Physics at the Electron-Ion Collider (EIC)

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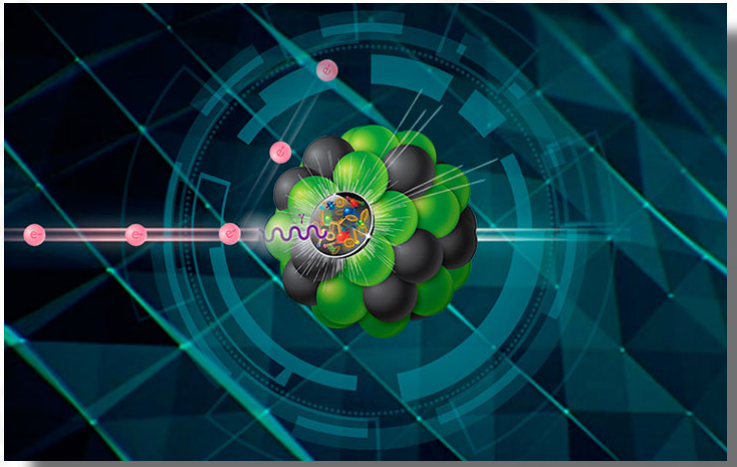
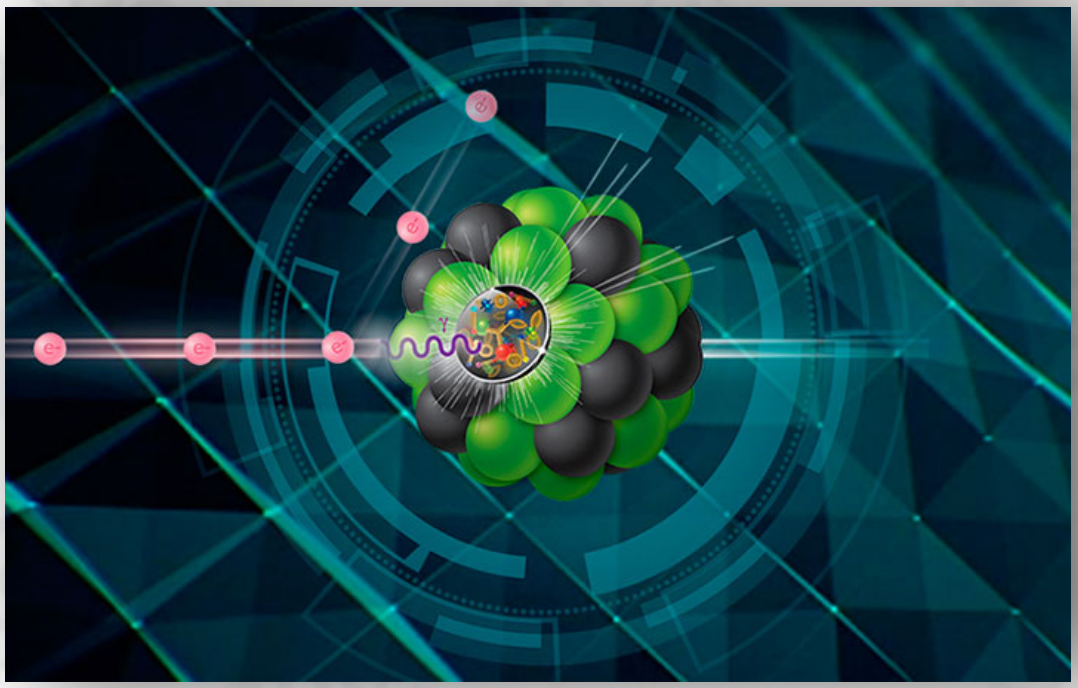


U.S. DEPARTMENT OF ENERGY | Office of Science

DOE NP contract: DE-SC0013405

Outline

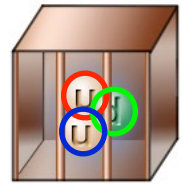
- Theoretical foundation
- EIC physics case development
- Selected EIC Physics Pillars
  - Global properties: Mass & Spin
  - Nucleon 3D structure
  - Low-x physics
- Summary



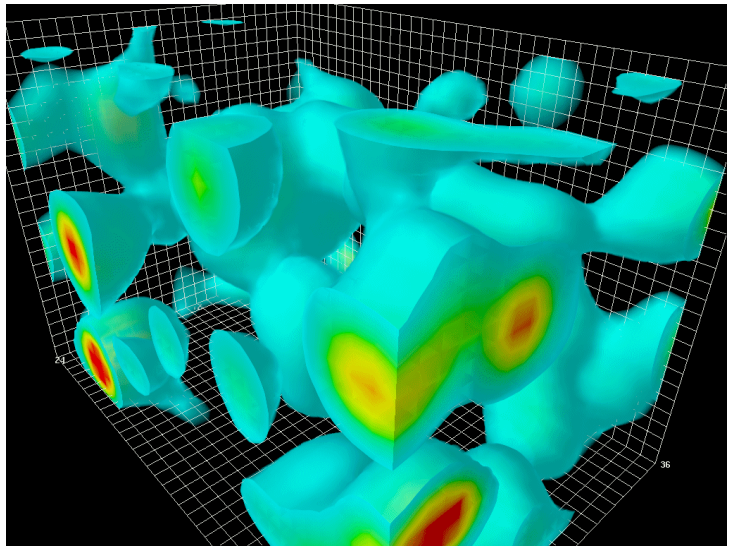
Theoretical foundation

- EIC - A QCD lab to explore the structure and dynamics of the visible world

$$\mathcal{L}_{QCD} = \sum_{j=1}^{n_f} \bar{\psi}_j \left(i D_\mu \gamma^\mu - m_j \right) \psi_j - \frac{1}{4} \operatorname{Tr} G^{\mu\nu} G_{\mu\nu}$$



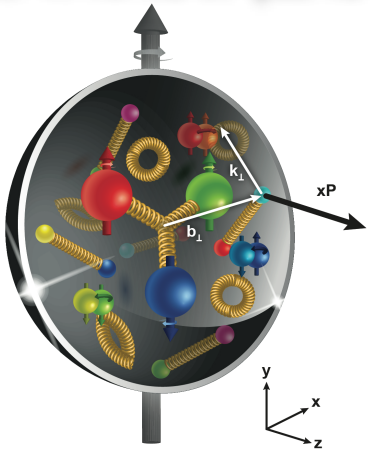
- Interactions arise from fundamental symmetry principles: $SU(3)_c$
- Properties of visible universe such as mass and spin (e.g. proton): Emergent through complex structure of the QCD vacuum



D. Leinweber: Quantum fluctuations in gluon fields

Major goal:

Understanding QCD interactions and emergence of hadronic and nuclear matter in terms of quarks and gluons



Essential elements looking forward:

1) Tomography of hadrons and nuclear matter in terms of quarks and gluons

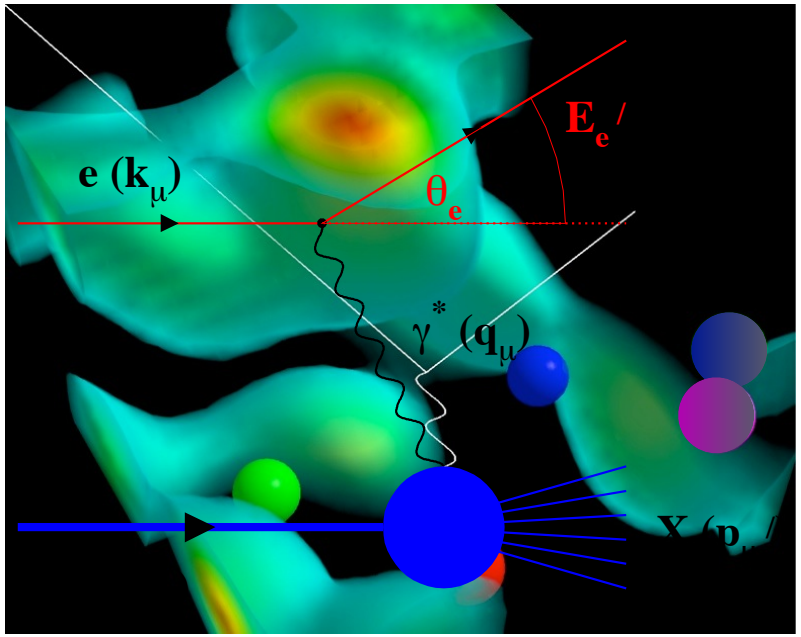
2) Synergy of experimental progress and theory

Theoretical foundation

DIS - Kinematics

$$k = \begin{pmatrix} E_e \\ 0 \\ 0 \\ -E_e \end{pmatrix}$$

$$p = \begin{pmatrix} E_P \\ 0 \\ 0 \\ E_P \end{pmatrix}$$



$$k' = \begin{pmatrix} E'_e \\ E'_e \sin\theta'_e \cos\phi'_e \\ E'_e \sin\theta'_e \sin\phi'_e \\ E'_e \cos\theta'_e \end{pmatrix}$$

$$p' = \begin{pmatrix} \sum_h E_h \\ \sum_h p_{X,h} \\ \sum_h p_{Y,h} \\ \sum_h p_{Z,h} \end{pmatrix}$$

$$Q^2 = -(k - k')^2 = -q^2$$

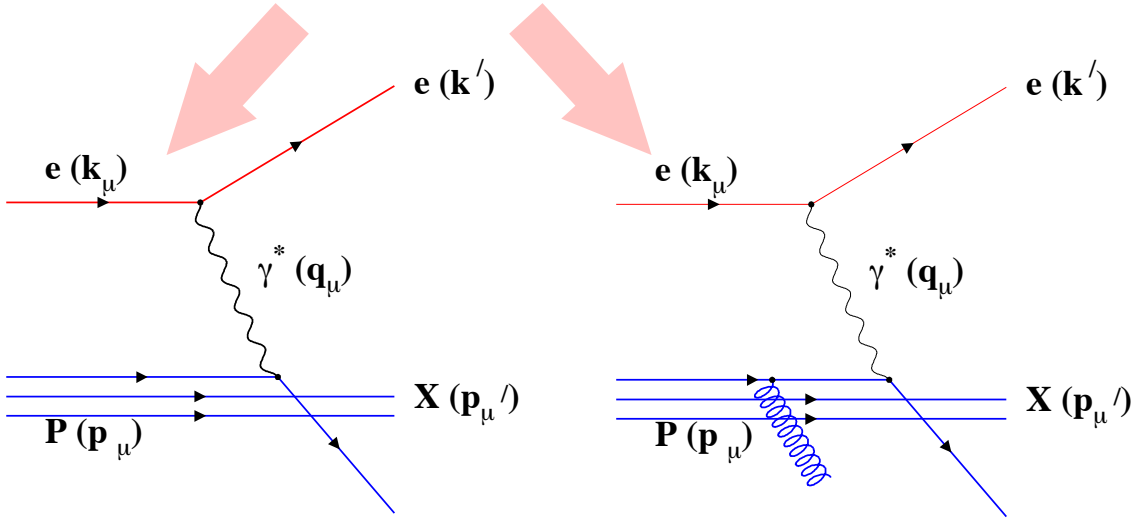
Measure of resolution power

$$x = \frac{Q^2}{2(p \cdot q)}$$

Measure of momentum fraction by struck quark

$$y = \frac{p \cdot q}{p \cdot k}$$

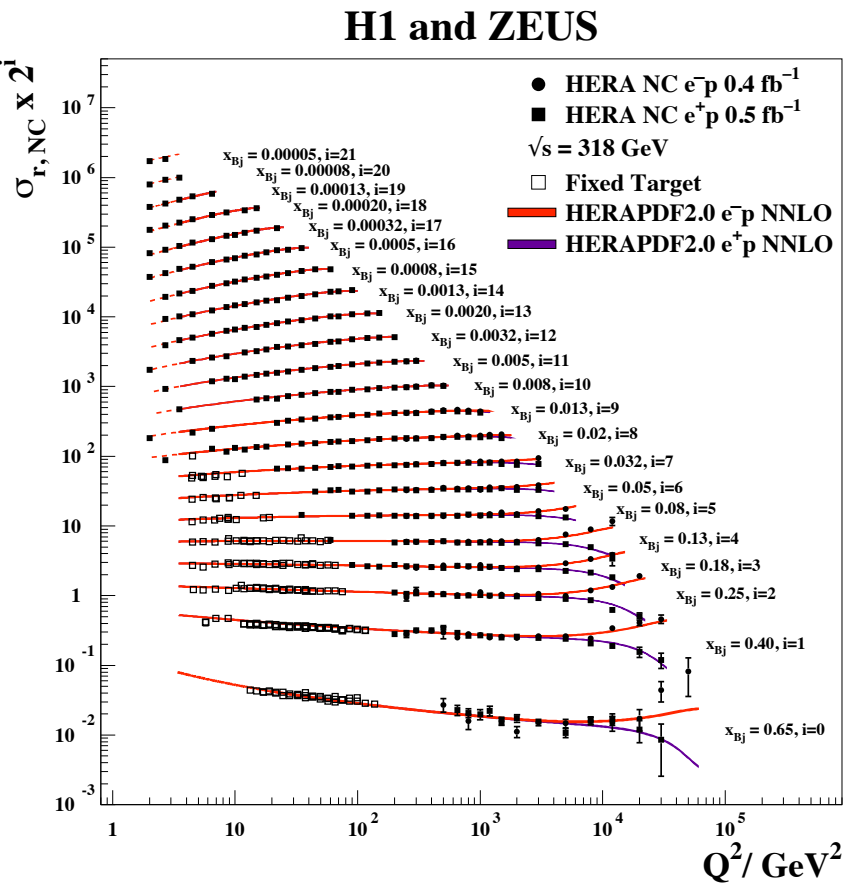
Measure of inelasticity



Theoretical foundation

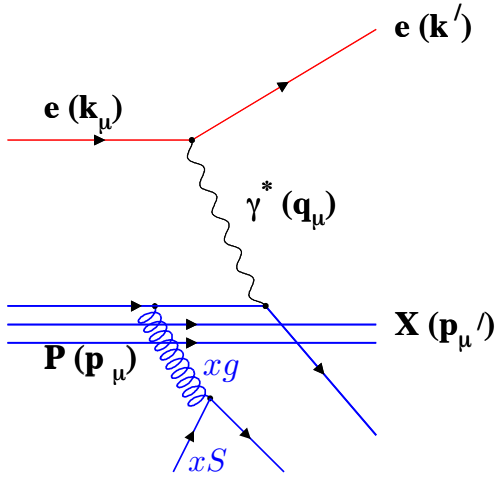
DIS - Parton structure: Unpolarized

H1 and ZEUS Collaborations (H. Abramowicz et al.), Eur.Phys.J. C75 (2015) no.12, 580.

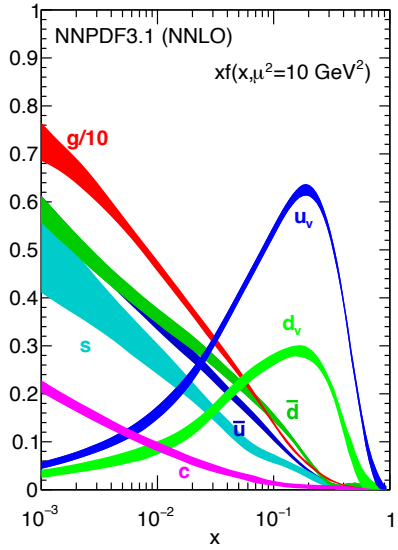


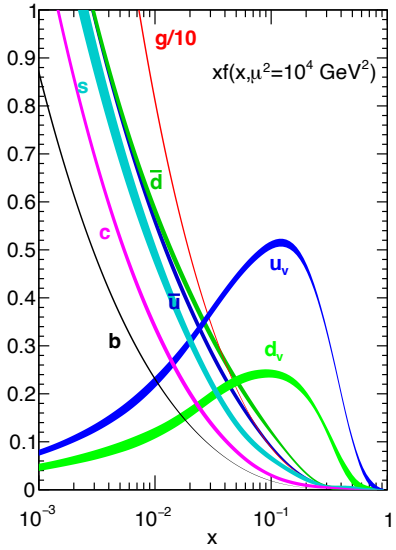
$$d\sigma_{eP} \propto F_2^P = \sum_i e_i^2 \, x \, (q_i + \bar{q}_i)$$

1990: J. I. Friedman, H. W. Kendall and R. E. Taylor: "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics."

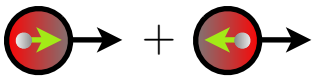


R. D. Ball et al., EPJ C77 (2017) 663.





$$f(x) =$$



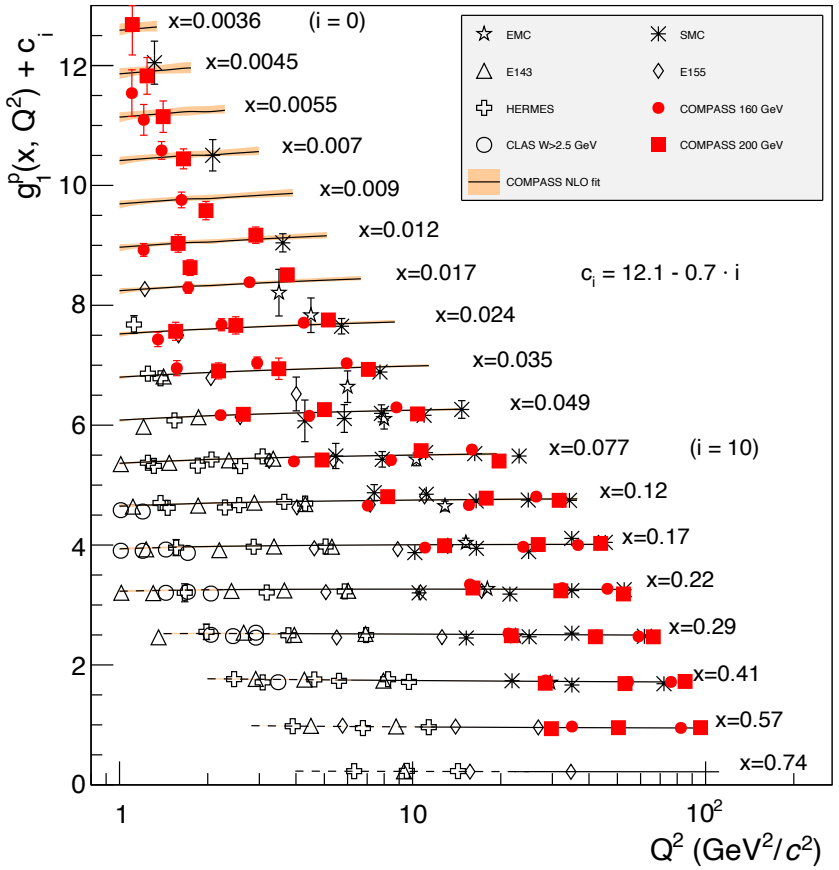
$$f^+(x) + f^-(x)$$

Measure of probability to find parton f with longitudinal momentum fraction x

Theoretical foundation

DIS - Parton structure: Polarized

COMPASS Collaboration (C. Adolph et al.), Phys.Lett. B753 (2016) 18.



$$g_1^P = \frac{1}{2}\sum_i e_i^2 \left(\Delta q_i + \Delta \bar{q}_i\right)$$

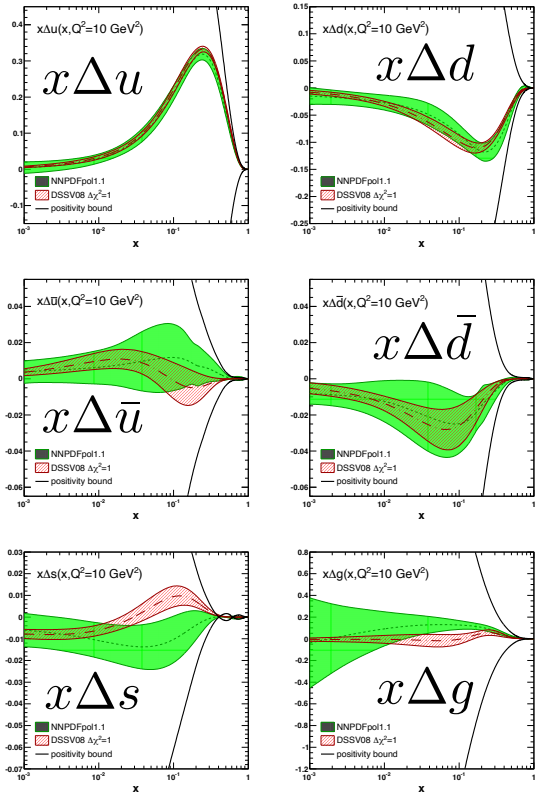
$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{} + \underbrace{\Delta G}_{} + \langle L_q \rangle + \langle L_g \rangle$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

$$\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x, Q^2) dx$$

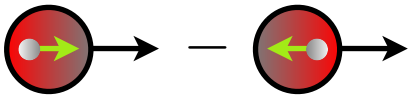
$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$

(R.L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990))



NNPDF Collaboration (Emanuele R. Nocera et al.), Nucl.Phys. B887 (2014) 276-308

$$\Delta f(x) =$$



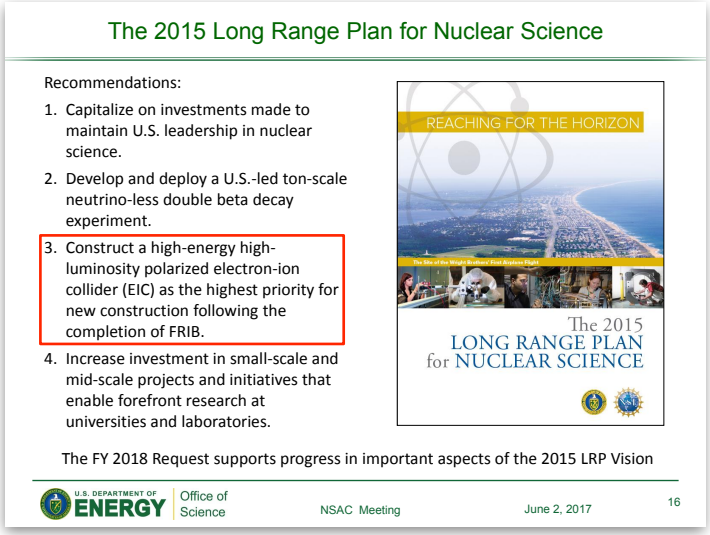
$$f^+(x) - f^-(x)$$

Measure of probability to find parton f with spin aligned to anti-anti-aligned to proton spin at momentum fraction x

EIC physics case development

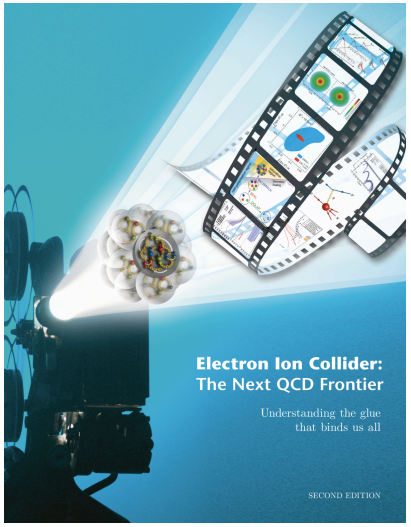
- Critical steps over the last couple of years - 1
  - INT Workshop series / Documentation of Physics Case - Whitepaper: "Understanding the glue that binds us all!"
    - INT Workshop: 2010
    - WP: 2012, updated in 2014 for LRP
  - 2015 Long-range plan (LRP):

T. Hallman



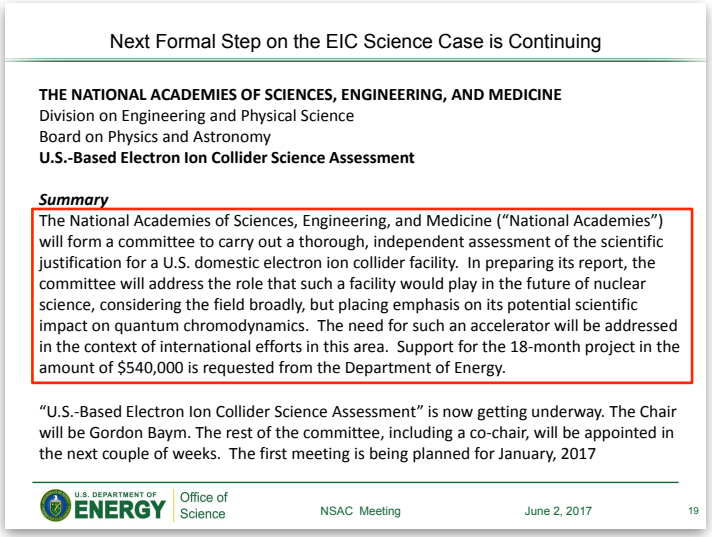
  - Request to review EIC Science Case by National Academy of Sciences, Engineering, and Medicine (NAS)

arXiv:1212.1701



Understanding the glue that binds as all!

T. Hallman

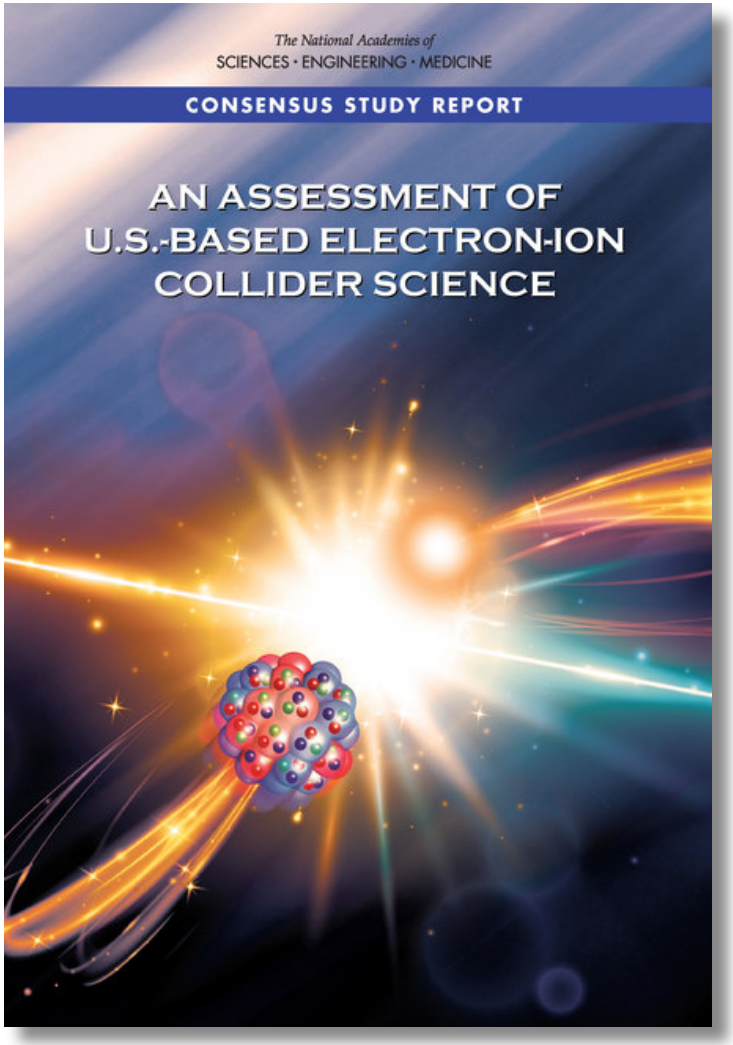


EIC physics case development

- NAS Webinar and NAS report release: 07/24/2018

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

Download pdf-file of final report!



- Webinar on Tuesday, July 24, 2018 - Public presentation and report release
- Gordon Baym (Co-chair): Webinar presentation

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

- Slides from Webinar: https://www.nap.edu/resource/25171/eic-public-briefing-slides.pdf
- Glowing" report on a US-based EIC facility!

EIC physics case development

- Volume 1-3: Executive Summary / Physics / Detector

arXiv:2103.05419

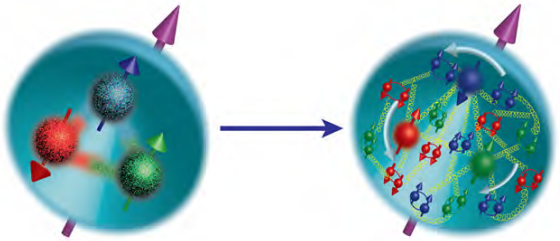
- ~400 authors / ~150 institutions / ~900 pages with strong international contributions!
- Review: Community review within EICUG and external readers (~30) worldwide covering physics and detector expert fields!
- Available on archive: https://arxiv.org/abs/2103.05419 / Planned publication!

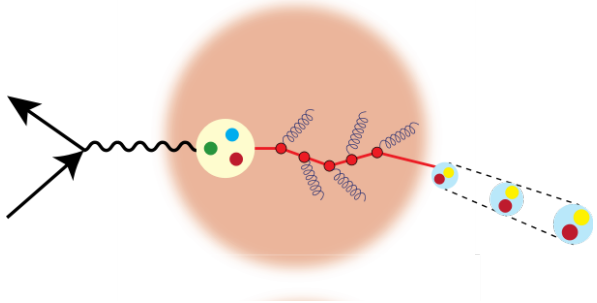
EIC Physics Pillars

Motivation - EIC program

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?





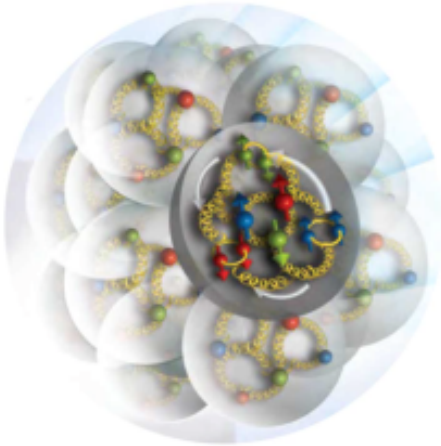
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

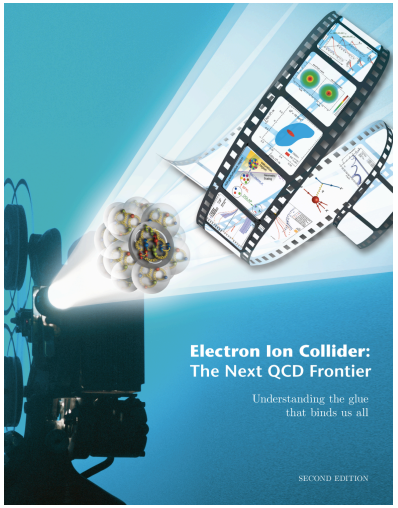
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



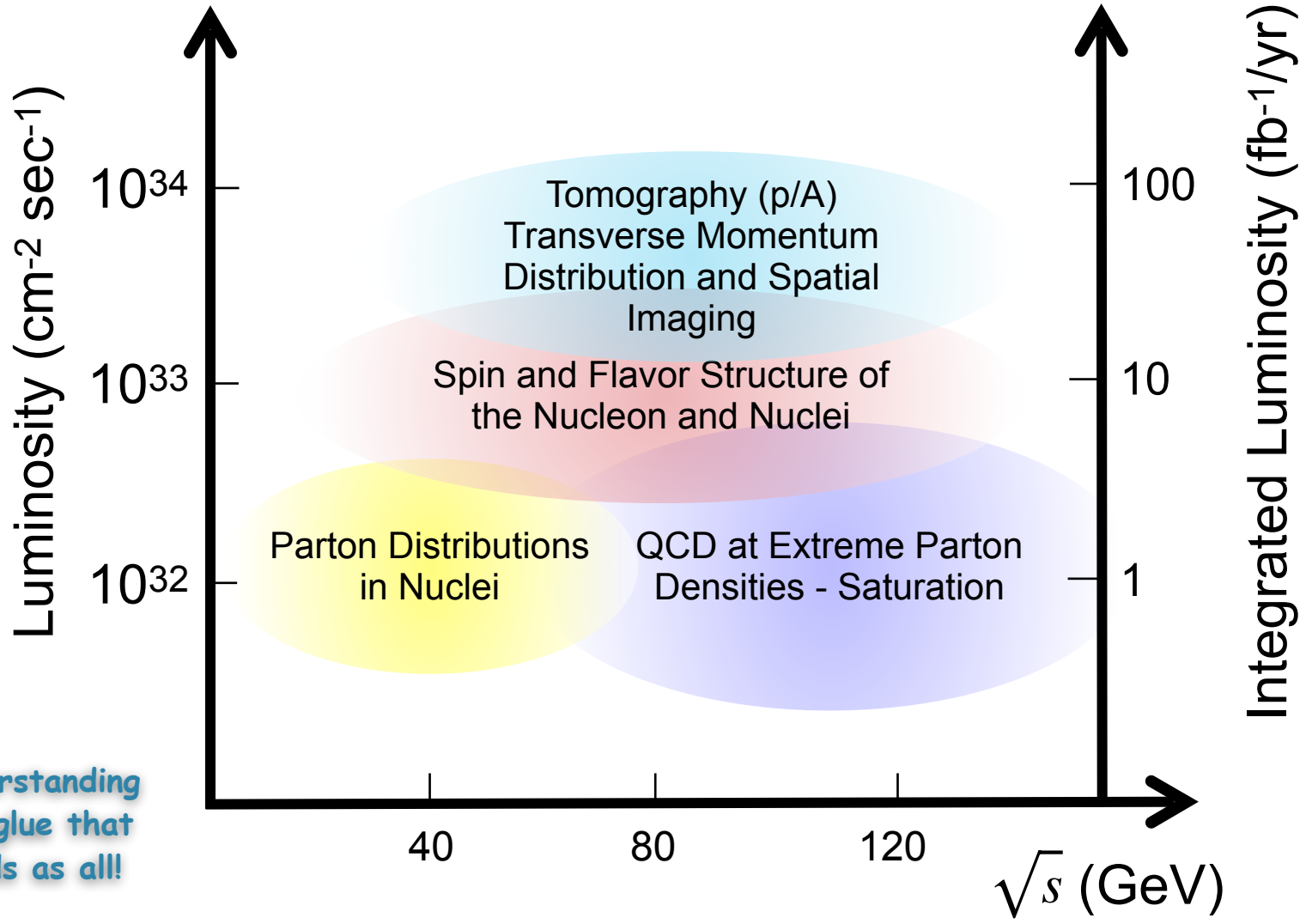
EIC Physics Pillars

- EIC: Study structure and dynamics of matter at high luminosity, high energy with polarized beams and wide range of nuclei
- Whitepaper:

arXiv:1212.1701

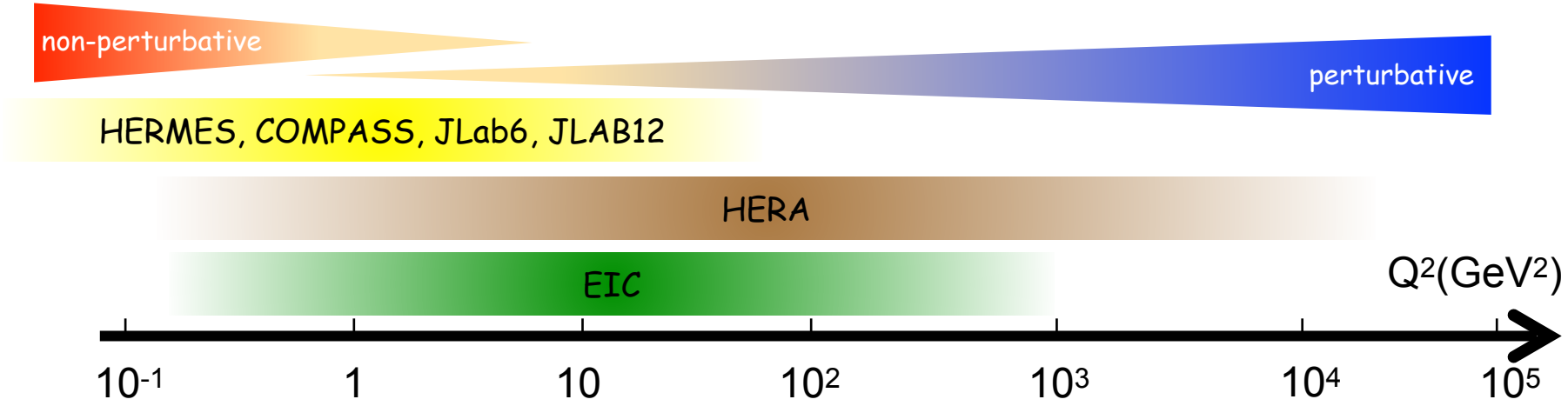


Understanding the glue that binds as all!



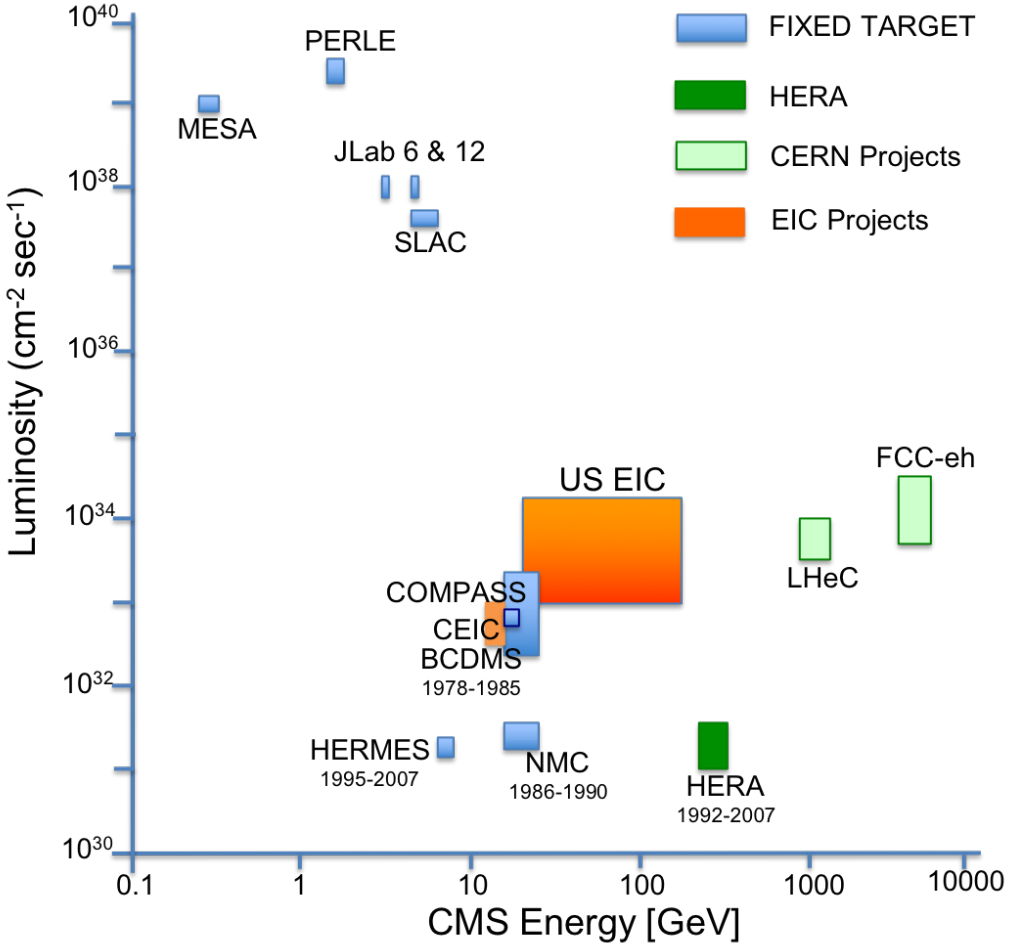
EIC Physics Pillars

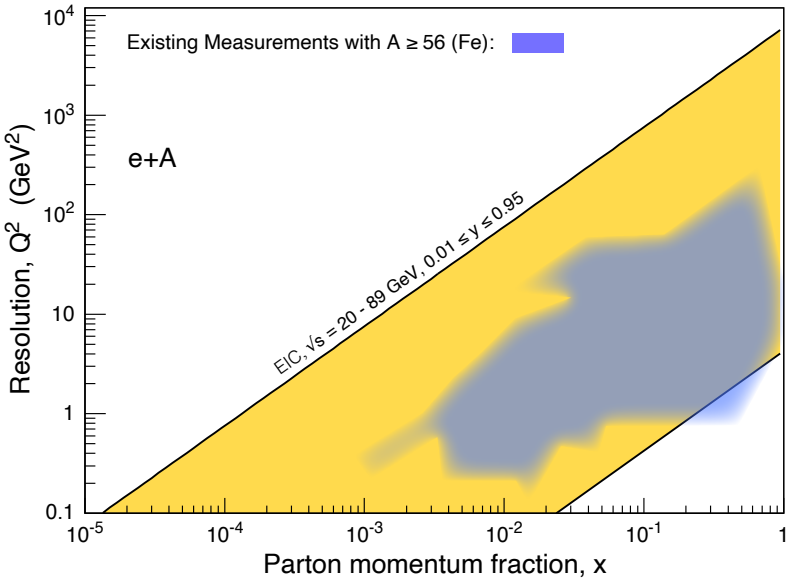
- Requirements
  - Machine:
    - High luminosity: 10^{33}cm^{-2}s^{-1} - 10^{34}cm^{-2}s^{-1} / 10-100 fb^{-1}/year
    - Flexible center-of-mass energy $\sqrt{s} = \sqrt{4\,E_e\,E_p}$: Wide kinematic range $Q^2 = s\,x\,y$
    - Highly polarized electron (0.7) and proton / light ion (0.7) beams: Spin structure studies
    - Wide range of nuclear beams (d to Pb/U): High gluon density
  - Detector:
    - Wide acceptance detector system including particle ID (e/h separation & π, K, p ID - flavor tagging)
    - Instrumentation for tagging of protons from elastic reactions and neutrons from nuclear breakup: Target / nuclear fragments in addition to low Q^2 tagger / polarimetry and luminosity (abs. and rel.) measurement



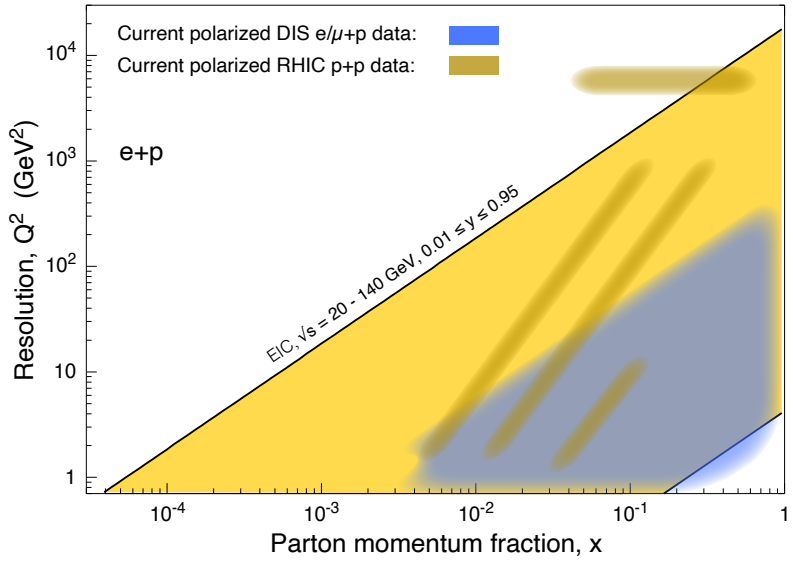
EIC Physics Pillars

- Luminosity / $\sqrt{s}$ / Kinematic coverage





eA



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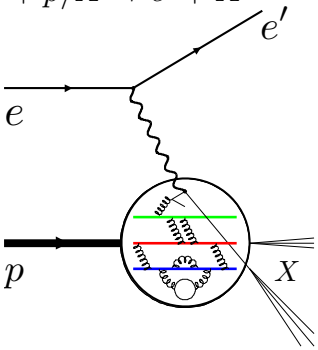
EIC Physics Pillars

Overview of processes and final states

$e + p/A \rightarrow e' + X$

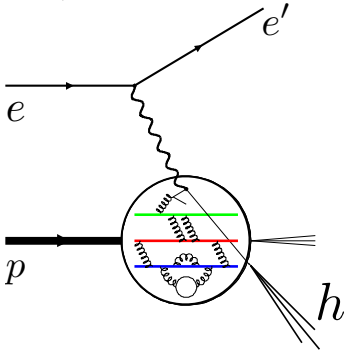


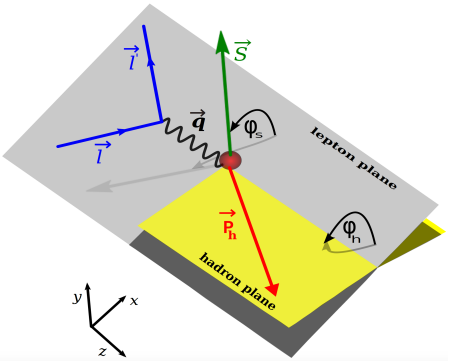
Inclusive DIS

- Inclusive: Unpolarized $f_i(x,Q^2)$ and helicity distribution $\Delta f_i(x,Q^2)$ functions through unpolarized and polarized structure function measurements (F_2, F_L, g_1)
- Define kinematics (x, y, Q^2) through electron (e-ID and energy+angular measurement critical) / hadron final state or combination of both depending on kinematic x-Q^2 region

Semi-Inclusive DIS (SDIS)

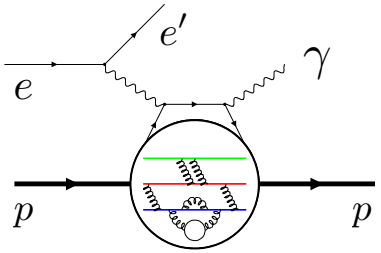
$e + p/A \rightarrow e' + h + X$





- SDIS: Flavor tagging through hadron identification studying FF / TMD's (Transverse momentum, k_T, dependence) requiring azimuthal asymmetry measurement - Full azimuthal acceptance
- Heavy flavor (charm / bottom): Excellent secondary vertex reconstruction

$e + p/A \rightarrow e' + N'/A' + \gamma/m$



Deeply-Virtual Compton Scattering (DVCS)

- Exclusive: Tagging of final state proton using Roman pot system studying GPD's (Impact parameter, b_T, dependence) using DVCS and VM production
- eA: Impact parameter determination / Neutron tagging using Zero-Degree Calorimeter (ZDC)

EIC Physics Pillars

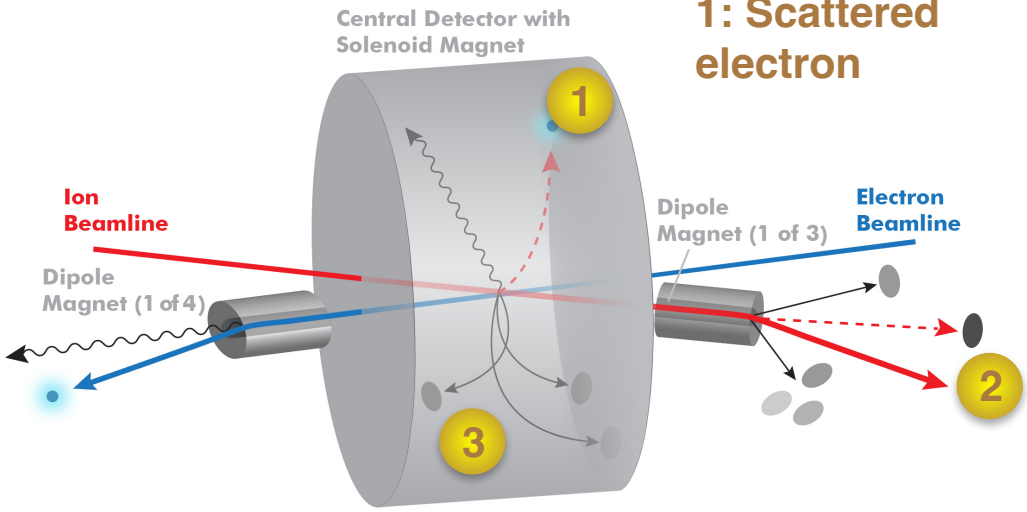
- Overview of general detector requirements

arXiv:2103.05419

1: Scattered electron

3: Nuclear and nucleonic fragments / scattered proton

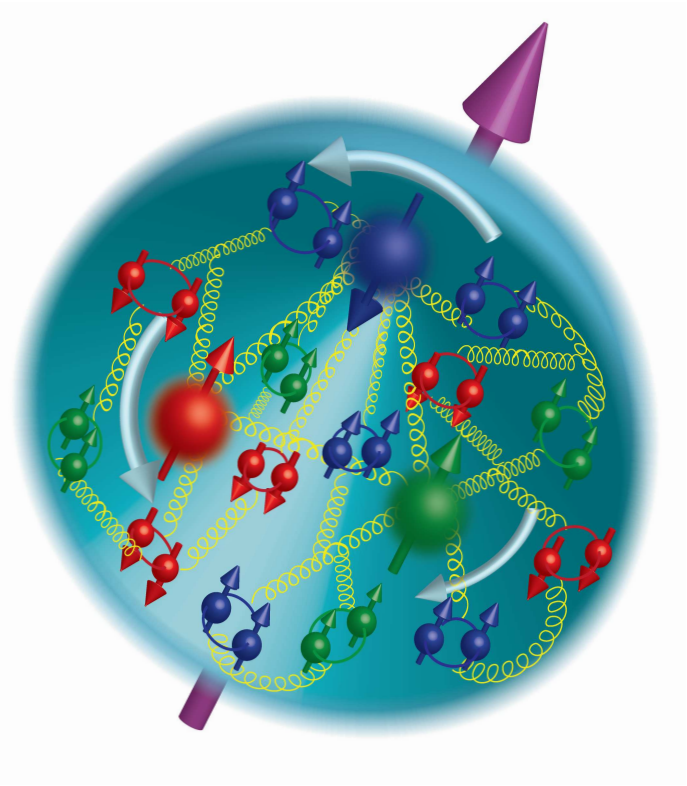
2: Fragmented particles (e.g. π, K, p) of struck quark



- Acceptance: Close to 4π coverage with a η-coverage (η = -ln(tan(θ/2)) of approximately η < |4| combined calorimetry (EM CAL and hadron CAL at least in forward direction) and tracking coverage
- Low dead material budget in particular in rear direction (~5% X/X_0)
- Good momentum resolution Δp/p ~ few %
- Electron ID for e/h separation varies with θ / η at the level of 1:10^4 / ~2%/√E for η<-2 and ~10%/√E for -2<η<1
- Particle ID for π/K/p separation over a wide momentum range (Forward η up to ~50GeV/c / Barrel η up to ~10GeV/c / Rear η up to ~7 GeV/c)
- High spatial vertex resolution ~ 10-20μm for vertex reconstruction
- Low-angel taggers:
  - Far Forward region: Proton (Roman pots) Neutron (Zero-Degree Calorimeter) detection
  - Far Backward region: Low Q^2 tagger
- Luminosity (Absolute and relative) and local polarization direction measurement

EIC Physics Pillars

Global properties: Mass



EIC Physics Pillars

Mass

A. Metz, Priv. com.

- Proton mass M - Relation to Energy-Momentum Tensor (EMT) $T^{\mu\nu}$

$$M = n\langle T^{\mu}_{\mu}\rangle = n\langle T^{00}\rangle\Big|_{P=0} \text{ with } n = \frac{1}{2M}$$

- Forward matrix element of $T^{\mu\nu}_{i\ R}$ (i=q,g): $\langle T^{\mu\nu}_{i\ R}\rangle = 2P^{\mu}P^{\nu}A_i(0) + 2M^2 g^{\mu\nu}\overline{C}_i(0)$

with gravitational form factors $A_i(0)$, $\overline{C}_i(0)$ at t=0. Conservation of EMT implies:

$$A_q(0) + A_g(0) = 0 \quad \overline{C}_q(0) + \overline{C}_g(0) = 0$$

- In the forward limit, $\langle T^{\mu\nu}_{i\ R}\rangle$ fully determined by two numbers!

EIC Physics Pillars

- Nucleon mass

A. Metz, Priv. com.

- Different sum rules based on a decomposition of T^{μ}_{μ} or T^{00}:
  - 2-term sum rule by Hatta, Rajan, and Tanaka : Decomposition of T^{μ}_{μ}

$$M = n\left(\langle (T_{q,\,R})^{\mu}_{\mu}\rangle + \langle (T_{g,\,R})^{\mu}_{\mu}\rangle\right)$$

Hatta, Rajan, Tanaka, JHEP 12 (2018) 008 / Tanaka, JHEP 01 (2019) 120

  - 2-term sum rule by Lorcé: Decomposition of T^{00}

$$M = n\left(\langle (T_{q,\,R})^{00}\rangle + \langle (T_{g,\,R})^{00}\rangle\right)$$

Lorcé, EPJC 78, 120 (2018)

  - 3-term sum rule by Rodini, Metz, Pasquini: Decomposition of T^{00}

$$M = n\left(\langle (\mathscr{H}_{q}\rangle + \langle (\mathscr{H}_{m}\rangle + \langle (\mathscr{H}_{g}\rangle\right)$$

Rodini, Metz, Pasquini, JHEP 09 (2020) 067 / Metz, Rodini, Pasquini, PRD 102 (2020) 114042

  - 4-term sum rule by Ji: Decomposition of T^{00}

$$M = n\left(\langle (\mathscr{H}_{q[Ji]}\rangle + \langle (\mathscr{H}_{m}\rangle + \langle (\mathscr{H}_{g[Ji]}\rangle + \langle (\mathscr{H}_{a}\rangle\right)$$

Ji, PRL 74, 1071 (1995) / PRD 52, 271 (1995)

Formulation in terms of two independent parameters reflecting

a) Parton momentum fraction and

b) Quark mass terms / relation to trace anomaly.

EIC: Constrain anomaly contribution (Gluon contr. to trace anomaly) through heavy quarkonium production!

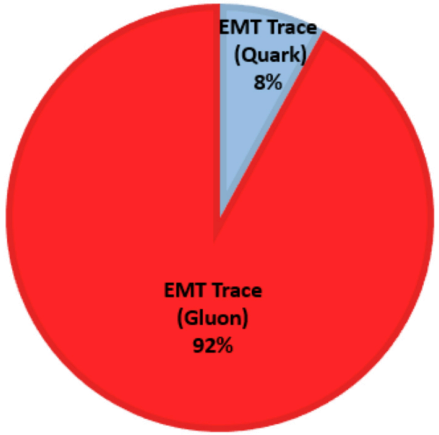
EIC Physics Pillars

- Comparison of different mass sum rules: D2 renormalization scheme

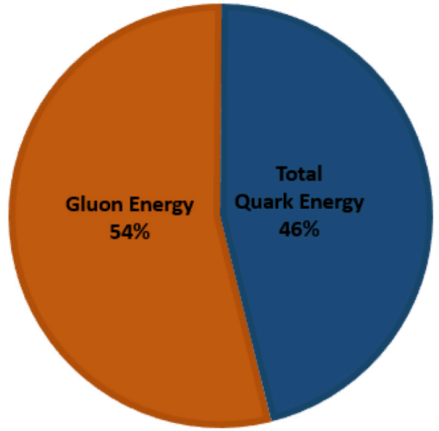
A. Metz, Priv. com.

2-term sum rule by Hatta, Rajan, and Tanaka

2 terms $T^{\mu}{}_{\mu}$



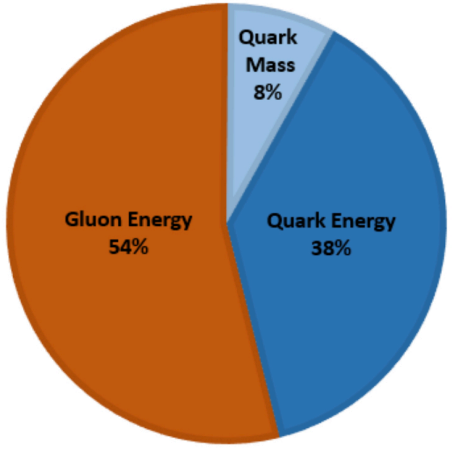
2 terms T^{00}



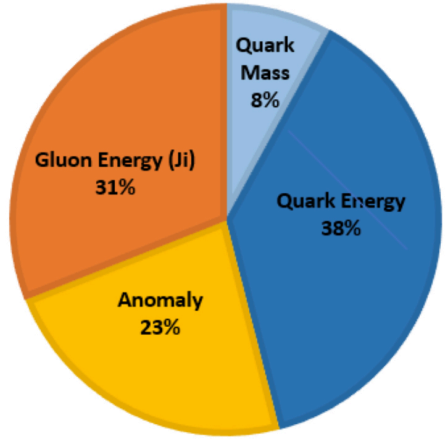
2-term sum rule by Lorcé

3-term sum rule by Rodini, Metz, Pasquini

3 terms T^{00}



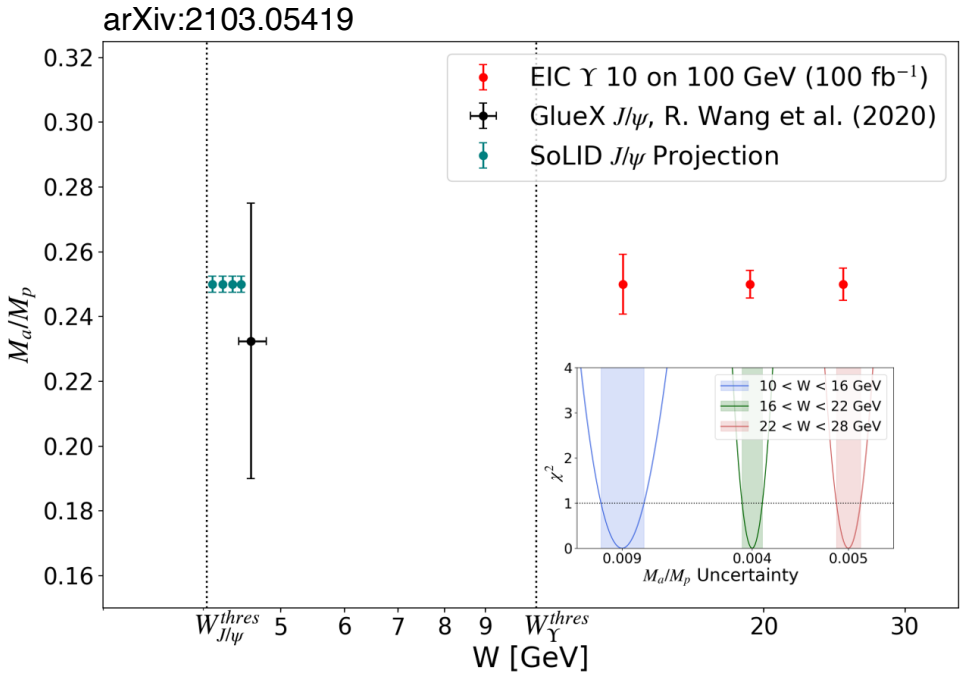
4 terms T^{00}

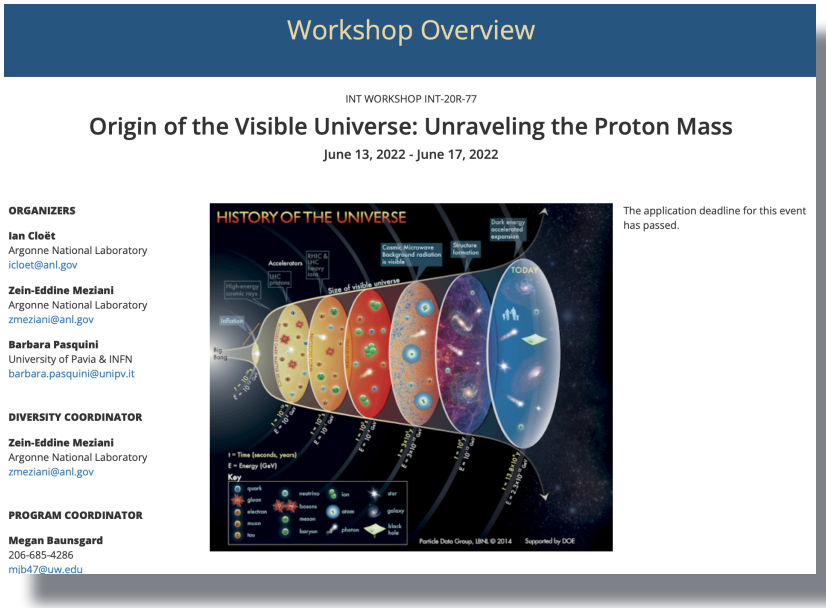


4-term sum rule by Ji

EIC Physics Pillars

- EIC constraint of anomaly to nucleon mass





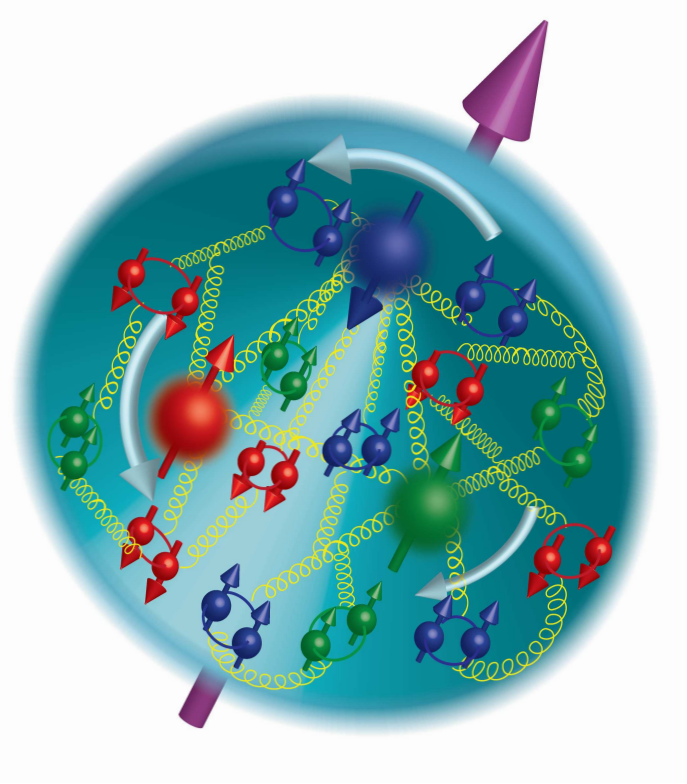
- First results from GlueX and anticipated SoLID experiment!

- INT workshop: "Origin of the Visible Universe: Unraveling the Proton Mass" June 13-17, 2022

  https://www.int.washington.edu/programs-and-workshops/20r-77

EIC Physics Pillars

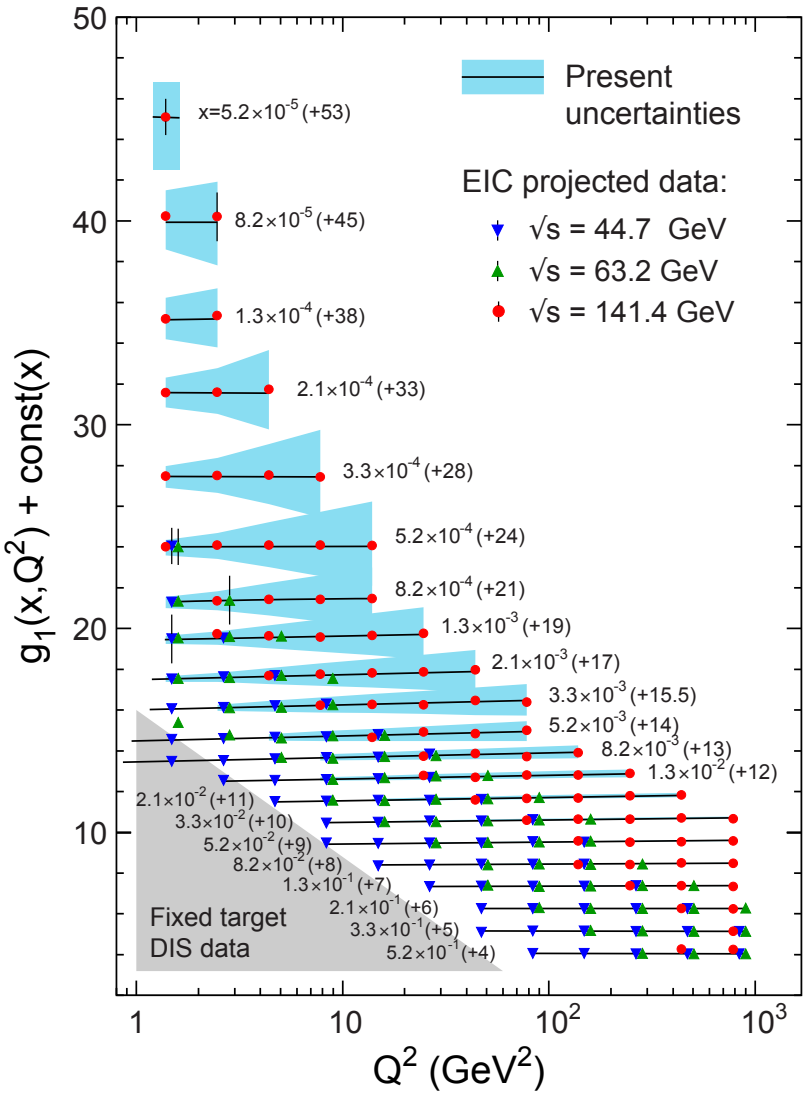
Global properties: Spin

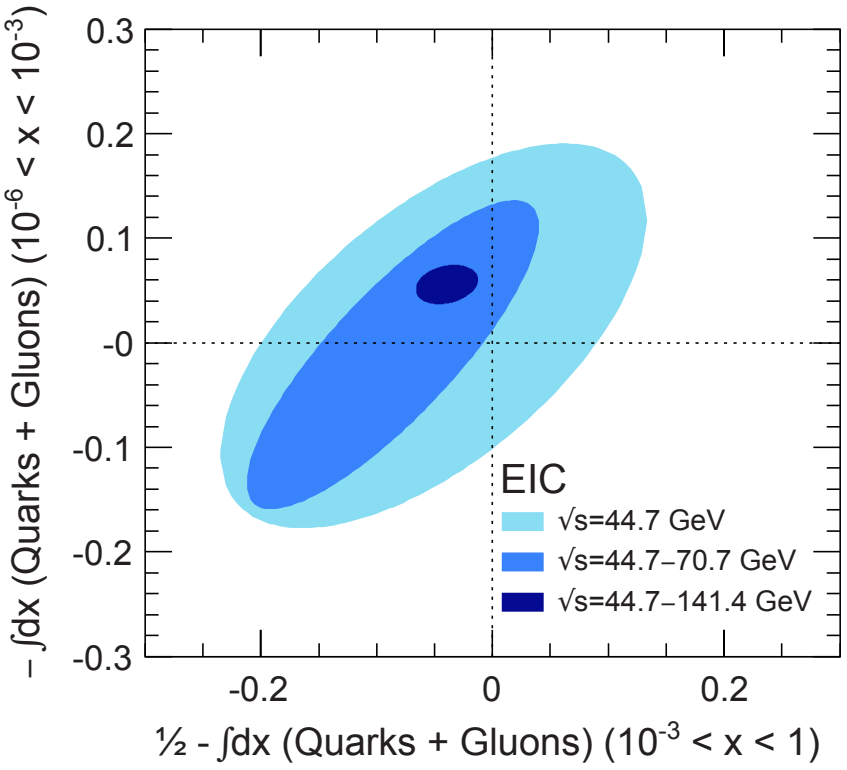


EIC Physics Pillars

Spin and Flavor Structure of the Nucleon

arXiv:1708.01527



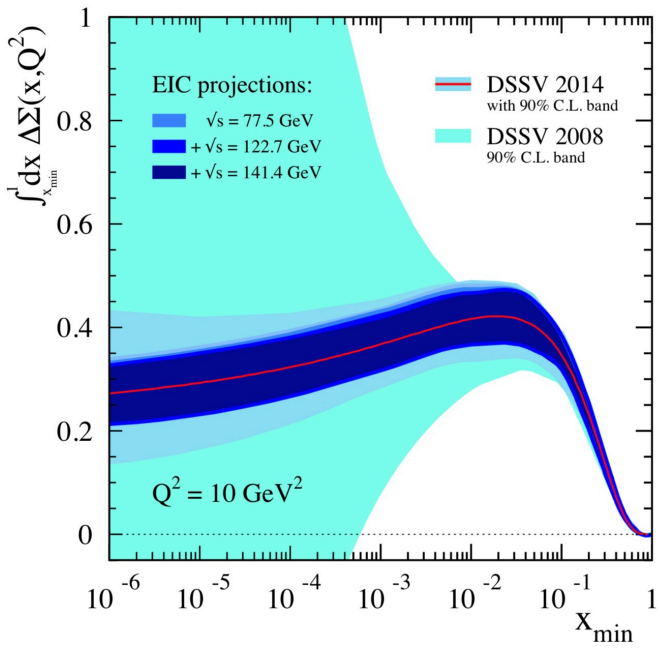


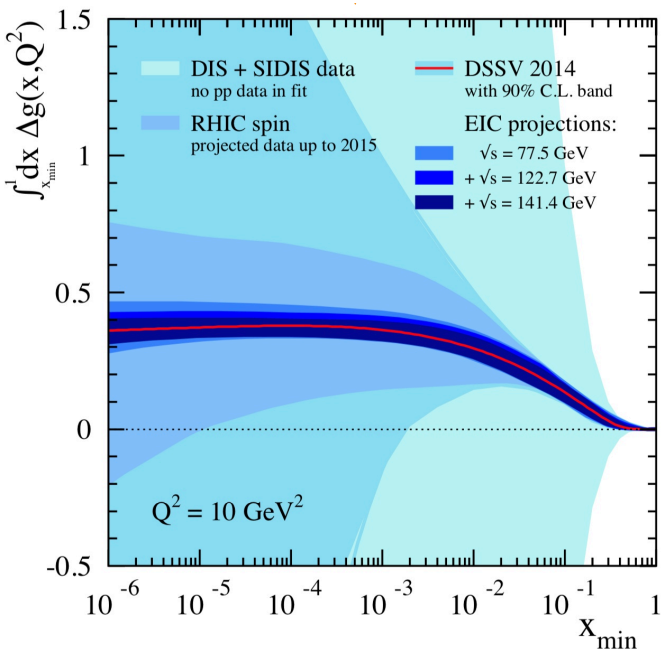
- g_1 stat. uncertainty projections for 10fb^{-1} for range of CME in comparison to DSSV14 predictions incl. uncertainties
- EIC impact on the knowledge of the integral of the quark + gluon spin contribution vs. orbital angular momentum

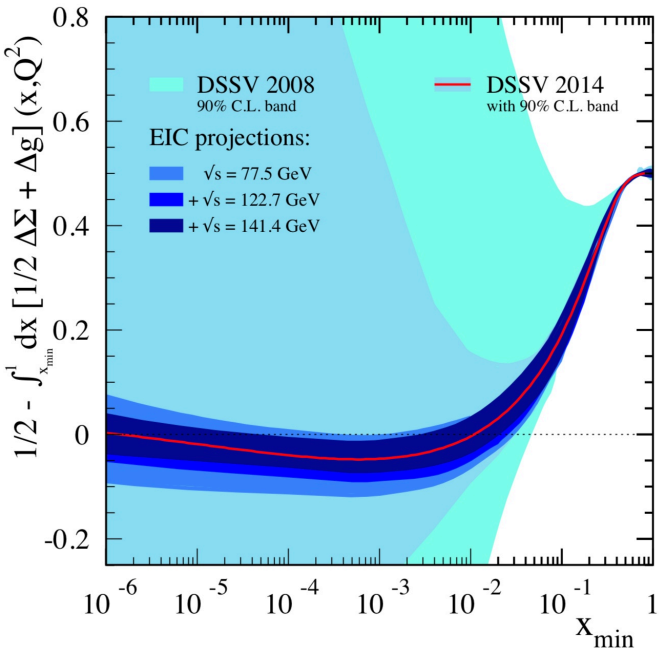
EIC Physics Pillars

Impact on proton spin

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







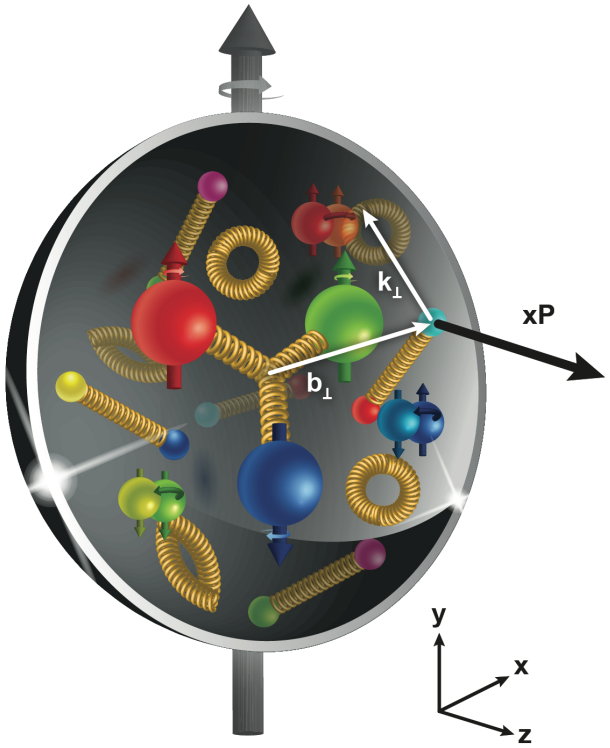
Quark Spin

Gluon Spin

Orbital Angular Momentum

EIC Physics Pillars

Nucleon 3D structure



EIC Physics Pillars

Transverse Momentum Distribution and Spatial Imaging

arXiv:1212.1701

$f(x, k_T)$ 1+2D

$\int d^2 b_T$ $W(x, b_T, k_T)$ $\int d^2 k_T$

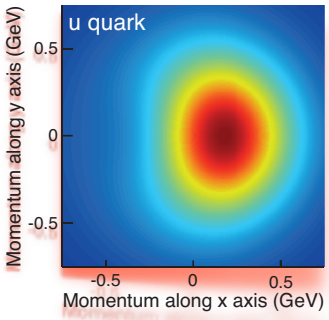
Wigner Distribution

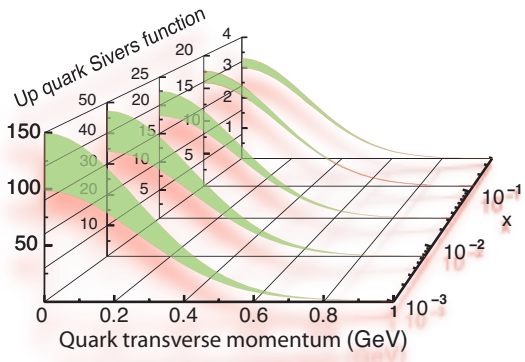
$f(x, b_T)$ 1+2D

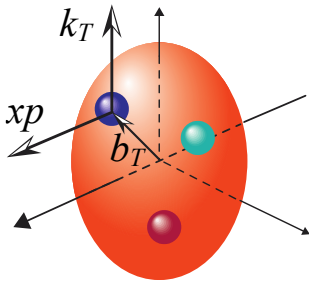
Transverse Momentum Distribution (TMD)

Impact Parameter Distribution

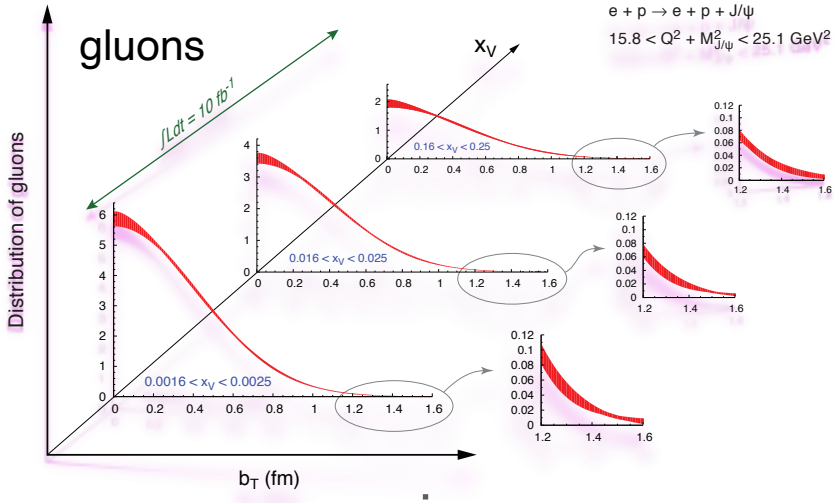
quarks







gluons



- Spin-dependent 1+2D momentum space (transverse) images from semi-inclusive scattering
- Spin-dependent 1+2D impact parameter (transverse) images from exclusive scattering

Fourier transf.
$b_T \longleftrightarrow \Delta$: $t = -\Delta^2$

$H(x, 0, t)$

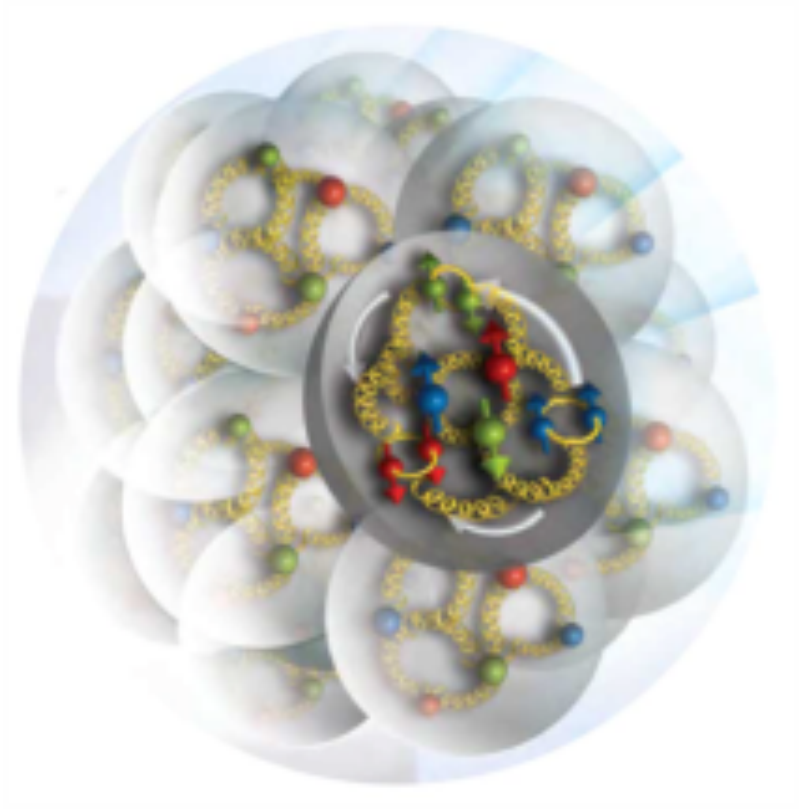
$\xi = 0$

$H(x, \xi, t)$

Generalized Parton Distribution (GPD)

EIC Physics Pillars

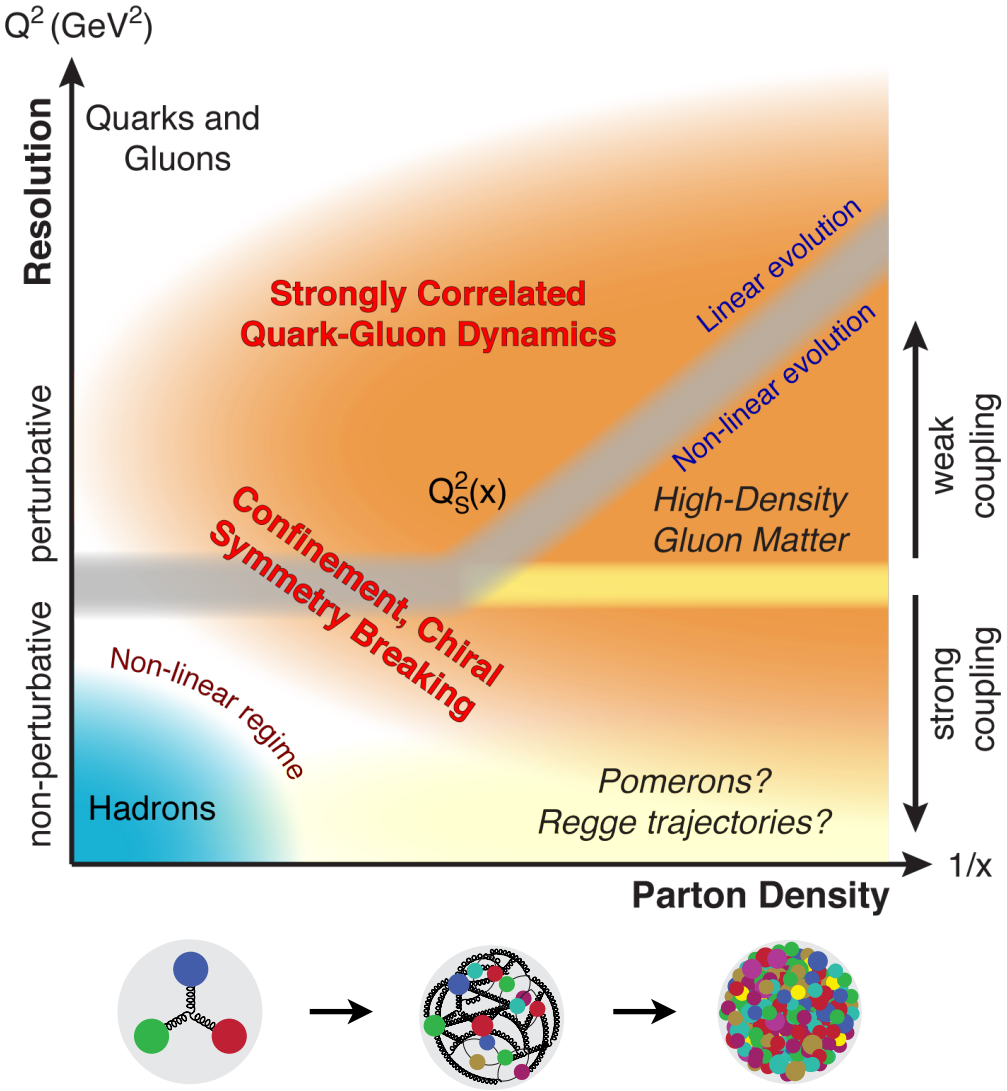
Low-x physics



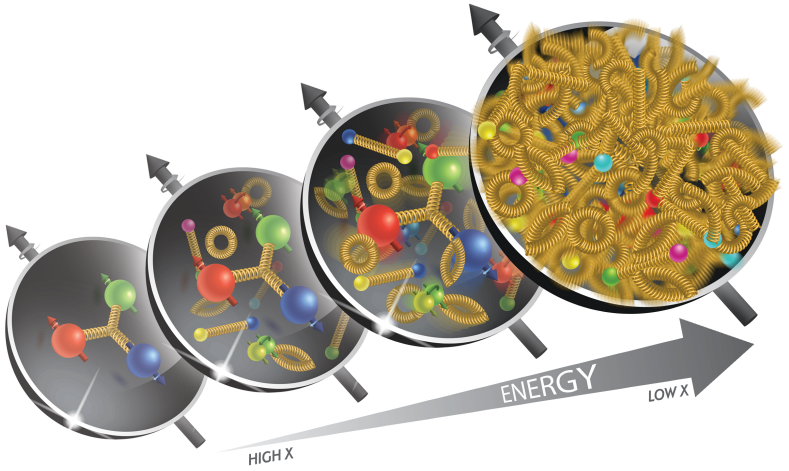
EIC Physics Pillars

QCD dynamics

arXiv:1708.01527



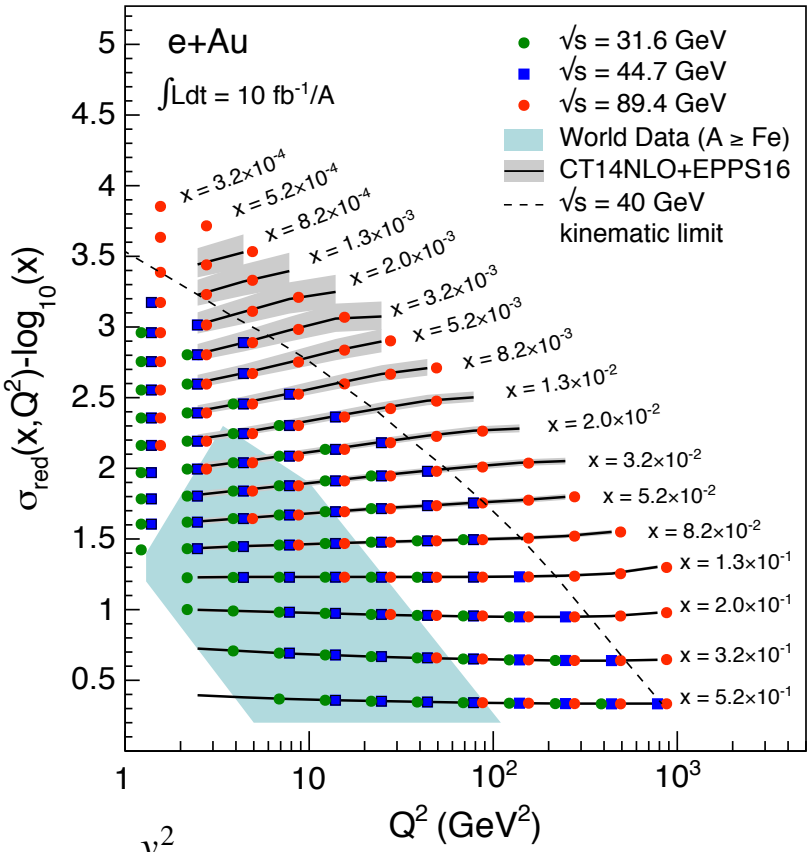
- Explore QCD landscape in various aspects over a wide range in x and Q^2
- Heavy nuclei at high energy critical to explore high-density gluon matter!

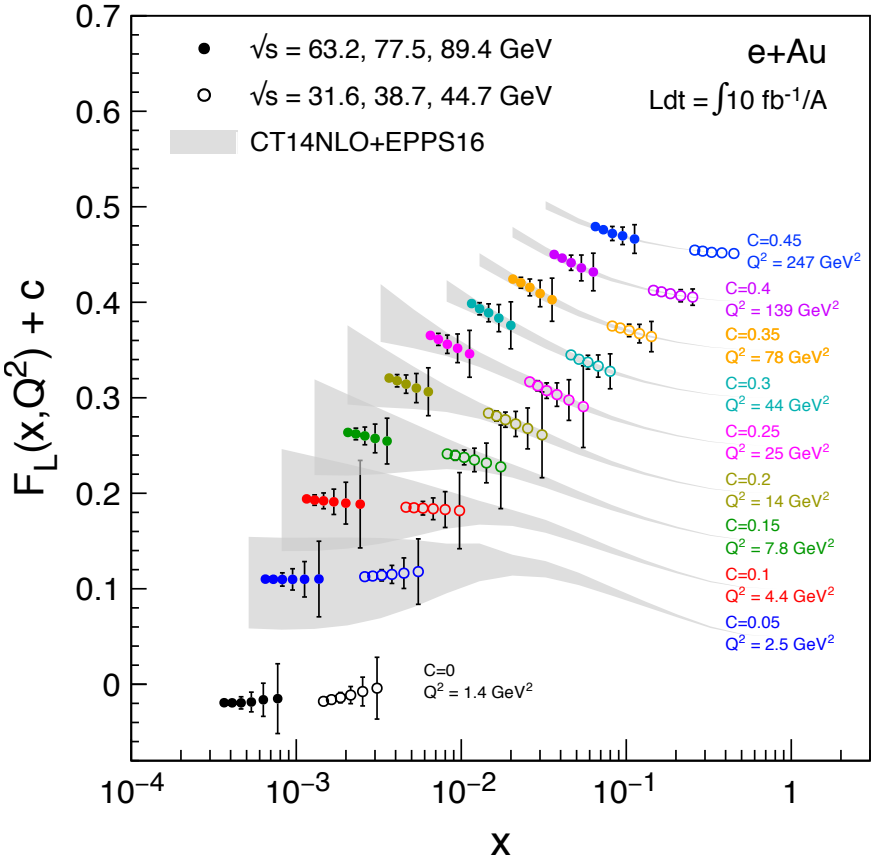


EIC Physics Pillars

Inclusive eA scattering measurements

arXiv:1708.01527





$$\sigma_{\text{red}} = F_2 - \frac{y^2}{Y_+} F_L$$

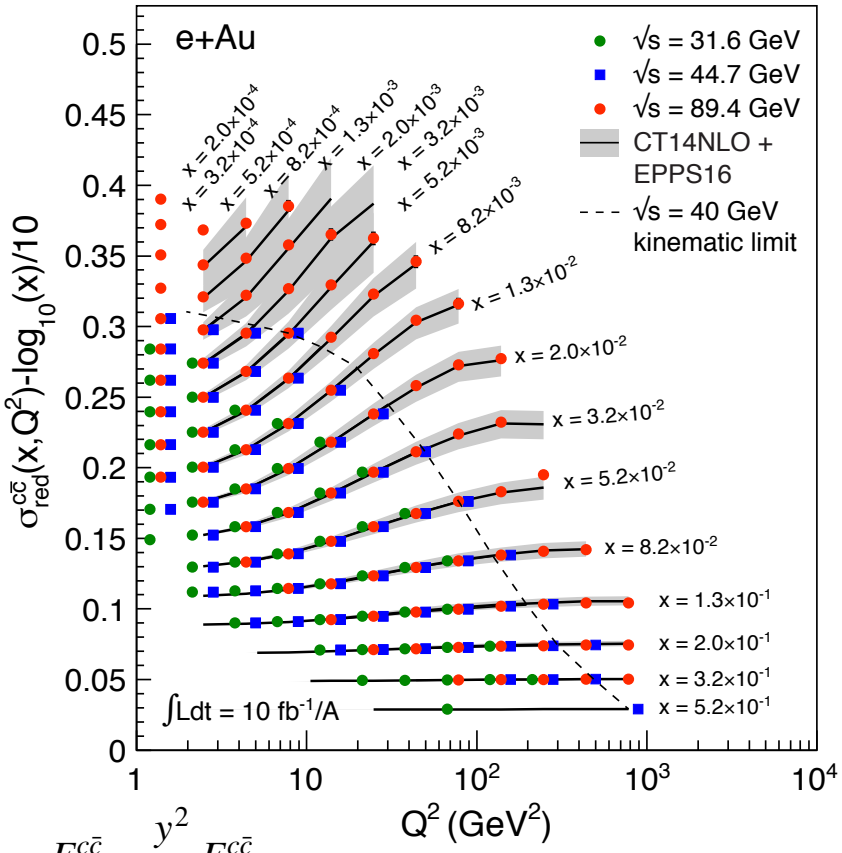
$$\left(\frac{d^2\sigma}{dx dQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)$$

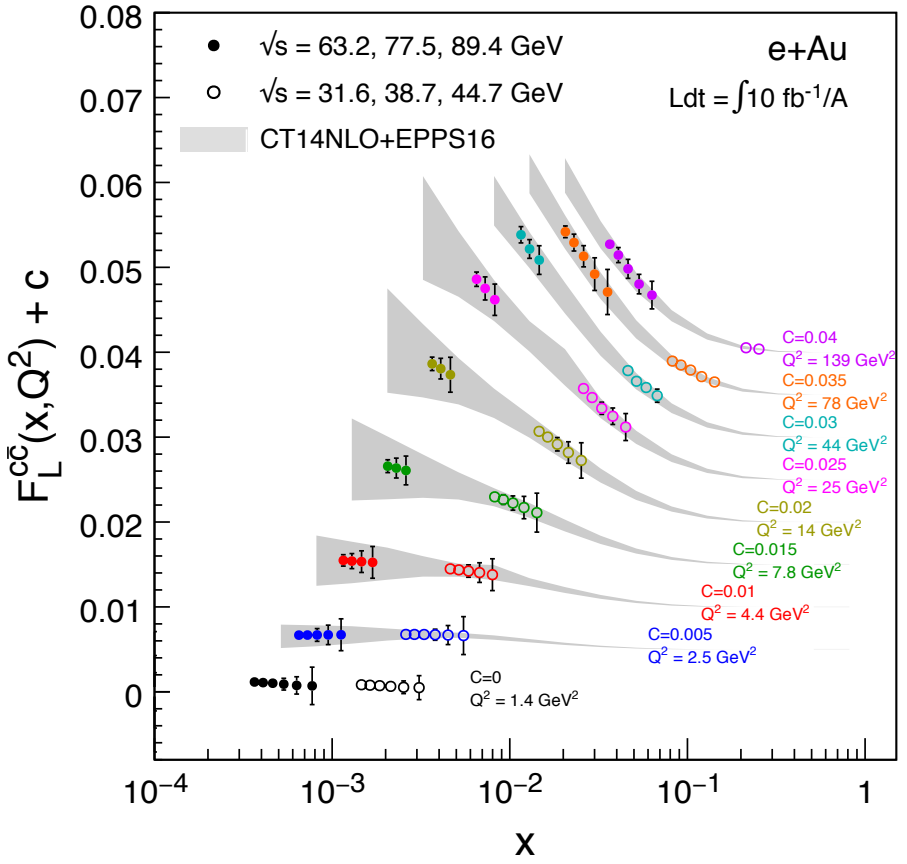
$$Y_+ = 1 + (1-y)^2$$

EIC Physics Pillars

Charm-associated eA scattering measurements

arXiv:1708.01527





$$\sigma_{\mathrm{red}}^{c\bar{c}} = F_2^{c\bar{c}} - \frac{y^2}{Y_+} F_L^{c\bar{c}}$$

$$\left(\frac{d^2\sigma}{dxdQ^2}\right)^{c\bar{c}} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2^{c\bar{c}} - \frac{y^2}{Y_+}F_L^{c\bar{c}}\right)$$

$$Y_+ = 1 + (1-y)^2$$

EIC Physics Pillars

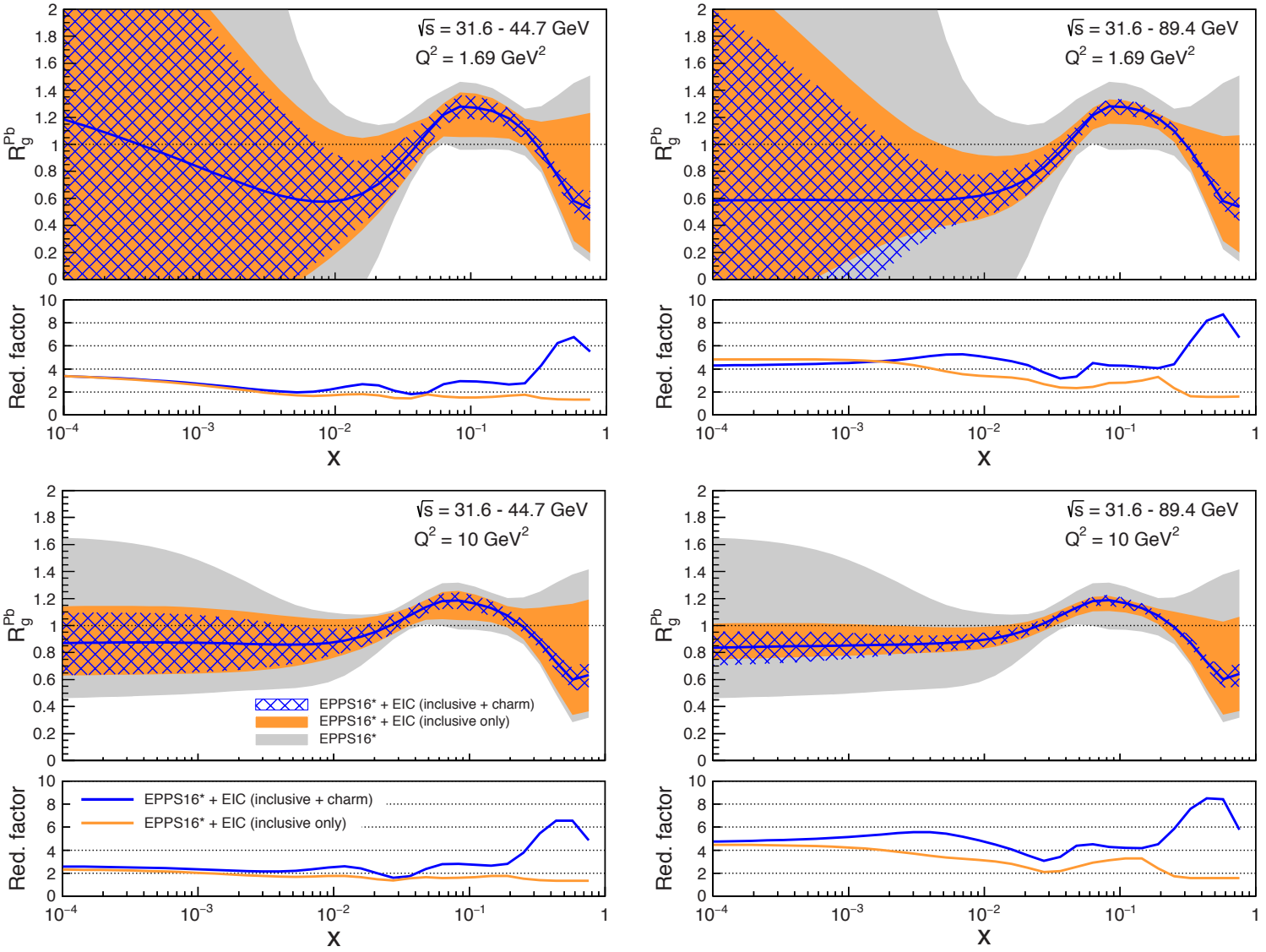
- Impact on nuclear gluon behavior in *eA* scattering

arXiv:1708.01527

Modifications of nuclear environment:

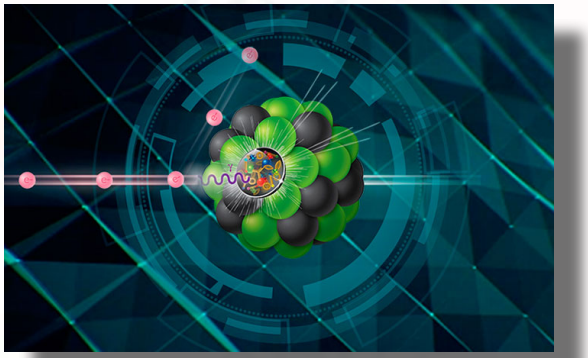
R_g^{Pb}

Ratio of gluon distribution in Pb compared to proton



Summary

- Over two decades, the nuclear physics community has developed the scientific and technical case for the Electron-Ion Collider, to push the frontiers of human understanding of the fundamental structure and dynamics of matter ➜ Emergent phenomena in QCD!



- Enormously profit from a diverse set of experiences among experimentalists and theorists at numerous institutions worldwide ➜ Critical for a broad EIC scientific program.
- The Yellow Report activity brought together the EIC community even under restricted conditions and resulted in a 3 Volume Series: Executive Summary / Physics / Detector ➜ Basis for Detector proposal efforts in 2021!
- Outstanding educational opportunities for multiple generations world-wide.

Thank you!

Thank you to my friends and faculty colleagues Andreas Metz and Alexey Prokudin for numerous EIC physics discussions!