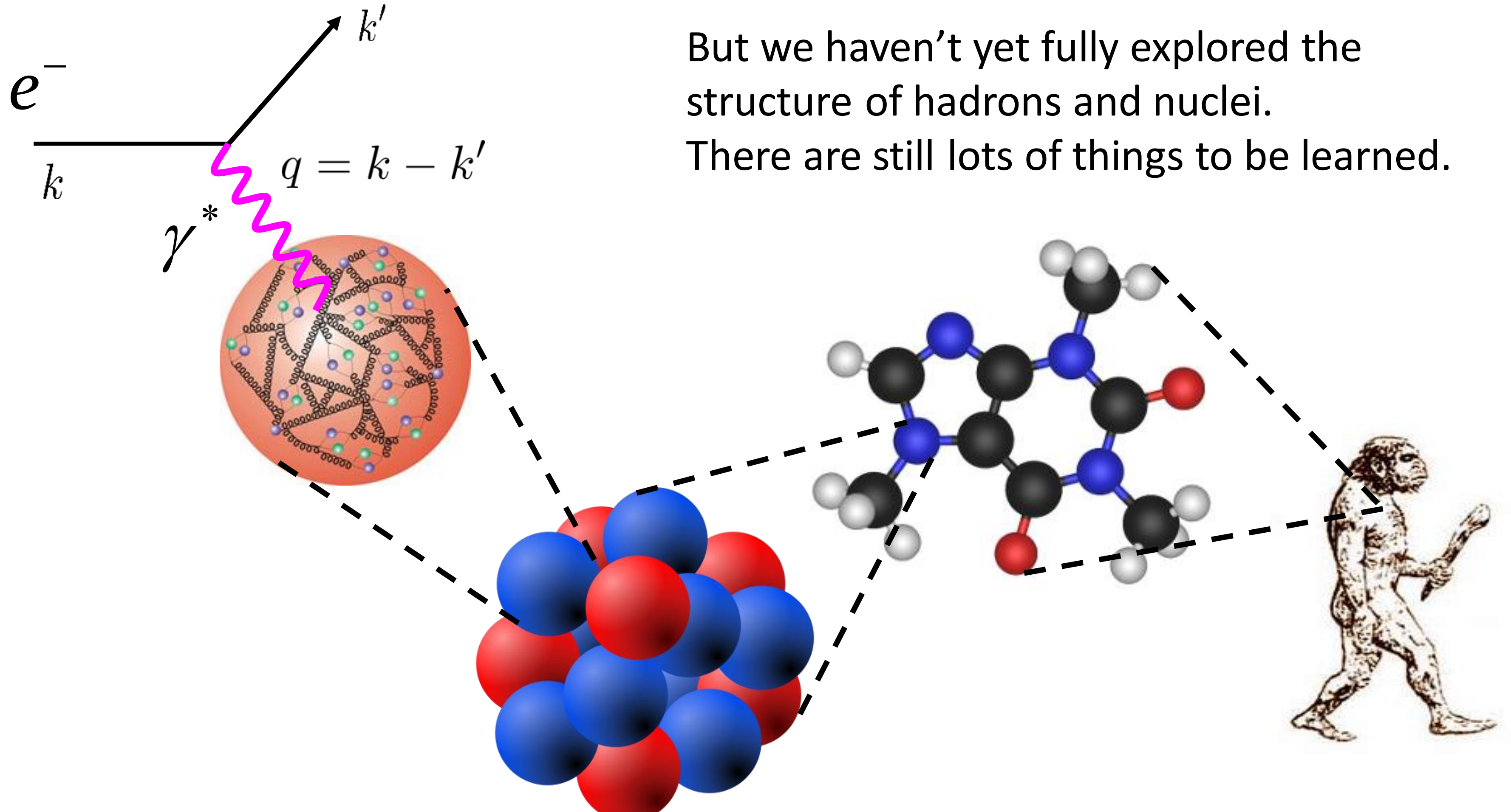
Theoretical perspectives on electromagnetic hadron physics

Yoshitaka Hatta
Brookhaven National Laboratory

Deep Inelastic Scattering
—Microscope to femtometer world

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

But we haven’t yet fully explored the structure of hadrons and nuclei.
There are still lots of things to be learned.



Future DIS experiments worldwide

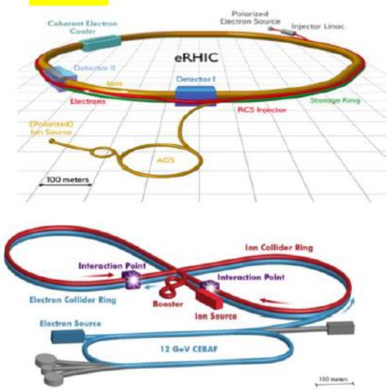
Planned DIS Colliders around the world

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

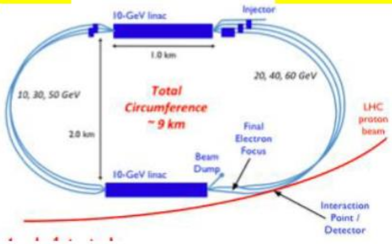
EIC



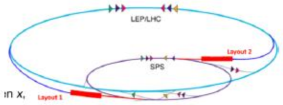
EicC

LHeC

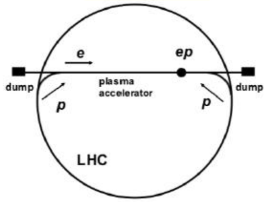
FCC-eh



PEPIC

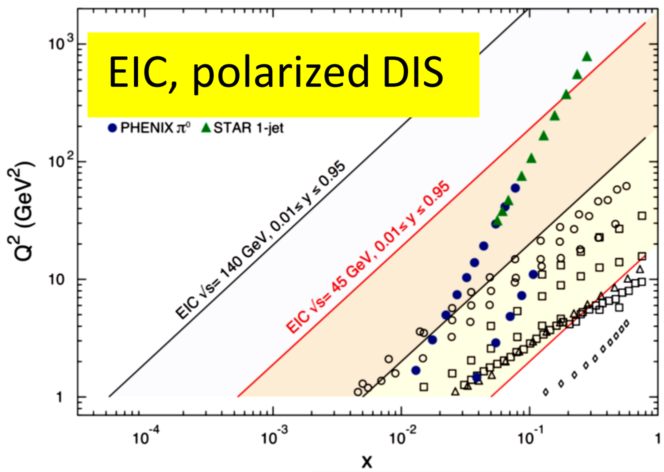


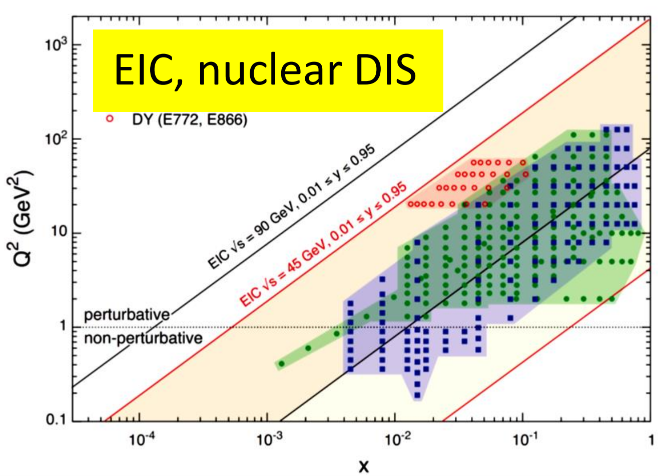
VHEeP

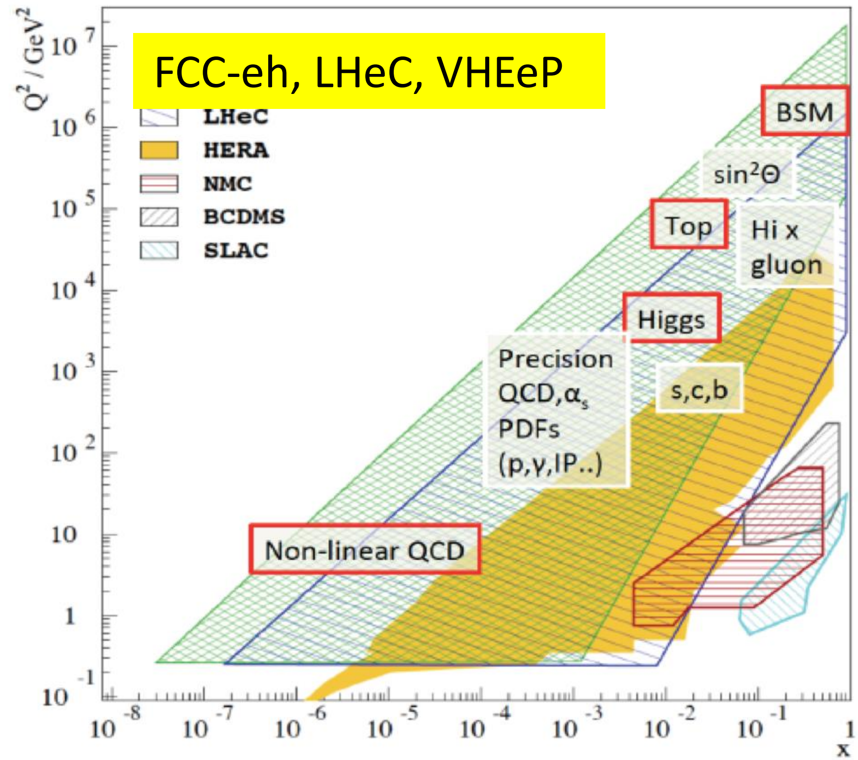


The era of precision EW, Higgs, pQCD, and precision study of nucleon and nuclear structures in the next 25~30 years.

Exploring *terra incognita*







Unprecedented coverage in kinematics.

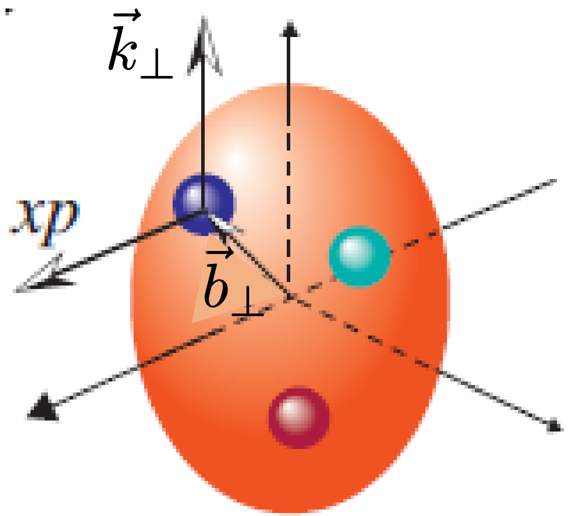
Tremendous physics opportunities for theory including lattice QCD!

Agenda

- TMD
- GPD
- Spin (longitudinal)
- Spin (transverse)
- Small-x
- Mass

Nucleon tomography
(TMD/GPD/Wigner)

Multi-dimensional tomography



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

Ordinary parton distribution functions (PDF) can be viewed as the 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

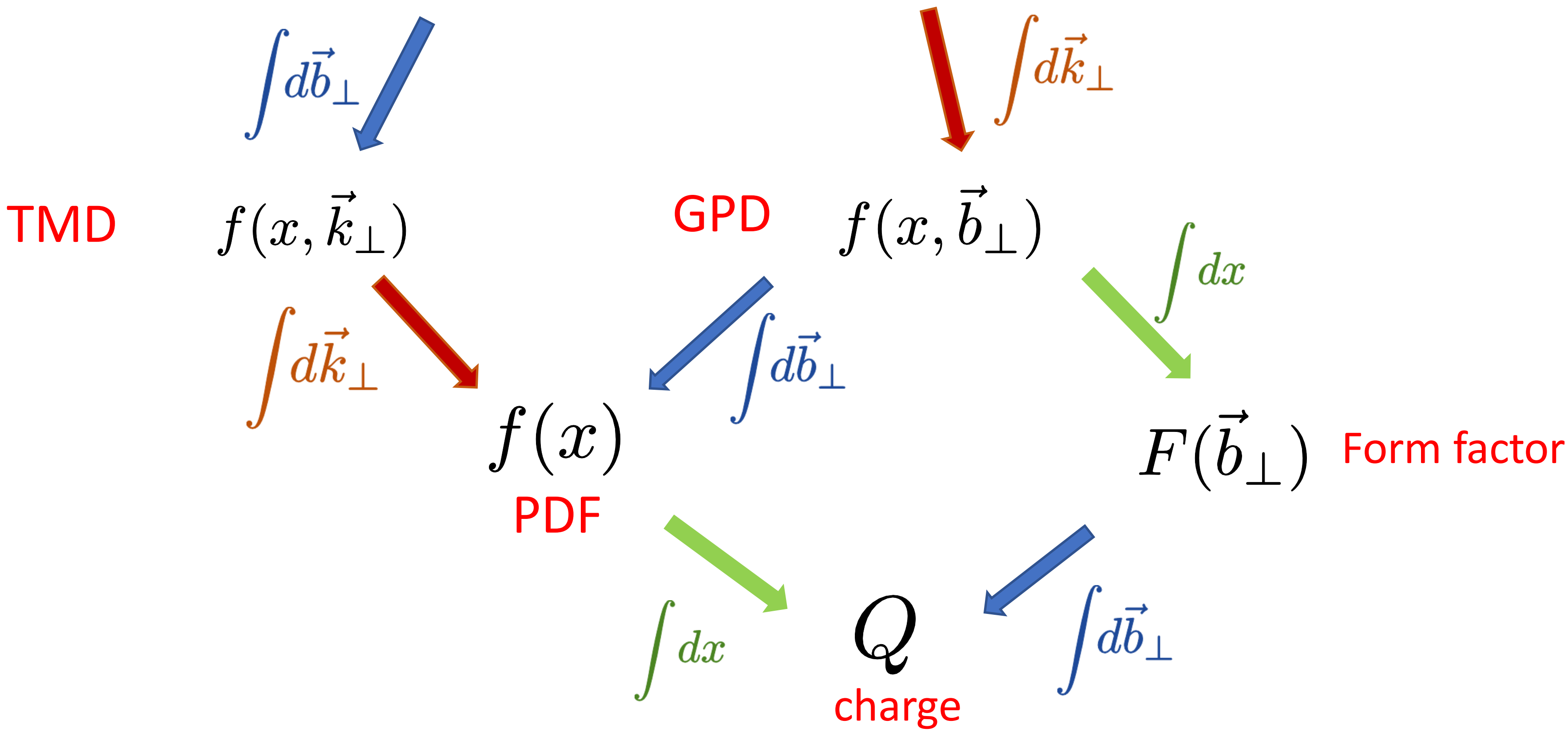
$u(x, \vec{b}_\perp)$ Generalized parton distribution (GPD) 3D tomography

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

PDF family tree

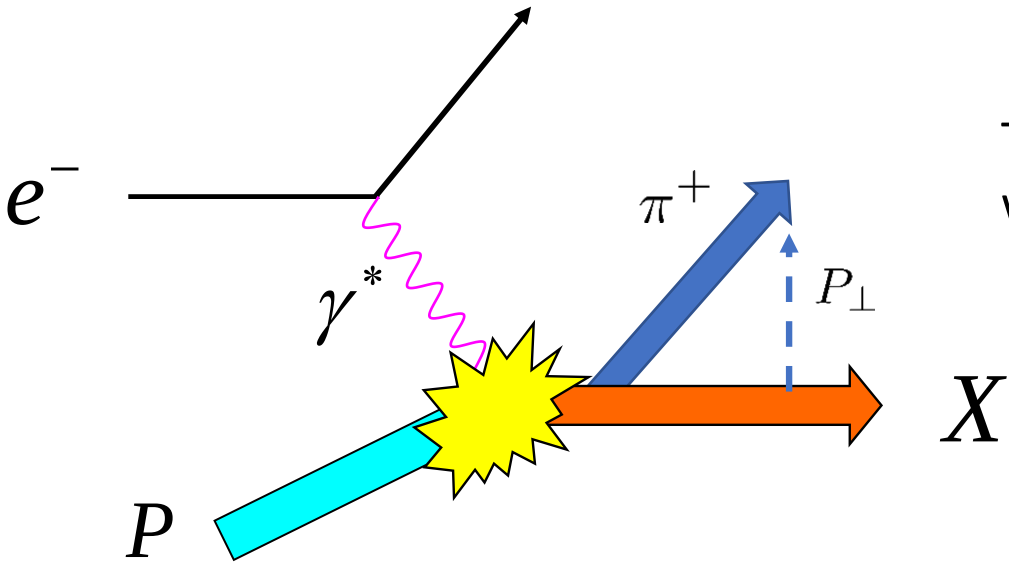
Wigner distribution—the `mother' distribution   Belitsky, Ji, Yuan (2003)

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



Semi-inclusive DIS

→ Talk by A. Prokudin



Tag one hadron species
with fixed transverse momentum $P_\perp$

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 FF

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

TMD is becoming precision physics

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

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

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

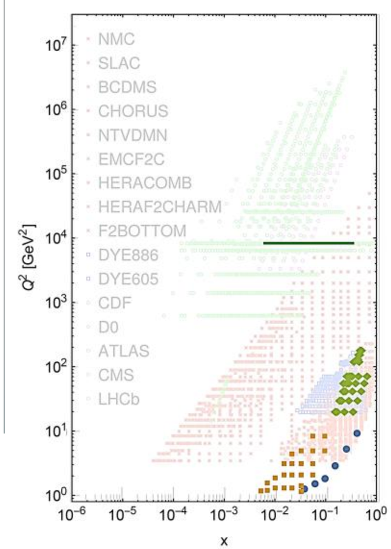
Recently computed to three loops
Li, Zhu (2017); Vladimirov (2017)

Computable from lattice QCD at large $r_\perp$
Ebert, Stewart, Zhao (2018)

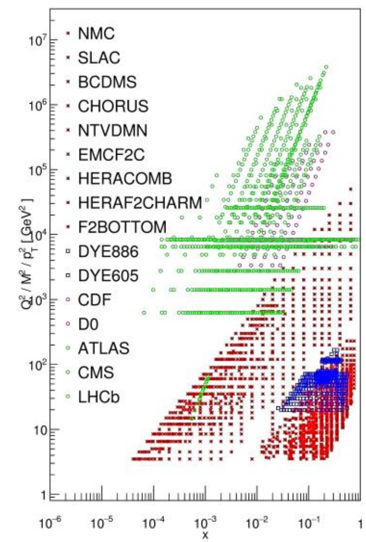
TMD global analysis

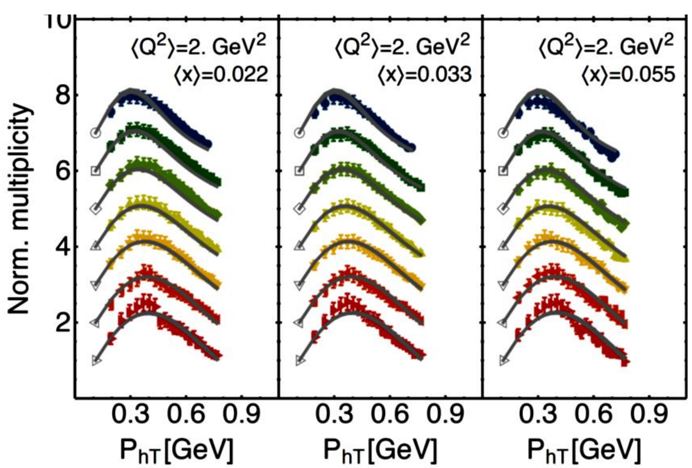
	Framework	W+Y	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	W	✘	✘	✔	✔	98
QZ 2001 hep-ph/0506225	NLO-NLL	W+Y	✘	✘	✔	✔	28 (?)
RESBOS resbos@msu	NLO-NNLL	W+Y	✘	✘	✔	✔	>100 (?)
Pavia 2013 arXiv:1309.3507	LO	W	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO	W	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	W	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	W	1 (x,Q^2) bin	1 (x,Q^2) 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



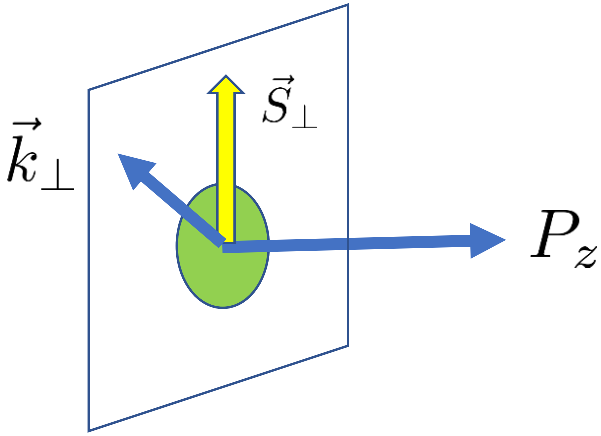


Still in its infancy.
Fully blossoms in the EIC era!

Universality up to a sign

Transversely separated bi-linear operator $\bar{\psi}(r_\perp)...\psi(0_\perp)$
→ Gauge link not unique.

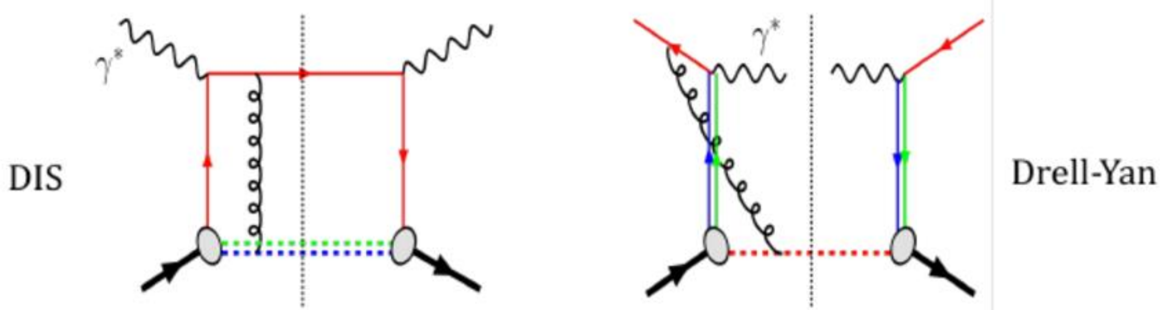
Sivers function for the transversely polarized nucleon



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

→ Single spin asymmetry

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



Test of time-reversal symmetry in QCD

Generalized parton distributions (GPD)

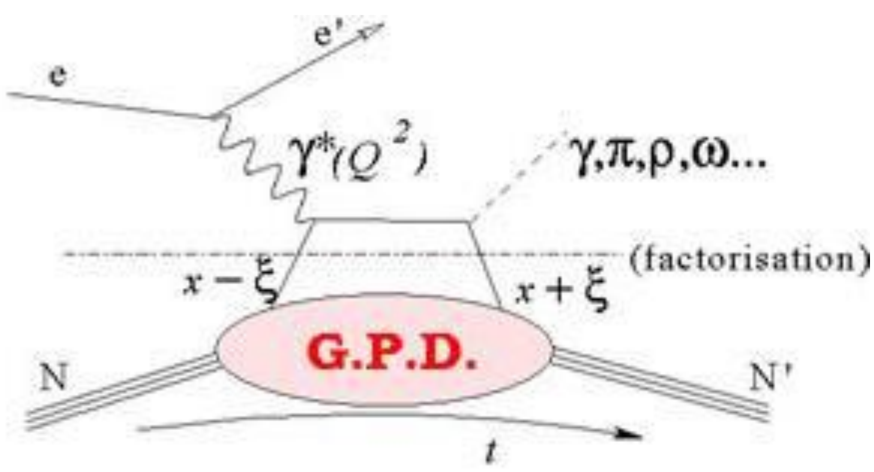
→Talk by D. Sokhan

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

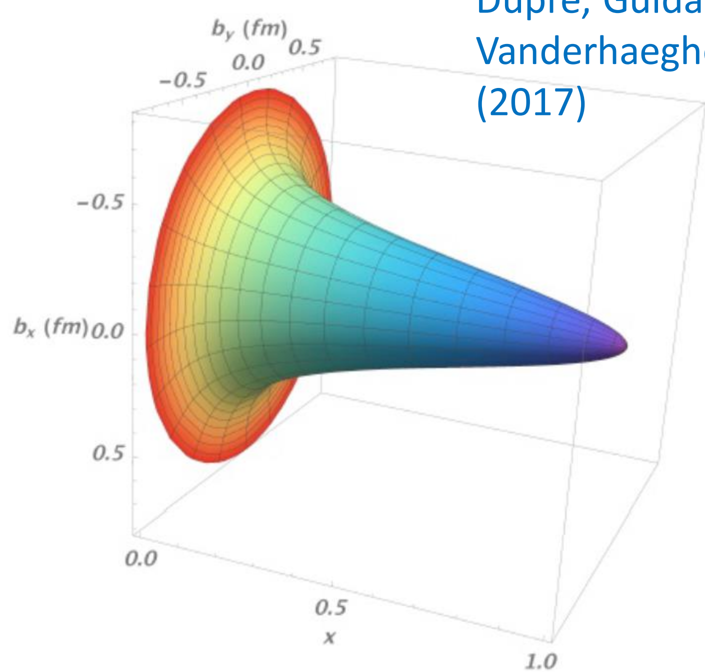
$$= H_q(x, \Delta) \bar{u}(P'S') \gamma^\mu u(PS) + E_q(x, \Delta) \bar{u}(P'S') \frac{i\sigma^{\mu\nu}\Delta_\nu}{2m} u(PS) \qquad \Delta = P' - P$$

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

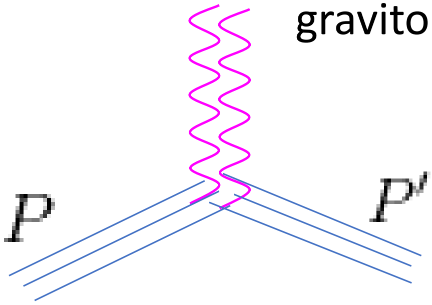
Measurable in
Deeply Virtual Compton Scattering (DVCS)



Dupre, Guidal, Vanderhaeghen (2017)



Nucleon gravitational form factors



$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = \bar{u}(P')\Big[A_{q,g}\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M}$$
$$+D_{q,g}\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} + \bar{C}_{q,g}M\eta^{\mu\nu}\Big]u(P)$$

All the form factors are interesting and measurable!

A, B Ji sum rule $J_{q,g} = \frac{1}{2}\int dx(H_{q,g}(x) + E_{q,g}(x)) = \frac{1}{2}(A_{q,g} + B_{q,g})$

D Pressure

$\bar{C}$ Mass, pressure

D-term: the last global unknown

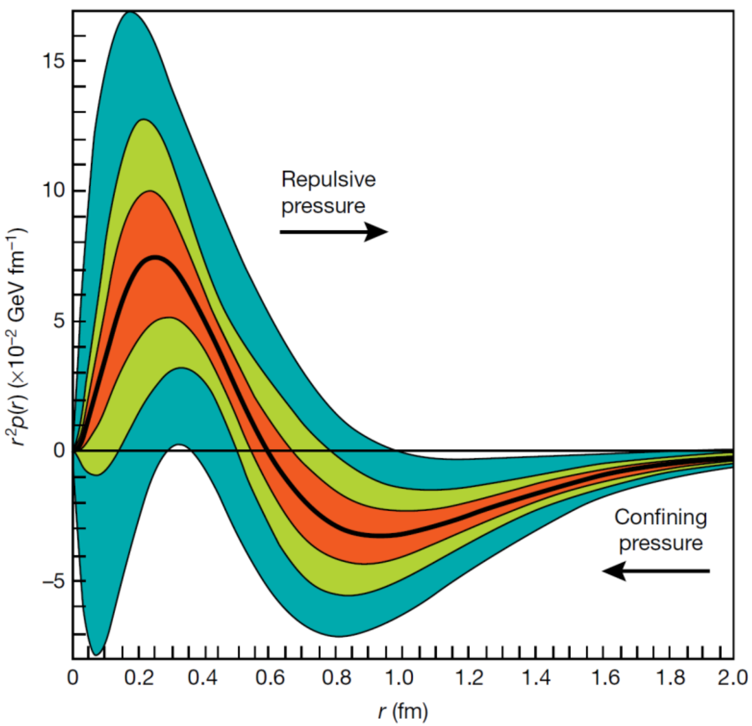
→ Talks by Elouadrhiri, Shanahan

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

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

Related to the radial pressure distribution inside a nucleon Polyakov, Schweitzer,…

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



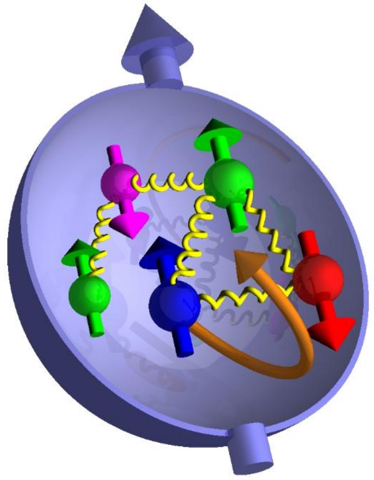
Burkert, Elouadrhiri, Girod (2018)
see, also, Kumericki (2019)

First extraction at JLab, large model dependence.
Need significant lever-arm in Q^2 to disentangle various moments of GPDs → EIC

→ Talks by R. Fatemi, B. Badelek

Proton Spin

Proton spin decomposition



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)

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

$\Delta\Sigma = 0.25 \sim 0.3$ `spin crisis'

Polarized PDF global analysis

Table by E. Nocera

Recent determinations of polarised PDFs

	DSSV	NNPDF	JAM
DIS	☑	☑	☑
SIDIS	☑	☒	☑
pp	☑ (jets, π^0)	☑ (jets, $W^\pm$)	☒
statistical treatment	Lagr. mult. $\Delta\chi^2/\chi^2 = 2\%$ Monte Carlo	Monte Carlo	Monte Carlo
parametrization	polynomial (23 pars)	neural network (259 pars)	polynomial (10 pars)
features	global fit	minimally biased fit	large-x effects
latest updates	DSSV08 PRD 80 (2009) 034030 DSSV14 PRL 113 (2014) 012001	NNPDFpol1.0 NPB 874 (2013) 36 NNPDFpol1.1 NPB 887 (2014) 276	JAM15 PRD 93 (2016) 074005 JAM17 PRL 119 (2017) 132001

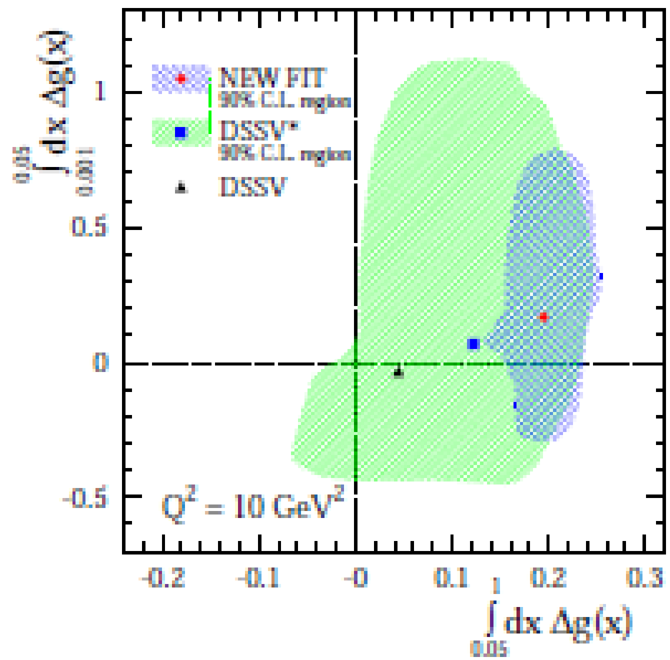
Evidence of nonzero ΔG

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

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

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

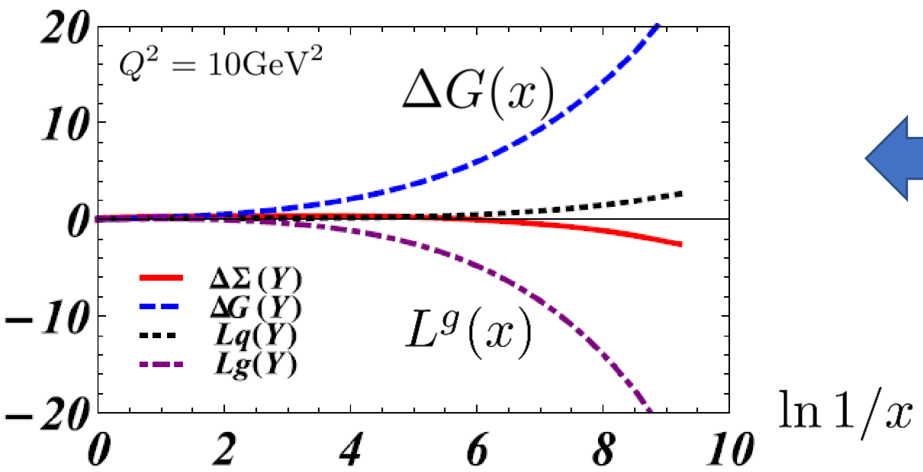
HUGE uncertainty from the small-x region



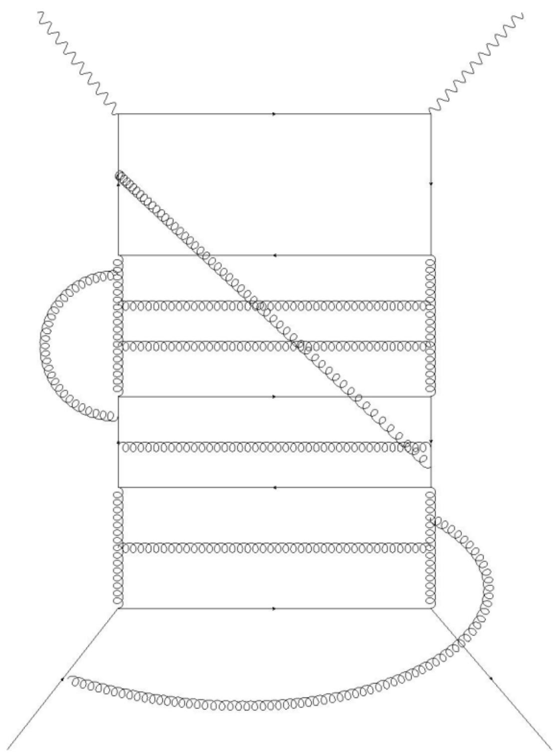
EIC will pin down the value of ΔG ,
....finally solve the spin puzzle?

No!

Don't forget Orbital Angular Momentum. It's there!



Significant cancellation at small-x from one-loop DGLAP
YH, Yang (2018)



All-loop resummation of small-x double logarithms $(\alpha_s \ln^2 1/x)^n$ gives Boussarie, YH, Yuan (2019)

$$L_g(x) \approx -2\Delta G(x)$$

Measuring OAM at EIC

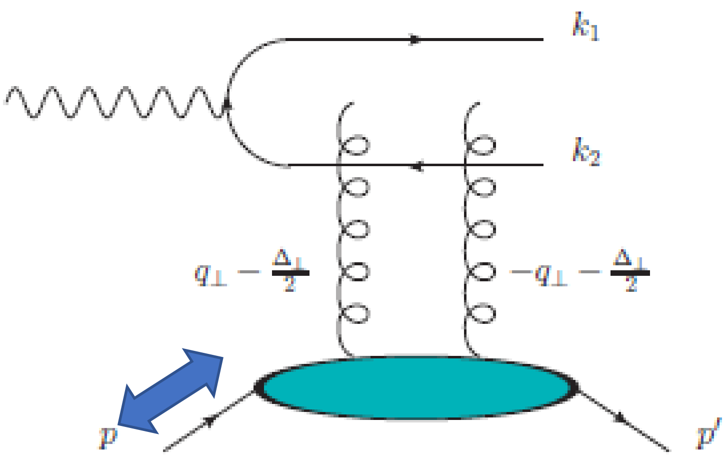
Ji, Yuan, Zhao (2016)
YH, Nakagawa, Xiao, Yuan, Zhao (2016)
Bhattacharya, Metz, Zhou (2017)

Exploit the connection between OAM and the Wigner distribution

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

Lorce, Pasquini
YH
Ji, Xiong, Yuan

Longitudinal single spin asymmetry in diffractive dijet production



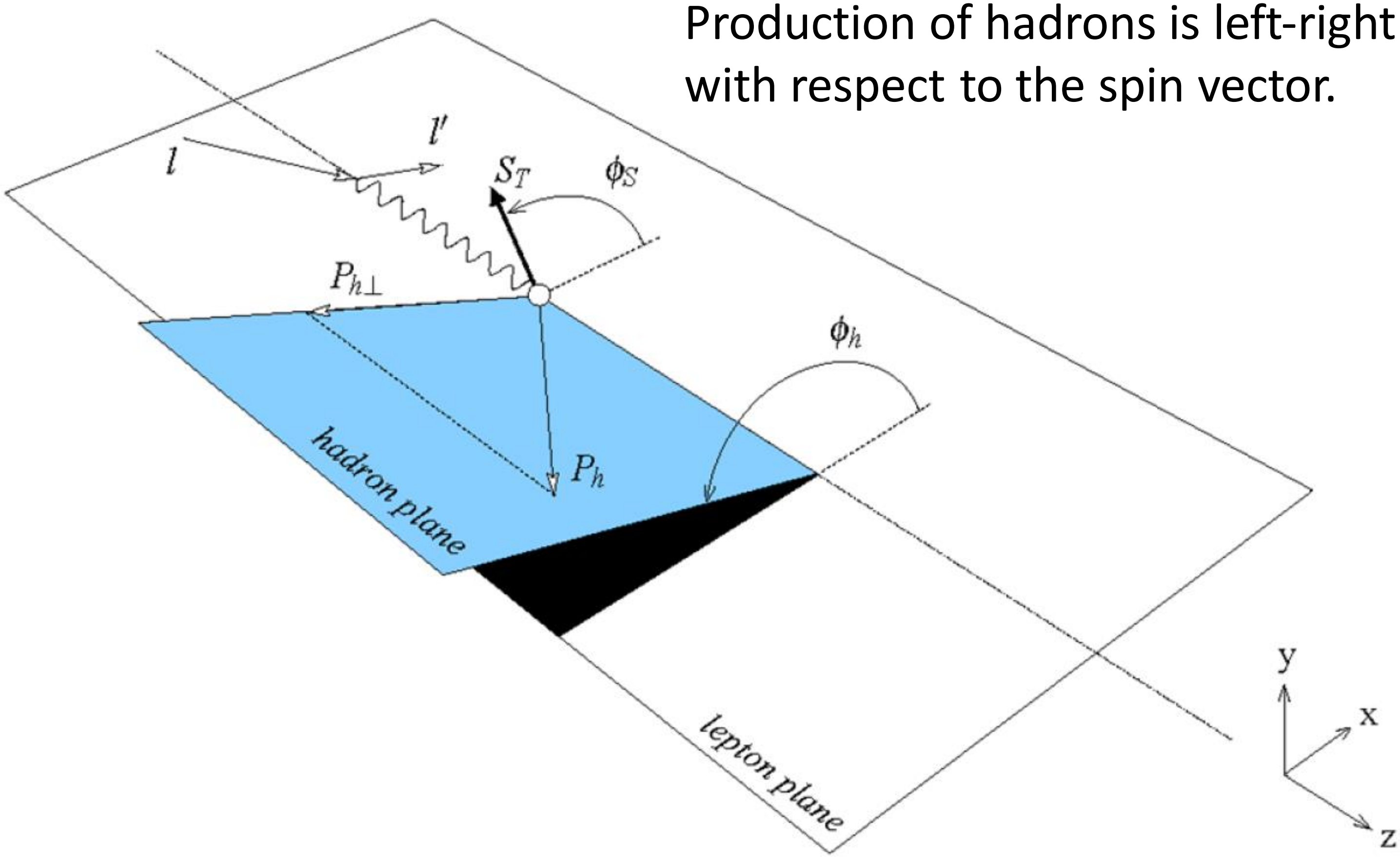
proton recoil momentum

$$\sigma^{\rightarrow} - \sigma^{\leftarrow} \propto \sin(\phi_P - \phi_\Delta)$$

dijet relative momentum

Single Spin Asymmetry (SSA) in SIDIS

Production of hadrons is left-right asymmetric with respect to the spin vector.



Known for 40 years.
Not yet fully understood.
New, surprising data still keep coming out.

Origins of SSA : Quest for an ` i '

Low-pT

- Sivers
- Collins fragmentation

High pT

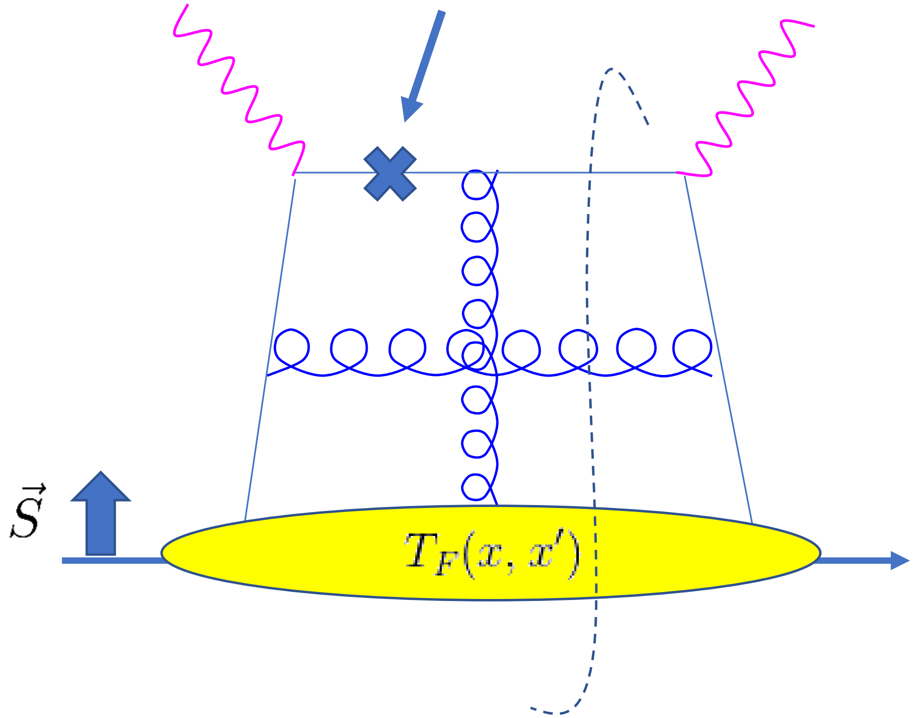
- Soft fermion pole (Efremov-Teryaev)
- Soft gluon pole (Qiu-Sterman)
- Hard pole

- Twist-3 fragmentation

This is the dominant one?

$$\frac{1}{k^2 + i\epsilon} = \mathrm{P}\frac{1}{k^2} - i\pi\delta(k^2)$$

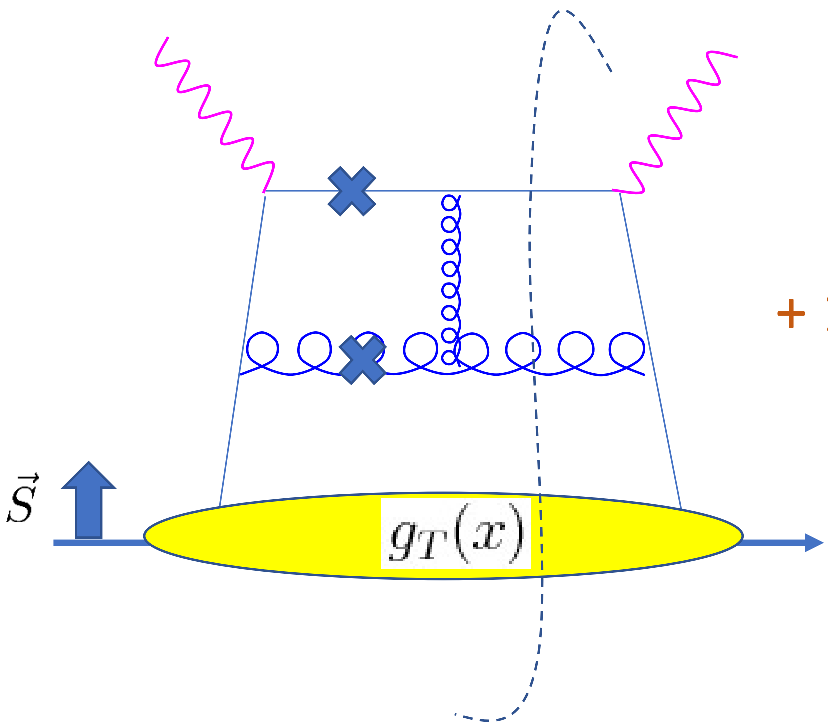
pick up the pole here



Kanazawa, Koike, Metz, Pitonyak (2014)
Gamberg, Kang, Pitonyak, Prokudin (2017)

Yet another mechanism of SSA in SIDIS

Benic, YH, Li, Yang, 1909.10684



+ 11 other diagrams

SSA of purely perturbative origin, first appears at two-loops

Suppressed by α_s, but g_T contains Wandzura-Wilczek part.

Many other possibilities in kT-factorization up to 2-parton, twist-3 TMDs.

$$
\begin{aligned}
d\sigma \;=\; & f_{1T}^{\perp} \otimes H^{(0)}_{\gamma^-,\gamma^+} \otimes D_1 + f_{1T}^{\perp} \otimes H^{(1)}_{\gamma^-,\gamma^x} \otimes D^{\perp} + f_{1T}^{\perp} \otimes H^{(2)}_{\gamma^-,\gamma_5\gamma^x} \otimes G^{\perp} \\
& + g_{1T} \otimes H^{(2)}_{\gamma_5\gamma^-,\gamma^+} \otimes D_1 + g_{1T} \otimes H^{(1)}_{\gamma_5\gamma^-,\gamma_5\gamma^y} \otimes G^{\perp} + g_{1T} \otimes H^{(2)}_{\gamma_5\gamma^-,\gamma^y} \otimes D^{\perp} \\
& + h_1 \otimes H^{(0)}_{\gamma_5\sigma^{y-},\gamma_5\sigma^{y+}} \otimes H_1^{\perp} + h_1 \otimes H^{(1)}_{\gamma_5\sigma^{y-},\gamma_5\sigma^{yx}} \otimes H^{*} + h_1 \otimes H^{(2)}_{\gamma_5\sigma^{y-},I} \otimes E^{*} \\
& + e_T \otimes H^{(1)}_{\gamma_5,\gamma_5\sigma^{y+}} \otimes H_1^{\perp} + e_T^{\perp} \otimes H^{(2)}_{I,\gamma_5\sigma^{y+}} \otimes H_1^{\perp} \\
& + f_T \otimes H^{(1)}_{\gamma^y,\gamma^+} \otimes D_1 + g_T \otimes H^{(2)}_{\gamma_5\gamma^y,\gamma^+} \otimes D_1 \\
& + h_T^{\perp} \otimes H^{(1)}_{\gamma_5\sigma^{yx},\gamma_5\sigma^{y+}} \otimes H_1^{\perp} + h_T \otimes H^{(1)}_{\gamma_5\sigma^{-+},\gamma_5\sigma^{y+}} \otimes H_1^{\perp},
\end{aligned}
$$

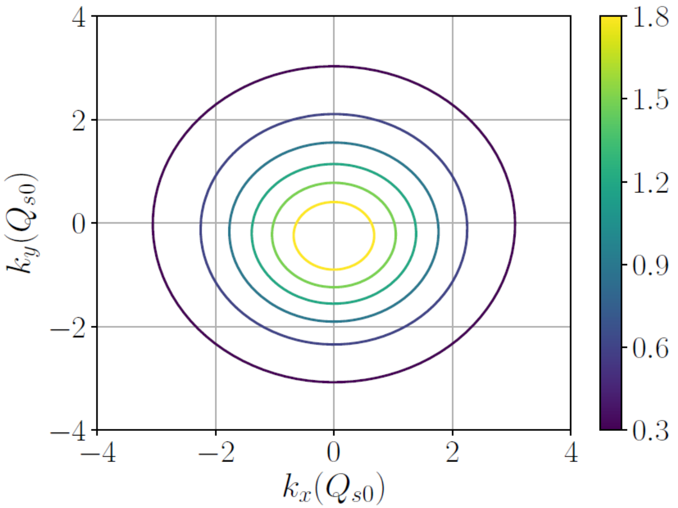
Gluon Sivers function

$$\frac{1}{xP^+}\int\frac{dz^-d^2z_\perp}{(2\pi)^3}e^{-ixP^+z^-+ik_\perp\cdot z_\perp}\langle PS_\perp|2\mathrm{Tr}[F^{+i}(z^-,z_\perp)U^{[\pm]}F^{+i}(0)U^{[\pm]}]|PS_\perp\rangle$$
$$=f_1^{[\pm\pm]}(x,k_\perp^2)-\frac{k_\perp\times S_\perp}{M}f_{1T}^{\perp[\pm\pm]}(x,k_\perp^2)\,,$$

Expected to be dominant in SSA of high-mass states (Open charm, jets), SSA in the backward region Interesting physics cases at EIC Zheng, Aschenauer, Lee, Xiao, Yin (2018)

At small-x, proportional to the Odderon amplitude
Zhou (2014)

$$f_{1T}^{g\perp}(k)\propto\int d^2r e^{ikr}\mathrm{Im}\mathrm{Tr}[U_rU_0^\dagger]$$

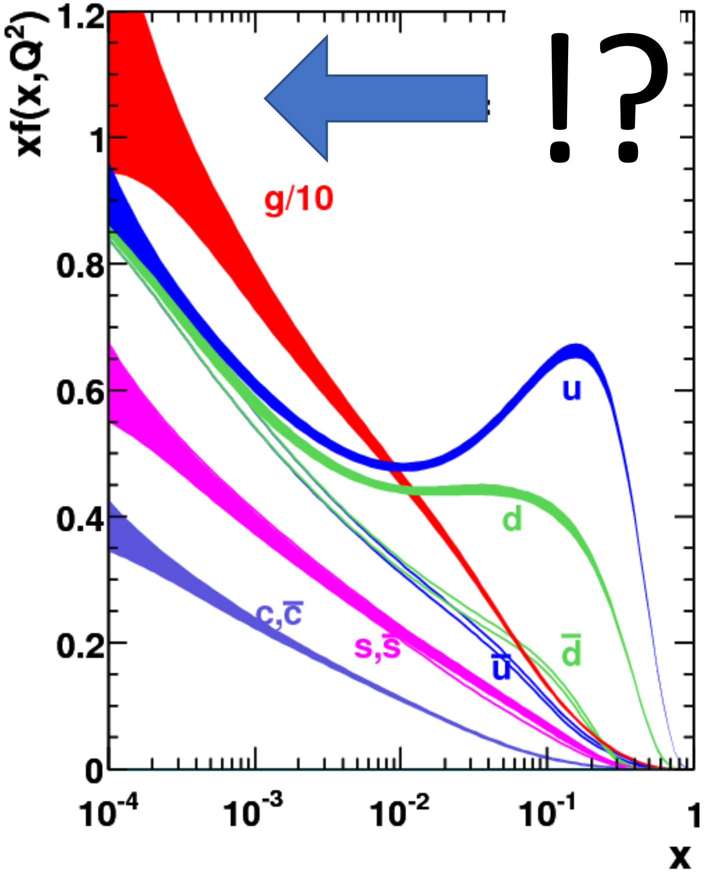


Yao, Hagiwara, YH (2019)

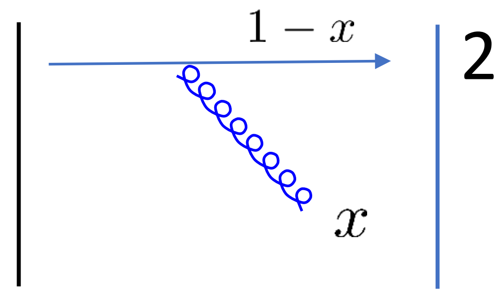
→ Talk by T. Lappi

Small-x

QCD at small-x



Probability to emit a soft gluon diverges



$$\propto \frac{1}{x}$$

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

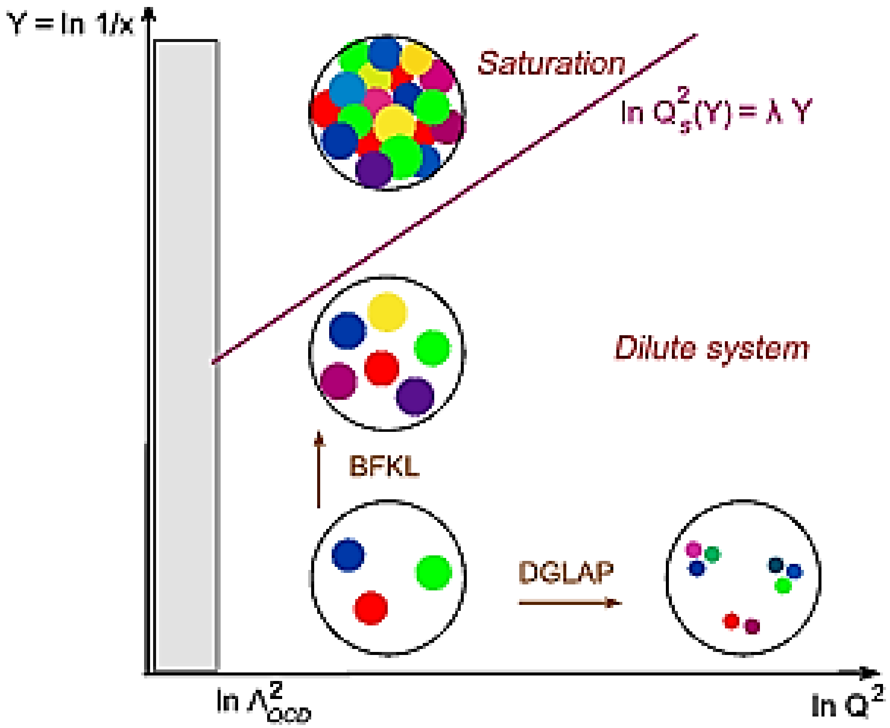
as predicted by BFKL
(Balitsky-Fadin-Kuraev-Lipatov)

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

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

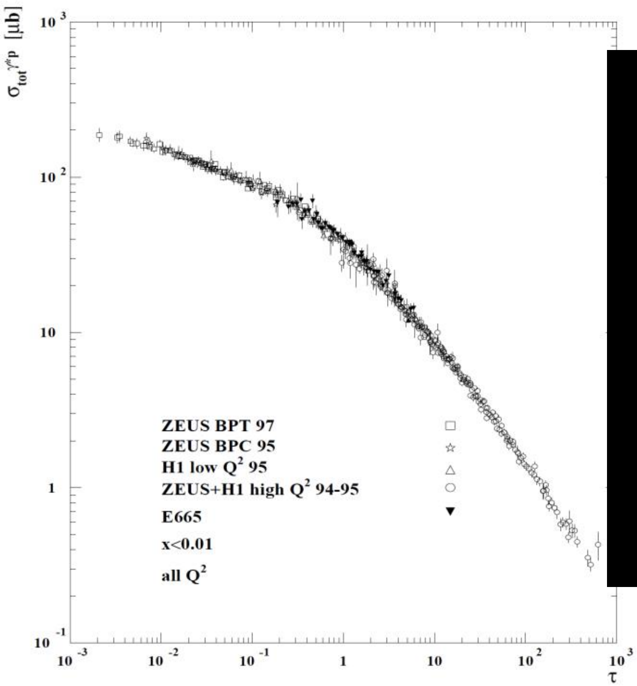
$$\frac{\alpha_s}{Q^2} xG(x, Q^2) = \pi R_p^2$$

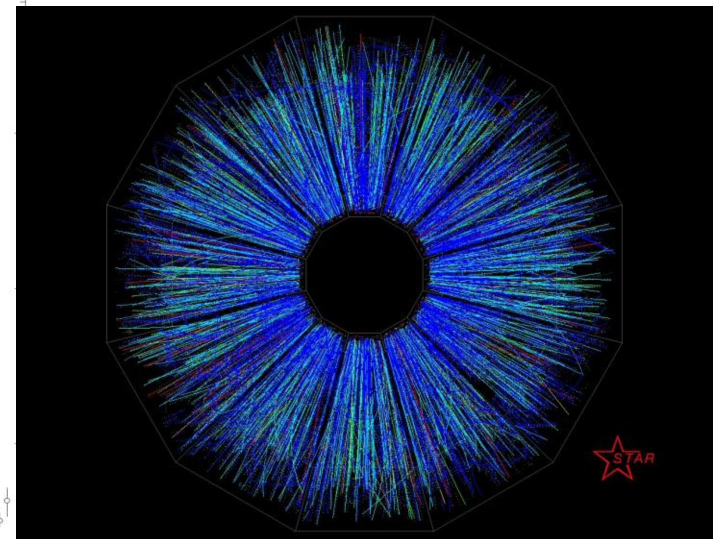
The saturation momentum

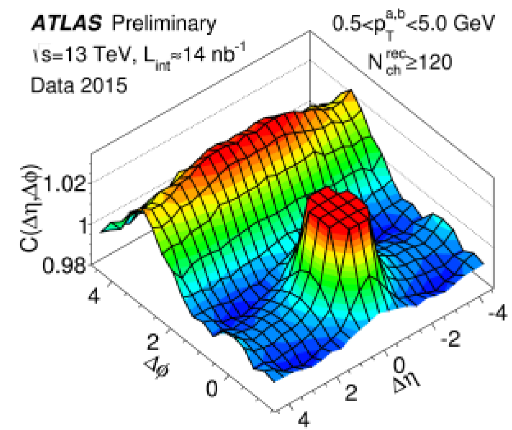
$$Q = Q_s(x) \gg \Lambda_{QCD}$$

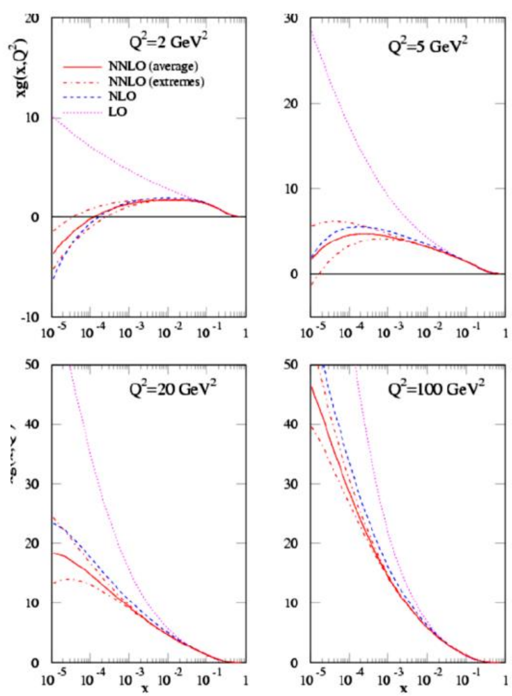
High density, but weakly coupled many-body problem

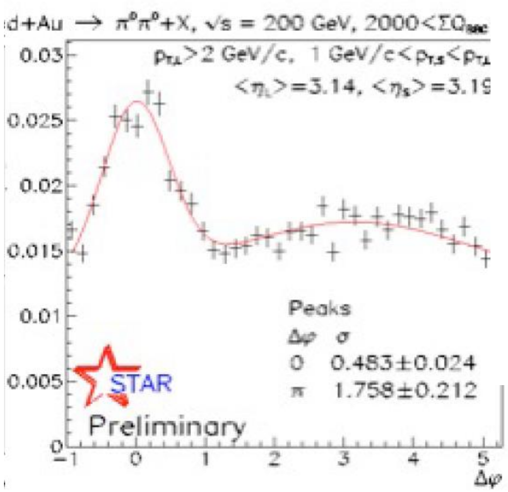
Has saturation been observed at HERA, RHIC, LHC?

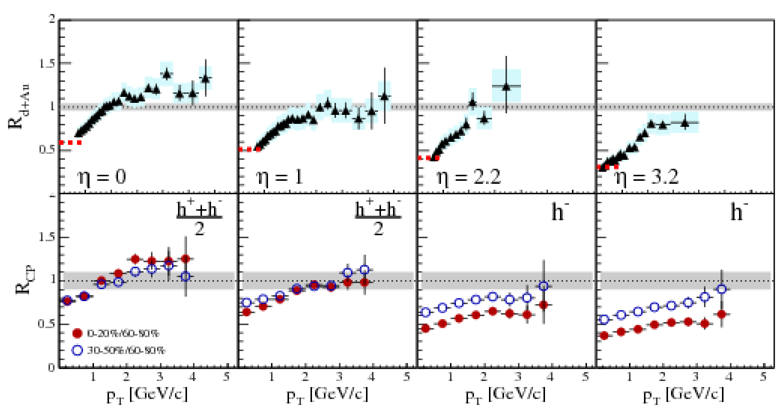








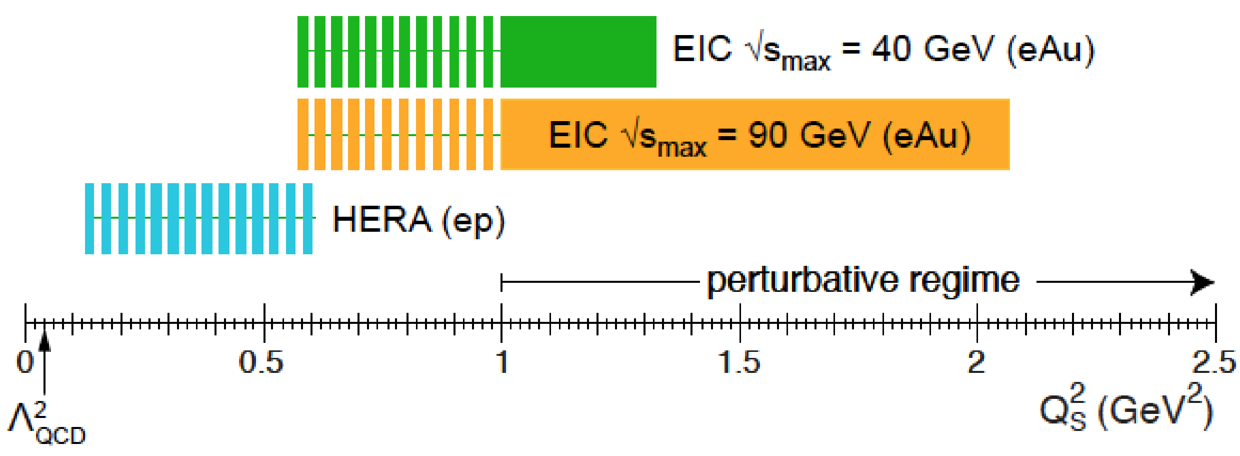




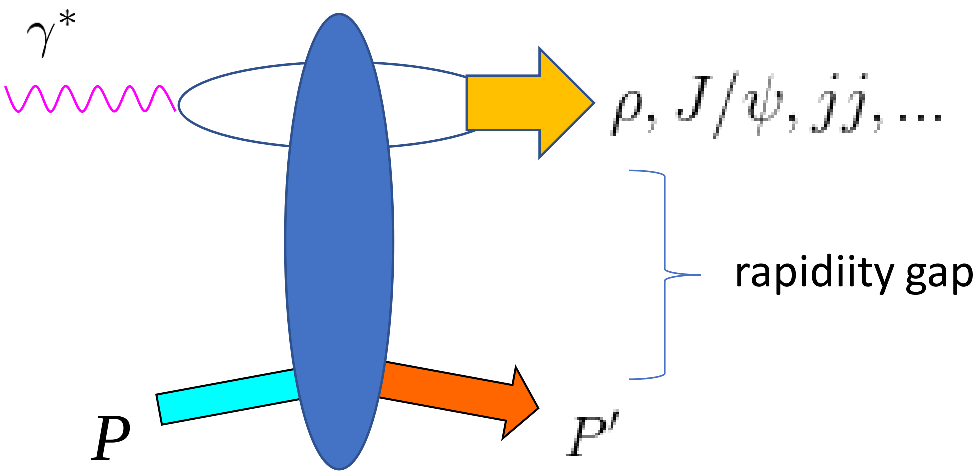
Gluon saturation: where to look for?

- Use lepton beam (DIS) No initial state interactions (advantage over LHC, RHIC)
- Go to higher energy → LHeC, FCC-he, VHEeP $x \sim 10^{-7}$
- Go to heavy nuclei → EIC

Nuclear enhancement of the saturation momentum $Q_s^2 \propto A^{1/3}$
(advantage over HERA)



Golden channel for saturation: Diffraction



Cross sections proportional to the square of the gluon distribution

→ More sensitive to saturation

- Total diffraction

Kowalski, Lappi, Marquet, Venugopalan (2008)

`Day 1 prediction'

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

Nucleus stays intact in every 1 out of 5 events!

- Incoherent diffraction→ Partonic fluctuations inside the proton (Good-Walker)

Schenke, Mantysaari (2016)

- Exclusive diffractive dijet → Wigner distribution

YH, Xiao, Yuan (2016)

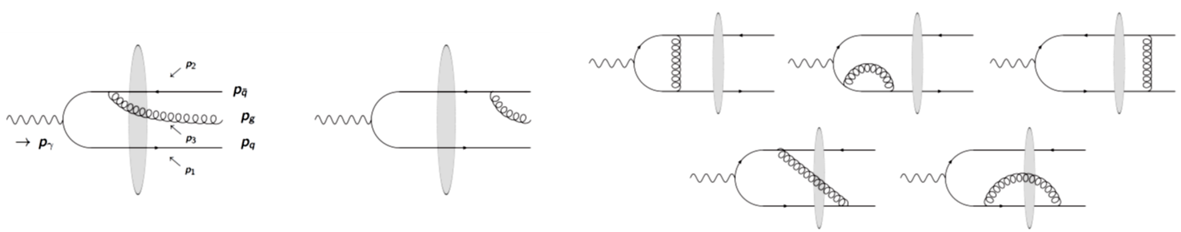
Can saturation become precision science?

- 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.

  E.g., exclusive diffractive dijet, vector mesons at NLO Boussarie, Grabovsky, Szymanowski, Wallon (2016)



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

Proton mass

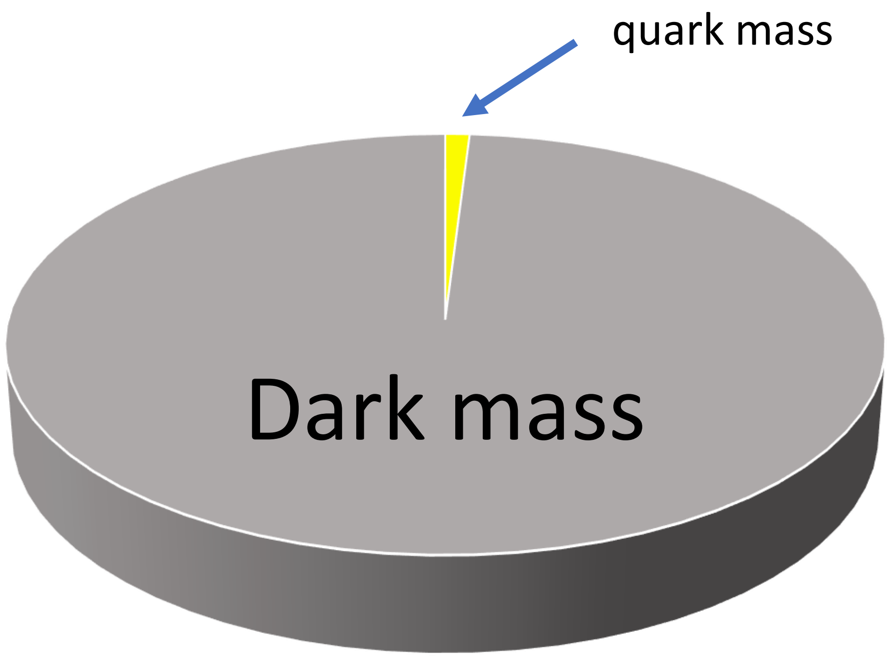
NAS report (July 2018)

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

- 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!



Higgs mechanism explains quark masses, but not hadron masses!

The trace anomaly

QCD Lagrangian conformally invariant at the classical level, but the invariance is broken by the trace anomaly.

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

Ji decomposition of the proton mass

quark/gluon kinetic energy

quark mass

$$M = M_q + M_g + M_a + M_m$$

trace anomaly

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

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

Purely gluonic operator, very difficult to compute in lattice QCD

Instead, we should look at low-energy scattering.

Purely gluonic operator. Use quarkonium as a probe.

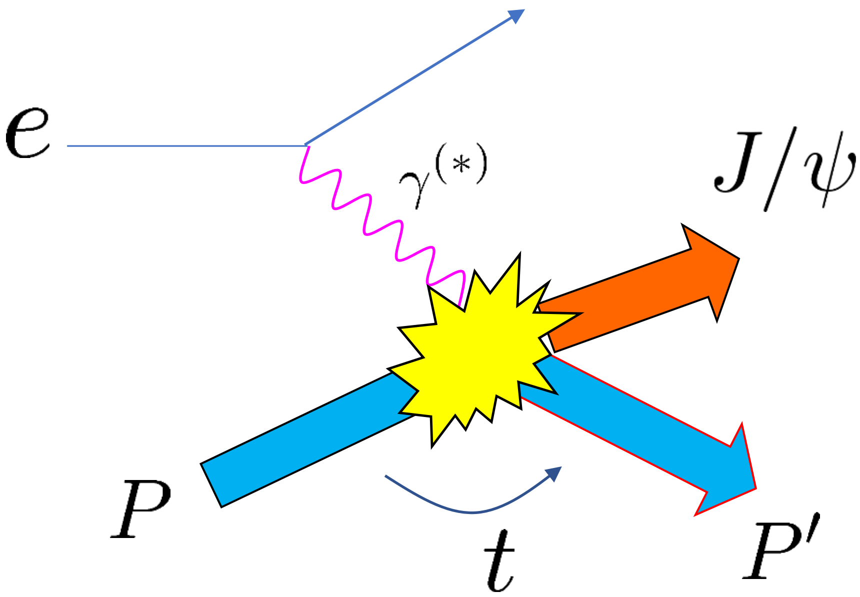
Luke-Manohar-Savage (1992)

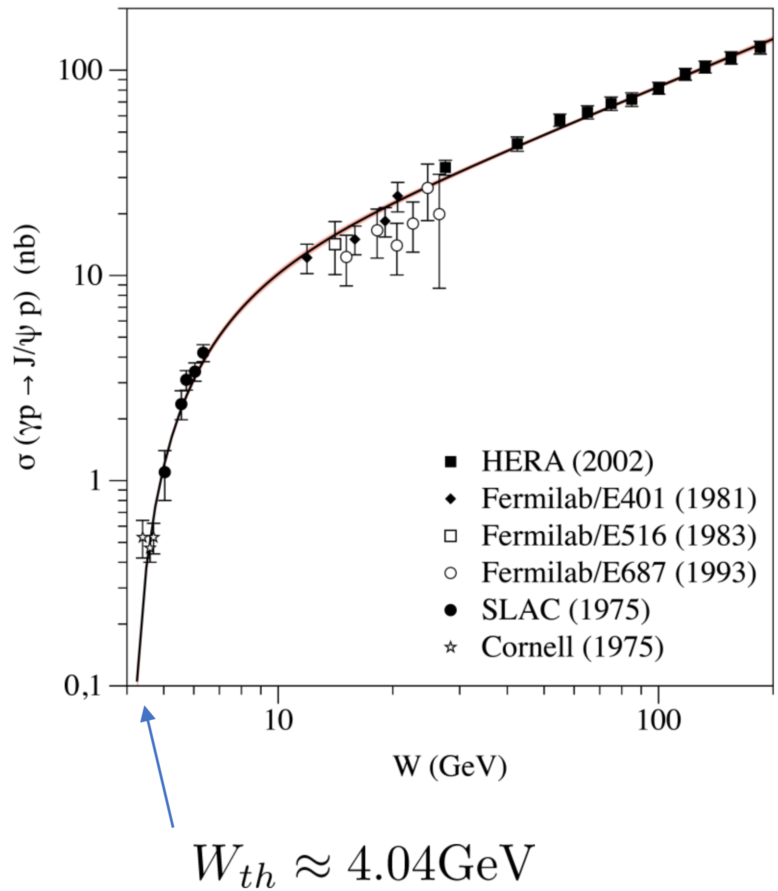
→ J/ψ photo-production near threshold.

Photo-production of J/ψ near threshold

Kharzeev, Satz, Syamtomov, Zinovjev (1998)
Brodsky, Chudakov, Hoyer, Laget (2000)

Sensitive to the matrix element $\langle P'|F^{\mu\nu}F_{\mu\nu}|P\rangle$





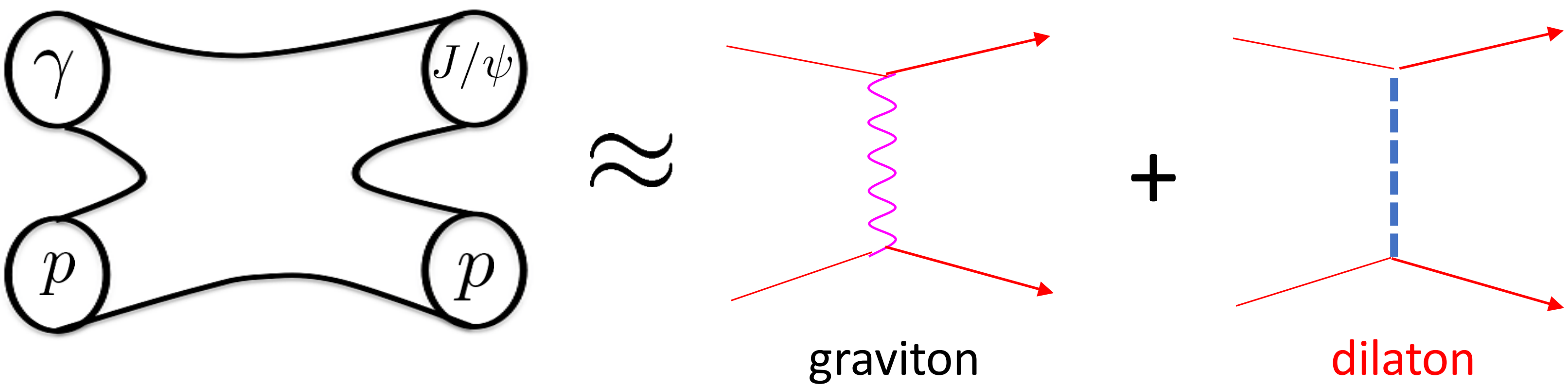
Straightforward to measure.
Ongoing experiments at JLab.

Difficult to compute from first principles
(need nonperturbative approaches)

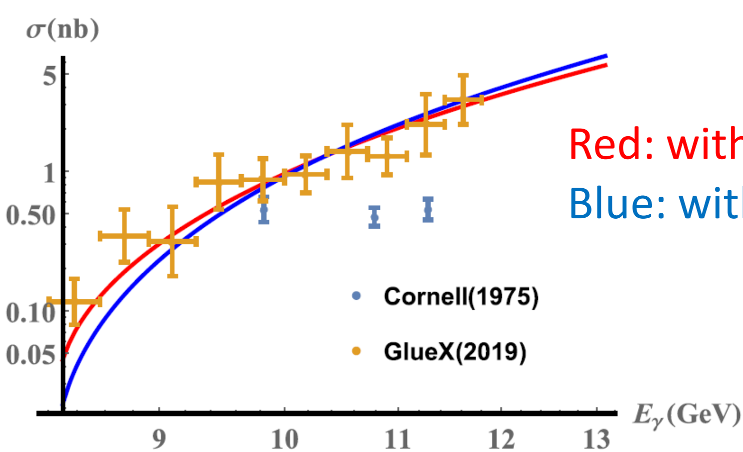
Holographic approach

YH, Yang (2018)
YH, Rajan, Yang (2019)

The operator $F^{\mu\nu}F_{\mu\nu}$ is dual to a massless string called dilaton



Fit of the latest JLab data GlueX collaboration 1905.10811



Red: with trace anomaly
Blue: without trace anomaly

Amplitude proportional to the gravitational form factors.

$d\sigma/dt$ sensitive to the gluon D-term.

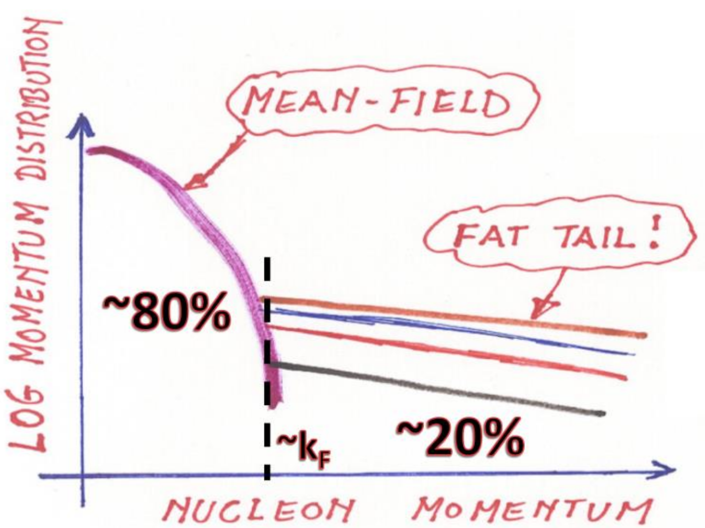
Sub-threshold photo-production of J/ψ

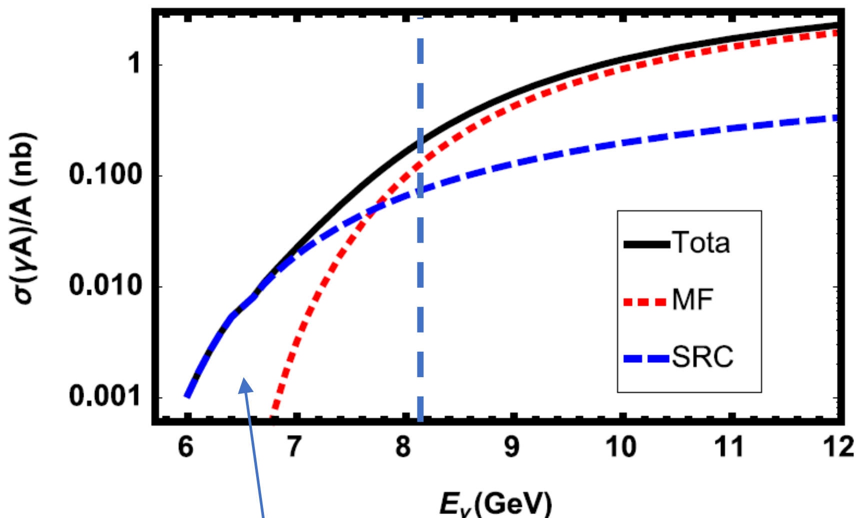
Xu, Yuan (2019)
YH, Strikman, Xu, Yuan, in progress

If the target is a nucleus, J/psi can be produced at lower photon energy

Cross section in this region is sensitive to the
short range correlation
in the target nucleus.

$E_\gamma = 8.2\,\mathrm{GeV}$
γp threshold





Completely dominated by the SRC contribution

Conclusion

- In 10-15 years from now, DIS experiments will be running in the US, China and Europe. Exciting times ahead.
- EIC will significantly advance our knowledge of the nucleon/nuclei, the fundamental building blocks of the universe.
- Great opportunity for lattice QCD, too.