

The Physics of the EIC

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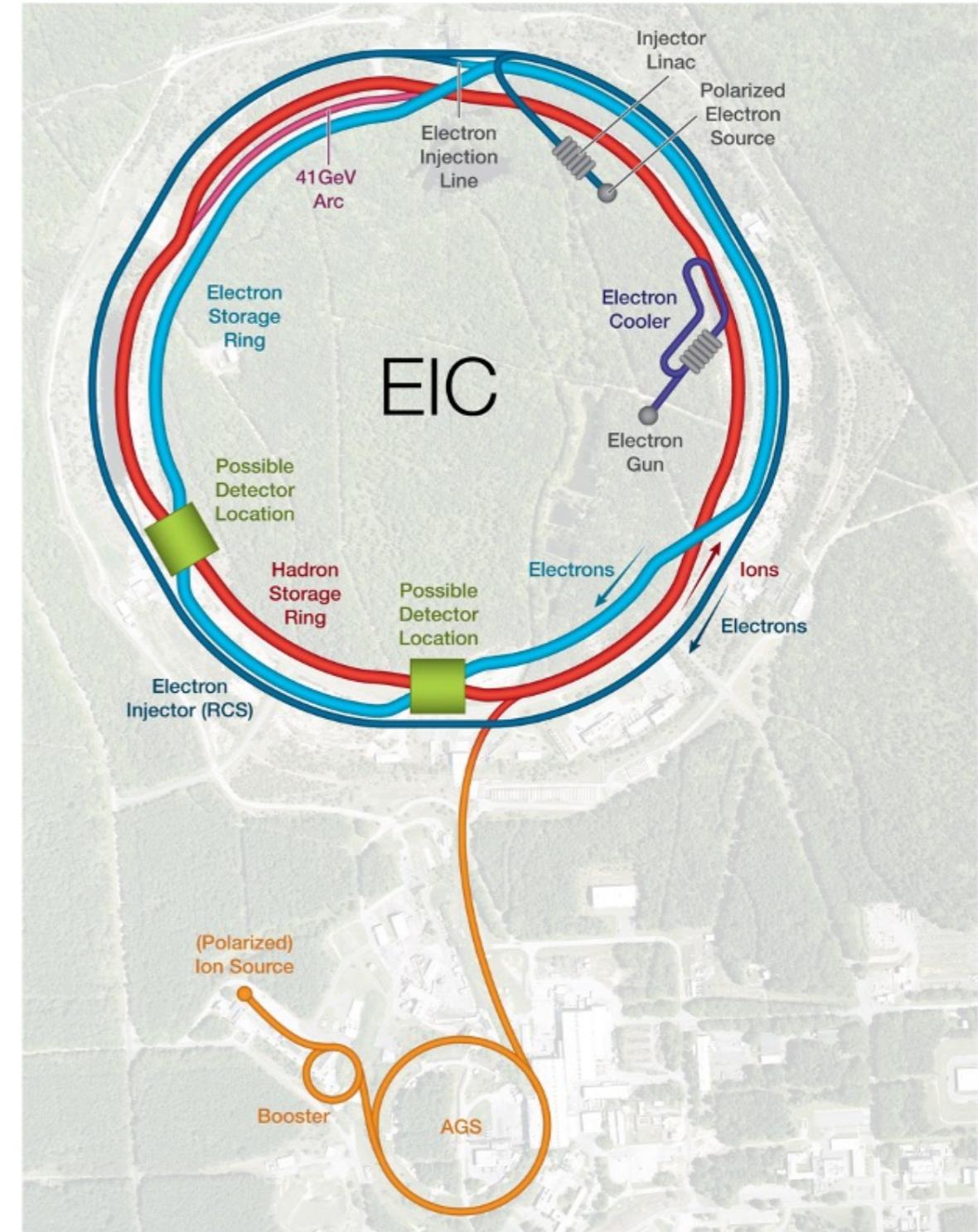
What is EIC ?

EIC: Electron-Ion Collider facility that will be built at Brookhaven National Laboratory using and upgrading existing RHIC complex.

Partnership between BNL and Jefferson Lab.

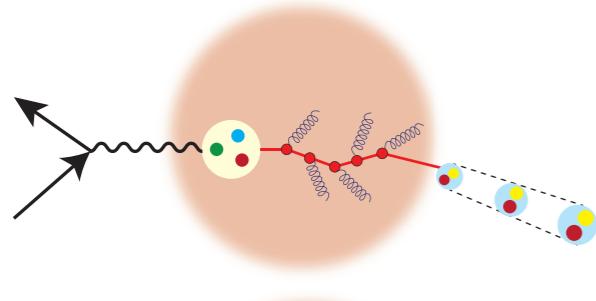
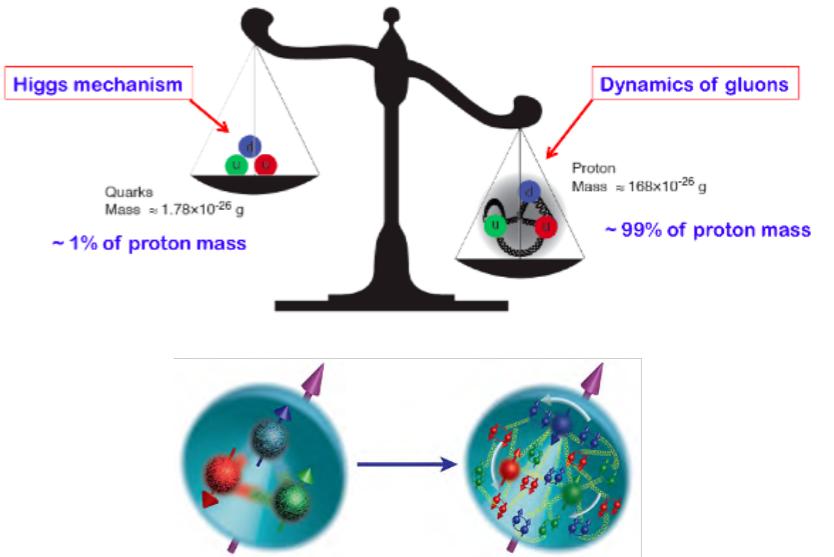
Capabilities of EIC

- **High luminosity** $10^{33} - 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
(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



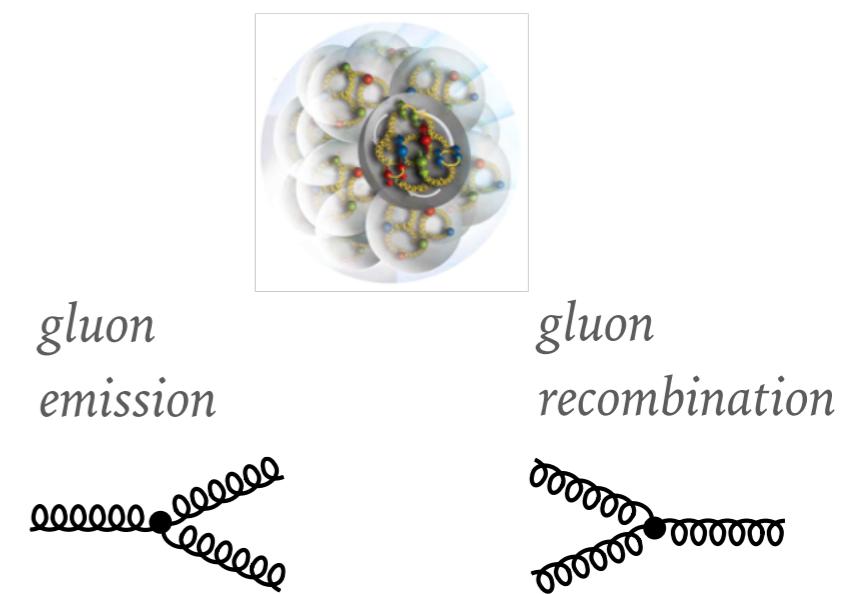
Core physics program of the EIC

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?

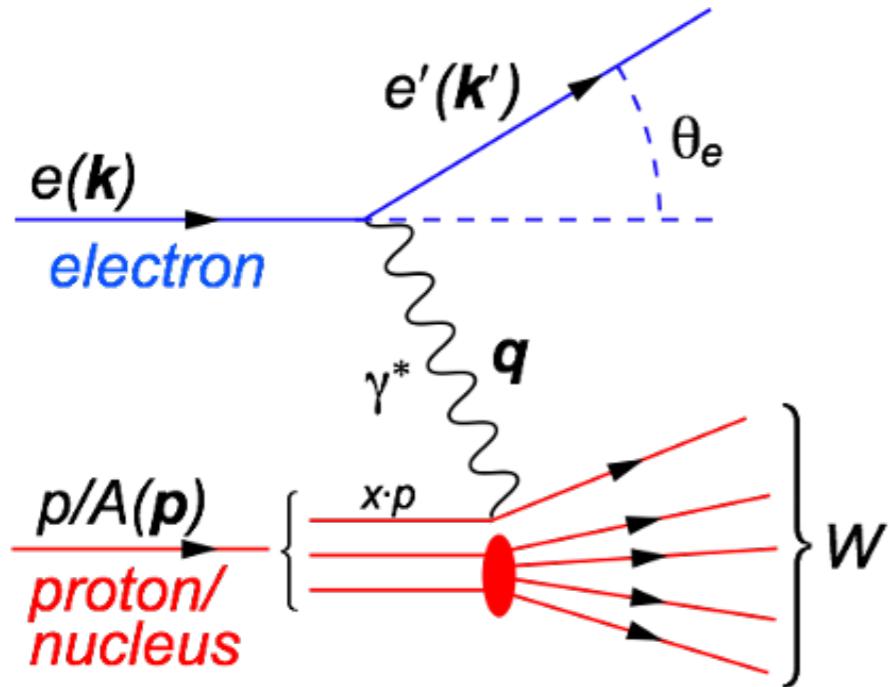


How do color-charged quarks and gluons, and colorless jets, **interact with a nuclear medium**? How do the **confined hadronic states emerge** from these quarks and gluons? How do the quark-gluon **interactions create nuclear binding**?

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?



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:

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

inelasticity

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

(minus) photon virtuality
resolution power

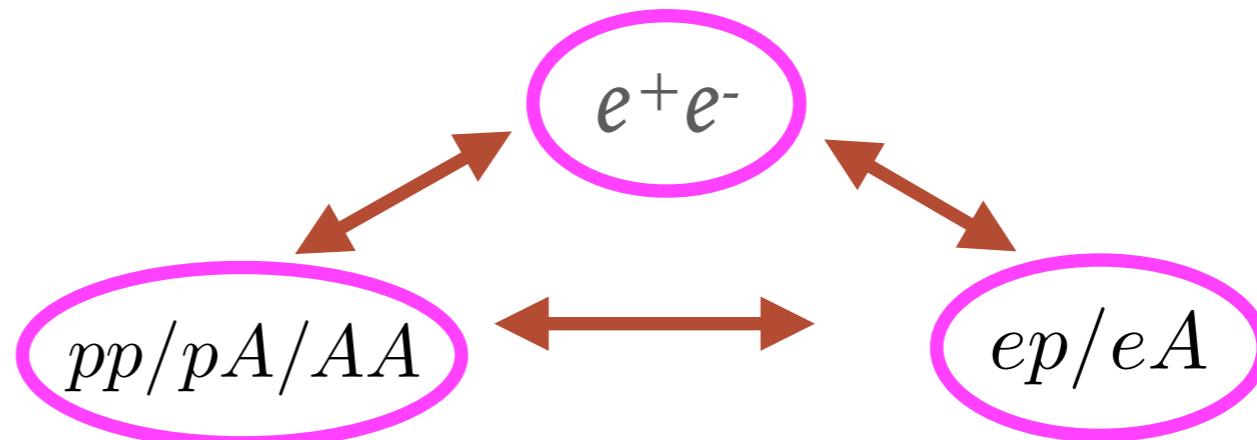
$$Q^2 = -q^2$$

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



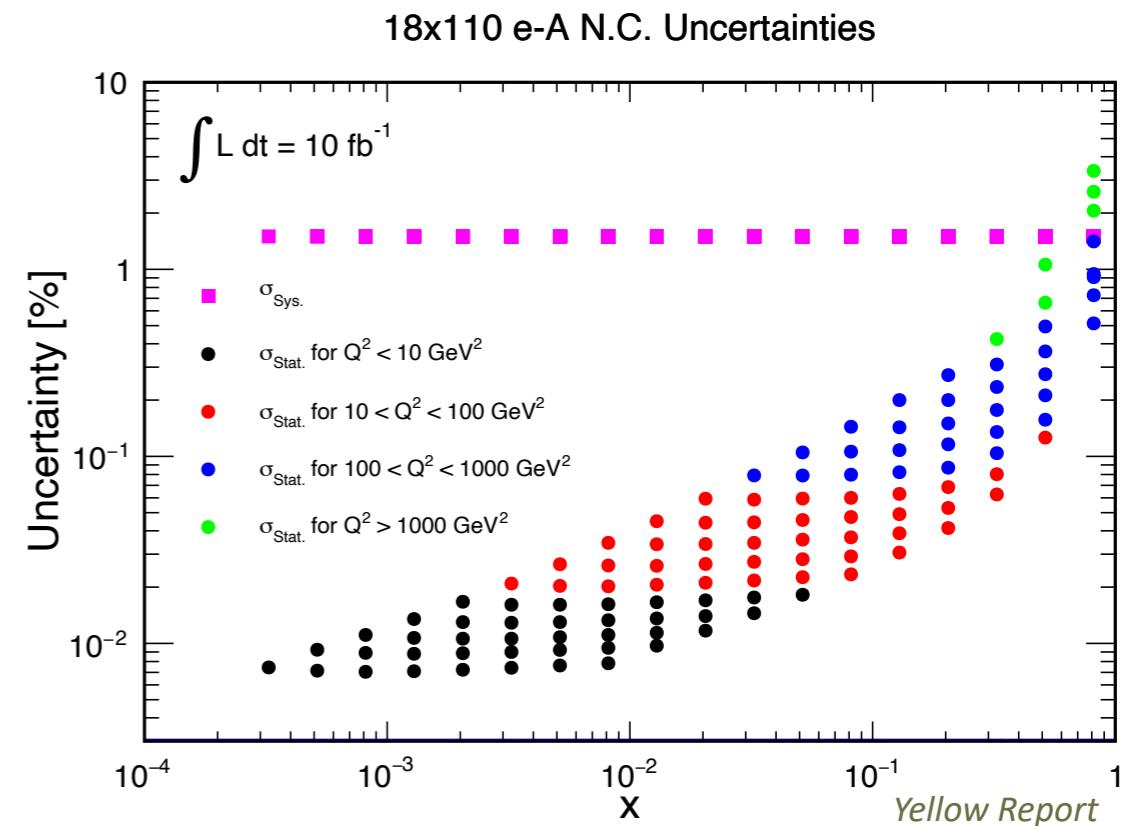
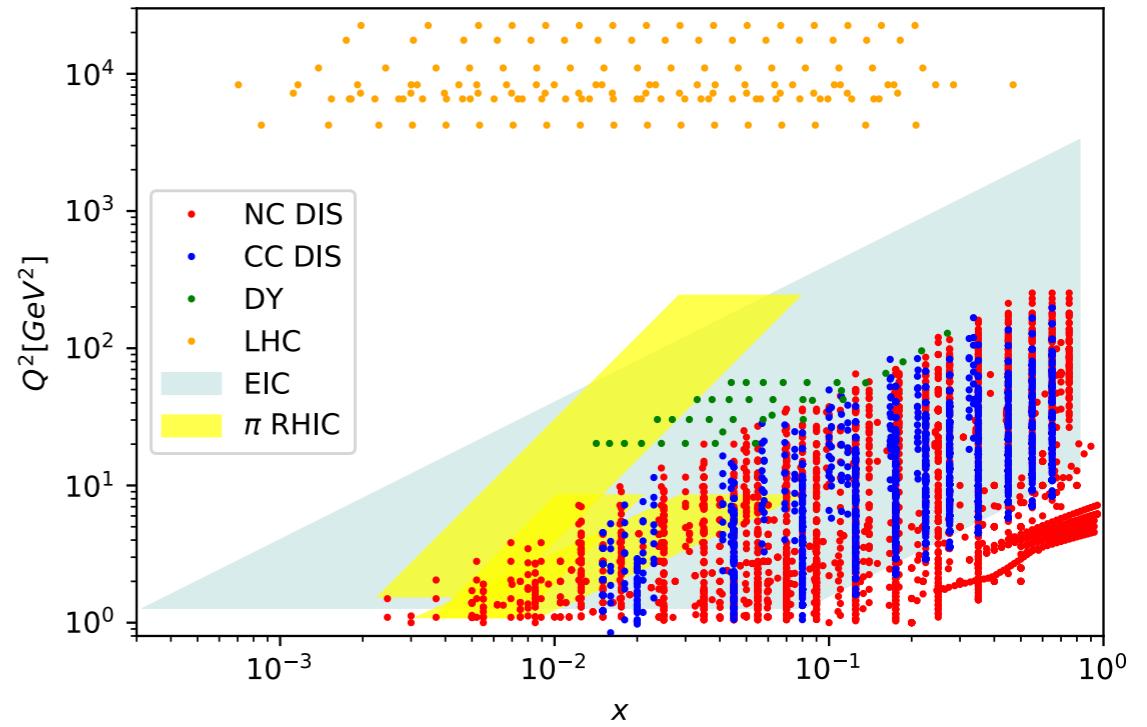
Global structure of nuclei

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha_{\text{em}}^2}{xQ^4} Y_+ \sigma_r(x, Q^2)$$

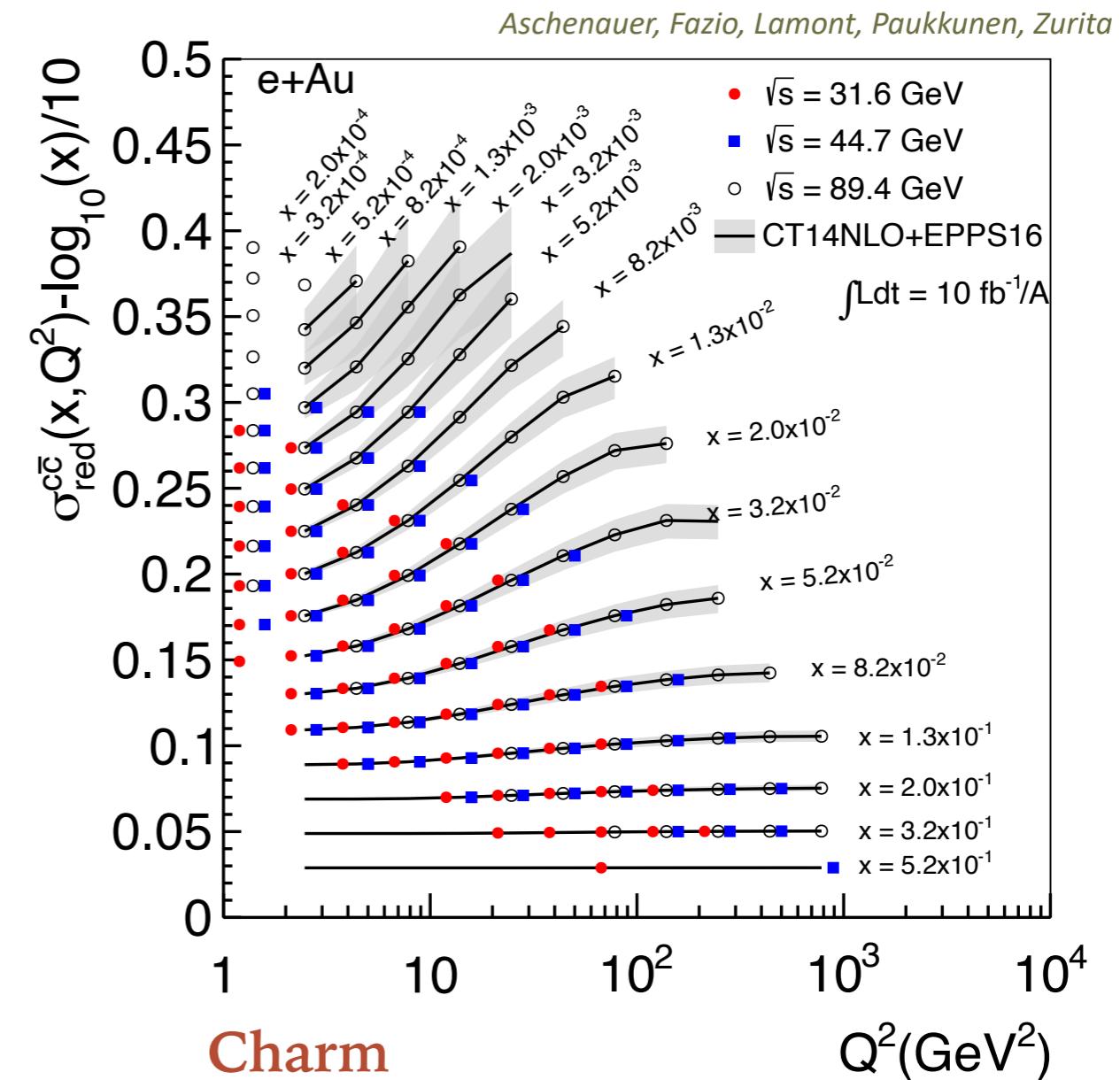
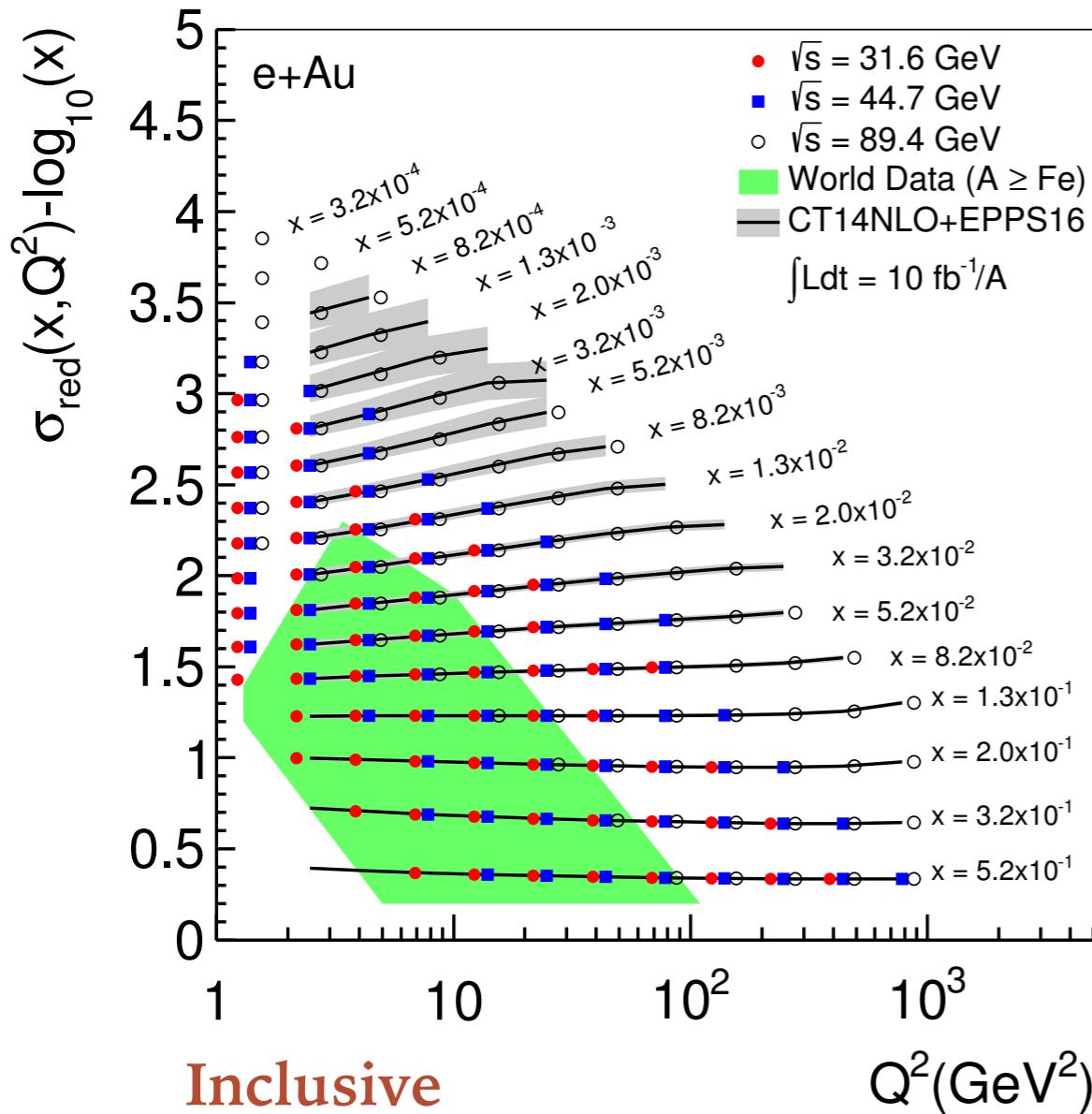
$$\sigma_r(x, Q^2) = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

$$Y_+ = 1 + (1 - y)^2$$

- 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



- 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

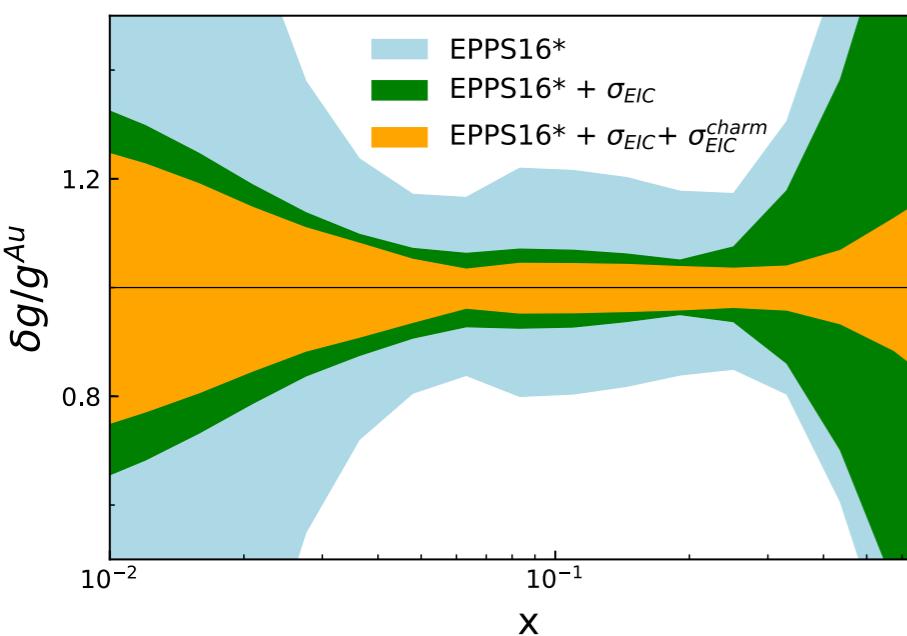
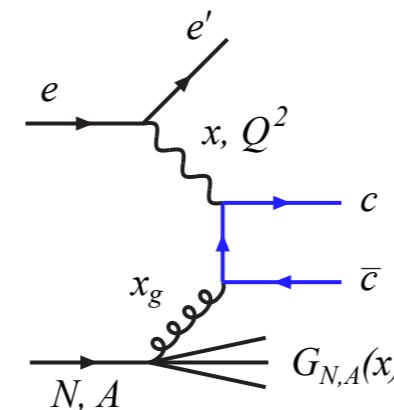
Collinear factorization

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

Nuclear modification in this framework:

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

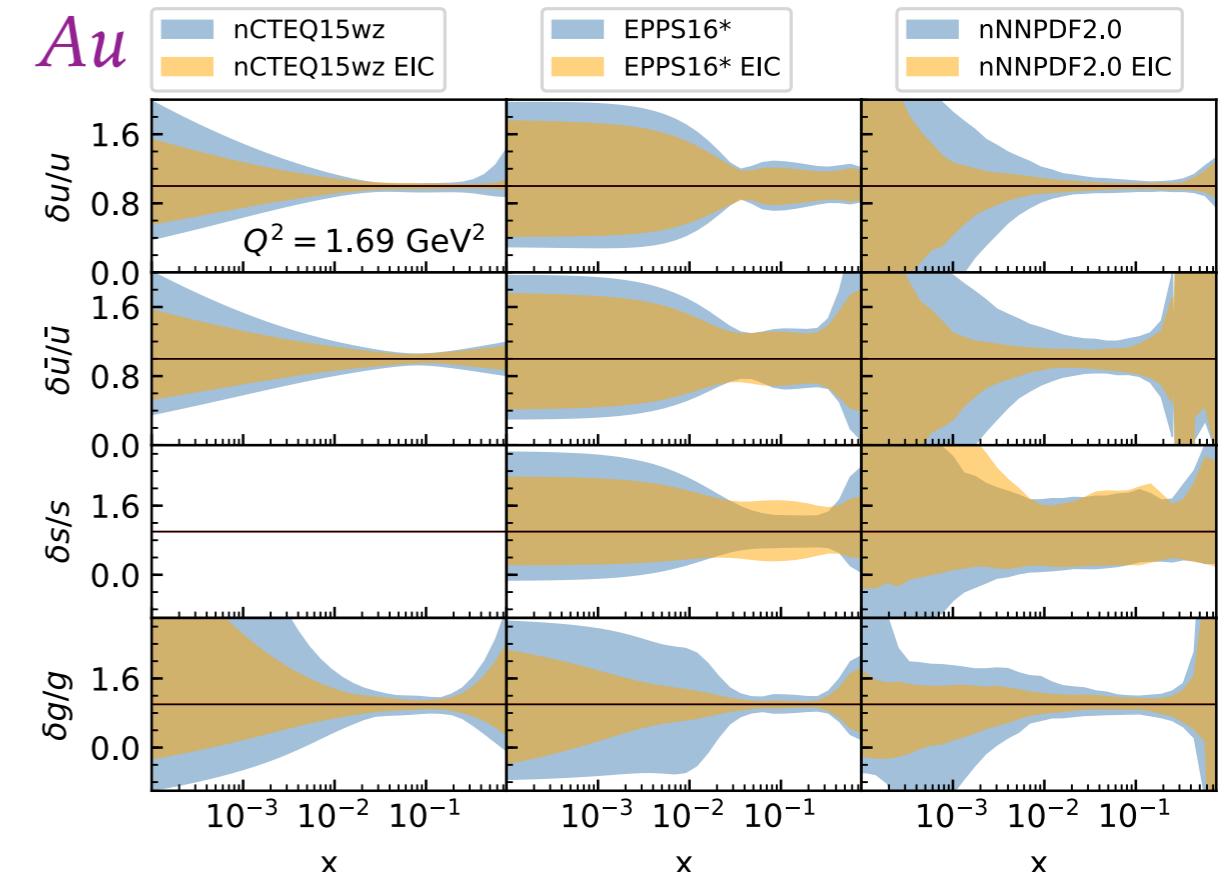
- Impact of **charm cross section** on the gluon PDF at high x
- Charm is produced mainly in the photon-gluon fusion process
- Further constraints: F_L



DGLAP : linear evolution

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

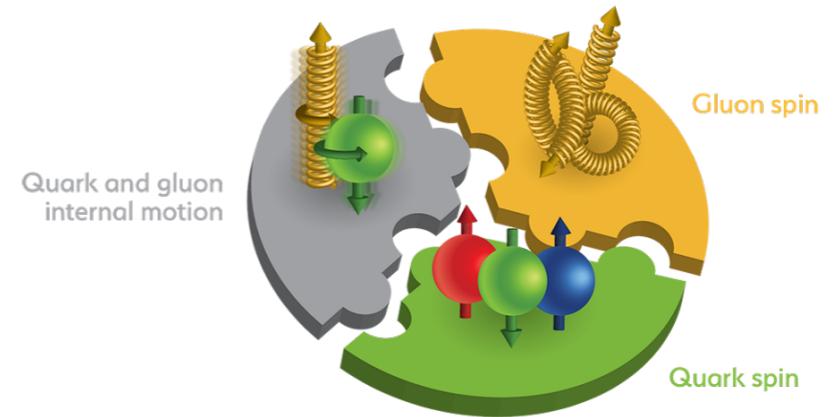
Yellow Report



Significant impact of EIC measurements on nuclear PDFs

Proton spin

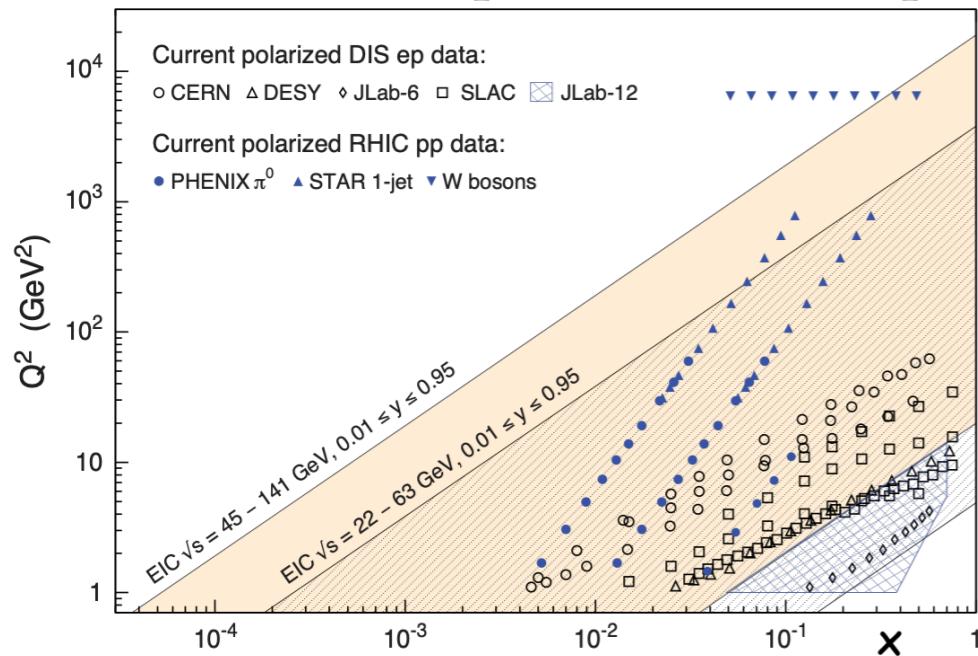
- Spin is fundamental property of particles. All elementary particles except Higgs carry non-zero spin.
- Proton spin cannot be explained within static picture.
- It depends on the intrinsic properties and interactions of quarks and gluons



$$\frac{1}{2} = \frac{1}{2} \int_0^1 dx \Delta\Sigma(x, Q^2) + \int_0^1 dx \Delta G(x, Q^2) + \int_0^1 dx \left(\sum_q L_q + L_g \right)$$

quark spin *gluon spin* *orbital angular momentum*

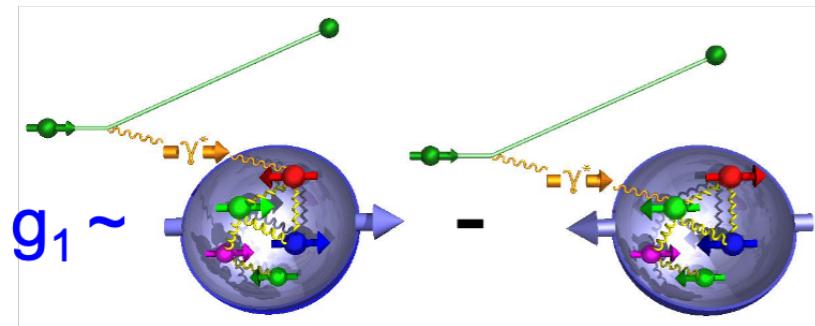
EIC kinematic plane vs current polarized data



- 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

$$\frac{1}{2} \left[\frac{d^2\sigma^{\leftrightarrow}}{dx dQ^2} - \frac{d^2\sigma^{\rightarrow}}{dx dQ^2} \right] \simeq \frac{4\pi\alpha^2}{Q^4} y (2-y) g_1(x, Q^2)$$



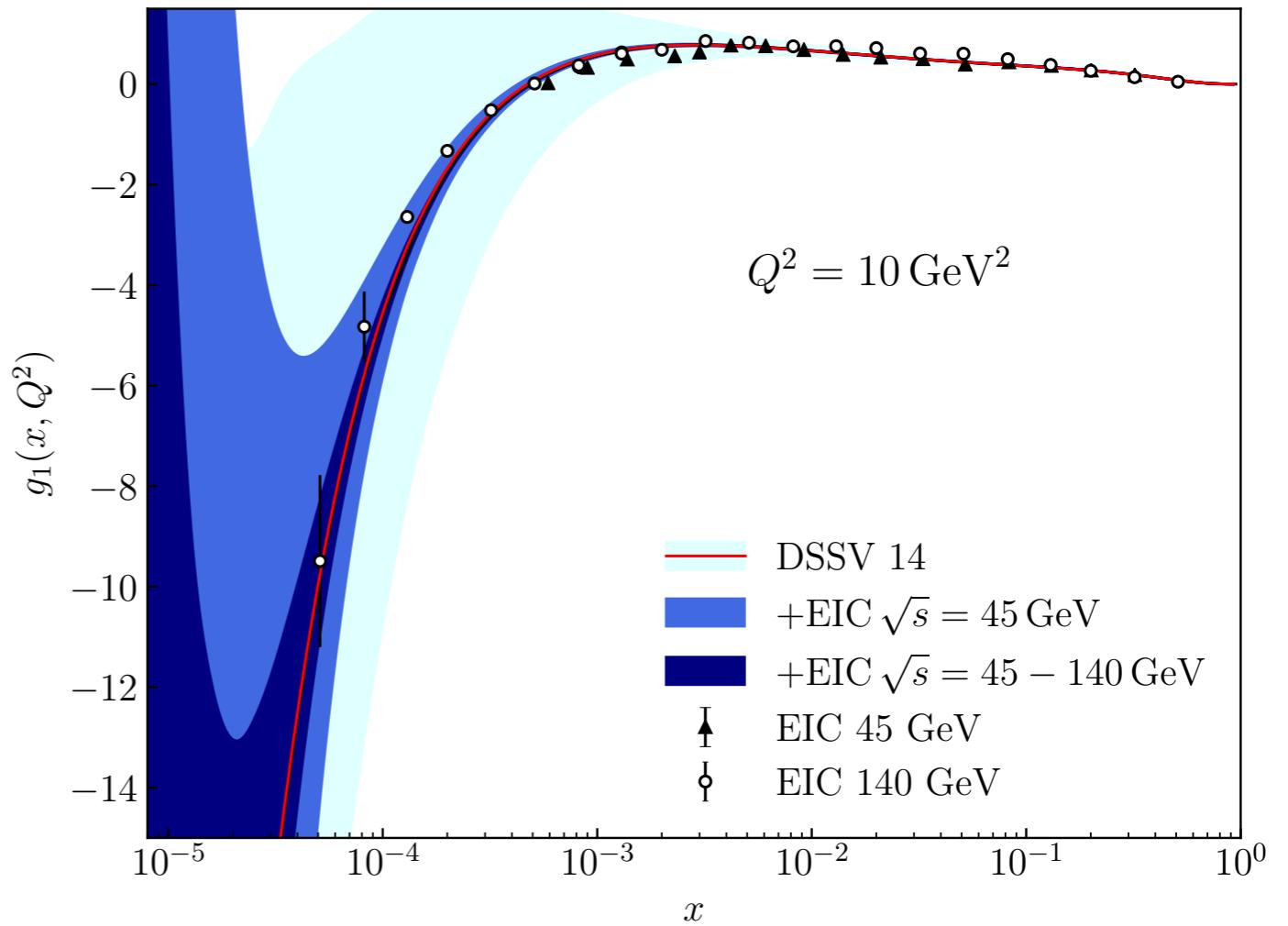
Quark contribution: integral over of g_1 over x from 0 to 1

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

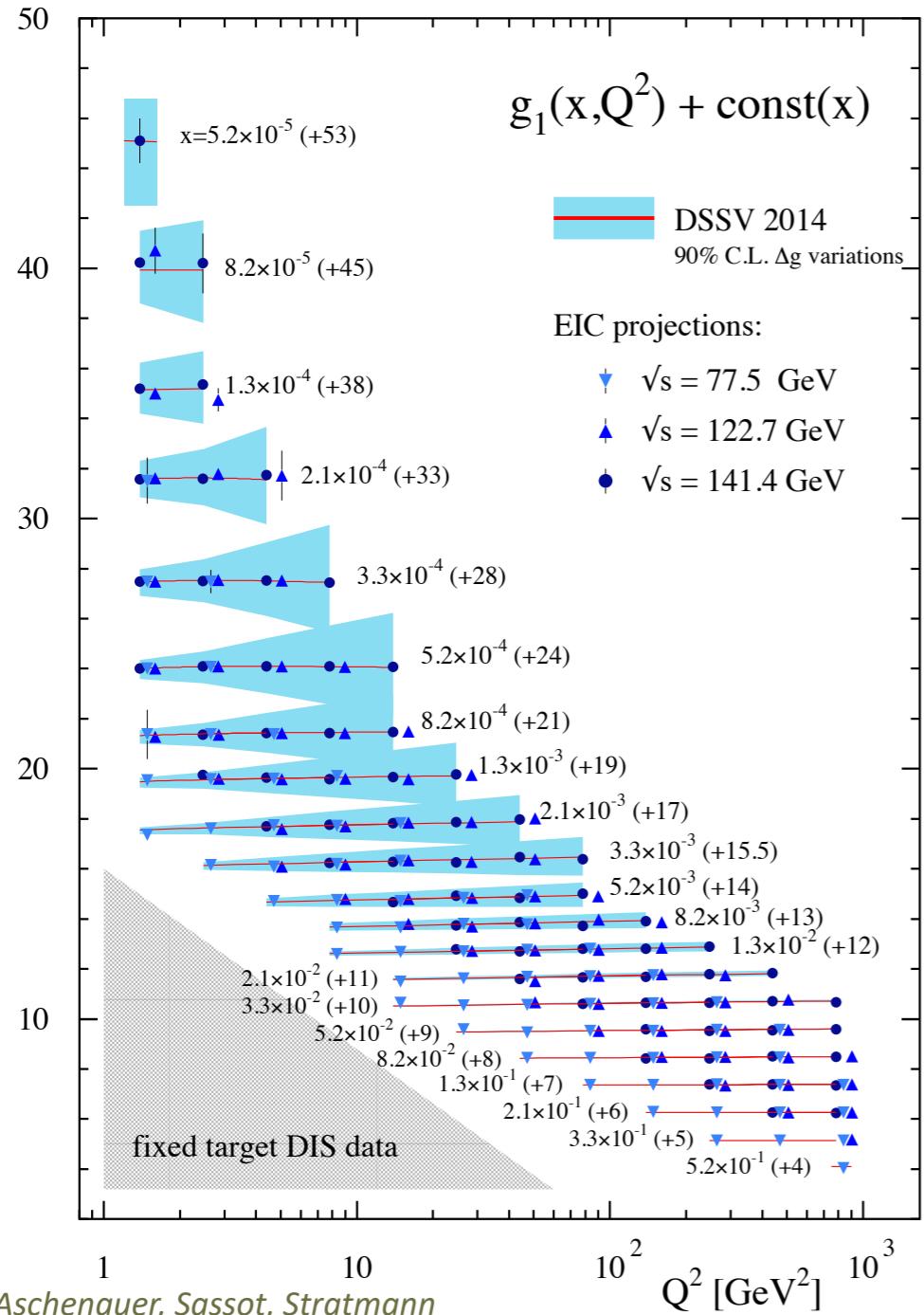
EIC projections leads to greatly reduced **uncertainties**



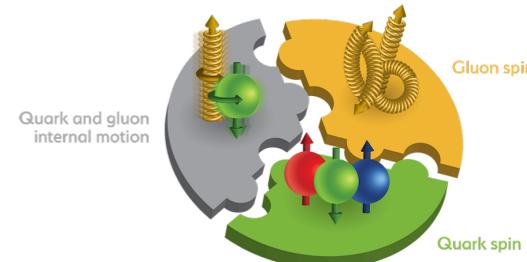
Borsa, Lucero, Sassot, Aschenauer, Nunes

Proton spin: constraints on the OAM

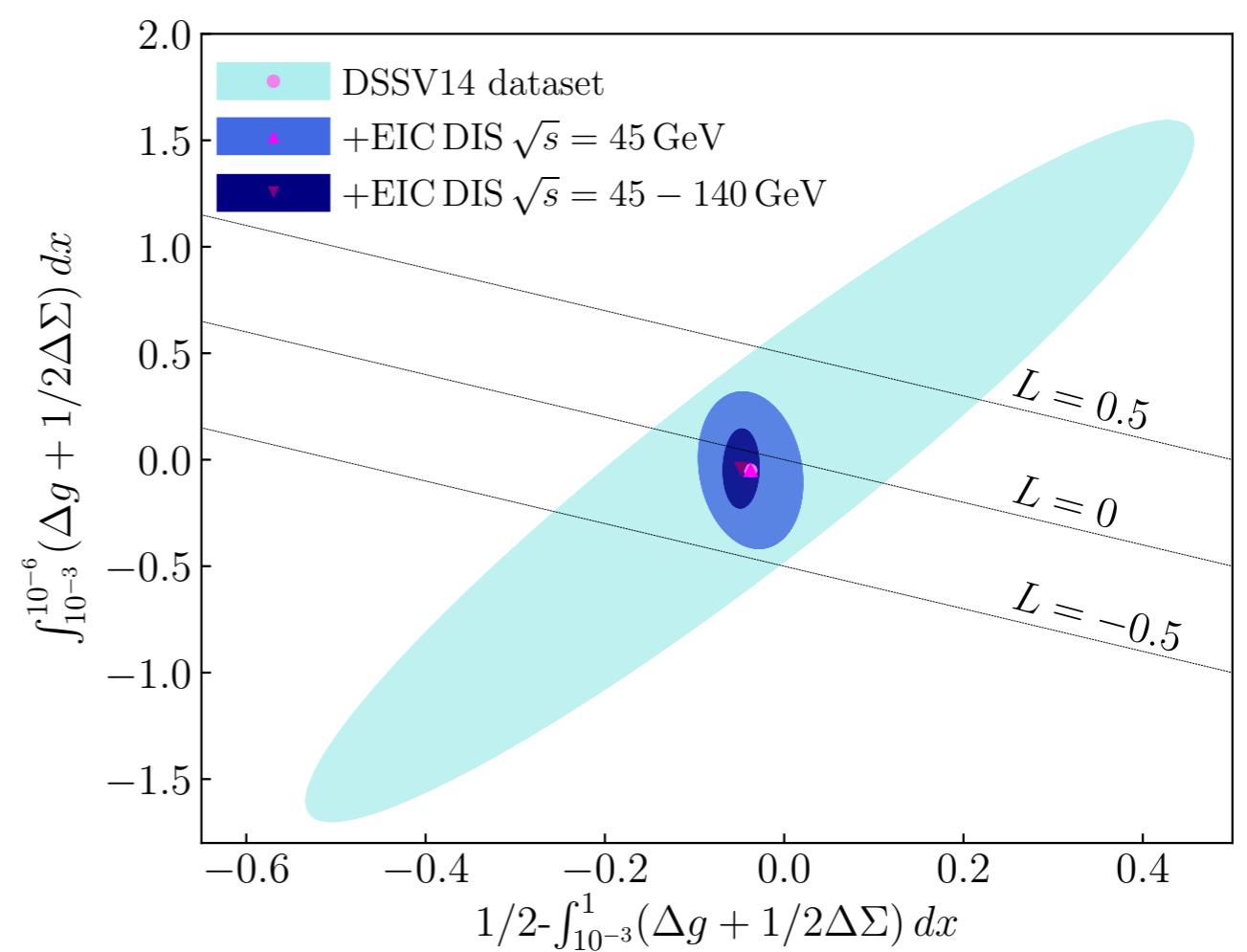
EIC projections over range of x and Q^2



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

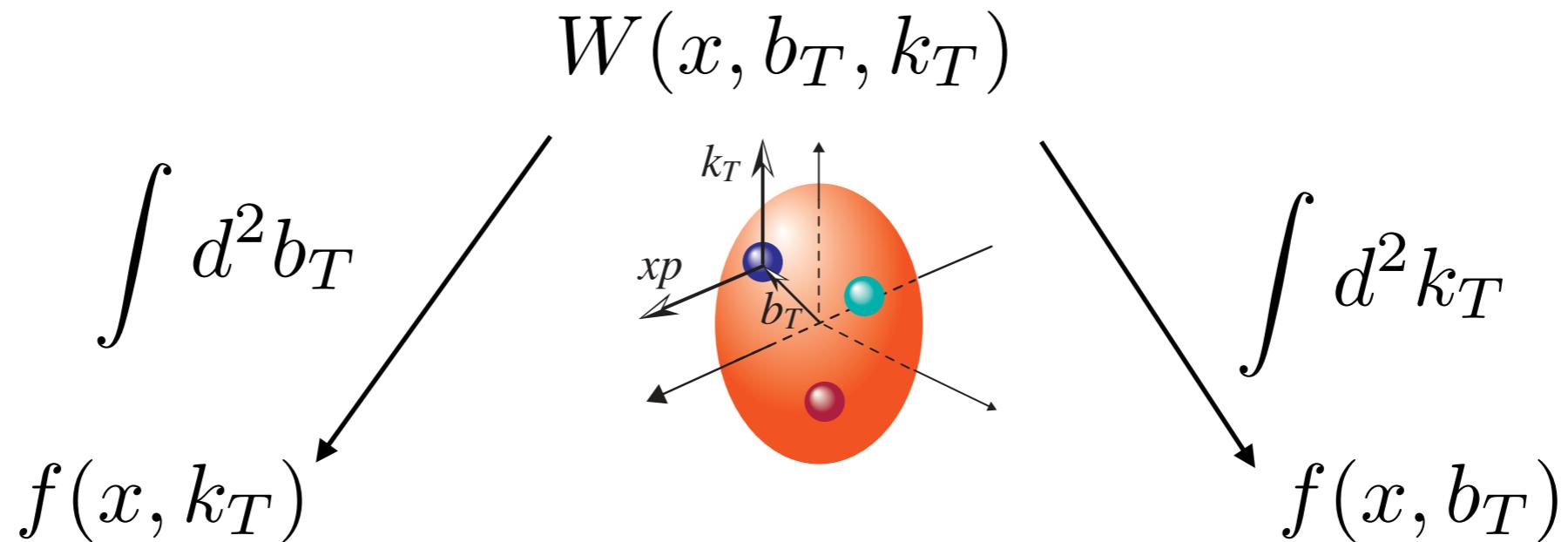


Borsa, Lucero, Sassot, Aschenauer, Nunes

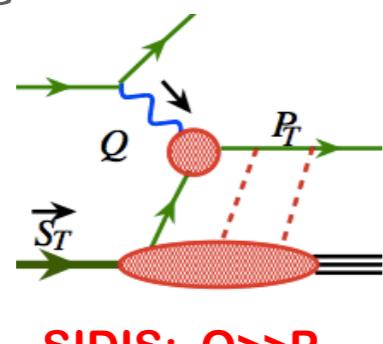


From 1D to 3D: imaging of nucleon

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

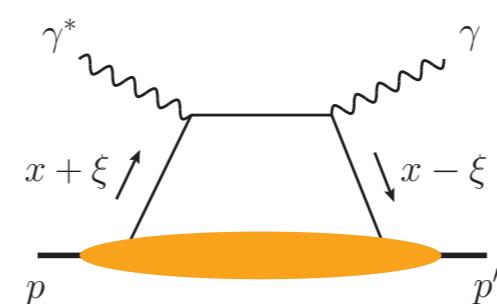


Transverse Momentum Dependent (TMDs),
measured from semi-inclusive DIS, also spin
dependent at EIC

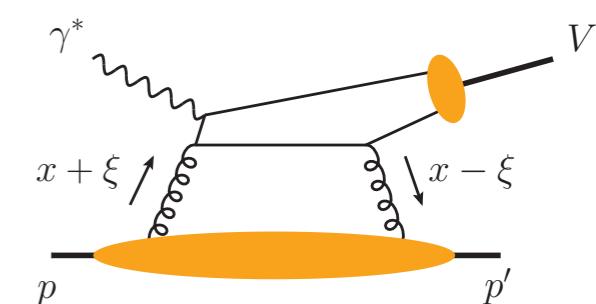


SIDIS: $Q >> p_T$

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



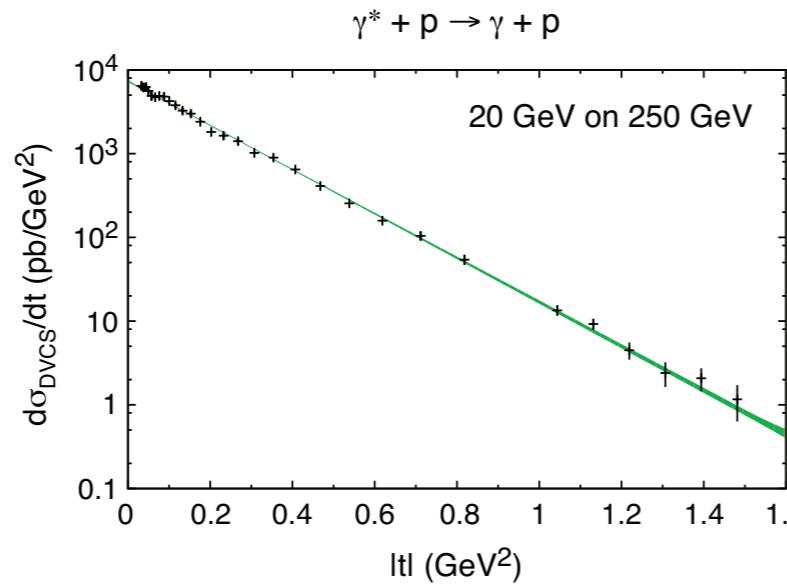
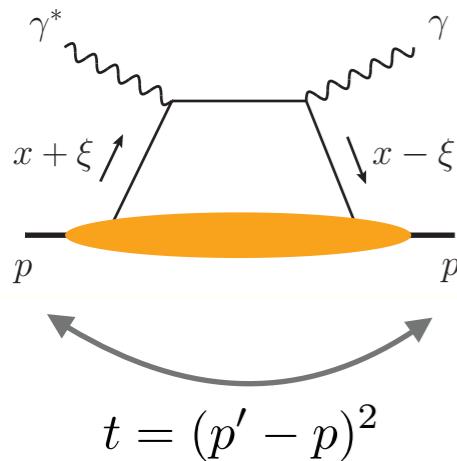
Deeply Virtual
Compton Scattering



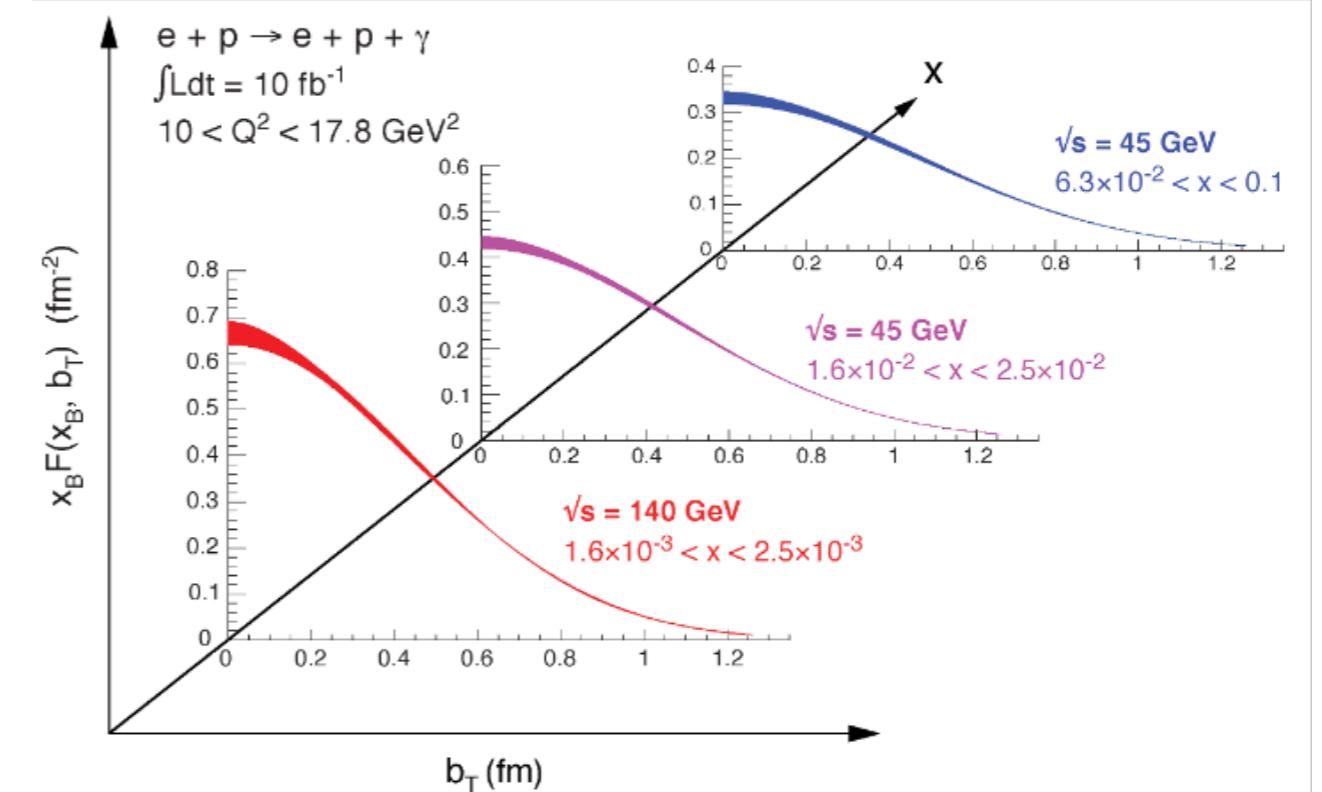
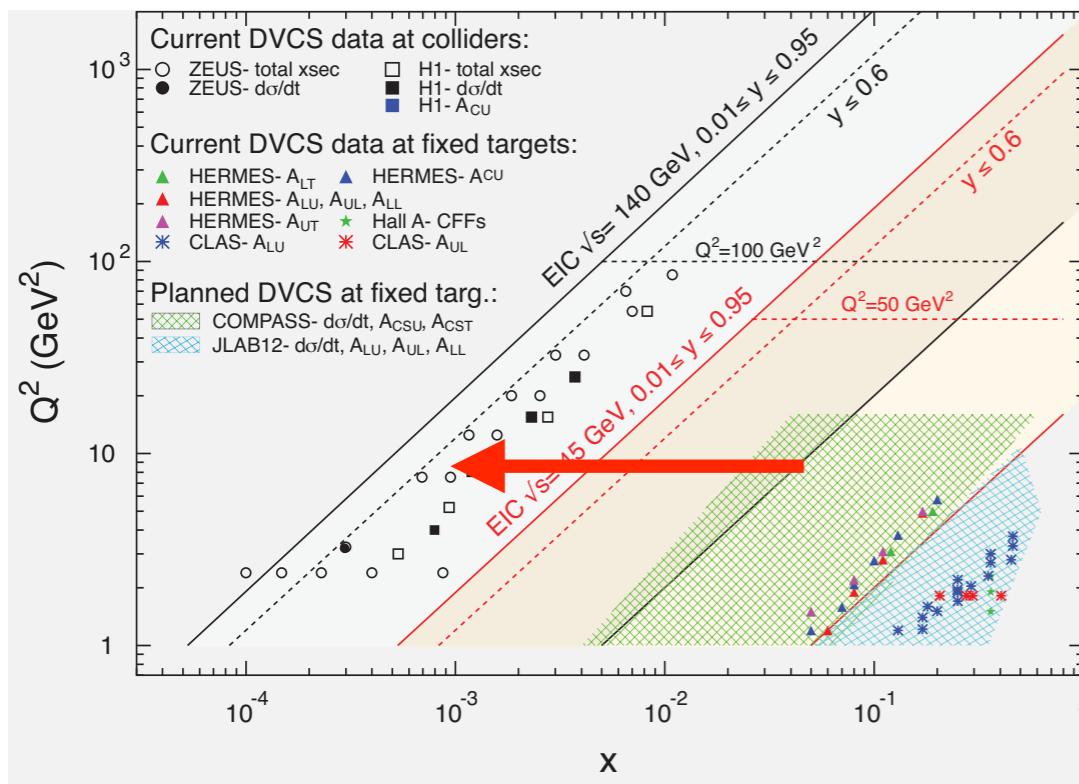
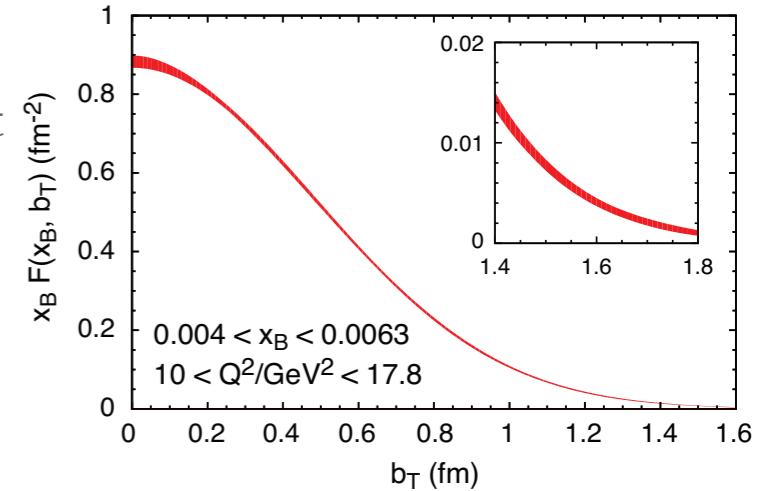
Elastic Vector Meson
production

Imaging of nucleon: quarks

DVCS
Quark information

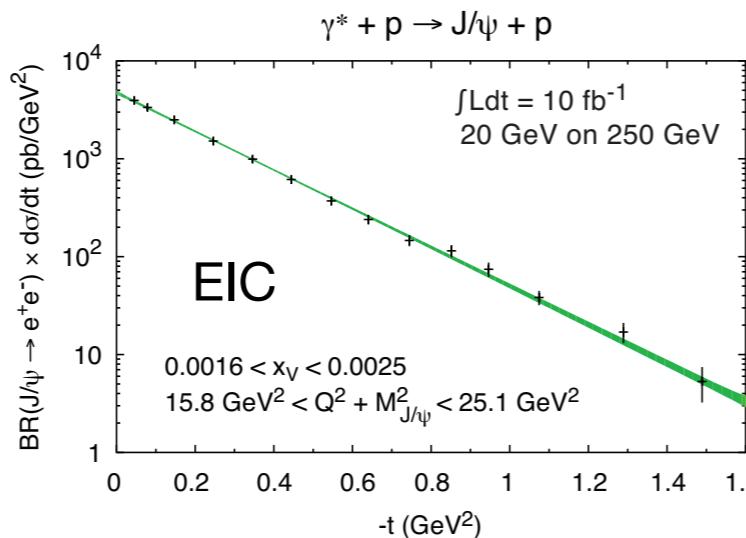
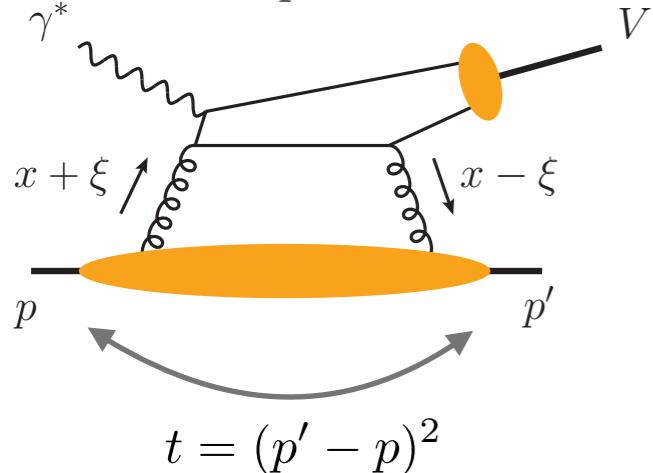


Fourier transform in t
provides spatial
distribution of quarks

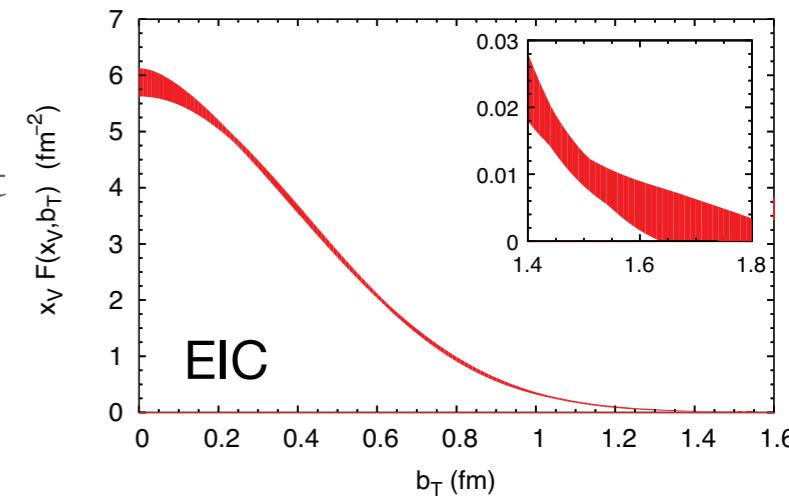


Imaging of nucleon: gluons

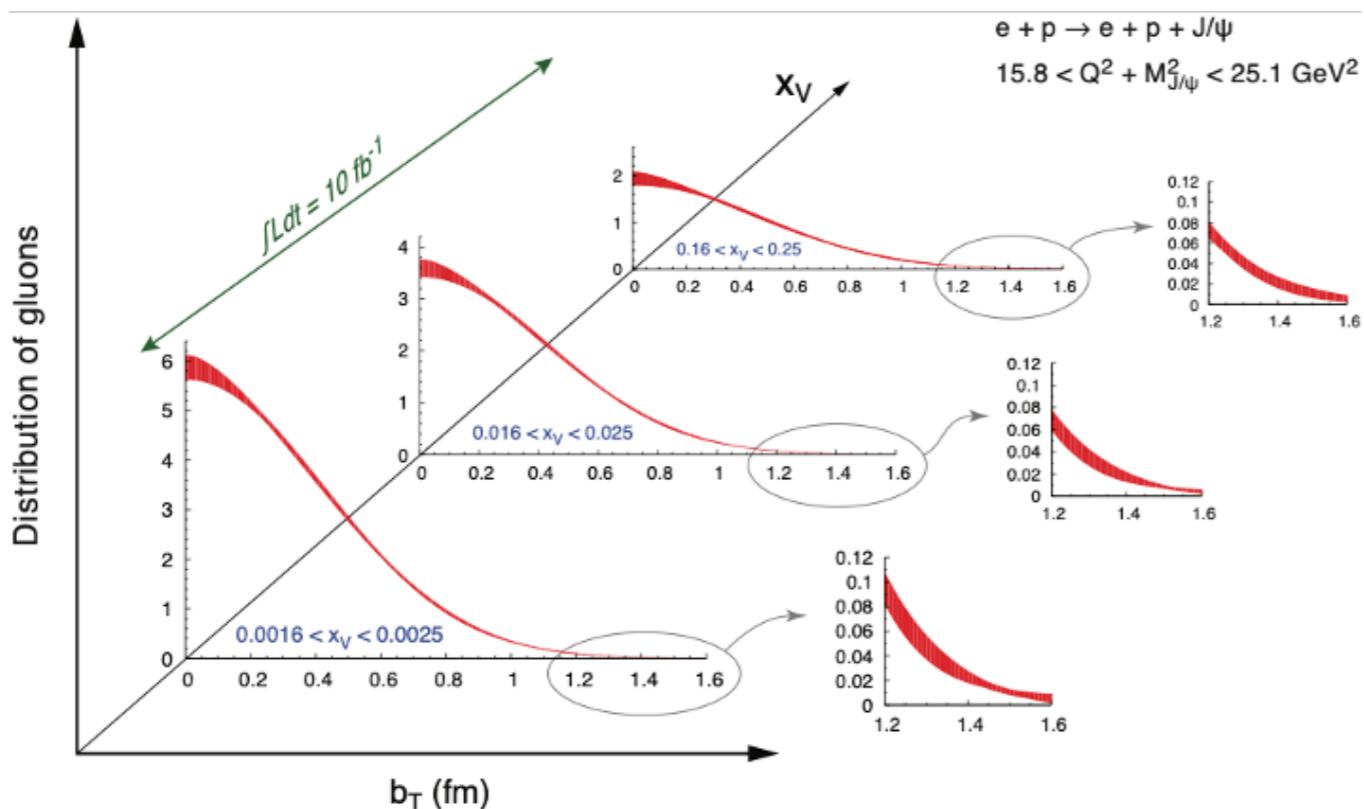
Elastic Diffractive Vector Meson production



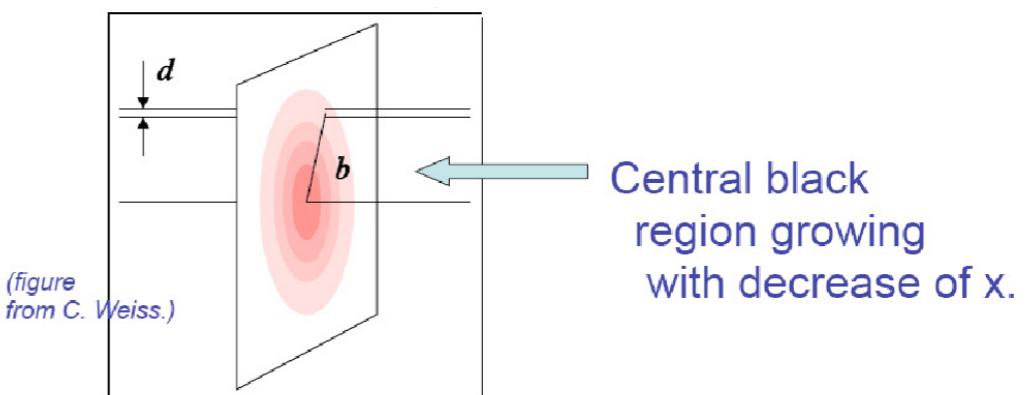
Fourier transform in t provides spatial distribution of gluons inside the nucleon



Extracted profiles for different x

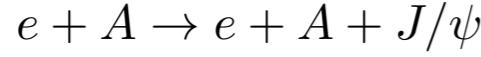


- Large $|t|$ probes small b : large density.
- Ideal for estimating the ‘blackness’ of the interaction: parton saturation

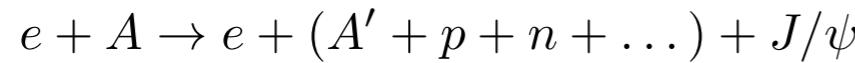


Imaging of nucleus

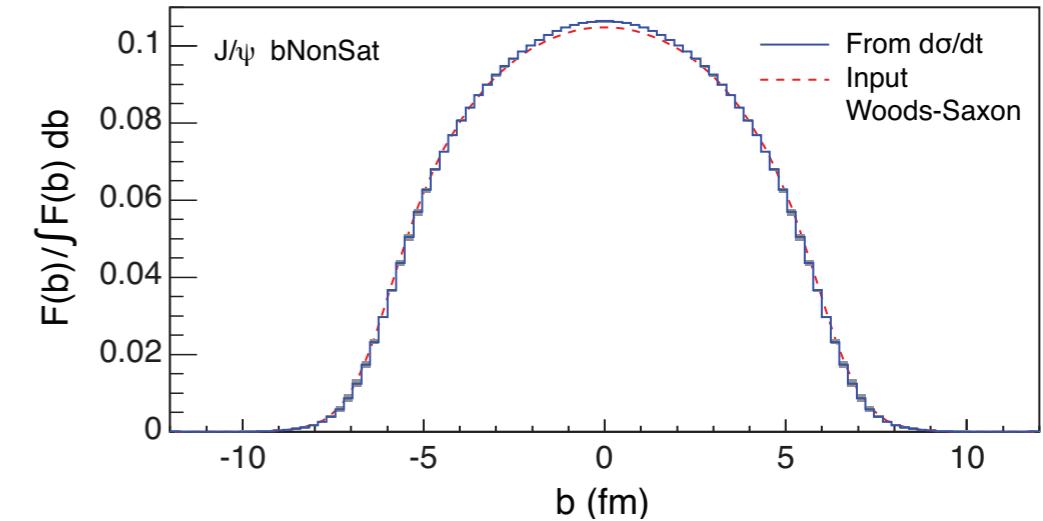
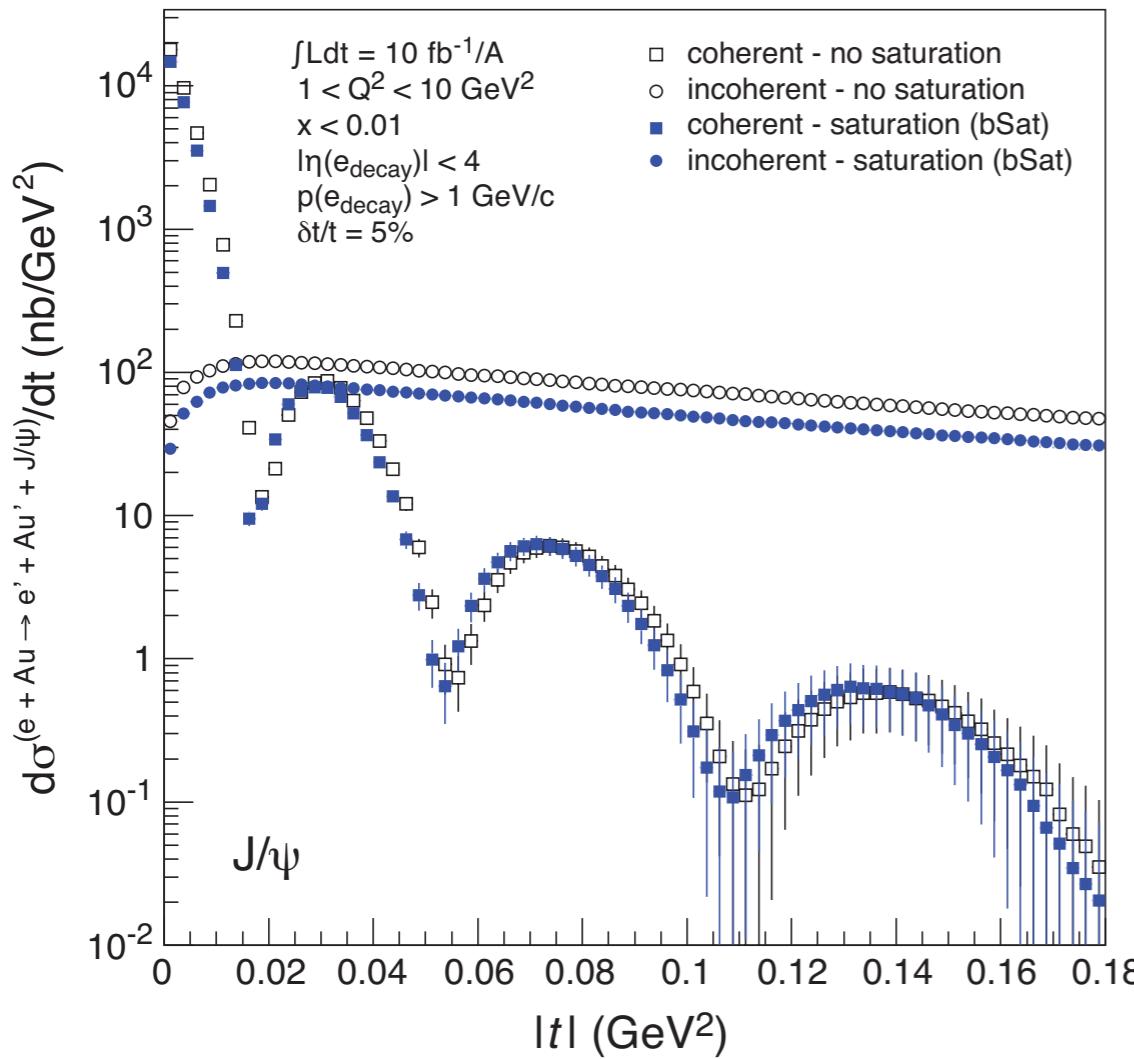
EIC, White paper



coherent: nucleus stays intact



incoherent: nucleus breaks up



$$t = -\Delta^2$$

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

- 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)
- Separation experimentally very challenging
- 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 resummed calculations in reactions with nuclei
- EIC will provide important input on **hadronization** mechanism in eA
- Different scenarios: **parton evolution in medium** or **hadron absorption**



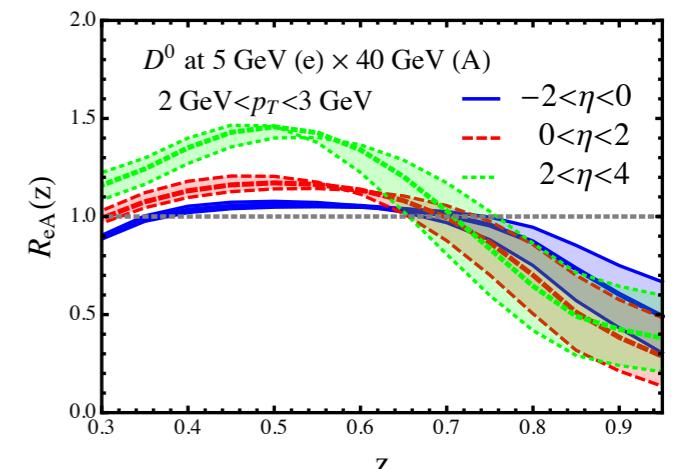
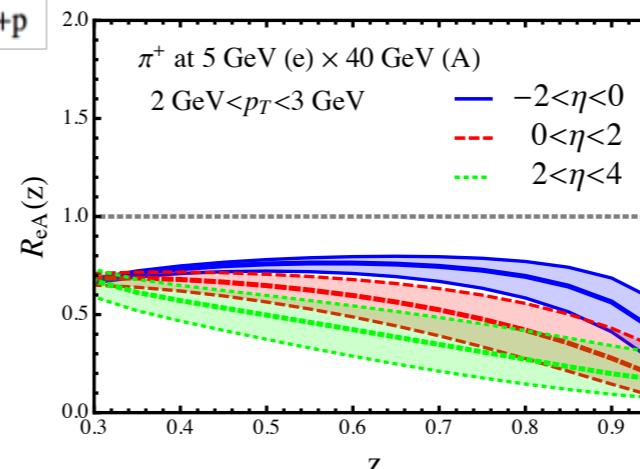
Parton energy loss and in-medium fragmentation function modification

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

$$R_{eA}^h(p_T, \eta, z) = \frac{\frac{N^h(p_T, \eta, z)}{N^{\text{inc}}(p_T, \eta)} \Big|_{e+Au}}{\frac{N^h(p_T, \eta, z)}{N^{\text{inc}}(p_T, \eta)} \Big|_{e+p}}$$

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

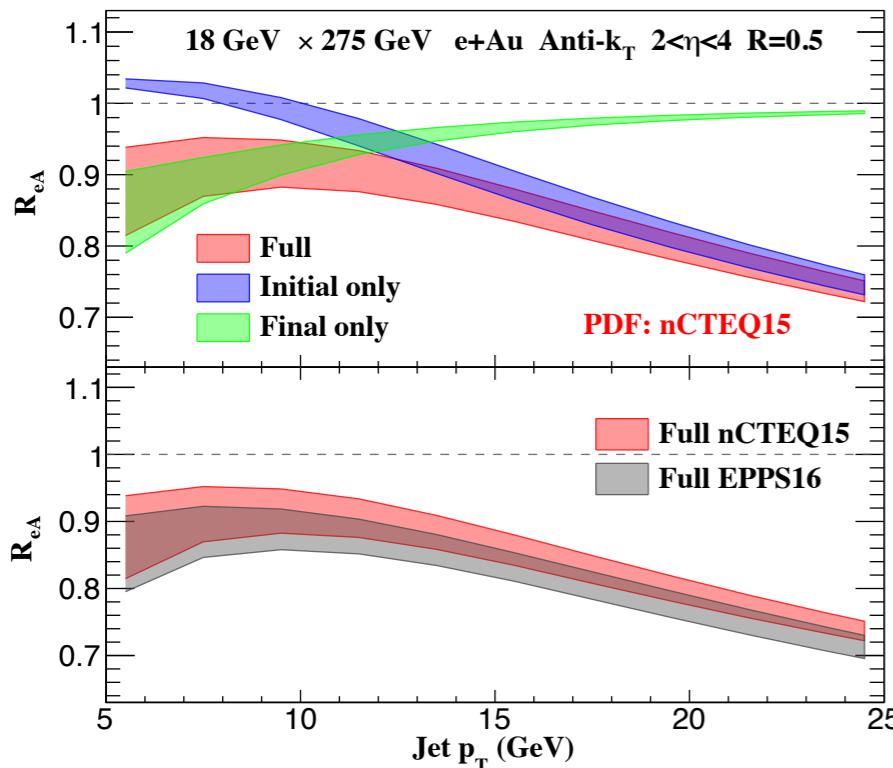
Jets emerged as a premier diagnostic tool for **hot** nuclear matter at RHIC and LHC

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

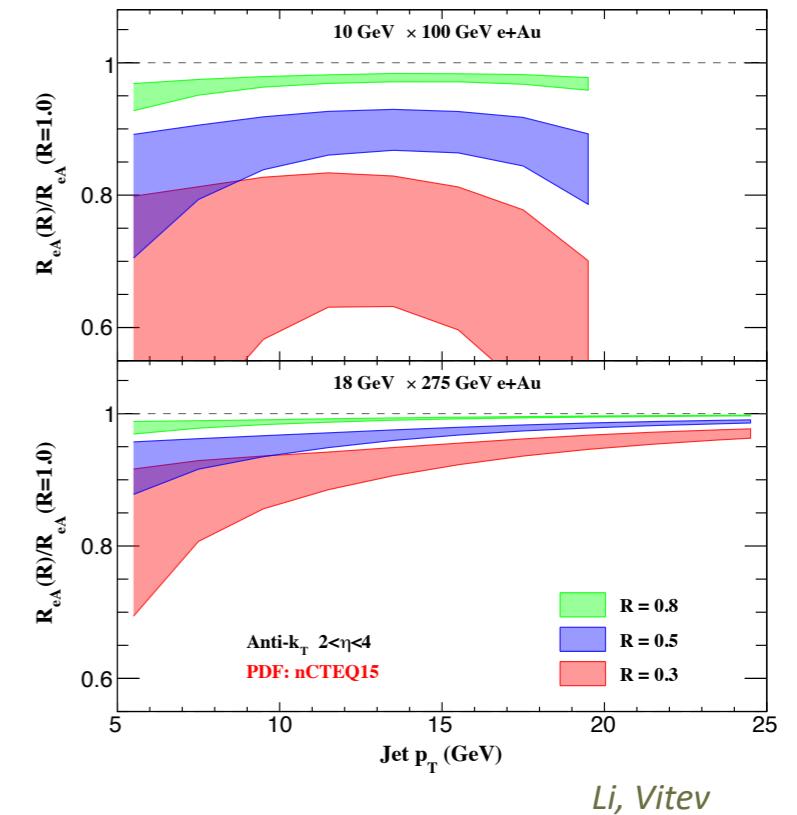
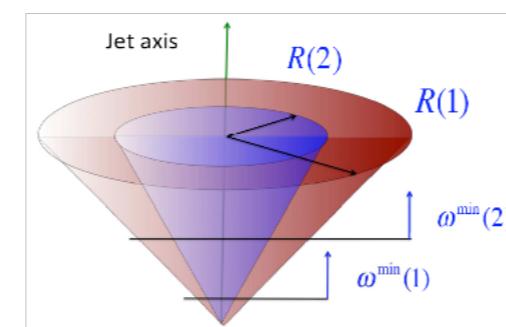
$$d\sigma \sim f_a(z, \mu) \otimes H_{ab}(x, z; p_T, \eta) \otimes J_b(z, \mu, R)$$

initial final

Yellow Report

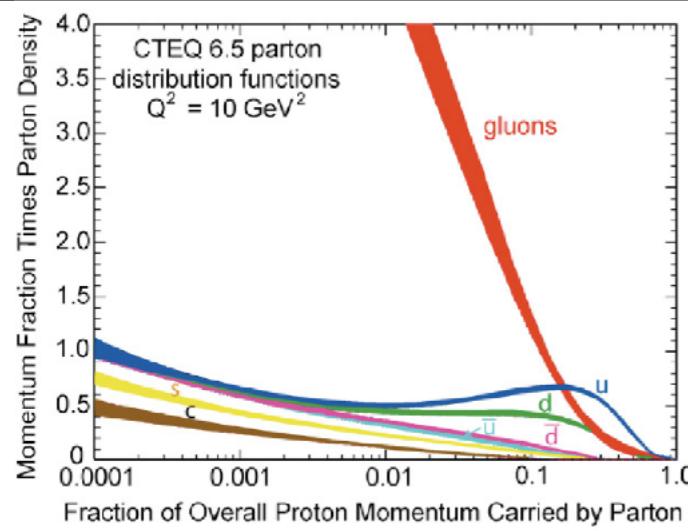


- IS (large and small p_T) vs FS (small p_T) contributions to nuclear ratio
 - Small nPDF effects
 - Ratios with different jet cone allow to separate parton shower effects

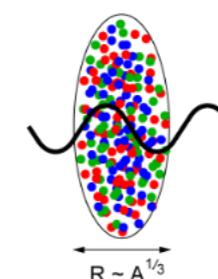


- Pioneer jet **substructure** studies with heavy quark initiated jets performed in a EIC regime very different from the one probed in heavy ion collisions *Li, Liu, Vitev*
 - Pave the way to a qualitatively new level of understanding of the role of **heavy quark mass**

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

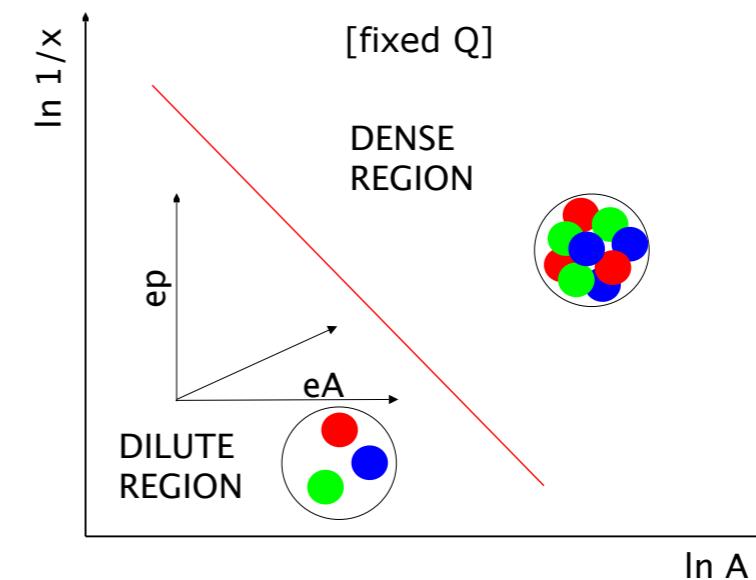
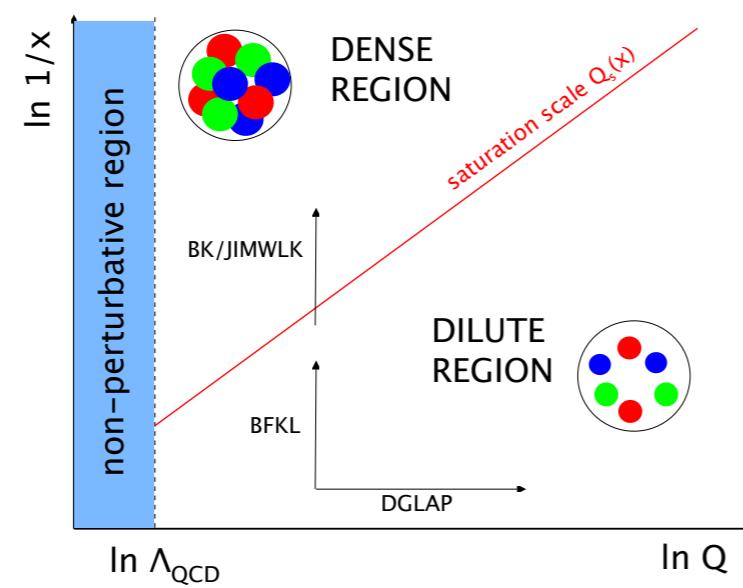


QCD at high energy (low x) and/or high density (large A) predicts **saturation** of gluons

Effective theory of QCD at high energy/density:

Color Glass Condensate CGC McLerran, Venugopalan,...

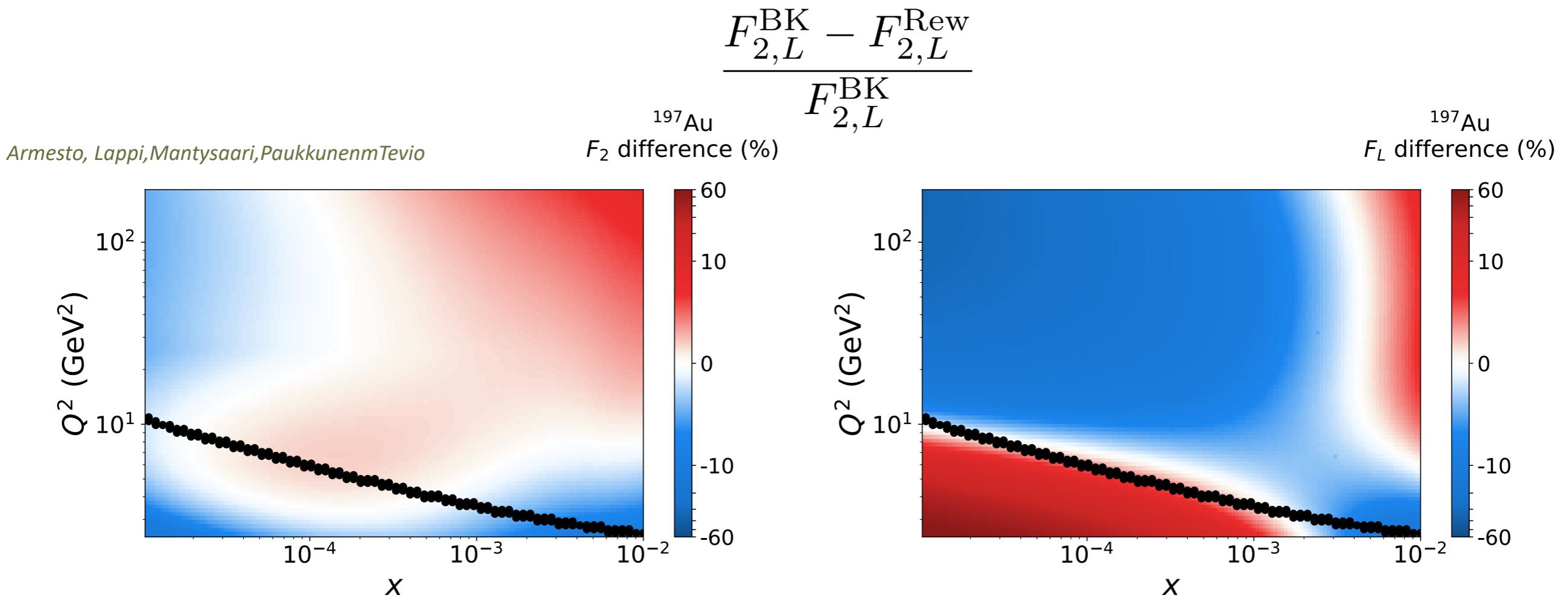
$$Q_s^2(x, A) \sim \frac{A^{1/3}}{x^\lambda}$$



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**

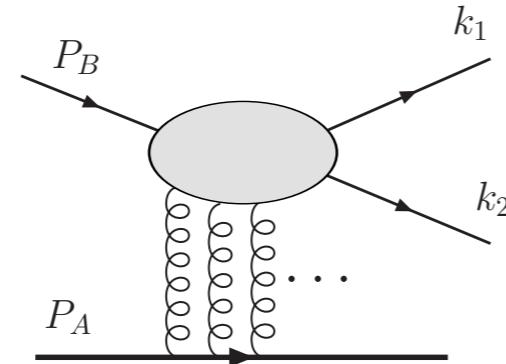


Heavy nucleus: difference between DGLAP and nonlinear are few % for F_2^A and up to 20% for F_L^A .

Longitudinal structure function can provide good sensitivity at EIC

Testing saturation through (de)correlations of hadrons

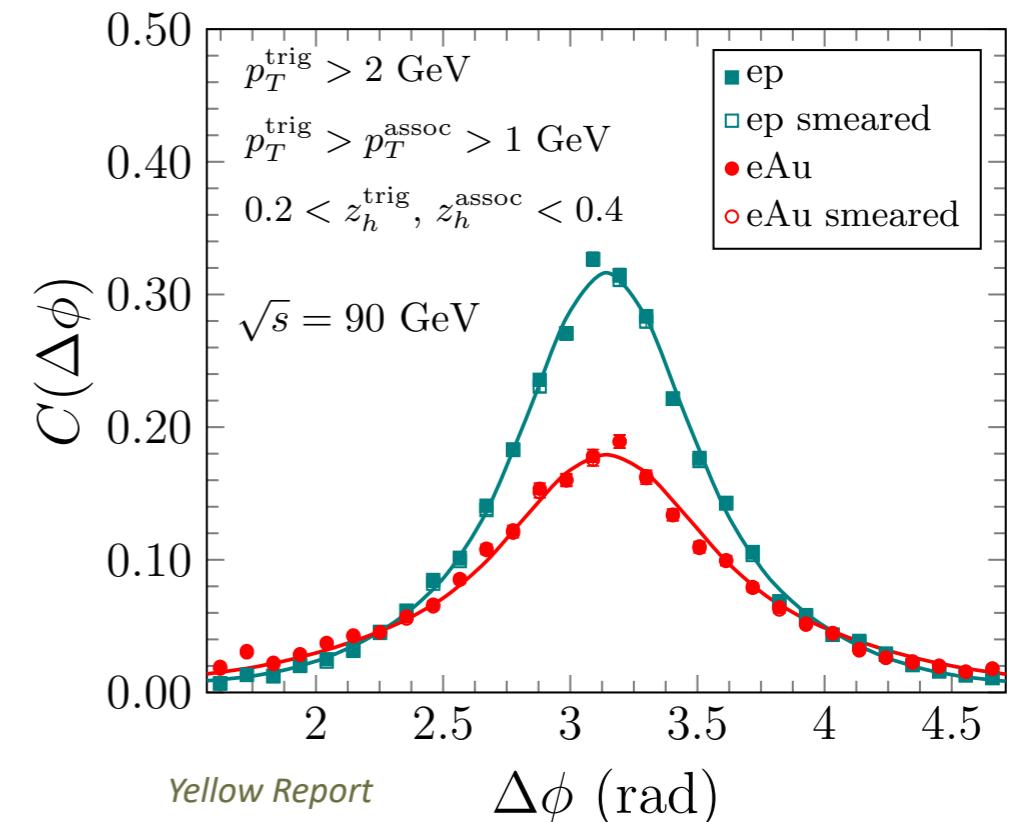
Azimuthal (de)correlations of two hadrons (dijets) in DIS in eA: direct test of the **Weizsäcker -Williams unintegrated gluon distribution**



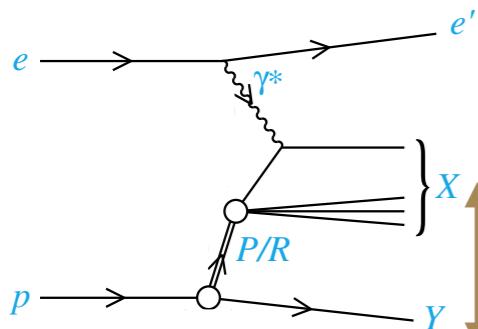
$$C(\Delta\phi) = \frac{1}{\frac{d\sigma_{\text{SIDIS}}^{\gamma^* + A \rightarrow h_1 + X}}{dz_{h1}}} \frac{d\sigma_{\text{tot}}^{\gamma^* + A \rightarrow h_1 + h_2 + X}}{dz_{h1} dz_{h2} d\Delta\phi}$$

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

- ▶ 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**



Inclusive diffraction at EIC

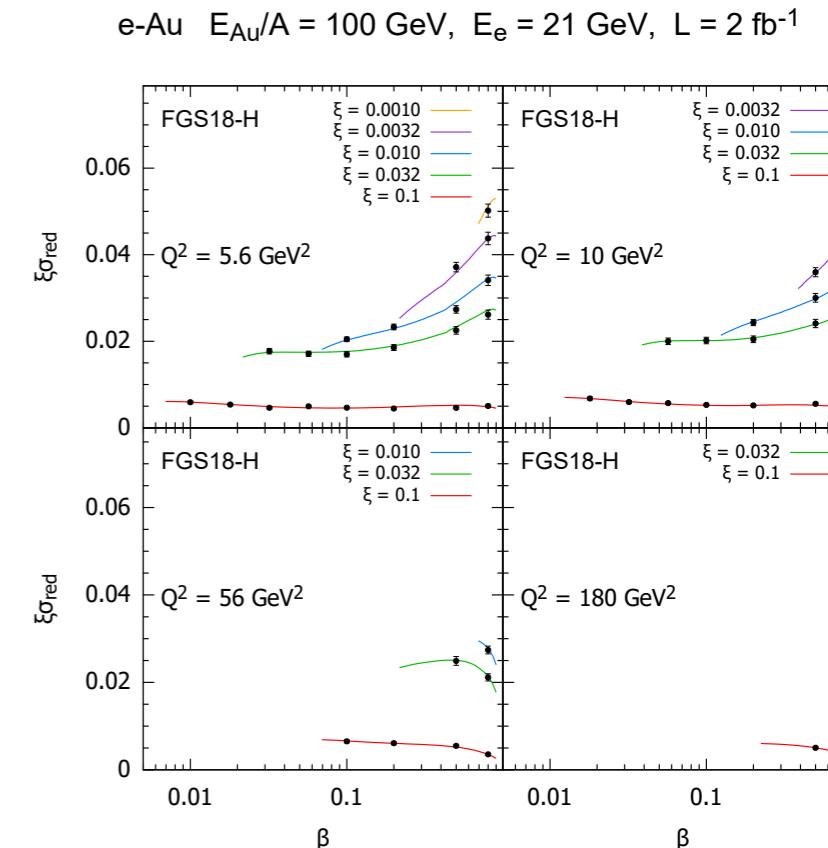
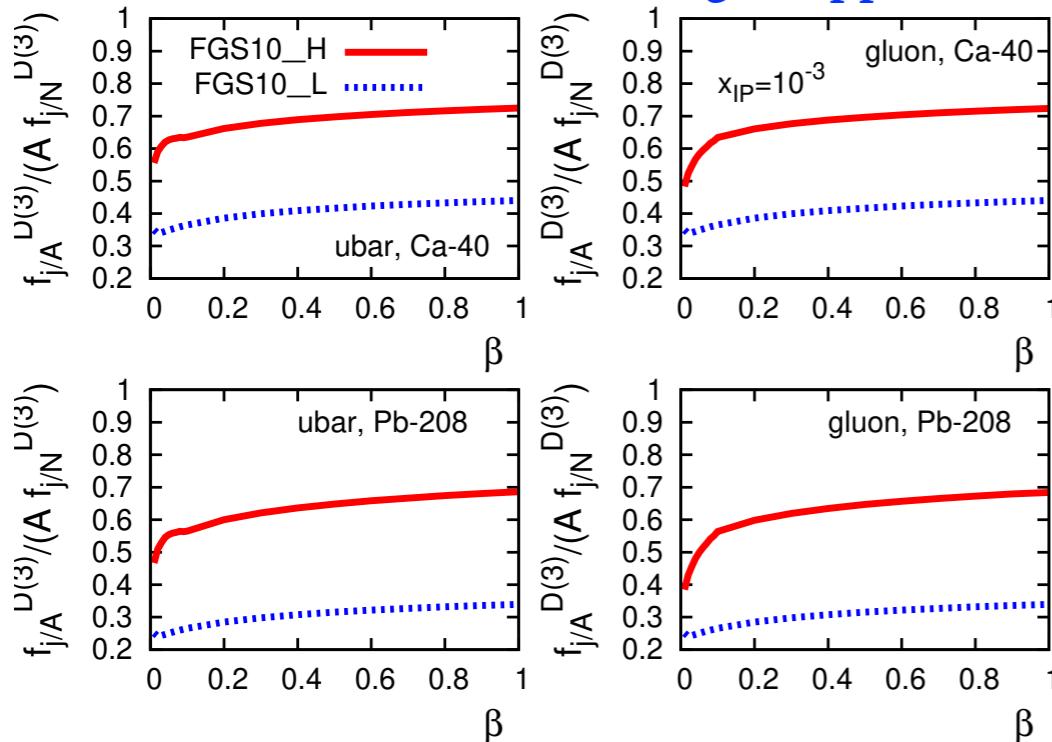


Diffraction: characterized by the **rapidity gap**
Interpretation : need **colorless exchange**

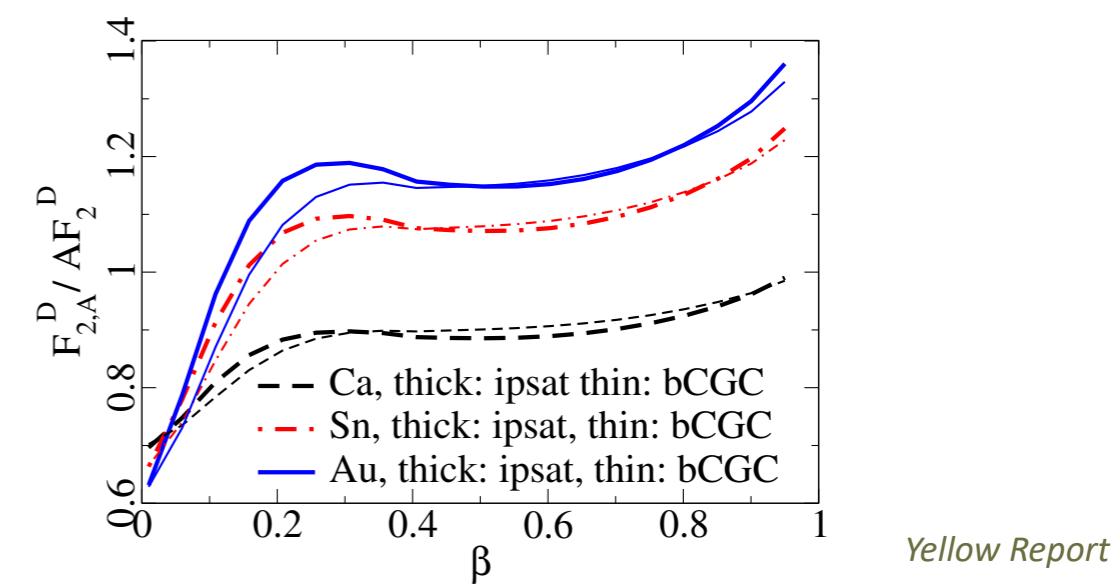
What is the nature of this exchange?

- 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



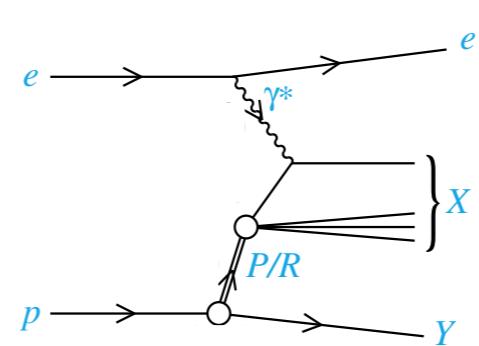
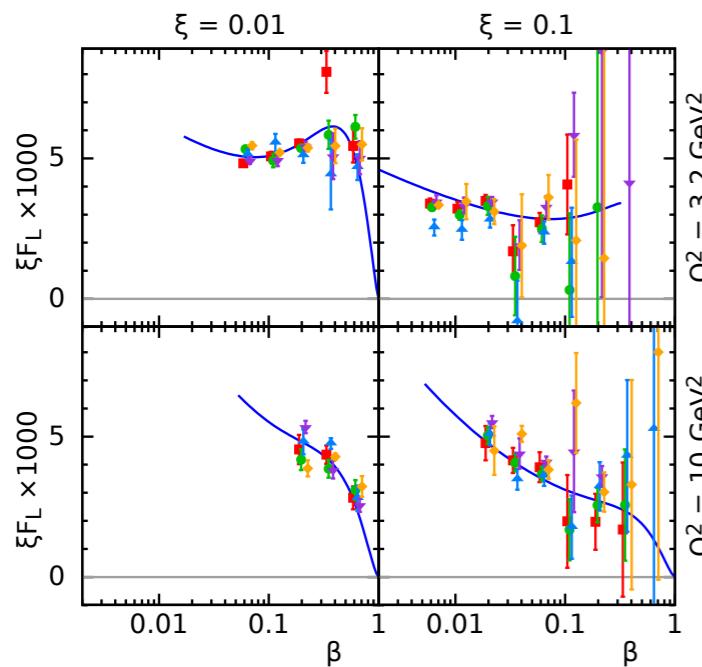
Diffraction in ep/eA

F_L^D diffractive longitudinal structure function

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

- Sensitive to **diffractive gluon density** (saturation, higher twists...).
- Only one extraction at HERA by H1, large errors. Challenging measurement.
- EIC : excellent prospects for F_L^D measurement.

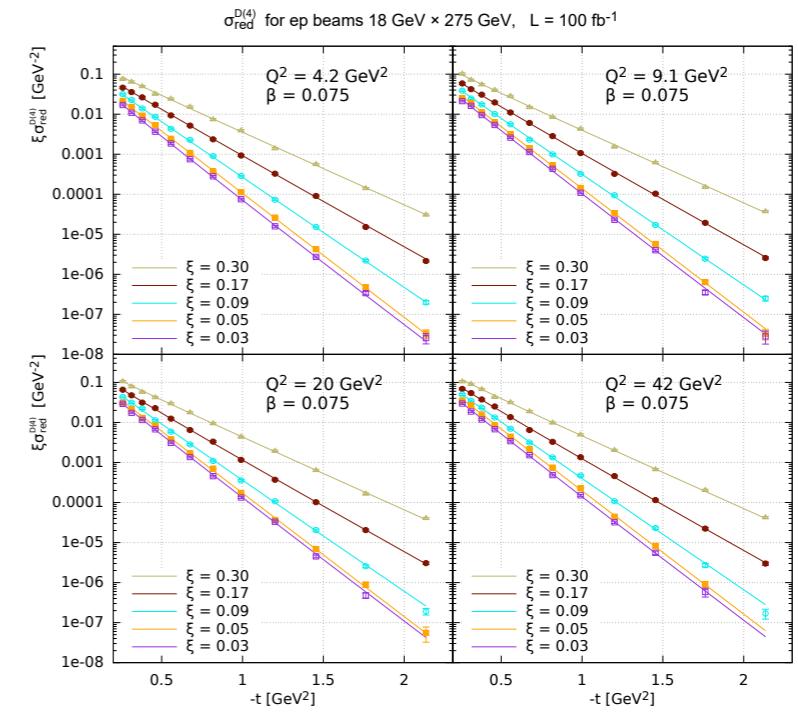
Armesto, Newman, Slominski, Stasto



EIC can reveal the details of the colorless exchange

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

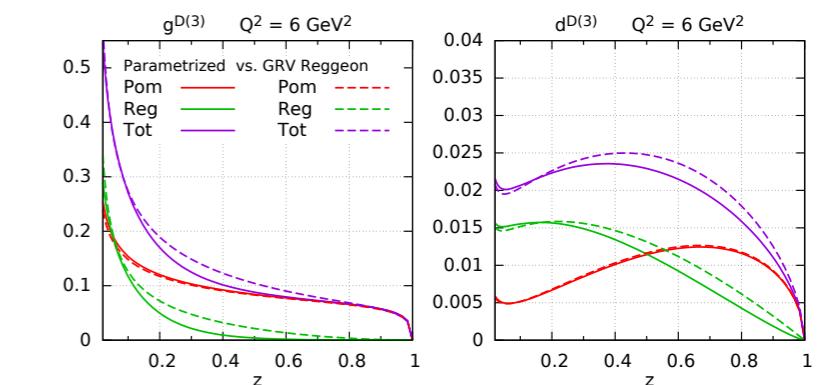
Precision measurement of **t-dependence** of $\sigma_r^{D(4)}$



Partonic content of the colorless exchange

gluon

quark

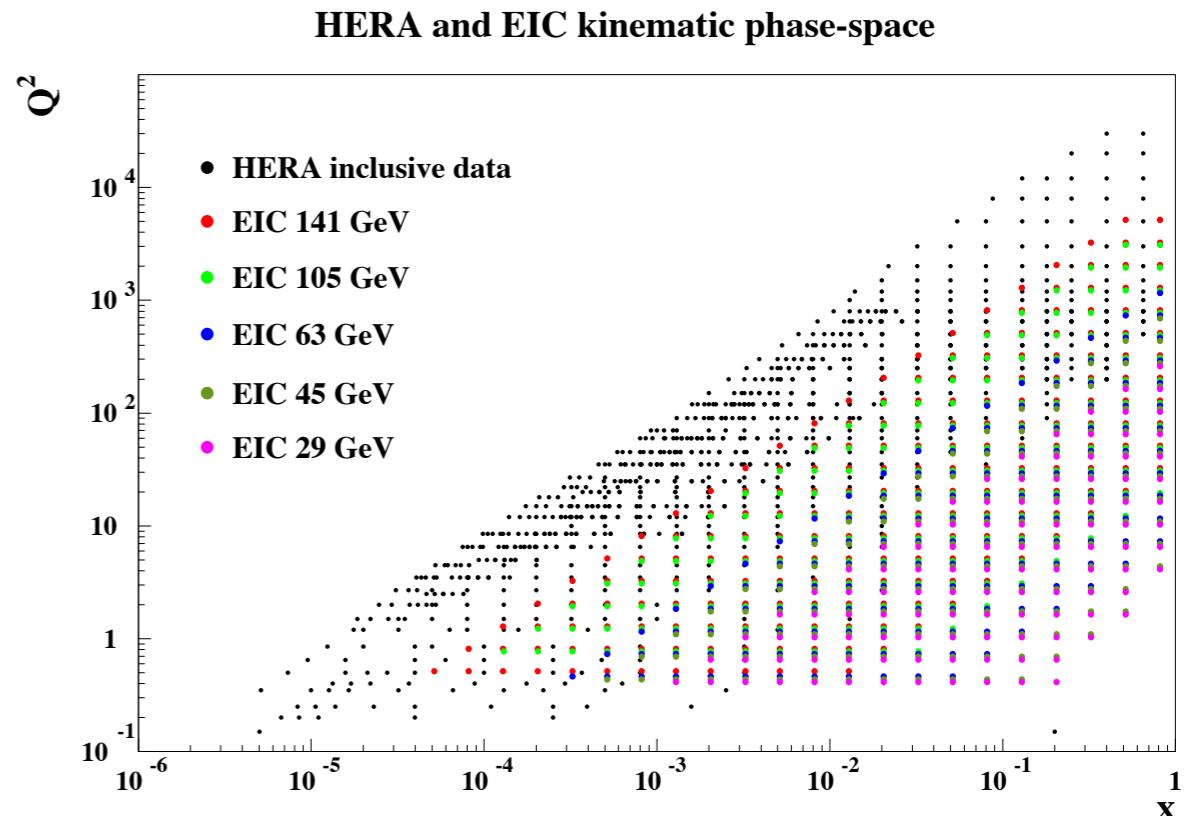
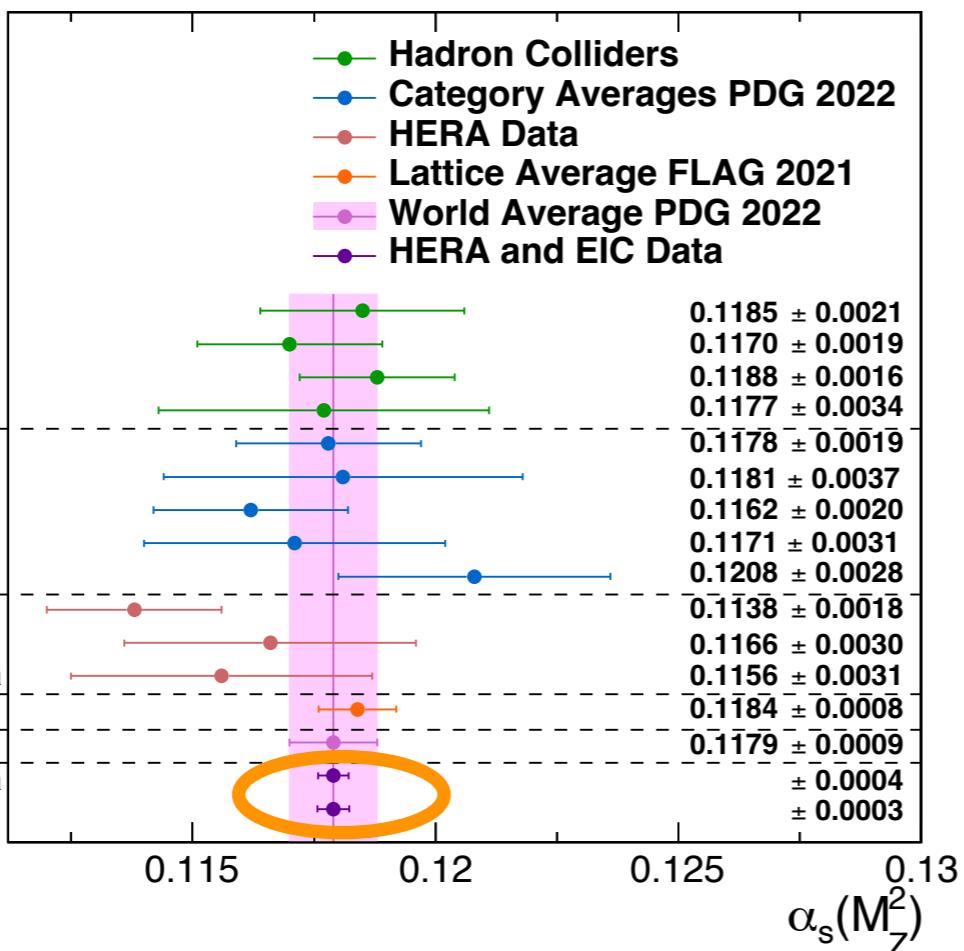


Extraction of α_s from HERA and EIC

- 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

ATLAS ATEEC
CMS Jets
W, Z Inclusive
tt Inclusive
 τ Decays
QQ Bound States
PDF Fits
 $e^+ e^-$ Jets and Shapes
Electroweak Fit
ZEUS Inclusive Jet Data (Prel.)
H1 Inclusive Jet/Dijet Data
H1 and ZEUS Inclusive + Jet Data
Lattice Average
World Average
HERA Incl + Jet and EIC Incl Data
HERA and EIC Inclusive Data

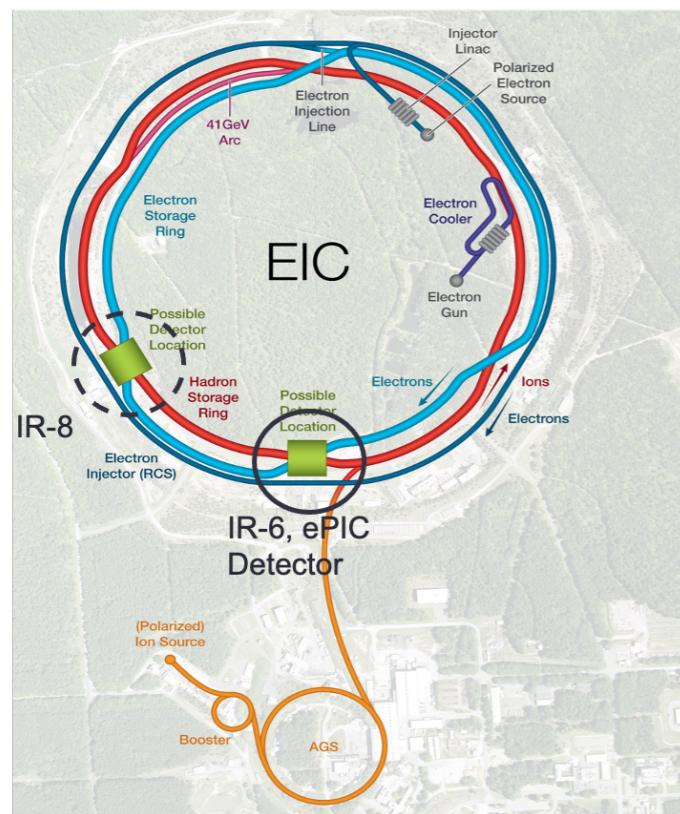
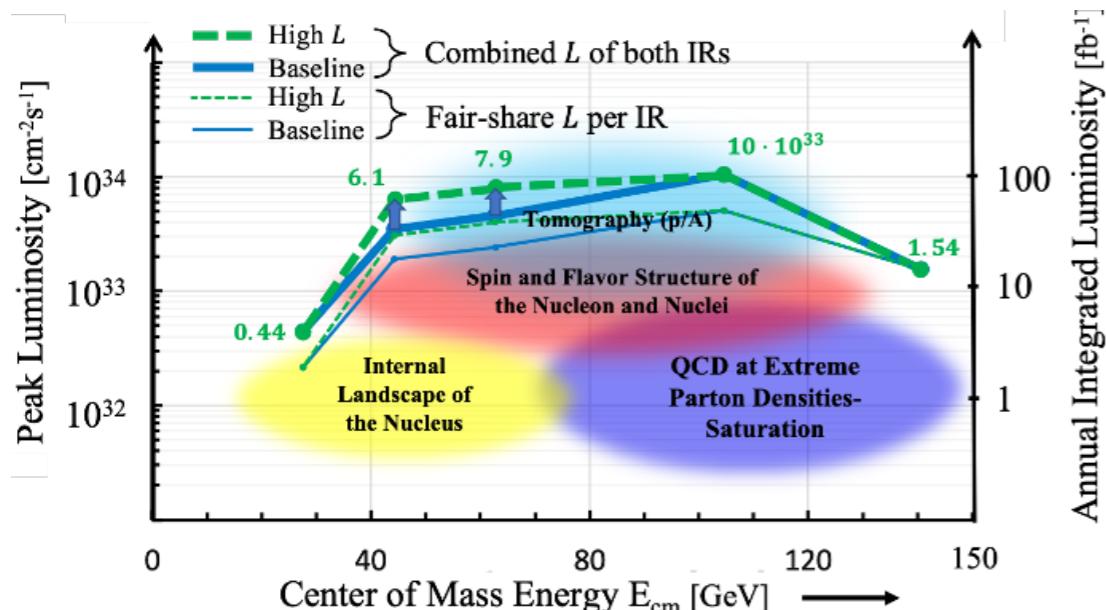


HERA inclusive (or inclusive + jets) + EIC inclusive data allows for **determination of α_s** with **unprecedented precision : $\leq 0.3\%$**

$$\alpha_s(M_Z^2) = 0.1161 \pm 0.0003 \text{ (exp)}$$

$$\pm 0.0001 \text{ (model + param)} \quad {}^{+0.0002}_{-0.0001} \text{ (scale)}$$

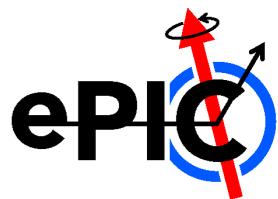
Machine design and parameters



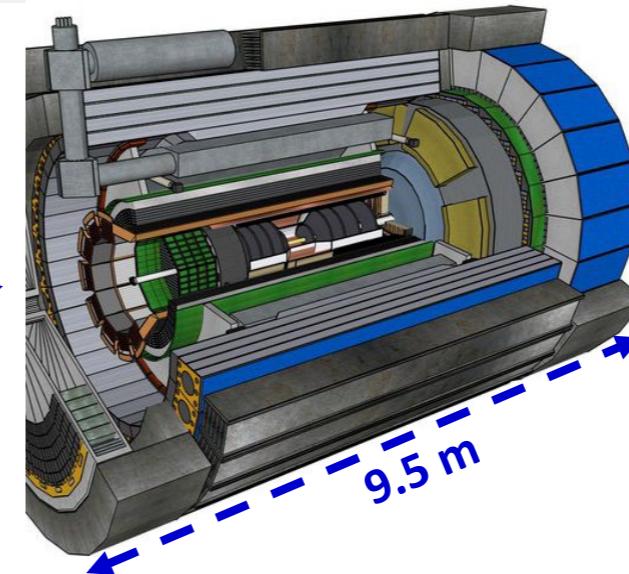
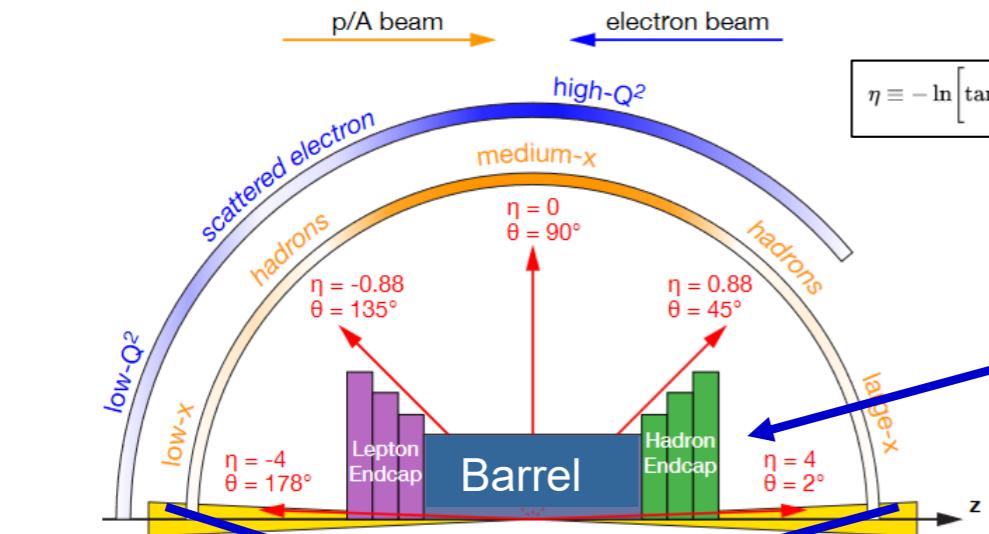
- Hadron storage ring (HSR): 41-275 GeV (based on RHIC)
 - up to 1160 bunches, 1A beam current (3x RHIC)
 - bright vertical beam emittance (1.5 nm)
 - strong cooling (coherent electron cooling, ERL)
- Electron storage ring (ESR): 2.5-18 GeV (new)
 - up to 1160 polarized bunches
 - high polarization by 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)
 - $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - superconducting magnets
 - 25 mrad crossing angle with crab cavities
 - spin rotators (produce longitudinal spin at IP)

Detector: ePIC

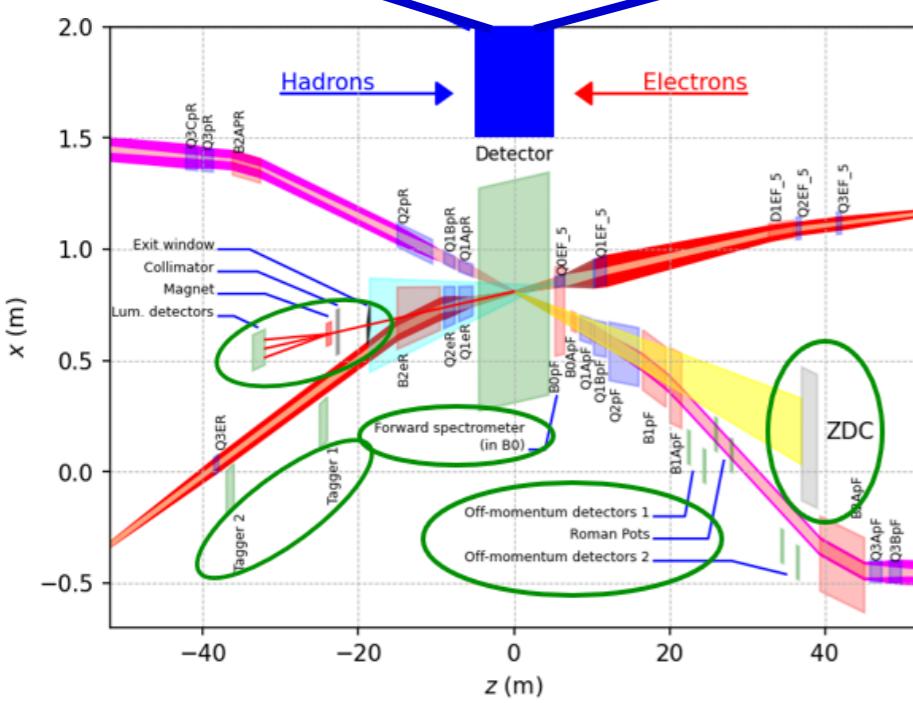
Slide from S. Dalla Torre talk at EICUG



ePIC, an extended detector



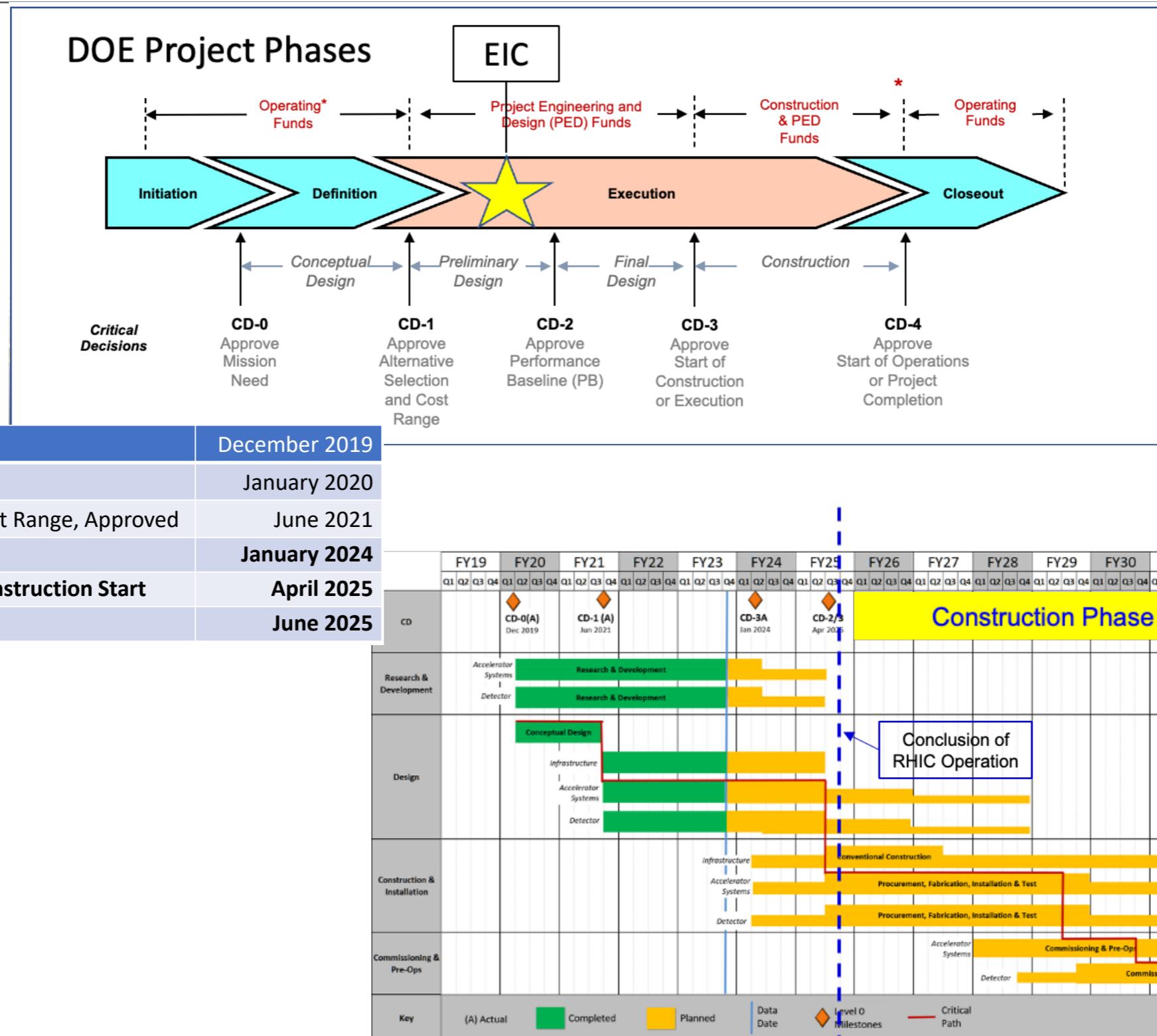
Central
Detector (CD)



Total size detector: ~75m
 Central detector: ~10m
Far Backward electron detection: ~35m
Far Forward hadron spectrometer: ~40m

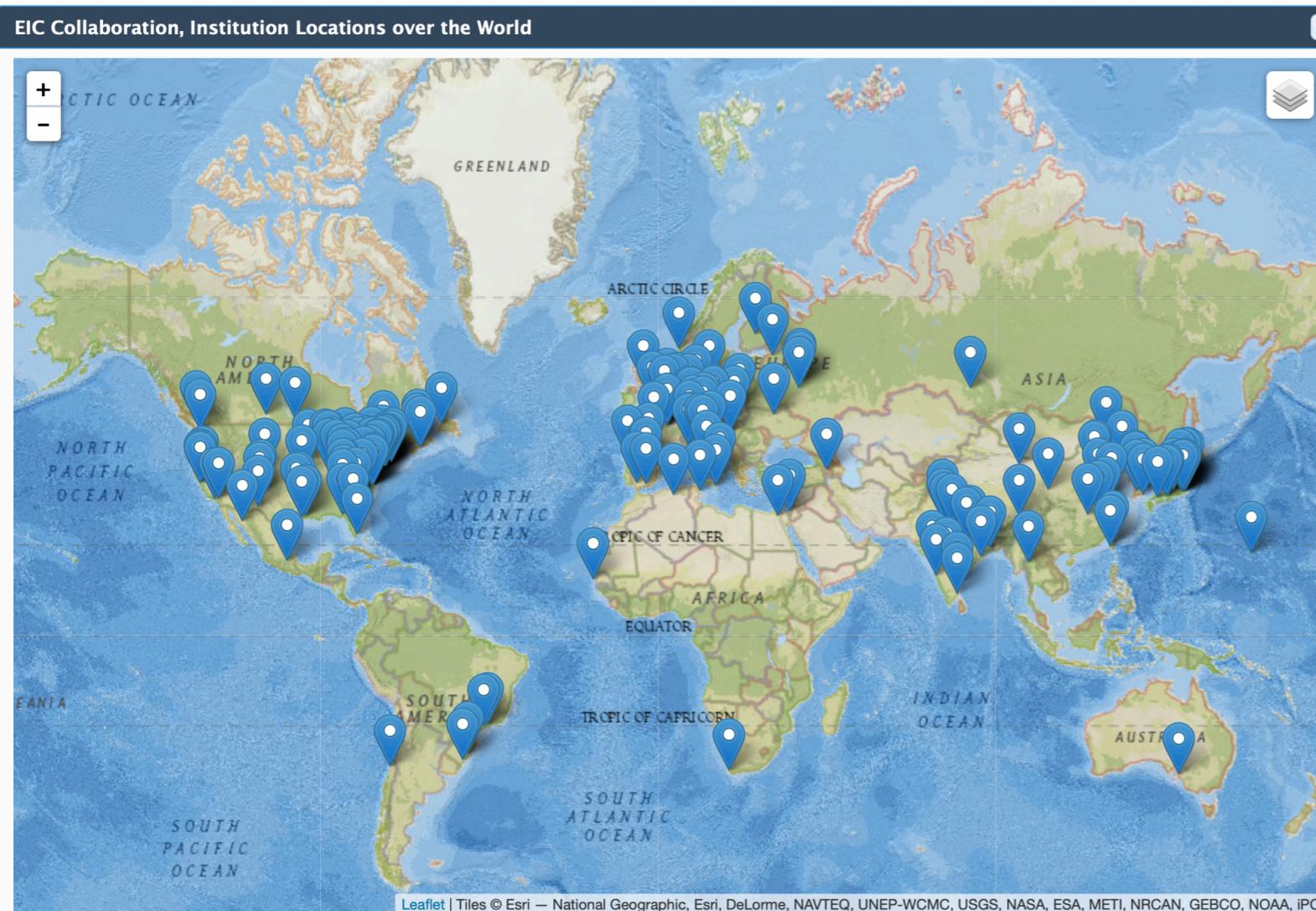
Auxiliary detectors needed to tag particles with very small scattering angles both in the **outgoing lepton** and **hadron beam** direction (B0-Taggers, Off-momentum taggers, Roman Pots, Zero-degree Calorimeter and low Q2-tagger).

Timeline



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**.



1411 members

879 experimentalists

359 theorists

158 accelerator scientists

9 computer scientists

4 support

2 other

283 institutions

37 countries

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

Status as of September 3, 2023

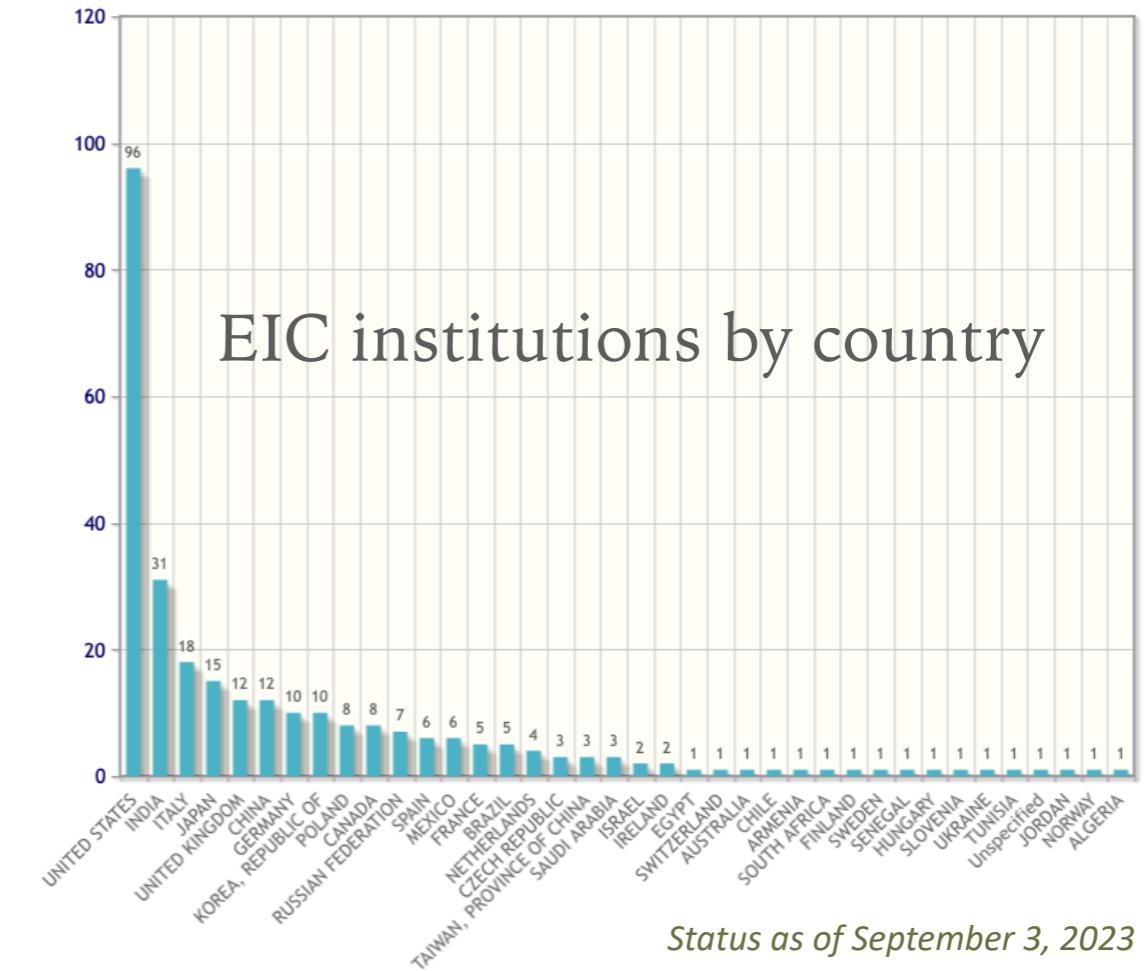
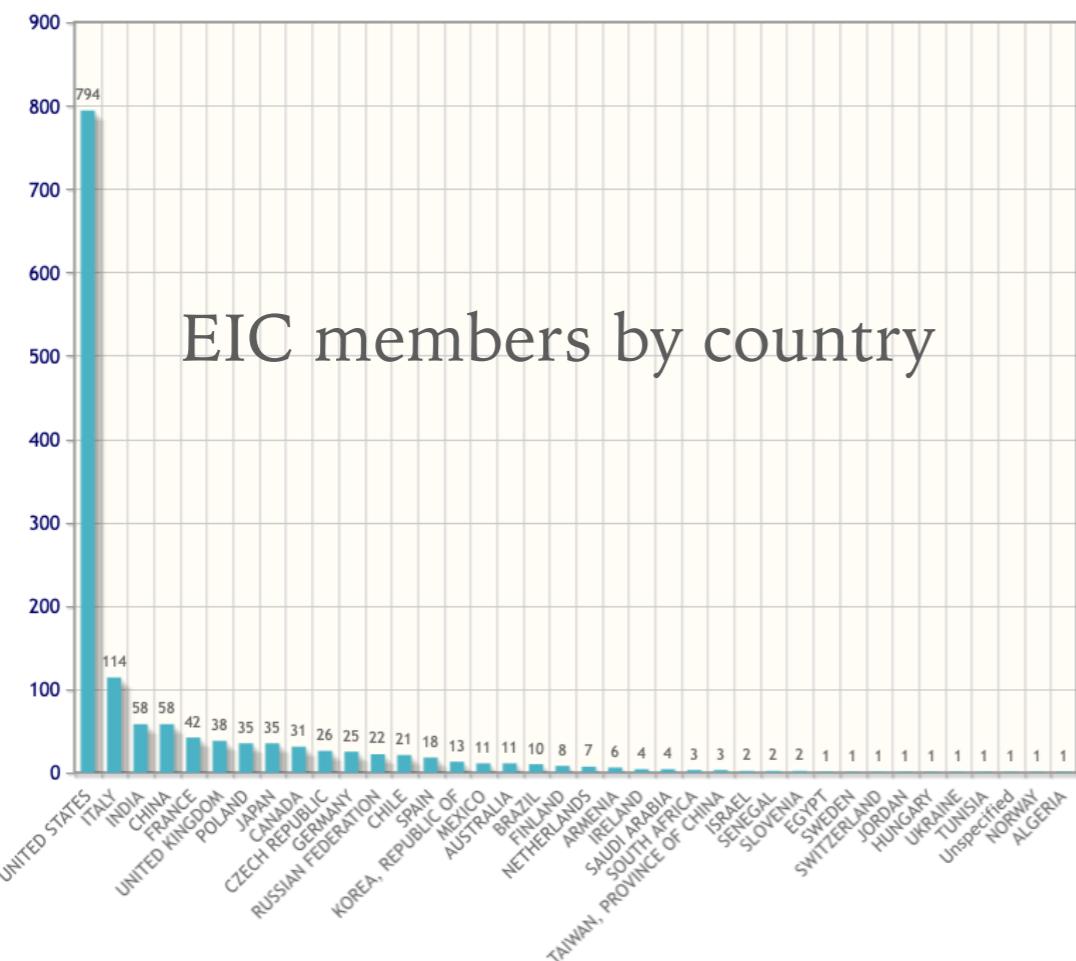
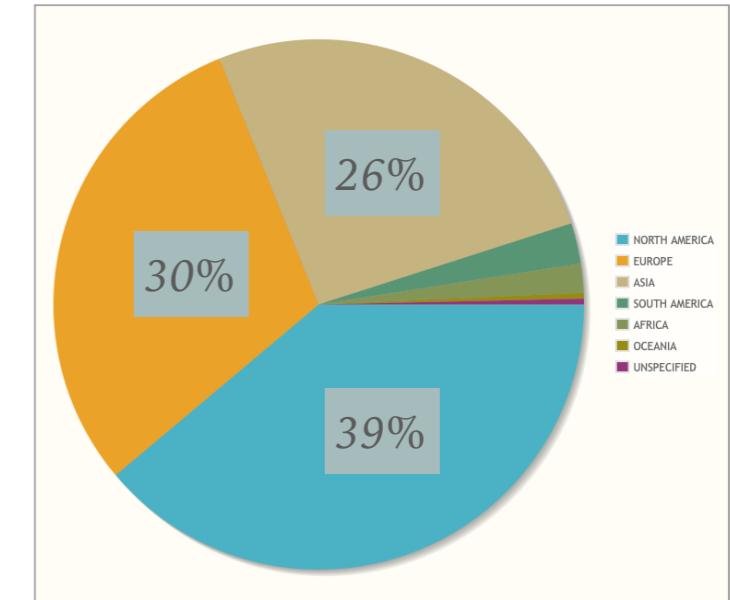
EIC Users Group

EIC is international at its core

Over 60% institutions are outside US

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

Strong community and still growing !



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...

Special thanks to Elke Aschenauer and Abhay Deshpande for help with preparation of this presentation!