Status and physics of EIC

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Young Nordic Future-Collider day

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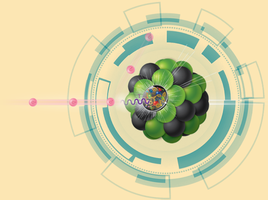
STRONG-2020

Outline

- DIS basics
- EIC project
- Dense gluons
- Spin
- 3D mapping



EIC–the most powerful microscope on Earth

"Microscope" Study matter with photons—light. "Most powerful": combination of

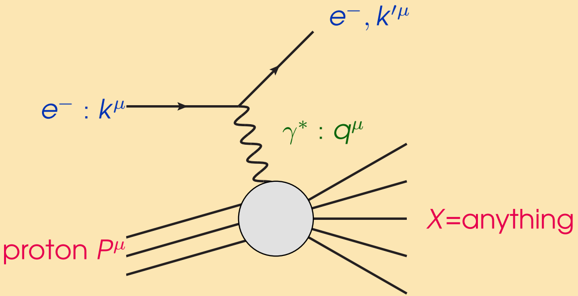
A Broad range of photon wavelength and frequency (x & Q^2) & targets

B High luminosity

- A. Accardi et al "Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all," Eur. Phys. J. A **52** (2016) no.9, 268 [arXiv:1212.1701 [nucl-ex]].
- R. Abdul Khalek, *et al.* "Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report," Nucl. Phys. A **1026** (2022), 122447 [arXiv:2103.05419 [physics.ins-det]].

Deep Inelastic Scattering (DIS)

= electron-proton/nucleus collision



$$q = k - k' \quad q^2 \equiv -Q^2$$

$$x = \frac{Q^2}{2P \cdot q}$$

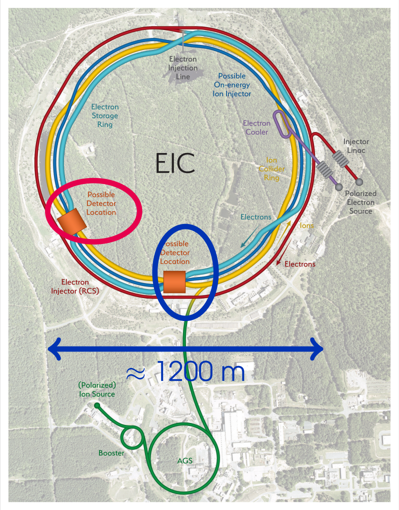
- EIC main goal: structure of the proton/nucleus. (LHeC, FCC-eh: more EW & BSM)
- DIS: measure outgoing electron: know exactly the photon q^μ
  (as opposed to proton-proton, Feynman: Swiss watches . . .) $\Longrightarrow x, Q^2$
- 2 variables for **virtual** photon. Interpretation:
  - $x \sim$ wavelength of photon in target rest frame $(1/x \sim$energy) "Longitudinal"
  - Q^2 "virtuality": $1/Q =$ wavelength in frame where photon energy=0 "Transverse"

EIC project

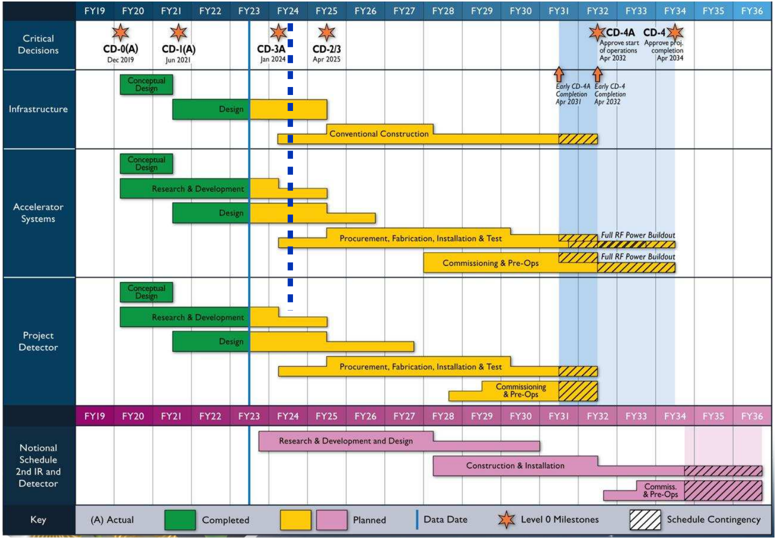
What is EIC

- At Brookhaven, Long Island

- Existing RHIC:
  - 100 GeV/nucleon ion beam
    (up to uranium $A = 238$)
  - 275 GeV polarized proton beam
- New 18GeV e^- beam
- 1–2 detectors (depends on funding)

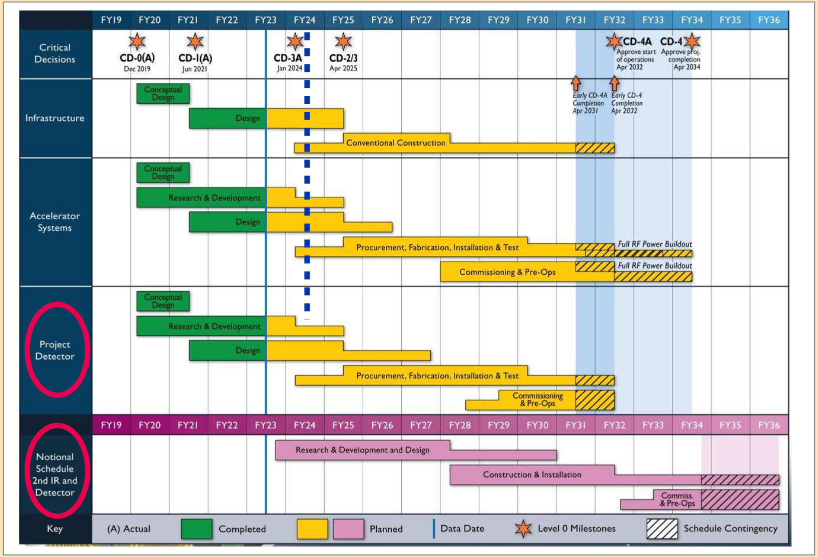


Schedule



(James Yeck, July 2023)

Schedule

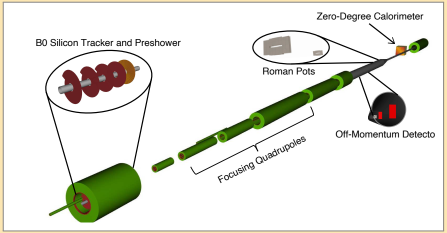


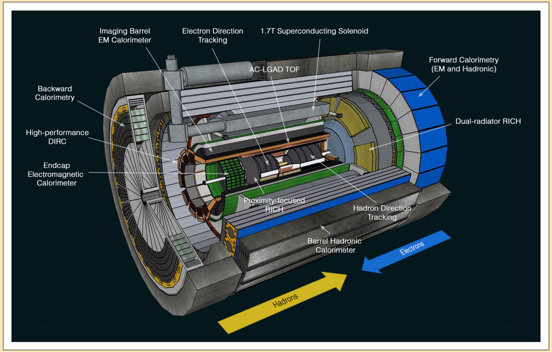
(James Yeck, July 2023)

ePIC detector

electron-Proton-Ion Collider detector

- “Project detector,” funded
- $-4 \lesssim \eta \lesssim 4$
- + Forward detectors





- 2nd detector (not named yet) later

- Main detector ∼10m long, ∼2T field
- Note asymmetry lepton–proton/ion

Characteristics and physics program

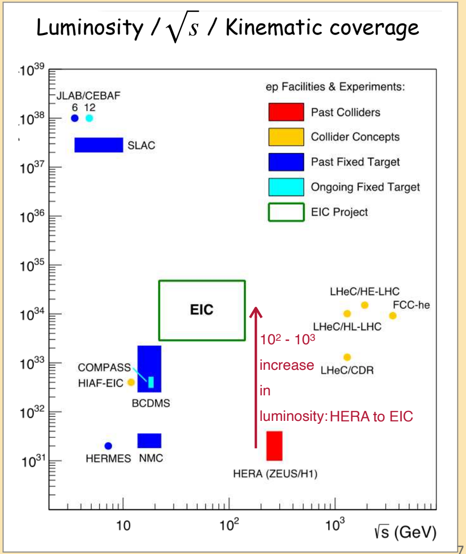
There was already HERA
(DESY, Hamburg, –2007)
$\sim$30GeV $e^{\pm}$ on $\sim$900GeV p

What is different with EIC? Physics driver:

- HERA: look for new particles
- EIC: understand quarks, gluons

3 key features

1. Nuclear beams $\Longrightarrow$ gluon saturation
2. Polarized proton $\Longrightarrow$ proton spin
3. Higher luminosity (factor $\lesssim$ 1000)



(B. Surrow)

Dense gluons

Cascade of gluons

Electric charge

- At rest: Coulomb electric field
- High velocity: cloud of photons
  (“equivalent photon approximation” ; Jackson)

$$\frac{dN}{d\omega} \sim \omega^{-1} \quad \text{(when } \omega \to 0\text{)}$$

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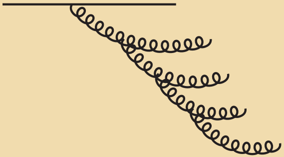
Color charge

- Moving color (e.g. valence quark) : cloud of gluons
- Gluons are source of new gluons: cascade

$$\frac{dN}{d\omega} \sim \omega^{-1-\#\alpha_s}$$



- Eventually becomes nonlinear—preserve unitarity

When do nonlinearities matter?

- Number of gluons in proton/nucleus $xG(x, Q^2)$
- Size of gluon probed $\sim 1/Q^2$
- Transverse space available πR^2
- Coupling α_s

Nonlinearities important when

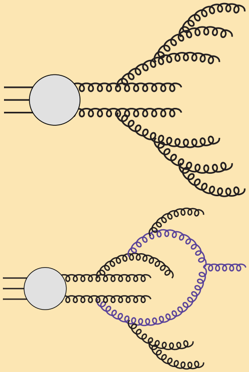
$$xG(x, Q^2) \gtrsim \frac{\pi R^2 Q^2}{\alpha_s}$$

Gluon saturation

Heavy nucleus, mass number A:

$$xG(x, Q^2) \sim A, \quad R \sim A^{1/3}$$

$\Longrightarrow$ Gain a factor ~ 6 with nuclear beam

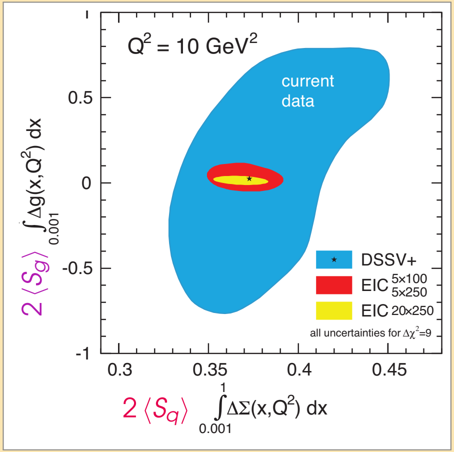


Spin

Proton spin

$$\frac{1}{2} = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle$$

- Already known: **proton spin puzzle**:
  quark spins: only $\sim 35\%$ of total $\frac{1}{2}$.
  (This is measuring helicity=longitudinal spin)



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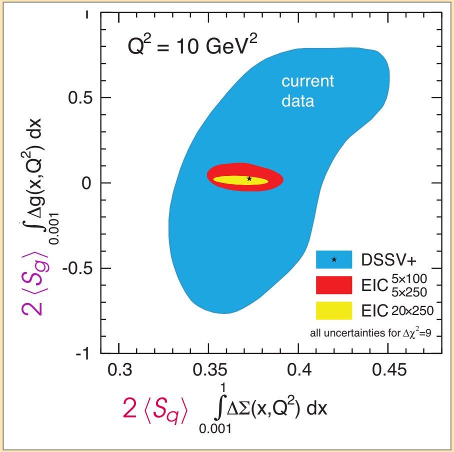
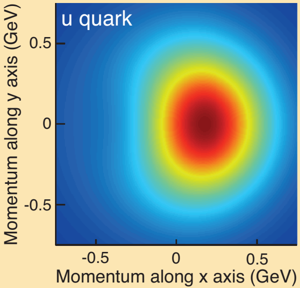
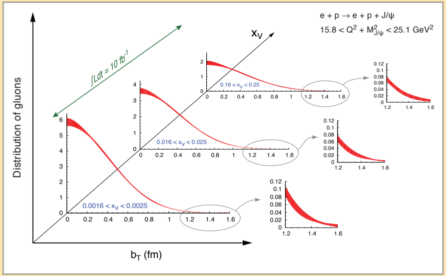
  (This is measuring helicity=longitudinal spin)
- EIC: measure gluon spin contribution
- Rest: orbital angular momentum **L**
- $\mathbf{L} = \mathbf{r} \times \mathbf{p}$: $\Longrightarrow$ measure **r** & **p** of partons!



Parton position and momentum

- Parton intrinsic momentum:
  - Access from produced particle **p** (SIDIS)
  - E.g. Sivers effect: correlation between
    - proton momentum (z)
    - proton spin (y)
    - produced particle (x)
- Parton coordinate: exclusive reactions
  - Outgoing proton intact
  - Momentum transfer $t = (p - p')^2$: Fourier conjugate of $\perp$ coordinate





3D mapping

3D mapping

Measurements differentially in

- $Q^2, x, \mathbf{k}, z$ (SIDIS)
- Q^2, x, M_X^2, t (diffraction)
- Q^2, x, t, ξ (GPD's)
- ...

Requires:

- Luminosity
- Detector coverage

3D mapping

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- $Q^2, x, \mathbf{k}, z$ (SIDIS)
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Requires:

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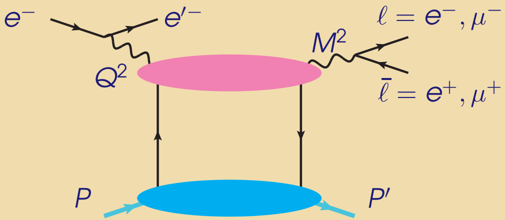
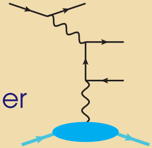
Extreme example: **TCS**

(Timelike Compton Scattering)



- $\sigma \sim \alpha_{\text{e.m.}}^4$
- $\sigma \sim 1/Q^4$ and $\sigma \sim 1/M^4$
- $\sigma \sim \exp\{Bt\}$, $t = (P - P')^2 < 0$
- Factor $\sim$100 bkg from Bethe-Heitler



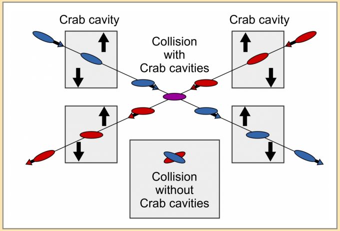
But you want to measure this!

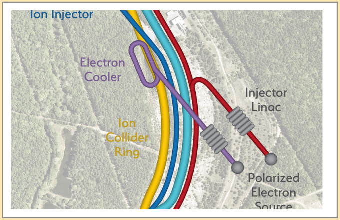
Luminosity

Requires strongly focusing the beam

- Crab cavities
  - Want focusing magnets close
    $\Longrightarrow$ separate beams quickly
  - Crossing angle 25 mrad = large
  - Crab cavities compensate crossing
- Electron cooling
  - Inject electron beam "along" protons
  - Coulomb interactions: thermalize
  - Thermal: $M\mathbf{v}_h^2 \sim m_e \mathbf{v}_e^2$
  - Electrons lighter
    $\Longrightarrow$ proton beam angular spread smaller

(Note cf LHC: pileup not a problem, cross sections are smaller)

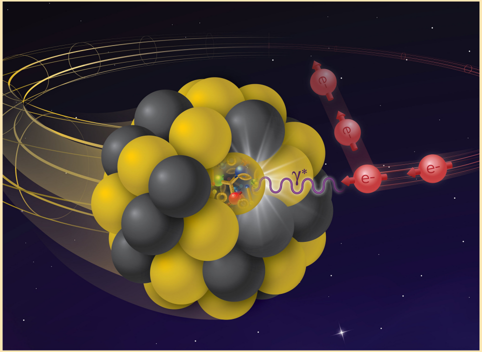




Conclusions

EIC: studying new aspect of glue

- First nuclear DIS collider:
  directly measure gluon saturation
- First spin-polarized DIS collider:
  understand nucleon spin
- Highest luminosity DIS collider:
  map out 3d structure of nucleon

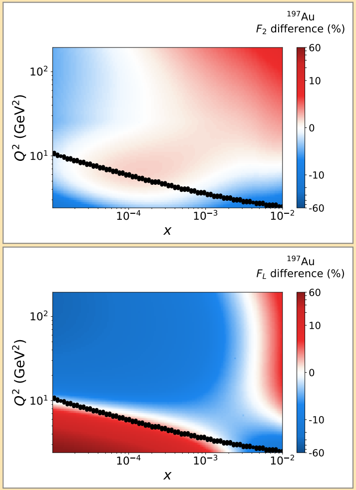


- Construction starting soon
- Expect data in early 2030's

Gluon saturation at EIC

Signals of gluon saturation

- Breakdown of DGLAP evolution:
  Gluon saturation should manifest itself in $\sim \frac{1}{Q^2}$ corrections



(DGLAP vs BK relative difference)

M- Tevio, T.L., H. Paukkunen 2022

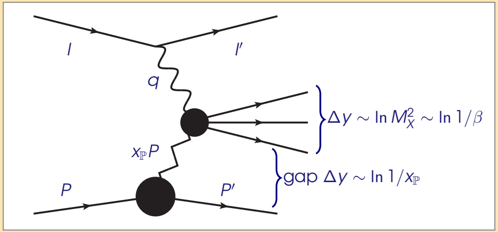
Gluon saturation at EIC

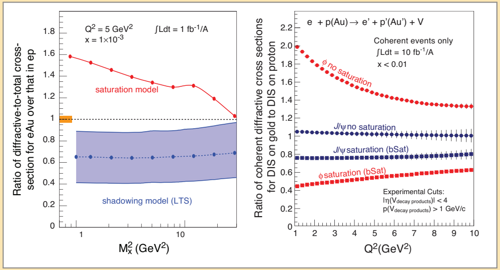
Signals of gluon saturation

- Breakdown of DGLAP evolution: Gluon saturation should manifest itself in $\sim \frac{1}{Q^2}$ corrections
- Enhancement of diffraction: Black disk: $\frac{1}{2}$ of events, $\sim$ 15% at HERA

(Diffractive DIS = exclusive reaction: target intact, colorless exchange

$\sigma_{\text{tot}} \sim 2\mathcal{N} \quad \sigma_{\text{diff}} \sim \mathcal{N}^2$)





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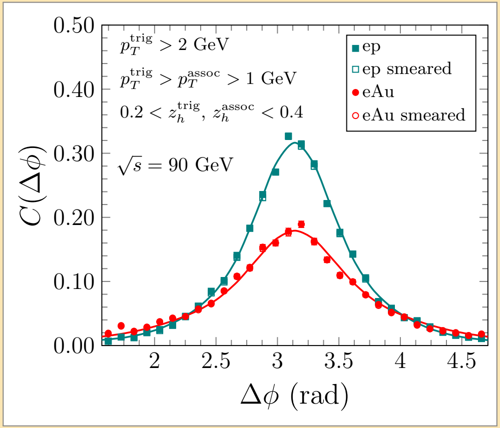
  (Diffractive DIS = exclusive reaction: target intact, colorless exchange
  $\sigma_{\mathrm{tot}} \sim 2\mathcal{N}$ $\quad \sigma_{\mathrm{diff}} \sim \mathcal{N}^2$)
- Angular correlations in dijets: Q_s is a momentum scale



($\Delta\varphi$-distribution in $e^- + p/A \to 2h + X$)

Some interesting exclusive reactions

- Exclusive vector mesons & DVCS (deeply virtual Compton)

$$\gamma^* + p/A \to \mathrm{VM} + p/A$$

  - VM = $J/\Psi, \rho, \phi, \Upsilon, \ldots$ or $= \gamma$
  - directly measure gluons, spatial distribution from t
  - Spin asymmetry $\Longrightarrow$ position space analogue of Sivers
- Diffractive dijets

$$\gamma^* + p/A \to p/A + 2j$$

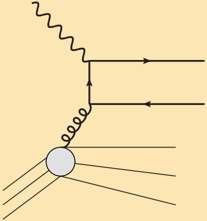
  - Gluon $\perp$ coordinate & momentum simultaneously (at least in principle)
- Sullivan process

$$\gamma^* + p \to \gamma^* + \pi^+ + n \to X + n$$

  - DIS off a pion

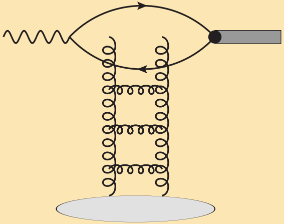
Why are exclusive reactions interesting for saturation?

Inclusive:



- Amplitude: $\gtrsim$1 gluon
- Cross section: $\gtrsim$2 gluons

Exclusive: need color neutral exchange



- Amplitude: $\gtrsim$2 gluons
- Cross section: $\gtrsim$4 gluons