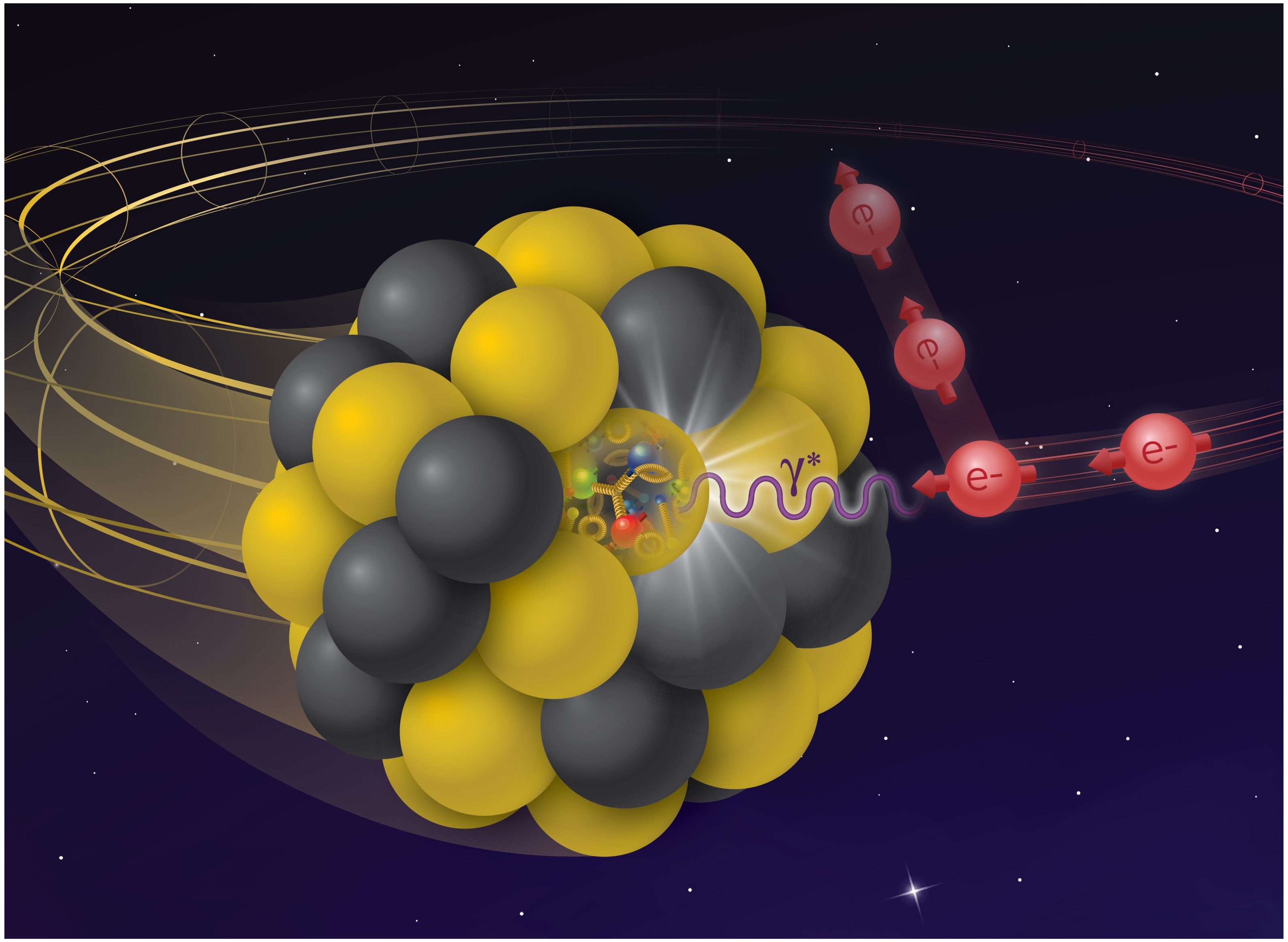


EIC physics

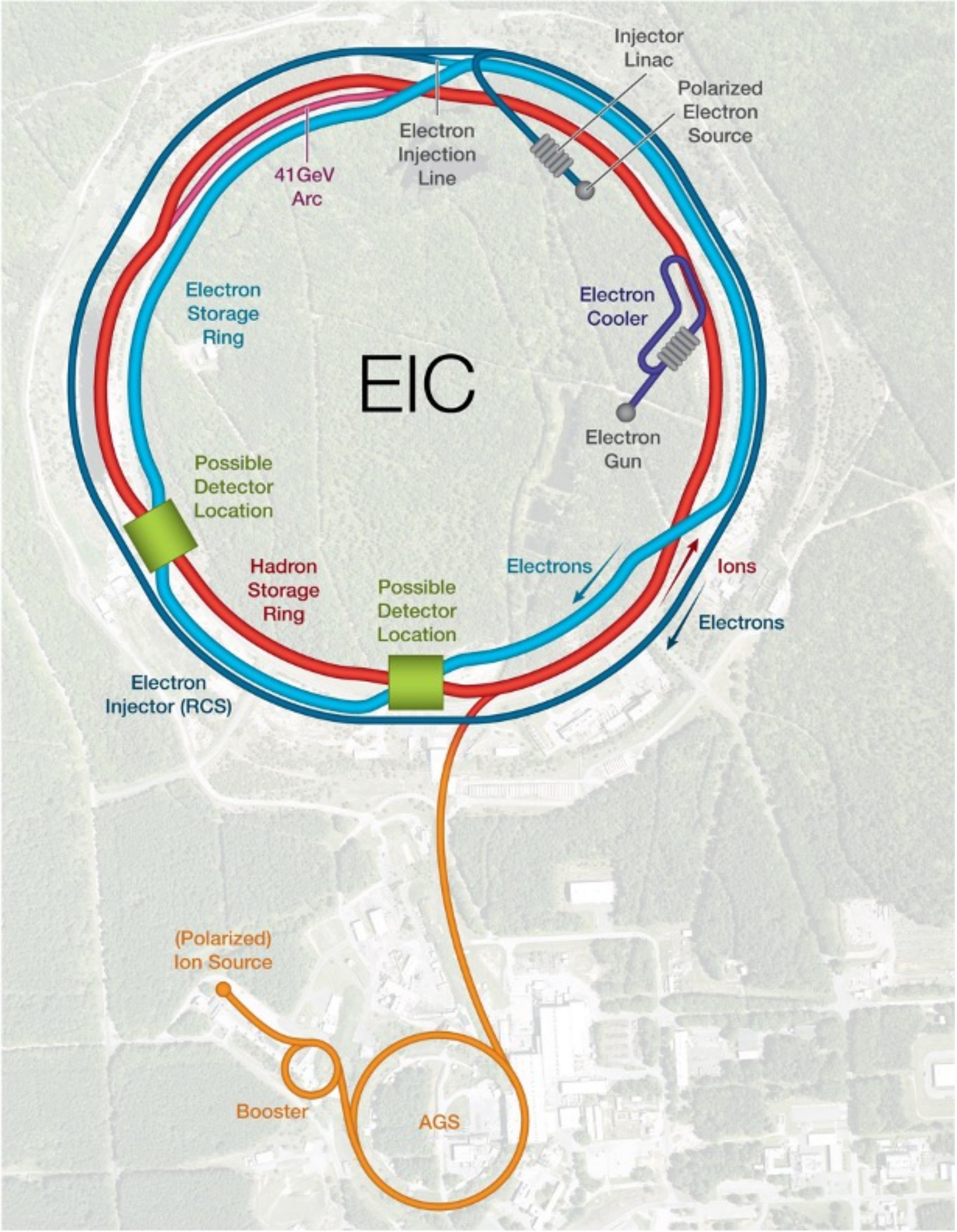
Anna Staśto

Penn State University

What is EIC ?

EIC: **E**lectron-**I**on **C**ollider facility that will be built at Brookhaven National Laboratory using and upgrading existing RHIC complex.

Partnership between BNL and Jefferson Lab.

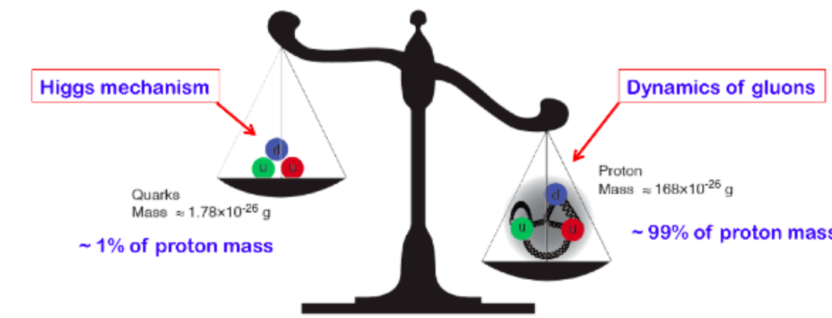


Capabilities of EIC

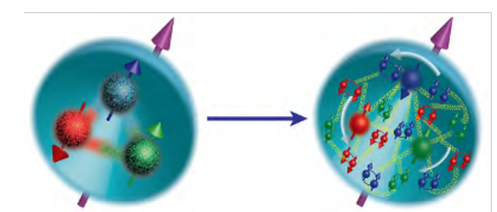
- **High luminosity** $10^{33} - 10^{34} cm^{-2} s^{-1}$ (100-1000 times more than HERA)
- **Variable** center of mass energies 20 -140 GeV
- Beams with different A: from **light nuclei (proton)** to the **heaviest nuclei (uranium)**
- **Polarized** electron and proton beams. Possibility of polarized light ions.
- Up to **two interaction regions**

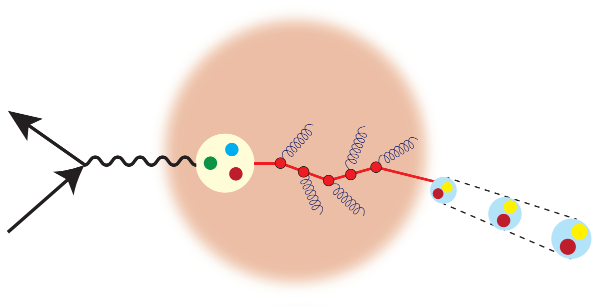
see also next talk by Michael Pitt

Core physics program of the EIC

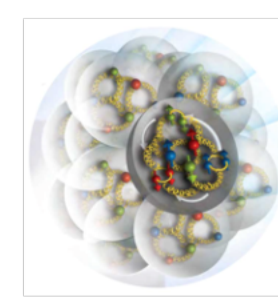


How are the sea quarks and gluons, and their spins, **distributed in space and momentum** inside the nucleon? How do the **nucleon properties (mass & spin) emerge** from their interactions?



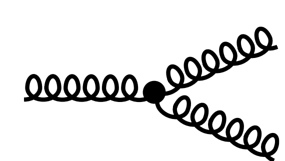


How do color-charged quarks and gluons, and colorless jets, **interact with a nuclear medium**? How do the **confined hadronic states emerge** from these quarks and gluons? How do the quark-gluon **interactions create nuclear binding?**

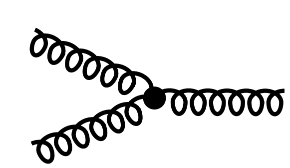


How does a **dense nuclear environment affect** the quark- and gluon- distributions? What happens to the **gluon density in nuclei**? Does it **saturate at high energy**, giving rise to a **gluonic matter with universal properties** in all nuclei, even the proton?

gluon emission



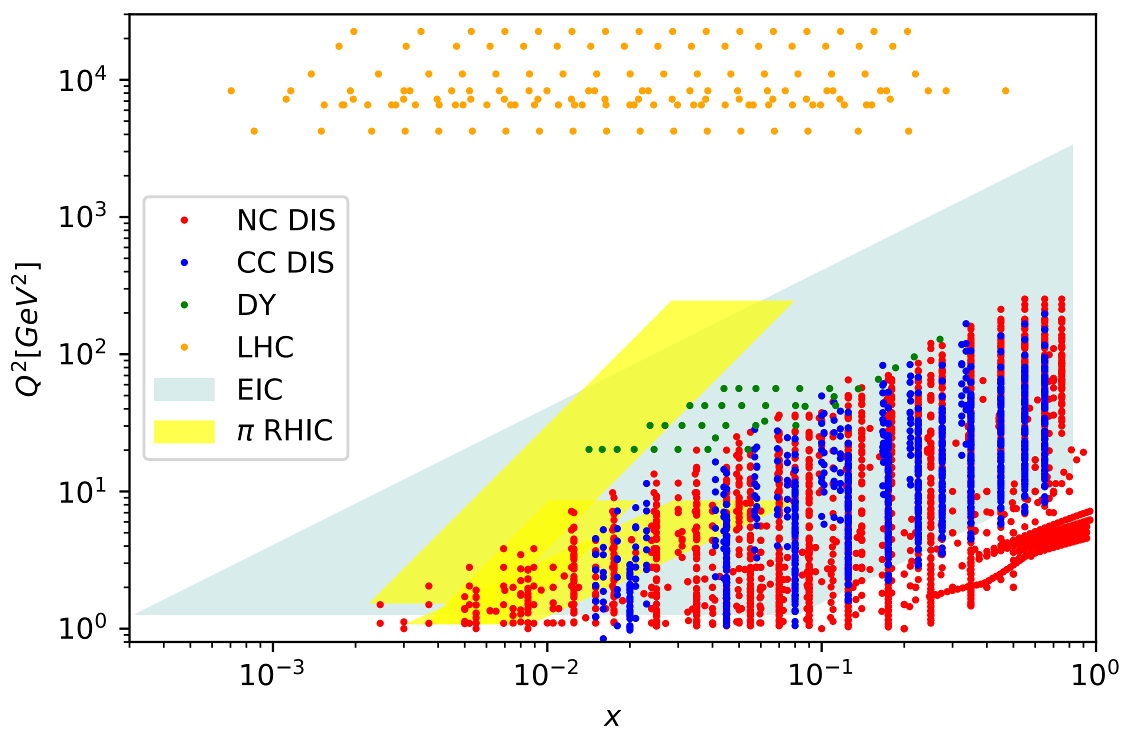
gluon recombination



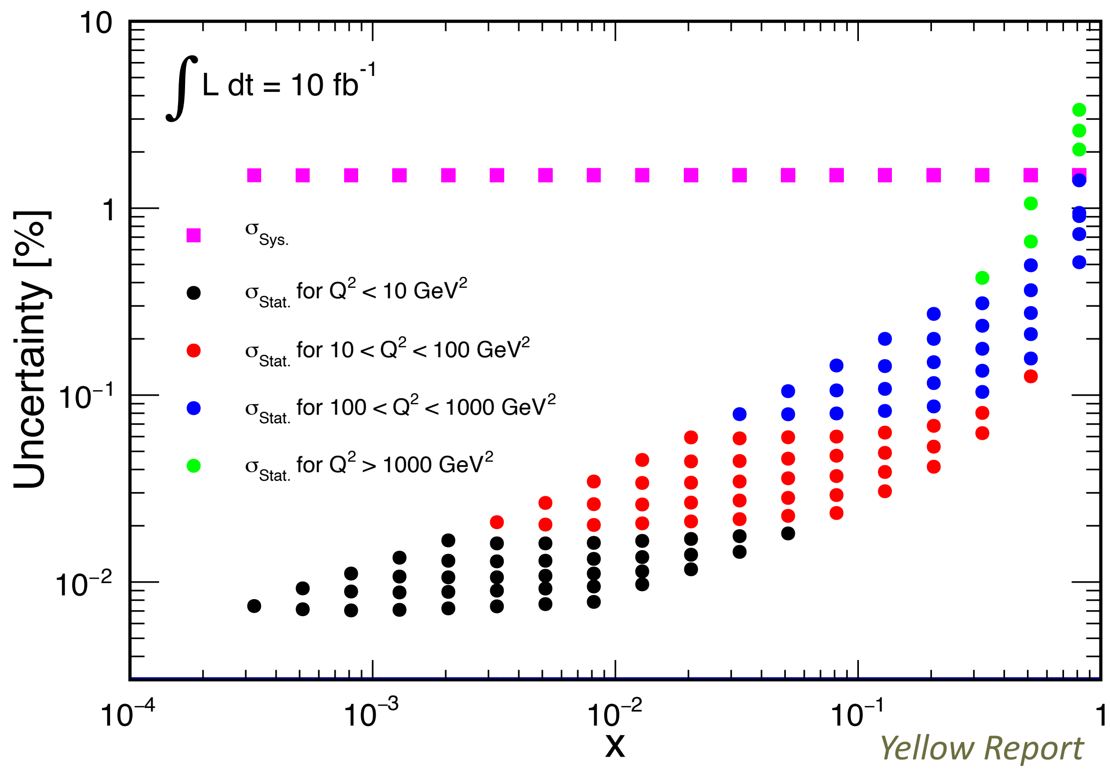
Global structure of nuclei

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha_{\rm em}^2}{xQ^4} Y_+ \, \sigma_{\rm r}(x,Q^2) \qquad Y_+ = 1+(1-y)^2$$

$$\sigma_{\rm r}(x,Q^2) = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$



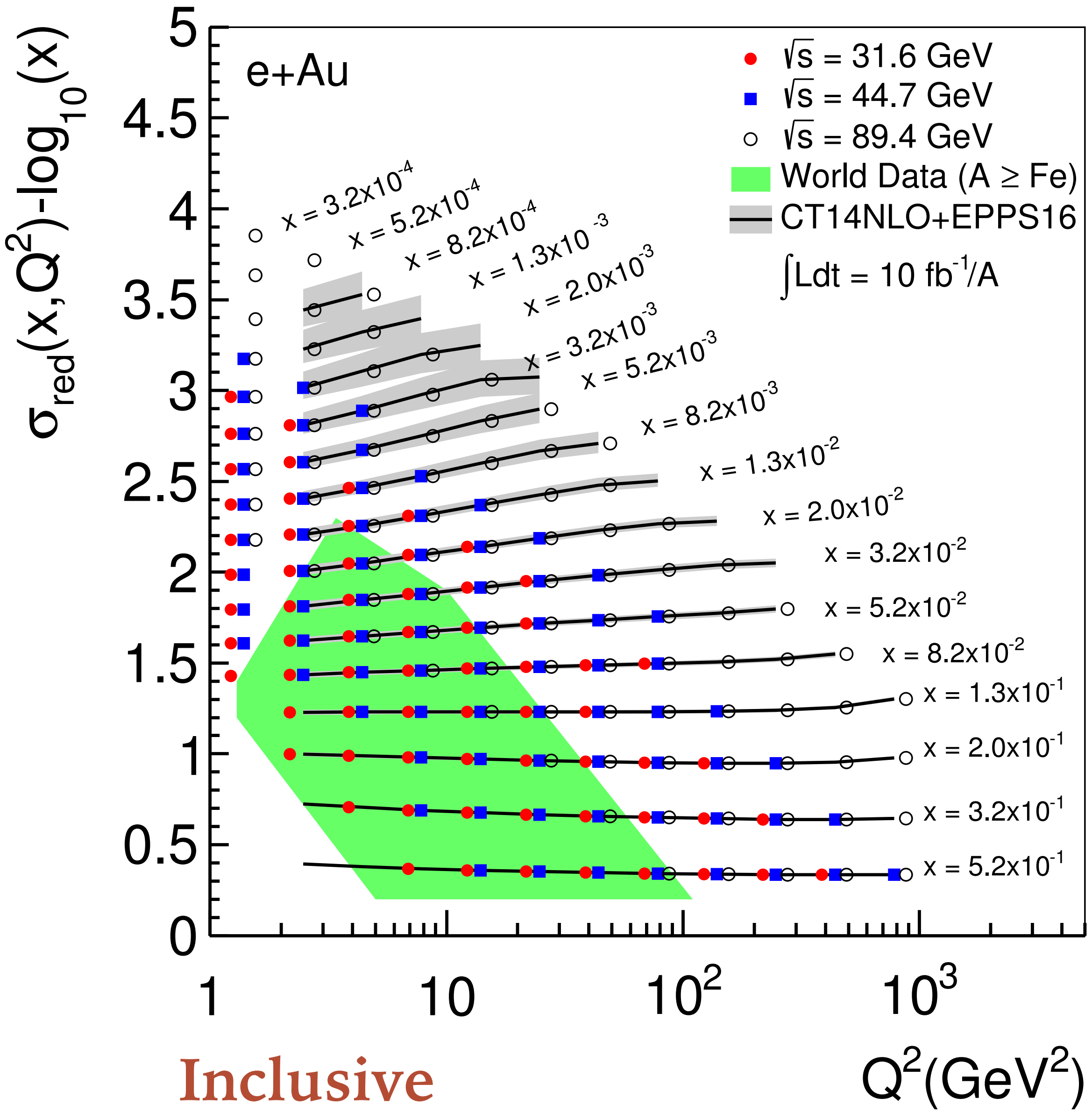
18x110 e-A N.C. Uncertainties



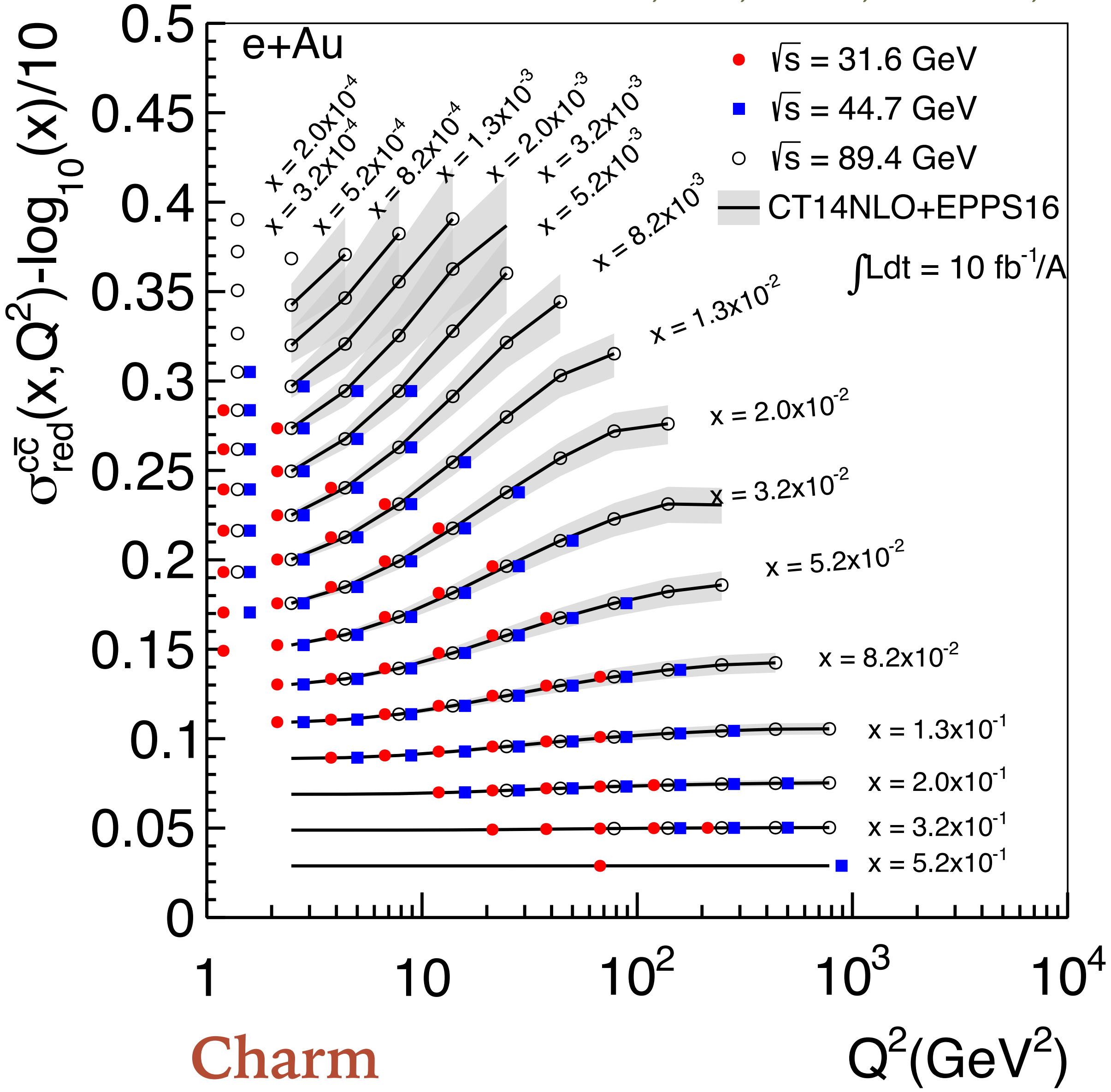
- Precise measurement of **nuclear structure functions** for wide range of nuclei and **wide kinematic range**
- Extraction of **nuclear PDFs** which are essential for understanding **nuclear structure**
- **Initial conditions for Quark-Gluon Plasma**
- Sys. uncertainties at most few %, stat. negligible
- Proton, deuteron and wide range nuclei structure function within **one facility:** reduction of uncertainties

Global nuclear structure: structure functions

Aschenauer, Fazio, Lamont, Paukkunen, Zurita



Inclusive



Charm

- Precision measurements of the reduced cross section
- Charm component in nuclei
- Errors much smaller than the uncertainties of QCD predictions

Impact of EIC on nuclear PDFs

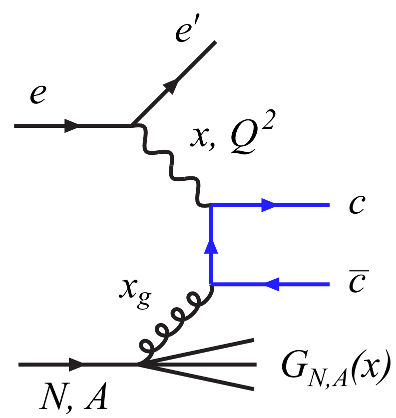
Collinear factorization

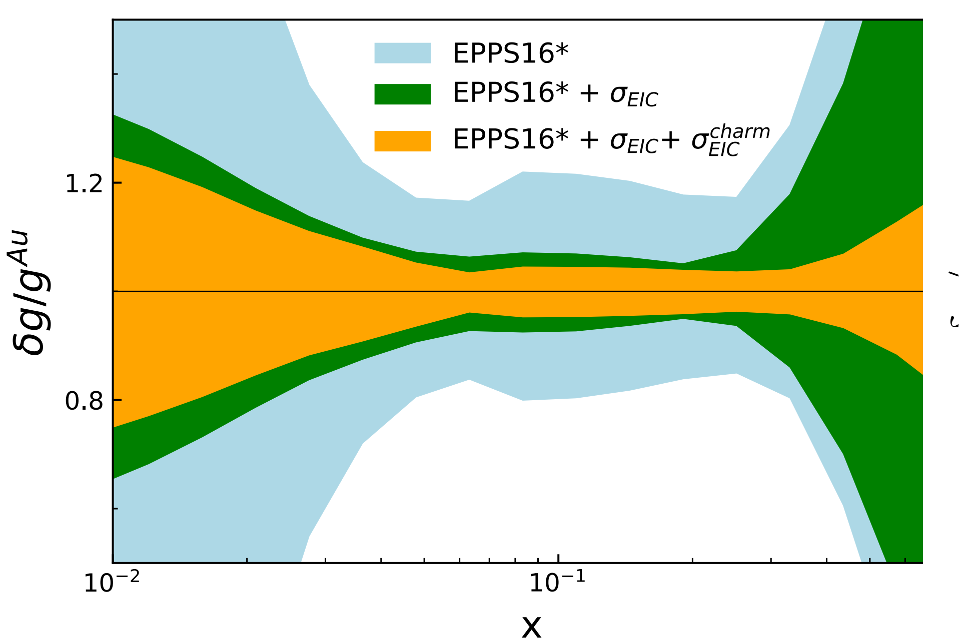
$$F_{2,L}(x,Q^2) = \sum_j \int_x^1 dz\, C_{2,L}(Q/\mu, x/z; \alpha_s)\, f_j(z,\mu) + \boxed{\ldots}$$

Nuclear modification in this framework:

initial condition at low scales, **linear evolution with scale**

- Impact of **charm cross section** on the gluon PDF at high x
- Charm is produced mainly in the photon-gluon fusion process
- Further constraints: $\mathbf{F_L}$

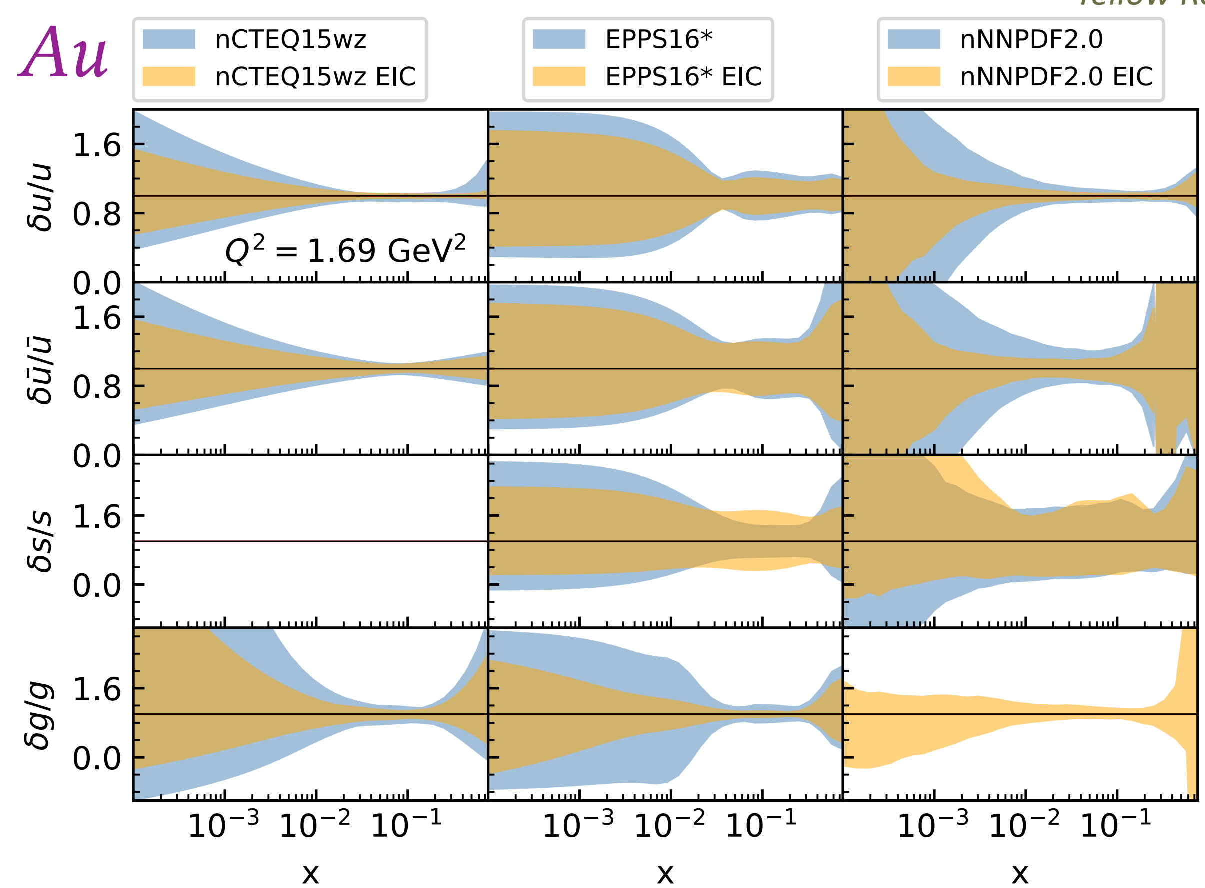




DGLAP : linear evolution

$$\frac{d}{d\ln\mu^2} f_j(z,\mu) = \sum_k \int \frac{d\xi}{\xi} P_{jk}(\xi,\alpha_s) f_k(z/\xi,\mu)$$

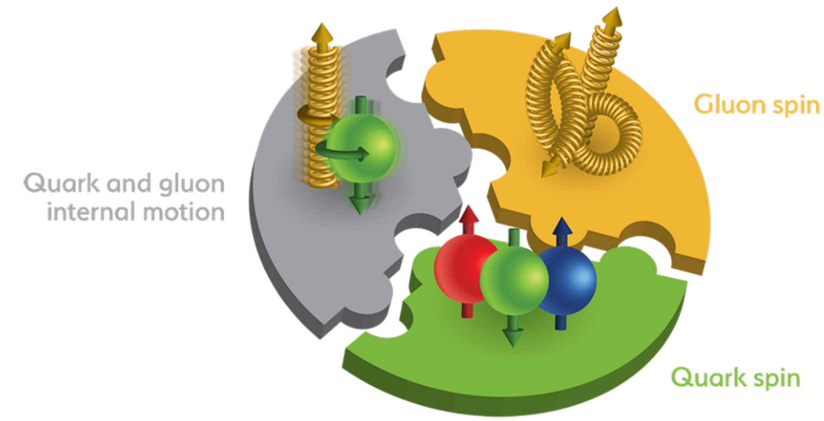
Yellow Report



Significant impact of EIC measurements on nuclear PDFs

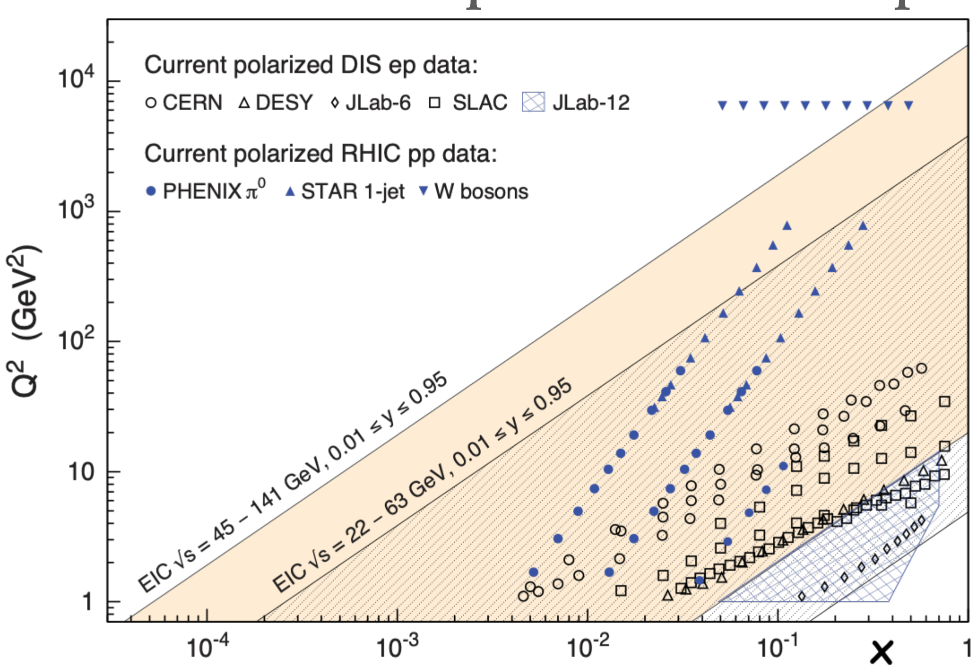
Proton spin

- **Spin** is fundamental property of particles. All elementary particles except Higgs carry non-zero spin.
- Proton spin cannot be explained within static picture.
- It depends on the intrinsic properties and interactions of quarks and gluons



$$\frac{1}{2} = \frac{1}{2}\underbrace{\int_0^1 dx\, \Delta\Sigma(x,Q^2)}_{\textit{quark spin}} + \underbrace{\int_0^1 dx\, \Delta G(x,Q^2)}_{\textit{gluon spin}} + \underbrace{\int_0^1 dx\, (\sum_q L_q + L_g)}_{\textit{orbital angular momentum}}$$

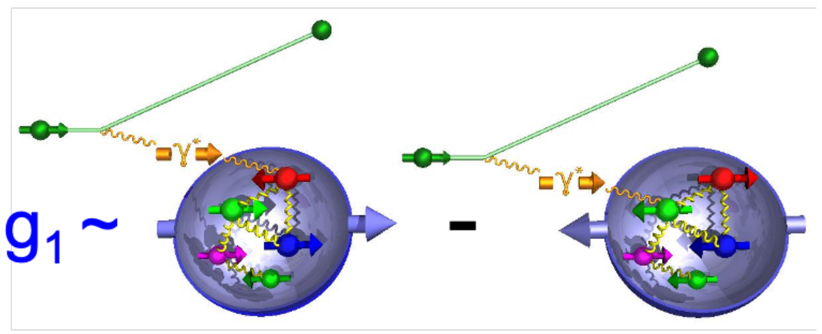
EIC kinematic plane vs current polarized data



- EIC extends range in (x,Q^2) by 1-2 orders of magnitude for polarized measurements.
- Possibilities for precision measurement of **structure function g1, gluon** contribution to proton spin, **quark** contribution, **strange** quark contribution also accessible, **polarized deuterons** allow for measurement of g_1 in a neutron

Proton spin

$$\frac{1}{2}\left[\frac{\mathrm{d}^2\sigma^{\rightleftarrows}}{\mathrm{d}x\,\mathrm{d}Q^2}-\frac{\mathrm{d}^2\sigma^{\rightrightarrows}}{\mathrm{d}x\,\mathrm{d}Q^2}\right]\simeq\frac{4\pi\,\alpha^2}{Q^4}y\,(2-y)\,g_1(x,Q^2)$$



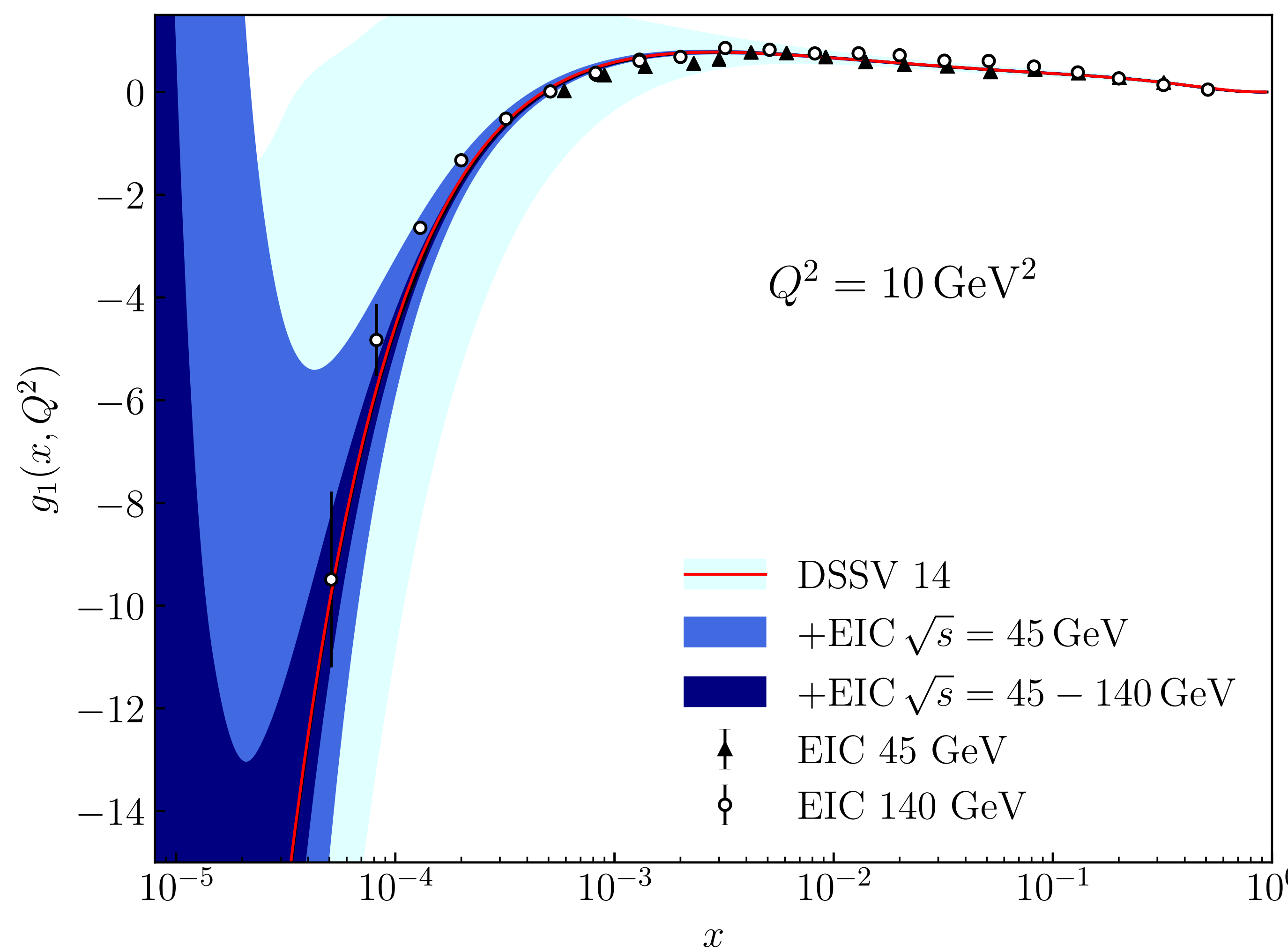
Quark contribution: integral over of g_1 over x from 0 to 1

Sensitive to **gluon** contribution Δg at higher orders: drive the scaling violations.

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

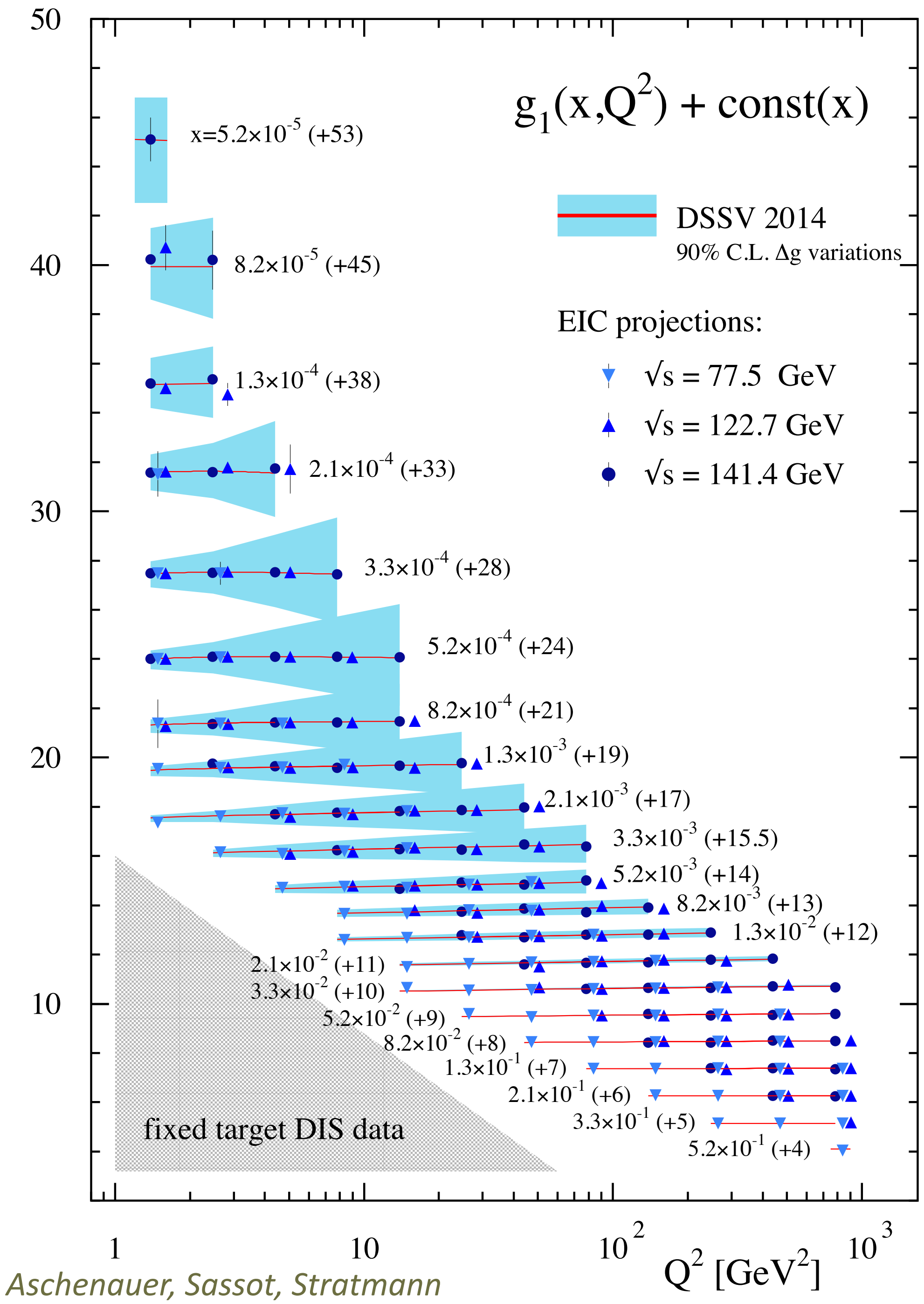
Current **uncertainties** for g_1 as a function of x for fixed Q^2

EIC projections leads to greatly reduced **uncertainties**



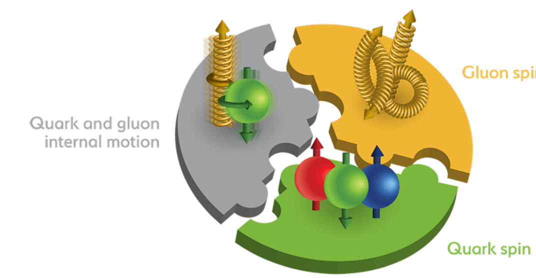
Borsa, Lucero, Sassot, Aschenauer, Nunes

Proton spin: constraints on the OAM

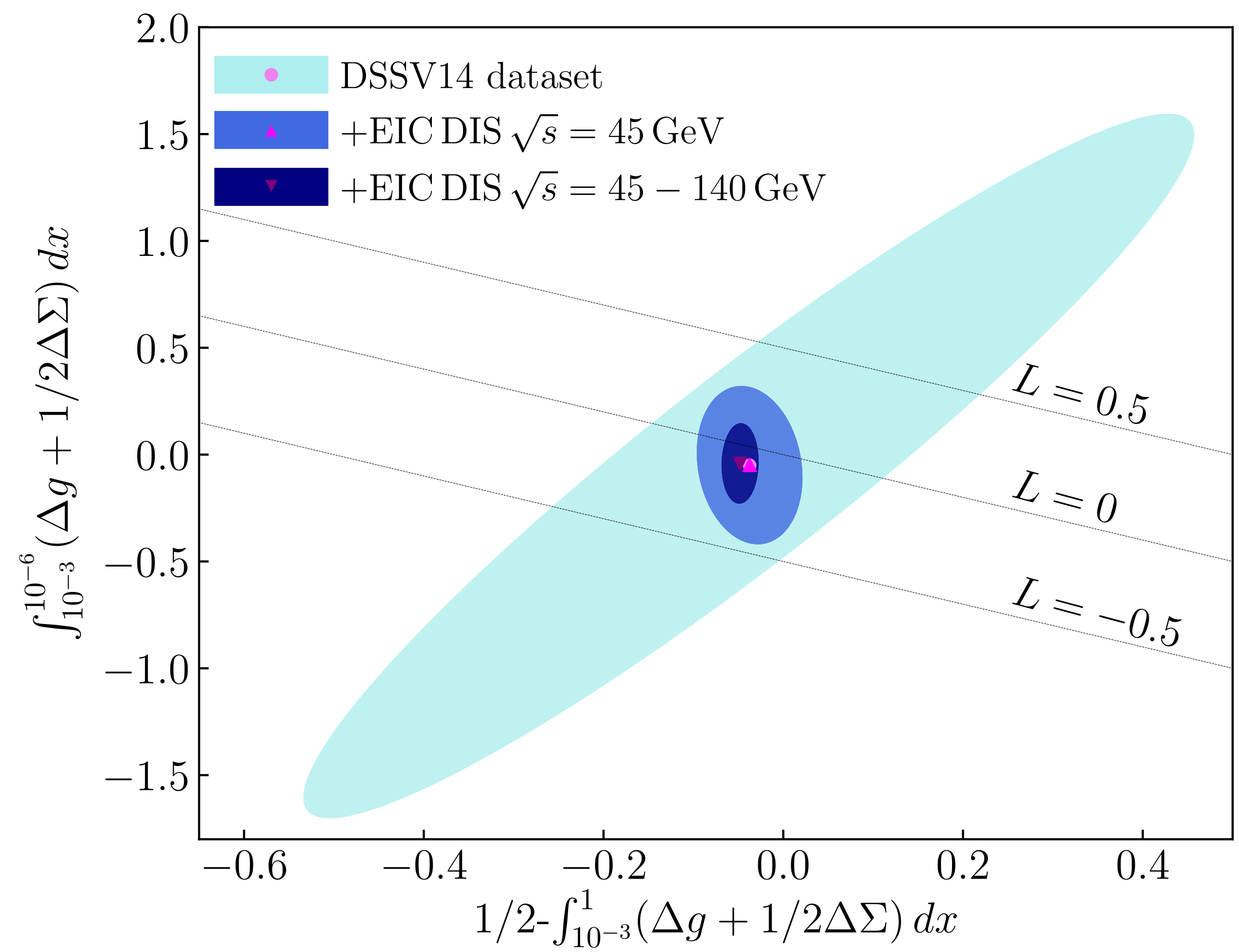


Aschenauer, Sassot, Stratmann

- Insight into quark and gluon contribution to proton spin.
- By subtracting these contributions one can constrain the parton **orbital angular momentum** contribution $L_q + L_g$.

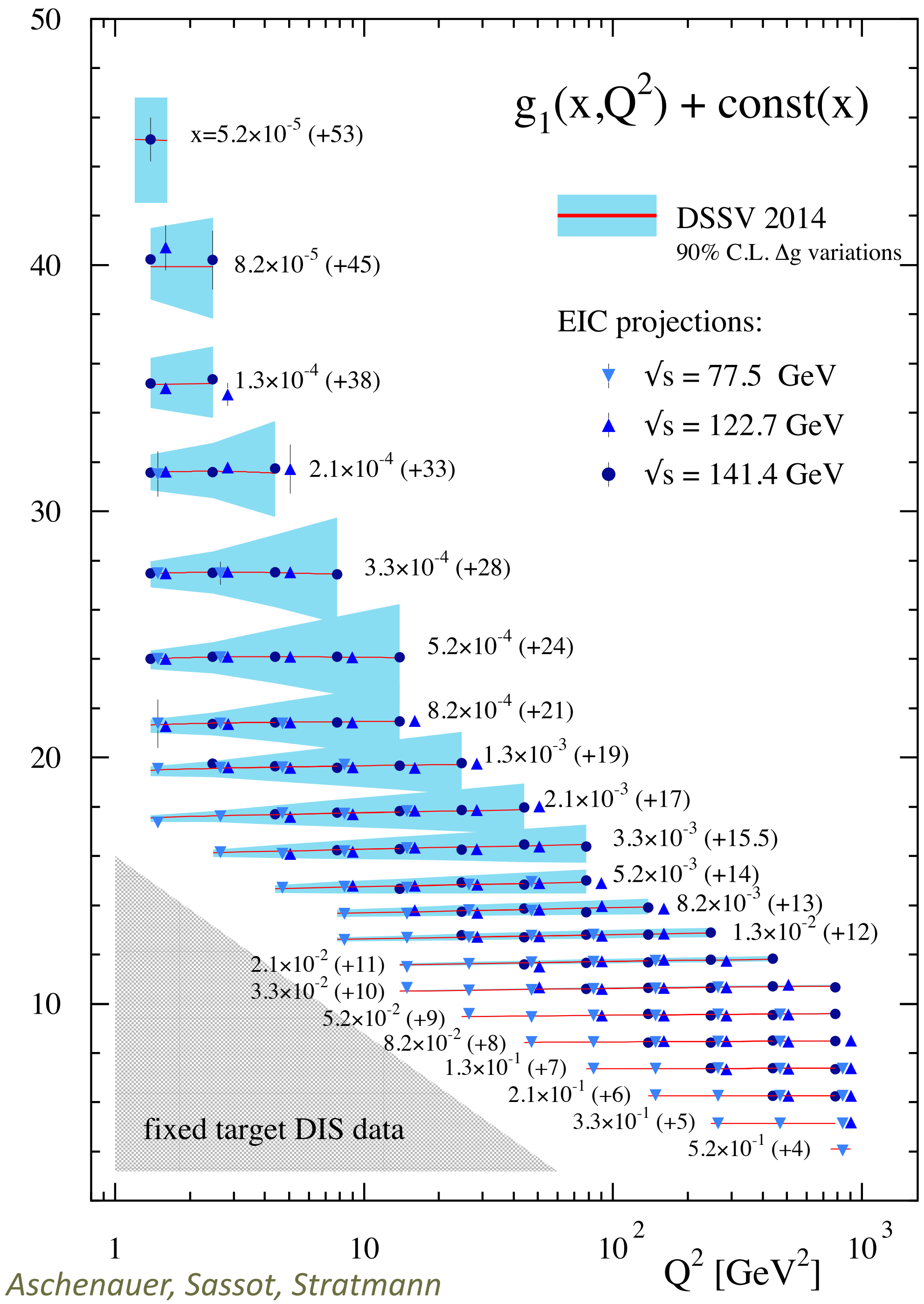


Borsa, Lucero, Sassot, Aschenauer, Nunes



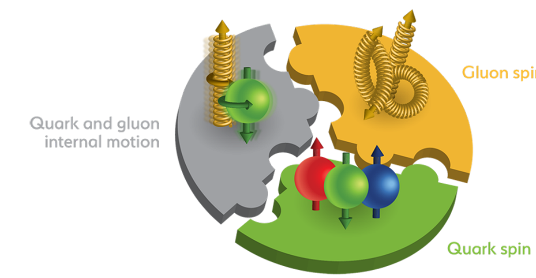
Proton spin: constraints on the OAM

EIC projections over range of x and Q^2

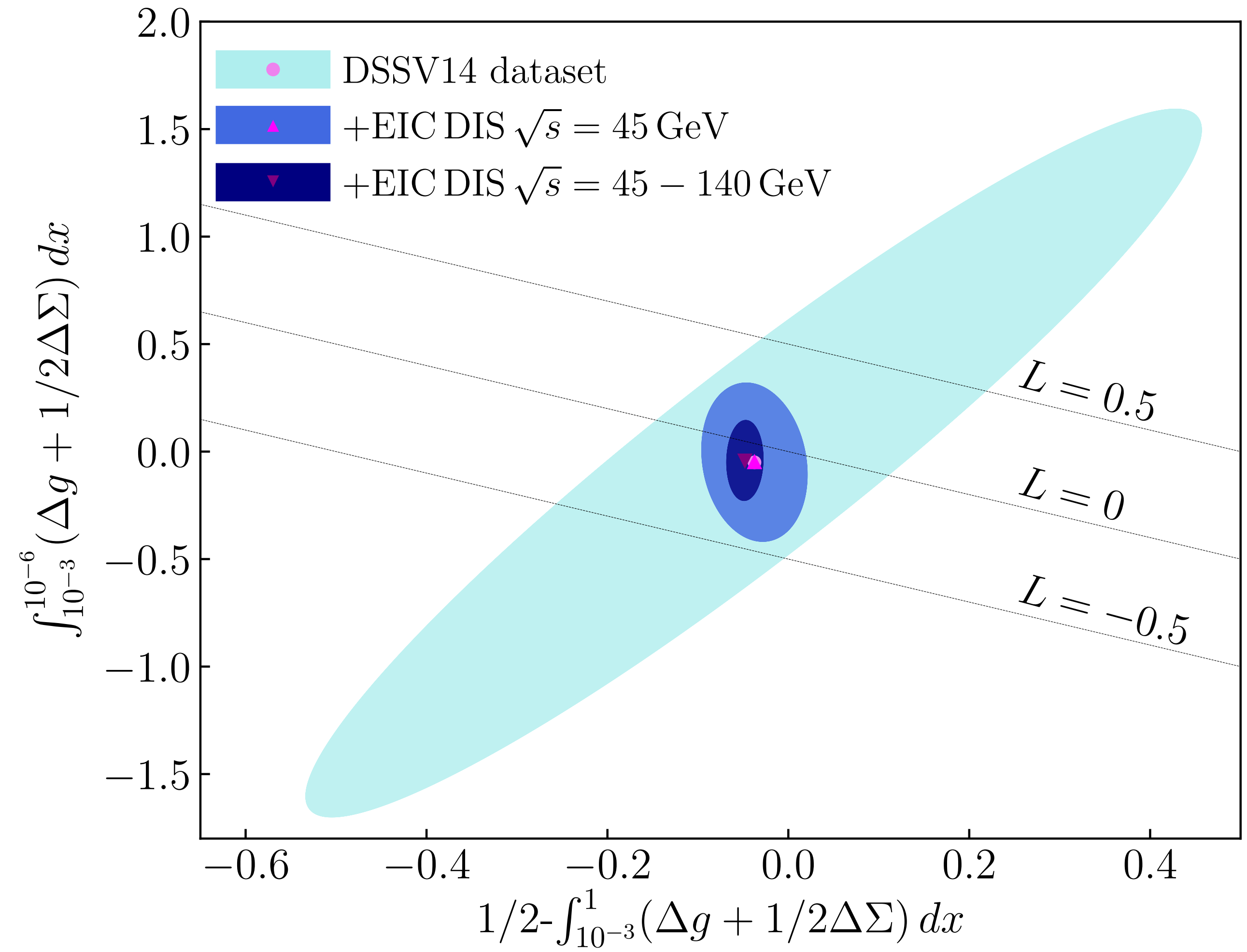


Aschenauer, Sassot, Stratmann

- ➤ Insight into quark and gluon contribution to proton spin.
- ➤ By subtracting these contributions one can constrain the parton **orbital angular momentum** contribution $L_q + L_g$.



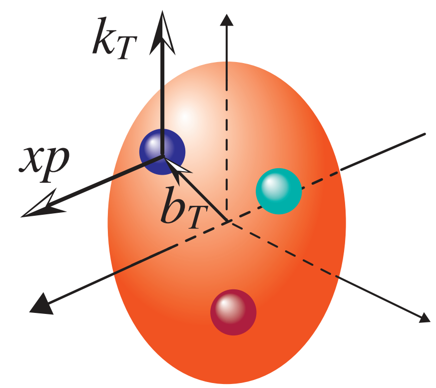
Borsa, Lucero, Sassot, Aschenauer, Nunes



From 1D to 3D: imaging of nucleon

- Integrated PDFs provide only distribution of partons in the **longitudinal momentum fraction**
- More detailed information : **Wigner** function

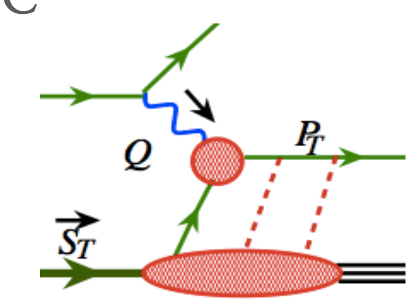
$$W(x, b_T, k_T)$$



$$\int d^2 b_T \quad \rightarrow \quad f(x, k_T)$$

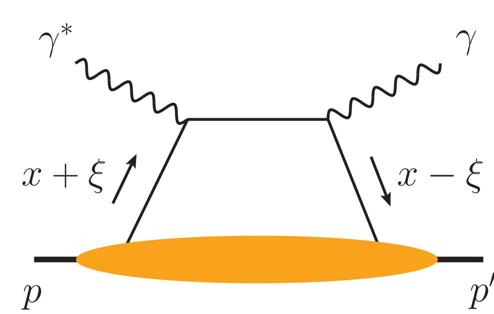
$$\int d^2 k_T \quad \rightarrow \quad f(x, b_T)$$

Transverse Momentum Dependent (TMDs), measured from semi-inclusive DIS, also spin dependent at EIC

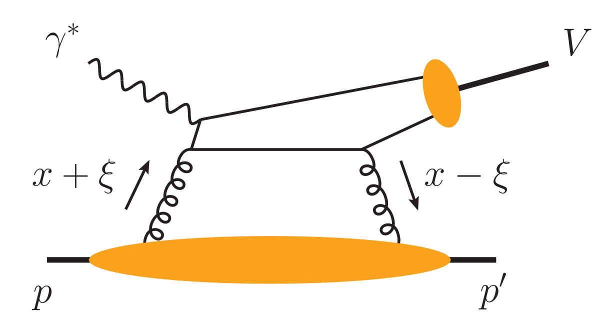


SIDIS: $Q \gg P_T$

Generalized Parton Densities (GPDs) from exclusive scattering, also spin dependent at EIC



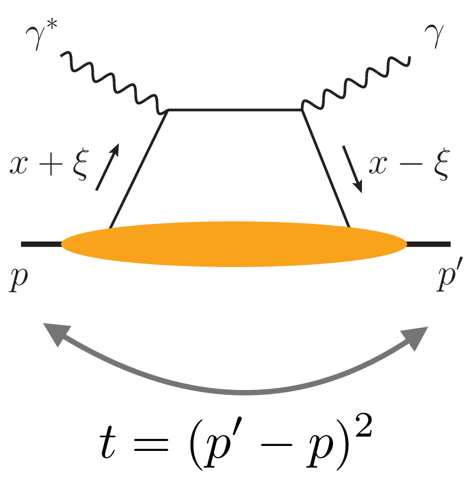
Deeply Virtual Compton Scattering

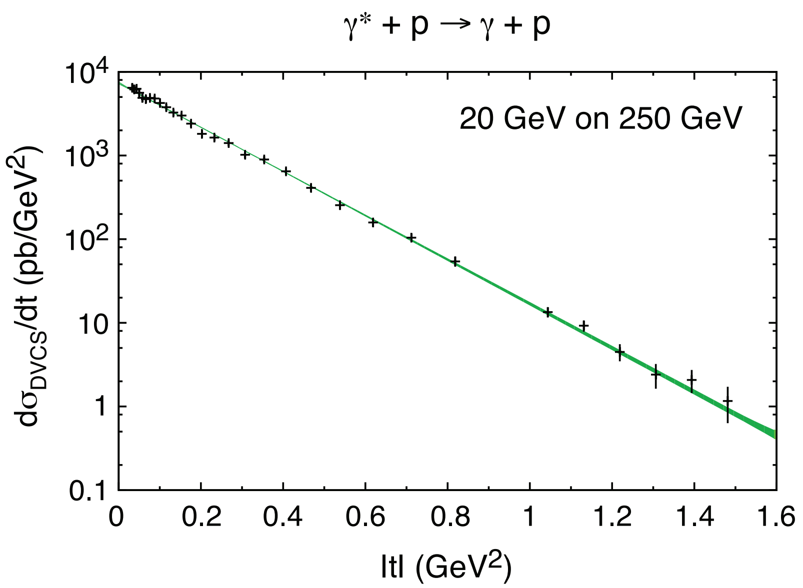


Elastic Vector Meson production

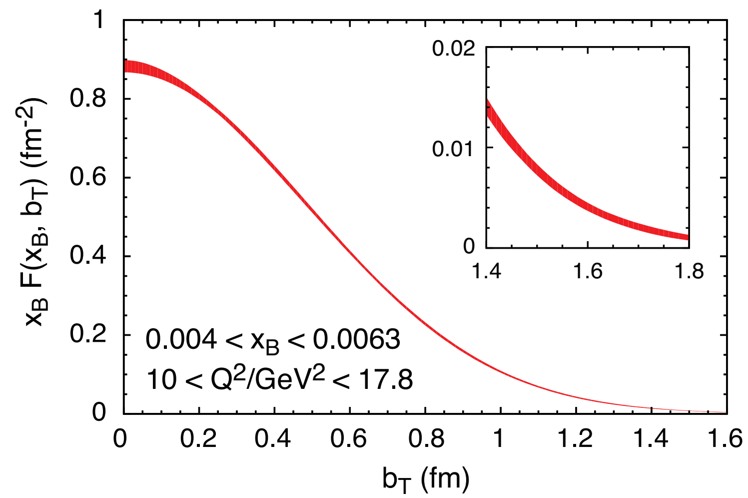
Imaging of nucleon: quarks

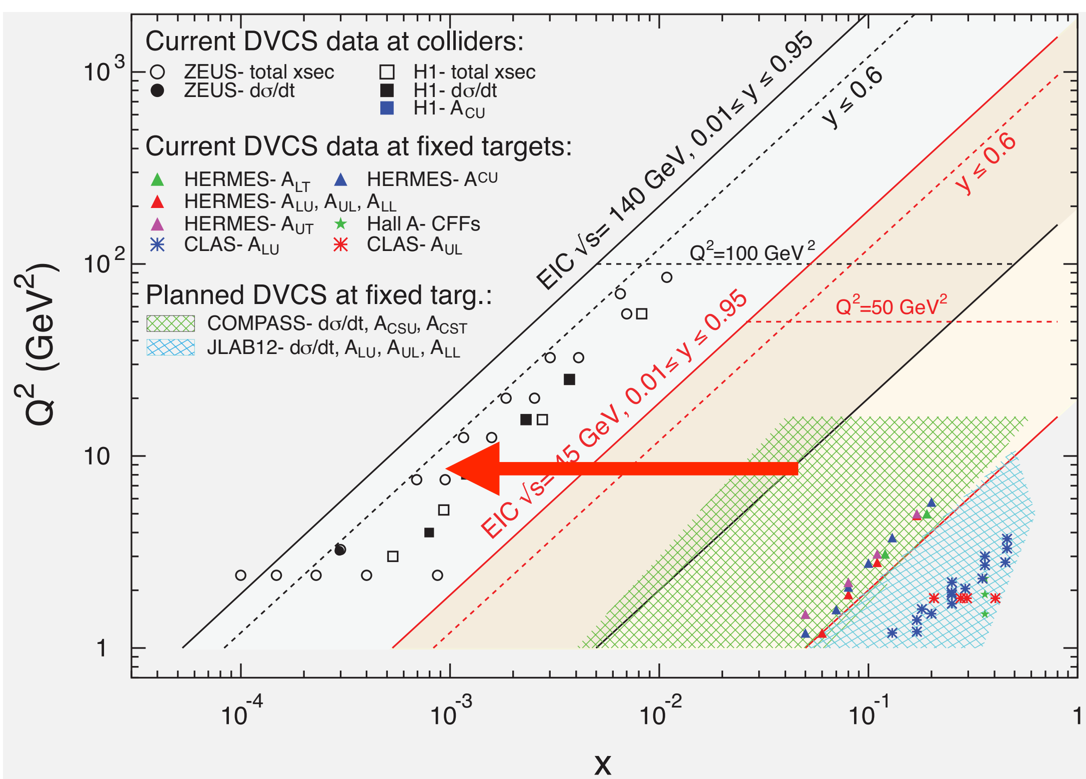
DVCS
Quark information

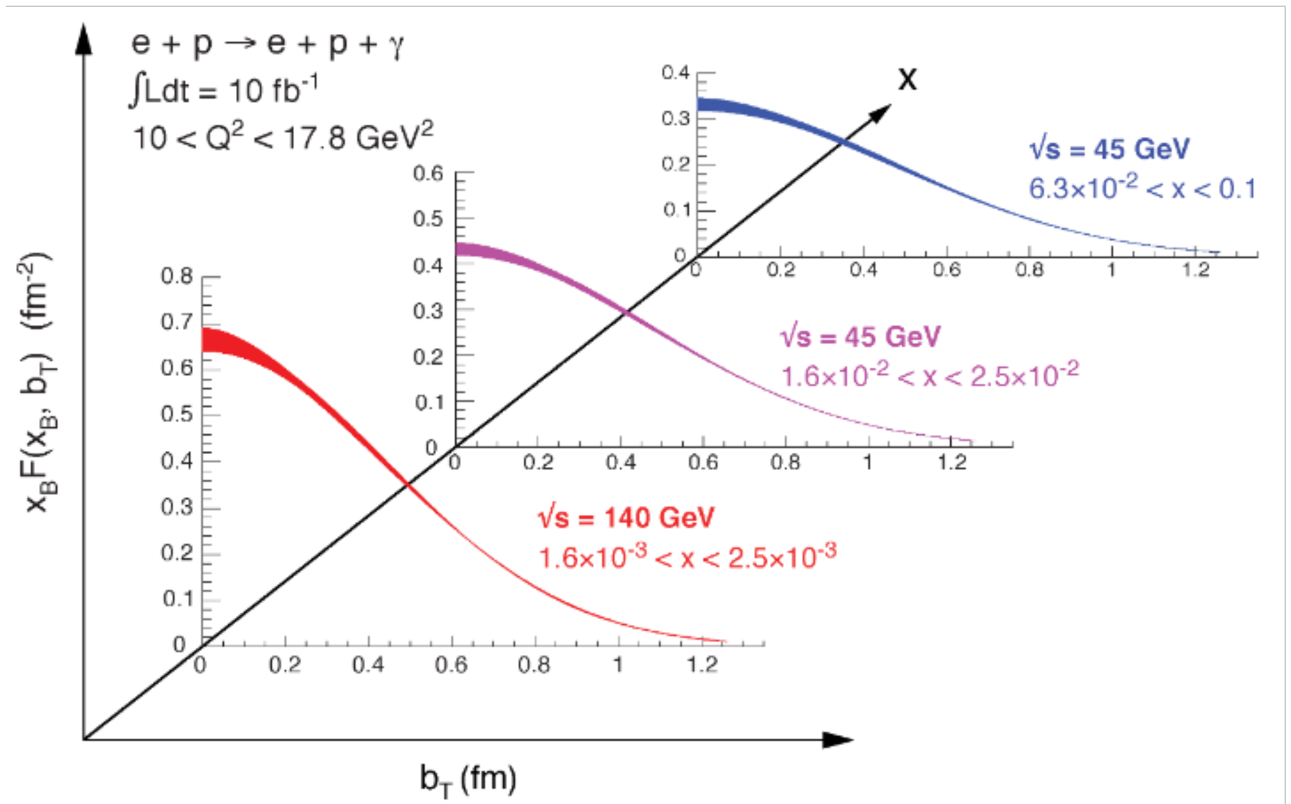




Fourier transform in t provides spatial distribution of quarks

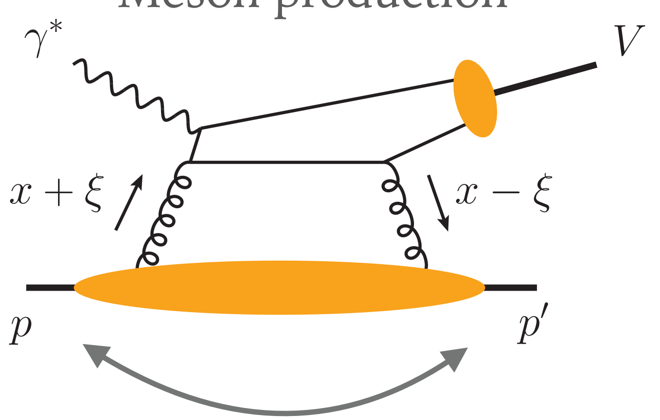




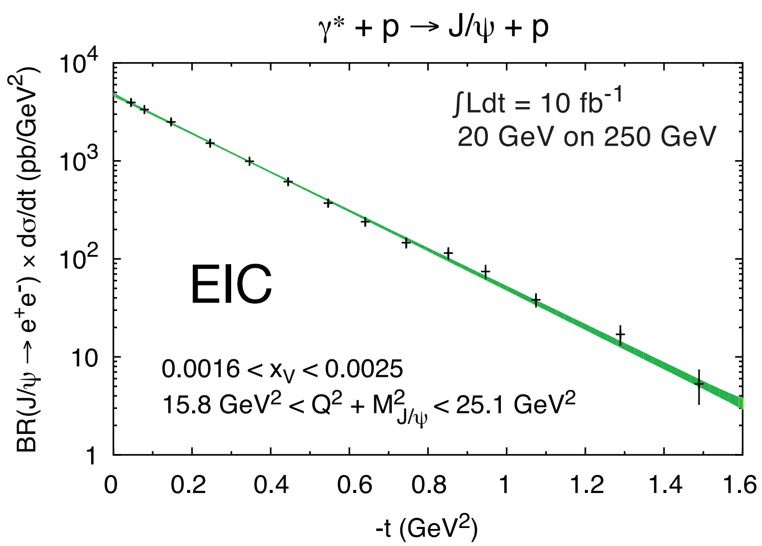


Imaging of nucleon: gluons

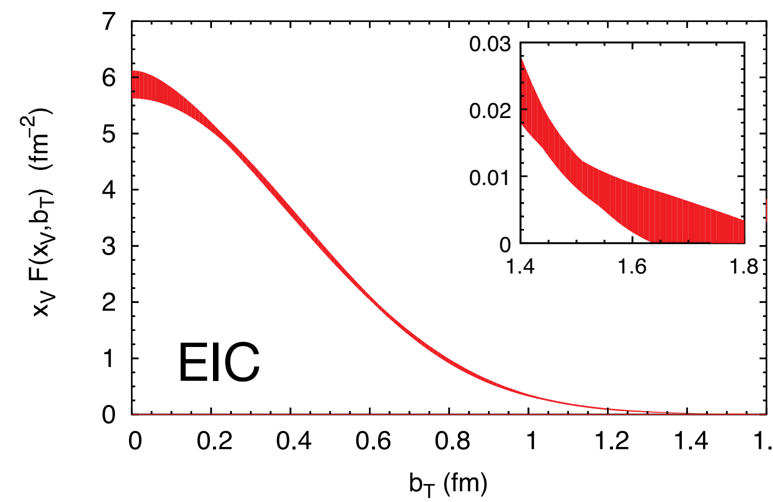
Elastic Diffractive Vector Meson production



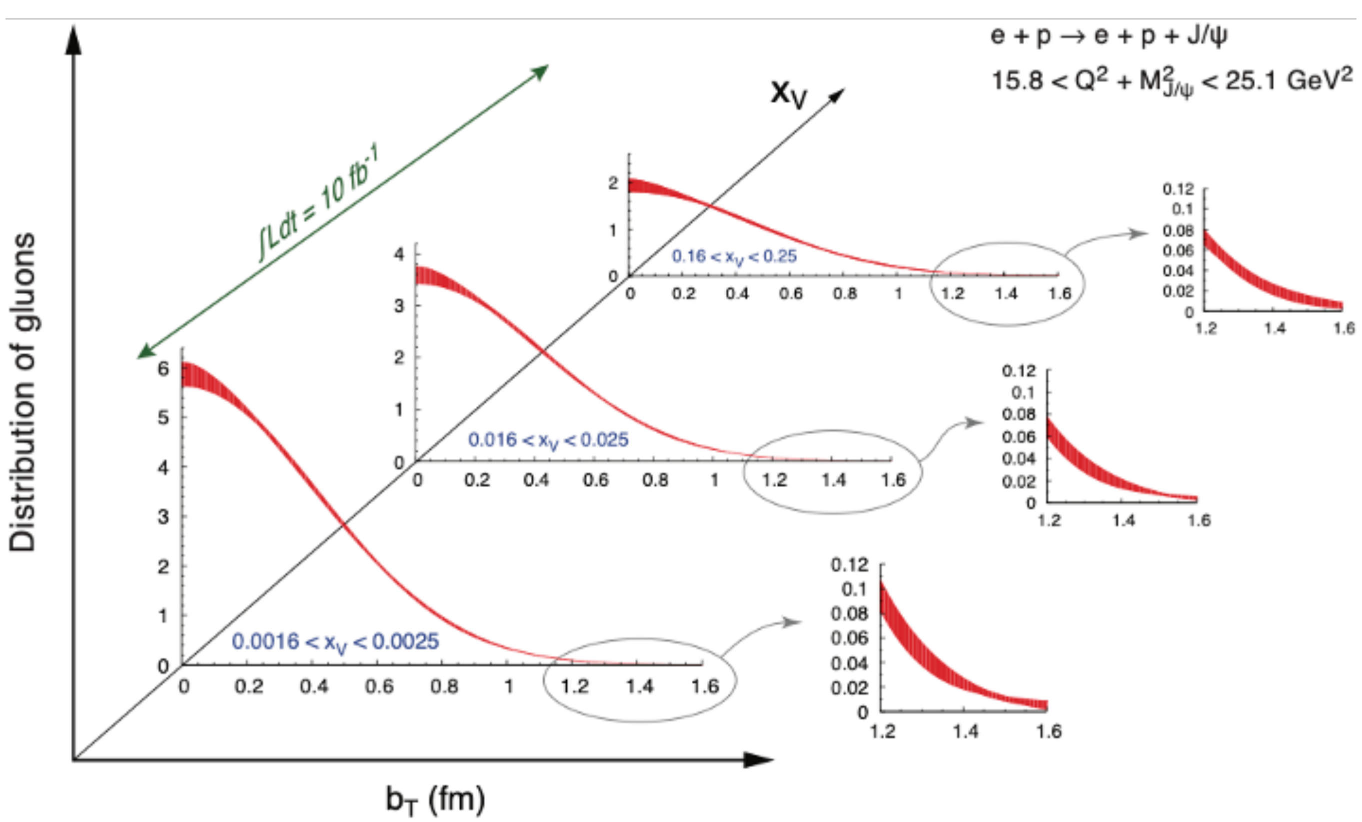
$$t = (p' - p)^2$$



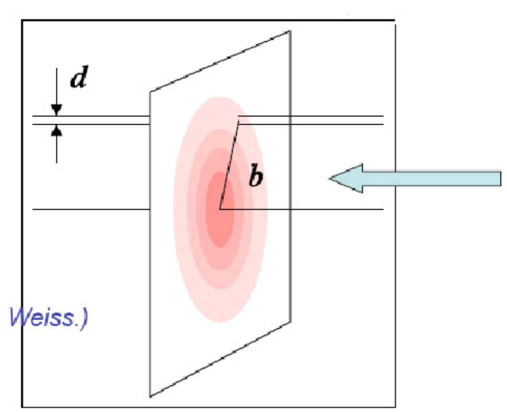
Fourier transform in t provides **spatial distribution** of gluons inside the nucleon



Extracted profiles for different x



- Large |t| probes small b : large density.
- Ideal for estimating the 'blackness' of the interaction: parton saturation



(figure from C. Weiss.)

Central black region growing with decrease of x.

Imaging of nucleus

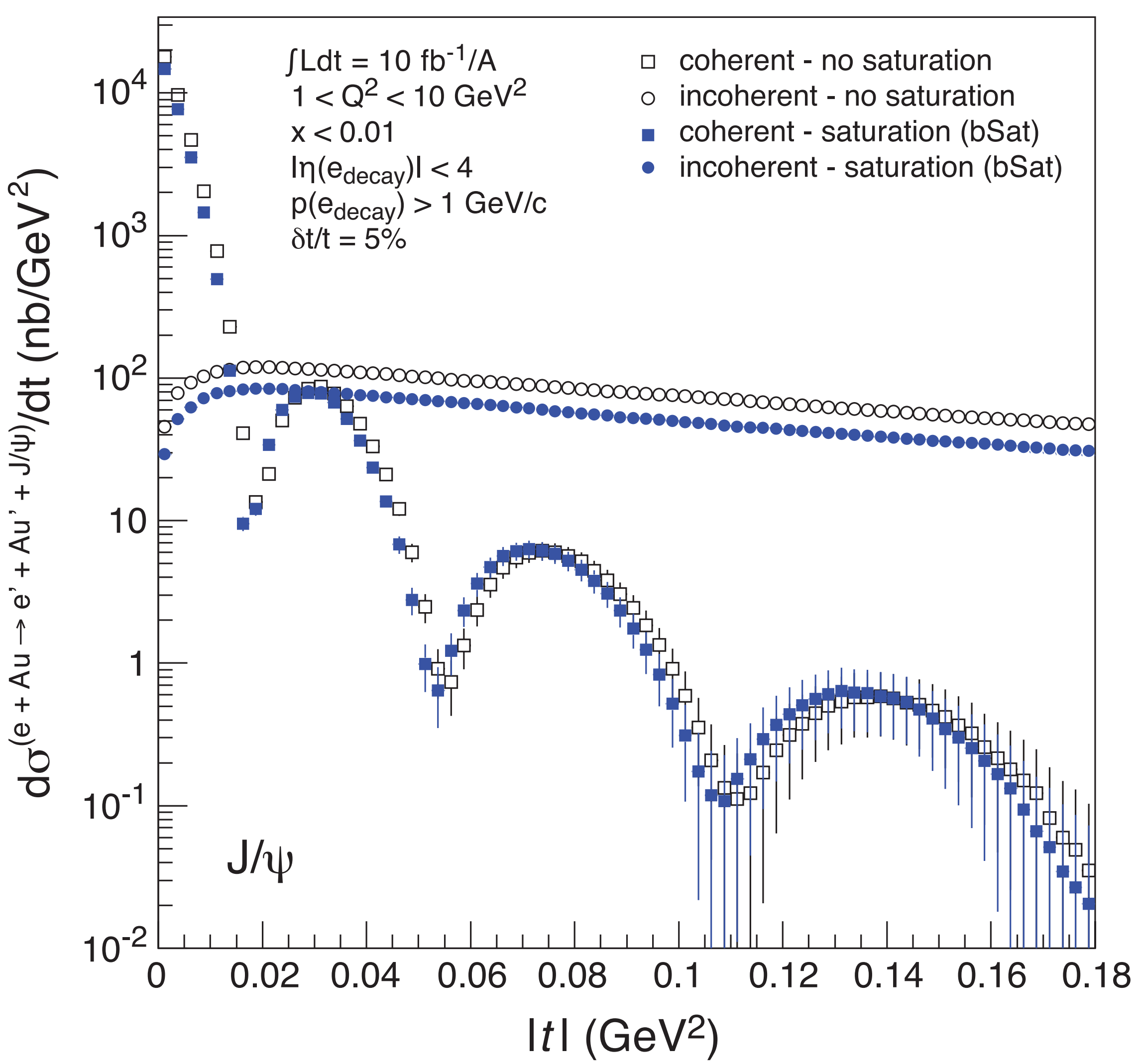
EIC, White paper

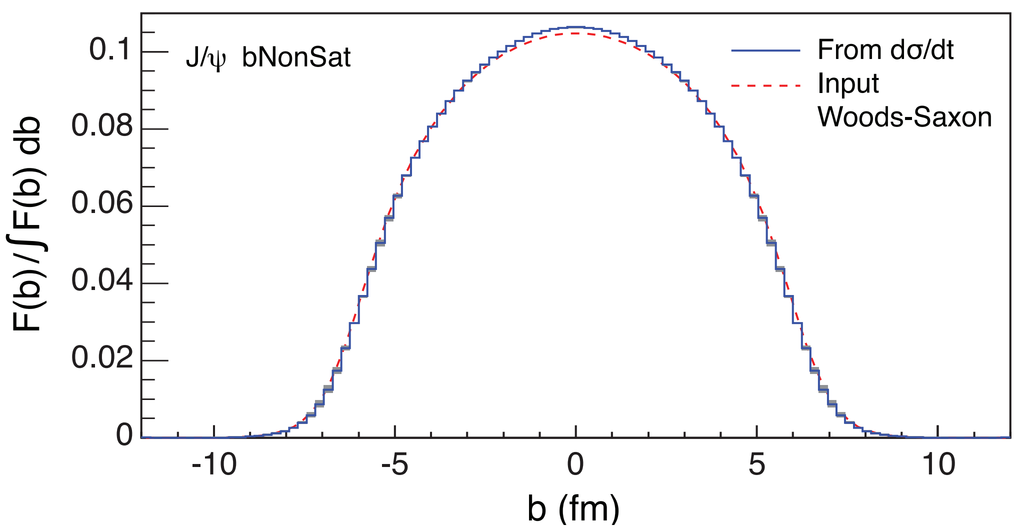
$$e + A \rightarrow e + A + J/\psi$$

coherent: nucleus stays intact

$$e + A \rightarrow e + (A' + p + n + \dots) + J/\psi$$

incoherent: nucleus breaks up



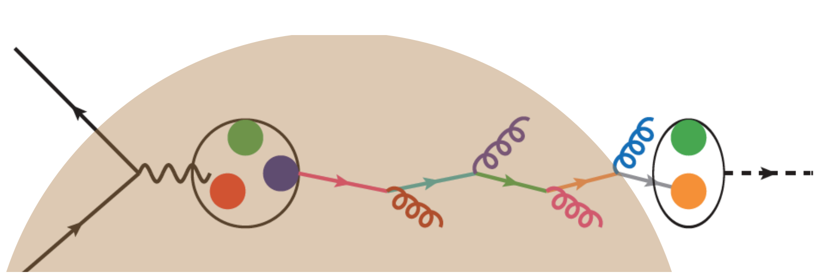


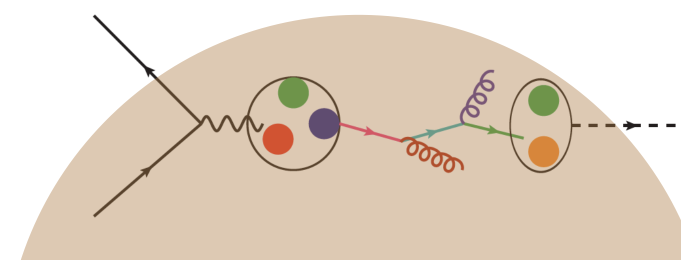
$$t = -\Delta^2 \qquad F(b) = \int_0^\infty \frac{\Delta\, d\Delta}{2\pi} J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}}$$

- Coherent: characteristic 'dips' in t-distribution. Sensitive to average geometry. Fourier transform: density profile
- Position of dips depends on density profile, non-linear effects, correlations
- Incoherent cross section provides information about lumpiness of the source (fluctuations)
- Experimentally very challenging (resolving dips) *see talk by Michael Pitt*
- Prospects for this process with **deuteron** and **light ions:** probing shadowing in a more controlled environment, separate **double**, **triple** scattering; spectator **tagging** on deuteron allows to study **SRC** and role of **gluons**

Passage of color charges through cold nuclear matter

- Modern theories of QCD in matter (such as $SCET_G$ and $NRQCD_G$) have enabled novel understanding of parton showers on matter. Capabilities to calculate higher order and resumed calculations in reactions with nuclei
- EIC will provide important input on **hadronization** mechanism in eA
- Different scenarios: **parton evolution in medium** or **hadron absorption**





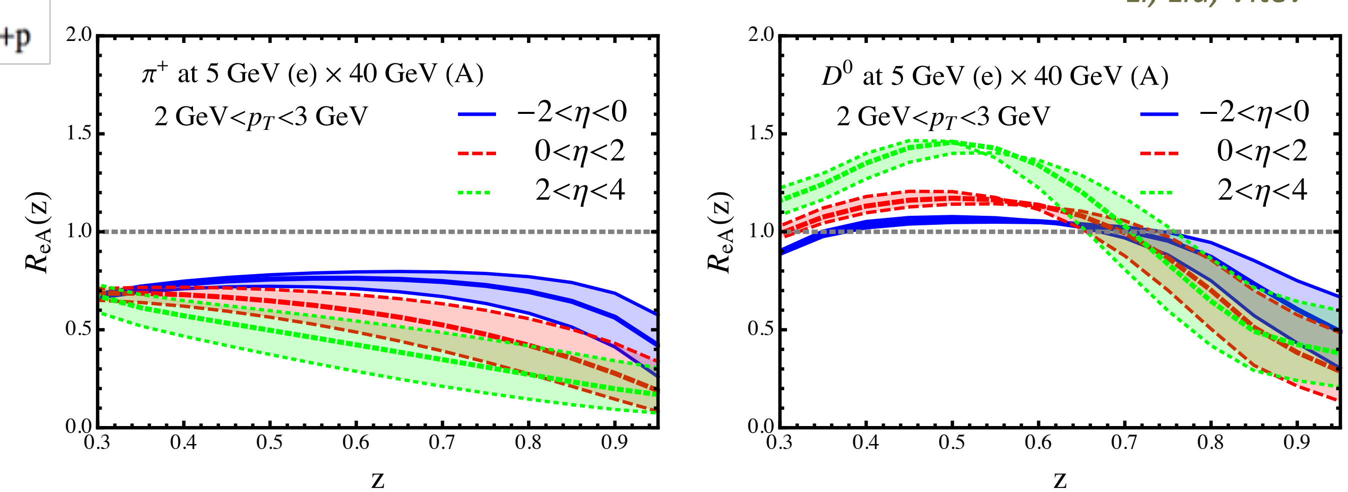
Parton energy loss and in-medium fragmentation function modification

$$\frac{d}{d\ln\mu^2}\tilde{D}^{h/i}(x,\mu) = \sum_j \int_x^1 \frac{dz}{z}\tilde{D}^{h/j}\left(\frac{x}{z},\mu\right)\left(P_{ji}(z,\alpha_s(\mu)) + P_{ji}^{\text{med}}(z,\mu)\right)$$

$$R^h_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\text{inc}}(p_T,\eta)}\right|_{\text{e+Au}}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\text{inc}}(p_T,\eta)}\right|_{\text{e+p}}}$$

Modification (e+A vs e+p) of light vs heavy mesons vs the fragmentation fraction z

Li, Liu, Vitev



Constrain the space-time picture of hadronization.

Differentiate **energy loss** and **hadron absorption** models (based on ability to measure heavy flavors)

Lower energy beams better for this process

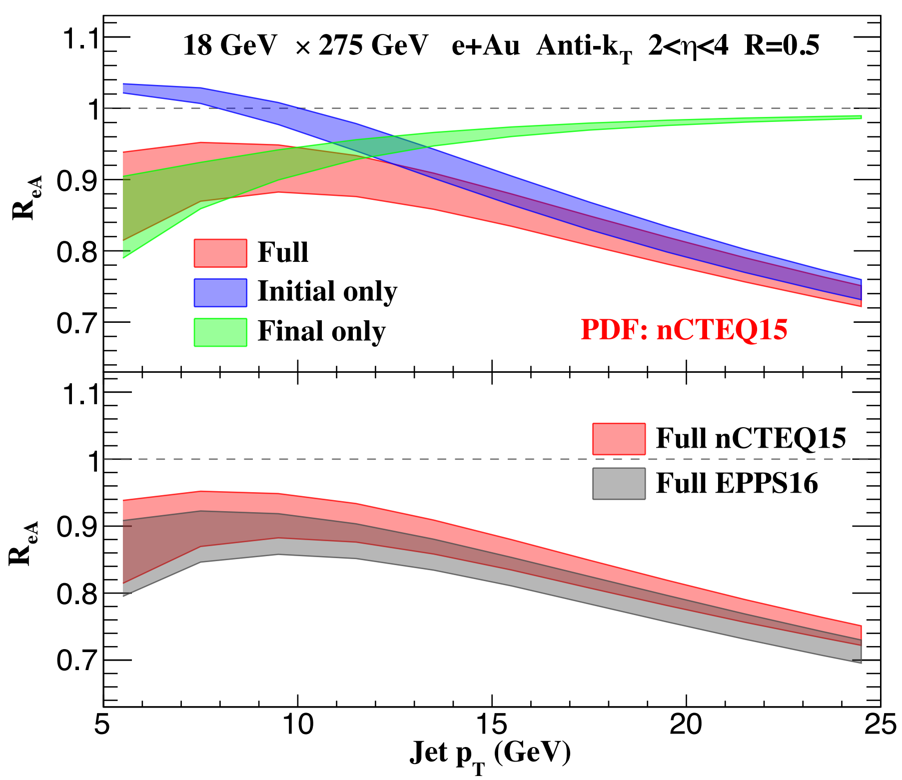
Jets as probes of cold nuclear matter

Jets emerged as a premier diagnostic tool for **hot** nuclear matter at RHIC and LHC

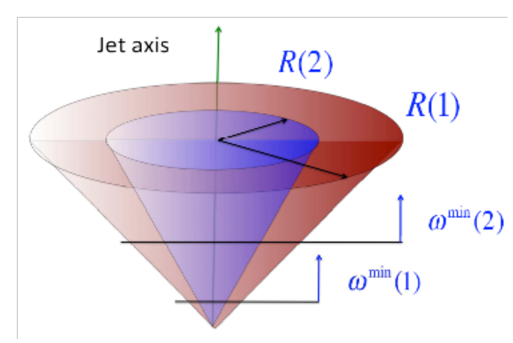
Also excellent probes for **cold** nuclear matter. Using jets, elucidate the properties of in-medium parton showers.

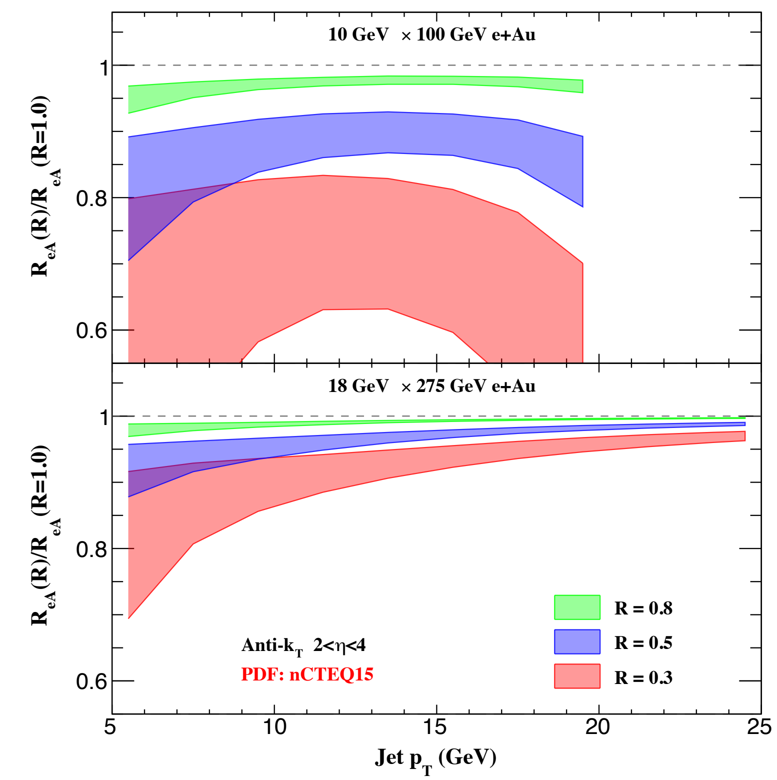
$$\underbrace{d\sigma \sim f_a(z,\mu)}_{\text{initial}}^{\text{PDF}} \otimes \overbrace{H_{ab}(x,z;p_T,\eta)}^{\text{partonic cross section}} \otimes \underbrace{J_b(z,\mu,R)}_{\text{final}}^{\text{jet function}}$$

Yellow Report



- IS (large and small p_T) vs FS (small p_T) contributions to nuclear ratio
- Small nPDF effects
- Ratios with different jet cone allow to separate parton shower effects

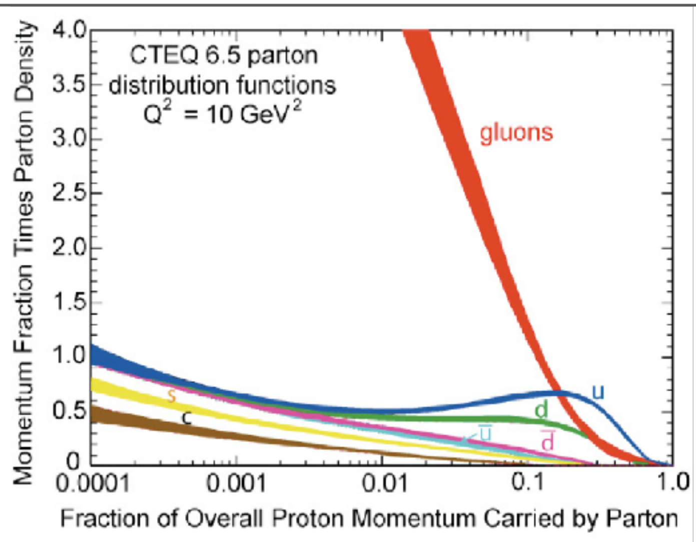




Li, Vitev

- Pioneer jet **substructure** studies with heavy quark initiated jets performed in a EIC regime very different from the one probed in heavy ion collisions *Li, Liu, Vitev*
- Pave the way to a qualitatively new level of understanding of the role of **heavy quark mass**

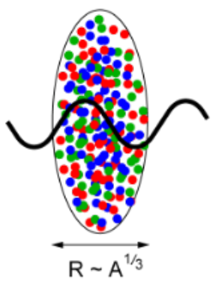
Studying saturation at EIC with nuclei



Does the rise of **gluon** $xg(x, Q^2)$ get **tamed**?

Important to understand for initial conditions in heavy ion collisions

Probe interacts **coherently** with nucleons

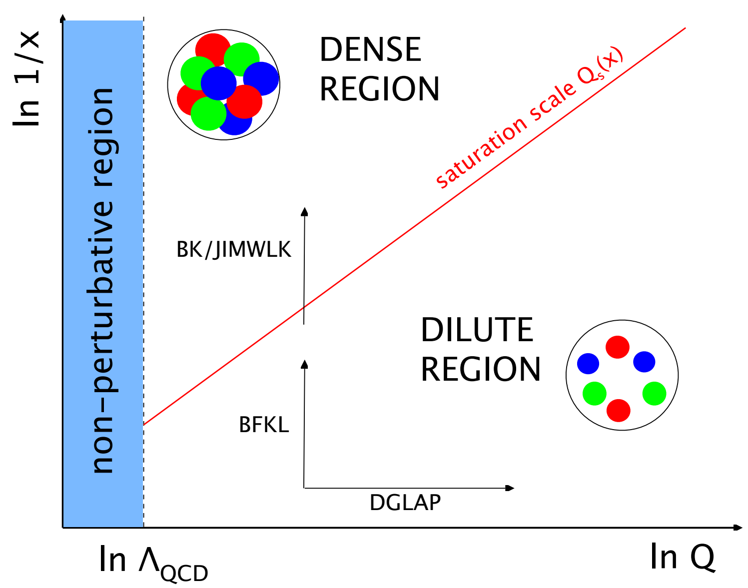


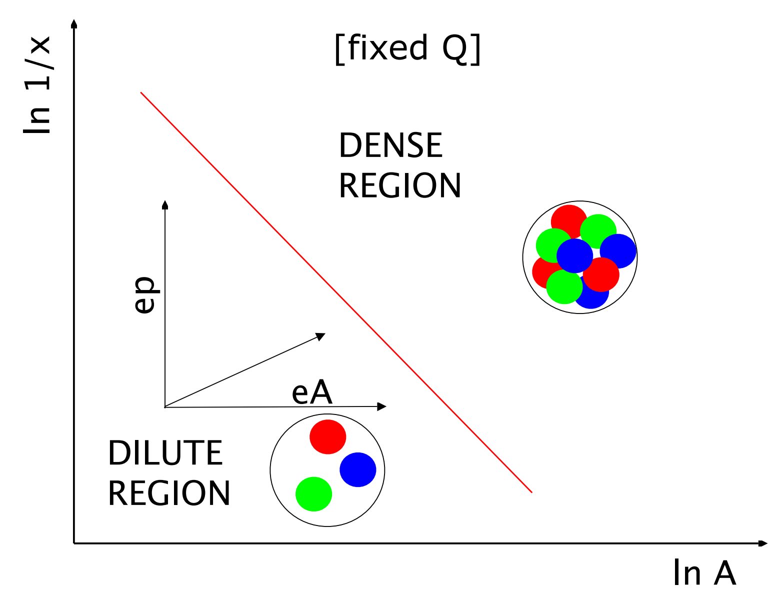
QCD at high energy (low x) and/or high density (large A) predicts **saturation** of gluons

$$Q_s^2(x, A) \sim \frac{A^{1/3}}{x^\lambda}$$

Effective theory of QCD at high energy/density:

Color Glass Condensate CGC *McLerran, Venugopalan,...*





Nuclei provide enhancement of the density : opportunities to test saturation at EIC

Testing saturation through inclusive structure functions at EIC

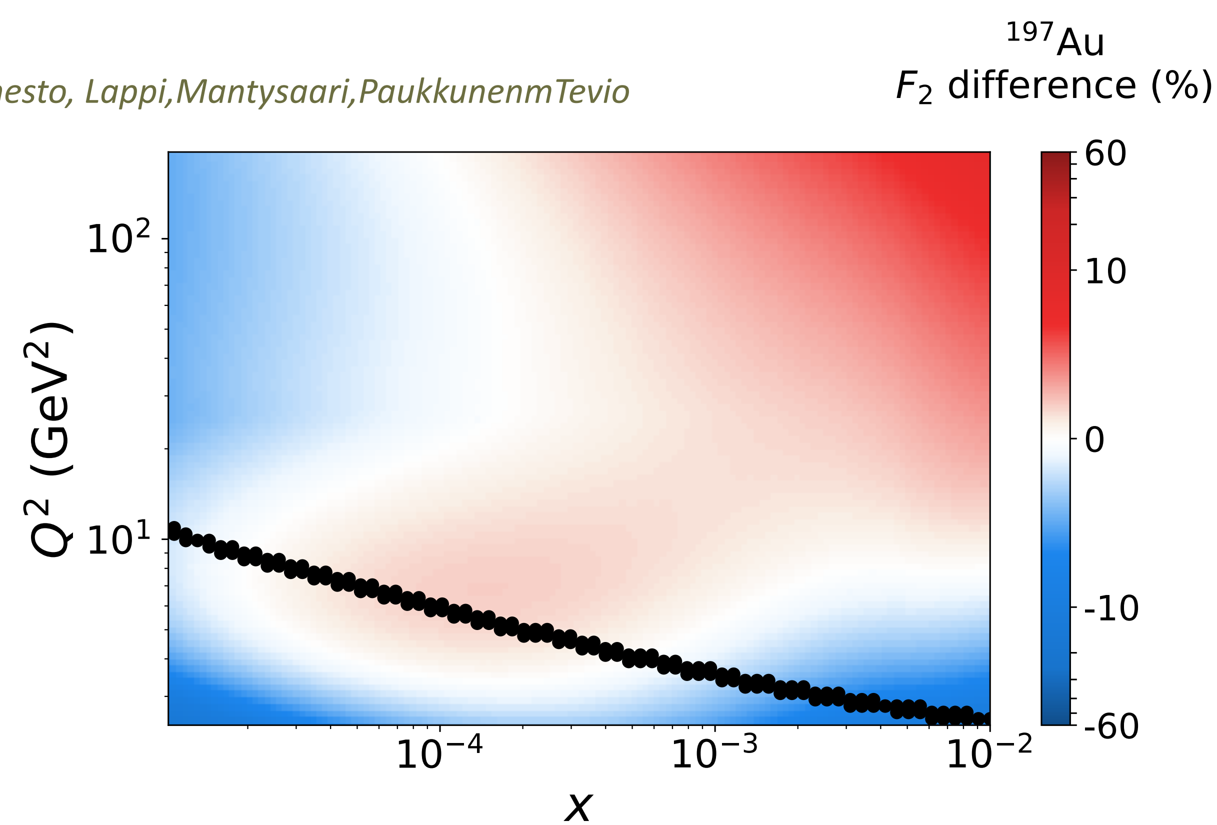
Study differences in evolution between **linear DGLAP** evolution and **nonlinear** evolution with **saturation**

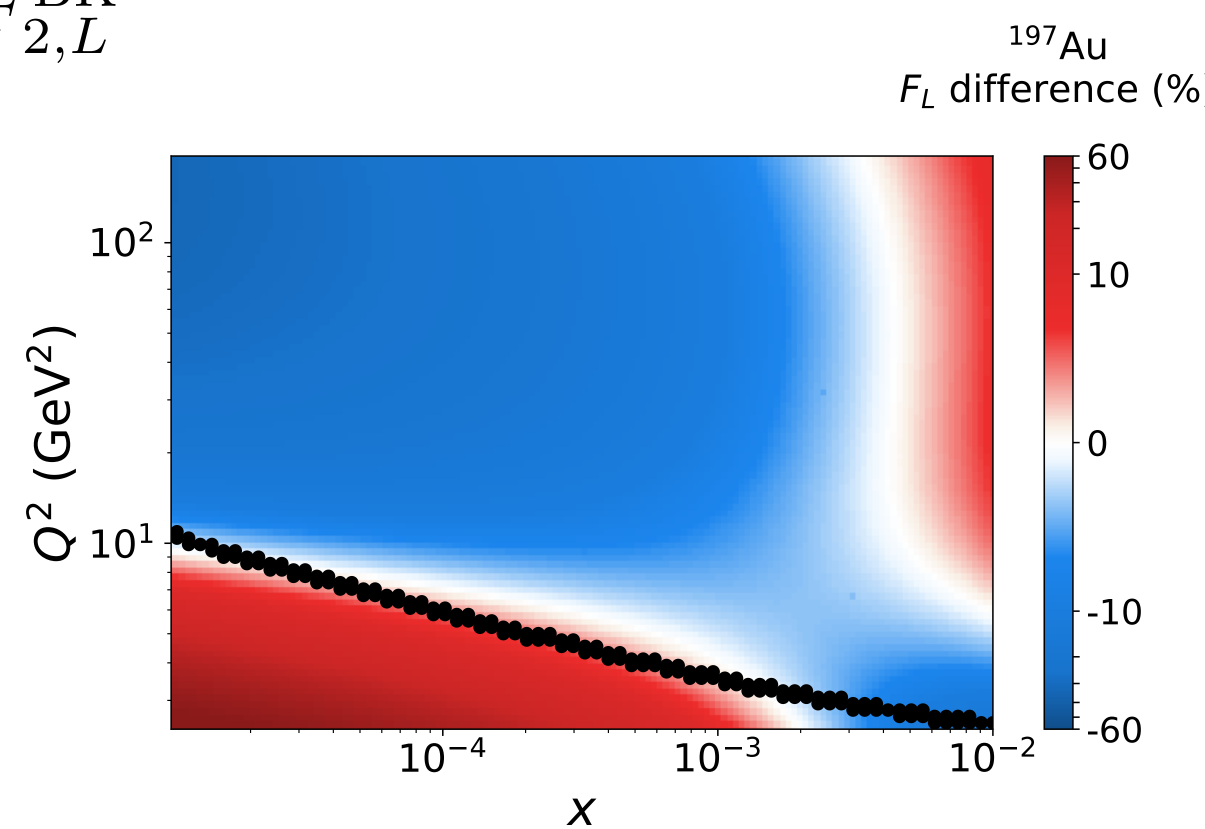
Matching of both approaches in the region where saturation effects expected to be small

Quantify differences away from the matching region: **differences in evolution dynamics**

$$\frac{F_{2,L}^{\mathrm{BK}} - F_{2,L}^{\mathrm{Rew}}}{F_{2,L}^{\mathrm{BK}}}$$

Armesto, Lappi,Mantysaari,PaukkunenmTevio



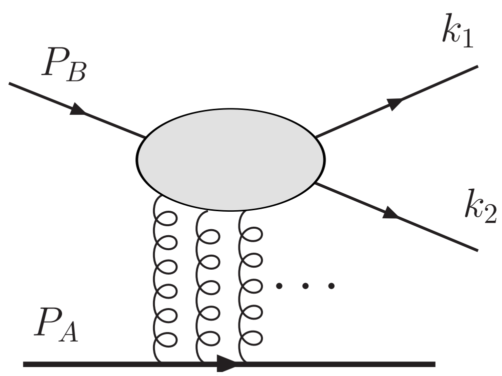


Heavy nucleus: difference between DGLAP and nonlinear are few % for F_2^A and up to 20% for F_L^A.

Longitudinal structure function can provide good sensitivity at EIC

Testing saturation through (de)correlations of hadrons

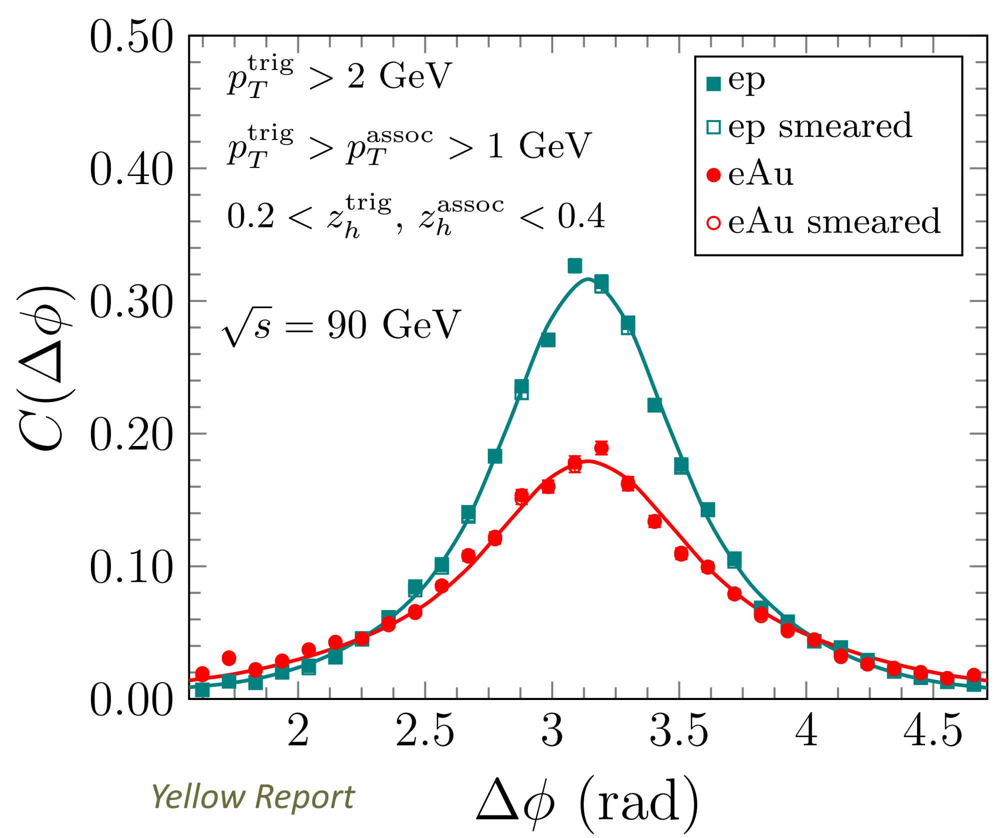
Azimuthal **(de)correlations of two hadrons** (dijets) in DIS in eA: direct test of the **Weizsacker -Williams unintegrated gluon distribution**



$$C(\Delta\phi) = \frac{1}{\frac{d\sigma_{\mathrm{SIDIS}}^{\gamma^*+A\to h_1+X}}{dz_{h1}}} \frac{d\sigma_{\mathrm{tot}}^{\gamma^*+A\to h_1+h_2+X}}{dz_{h1}dz_{h2}d\Delta\phi}$$

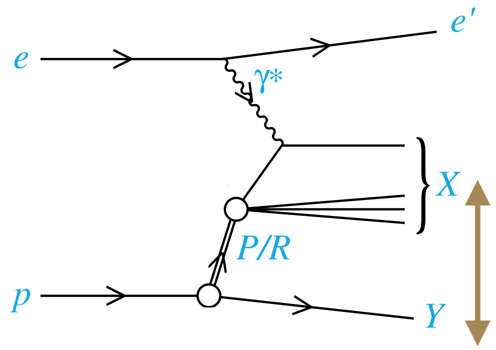
$$\frac{d\sigma^{\gamma^*+A\to h_1+h_2+X}}{dz_{h1}dz_{h2}d^2p_{h1T}d^2p_{h2T}} \sim \mathcal{F}(x_g,q_T)\otimes\mathcal{H}(z_q,k_{1T},k_{2T})\otimes D_q(z_{h1}/z_q,p_{1T})\otimes D_q(z_{h2}/z_q,p_{2T})$$

- Clear differences between the ep and eA: **suppression** of the correlation peak in **eA** due to **saturation** effects (including the **Sudakov resummation)**
- Further observables: azimuthal correlations of dihadrons/dijets in diffraction, photon+jet/dijet.
- Possibility to test various **CGC correlators**



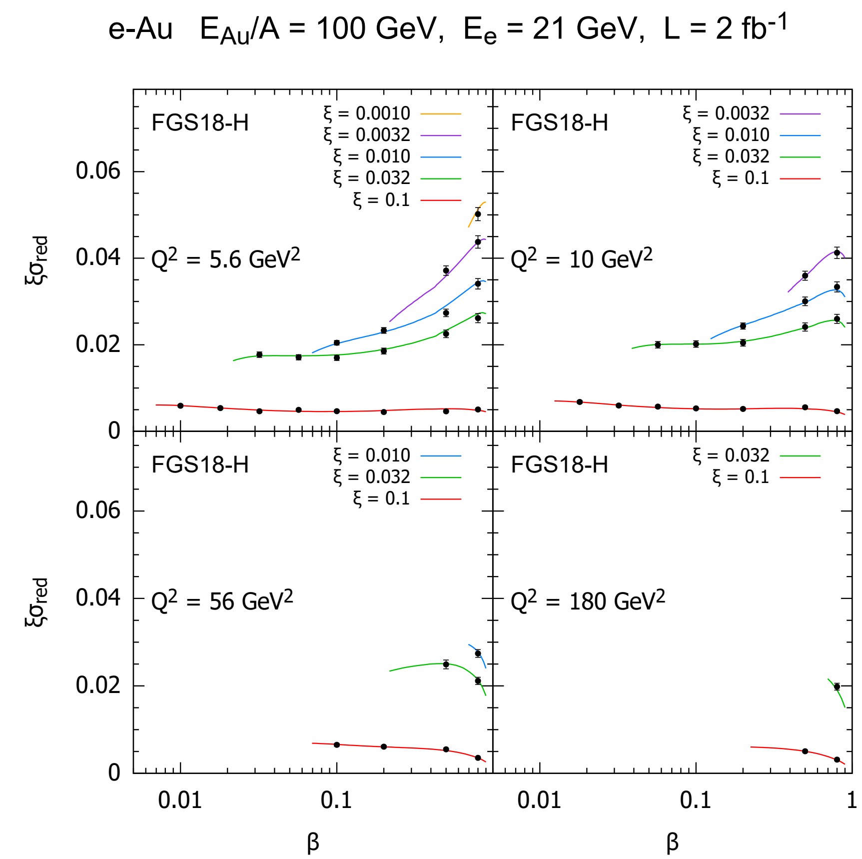
Yellow Report

Inclusive diffraction at EIC



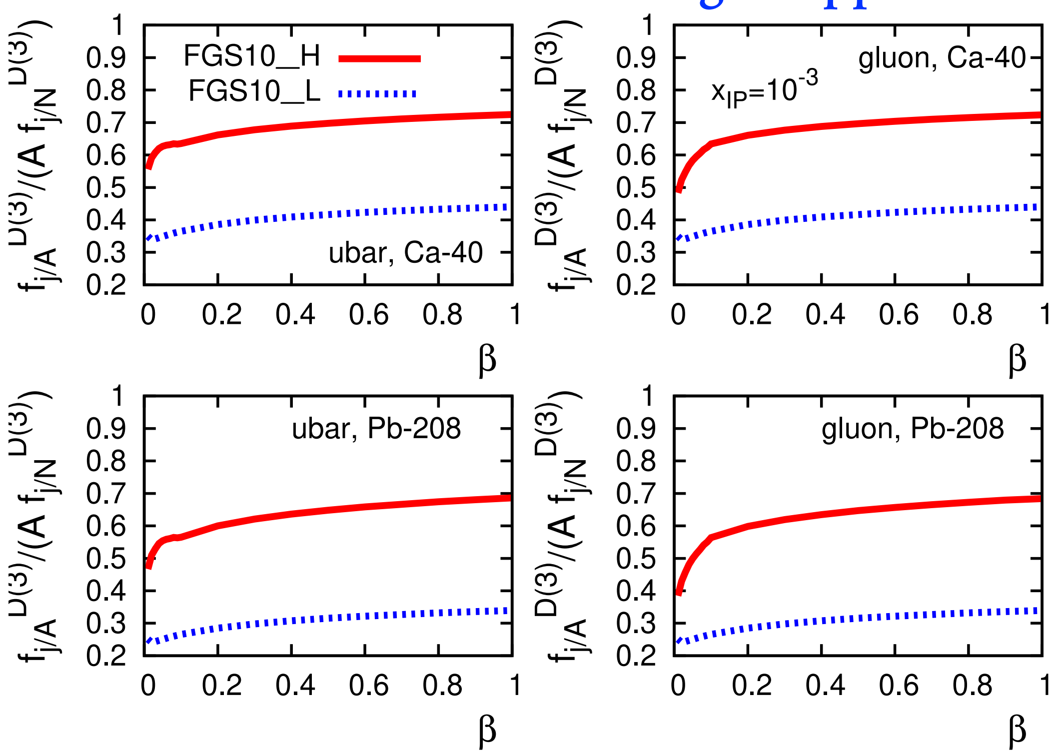
Diffraction: characterized by the **rapidity gap**
Interpretation : need **colorless exchange**

What is the nature of this exchange?

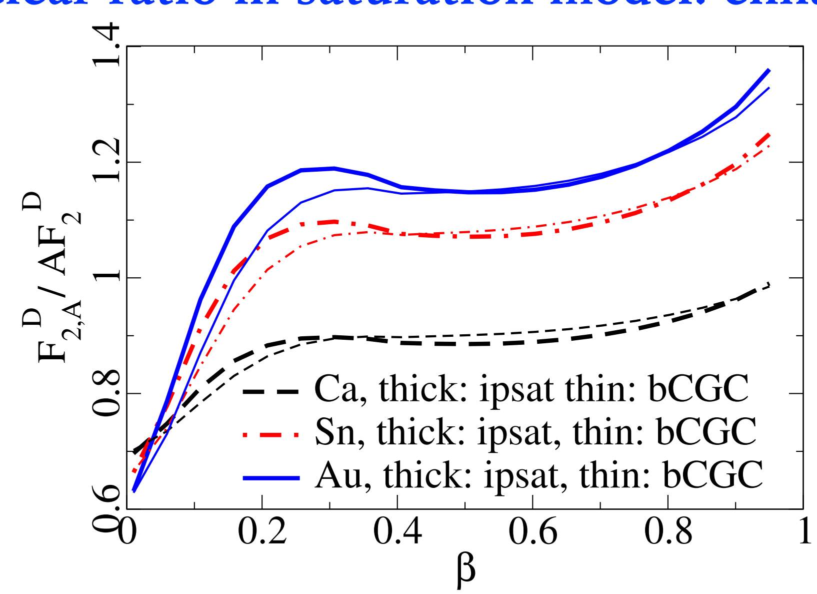


- Extraction of **nuclear diffractive parton distributions** would be possible for the first time
- Diffractive to inclusive ratio and the ratio of diffraction in nuclei to that in protons are **sensitive probes to different models**

Nuclear ratio in LT shadowing : suppression

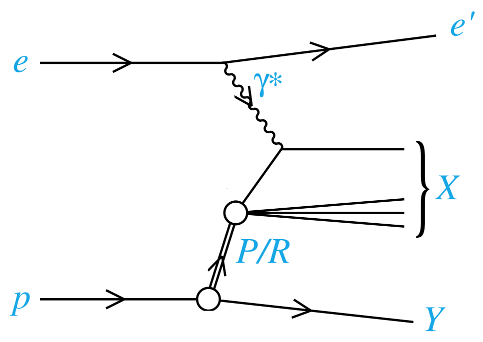


Nuclear ratio in saturation model: enhancement



Yellow Report

Diffraction in ep/eA: extraction of Reggeon

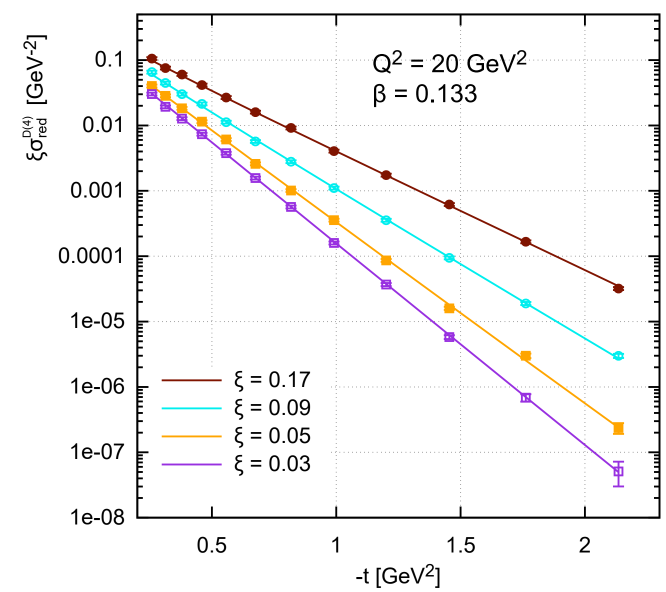


EIC can reveal the details of the colorless exchange:

constraints on Reggeon

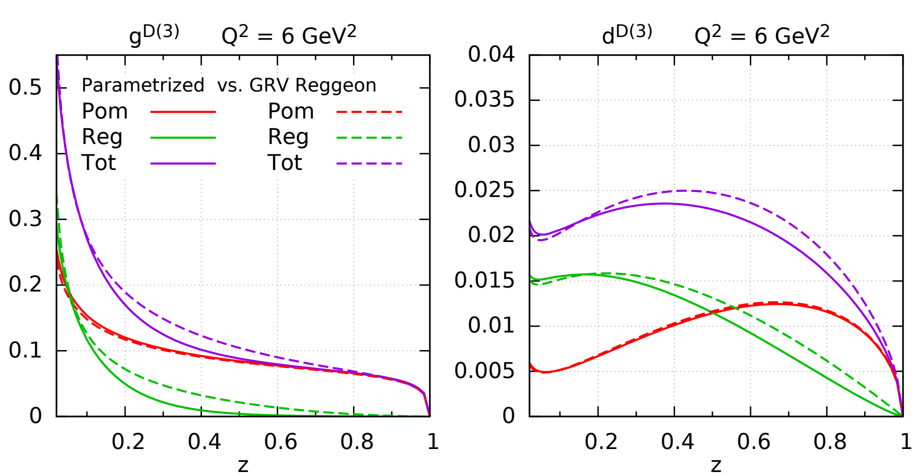
$\sigma_r^{D(4)}$ and extraction of Reggeon/Pomeron

Precision measurement of **t-dependence** of $\sigma_r^{D(4)}$



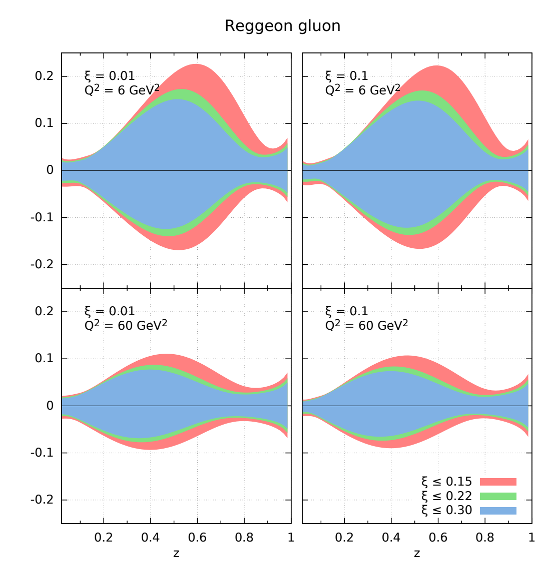
Partonic content of the colorless exchange

gluon **quark**

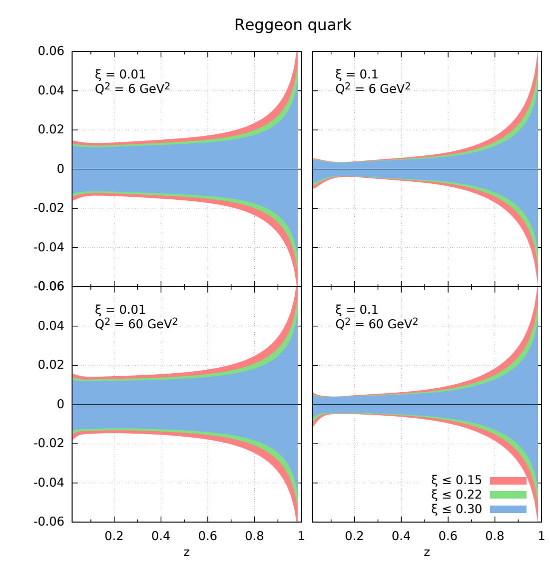


Armesto, Newman, Slominski, AS

Reggeon gluon



Reggeon quark



Diffraction in ep/eA: longitudinal structure function

F_L^D diffractive longitudinal structure function

$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{Y_+} F_L^{D(3)}$$

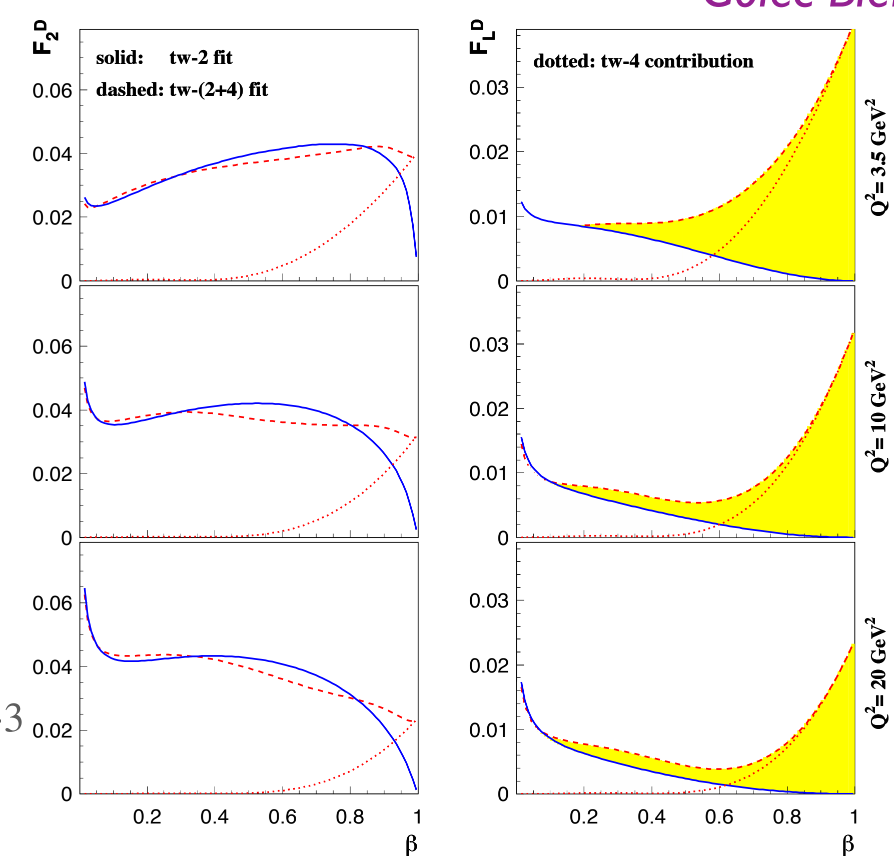
F_L^D vanishes in the parton model, similarly to inclusive case
Gets non-vanishing contributions in QCD
As in inclusive case, particularly sensitive to the diffractive **gluon density**
Expected large **higher twists**, provides test of the **non-linear, saturation phenomena**

Golec-Biernat, Łuszczak

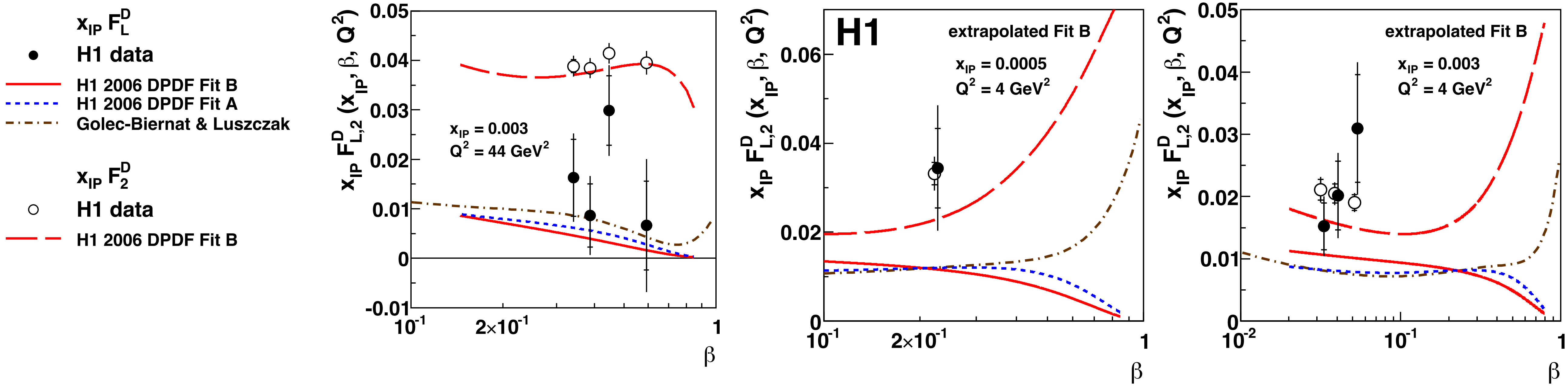
Theoretical studies indicate important role of twist 4 contributions to F_L^D

F_2^D affected less by higher twists

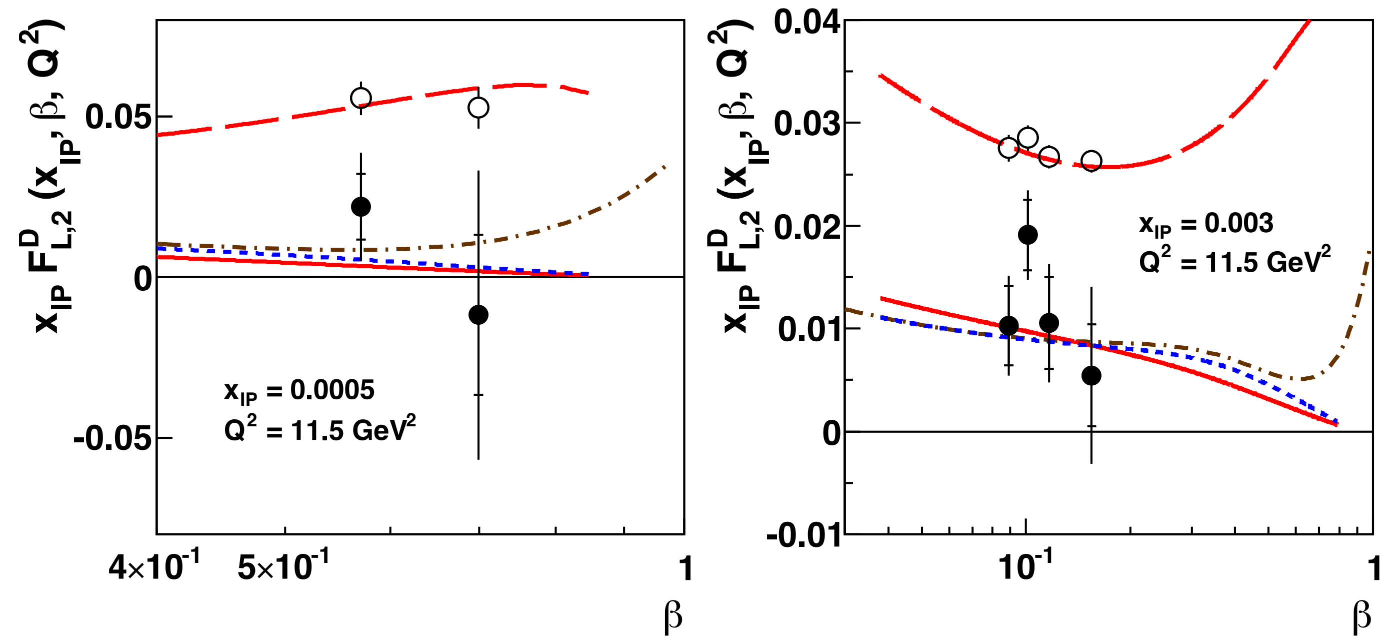
$x_{I\!P} \equiv \xi = 10^{-3}$



$F_L^{D(3)}$ at HERA



H1 conclusions:



Measurements of σ_r^D consistent with predictions from the models

Extracted F_L^D has a tendency to be higher than the predictions, though compatible with model predictions within errors

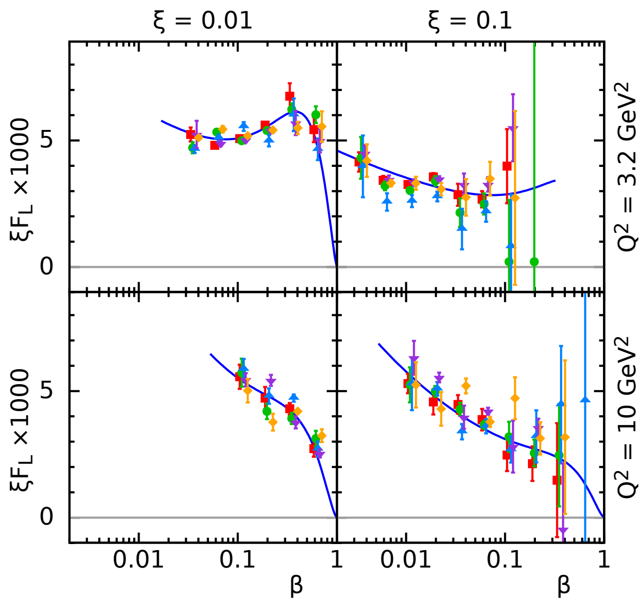
Overall: $0 < F_L^D < F_2^D$

Diffraction in ep/eA: longitudinal structure function

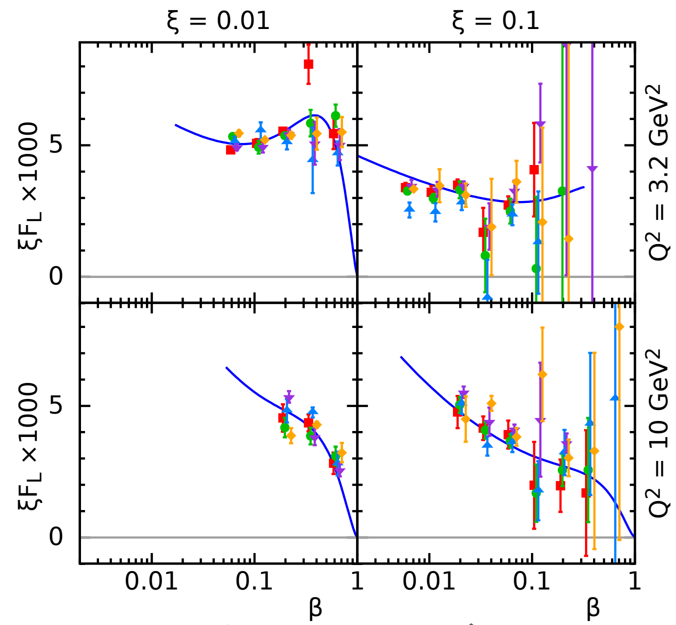
Simulations for the EIC of F_L^D

Armesto, Newman, Slominski, AS

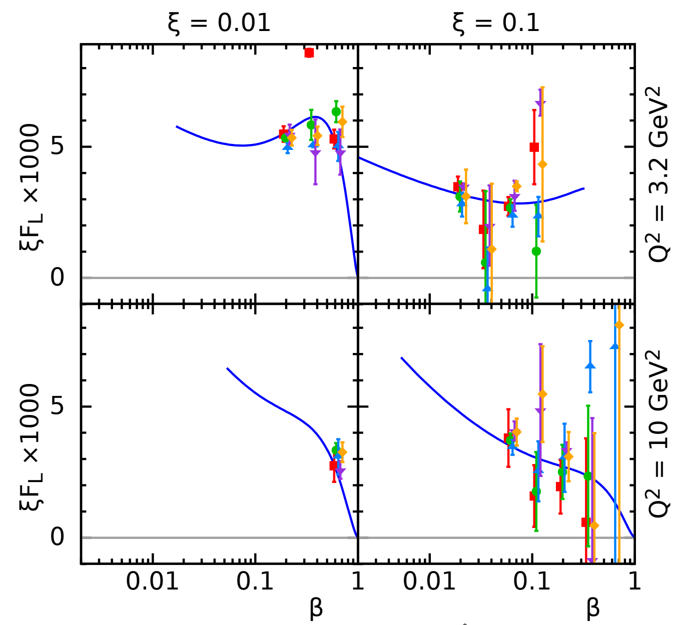
- Cross section generation from ZEUS-SJ diffractive PDFs evolved with DGLAP
- Assumed δ_{sys}=1-2%, extrapolated from HERA 2% uncorrelated systematics; normalization/correlated systematics negligible effect on extraction of F_L^D
- δ_{stat} from 10 fb^{-1} integrated luminosity
- Several random samples are generated



17 energies



9 energies



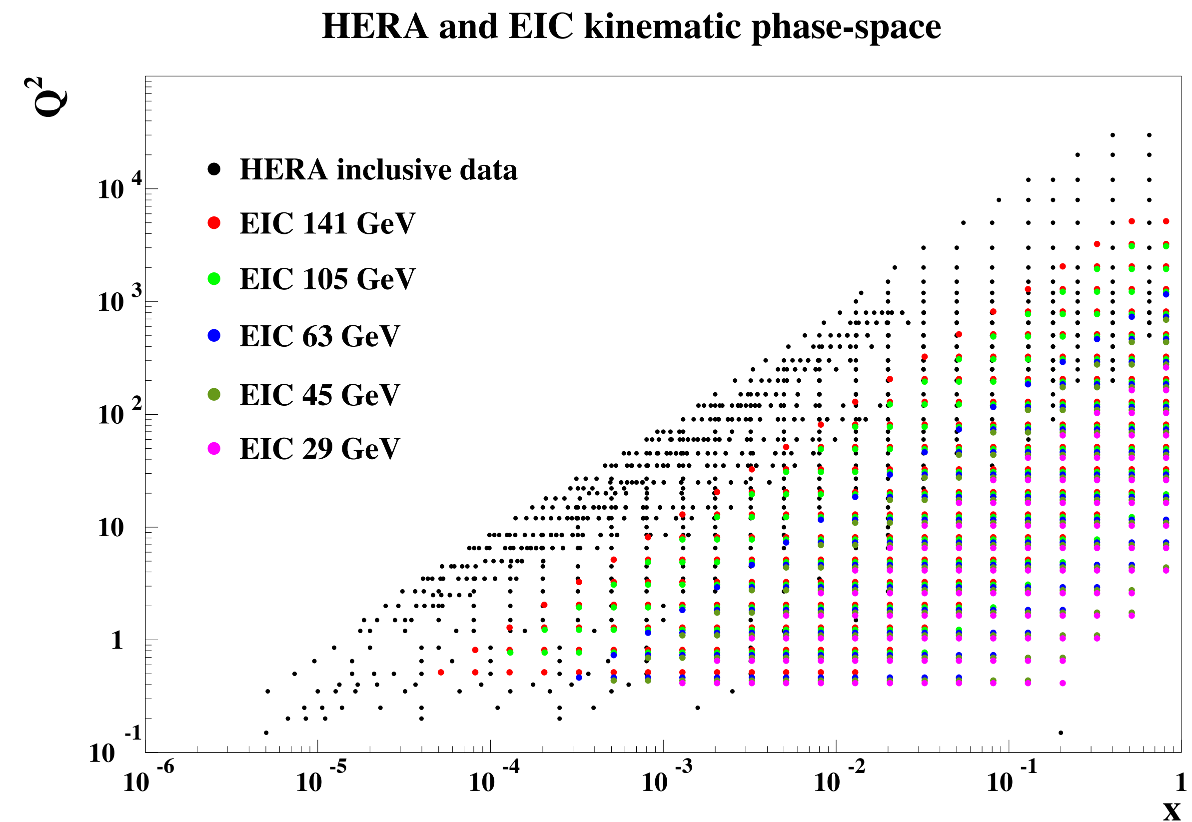
5 energies

Small differences between S-17 and S-9, small reduction to range and increase in uncertainties.
More pronounced reduction in range and higher uncertainties in S-5.

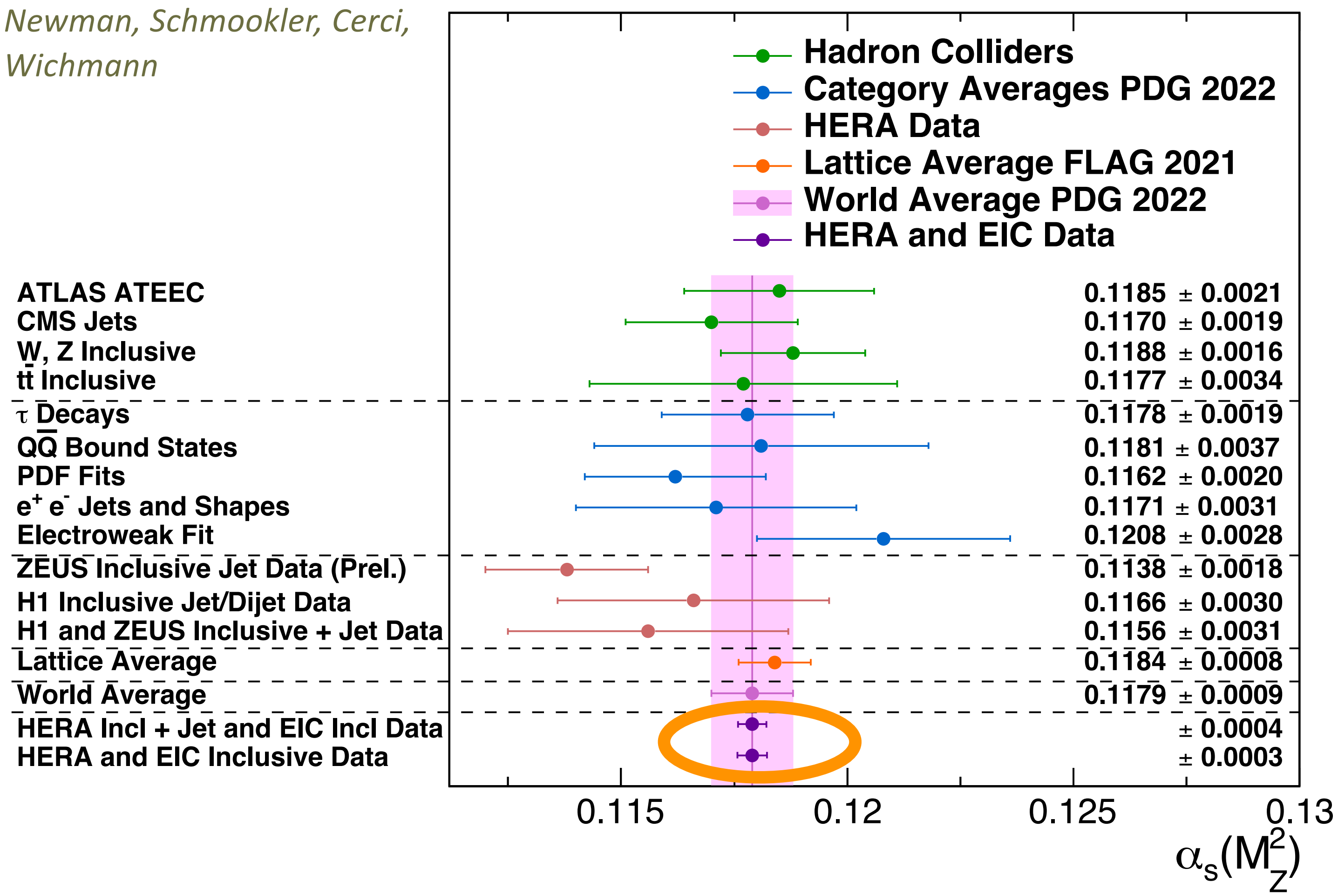
An extraction of F_L^D possible with EIC-favored set of 5 energy combinations

Extraction of α_s from HERA and EIC

- Inclusive DIS cross section sensitive to α_s
- Need to know with **high precision**, α_s essential for **SM** calculations, and for constraints on **BSM**
- EIC complementary to HERA



Cerci, Demiroglu, Deshpande, Newman, Schmookler, Cerci, Wichmann

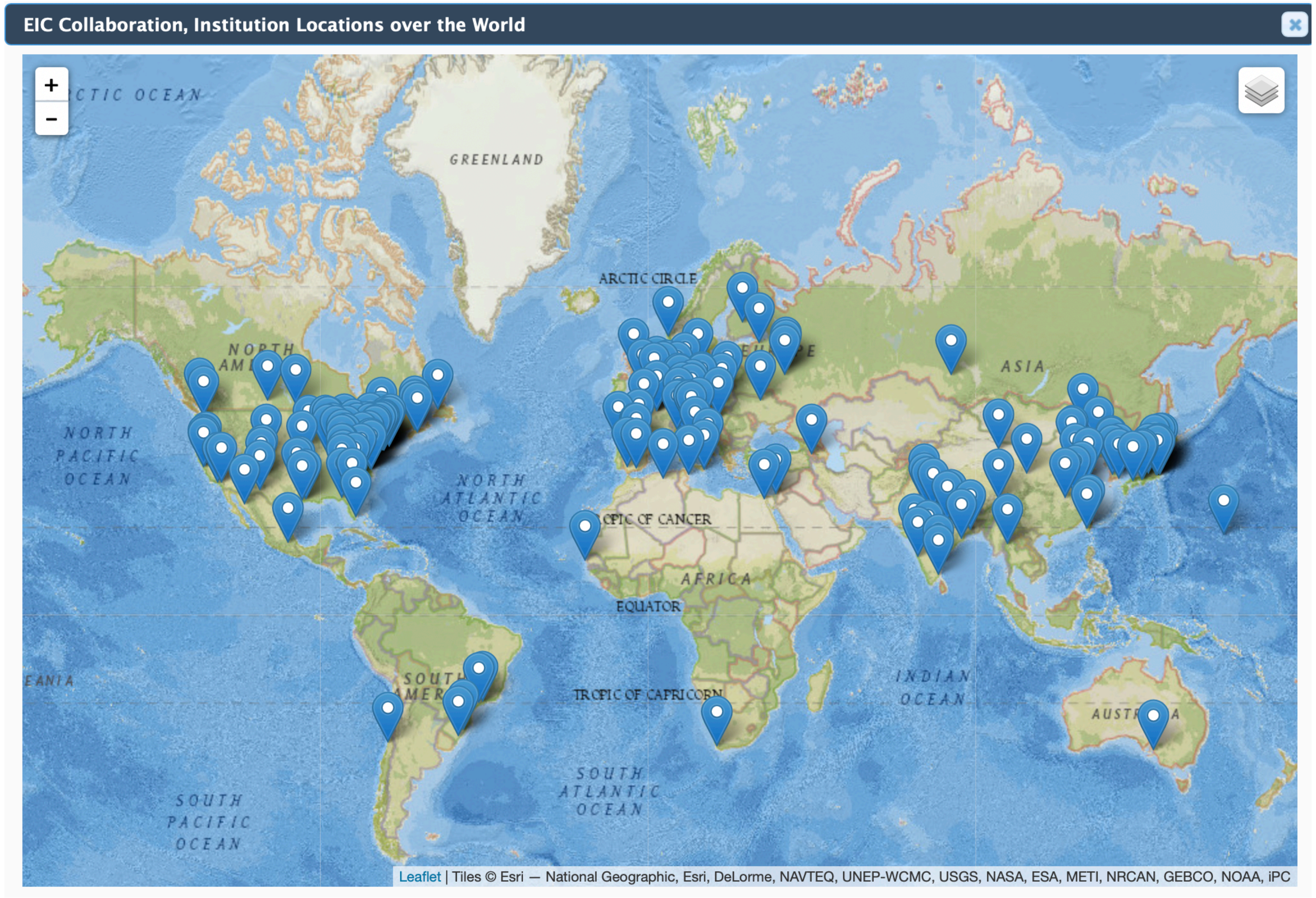


HERA inclusive (or inclusive + jets) + EIC inclusive data allows for **determination of α_s** with **unprecedented precision : $\leq 0.3\,\%$**

$$\alpha_s(M_Z^2) = 0.1161 \pm 0.0003\ (\text{exp}) \pm 0.0001(\text{model}+\text{param})\ {}^{+0.0002}_{-0.0001}\ (\text{scale})$$

EIC Users Group

The **Electron-Ion Collider User Group (EICUG)** is an international affiliation of scientists dedicated to developing and promoting the scientific, technological, and educational goals and motivations for a new high energy **Electron-Ion Collider**.



1530 members

- 1006 experimentalists
- 374 theorists
- 133 accelerator scientists
- 10 computer scientists
- 4 support
- 3 other

294 institutions

40 countries

https://www.eicug.org/index.html

Status as of June 7, 2024

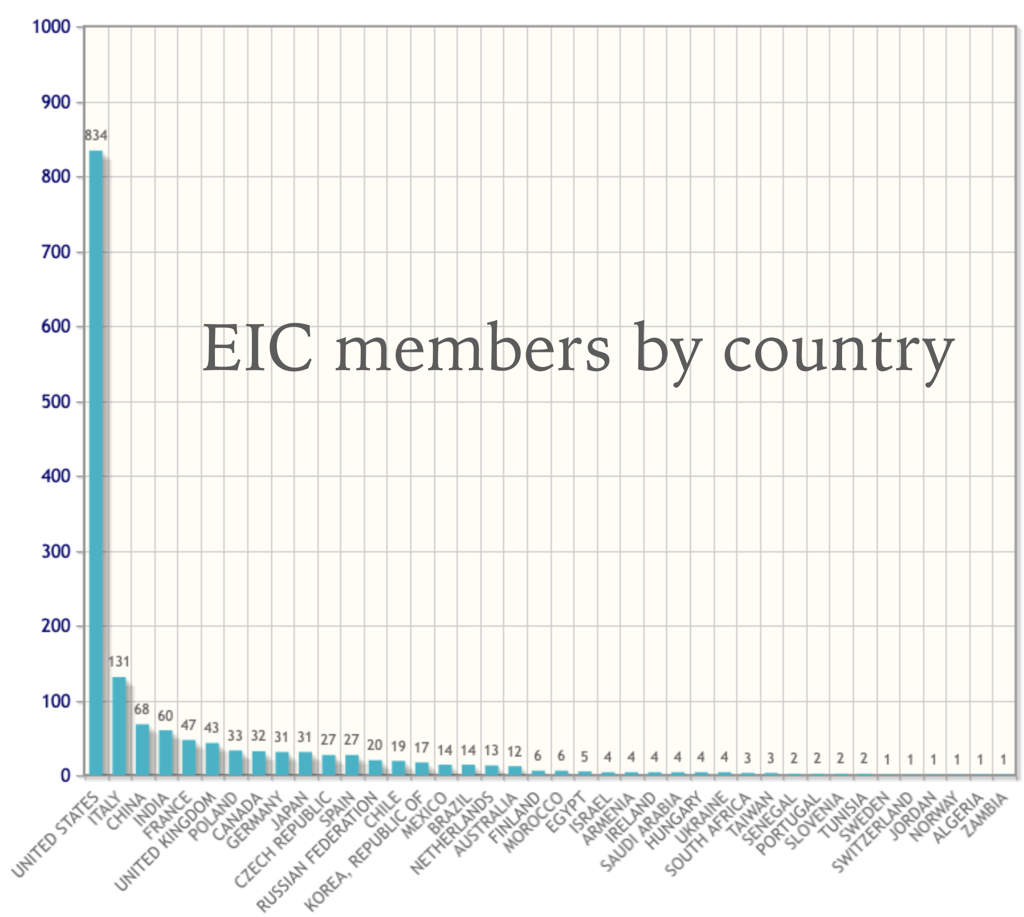
EIC Users Group

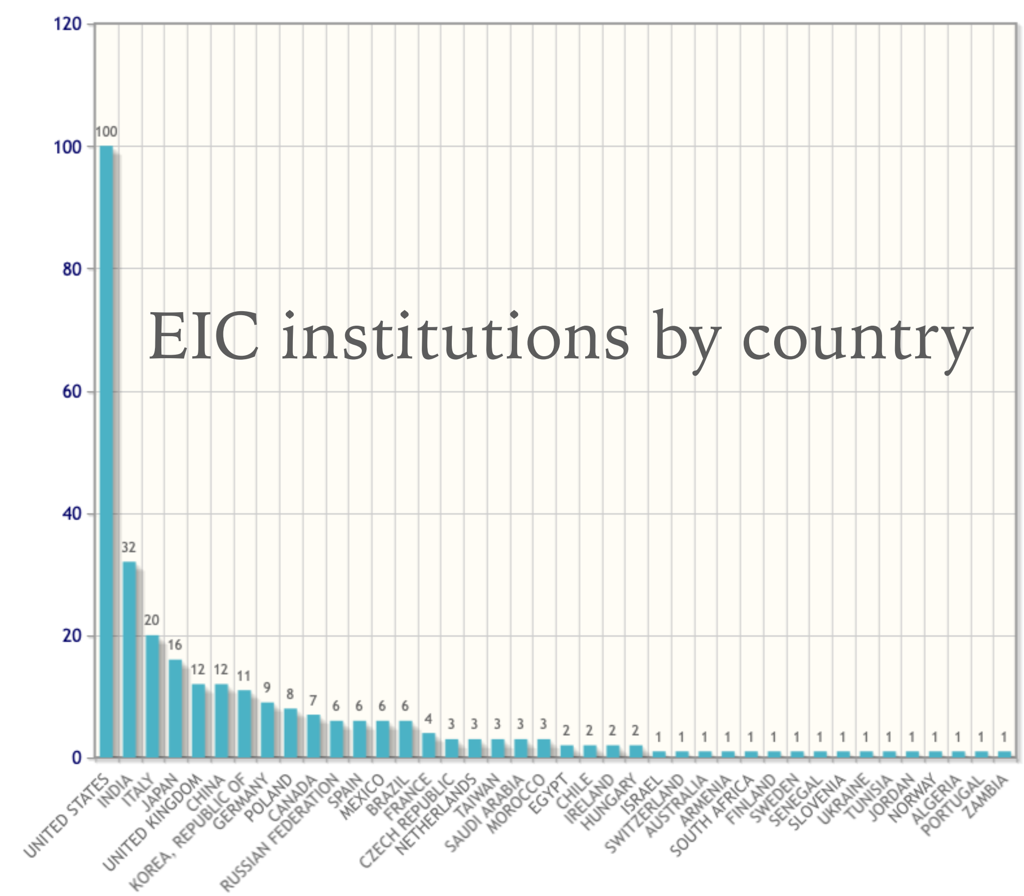
EIC is international at its core

Last annual meeting: July 25-31, 2023, Warsaw, Poland

Next annual meeting: July 22-27, 2024, Lehigh University, Bethlehem, Pennsylvania

Strong community and still growing !





Status as of June 7, 2024

Summary

Electron Ion Collider : high energy, high luminosity, polarized, electron-proton and electron-ion collider, funded by DoE, will be built in this decade and start operating in 2030's

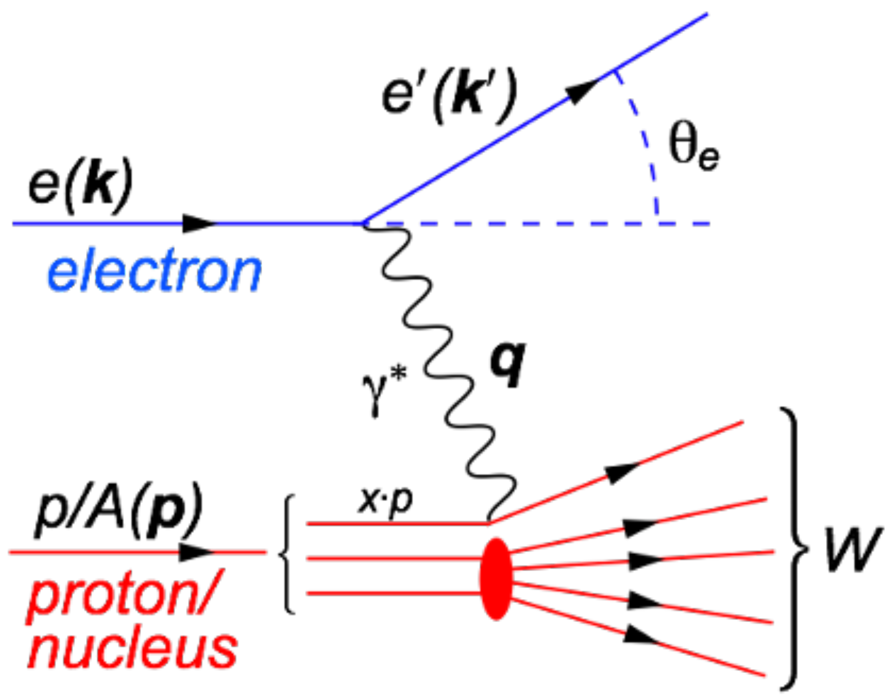
- **Precision tool** which will address most profound unanswered questions in QCD
- One of the most **challenging** and **versatile** accelerator complexes ever built
- EIC is a project with strong **international** engagement
- **ePIC** collaboration: 1st detector collaboration formed
- **2nd** detector: under consideration, needs additional funding

Please join and contribute! *Everybody is welcome: engineers, designers, technicians, administrators, theorists, experimentalists, accelerator physicists…*

Especially early career scientists: *postdocs, undergraduate and graduate students…*

Backup

Deep Inelastic Scattering



DIS: Deep Inelastic e/p(A) scattering

- **Electromagnetic probe** allows for very **precise** exploration of hadron structure: excellent **microscope**
- **Control** over kinematics of the process

electron-proton cms energy squared:

$$s = (k+p)^2$$

(minus) photon virtuality resolution power

$$Q^2 = -q^2$$

inelasticity

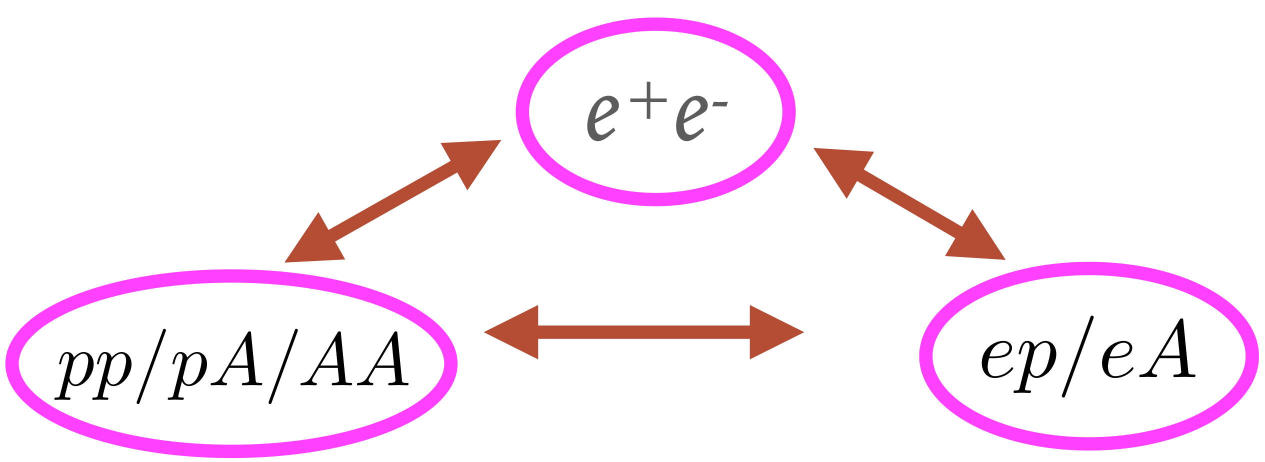
$$y = \frac{p \cdot q}{p \cdot k}$$

Bjorken x: momentum fraction of struck quark

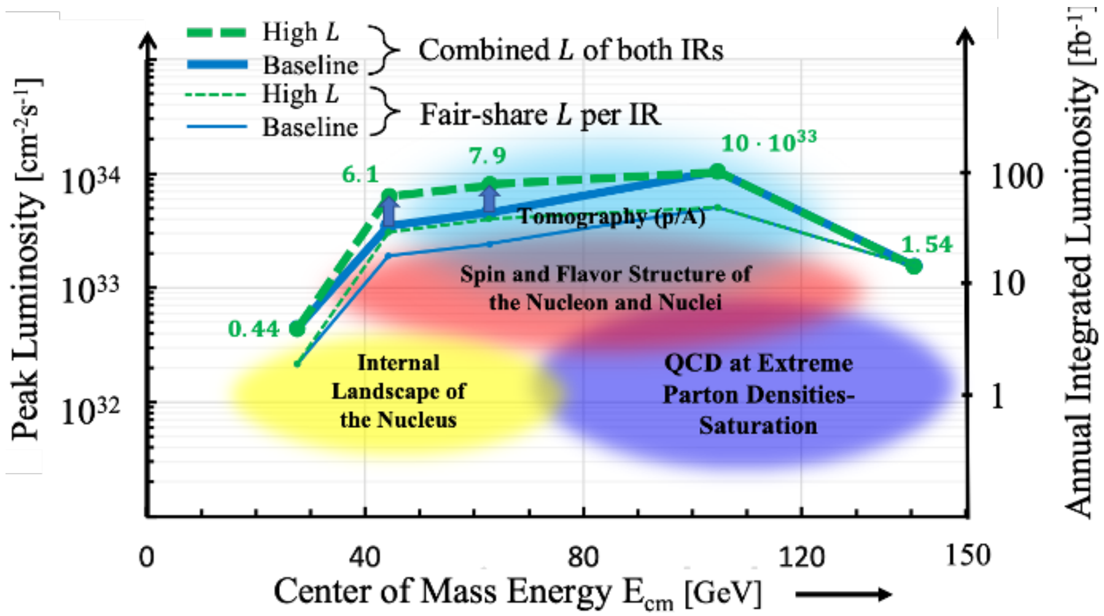
$$x = \frac{-q^2}{2p \cdot q}$$

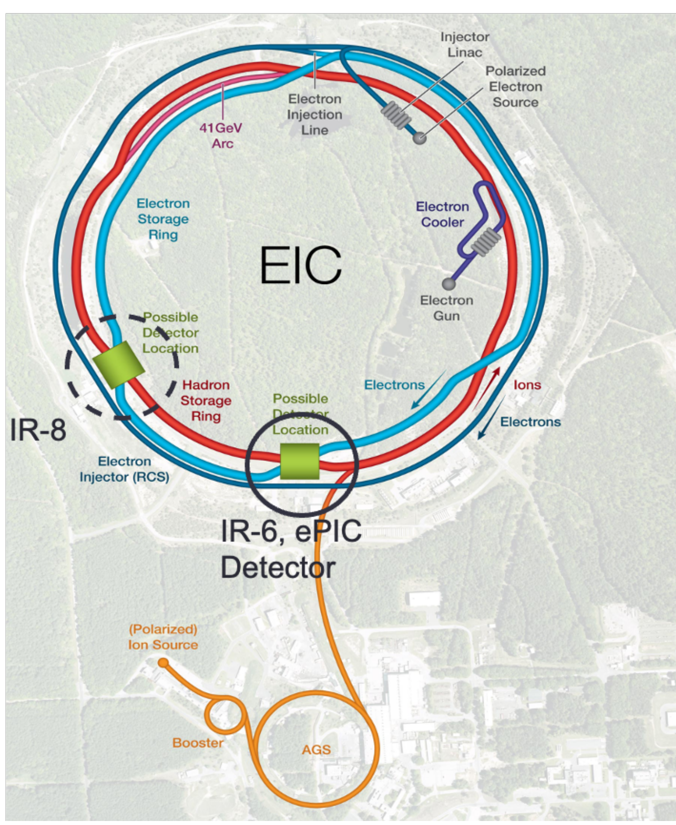
Complementarity:

For full understanding of QCD and EW need to run various experiments with 0,1,2 initial state hadrons



Machine design and parameters





- **Hadron storage ring (HSR): 41-275 GeV** (based on RHIC)

  up to 1160 bunches, 1A beam current (3x RHIC)

  bright vertical beam emittance (1.5 nm)

  strong cooling (coherent electron cooling, ERL)
- **Electron storage ring (ESR): 2.5–18 GeV** (new)

  up to 1160 polarized bunches

  high polarization by continual reinjection from RCS

  large beam current (2.5 A) ➔ 9 MW SR power

  superconducting RF cavities
- **Rapid cycling synchrotron (RCS): 0.4-18 GeV** (new)

  2 bunches at 1 Hz; spin transparent due to high periodicity
- **High luminosity interaction region(s)** (new)

  $L = 10^{34}\, cm^{-2}s^{-1}$

  superconducting magnets

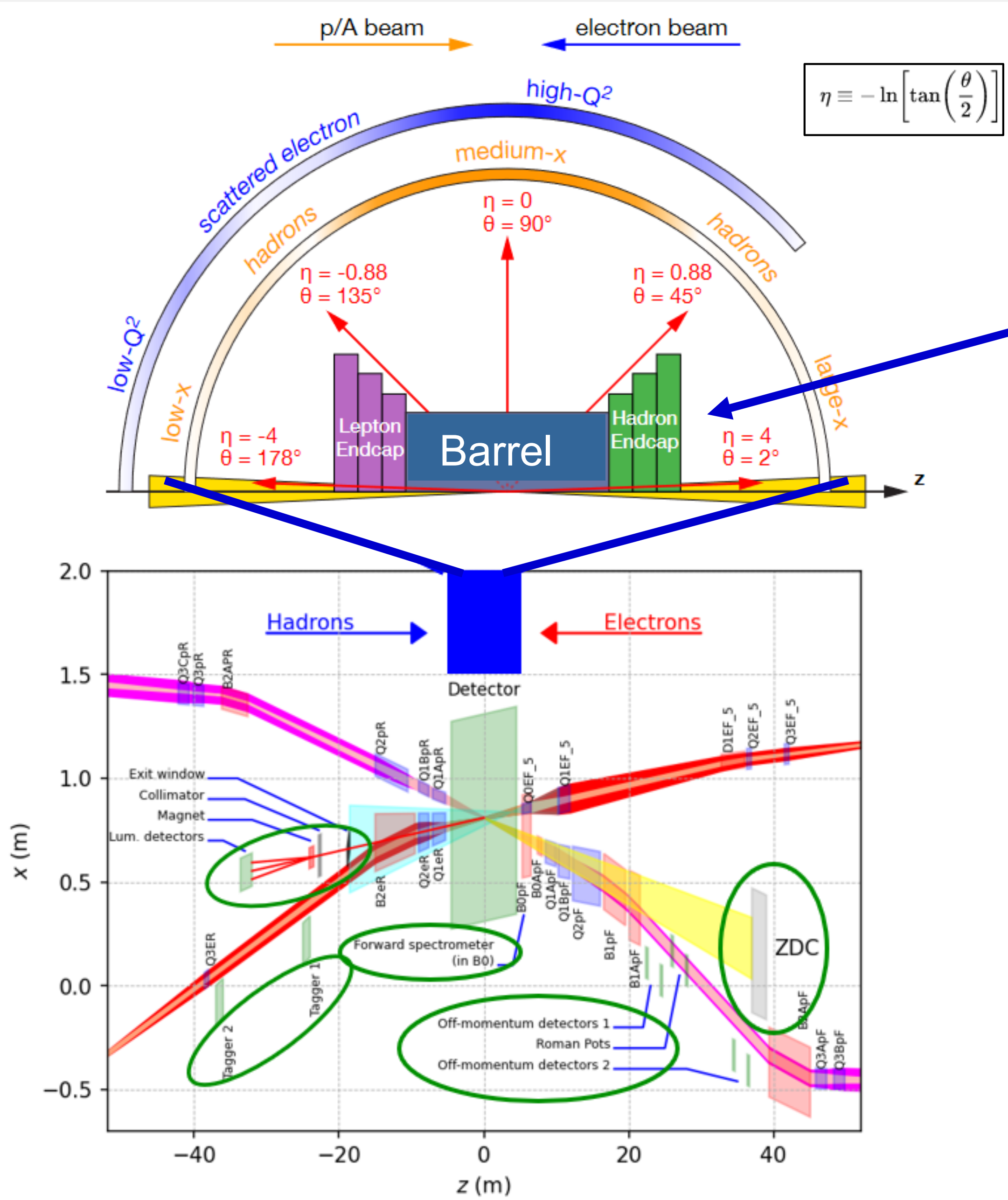
  25 mrad crossing angle with crab cavities

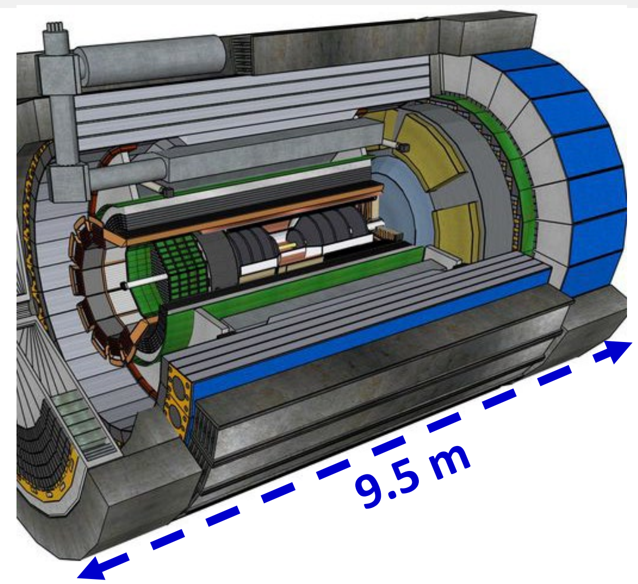
  spin rotators (produce longitudinal spin at IP)

Detector: ePIC

Slide from S. Dalla Torre talk at EICUG

ePIC, an extended detector





Central Detector (CD)

Total size detector: ~75m

Central detector: ~10m

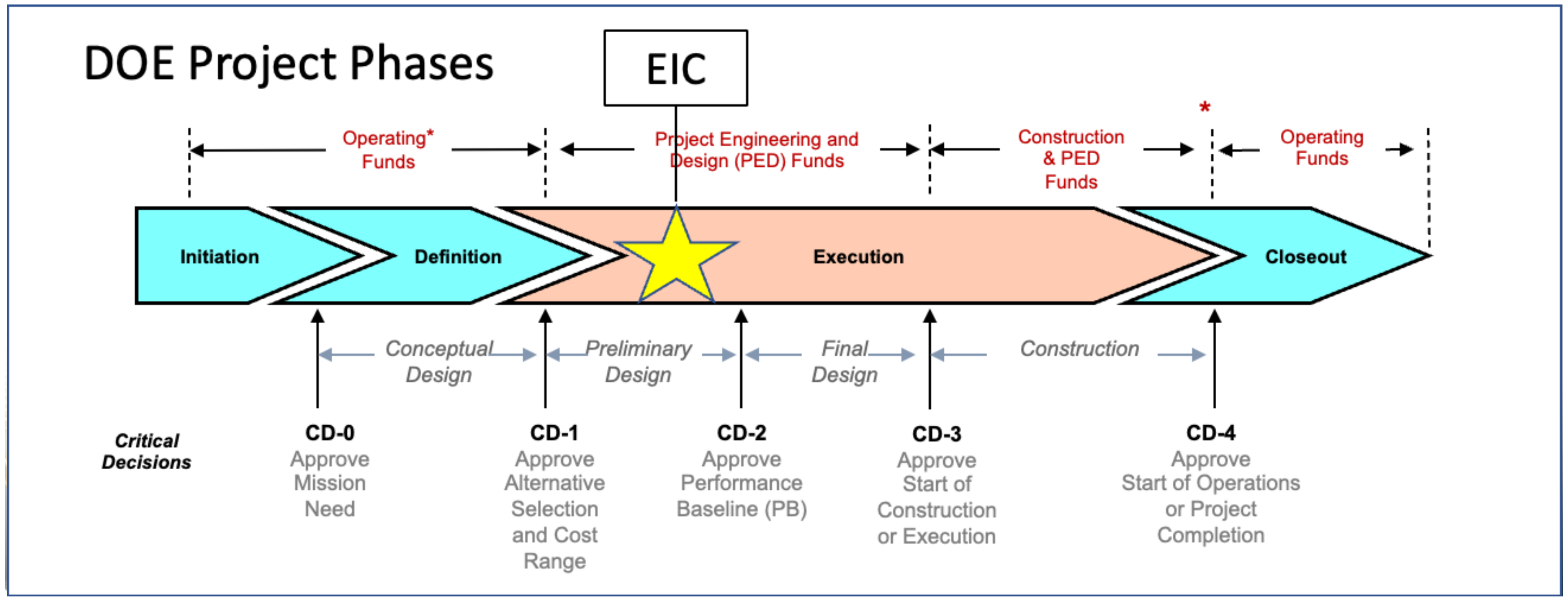
Far Backward electron detection: ~35m

Far Forward hadron spectrometer: ~40m

Auxiliary detectors needed to tag particles with very small scattering angles both in the outgoing lepton and hadron beam direction (B0-Taggers, Off-momentum taggers, Roman Pots, Zero-degree Calorimeter and low Q2-tagger).

EICUG annual meeting, July 25-26, 2023 ePIC Collaboration (J. Lajoie, S. Dalla Torre) 19

Timeline



Current EIC Critical Decision Plan

CD-0/Site Selection December 2019 ✓

CD-1 June 2021 ✓

CD-3A ESAAB March 25th 2024

CD-3B October 2024

CD-2/3 April 2025

early CD-4 October 2032

CD-4 October 2034