The science of Electron-Ion Collider

Yoshitaka Hatta

BNL/Yukawa inst. Kyoto

OCTOBER 1 – NOVEMBER 16, 2018 • SEATTLE, WASHINGTON

PROBING NUCLEONS AND NUCLEI IN HIGH ENERGY COLLISIONS

ORGANIZERS
Yoshitaka Hatta, *Kyoto University/BNL*
Yuri Kovchegov, *The Ohio State University*
Cyrille Marquet, *CPHT - Ecole Polytechnique*
Alexei Prokudin, *Penn State University Berks*

PROGRAM STRUCTURE

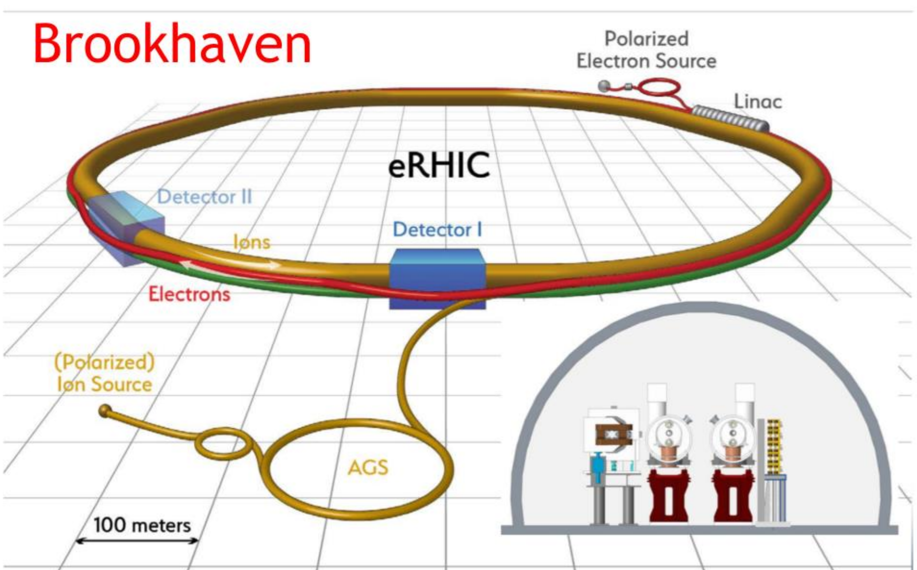
Week 1 Week 2 Week 3 Week

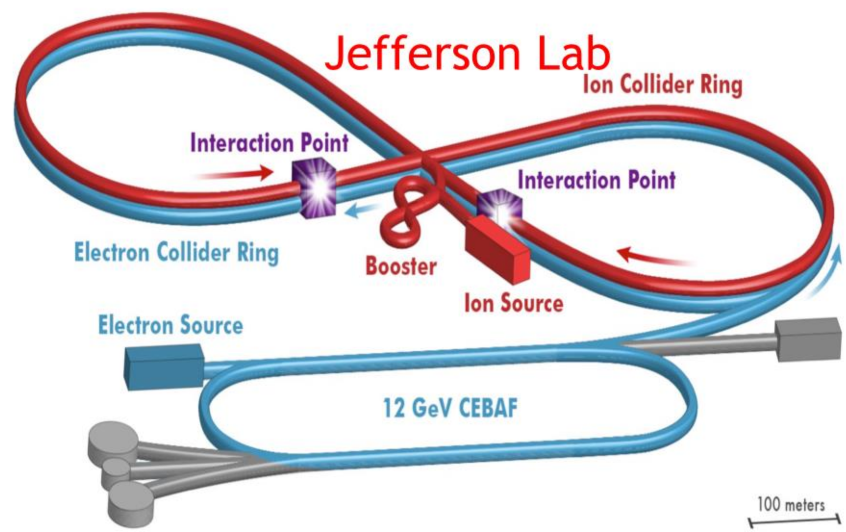
Electron-Ion Collider (EIC)

A future high-luminosity polarized ep, eA collider dedicated to the study of the nucleon and nucleus structure.

Center-of-mass energy	$20 \lesssim \sqrt{s} \lesssim 140\,\mathrm{GeV}$
Luminosity	$\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

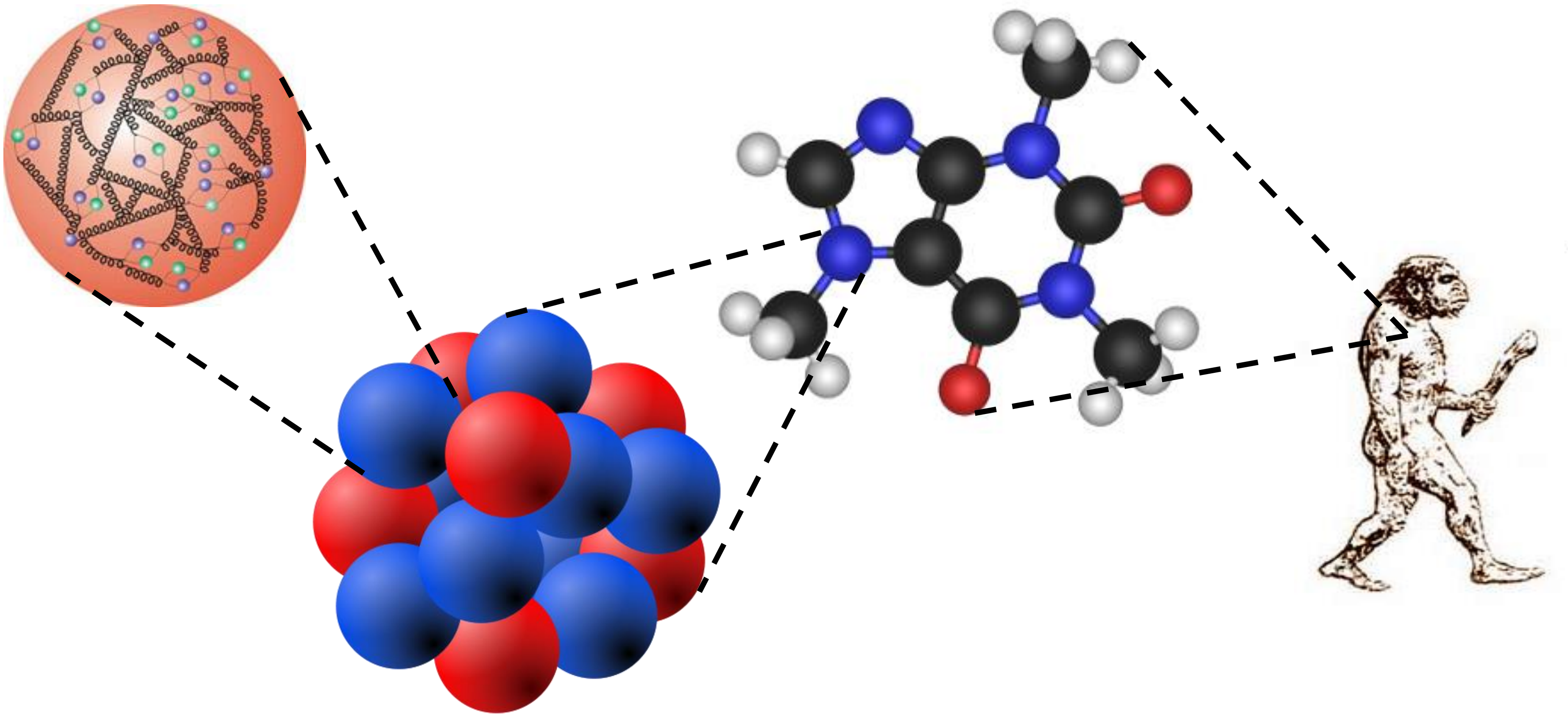
2 possible realizations





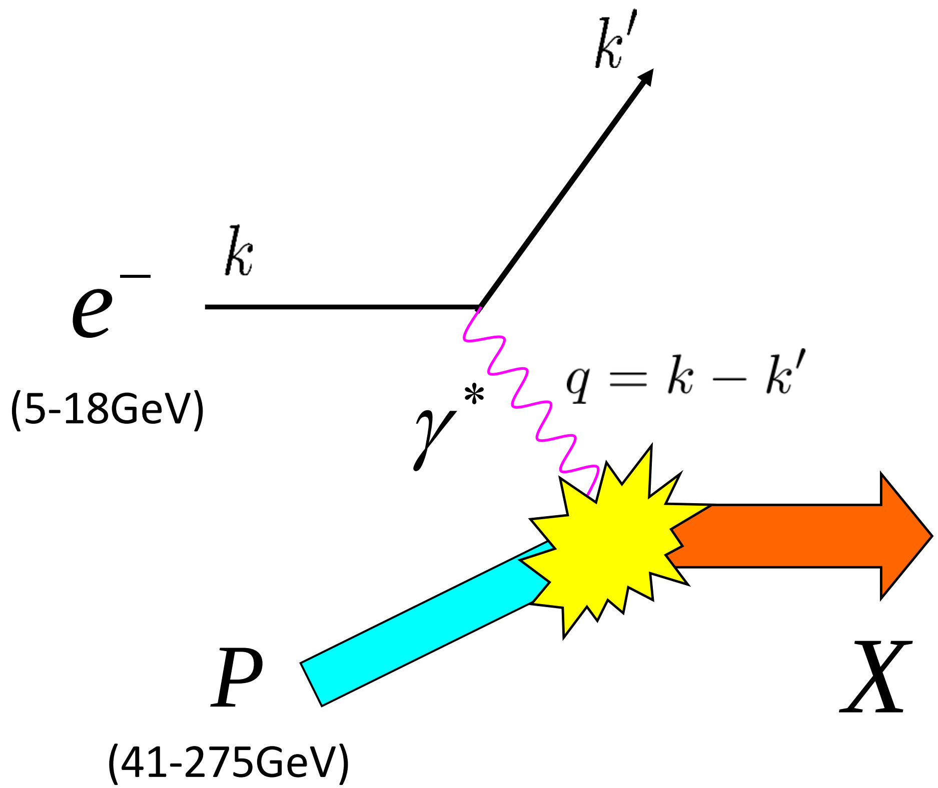
Understand the glue that binds us all

Nucleons and nuclei—the fundamental building blocks of the visible universe.
Understand their structure in QCD, namely, in terms of quarks and gluons.



Especially the role of gluons—the least understood particle in the Standard Model.
How do they give rise to the nucleon's mass, spin, etc?

Experiment at EIC: Deep Inelastic Scattering (DIS)



proton, deuteron, helium, gold…
any nucleus of your choice!

Electron, proton and light nuclei can be polarized.

Two most important kinematic variables

$$Q^2 = -q^2$$ photon virtuality (resolution)

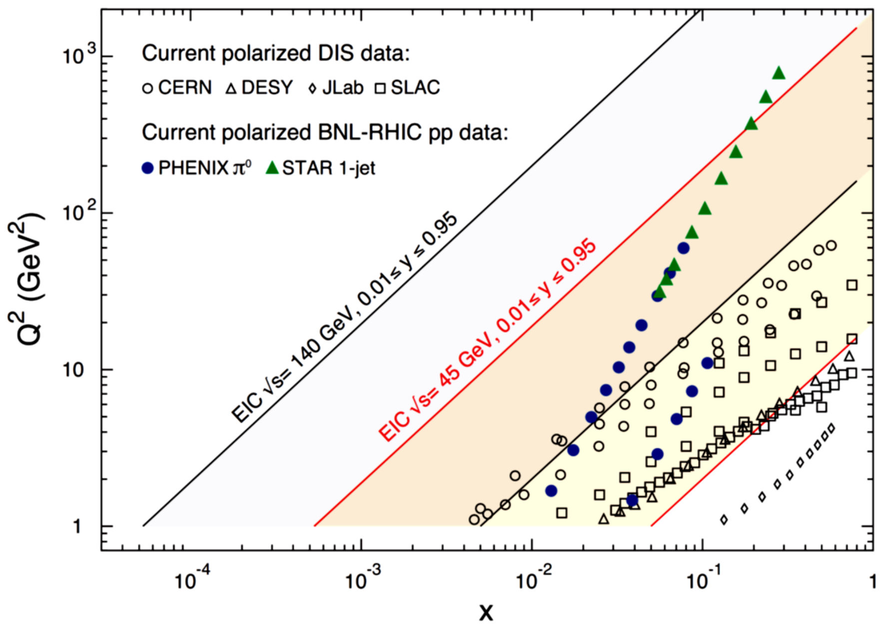
$$x = \frac{Q^2}{2P \cdot q}$$ Bjorken variable (inverse energy)

Roughly, $$x \approx \frac{E_{parton}}{E_{proton}}$$

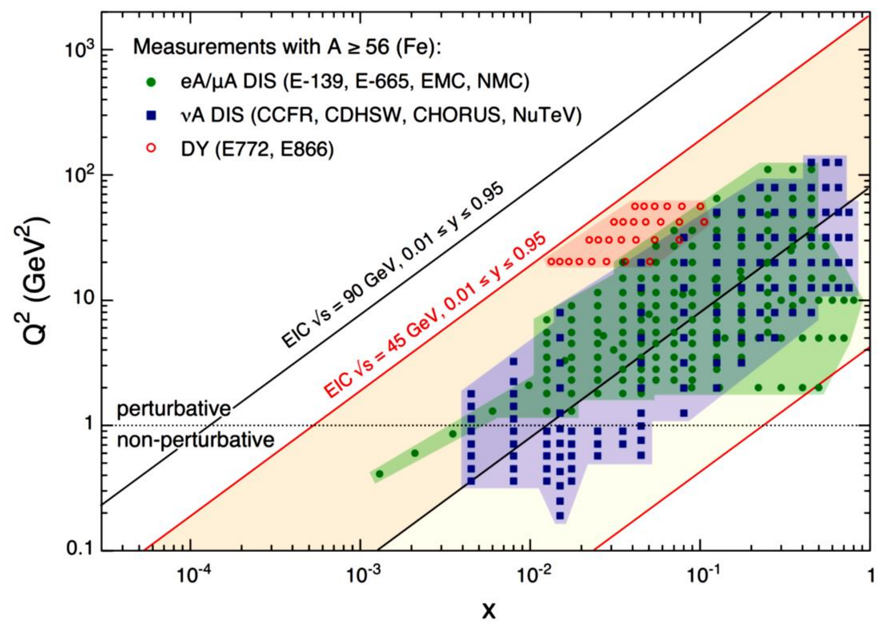
Momentum fraction carried by the participating parton

EIC Kinematical coverage

Polarized DIS



Nuclear DIS

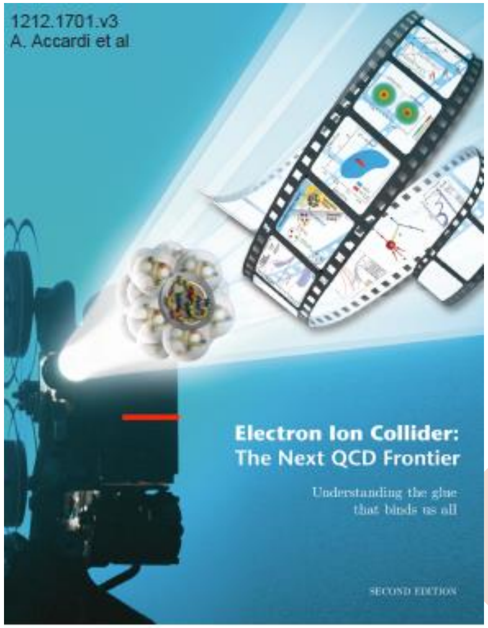


High resolution

High energy

Unprecedented coverage in kinematics.
Tremendous physics opportunities!

Scientific goals of EIC



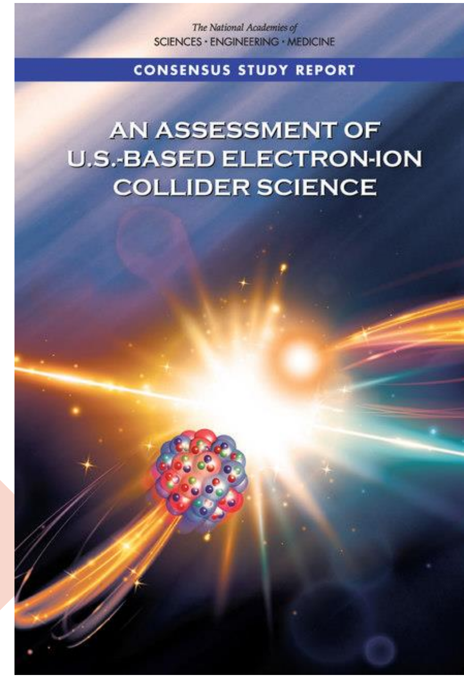
White paper
arXiv:1212.1701

Origin of nucleon mass

Origin of nucleon spin

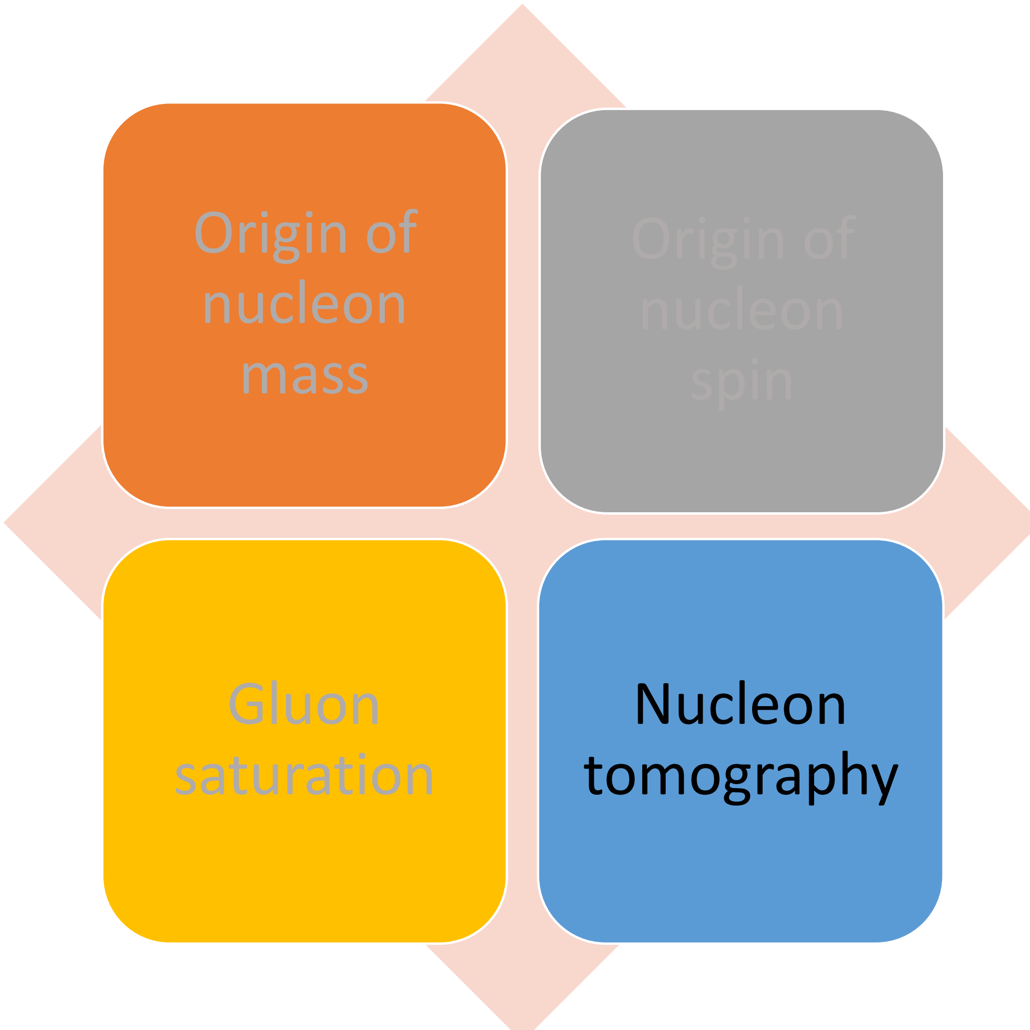
Gluon saturation

Nucleon tomography



NAS report
July 2018

Scientific goals of EIC

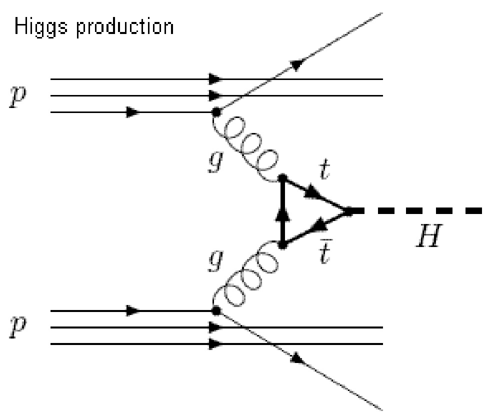


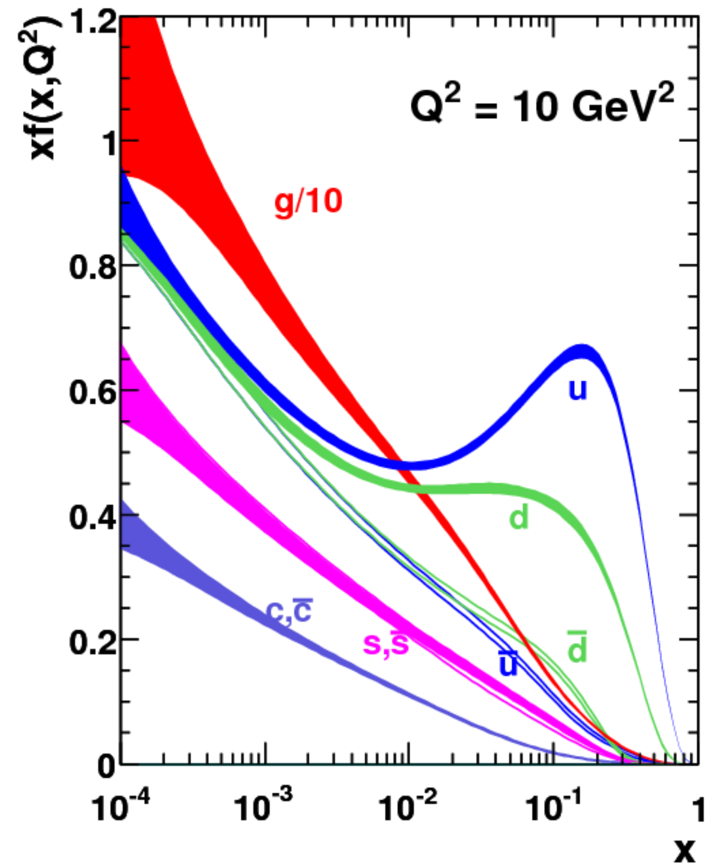
Parton distribution function

$$u(x) = \int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle P|\bar{u}(-z^-/2)\gamma^+ u(z^-/2)|P\rangle$$

Number distribution of up quarks
with momentum fraction x inside the proton

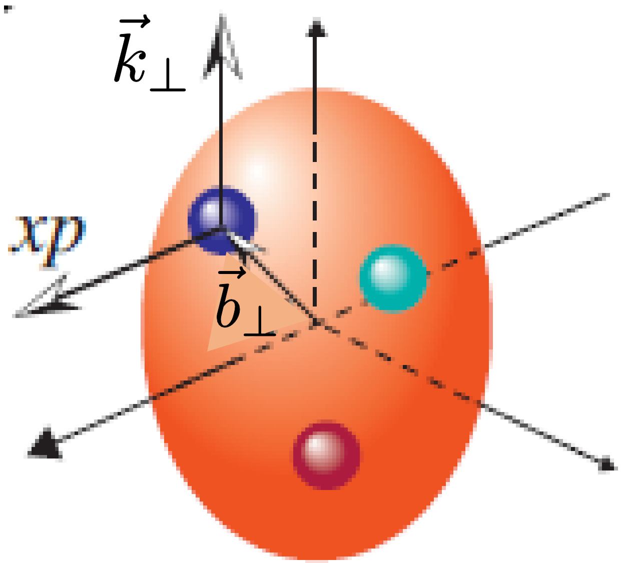
QCD factorization $\quad \sigma = \sigma_0 \otimes g(x_1) \otimes g(x_2)$





Universality of PDF—the same function can be used for different processes.
Fundamental to the predictive power of pQCD

Multi-dimensional tomography



The nucleon is much more complicated!
Partons also have transverse momentum $\vec{k}_\perp$
and are spread in impact parameter space $\vec{b}_\perp$

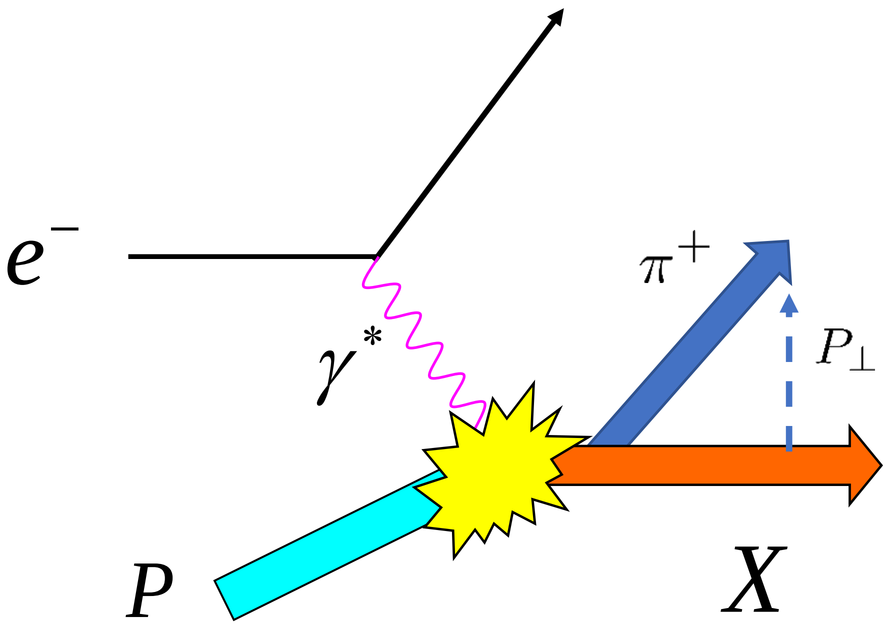
$u(x) \rightarrow$

$u(x, \vec{k}_\perp)$ Transverse momentum dependent distribution (TMD) 3D tomography

$u(x, \vec{b}_\perp)$ Generalized parton distribution (GPD) 3D tomography

$u(x, \vec{b}_\perp, \vec{k}_\perp)$ Wigner distribution 5D tomography

Measuring TMD : Semi-inclusive DIS



Measure particular hadron species with fixed transverse momentum $P_\perp$ plus anything else.

When $P_\perp$ is small, TMD factorization

Collins, Soper, Sterman;
Ji, Ma, Yuan,…

$$\frac{d\sigma}{dP_\perp} = H(\mu)\int d^2q_\perp d^2k_\perp f(x,k_\perp,\mu,\zeta)D(z,q_\perp,\mu,Q^2/\zeta)\delta^{(2)}(zk_\perp + q_\perp - P_\perp) + \cdots$$

TMD PDF TMD frag. func.

Open up a new class of observables where perturbative QCD is applicable!

TMD evolution

Define Fourier transform
$$\int d^2k_\perp e^{ik_\perp r_\perp} f(k_\perp ...) = f(r_\perp ...)$$

RG equation

$$\frac{\partial}{\partial \ln \mu} f(x, r_\perp, \mu, \zeta) = \gamma_F f(x, r_\perp, \mu, \zeta)$$

Known to three loops
Moch, Vermeseren, Vogt (2005)

Collins-Soper equation

$$\frac{\partial}{\partial \ln \zeta} f(x, r_\perp, \mu, \zeta) = -\mathcal{D}(r_\perp) f(x, r_\perp, \mu, \zeta)$$

Recently computed to three loops!
Li, Zhu (2017); Vladimirov (2017)

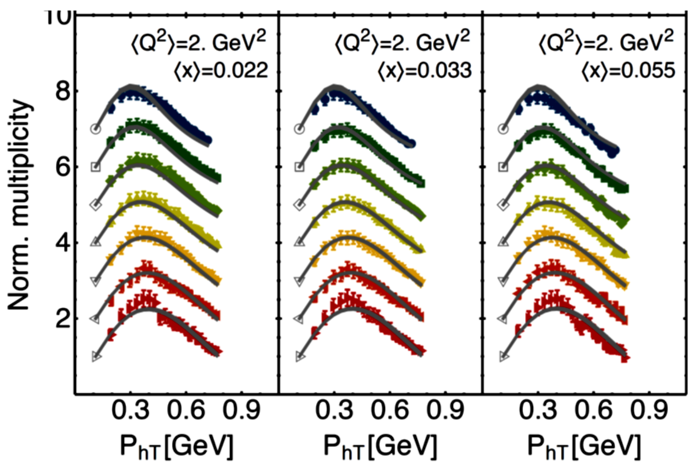
TMD global analysis

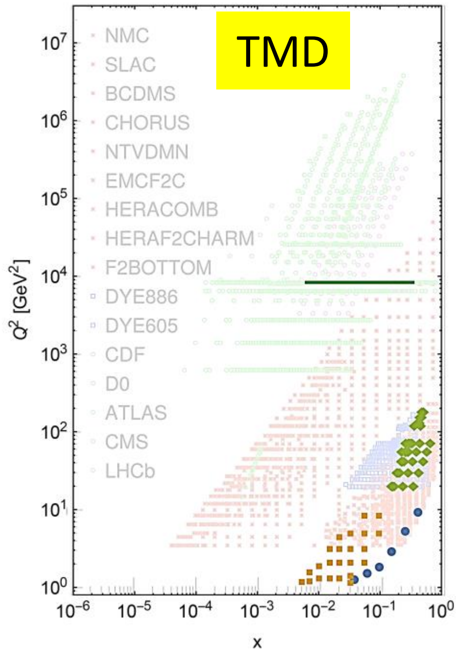
Global analysis of TMD based on ~8000 data points from SIDIS, Drell-Yan.

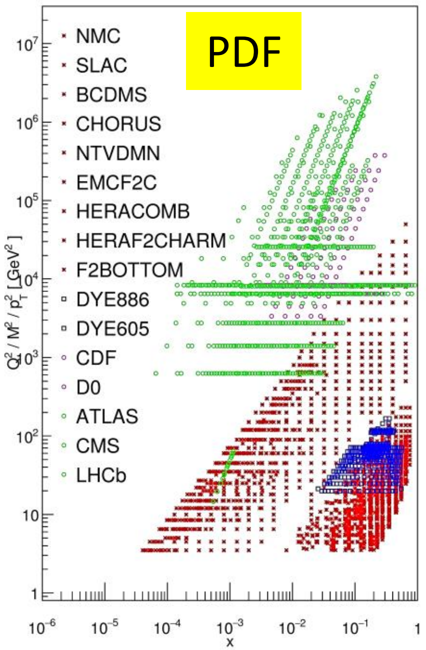
Bacchetta, Delcarro, Pisano, Radici, Signori (2017)

arTeMiDe state-of-the-art (NNLO+NNLL) implementation Scimemi, Vladimirov (2017)

TMDlib public library Hautmann, Jung, Mulders,…



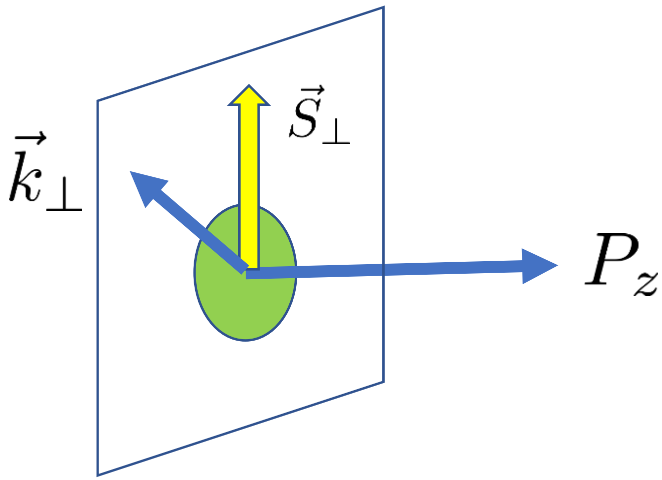




Still in its infancy. Fully blossoms in the EIC era!

Universality up to a sign

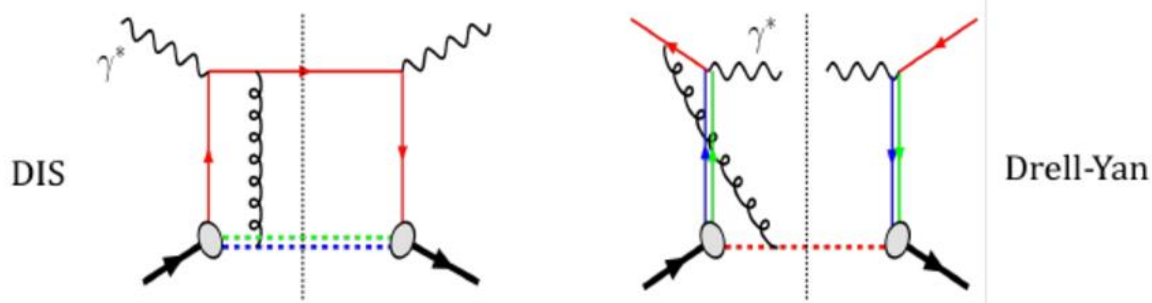
Sivers function for the transversely polarized nucleon



$$\sim \vec{S}_\perp \times \vec{k}_\perp f_{1T}^\perp(x, k_\perp)$$

→ Single spin asymmetry

The same function, but with opposite signs in DIS and Drell-Yan. (Collins, 2002)



Experimental test at Compass and RHIC. Continue at EIC.
EIC can also probe gluon Sivers function from open charm SSA.

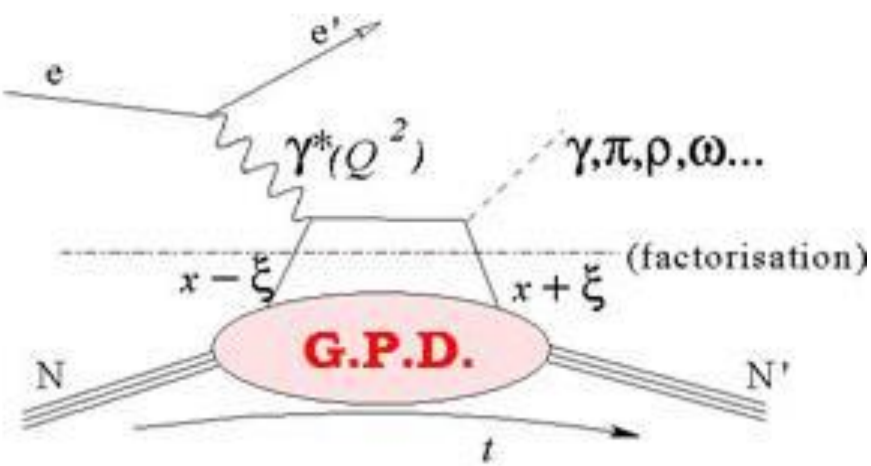
Generalized parton distributions (GPD)

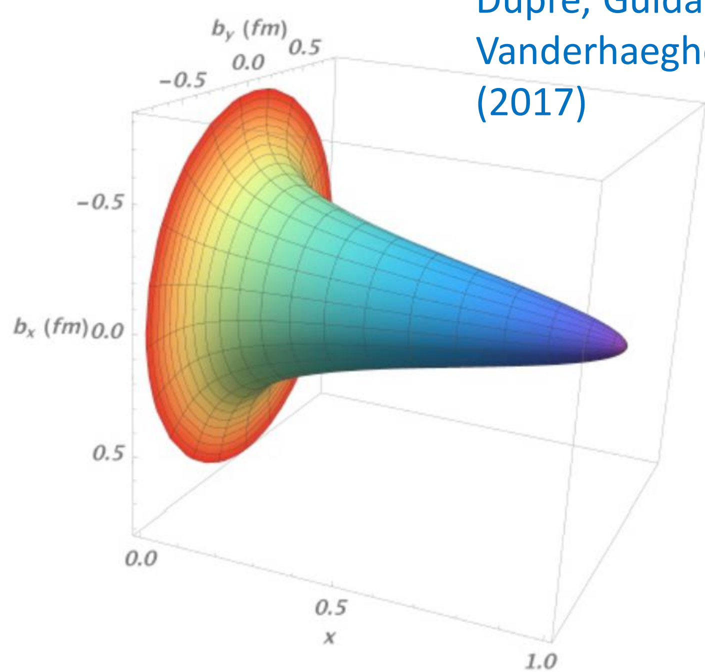
$$P^+ \int \frac{dy^-}{2\pi} e^{ixP^+y^-} \langle P'S'|\bar{\psi}(0)\gamma^\mu\psi(y^-)|PS\rangle$$

$$= H_q(x,\Delta)\bar{u}(P'S')\gamma^\mu u(PS) + E_q(x,\Delta)\bar{u}(P'S')\frac{i\sigma^{\mu\nu}\Delta_\nu}{2m}u(PS) \qquad \Delta = P' - P$$

Fourier transform → Distribution of partons in impact parameter space $b_\perp$

Measurable in
Deeply Virtual Compton Scattering (DVCS)





Dupre, Guidal, Vanderhaeghen (2017)

Towards measuring GPD E at the EIC

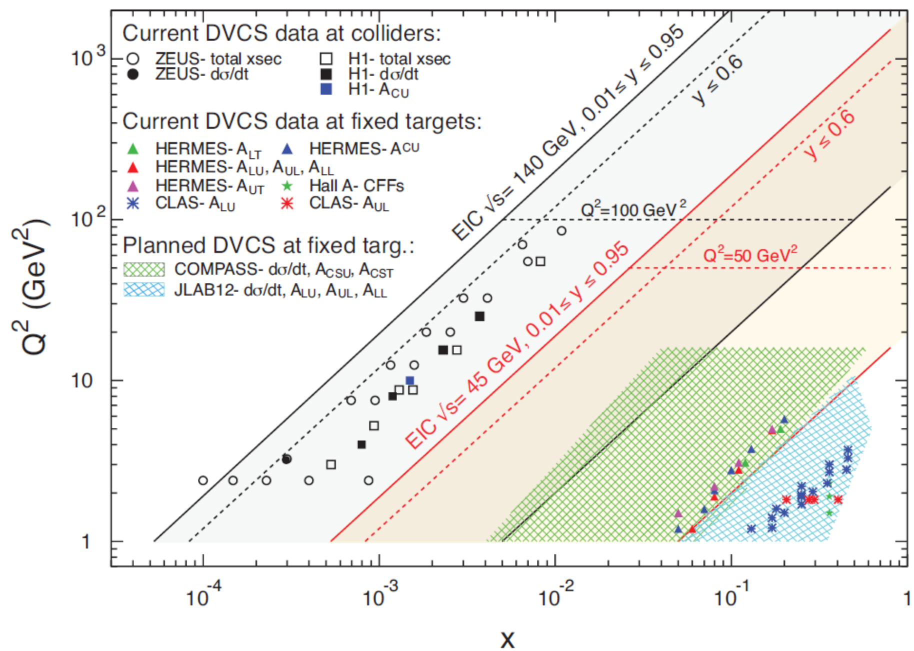
Ji sum rule for proton spin $$\frac{1}{2} = J_q + J_g$$

$$J_q = \frac{1}{2}\int dx (H_q(x) + E_q(x)) \qquad J_g = \frac{1}{4}\int dx (H_g(x) + E_g(x))$$

Currently very little is known about E_q, nothing about E_g from experiments.

At EIC, we can get a handle on E_q.
Aschenauer, Fazio, Kumericki, Muller (2013)

E_g is still challenging, but EIC is the only hope.



D-term: the last global unknown

$$\langle P'|T^{\mu\nu}|P\rangle = \bar{u}(P')\left[A(t)\gamma^{(\mu}\bar{P}^{\nu)} + D(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M}\right]u(P) \qquad t = \Delta^2$$

$D(t=0)$ is a conserved charge of the nucleon, just like mass and spin!

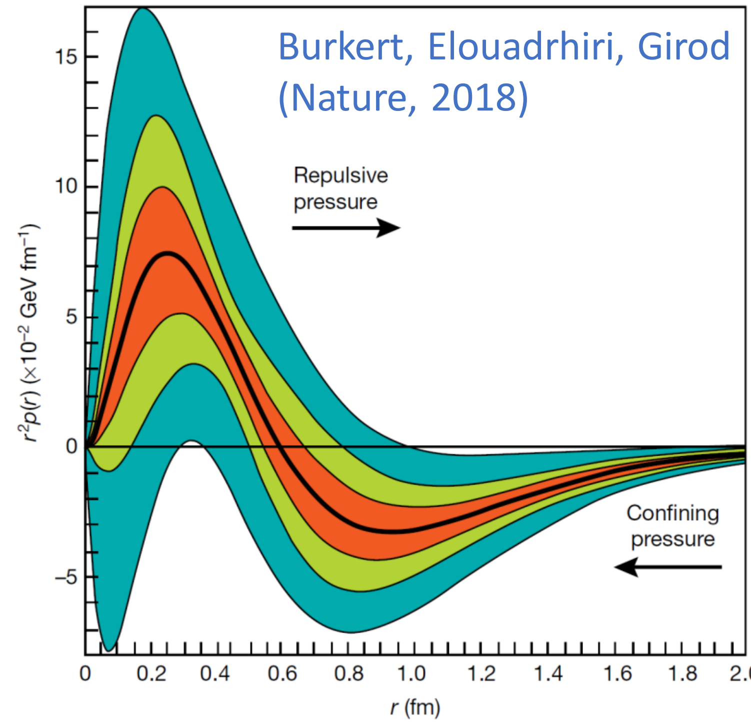
	Proton	Neutron
Mass	938.3MeV	939.6MeV
Spin	½	½
Charge	+1	0
D-term	?	?

Pressure and stability of the nucleon

D-term related to the radial pressure distribution inside a nucleon Polyakov, Schweitzer,…

$$\langle P'|T^{ij}|P\rangle \sim (\Delta^i\Delta^k - \delta^{ik}\Delta^2)D(t)$$

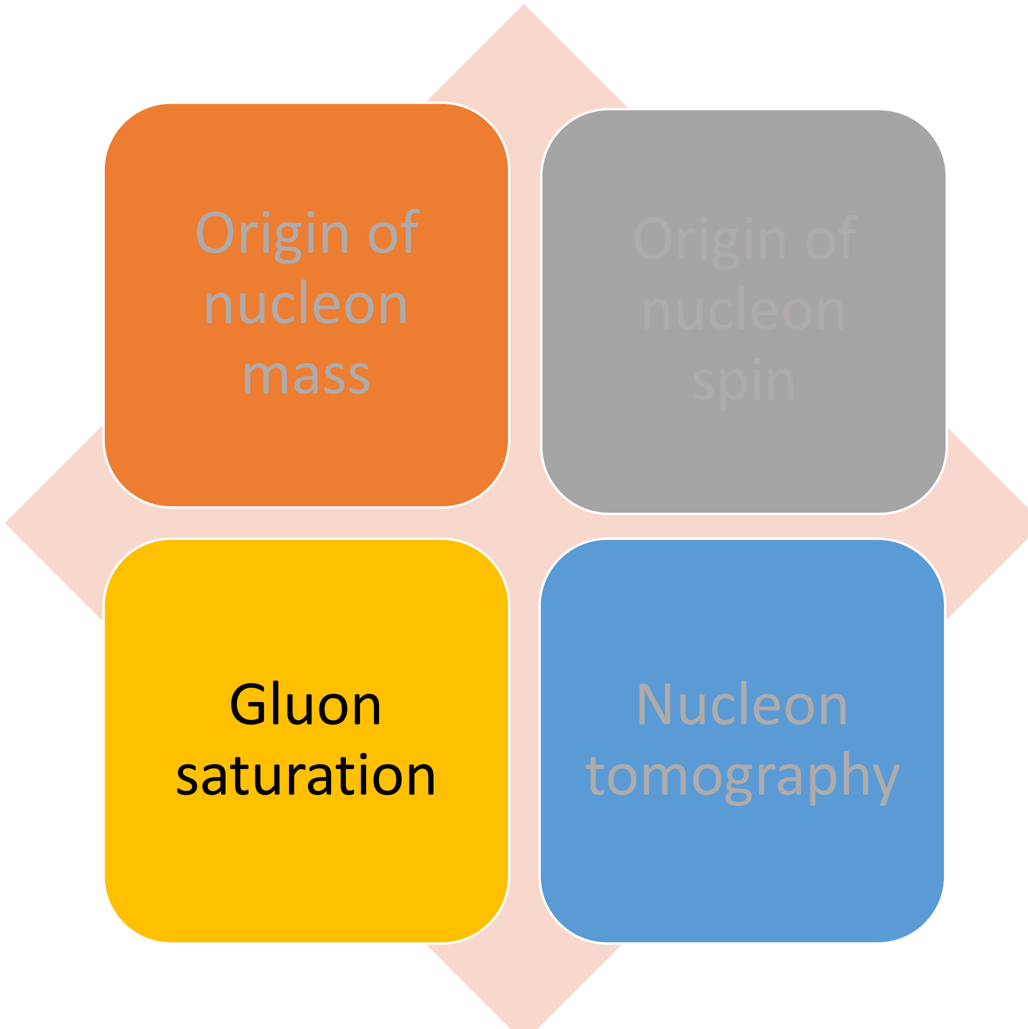
$$T^{ij}(r) = \left(\frac{r^i r^j}{r^2} - \frac{1}{3}\delta^{ij}\right)s(r) + \delta^{ij}p(r)$$



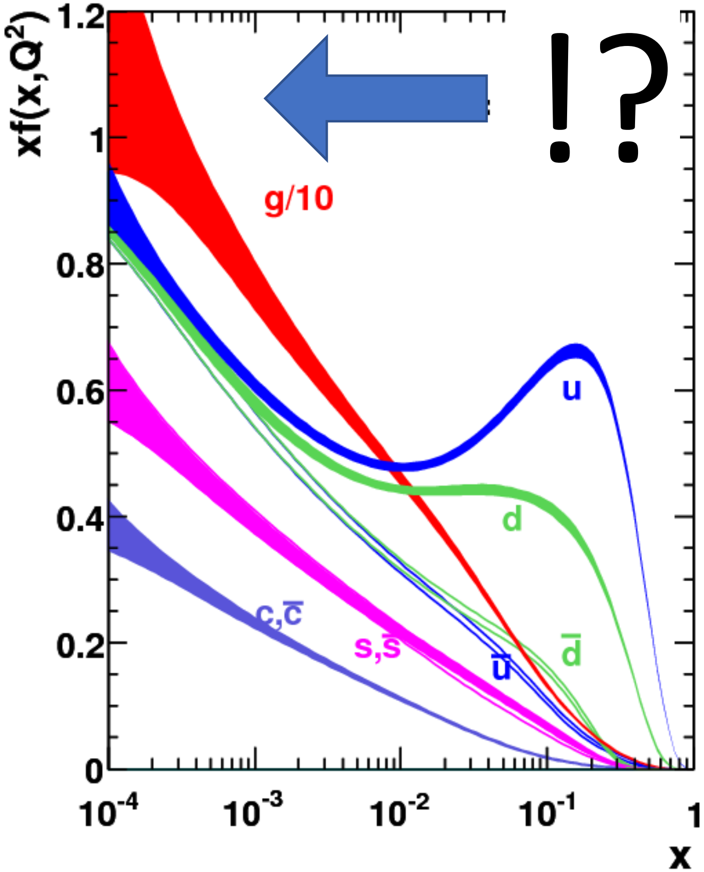
Enters DVCS as the subtraction constant in the dispersion relation between the real and imaginary parts of amplitude. Teryaev (2005)
First extraction from Jlab.

Large model dependence so far.
Need significant lever arm in Q^2 to disentangle different moments of GPDs → EIC
Also measure the gluon D-term. ←talk by Detmold

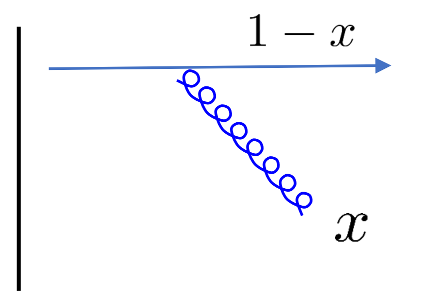
Scientific goals of EIC



QCD at small-x



Probability to emit a soft gluon diverges



$$\Big|\ \cdots\ \Big|^2 \propto \frac{1}{x}$$

A myriad of small-x gluons
in a high energy hadron/nucleus!

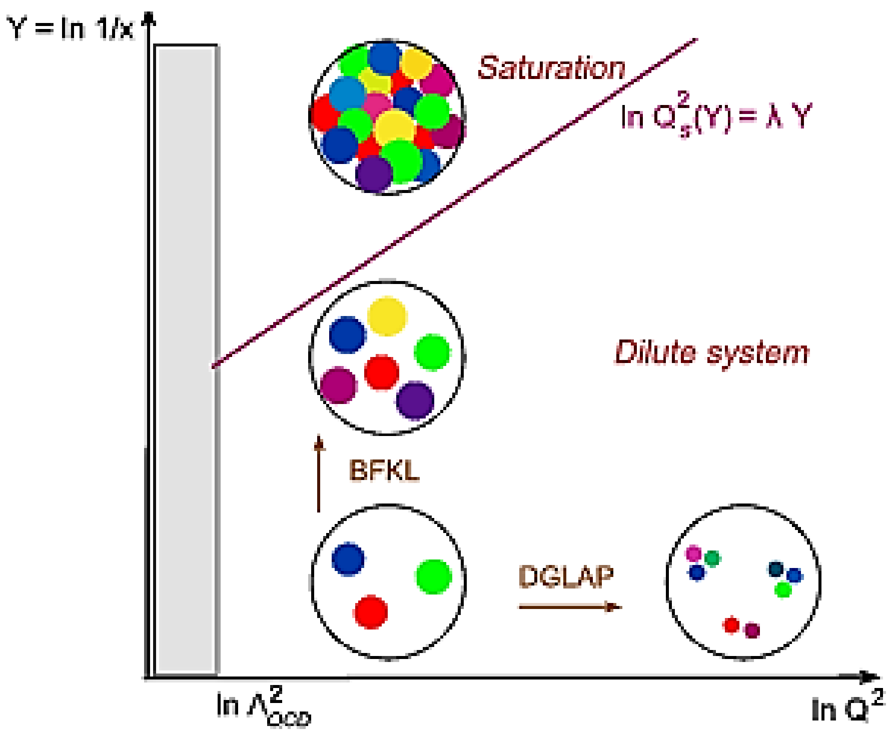
BFKL (Balitsky-Fadin-Kuraev-Lipatov)
resummation

$$\sum_n \frac{1}{n!}\left(\alpha_s \ln 1/x\right)^n \sim \left(\frac{1}{x}\right)^{\alpha_s}$$

Gluon saturation

The gluon number eventually saturates, forming the universal QCD matter at high energy called the Color Glass Condensate.

Gribov, Levin, Ryskin (1980); Mueller, Qiu (1986); McLerran, Venugopalan (1993)



Gluons overlap when

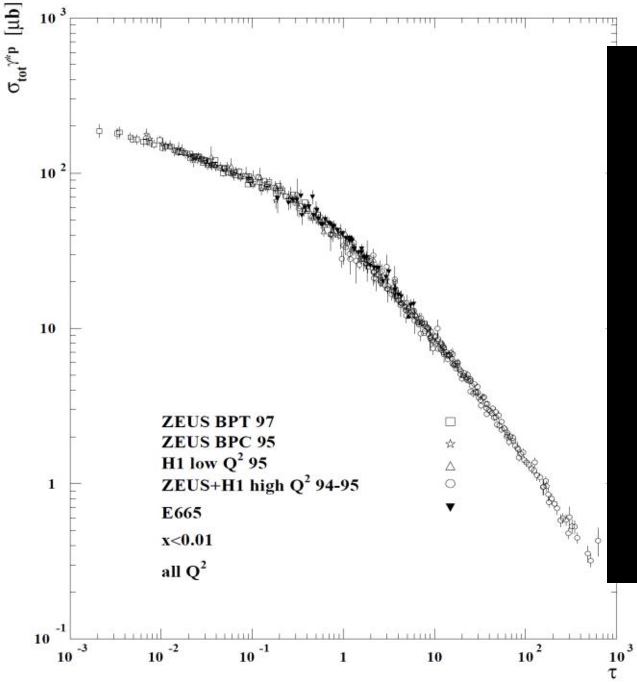
$$\frac{\alpha_s}{Q^2} xG(x, Q^2) = \pi R_p^2$$

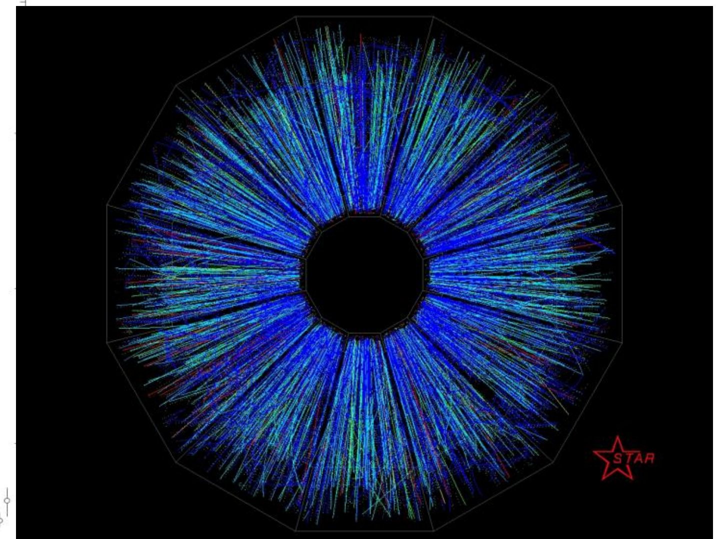
The saturation momentum

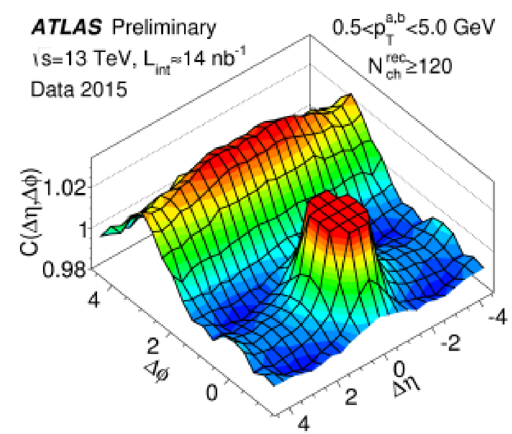
$$Q = Q_s(x) \gg \Lambda_{QCD}$$

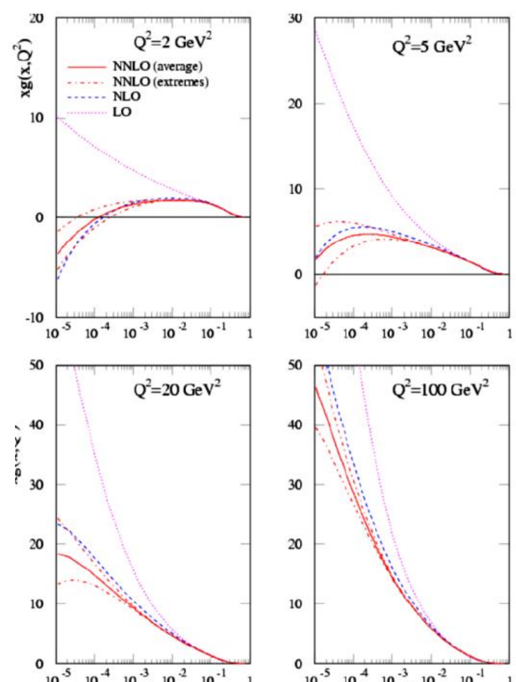
High density, but weakly coupled many-body problem

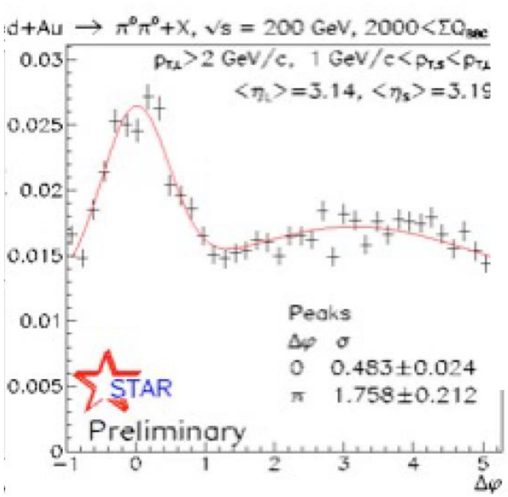
Has saturation been observed at HERA, RHIC, LHC?

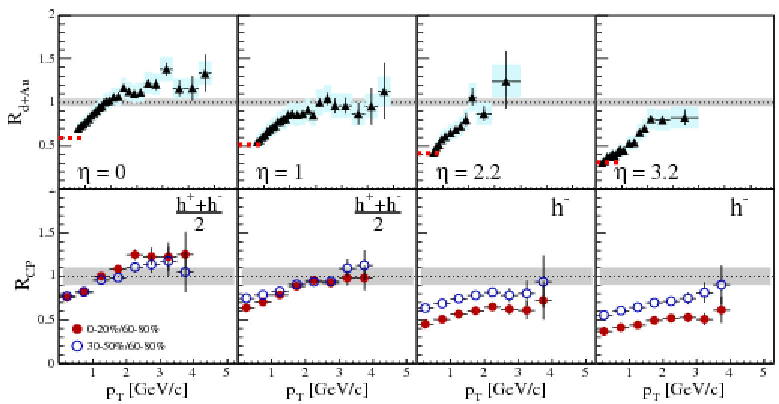








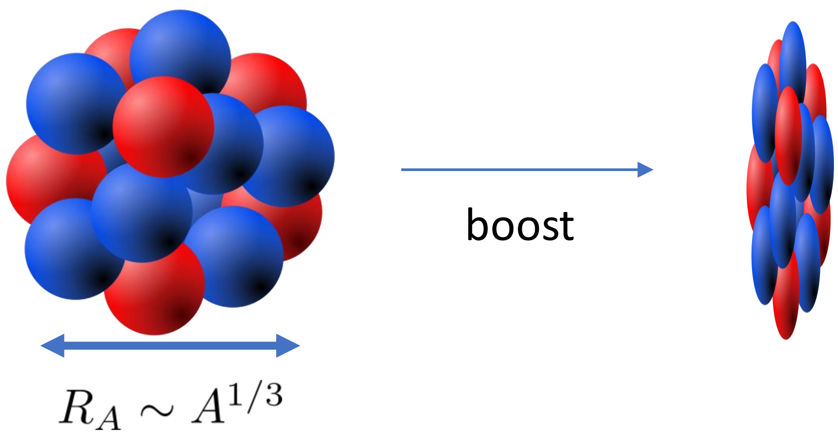




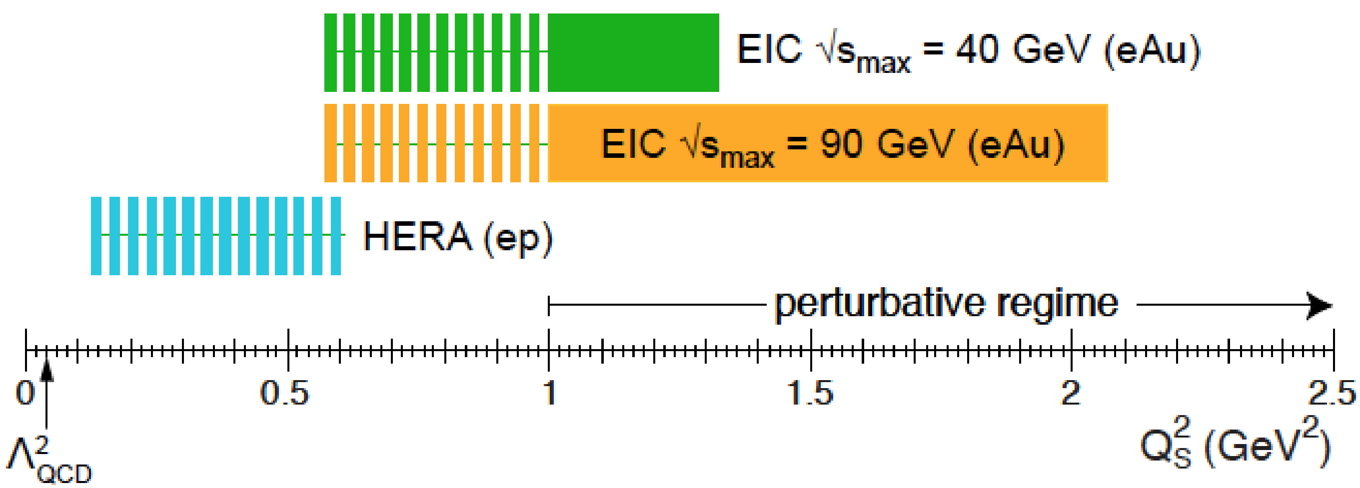
eA collision at EIC : ideal place to study saturation

No initial state interactions (advantage over LHC, RHIC)

Nuclear enhancement of the saturation momentum (advantage over HERA)



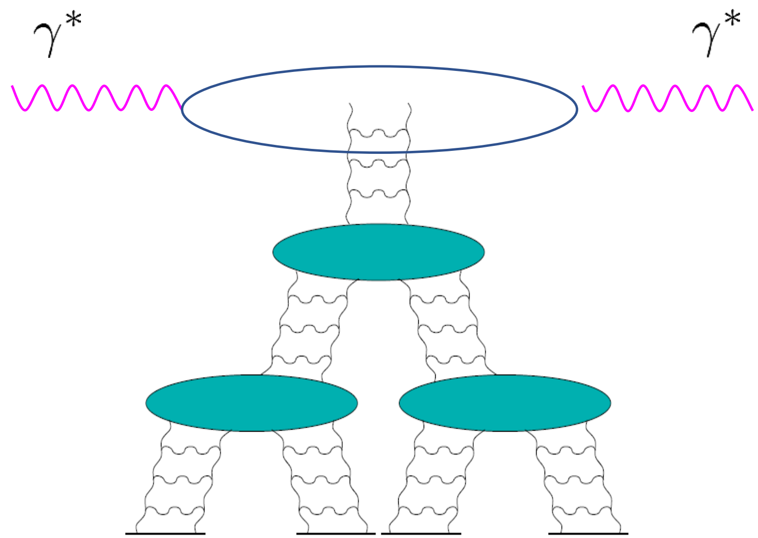
$$Q_s^2 \propto A^{1/3}$$



BK-JIMWLK equation

Balitsky
Kovchegov
Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner

Photon-nucleus scattering at high energy



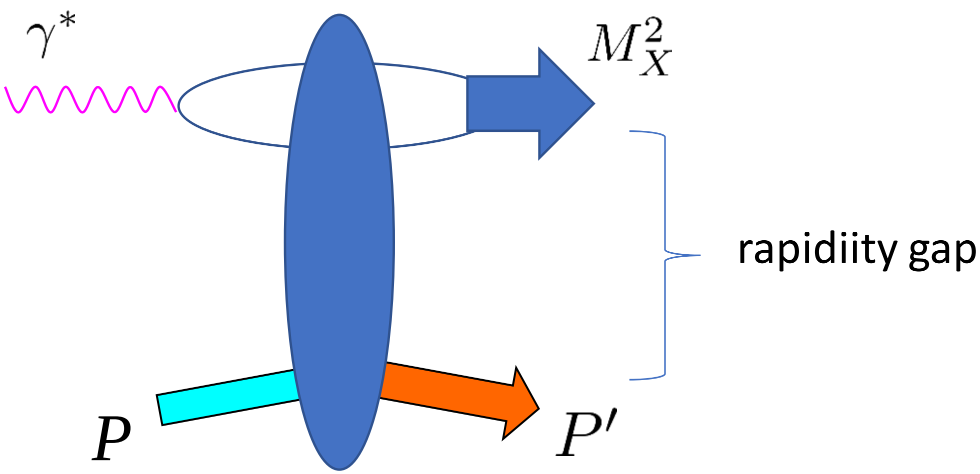
$$\equiv S$$

Leading Logarithmic (LL) evolution of the scattering amplitude with energy

$$\frac{\partial}{\partial \ln 1/x} S(r_\perp) = \frac{N_c \alpha_s}{2\pi} \int d^2 r_\perp \frac{r_\perp^2}{z_\perp^2 (r_\perp - z_\perp)^2} \left(S(z_\perp) S(z_\perp - r_\perp) - S(r_\perp)\right)$$

Extension to NLL Balitsky, Chirilli (2008)
Even to NNLL? Caron-Huot (2016)
Need collinear improvement Iancu, Mueller, Soyez, Triantafyllopoulos (2015); YH, Iancu (2016)

Golden channel for saturation: Diffraction



Cross sections proportional to the square of the gluon distribution

More sensitive to saturation!

`Day 1 prediction' Kowalski, Lappi, Marquet, Venugopalan (2008)

$$\left.\frac{\sigma_{diff}}{\sigma_{tot}}\right|_{eA} \approx 20\% > \left.\frac{\sigma_{diff}}{\sigma_{tot}}\right|_{ep}$$

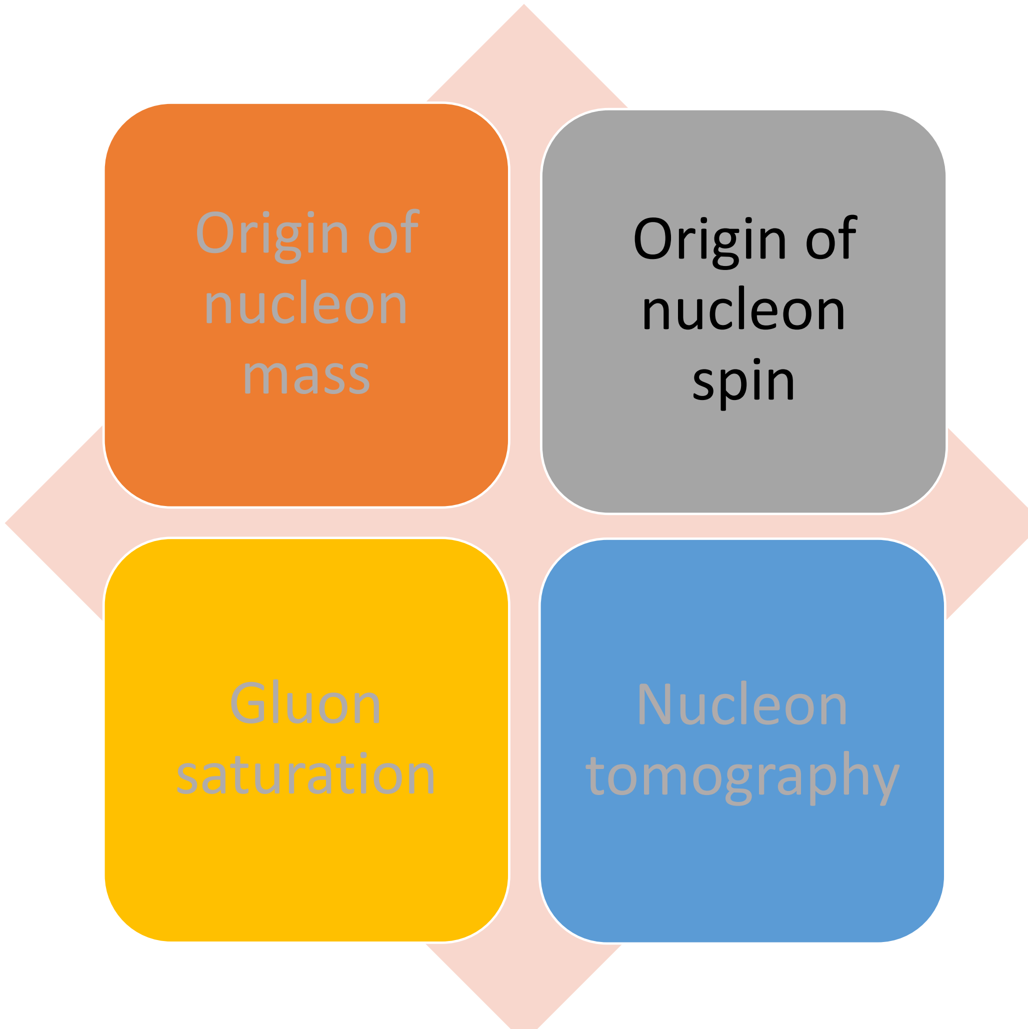
Nucleus stays intact in every 1 out of 5 events!

State-of-the-art: NLL + NLO

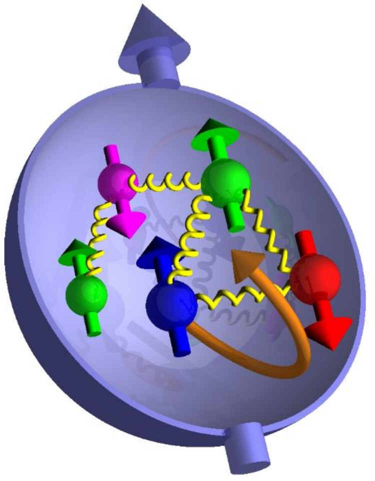
Complete NLO calculation for exclusive diffraction (vector meson, dijet production)

Boussarie, Grabovsky, Szymanowski, Wallon (2016)

Scientific goals of EIC



The proton spin problem



The proton has spin ½.
The proton is not an elementary particle.

Jaffe-Manohar sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

Quarks' helicity

Gluons' helicity

Orbital angular Momentum (OAM)

In the quark model,

$$|P,+\rangle = \frac{1}{3\sqrt{2}}\left\{|uud\rangle(2|++-\rangle - |+-+\rangle - |-++\rangle) + perm\right\}$$

$$\Delta\Sigma = 1$$

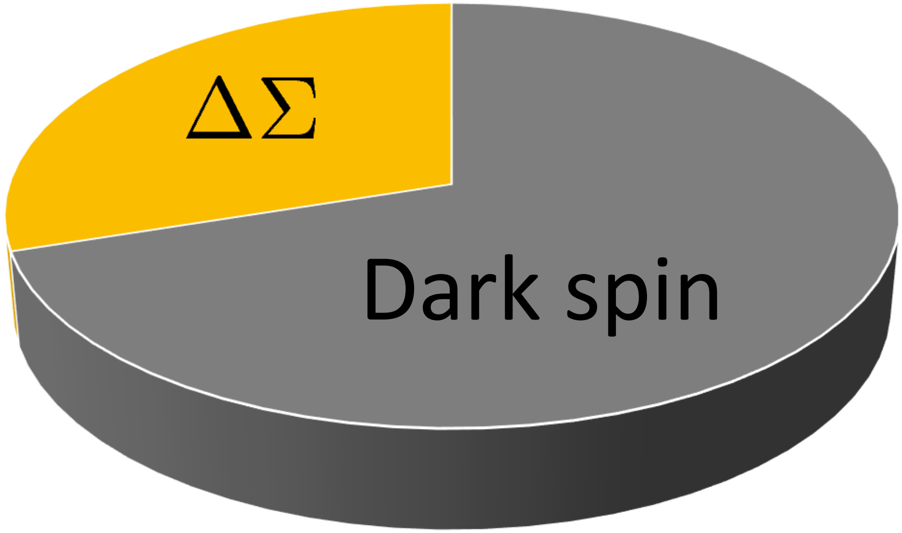
Spin crisis

In 1987, EMC (European Muon Collaboration) announced a very small value of the quark helicity contribution

$$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14 \quad !?$$

Recent value from NLO global analysis

$$\Delta\Sigma = 0.25 \sim 0.3$$



Gluon polarization ΔG

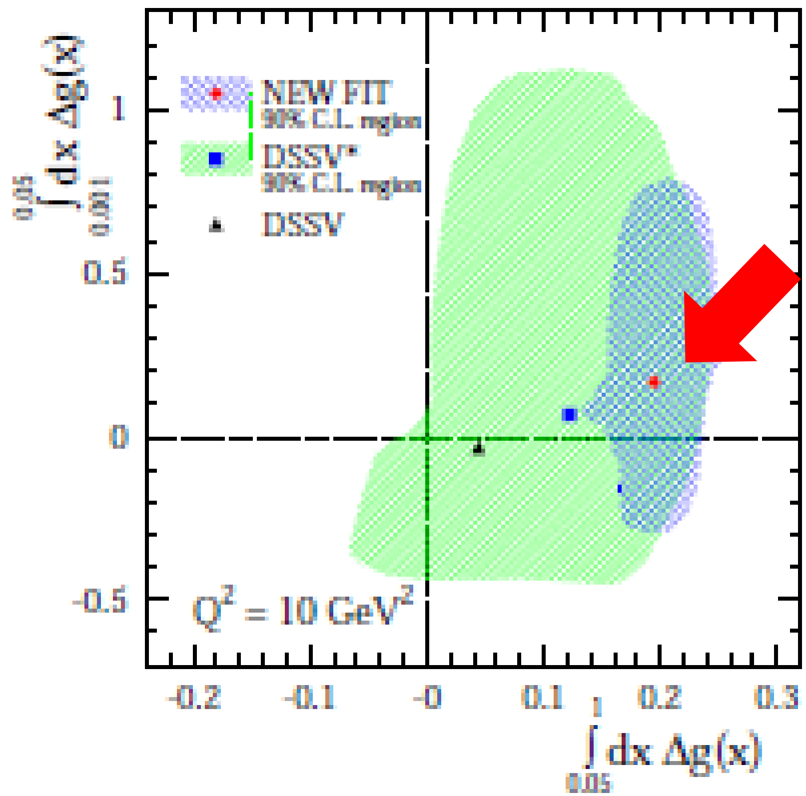
$$\Delta G = \int_0^1 dx \Delta G(x)$$

Result from the NLO global analysis
after the RHIC 200 GeV pp data

DeFlorian, Sassot, Stratmann, Vogelsang (2014)

$$\int_{0.05}^{1} dx \Delta G(x, Q^2) \approx 0.2^{+0.06}_{-0.07}$$

$(Q^2 = 10\text{GeV}^2)$



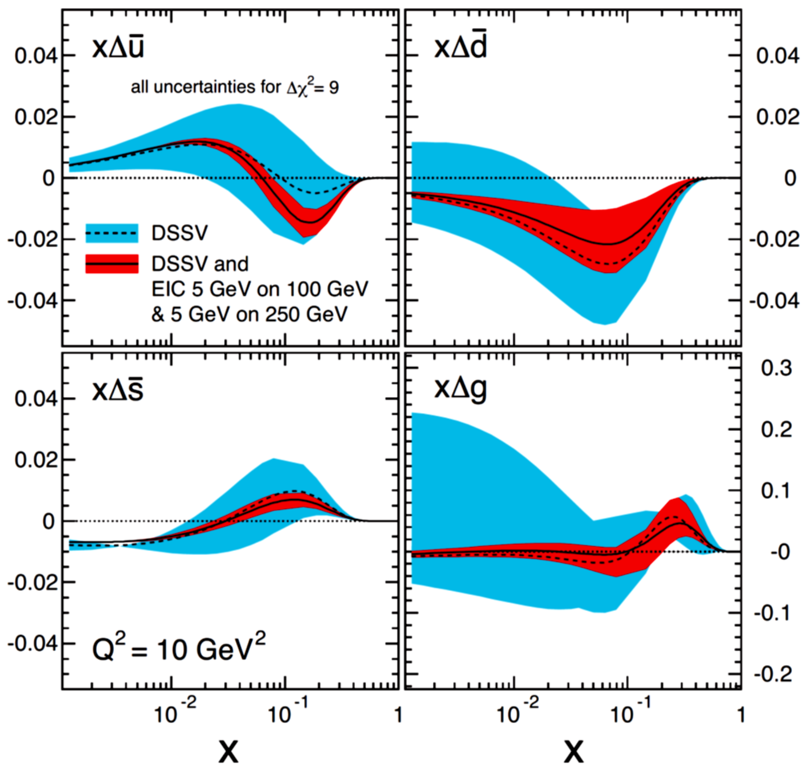
HUGE uncertainty from the small-x region

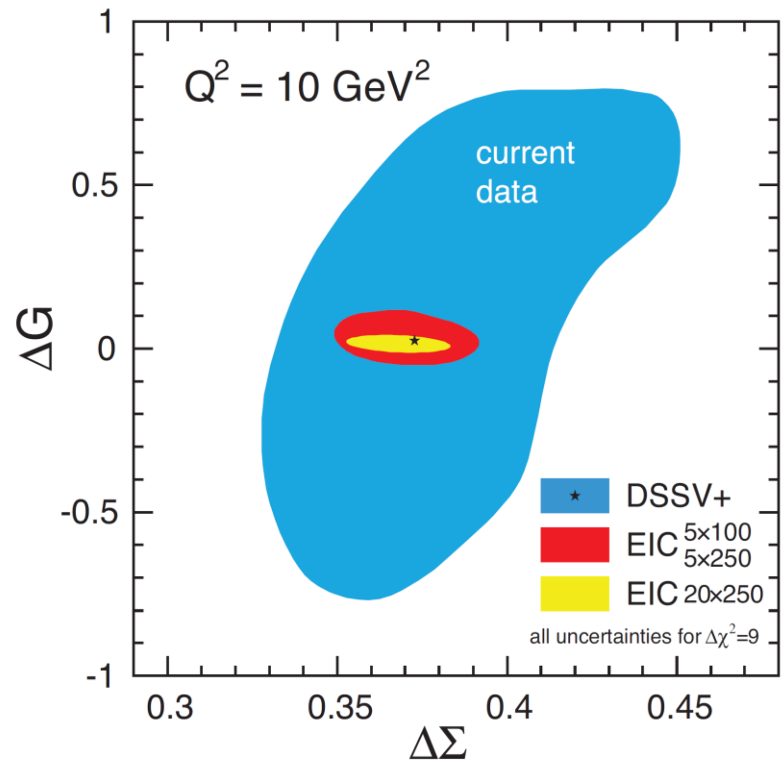
Small-x evolution revisited.

Kovchegov, Pitonyak, Sievert (2016~)

Helicity measurements at EIC

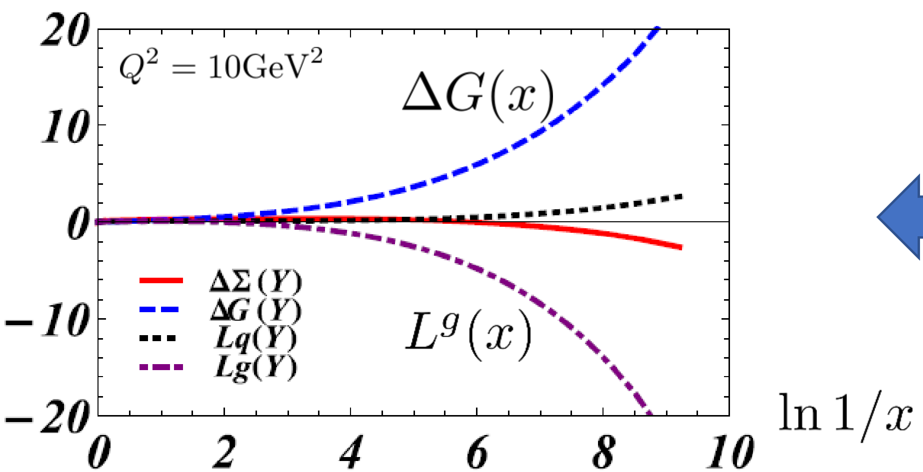
After one-year of data taking at EIC…





Wider coverage in x and Q^2… finally solve the spin puzzle? No!

Don’t forget orbital angular momentum. It’s there!



Significant cancellation between helicity and OAM at small-x.
YH, Yang (2018)

Understanding of the nucleon spin structure cannot be complete without OAM. EIC should seriously address it.

You can not learn about OAM from TMD or GPD.

OAM and the Wigner distribution

What exactly is $L^{q,g}$ in the Jaffe-Manohar sum rule?
Controversial issue for a long time, but not anymore!

The Wigner distribution naturally defines OAM

Lorce, Pasquini, (2011);
YH (2011)

$$L^{q,g} = \int dx \int d^2b_\perp d^2k_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z W^{q,g}(x, \vec{b}_\perp, \vec{k}_\perp)$$

One can also define the `PDF' of OAM

$$L^{q,g}(x) = \int d^2b_\perp d^2k_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z W^{q,g}(x, \vec{b}_\perp, \vec{k}_\perp)$$

Warning: this is not a twist-2 PDF. It has twist-three components. YH, Yoshida (2012)

Accessing OAM at EIC

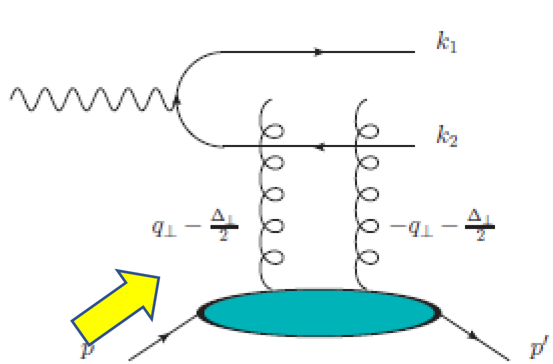
Ji, Yuan, Zhao (2016)
YH, Nakagawa, Xiao, Yuan, Zhao (2016)
Bhattacharya, Metz, Zhou (2017)

Measuring OAM = Measuring Wigner

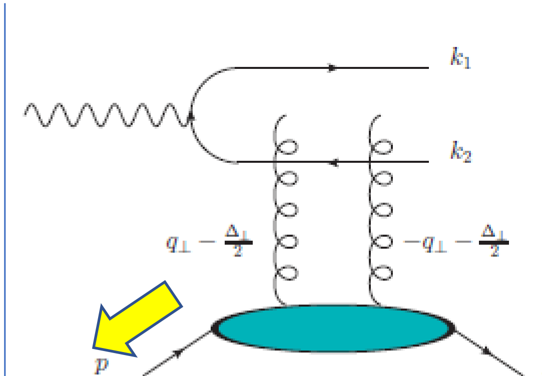
Unprecedented challenge, but there is some hope. YH, Xiao, Yuan (2016)

Longitudinal single spin asymmetry in diffractive dijet production

$d\Delta\sigma \sim$ |



$|^2$ - |



$|^2$

Look for the azimuthal angular dependence

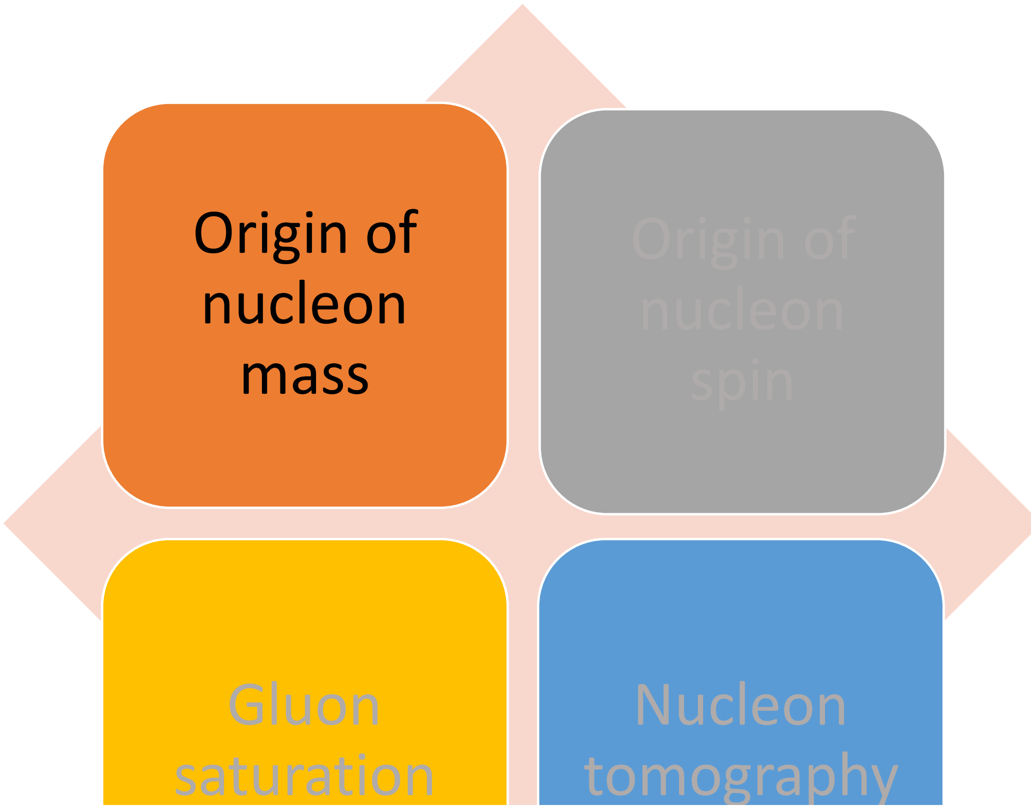
$$d\Delta\sigma = \sin(\phi_P - \phi_\Delta) d\tilde{\sigma}$$

dijet relative momentum

proton recoil momentum

Need more work, more new ideas!

Scientific goals of EIC



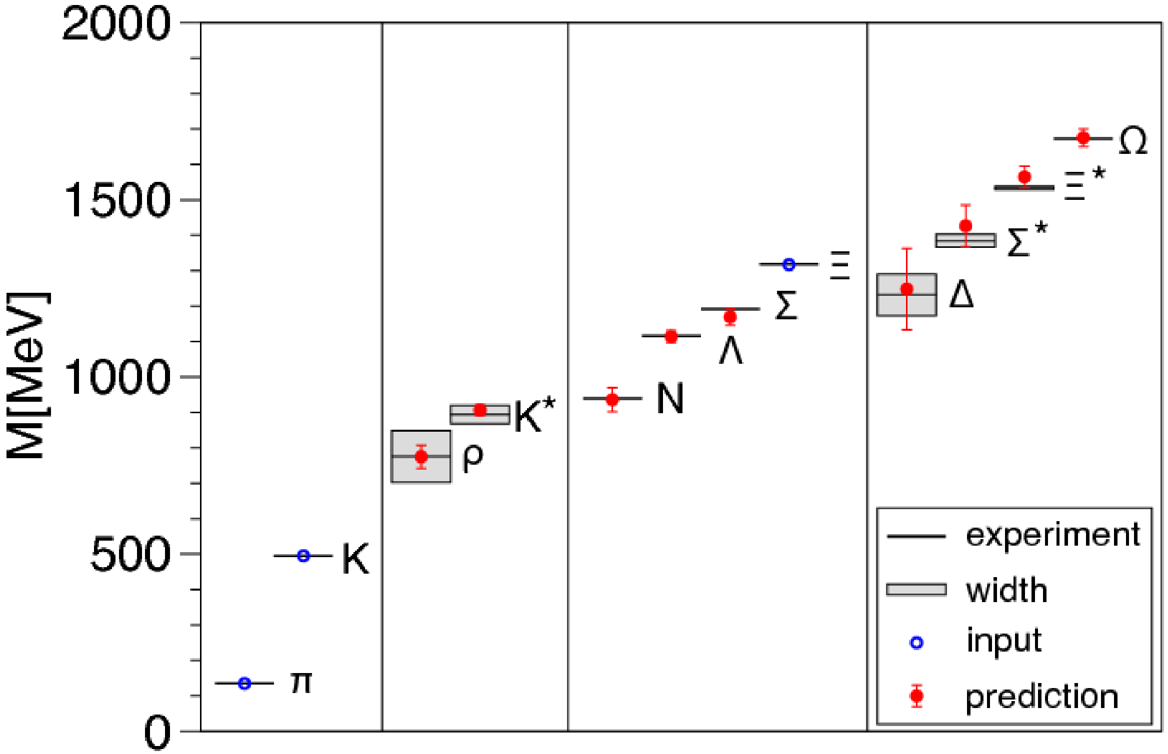
NAS report (2018/07)

Finding 1: An EIC can uniquely address three profound questions about nucleons-protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

Nucleon mass, what's the issue?

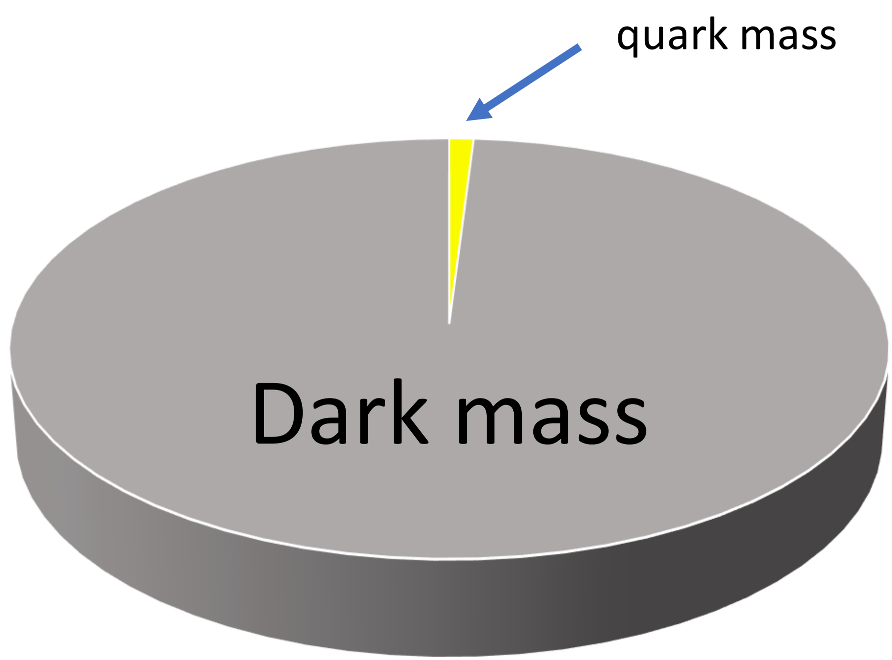
Durr, et al. (2009)



Lattice QCD can reproduce the hadron masses with great precision.

Proton mass crisis

u,d quark masses add up to ~10MeV, only 1 % of the proton mass!



Higgs mechanism explains quark masses, but not hadron masses!

In relativity, mass and energy are equivalent. The `missing mass' comes from the kinetic energy of quarks and gluons?

Mass from trace anomaly

QCD Lagrangian approximately scale (conformal) invariant.
Why is the proton mass nonvanishing in the first place?

→ Conformal symmetry is explicitly broken by the trace anomaly.

QCD energy-momentum tensor

$$T^{\mu\nu} = -F^{\mu\lambda}F^{\nu}{}_{\lambda} + \frac{\eta^{\mu\nu}}{4}F^2 + i\bar{q}\gamma^{(\mu}D^{\nu)}q$$

Trace anomaly

$$T^{\mu}_{\mu} = \frac{\beta(g)}{2g}F^2 + m(1+\gamma_m(g))\bar{q}q$$

Mass generation

$$\langle P|T^{\mu}_{\mu}|P\rangle = 2M^2$$

Can we measure the trace anomaly $\langle P|F^{\mu\nu}F_{\mu\nu}|P\rangle$?

The operator $F^{\mu\nu}F_{\mu\nu}$ is twist-four,
highly suppressed in high energy scattering.

Instead, we should look at low-energy scattering.

Purely gluonic operator. Use quarkonium as a probe.

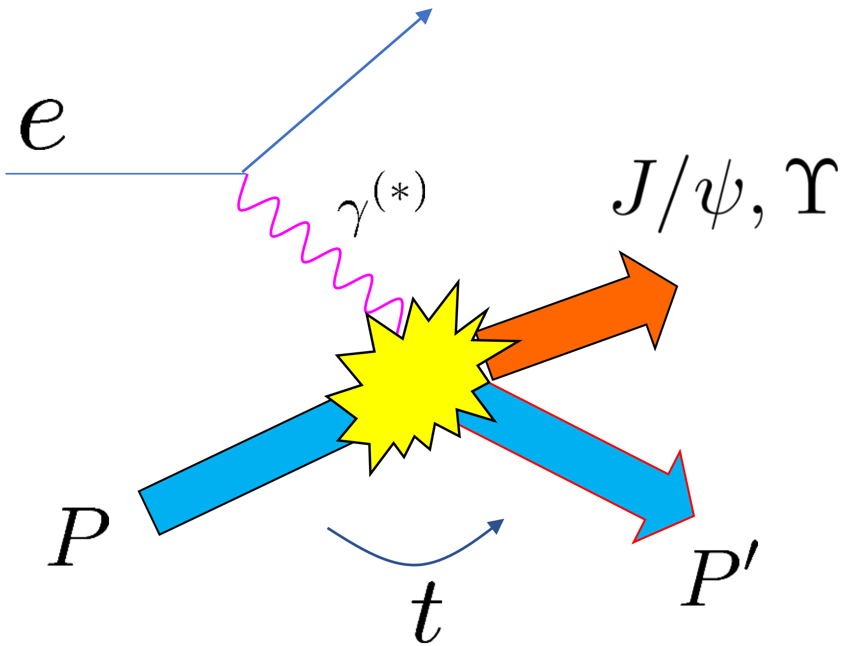
Luke-Manohar-Savage (1992)

→ J/ψ production near threshold.

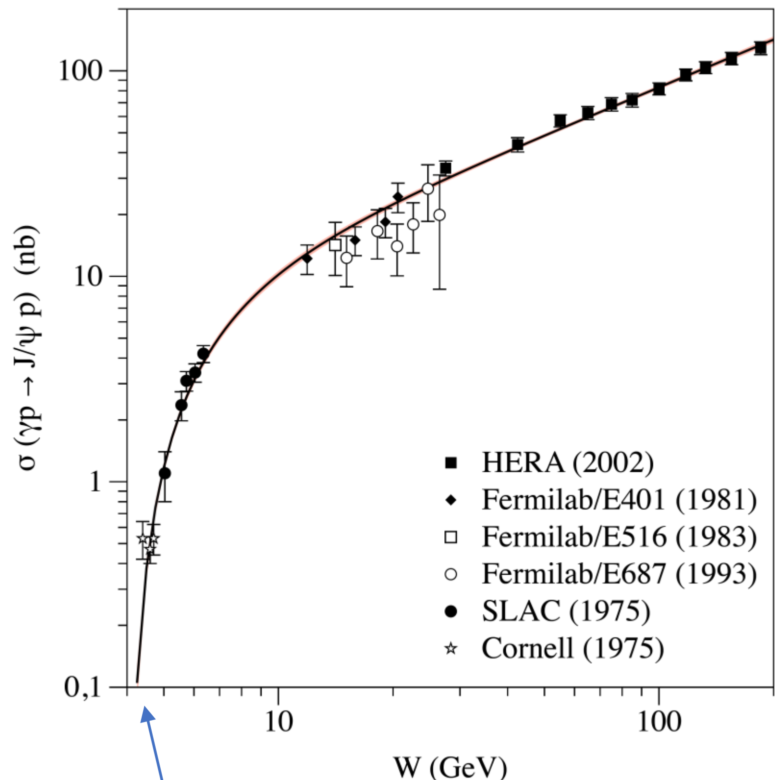
Kharzeev, Satz, Syamtomov, Zinovjev (1998)

Photo-production of J/ψ and Υ near threshold

(Jlab) (EIC)



$$\sigma_{tot}^{\gamma p} = \int_{t_{min}}^{t_{max}} dt \frac{d\sigma}{dt}$$



$W_{th} \approx 4.04\text{GeV}$

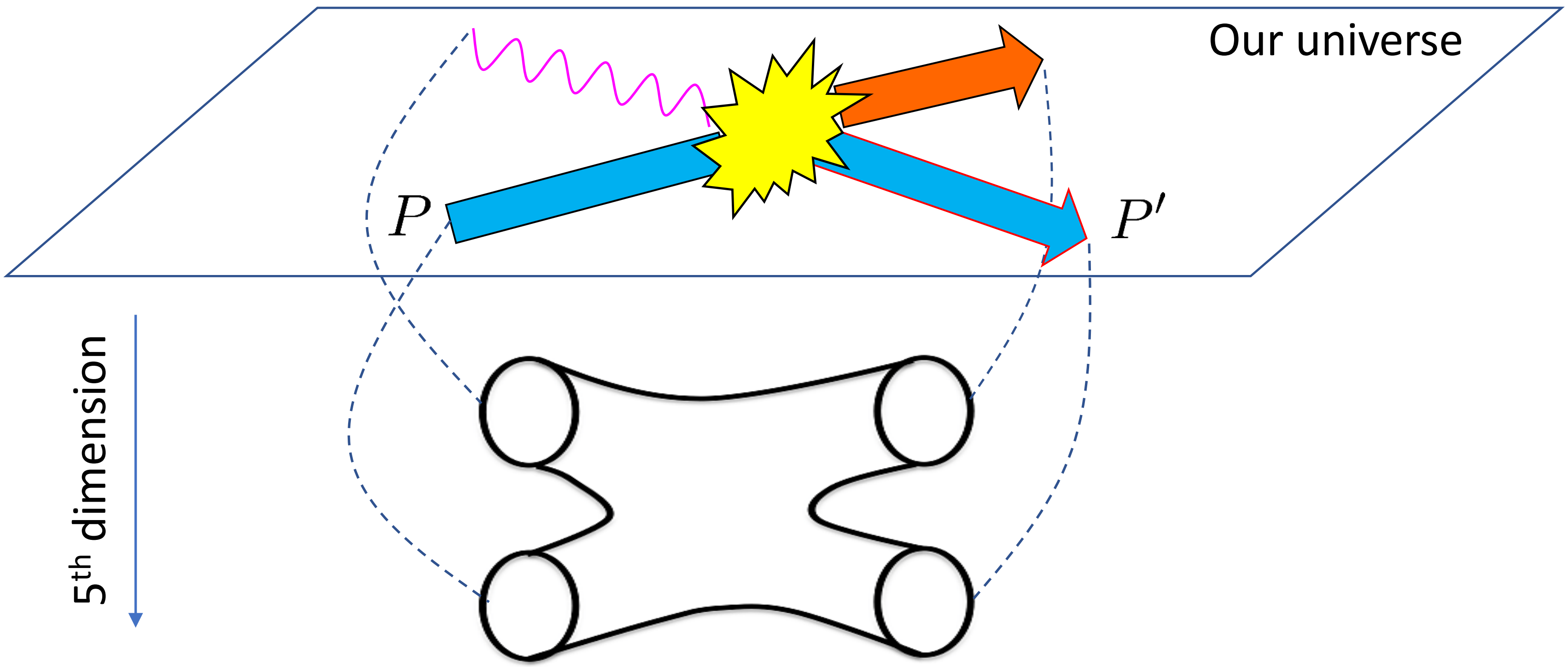
QCD factorization difficult to establish.
Need nonperturbative methods.

Holographic approach

YH, Yang (2018)

Scattering of hadrons in QCD(-like theories)

$\approx$ scattering of closed strings in asymptotically AdS_5



$$\langle P|\epsilon\cdot J(0)|P'k\rangle \approx -\frac{2\kappa^2}{f_\psi R^3}\int_0^{z_m} dz\,\frac{\delta S_{D7}(q,k,z)}{\delta g_{\mu\nu}}\frac{z^2R^2}{4}\langle P|T^{gTT}_{\mu\nu}|P'\rangle$$

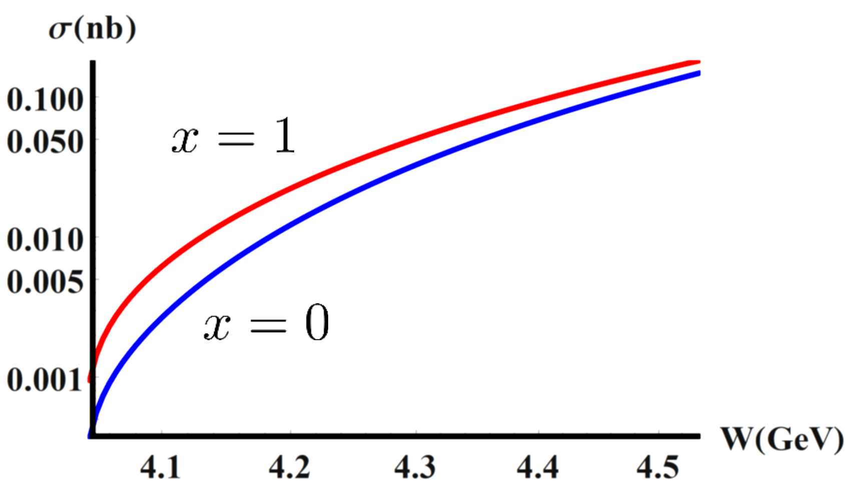
$\leftarrow$ graviton exch.

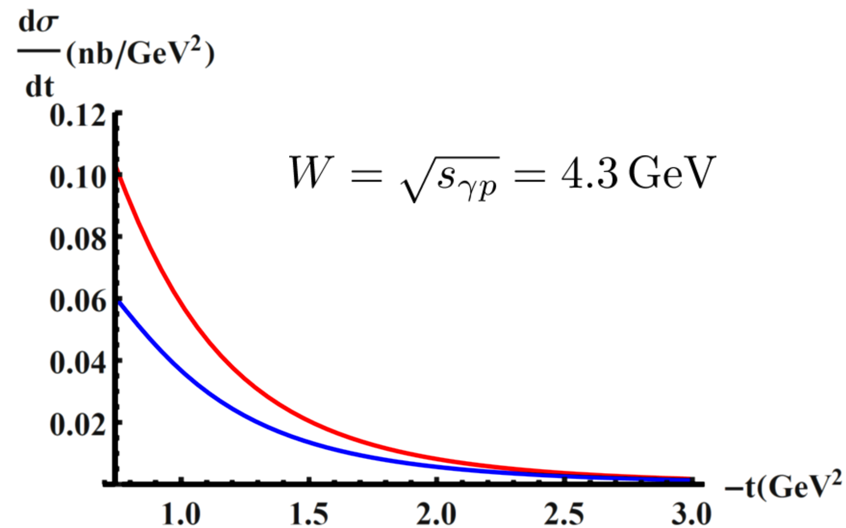
$$+\frac{2\kappa^2}{f_\psi R^3}\frac{3}{8}\int_0^{z_m} dz\,\frac{\delta S_{D7}(q,k,z)}{\delta\phi}\frac{z^4}{4}\langle P|\frac{1}{4}F^{\mu\nu}_a F^a_{\mu\nu}|P'\rangle$$

$\leftarrow$ dilaton

YH, Yang (2018)

$$M = \frac{1}{2M}\langle P|\underbrace{\frac{\beta}{2g}F^2}_{x} + \underbrace{m(1+\gamma_m)\bar{q}q}_{1-x}|P\rangle$$





Gluon condensate enhances the cross section.
The closer to threshold, the larger the effect is.

At EIC, use Υ instead.

$$W_{th}^{\gamma p} = 10.4\mathrm{GeV}$$

$$t_{min} \approx -8.1\mathrm{GeV}^2$$

Conclusion

- EIC will significantly advance our knowledge of the nucleons/nuclei, the fundamental building blocks of the universe.
- Many challenges ahead—The deepest questions can only be answered by going to higher twists.

Tomography	twist-2
Saturation	all twists
Spin	twist-2 (helicity) & twist-3 (OAM)
Mass	twist-4

EIC = higher twist machine