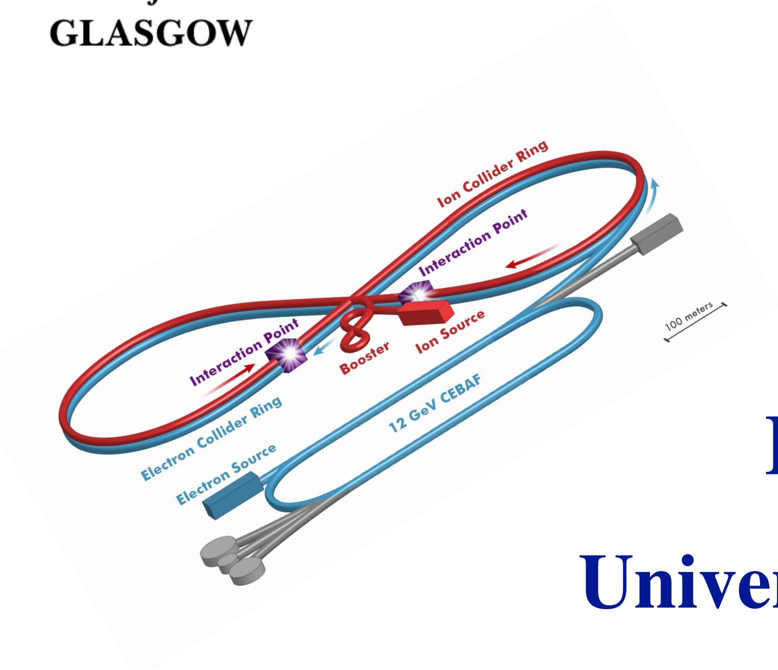
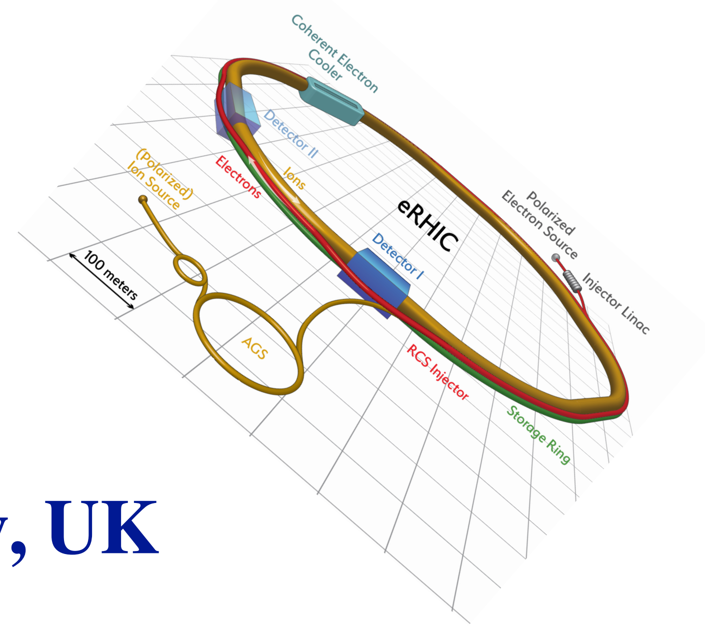
UNIVERSITY
of
GLASGOW

The Electron-Ion Collider





Daria Sokhan

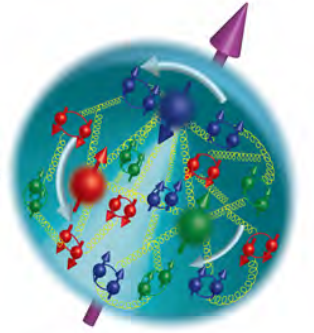
University of Glasgow, UK

“Probing exotic structure of short-lived nuclei by electron scattering”

ECT* Trento, Italy — 17th July 2018

Outline

- Overview of the EIC
- The physics motivation: what is the EIC for?
- The two proposed accelerator designs: JLEIC and eRHIC
- Detector requirements and concepts
- Current status



Electron-Ion Collider: overview

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

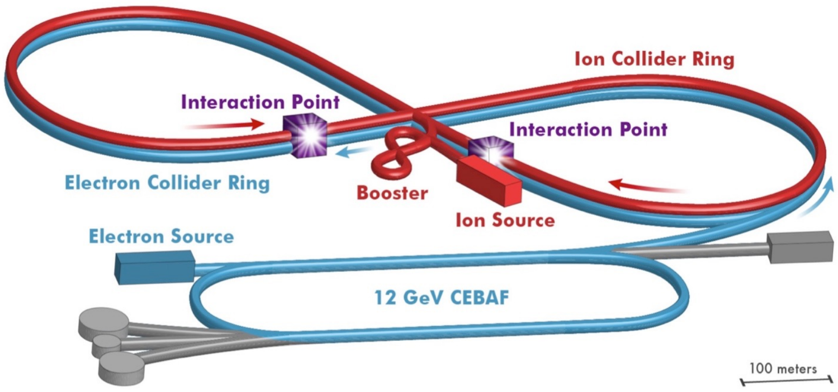
- Polarized beams: e, p, d/^{3}He
- Wide range of nuclei
- 20 - 100 (upgradable to 140) GeV variable CoM
- Polarisation ~ 70%

Two proposals:

- **JLEIC**: 3 - 10 GeV e-, up to 100 GeV/u ions, Luminosity L ~ 10^{34} cm^{-2}s^{-1}
- **eRHIC**: 5 - 18 GeV e$^-$/e$^+$, 50-275 GeV (p) and <100 GeV/u ions, L ~ 10^{33} cm^{-2}s^{-1}

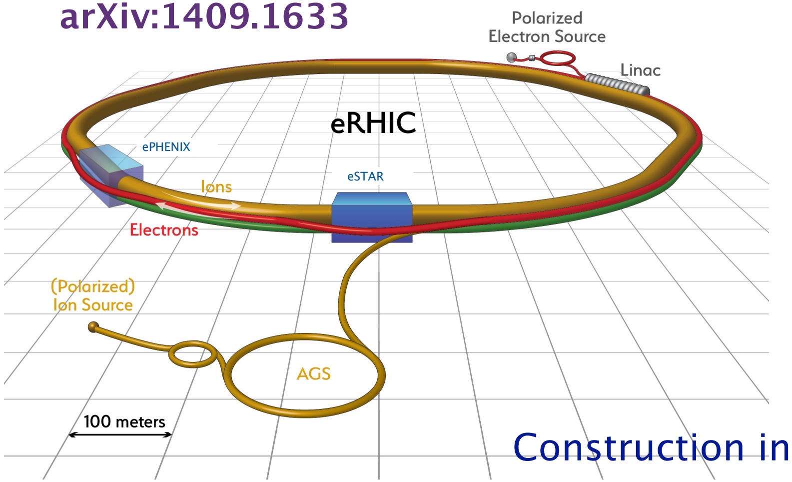
JLEIC @ Jefferson Lab

arXiv:1504.07961



eRHIC @ Brookhaven National Lab

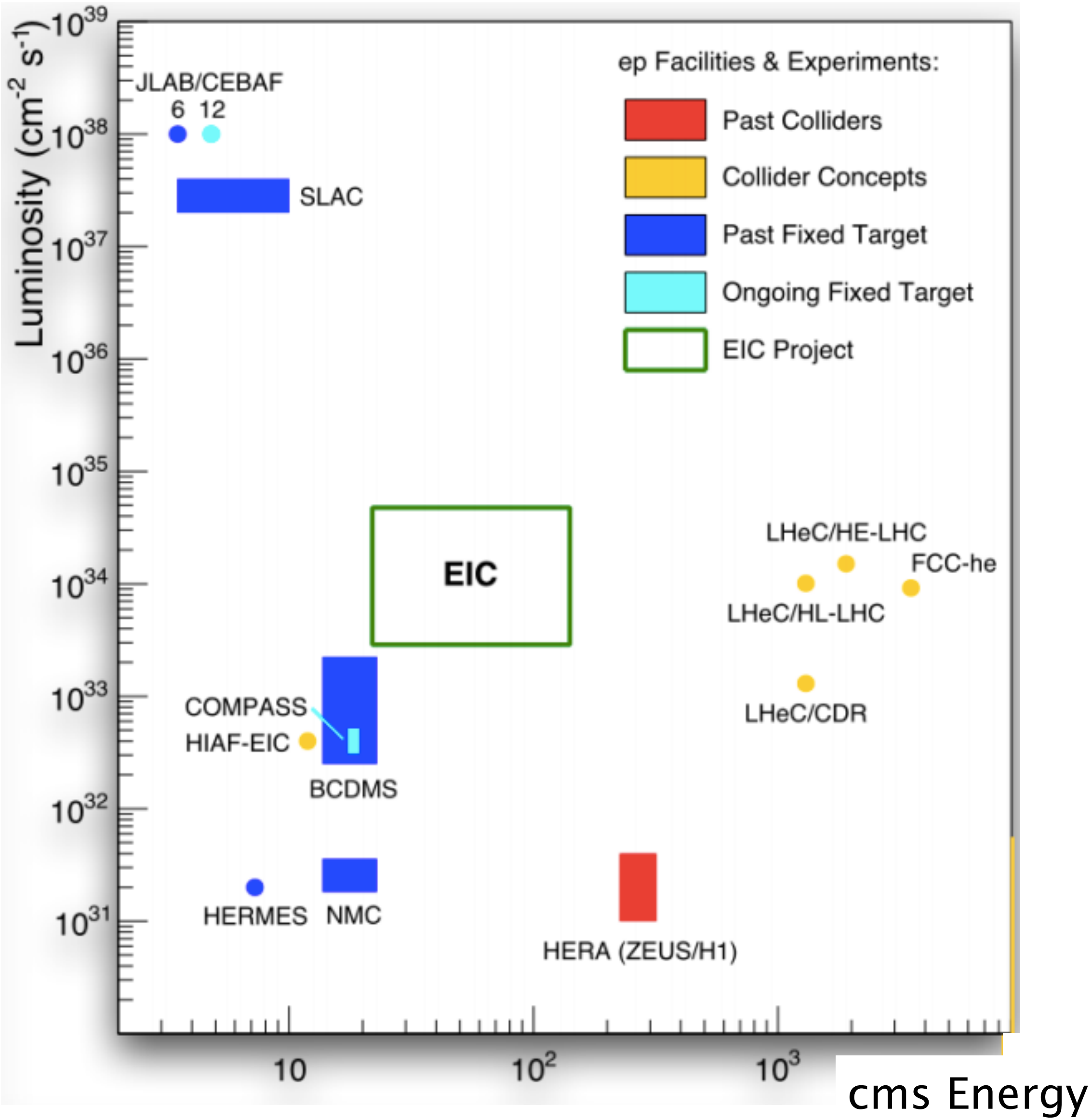
arXiv:1409.1633

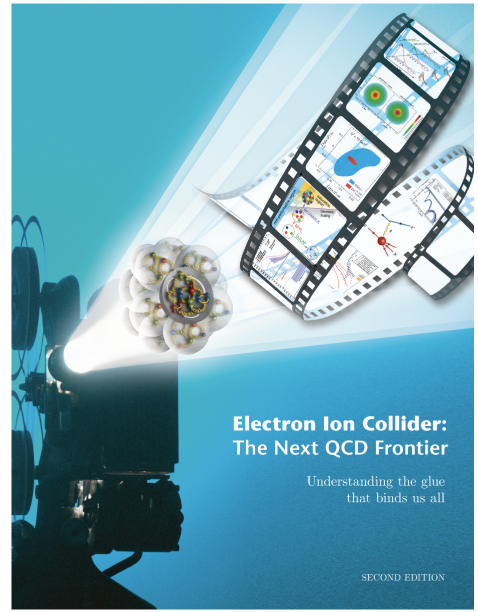


Construction in 2020s

Design in flux: physics case evolving, machine and detector design developing.

EIC in context



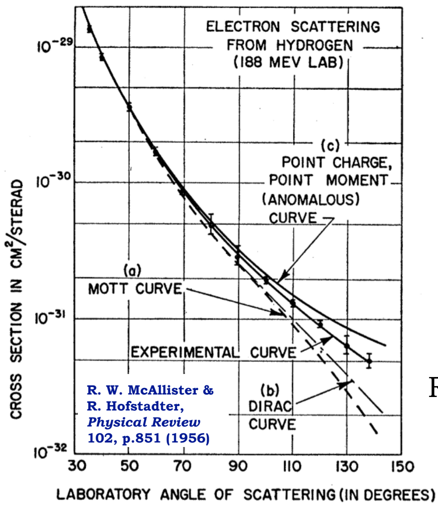


2012 EIC White Paper,
Eur. Phy. J. A 52, 9 (2016)

EIC box includes different baseline designs

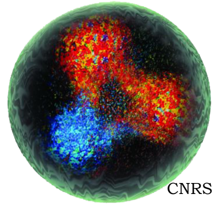
A (very abridged) history of the nucleon

- **Before 1956:** the nucleon is point-like and fundamental…



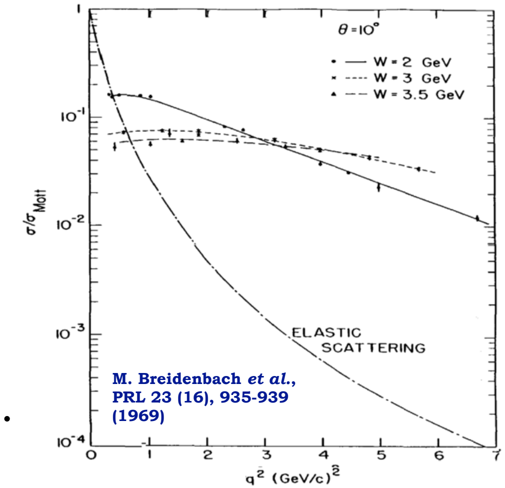
Robert Hofstadter
1915 - 1990
(Wikipedia)

1956: Elastic scattering at SLAC: the proton has internal structure!
Hofstadter: Nobel Prize 1961.

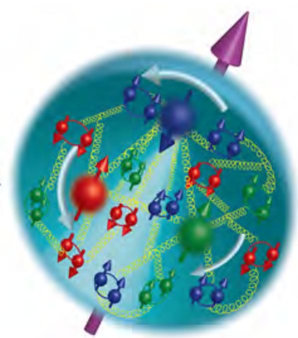


1960s: the Quark Model. Nucleons are composed of three valence quarks!
Gell-Mann (Nobel Prize 1969), Zweig.

1968: Deep Inelastic scattering at SLAC: scaling observed. The proton consists of point-like charges: partons!
Friedman, Kendall, Taylor: Nobel Prize 1990

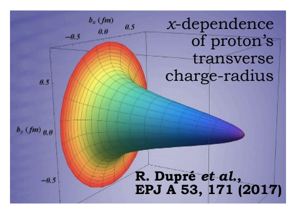


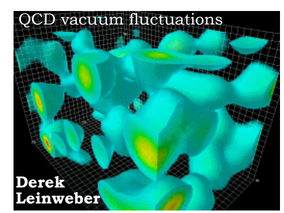
1972: Theory of QCD developed.

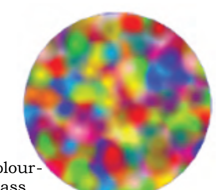


1970s-1990s: Deep Inelastic Scattering reveals a rich structure: quark-gluon sea, flavour distributions, puzzles of spin… what you see depends on how closely you look!

21st Century: High-precision imaging of quarks and gluons. 3D tomography of the nucleon: spatial and momentum distributions inside it across all scales.



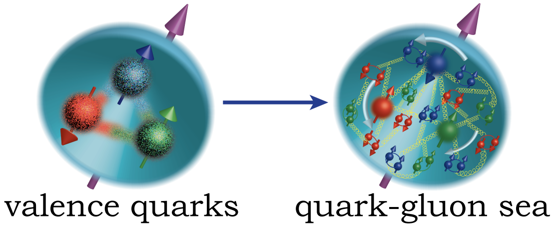




Colour-Glass Condensate

What is the EIC for?

- Designed primarily for the study of hadron physics:
    - What is the origin of nucleon mass? How is it generated from the almost massless quarks and massless gluons?
    - What is the quark-gluon origin of the nuclear force?
    - How do hadrons and nuclei emerge from quarks and gluons? What is the nature of confinement?
- 3D tomography of the nucleon: distributions of partons from the valence quark region to the quark-gluon sea.



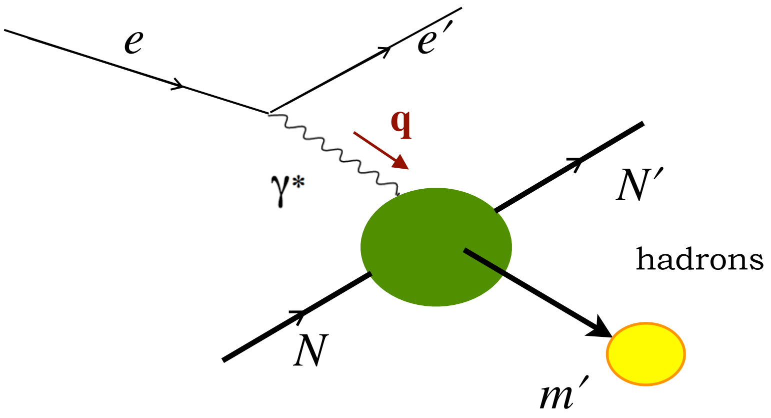
- Nucleon spin puzzle: decomposition of nucleon spin — contribution of gluons.

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

- Effect of nuclear medium on the propagation of a colour charge: insight into hadronisation and the EMC effect.
- Search for gluon saturation: a new form of matter.

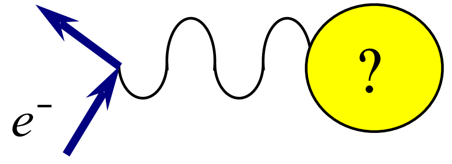
The list is NOT exhaustive…

Kinematics in the Deep Inelastic regime

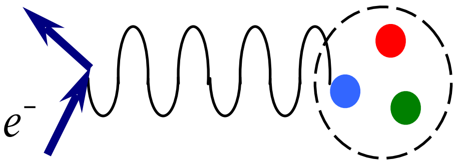


$$Q^2 = -\mathbf{q}^2 = -(\mathbf{p_e} - \mathbf{p_e}')^2$$

virtuality of exchanged photon / resolution:



$Q^2 \sim \mathrm{MeV}^2$

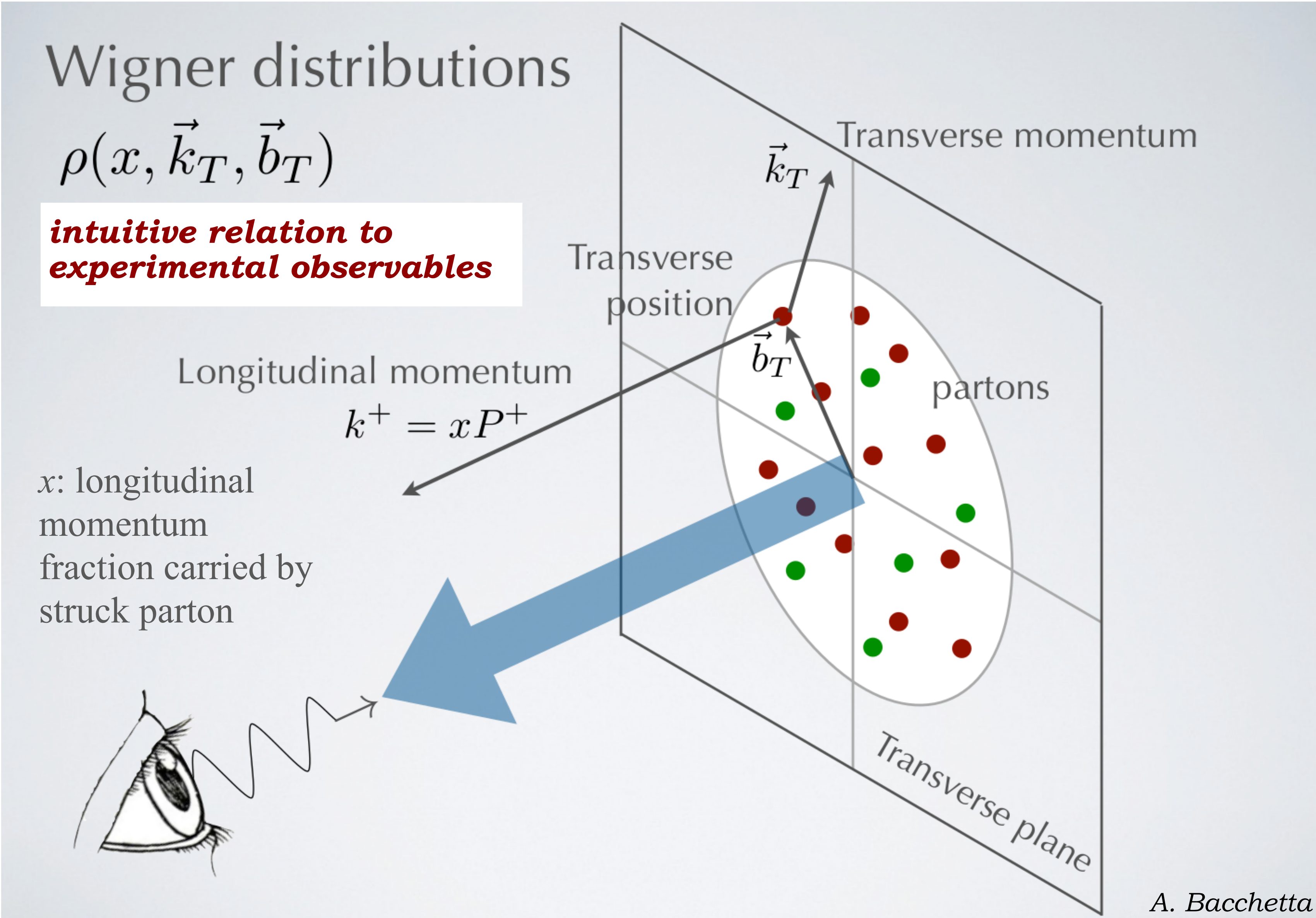


$Q^2 >> \mathrm{GeV}^2$

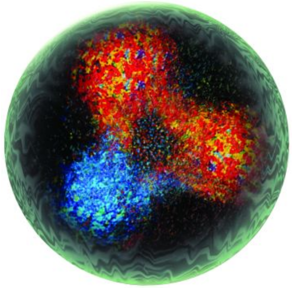
Bjorken variable: $x_B = \dfrac{Q^2}{2\mathbf{p_n} \cdot \mathbf{q}}$

In Deep Inelastic Scattering, can be equated to ***x*** *(fraction of longitudinal momentum of nucleon carried by struck quark)*

A constructivist view of the nucleon



Images of the nucleon

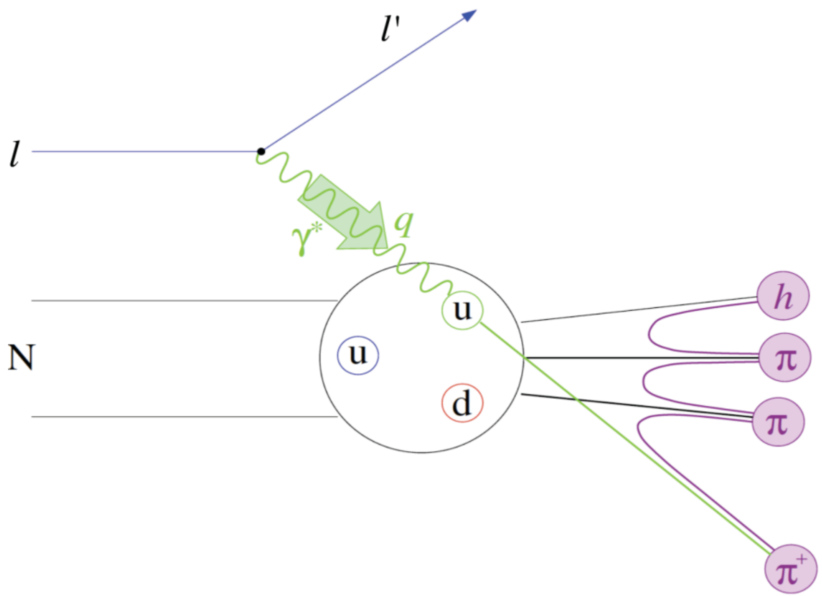


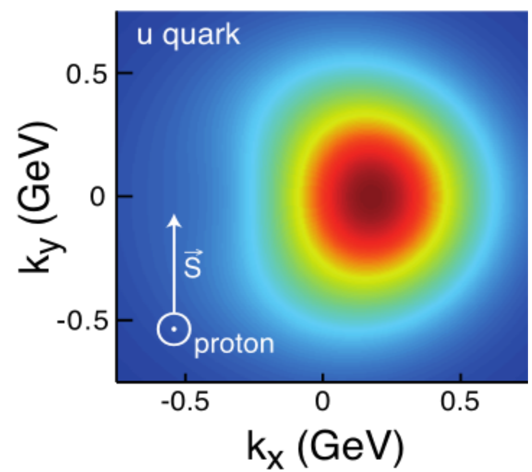
Wigner function:
full phase space parton distribution of the nucleon

$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

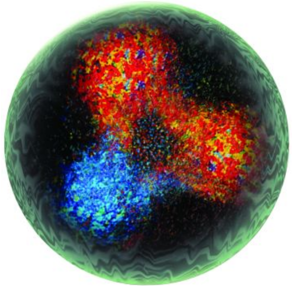
- Semi-inclusive Deep Inelastic Scattering (SIDIS)





Sivers function: Alexei Prokudin, 2012
(using M. Anselmino et al., J. Phys. Conf. Ser. 295, 012062 (2011))

Images of the nucleon

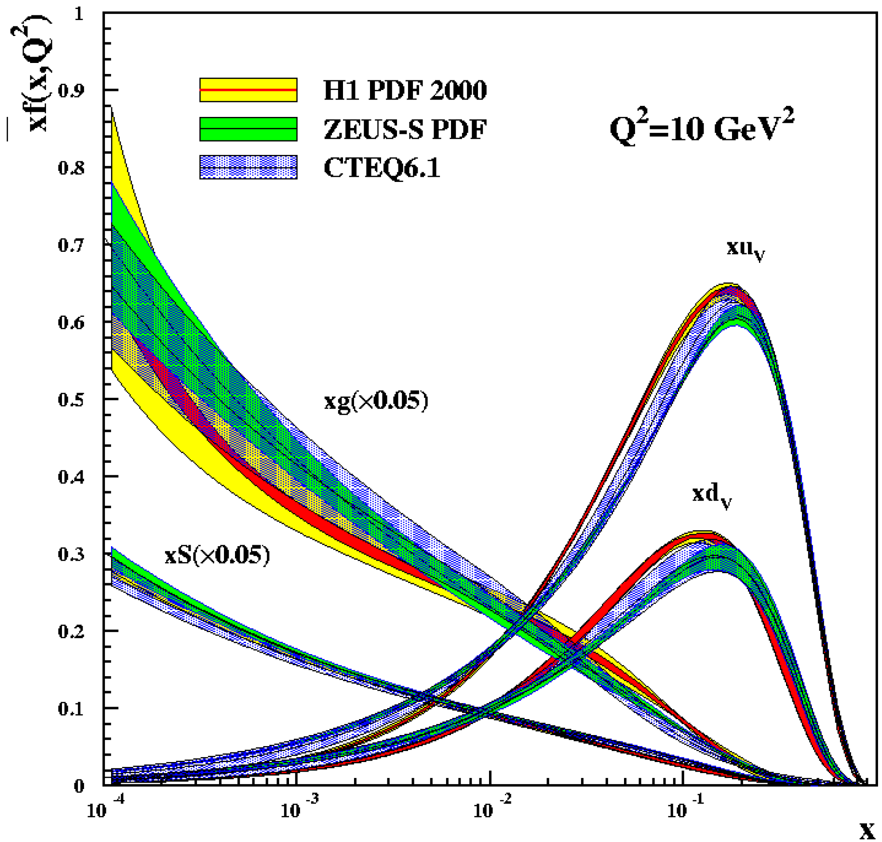


Wigner function:
full phase space parton
distribution of the nucleon

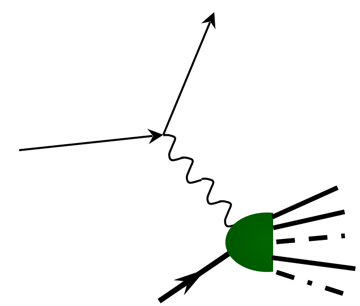
$$\int d^2 b_T$$

Transverse
Momentum
Distributions
(TMDs)

$$\int d^2 k_T$$

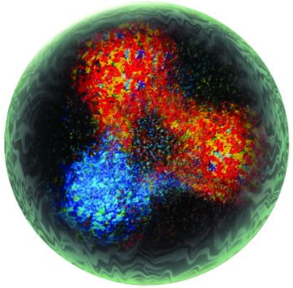


Parton Distribution
Functions (PDFs)



* Deep Inelastic
Scattering (DIS)

Images of the nucleon



Wigner function:
full phase space parton
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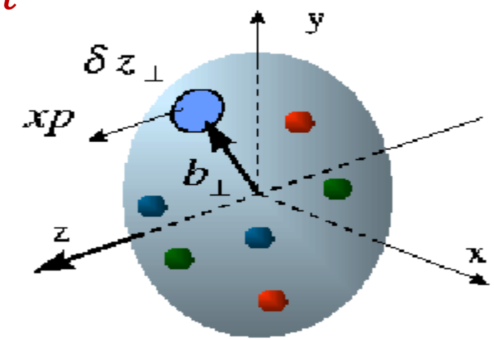
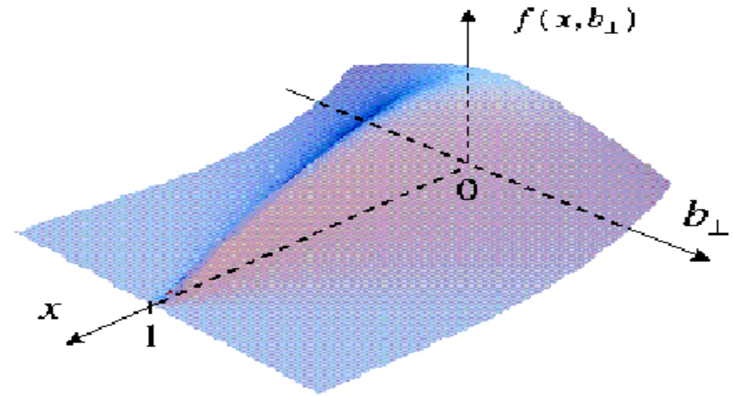


$$\int d^2 k_T$$

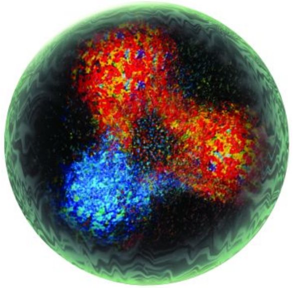
Generalised Parton
Distributions (GPDs)

- relate, in the infinite momentum frame, transverse position of partons ($b_\perp$) to longitudinal momentum (x).



* Deep exclusive reactions, e.g.: Deeply Virtual Compton Scattering, Deeply Virtual Meson production.

Images of the nucleon

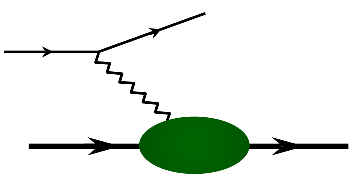


Wigner function:
full phase space parton
distribution of the nucleon

$$\int d^2 k_T$$

Generalised Parton
Distributions (GPDs)

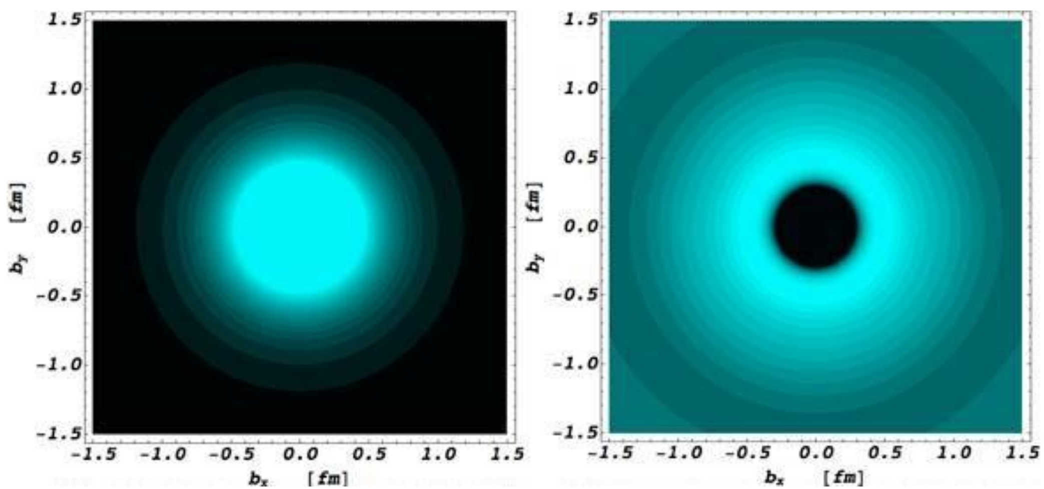
$$\int dx$$



Elastic scattering

Form Factors
eg: $G_{E,}\ G_M$

Fourier Transform of electric Form Factor: transverse charge density of a nucleon

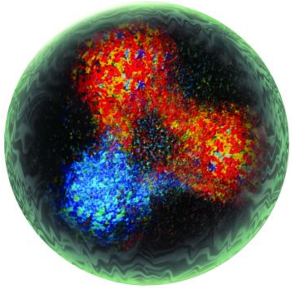


proton

neutron

C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)

Images of the nucleon



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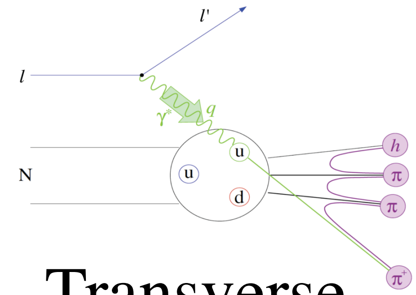
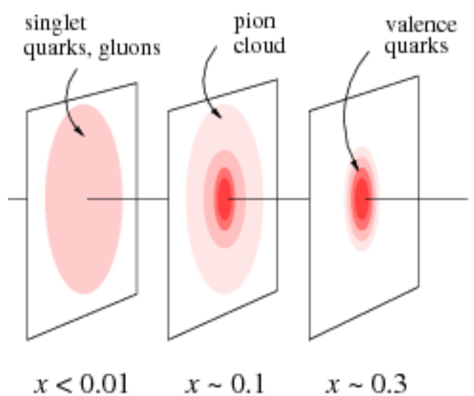


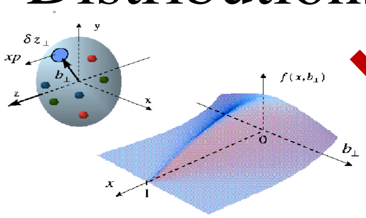
$\int d^2 k_T$

$\int d^2 b_T$

Transverse Momentum Distributions (TMDs)

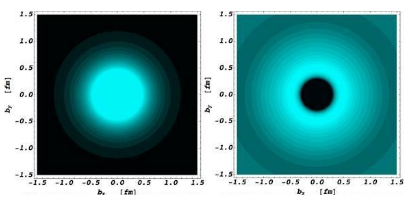
Generalised Parton Distributions (GPDs)





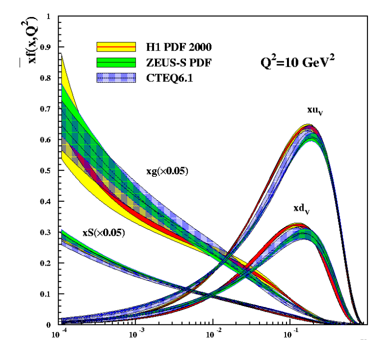
$\int dx$

$\int d^2 k_T$



Form Factors
eg: G_E, G_M

Parton Distribution Functions (PDFs)

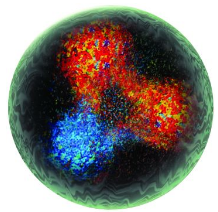


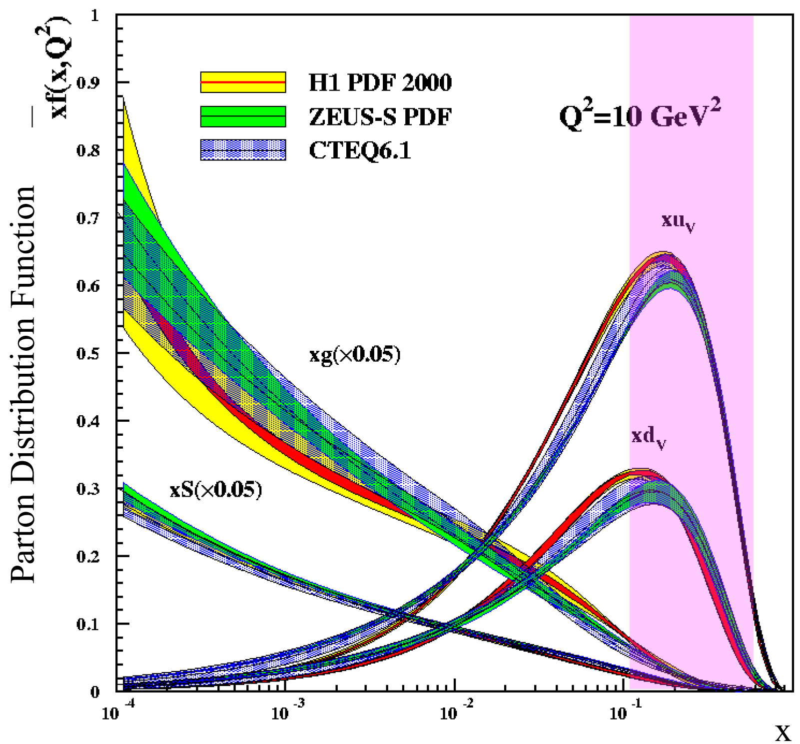
Nucleon at different scales

Valence quarks

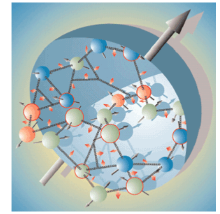
Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$

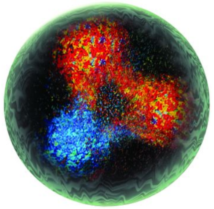




Nucleon at different scales



Valence quarks



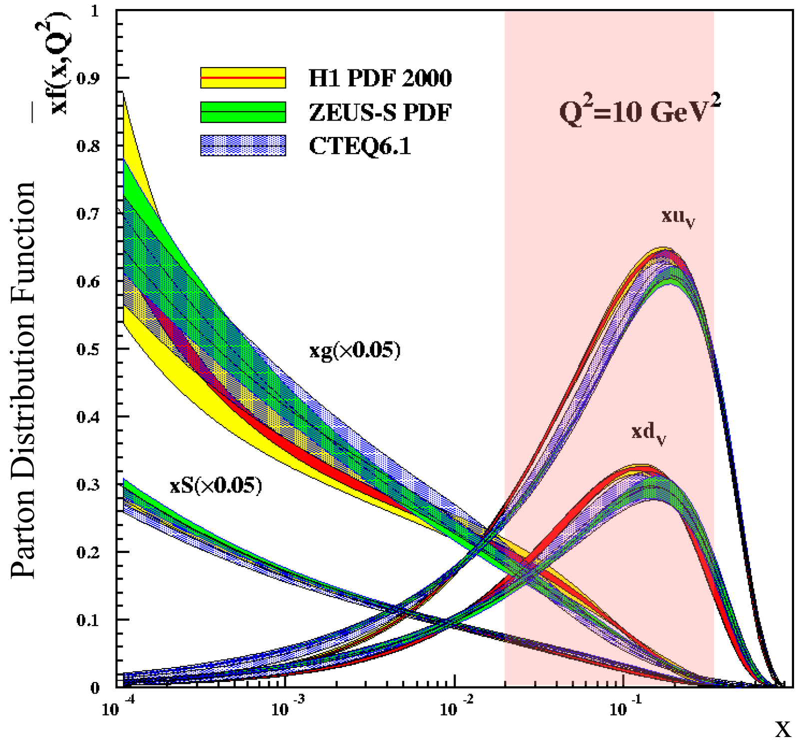
Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$

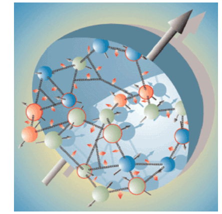
Sea quarks

HERMES: fixed gas-target electron/positron scattering

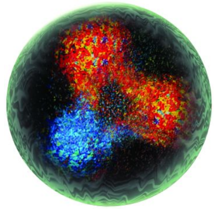
$0.02 < x_B < 0.3$



Nucleon at different scales

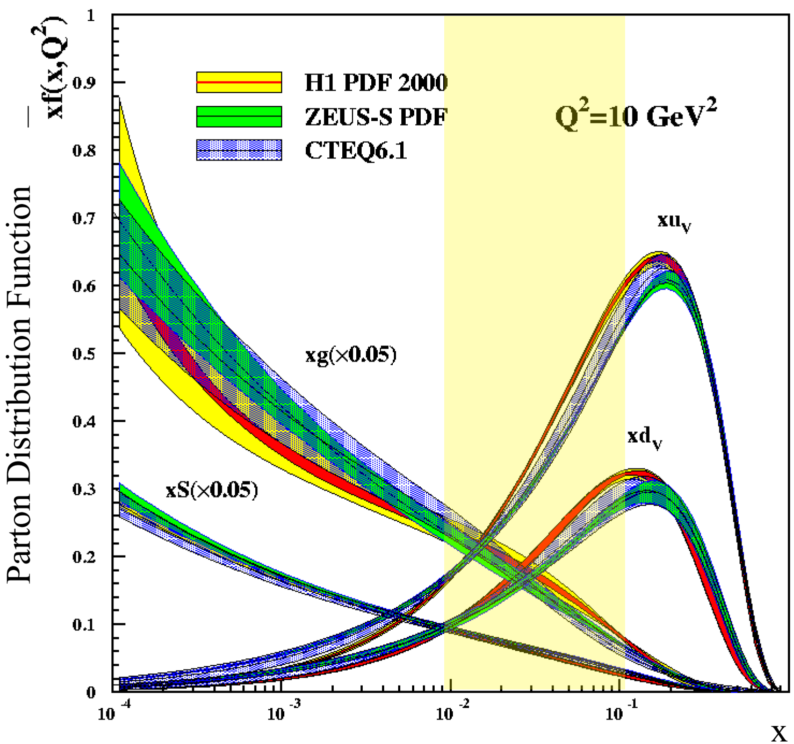


Valence quarks



Jefferson Lab: fixed-target electron scattering

$$0.1 < x_B < 0.7$$



Sea quarks

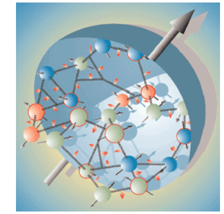
HERMES: fixed gas-target electron/positron scattering

$$0.02 < x_B < 0.3$$

COMPASS: fixed-target muon scattering

$$0.01 < x_B < 0.1$$

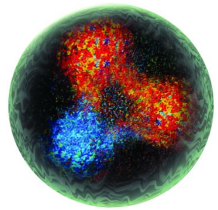
Nucleon at different scales

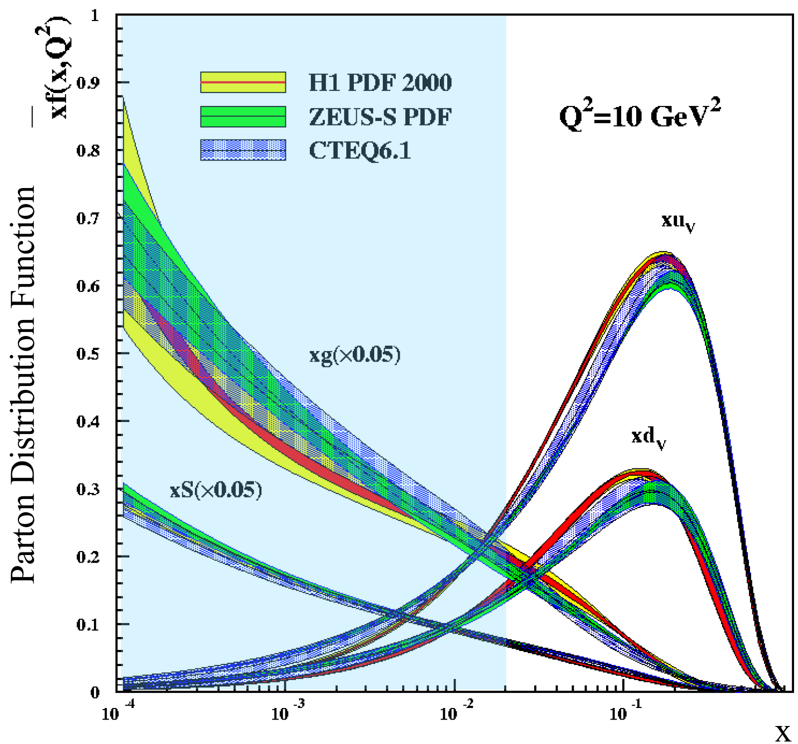


Valence quarks

Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$





Sea quarks

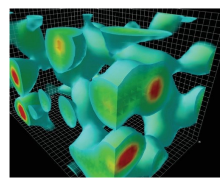
HERMES: fixed gas-target electron/positron scattering

$0.02 < x_B < 0.3$

COMPASS: fixed-target muon scattering

$0.01 < x_B < 0.1$

The glue

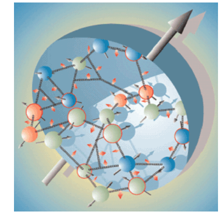


Derek Leinweber

ZEUS/H1: electron/positron-proton collider

$10^{-4} < x_B < 0.02$

Nucleon at different scales



Valence quarks

Jefferson Lab: fixed-target electron scattering

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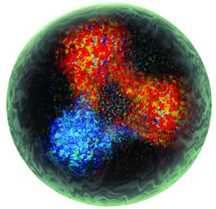

Sea quarks

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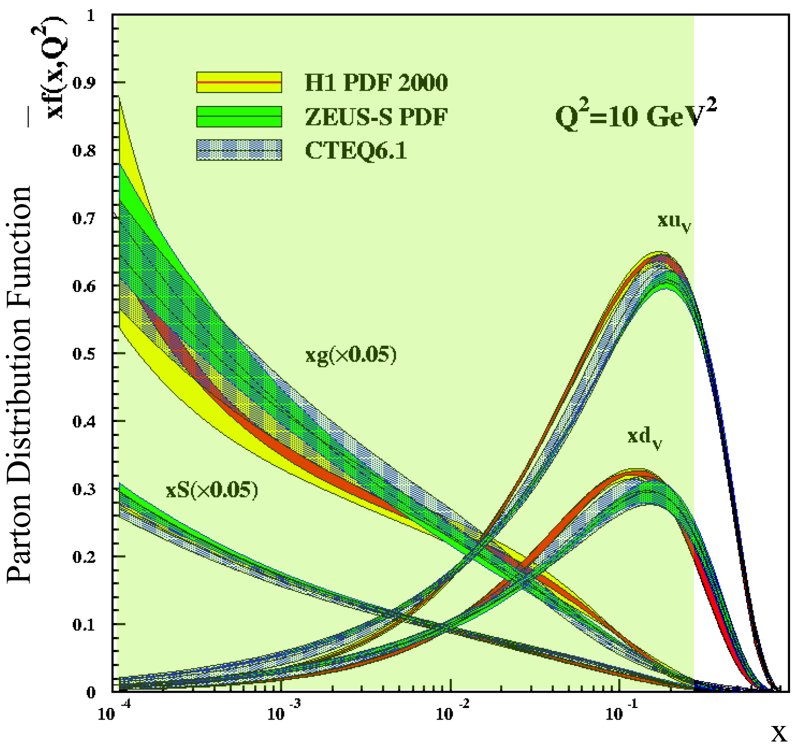
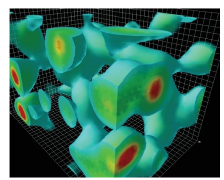


The glue



Derek Leinweber

ZEUS/H1: electron/positron-proton collider

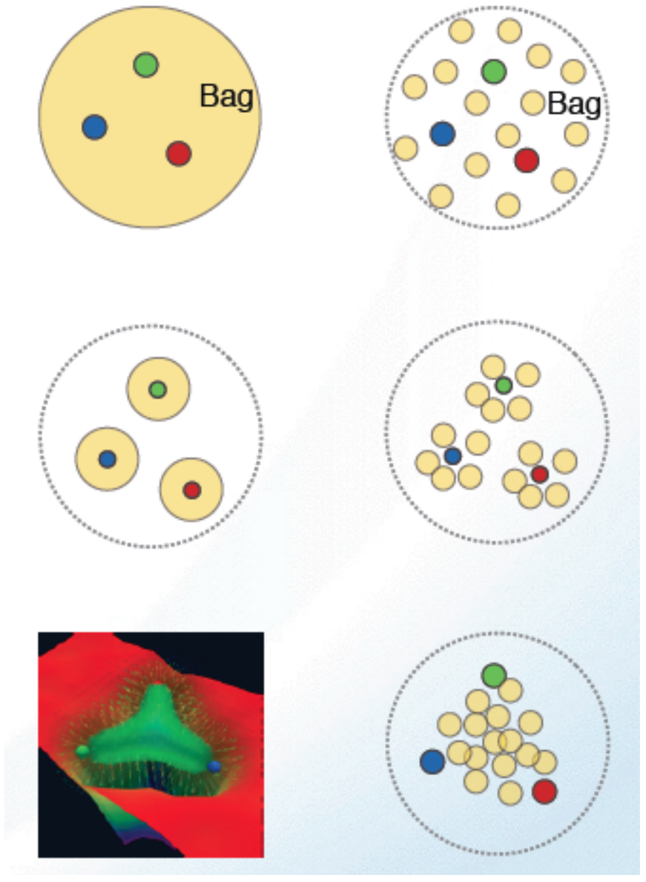
$10^{-4} < x_B < 0.02$

EIC: $10^{-4} < x_B < 0.3$

Luminosity 100 - 1000 times that of HERA

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

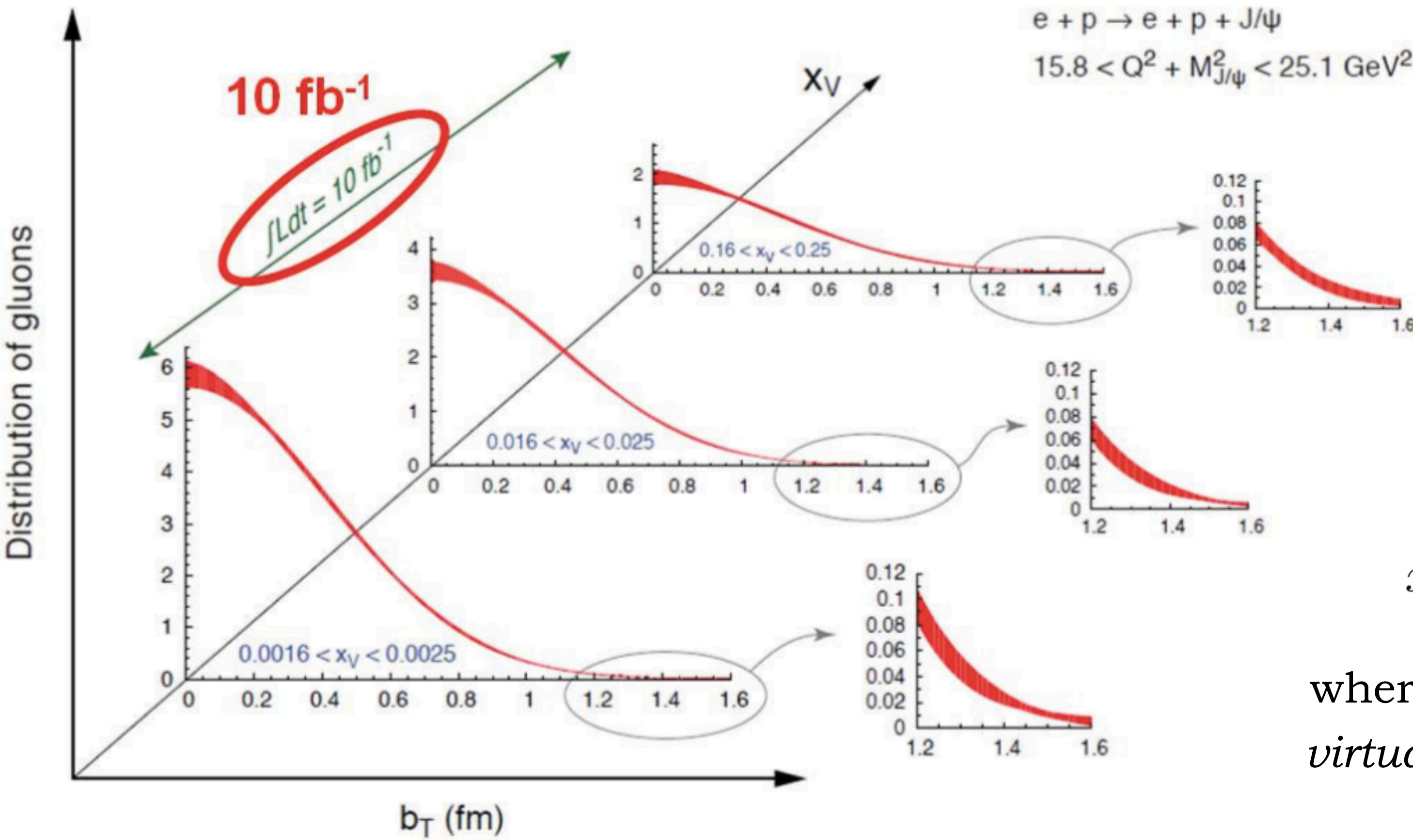
Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks:

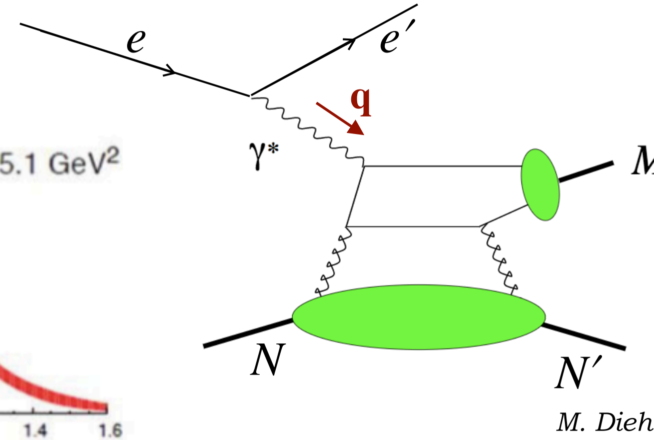
Gluon radius < Charge Radius

Need transverse images of the quarks and gluons in confinement

Nucleon tomography: imaging glue

- Gluon GPDs can be accessed through deeply virtual meson production (DVMP), eg: J/Ψ
- Access to spatial distributions of gluons at different longitudinal momentum fractions:





Gluon momentum fraction related to:

$$x_V = x_B(1 + M^2_{J/\Psi}/Q^2)$$

where $Q^2 = -\mathbf{q}^2 = -(\mathbf{p}_e - \mathbf{p}_e')^2$

virtuality of exchanged photon

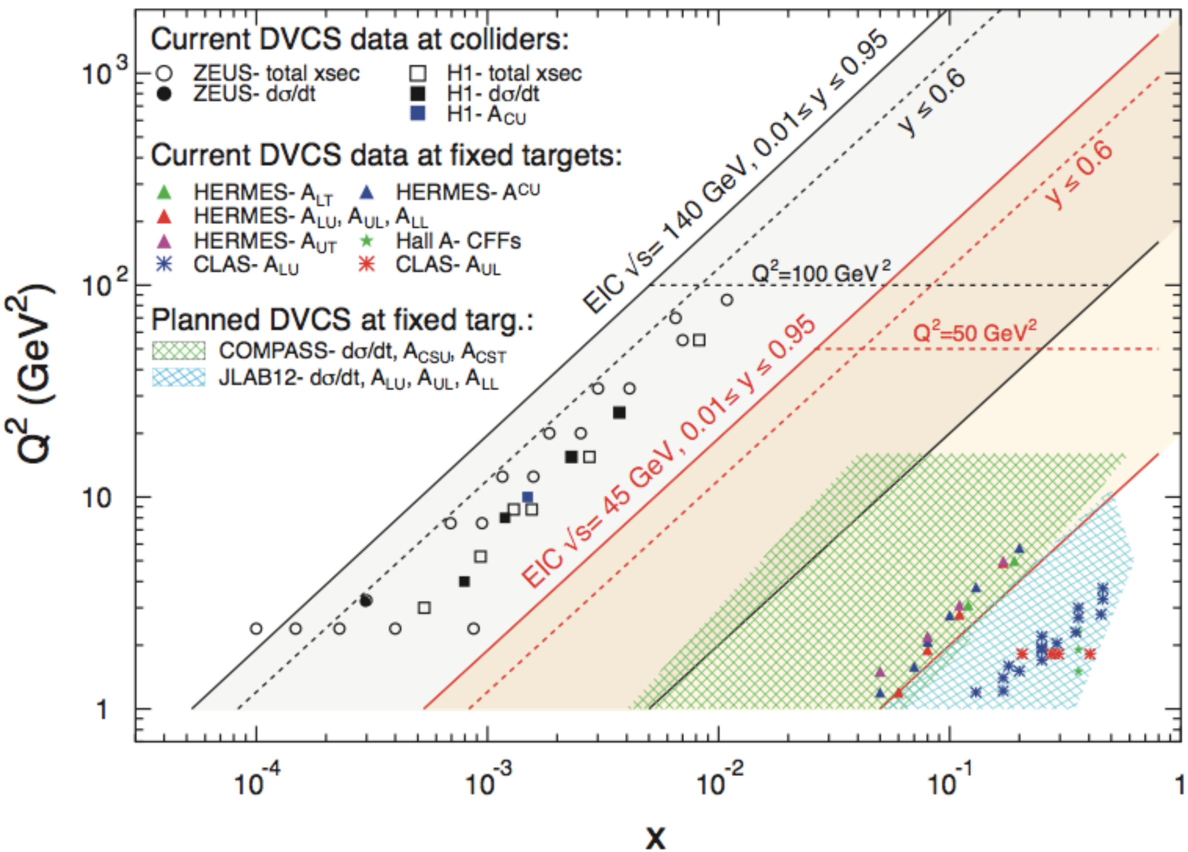
Bjorken variable $x_B = \dfrac{Q^2}{2\mathbf{p}_n \cdot \mathbf{q}}$

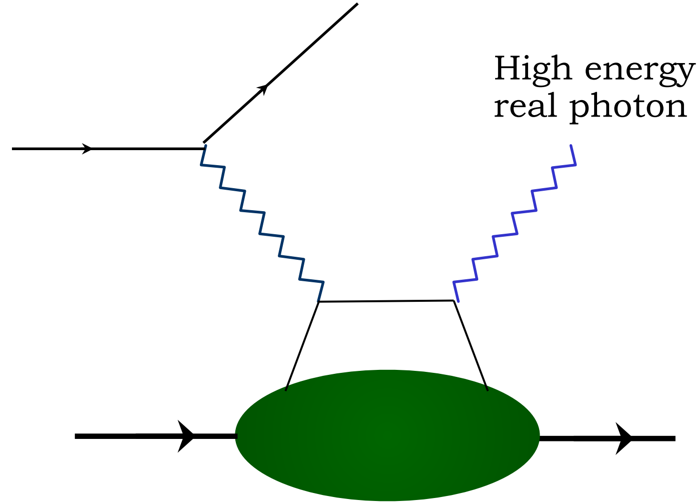
EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

Nucleon tomography: imaging quarks

- Quark GPDs are accessible in a related process: Deeply Virtual Compton Scattering (DVCS)

DVCS kinematic reach at the EIC:





- 3D images of sea quark and gluon distributions from exclusive reactions: DVCS and DVMP.

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

The Nucleon Spin Puzzle

✳ What contributes to nucleon spin?

✳ 1980's: European Muon Collaboration (EMC) measures contribution of valence quarks to proton spin to be ~ 30 %. Subsequent deep inelastic scattering (DIS) experiments confirm.

Where is the rest? → **Proton spin crisis!**

Quark spin: extracted from helicity distributions measured in polarised DIS.

Gluon spin and OAM: measurements of DIS and polarised proton collisions indicate gluon spin ΔG contribution is very small, although in a different decomposition.

$$J_N = \frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

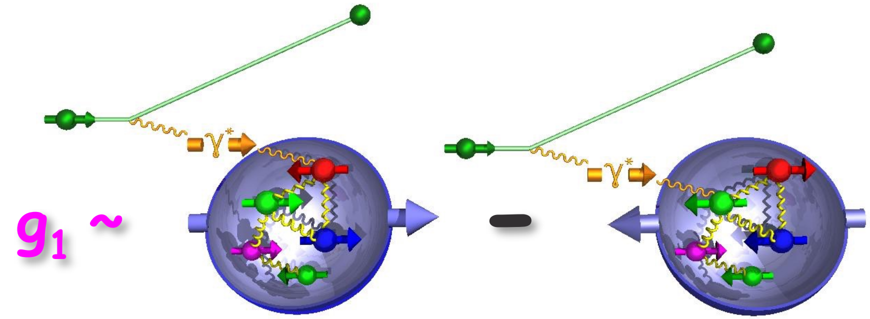
Quark orbital angular momentum (OAM): can be accessed, in Ji's decomposition, via **GPDs**, which contain information on total angular momentum, J_q.

Caveat:

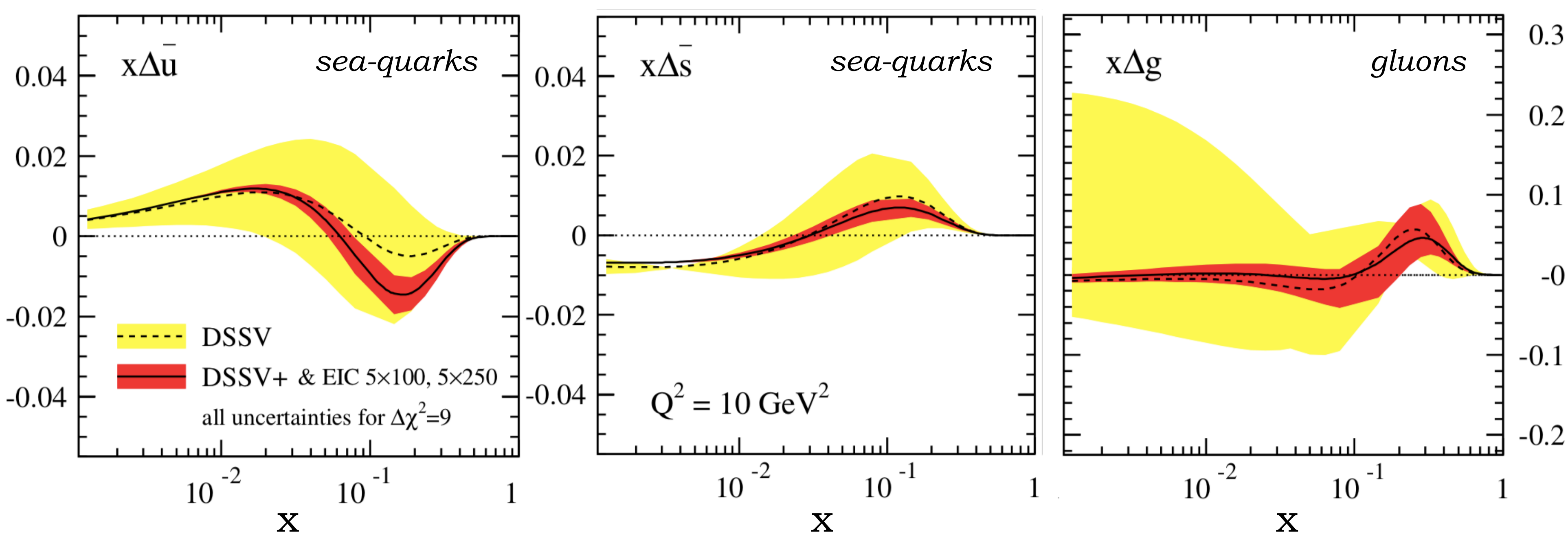
In Ji's decomposition of nucleon spin, the gluon spin and OAM terms cannot be separated.

Gluon spin

- DVMP: GPDs provide access to the orbital angular momentum carried by the sea quarks
- DIS and SIDIS will contribute extremely precise measurements of the helicity distributions of gluons.



$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx$$

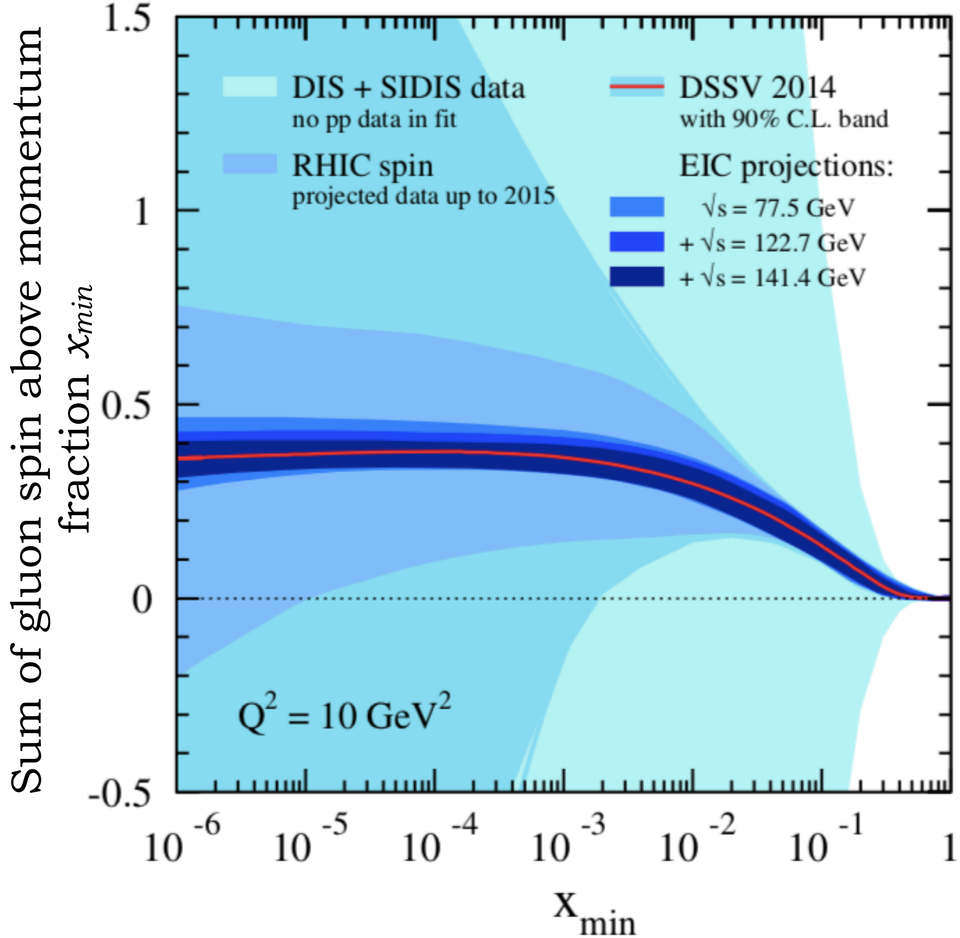


E. Aschenauer *et al.*,
Phys. Rev. D 86, 054020 (2012)

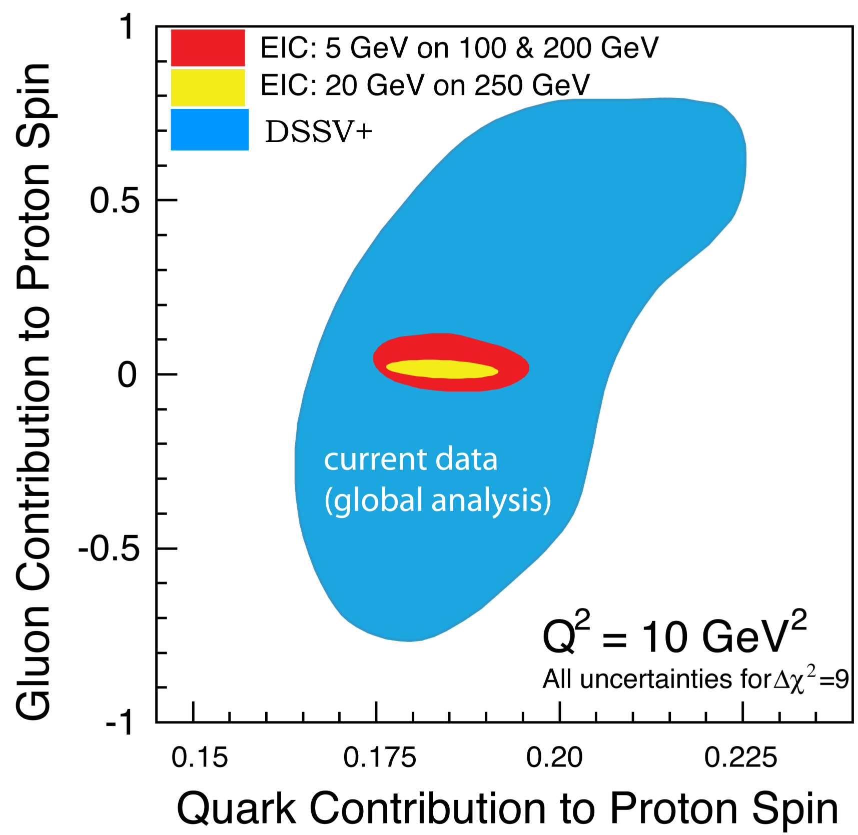
DSSV: D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, Phys. Rev. **D 80**, 034030 (2009).

DSSV+: arXiv:1112.0904 [hep-ph]

EIC reach for gluon spin



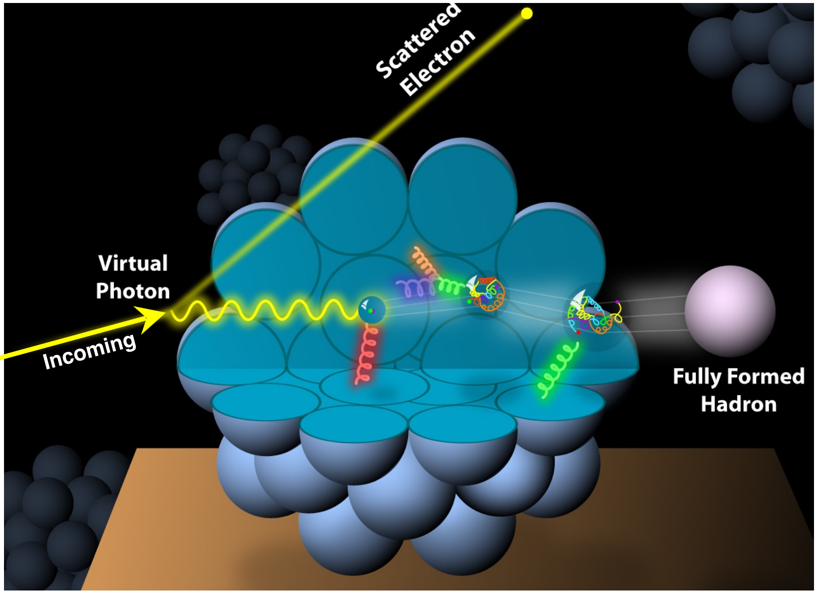
E. Aschenauer *et al.*, Phys. Rev. D 92, 094030 (2015)



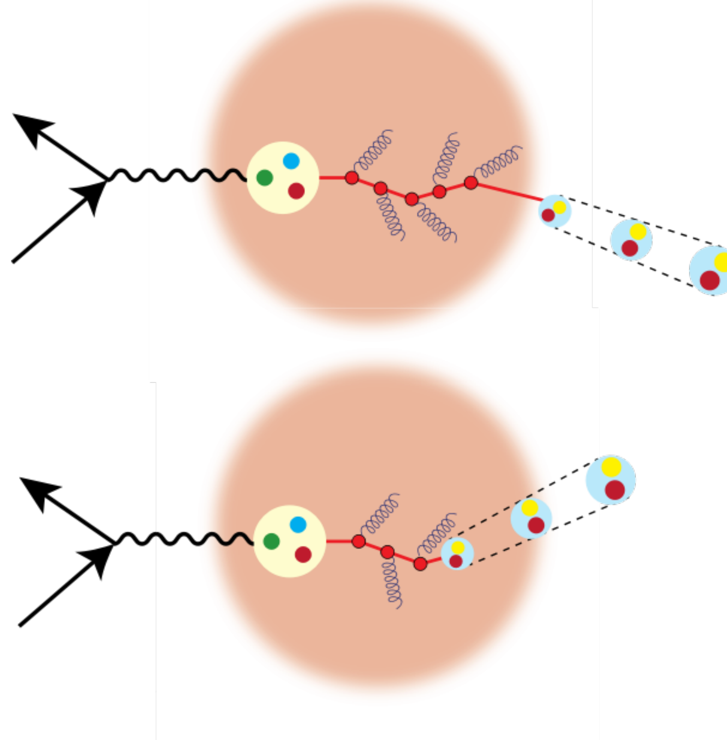
DSSV+: D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, arXiv:1112.0904 [hep-ph]

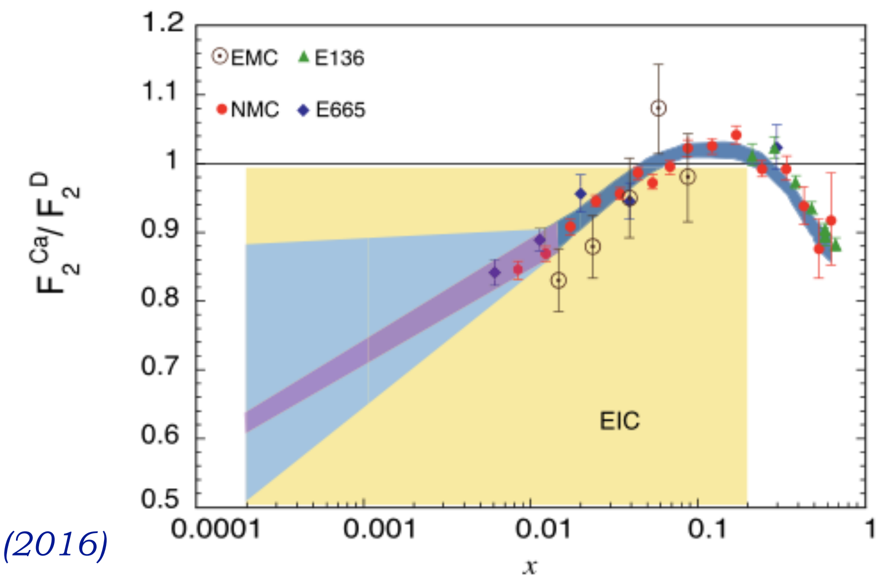
E. Aschenauer *et al.*, Phys. Rev. D 86, 054020 (2012)

Hadronisation



Courtesy of E. Aschenauer

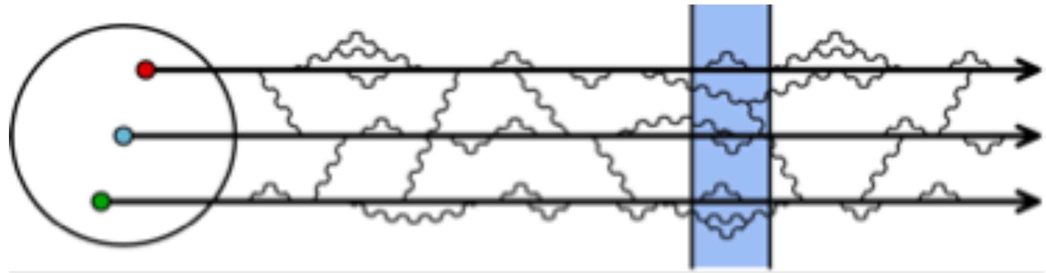




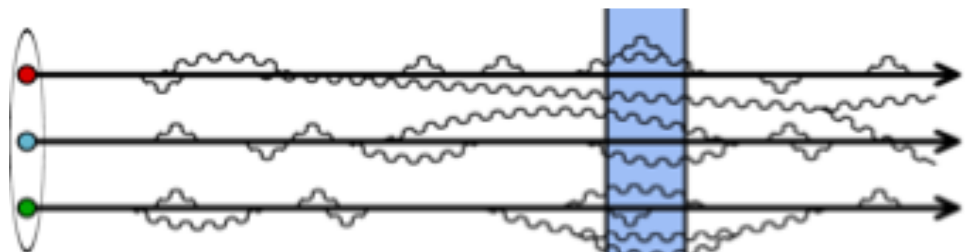
- How does the nuclear environment affect the distributions of quarks and gluons and their interactions inside nuclei?
- How does nuclear matter respond to fast moving color charge passing through it?
- Are there differences for light and heavy quarks?

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

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.

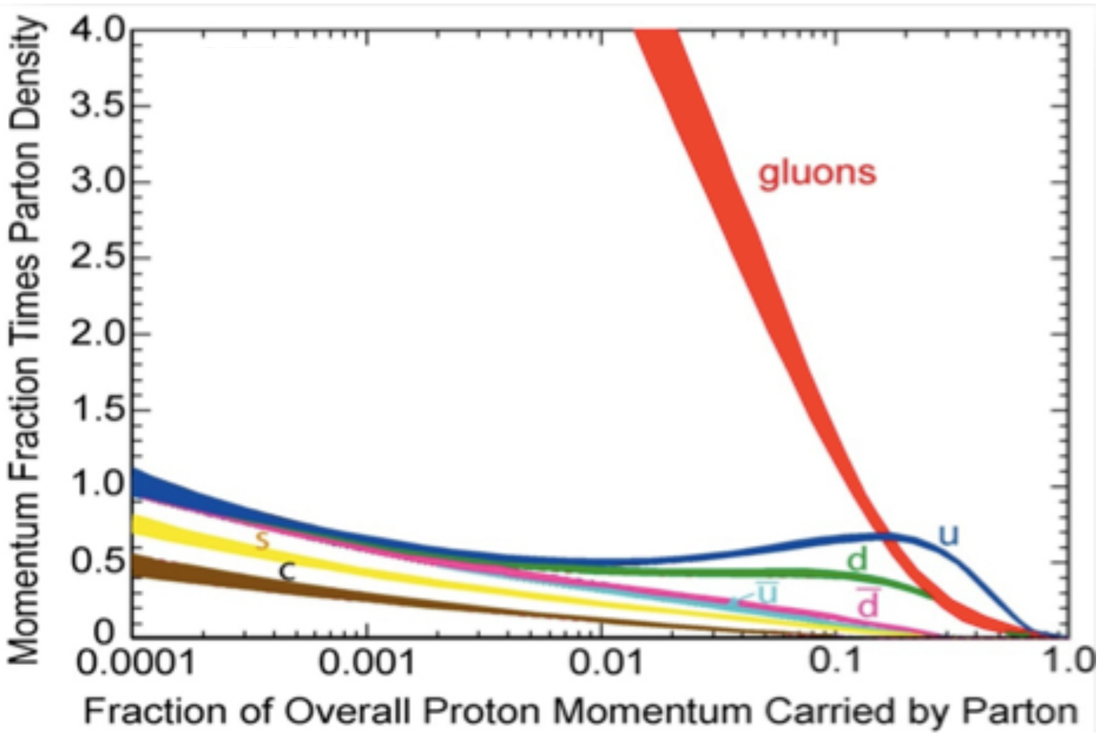
* Nucleon probed at high energies, time dilation of strong interaction processes: gluons appear to live longer, emitting more and more gluons. Runaway growth! Runaway growth?

Saturation of gluon density

- Runaway growth of glue at low-x:

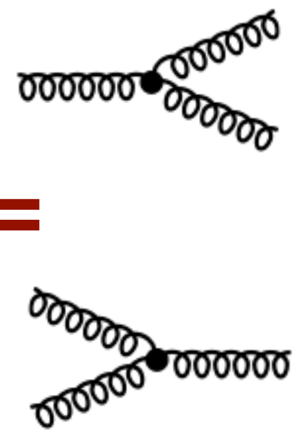
"…A small color charge in isolation builds up a big color thundercloud…."

F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004



But somewhere it must saturate…

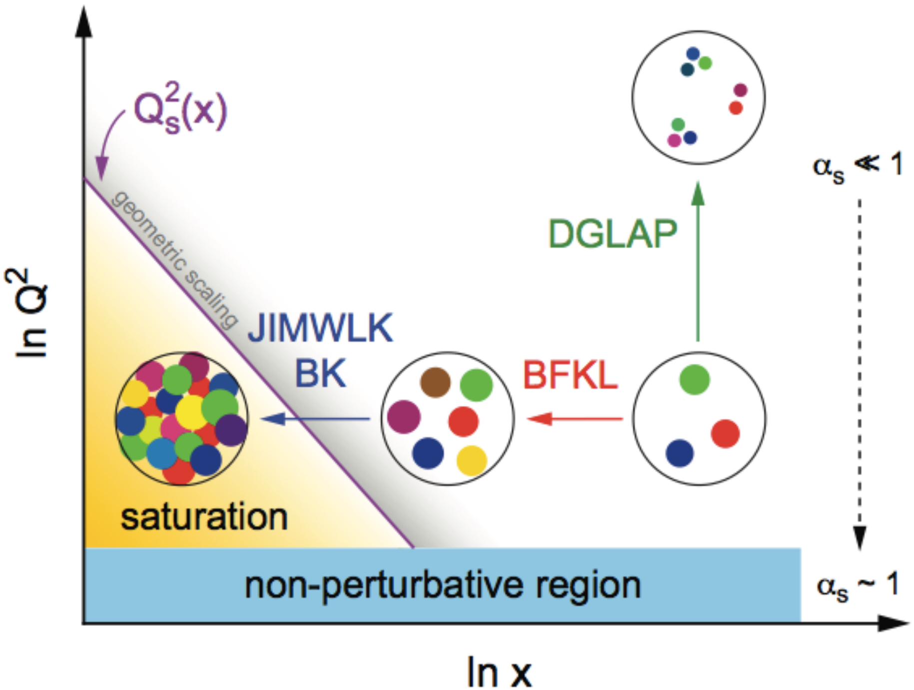
rate of



rate of

Courtesy of A. Deshpande

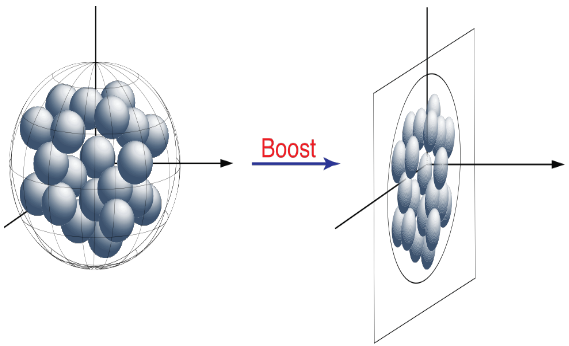
Phases of hadronic matter

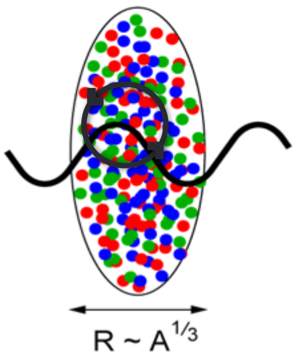


Recombination of gluons leads to saturation of gluon densities.

Possible effective theory:
Colour Glass Condensate.

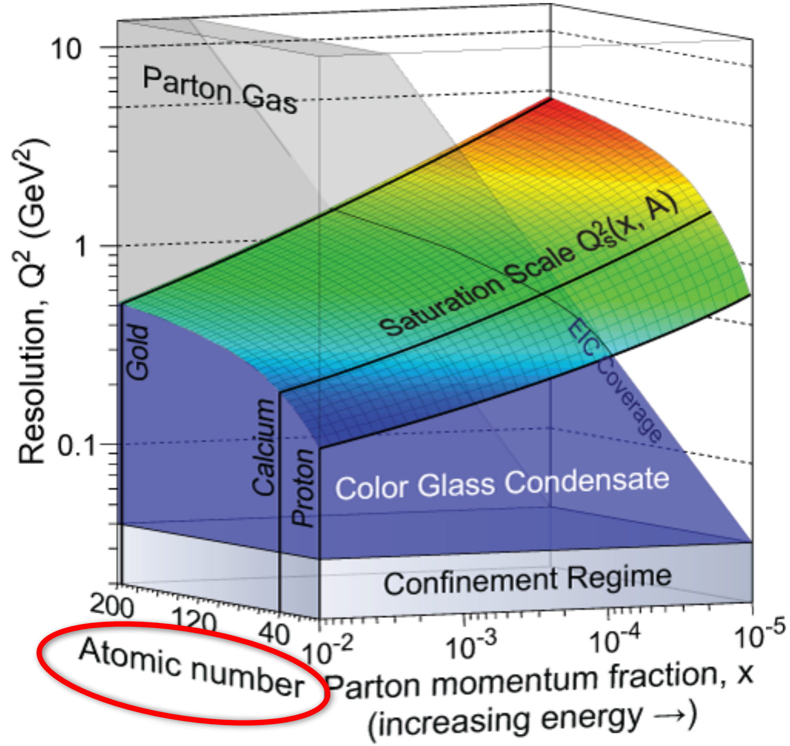
Can we reach saturation at EIC?





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

saturation scale



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

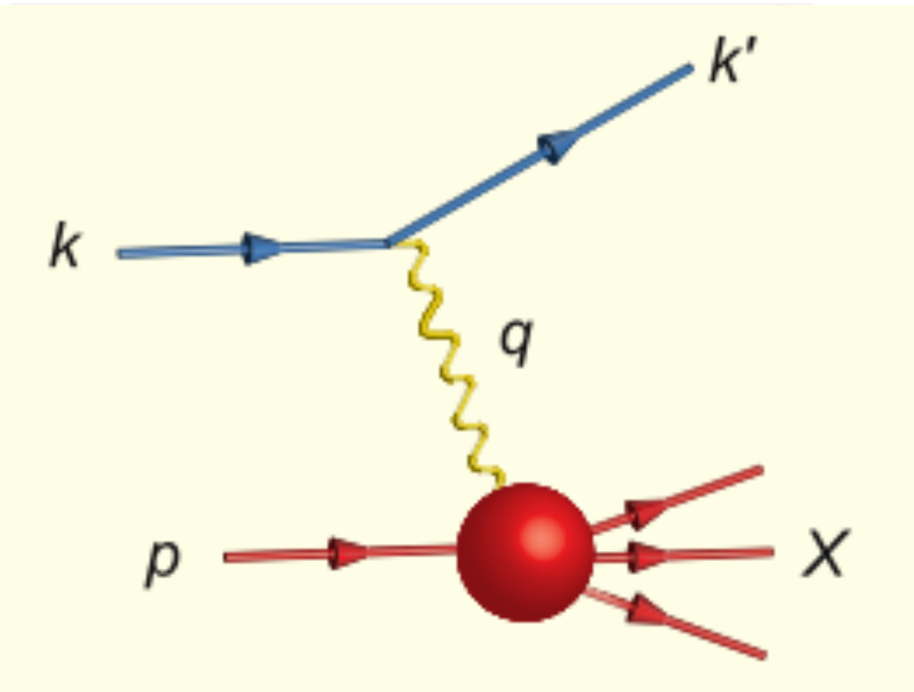
Saturation regime would be accessible at much lower energy in *e-A* collisions than *e-p*. You do not need a TeV collider!

Courtesy of A. Deshpande

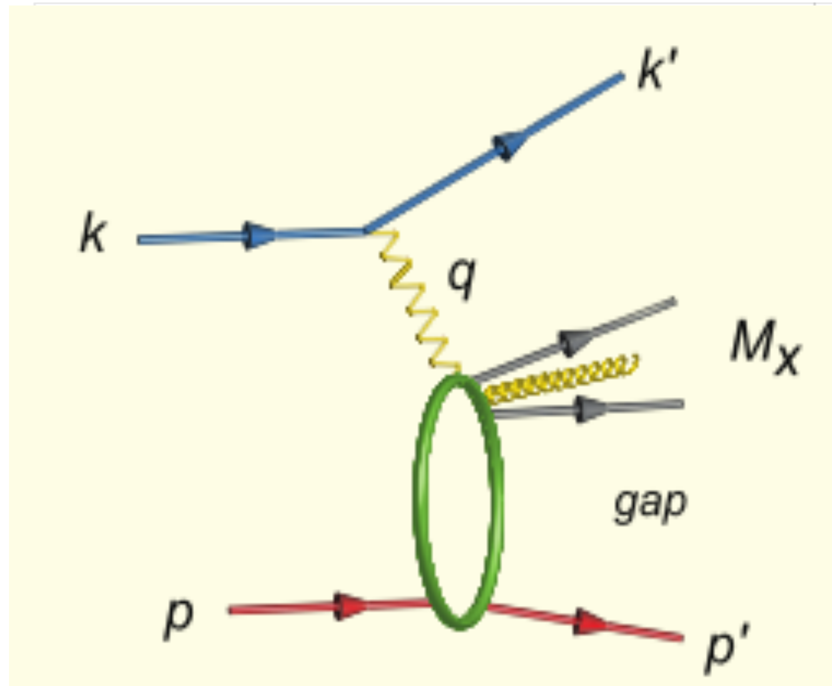
A sign of gluon saturation

A powerful signature is diffractive cross-sections:

Deep Inelastic Scattering



Diffractive Scattering



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

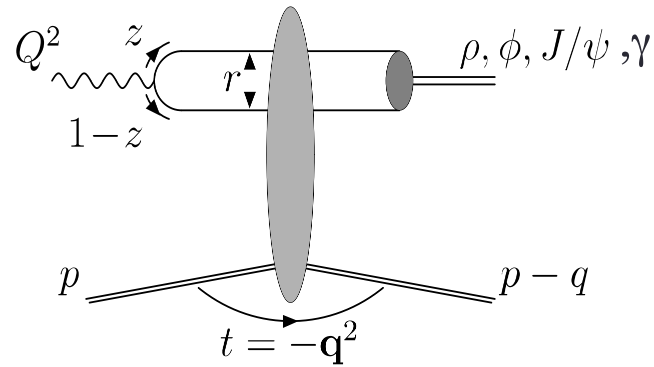
Saw ~10% diffractive events at HERA.

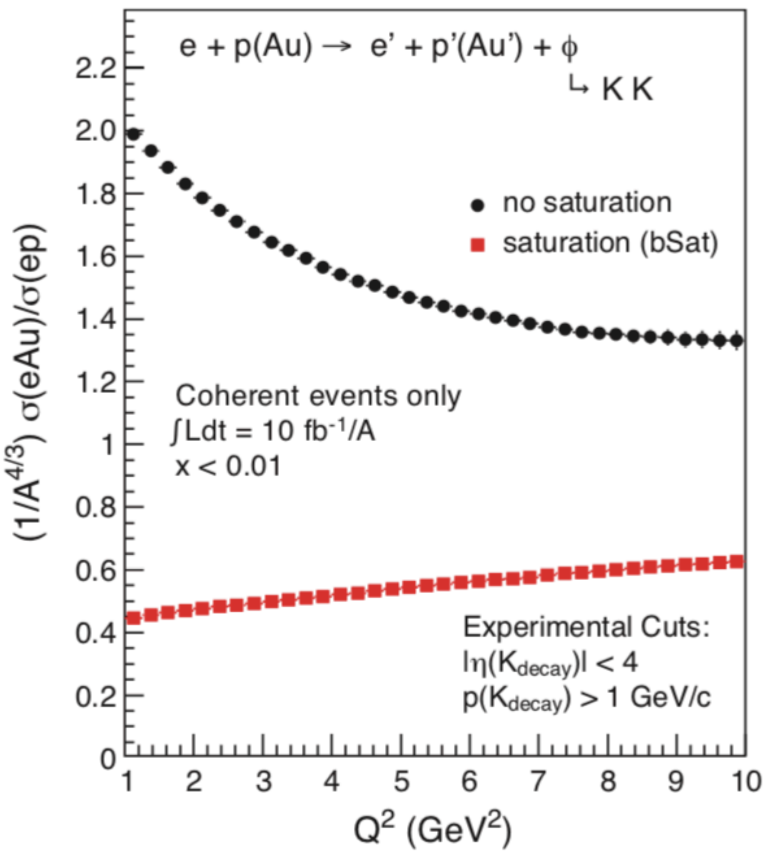
Courtesy of A. Deshpande

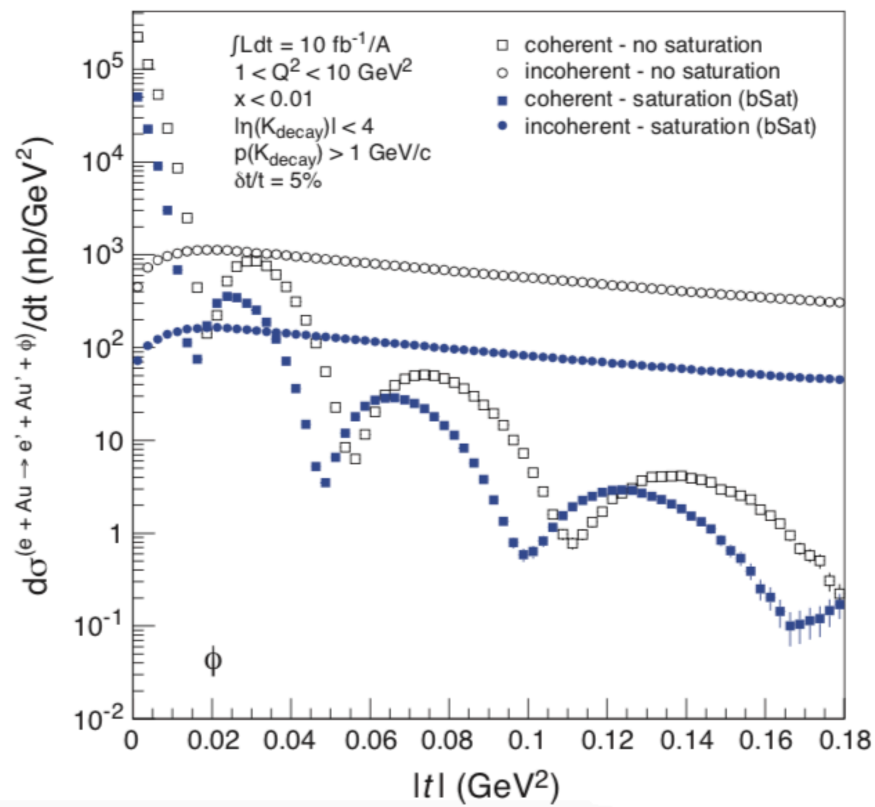
EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

Gluon saturation

Modified transverse gluon distributions?





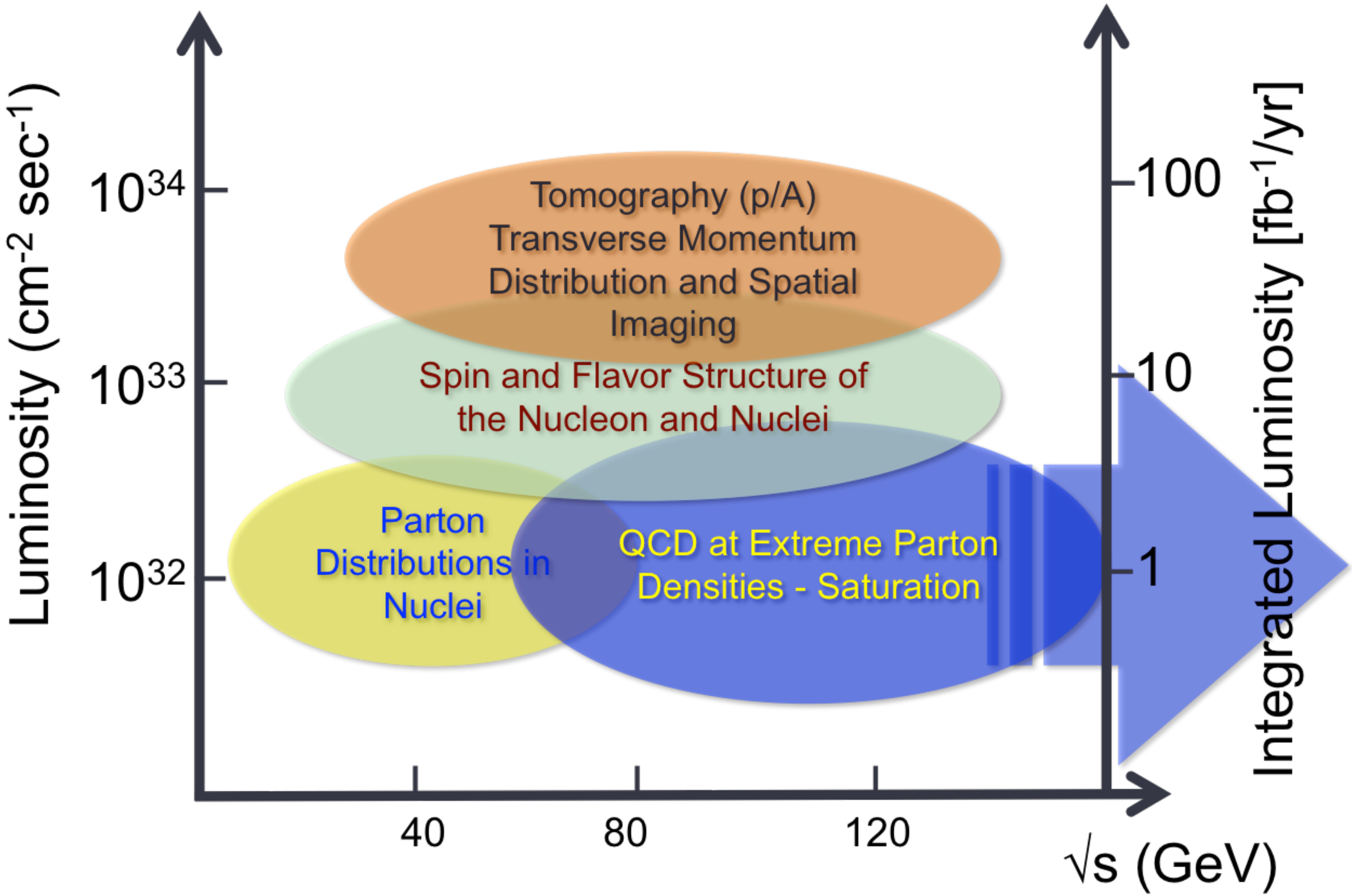


EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

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.

What will we be able to do?



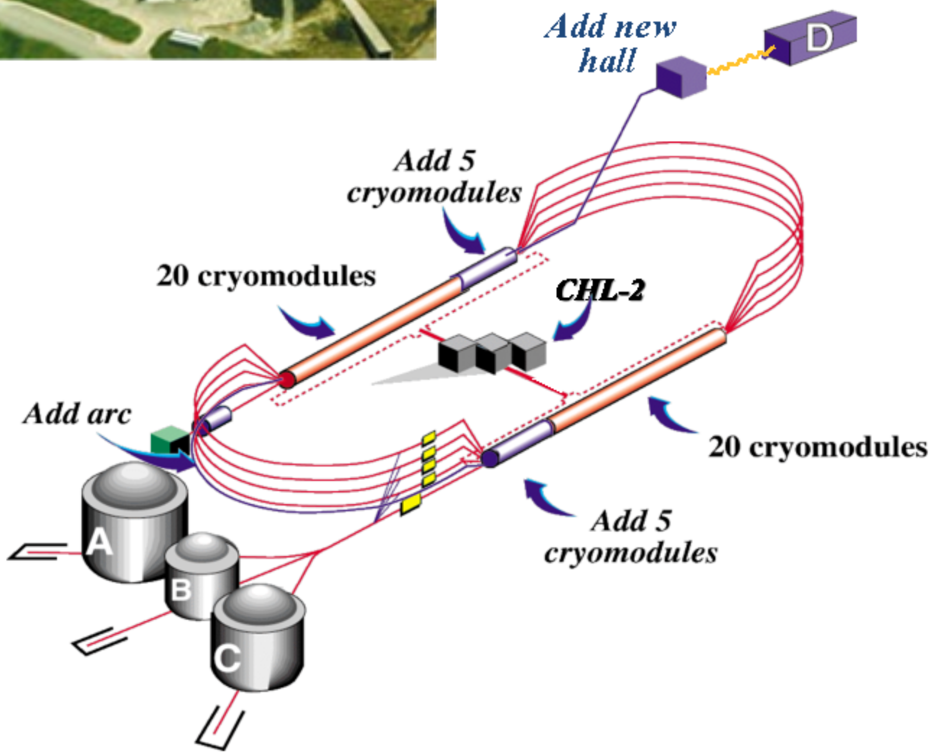
year =10^7 sec

Jefferson Lab, Virginia, USA

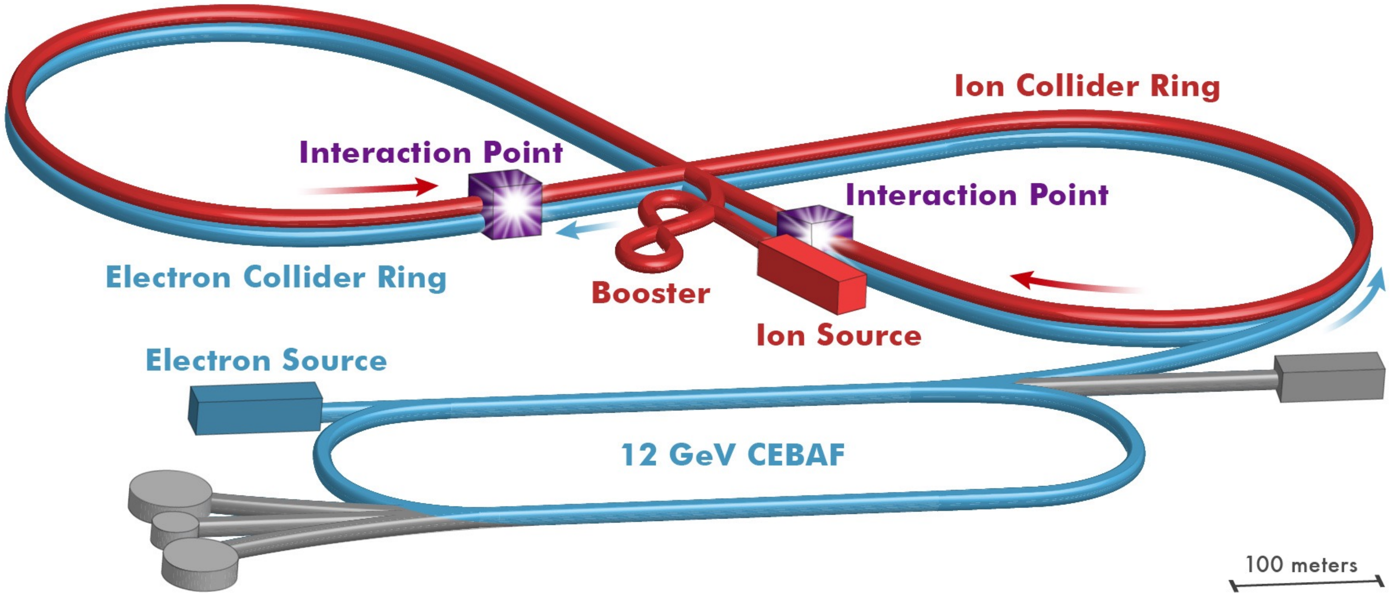
Jefferson Lab

CEBAF: Continuous Electron Beam Accelerator Facility.

- Energy up to 11 GeV (Halls A, B, C), 12 GeV Hall D
- Energy spread $\delta E/E_e \sim 10^{-4}$
- Electron polarisation up to >80%, measured to 3%
- Beam size at target < 0.4 mm

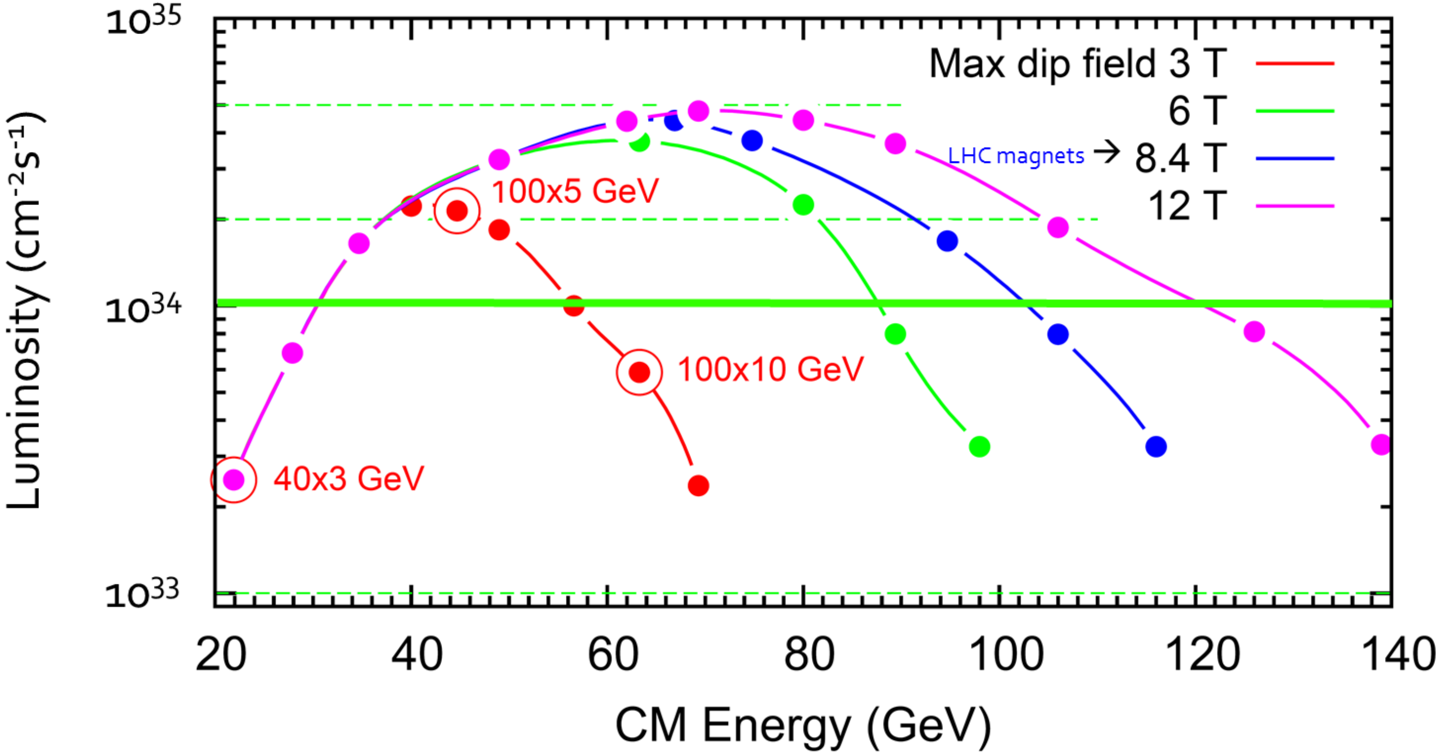


JLEIC



- Use CEBAF as full-energy injector (polarisation ~85%). Addition of an ion source, booster, and a figure-of-8 collider ring for electrons and ions.
- 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)

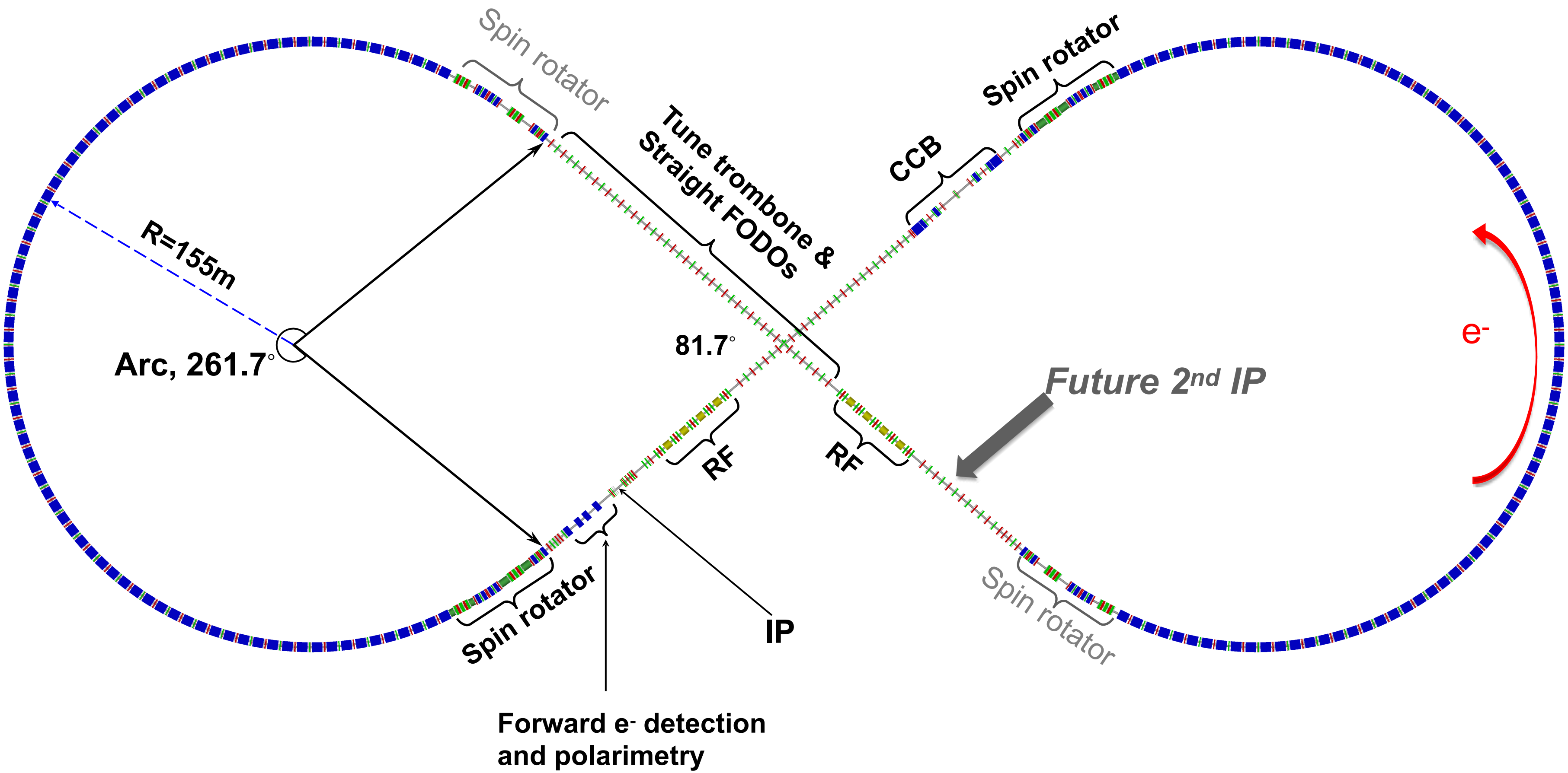
JLEIC Reach



CM Energy (in each scenario)	Main luminosity limitation
low	space charge
medium	beam-beam
high	synchrotron radiation

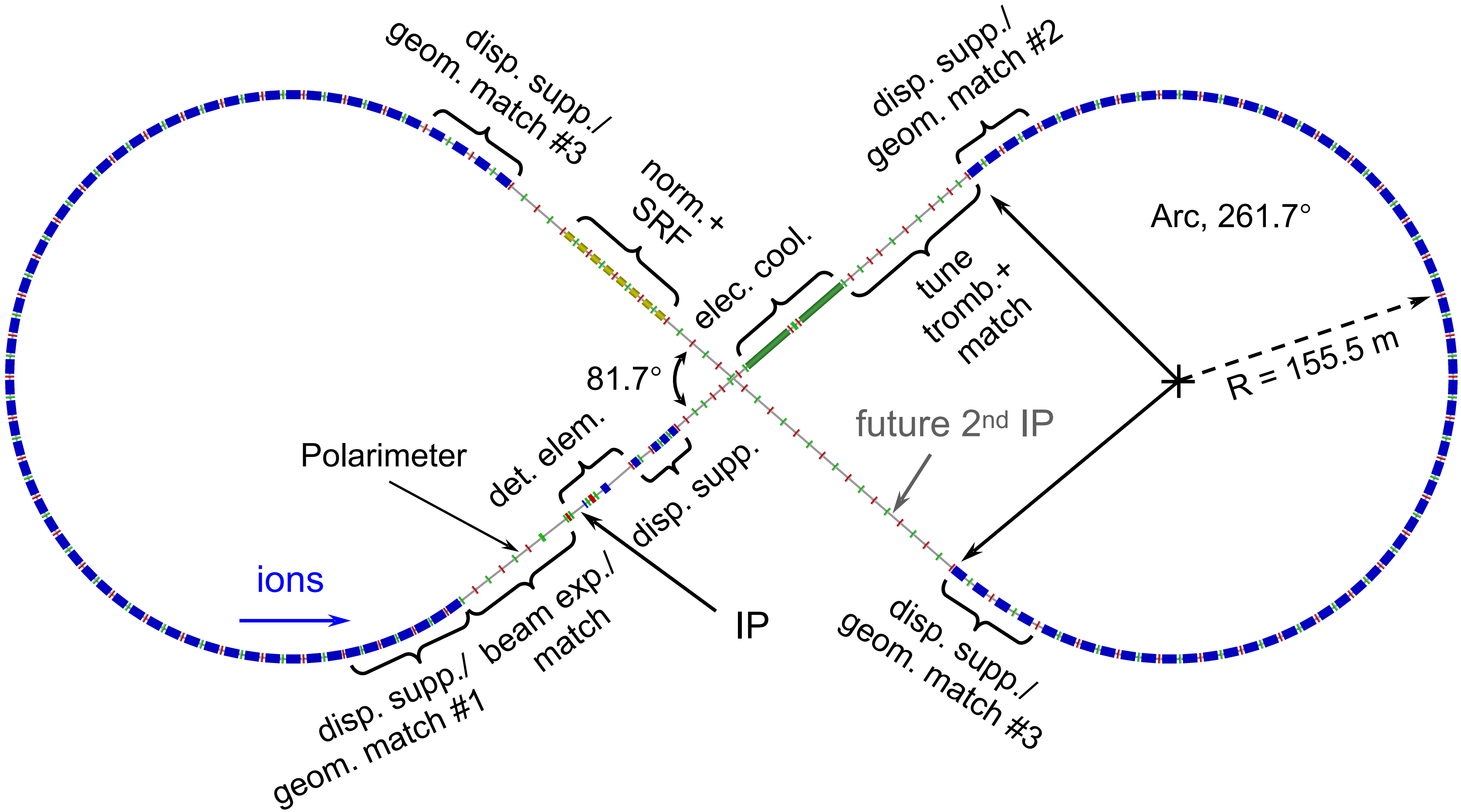
Courtesy of V. Morozov (JLab)

JLEIC: electron ring



Courtesy of V. Morozov (JLab)

JLEIC: ion ring

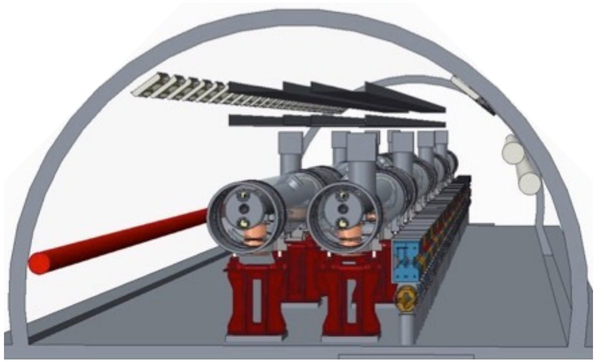


- Protons: 100 GeV/u (63 GeV/u in COM with 10 GeV e)
  Lead: 40 GeV/u (40 GeV/u in COM with 10 GeV e)

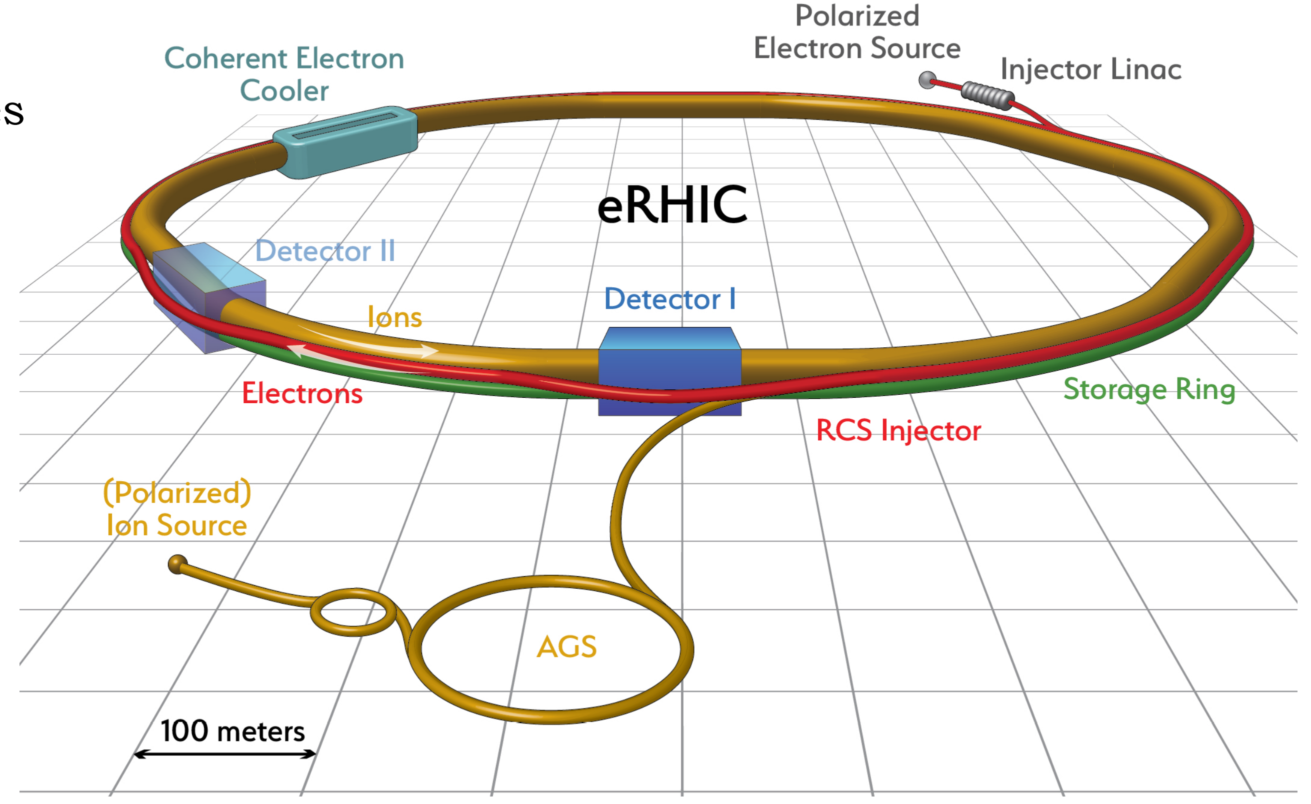
Courtesy of V. Morozov (JLab)

Brookhaven National Lab, NY, USA

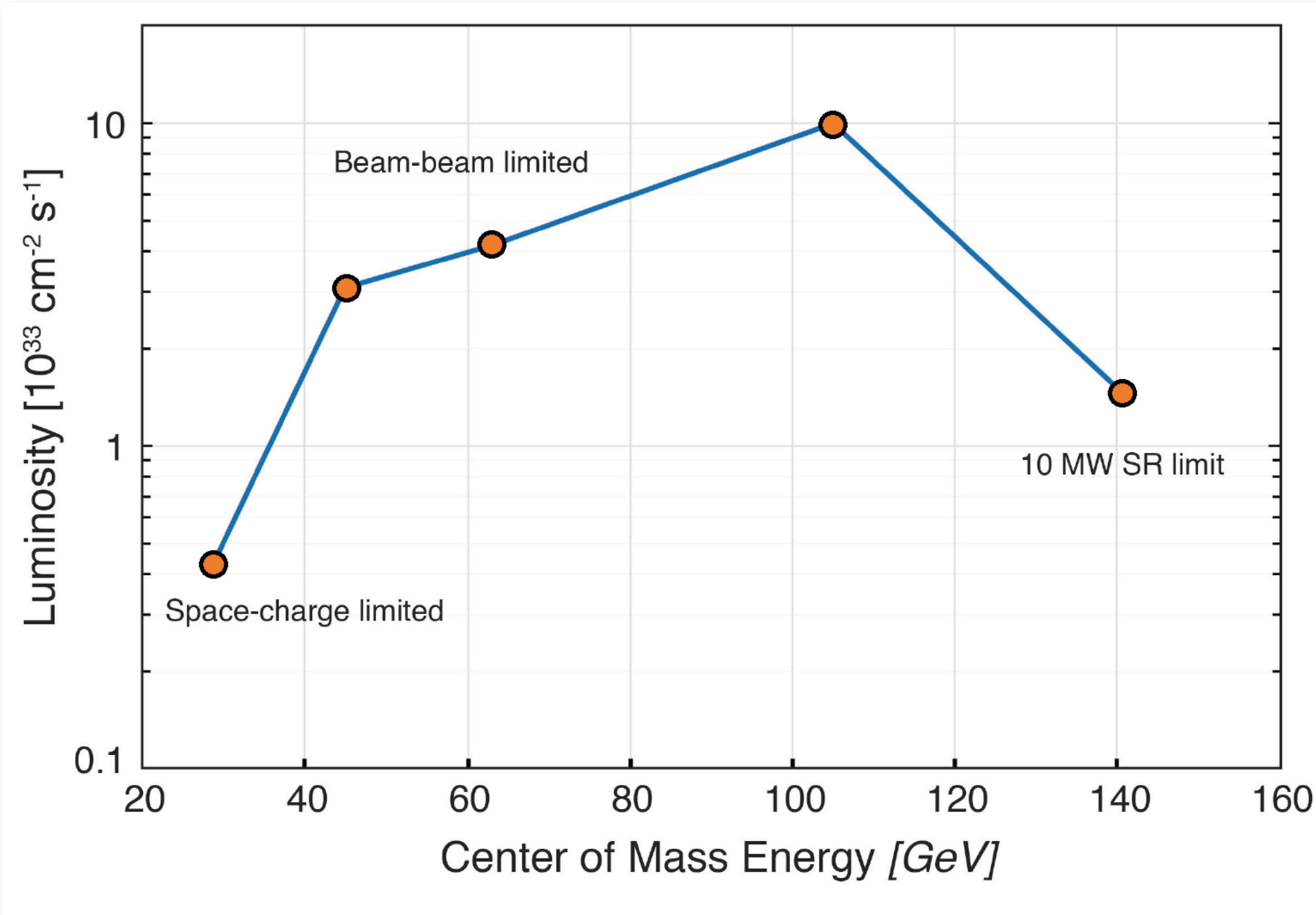
eRHIC



- Exploit current 275 GeV proton collider by adding a 5-18 GeV electron storage ring in the same tunnel.
- High luminosity requires novel technologies of hadron cooling — currently most promising is micro-bunched electron-beam cooling with 2 plasma amplification stages.
- 29 - 141 GeV CoM energies
- Polarised electron source and 400 MeV SLAC-type injector LINAC, 10 nA.
- Harmonic spin matching for higher polarisation (~80%).
- Highest risk in the design: hadron cooling for high luminosity (factor of ~3).

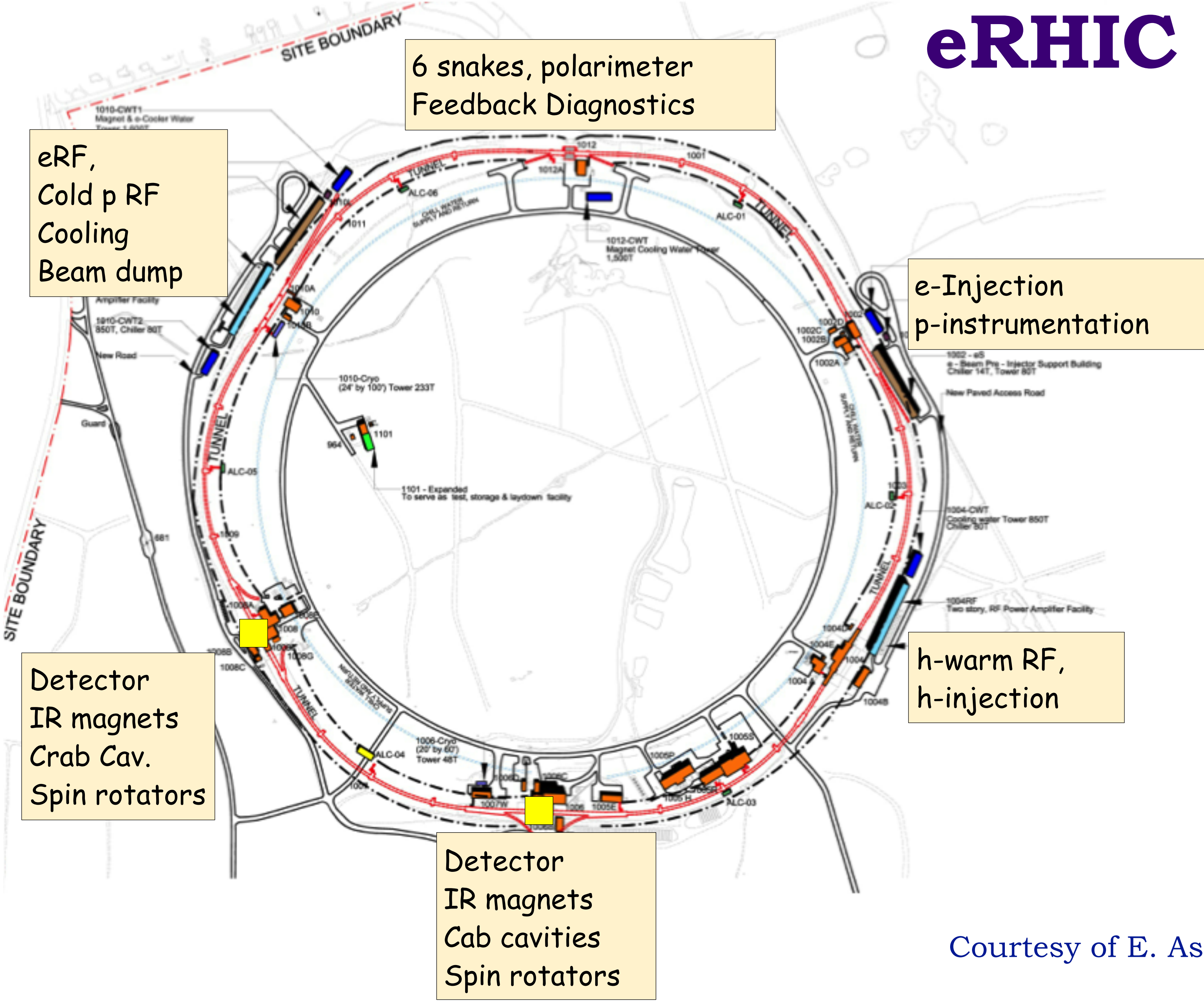


eRHIC Reach



Courtesy of E. Aschenauer (BNL)

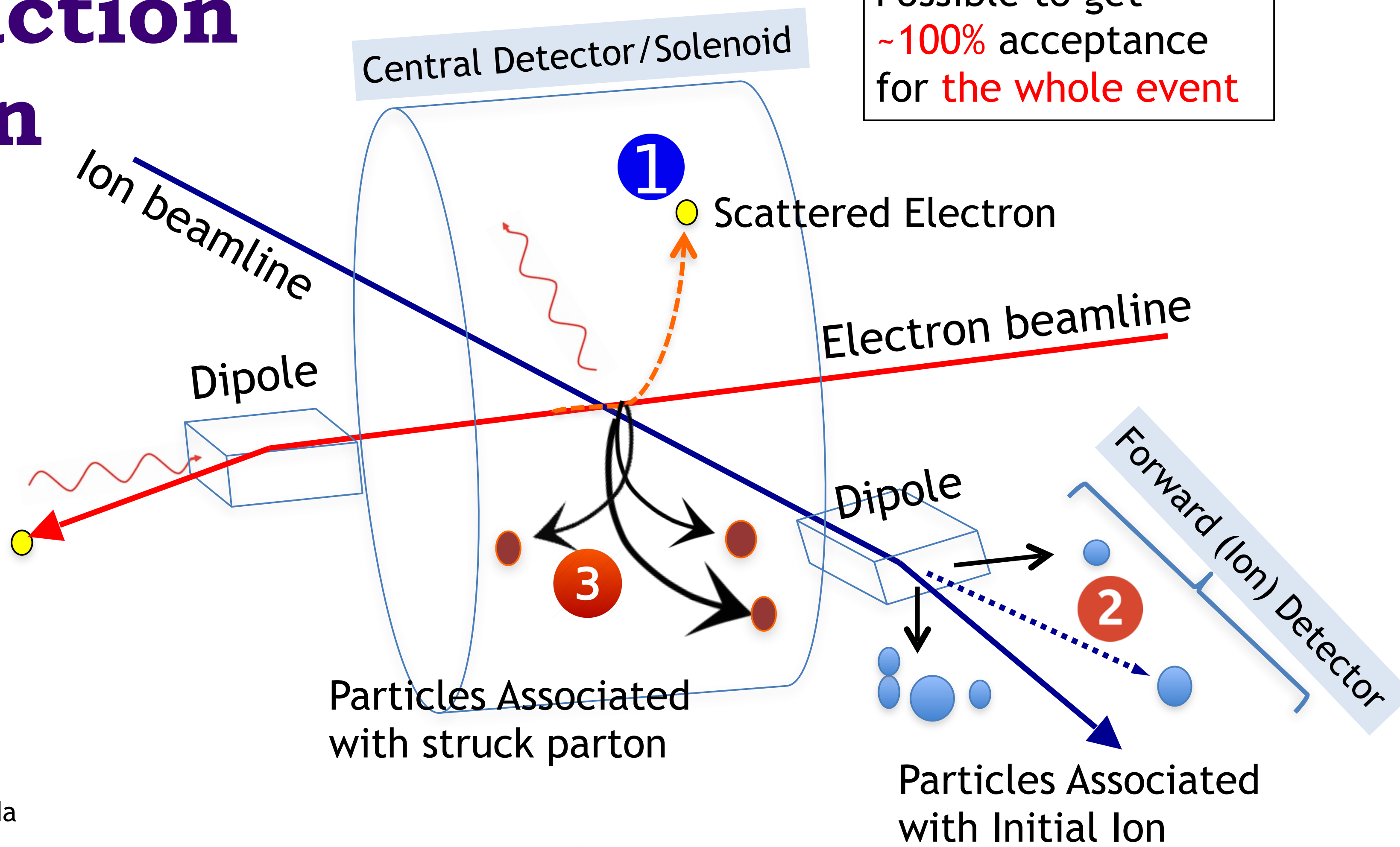
eRHIC design



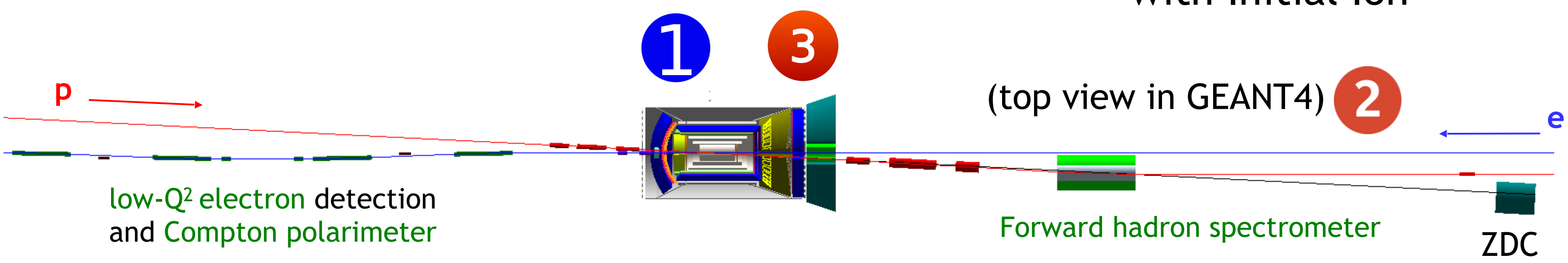
Courtesy of E. Aschenauer (BNL)

Interaction Region

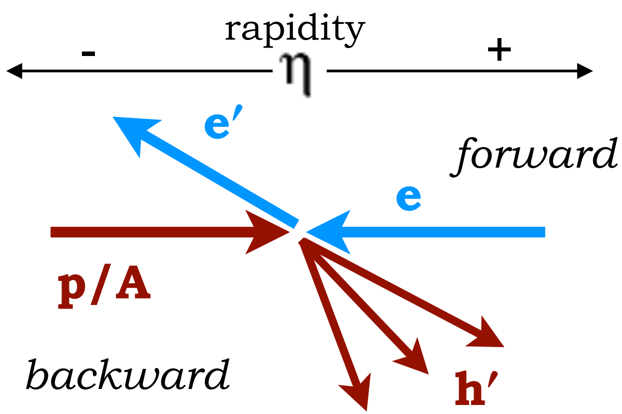
Possible to get ~100% acceptance for the whole event



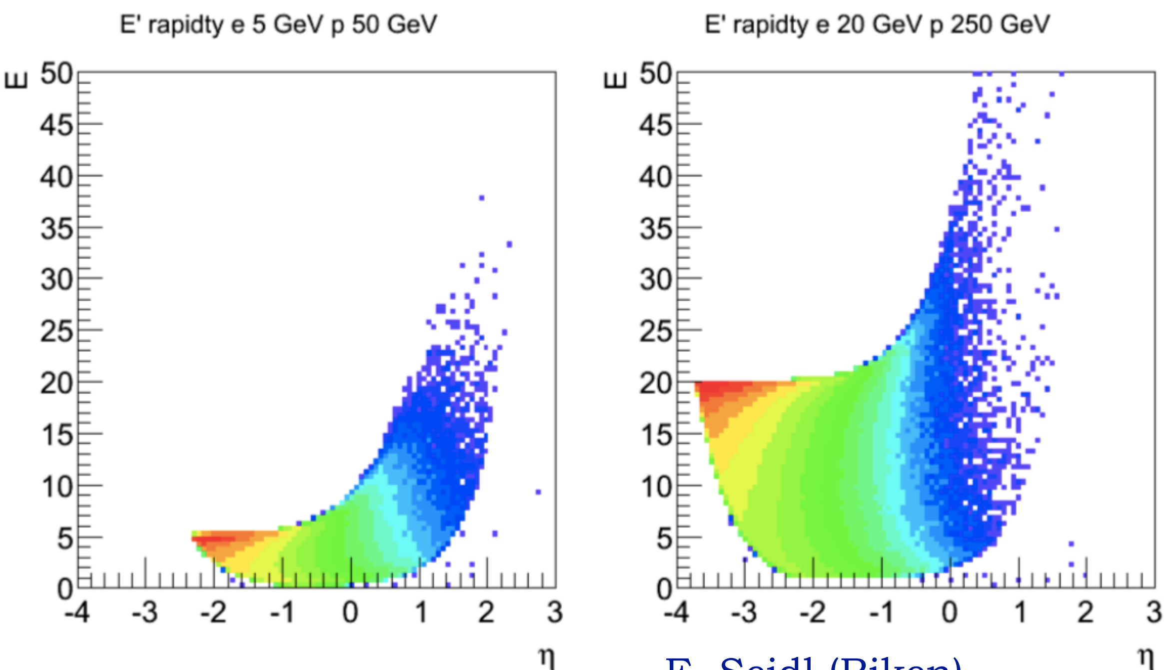
Courtesy of R. Yoshida



Detector Requirements: leptons



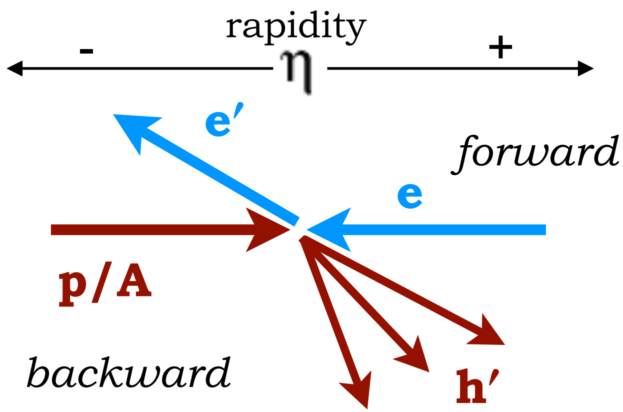
* **Electron**: PID, tracking, energy measurement
  - Backward: electron E < 20 GeV, central region E < 50 GeV.
  - Require good electron/hadron separation.
  - EM Calorimeters, Silicon / TPC / GEM tracking
  - Kinematic range of x and Q^2 determined by electron acceptance.

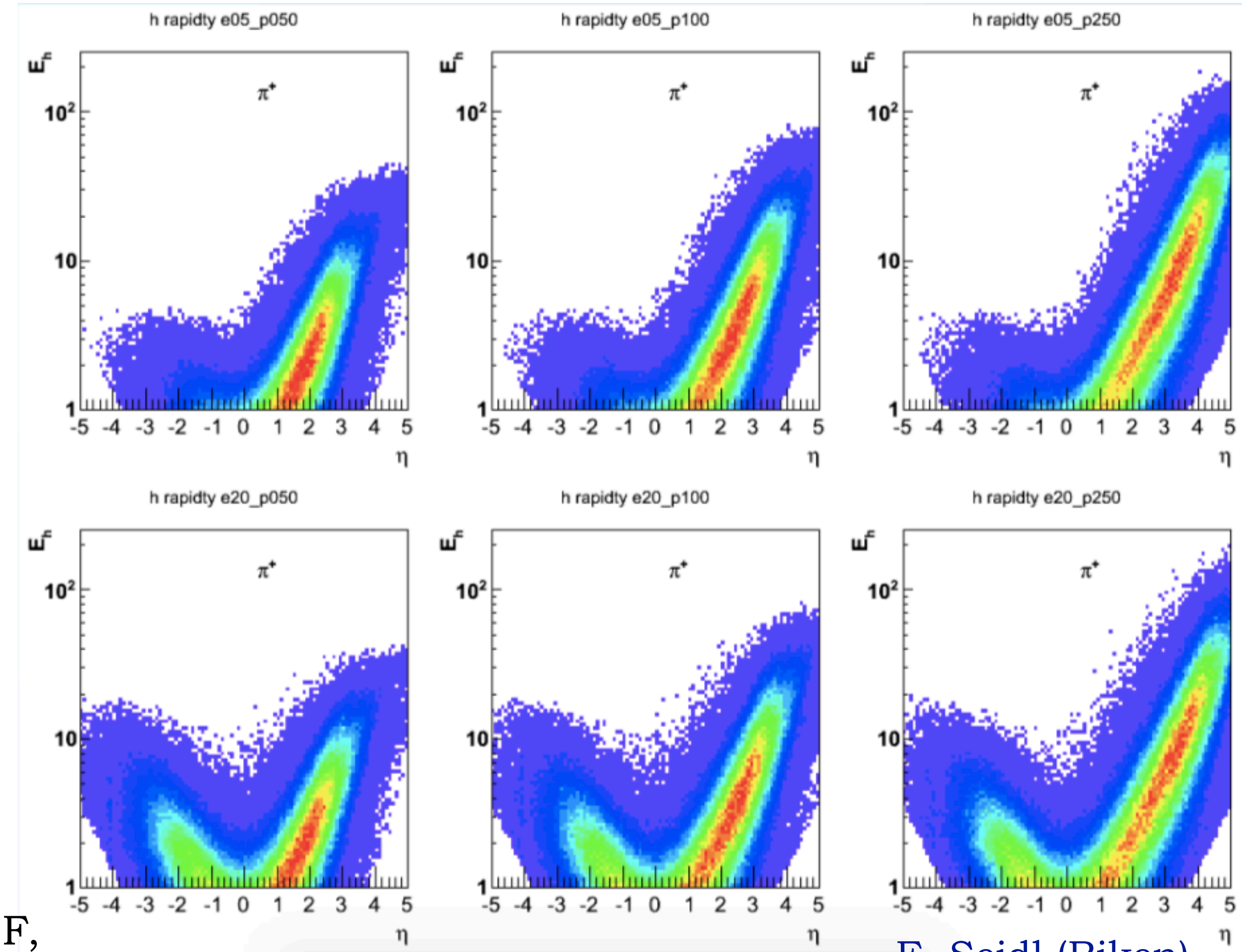


E. Seidl (Riken)

* Very low Q^2 (quasi-real photons): electrons very close to the beam-line, need to consider in the design of the interaction region (coordination with accelerator experts).

Detector Requirements: hadrons





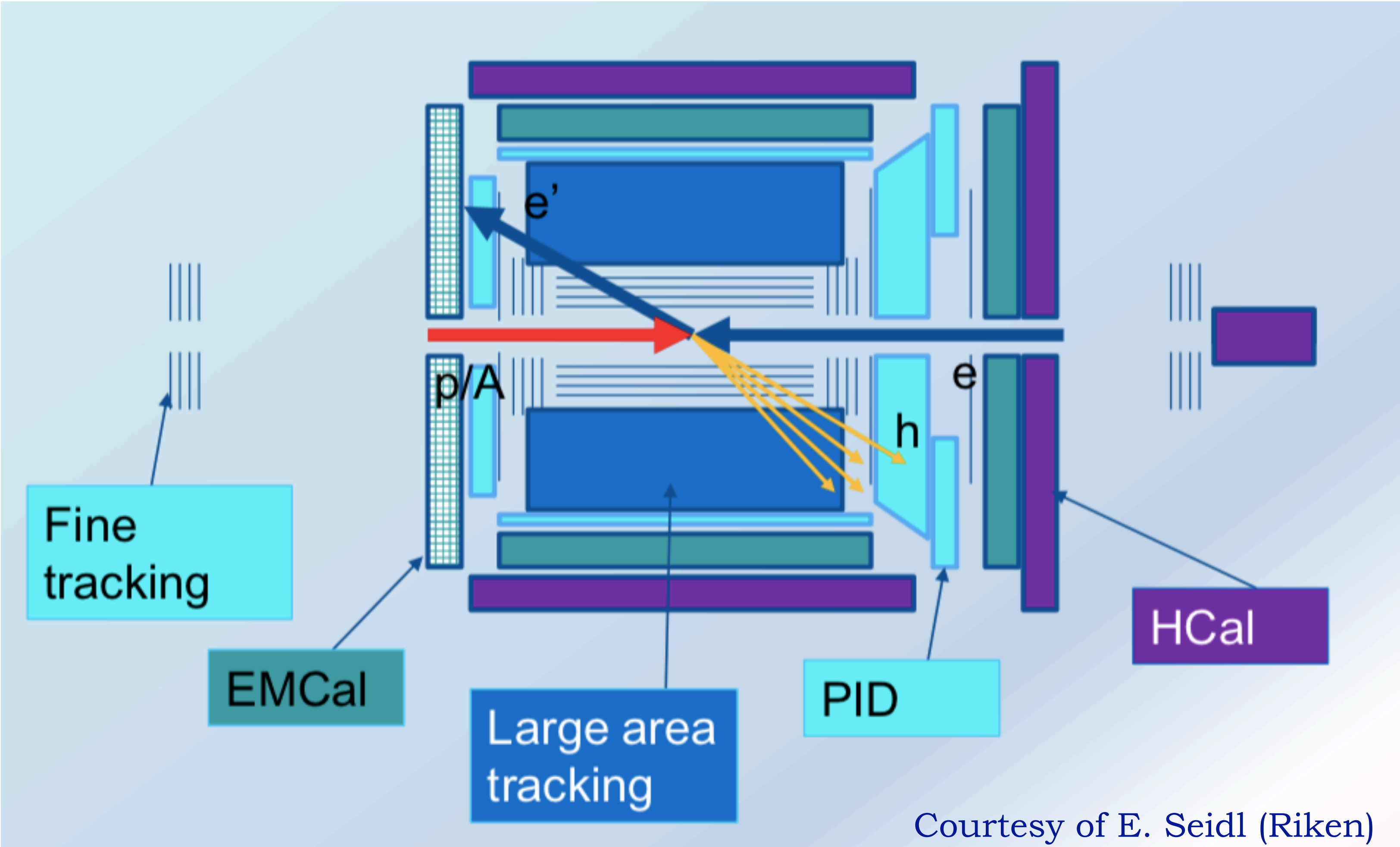
E. Seidl (Riken)

✱ **Hadron** PID, tracking, momentum and energy measurement:

- Forward region E < 100 GeV, central region ~ a few GeV, backward region < 20 GeV.
- Central region DIRC / fast TOF, forward region: RICH, hadronic calorimeters, Roman pots (protons), zero-degree calorimeter (neutrons).

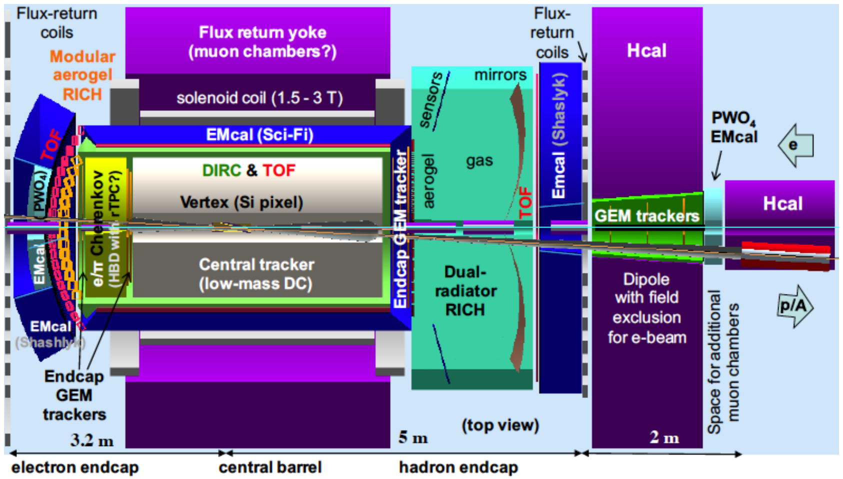
✱ High energy **photons** for Deeply Virtual Compton Scattering: EM calorimeter (backward).

Generic Detector Concept

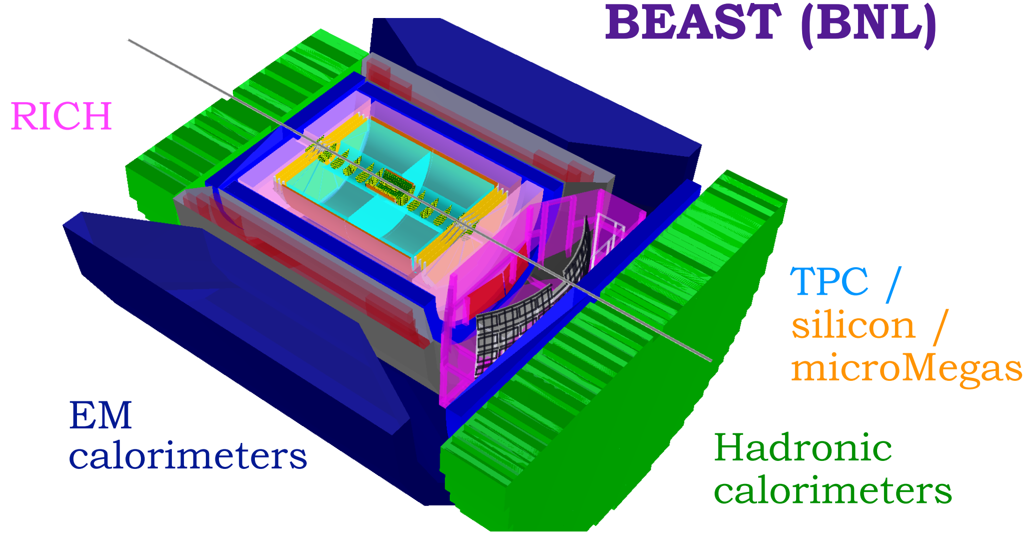


Main detector designs

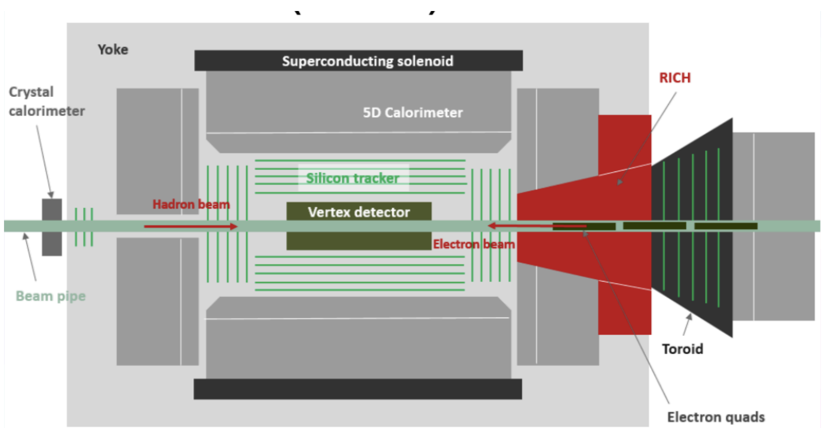
JLEIC detector (JLab)



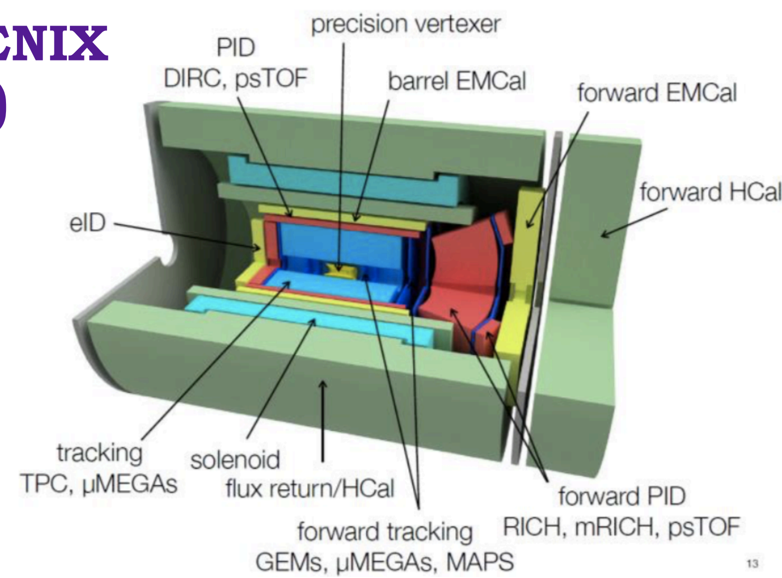
BEAST (BNL)



TOPside (Argonne)



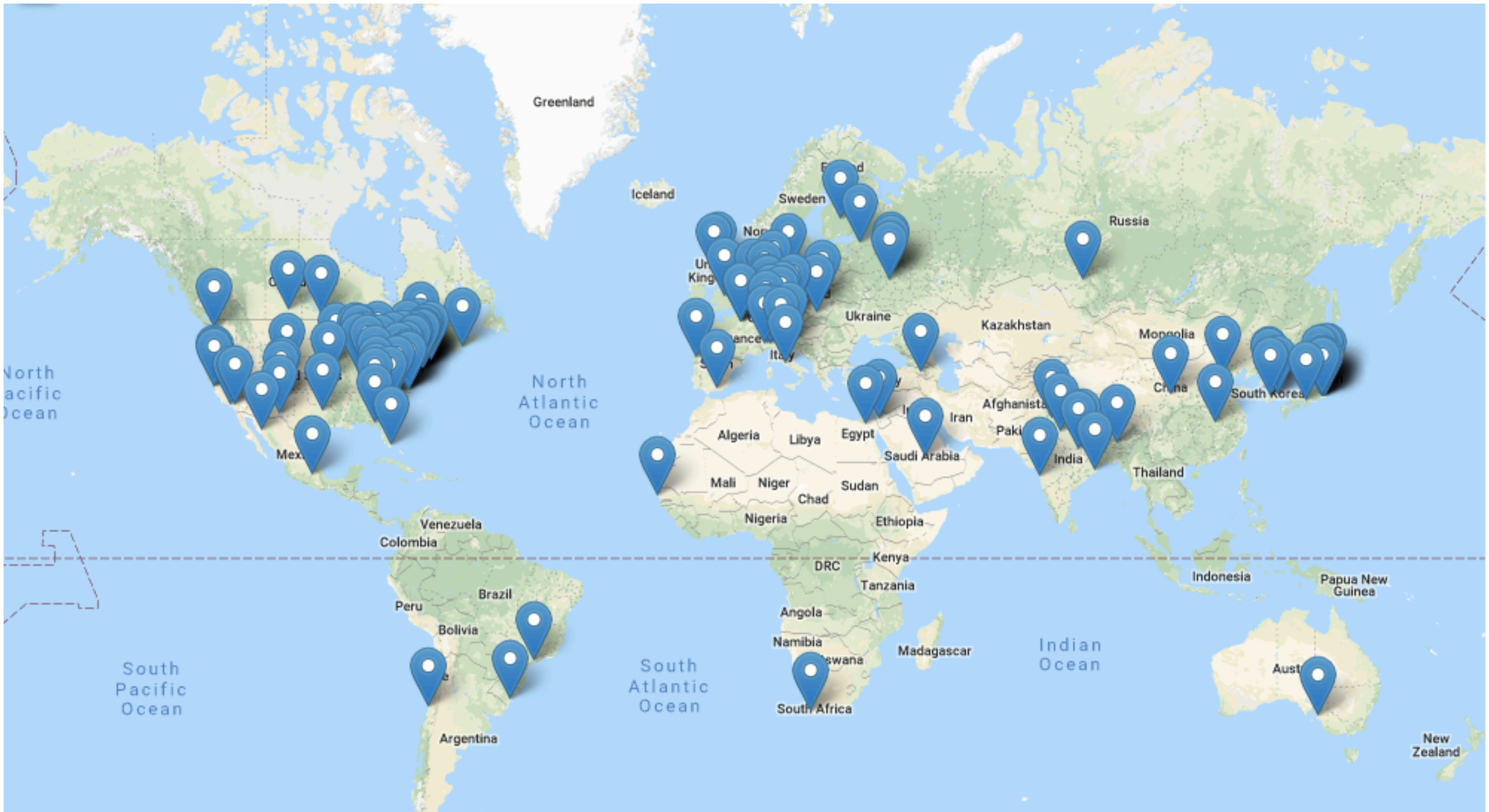
ePHENIX (BNL)



The EIC Users Group

795 members, 170 Institutes, 29 Countries

453 experimentalists, 158 theorists, 142 accelerator-physicists, 42 other



www.eicug.org

and growing…

EIC timeline

- ✦ **2007 Nuclear Physics Long Range Plan**: *"The EIC is embodying the vision of reaching the next QCD frontier"*
- ✦ **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, representatives (including one for Europe) are elected to the board. Bi-annual meetings in the US.**
- ✦ **2017 First European meeting of EICUG held in Trieste, Italy, in July.**
- ✦ **2017 National Academies of Science, Engineering and Medicine review of the science case. *Expect report — literally — any minute...***
- ✦ **Indications of a favourable result, *CD0 (approval of mission need) ~ 2019.***
- ✦ ***Construction: ~ some time in the 2020s!***

Conclusions

- The EIC will be the first electron ion collider providing polarised electrons and light ions, and unpolarised heavy ions.

- Combing a large variable centre-of-mass energy reach and an extremely high luminosity, it will allow measurements of very low cross-section processes from the valence quark region to the quark-gluon sea.

- Two sites in the US are considered for the construction of the facility: Jefferson Lab and Brookhaven National Lab.

- Several detector designs are currently under development: international effort.

- Main challenges on EIC design: hadron cooling for high luminosity, sufficient machine-element free space around interaction point (~5m) for detectors, particle detection and PID close to the beam-line: requires co-ordination between accelerator and detector scientists.

- EIC project under review by the National Academies of Science. CD0 approval expected soon!

Thank you!