How EIC can help us to understand heavy-ion collisions

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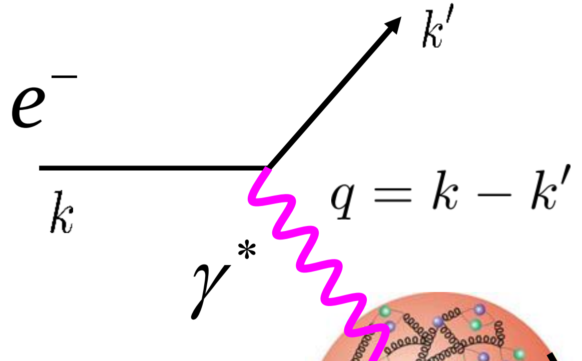
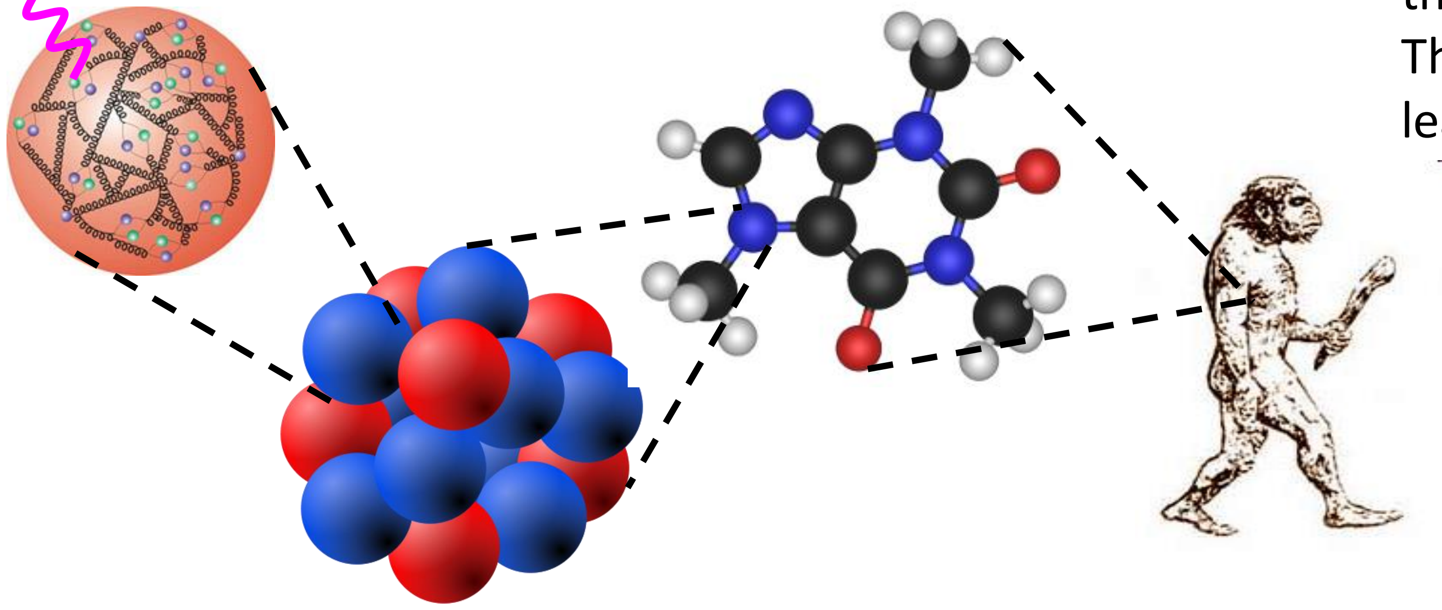
Outline

- TMD
- GPD
- Spin
- Saturation
- Initial geometry
- Jets
- Proton mass

Understanding that glue that binds us all

Since the discovery of quarks, DIS has been instrumental to our understanding of the smallest building blocks of our universe.





But we have not yet fully explored the structure of nucleon/nuclei. There are still lots of things to be learned.

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?

Future DIS experiments worldwide

Planned DIS Colliders around the world

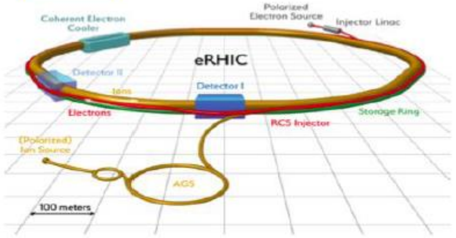
R. Yoshida, talk at DIS2019

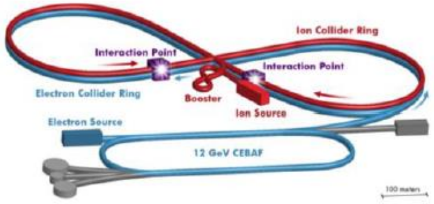
Facility	Years	E_{cm} (GeV)	Luminosity ($10^{33} cm^{-2} s^{-1}$)	Ions	Polarization
EIC in US	> 2028	$20 - 100 \rightarrow 140$	2 - 30	$p \rightarrow U$	e, p, d, ^{3}He, Li
EIC in China	> 2028	16 - 34	$1 \rightarrow 100$	$p \rightarrow Pb$	e, p, light nuclei
LHeC (HE-LHeC)	> 2030	200 - 1300 (1800)	10	depends on LHC	e possible
PEPIC	> 2025	$530 \rightarrow 1400$	$< 10^{-3}$	depends on LHC	e possible
VHEeP	> 2030	1000 - 9000	$10^{-5} - 10^{-4}$	depends on LHC	e possible
FCC-eh	> 2044	3500	15	depends on FCC-hh	e possible

EPPSU DIS Input

EIC

United States



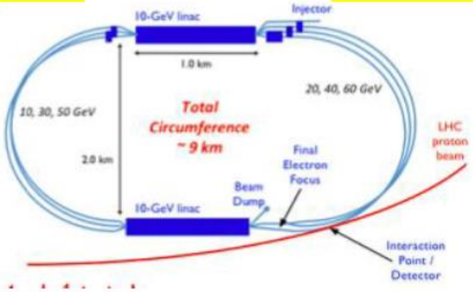


EicC

China

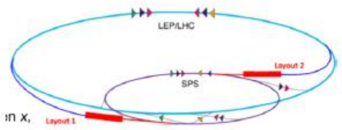
LHeC

FCC-eh

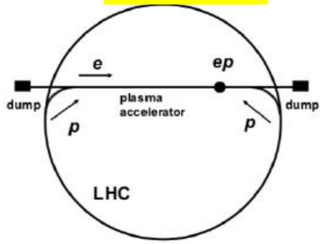


Europe (CERN)

PEPIC



VHEeP



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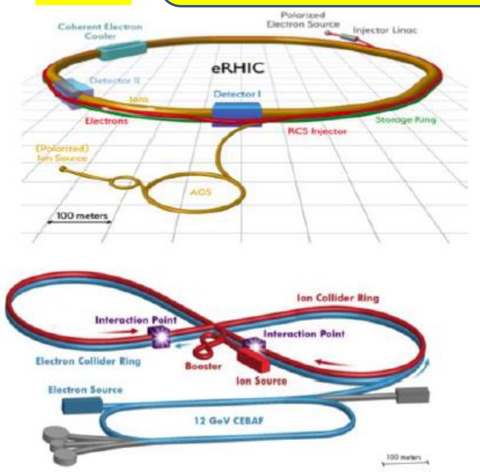
LHeC (					possible
PEPIC					possible
VHEeP					possible
FCC-eh					possible

EPPSU DIS Input

The era of precision EW, pQCD, and precision study of nucleon and nuclear structures in the next 20-30 years!

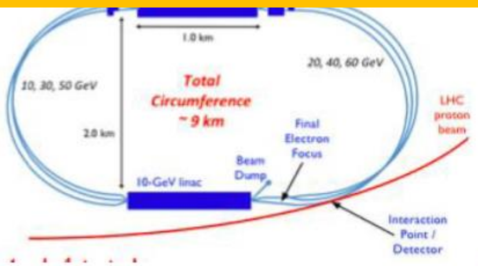
EIC

Un



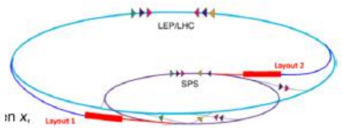
EicC

China

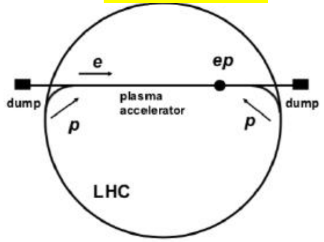


Europe (CERN)

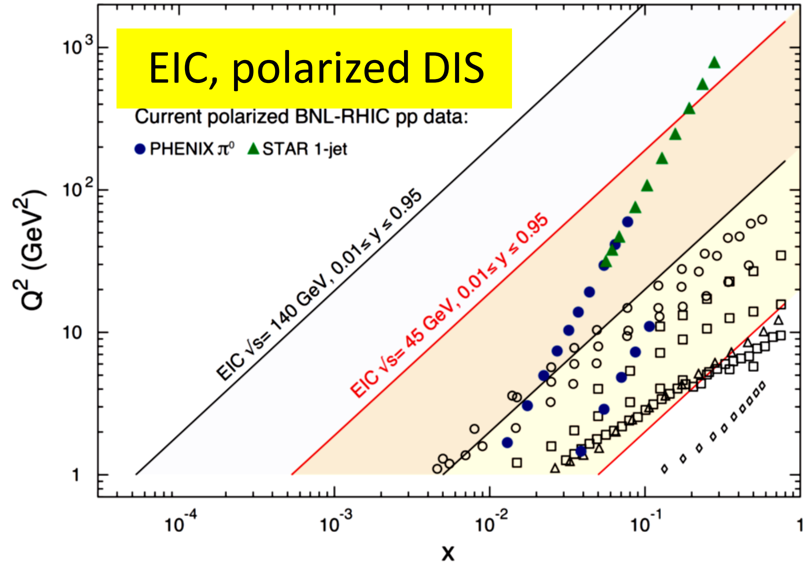
PEPIC

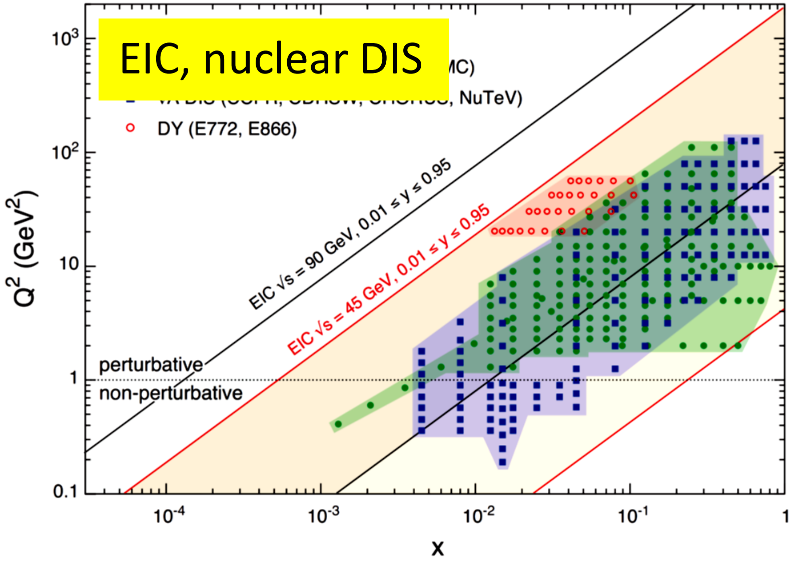


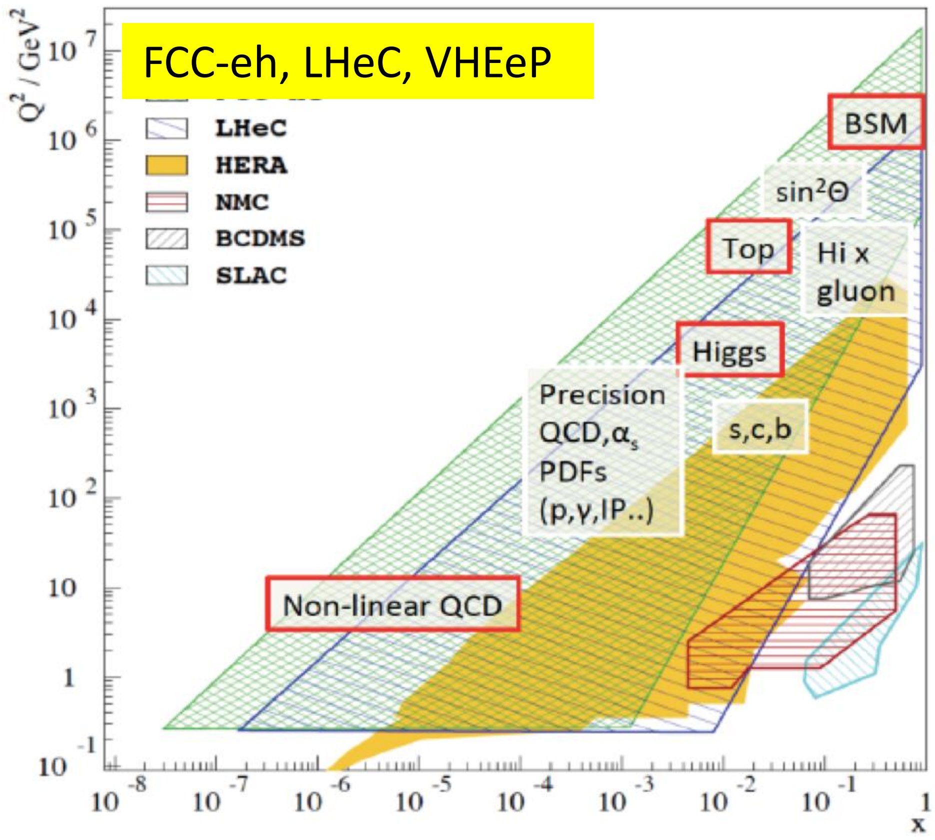
VHEeP



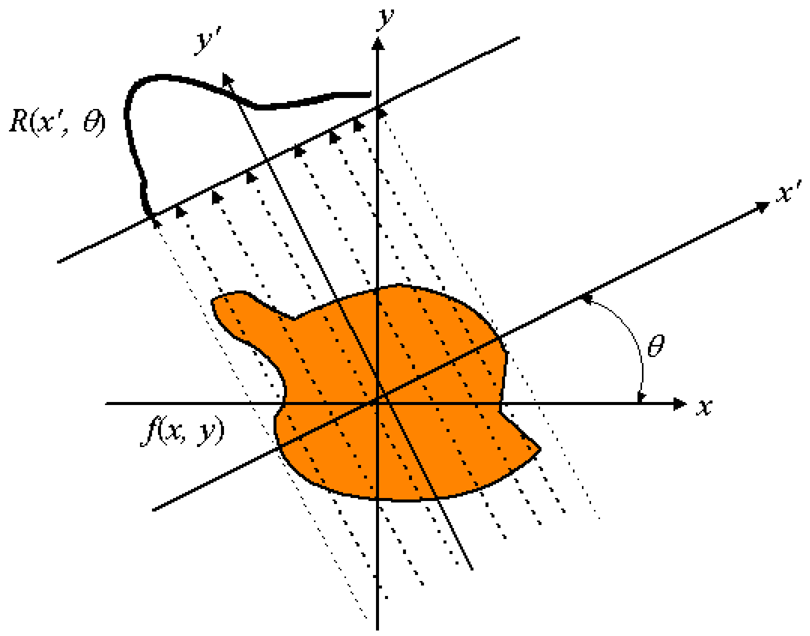
Exploring *terra incognita*



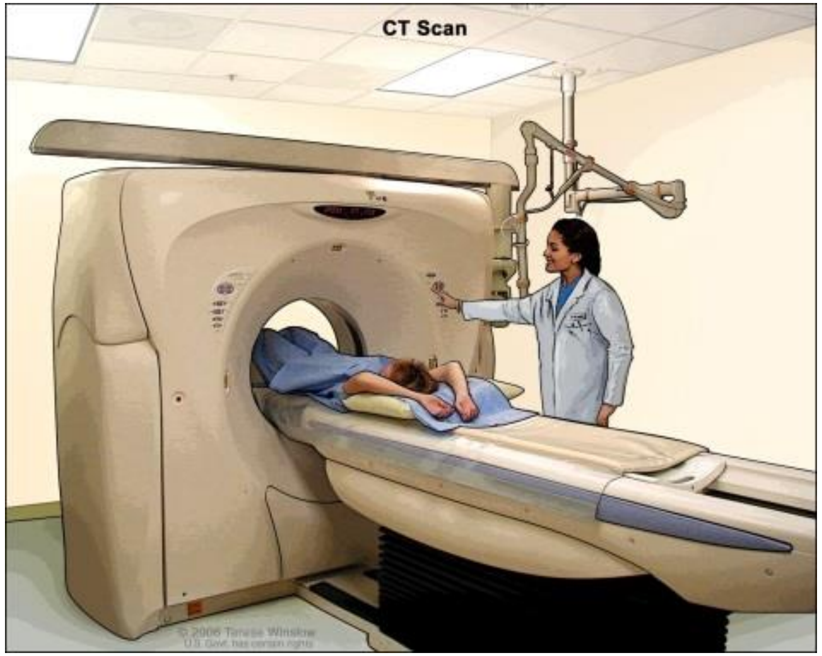




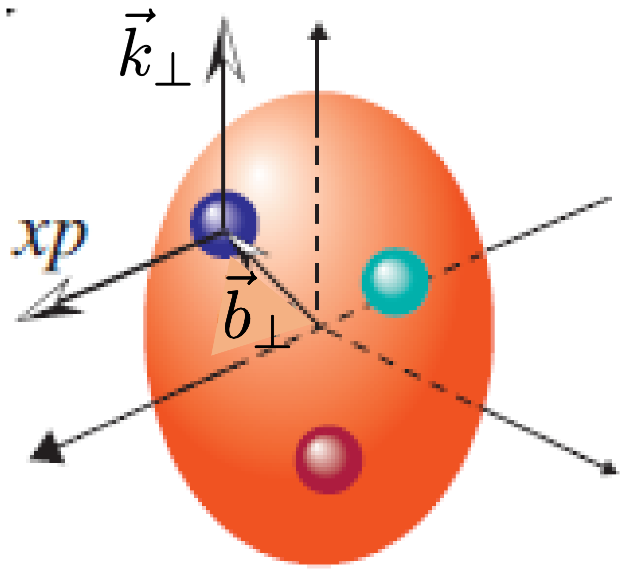
Unprecedented coverage in kinematics.
Tremendous physics opportunities.



Tomography
(TMD, GPD)



Multi-dimensional tomography



$$u(x) = \int \frac{dz^-}{4\pi} \langle P|\bar{u}(0)\gamma^+ u(z^-)|P\rangle \qquad x = \frac{E_{parton}}{E_{proton}}$$

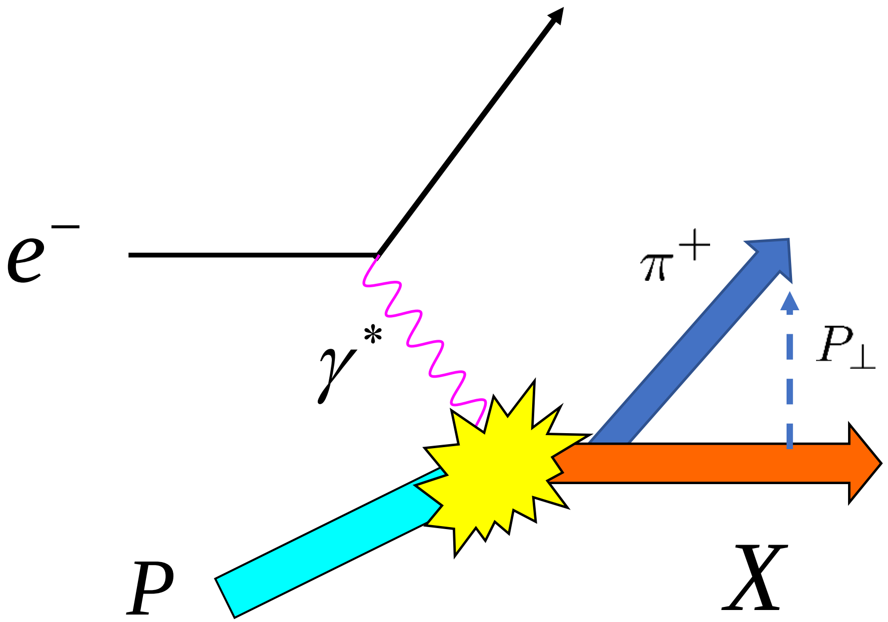
Ordinary PDF → 1D tomographic image of the nucleon

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

$u(x)$ →

- $u(x, \vec{k}_\perp)$ 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,...

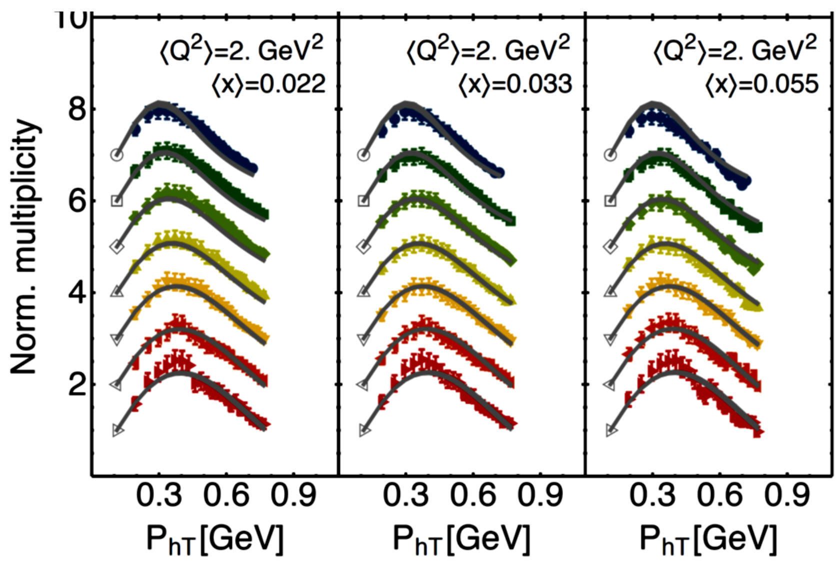
$$\frac{d\sigma}{dP_\perp} = H(\mu)\int d^2q_\perp d^2k_\perp f(x,k_\perp,\mu,\zeta)D(z,q_\perp,\mu,Q^2/\zeta)\delta^{(2)}(zk_\perp+q_\perp-P_\perp)+\cdots$$

TMD PDF TMD frag. function

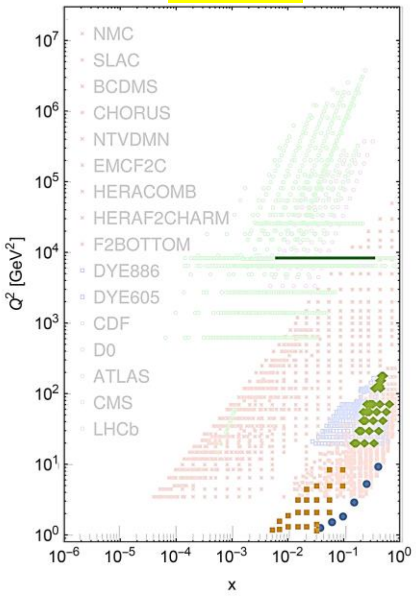
Open up a new class of observables where perturbative QCD is applicable!

TMD global analysis

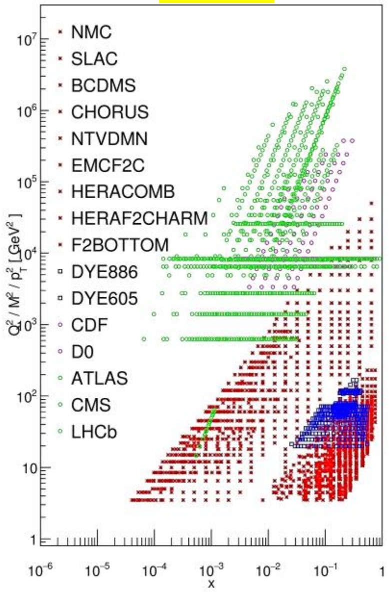
	Framework	W+Y	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	W	✘	✘	✔	✔	98
QZ 2001 hep-ph/0506225	NLO-NLL	W+Y	✘	✘	✔	✔	28 (?)
RESBOS resbos@msu	NLO-NNLL	W+Y	✘	✘	✔	✔	>100 (?)
Pavia 2013 arXiv:1309.3507	LO	W	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO	W	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	W	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	W	1 (x,Q²) bin	1 (x,Q²) bin	✔	✔	500 (?)
SIYY 2014 arXiv:1406.3073	NLO-NLL	W+Y	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	W	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	W	✘	✘	✔	✔	309
BSV 2019 arXiv:1902.08474	NNLO-NNLL	W	✘	✘	✔	✔	457



TMD



PDF



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

TMD in heavy-ions: Unintegrated gluon distribution at small-x

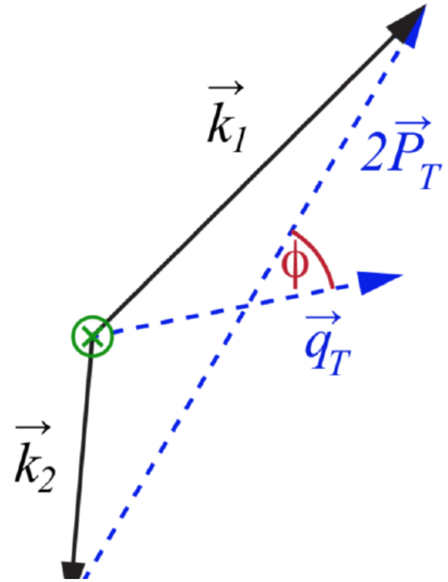
$$\frac{1}{P^+}\int\frac{d^3k}{(2\pi)^3}e^{ik_\perp\cdot z_\perp}\langle P|F^{+i}(z)WF^{+j}(0)|P\rangle=\frac{\delta^{ij}}{2}xG(x,k_\perp)-\frac{1}{2}\left(\delta^{ij}-2\frac{k_\perp^i k_\perp^j}{k_\perp^2}\right)xh_\perp(x,k_\perp)$$

unpolarized gluon   linearly polarized gluon

Can be constrained at EIC

$\cos 2\phi$ correlation in dijet angular distribution   Metz, Zhou (2011) + many others

$$\frac{d\sigma}{dP.S.}\propto xG(x,k_\perp)+\cos(2\phi)\,xh_\perp(x,k_\perp)$$



Applications in heavy-ions

- Angular correlation in UPC $\gamma\gamma\to e^+e^-$ talk by Brandenburg on Monday
- Initial axial charge fluctuations in heavy-ion   Lappi, Schlichting (2017)

$$\langle\dot\nu(\mathbf{x})\dot\nu(\mathbf{y})\rangle=\frac{3g^4N_c^2(N_c^2-1)}{32}\left[\left(G^{(1)}_{(U)}(\mathbf{x},\mathbf{y})\right)^2\left(G^{(1)}_{(V)}(\mathbf{x},\mathbf{y})\right)^2-\left(h^{(1)}_{\perp(U)}(\mathbf{x},\mathbf{y})\right)^2\left(h^{(1)}_{\perp(V)}(\mathbf{x},\mathbf{y})\right)^2\right]$$

Generalized parton distributions (GPD)

Non-forward matrix element of the collinear operator

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

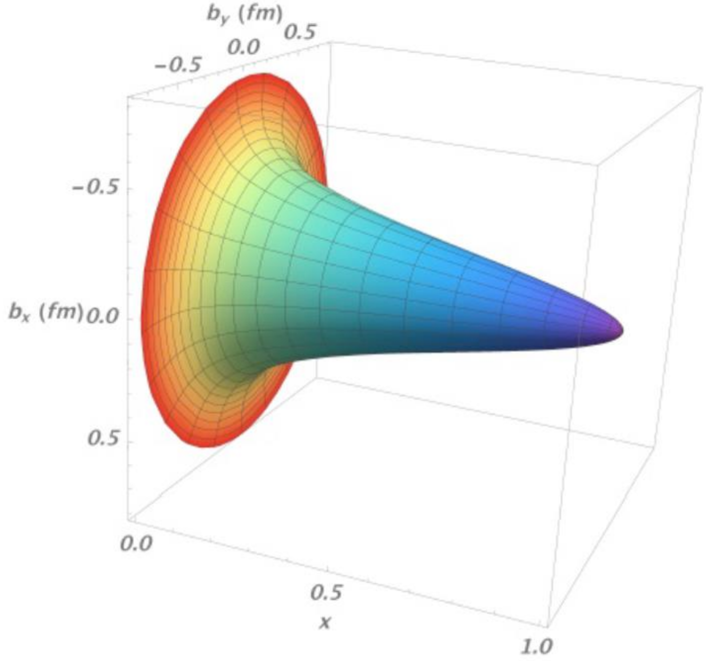
$$= H_q(x,\Delta)\bar{u}(P'S')\gamma^\mu u(PS) + E_q(x,\Delta)\bar{u}(P'S')\frac{i\sigma^{\mu\nu}\Delta_\nu}{2m}u(PS)$$

$$\Delta = P' - P$$

Distribution of partons in impact parameter space

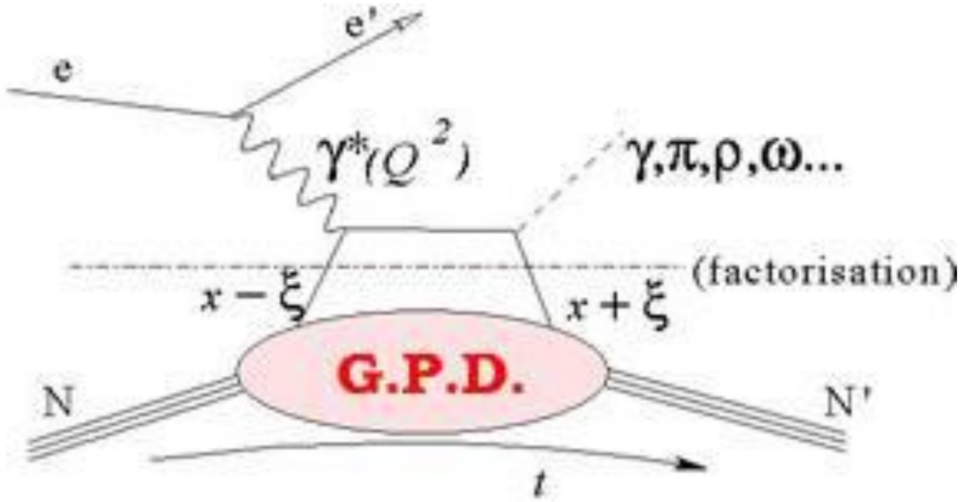
Fourier transform

$\Delta_\perp \to b_\perp$

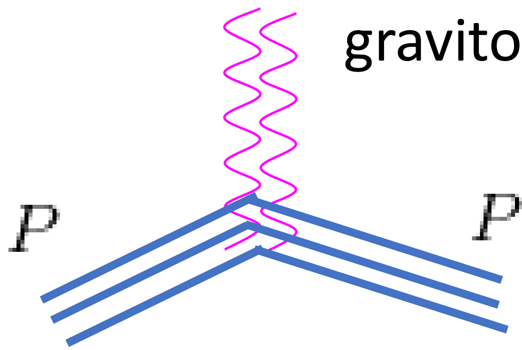


Dupre, Guidal, Vanderhaeghen (2017)

Measurable in Deeply Virtual Compton Scattering (DVCS)



Nucleon gravitational form factors



$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = \bar{u}(P')\Bigg[A_{q,g}\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M}$$

$$+D_{q,g}\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} + \bar{C}_{q,g}Mg^{\mu\nu}\Bigg]u(P)$$

All the form factors are interesting and measurable!

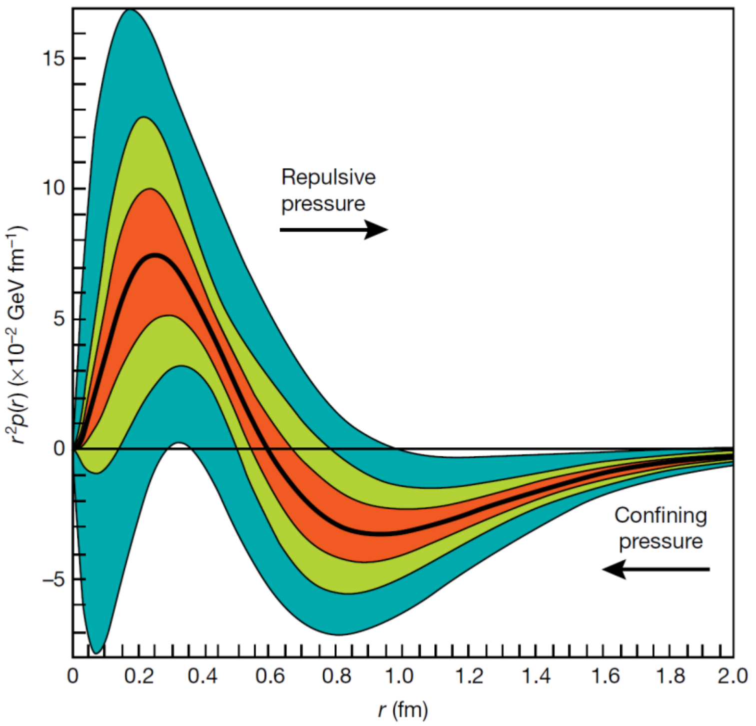
$A_{q,g}$ Momentum fraction

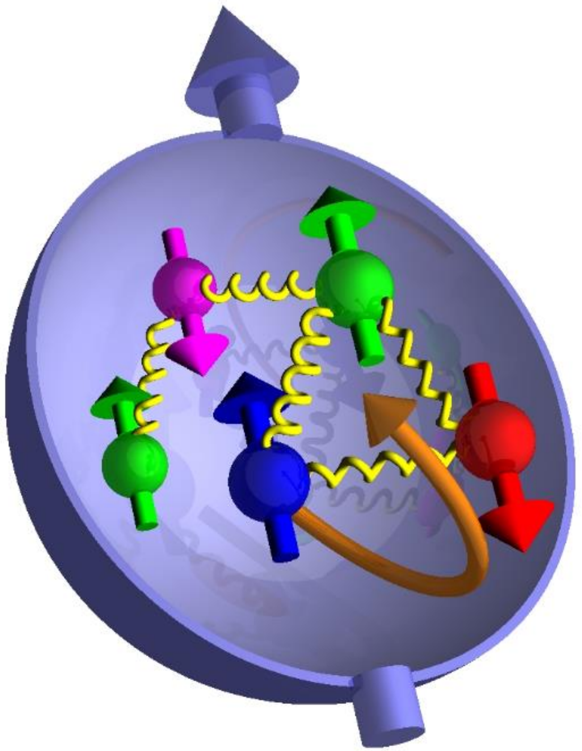
$B_{q,g}$ Ji sum rule

$D_{q,g}$ `Pressure' and `shear' inside proton

$\bar{C}_{q,g}$ Mass, pressure

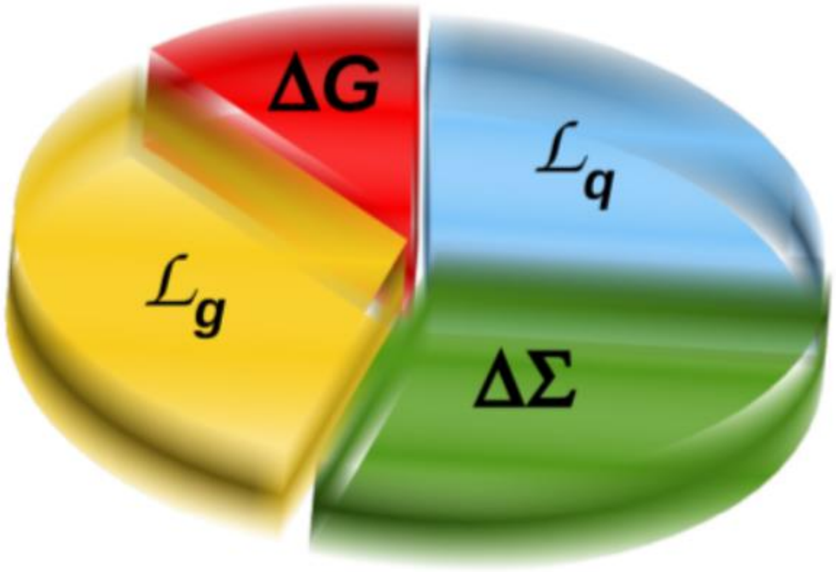
Burkert, Elouadrhiri, Girod (2018)





Proton spin

Proton spin puzzle



The proton has spin ½.

The proton is not an elementary particle.

➡ Jaffe-Manohar sum rule

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

Quark spin

Gluon spin

Orbital angular momentum (OAM)

$\Delta\Sigma = 1$ in the quark model

$\Delta\Sigma = 0.25 \sim 0.3$

Experiments revealed that less than 30% of the proton spin comes from quark spin.

\`Spin crisis’

Evidence of nonzero ΔG

RHIC spin program elucidated that the gluon spin contribution is significant!

$$\int_{0.05}^{1} dx \Delta g(x, Q^2 = 10\,\text{GeV}^2) = 0.20^{+.06}_{-.07} \qquad \text{DSSV++}$$

$$\int_{0.05}^{0.2} dx \Delta g(x, Q^2 = 10\,\text{GeV}^2) = 0.17 \pm 0.06 \qquad \text{NNPDFpol1.1}$$

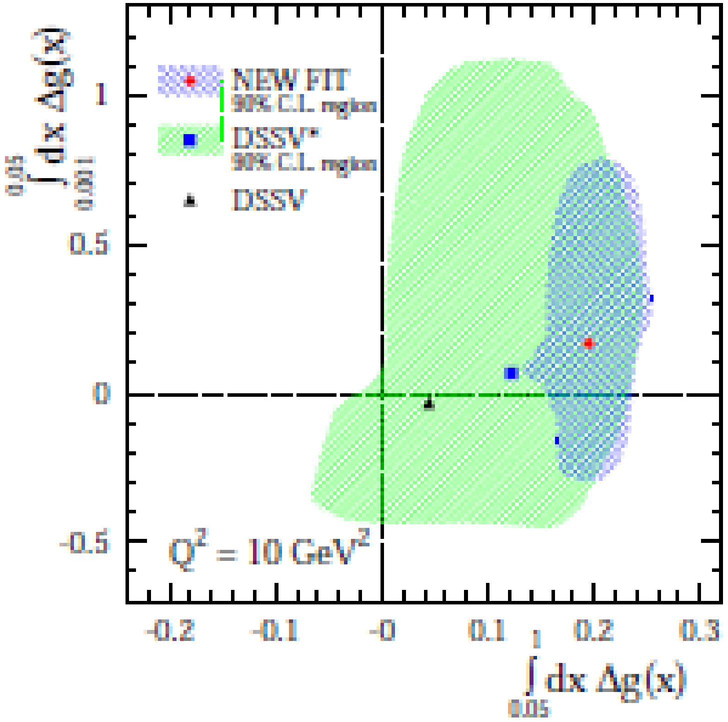
$$\int_{0.001}^{0.8} dx \Delta g(x, Q^2 = 1\,\text{GeV}^2) = 0.5 \pm 0.4 \qquad \text{JAM15}$$

Beware, there is huge uncertainty from the small-x region

EIC will finally pin down the value of ΔG

- How does spin behave at small-x?
  Is saturation important for spin?
  Kovchegov, Pitonyak, Sievert; Boussarie, YH, Yuan

- What is the role of the orbital angular momentum?
  Can we measure OAM?



Orbital angular momentum of partons

QCD Wigner distribution Belitsky, Ji, Yuan (2003)

$$W(x,\vec{k}_\perp,\vec{b}_\perp)=\int\frac{d^2\Delta_\perp}{(2\pi)^2}\frac{d^3z}{16\pi^3}e^{ixP^+z^--i\vec{k}_\perp\cdot\vec{z}_\perp}\langle P-\frac{\Delta}{2}|\bar{\psi}(b-\frac{z}{2})\gamma^+W\psi(b+\frac{z}{2})|P+\frac{\Delta}{2}\rangle$$

Define

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

Lorce, Pasquini (2011); YH (2011); Xiong, Ji, Yuan (2012)

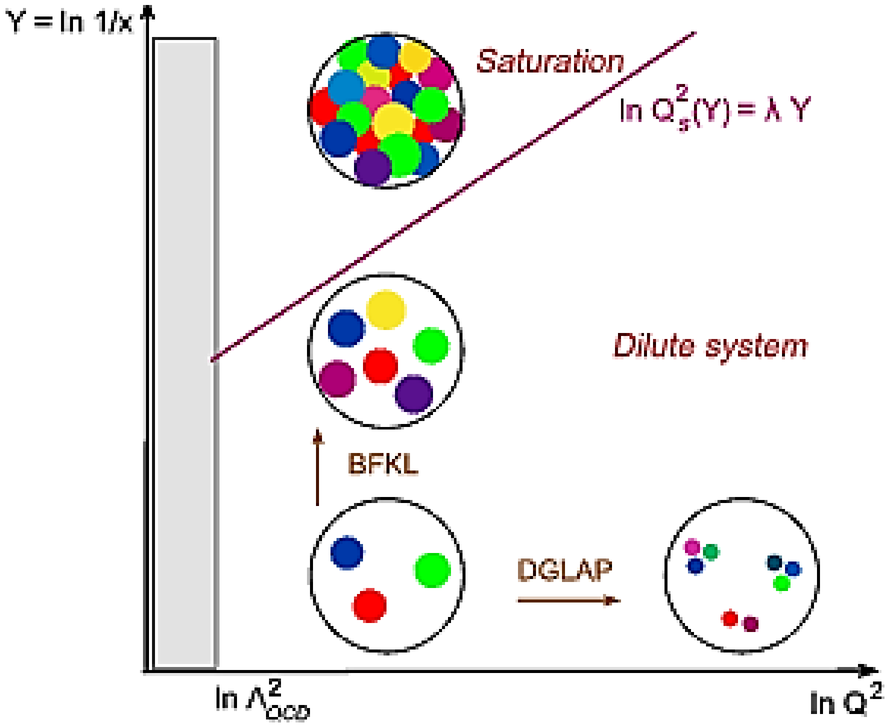
Similar discussions in heavy-ion community in the context of global polarization.

$$\frac{d\Pi^\alpha(p)}{d^3p}\approx\frac{\hbar}{2mE_p}\int d\Sigma_\lambda p^\lambda\tilde{\Omega}^{\alpha\sigma}p_\sigma f_{\rm FD}(x,p)(1-f_{\rm FD}(x,p)),$$

vorticity

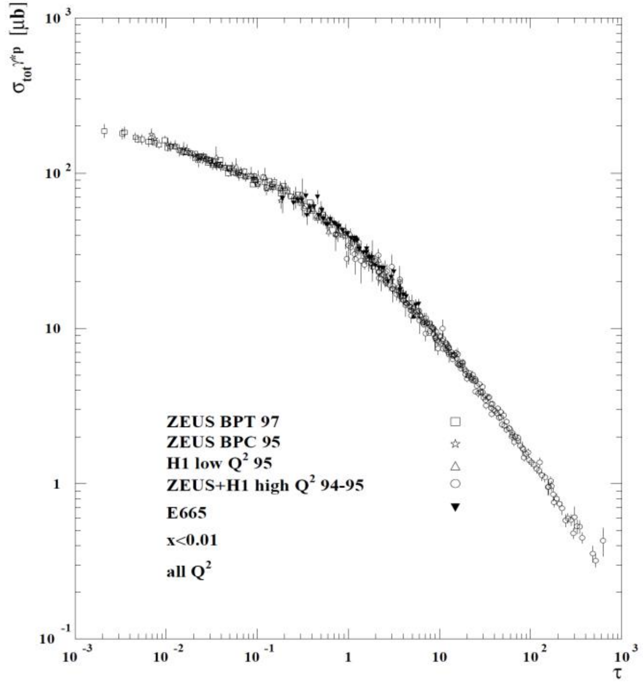
Becattini, Chandra, Del Zanna, Grossi (2013)
Fang, Pang, Wang, Wang (2016)
Becattini, talk on Wednesday

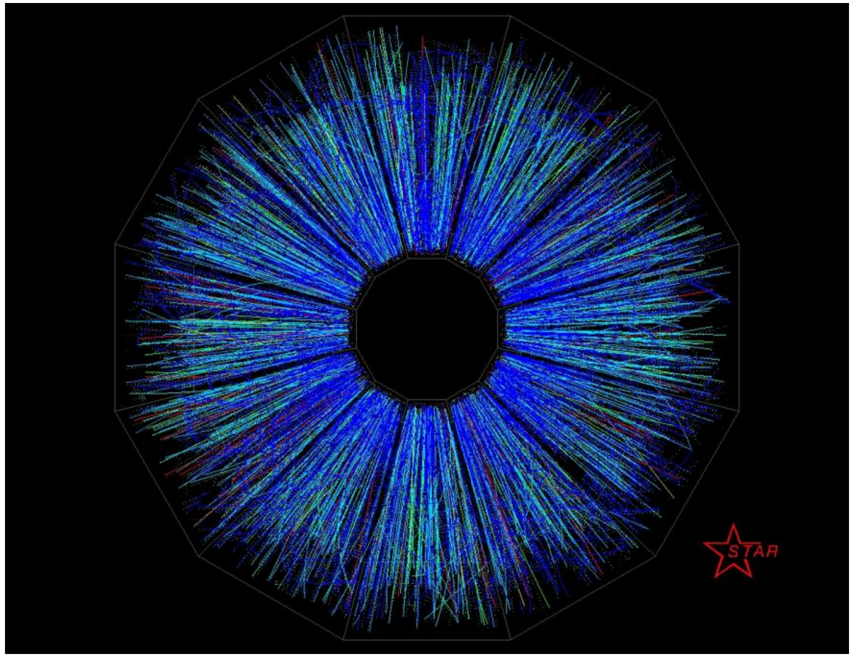
Saturation

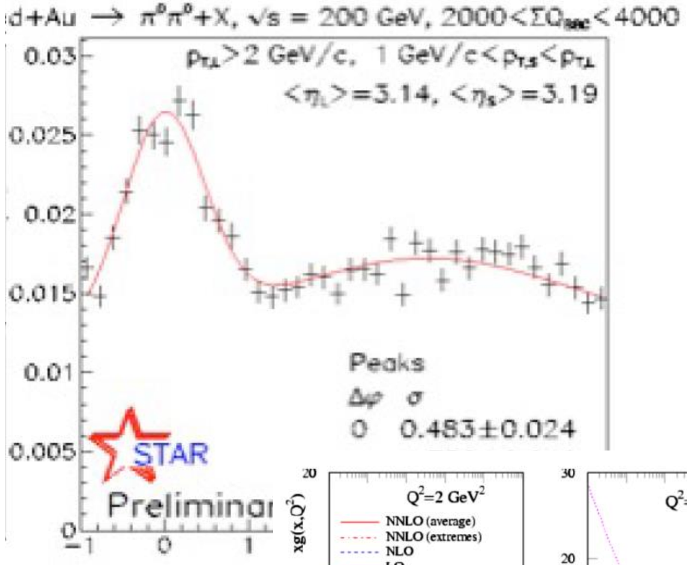


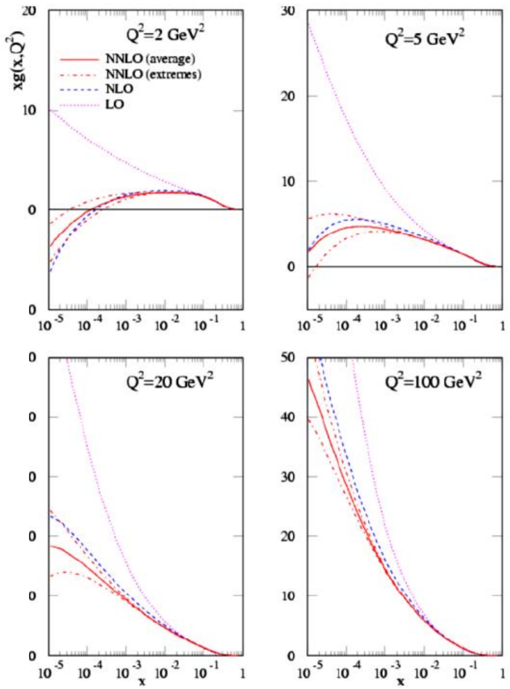
Y = ln 1/x
Saturation
ln Q$_s^2$(Y) = λ Y
Dilute system
BFKL
DGLAP
ln Λ$^2_{QCD}$
ln Q^2

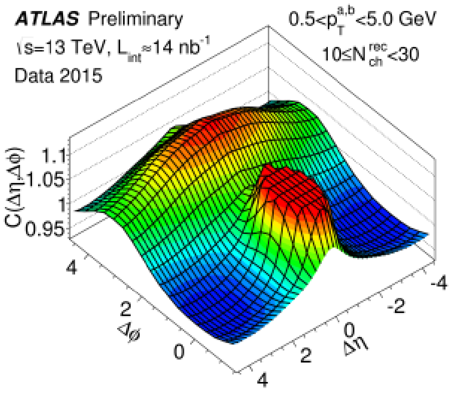
Has saturation been observed at HERA, RHIC, LHC?

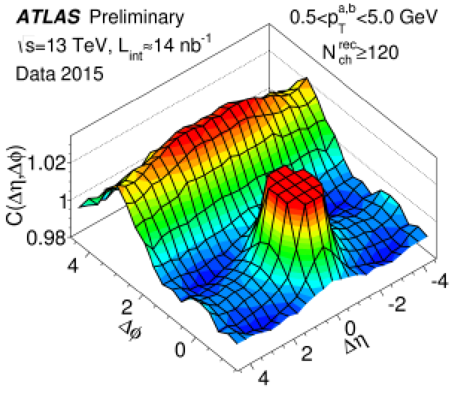


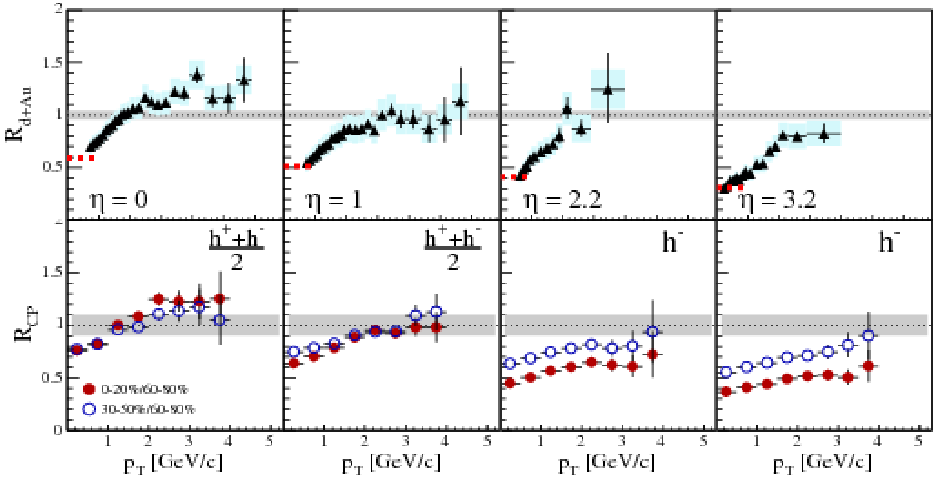








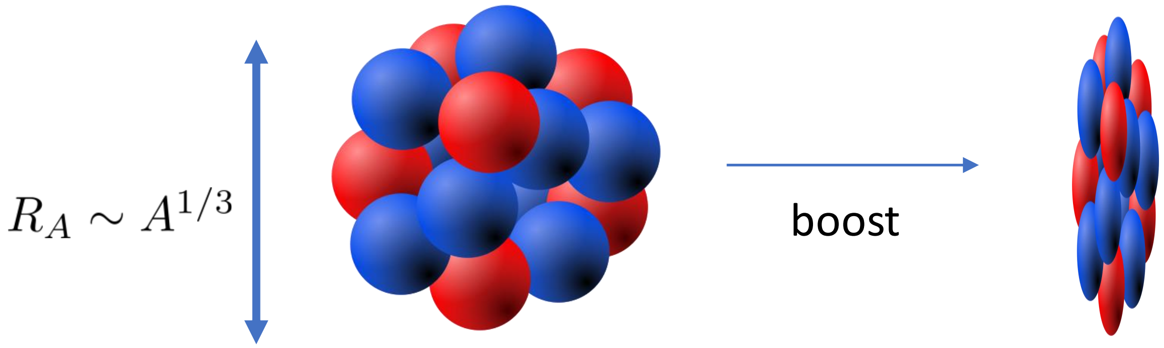




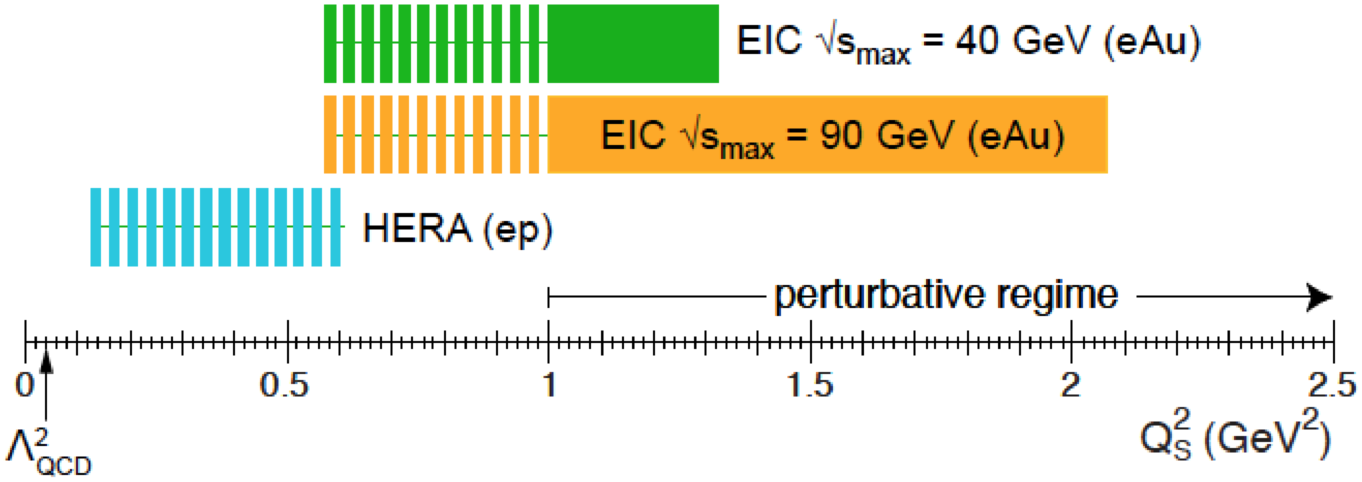
EIC: Dream machine for saturation

No initial state interactions (advantage over LHC, RHIC)

Nuclear enhancement of the saturation momentum (advantage over HERA)



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



At EIC, for heavy nuclei, Q_s becomes perturbative!

(It wasn't the case at HERA actually…)

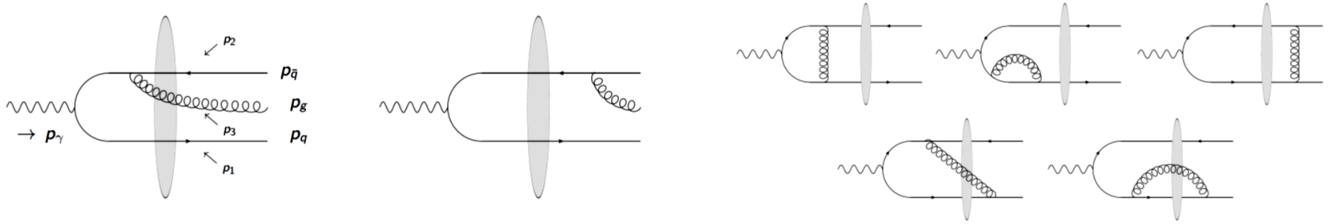
Can saturation become precision physics?

No all-order proof of factorization.
`Leading order' already contains infinitely many diagrams with infinitely many twists.

NLL Balitsky-Kovchegov (BK) Balitsky, Chirilli (2008)
NNLL BK Caron-Huot, Herranen (2016)

Factorization should be checked order by order. Currently NLO for a few processes.
Chirilli, Xiao, Yuan; Beuf; Mulian, Iancu; Roy, Venugopalan…

e.g., NLO exclusive diffractive dijet, vector meson production at EIC



Boussarie, Grabovsky, Szymanowski, Wallon (2016)

Need also `collinear improvement' Iancu, talk on Wednesday

NLO global analysis of the dipole S-matrix at EIC? cf. Albacete, Armesto, Milhano, Salgado (2009)

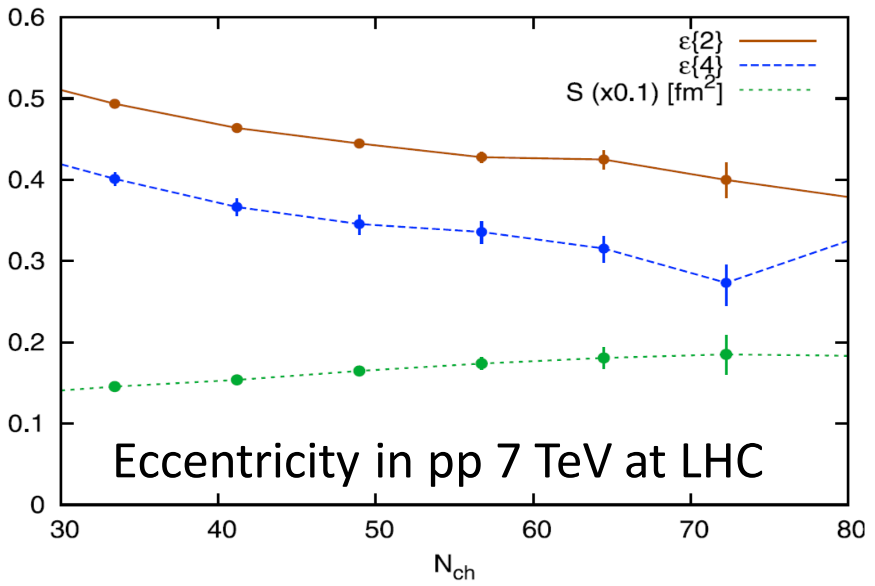
Initial geometry

Initial geometry and fluctuations

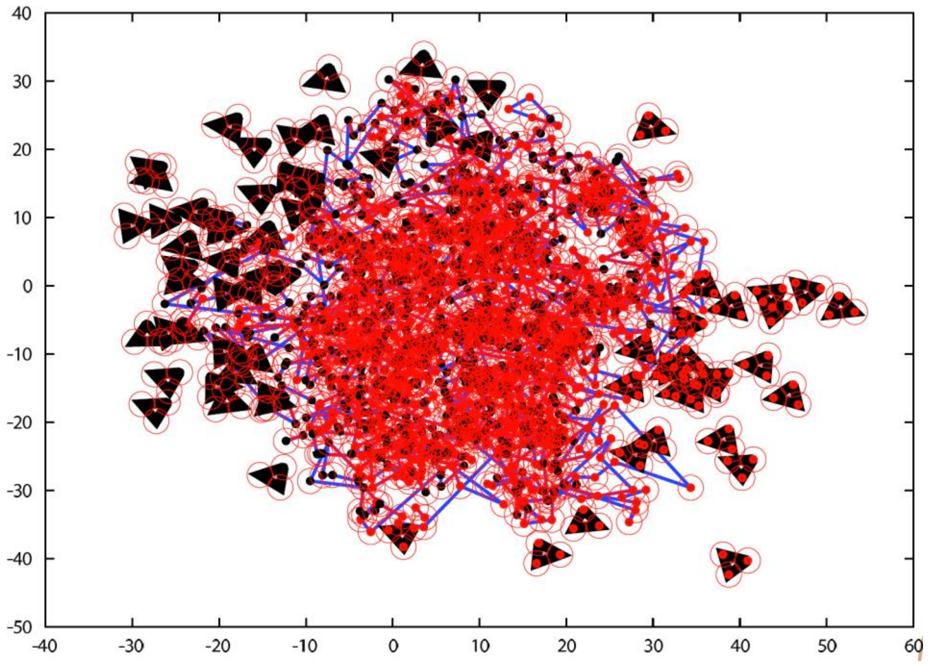
Proton/nucleus wavefunction at small-x full of fluctuations and correlations

DIPSY Monte Carlo event generator based on Mueller's dipole model.
Includes BFKL cascade and saturation. Avsar, Flensburg, Gustafson, Lonnblad

Dipole evolution implementated in PYTHIA8, can simulate large nucleus and virtual photon
→ Full simulation of $\gamma^* A$ including final states! Bierlich, Rasmussen (2019)



Avsar, Flensburg, YH, Ollitrault, Ueda (2011)



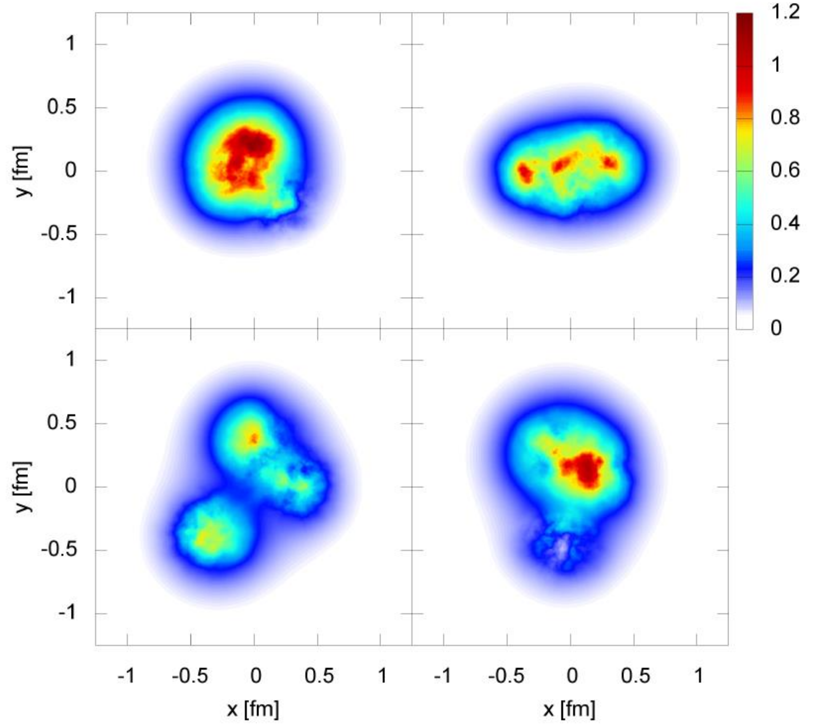
Incoherent diffraction

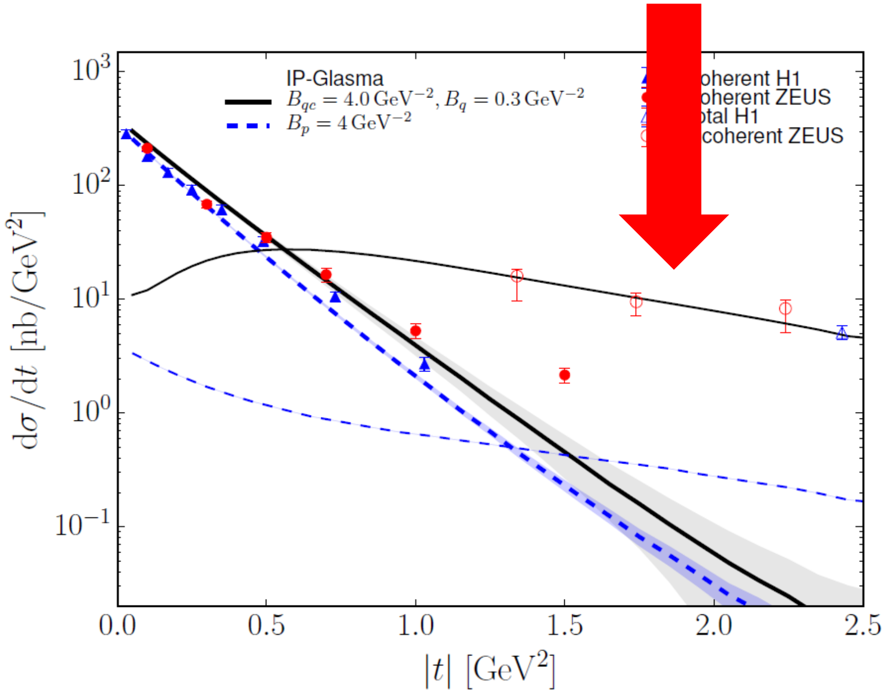
Probe of fluctuations inside the target (Good-Walker picture)

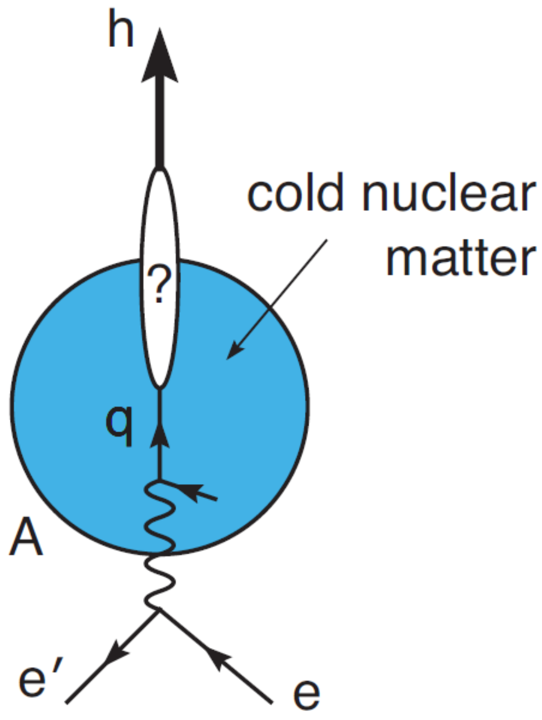
$$\left.\frac{d\sigma^{diff}}{dt}\right|_{incoherent} = \langle T^2\rangle - \langle T\rangle^2$$

Bumpy initial condition + b-dependent JIMWLK   Mantysaari, Schenke (2016,2019)

Good description of the HERA data at large- t . Extension to light nuclei→ EIC







Jets

Jets at EIC

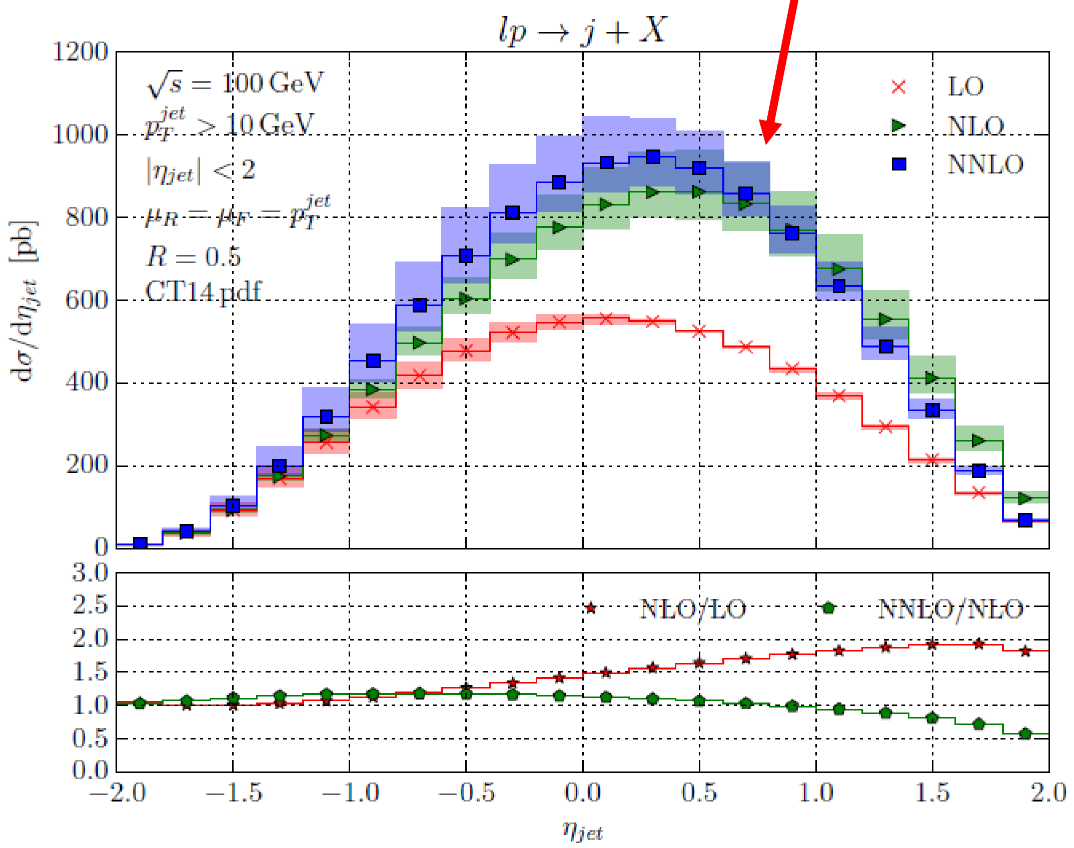
Compared to jets at LHC,

Smaller p_T , smaller multiplicity

Less underlying events and pileups
Stronger power corrections.

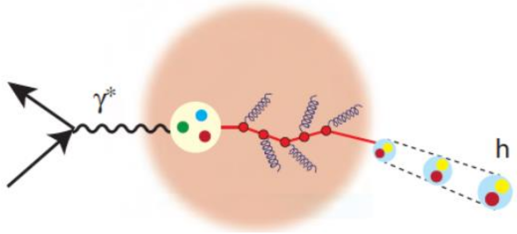
New opportunities for jet physics

Perturbation theory stabilizes at NNLO!



NNLO single inclusive jet in ep collisions at EIC
Abelof, Boughezal, Liu, Petriello (2016)

Jet quenching at EIC



hadronization

outside the medium

Clean environment to study jet quenching

The effects will be small compared to AA, precision required.

→ useful to discriminate different approaches to jet quenching.

Insights into hadronization

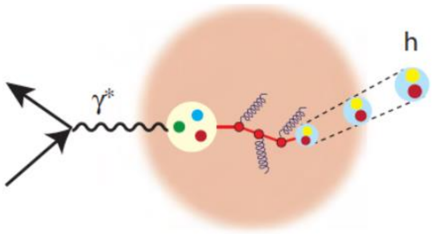
Vitev, talk at POETIC2019

Vitev, Sievert (2018)

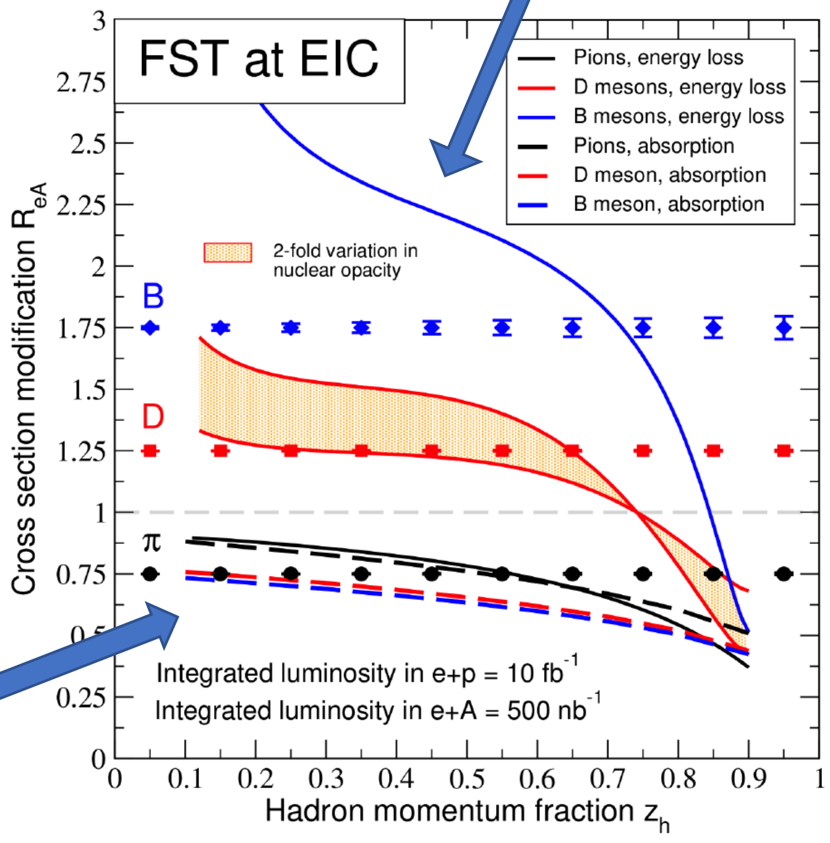
Heavy-flavor R_{eA}

→sensitive to different

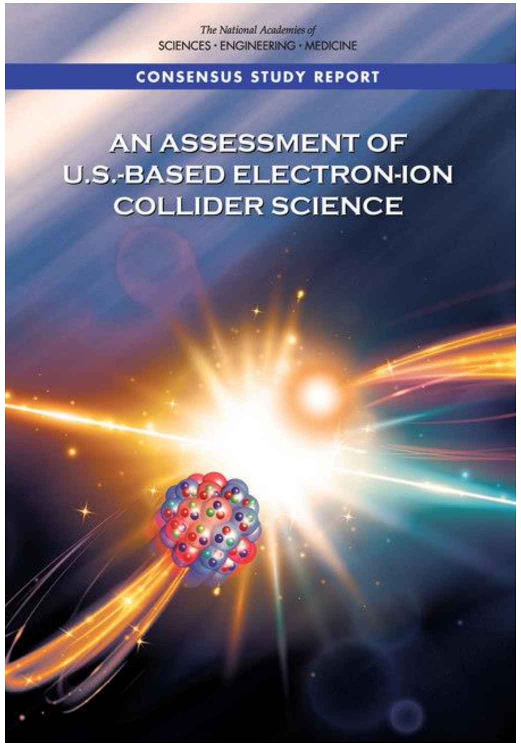
scenarios of hadronization



hadronization inside



Proton mass



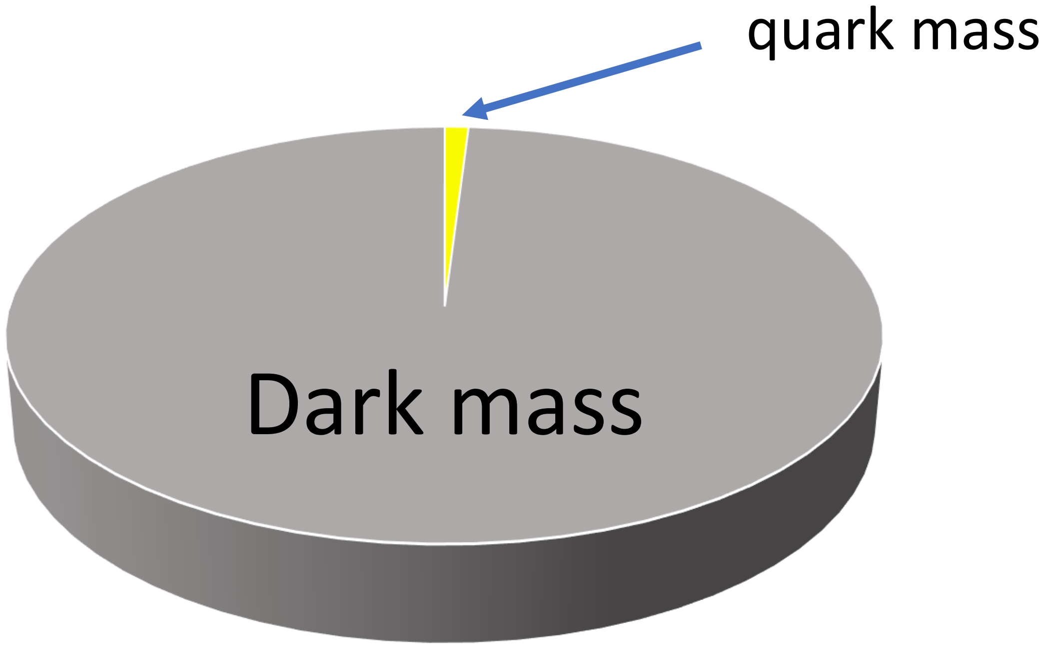
NAS report (July 2018)

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

- $\boxed{\text{How does the mass of the nucleon arise?}}$
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

Proton mass crisis

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



QCD trace anomaly $\quad T^{\mu}_{\mu} = \frac{\beta(g)}{2g} F^2 + m(1+\gamma_m(g))\bar{q}q \qquad \langle P | T^{\mu}_{\mu} | P \rangle = 2M^2$

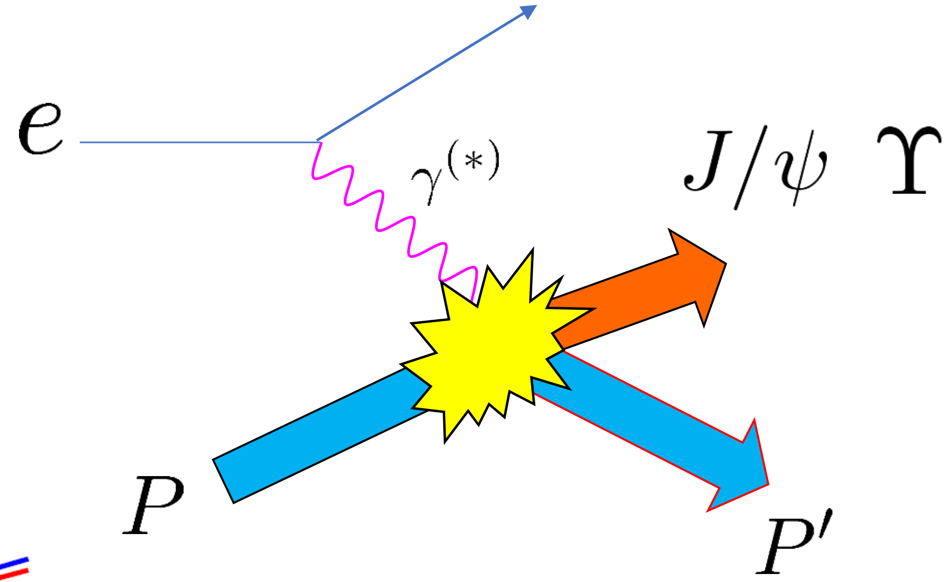
Nonperturbative gluon condensate $\langle P | F^{\mu\nu} F_{\mu\nu} | P \rangle$ responsible for hadron masses.

Photo-production of J/ψ near threshold

Kharzeev, Satz, Syamtomov, Zinovjev (1998)

Sensitive to the gluon condensate

$$\langle P' | F^{\mu\nu} F_{\mu\nu} | P \rangle$$



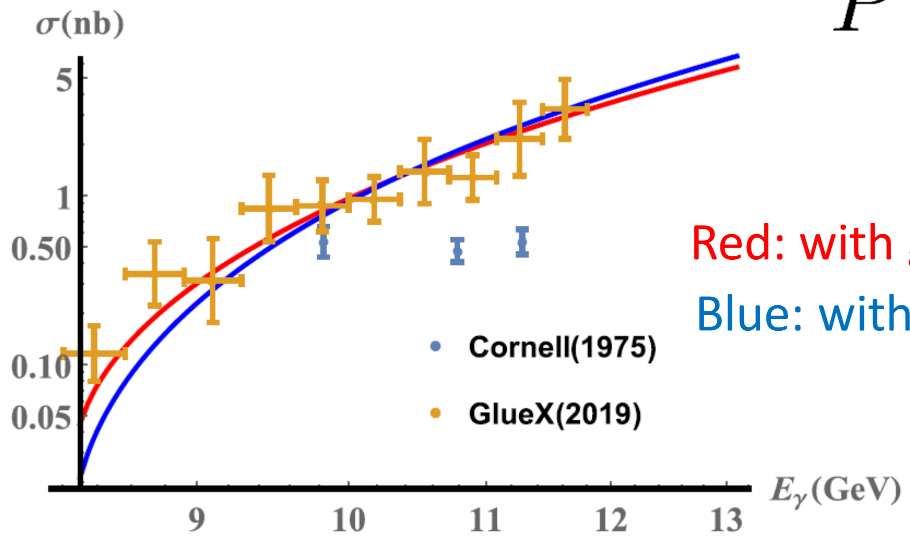
Ongoing experiments at JLab

Can be an interesting physics case at EIC, especially in China

Holographic calculation fitted to the latest JLab data.

YH, Yang (2018)

YH, Rajan, Yang (2019)



Red: with gluon condensate

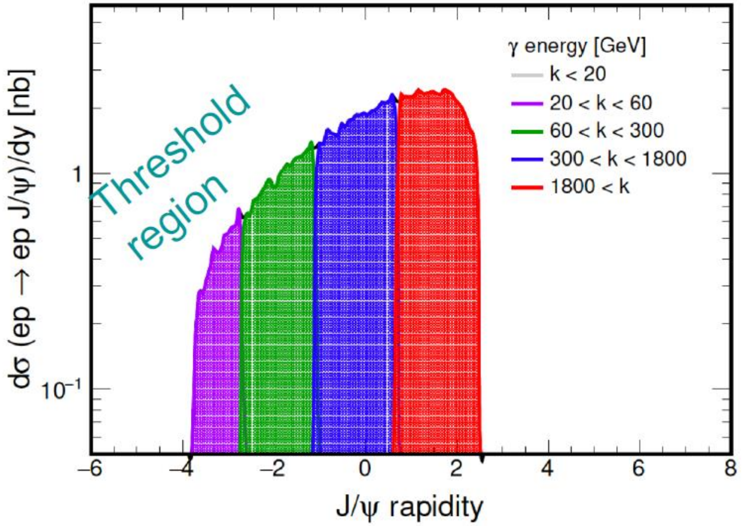
Blue: without gluon condensate

Threshold production at high energy colliders ?

EIC photo-production limit

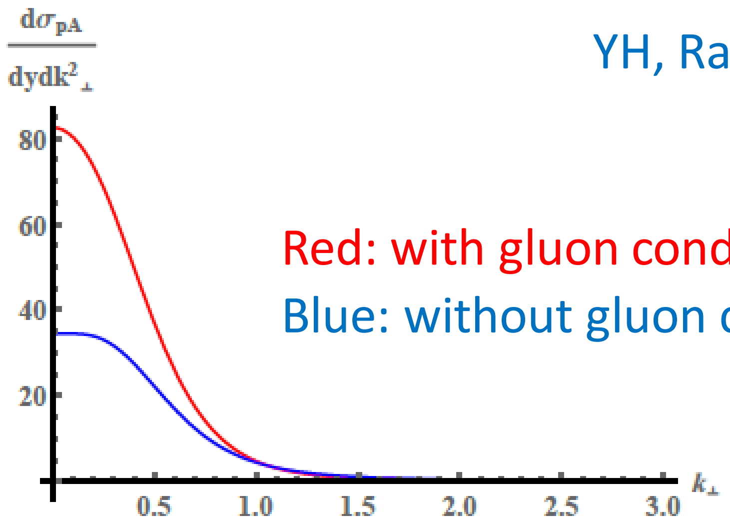
eSTARlight Monte Carlo

Lomnitz, Klein (2018),
Klein, talk at POETIC 2019



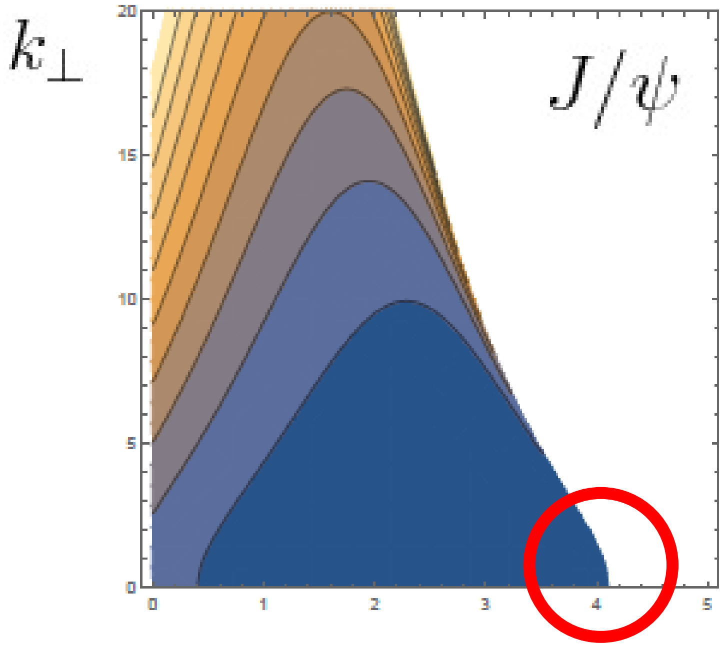
RHIC, Ultra-peripheral pA collisions

YH, Rajan, Yang (2019)



Red: with gluon condensate

Blue: without gluon condensate



Challenging to measure, need forward detectors.
Heavy-ion can help us to understand EIC physics!

Conclusion

- In 10-15 years from now, DIS experiments will be running in the US, China and Europe.
- Tremendous physics opportunities for theory, experiments, and lattice QCD
- Many feedbacks to heavy-ion physics, especially gluon saturation and initial geometry
- Conversely, heavy-ion can help us to understand EIC physics
  → Ultra-peripheral collision (UPC)