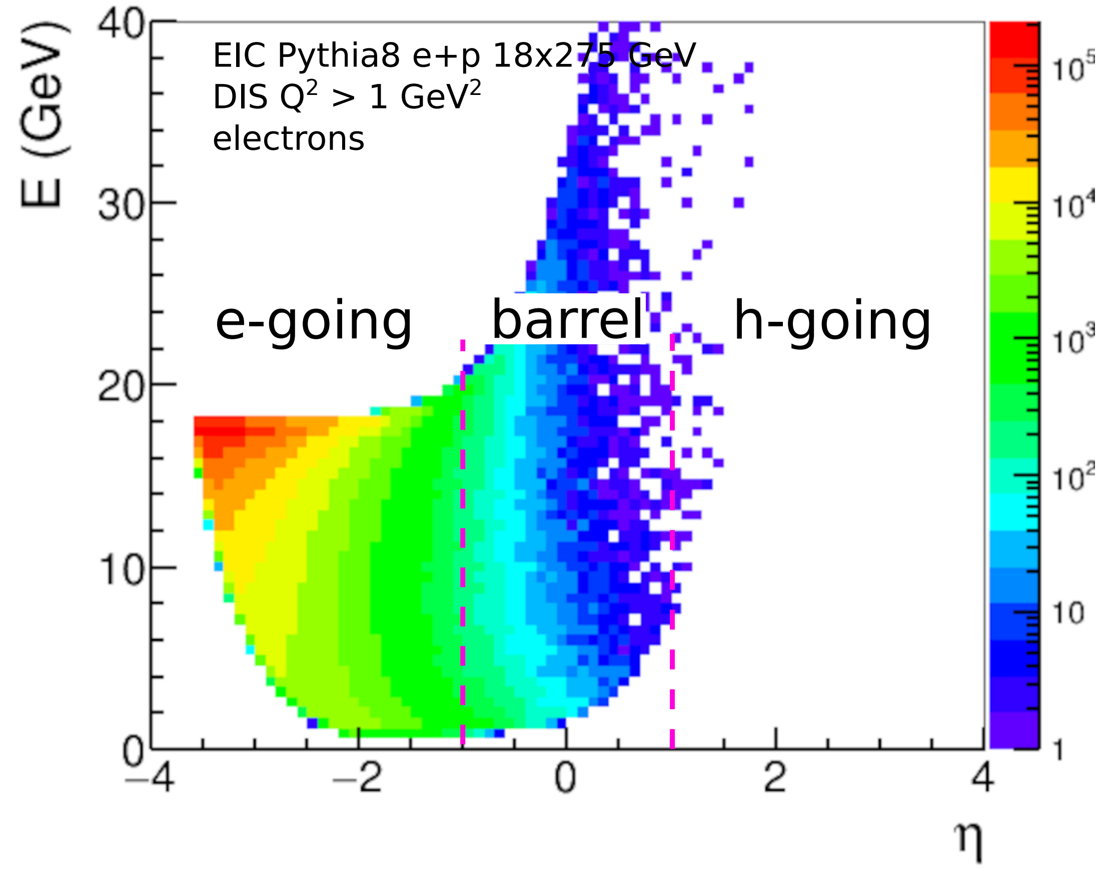
Jet kinematics



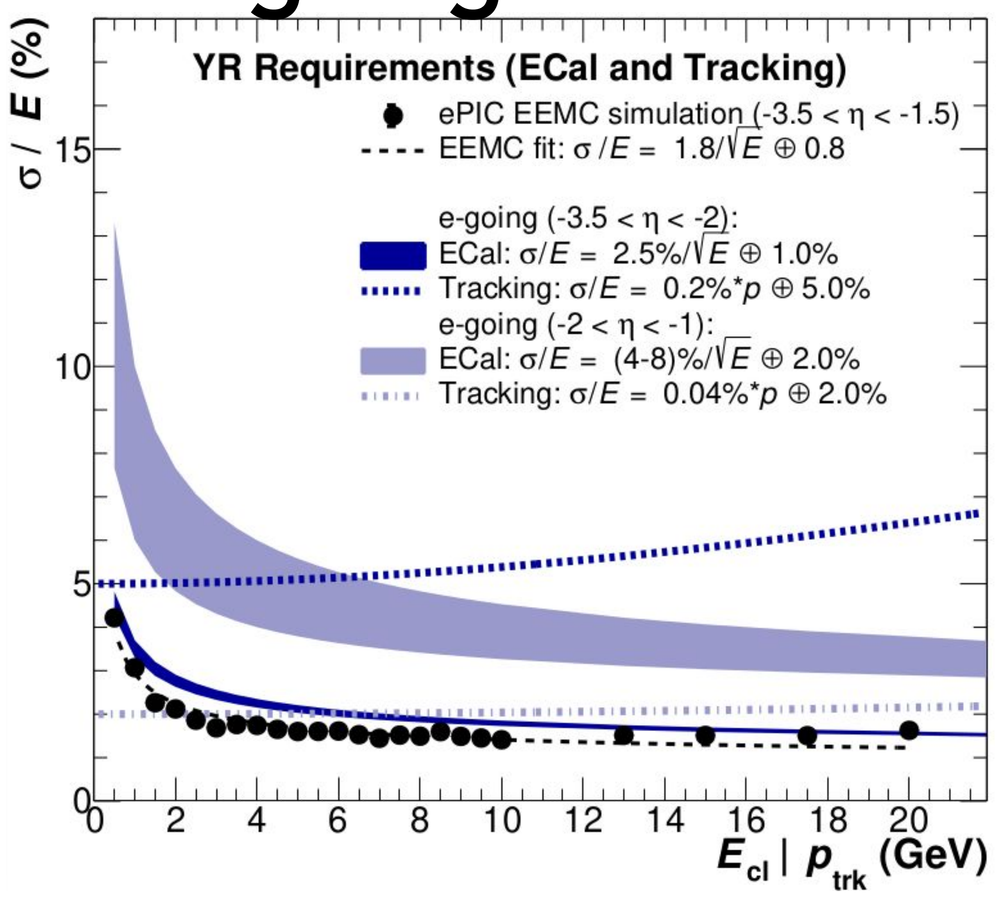
LFHCal energy reso.



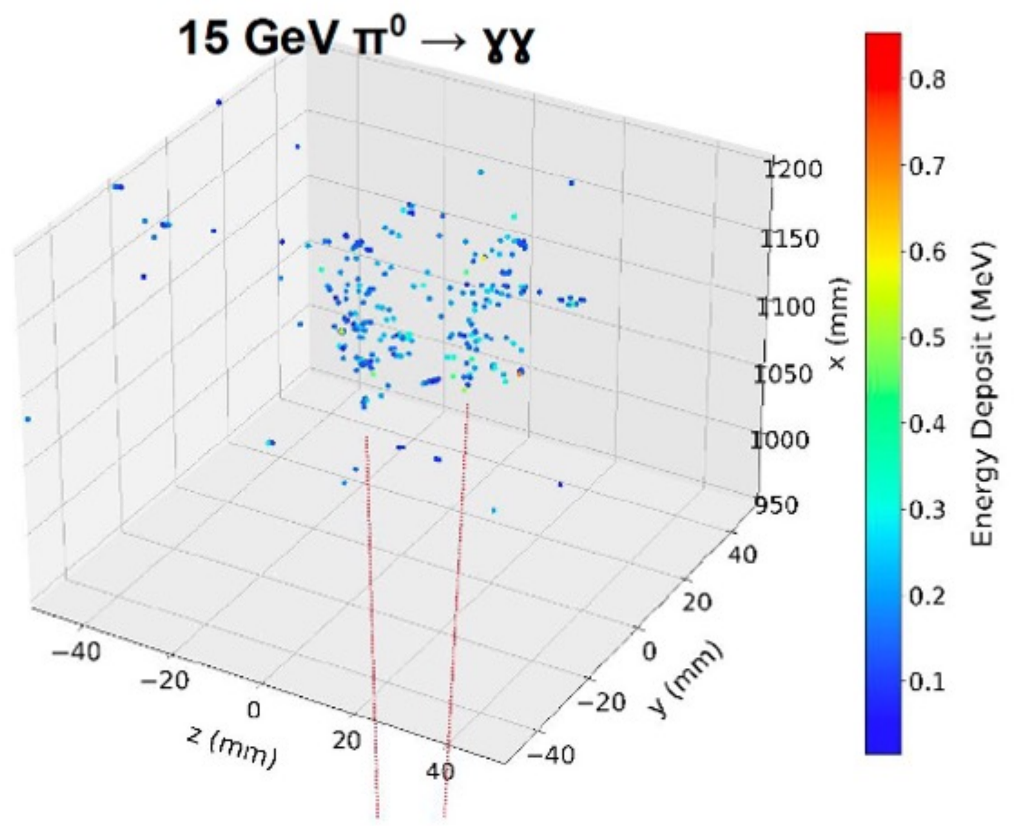
Scattered electron



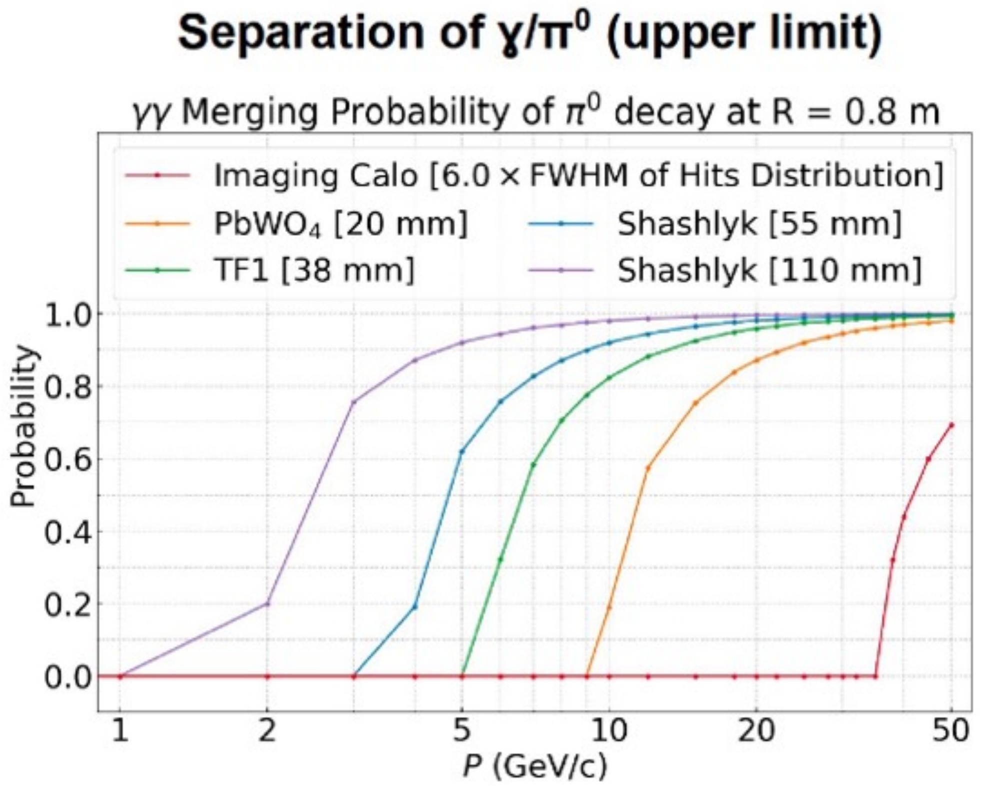
e-going E reso.



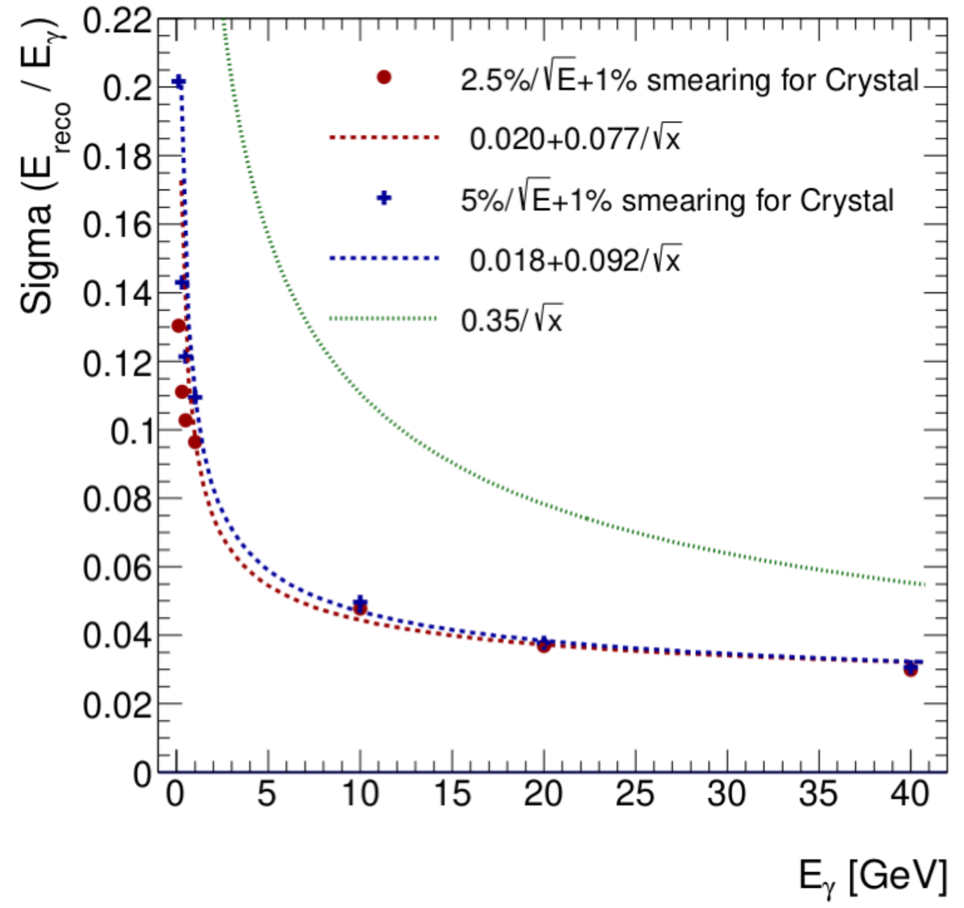
Shower imaging



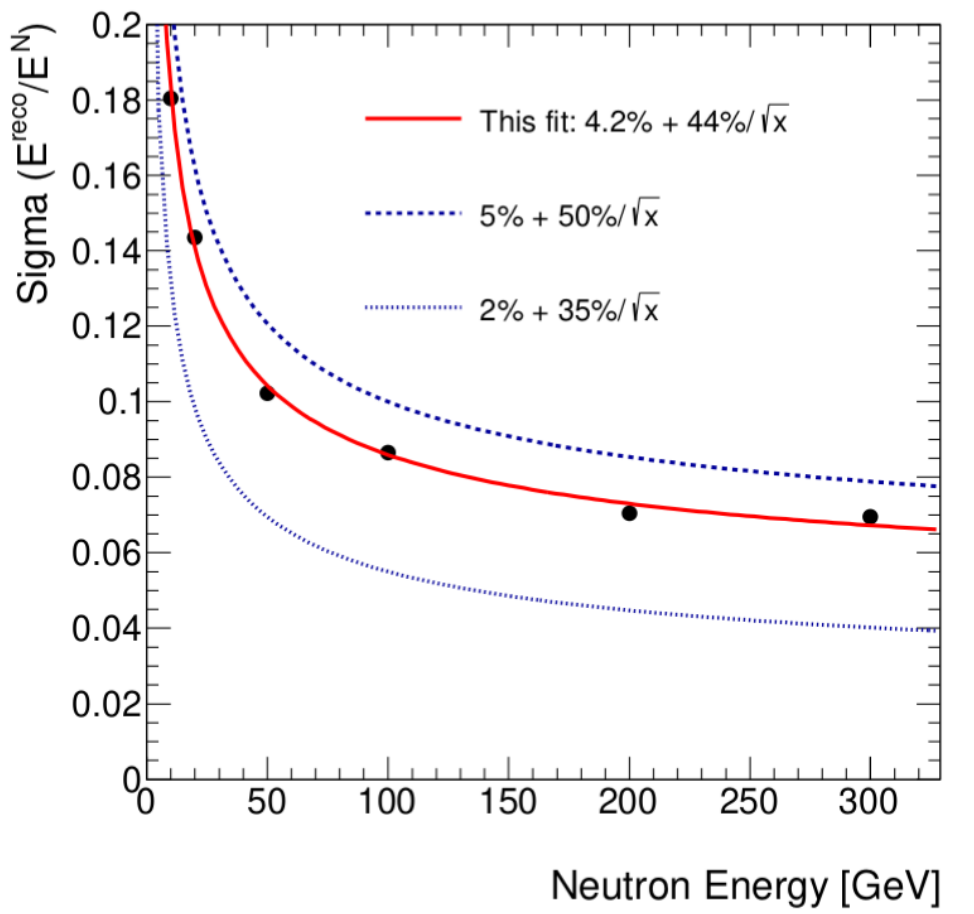
Cluster merging prob.



ZDC EMCal reso.

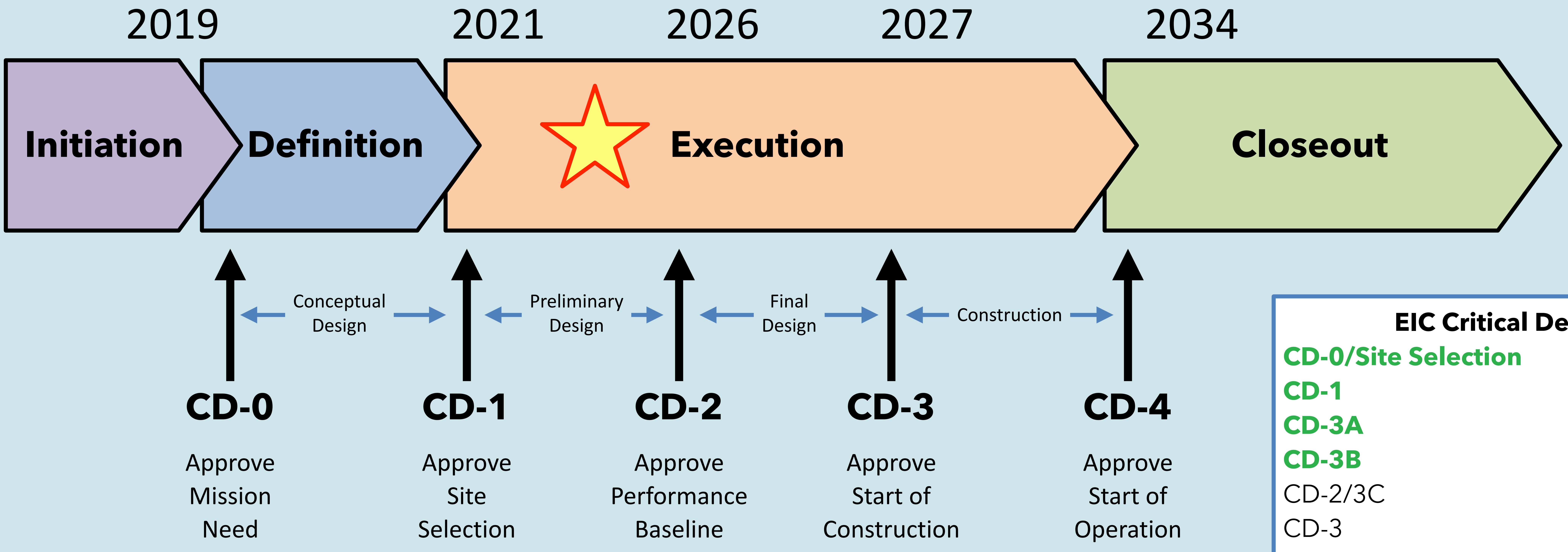


ZDC HCal reso.



ePIC and EIC schedule (best guess)

EIC Critical Decisions Status and Plans



EIC Critical Decision Plan	
CD-0/Site Selection	**December 2019**
CD-1	**June 2021**
CD-3A	**March 2024**
CD-3B	**January 2025**
CD-2/3C	Q2 FY26
CD-3	Q2 FY27
Early CD-4	Q1 FY34
CD-4	Q4 FY35

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  - EIC advances the understanding of QCD by precision measurement
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Despite different methods, both are evolving toward the same goal of further understanding QCD

Backup slides

Electron-Ion Collider

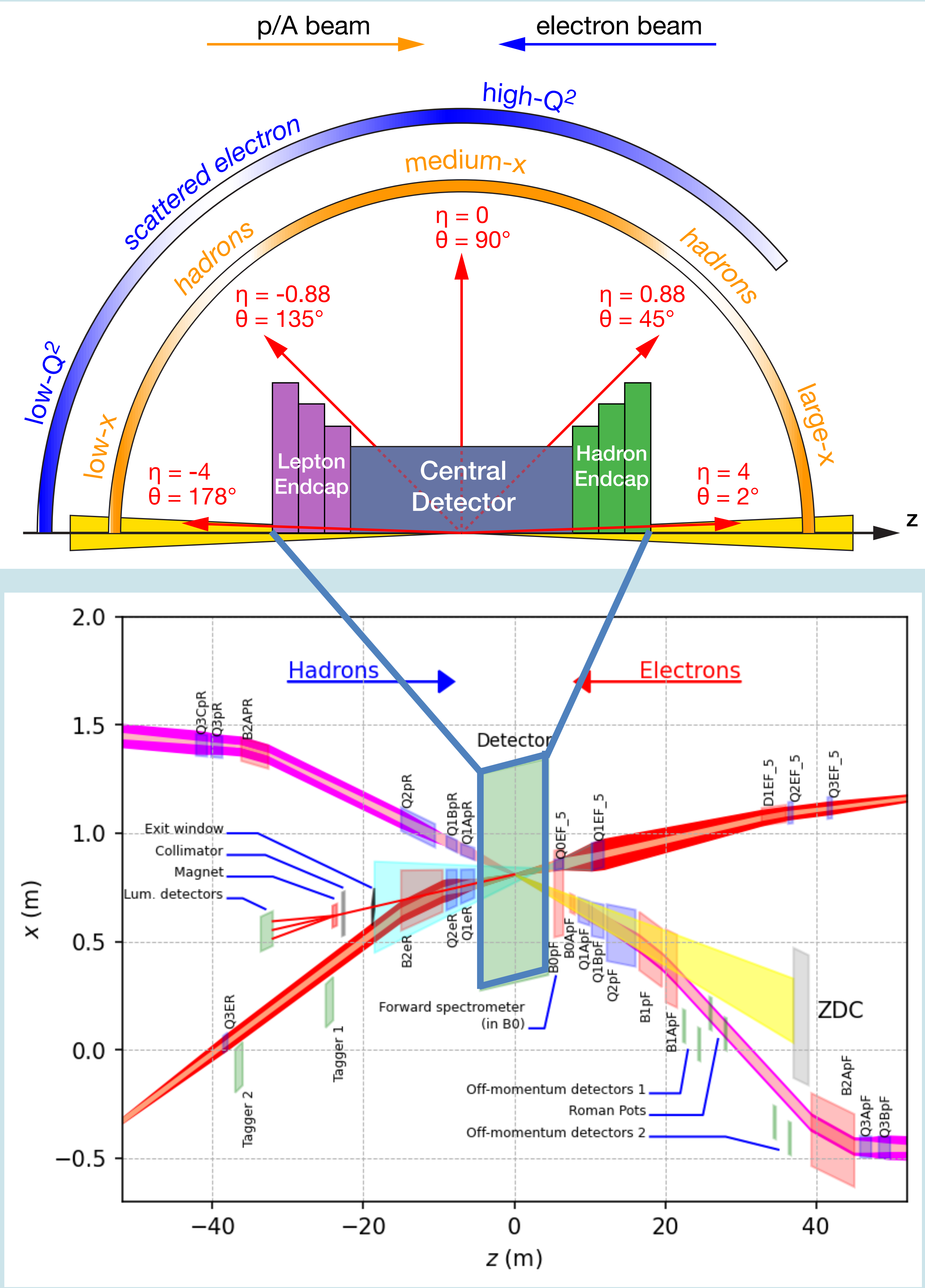
- Electron-Ion Collider (EIC) is the next-generation epoch-making accelerator to explore the quark-gluon structure of matter to be built at BNL
  - Recommended as the highest priority for facility construction by the Nuclear Science Advisory Committee

- The main goal is to gain further understanding of Quantum Chromodynamics (QCD), especially new insights into gluon dynamics
  - Variable collision energies & wide acceptance detector to cover wide kinematic range (x, Q^2)
  - High luminosity to enhance rare probe statistics (heavy flavor hadrons have sensitivity to gluons)

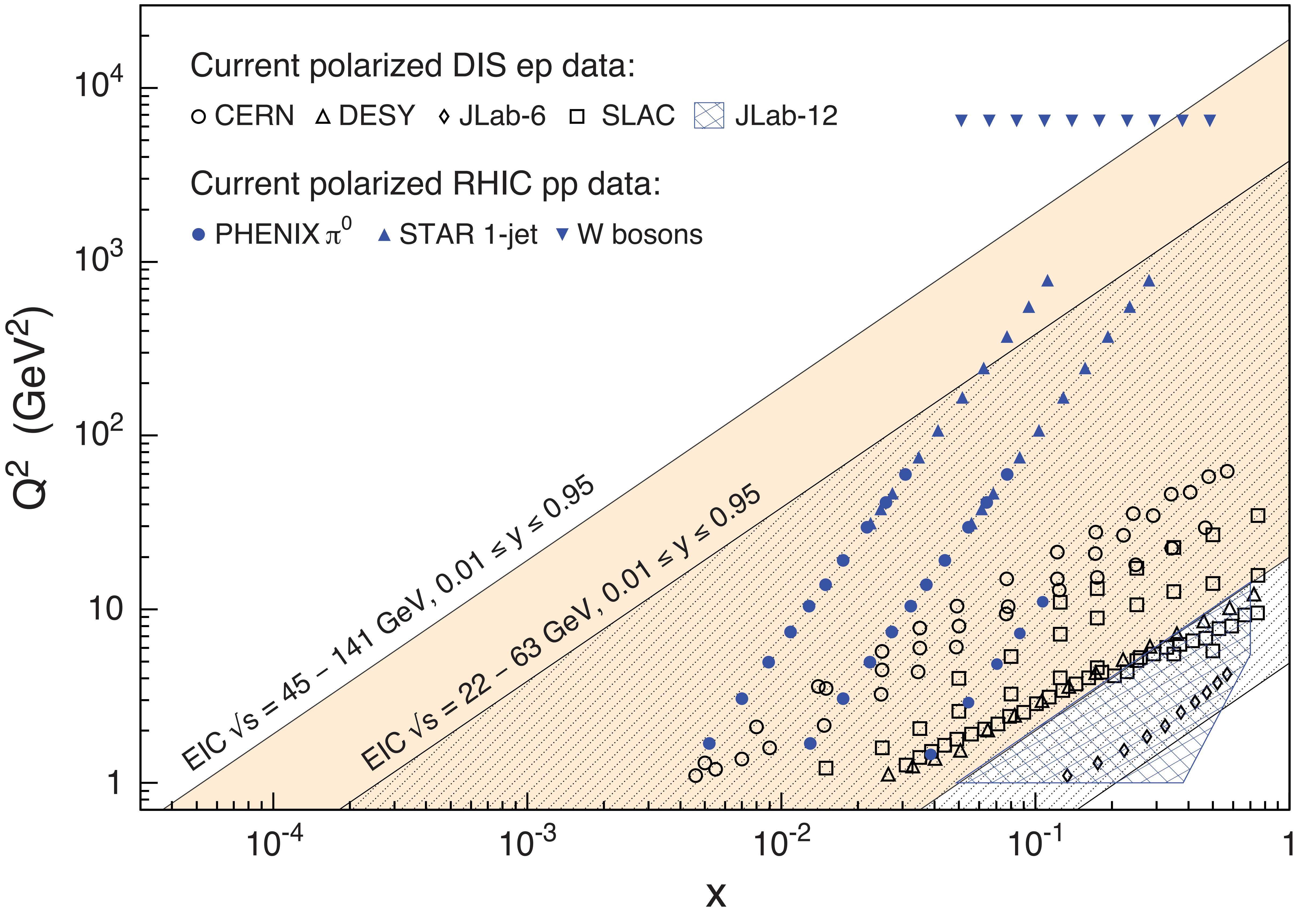
- EIC provides complementary information to Heavy Ion Collision (HIC)
  - The strength of Deep Inelastic Scatterings (DIS) lies in their precision!

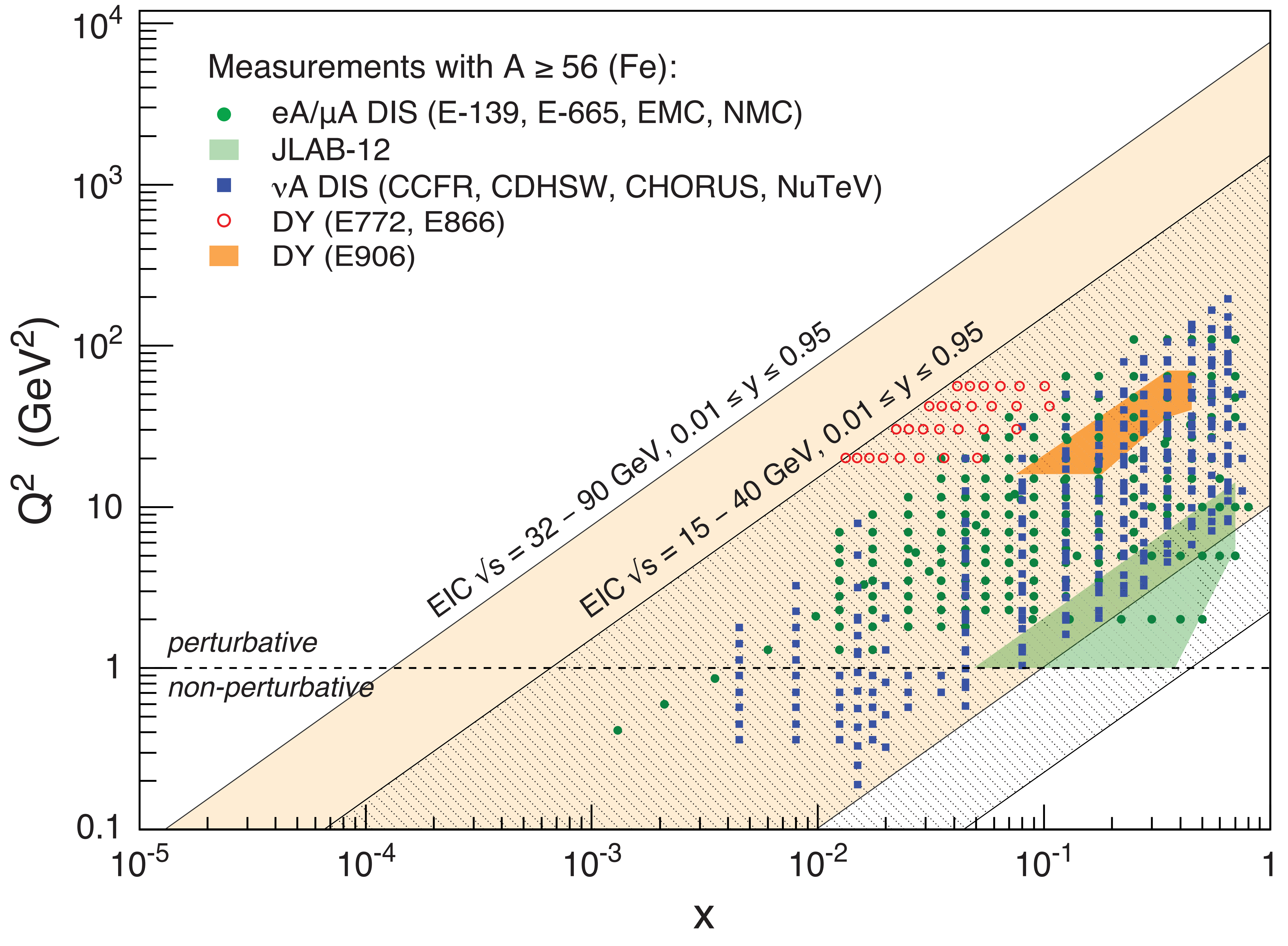
Observable and Detector Requirements

- The detector must be encapsulated to detect all particles
  - Barrel, forward, and far-forward regions are covered by tracking, PID, calorimetry
  - Detection of the scattered (undestroyed) proton is crucial for the EIC
- Scattered electron identification and an excellent energy resolution system must be installed
  - Tracking + EM Calorimetry
- Heavy flavor hadron tagging detectors are essential for measuring gluon-participated events
  - Vertex + Tracking + Particle identification
  - The HERA experiments didn't have PID detectors



The range in x v.s. Q^2 accesible with EIC





Energy-Momentum Tensor (EMT)

- Energy-Momentum Tensor (EMT) contains several kinematic information

$$T^{\mu\nu} = \underbrace{i\bar{\psi}\gamma^{(\mu}D^{\nu)}\psi}_{\text{Quark}} + \underbrace{\frac{\eta^{\mu\nu}}{4}F^2 - F^{\mu\lambda}F^{\nu}_{\lambda}}_{\text{Gluon}}$$

- Mass is encoded in QCD EMT

$$M = \frac{\langle P | \int d^3x T^{00}(x) | P \rangle}{\langle P | P \rangle} = E_q + E_g + \chi_{m_q} + T_a$$

- EMT contains the distribution of mass, orbital angular momentum and pressure

$$T^{\mu\nu} = \begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

Energy density

Momentum density

Energy flux

Momentum flux

Shear stress

Normal stress

$$T^{\mu\nu} = \overbrace{T^{\mu\nu}_q}^{\text{Quark}} + \overbrace{T^{\mu\nu}_g}^{\text{Gluon}}$$

Total EMT satisfies the conservation low

$$\partial^\mu T_{\mu\nu} = 0$$

Trace Anomaly in QCD

- The scale invariance is broken at the quantum level in QCD
  - In a nutshell, the scale invariance broken is induced by the non-zero vacuum energy

$$\langle P | T^{\mu}_{\mu} | P \rangle = 2M^2$$

- The trace can be decomposed into quark and gluon term
  - Gluon term and quark term come from gluon condensate and quark condensate

Quark condensate **Gluon condensate**

$$T^{\mu}_{\mu} = m\bar{\psi}\psi + m\gamma_m\bar{\psi}\psi + \frac{\beta(g)}{2g}F^{\mu\nu}F_{\mu\nu}$$

$T^{\mu}_{q\mu}$ $T^{\mu}_{g\mu}$

$$M = E_q + E_g + \chi_{m_q} + T_a$$

- The total trace anomaly is the renormalization scheme/scale invariant
  - Each component is the renormalization scheme/scale dependent (Y. Hatta, A. Rajan and K. Tanaka, JHEP 12, 008 (2018))
  - This decomposition implies that in the chiral limit entire hadron mass from gluons!

Gravitational Form Factor (GFF)

- Gravitational Form Factors (GFFs) are encoded into EMT
- EMT of spin-1/2 particle can be decomposed into several tensors (tensor decomposition) with variables $P = (p' + p)/2, \quad \Delta = (p' - p)/2, \quad t = \Delta^2$

$$\langle N(p') | T^{\mu\nu} | N(p) \rangle = \bar{u}(p') \left[A_a(t) \frac{P_\mu P_\nu}{m} + J_a(t) \frac{iP_{(\mu}\sigma_{\nu)\rho}\Delta^\rho}{2m} + D_a(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu}\Delta^2}{4m} + m\bar{C}_a(t) g_{\mu\nu} \right] u(p')$$

Sov. Phys. JETP 16, 1343 (1963)

- The factors, $A(t)$, $J(t)$, $D(t)$ and $\bar{C}(t)$, are called the GFFs similar to F_1 and F_2 in the EM form factor
- Each factor has meaning as a physics variable

  $A(t)$: Momentum fraction
  $J(t)$: Ji sum rule (spin)
  } **Twist-2**

  $D(t)$: Pressure
  $\bar{C}(t)$: Trace anomaly
  } **Twist-4**

Twist-N term is suppressed by $1/Q^{N-2}$

$$\sigma(Q) \sim \sigma_0(\ln Q) + \left(\frac{\Lambda_{QCD}}{Q}\right) \sigma_1(\ln Q) + \left(\frac{\Lambda_{QCD}}{Q}\right)^2 \sigma_2(\ln Q) + \cdots$$

Twist-2 ($\sigma_0(\ln Q)$) **Twist-4** ($\left(\frac{\Lambda_{QCD}}{Q}\right)^2 \sigma_2(\ln Q)$)

How to Access the Trace Anomaly Term $\bar{C}(t)$?

- The gamma exchange between electron and proton is used to extract FFs, F1 and F2
- Interaction via graviton between electron and proton should be used to measure EMT
  - The strength of the interaction is 10^{-37} times weaker than the EM interaction
- Mimic the gravitational interaction by gamma or gluon interactions
  - Mathematically 2 gluons or 2 gammas exchange in a process can access EMT   Phys.Rev.D55:7114-7125,1997