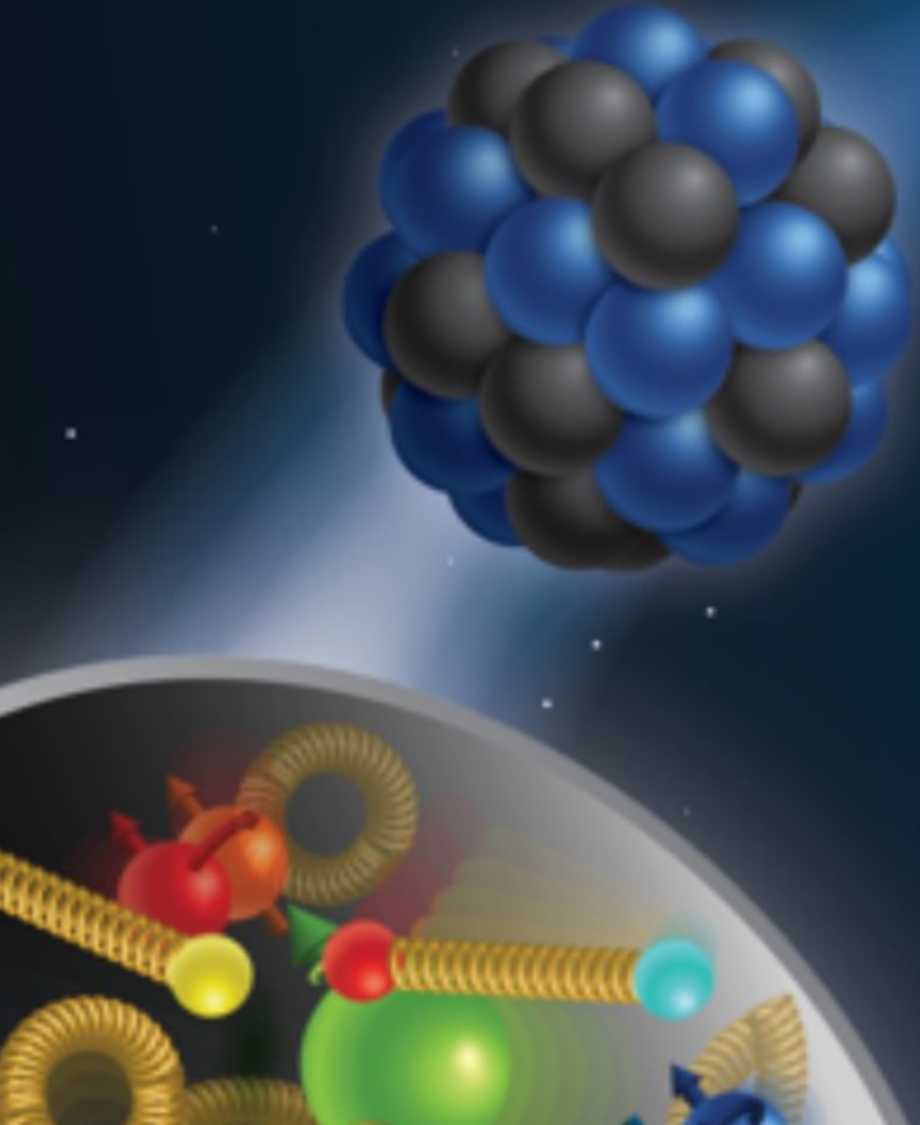

Physics Prospects and Performance of Proposed EIC detectors

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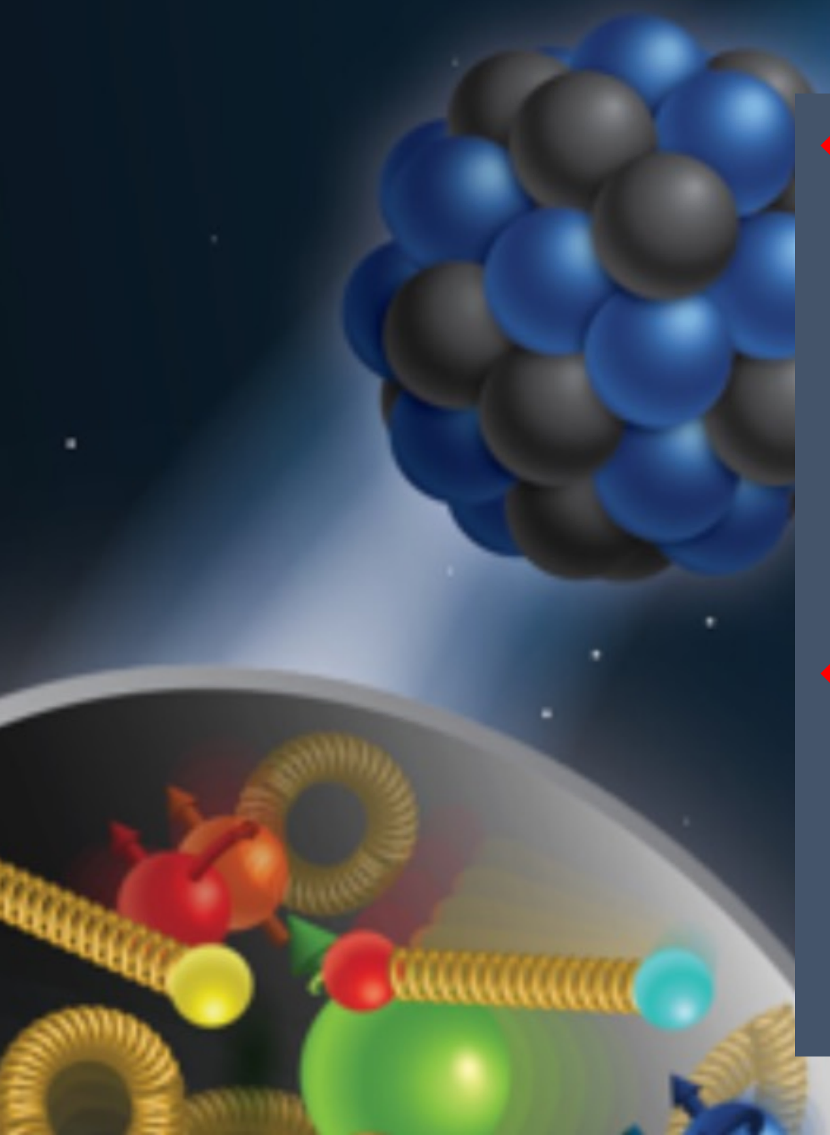
Giornata Nazionale EIC_net
Sezione INFN di Torino December 19-21, 2021

UNIVERSITÀ DELLA CALABRIA
Dipartimento di FISICA
INFN
Gruppo Collegato di Cosenza
Istituto Nazionale di Fisica Nucleare

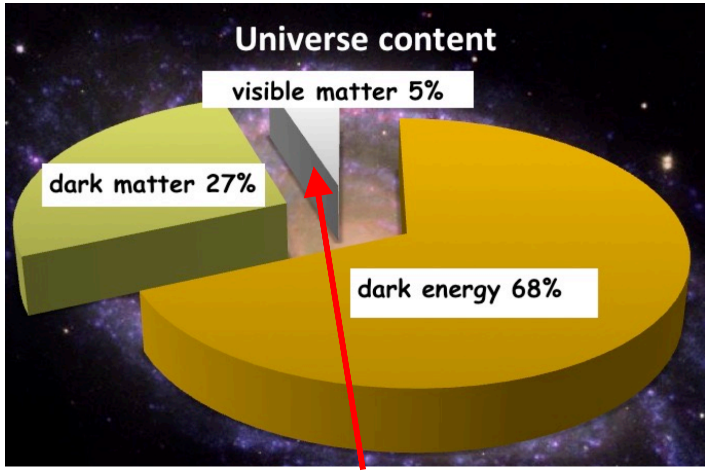
Plan of the Talk



- Physics Highlights
  - Spin Physics
  - Partonic Imaging
  - Structure of Nuclei
  - Gluon Saturation
- Detector Proposals still not made public
  - My talk will be largely based on ATHENA
  - plots from other Detector concepts taken from:

    https://indico.bnl.gov/event/13614/

Understanding the properties of visible matter



This is us !!!
protons, neutrons, electrons

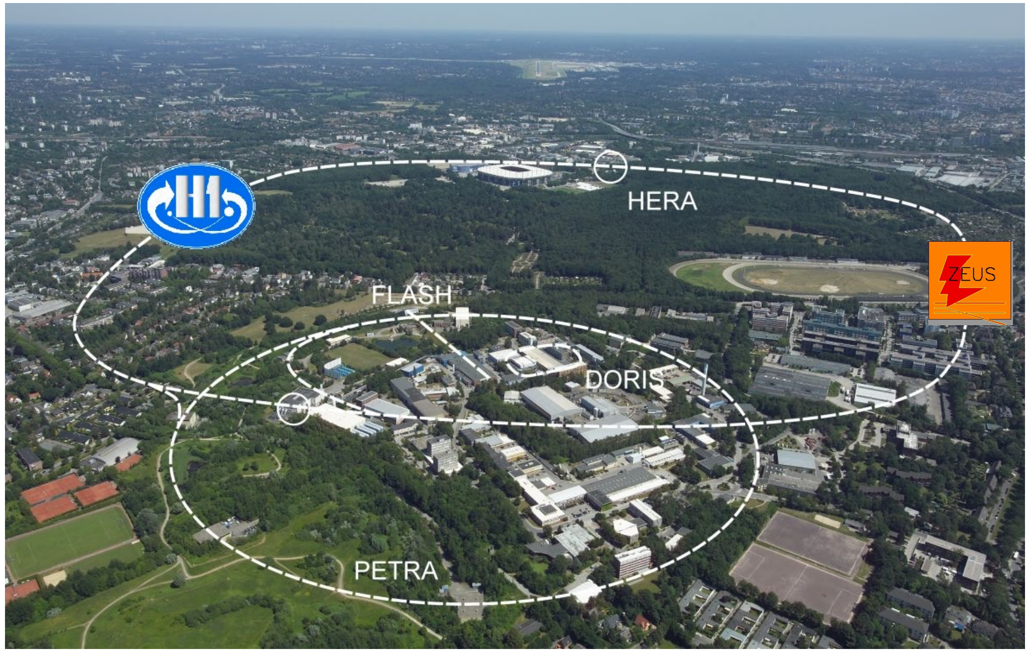
Proton:

The Higgs mechanism is responsible for quarks mass

Quark-Masses: ~1% M_p

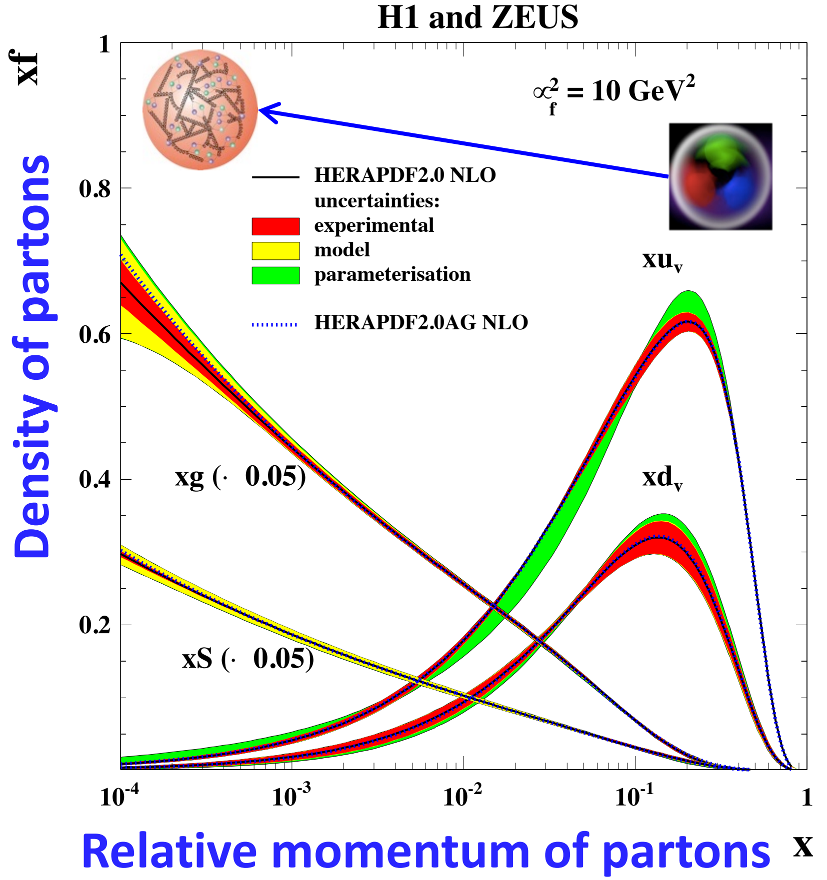
All strongly interacting matter is an emergent consequence of many-body quark-gluon dynamics in QCD

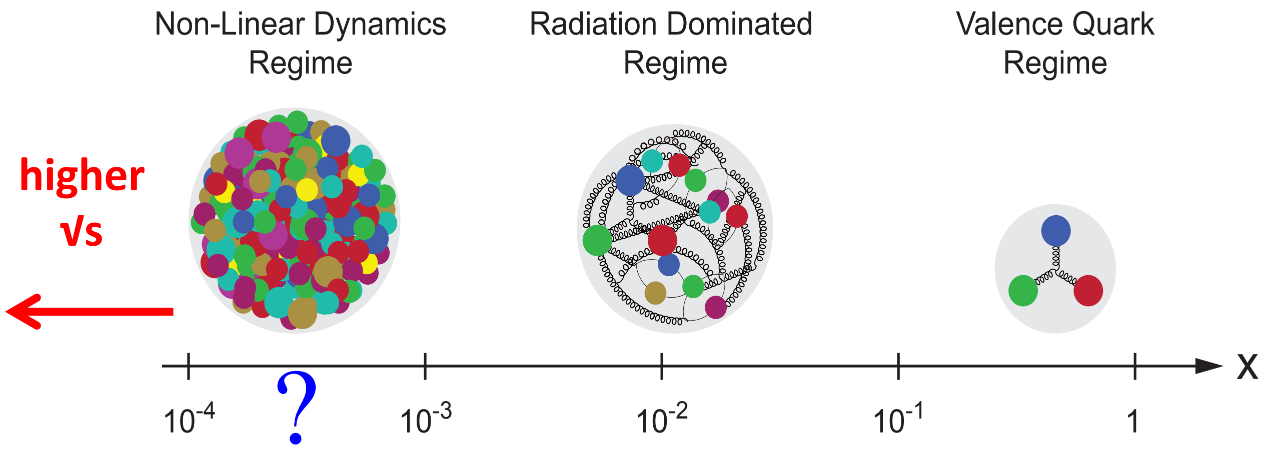
To investigate the nucleon's partonic structure, HERA, the previous and only electron (projectile beam) → proton (target beam) collider, was built



What did HERA found?

HERA studied in detail the one-dimensional picture of a free proton



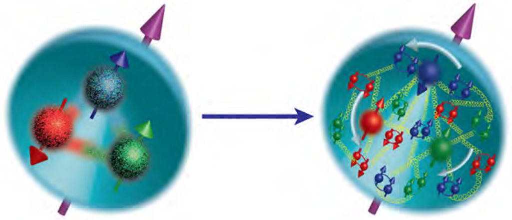


HERA discovery:
Gluon density dominates at x < 0.1

Limits of HERA: Low luminosity; no nuclei; no polarization of the proton beam

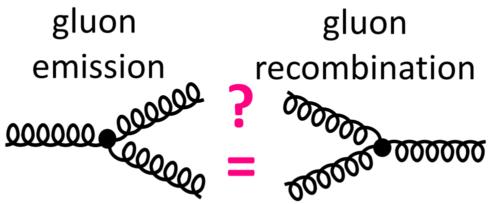
Need a high lumi, highly polarized e+p(A) collider to resolve quark and gluon spatial, momentum and spin structure in multi-dimensions in both protons and nuclei → **EIC**

Most compelling physics GOALS



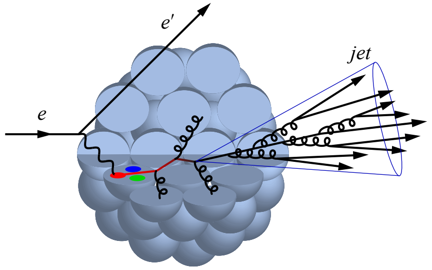
How are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

- How do the nucleon properties emerge from them and their interactions?



What happens to the gluon density in nuclei?

- Does it saturate at high energy?
- Does this saturation give rise to a gluonic matter with universal properties in all nuclei, even proton?



How does a dense nuclear environment affect the quarks and gluons, their correlations and 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?

Ingredients for a high resolution "femtoscope"

Large center-of-mass coverage:

Access to wide kinematic range in x and Q^2

Polarized electron and hadron beams:

- access to spin structure of nucleons and nuclei
- Spin vehicle to access the 3D spatial and momentum structure of the nucleon
- Full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei

Nuclear beams:

- Accessing the highest gluon densities → amplification of saturation phenomena

High luminosity:

- Detailed mapping the 3D spatial and momentum structure of nucleons and nuclei
- Access to rare probes

All these requirement can be addressed by the future **Electron-Ion Collider**

The Electron-Ion Collider

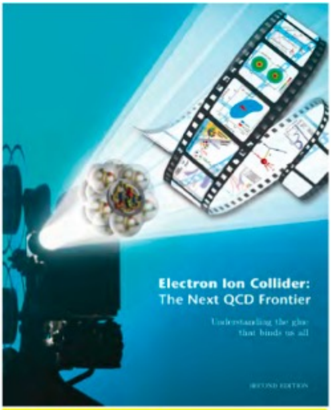
For e-N collisions at the EIC:

✓ **High Luminosity:** up to 10^{34} cm^{-2}sec^{-1}
100-1000 times HERA

✓ **Flexible √s** = 30-140 GeV (per nucleon)

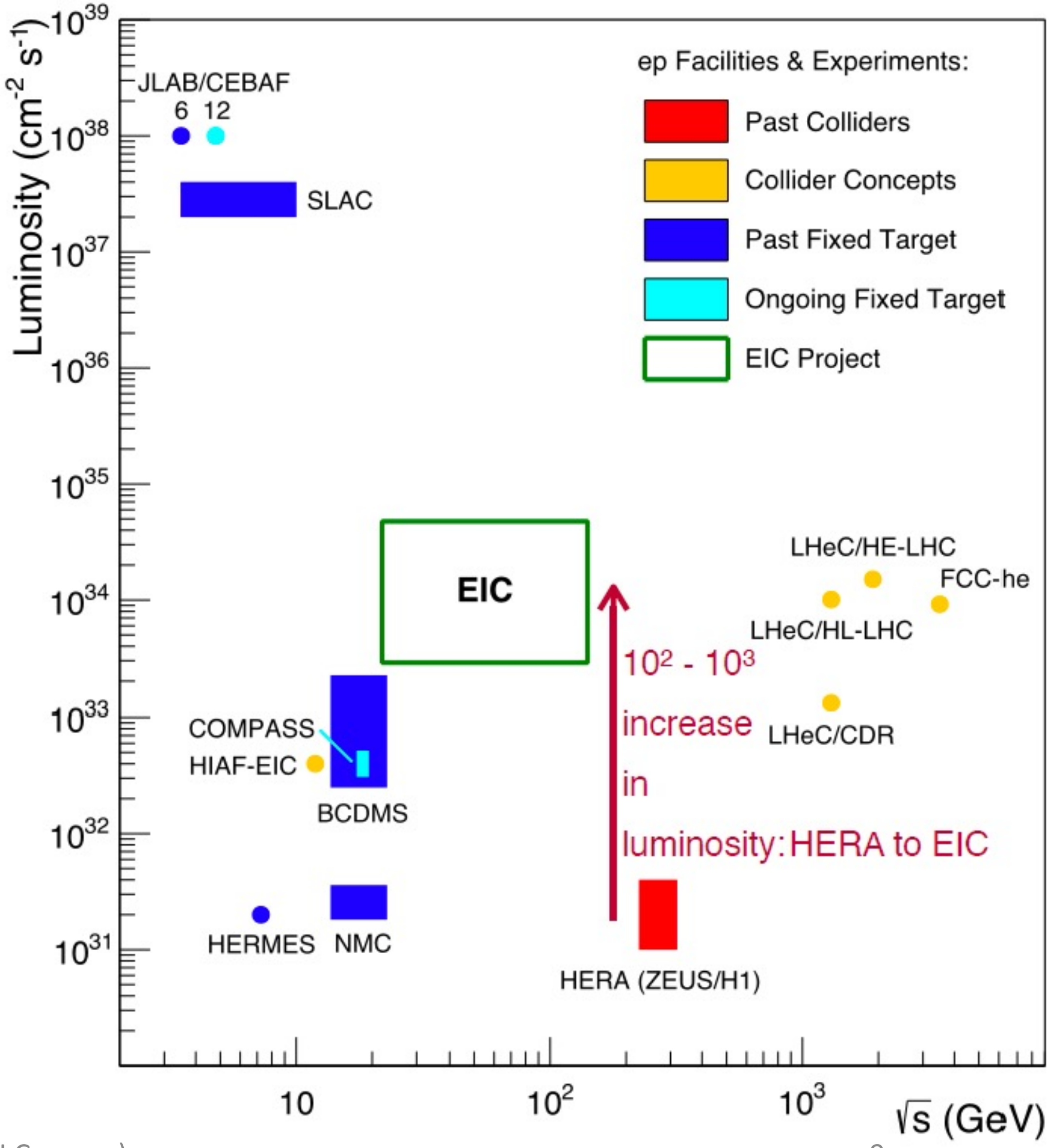
✓ **Highly polarized beams:** e (80%); p, D/^{3}He (70%)

✓ **Wide range of nuclear beams:** (D to Pb/U)



1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

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



What process must be measured?

Parton Distributions in nucleons and nuclei

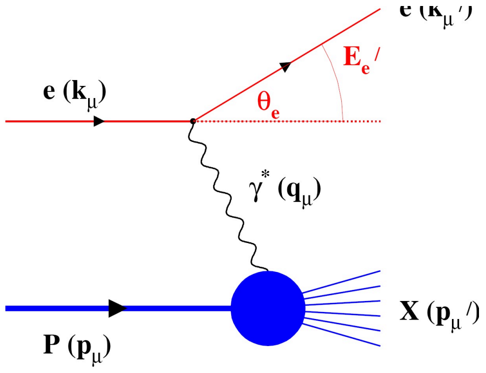
QCD at Extreme Parton Densities - Saturation

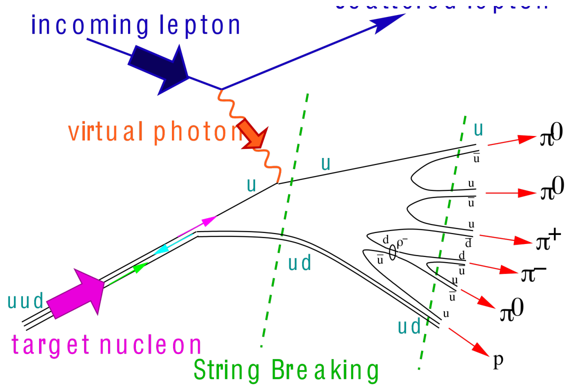
Spin and Flavor structure of nucleons and nuclei

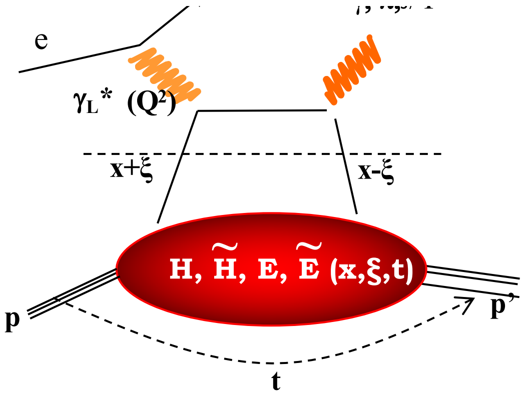
Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging



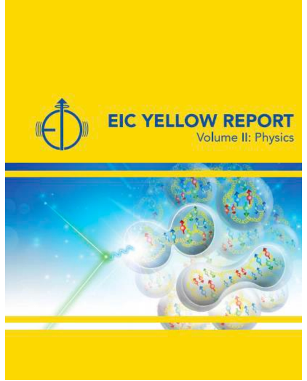




Inclusive DIS | Semi-Inclusive DIS | Exclusive Reactions

$\int \mathcal{L}dt$:	$1\ \mathrm{fb}^{-1}$	$10\ \mathrm{fb}^{-1}$	$100\ \mathrm{fb}^{-1}$

Requirements for a "general-purpose" detector



The Yellow Report Initiative (Jan-Dec 2020) – to advance the state of the documented physics studies (W.P., INT Reports) and detector concepts in preparation for the realization of the EIC.

Report released in March 2021: arXiv:2103.05419

Enormous community effort: 902 pages, 415 authors, 151 institutions

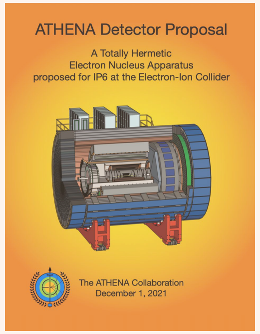
Overall detector requirements:

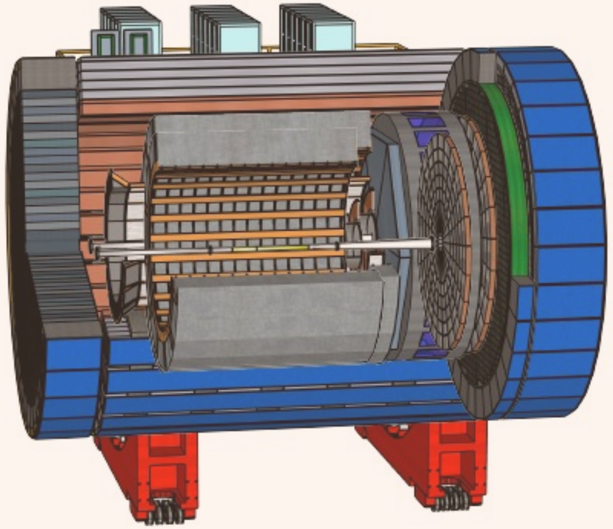
- **Hermeticity:** large acceptance in pseudorapidity, -4 $\lesssim \eta \lesssim$ 4 [exclusive and diffractive channels]
- **Good momentum resolution in central region**
  - DIS and SIDIS channels that use the hadronic state to reconstruct kinematics
- **Minimum p_T:** 100 MeV for pions, 135 MeV for kaons
- **Electron ID:** π suppression of 10^4 (for eg. PVDIS). 3σ e/π separation for spectroscopy
- **Good γ detection threshold at zero angle (ZDC):** separate coherent/incoherent in e+A VMP.
- **Hadron ID:** required over a large momentum range for SIDIS/TMD measurements
- **ECAL:** $(10-12)\%/\sqrt{E} \oplus (1-3)\%$ in central region for jets, $(1-2)\%/\sqrt{E} \oplus (1-3)\%$ at backwards rapidities (DIS electron reconstruction)
- **HCAL:** $50\%/\sqrt{E} \oplus 10\%$ (jets), with a minimum threshold of 500 MeV
- **Far Forward instrumentation:** measure the diffractive protons

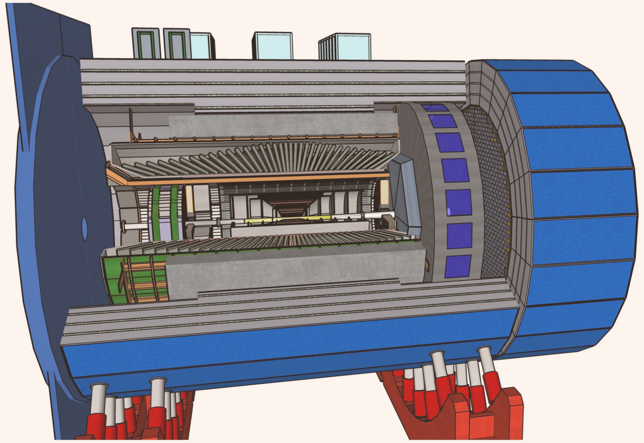
Proposed EIC detectors

Two proposals for a general purpose «project detector»

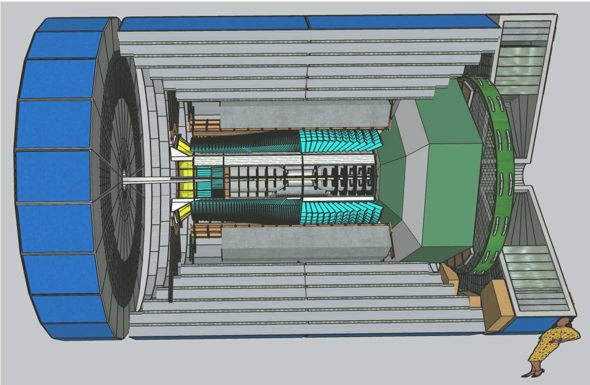
ATHENA

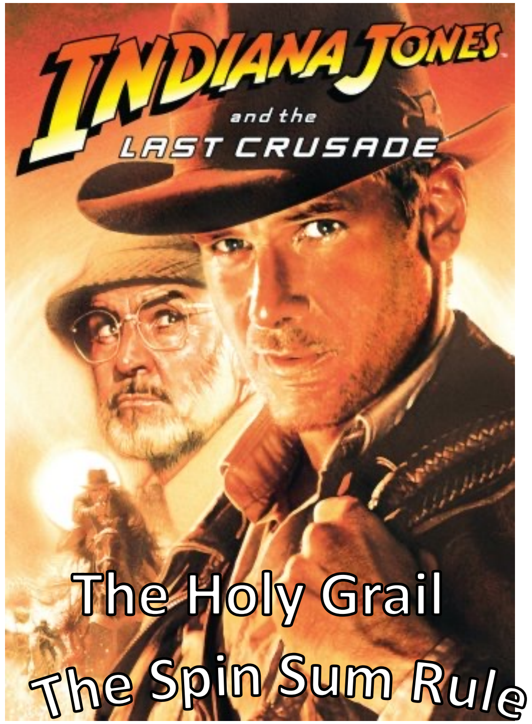




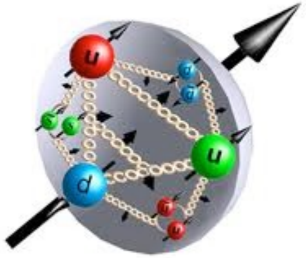


A proposals for a (still general purpose) complementary detector





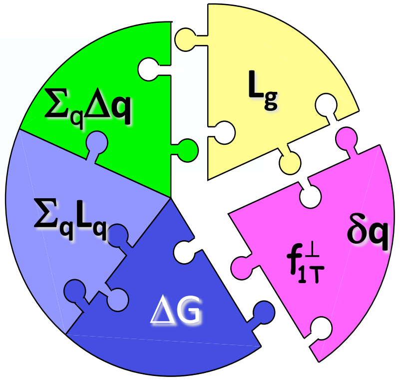
Spin Physics



- what is the polarization of gluons at small *x* where they are most abundant?
- what is the flavor decomposition of the polarized sea depending on *x*?

Determine quark and gluon contributions to the proton spin

Proton's helicity structure



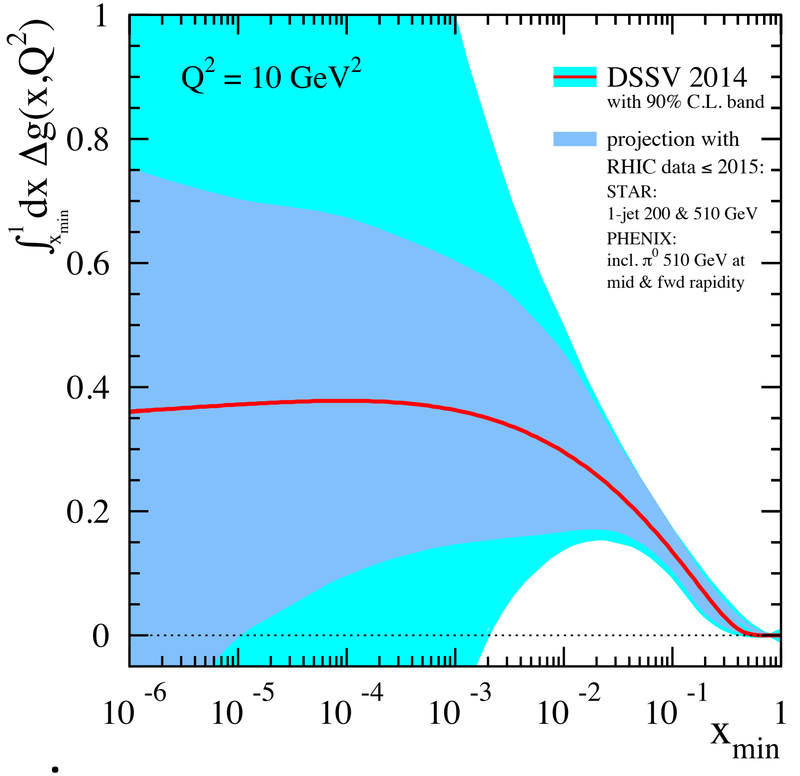
Jaffe and Manohar "sum rule" [Nucl. Phys. B337, 509 (1990)]

$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} \,|\, J^z_{QCD} \,|\, P, \frac{1}{2} \right\rangle = \underbrace{\sum_q \frac{1}{2} S^z_q}_{\text{total u+d+s quark spin}} + \overbrace{S^z_g}^{\text{gluon spin}} + \underbrace{\sum_q L^z_q + L^z_g}_{\text{angular momentum}}$$

What we know: $$\int_{0.05}^{1.0} dx \Delta g \sim 0.2 \pm^{0.06}_{0.07} \,@\, 10 \text{ GeV}^2$$

DIS (fixed targ.) + RHIC (till 2009)
[Phys. Rev. Lett. 113, 012001 (2014)]

First time a significant non-zero $\Delta g(x)$

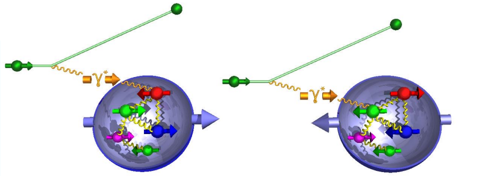


RHIC: All data until 2015 factor 2 reduced uncertainties at x ~ 10^{-3}

Expected impact of the EIC:

The x-range will be extended by two orders of magnitude, allowing an extremely precise measurement in the earlier poorly known area

Proton's helicity structure

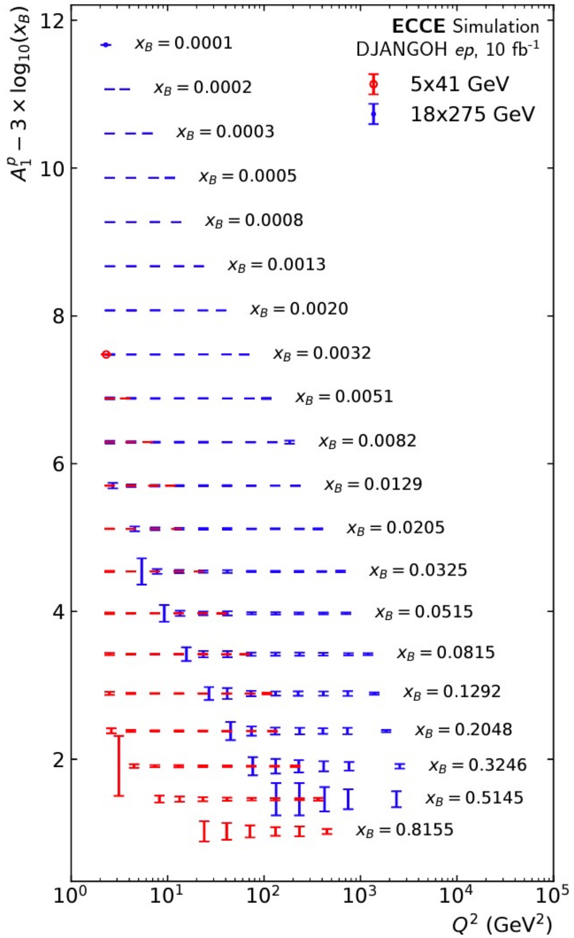


$\Delta g(x,Q^2)=g_{\rightrightarrows}(x,Q^2)-g_{\rightleftarrows}(x,Q^2)$

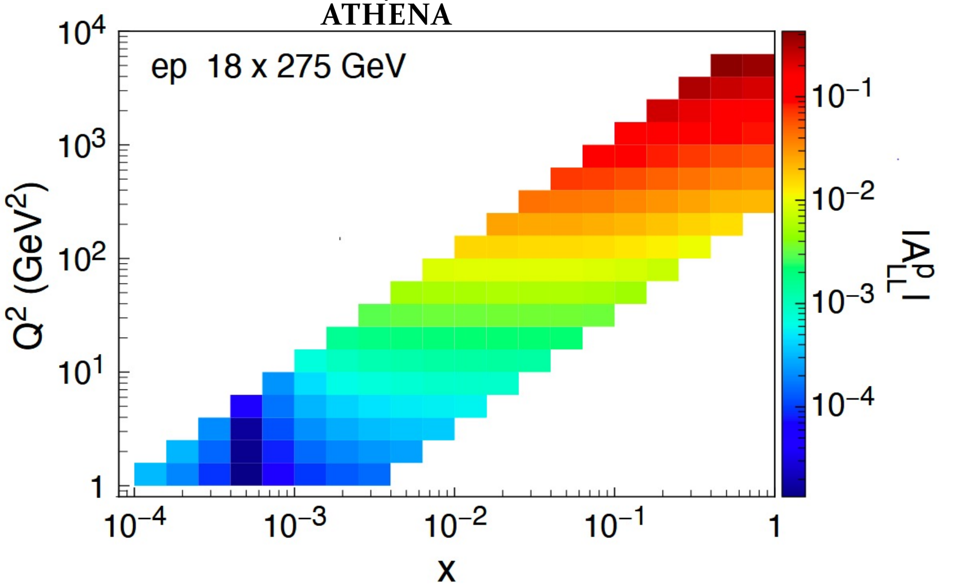
- **Observable:** Longitudinal double spin asymmetries (A_{LL})
- **DIS** scaling violations determine **gluons** at small x

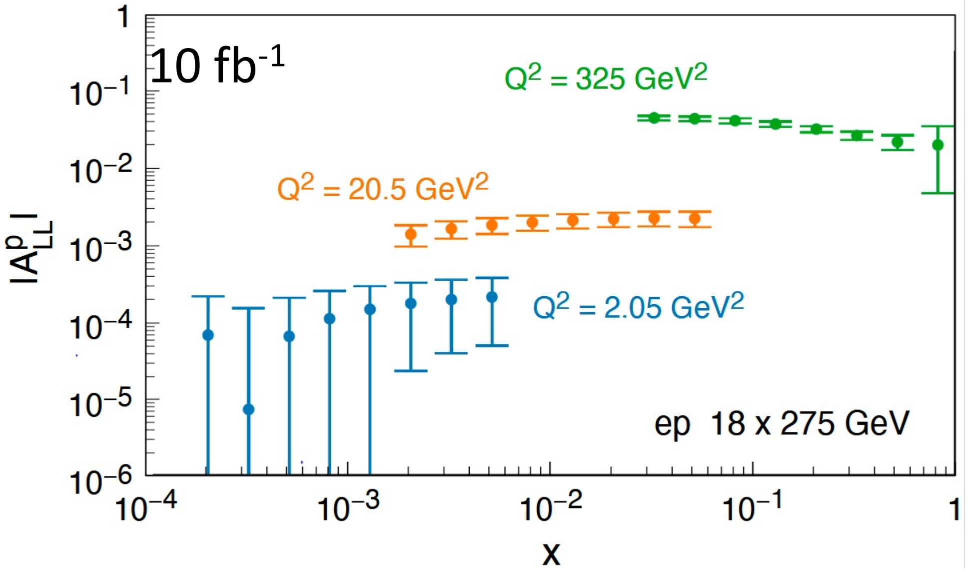
Key:
- Acceptance
- electron id

ECCE Inclusive double spin asymmetry $A_1(x)$ → $\dfrac{dg_1}{d\log(Q^2)}$ **g_1 scaling violation** → $\propto -\Delta g$



ATHENA - Double spin asymm. in NC DIS





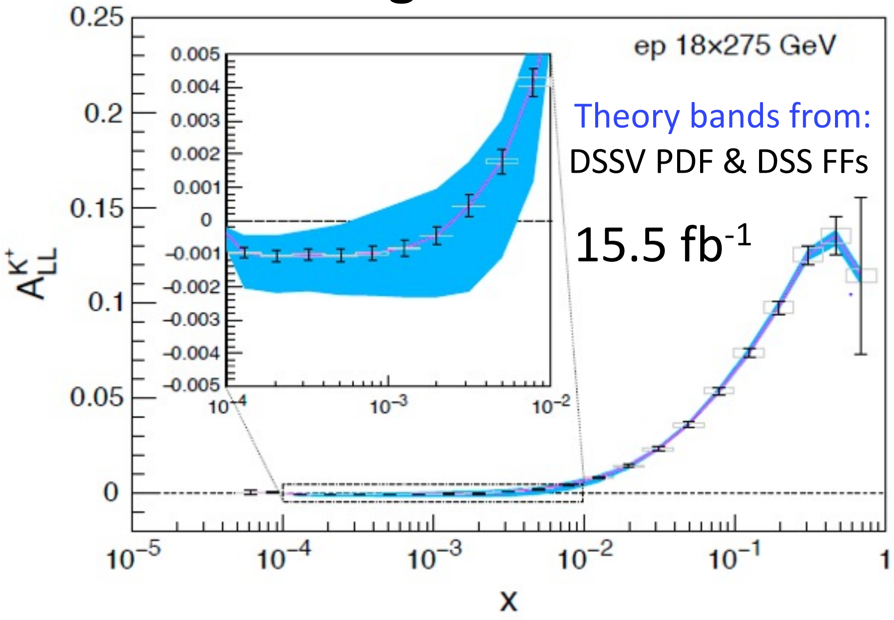
Proton's helicity structure from SIDIS

- **Observable:** Longitudinal double spin asymmetries (A_{LL})
- Furthermore **SIDIS** data provide detailed **separation of sea quark**
  - Do see quark helicities vanish at small x ?

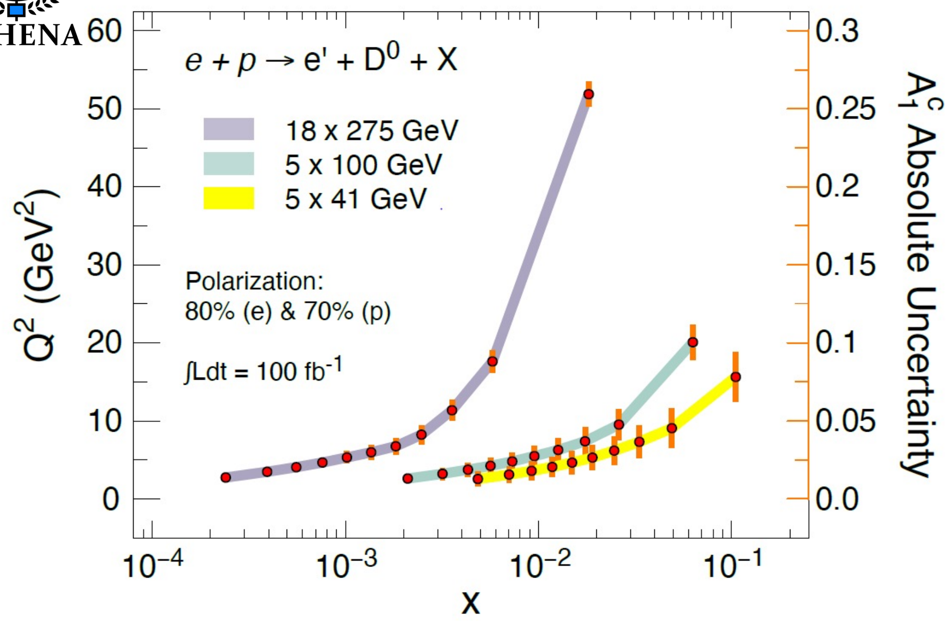
Key:

- PID (barrel, forward
- Vertexing for charm tagging

Charged kaons



Charm production



g helicity from c production

$(\mathrm{e}+\mathrm{p} \rightarrow e' + D^0 + X)$:

$A_1^c \sim g_1^c / F_1^c$

The spin sum rule

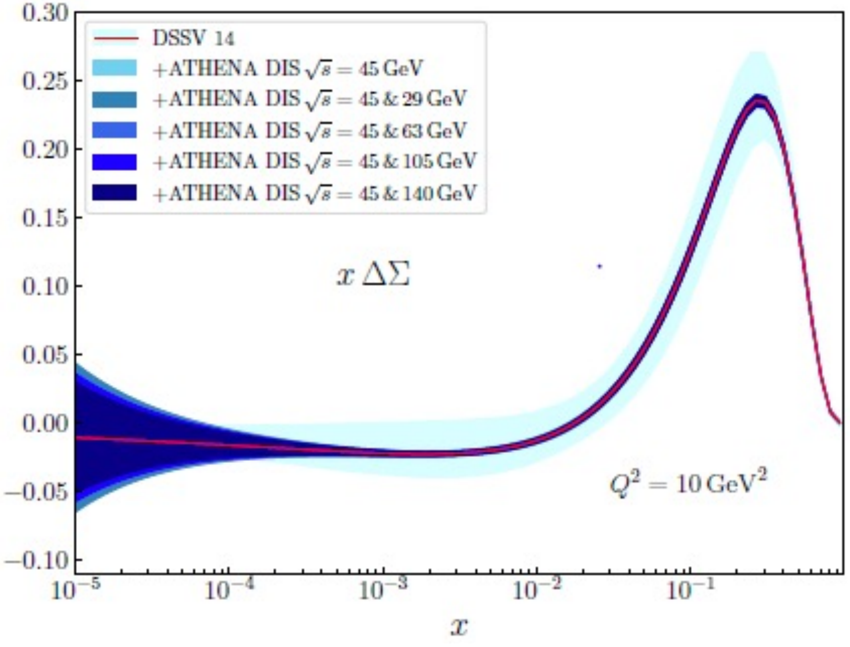
ATHENA

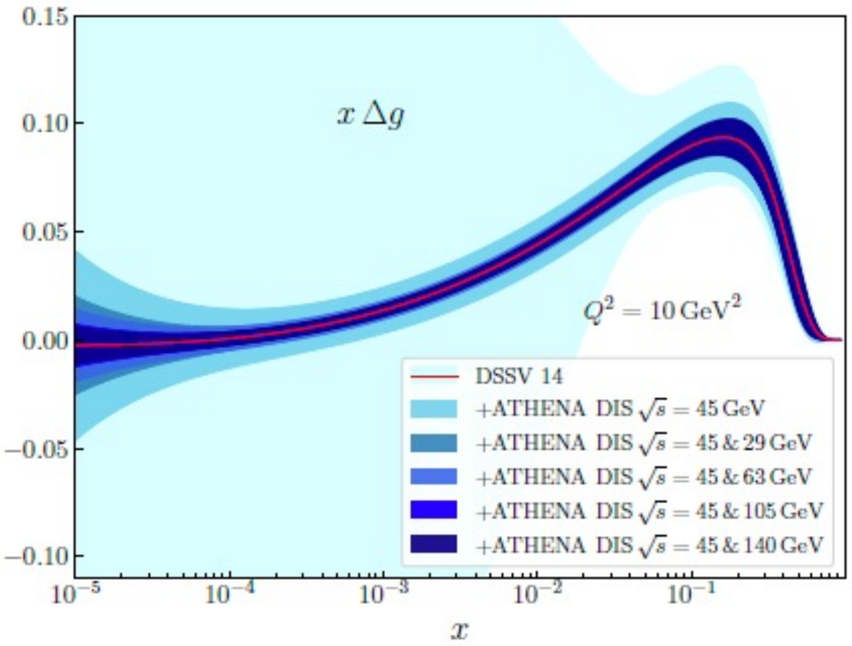
New global fit by
JAM/DSSV collaboration

q spin $\Delta\Sigma$ g spin Δg

$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} \left| J^z_{QCD} \right| P, \frac{1}{2} \right\rangle = \boxed{\sum_q \frac{1}{2} S^z_q} + \boxed{S^z_g} + \sum_q L^z_q + L^z_g$$

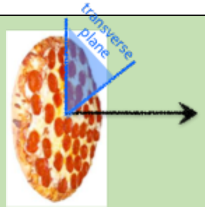
1/2 - Quarks - Gluons = orb. angular momentum



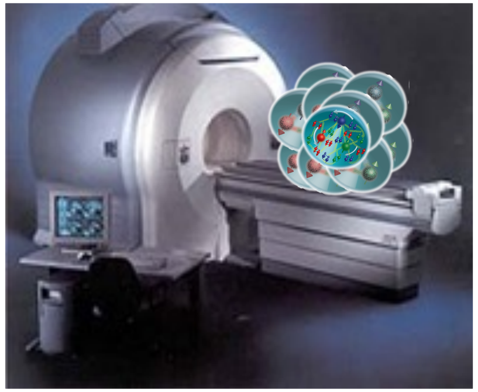


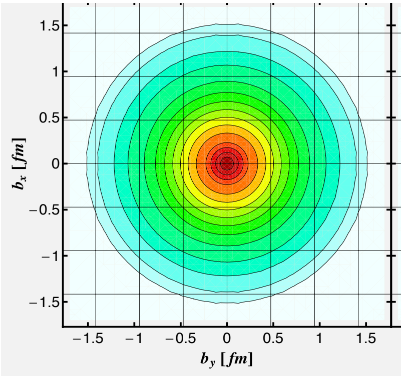
EIC: the Ultimate Multi-dimension Experience!

Proton Imaging



- In a fast-moving nucleon the longitudinal size squeezes like a “pizza” but transverse size remains about 1 fm
- what is the spatial and momentum distribution of quarks and gluons in nucleons/nuclei?





Can we produce tomographic images at a partonic scale?

Multidimensional imaging of quarks and gluons

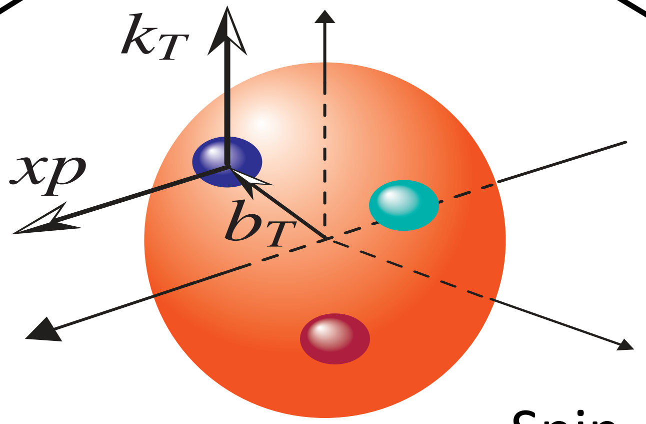
Wigner functions

offer unprecedented insight into confinement and chiral symmetry breaking

$W(x,b_T,k_T)$

Momentum space $\int d^2b_T$ $\int d^2k_T$ *Coordinate space*

$f(x,k_T)$



$f(x,b_T)$

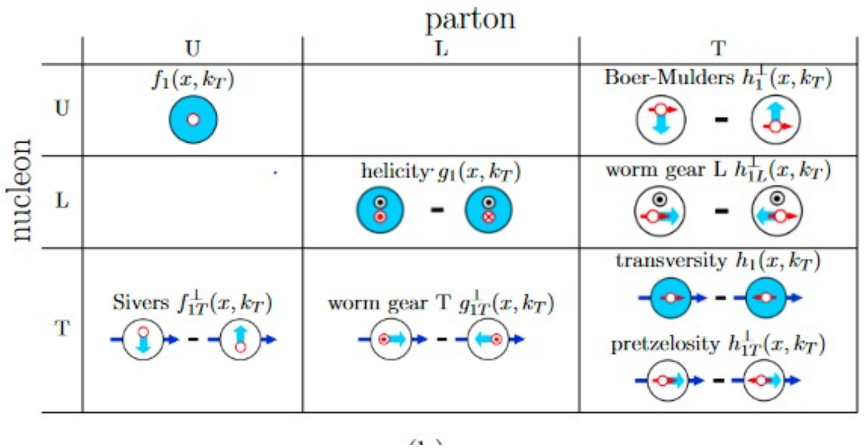
Spin-dependent 3D **momentum space** images from **semi-inclusive scattering**
→ **TMDs**

Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from **exclusive scattering**
→ **GPDs**

Direct access to $W(x,b_T,k_T)$
for gluons through exclusive di-jets measurements at an EIC under investigation

Momentum tomography

Transverse Momentum Dependent distributions (TMDs)
are PDFs depending on transverse momentum



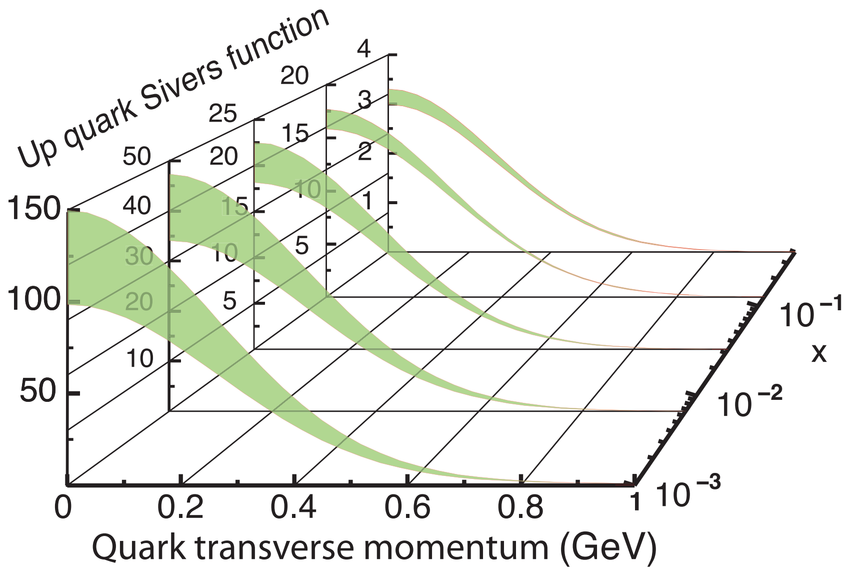
At low k_T, these functions cannot be perturbatively calculated

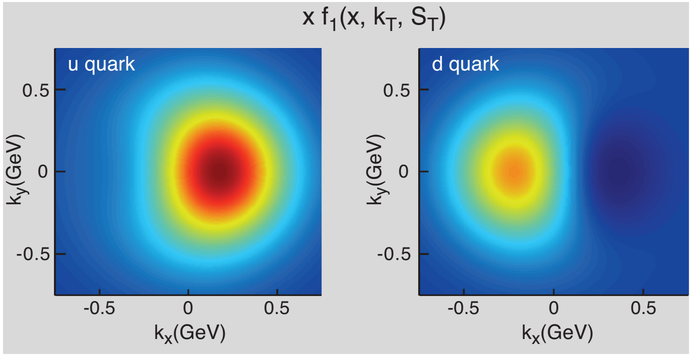
→ need precision measurement

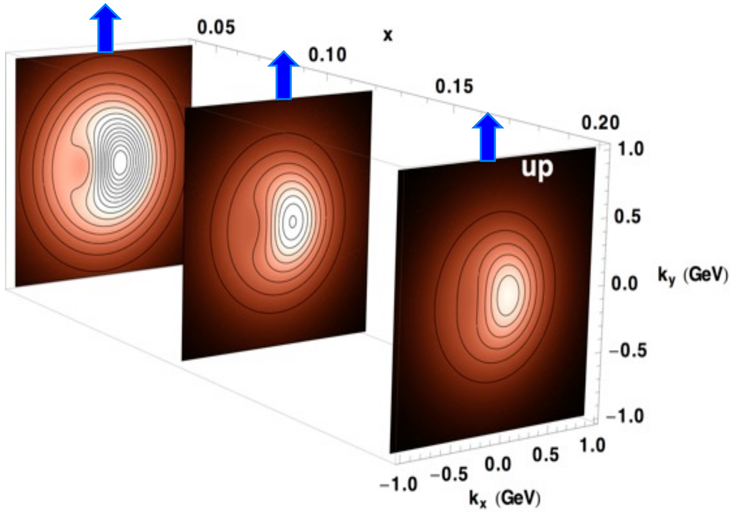
What we want to measure:

$$\frac{d\sigma}{dx\, dQ^2\, dz\, d\phi_S\, d\phi_h\, dp_T^h}$$

- **6-fold differential cross sections in SIDIS**
- **Azimuthal asymmetries and their modulations**

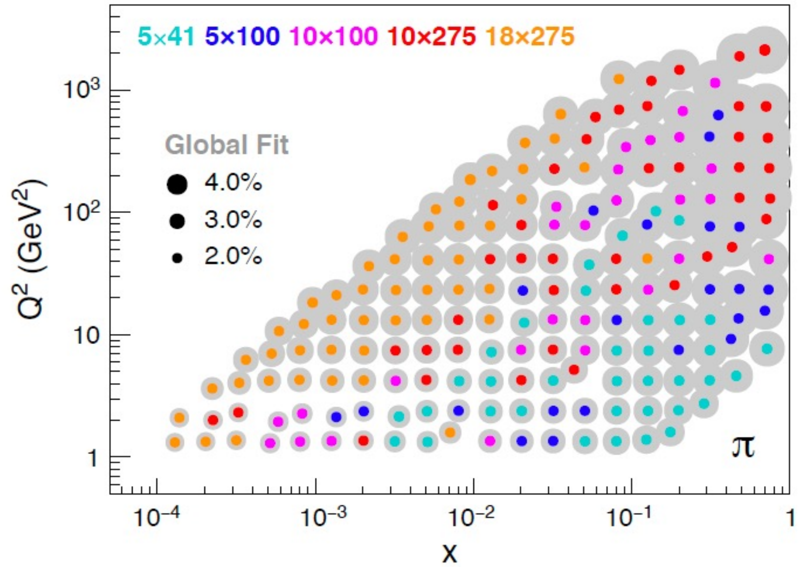




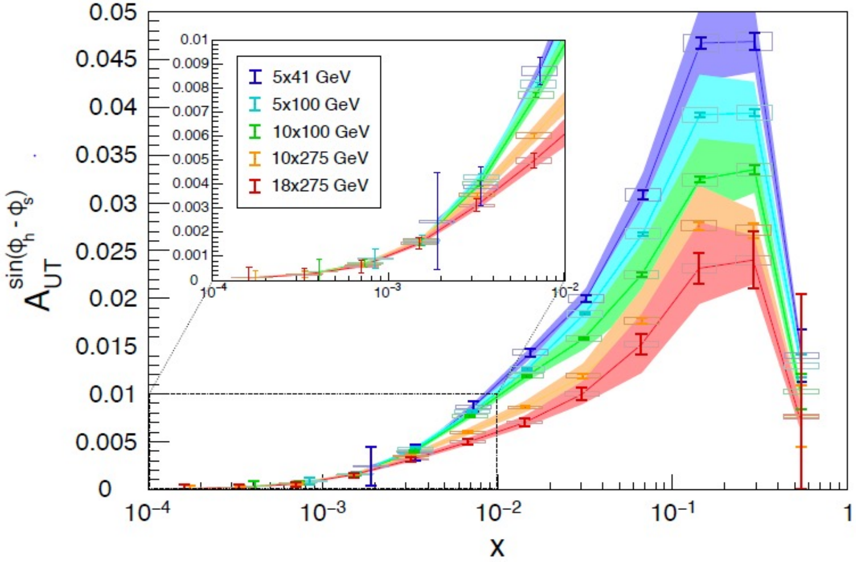


Momentum tomography – SIDIS, Heavy Flavor, Jets

Unpolarized cross section uncertainties

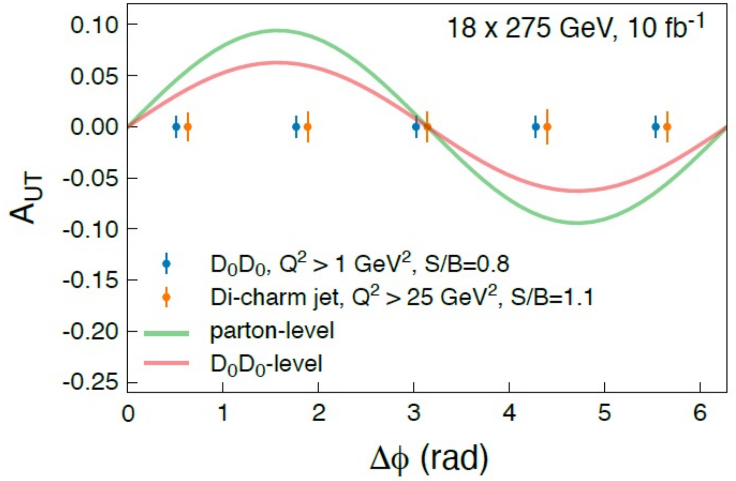


Projected Sievers asymmetries

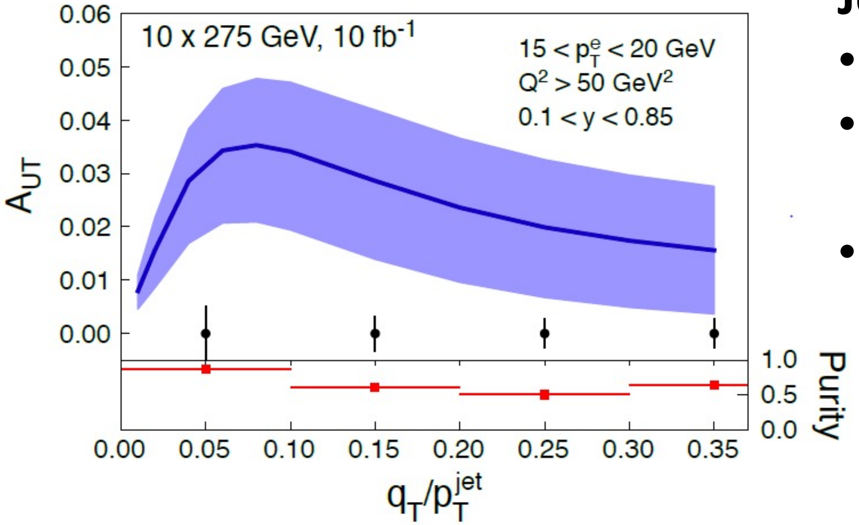


Heavy flavor

Sensitivity for Sivers in di-charm



Sensitivity for Sivers in **lepton-jet**



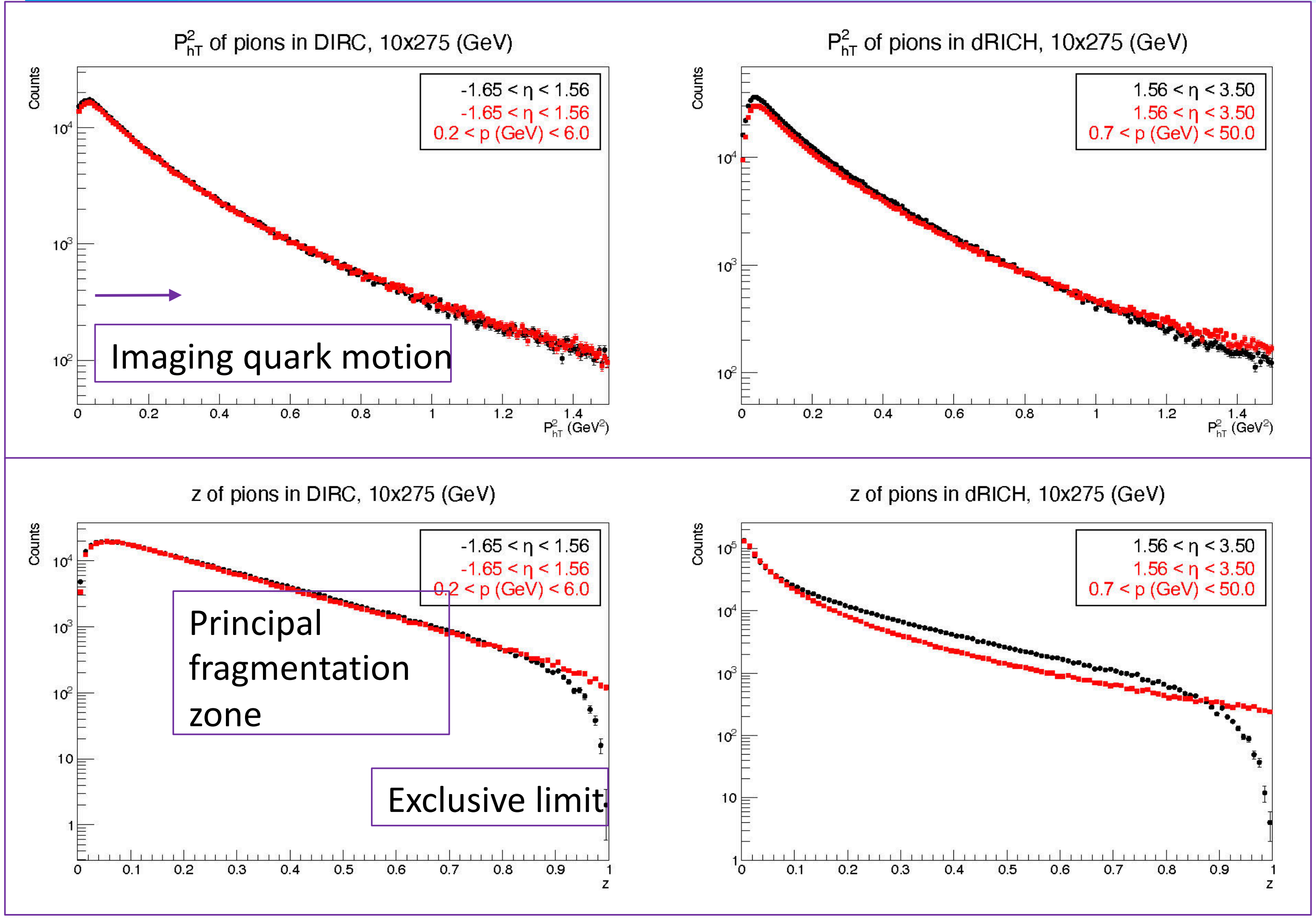
Jets:

- excellent proxies for partons
- probe **quark TMDs** without convolution with FF
- di-jets can probe **gluon Sivers**

Key:

- Azimuthal acceptance
- PID
- Acceptance
- Vertexing (heavy flavor)
- Quality of tracking
- HCal (for jets)

Momentum tomography

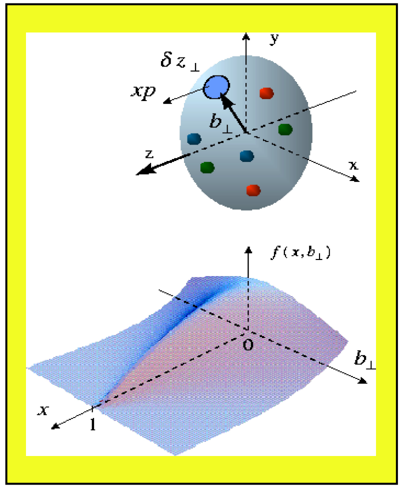


SIDIS in CORE
10x275 GeV^2

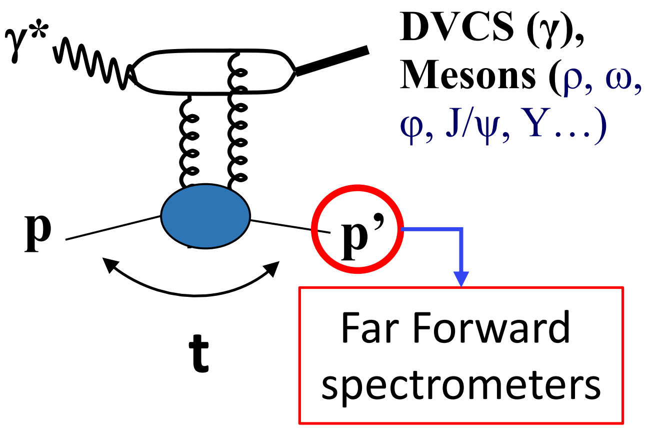
- Black = all pions
- Red = Identified π
- $z = \frac{p_h \cdot P}{q \cdot P}$
- Full z-range covered, independent of PID threshold

Spatial tomography

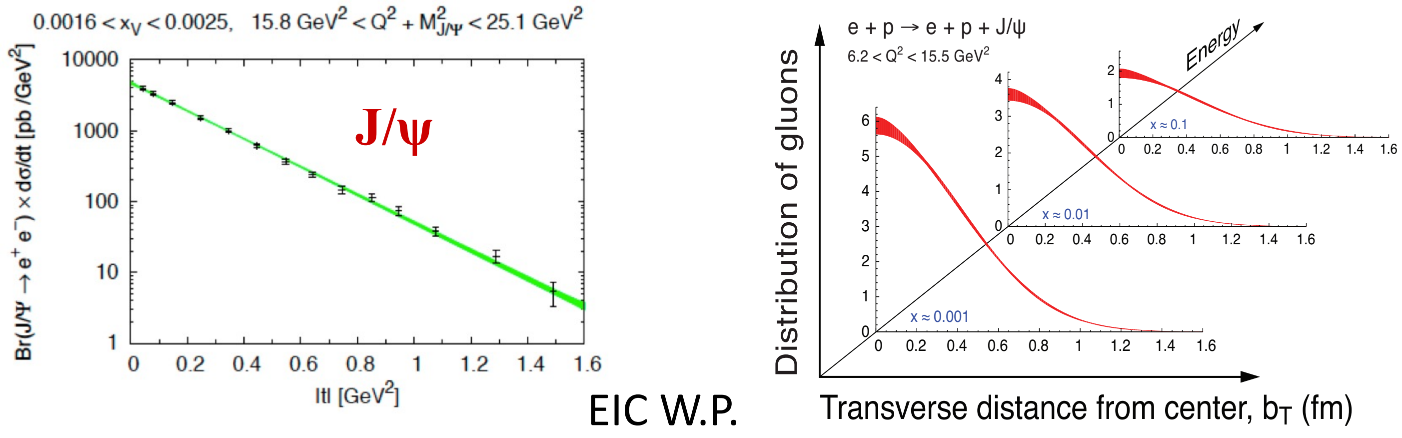
- ❖ **Hard Exclusive processes probe specific components of GPDs**
  - DVCS, TCS -> whole set of GPDs
  - heavy vector mesons (J/ψ, Y) -> gluon GPDs
  - light vector mesons (ρ^0; ρ^+; ω) -> quark flavors GPDs
  - light pseudoscalar mesons (π^+; π^0; η) -> helicity-flip GPDs
- ❖ **GPDs also sensitive to**
  - Distribution of forces inside the proton
  - Contribution from orbital angular momentum to proton spin
  - Energy-Momentum Tensor trace anomaly → origin of *p*-mass



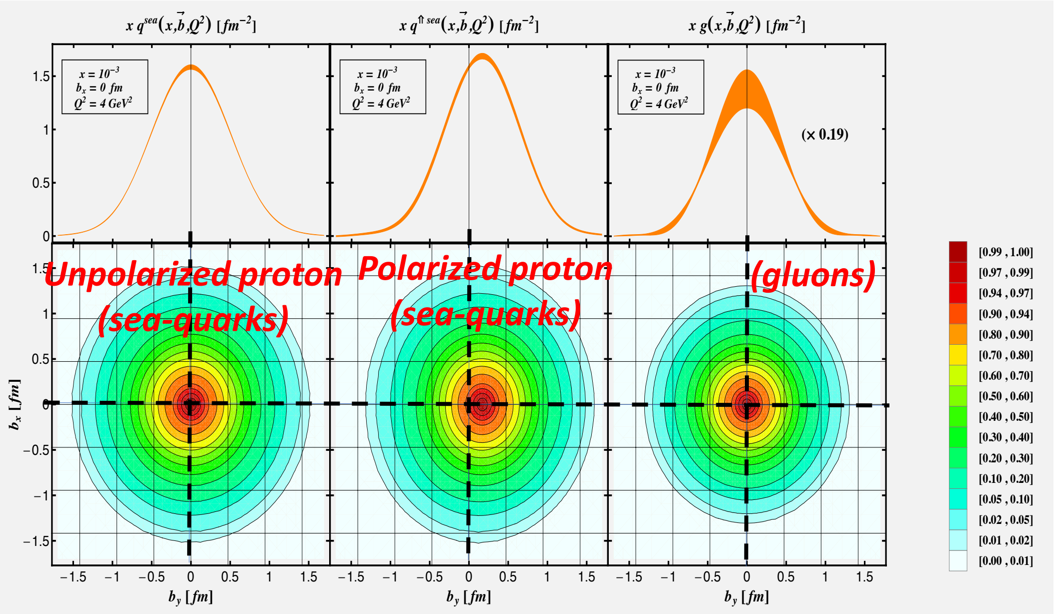
Exclusive Processes



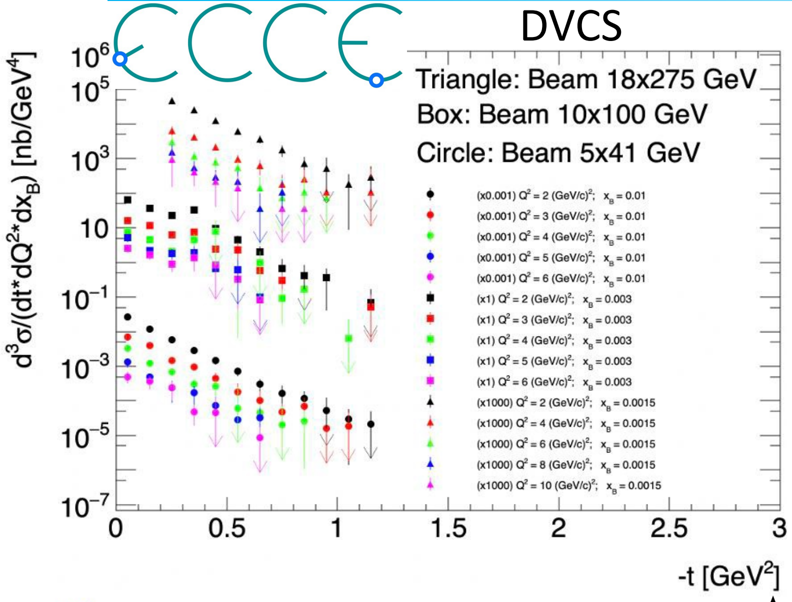
Fourier transform

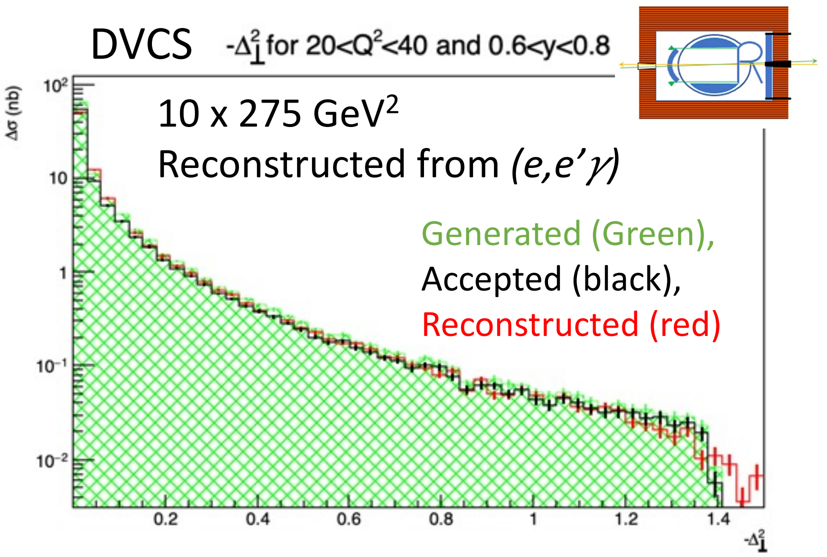


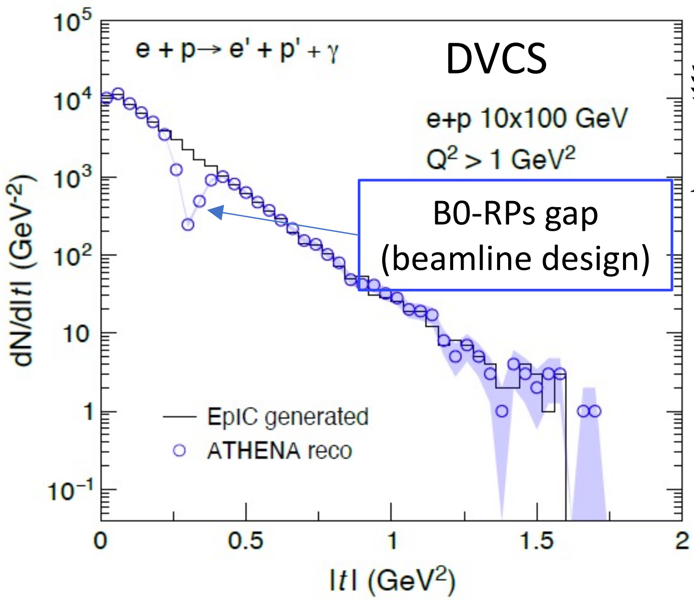
EIC W.P.

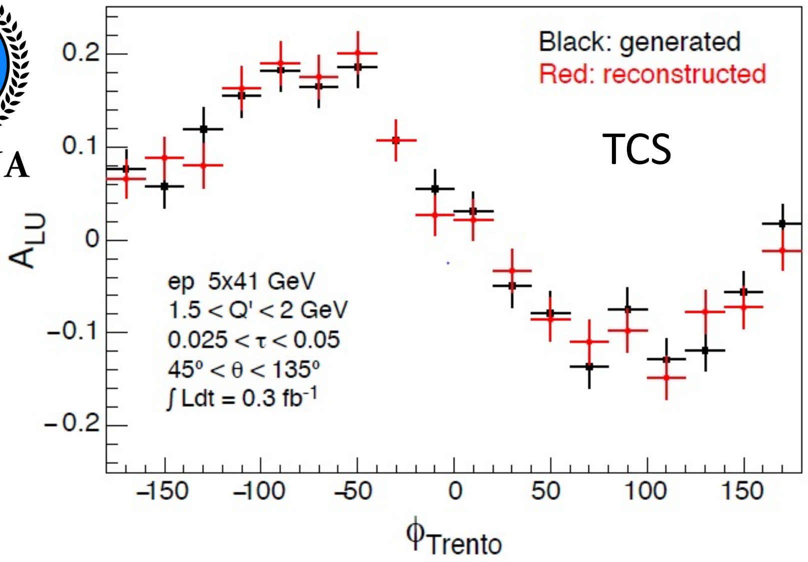


Spatial tomography – DVCS/TCS









Observables:

$d\sigma/dt$; A_{LU}; A_{UT}

Asymmetries (DVCS & TCS):

GPDs via amplitude-level interference with Bethe-Heitler

Key:

- Acceptance (including FF)
- γ/π^0 separation in ECAL
- t- lever arm in FF spectrometers

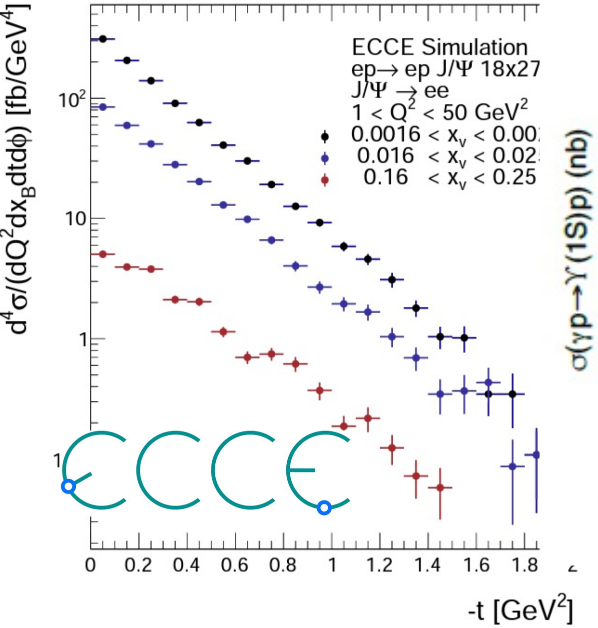
Timelike Compton Scattering (TCS)

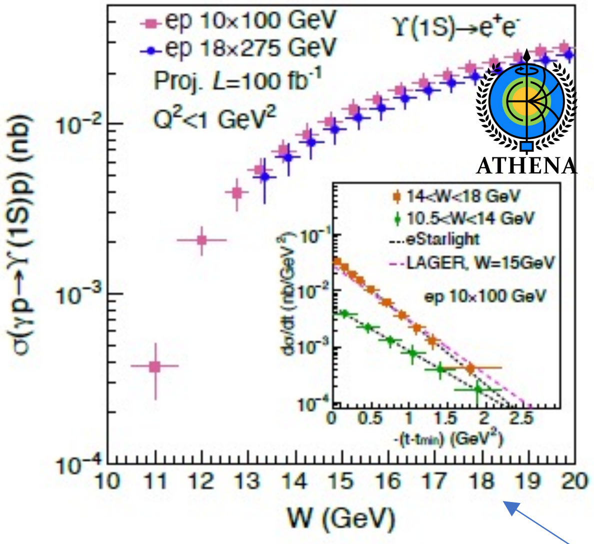
$\gamma p \rightarrow \gamma^* p \; (\gamma^* \rightarrow l^+ l^-)$

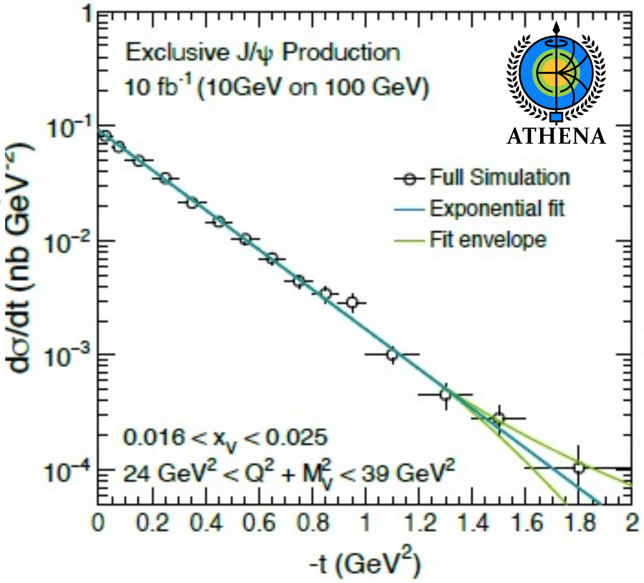
- Q': invariant mass of $l^+ l^-$
- $\tau = Q^2 = \left(s - m_p^2\right)$ equivalente to x_B

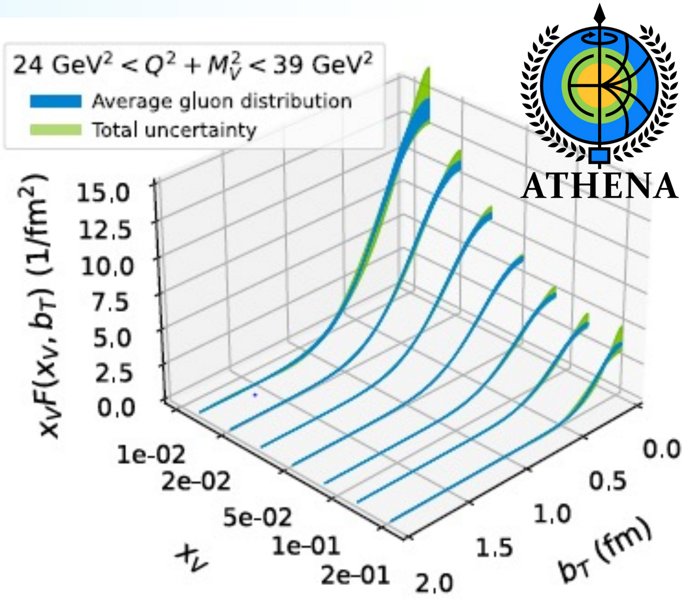
Spatial tomography - VMs

$\vec{e} + \vec{p} \rightarrow e + p + \vec{V}$

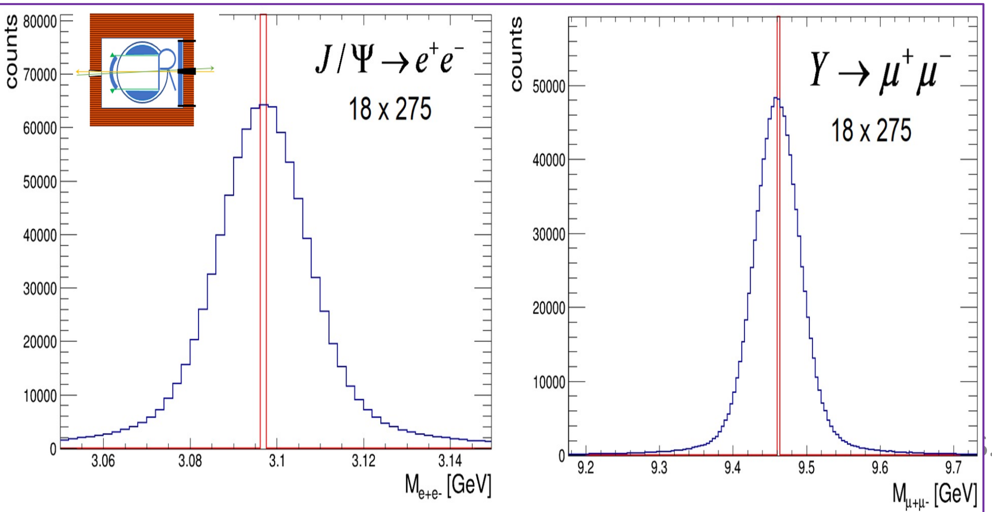








VMs invariant mass at CORE

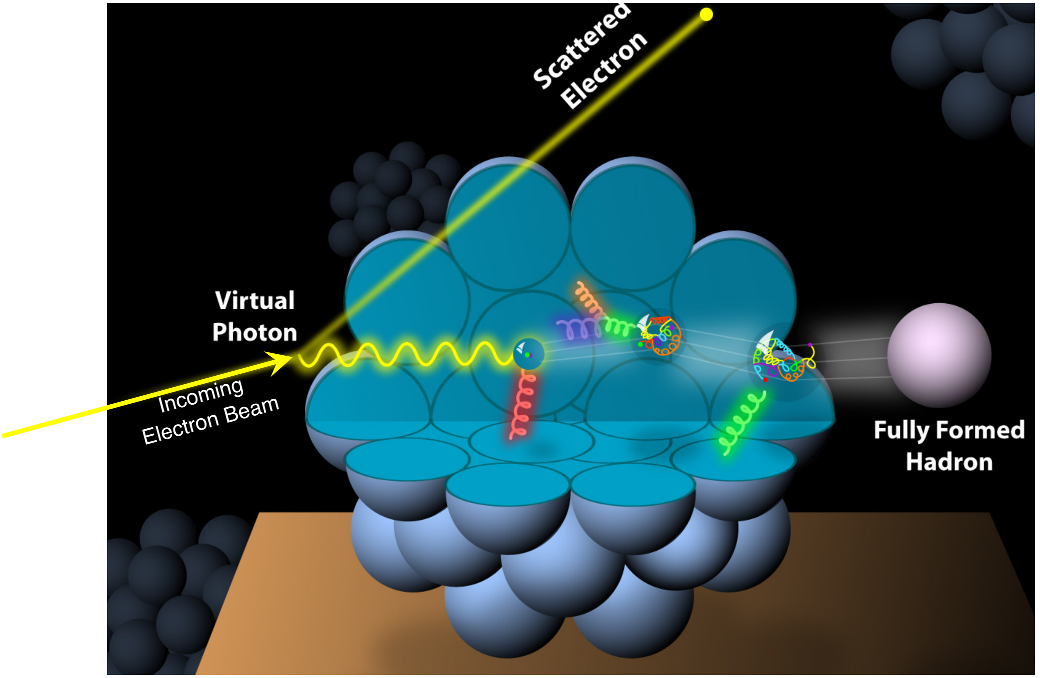


Υ Photopoduction near threshold and electro-production ($Q^2 < 1$ GeV^2) -> origin of *p*-mass

Key:

- Acceptance and low material for VM decay leptons
- Resolution of lepton pair inv. mass
- Muon id
- Scattered electrons over full kinem.
- t- lever arm in FF spectrometers

And what about the nuclei?



- How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?
- Where does the saturation of the gluon density set in?

Nuclear Structure Functions

Inclusive DIS on e+A analog to e+p:

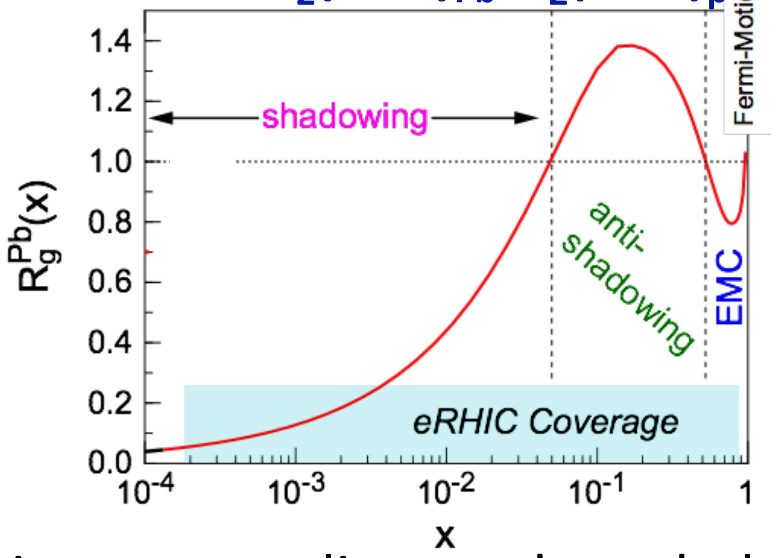
$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark

gluons
(or tag on F_2-charm)

Theory/models have to be able to describe the structure functions and their evolution

Ratio:$F_2(x,Q^2)_{Pb}/F_2(x,Q^2)_p$



DGLAP evolution model:
predicts Q^2 but not A-dependence and x-dependence

Saturation models:
predict A-dependence and x-dependence but not Q^2

→ Need: large Q^2 lever-arm for fixed x, A-scan

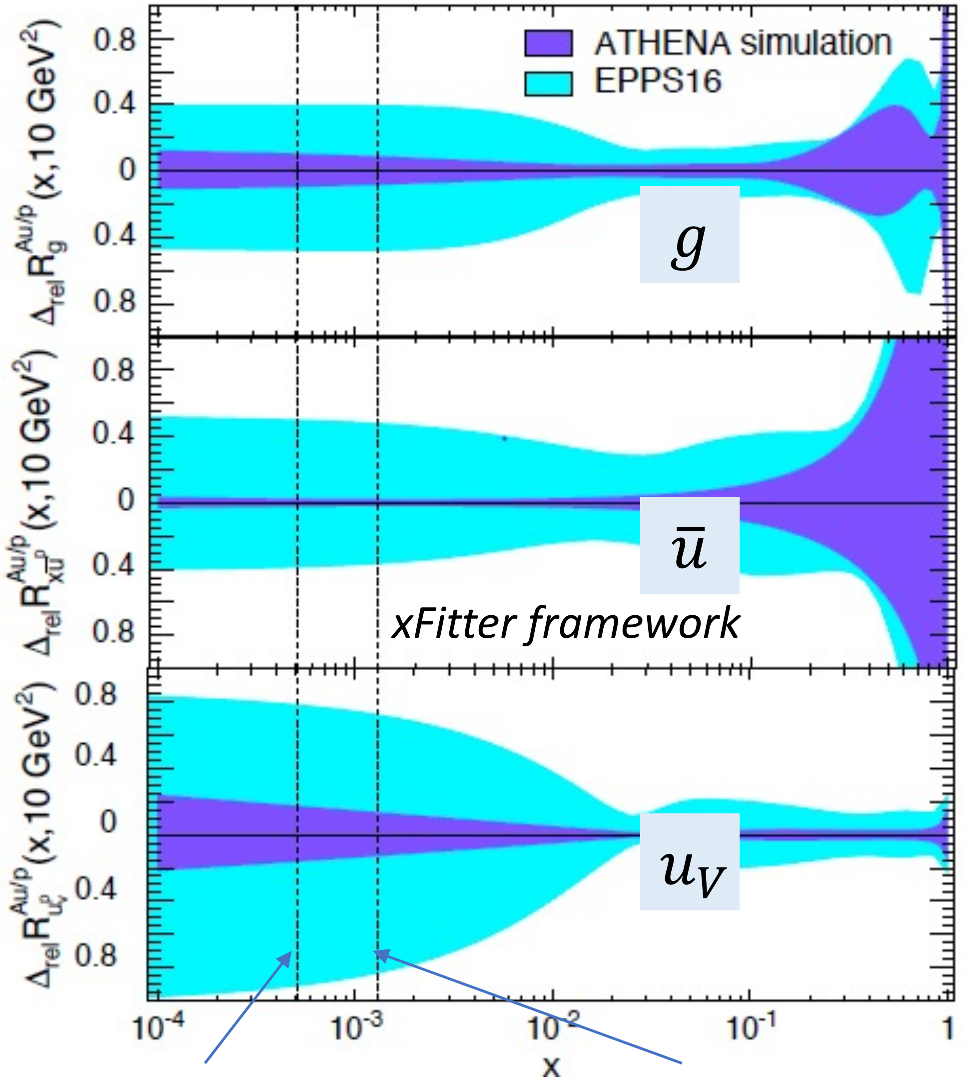
- Aim at extending our knowledge on structure functions into the realm where gluon saturation effects emerge ⇒ different evolution

An EIC provides a factor 10 larger reach in Q^2 and low-x compared to available data

Charm production at EIC:
Direct access to gluons at medium to high *x* by tagging **photon-gluon fusion**

Collinear PDFs on protons and nuclei

nPDFs: Au/p



Minimum x for p fit

Minimum x for A fit

Impact after global fits

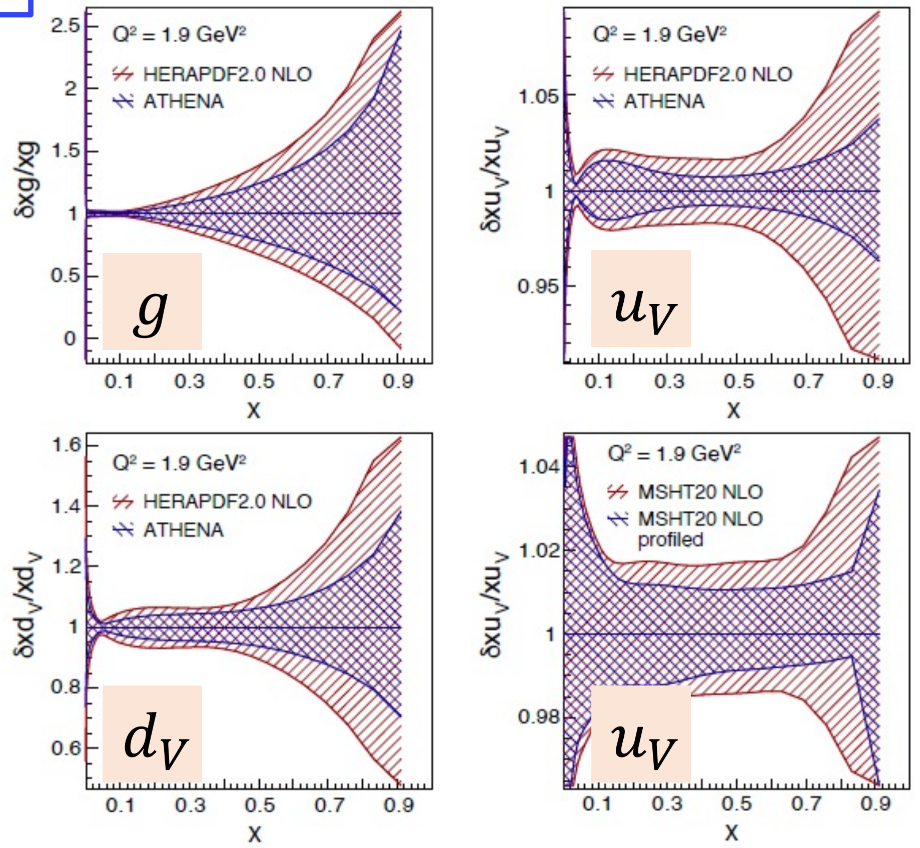
gluon nPDFs

- constrained at the ~10% level over large x-arm

proton PDFs

- impact on HERA + LHC global fits
- EIC/ATHENA constrains the high-x region

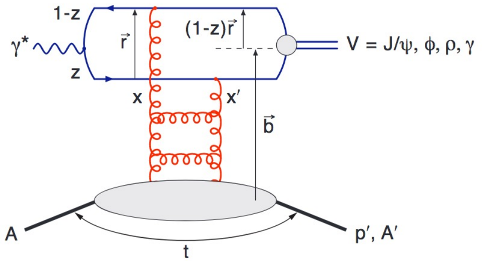
proton PDFs



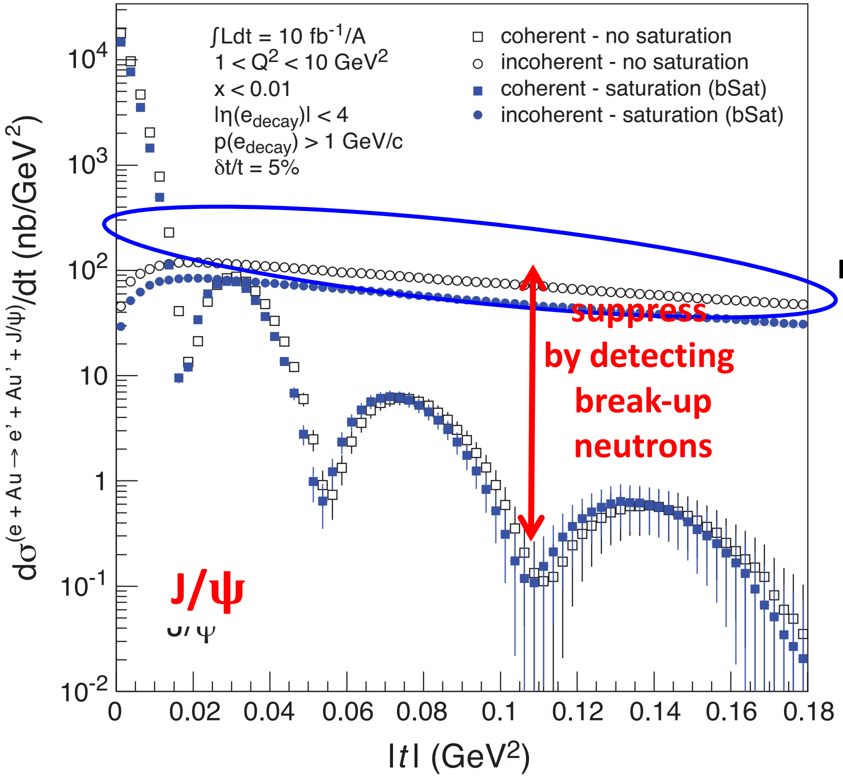
Key:

- Fine resolution in *y* over a large phase space

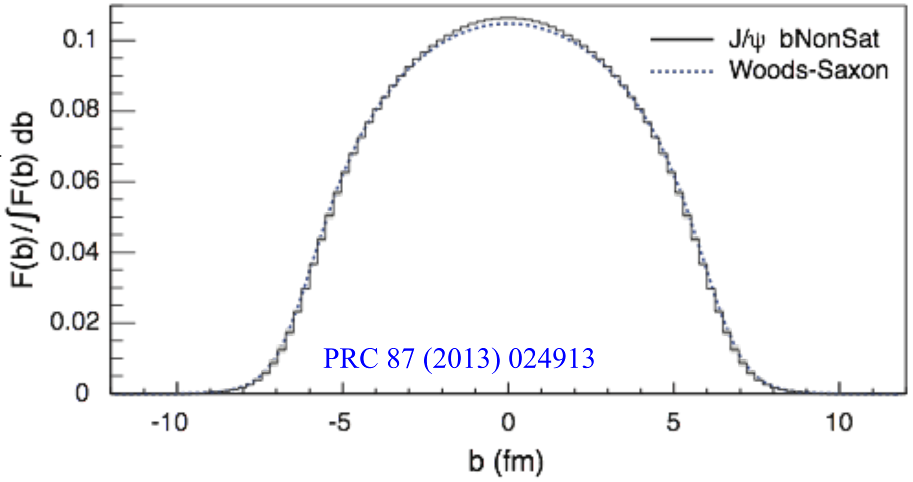
Imaging of gluons in Nuclei



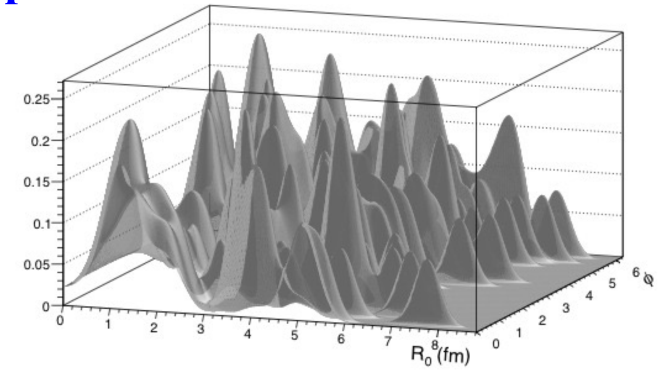
Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi$



Fourier Transform

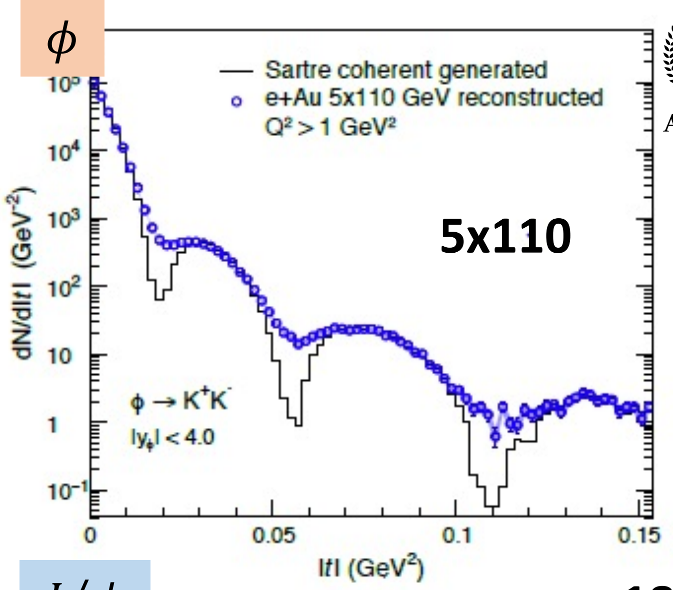


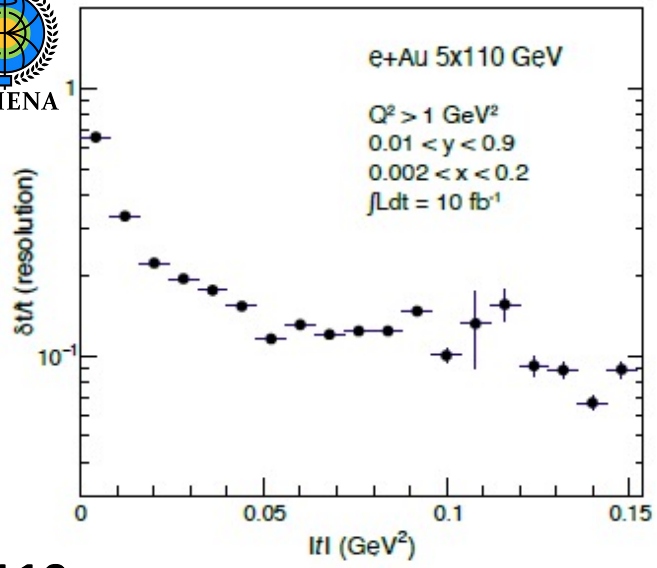
possible Source distribution with $b_T^g = 2\ GeV^{-2}$

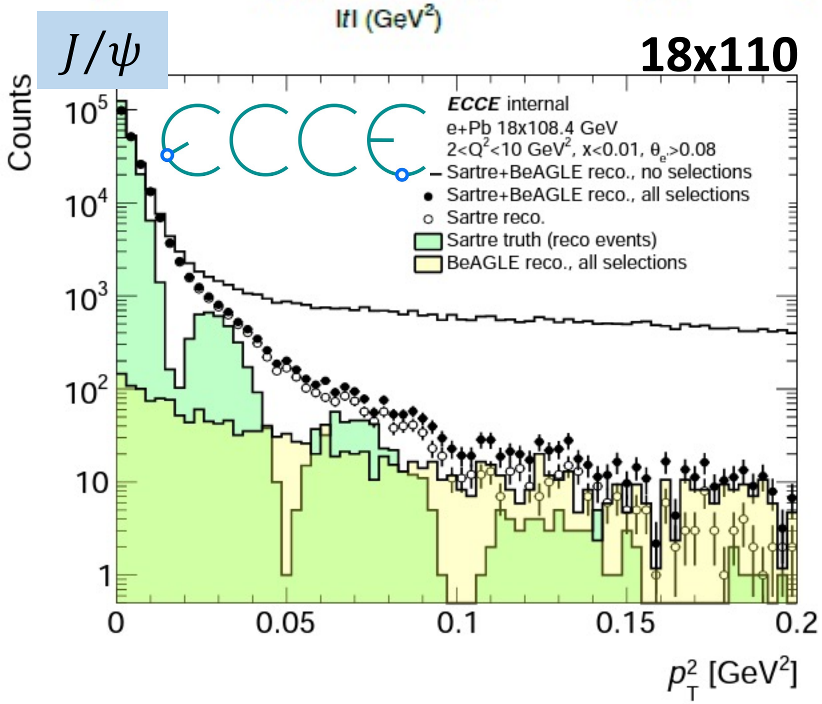


- Nuclear modifications of GPDs & gluon saturation
- Coherent part probes "shape of black disc"
- Incoherent part (large *t*) sensitive to "lumpiness" of the source [= proton] (fluctuations, hot spots, ...)

Imaging of gluons in Nuclei







EIC Yellow Report:

➢ Measuring up to two minima required for High quality Fourier transform

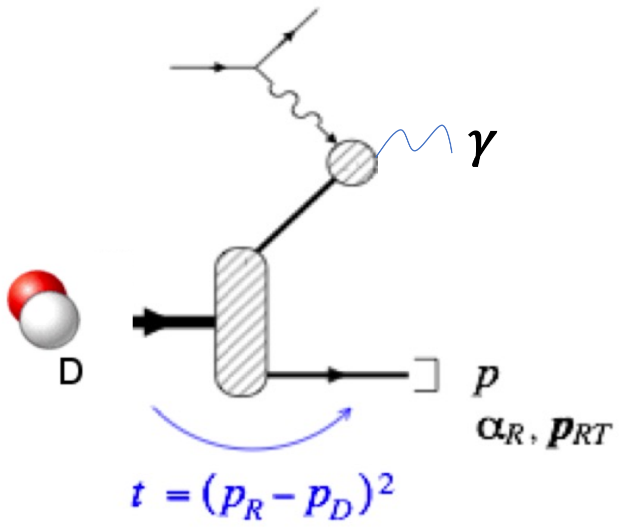
Key:

- High resolution reconstruction of the event kinematics and the final-state VM decays:
  → 3T solenoid (higher field helps!)
- high-purity coherent sample:
  - veto the nuclear breakups using FF
  - PID to suppress vector meson

Note:

- Simulations (both experiment) do not yet include pid
- *t* is reconstructed from scattered *e* and VM
- **ECCE plot:** note how at higher $\sqrt{s}$ it's harder to get to the minima (same confirmed by ATHENA)

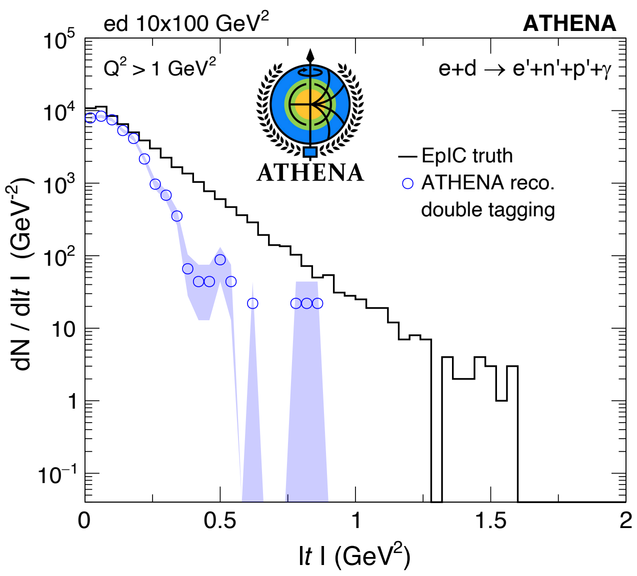
Study of neutrons with light nuclei

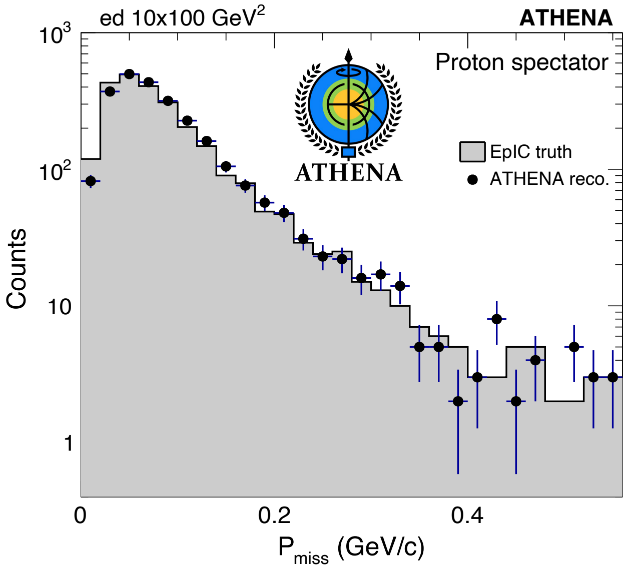


- Possibility to study neutron structure
- DVCS on neutron compared to proton is important for flavor u/d separation

DVCS on incoherent D (D breaks up) but coherent on the neutron, the "double tagging" method

- **Tag DIS on a neutron (by the ZDC)**
- **Measure the recoil proton momentum**
- **The recoil proton momentum cone is**
  - $\alpha_R = (E_R + p_{R||})/(E_D + p_{D||})$ **and** p_{RT}
- Gives you a free neutron structure, not affected by final state interactions

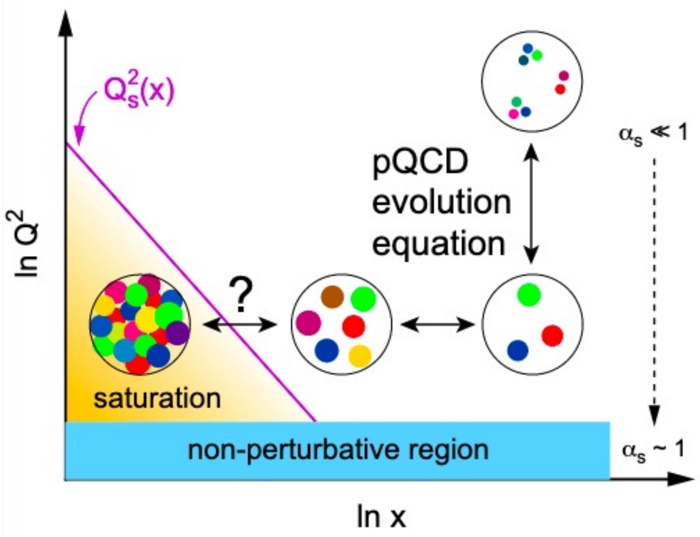




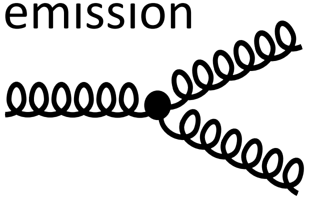
ATHENA – DVCS on e+D:

- 80-90% acceptance at low |t|,
- |t|-acceptance loss at higher value mostly due to the loss in tagging the active neutron in ZDC.
- Alternatively, |t| can be measured via scattered e and γ → higher acceptance at large |t|.
- Proton momentum is well reconstructed

A window into the Gluon Saturation regime

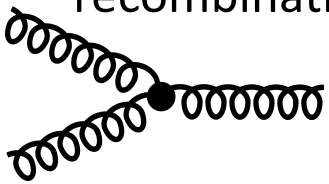


gluon emission



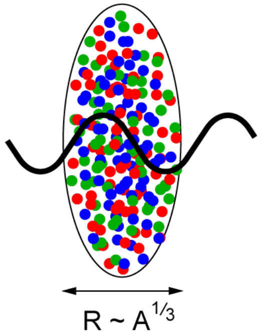
?=?

gluon recombination



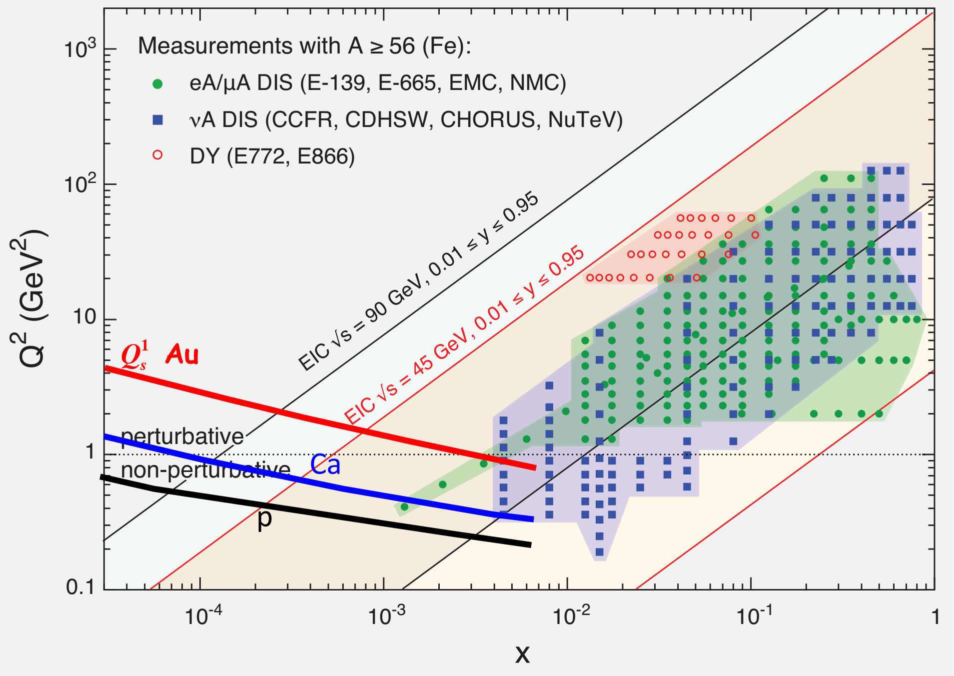
$$(Q_s^A)^2 \sim cQ_o^2\left(\frac{A}{x}\right)^{1/3}$$

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



Probe interacts coherently with all nucleons

Gold: 197 times smaller effective *x* !



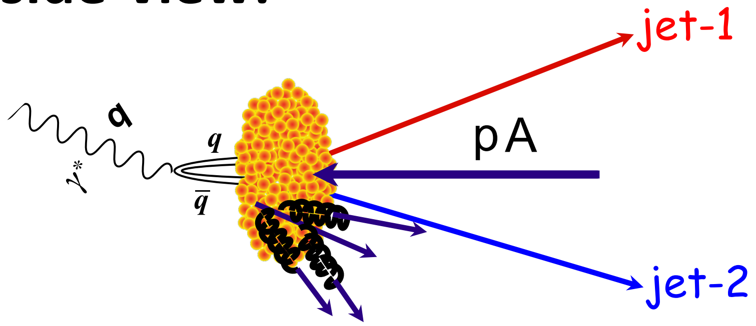
→ EIC will map the transition between a non-saturated and a saturated regime with high precision, by making use of a large range of nuclei and spin

→ With its flexible ion source we will be able to measure the A-dependence of the saturation scale $Q_s(x)$

→ a fundamental landmark of QCD

Saturation via Di-hadron correlations

side-view:

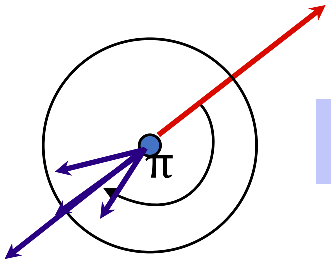


Low gluon density (ep):

pQCD predicts 2→2 process

⇒ back-to-back di-jet

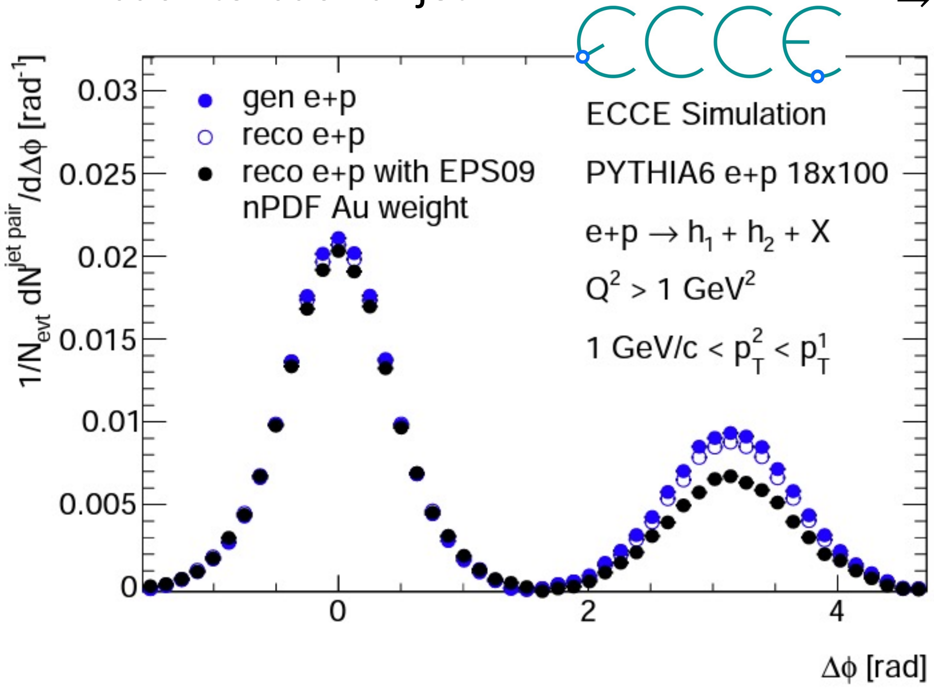
beam-view:



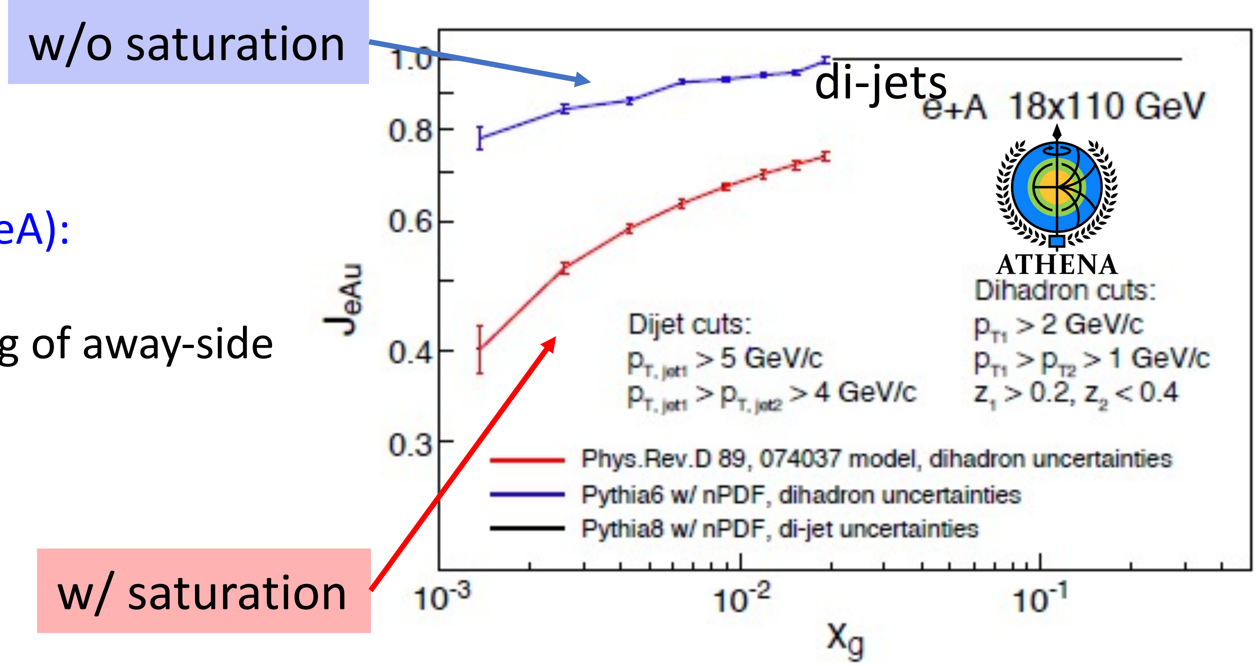
High gluon density (eA):

2 → many process

⇒ expect broadening of away-side



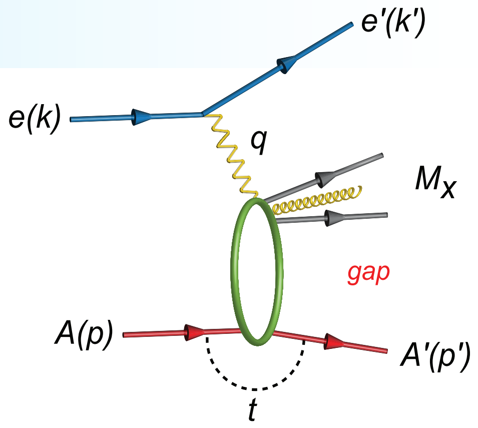
Relative yield of correlated back-to-back hadron pairs in e+Au/e+p scaled down by $A^{1/3}$ (the number of nucleons at a fixed impact parameter)



Key:

- Quality detection at mid rapidity
- Reconstruction of dijets sensitive to saturation effects

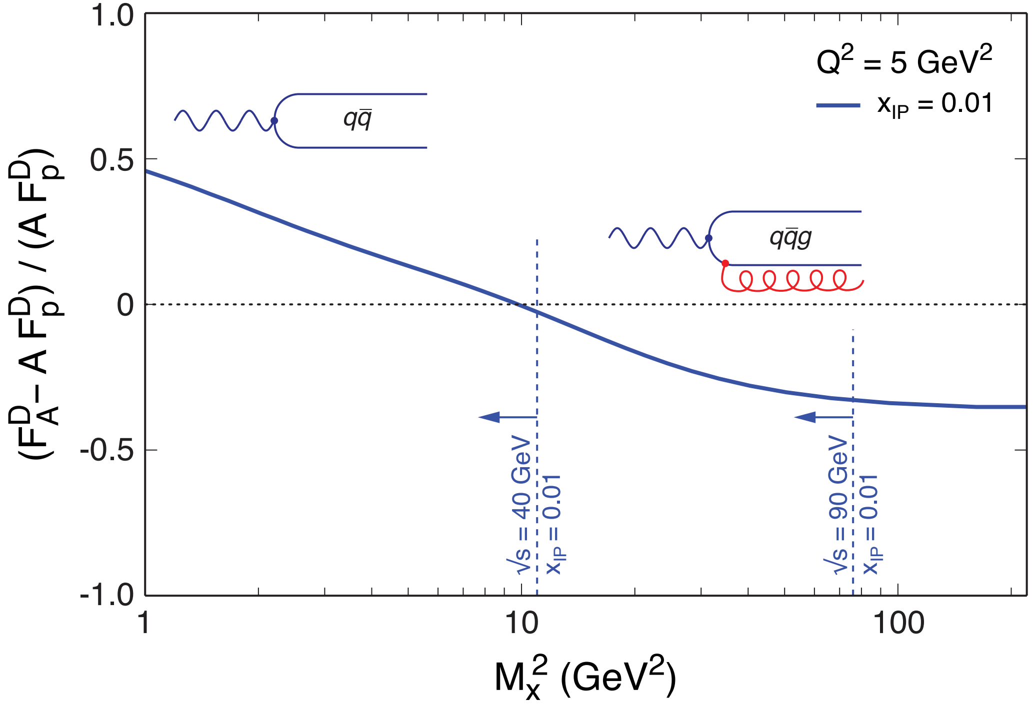
Saturation via Diffraction



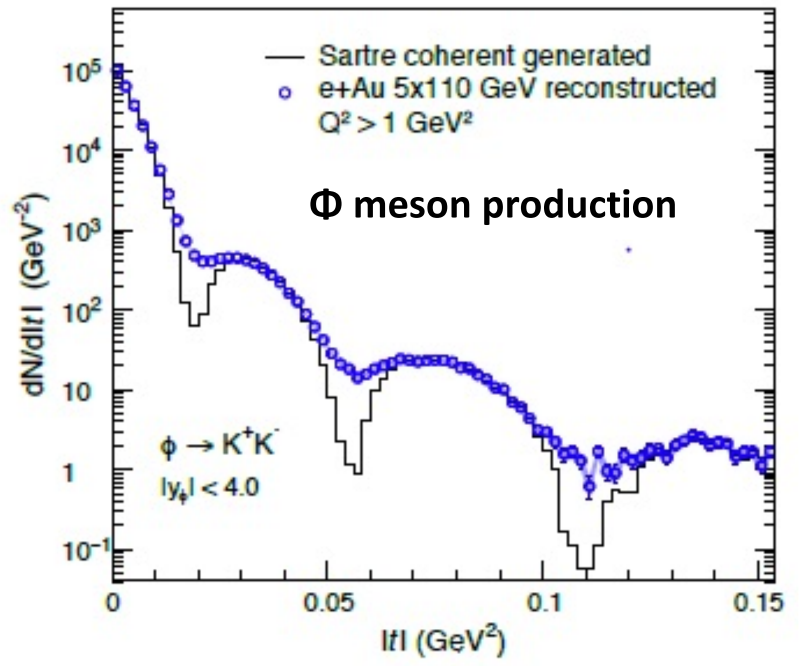
Diffraction

High sensitivity to gluon density in linear regime $\sigma \sim [g(x,Q^2)]^2$

Transition in M_x



Exclusive VMP



Summary

- **The EIC (with a state of art detector) will allow us to obtain the answers to the big questions discussed**
  - ✓ Solve the proton spin puzzle
  - ✓ How visible matter emerges from quarks and gluons, confined in hadrons?
  - ✓ 3D imaging in momentum and coordinate space of nucleons and nuclei
    - ✓ Investigate the origin of proton mass
  - ✓ Map the region of the transition from non-saturated to saturated regime
  - ✓ And much more I had no time to cover: e.g. Spectroscopy, Cold Nuclear matter, Wigner fnc., separation of Υ states...

- Excellent proposals have been presented for possible collider detector with high resolution, wide acceptance and good particle identification

- However the selection process goes... let us remember:
  - we are one single dedicated and enthusiastic community worldwide.
  - we made through the site selection process together
  - we aim to remain together for many decades to come!