The Project of an Electron-Ion Collider in USA

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Outline:

- EIC: goals, fundamental problems, main parameters
- Key experiments of EIC physics program
- EIC realization at BNL
- Status of EIC project

HEPD Seminar, PNPI, March 3, 2020

Electron-Ion Collider: goals

Electron-Ion Collider in USA is the project of a new collider of polarized electrons and ions on the base of RHIC@BNL (eRHIC).

• To provide continuity of the U.S. high-energy nuclear physics program after **2025-2030**, when RHIC and JLab@12 GeV will complete their programs.

• To unite RHIC and JLab users and attract the international community.

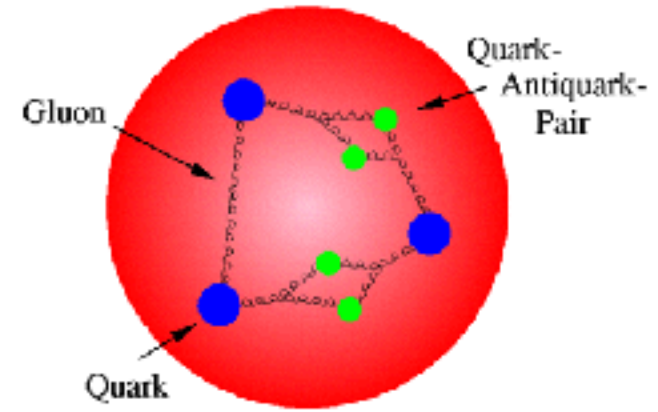
• To have a facility to test new concepts and technologies in accelerator physics.

• To answer a central question of nuclear physics on the nature of visible matter around us: **How do quarks and gluon form nucleons and nuclei?**

• To expand kinematic boundaries and precision of planned measurements: EIC should be a discovery and precision machine and a world-leading facility to study Quantum Chromodynamics (QCD).

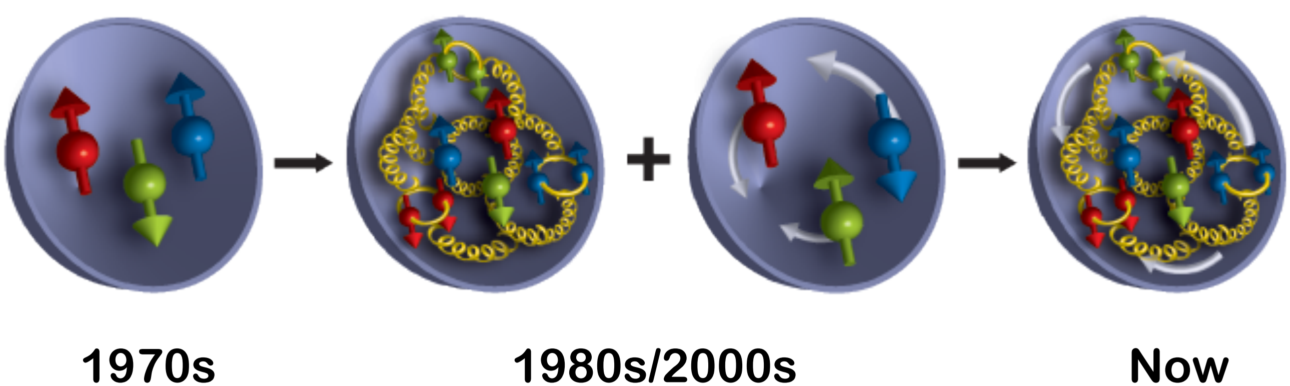
EIC: fundamental problems

• **Proton mass puzzle**: current quarks of the QCD Lagrangian carry ~10% of the proton mass. What is the role of quark-anquark quantum fluctuations and gluons?



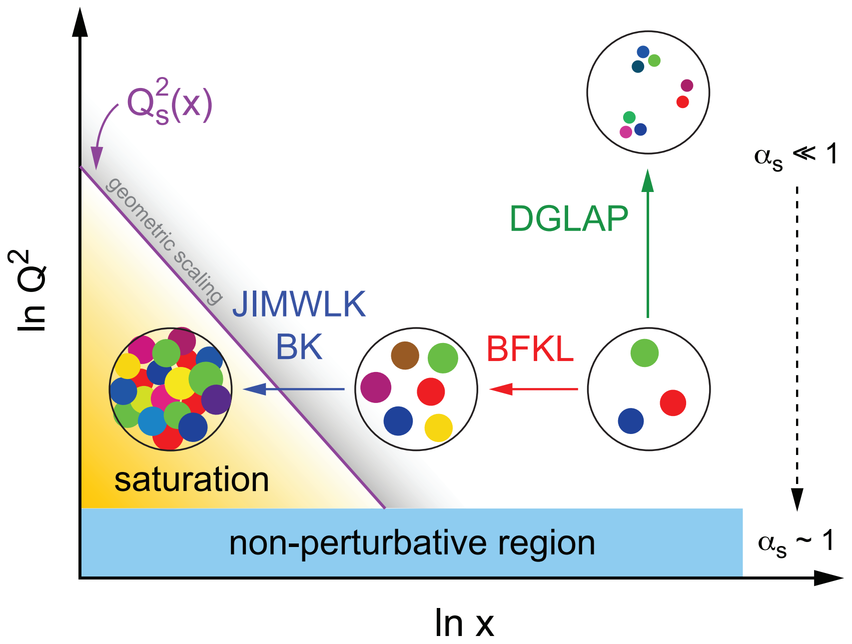
$$\mathcal{L}_{QCD} = \bar{\psi}_i(i(\gamma^\mu D_\mu)_{ij} - m\delta_{ij})\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

• **Proton spin puzzle**: quarks carry ~30% of the proton spin. What is the role of gluons and parton orbital motion? How are quarks and gluons distributed in coordinate and momentum space?

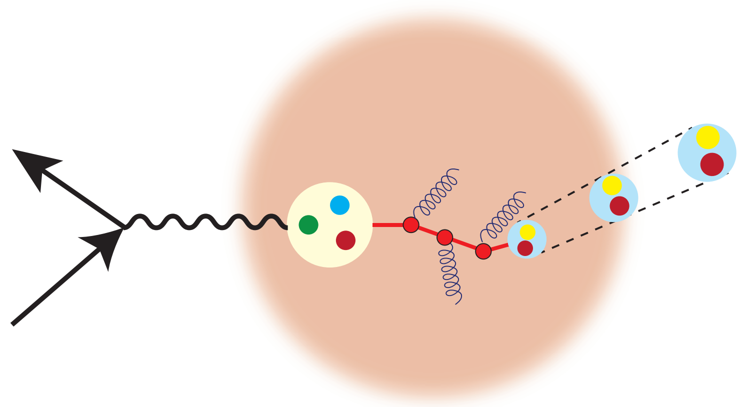


EIC: fundamental problems (2)

• **Gluon density in nuclei at high energies**: How does nuclear matter effect the gluon density? Does gluon saturation take place at high gluon density and what are its properties?



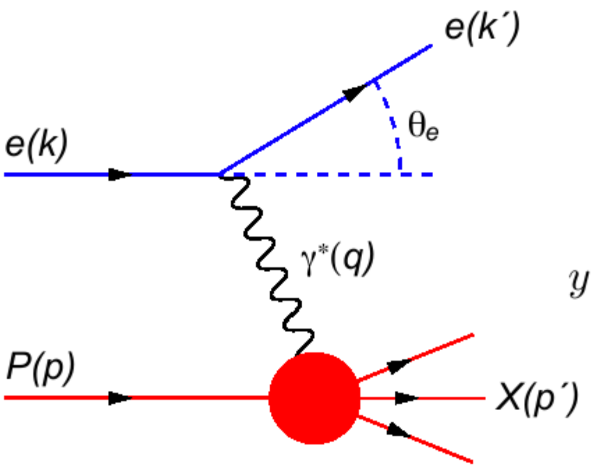
• **Nature of hadronization and confinement**: How do fast color changes interact with nuclear medium?



- important for heavy ion physics
- EIC allows us to control the photon energy and the size of nuclear matter

EIC: "QCD microscope"

- The cleanest way to study microscopic structure of hadrons is to use deep inelastic scattering (DIS):



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

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

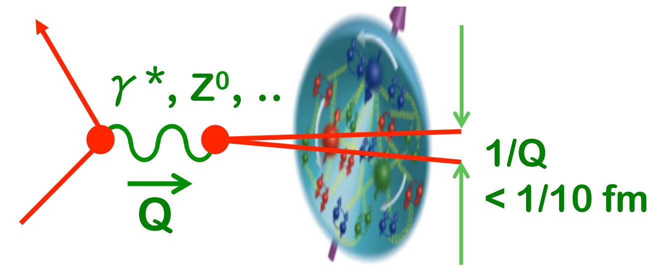
Measure of resolution power or "Virtuality"

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

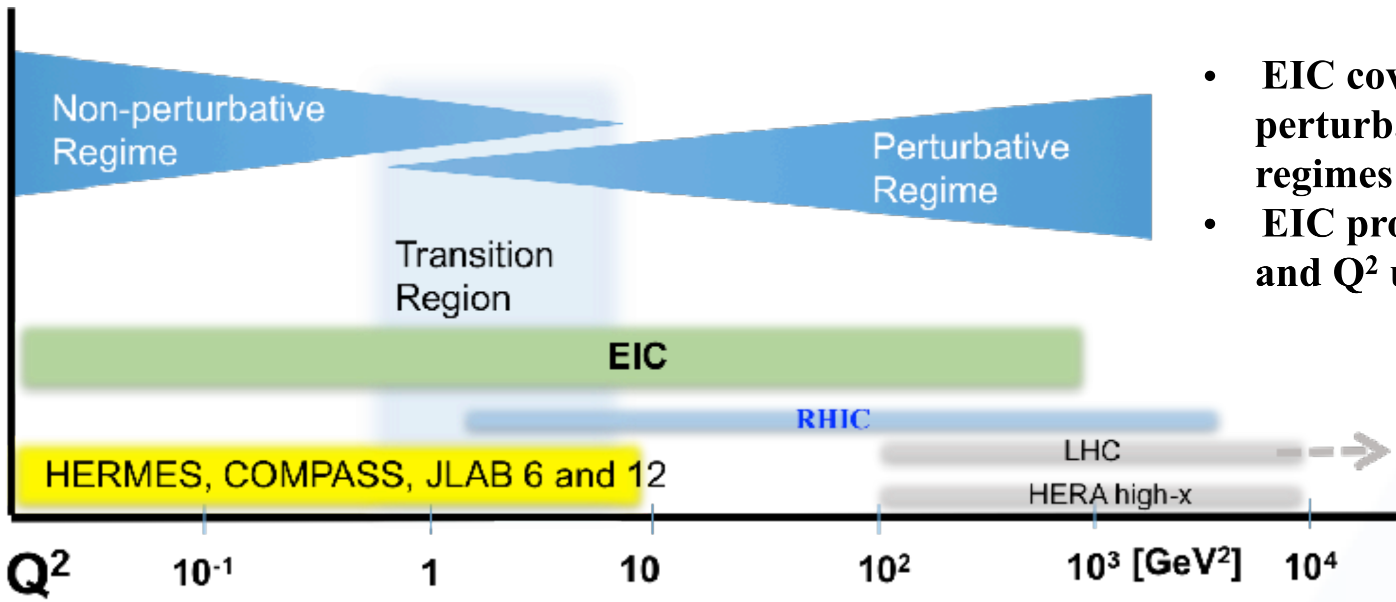


$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

- Main characteristics and advantages:
  - point-like probe → clean theoretical description and interpretation
  - control over parton kinematics
  - possibility to study semi-inclusive and exclusive (elastic) final states → 3D parton structure.

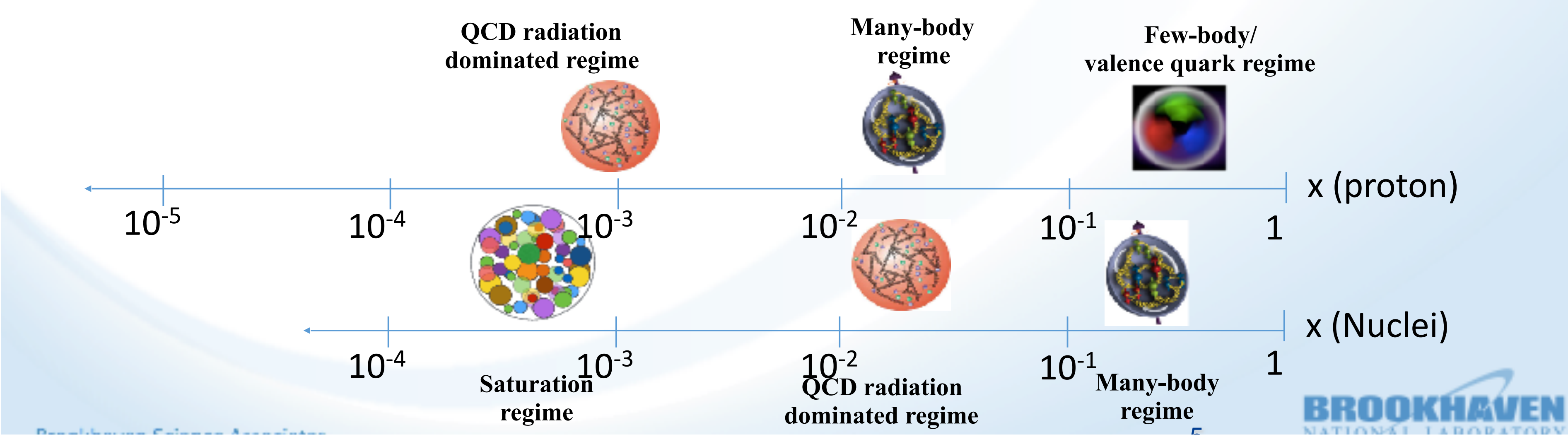
Main EIC parameters: energy

- Center of mass energy $\sqrt{s}$ ~20-140 GeV→ wide coverage in Q^2 and x.



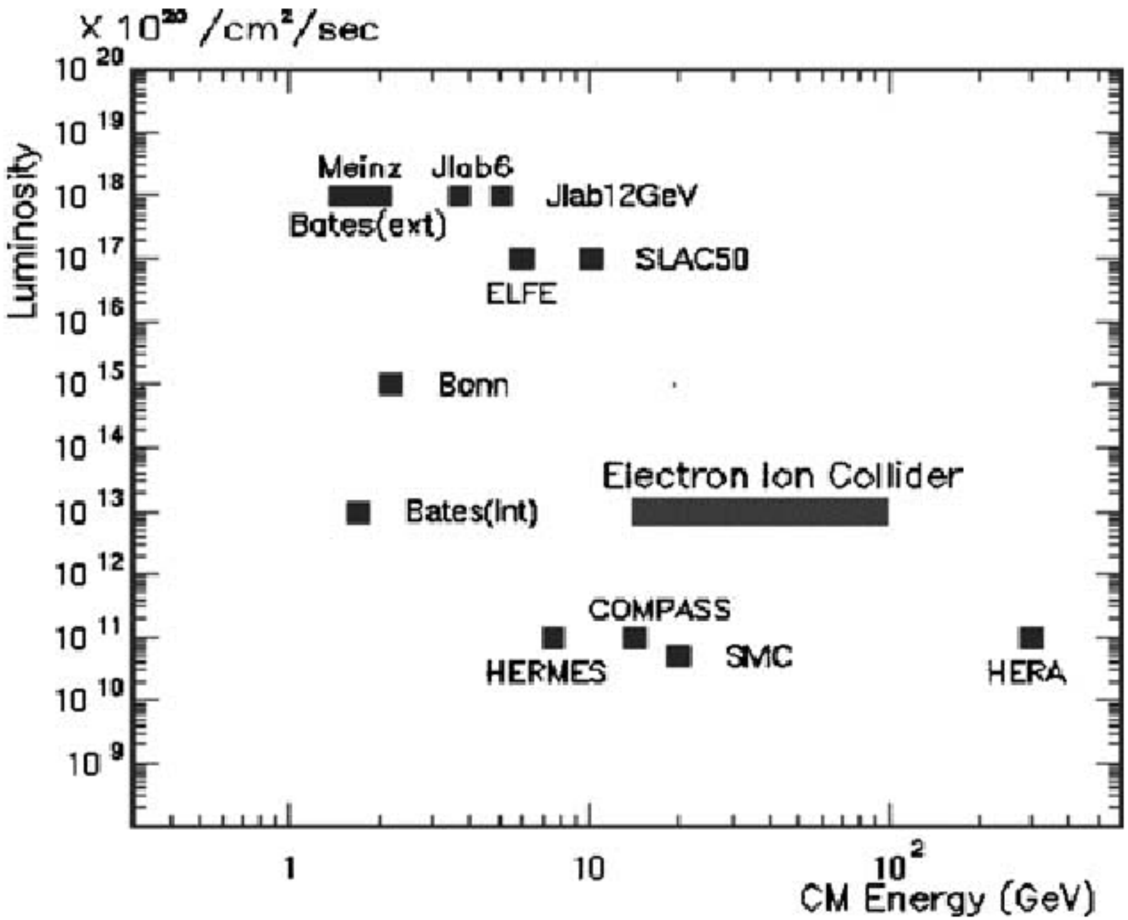
- EIC covers non-perturbative, perturbative and transition regimes
- EIC provides long evolution range and Q^2 up to ~1000 GeV^2 (0.01 fm)

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

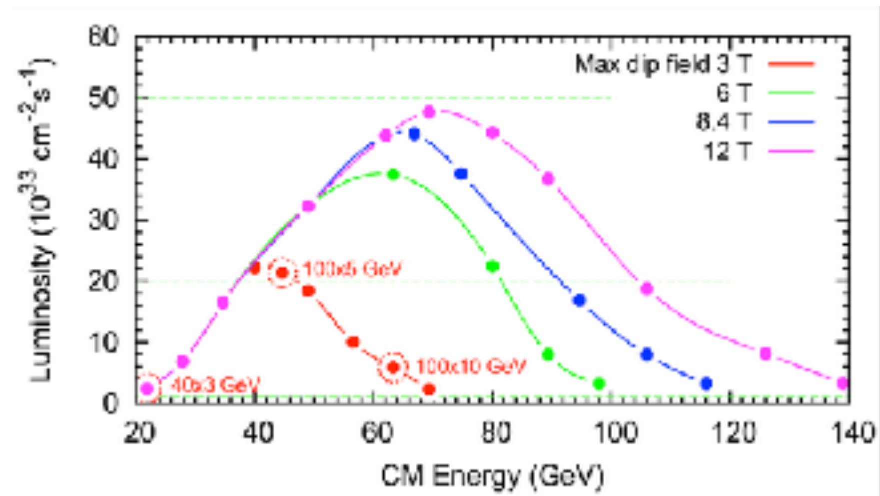


Main EIC parameters: luminosity

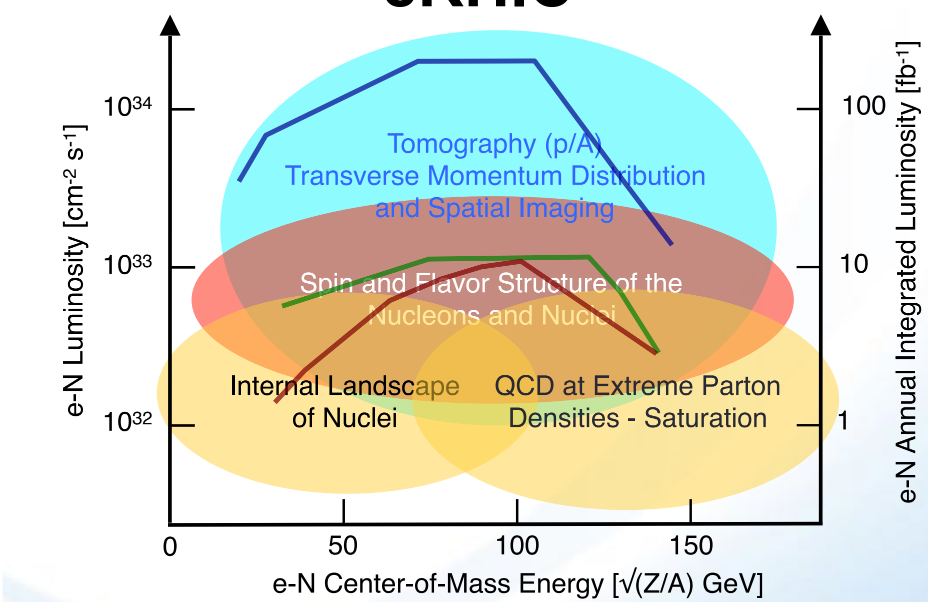
- High luminosity $10^{33\text{-}34}$ $cm^{-2}s^{-1}$ → precision measurement of semi-inclusive and exclusive processes.



JLEIC

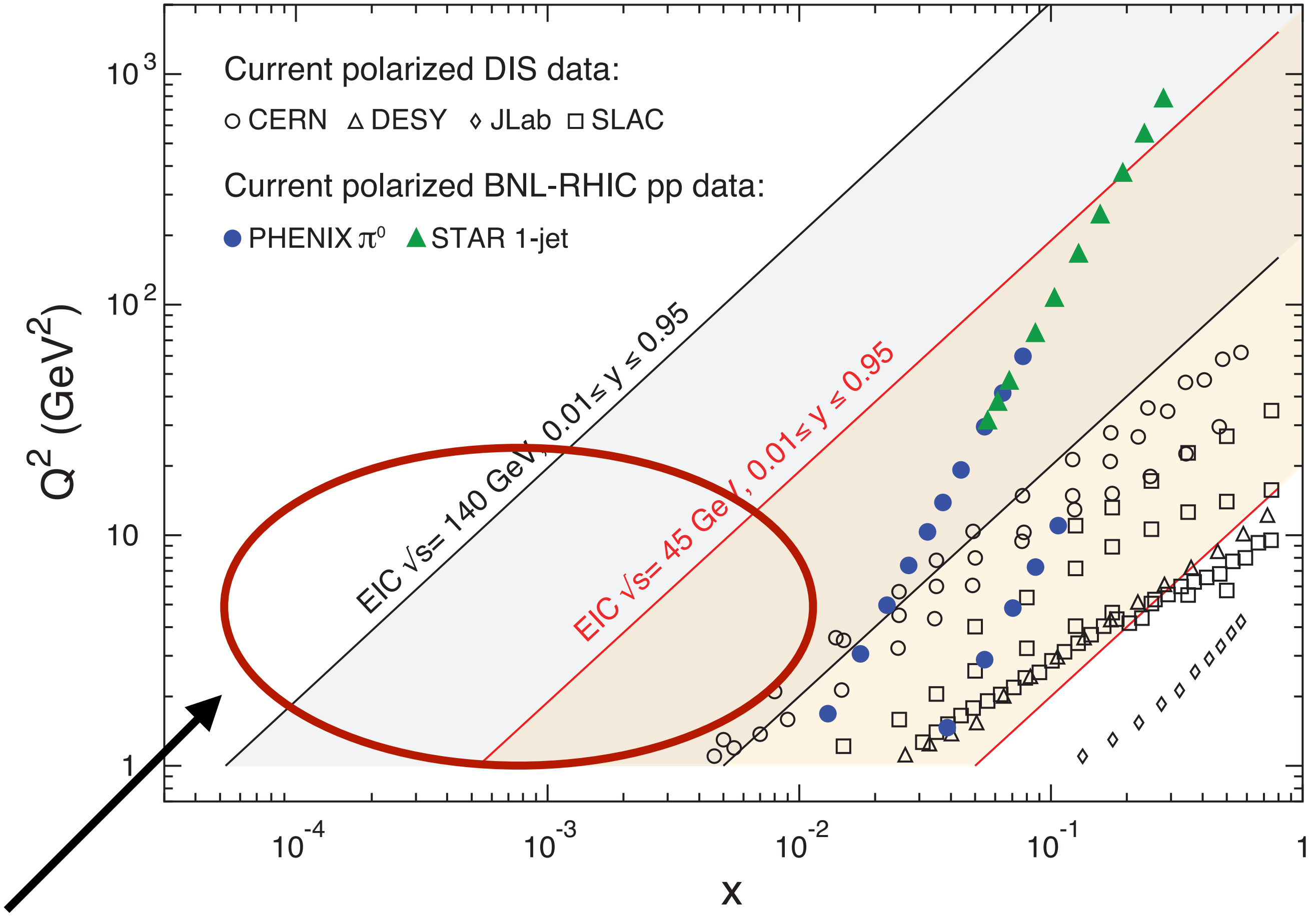


eRHIC



Main EIC parameters: polarization

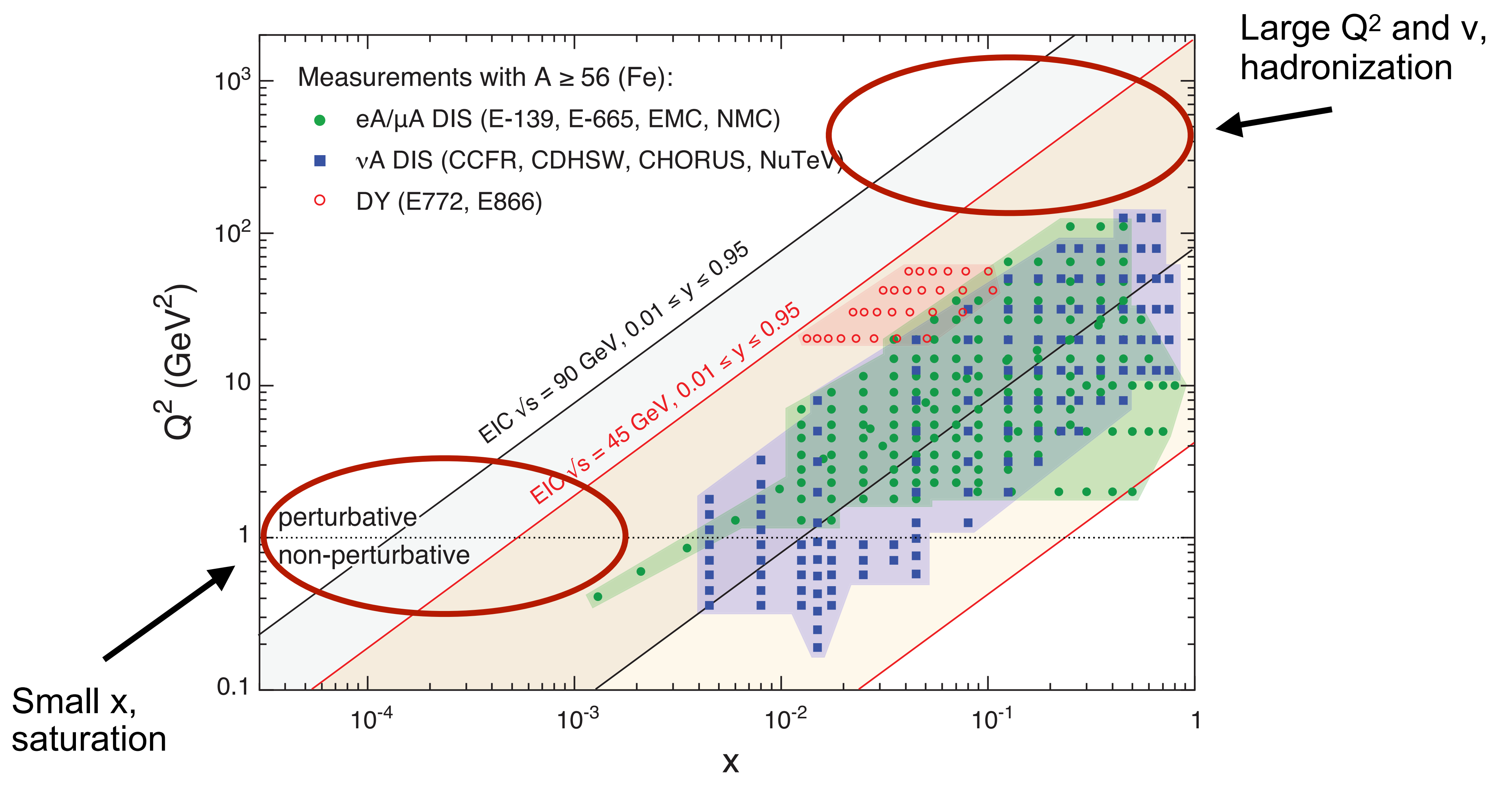
• High degree of polarization ~70% of beams of electrons, protons, light nuclei (D, He-3) → polarized DIS, 3D parton distributions from semi-inclusive (TMDs) and exclusive processes (GPDs).



• Wide region of Q^2 and small x in polarized DIS → determination of the gluon contribution ΔG to the proton spin.

Main EIC parameters: nuclei

- Acceleration of light (D, He-3) and heavy (U, Pb) nuclei → **for the first time nuclear DIS at a collider** → quark and gluon nuclear densities at small x, search for possible saturation of the gluon density.

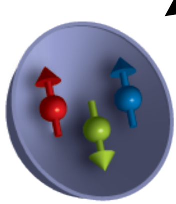


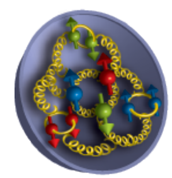
Key experiments: gluon polarization

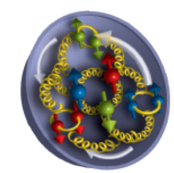
- Proton spin in QCD:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Orbital angular momentum of partons:
unknown, access via GPD and TMD calculations in lattice QCD







Quark polarization:
measured well with fixed targets

$$\frac{1}{2}\sum_{q=u,d,s}\int dx(\Delta q(x) + \Delta\bar{q}(x)) \sim 30\%$$

→ “spin crisis”.

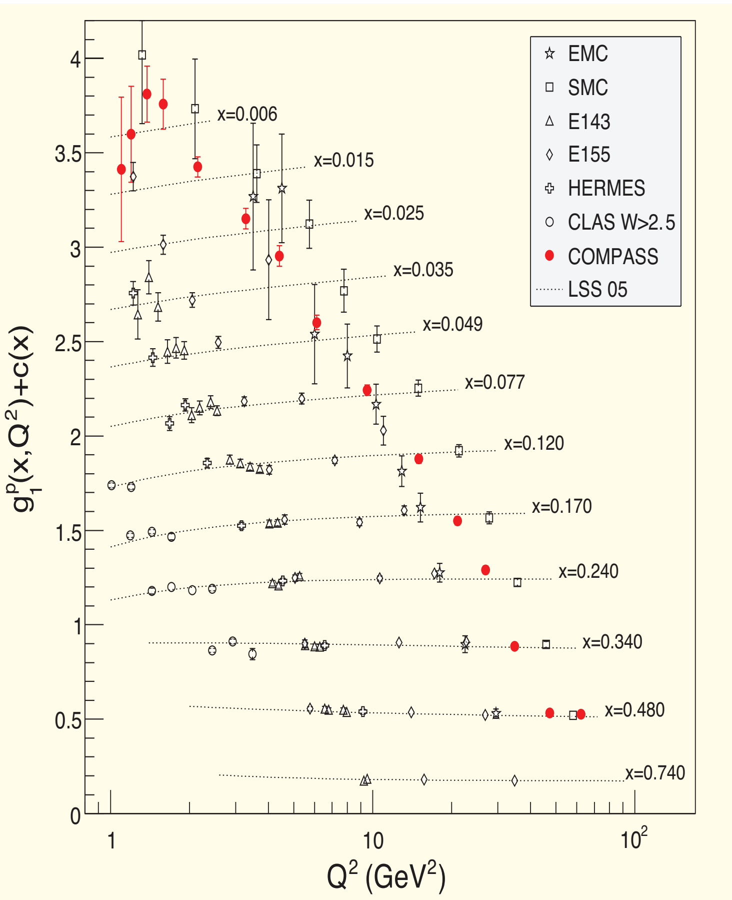
Gluon polarizarion: RHIC spin physics, large uncertainty due to small-x region contribution

$$\Delta G = \int_{x_{min}}^{x_{max}} dx\Delta g(x) \sim 0 \pm 20\%$$

Key experiments: gluon polarization (2)

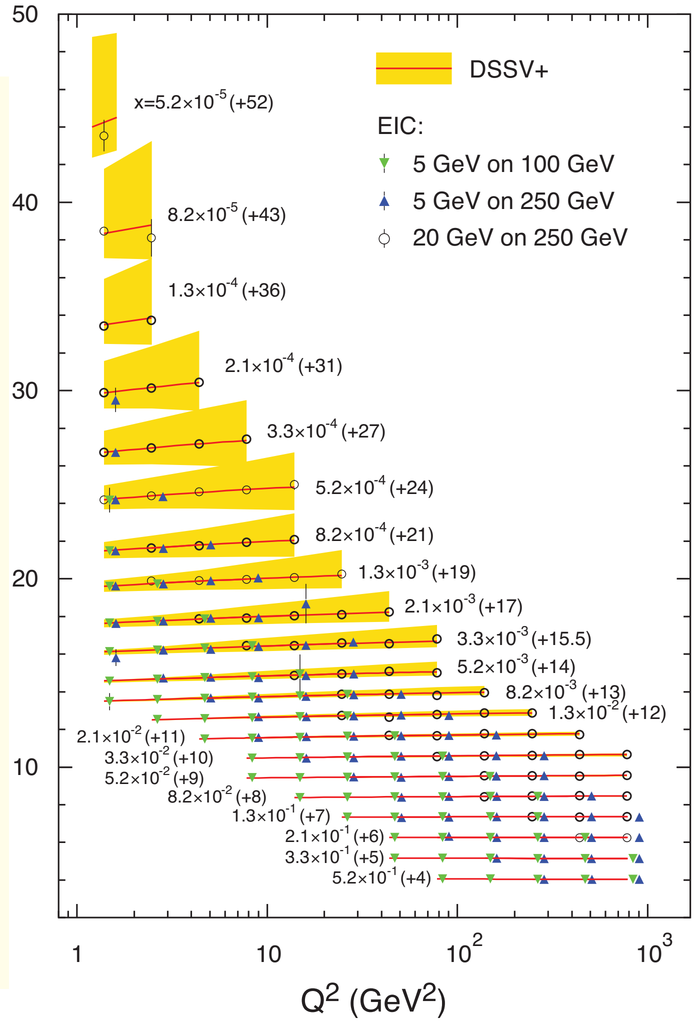
• Measurement of proton spin-dependent structure function $g_1^p(x,Q^2)$ and extraction of $\Delta g(x)$ using scaling violations:

World data



EIC →

$$\frac{dg_1^p(x,Q^2)}{d\log Q^2} \propto -\Delta g(x,Q^2)$$



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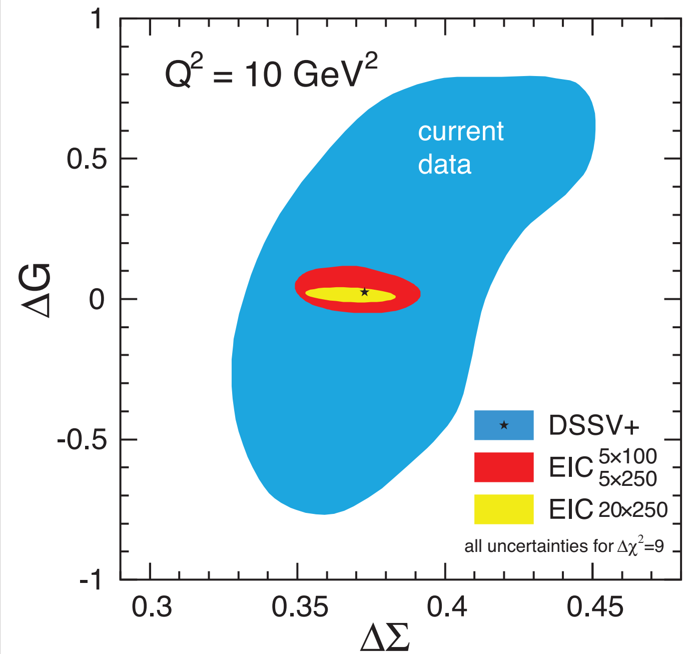
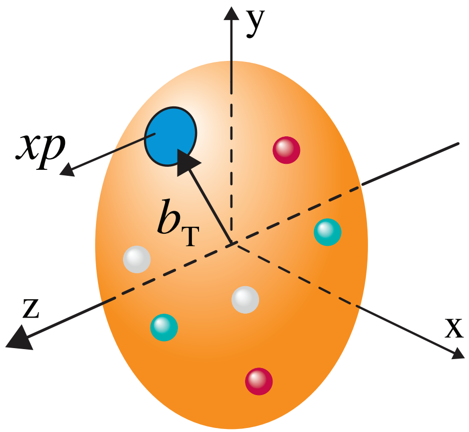
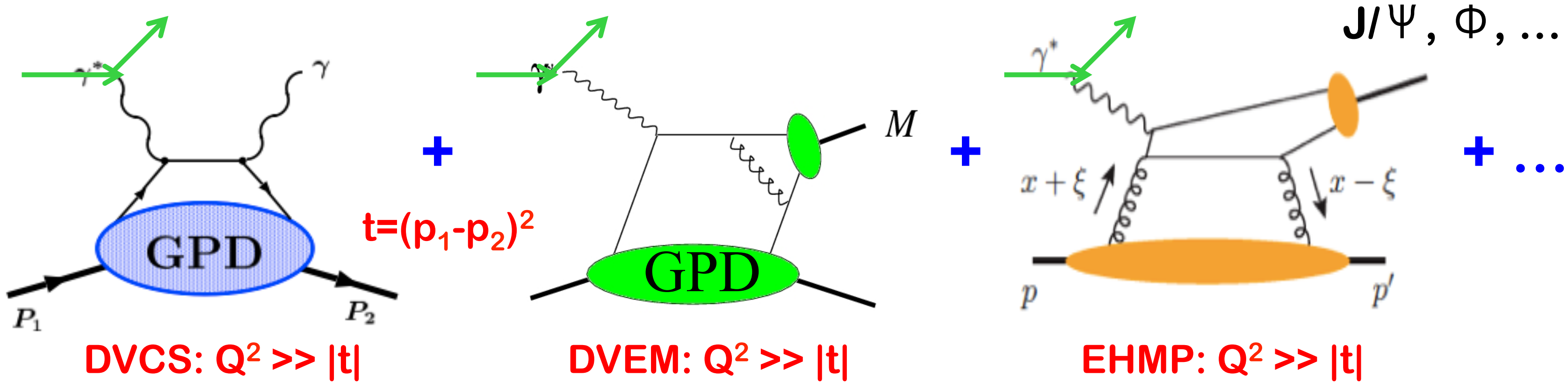


Key experiments: 3D parton distributions

- Determination of 3D parton distributions requires two scales: large Q^2 for parton localization and small (t, kT) for distances O(fm).

- Examples: hard exclusive processes, hybrid between inclusive and elastic scattering





Deeply virtual Compton scattering (DVCS)

Deeply virtual meson production (DVMP)

- Fourier transformation w/respect momentum transfer *t* gives b_T-dependence.

Key experiments: 3D parton distributions (2)

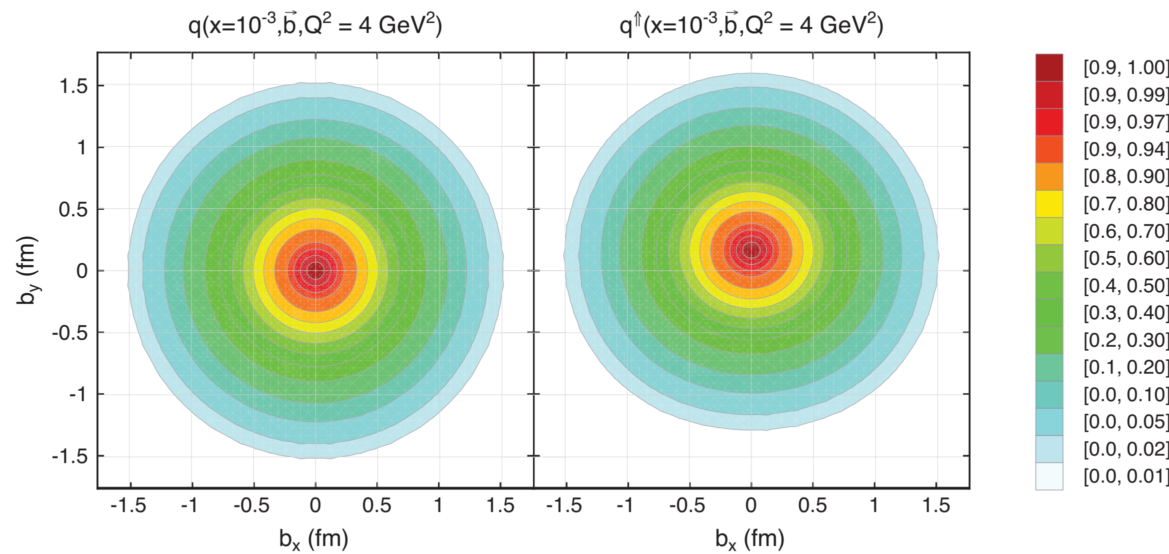
- Cross sections are expressed in terms of generalized parton distributions (GPDs), encoding QCD tomography of the target.
- GPDs are important for resolution of the proton “spin crisis”:

$$J^q = \frac{1}{2}\int dx\, x[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)] = \frac{1}{2}\Delta q + L_q$$

- GPDs contain information on sheer forces experienced by partons in proton/ nuclei and also possible non-nucleonic degrees of freedom in nuclei.

- In the case of transversely-polarized target, b_T-dependence of GPDs depends on spin-orbit correlations:

$$f^{\Uparrow}(x,\boldsymbol{b}_T) = f(x,\boldsymbol{b}_T^2) + \frac{(\boldsymbol{S}_T\times\boldsymbol{b}_T)^z}{M}\frac{\partial}{\partial\boldsymbol{b}_T^2}\,e(x,\boldsymbol{b}_T^2)$$



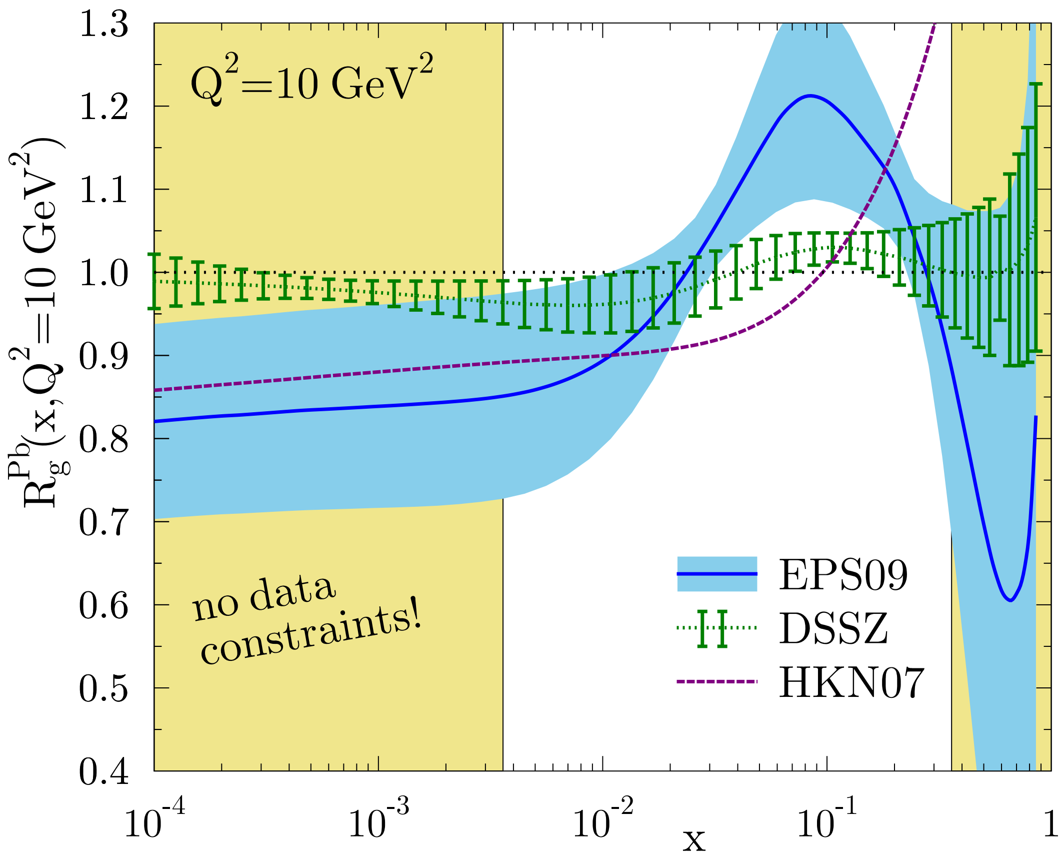
Key experiments: nuclear gluon distribution

• Nuclear gluon distribution $g_A(x,\mu^2)$ = density of gluons in nuclei as function of momentum fraction x at resolution μ, necessary input for phenomenology of hard processes with nuclei at high energies (RHIC, LHC).

$$R_g(x,Q^2) = \frac{g_A(x,Q^2)}{A g_p(x,Q^2)}$$

• $g_A(x,\mu^2)$ is known from available data with significant uncertainties (fixed-target DIS , dA@RHIC, pA@LHC) due to:

- limited range of energies, Q^2 and x
- indirect determination using scaling violation (Q^2 dependence $F_{2A}(x,Q^2)$)



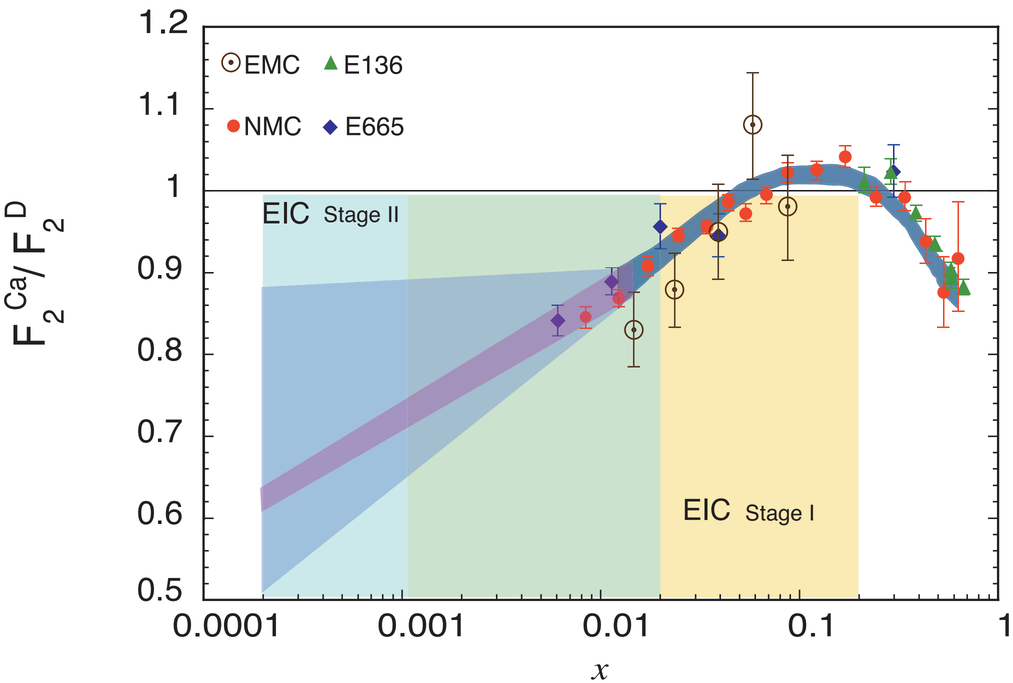
Key experiments: nuclear gluon distribution (2)

- High and *variable* energies at EIC will allow one to measure the nuclear structure functions $F_{2A}(x,Q^2)$ and $F_{LA}(x,Q^2)$ in a wide range of x, Q^2 - “first-day measurement”

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

- Longitudinal structure function $F_{LA}(x,Q^2)$ directly probes $g_A(x,\mu^2)$.

$$F_L(x,Q^2) = \frac{2\alpha_s(Q^2)}{\pi}\int_x^1 \frac{dy}{y}\left(\frac{x}{y}\right)^2 \sum_q^{n_f} e_q^2 \left[\left(1-\frac{x}{y}\right) y g(y,Q^2) + \frac{2}{3}\left(q(x,Q^2)+\bar{q}(x,Q^2)\right)\right]$$



Nuclear gluon density from J/ψ photoproduction on nuclei at the LHC

• Before EIC, new constraints on $g_A(x,\mu^2)$ at small x were obtained by analyzing the data on coherent photoproduction J/ψ on nuclei in Pb-Pb ultreperipheral collisions (UPCs), Guzey Zhalov, Kryshen, Strikman, 2012-2017

• The cross section is proportional to the gluon density squared → the ratio of cross sections of the nucleus/proton = factor of nuclear modification/ suppression of $g_A(x,\mu^2)$.

$$S(W_{\gamma p}) \equiv \left[\frac{\sigma^{\exp}_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})}{\sigma^{\rm IA}_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})}\right]^{1/2}$$

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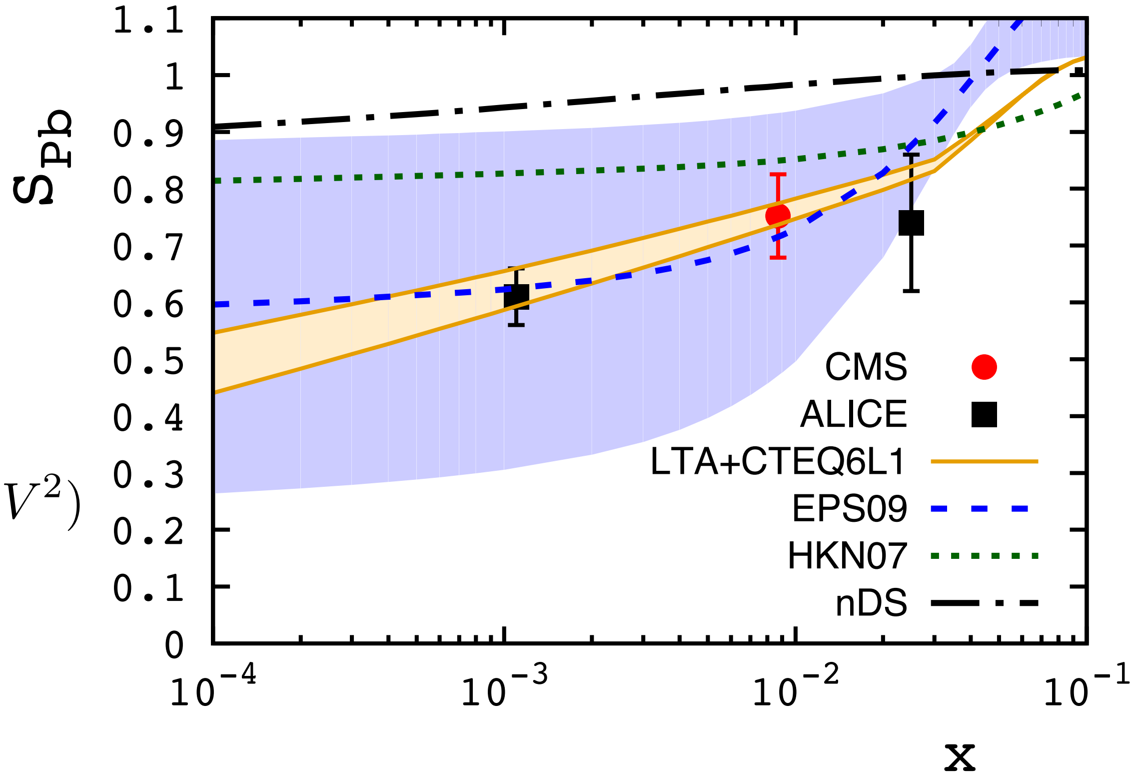
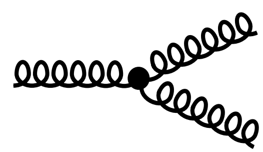
$$S_{Pb}(W_{\gamma p}) = R_g(x = \frac{M^2_{J/\psi}}{W^2_{\gamma p}}, Q^2 = 3\ GeV^2)$$

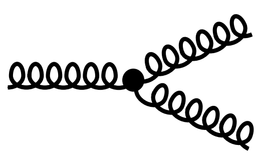
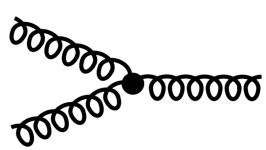


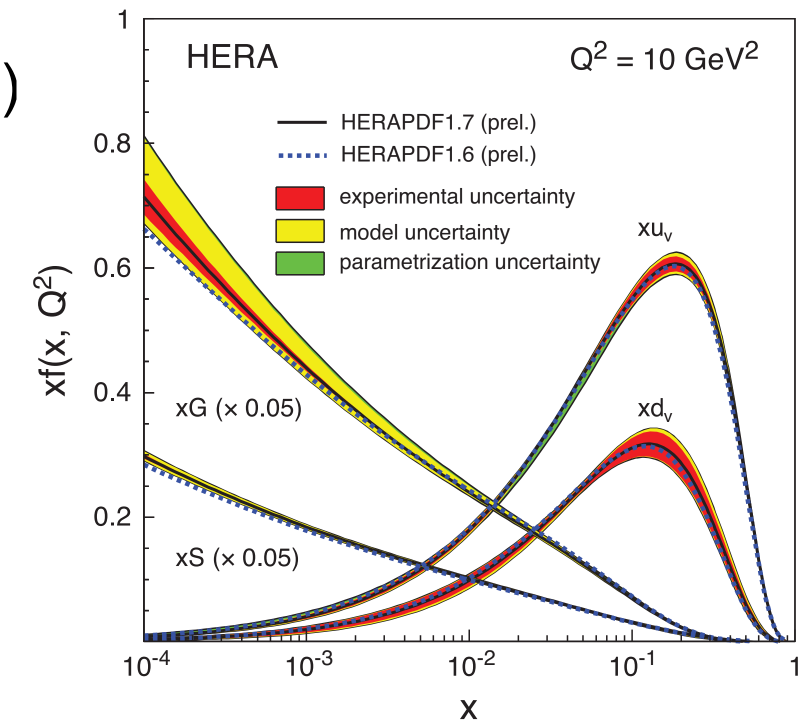
Key experiments: gluon saturation

- As the collision energy increases (x decreases) the gluon density increases due to gluon radiation (DGLAP, BFKL):



- At some point, radiation is compensated by recombination → saturation

 =  at Q_s



- A new dynamical saturation scale Qs from the estimate $\rho \times \sigma_{gg \to g} \sim 1$

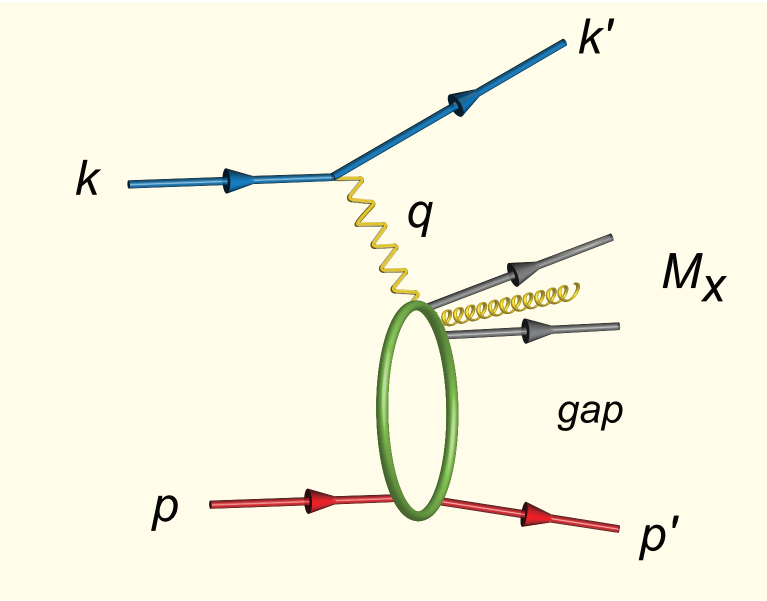
$$Q_s^2 \sim \frac{\alpha_s x G_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3} \frac{1}{x^{0.3}}$$

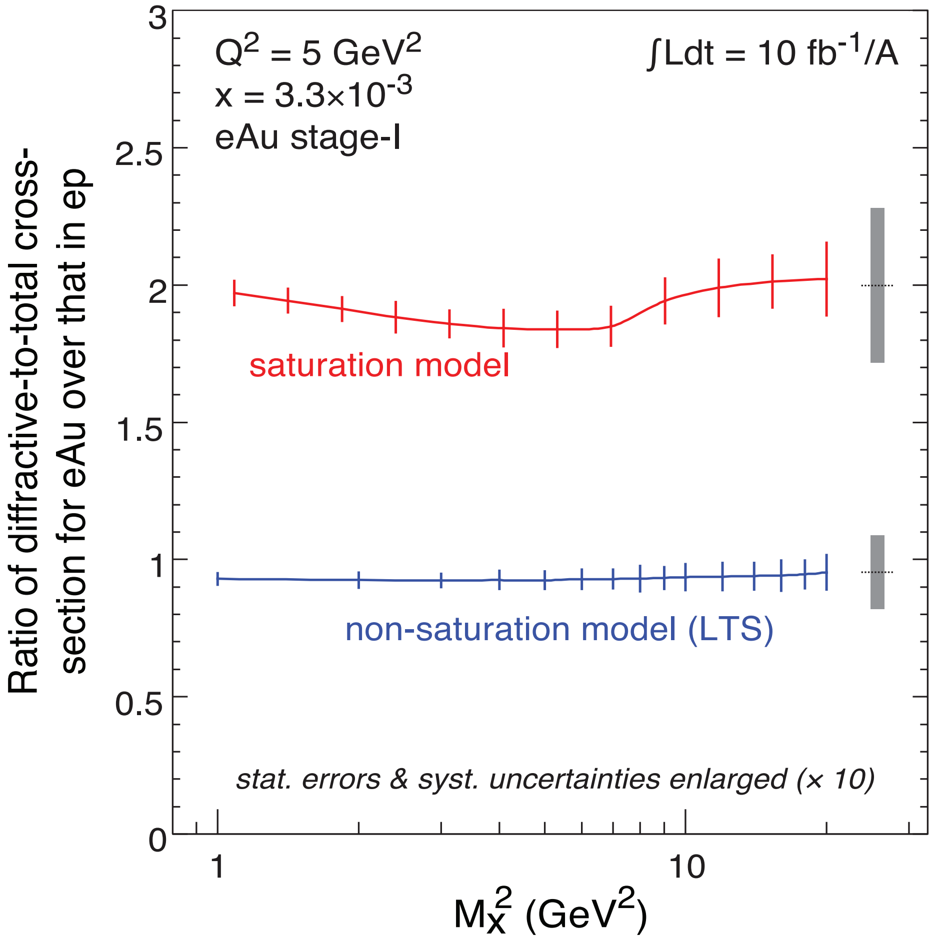
- Nuclear enhancement of Qs is a kew factor for EIC!

Key experiments: gluon saturation (2)

- The regime of gluon saturation was theoretically predicted in the color glass condensate (CGC) framework.
- Despite may successful phenomenological applications at RHIC and LHC, there is no convincing evidence of onset of this new regime of low-x QCD.
- At EIC, it is proposed to look for saturation by studying inclusive, diffractive and exclusive DIS.

Diffractive DIS

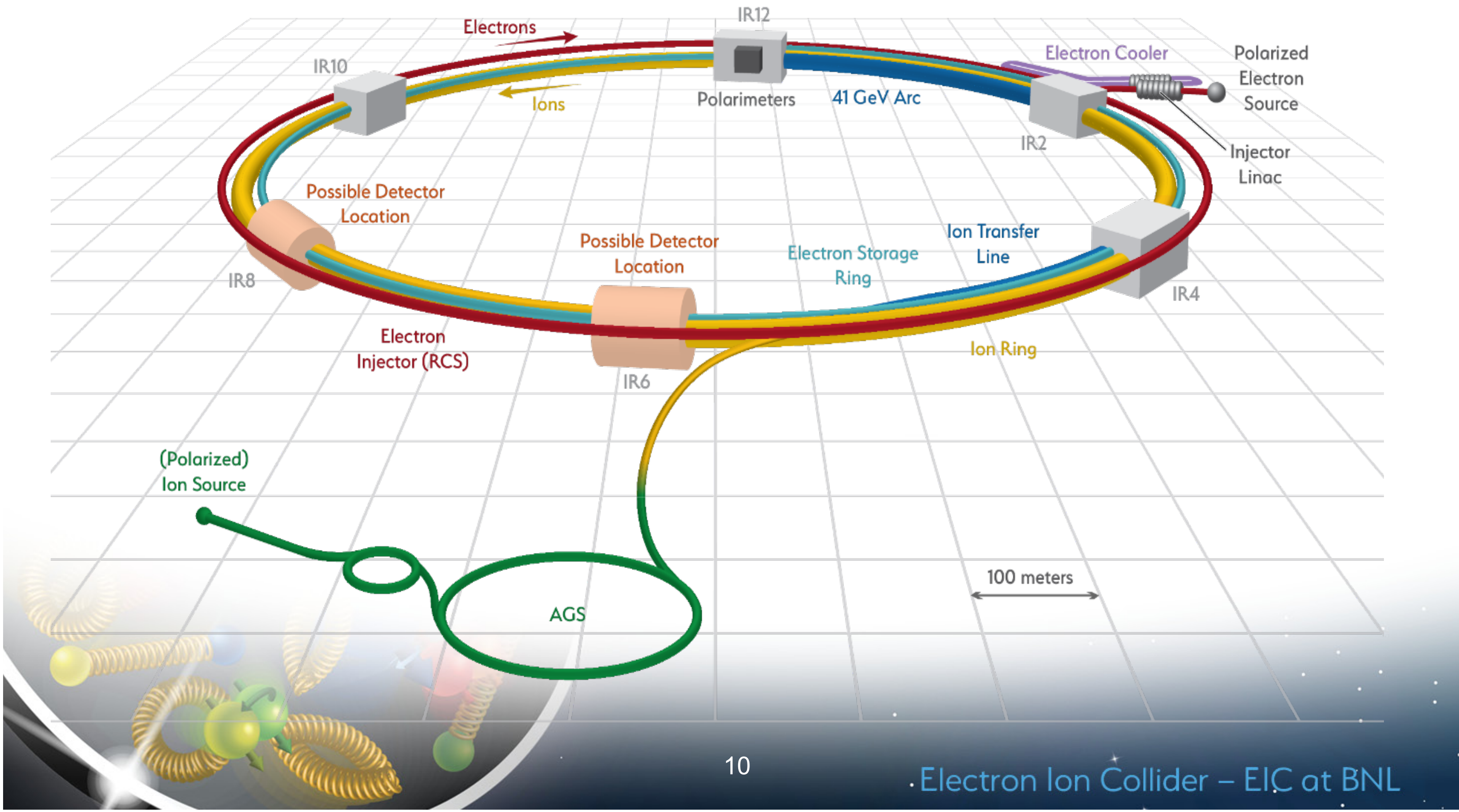




Realization of EIC at BNL

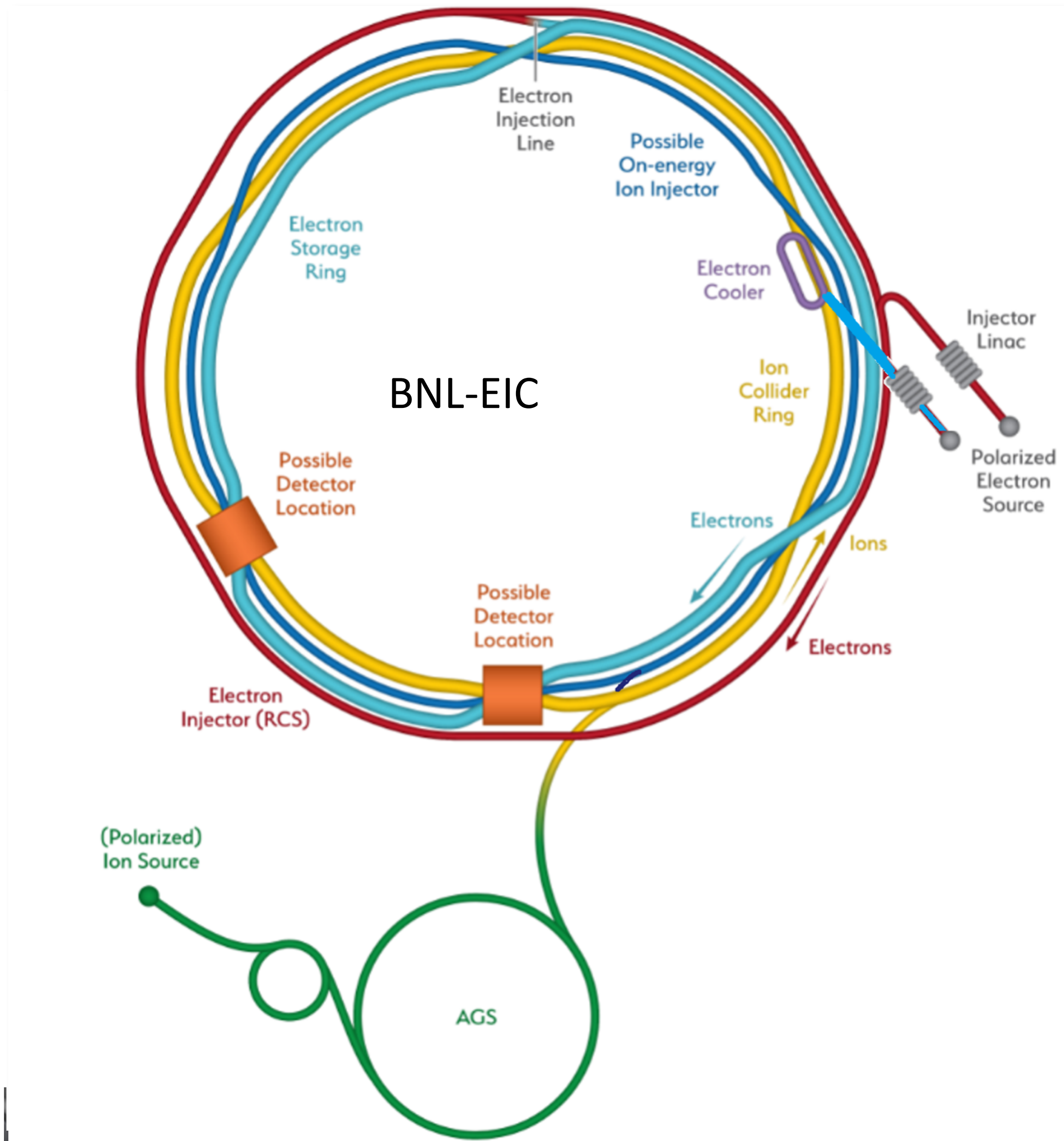
EIC @ BNL

The design aims at the construction of an Electron-Ion-Collider (eRHIC) leveraging the existing RHIC accelerator complex and its infrastructure.

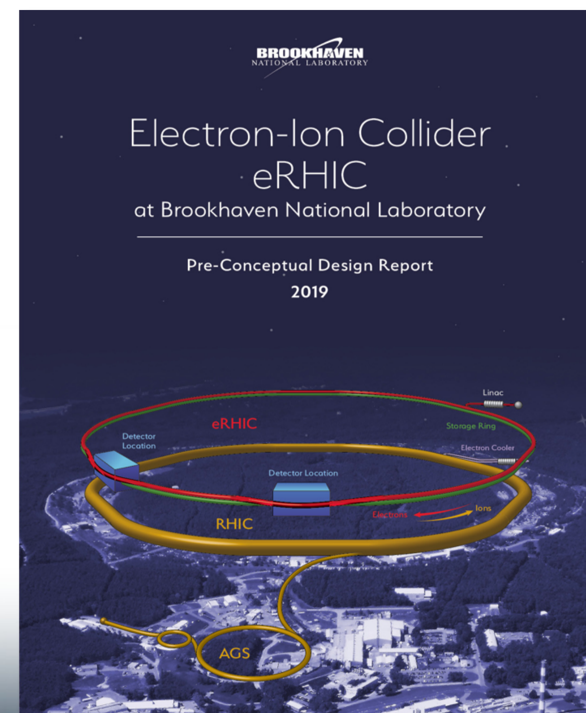


Realization of EIC at BNL (2)

How RHIC is transformed into an EIC

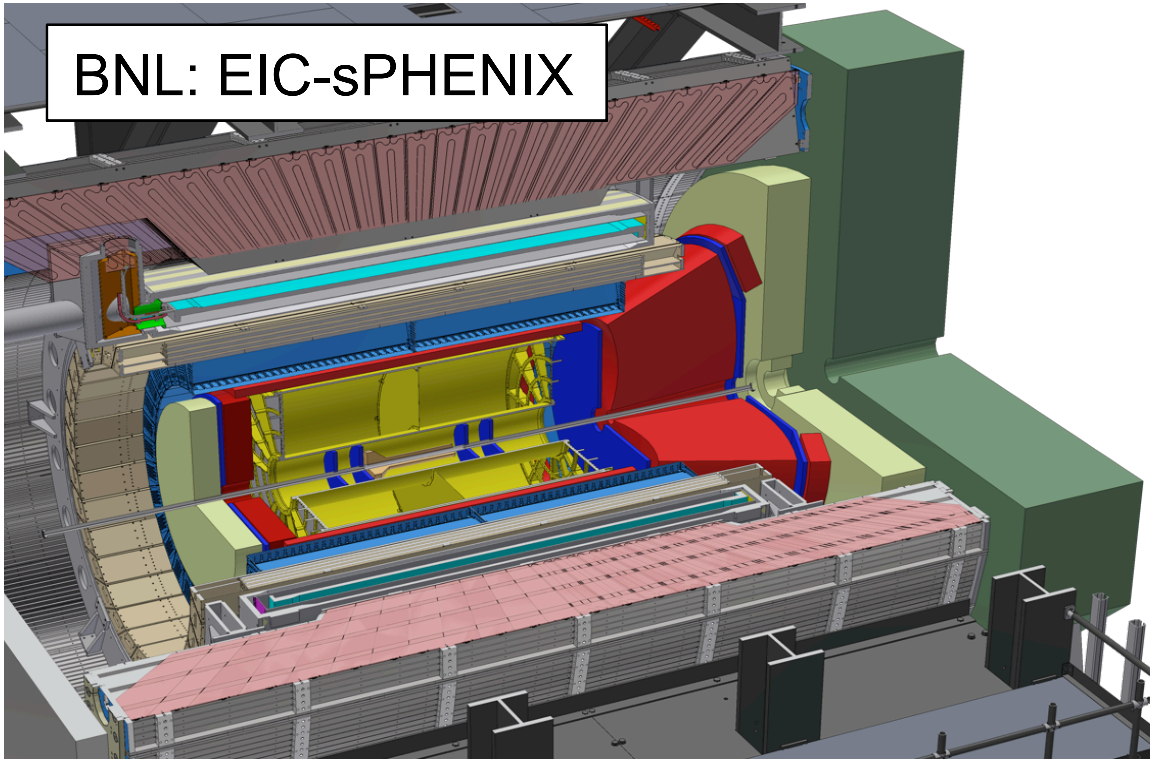


- Hadron Storage Ring
- Electron Storage Ring
- Electron Injector Synchrotron
- Possible on-energy Hadron injector ring
- Hadron injector complex



EIC Detector

- Pre-conceptual designs from JLab and BNL
- Option at BNL: sPHENIX → ePHENIX
- Possibility of a second, possibly differently optimized detector in existing Hall 2



Ongoing studies: optimizing inclusive, semi-inclusive and exclusive DIS measurements: *Particle tracking, Electromagnetic calorimetry, hadronic calorimetry, particle identification technologies: for flavor separation/heavy-light quarks, jets, Interaction region design and integration with the EIC detector, background studies, synchrotron radiation issues near and far from the IR, beam-gas interactions….*

Additionally: *Electron and proton beam polarimetry, precision polarimetry measurements*

Various preliminary concepts for EIC detector exist, design optimization on-going

EIC Detector (2)

Current EIC detector concepts

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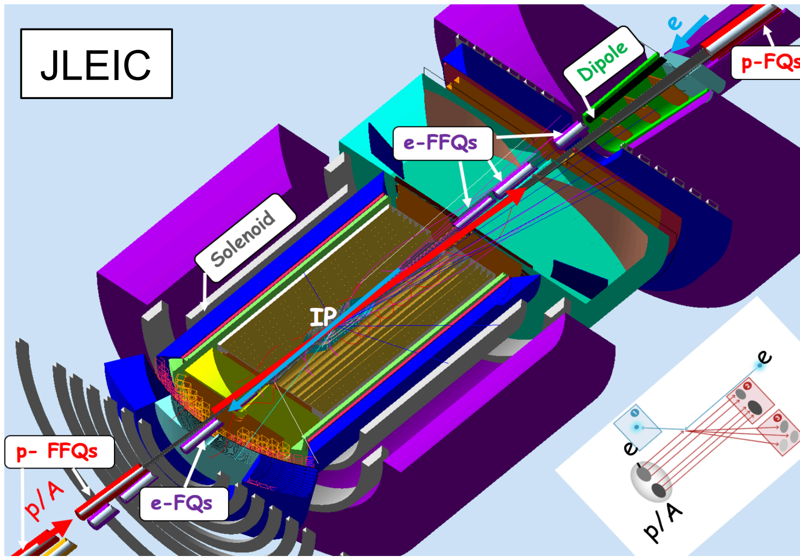
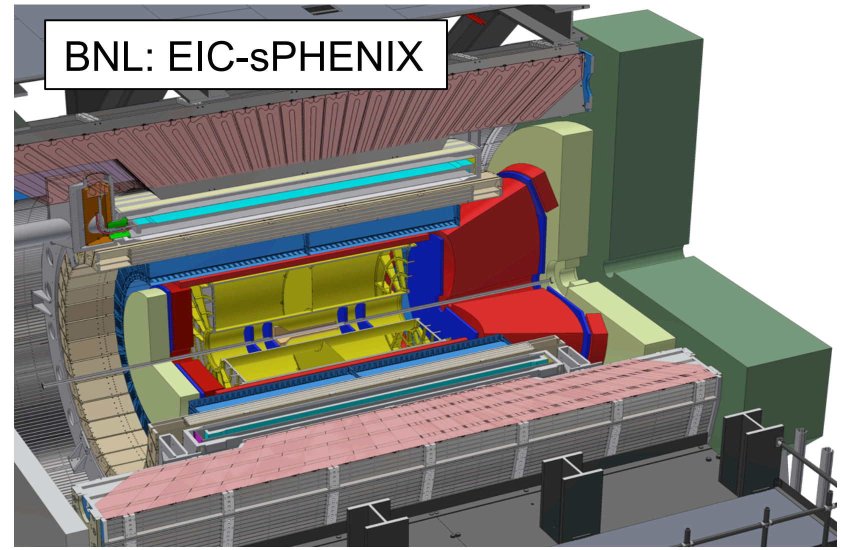
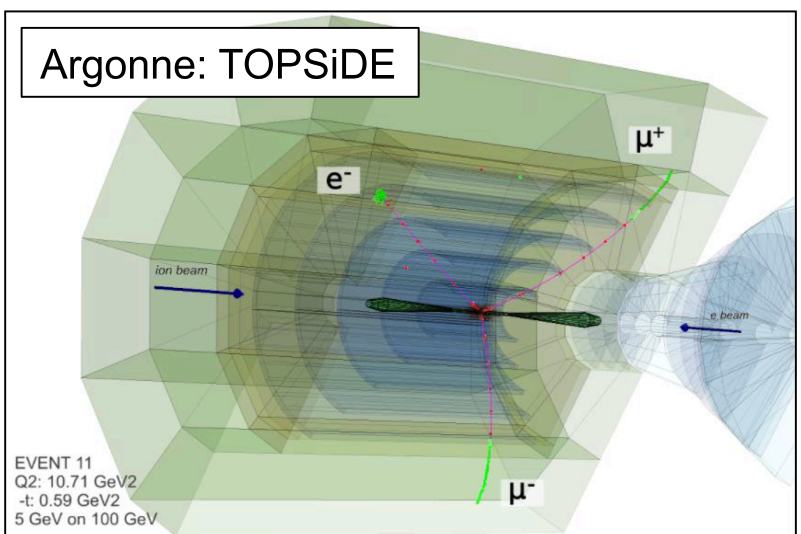
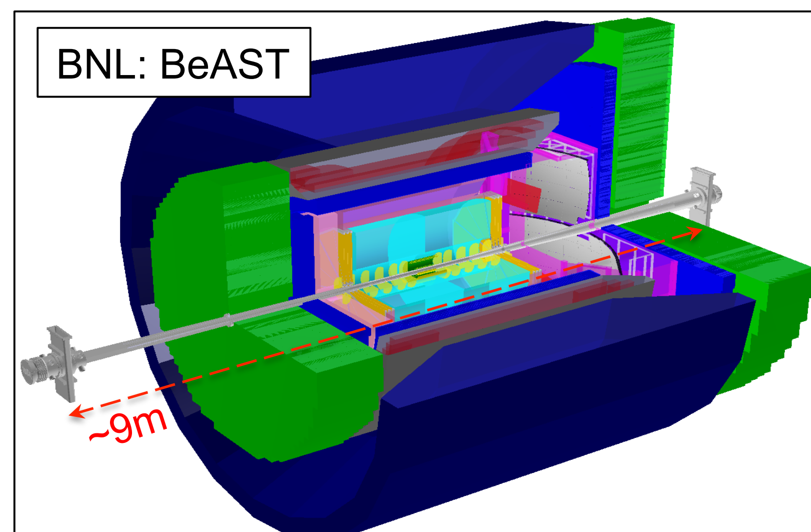
Kiselev



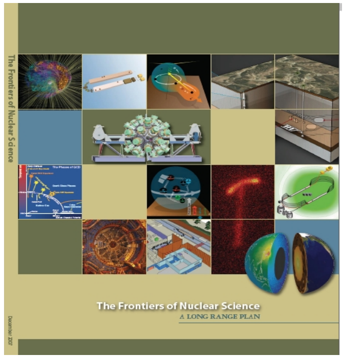




Time OPtimized Silicon Detector for EIC

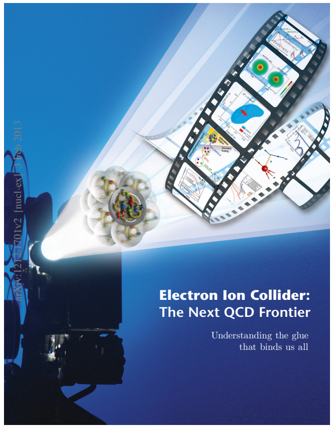


A U.S-based EIC: status



- 2007 NSAC Long Range Plan: recommendation to develop a conceptual of the accelerator and detector guided by the physics program

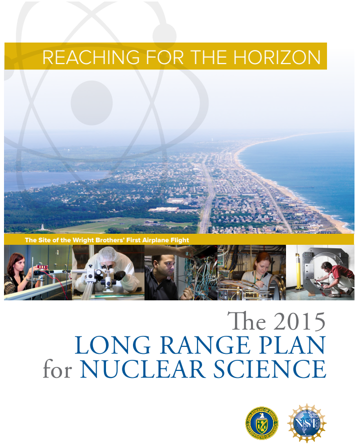
- 2010: 10-week INT program (Seattle, USA) “Gluons and quark sea at high energies”, arXiv:1108.1713



- 2013: EIC White Paper, arXiv:1212.1701, EPJ A52 (2016) 268

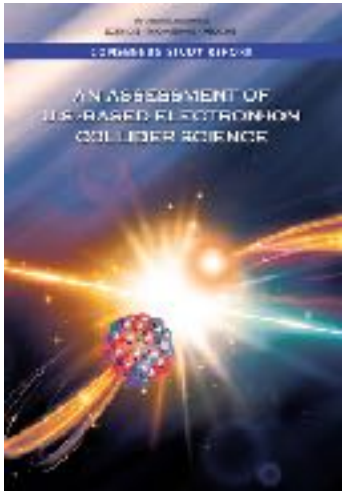
- 2015 NSAC Long Range Plan:

“We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.”



- 2017 assessment of NAS: Full support.

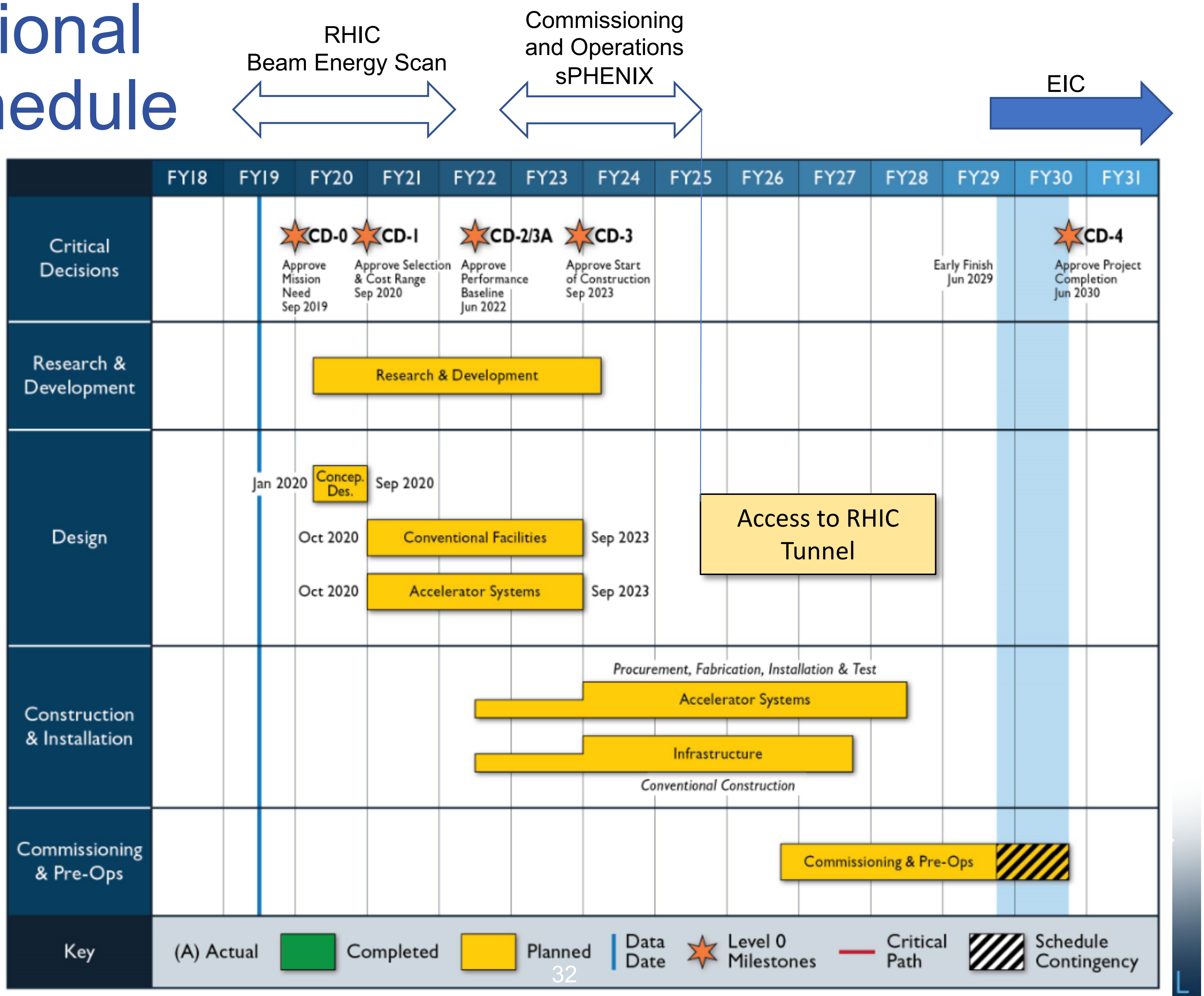
“An EIC is timely and has the support of the nuclear science community. The science that it will achieve is unique and world leading…”



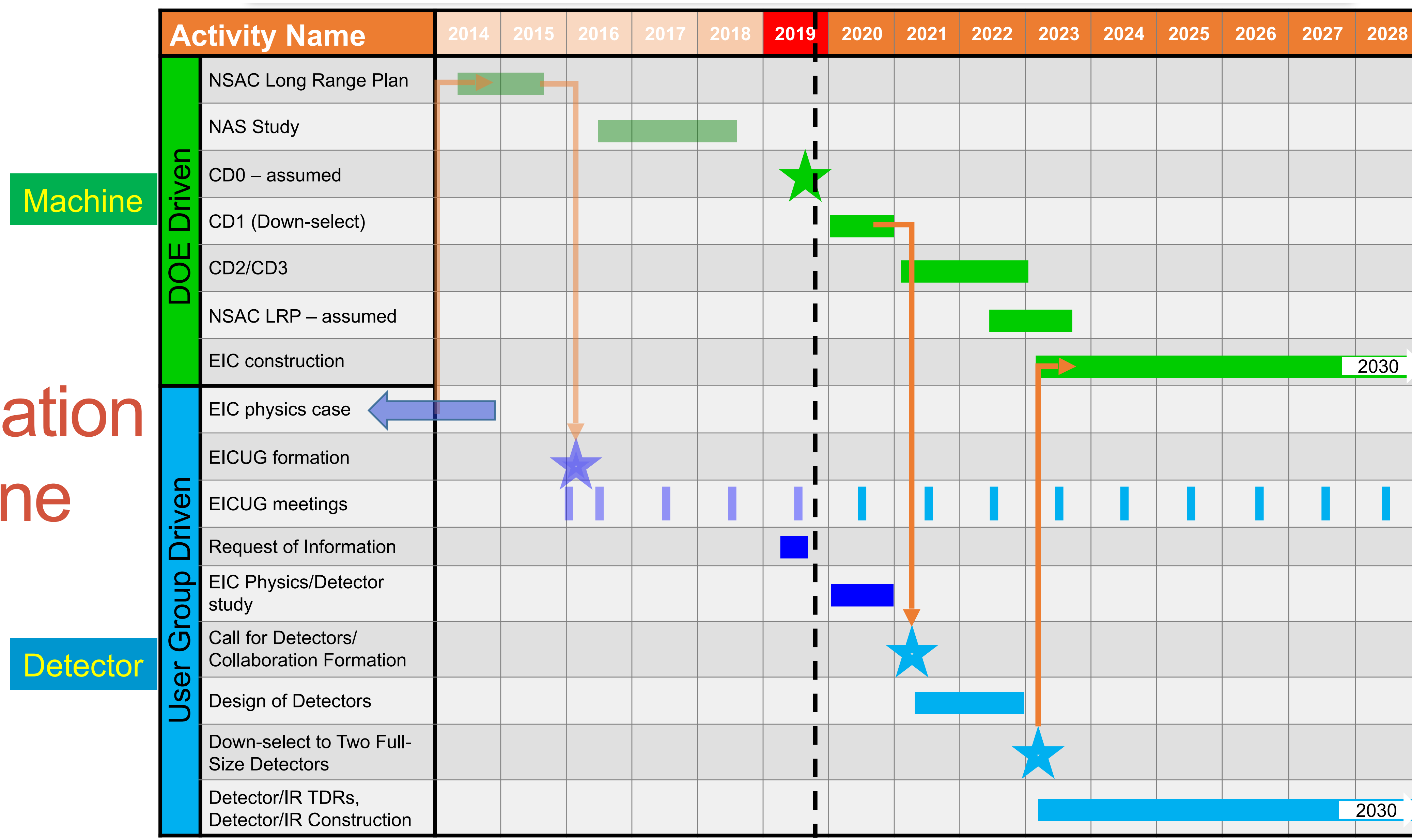
- **Dec. 2019, CD-0** “Approve Mission Need”: DOE selects BNL for building EIC.

EIC timeline

Notional Schedule



EIC timeline



EIC: organization

- EIC working groups at BNL, https://wiki.bnl.gov/eic/ and JLab, https://eic.jlab.org/wiki/index.php/Main_Page

- Electron-Ion Collider User Group since 2016: > 950 scientists from > 189 institutes and universities, http://www.eicug.org/web/ : Steering Committee, Institutional Board, Speaker's Committee

- Yearly POETIC (Physics Opportunities at an Electron-Ion Collider) conferences.

- EIC talks at all major particle and nuclear physics conferences.

- EIC Yellow Report for EIC Physics and Detectors, 2020:
  - quantify measurements for EIC physics (existing and new)
  - study detector concepts based on those physics measurements
  - series of workshops
  - final document Jan - Apr 2021

Summary

- High-energy and high-luminosity polarized EIC is viewed as a key facility to study fundamental questions of QCD.

- The main aim of the EIC physics program is to understand the microscopic nature of the visible matter in the language of quarks and gluons of QCD.

- In particular, it is planned to study:
  - the spin- and 3D-structure of the proton
  - the role of nuclear matter in the distribution of quarks and gluons
  - propagation of color charges (hadronization)
  - possible onset of a new regime of high-density saturated gluonic matter.

- EIC has full support of the U.S. nuclear physics community. Next steps is to prepare the EIC Yellow Report and obtain CD1 (design choice).