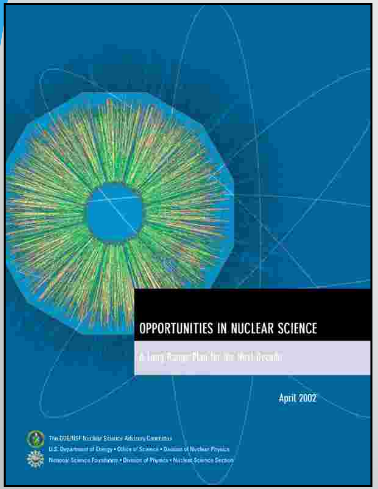
Physics program of EIC: towards the realization

Olga Evdokimov (University of Illinois at Chicago)

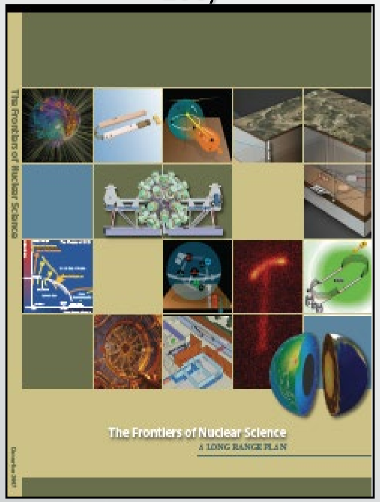
Scientific Case for the Electron-Ion Collider

- 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

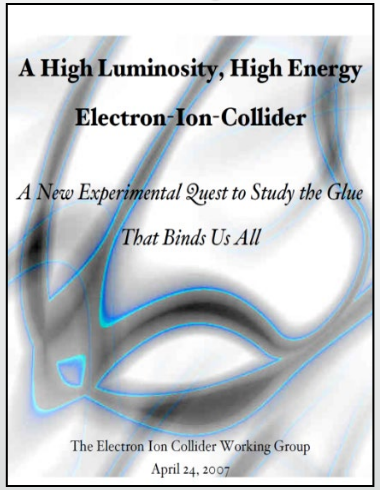
2002



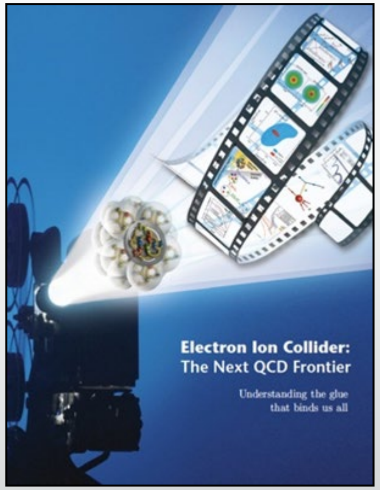
2007



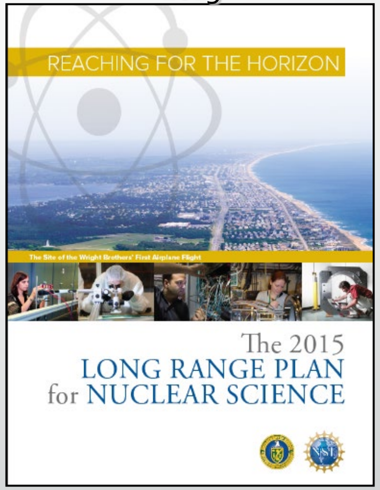
2009



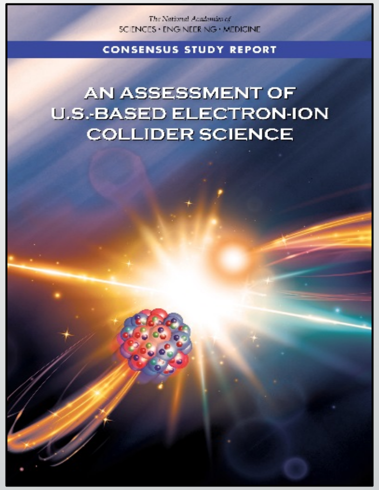
2012



2015



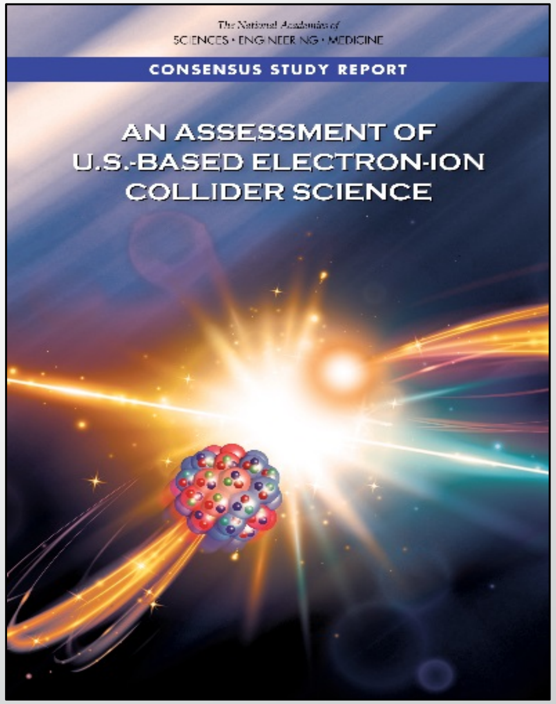
2018



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

EIC Physics Pillars

2018



- 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

EIC in the Making

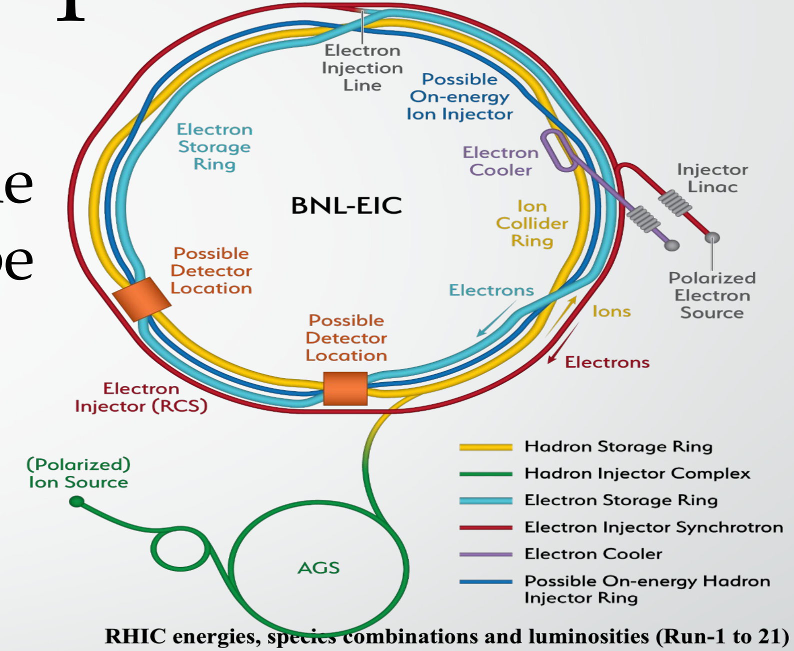
Milestone	Date
DOE "Mission Need" Approved	January 22, 2019
DOE Independent Cost Review	July 2019
DOE EIC Site Assessment	October 2019
CD0 Approval	December 19, 2019
DOE Site Selection Announced	**January 9, 2020**
BNL TJNAF Partnership Agreement	May 7, 2020
DOE Office of Science Status Review	September 9-11, 2020
Independent EIC Conceptual Design Review	November 16-18, 2020
DOE CD-1 Readiness Review	January 26-29, 2021
DOE Independent Cost Review	January - February 2021
CD-1 Approved	**July 6, 2021**

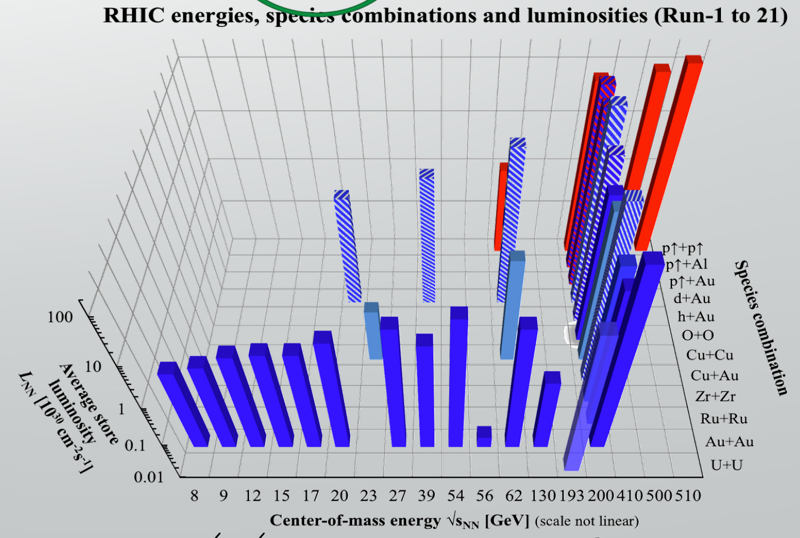
https://www.bnl.gov/newsroom/news.php?a=118765

EIC Machine Design and Requirements

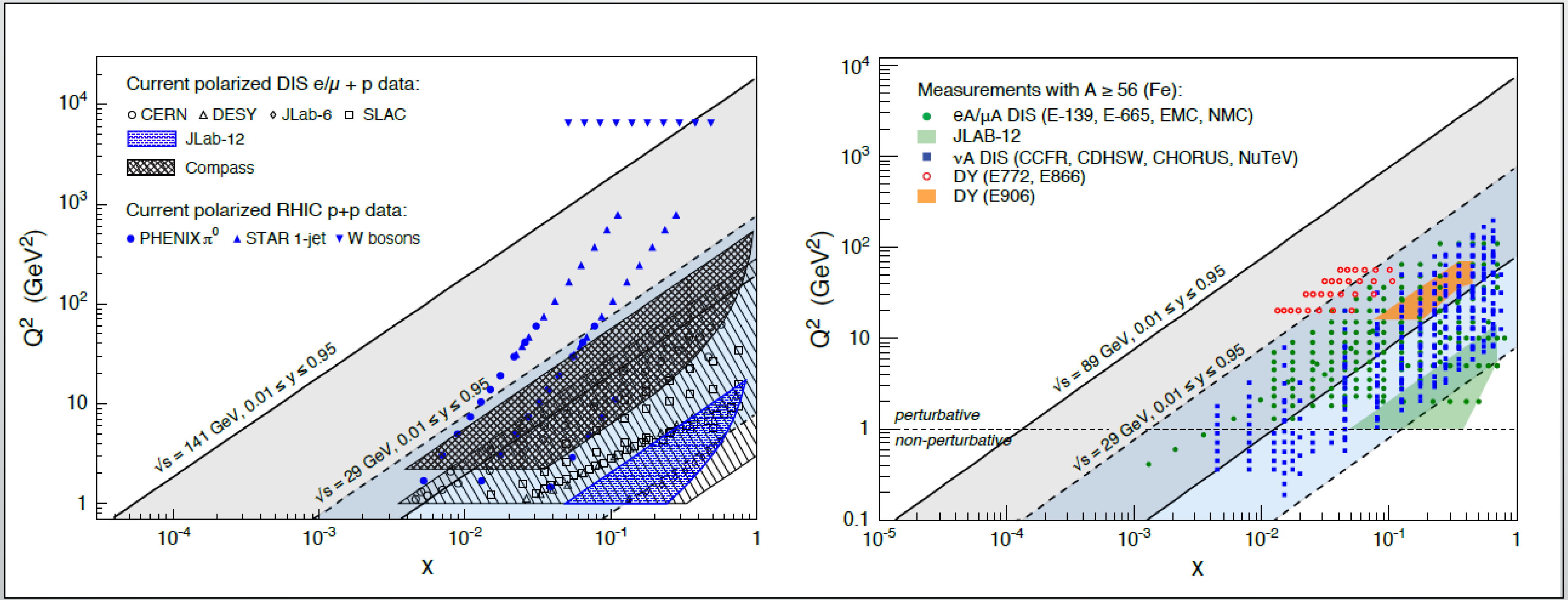
- NP Community and NSAC defined the requirements for the new facility which will be hosted by BNL in partnership with TJNAF
  - High luminosity (10^{33}– $10^{34}\ cm^{-1}s^{-1}$)
  - High polarization for electrons / light ions (70%)
  - Wide range of $\sqrt{s_{ep}}$ $(20 - 140\ GeV)$
  - Variety of 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

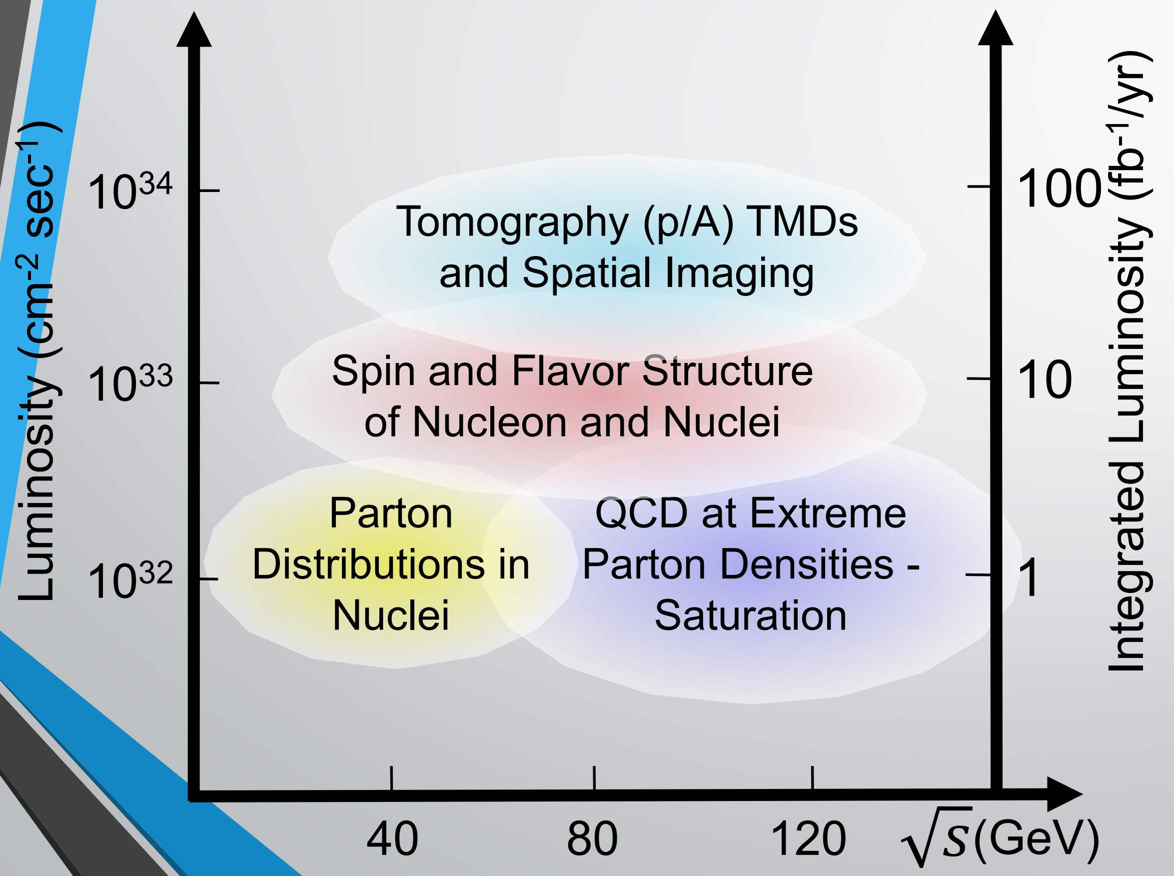
Polarized eA

- Extension of existing polarized beam measurements:

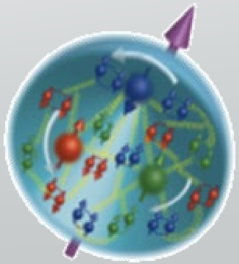
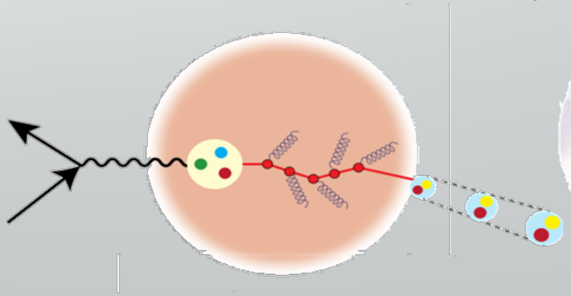
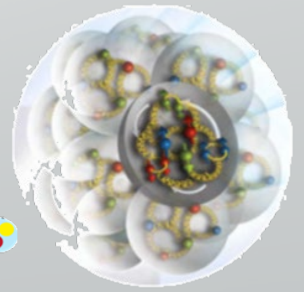
  $\times$ 100 in x at a fixed Q^2 and by $\times$ 100 in Q^2 at a fixed x

EIC – a New QCD Laboratory

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

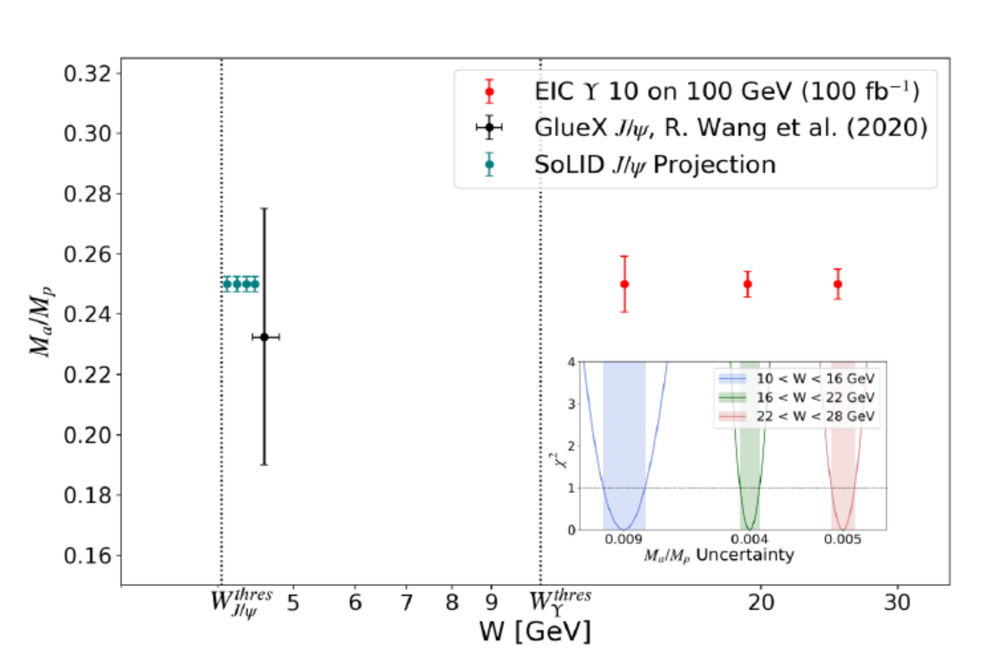


- Major physics goals:
  - Understanding the properties of hadrons (mass, spin)
  - Complete (3D) imaging of hadrons
    - PDF, TMD, GPD
  - Properties of QCD nuclear matter at high parton densities
  - Emergence of hadrons
    - Hadronization, universality tests

EIC Input on Proton Mass

- Possible decomposition of contributions:



Quantum fluctuations
Quark mass + Trace anomaly

$$M = \underbrace{E_q + E_g}_{} + \overbrace{\chi_{m_q} + T_g}^{}$$

Relativistic motion
Quark energy + Gluon energy

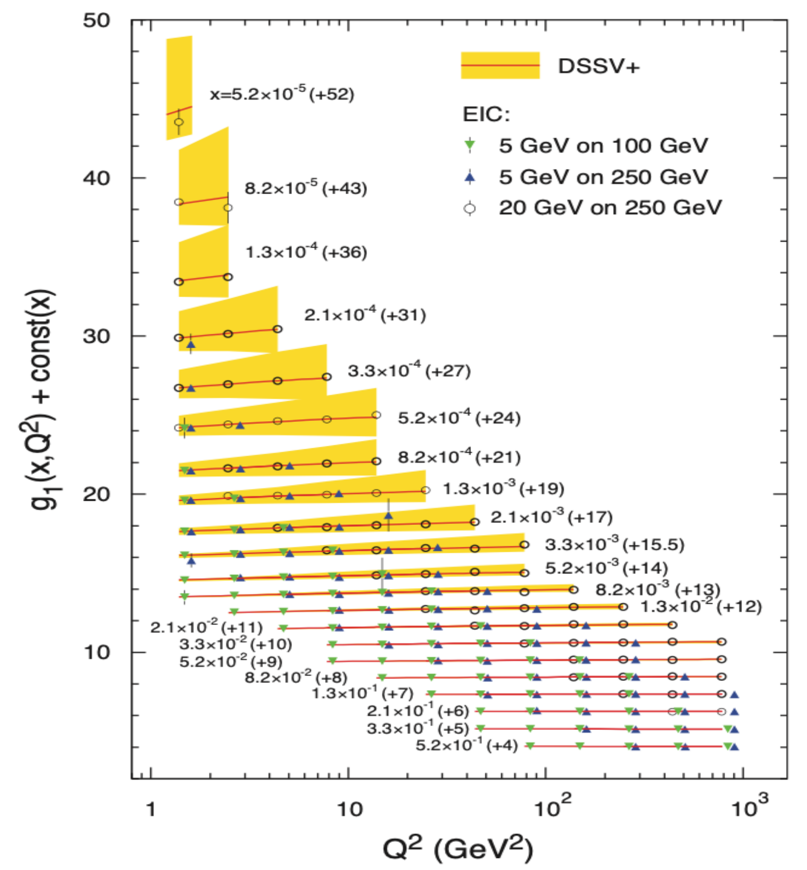
PRL121(2018)212001

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

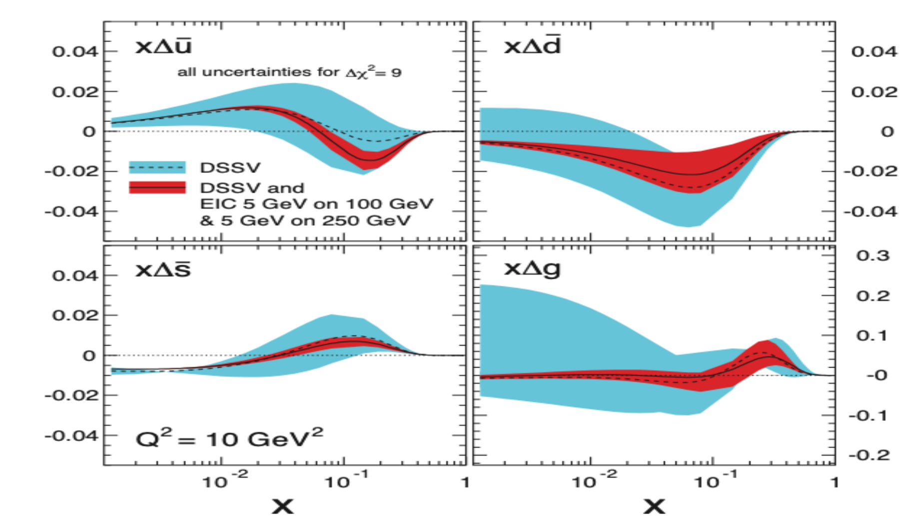


g_1 uncertainty projections for 10fb^{-1} for range of CME compared to DSSV+

- 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

$$g_1(x) \sim \quad - \quad$$

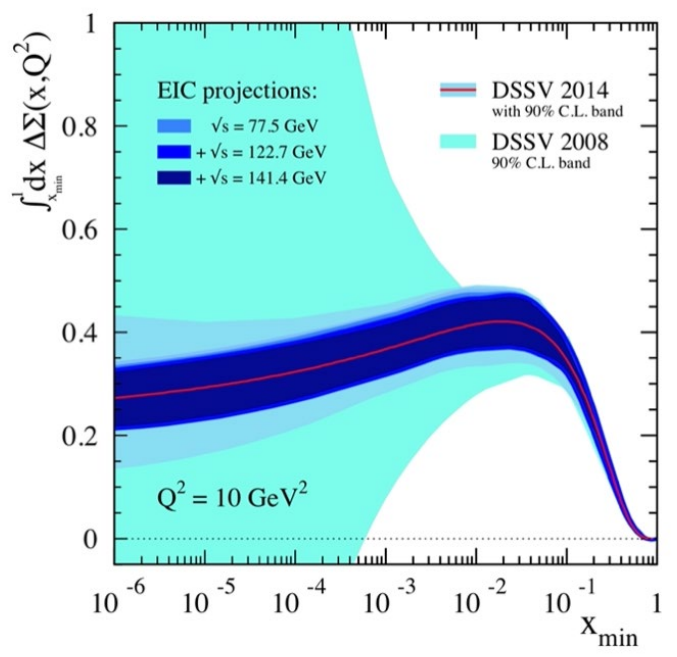
$$f^+(x) - f^-(x)$$

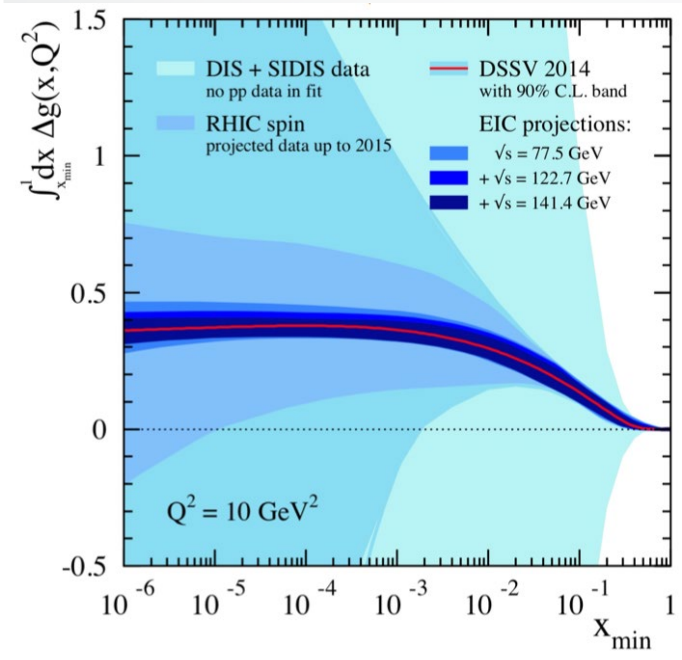


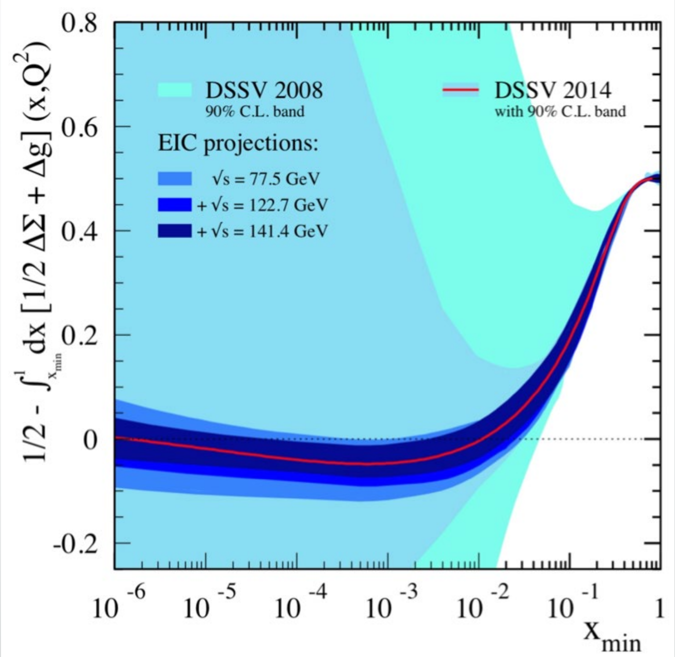
- EIC impact on spin and flavor structure of the proton: helicity distributions of anti-u, anti-d, s quarks and gluon

EIC Expected Impact Example

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



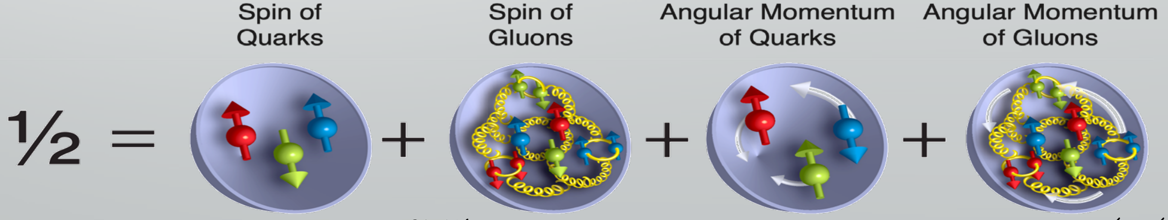




Quark Spin

Gluon Spin

Orbital Angular Momentum

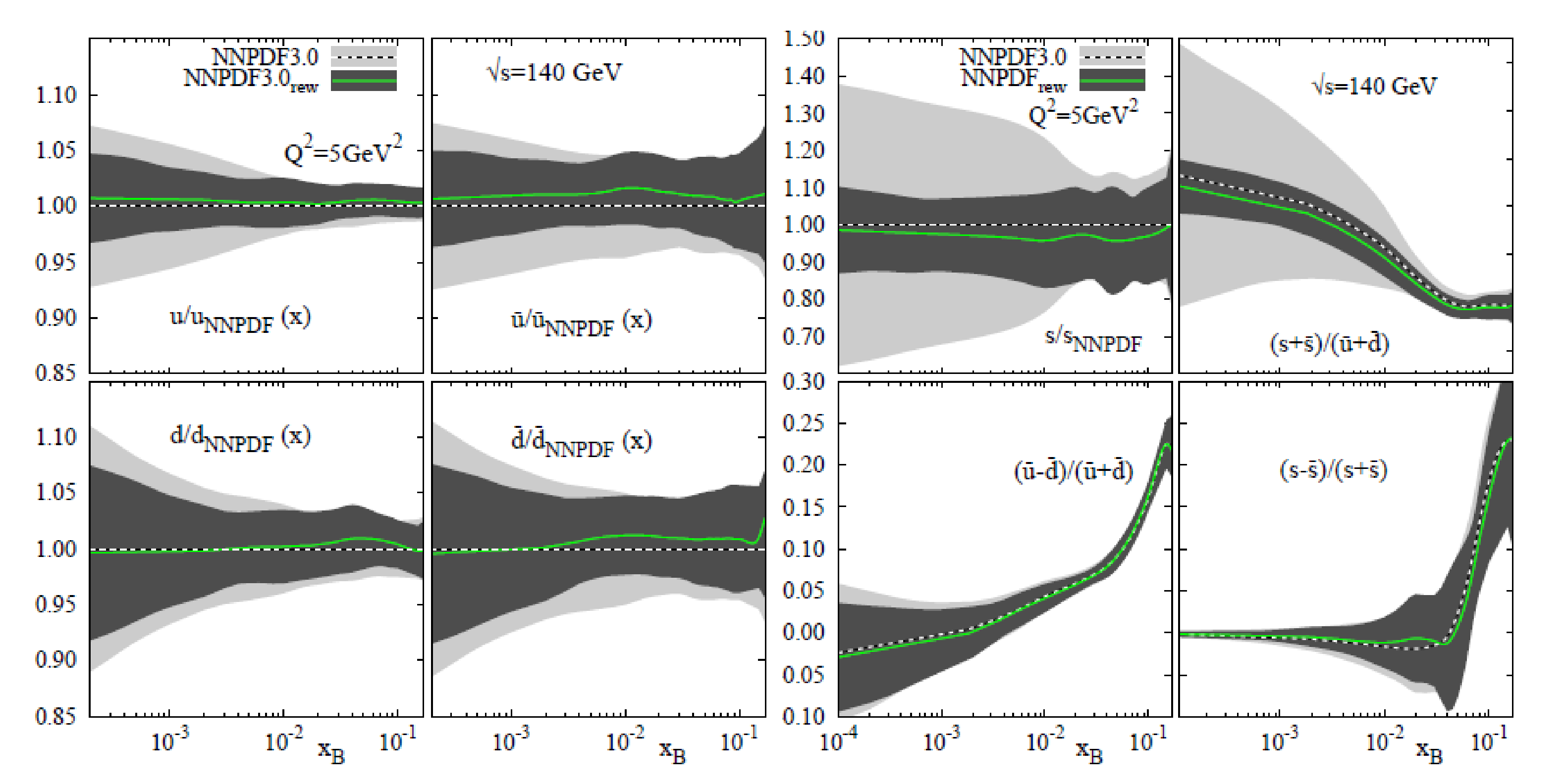


Parton Distribution Functions

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

JHEP 05(2006) 026

- Moderate impact on up, down, anti-up and anti-down
- Major improvement for strange PDFs, especially at low x, and s/light

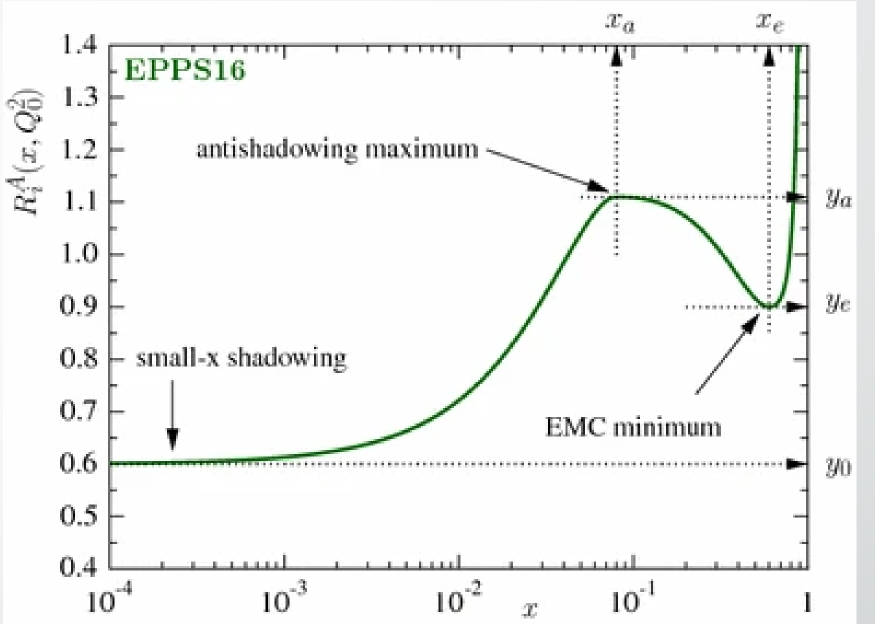


eA: Nuclear PDF effects

"Why QGP aficionados should care:"

Parton distribution functions for bound nucleons are different than that of a free proton, they are connected as (EPPS16, *EPJ C77(2017)163*):

$$f^i_{p/A}(x_i, Q^2) = R^i_A(x_i, Q^2) f^i_p(x_i, Q^2)$$



Nuclear PDF effects are critical to properly map QGP properties → inclusive DIS in eA collisions

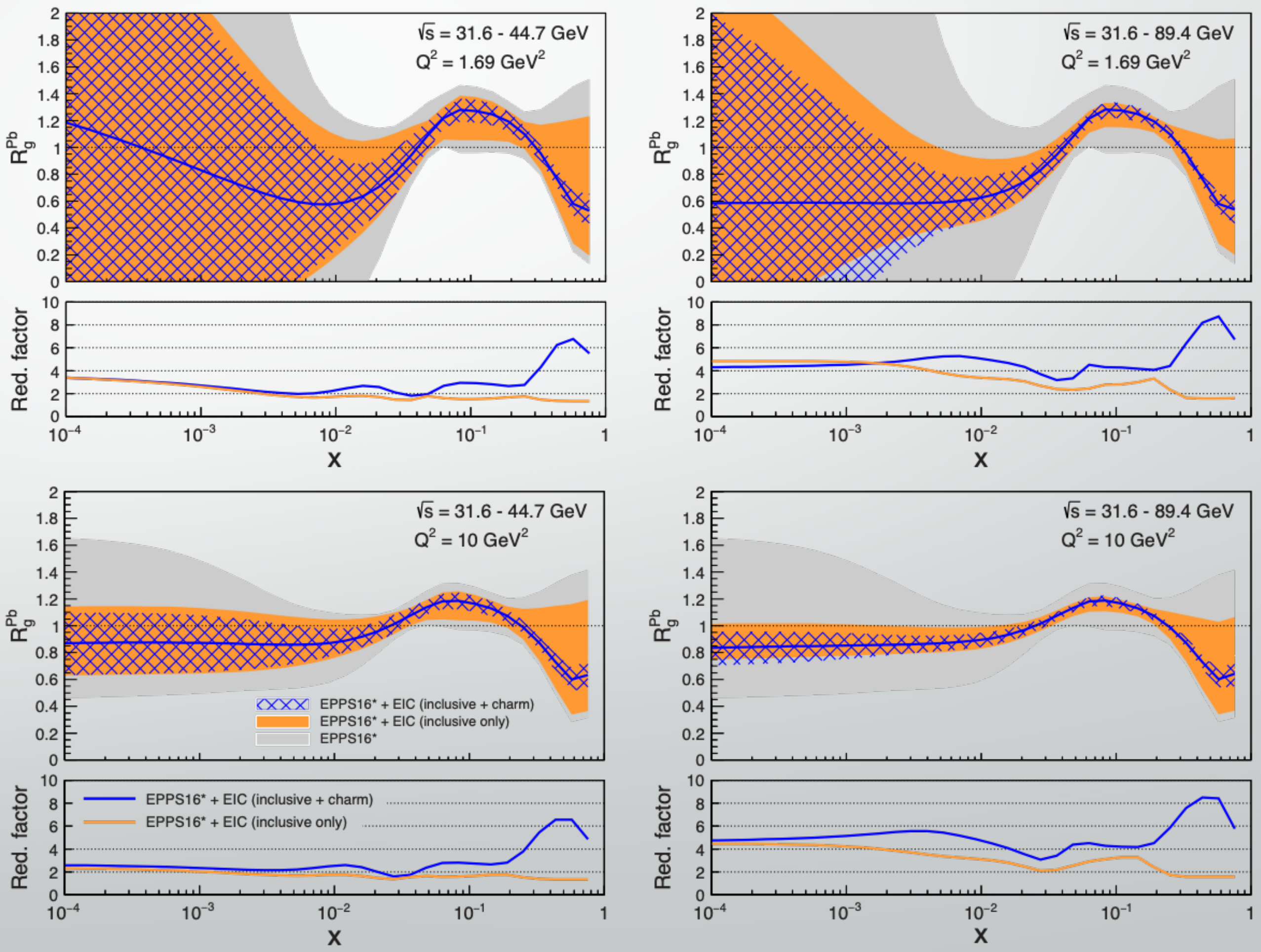
$$\frac{d^2\sigma^{eA\to eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2)\right]$$

Measurements of the structure functions and their evolution at EIC will allow precise extraction of nPDFs together with extending F_2 and F_L into low-x regime relevant for gluon saturation

eA: Nuclear PDF effects

- 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
- Provides critical input on initial state for heavy ion collisions

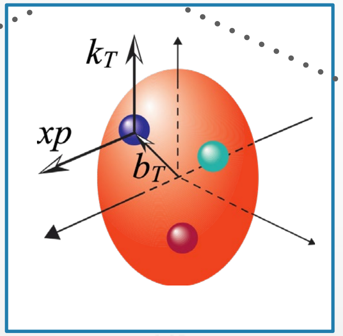
arXiv:1708.01527



PDF Complexity

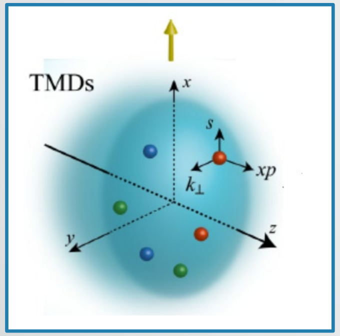
arXiv:1212.1701

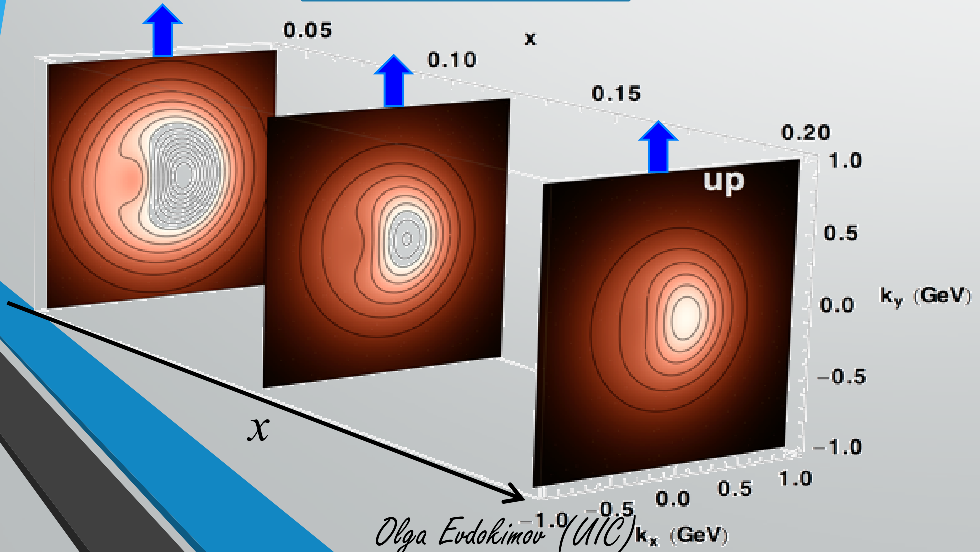
- Wigner Functions $W(x, k_T, b_T)$



$\int d^2 b_T$

Transverse Momentum Dependent distributions



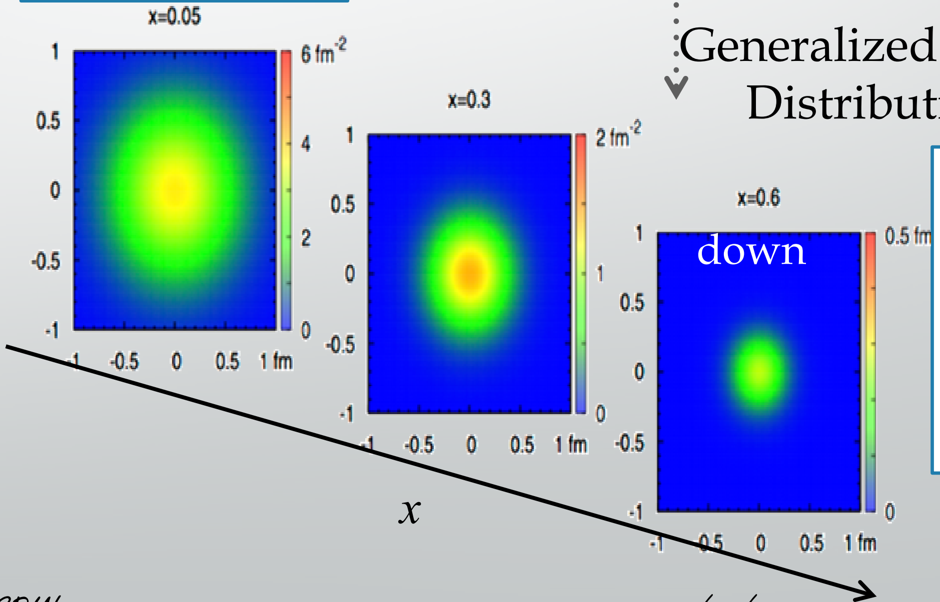


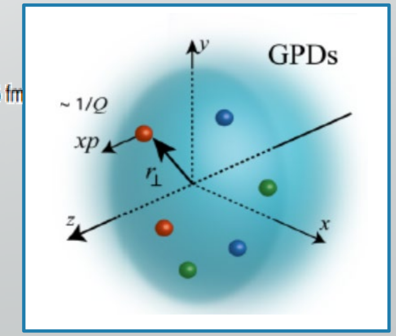
$\int d^2 k_T$

Impact Parameter Dependent distributions $f(x, b_T)$

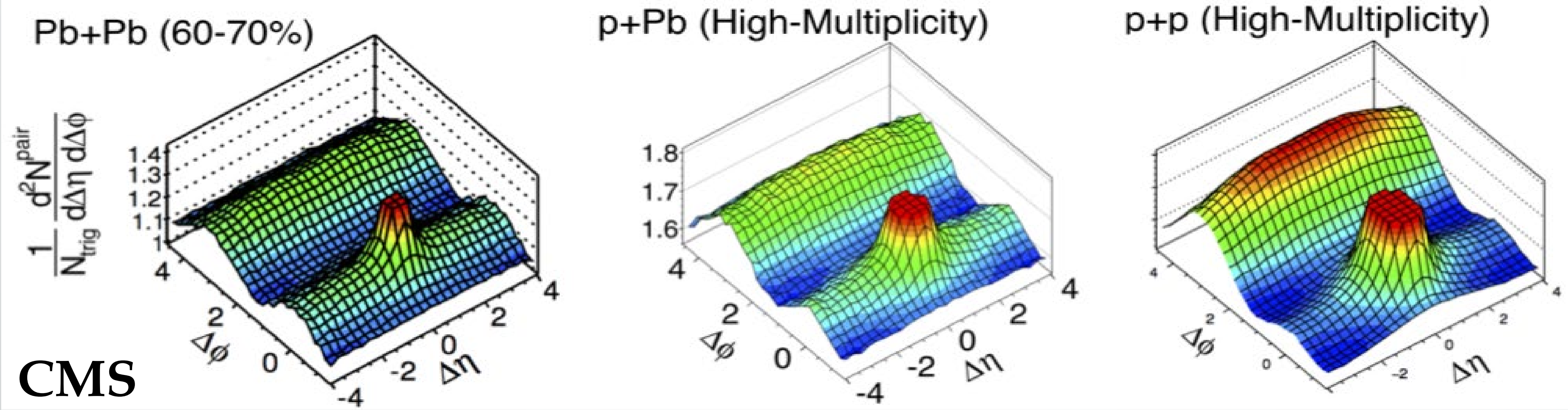
Fourier Transform

Generalized Parton Distributions

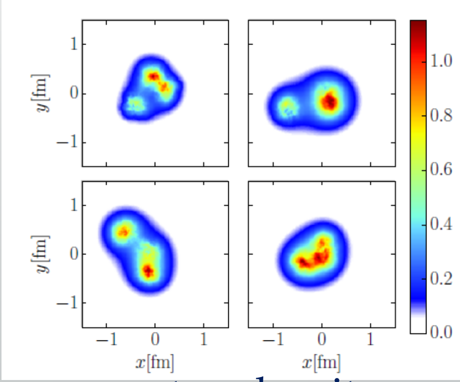




eA: Collective Phenomena in Small Systems



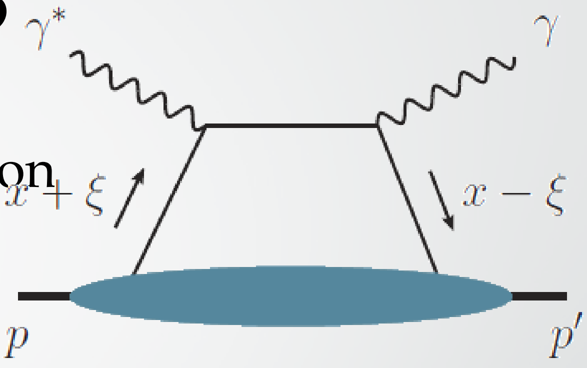
PRD 94(2016)034042



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 testing QGP formation in small systems

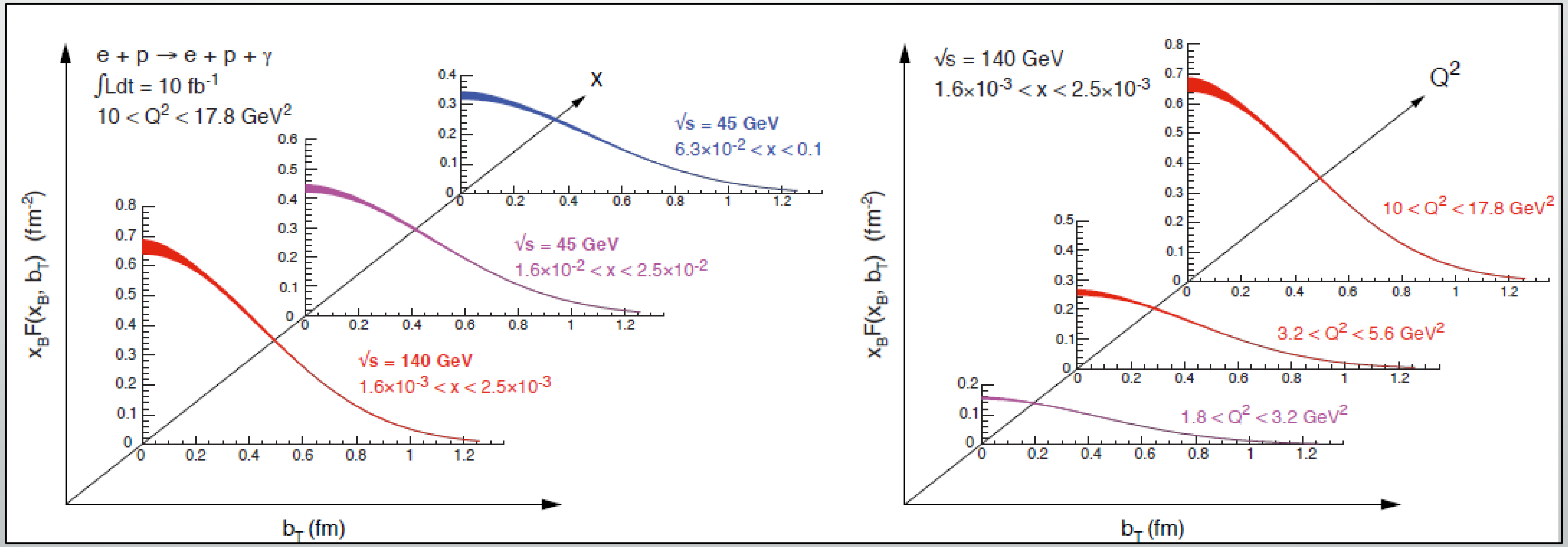
EIC: 2D Spatial Imaging



- 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

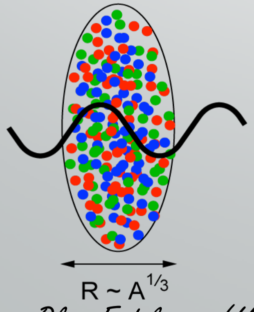
arXiv:1708.01527

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



EIC eA: Gluon Saturation

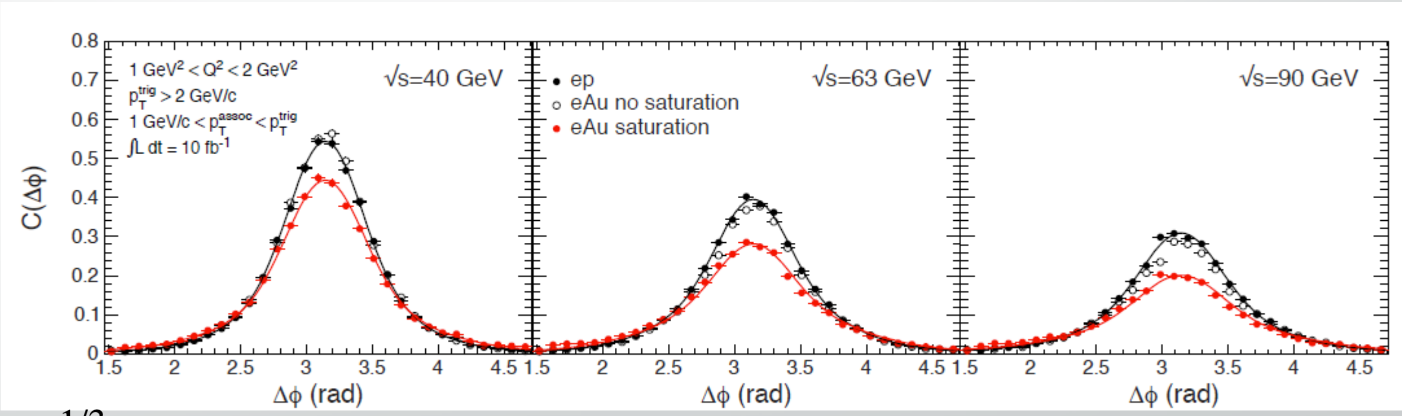
- Could the gluon density G(x, Q^2) continuously grow?
- New idea: Non-Linear Evolution
  - Recombination compensates gluon splitting
  - New evolution equations
  - Saturation of gluon densities characterized by scale $Q_s(x)$
- Saturation → Color-Glass-Condensate (CGC)
- Experimentally, nucleus serves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



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

- 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

EIC Users Group

EICUG Annual Meetings

2016 UC Berkeley, CA

2016 Argonne, IL

2017 Trieste, Italy

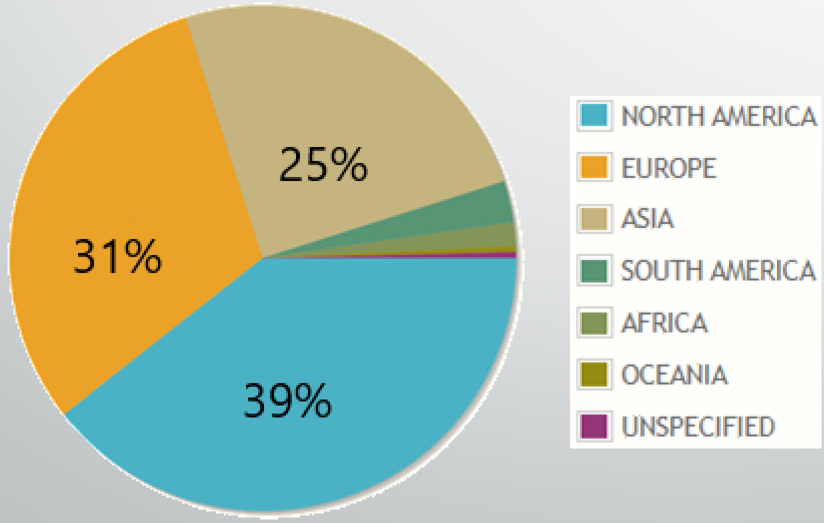
2018 Washington, DC

2019 Paris, France

2020 Miami, FL

2021 VVU/UCR

2022 Warsaw, Poland



EIC User Group:

- 1296 members
- 264 institutions
- 36 countries (7 world regions)

Community Effort to Define EIC Detector

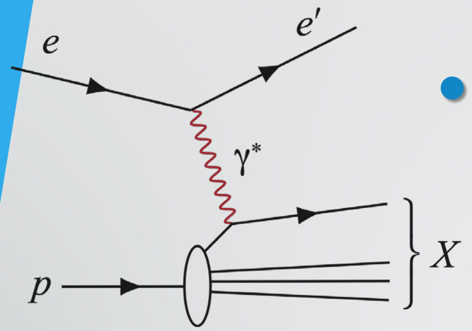
- Major effort in 2019-2021: the Yellow Report
- After EIC CD0, EICUG announced the start of a Yellow Report study in preparation of the EIC program:
- Quantify physics measurements for existing or new physics topics and implications for detector design ("Physics WG")
- Study detector concepts based on the requirements defined above, and quantify implications for physics measurements ("Detector WG")

- A year-long effort with 4 dedicated Yellow Report workshops:
  - 1st YR Workshop: March 19-21, 2020: Temple University, US
  - 2nd YR Workshop: May 22-24, 2020: INFN Pavia, Italy
  - 3rd YR Workshop: September 17-19, 2020, CUA, Washington DC, US
  - 4th YR Workshop: November 19-21, 2020: UCB, Berkeley, US
- Yellow Report summarized the developed input for conceptual and technical design report

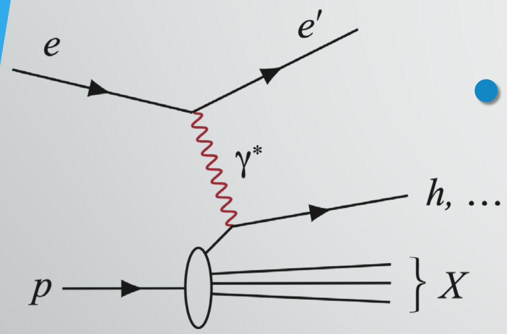
Community Effort to Define EIC Detector

- ~400 authors / ~150 institutions / ~900 pages with strong international contributions!
- Review, community input, and editorial process completed: https://arxiv.org/abs/2103.05419
- Best reference guide for EIC detector requirements and technologies

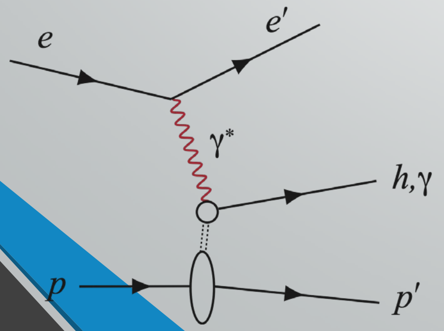
EIC Detector Requirements



- **Inclusive:** fine binning in x, Q^2



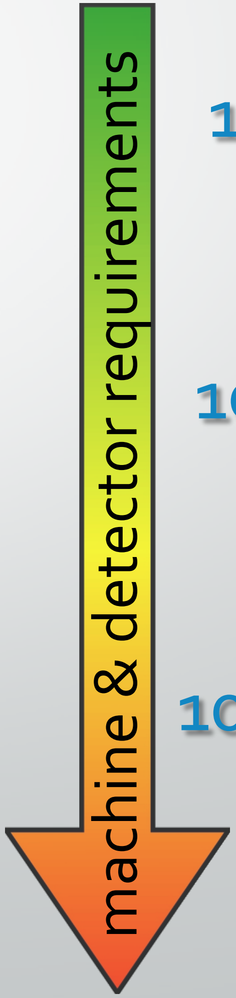
- **SIDIS:** 5-dimensional binning in x, Q², z, p_T, θ



- **Exclusive:** 4-dimensional binning in x, Q^2, t, θ

- Hermetic coverage, e ID, reaching lowest x, Q^2
- Hadron PID over wide range is critical
- Forward, backward region is key

$\int \mathcal{L}dt$

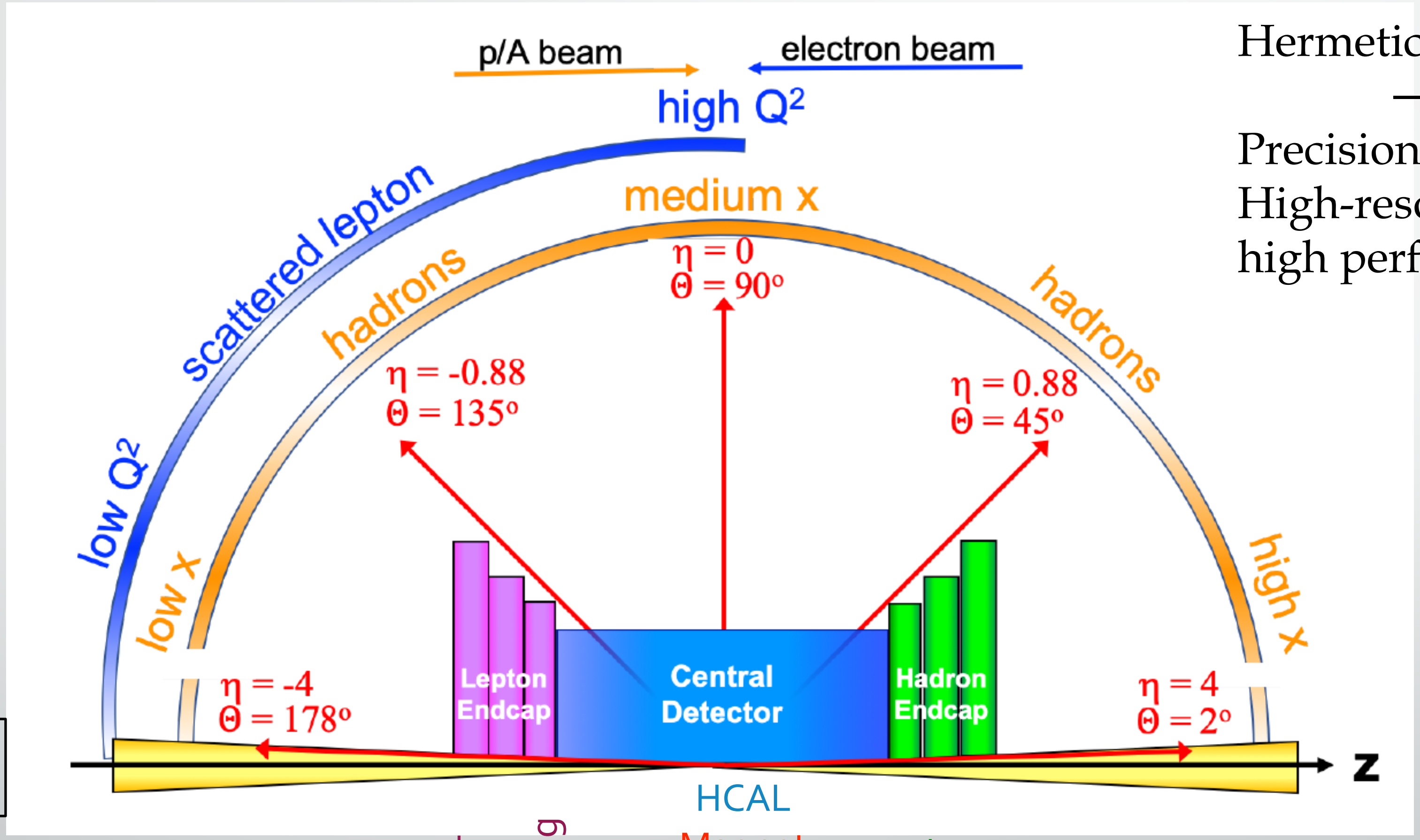


1 fb^{-1}

10 fb^{-1}

10-100 fb^{-1}

EIC General Purpose Detector Schematics



Hermetic coverage

$$-4.0 \lesssim \eta \lesssim 4.0$$

Precision low mass tracking
High-resolution calorimetry
high performance PID

very low Q^2
scattered lepton

Bethe-Heitler
photons
for luminosity

Luminosity Detector

Low Q^2-Tagger

HCAL
EMCAL
PID
Tracking

HCAL
Magnet
EMCAL
PID
Tracking
Vertexing

Tracking
PID
EMCAL
HCAL

particles from nuclear
breakup and
from diffractive reactions

ZDC

Forward Tracking

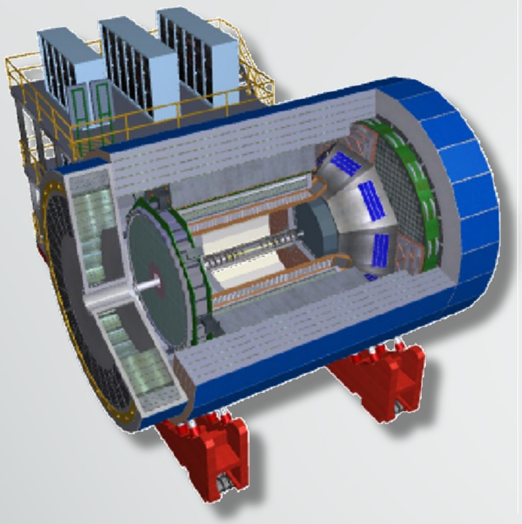
EIC Now and Next Steps

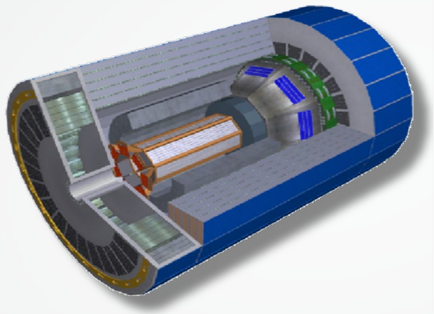
- Part 1 (40 pages): Science and performance estimation of conceptual detector design together with technology choices, R&D needs, and risks
- Part 2 (20 pages): Collaboration roster and structure, timescale, and cost

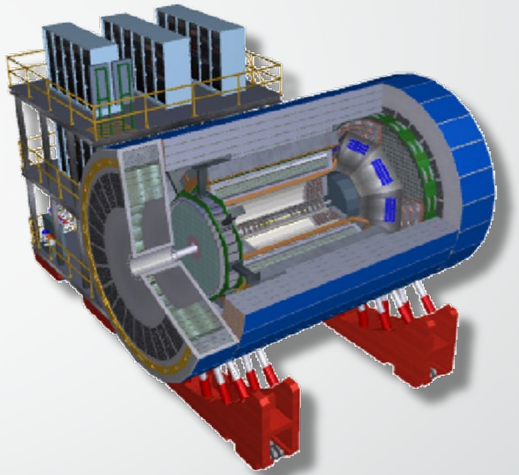
Milestone	Date
Call for Detector Proposals	March 12, 2021
Detector Proposals Due	December 1, 2021
Selection of Project Detector	March, 2022
Agreements for In-kind	Mid 2022
Goal for CD-2 Approval	Q1FY2023
Goal for CD-3 Approval	Q4FY2023

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

EIC Now and Next Steps







ATHENA: **A** **T**otally **H**ermetic **E**lectron-**N**ucleus **A**pparatus

Concept: General purpose detector inspired by YR with a new central magnet of up to 3T

https://www.athena-eic.org

CORE: **CO**mpact detecto**R** for the **E**ic

Concept: Nearly hermetic, general-purpose compact detector, 2T baseline

https://userweb.jlab.org/~hyde/EIC-CORE/

ECCE: **E**IC **C**omprehensive **C**hromodynamics **E**xperiment

Concept: General purpose detector based on 1.5T BaBar magnet

https://www.ecce-eic.org

Summary and Outlook

- The scientific case for the EIC has been in developed for over two decades of efforts of nuclear physics community
- An Electron-Ion Collider will be a new collider facility capable of revolutionizing our knowledge of QCD in the next decades
- The machine design well established: meets all the requirements on 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
- EIC Detectors requirements are challenging: Hermiticity (forward and backward coverage) & Precision
- EIC R&D program is a vital part of the EIC efforts: many technologies at hand or within reach (many ideas for future)
- Physics requirements and detector concepts developed for Yellow Report
- International participation is expected and welcome in all aspects of accelerator and detector developments

Thank you!

The UIC Group's work is supported by DOE-NP