Image credit: Jefferson Lab

Physics opportunities with the Electron Ion Collider

Olga Evdokimov (University of Illinois at Chicago)

Outline: the road to the EIC

EIC Foundations

- Science case developments
- EIC specifications

Overview of the EIC Physics Opportunities

- “Pillar” measurements
- Synergies/impact for other fields

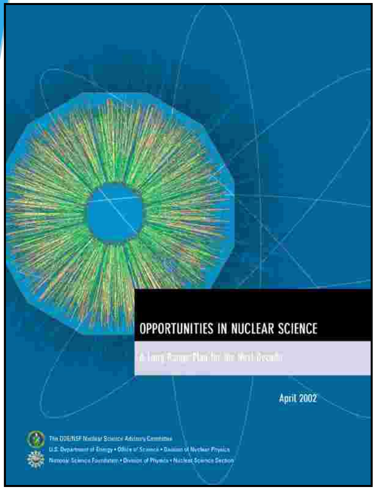
The Road to the EIC realization

- EIC timeline
- EIC Detector(s)

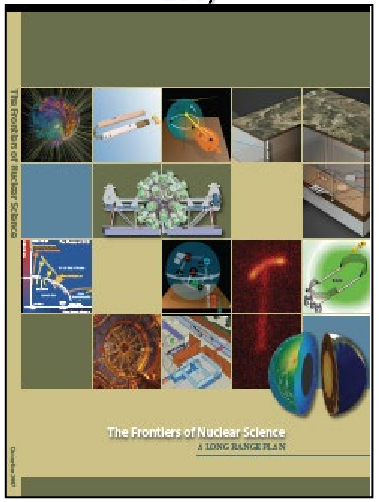
Scientific Case for the Electron-Ion Collider

- EIC: long time in the making and planning
- EIC potential and prospects are discussed in the US Long Rage Planning from 2002
- EIC is a key element of the Long-Range Plan in 2015

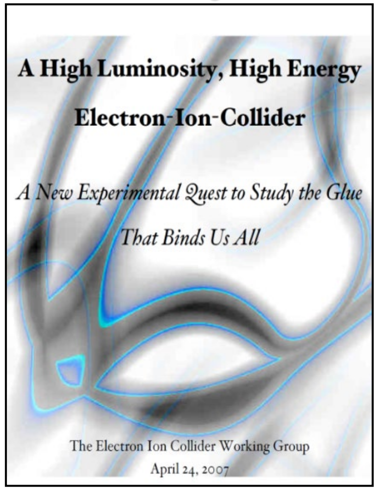
2002



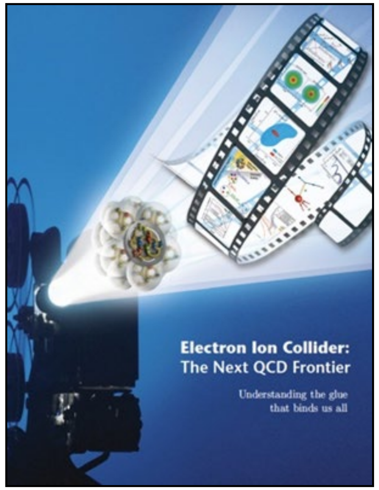
2007



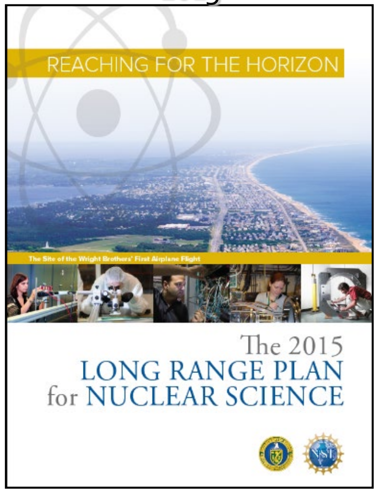
2009



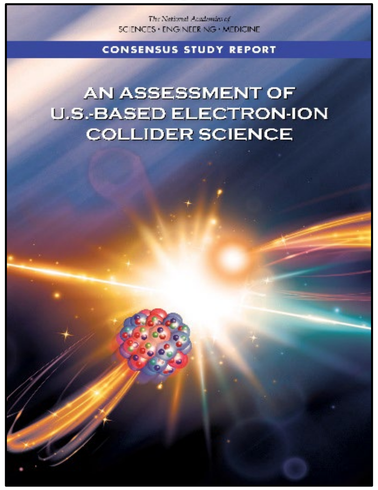
2012



2015



2018



- NAS assessment: *"The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely."*

EIC Physics Pillars

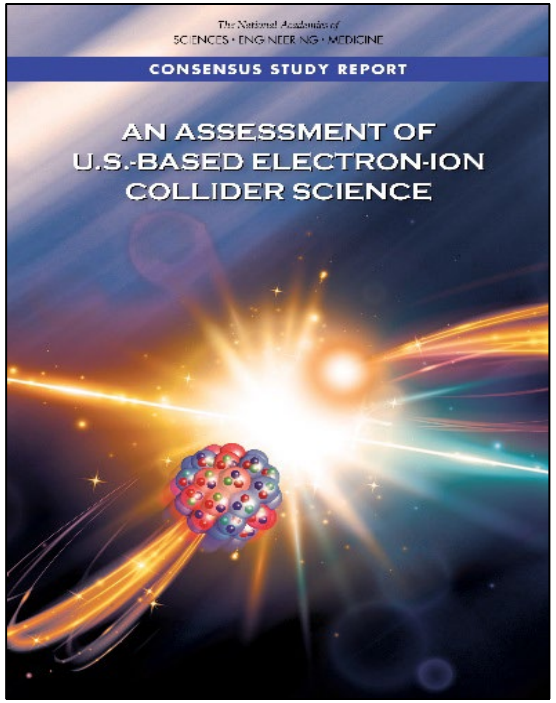
- 2018 National Academy of Science Report: An Assessment of US-based Electron-Ion Collider Science

“EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems of gluons?”

https://www.nap.edu/catalog/25171/an-assessment-of-us-based-electron-ion-collider-science

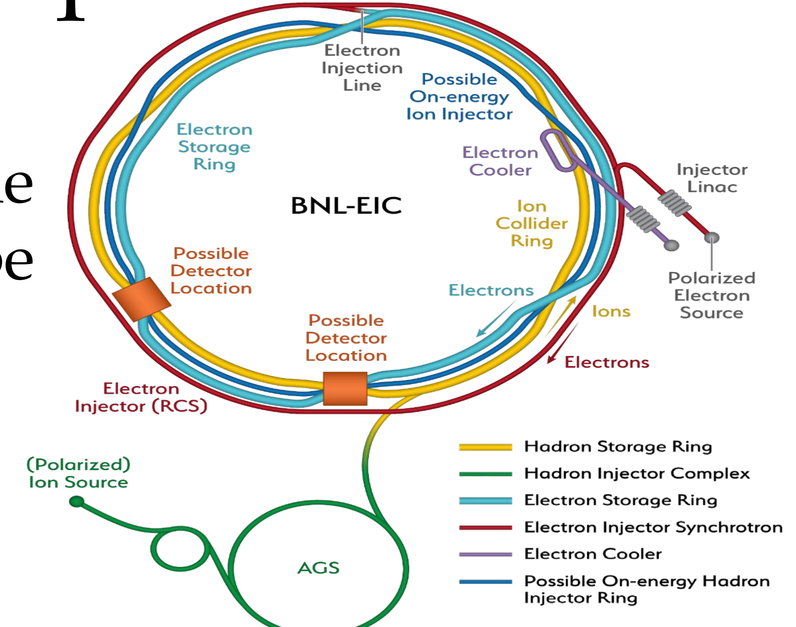
2018

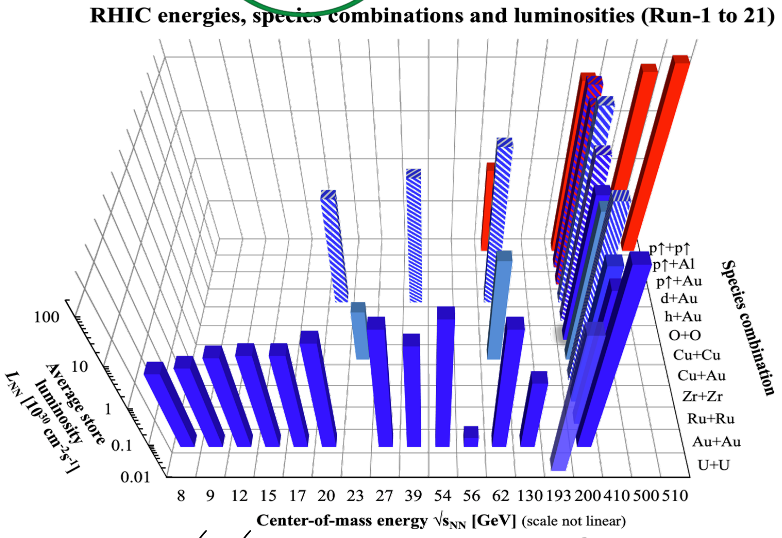


EIC Machine Design and Requirements

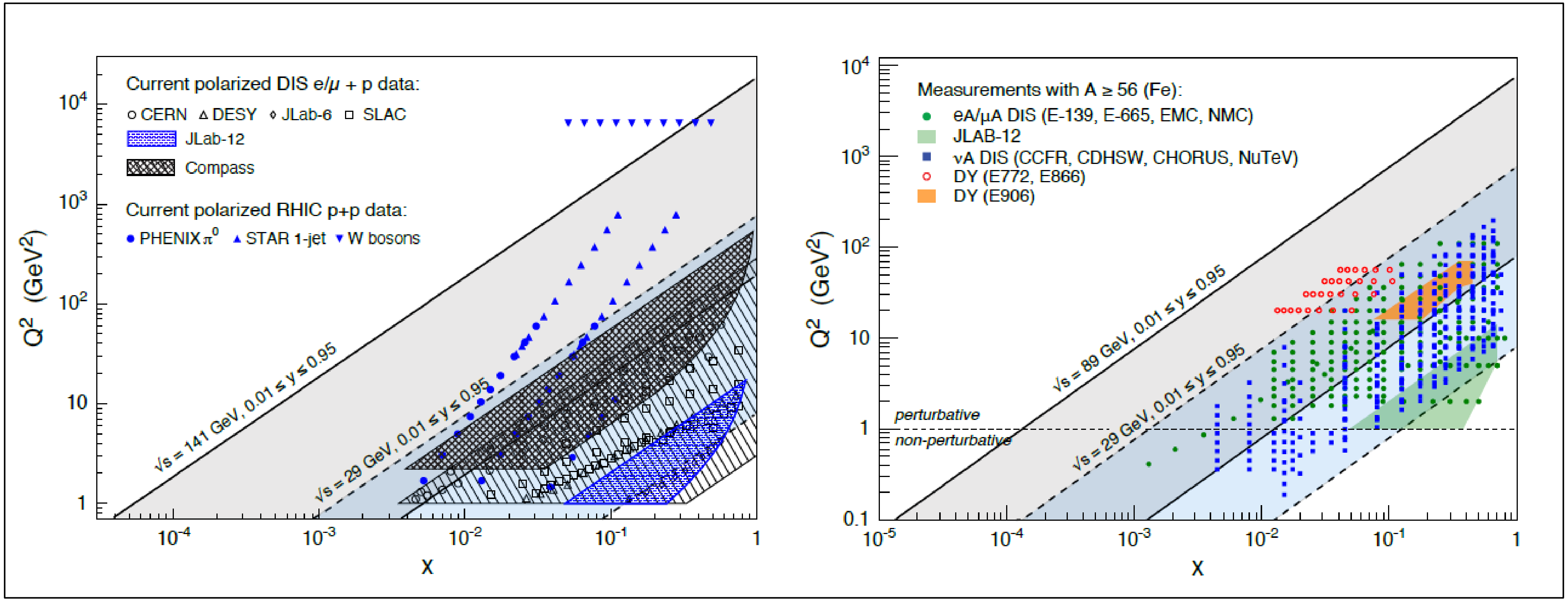
- NP Community and NSAC defined the requirements for the new facility which will be hosted by BNL in partnership with TJNAF
  - High luminosity (10^{33}– $10^{34}\ cm^{-1}s^{-1}$)
  - High polarization for electrons / light ions (70%)
  - Wide range of $\sqrt{s_{ep}}$ ($20 - 140\ GeV$)
  - Variety of ion species (p to U)
- Hadron ring with 2 IRs exists and operational
  - Adding electron ring with beams 5 - 18 GeV

www.eicug.org/web/sites/default/files/EIC_CDR_Final.pdf





EIC Kinematic Reach



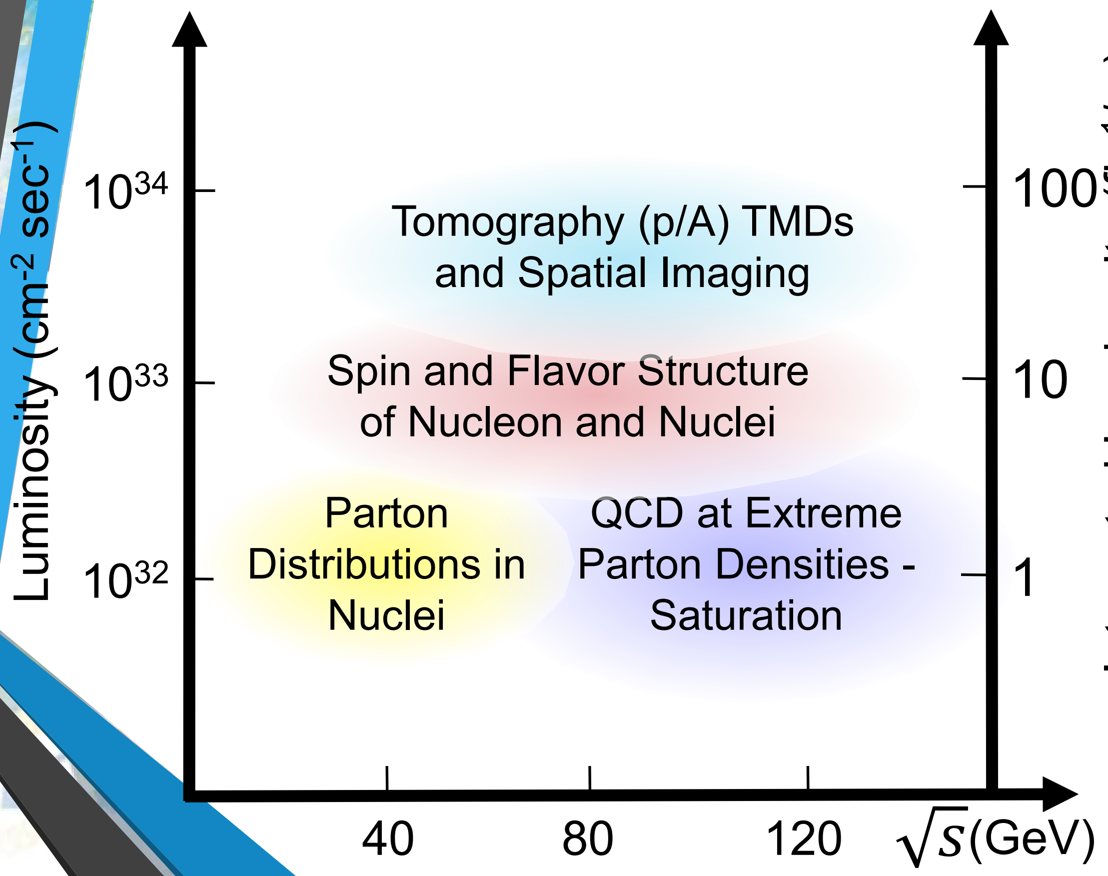
Polarized ep　　　　Polarized eA

- Extension of existing polarized beam measurements:

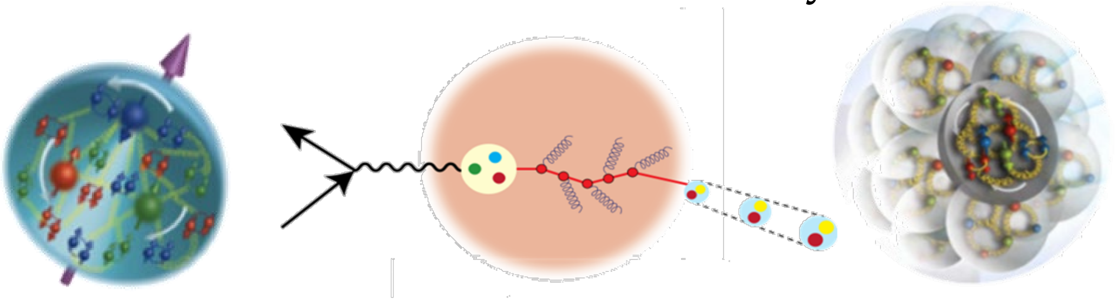
  × 100 in x at a fixed Q^2 and by × 100 in Q^2 at a fixed x

EIC – a New QCD Laboratory

EIC is envisioned as a premier facility to study the structure and dynamics of the visible matter



- Major physics goals:
  - Understanding the properties of hadrons (mass, spin)
  - Complete (3D) imaging of hadrons
    - PDF, TMD, GPD
  - Properties of QCD nuclear matter at high parton densities
  - Emergence of hadrons
    - Hadronization, universality tests



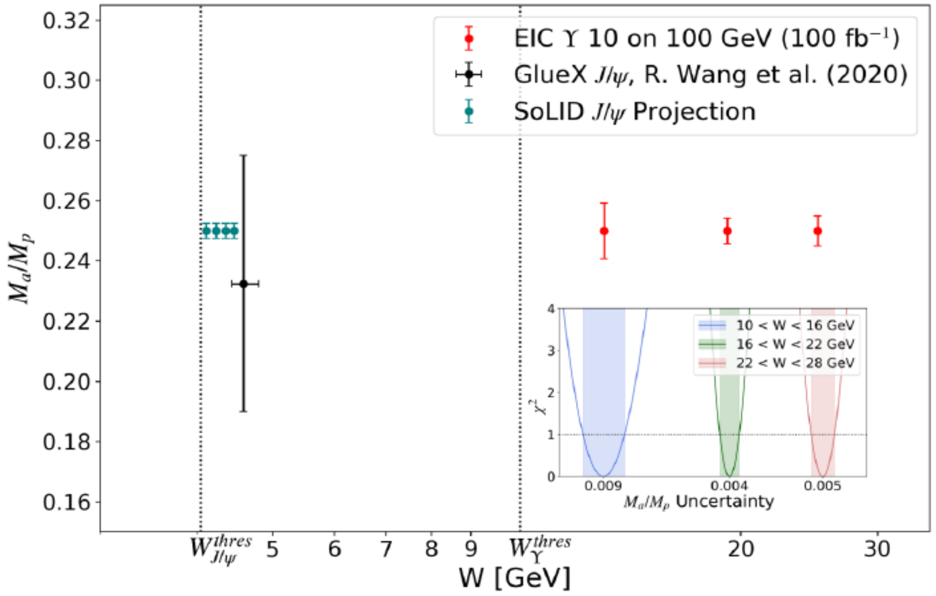
EIC Input on Proton Mass

- Possible decomposition of contributions:

Quantum fluctuations
Quark mass + Trace anomaly

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

Relativistic motion
Quark energy + Gluon energy



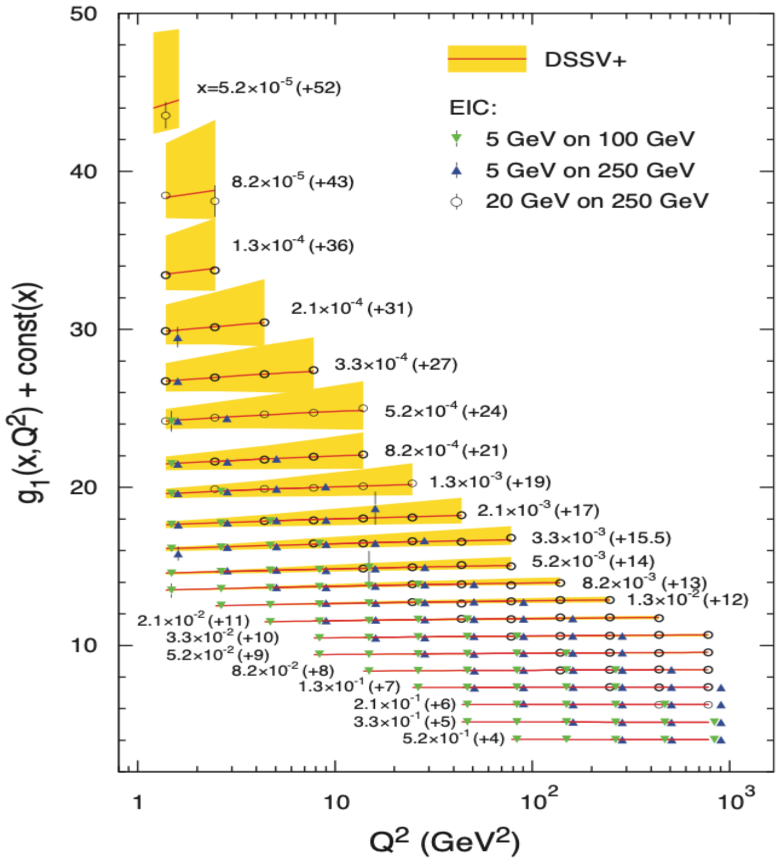
PRL121(2018)212001

quark condensate ~9%
quark energy ~32%
gluonic field energy ~37%
anomalous gluonic contribution ~23%

- EIC will deliver crucial input through dedicated measurements of exclusive production of J/ψ and Υ close to the production threshold
- Hadron mass through chiral-symmetry features will also be studied with light mesons (π, K, φ)

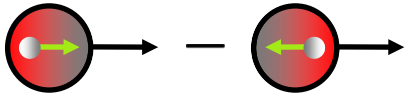
EIC Input on Proton Spin

arXiv:1212.1701

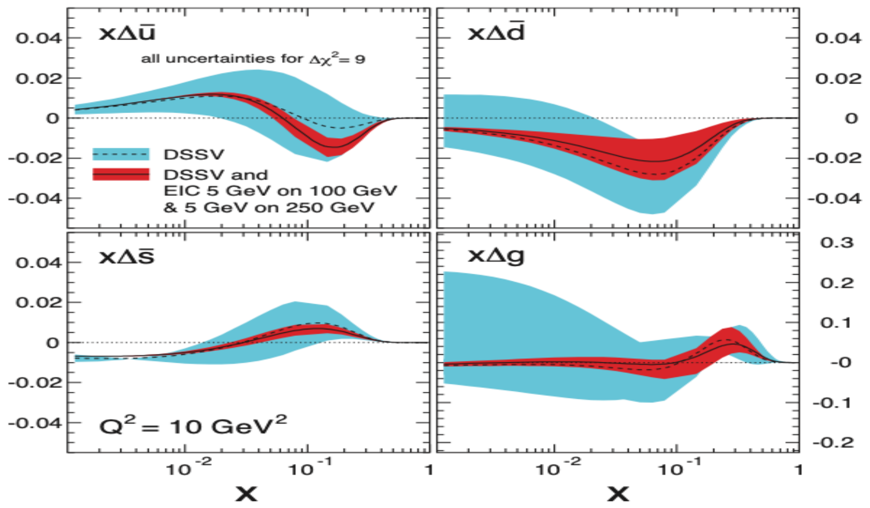


g_1 uncertainty projections for $10fb^{-1}$ for range of CME compared to DSSV+

- Contribution of quarks and gluons to the spin of the proton are constrained via x, Q^2 behavior of the cross-section difference g_1

$g_1(x) \sim$ 

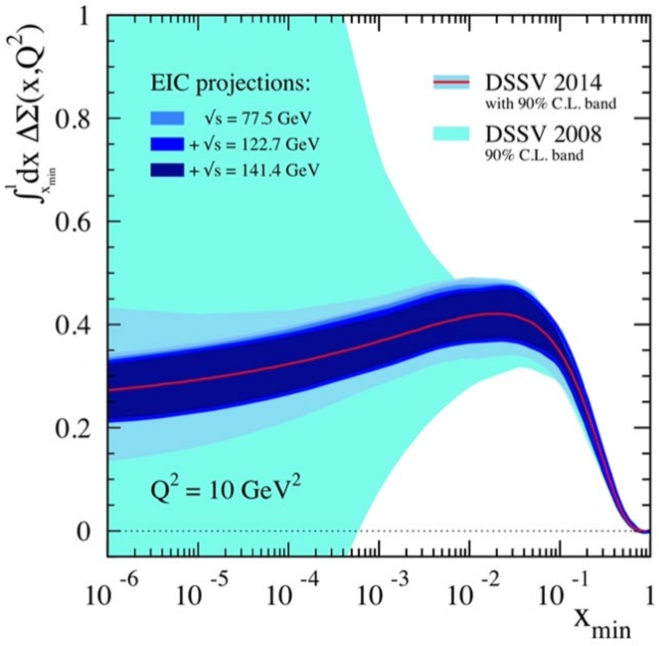
$f^+(x) - f^-(x)$

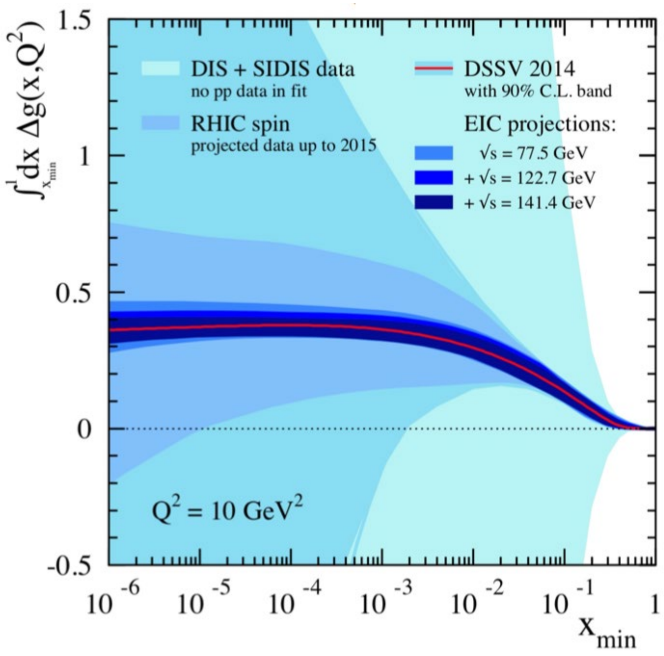


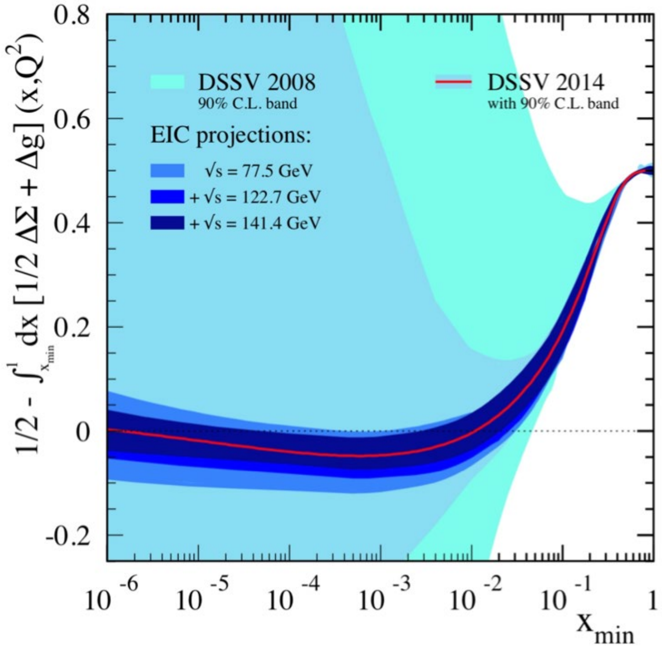
- EIC impact on spin and flavor structure of the proton: helicity distributions of anti-u, anti-d, s quarks and gluon

EIC Expected Impact Example

E. Aschenauer, R. Sassot and M. Stratmann, Phys. Rev. D92 (2015) 094030.



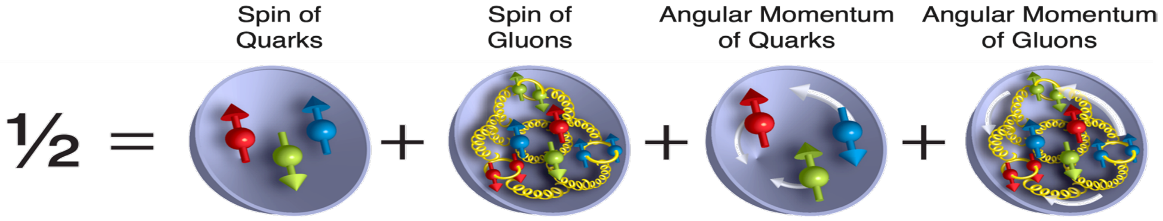




Quark Spin

Gluon Spin

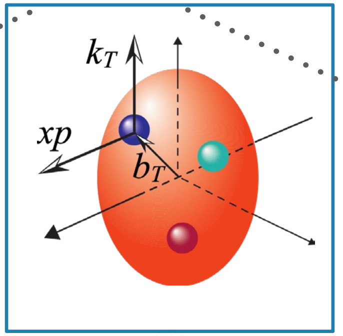
Orbital Angular Momentum



PDF Complexity

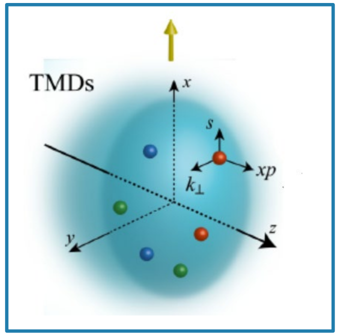
- Wigner Functions $W(x, k_T, b_T)$

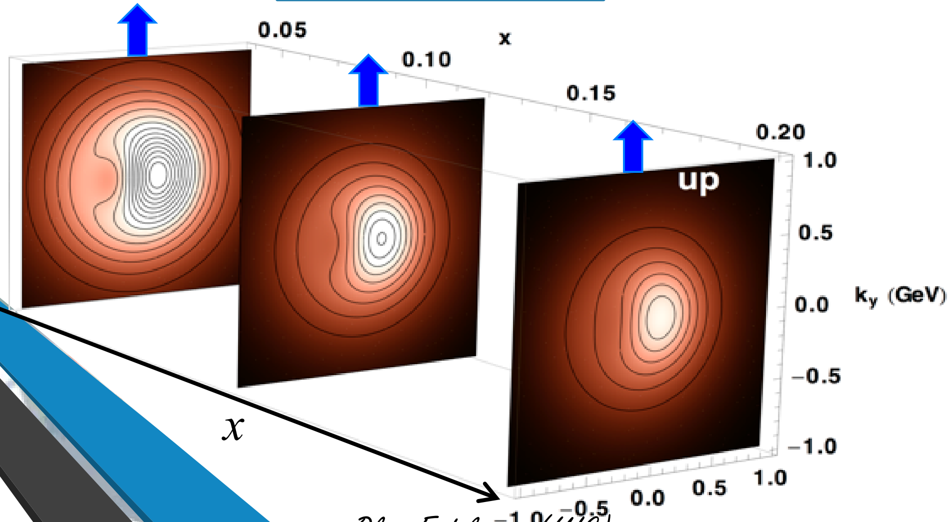
arXiv:1212.1701



$\int d^2 b_T$

Transverse Momentum Dependent distributions





x

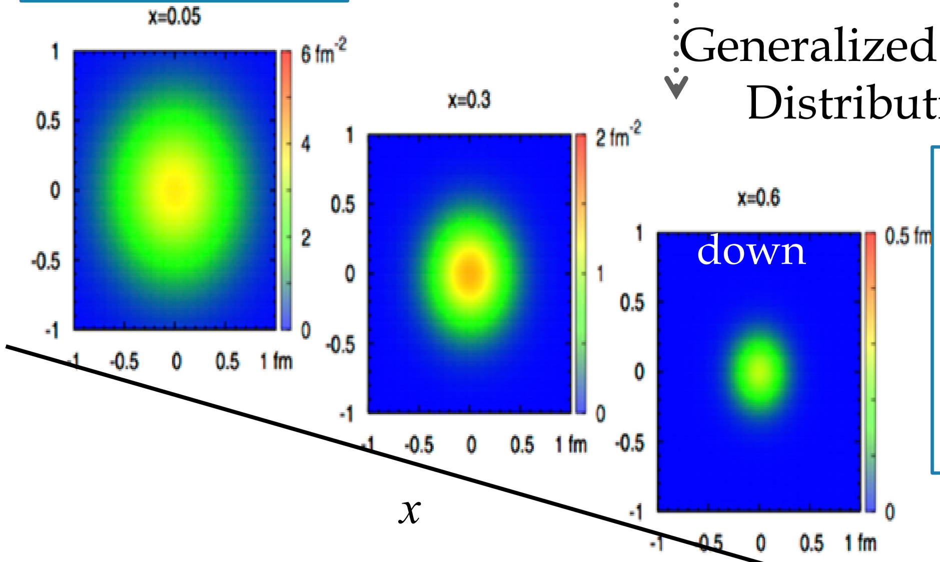
$\int d^2 k_T$

Impact Parameter Dependent distributions

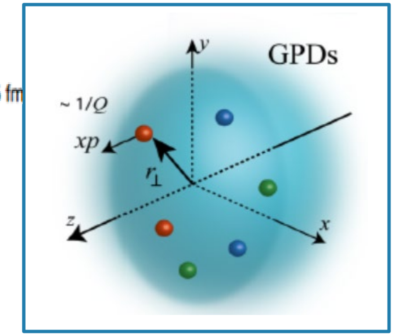
$f(x, b_T)$

Fourier Transform

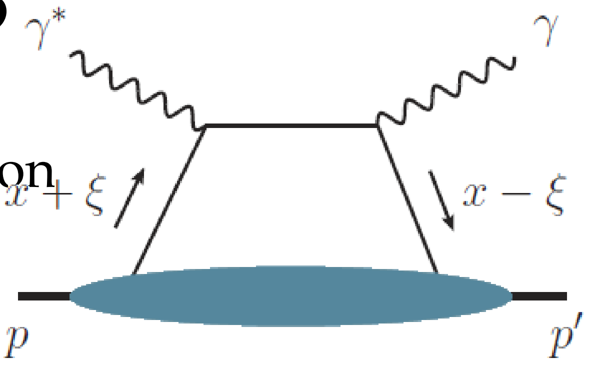
Generalized Parton Distributions



x



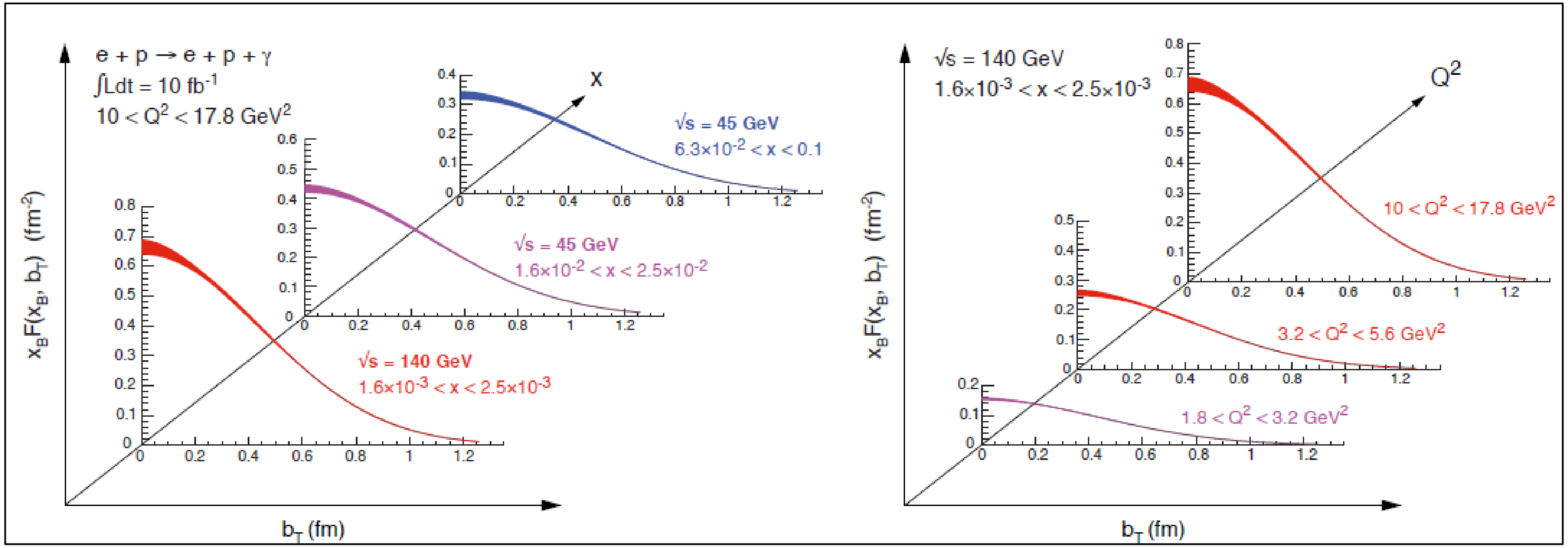
EIC: 2D Spatial Imaging



- EIC will enable precise mapping the spatial quark and gluon structure of the proton in (x, Q^2)
- GPDs "golden channel" – DVCS
- Also, together with direct helicity measurements for quarks and gluons, GPD provide additional insight into quark and gluon orbital momenta

arXiv:1708.01527

Projected precision of the EIC GPDs from Fourier transform of the unpolarized DVCS cross-sections vs |t|

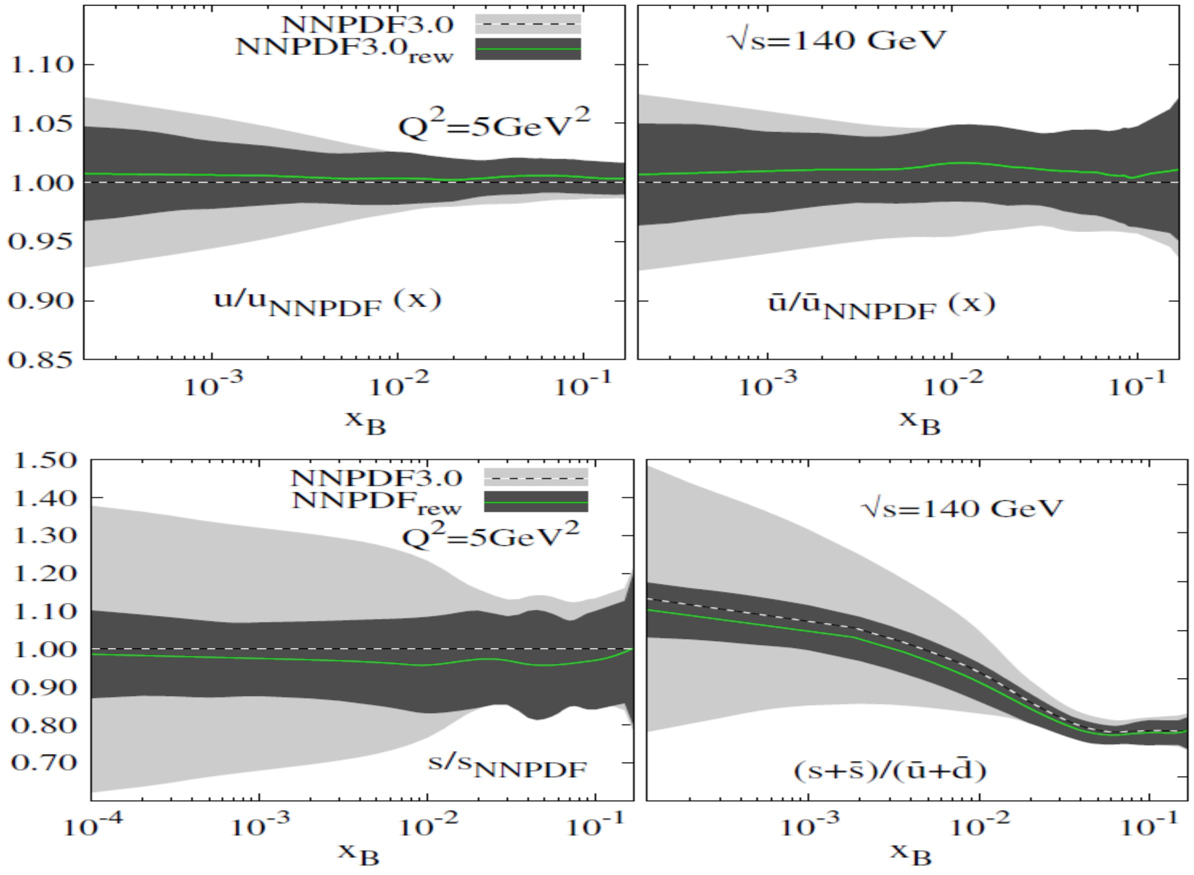


Parton Distribution Functions

- Expected impact on the unpolarized sea quark PDFs from EIC SIDIS measurements for identified pions and kaons

PRD 99 (2019) 094004

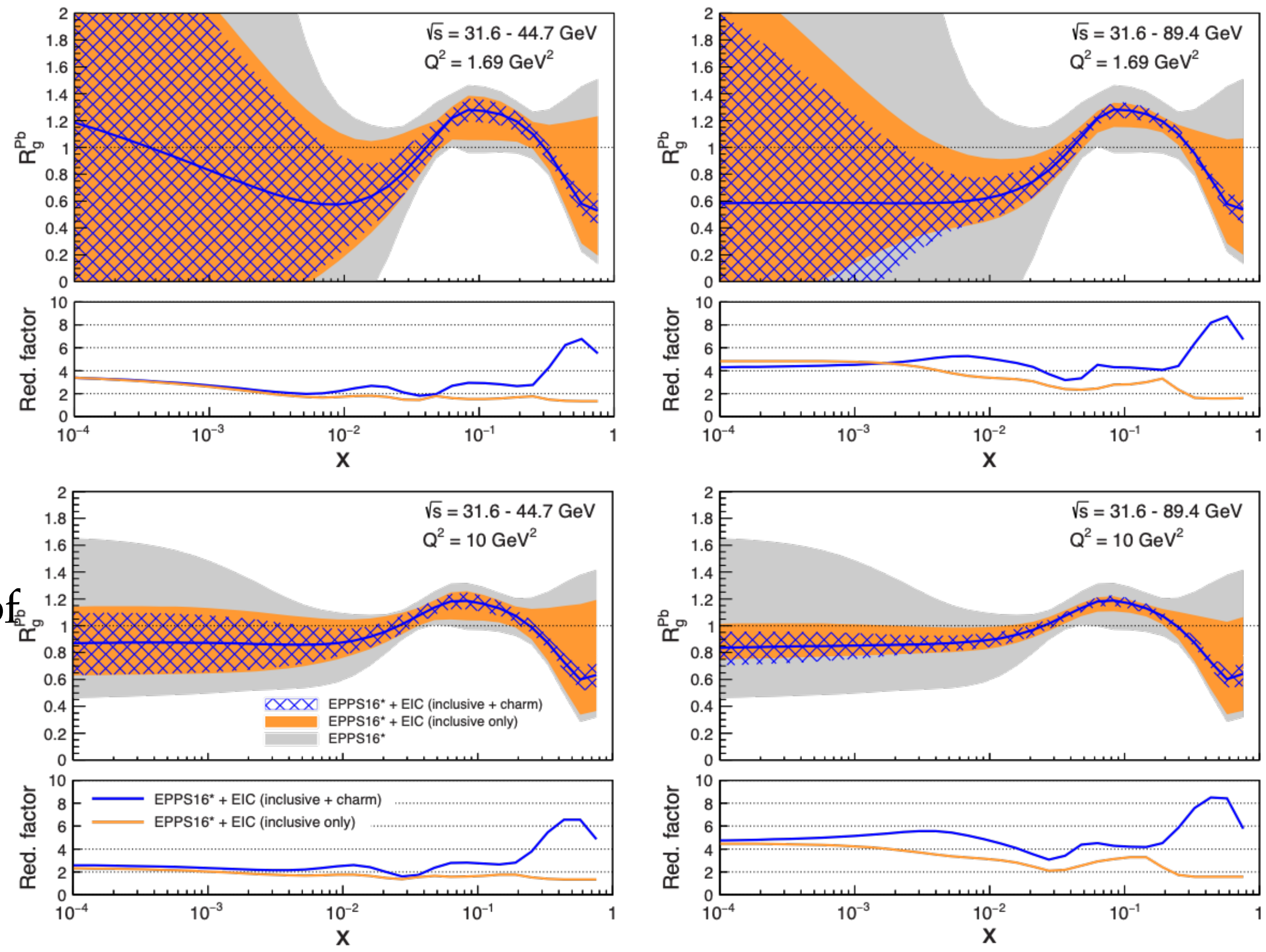
- Moderate impact on up, down, anti-up and anti-down
- Major improvement for strange PDFs, especially at low x, and s/light
- PDF improvements for gluon content and flavor structure of the sea have significant implications for HL LHC in the EW sector
- Impacts: HEP (Higgs cross section, α_s, W mass (PDF + TMD), …); HIN (reference, extrapolations)



eA: Nuclear PDF effects

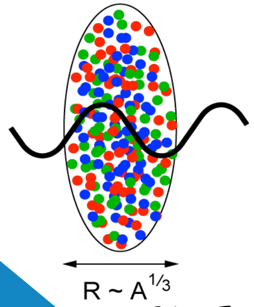
- Parton distribution functions for bound nucleons are different than that of a free proton
- Nuclear modification R_g^{Pb}: ratio of gluon distributions in Pb and in p
- Projected precision of EIC measurements allows for substantial reduction of nPDF uncertainties
- Complementary to RHIC and LHC pA data, and has no potential complications of disentangling initial and final state effects
- Impacts: HIN (initial state; jet quenching baseline, low-x regime relevant for gluon saturation,…)

arXiv:1708.01527

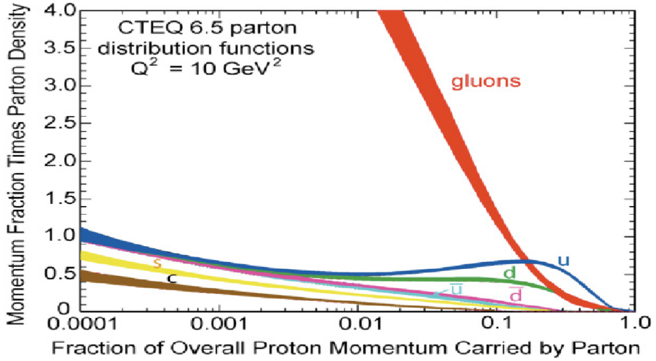


EIC eA: Gluon Saturation

- Could the gluon density $G(x, Q^2)$ continuously grow?
- New idea: Non-Linear Evolution
  - Recombination compensates gluon splitting
  - New evolution equations
  - Saturation of gluon densities characterized by scale $Q_s(x)$
- Saturation → Color-Glass-Condensate
- Experimentally, nucleus serves as Q_s amplifier

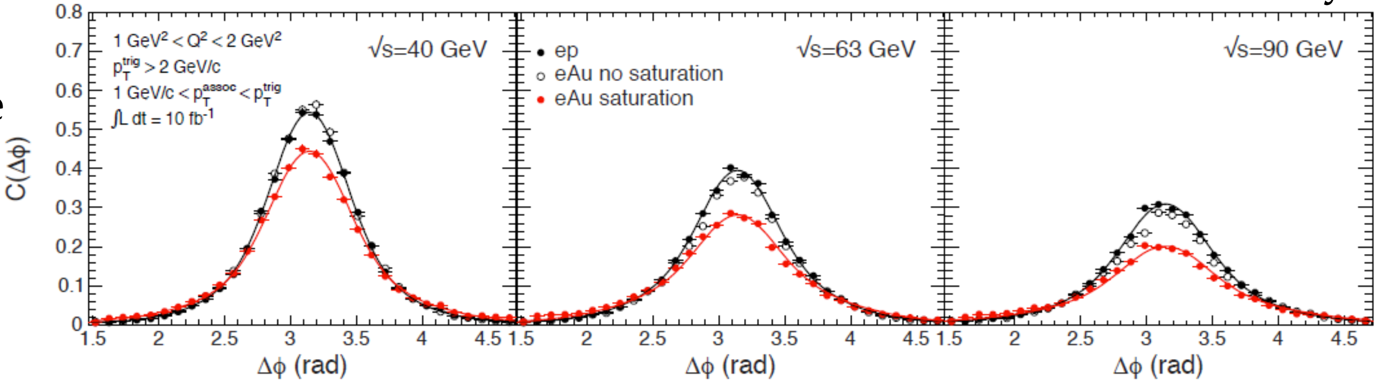


$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$



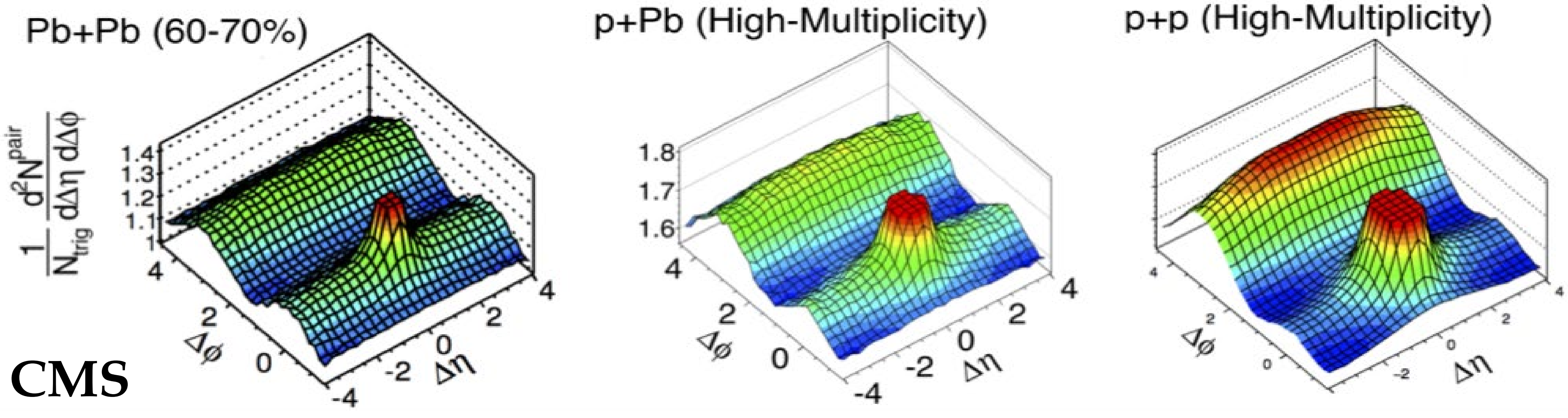
- Di-hadron correlations are sensitive to the transverse momentum dependence of the gluon distribution and gluon correlations

2→2 vs. 2→many

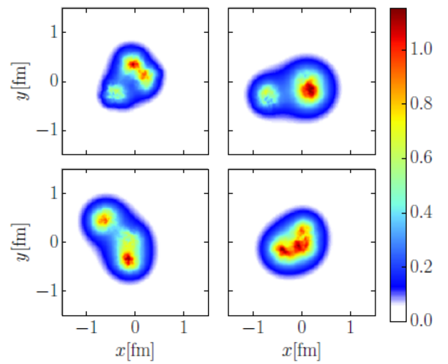


- EIC allows to study the evolution of Q_s with x
- Impacts: HIN (initial state), CGC discovery?,…

eA: Collective Phenomena in Small Systems



PRD 94(2016)034042



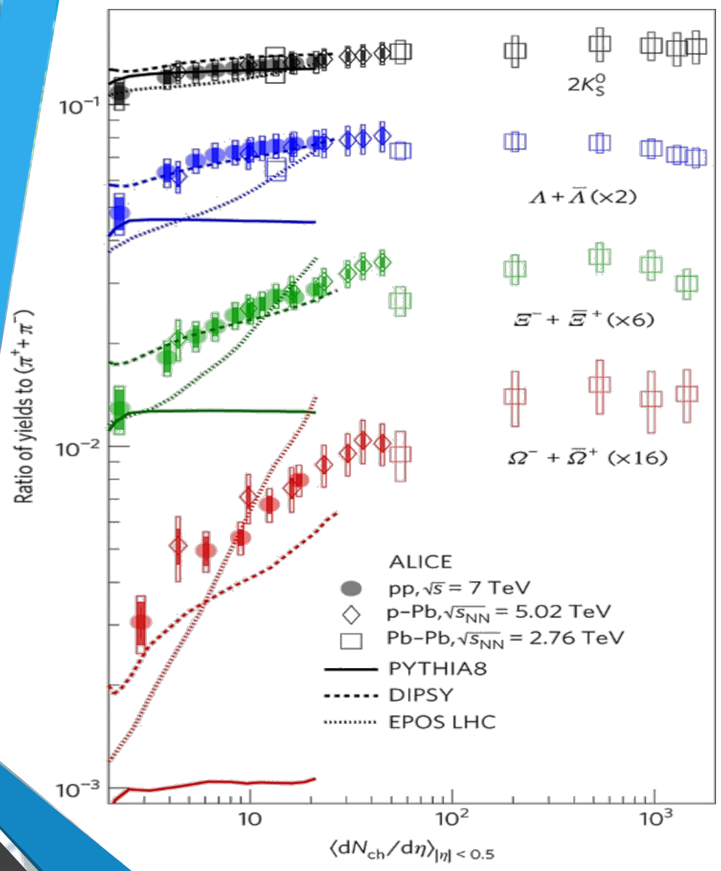
proton density
$x \sim 10^{-3}$

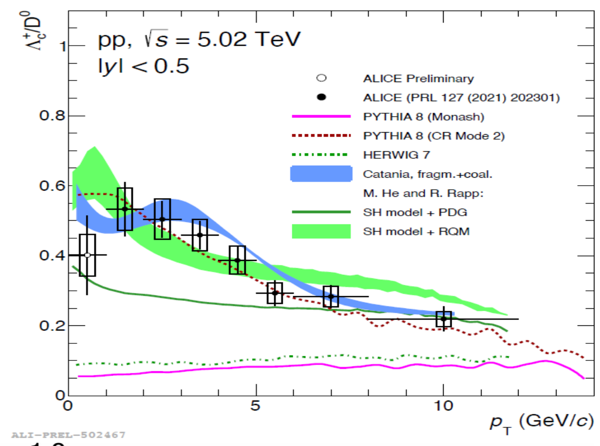
- Long range correlations: everywhere! AA collisions, pA, high multiplicity pp
  - Can the system that small reach an equilibrium?
  - Is this a manifestation of initial state phenomena? CGC?
- NOT reproduced in any established MC generators
- Understanding of proton structure is critical for reproducing the signals

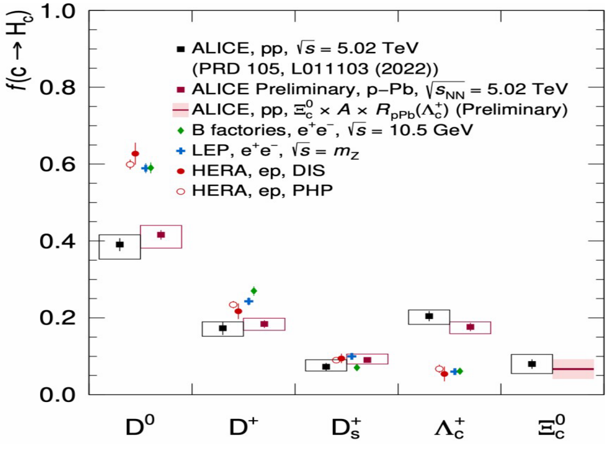
- Impacts: HIN (QGP formation in small systems, initial state,…)

(Selected aspects of) Hadronization, ep

Nature Physics 13 (2017) 535



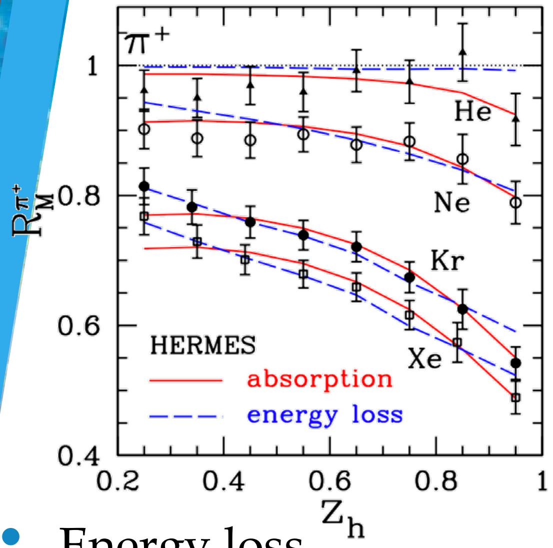


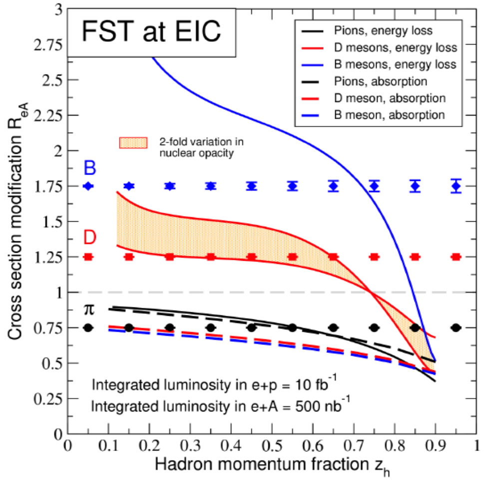


- Strangeness and baryon-to-meson enhancements, once envisioned as QGP signatures are seen in small systems at RHIC and LHC
- Strangeness:
  - multiplicity dependent enhancements in pp collisions of similar levels as pA and peripheral AA
- Charm sector
  - $\Lambda c/D0$: enhancements over $e+e-$ for pp and AA
  - Charm-fragmentation fractions appear non universal

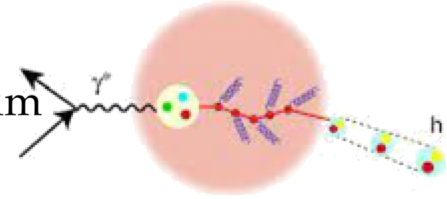
Impacts: HIN, HEP, Hadronic physics (understanding of hadronization)

(Selected aspects of) Hadronization, eA

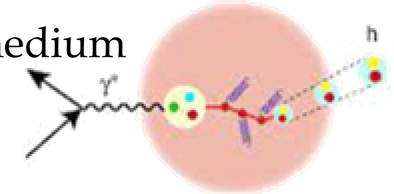




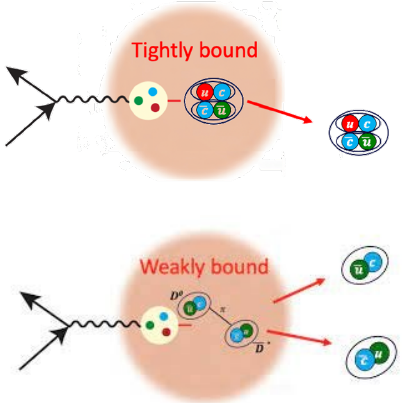
- Energy loss
  - hadronization outside the medium
  - gluon radiation off struck quark

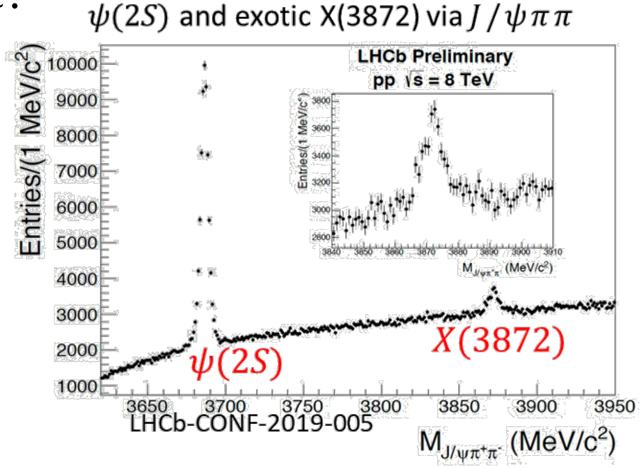


- Prehadron absorption
  - color neutralization inside the medium
  - Prehadron-nucleon scatterings



- Exotic hadron structure:
- Example: X(3872) – compact tetraquark vs. hadronic molecule?





Matt Durham EIC @ Snowmass

- Impacts: Differentiating between E-loss absorption models; CNM transport properties; Hadron structure

Community Effort to Define EIC Detector

- Major EIC User Group effort in 2019-2021: the Yellow Report

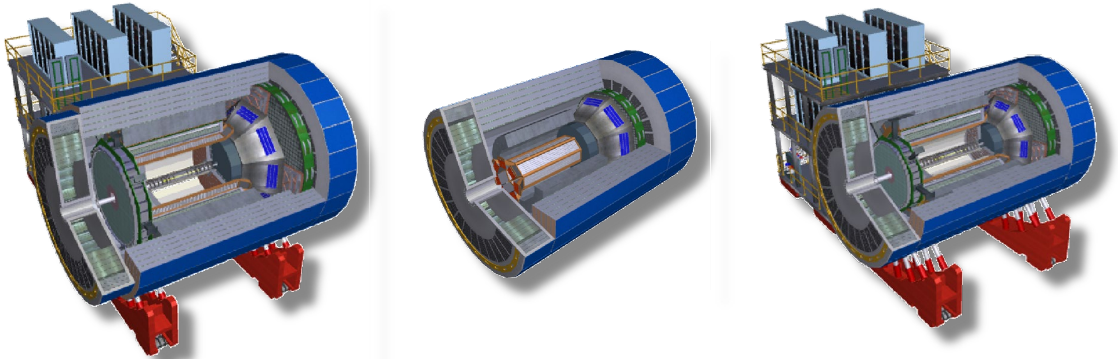
NPA 1026 (2022)122447
https://arxiv.org/abs/2103.05419

- Quantify physics measurements for existing or new physics topics and implications for detector design
- Study detector concepts based on defined requirements and quantify technology implications for physics measurements
- ~400 authors / ~150 institutions / ~900 pages with strong international contributions!

Towards EIC Detector

Issued in March 2021, due by Dec. 1, 2021

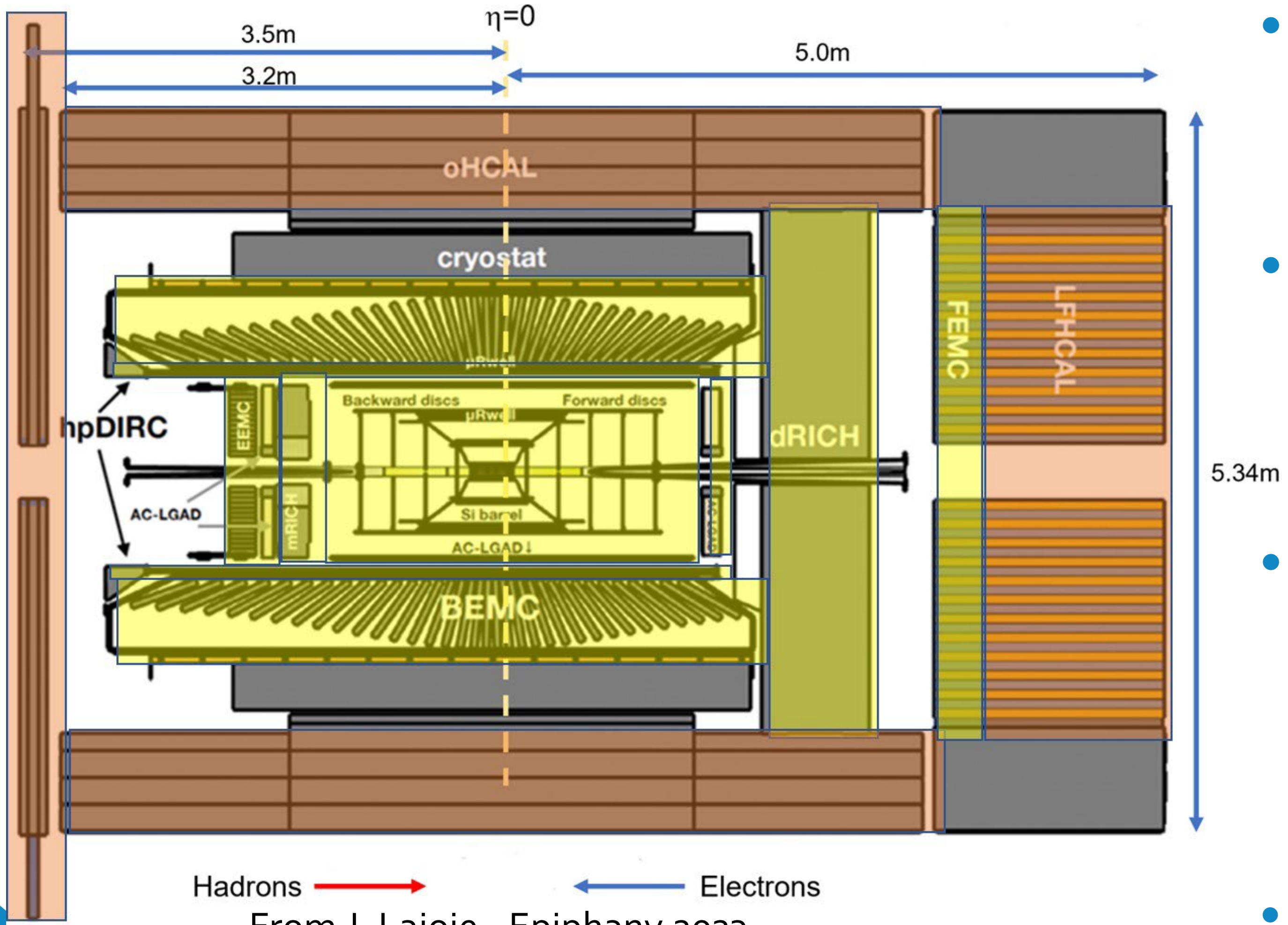
Converting EIC physics requirements into detector concepts: three detector proposals in preparation: **ATHENA / CORE / ECCE**



ATHENA CORE ECCE

- EIC Detector Proposal Advisory Panel (DPAP) review, with final report by March 8th, 2022
- DPAP selected ECCE as the reference design and recommended consolidation of ECCE and ATHENA efforts
- Spring/Summer 2022 – the two teams join the efforts and begin collaboration formation and further detector design optimization
- **ePIC** Collaboration was formed with Charter adoption on Dec. 14th, 2022

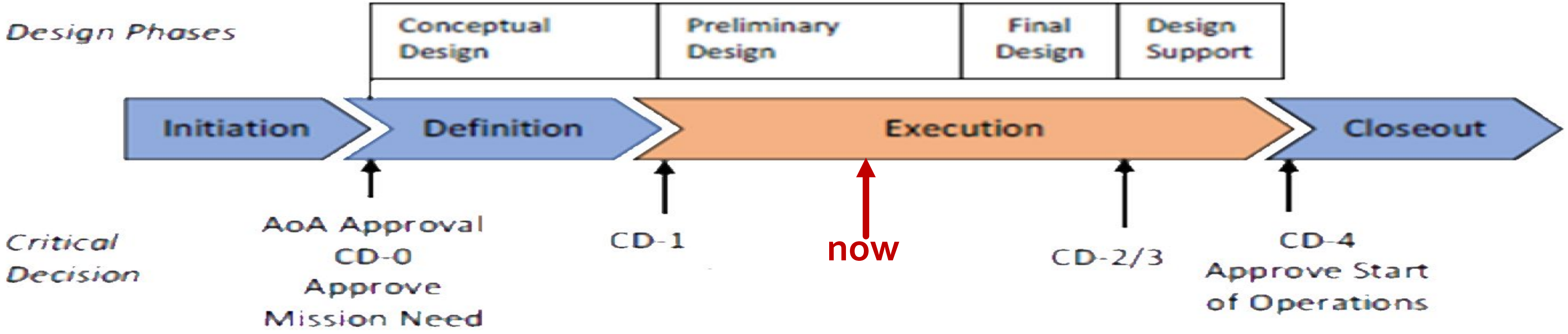
Developing ePIC Detector



From J. Lajoie - Epiphany 2023

- Tracking:
  - New 1.7T solenoid
  - Si MAPS Tracker
  - MPGDs (mRWELL/mMegas)
- PID:
  - hpDIRC
  - mRICH/pfRICH
  - dRICH
  - AC-LGAD (~30ps TOF)
- Calorimetry:
  - SciGlass/Imaging Barrel EMCal
  - PbWO4 EMCal (backward)
  - Finely segmented EMCal +HCal (forward)
  - Outer HCal (sPHENIX re-use)
  - Backwards HCal (tail-catcher)
- (And a suit of far froward/backward detectors)

EIC Project Timeline/Schedule

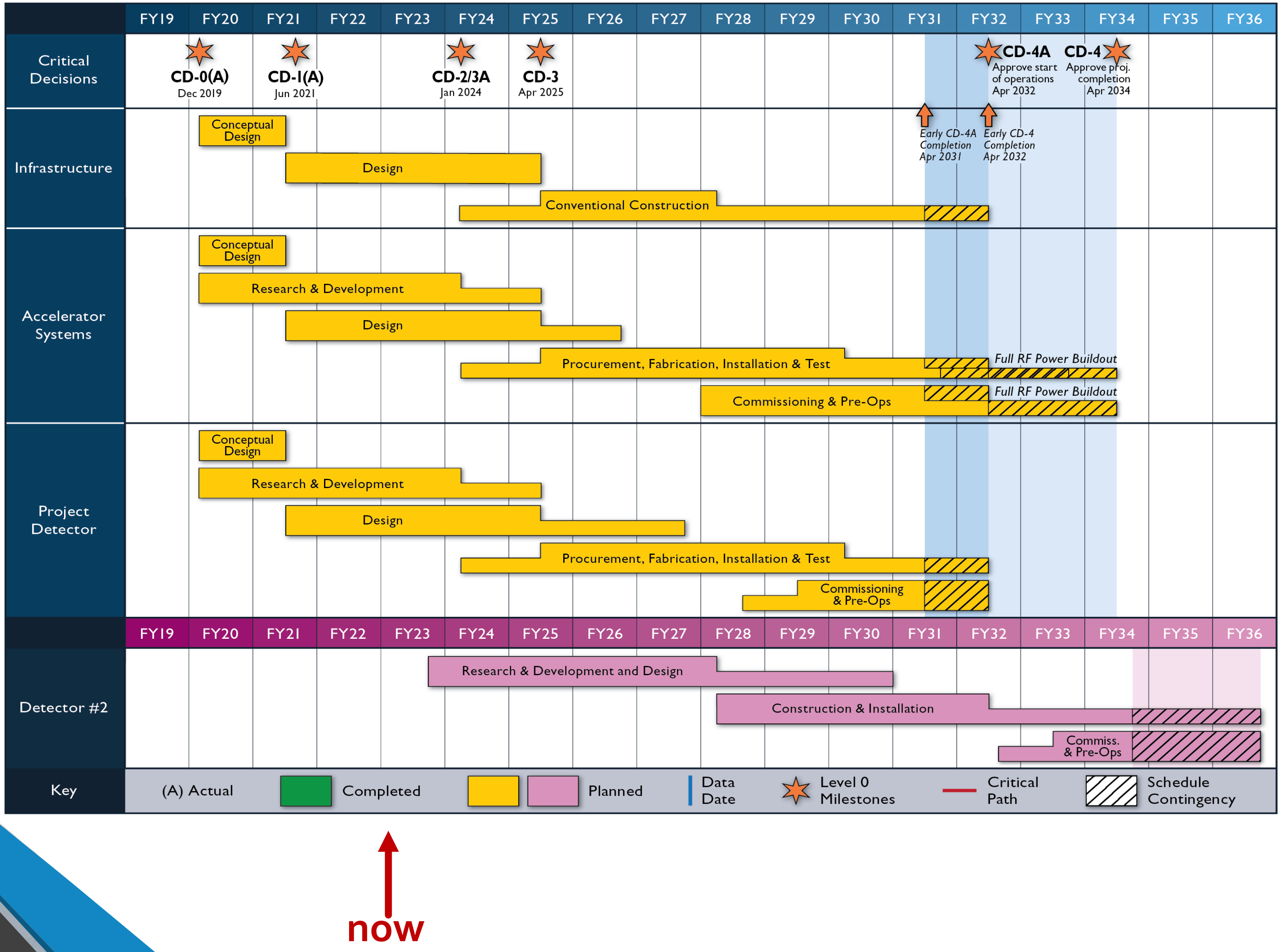


- CD-0 ("Mission Need") Approved January 22, 2019
- Site selection Announced January 9, 2020
- CD-1 (Alternative Selection /Cost Range) Approved July 6, 2021

- CD-2 (Performance Baseline)
- CD-3a (Long Lead Procurement)
  - CD-2/3A Review and ICR (needs pre-TDR) October 2023 (expected)
  - CD-2/3A ESAAB Approval January 2024 (expected)

- CD-3 (Start of Construction)
  - CD-3 Review (needs TDR) January 2025 (expected)
  - CD-3 ESAAB Approval April 2025 (expected)
- CD-4 (Project completion/start of operations)

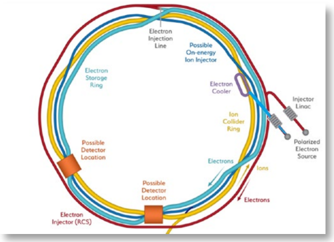
EIC Project Timeline/Schedule



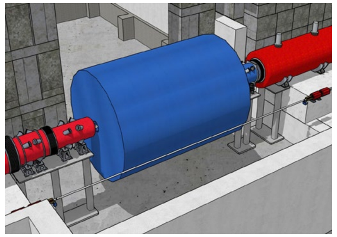
- Inflation Reduction Act of 2022 made a major impact on funding ramp up/risk mitigation
- Possible early completion of CD4A (collisions in 2031!)
- Pressure on ePIC to be ready for commissioning by early projected finish
- 2nd IR (IP8)
  - Later start ~ 5 years
  - Detector-2 Working group is in place
  - Complementary design/technology options and physics opportunities

Summary

- Electron-Ion Collider will be a new collider facility capable of revolutionizing our knowledge of QCD in the next decades
- EIC machine design high luminosity, high polarization for electron and light hadron beams, a wide range of center of mass energies, variety of ion beams with up to high A
- It will enable tackling profound open questions with broad implications for many subfields
- The design of the first EIC detector – ePIC – is in advanced stages and will be going through the CD review phases as part of the project. ePIC Collaboration has been formed at the end of 2022.
- Strong EICUG community support for the second detector; case developments are underway



ePIC



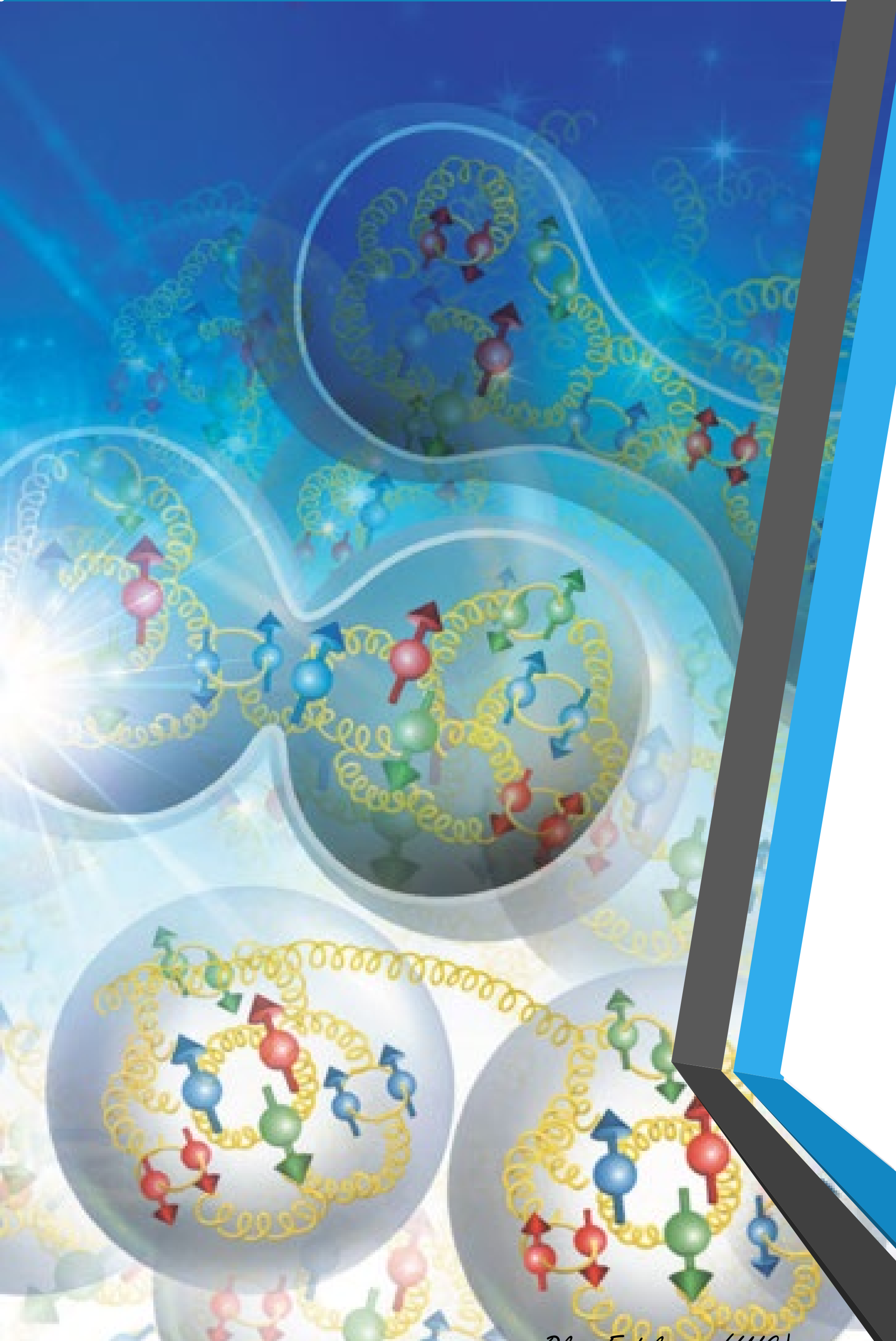


Image credit: Jefferson Lab

Thank you!

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