The Electron-Ion Collider

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UK Nuclear Physics Community Meeting,
University of Warwick,
7th January 2020

Electron-Ion Collider

World's first polarized electron-proton/light ion and electron-Nucleus collider.

For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 3 – 10 (18) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}s^{-1}
- ✓ 20 – 100 (140) GeV Variable CoM

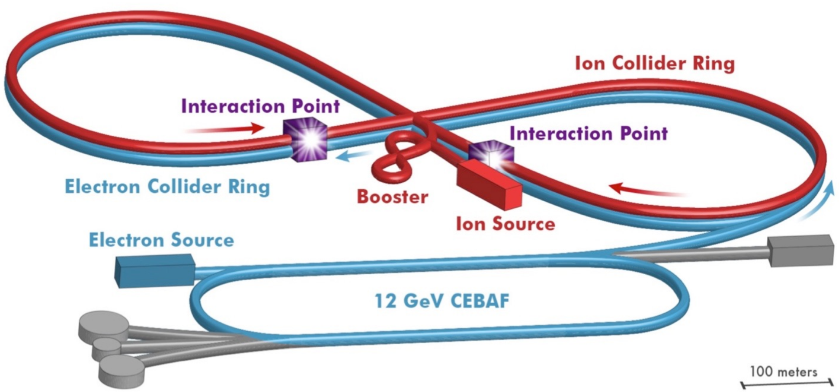
For e-A collisions at the EIC:

- ✓ **Wide range of nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable centre of mass energy

Two proposals for realisation of the science case:

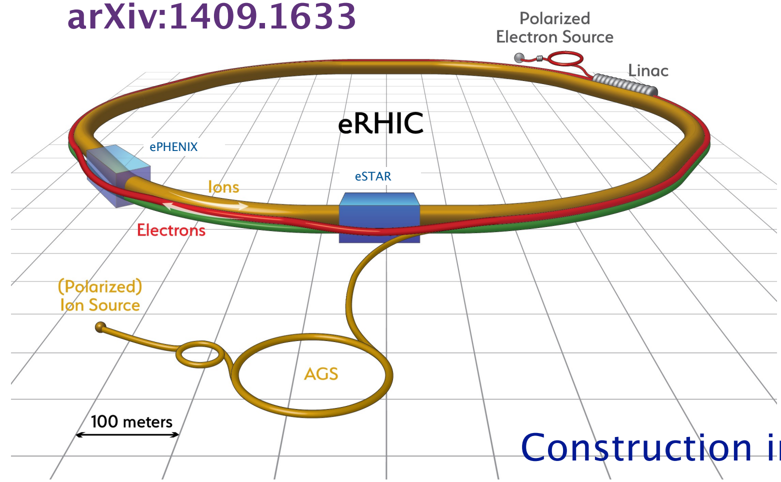
JLEIC @ Jefferson Lab

arXiv:1504.07961



eRHIC @ Brookhaven National Lab

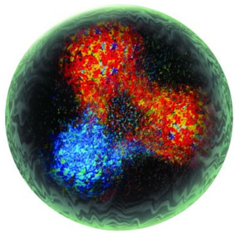
arXiv:1409.1633



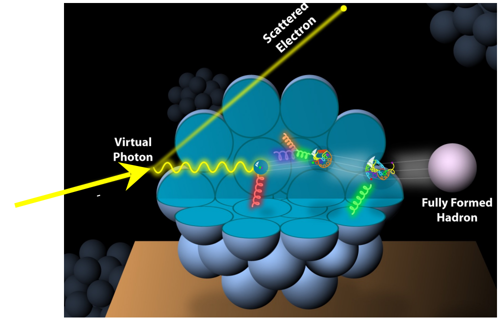
Construction in 2020s

Capabilities of both machine designs converging.

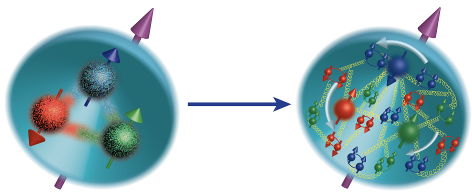
What will the EIC address & how?



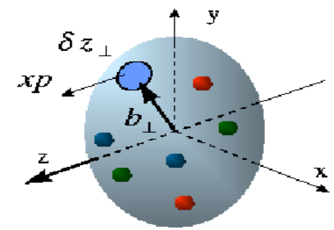
- How do hadrons and nuclei emerge from quarks and gluons? What is the nature of confinement?
- What is the quark-gluon origin of the nuclear force?
- How does colour charge propagate through nuclear matter?



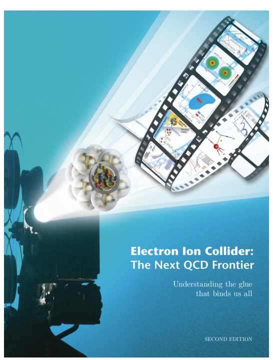
Courtesy of E. Aschenauer



- What is the full composition of nucleon spin? How much do sea quarks and glue contribute?



- What is the origin of nucleon mass and what is the role of glue in it?
- Where does gluon saturation set in?



2012 EIC White Paper:
Eur. Phy. J. A52, 9 (2016)

Yellow Report in preparation: 12-18 months, started Dec 2019. Intensive study of the diverse physics case & the detector concepts to enable it. Two main working groups:

- Physics (*Daria Sokhan sub-convener for Exclusive Processes*),
- Detector (*Peter Jones one of four conveners*).

http://www.eicug.org/web/content/yellow-report-initiative

EIC timeline

- **2007 Nuclear Physics Long Range Plan** "*The EIC is embodying the vision of reaching the next QCD frontier*"

- **EIC generic detector R&D funds**: since 2011. Consortia formed (eg: PID, software). UK project: ***"Precision Central Silicon Tracking and Vertexing", Laura Gonella et al., Birmingham.***

- **2012 EIC White Paper,** *Eur. Phy. J. A 52, 9 (2016)*

- **2015 Nuclear Physics Long Range Plan** "*high-energy, high-luminosity polarised EIC as the highest priority for new facility construction following completion of FRIB*"

- **2016** EIC Users Group acquires formal charter and a board of elected representatives (***Paul Newman, Birmingham, current member of Elections & Nominating Committee***).

- **2017-18 National Academies of Science (NAS) Review:** "*the science questions that an [EIC] would answer are centra to completing our understanding of atomic nuclei… An EIC can **uniquely** address three profound questions about nucleons … and how they are assembled to form the nuclei of atoms*"

EIC timeline continued

- **2018 "Probing Nucleons and Nuclei in High Energy Collisions"**: 7-week workshop programme @ INT, Seattle, to address the physics of EIC (Proceedings in preparation).
- **DOE funds for accelerator R&D**: $9-11M / year for FY18 and FY19.
- 2019 DOE completed an **Independent Cost Review Exercise**.
- Aug 2019: **DOE-led EIC meeting with international funding agencies** / government representatives in London.
- 2019: Panel appointed by DOE to **assess site options** for "best value" had been convened and met.
- **EIC Yellow Report** in preparation (process started Dec 2019). **Conveners / sub-conveners: Peter Jones (Birmingham), Daria Sokhan (Glasgow).**
- Next stage: ***CD0*** (formally establishing mission need), expected within months. Strong possibility that site selection / **CD1** (approve alternative selection and cost range) will be announced concurrently.
- European meetings of the EIC Users Group (EICUG): Trieste, Italy (2017), Paris, France (2019).
- Construction to start in 2020s.

Current UK involvement / interest

UNIVERSITY of GLASGOW

JAI John Adams Institute for Accelerator Science

THE UNIVERSITY of LIVERPOOL

The Cockcroft Institute of Accelerator Science and Technology

UNIVERSITY of York

UNIVERSITY OF BIRMINGHAM

UNIVERSITY OF DERBY

Science & Technology Facilities Council Daresbury Laboratory

Plus some tentative interest from other groups…

UK involvement

✦ **Horizon-2020 European Integrating Initiative in Hadron Physics funds: 325k€** *(2019-23), half of the funds to UK*

"Challenges for next-generation DIS facilities"

Spokespeople: Daria Sokhan (Glasgow) and Francesco Bossi (CEA Saclay, France)

Glasgow, Birmingham, York, INFN, Saclay, CNRS, …

A collaborative European effort focussed on EIC detector R&D (tracking, vertexing and PID) and simulations. One PDRA post (Glasgow).

✦ **DoE funds through EIC detector R&D programme: $250k over past 3 years.** *(ongoing: 2017-19)*

"Precision Central Silicon Tracking & Vertexing for the EIC"

Birmingham: Laura Gonella, Peter Jones, Paul Newman, Phil Allport, H. Wennlöf

Successful collaboration of nuclear, particle and instrumentation groups, synergies with existing R&D projects. Collaboration with RAL on design of fully-depleted MAPS pixel sensor. Expected time resolution: ~ 1ns: time-stamping of individual bunch crossings. Prototype to be fabricated in 2020.

Accelerator R&D in ERL technology: synergies with currently funded projects (UK-FEL), direct relevance for EIC. **3 new PhD projects funded, started 2018** (Cockcroft), SOIs in preparation

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EIC: one of the 52 priority projects in the **UKRI Developing a World Class Research Programme** initiative.

Summary

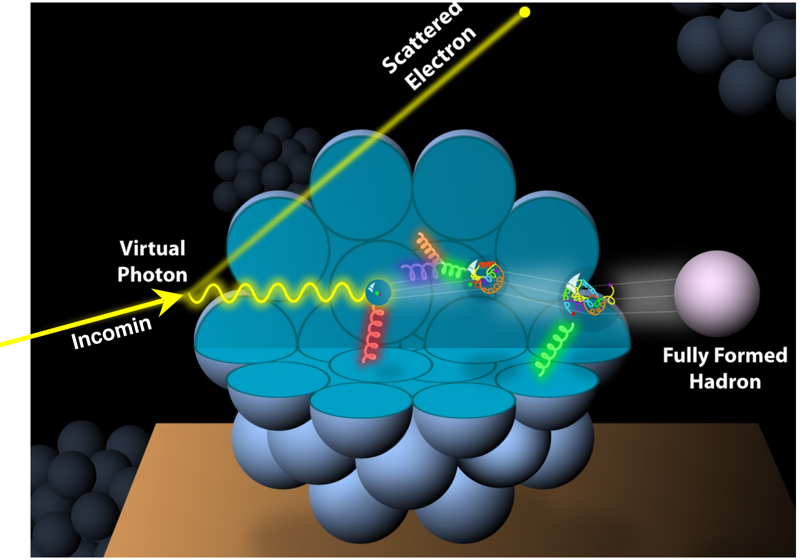
- Electron-Ion Collider is becoming the highest priority for US nuclear physics.
- The EIC Community: 973 members, 199 institutes, 30 countries. http://www.eicug.org
- The US EIC leadership is **actively seeking** UK, and other European, involvement and significant contributions, e.g.:
    - Funding has been granted to the Birmingham project on tracking R&D.
    - Concrete accelerator projects have been initiated with both JLab and BNL.
- Enthusiastic **involvement of European colleagues**, e.g.: EIC featured in the 2017 NuPECC Long Range Plan: *"NuPECC highly recognises the science of the EIC project …representing an opportunity for a major step forward in the field of hadron physics."*

  "The large communities working on hadron structure both in Europe and the US are working towards and eagerly waiting for the approval of the first polarised Electron-Ion Collider."
- Funds for dedicated EIC R&D allocated through the **Horizon-2020 framework**.
- Scale of UK **involvement is ramping up**: funds from international sources, work towards accelerator and nuclear/detector physics SOIs.

EIC start of operations expected within this decade.

Thank you

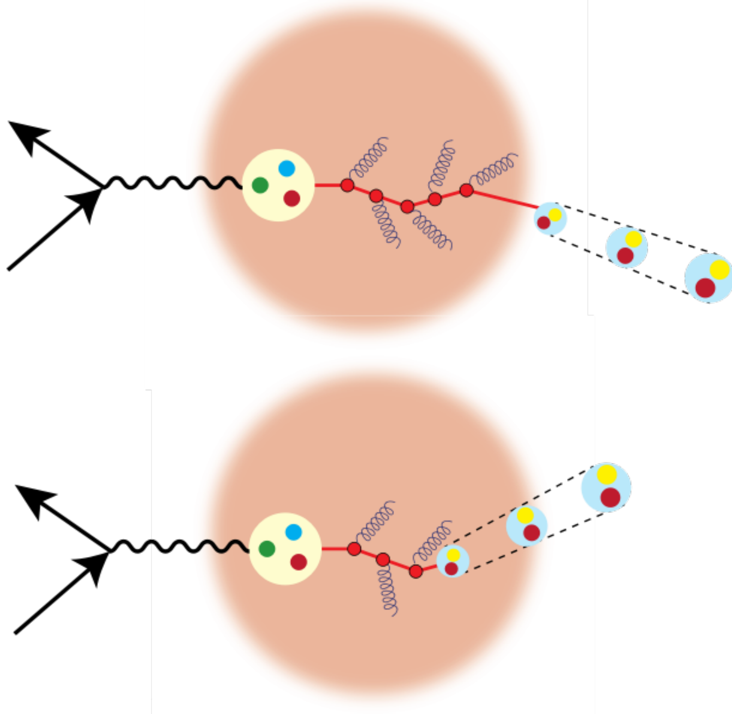
Back-up

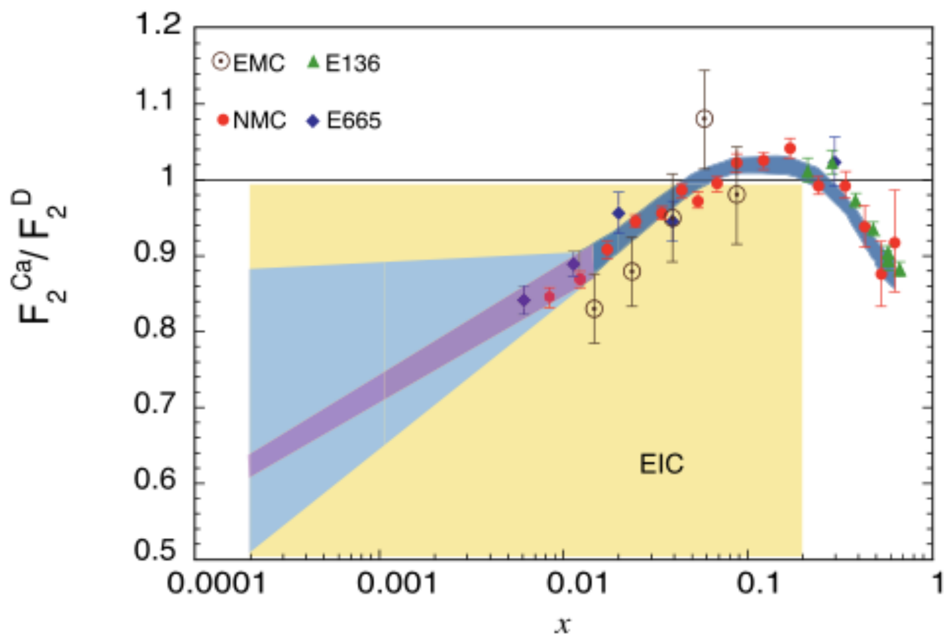


Courtesy of E. Aschenauer

Hadronisation

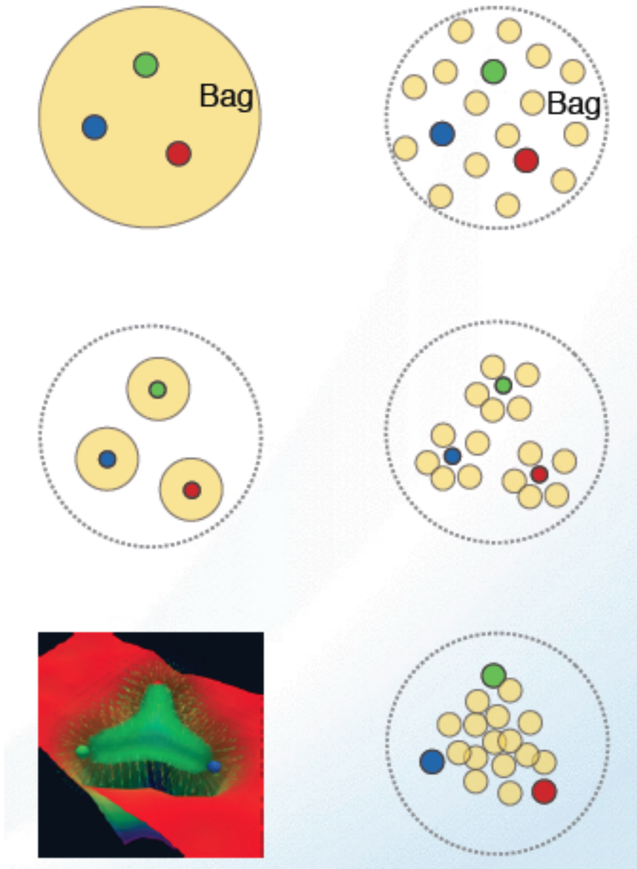
- How does the nuclear environment affect the quark-gluon distributions and their interactions inside nuclei?
- How does matter respond to a fast moving colour charge?
- Are there differences for light and heavy quarks?





Interpretations of the nucleon

What do spatial distributions tell us?



Courtesy of A. Deshpande

Bag Model: Gluon field distribution is wider than the fast moving quarks.

Gluon radius > Charge Radius

Constituent Quark Model: Gluons and sea quarks hide inside massive quarks.

Gluon radius ~ Charge Radius

Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks:

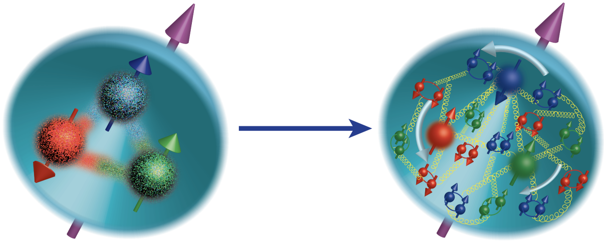
Gluon radius < Charge Radius

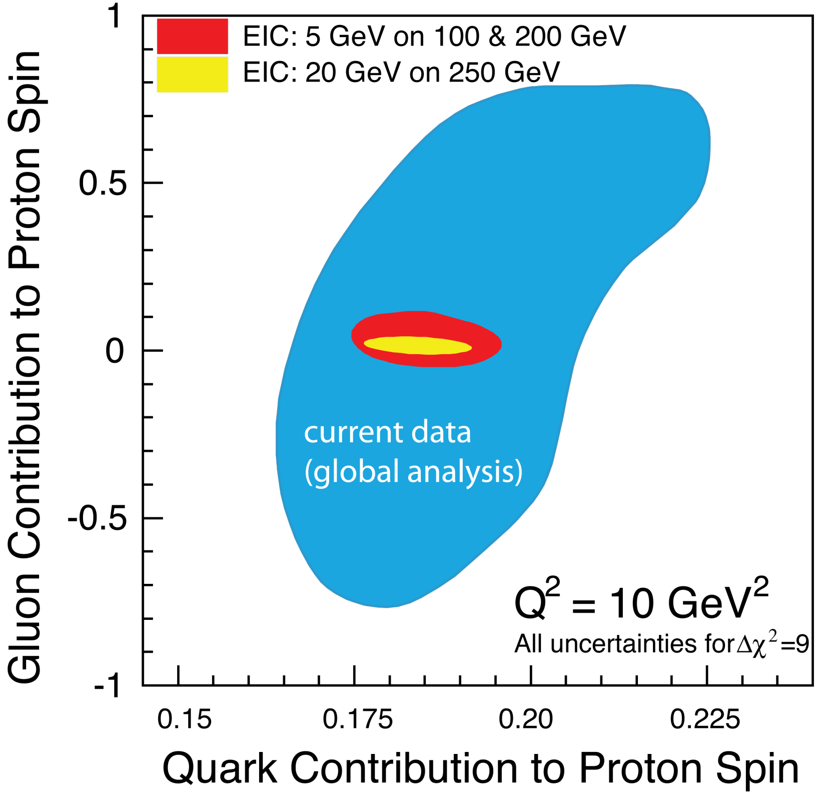
Need transverse images of the quarks and gluons in confinement: form factors

The puzzle of nucleon spin

* Gluons carry a sizeable fraction of nucleon momentum and give rise to transverse momentum of quarks. What is their contribution to nucleon spin? How do sea quarks contribute?

$$J_q = \frac{1}{2}\Delta\Sigma + L_q + J_g$$





* 3D imaging of hadrons across the widest range of scales.

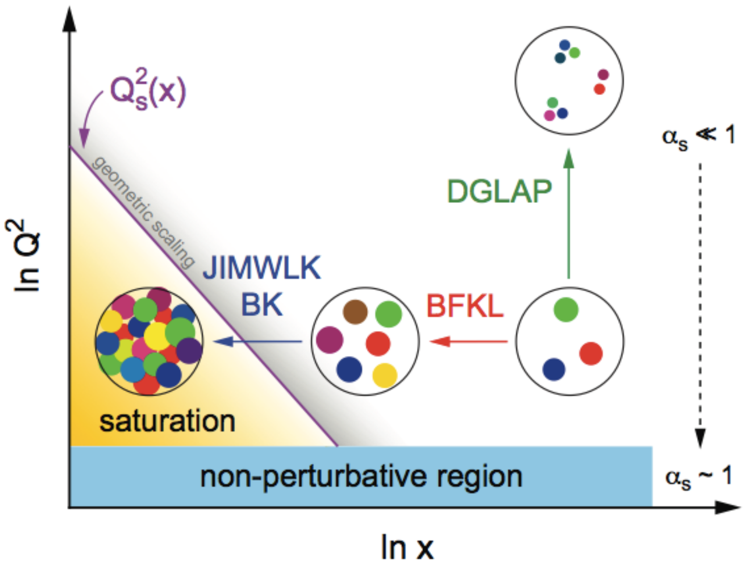
Saturation of gluon density

- Runaway growth of glue at low-x:

  "…A small color charge in isolation builds up a big color thundercloud…."

  F. Wilczek, in "Origin of Mass"

  Nobel Prize, 2004

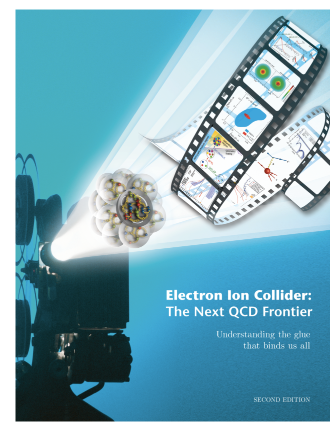


But somewhere it must saturate…

rate of  = rate of 

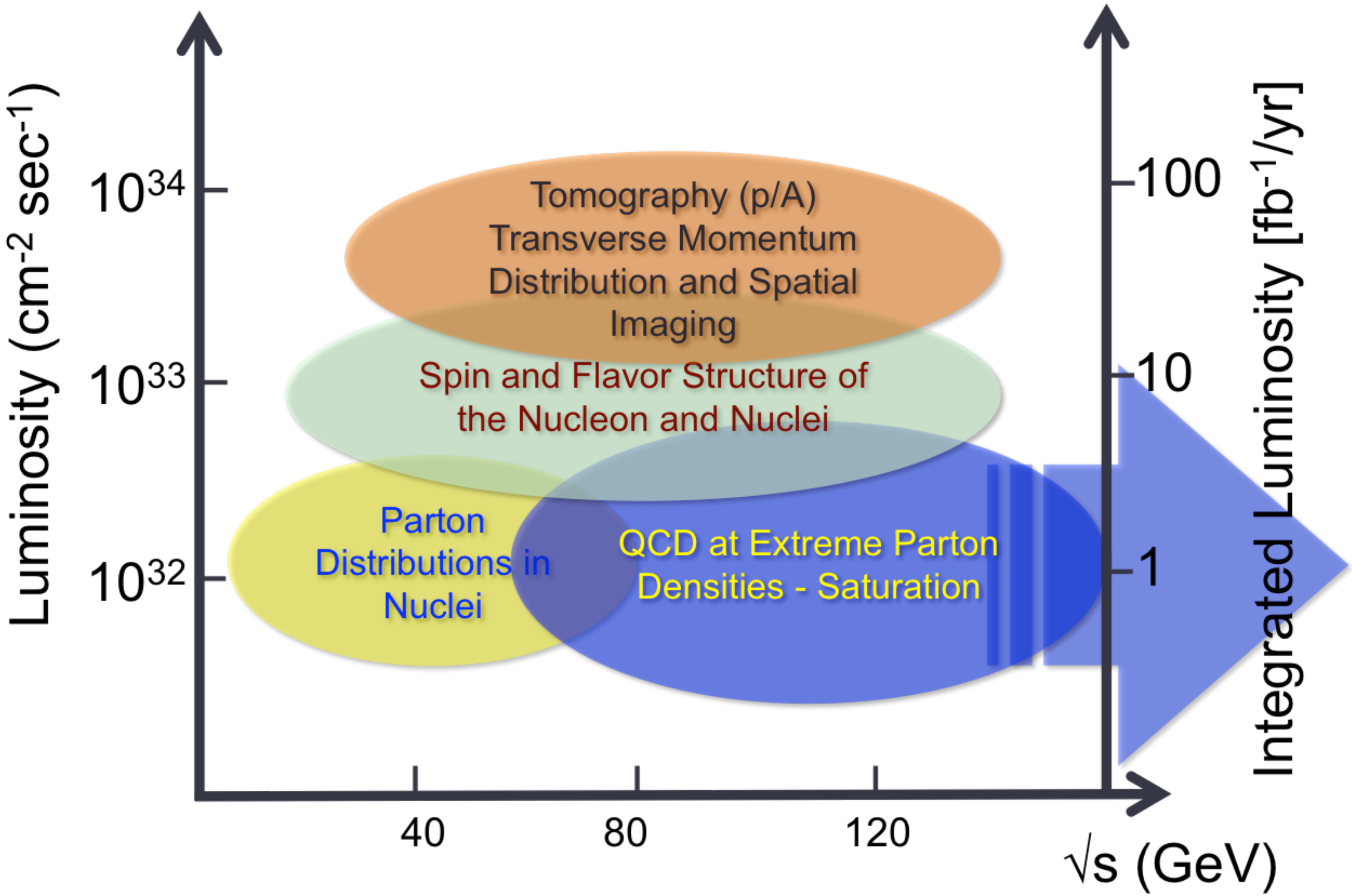
Possible effective theory for the saturated phase: Colour Glass Condensate.

2012 EIC White Paper: *Eur. Phy. J. A 52, 9 (2016)*



Physics case has already evolved far beyond it!

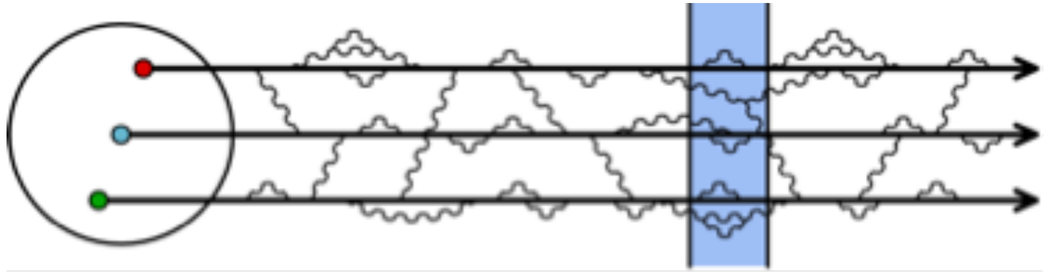
What will the EIC be able to do?



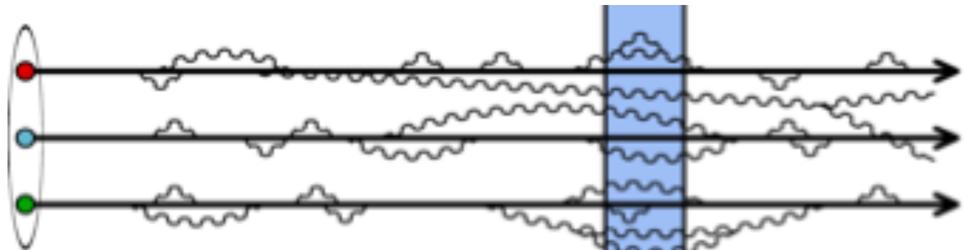
year =10^7 sec

Runaway glue

* Nucleon probed at low Q^2, high x.



* Nucleon probed at large Q^2, low x.

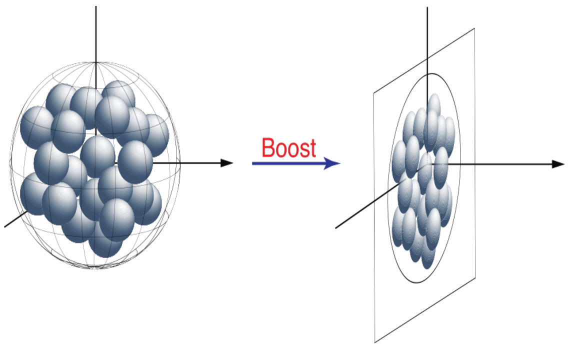


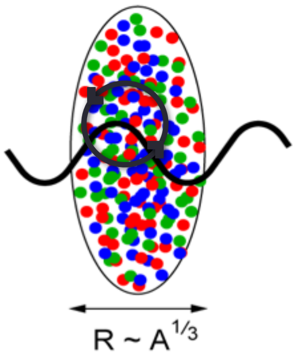
Courtesy of A. Deshpande

* Gluons are charged under colour: can generate (and absorb) other gluons.

* Nucleon probed at high energies, time dilation of strong interaction processes: gluons appear to live longer, emitting more and more gluons. Runaway growth! Runaway growth?

Can we reach saturation at EIC?

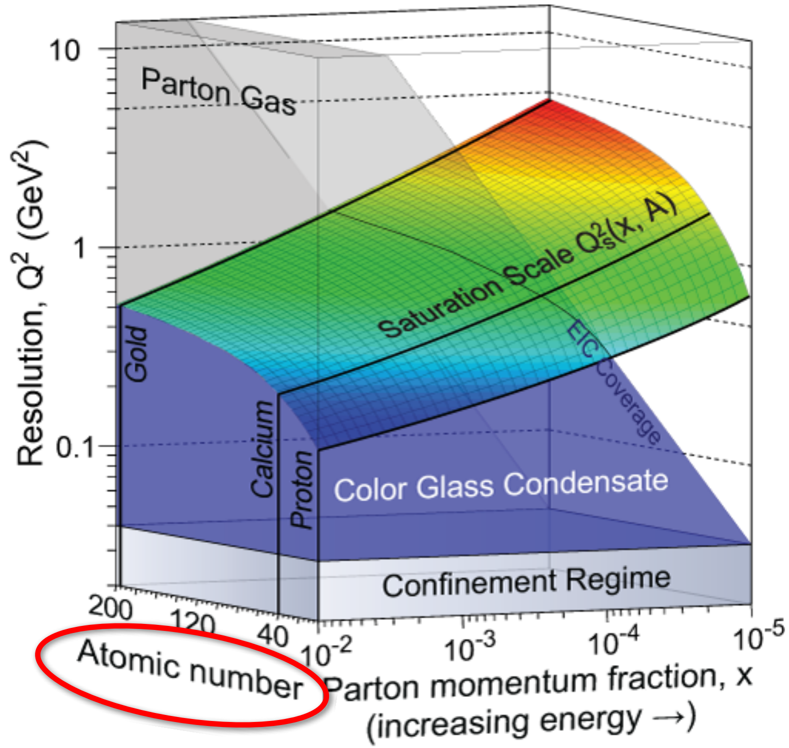




$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

saturation scale

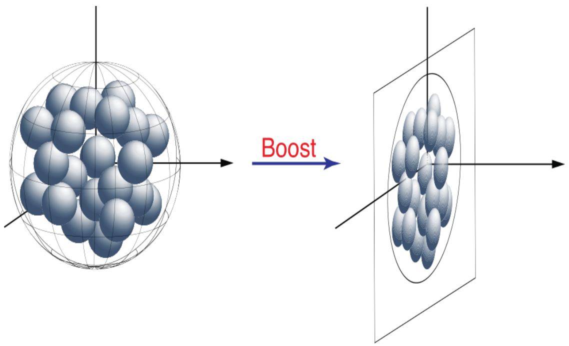
$$L \sim (2m_N x)^{-1} > 2\, R_A \sim A^{1/3}$$

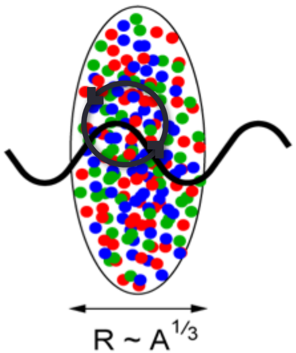


Saturation regime would be accessible at much lower energy in e-A collisions than e-p. You do not need a TeV collider!

Courtesy of A. Deshpande

Can we reach saturation at EIC?

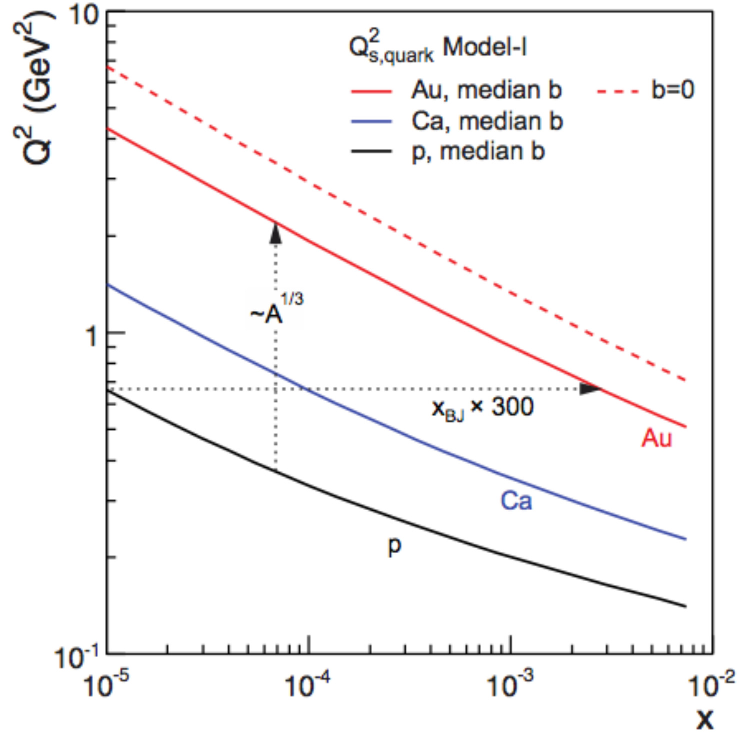




$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

saturation scale

$L \sim (2m_N x)^{-1} > 2 R_A \sim A^{1/3}$



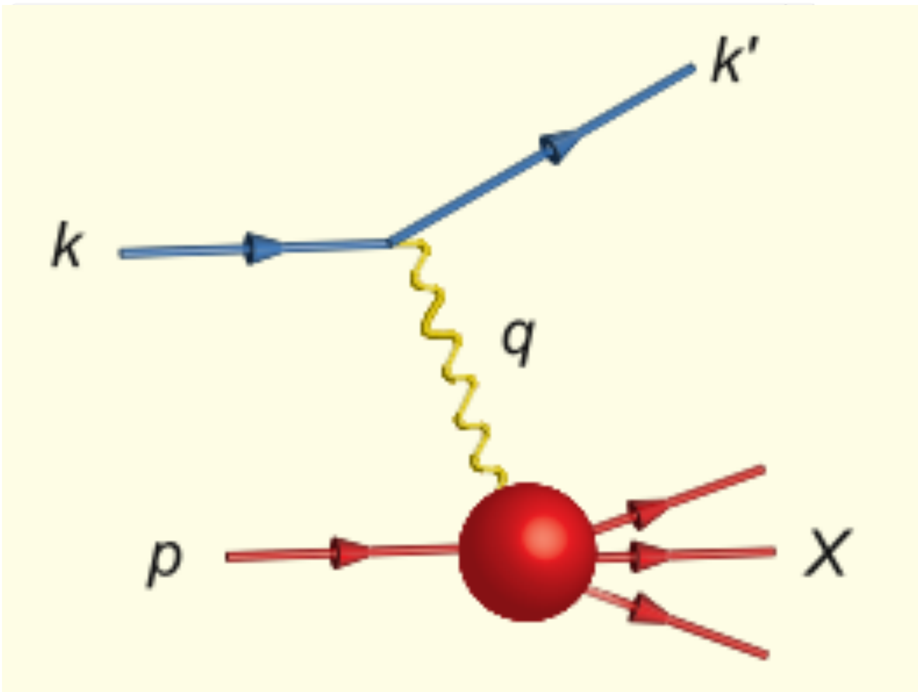
Saturation regime would be accessible at much lower energy in e-A collisions than e-p. You do not need a TeV collider!

Courtesy of A. Deshpande

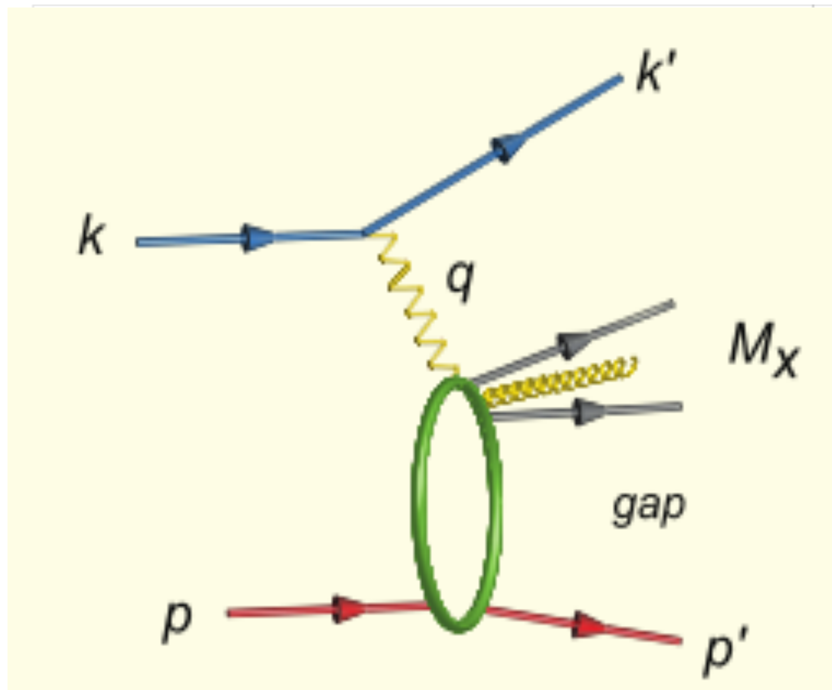
A sign of gluon saturation

A powerful signature is diffractive cross-sections:

Deep Inelastic Scattering



Diffractive Scattering



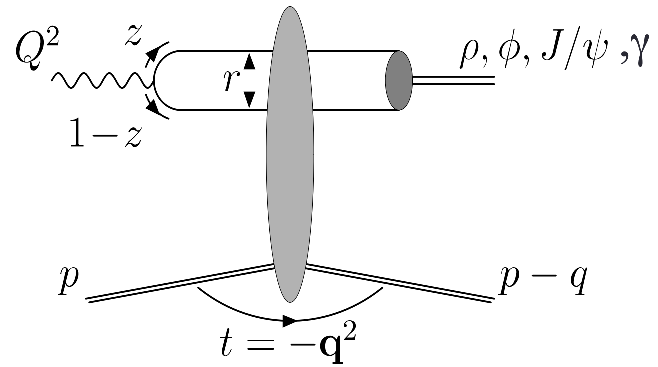
$$\sigma_{\rm diff} \propto [g(x, Q^2)]^2$$

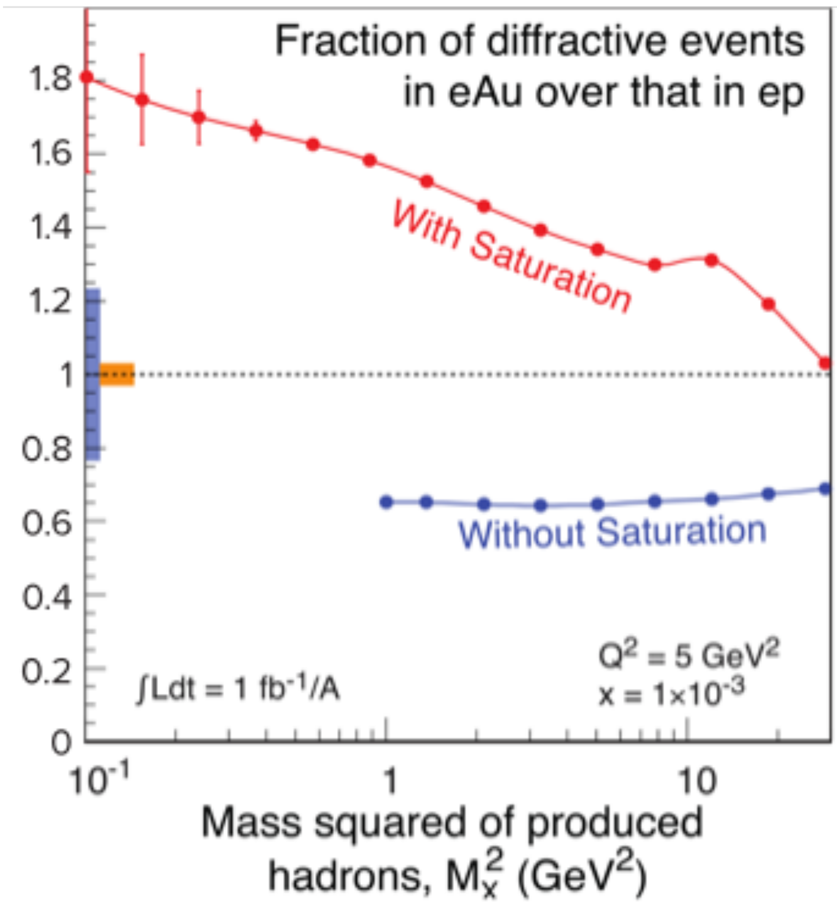
Saw ~10% diffractive events at HERA.

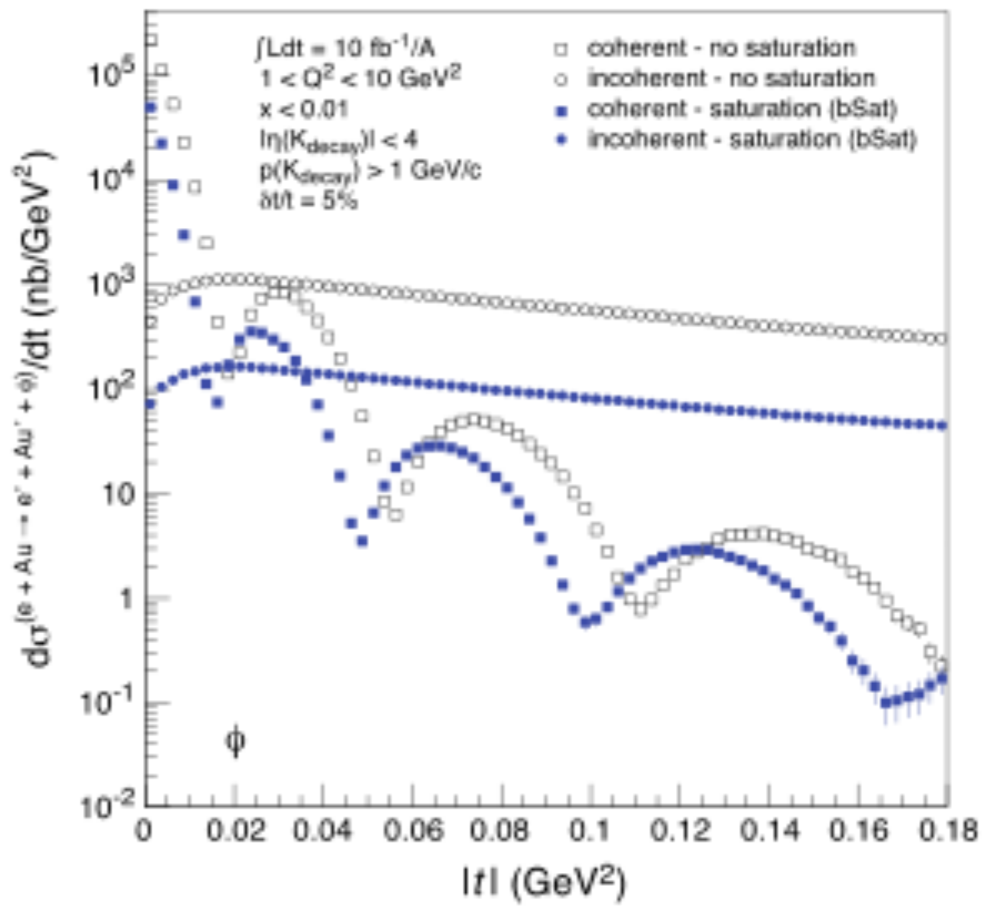
Courtesy of A. Deshpande

Gluon saturation

Modified transverse gluon distributions?





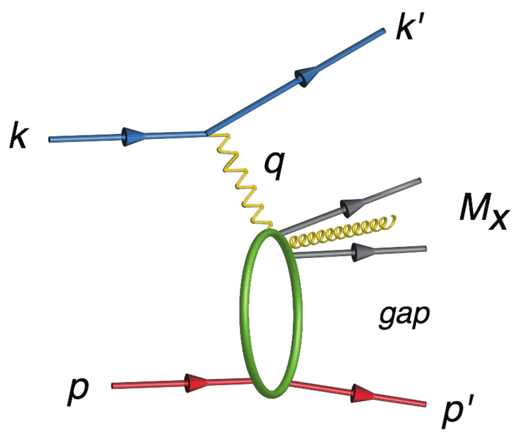


Courtesy of A. Deshpande

Saturation/CGC: What to measure?

Many ways to get to gluon distribution in nuclei, but diffraction most sensitive:

$$\sigma_{\text{diff}} \propto [g(x, Q^2)]^2$$

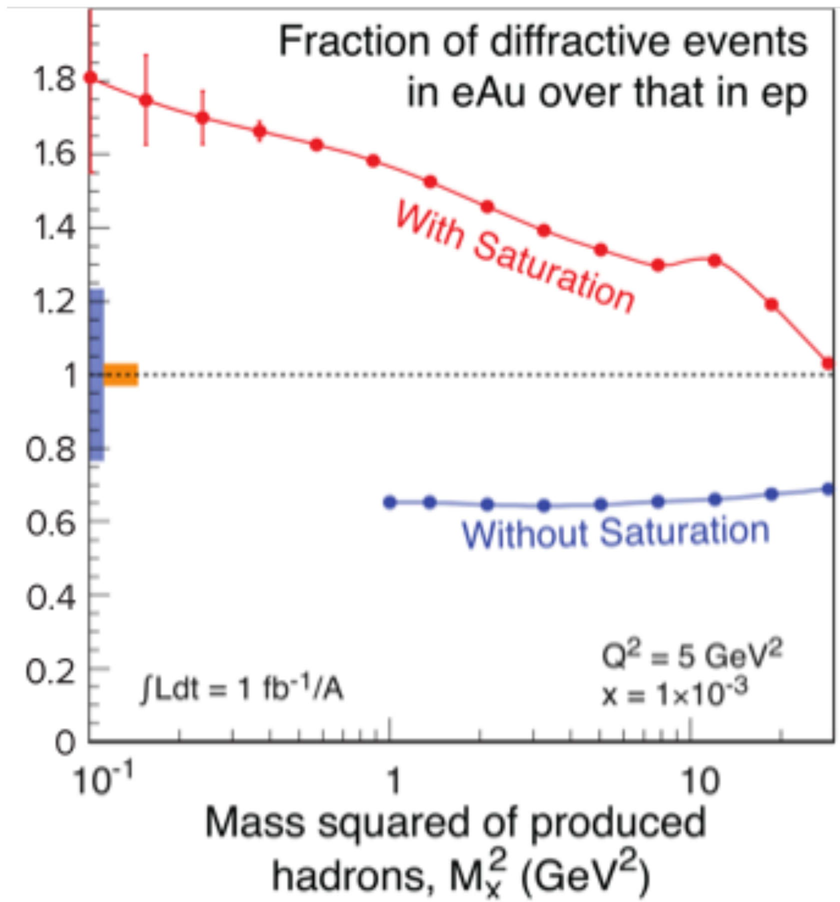


At HERA

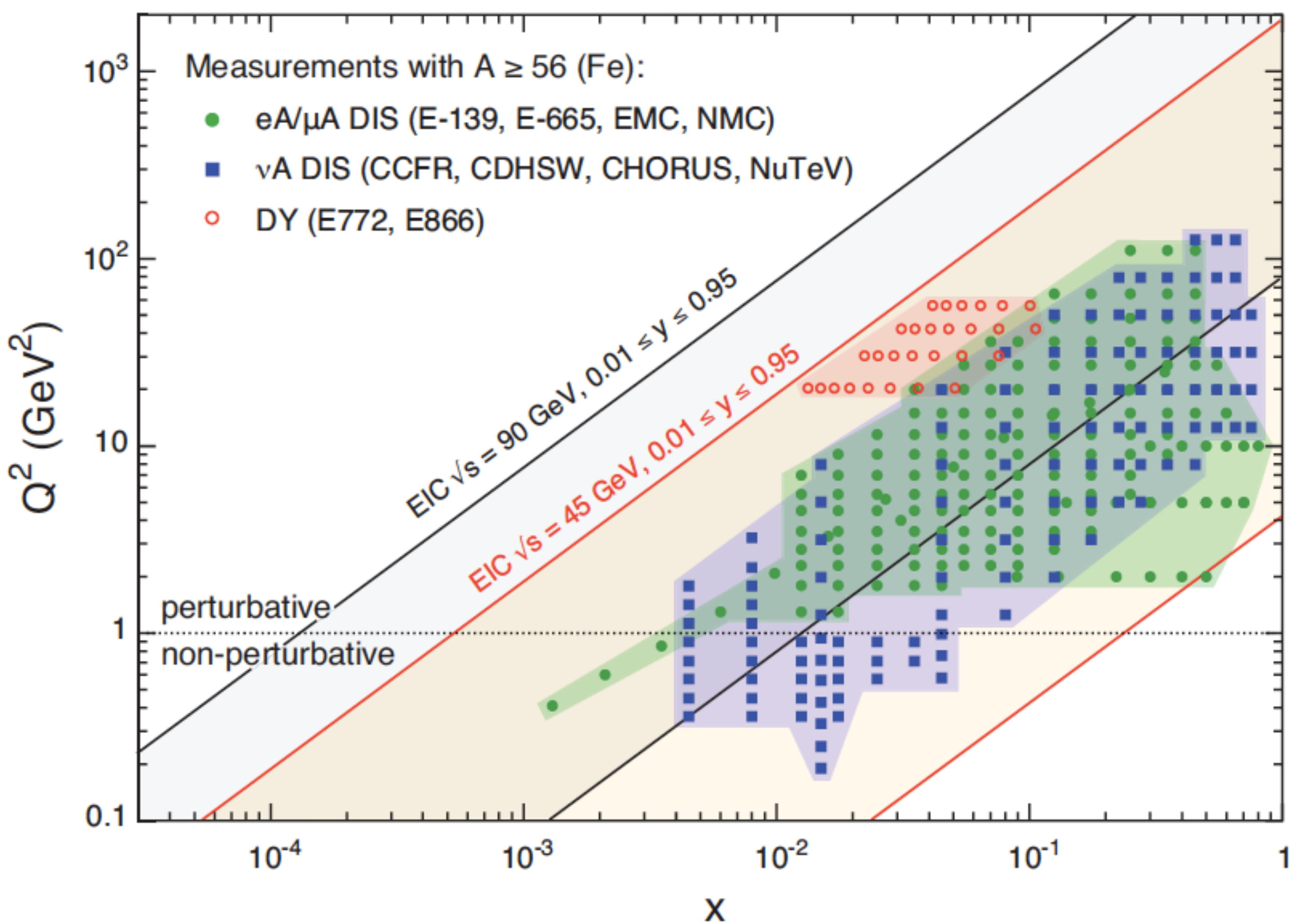
ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

eA: 25-30% diffractive



EIC Reach: electron / heavy-ion

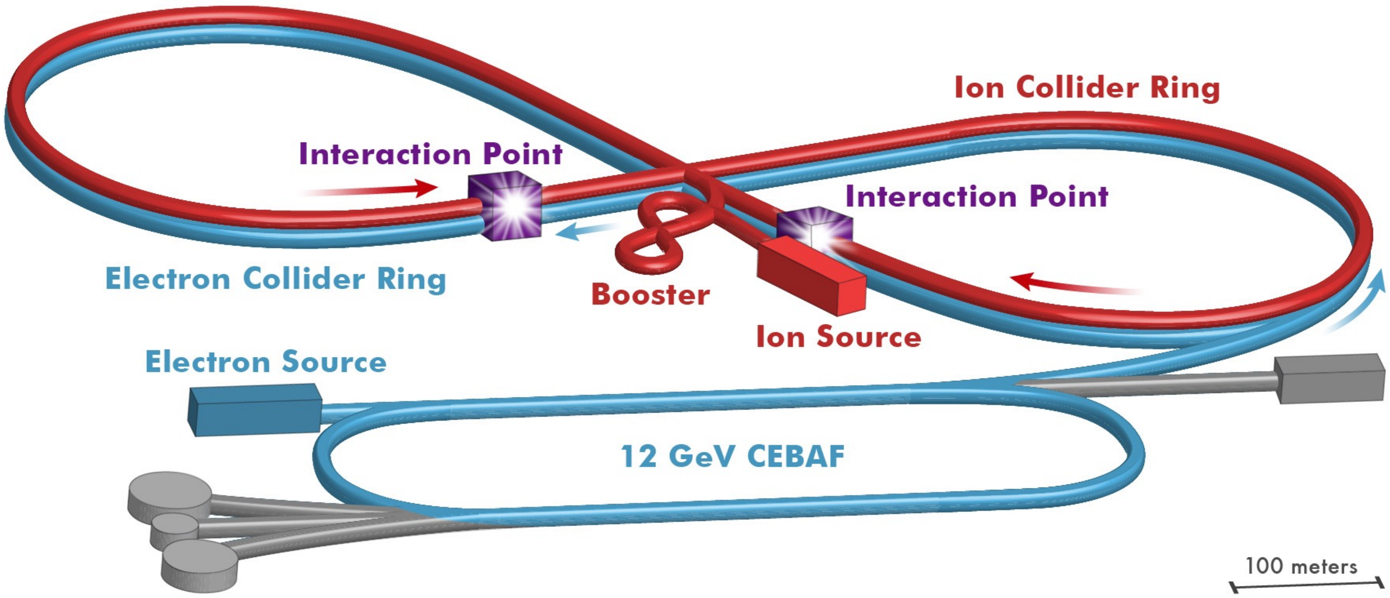


EIC White Paper, arXiv:1212.1701v3 [nucl-ex]

What do we want from the machine?

- Parton imaging in 3D: high luminosity, 10^{33-34} cm^{-2} s^{-1} and above.
- Wide coverage of phase space from low to high x and up to high Q^2: variable centre of mass energy.
- Spin structure: high polarisation of electrons (0.8) and light nuclei (0.7).
- Studies of hadronisation, search for saturation at high gluon densities: a wide range of ion species up to the heaviest elements (p -> U).
- Flavour tagging: large acceptance detectors with good PID capabilities.

JLEIC

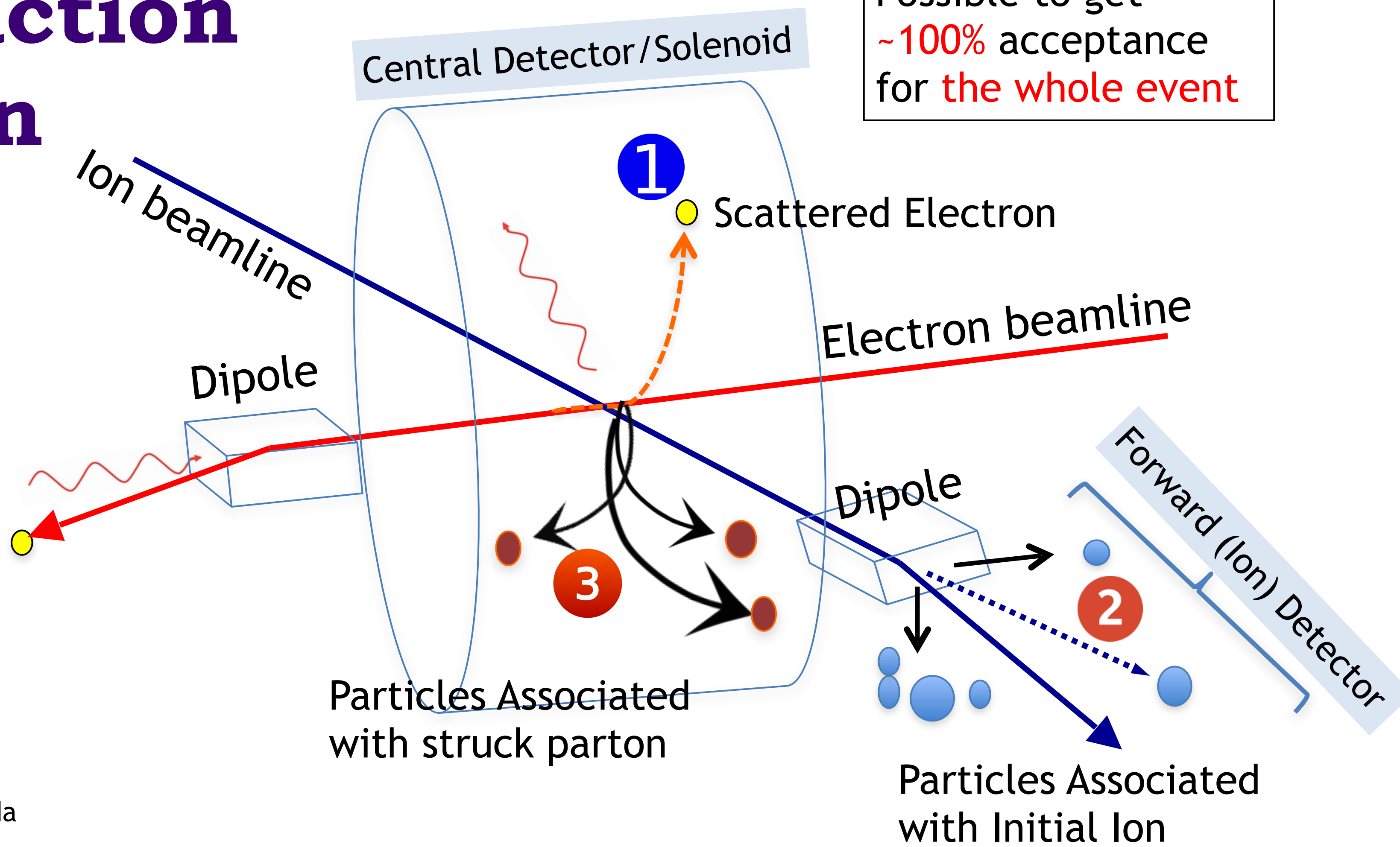


- High luminosity reached through small beam size (small emittance through cooling and low bunch charge with high repetition).

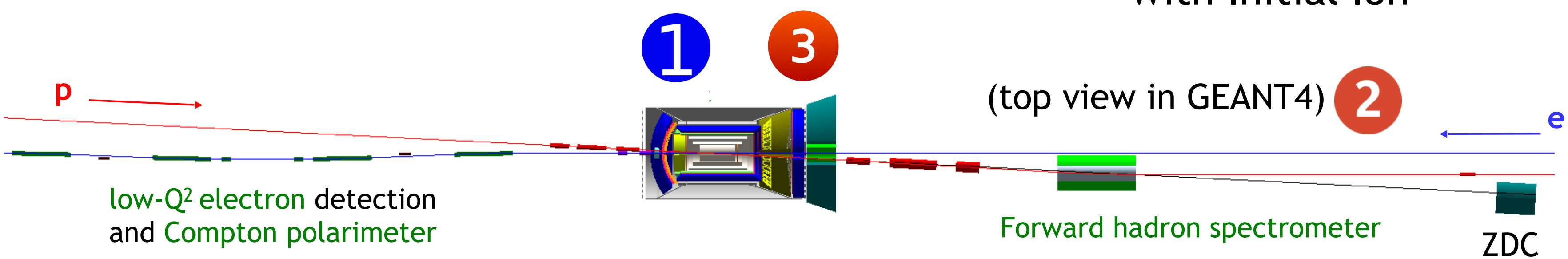
- High polarisation through figure-of-8 design (net spin precession is zero, spin controlled with small magnets)

Interaction Region

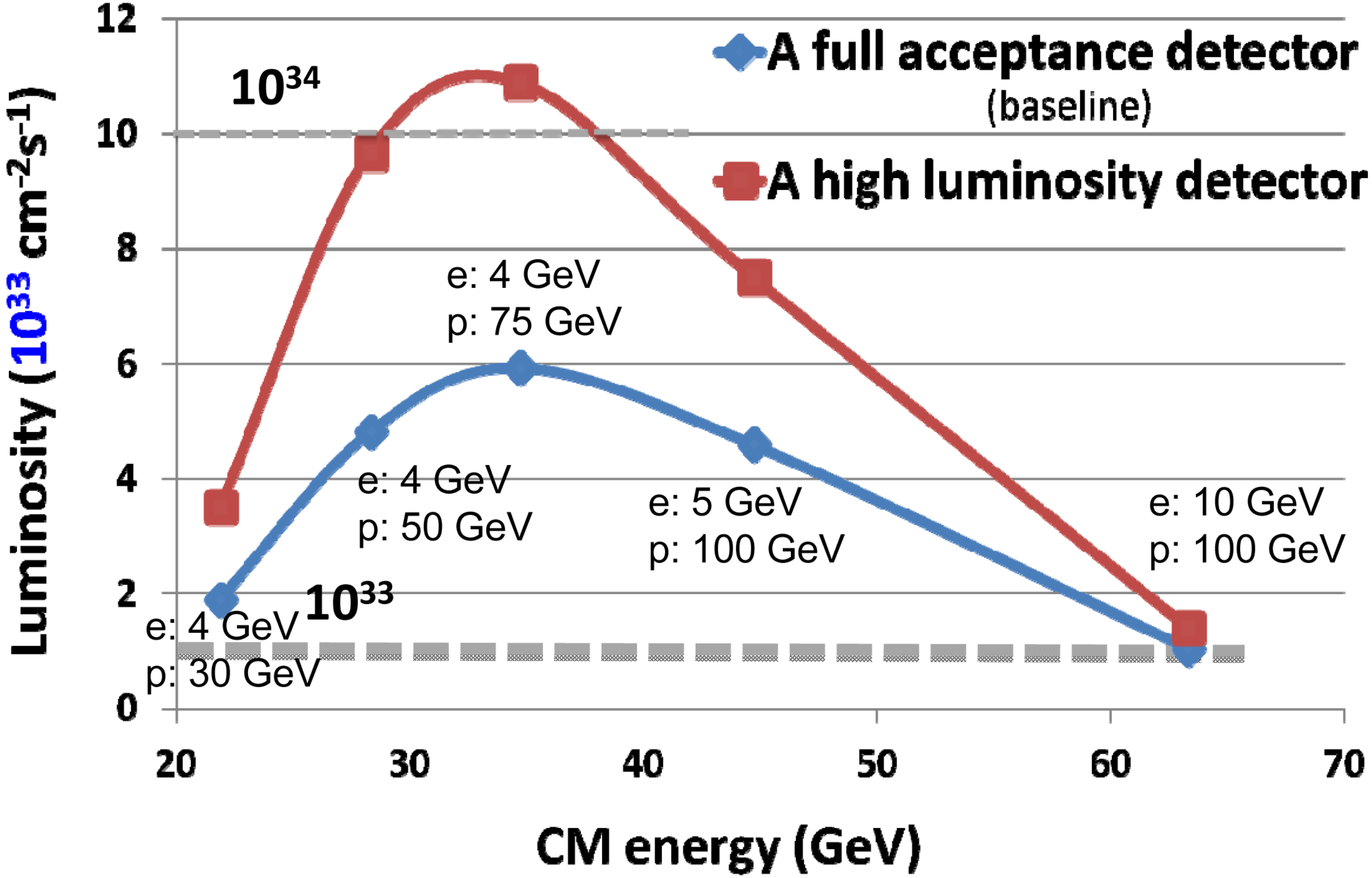
Possible to get ~100% acceptance for the whole event



Courtesy of R. Yoshida

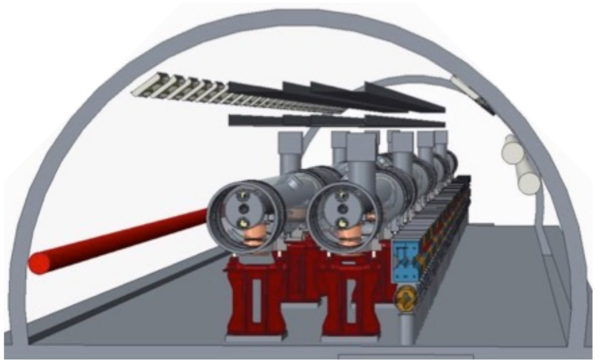


The JLEIC options

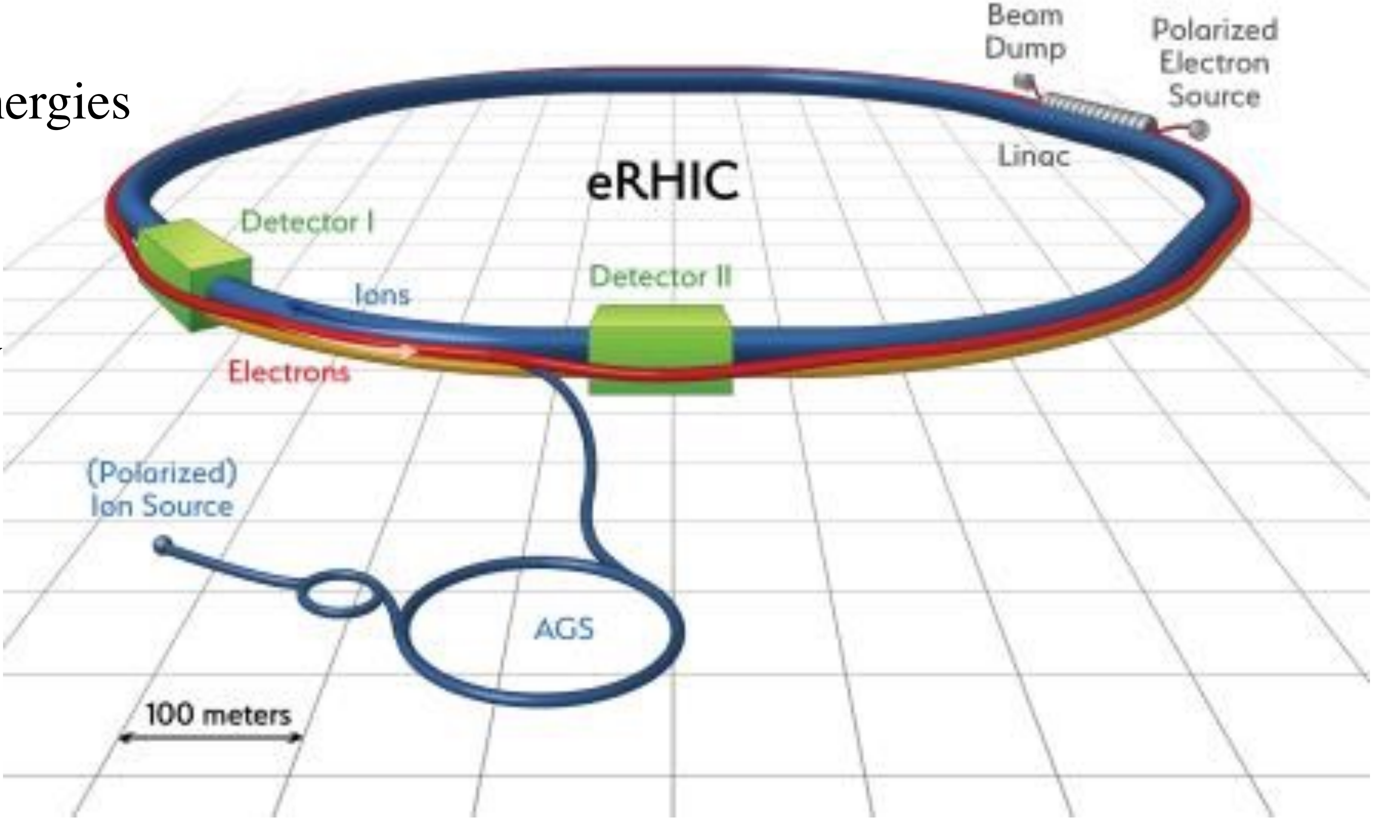


Courtesy of F. Pilat

eRHIC



* Exploit current 275 GeV proton collider by adding 18 GeV electron accelerator in the same tunnel.
* High luminosity requires novel technologies of coherent electron cooling.
* 20 - 140 GeV CoM energies
* Two designs under consideration for electrons: ERL (energy recovery LINAC) and high intensity electron storage ring.



GPD opportunities at the EIC: I

DVCS

- Nucleon tomography at low x: sea quarks and gluons. Gluon distributions accessible via a log dependence of GPDs on Q^2.
- Access phase of the Compton amplitude through beam-charge asymmetry (using electron and positron beams) or Rosenbluth separation of cross-sections at different electron energies.

TCS

- Asymmetries carry similar information to beam-charge asymmetry in DVCS, without need for positron beams.

DVMP

- Flavour-separation of contributions from q and $\bar{q}$ and from gluons.
- J/Ψ production direct access to gluon GPDs.
- Vector meson production allows separation of cross-sections for longitudinal, σ_L, and transverse, σ_T, photon polarisation.
- $\pi^+\pi^-$ production is sensitive to differences in q and $\bar{q}$ distributions.

GPD opportunities at the EIC: II

DDVCS

- Direct access to x-dependence of GPDs.

Measurements on other hadrons

- Could potentially measure DVCS/DVMP off the virtual pion.

- Light nuclei (He, deuteron) allow measurements off the neutron: flavour separation of GPDs.

- Nuclear DVCS /DVMP: tomography of the nucleus, parton saturation.

- Scattering and J/Ψ-production off nuclei with multi-nucleon knockout: short-range correlations, contribution of glue.

Wide range of Q^2 in the valence region will complement valence measurements: can observe scaling violations.