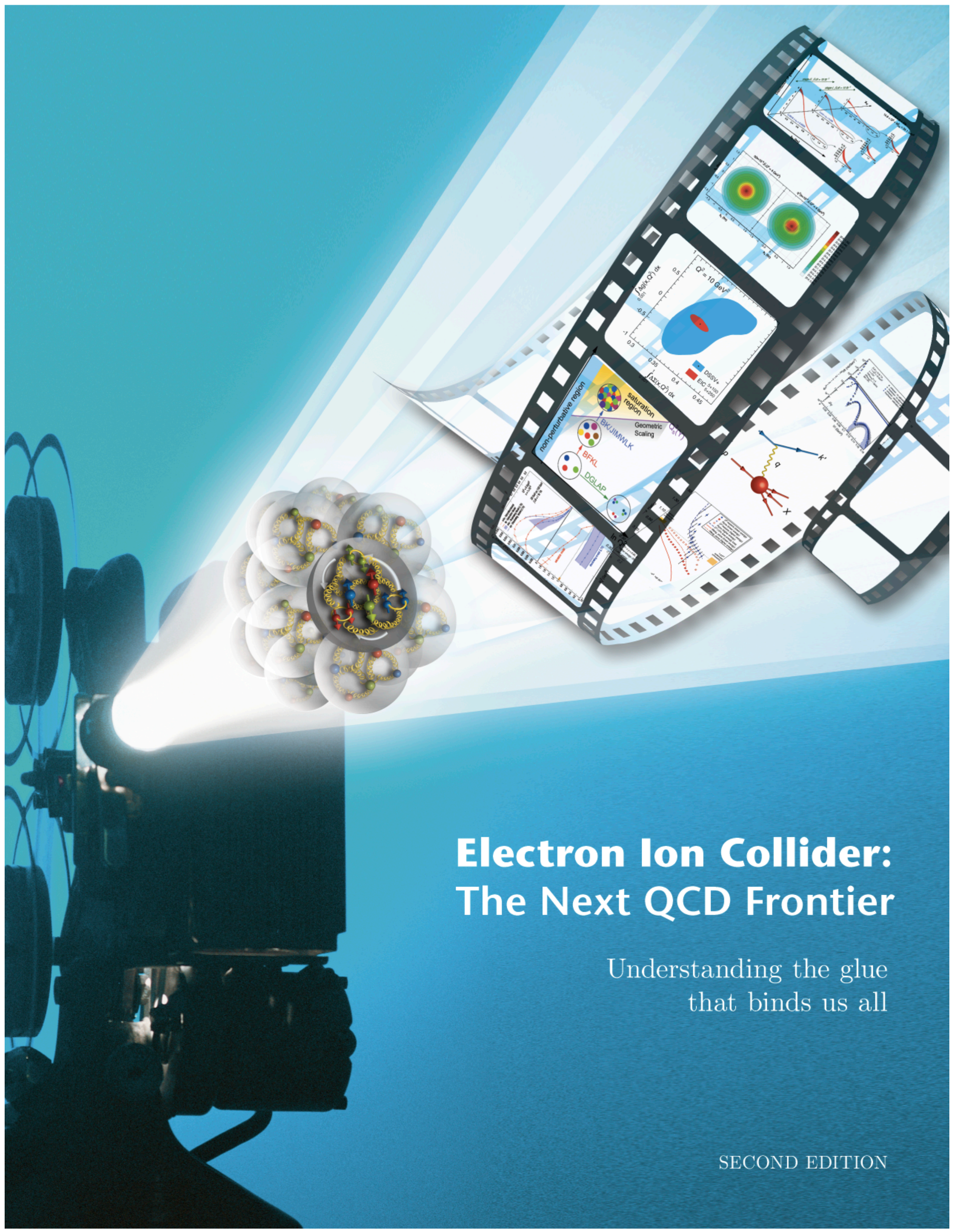
Understanding the glue that binds us all

Daniël Boer, University of Groningen, The Netherlands

EICUG meeting, Paris, July 22, 2019

White paper of the U.S.-based Electron-Ion Collider, 2016



The Electron-Ion Collider (EIC) aims to address three key questions:

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

The EIC physics case is to a large extent aimed at understanding the physics of gluons

This talk will be about gluons

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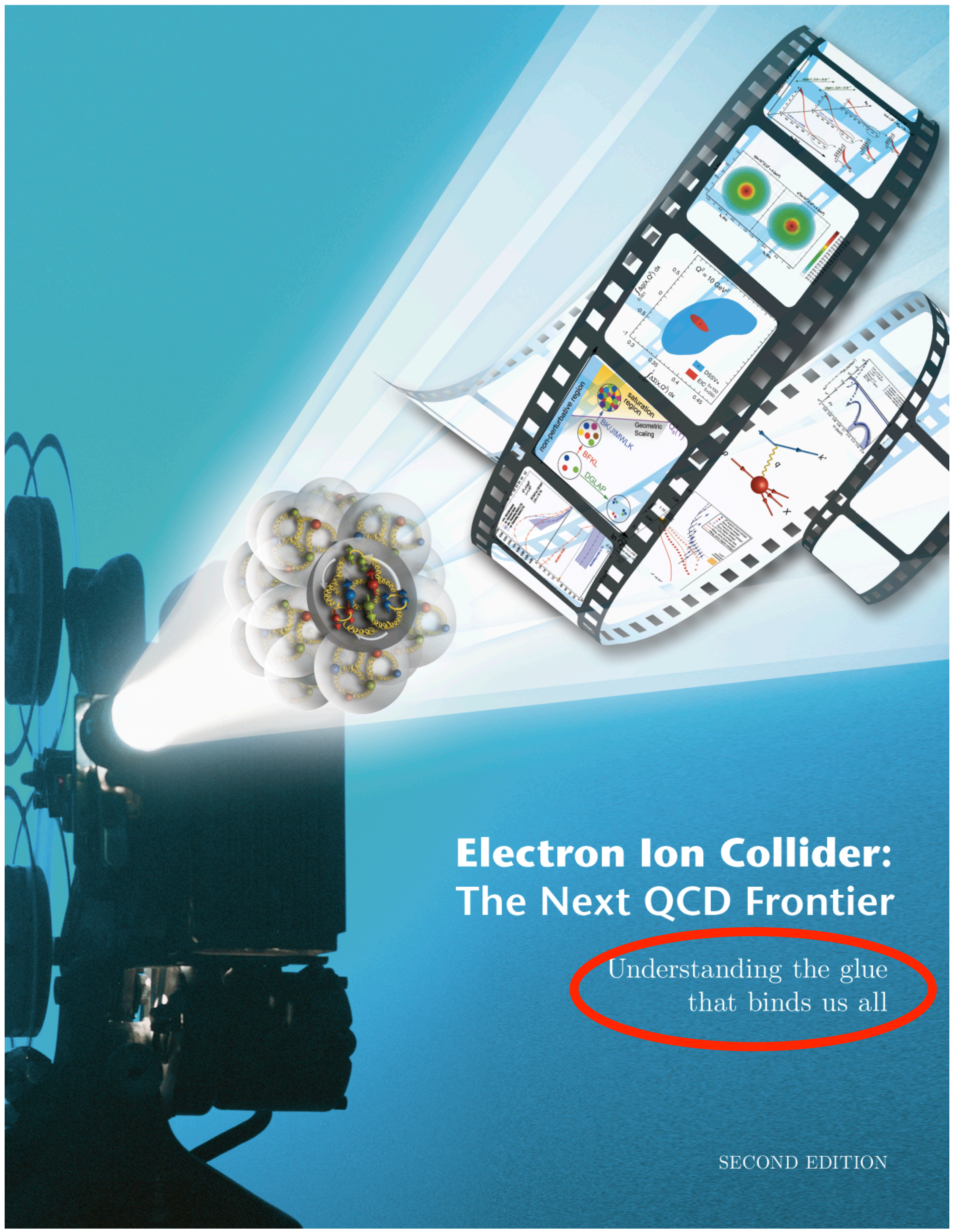

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2019: 40 years of gluons

- 1972 - theoretical proposal of gluons as carriers of the strong force, birth of QCD

  Fritzsch, Gell-Mann, 1972; paper with Leutwyler, 1973

- 1979 - first experimental evidence for gluons from e^+e^- collisions at the DORIS and PETRA storage rings at DESY, Hamburg

In June 1979 the first evidence for gluons was presented at the Geneva International Conference: 3-gluon decay of the Υ(9.46) particle (PLUTO experiment at DORIS) and 3-jet events ($q\bar{q}g$) (experiments at PETRA)

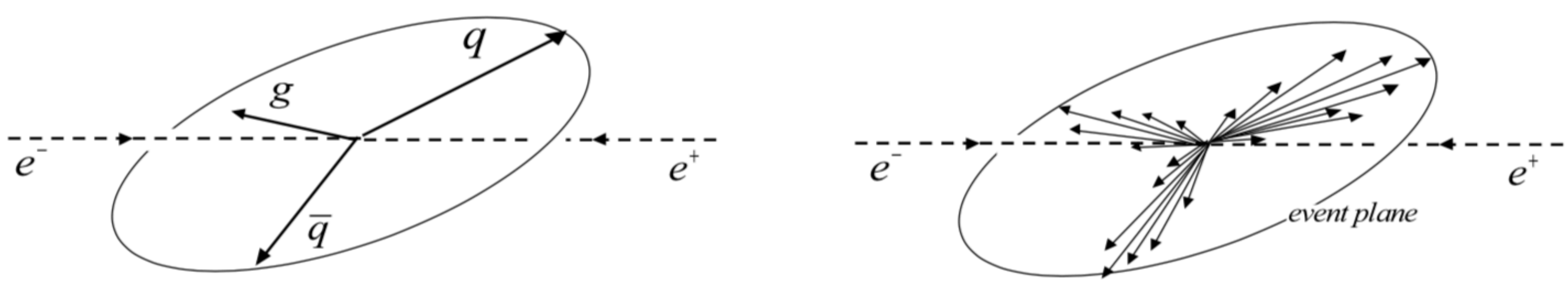
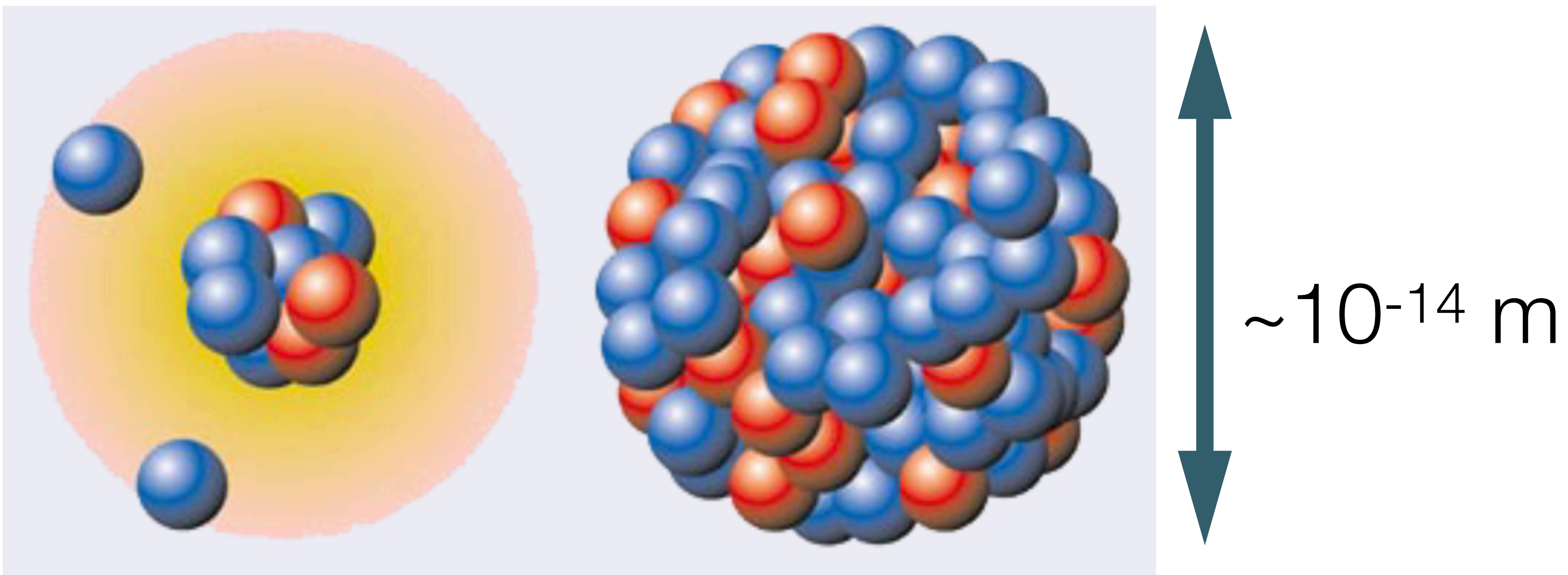


Figure from the review by P. Söding, EPJH 35 (2010) 3

The strong nuclear force

The force binding protons and neutrons into nuclei of atoms

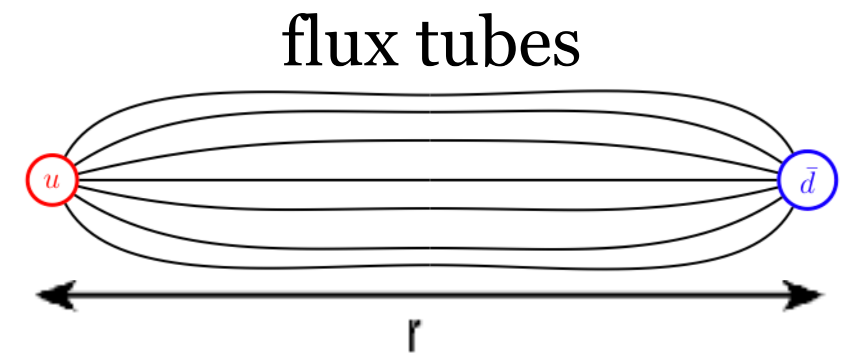


^{11}Li ^{208}Pb

The force is extremely short range

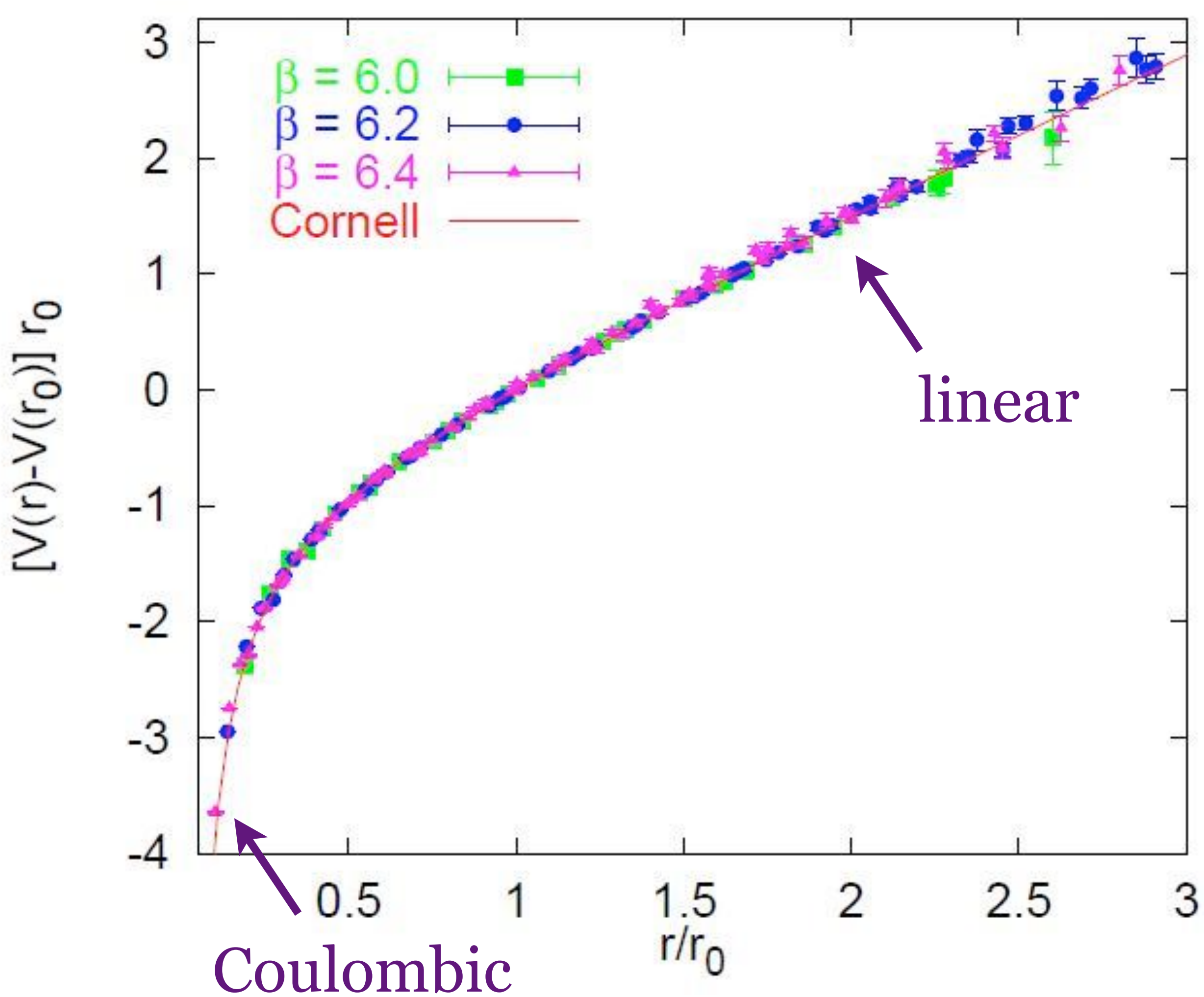
The gluons are the carriers of the strong force

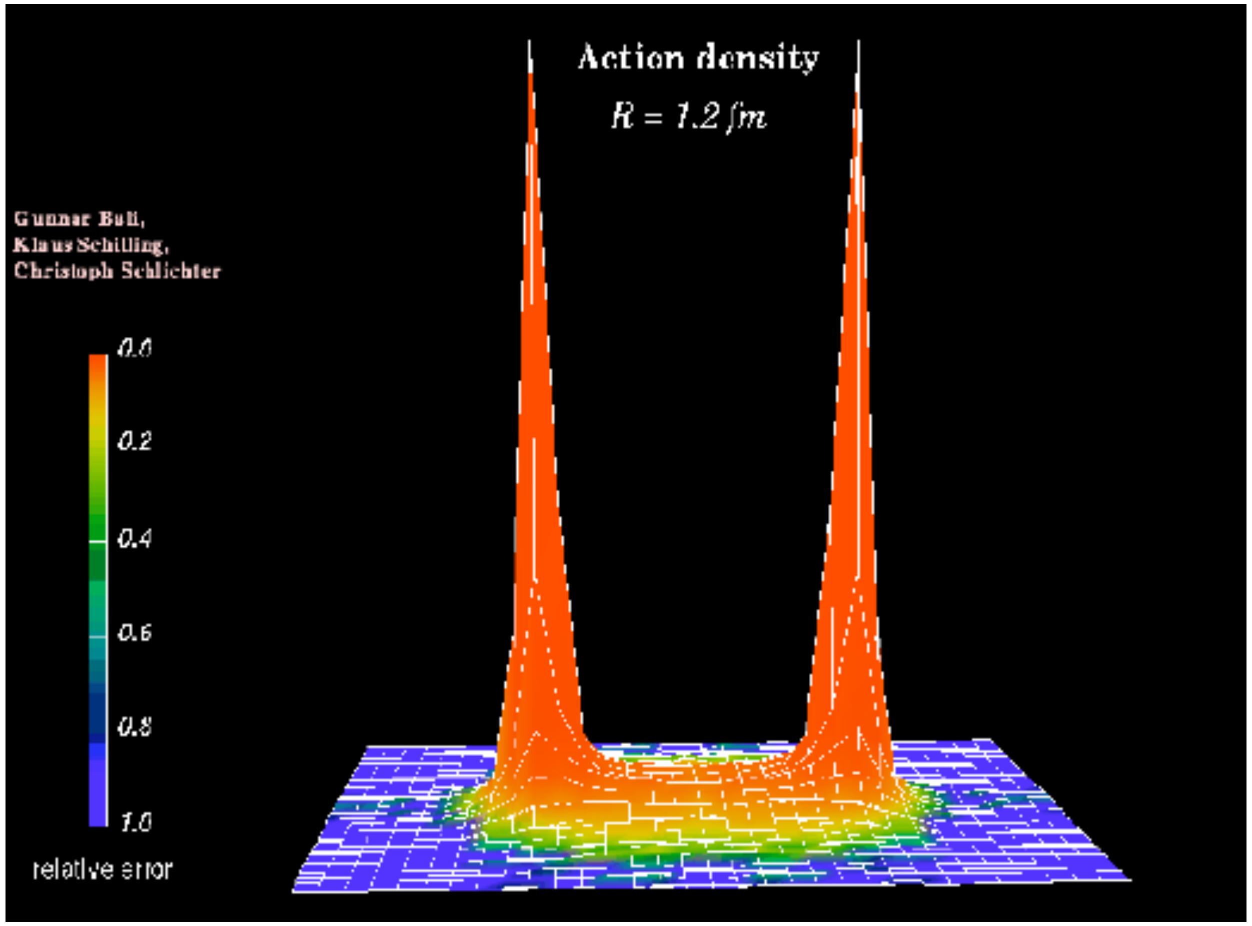
Confinement



Separating quarks costs increasingly more energy → quark confinement

From lattice QCD:





Bali, Schilling, Schlichter
Phys. Rev. D 51 (1995) 5165

Force carriers themselves also subject to confinement → flux tubes

Gluon contribution to the proton mass

Lattice QCD: gluons contribute more than half the proton mass of 938 MeV

Close to 1/4 goes into confining the quarks, around 1/3 is from the energy of the gluons themselves

Yang, Liang, Bi, Chen, Draper, Keh-Fei Liu and Zhaofeng Liu, PRL 2018

→ information about the average gluonic fields in the QCD vacuum

Xiangdong Ji, PRL 1995

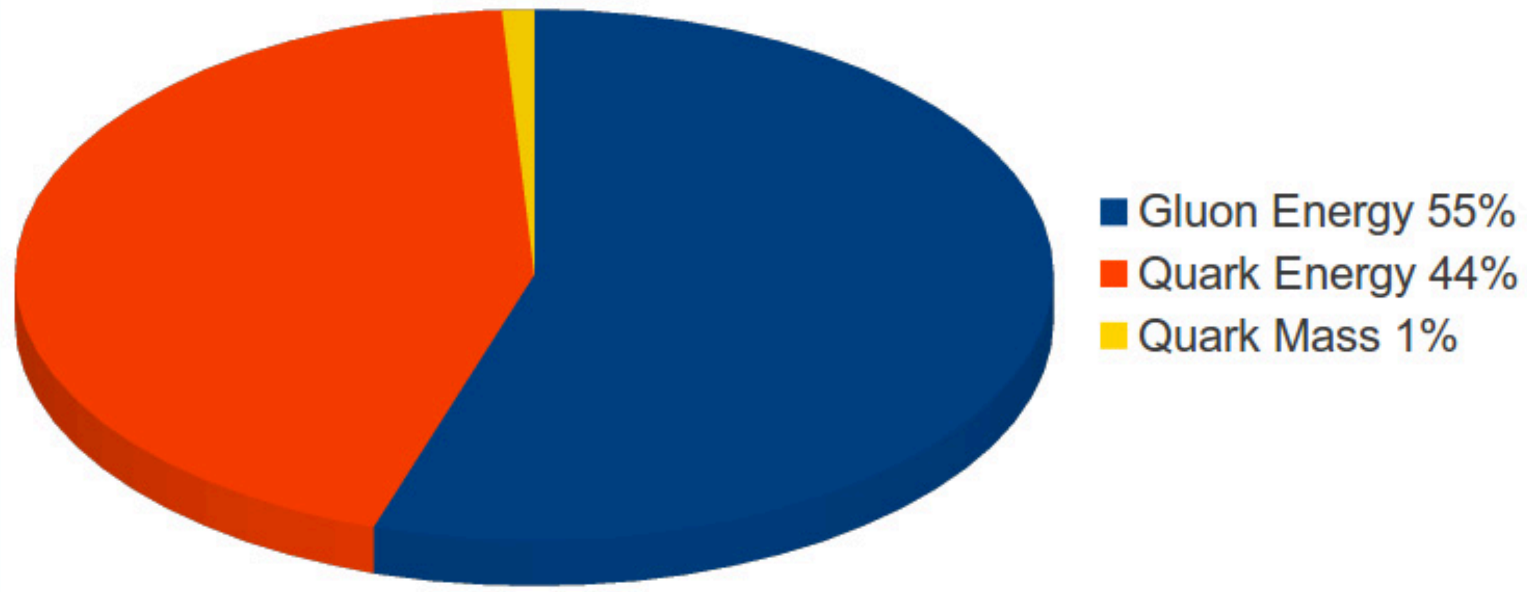


Figure by T. Schaefer

These are average numbers

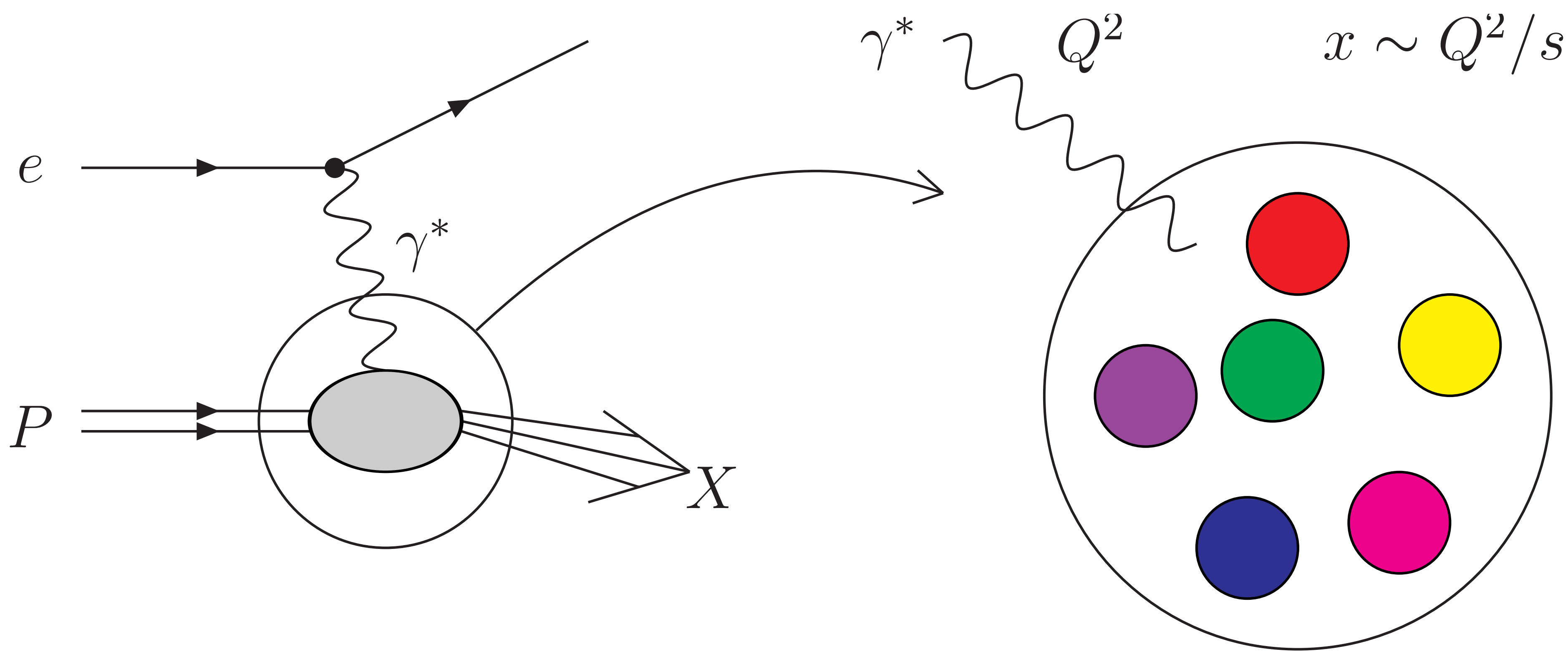
EIC will further study its subdivision as a function of various kinematic variables

Probing gluons

The confinement distance is of proton size (~10^{-15} m)

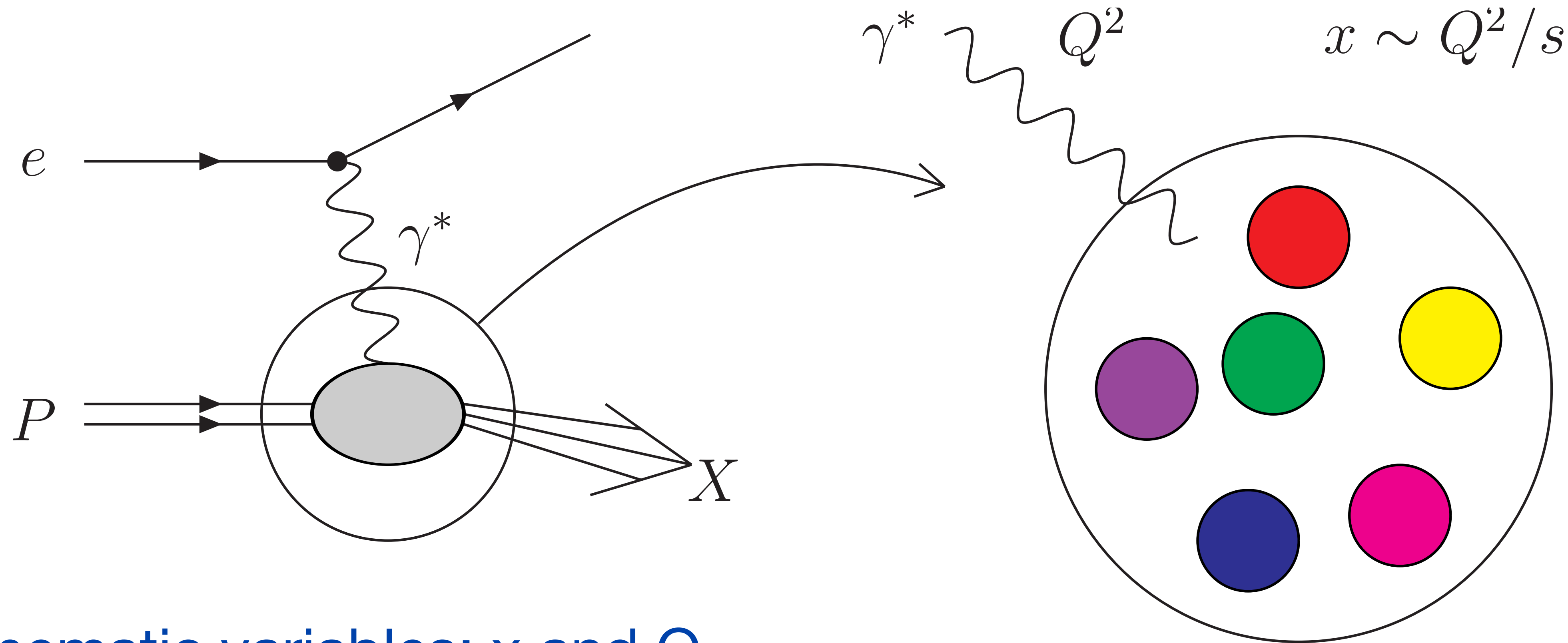
To look inside the proton requires energies larger than 200 MeV

The Electron-Ion Collider collides electrons and protons or nuclei with energies in the range 20-100 GeV (upgradable to 140 GeV)

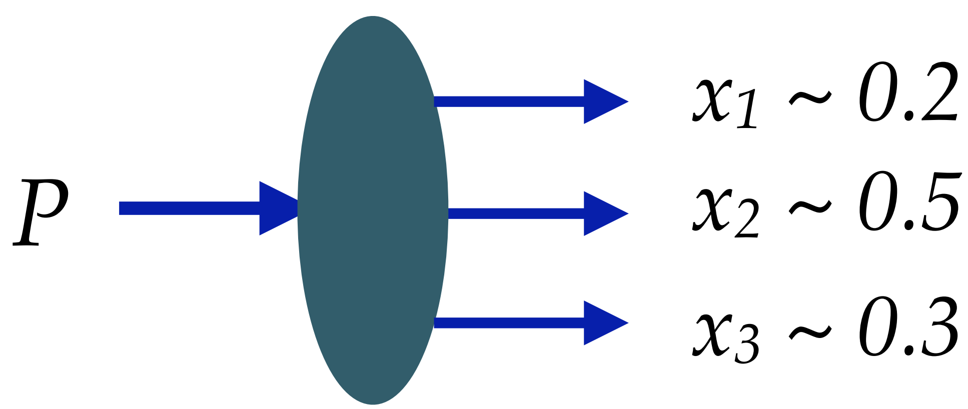


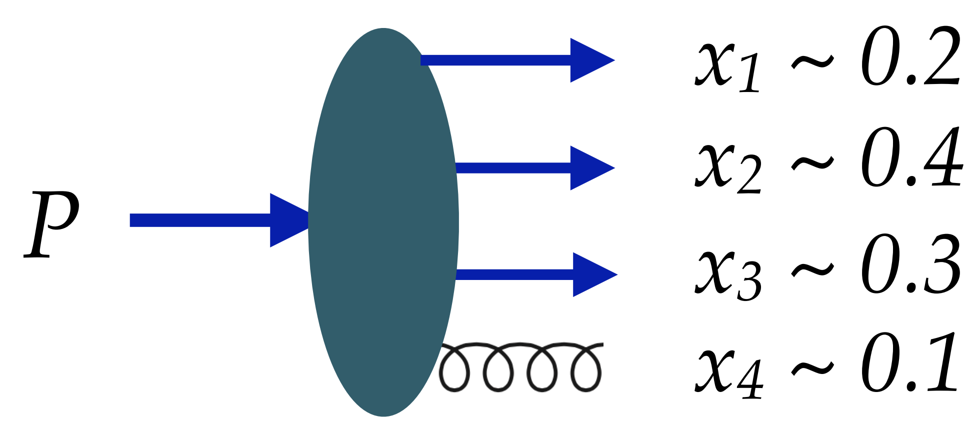
Deep inelastic scattering

Scattering off a proton at high energy = scattering off quarks and gluons



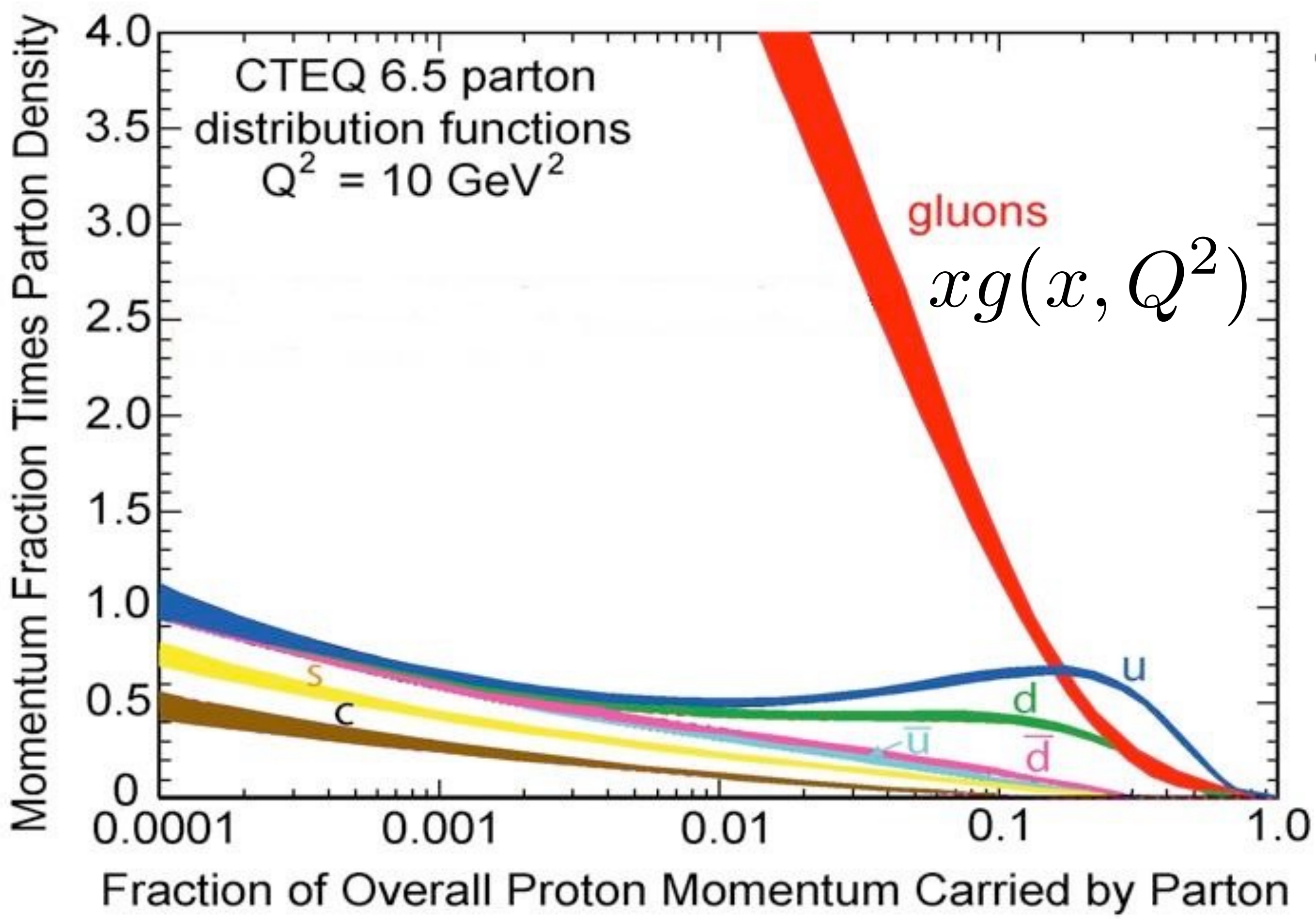
Two kinematic variables: x and Q

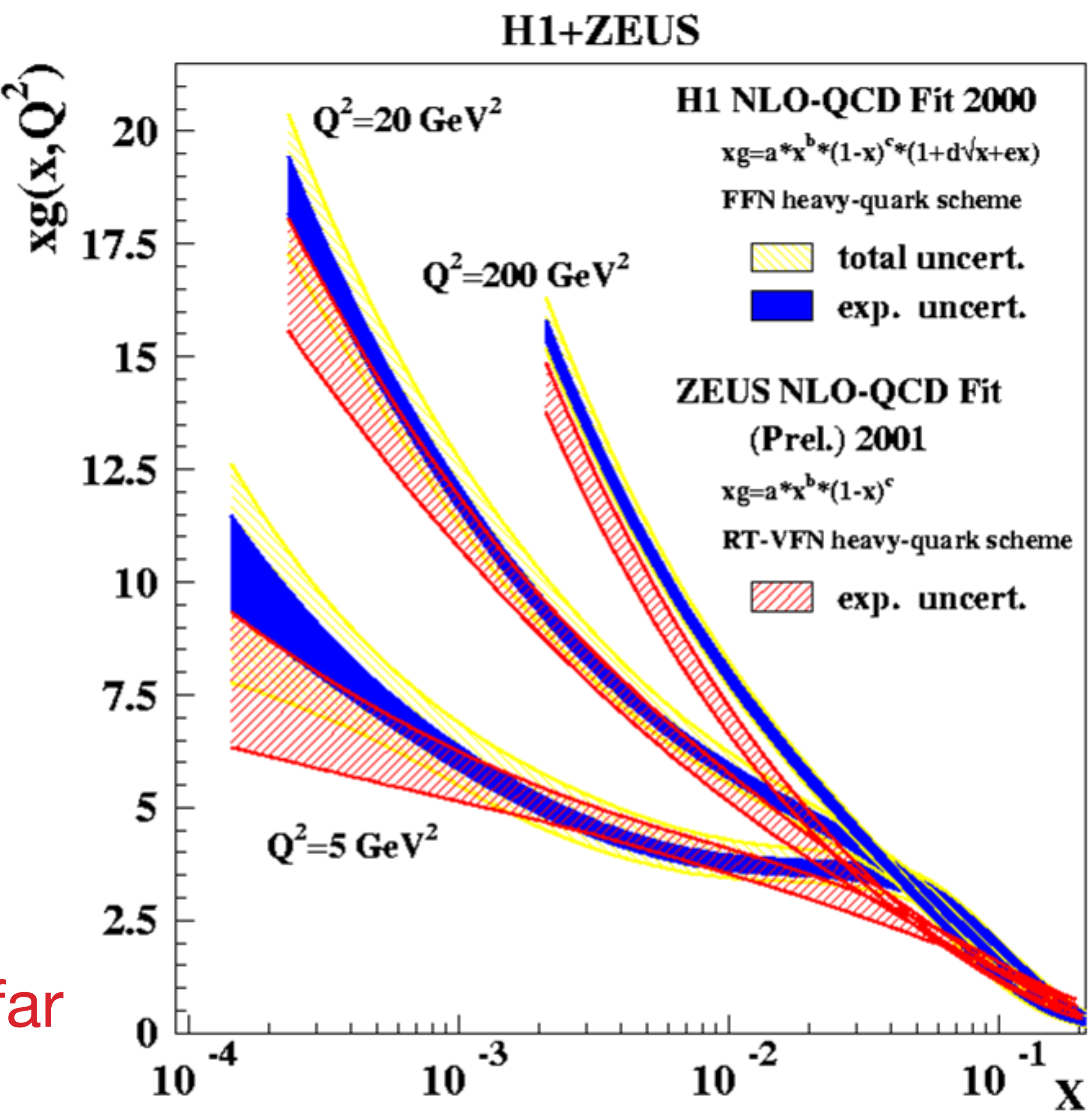




Gluon distribution

$g(x,Q^2)$ = probability of finding a gluon with momentum fraction x inside the proton at the energy scale Q





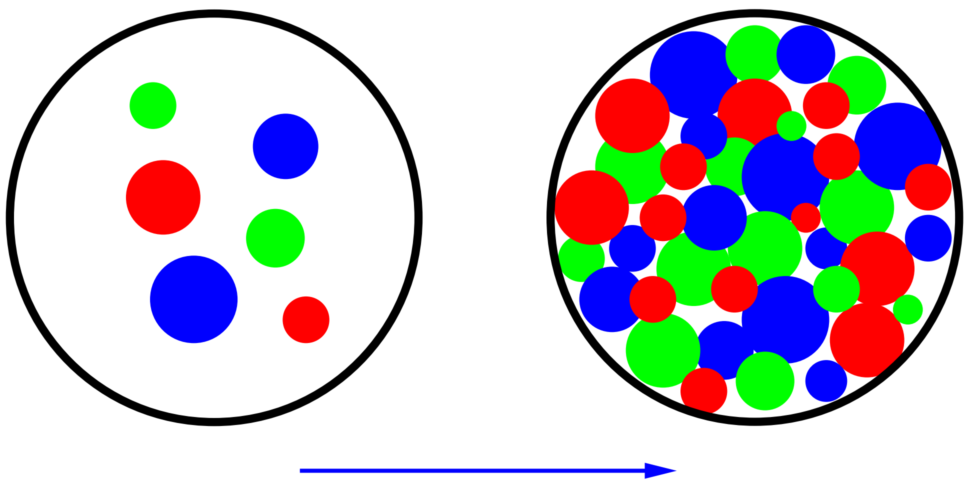
For small x values gluons dominate by far

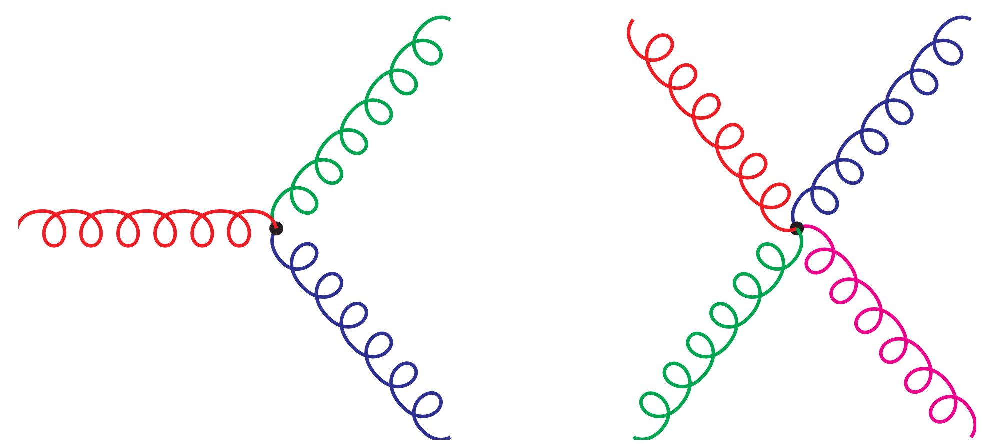
→ very high gluon density

High gluon density

What are the emergent properties of a dense system of gluons?

To answer this question study the small x region and use large nuclei (eA at EIC)



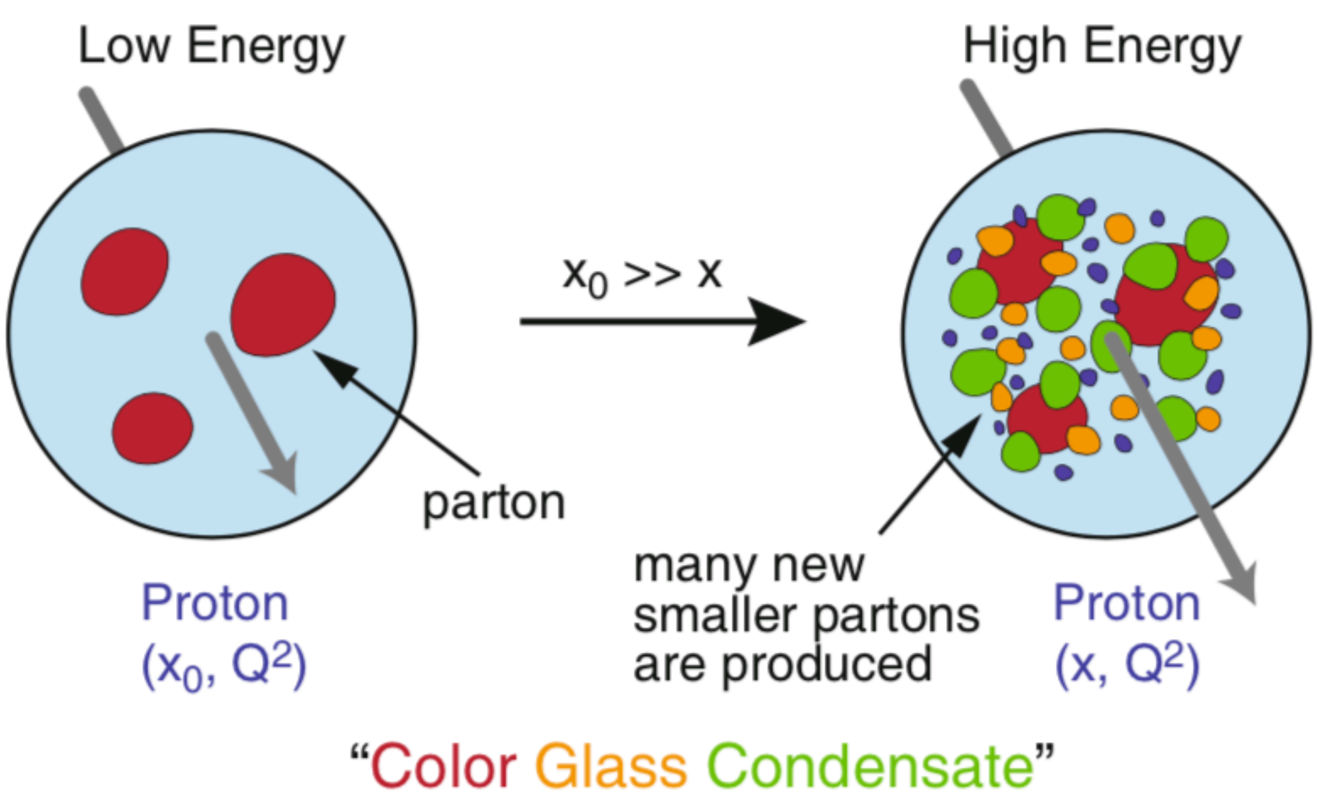


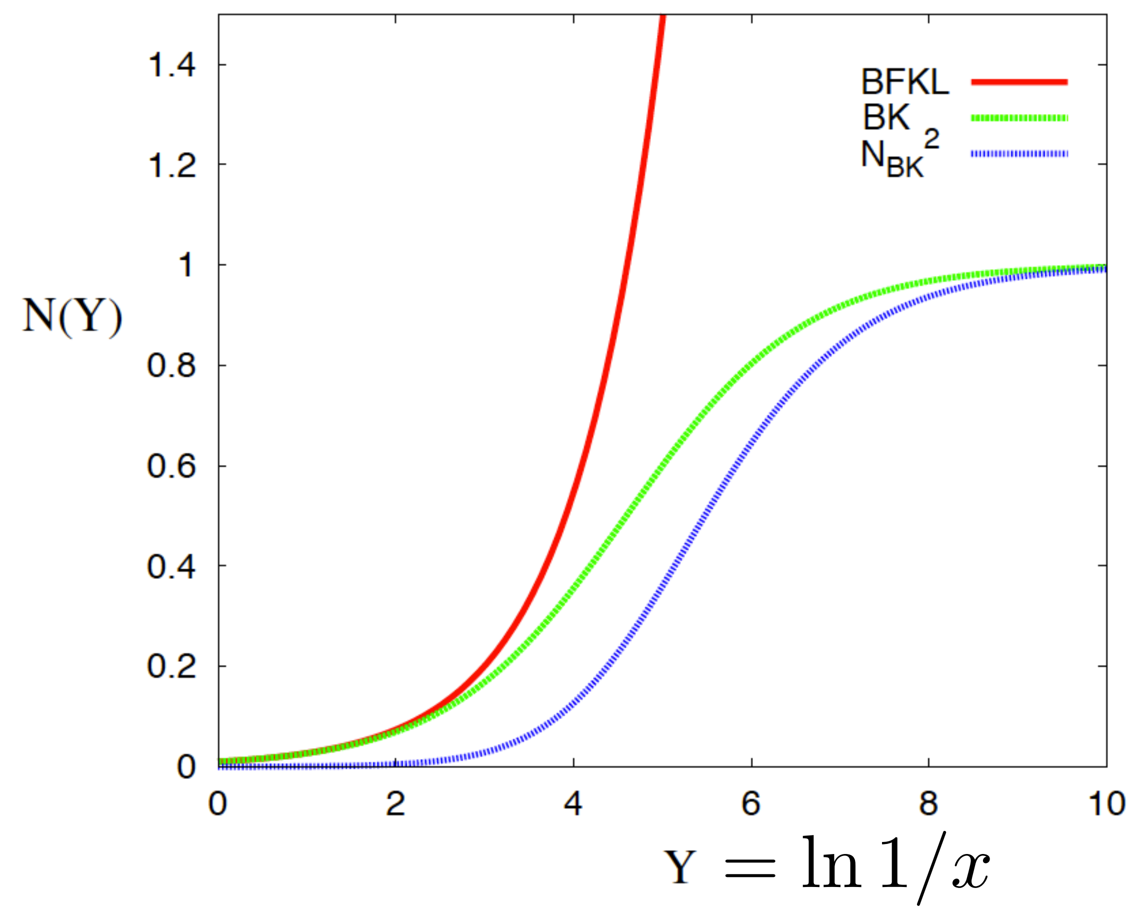
When x decreases, the density of gluons (n) increases

At some point n becomes so large ($n \to O(1/\alpha_s)$) that the probability for gluons to interact approaches 1 ($n \times \sigma_{gg} \to 1$)   [No such effect arises for photons]

Scattering off a proton becomes scatter off multiple gluons simultaneously

Gluon saturation



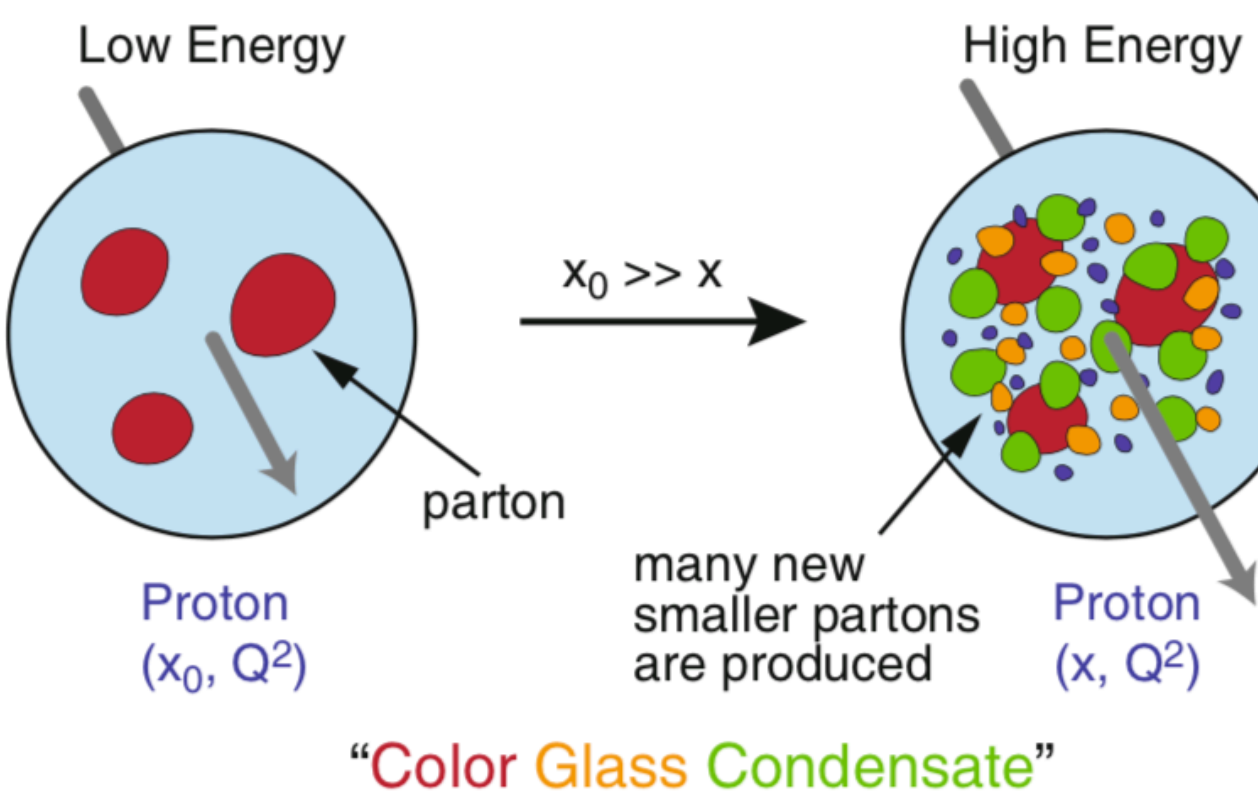


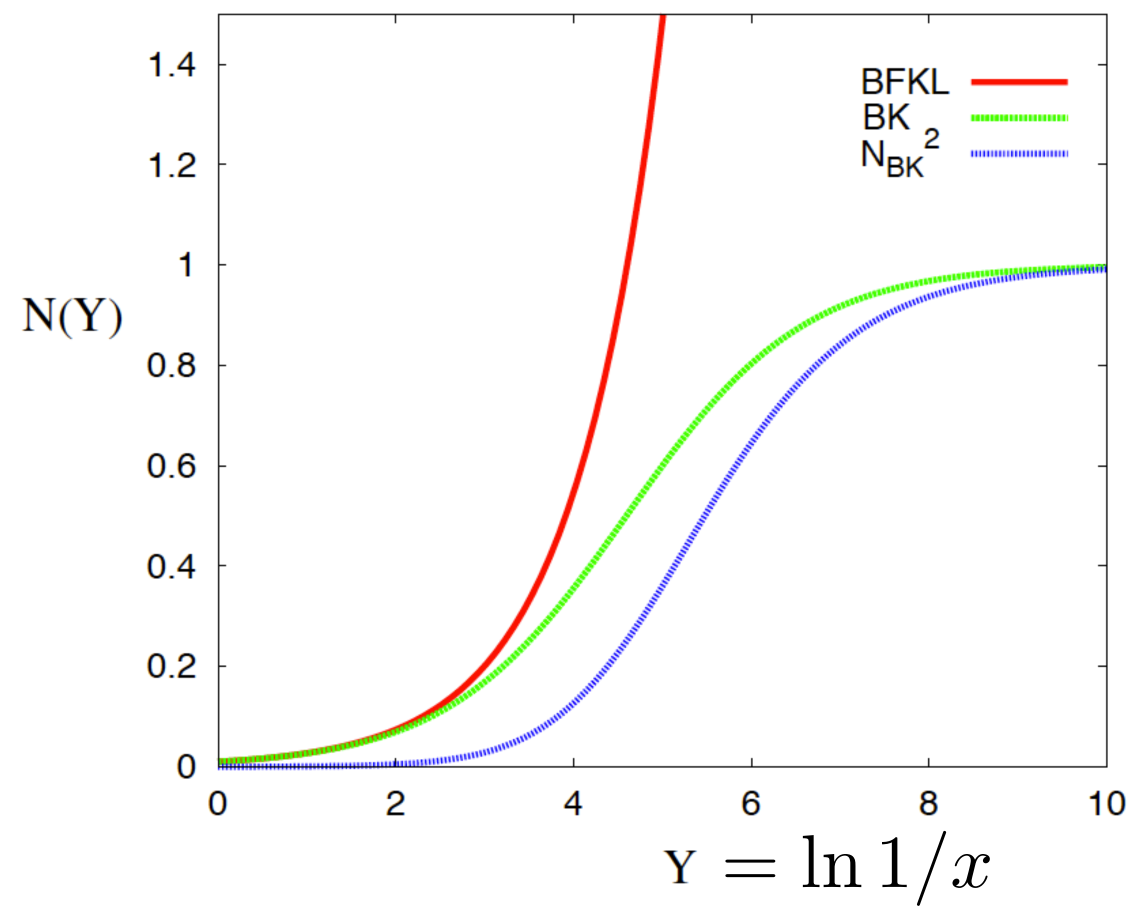
Scatter off multiple gluons simultaneously will probe their collective effect

It is expected to moderate the exponential growth of the gluon density

→ ultimately saturating into a state dubbed the **Color Glass Condensate**

Gluon saturation





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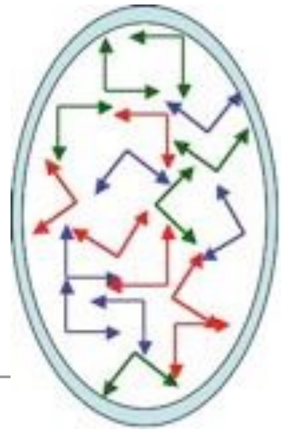
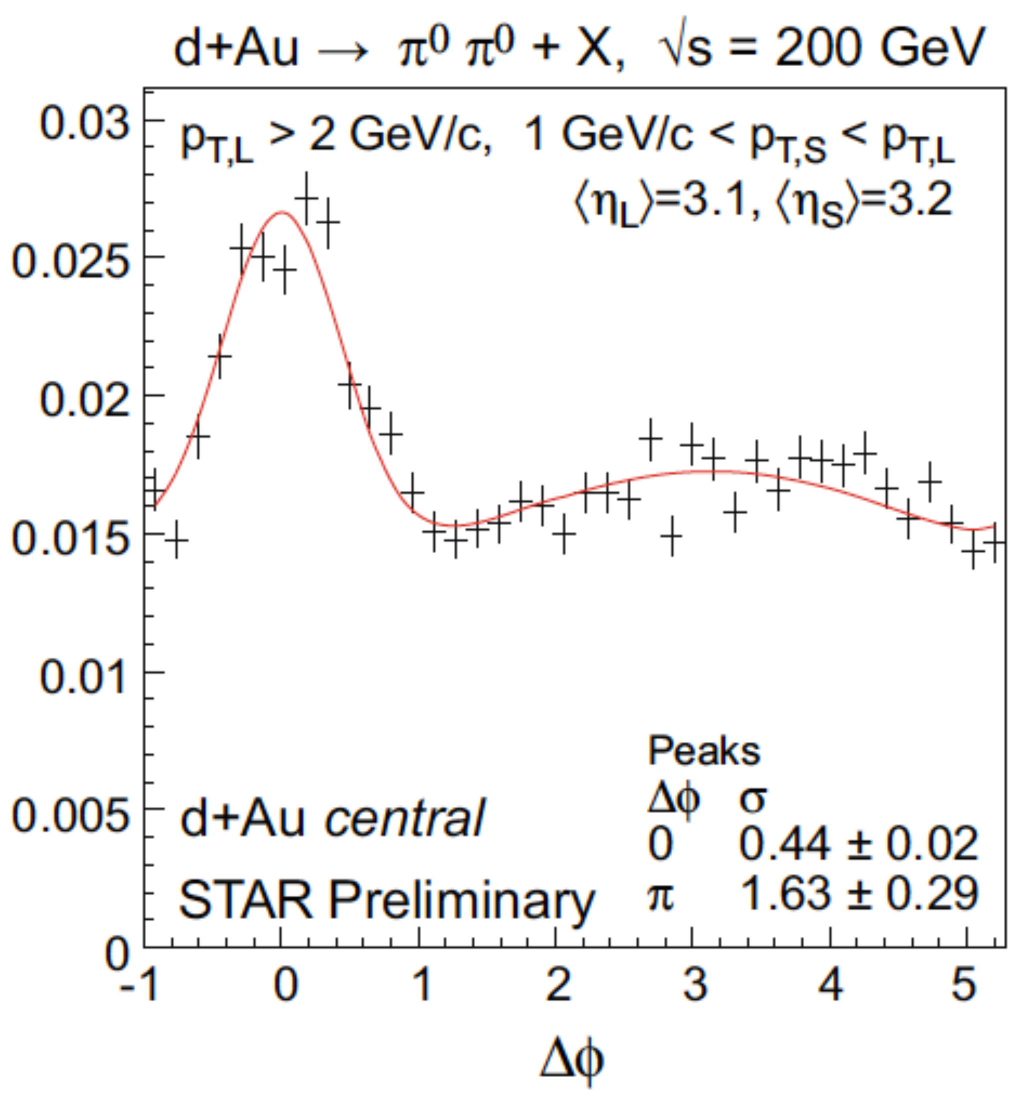
Never directly observed in the gluon distribution yet

CGC experimental signatures

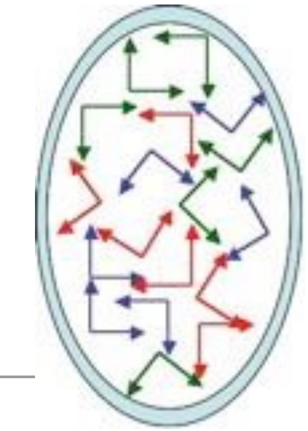


Several expected signatures of the Color Glass Condensate (CGC) have been seen in the data (HERA, RHIC and LHC), but no conclusive evidence yet



Broadening of back-to-back peak

CGC experimental signatures



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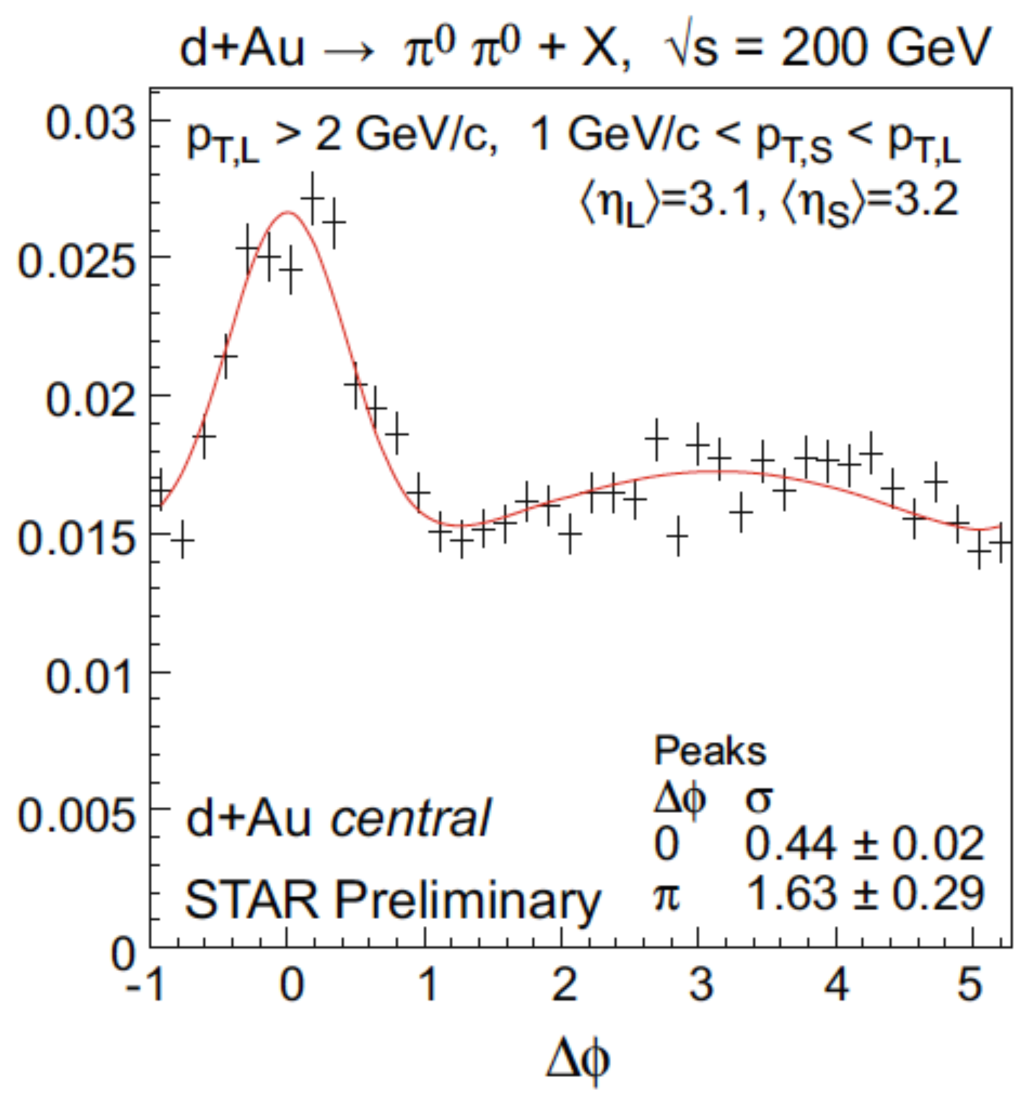
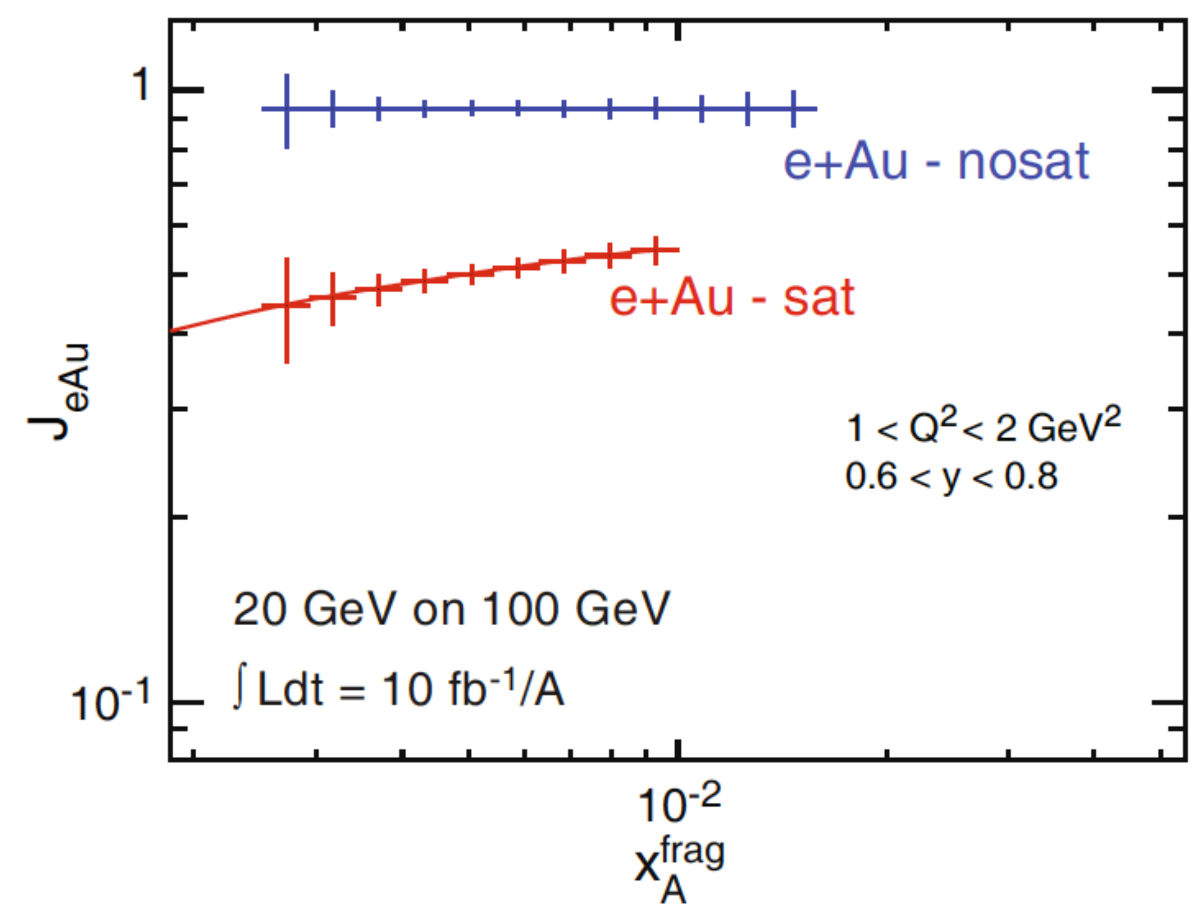


Broadening of back-to-back peak

Comparison of eAu versus ep collisions at EIC with and without saturation:



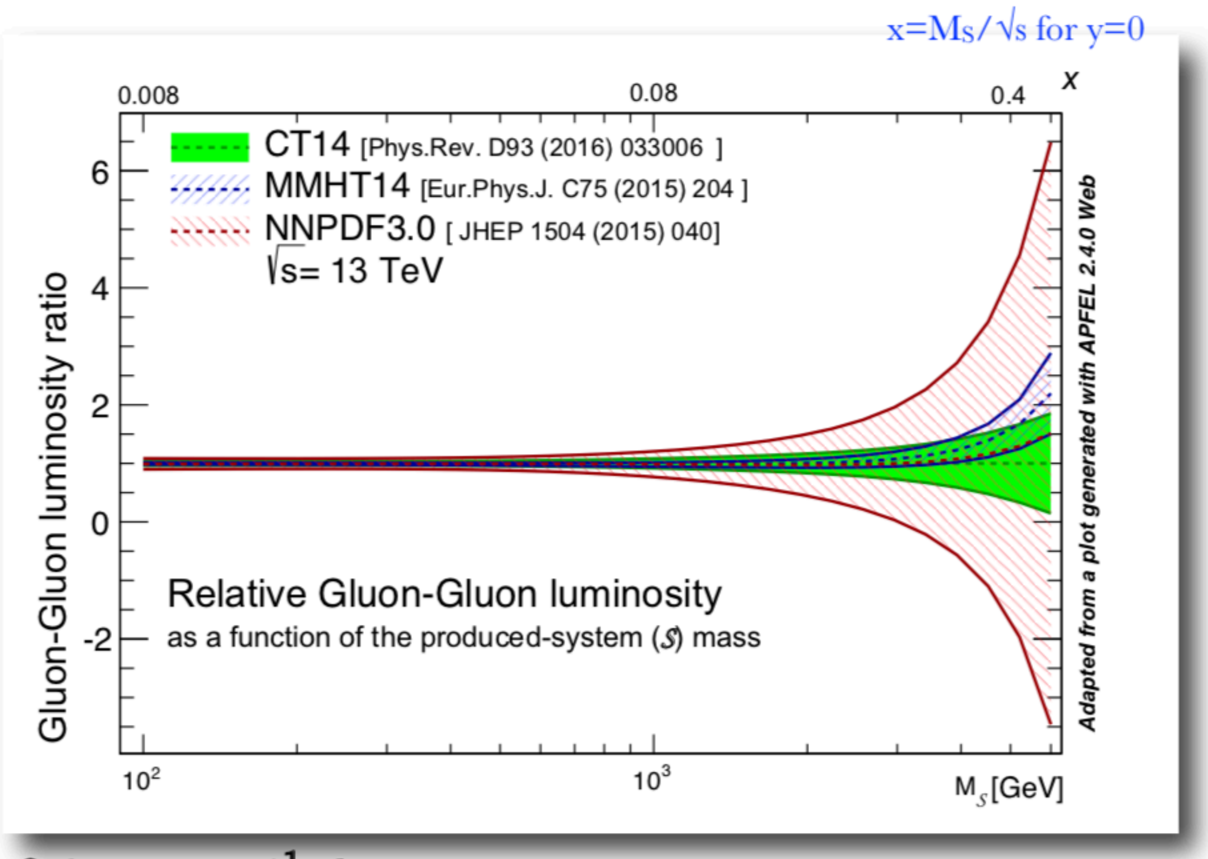
Accardi *et al.*, EPJA (2016)

Gluons at large x

Nuclear dependence of gluons at large x also displays many interesting features

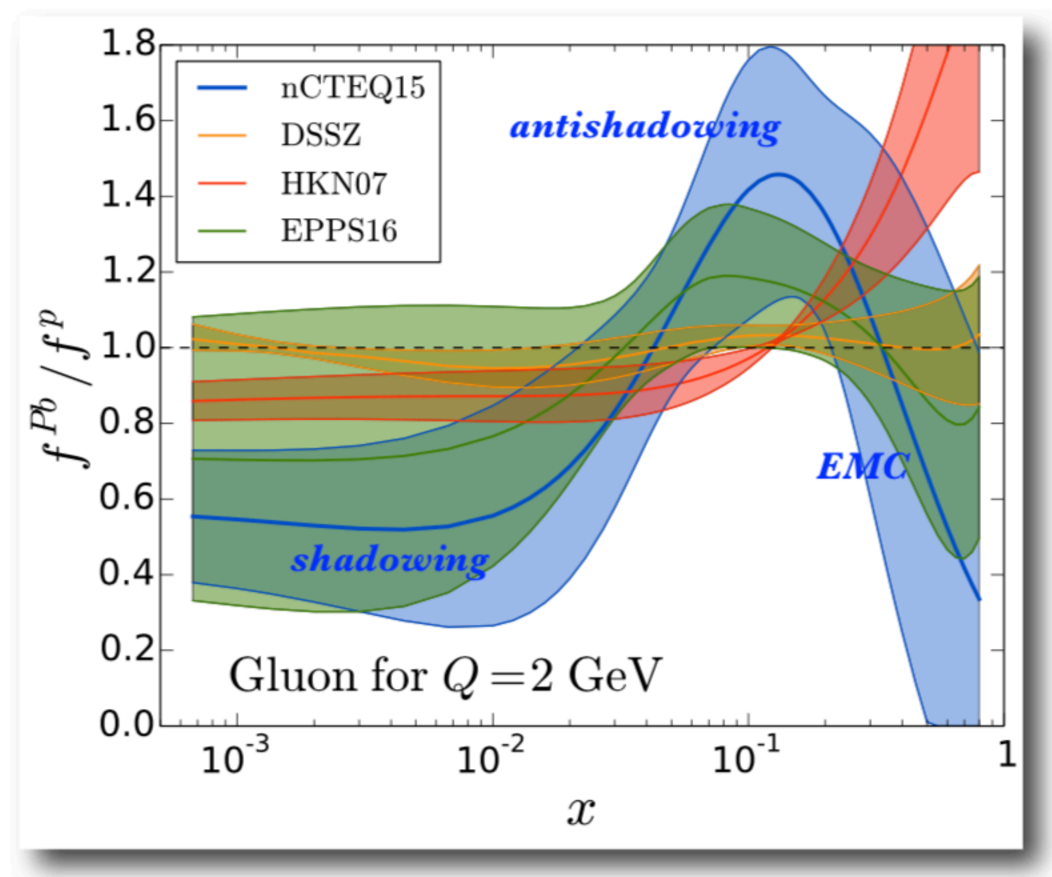
Gluons at large x matter for Beyond the Standard Model physics searches

gg luminosity



$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \frac{1}{s}\int_{\tau}^{1}\frac{dx}{x} f_a(x, M_S^2)\, f_b(\tau/x, M_S^2), \qquad \tau = M_S^2/s$$

gluon nuclear PDF (Pb)



From M. Echevarria, DIS2019 & 1807.00603

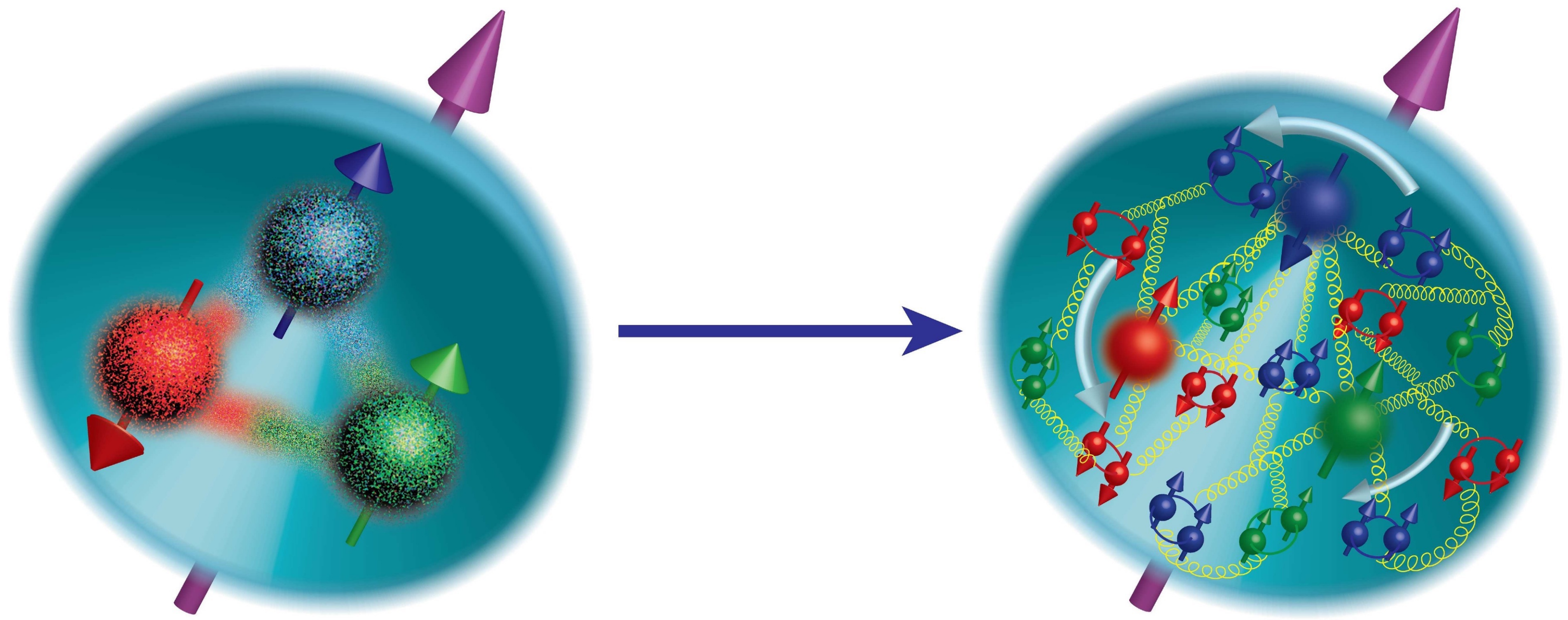
eA never studied in a collider - EIC and perhaps LHeC (no polarization)

Proton spin decomposition

In general, one expects the following spin decomposition or “sum rule” to hold

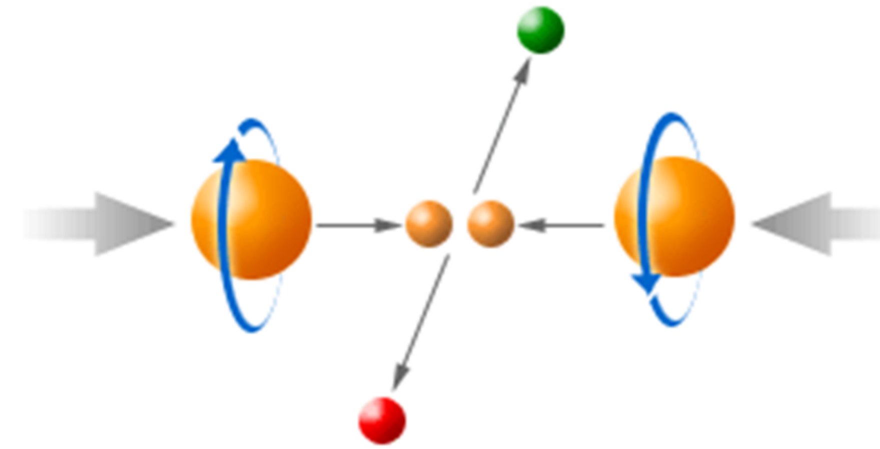
$$\text{proton spin} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Sum of the contributions to the proton spin adds up to ½

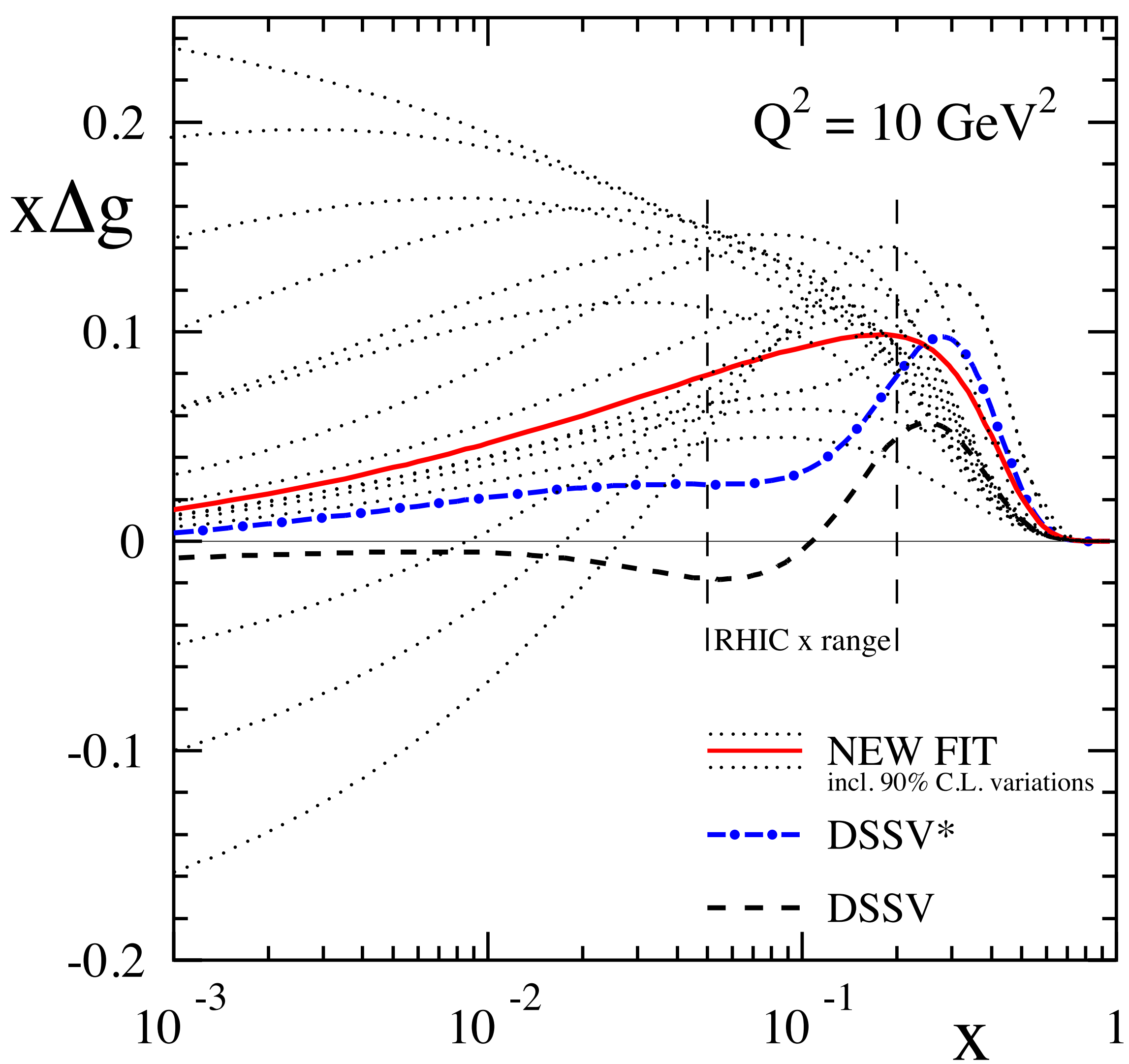


Spin puzzle - only about 1/3 of the proton spin comes from the quarks

Gluon contribution to the proton spin



RHIC - the world's only polarized proton-proton collider



At RHIC Δg(x) is obtained from:

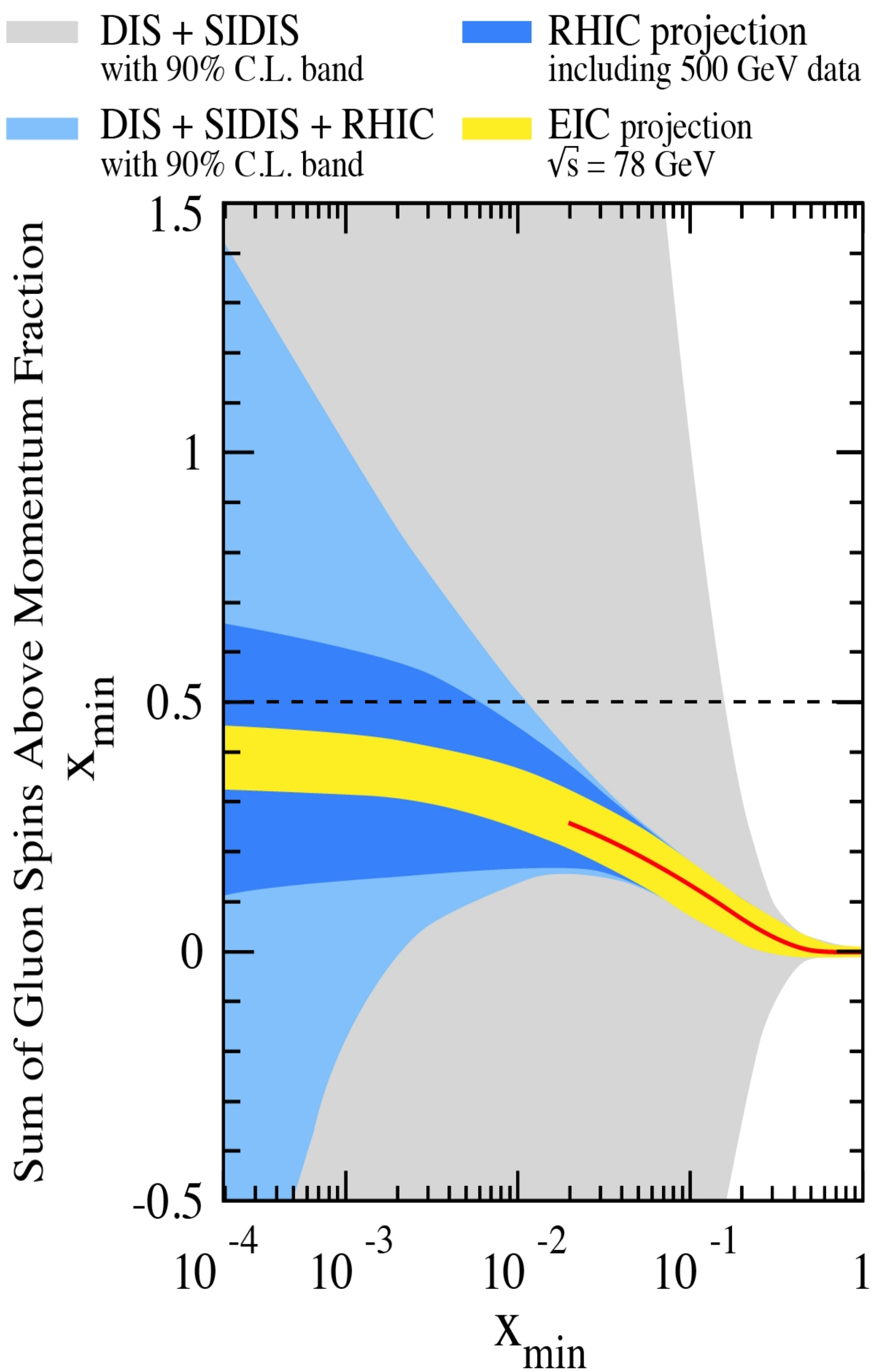
$$A_{LL} = \frac{\sigma(\vec{p}\,\vec{p} \to \mathrm{jet}\ X) - \sigma(\vec{p}\,\overleftarrow{p} \to \mathrm{jet}\ X)}{\sigma(\vec{p}\,\vec{p} \to \mathrm{jet}\ X) + \sigma(\vec{p}\,\overleftarrow{p} \to \mathrm{jet}\ X)}$$

Large uncertainties still, but ΔG is nonzero

de Florian, Sassot, Stratmann, Vogelsang, PRL 2014

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

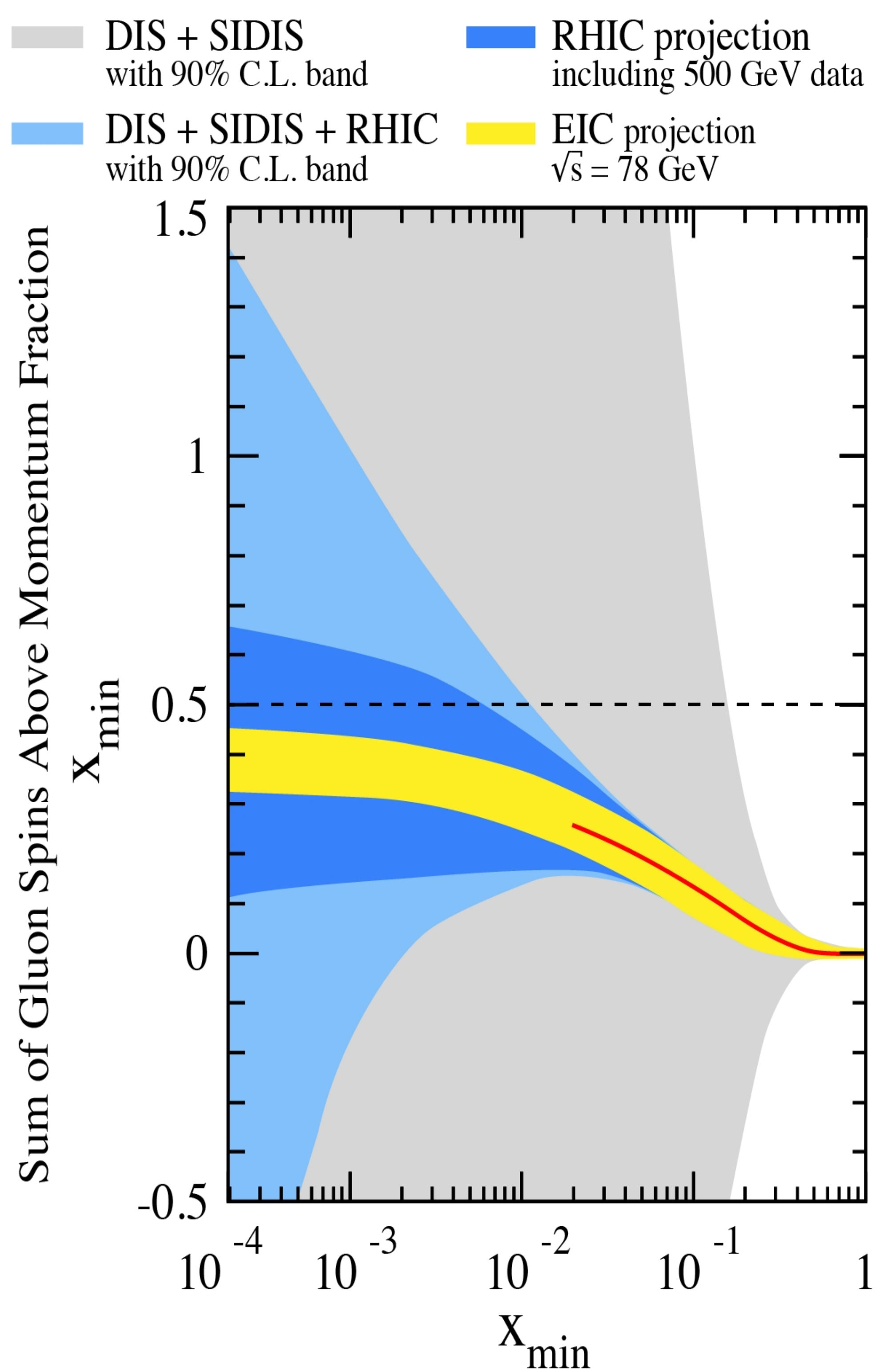
ΔG at EIC



$$\Delta G = \lim_{x_{\min}\to 0} \int_{x_{\min}}^{1} \Delta g(x)\, dx$$

For $\Delta G \approx 0.33$ (2/3 of proton spin) there would be little room for orbital angular momentum L_z

ΔG at EIC



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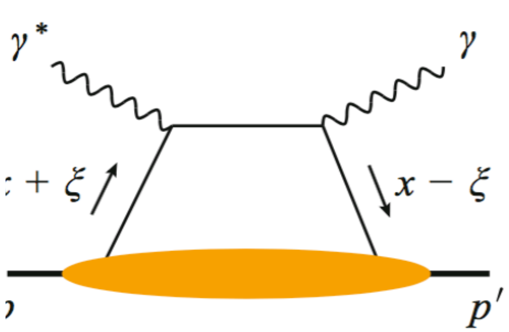
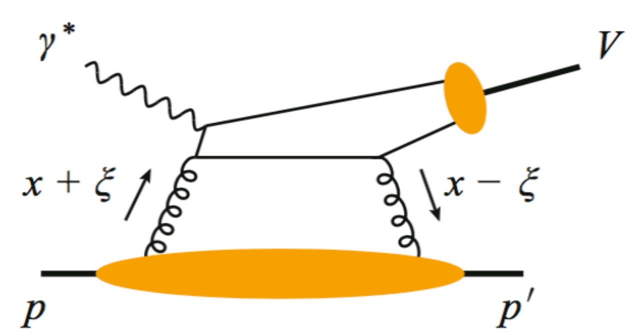
Importance of L_z remains to be seen

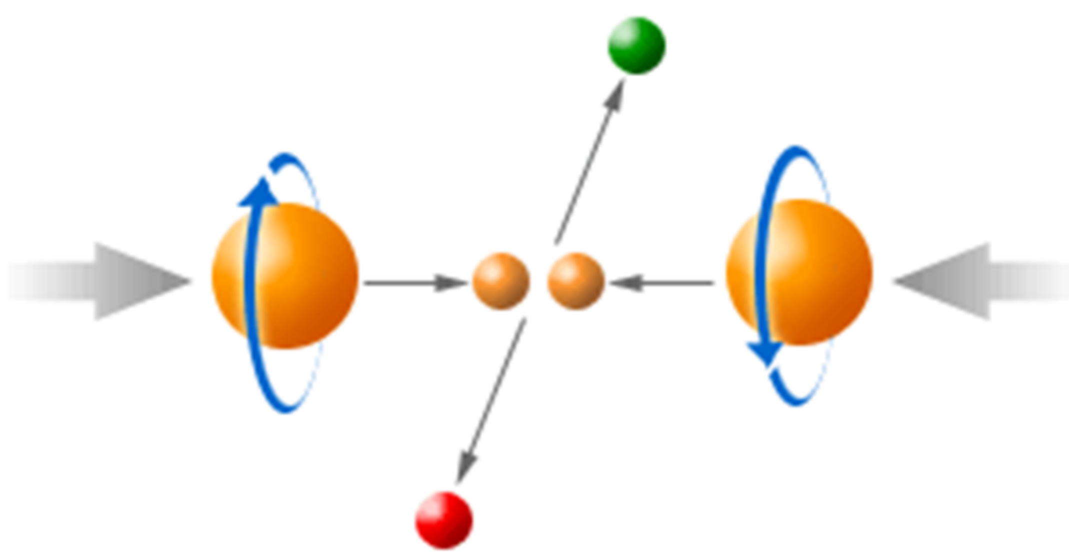
Independent estimates of L_z can be obtained from DVCS (also at EIC)

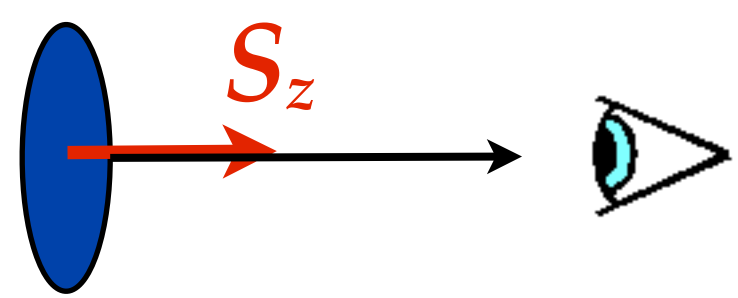




Transverse spin structure

The proton spin decomposition refers to spin along the momentum direction:





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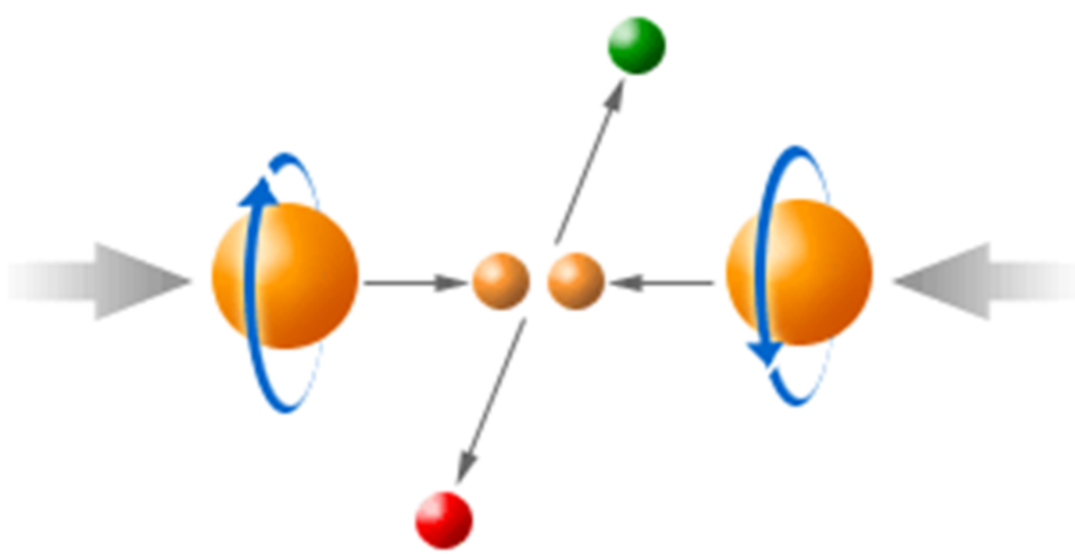

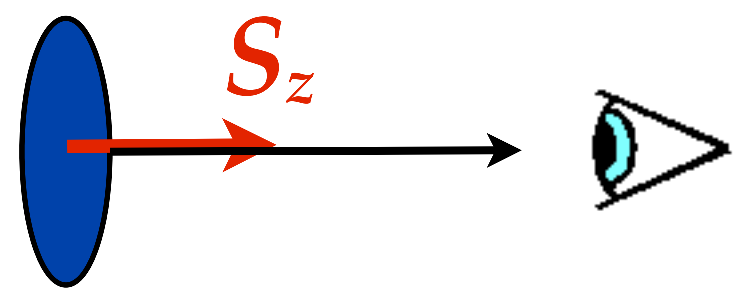

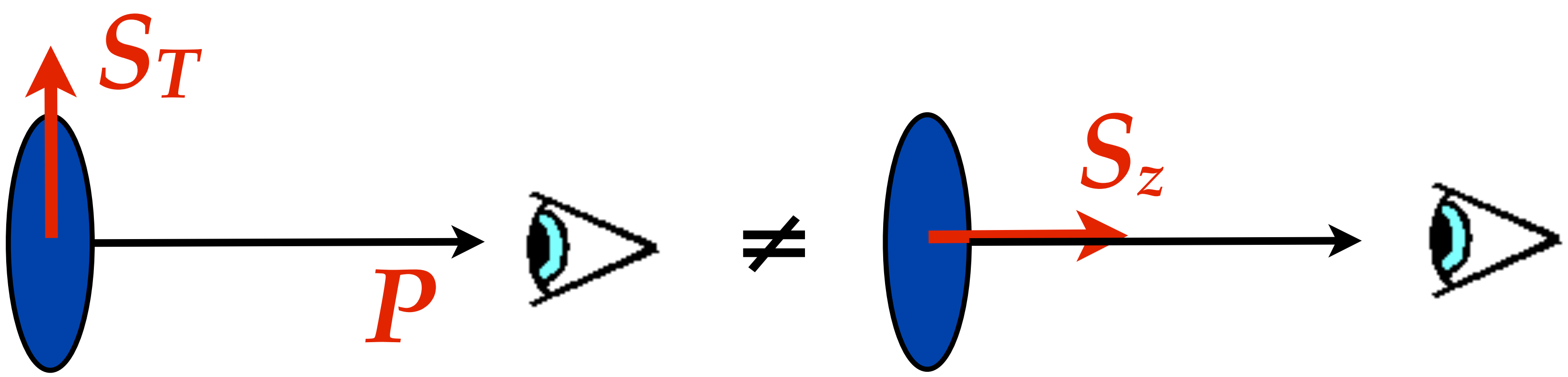

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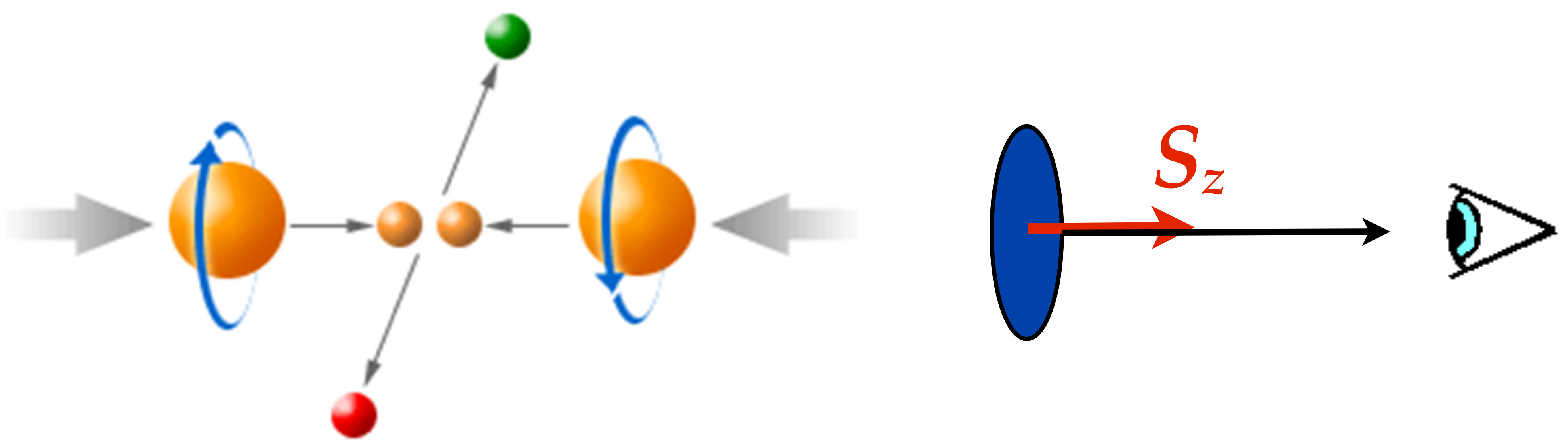
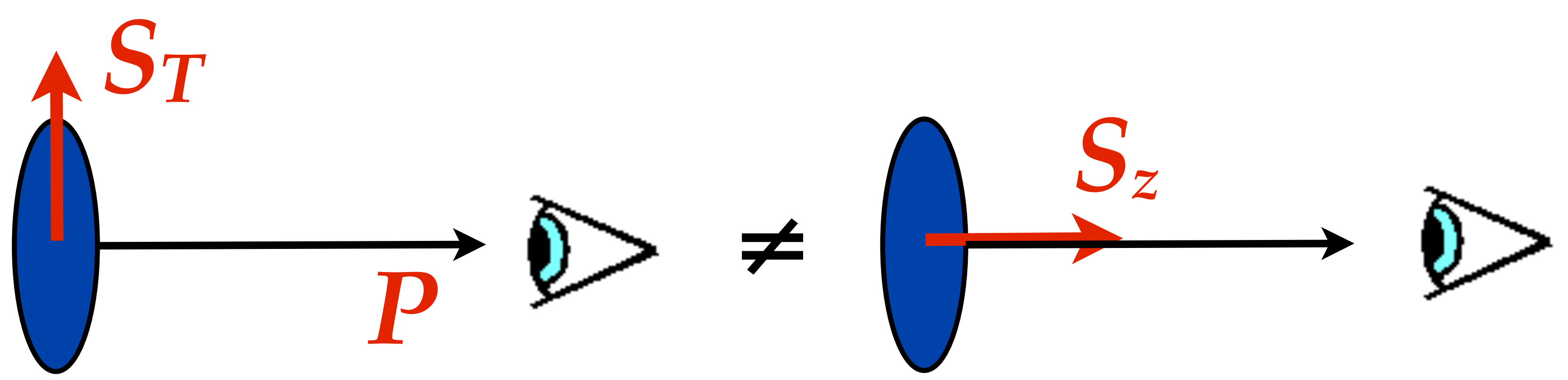




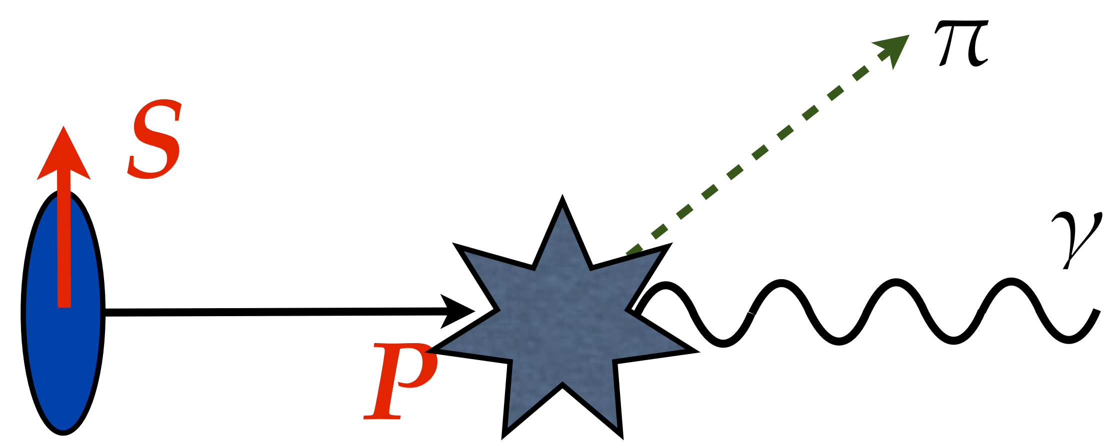
What one sees to the left and right of the plane spanned by P & S_T may differ

A left-right asymmetry is called the Sivers effect

Sivers, 1989/90

Sivers effect at EIC

Sivers effect in pion production in DIS clearly observed by HERMES (2009) & COMPASS (2010)



Quark Sivers effect also confirmed using lattice QCD

Musch, Hägler, Engelhardt, Negele & Schäfer, 2012

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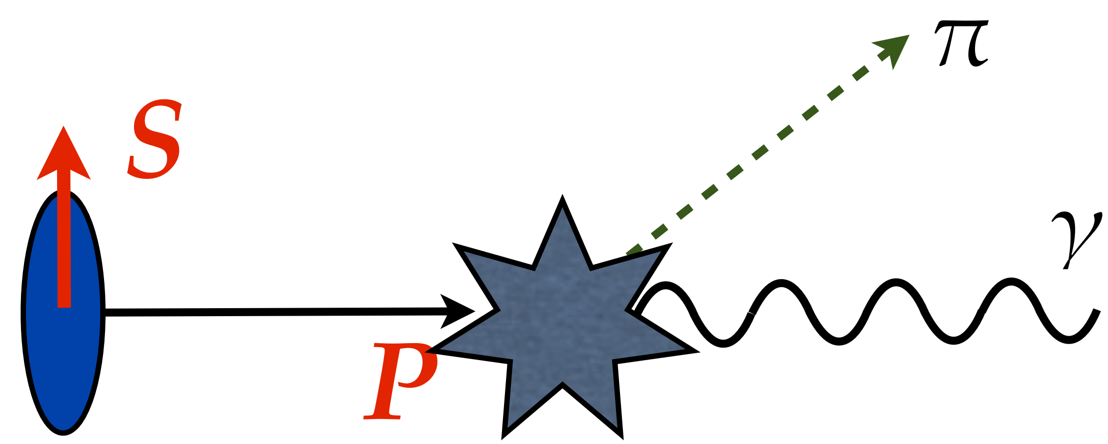

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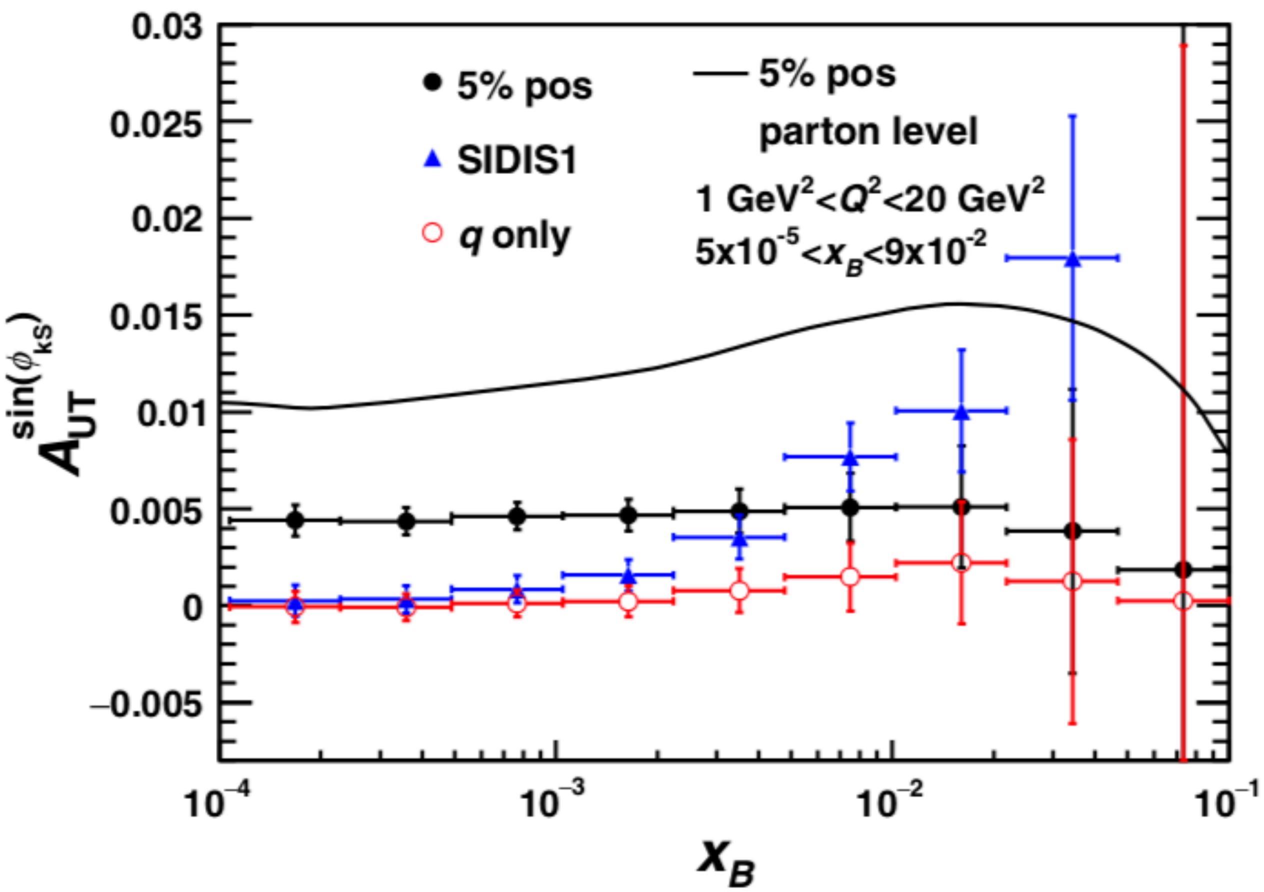


Gluon Sivers asymmetry measurement by COMPASS using high-p_T hadrons: $A = -0.26 \pm 0.09(\text{stat}) \pm 0.06(\text{syst})$

It is a main objective of the EIC to study the Sivers effect for gluons

E.g. in dijet production

Zheng, Aschenauer, Lee, Xiao, Jin, 2018

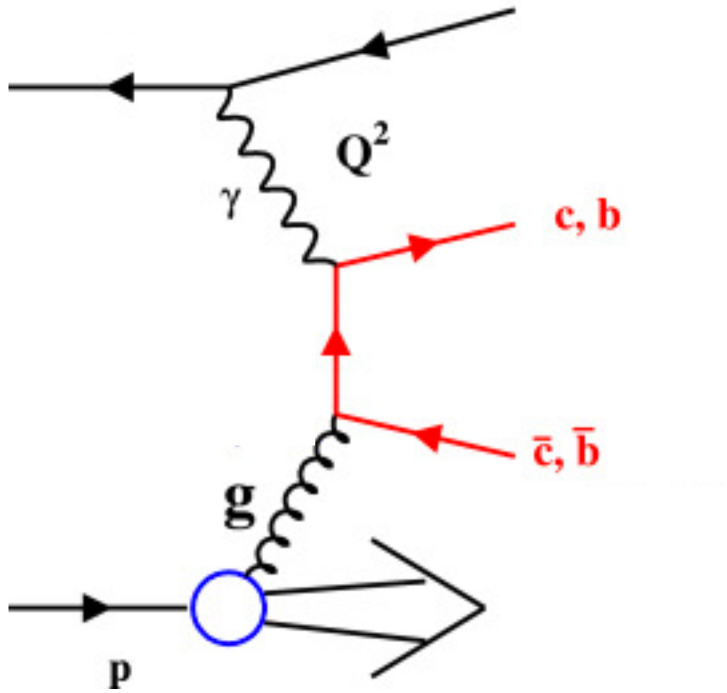
Transverse momentum dependence

Sivers effect requires nonzero transverse momentum (w.r.t. proton momentum)

Inclusive Deep Inelastic Scattering (ep→e'X) is not sensitive to it

Dijet or heavy quark pair production is sensitive to gluon transverse momentum

$$ep \to e' Q\bar{Q} X$$



Very little is known about this transverse momentum distribution experimentally, besides the fact that the average k_T for gluons is larger than for quarks

Gluon TMDs

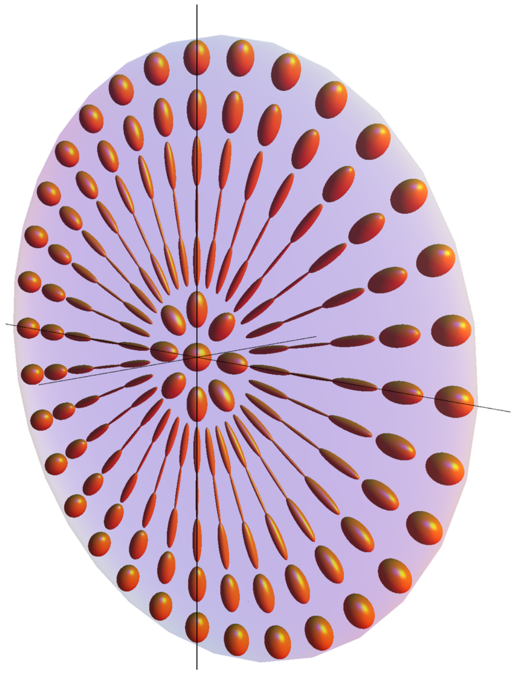
Transverse momentum dependent distributions involve more than just:

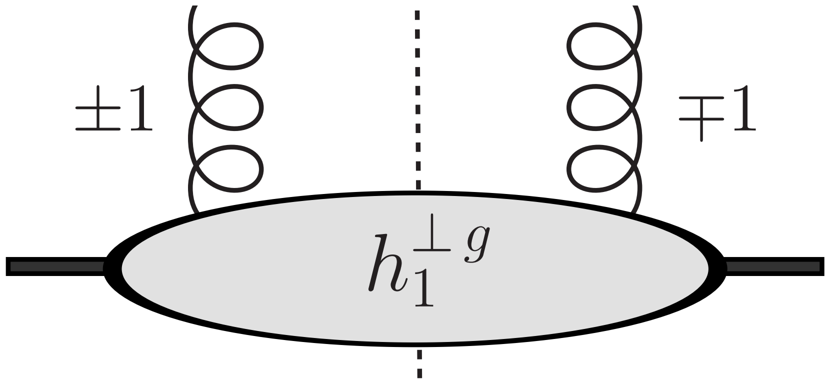
$$g(x, Q^2) \rightarrow g(x, k_T, Q^2)$$

It turns out that gluons inside *unpolarized* protons can be polarized!

Mulders, Rodrigues, 2001

Linear polarization of gluons





an interference between
±1 helicity gluon states

Size unknown and upon integration over transverse momentum it averages out

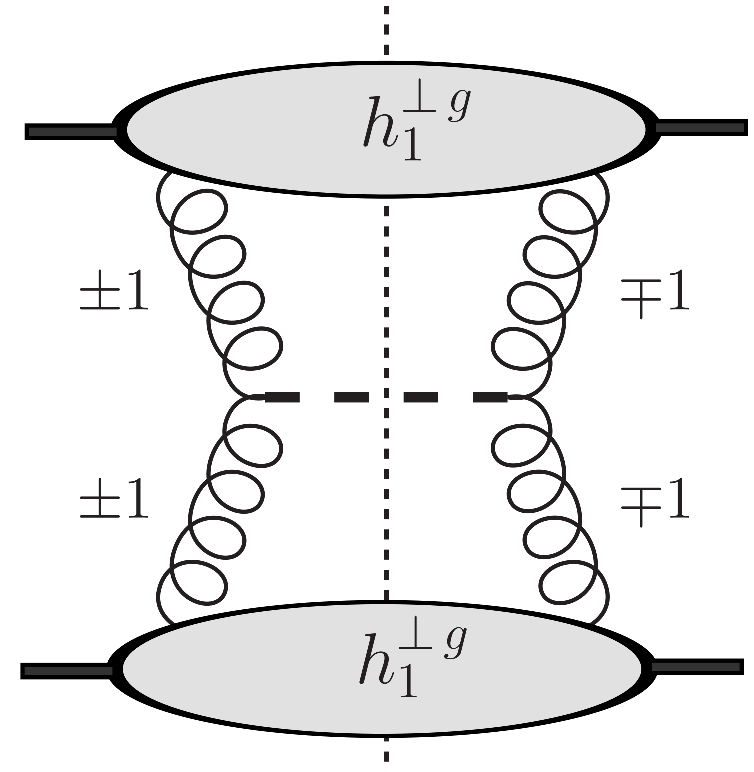
Linear gluon polarization at EIC

It affects Higgs production at the LHC

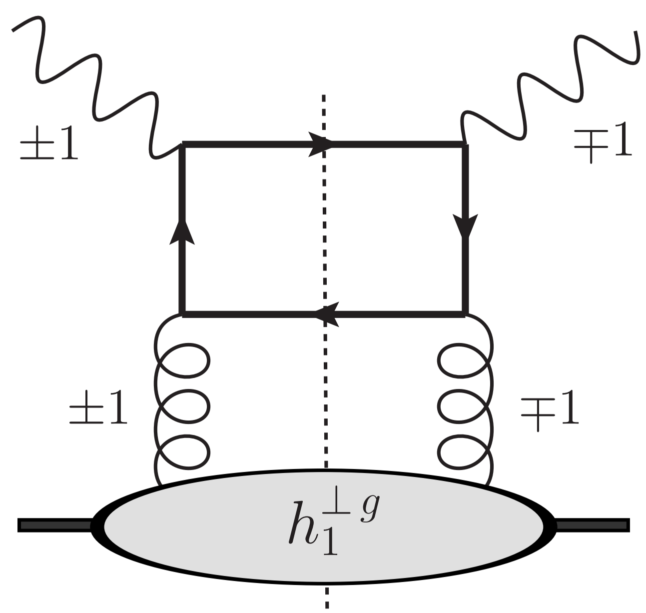
D.B., den Dunnen, Pisano, Schlegel, Vogelsang, 2011
Sun, Xiao, Yuan, 2011

It remains to be seen whether this can be exploited

At EIC it certainly can!



$$ep \to e' Q\bar{Q} X$$



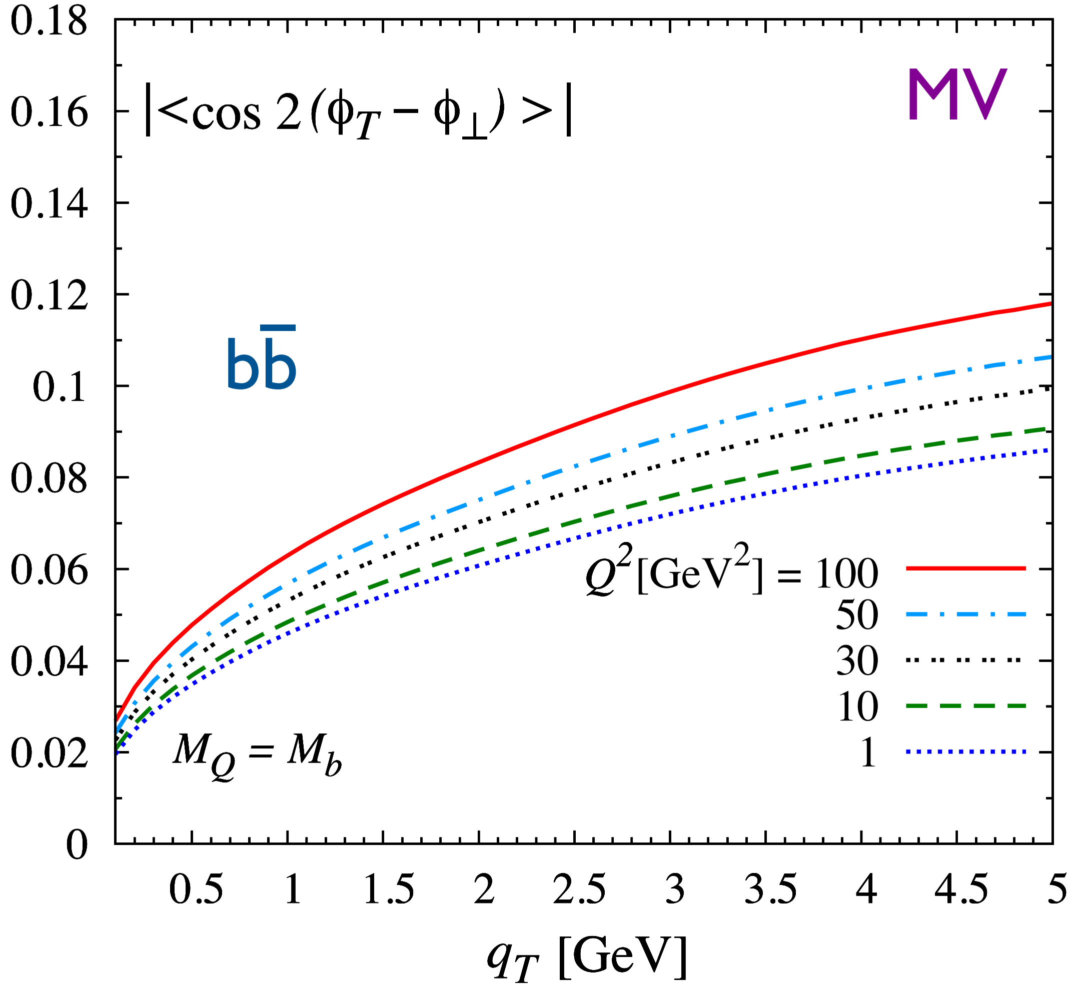
$\cos 2(\phi_T - \phi_\perp)$ angular distribution

$\phi_{T/\perp}$ are the angles of $K_\perp^Q \pm K_\perp^{\bar{Q}}$

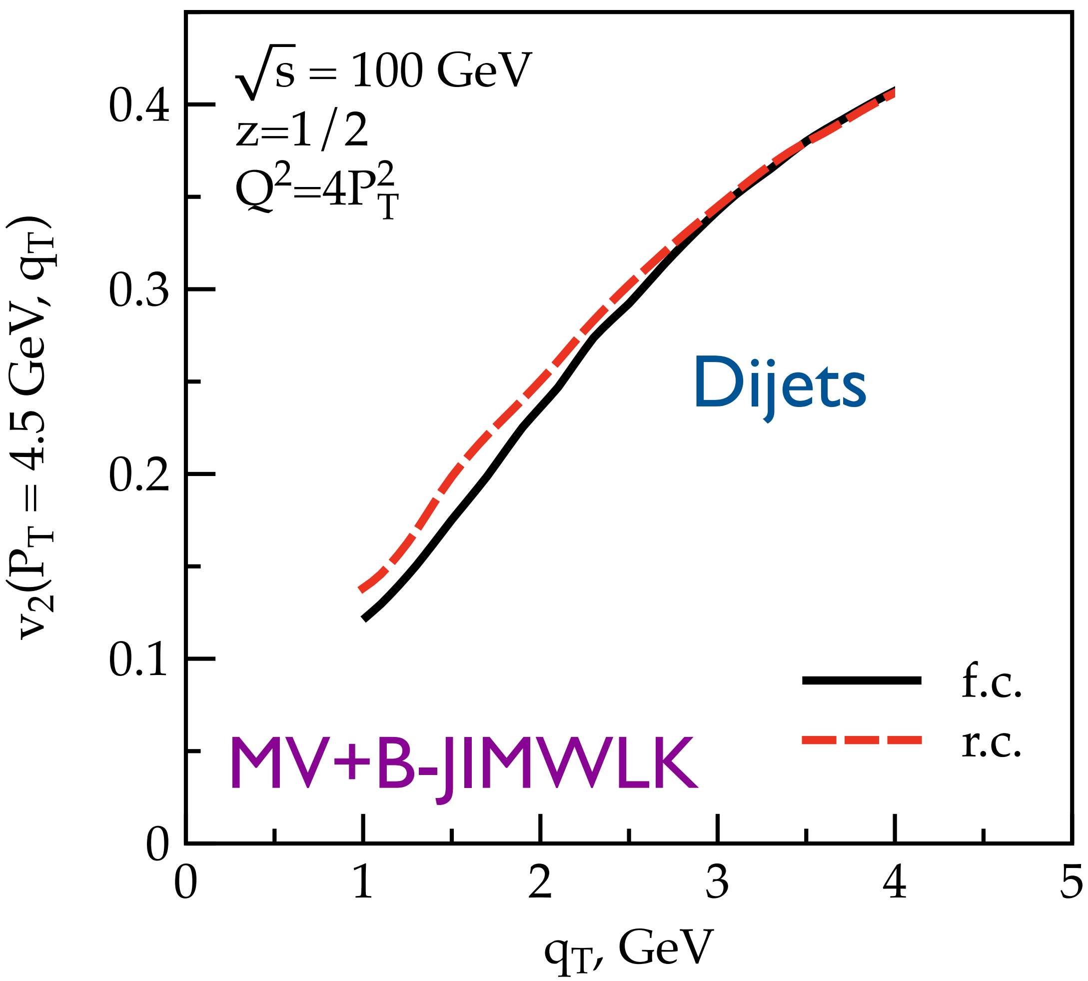
D.B., Brodsky, Mulders & Pisano, 2010

Linear gluon polarization at EIC

$h_1^{\perp g}$ is expected to keep up with the growth of the unpolarized gluons as $x \to 0$



D.B., Pisano, Mulders, Zhou, 2016



Dumitru, Lappi, Skokov, 2015

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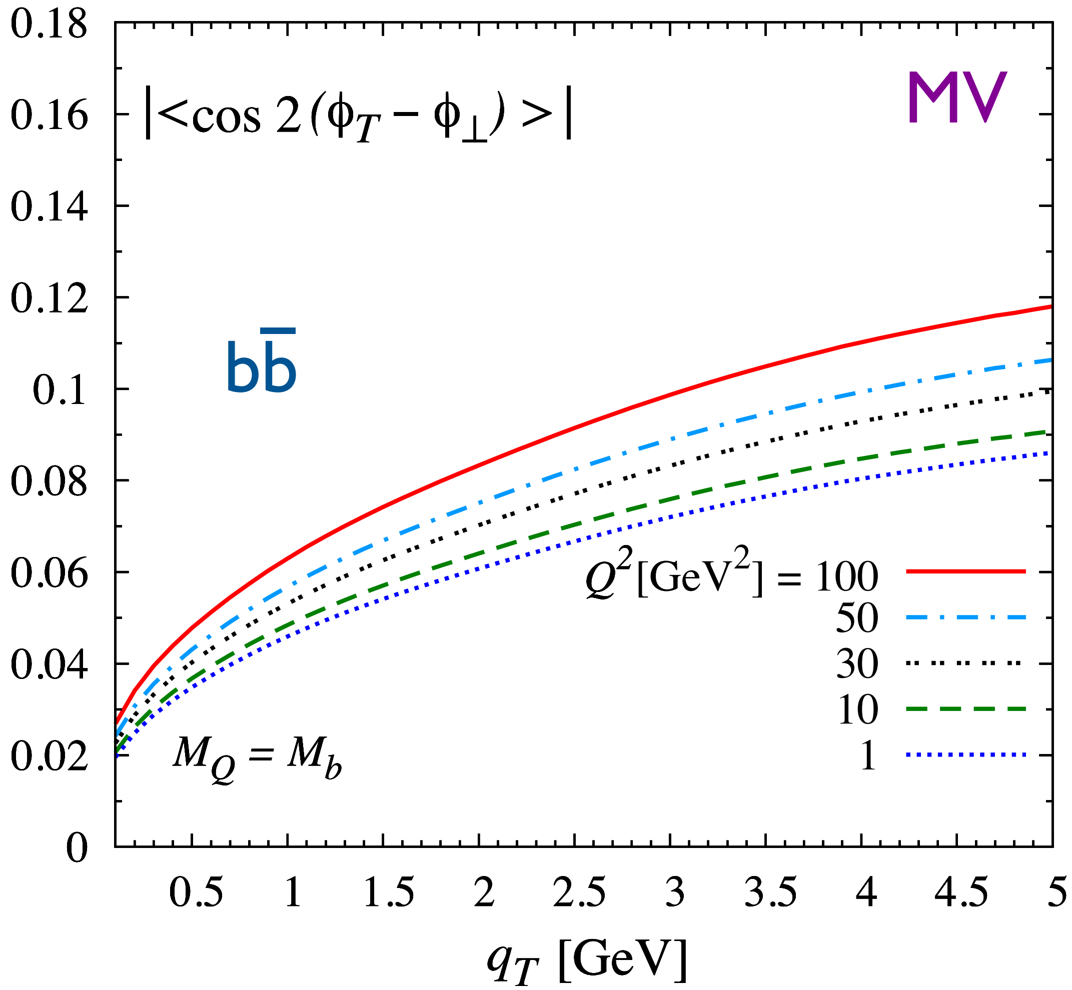

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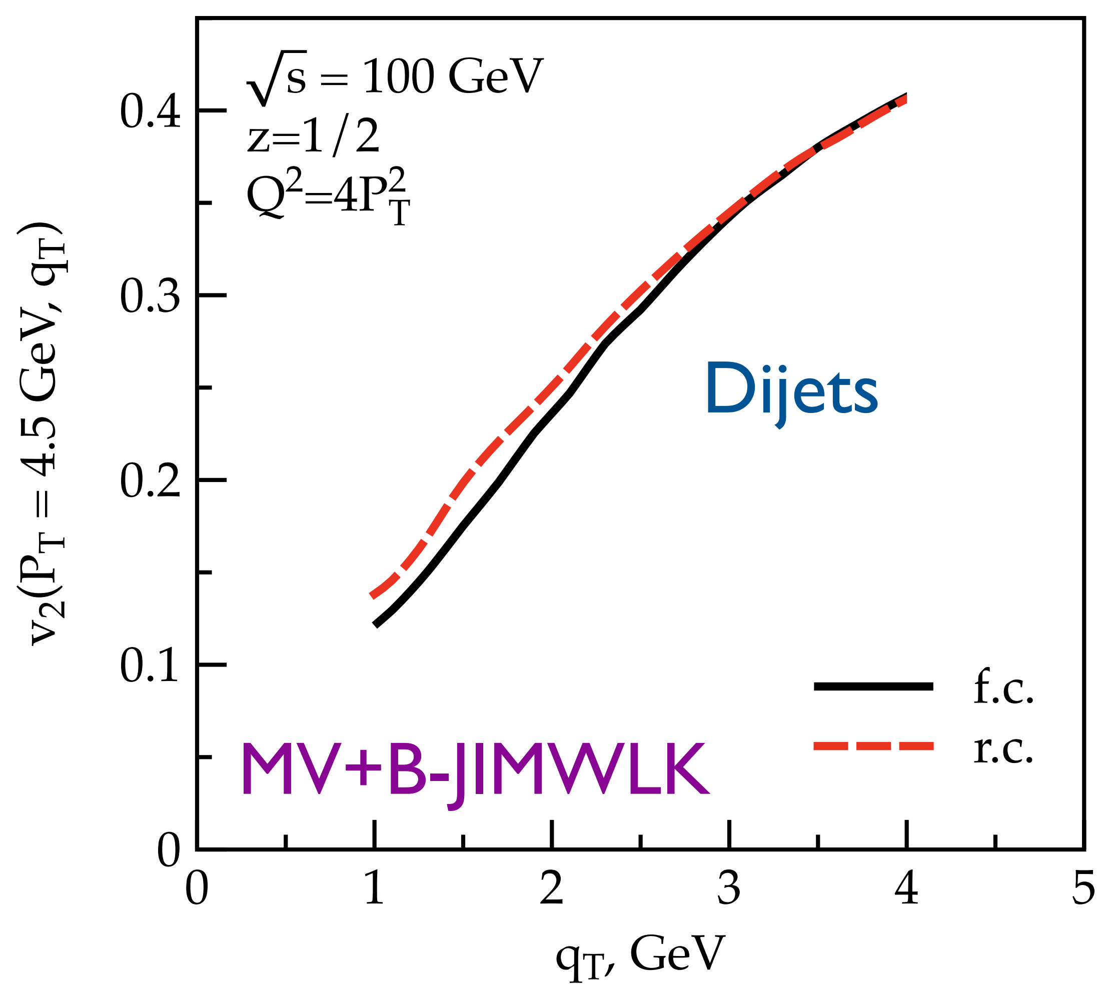


Dumitru, Lappi, Skokov, 2015

CGC gluons are linearly polarized, the size of the effects depends on the process

Nucleon tomography: spatial distributions

GPDs: off-forward PDFs (proton stays intact but gets a kick)

Give access to the transverse spatial distributions

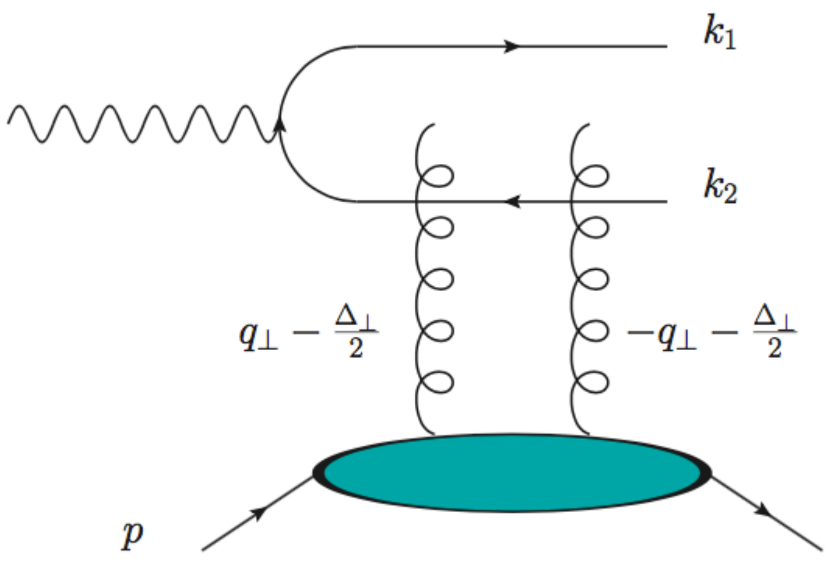
GTMD = off-forward TMD = Fourier transform of a Wigner distribution

$$G(x, \boldsymbol{k}_T, \boldsymbol{\Delta}_T) \overset{FT}{\longleftrightarrow} W(x, \boldsymbol{k}_T, \boldsymbol{b}_T)$$

Meißner, Metz, Schlegel, 2009 Ji, 2003; Belitsky, Ji & Yuan, 2004

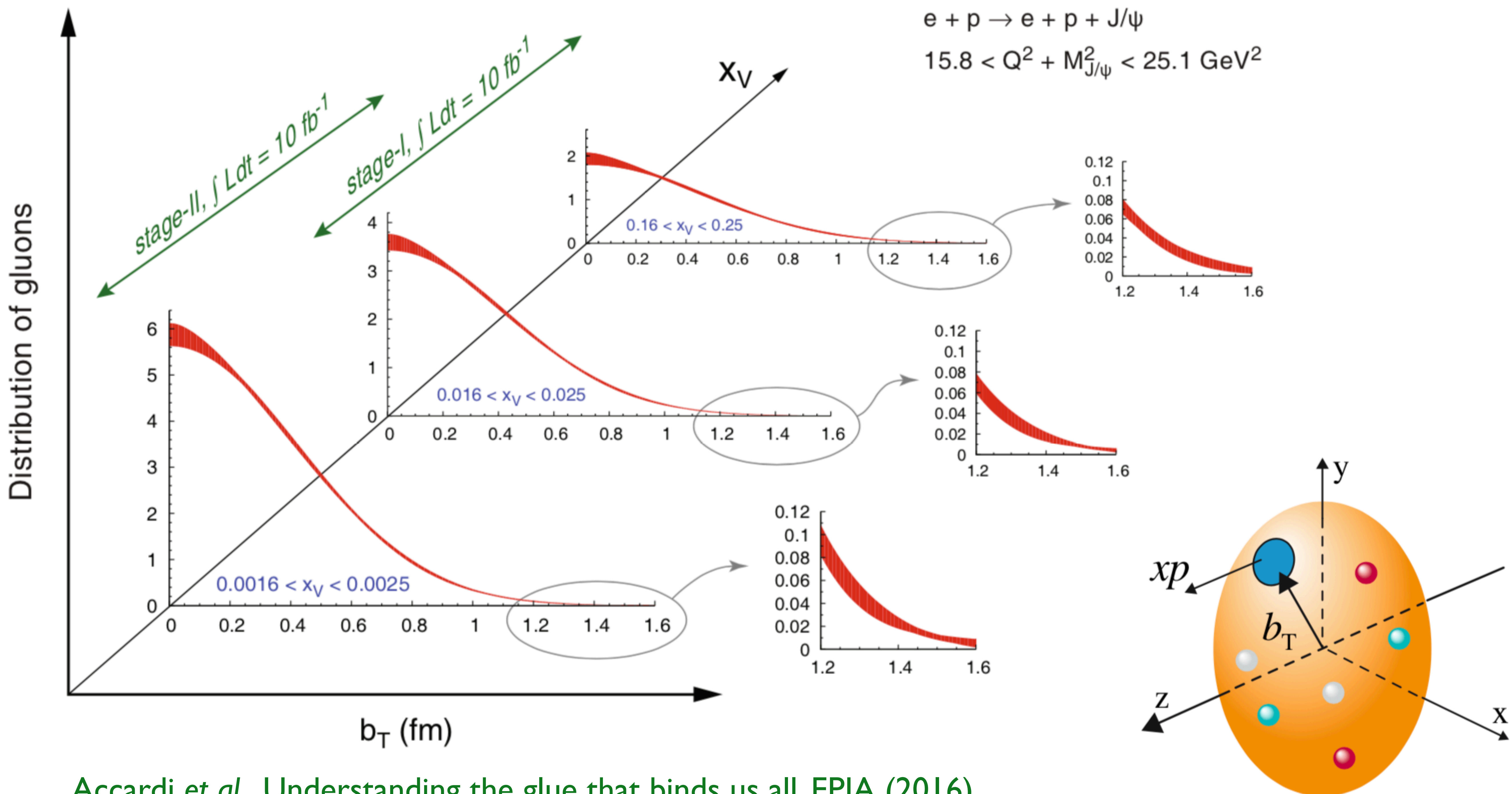
Diffraction dijet production in eA at EIC could be used to probe gluon GTMDs for the first time

Altinoluk, Armesto, Beuf, Rezaeian, 2016;
Hatta, Xiao, Yuan, 2016



Gluon GPD from exclusive J/ψ production

Projected precision of the transverse spatial distribution of gluons

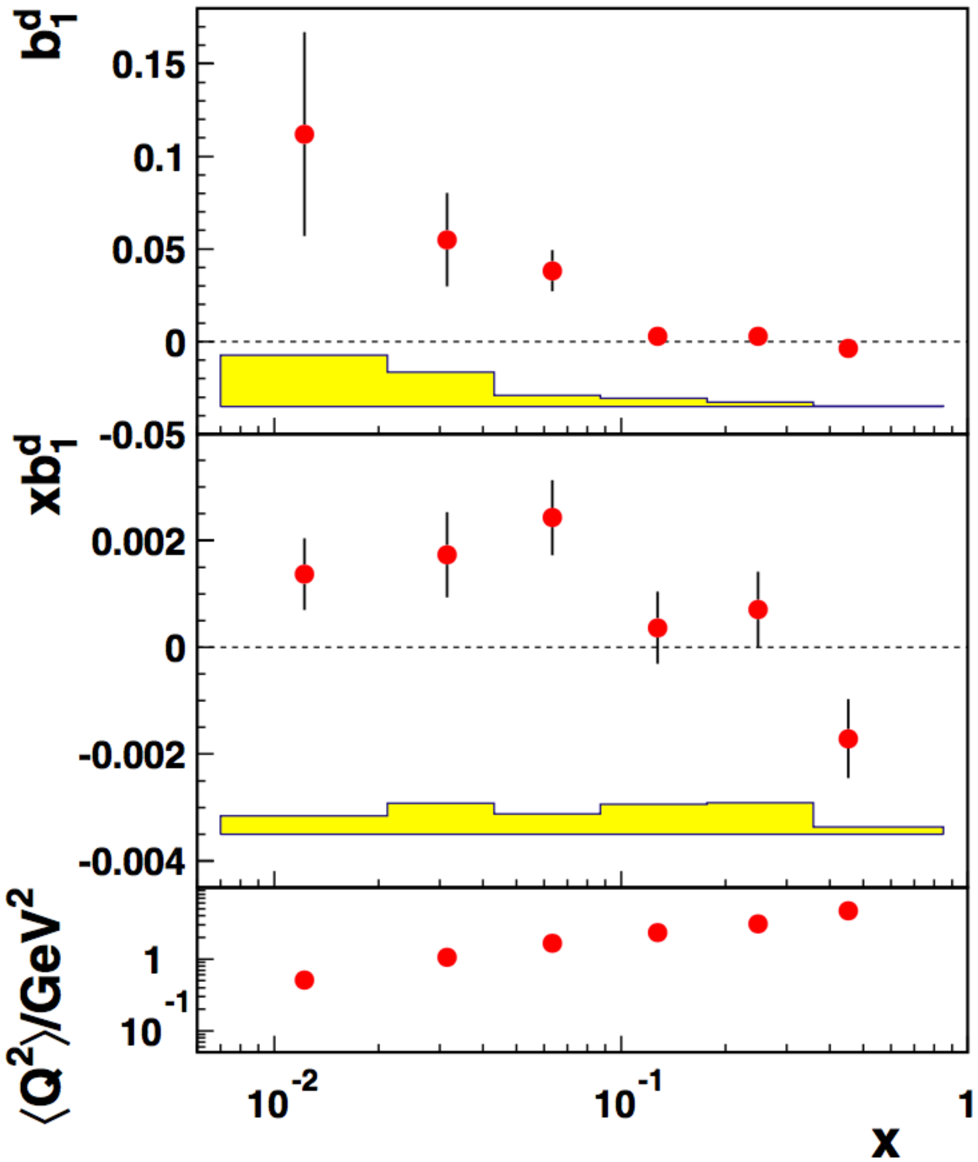


Accardi *et al.*, Understanding the glue that binds us all, EPJA (2016)

Polarized deuteron opportunities

The longitudinal tensor polarization structure function b_1 has been extracted

It needs to be measured more precisely and over a wider x range



Airapetian et al. (HERMES Collaboration)
Phys. Rev. Lett. 95 (2005) 242001

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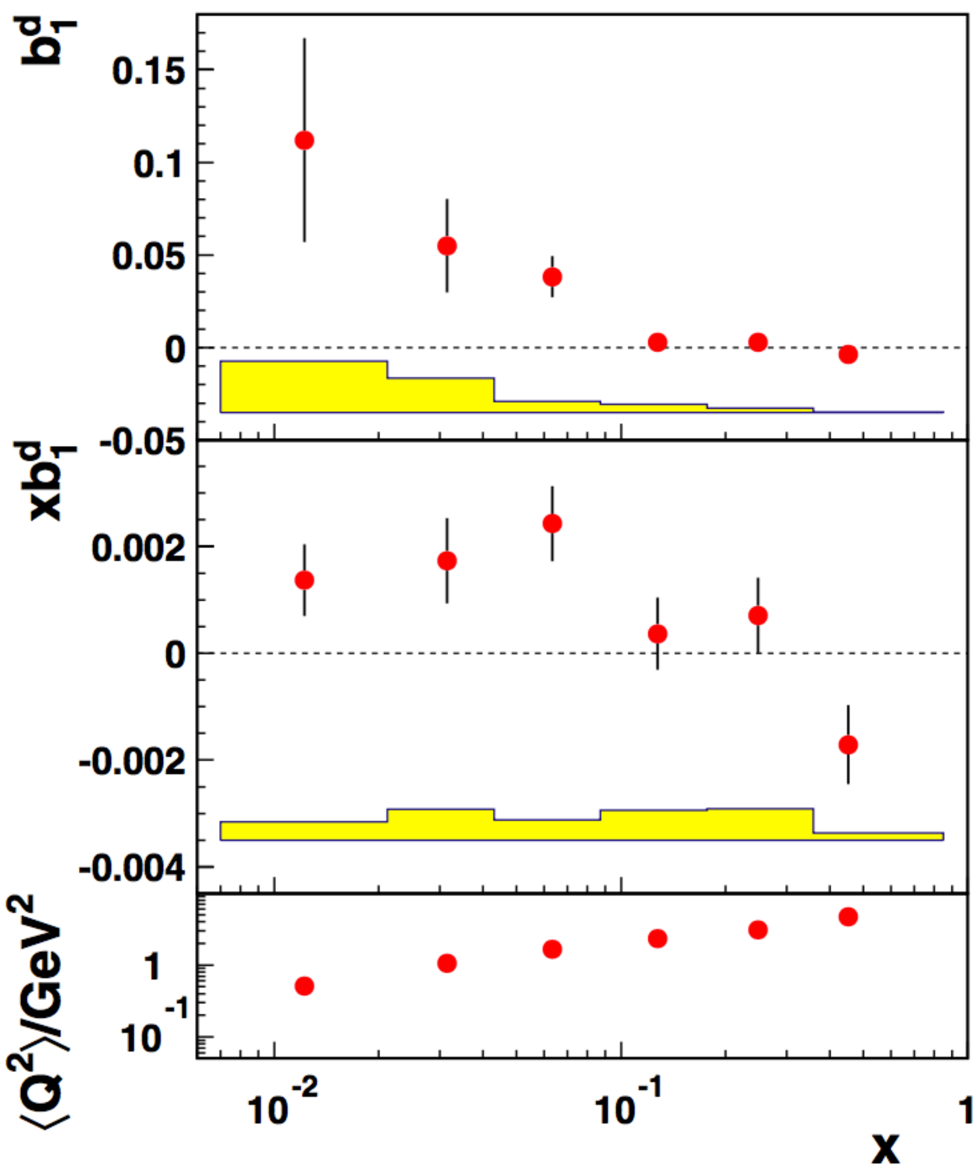
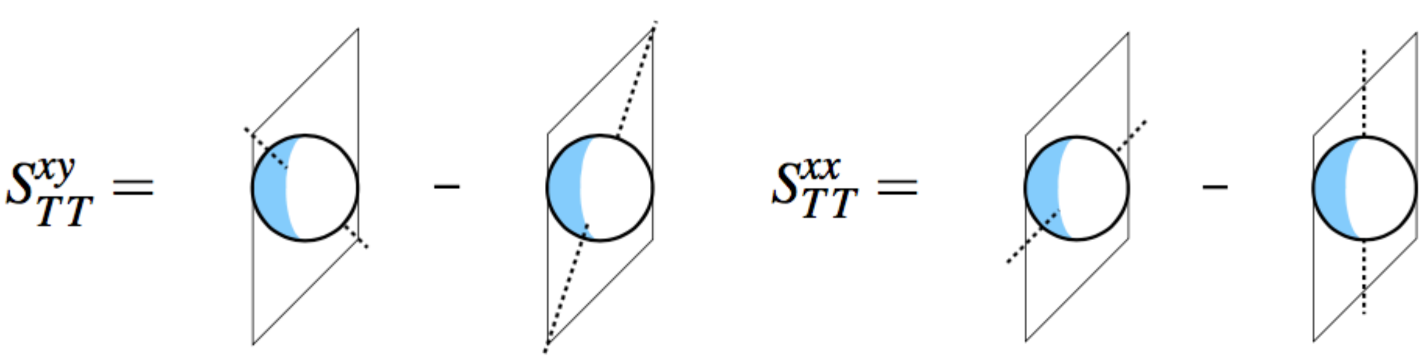


Airapetian et al. (HERMES Collaboration)
Phys. Rev. Lett. 95 (2005) 242001

In the transverse tensor polarization case
there is a contribution solely from gluons

Jaffe, Manohar, Phys. Lett. B 223 (1989) 218
Artru, Mekhfi, Z. Phys. C 45 (1990) 669



Bacchetta, Mulders, PRD 62 (2000) 114004

not yet measured

Conclusions

- Even 40 years after their experimental discovery, the physics of gluons is still largely unexplored, especially regarding nuclear and spin effects
- The U.S.-based Electron-Ion Collider aims to measure such gluon effects through extraction of many different gluon distributions
- This yield lots of new and unique information ranging from collective effects to spin effects
- There is lots of synergy with pp, pA & AA studies at the LHC in a similar x range but in a less clean environment (and without polarization)

Back-up slides

Average momentum

Gluons carry a substantial fraction of the momentum of the proton

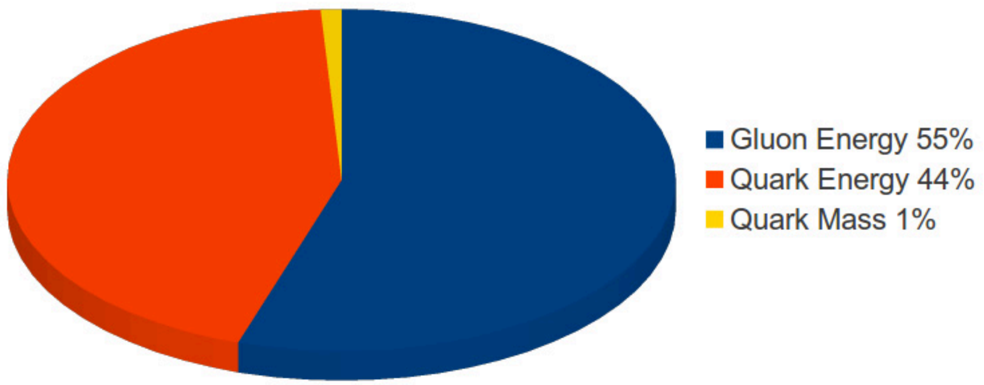
Asymptotically ($Q^2 \to \infty$):

$$\langle x \rangle_g \equiv \int_0^1 dx\, x\, g(x, Q^2) = \frac{16}{16 + 3N_f} - \mathcal{O}(\alpha_s(Q^2))$$

N_f = number of (active) quark flavors

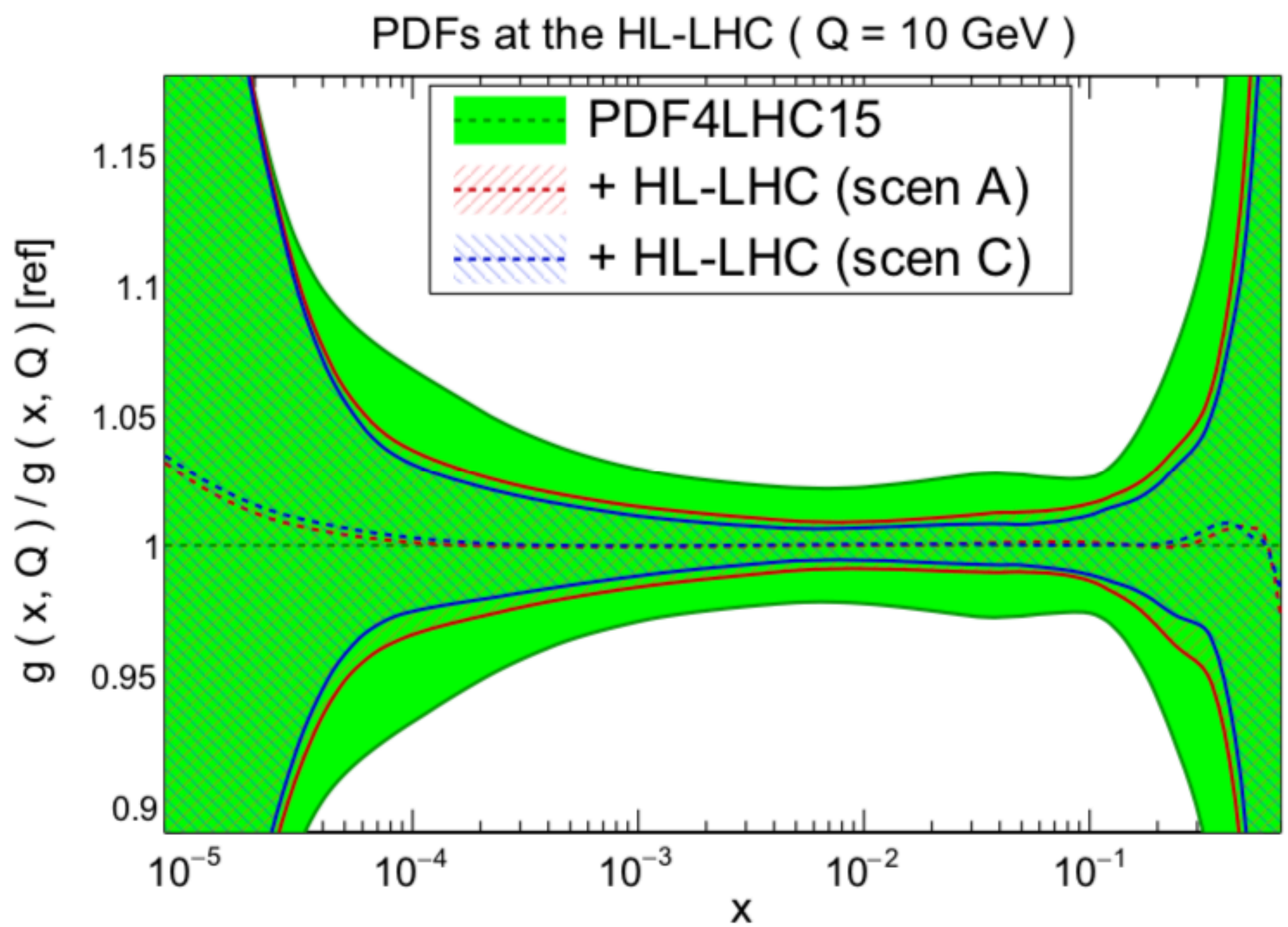
In experiments for Q^2 = 10 – 40 GeV^2 the fraction is close to 50%

This number enters in the mass decomposition:



The total number of gluons inside a proton is not bounded

EIC and LHC



The precision on the gluon distribution that one expects ultimately from the HL-LHC

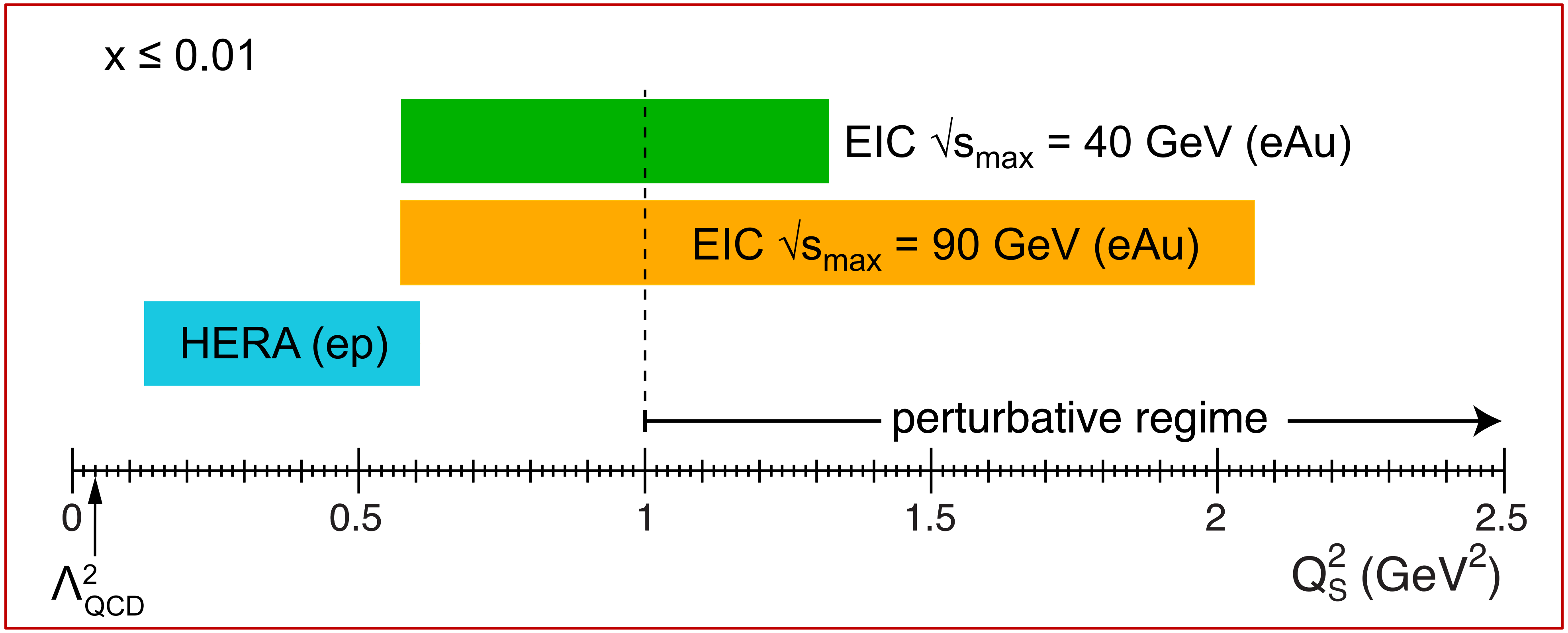
Khalek, Bailey, Gao, Harland-Lang, Rojo, EPJC 78 (2018) 962

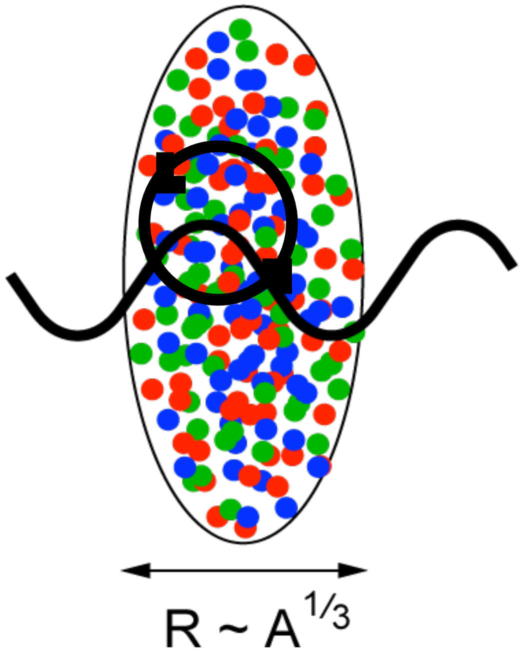
The EIC will span a similar range in x - synergy but largely complementary

The EIC's uniqueness w.r.t. HERA and LHC is in the polarization and in eA

Q: What are the emergent properties of a dense system of gluons?
A: Study the small x region and use large nuclei

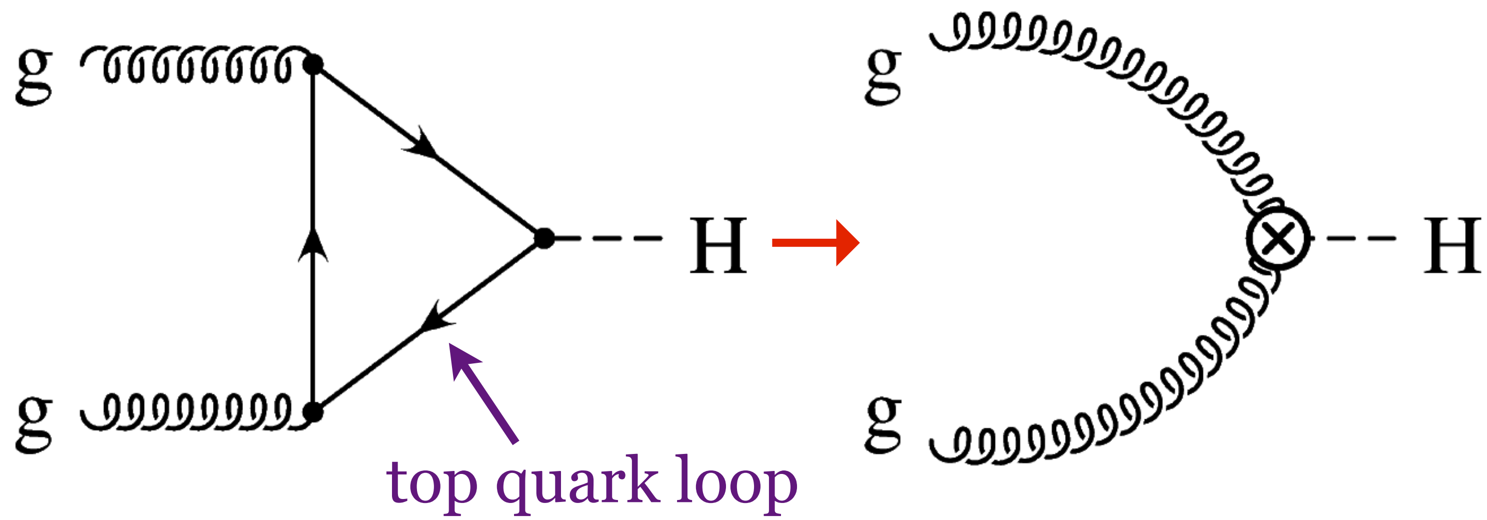
Saturation scale



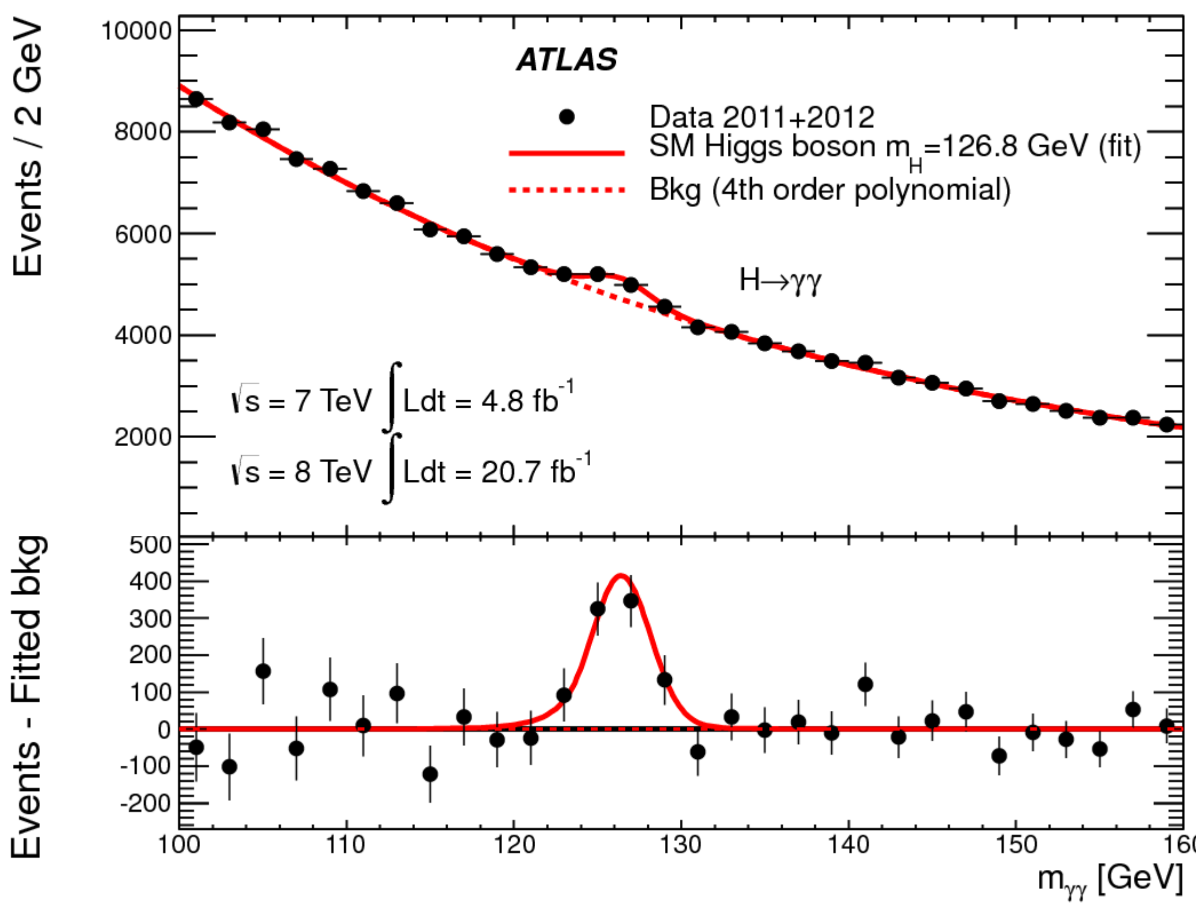


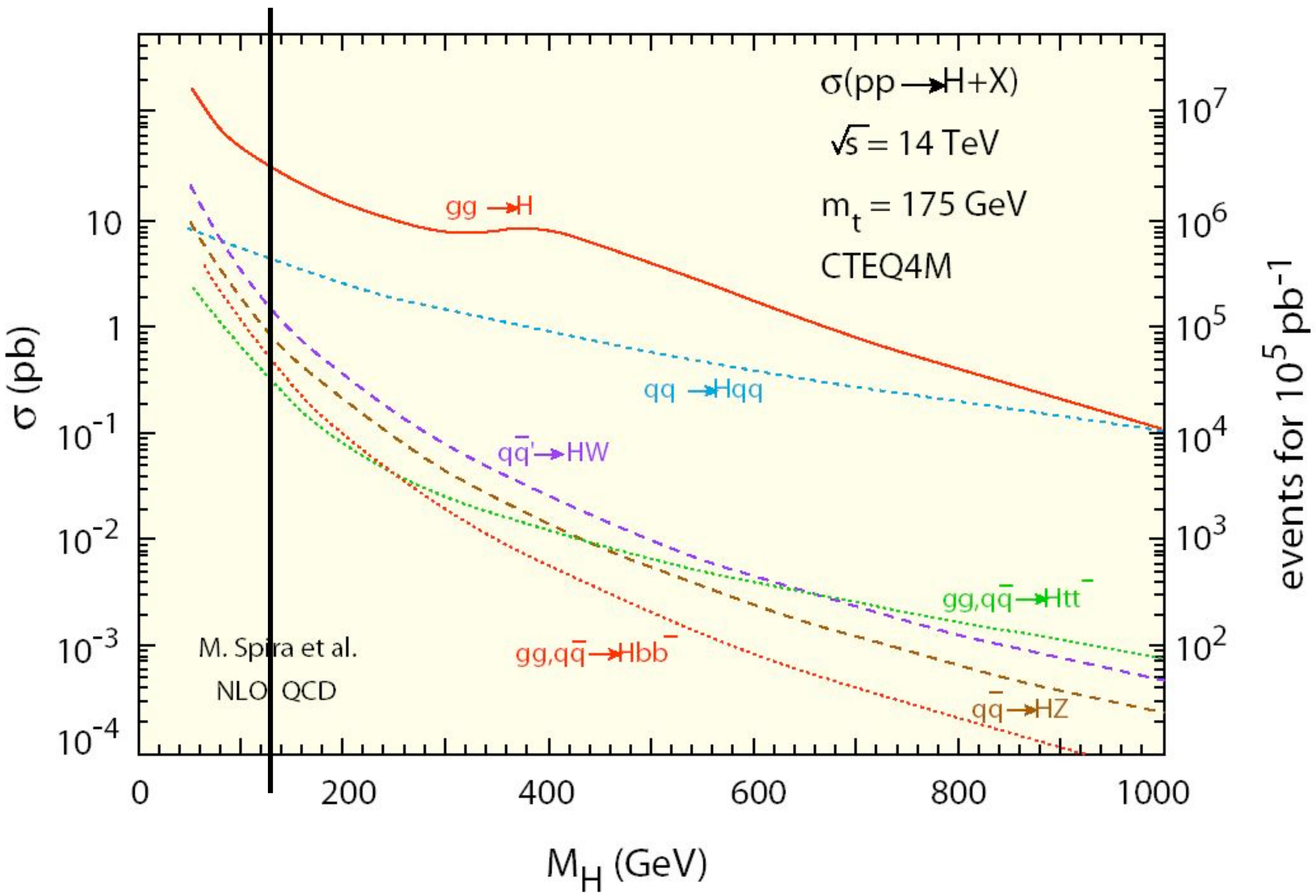
$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

Higgs production happens predominantly via gg → H



Gluons in Higgs production at LHC have x ~ 0.01 (in the well measured range)

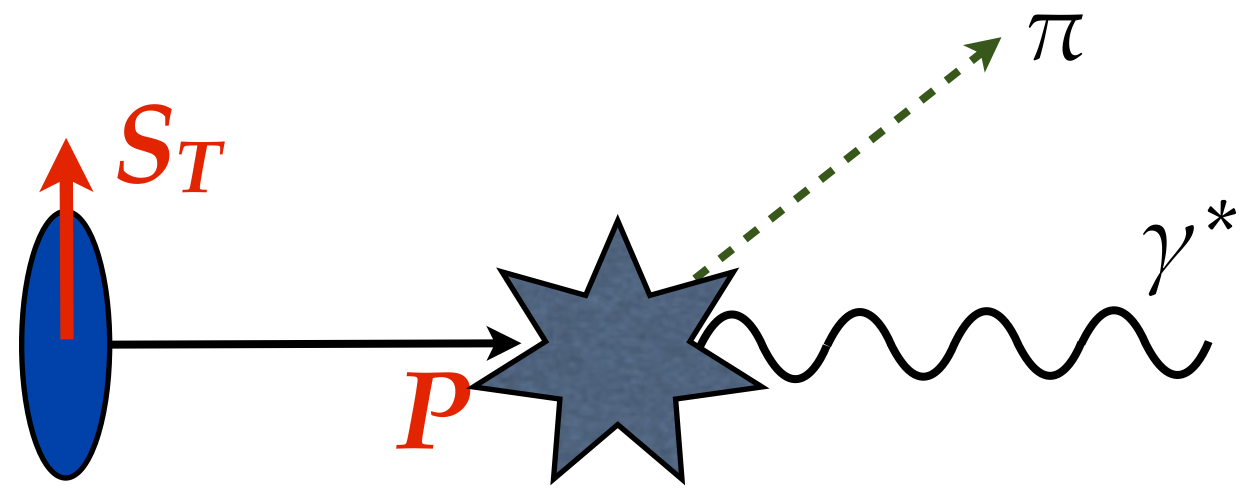




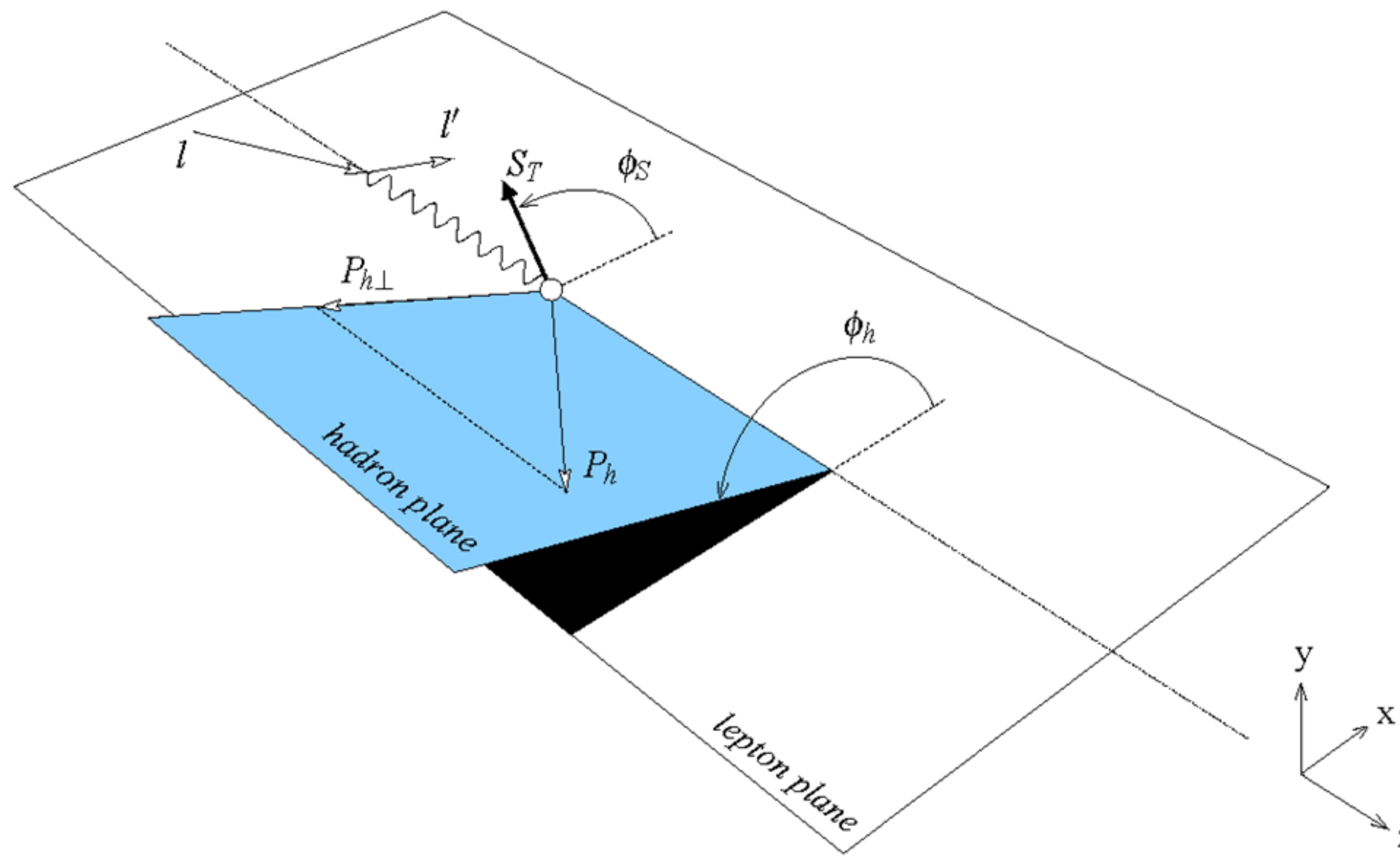
Discovery of new heavy particles (bumps) does not require knowledge on gluon distributions, but to extract the properties of the new particles does

Sivers effect in SIDIS

Measure pion distribution in DIS:



The Sivers effect should lead to a sin(φ_h -φ_S) asymmetry in semi-inclusive DIS
[Boer & Mulders, '98]



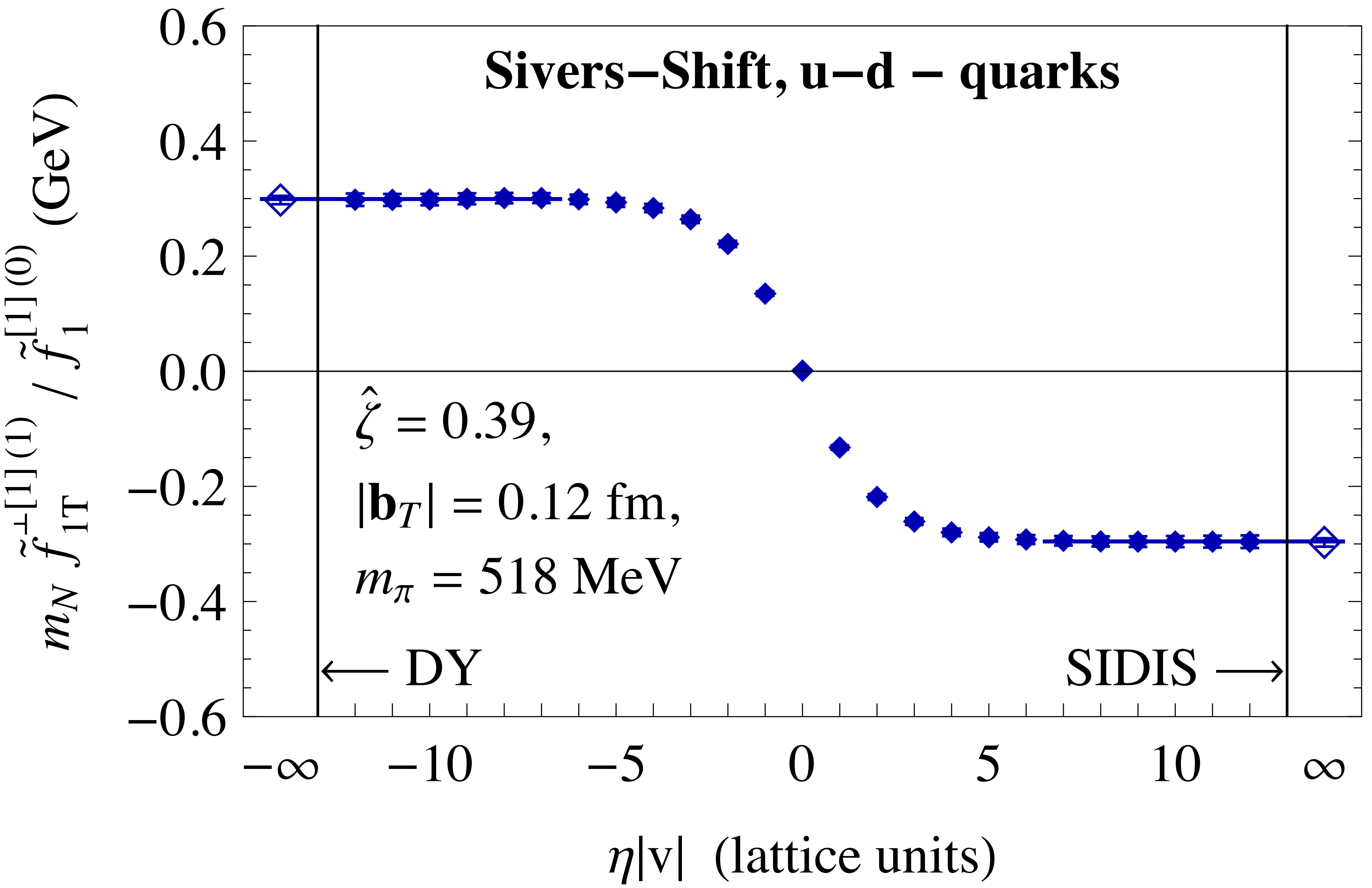
$$e\,p \to e'\,h\,X$$

Clearly observed by HERMES (PRL 2009) and COMPASS (PLB 2010)

Sivers effect on the lattice

The "Sivers shift" <k_T x S_T> (the average transverse momentum shift orthogonal to transverse spin S_T) can be calculated on the lattice

Boer, Gamberg, Musch, Prokudin, 2011



Musch, Hägler, Engelhardt, Negele & Schäfer, 2012

This is a first-principle demonstration that the Sivers effect is nonzero for quarks

It is a main objective of the EIC to measure the Sivers effect for gluons

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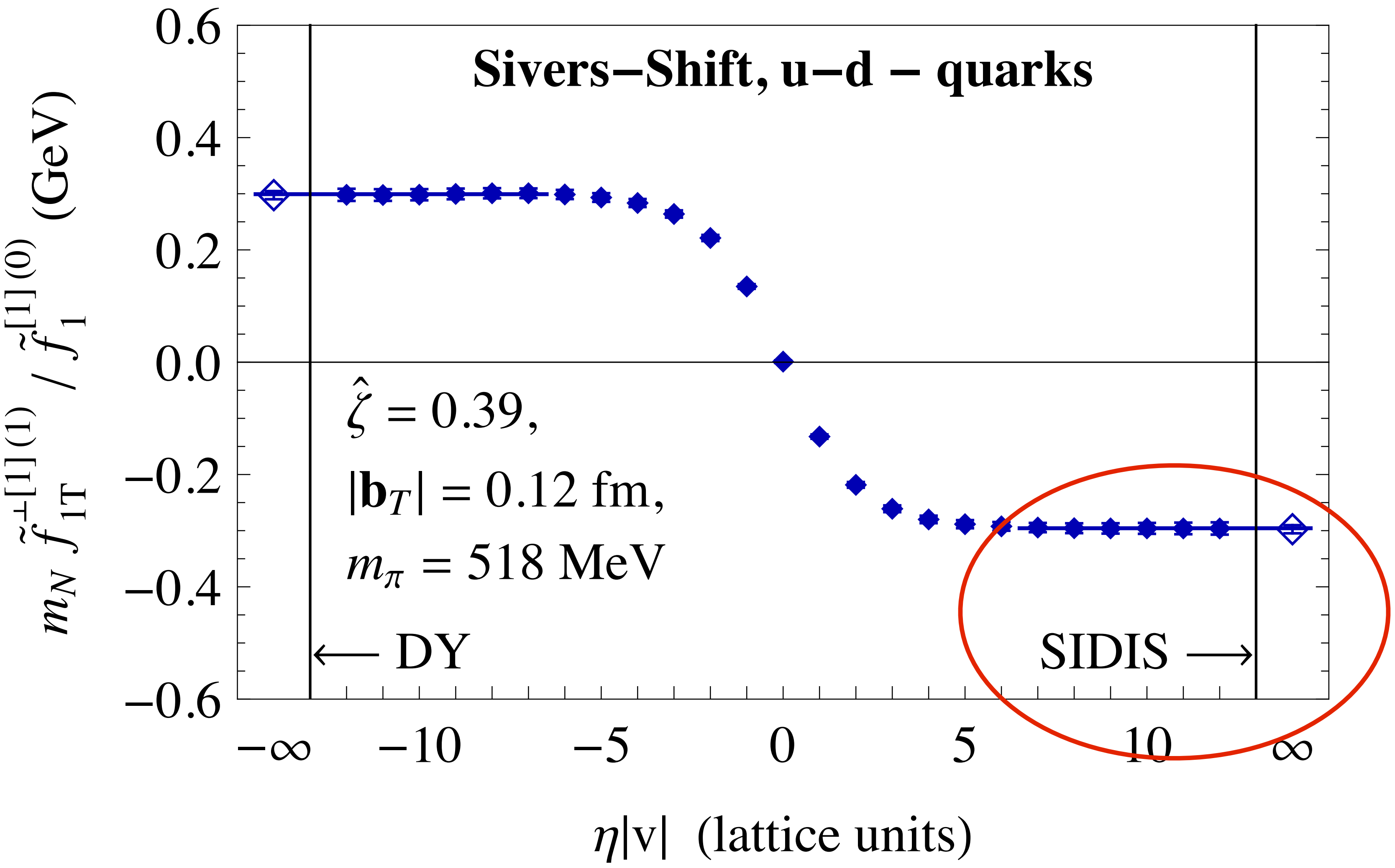

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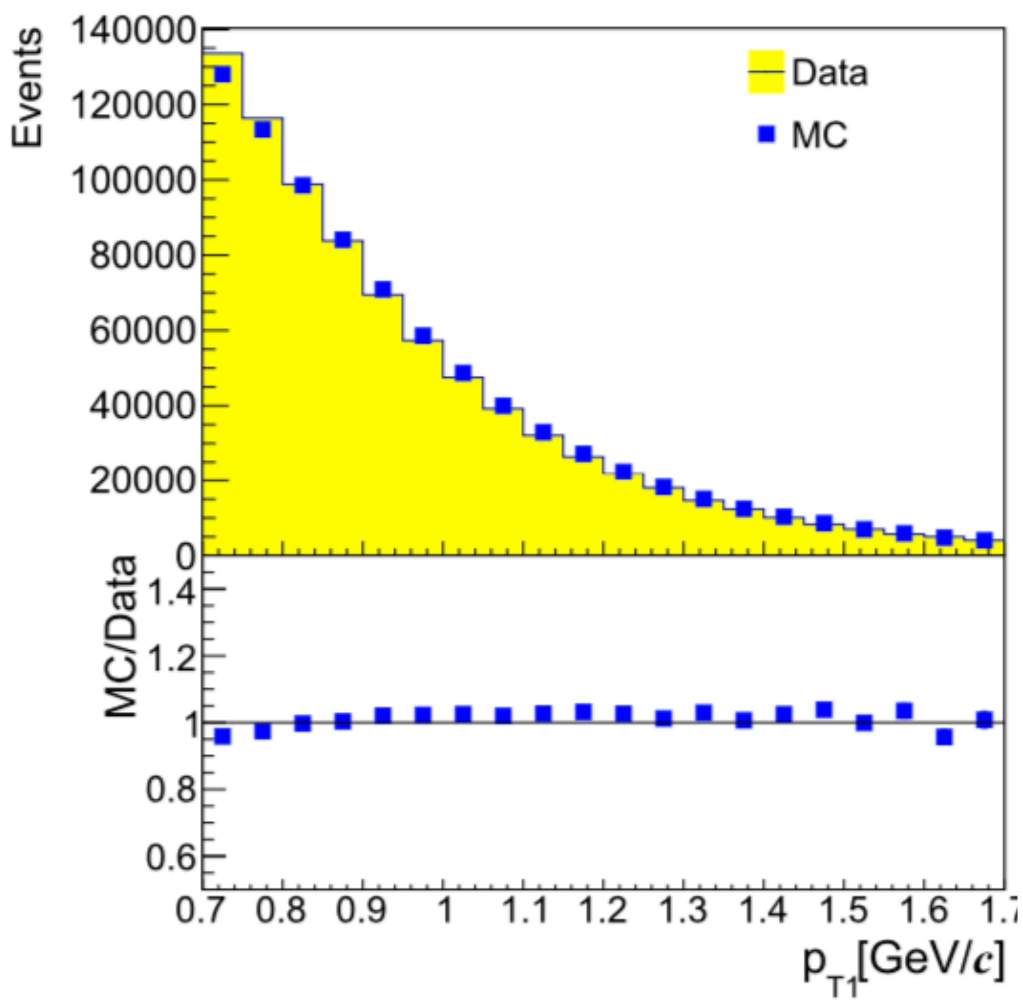
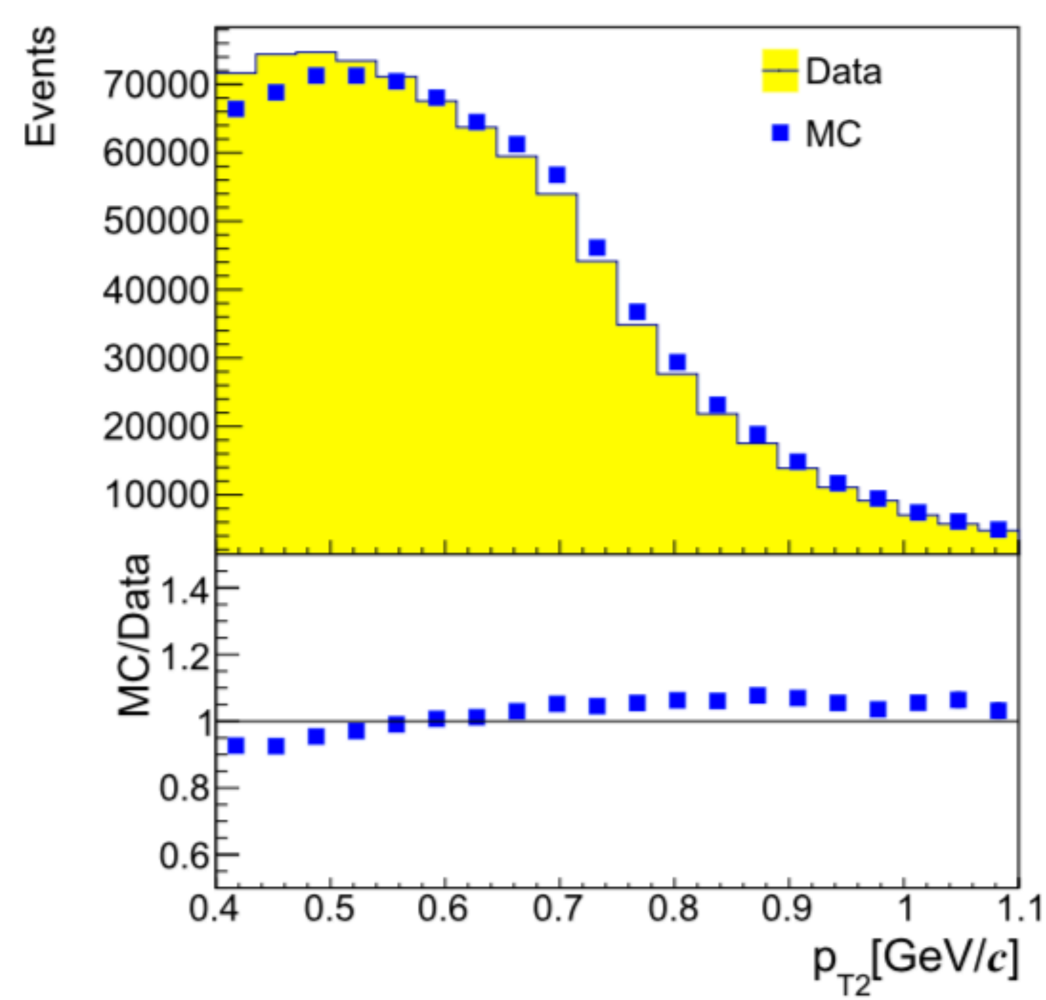
Gluon Sivers effect at COMPASS

First measurement of gluon Sivers asymmetry by COMPASS with high-p_T hadrons:
$A = -0.23 \pm 0.08(\text{stat}) \pm 0.05(\text{syst})$, for protons+deuterons combined

Not yet 3σ and likely large theoretical uncertainty due to p_T not being very high



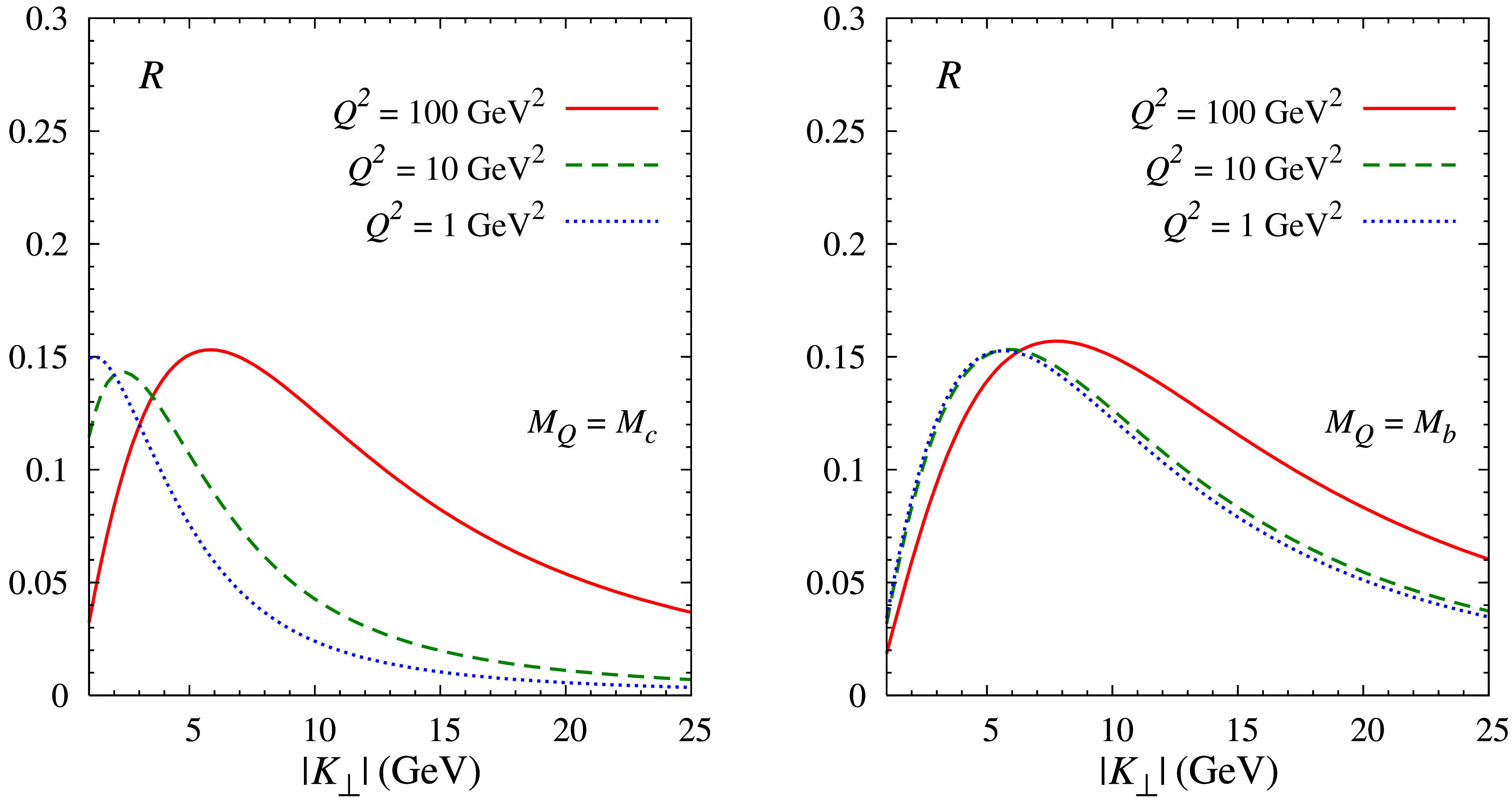


$\langle x_g \rangle = 0.15$

Physics Letters B 772 (2017) 854

Maximum asymmetries in heavy quark production

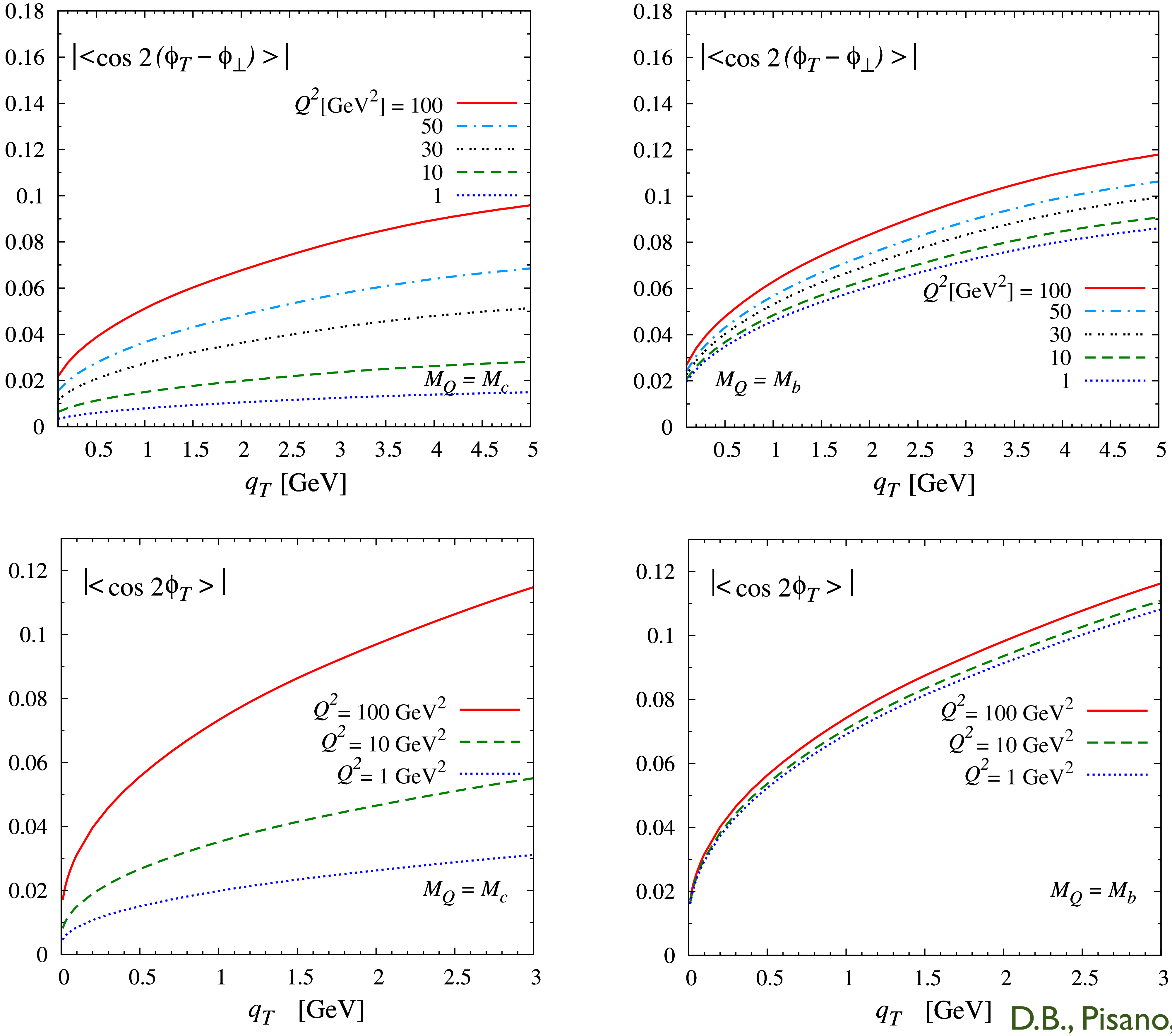
$ep \to e' Q\bar{Q} X$ $R = \text{bound on } |\langle \cos 2(\phi_T - \phi_\perp) \rangle|$



[Pisano, D.B., Brodsky, Buffing & Mulders, JHEP 10 (2013) 024]

Maximal asymmetries can be substantial (for any Q^2 and for both charm & bottom)

Heavy quark pair production at EIC



small x model
similar in size

$|\boldsymbol{K}_\perp| = 10\,\mathrm{GeV}$
$z = 0.5$
$y = 0.3$

$|\boldsymbol{K}_\perp| = 6\,\mathrm{GeV}$
$z = 0.5$
$y = 0.1$

D.B., Pisano, Mulders, Zhou, 2016

Dijet production at EIC

$h_1^{\perp g}$ (WW) is accessible in dijet production in eA collisions at a high-energy EIC

[Metz, Zhou 2011; Pisano, D.B., Brodsky, Buffing, Mulders, 2013; D.B., Pisano, Mulders, Zhou, 2016]

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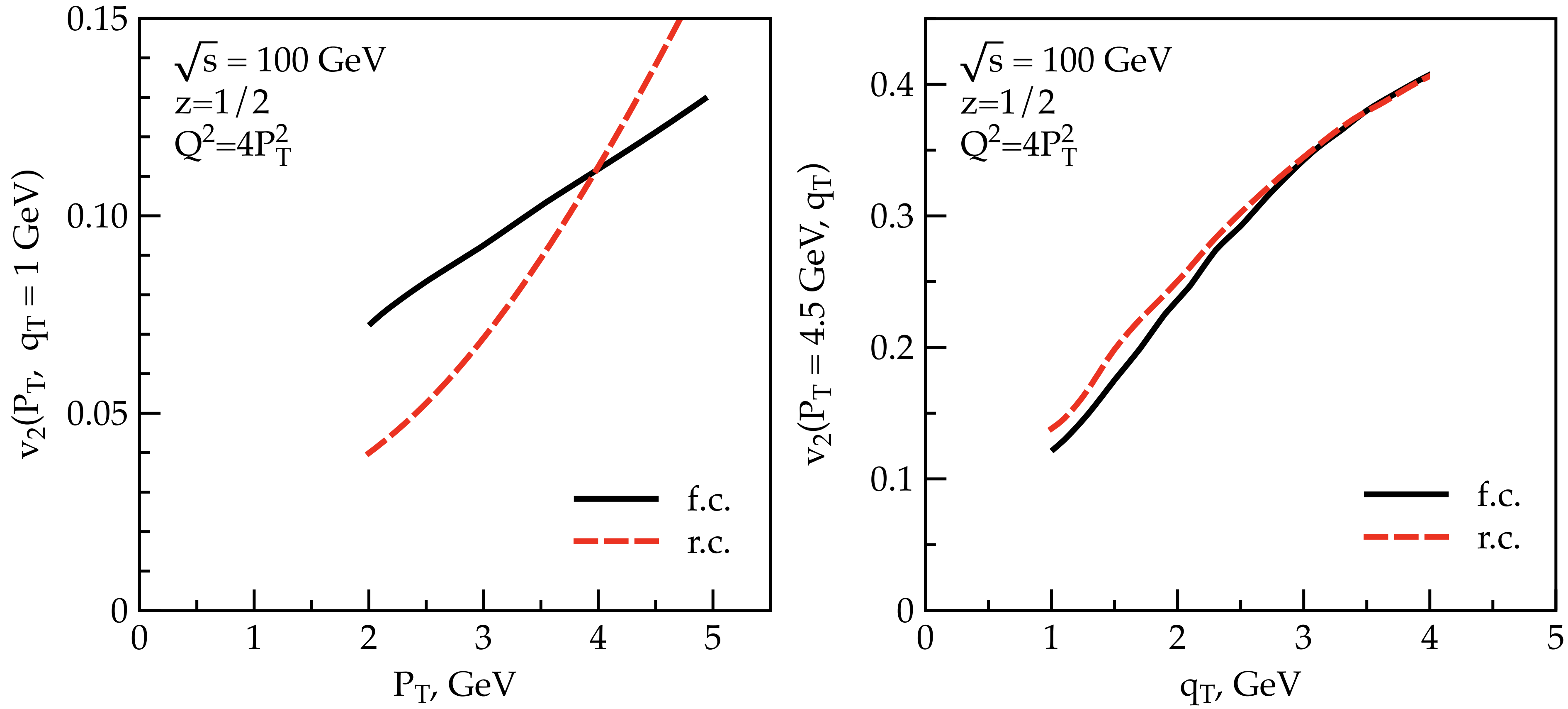
Polarization shows itself through a cos2ϕ distribution



Large effects are found

Dumitru, Lappi, Skokov, 2015

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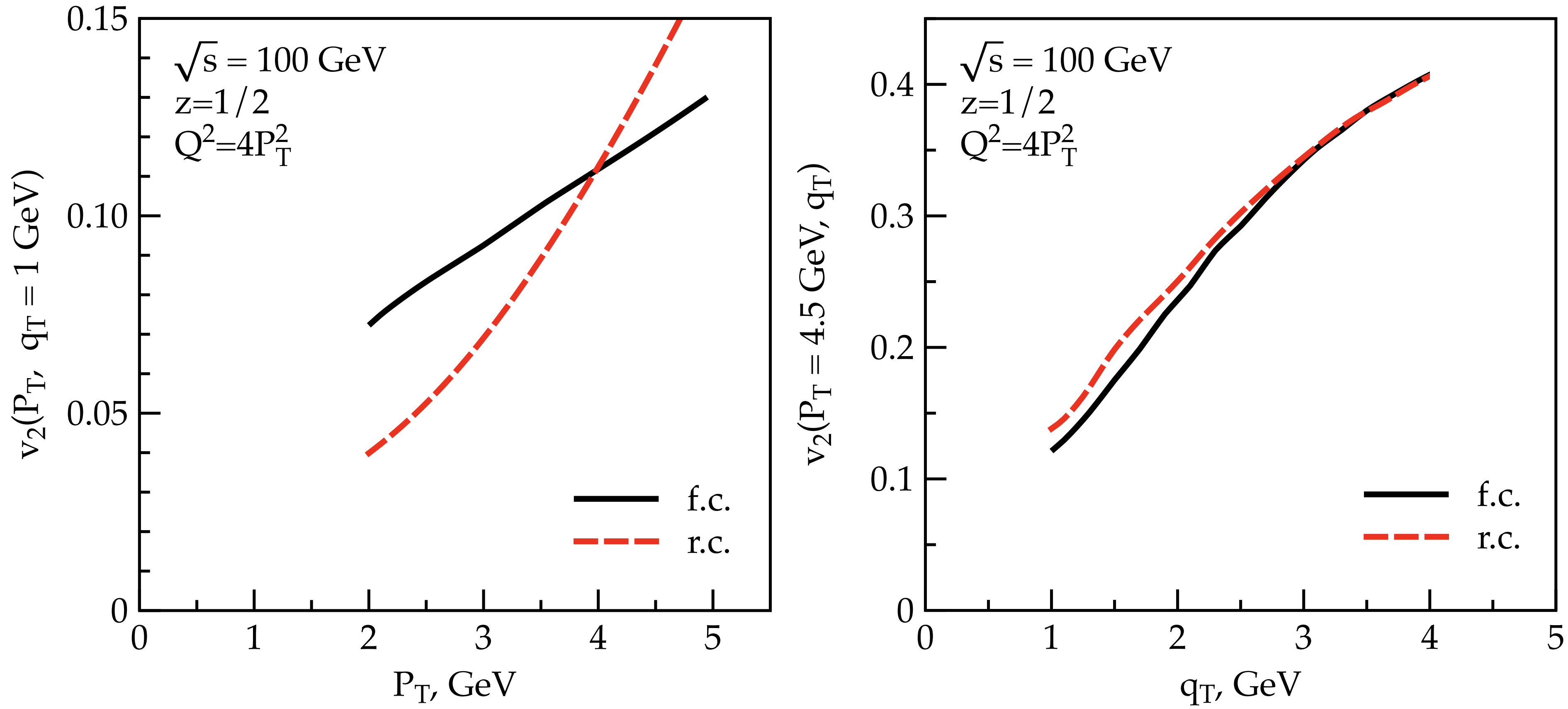
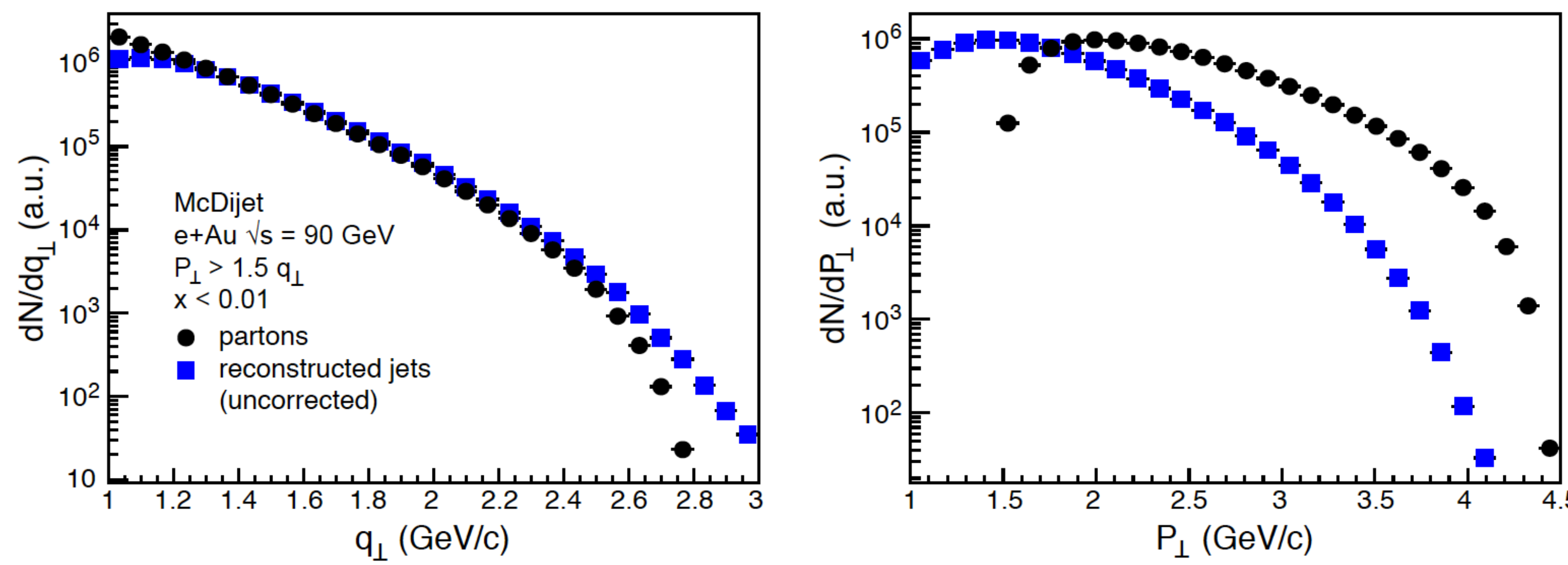


Large effects are found

Dumitru, Lappi, Skokov, 2015

cos2ϕ has opposite signs for L and T γ^* polarization

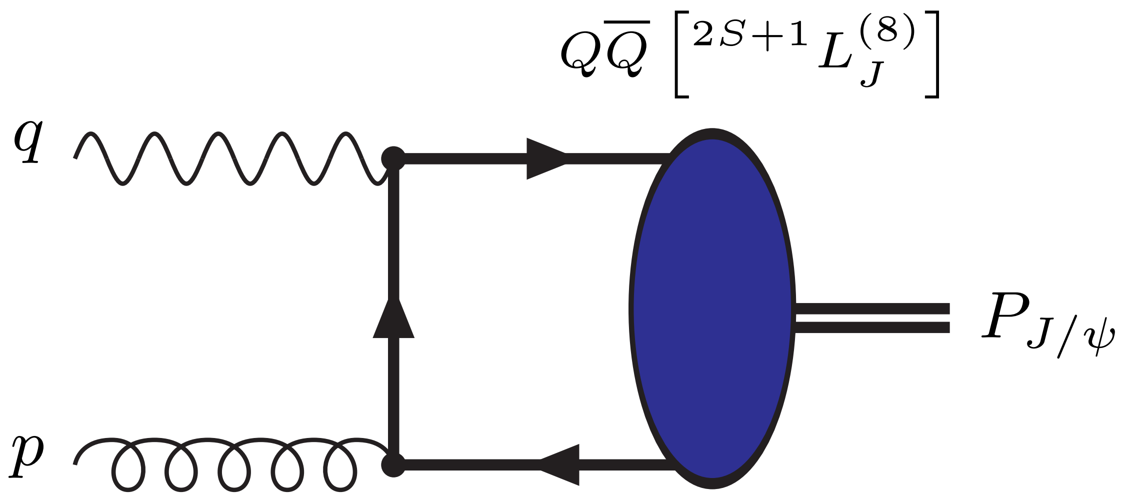
Dumitru, Skokov, Ullrich, 2018



Quarkonia

$$e\,p^{\uparrow} \to e'\,\mathcal{Q}\,X \text{ with } \mathcal{Q} \text{ either a } J/\psi \text{ or a } \Upsilon \text{ meson}$$

[Godbole, Misra, Mukherjee, Rawoot, 2012/3; Godbole, Kaushik, Misra, Rawoot, 2015; Mukherjee, Rajesh, 2017; Rajesh, Kishore, Mukherjee, 2018]



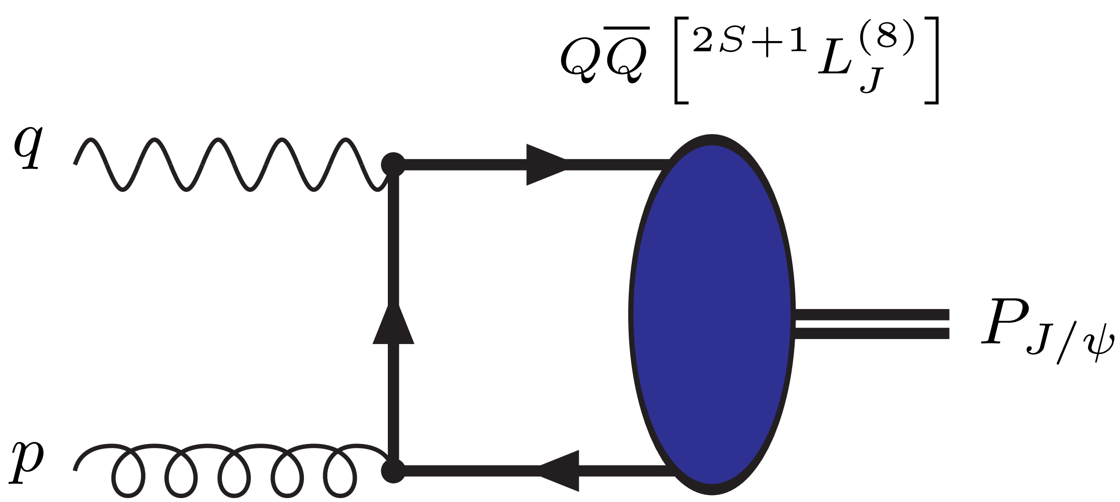
One either uses the Color Evaporation Model or NRQCD for Color Octet (CO) states

$$A^{\sin(\phi_S-\phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p}\,\frac{f_{1T}^{\perp\,g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}$$

Quarkonia

$e\,p^{\uparrow} \to e'\,\mathcal{Q}\,X$ with $\mathcal{Q}$ either a J/ψ or a Υ meson

[Godbole, Misra, Mukherjee, Rawoot, 2012/3; Godbole, Kaushik, Misra, Rawoot, 2015; Mukherjee, Rajesh, 2017; Rajesh, Kishore, Mukherjee, 2018]



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Other asymmetries depend on the quite uncertain CO NRQCD LDMEs, but one can consider ratios of asymmetries to cancel them out at leading order

[Bacchetta, Boer, Pisano, Taels, arXiv:1809.02056]

$$\frac{A^{\cos 2\phi_T}}{A^{\sin(\phi_S+\phi_T)}} = \frac{\boldsymbol{q}_T^2}{M_p^2}\,\frac{h_1^{\perp\,g}(x,\boldsymbol{q}_T^2)}{h_1^g(x,\boldsymbol{q}_T^2)}$$

$$\frac{A^{\cos 2\phi_T}}{A^{\sin(\phi_S-3\phi_T)}} = -\frac{1}{2}\,\frac{h_1^{\perp\,g}(x,\boldsymbol{q}_T^2)}{h_{1T}^{\perp\,g}(x,\boldsymbol{q}_T^2)}$$

$$\frac{A^{\sin(\phi_S-3\phi_T)}}{A^{\sin(\phi_S+\phi_T)}} = -\frac{\boldsymbol{q}_T^2}{2M_p^2}\,\frac{h_{1T}^{\perp\,g}(x,\boldsymbol{q}_T^2)}{h_1^g(x,\boldsymbol{q}_T^2)}$$

CO NRQCD LDMEs @ EIC

But one can also consider ratios where the TMDs cancel out at leading order and one can obtain new experimental information on the CO NRQCD LDMEs

This requires a comparison to the process $ep \to e' Q\bar{Q} X$

$$\mathcal{R}^{\cos 2\phi} = \frac{\int d\phi_T \cos 2\phi_T \, d\sigma^{\mathcal{Q}}(\phi_S, \phi_T)}{\int d\phi_T \, d\phi_\perp \cos 2\phi_T \, d\sigma^{Q\overline{Q}}(\phi_S, \phi_T, \phi_\perp)}$$

$$\mathcal{R} = \frac{\int d\phi_T \, d\sigma^{\mathcal{Q}}(\phi_S, \phi_T)}{\int d\phi_T \, d\phi_\perp \, d\sigma^{Q\overline{Q}}(\phi_S, \phi_T, \phi_\perp)}$$

Two observables depending on two unknowns:

$$\mathcal{O}_8^S \equiv \langle 0 | \mathcal{O}_8^{\mathcal{Q}}(^1S_0) | 0 \rangle$$

$$\mathcal{O}_8^P \equiv \langle 0 | \mathcal{O}_8^{\mathcal{Q}}(^3P_0) | 0 \rangle$$

$$\mathcal{R}^{\cos 2\phi_T} = \frac{27\pi^2}{4} \frac{1}{M_Q} \left[\mathcal{O}_8^S - \frac{1}{M_Q^2} \mathcal{O}_8^P \right]$$

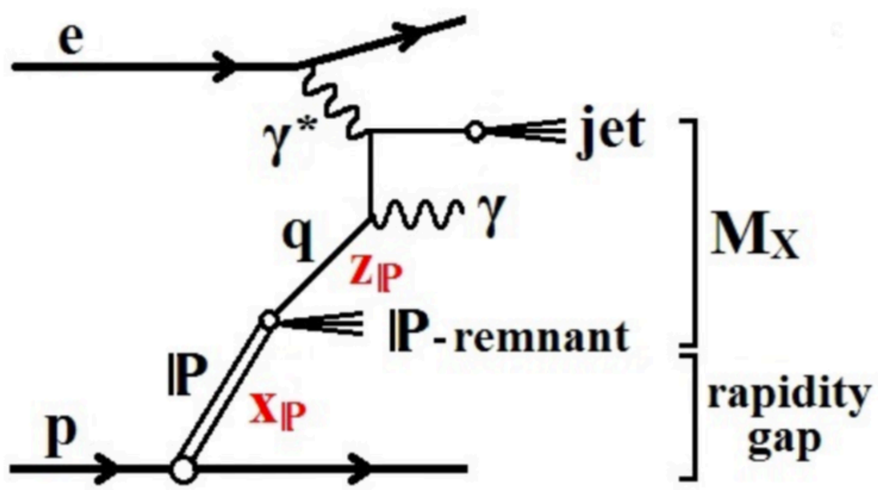
$$\mathcal{R} = \frac{27\,\pi^2}{4} \frac{1}{M_Q} \frac{[1 + (1-y)^2]\, \mathcal{O}_8^S + (10 - 10y + 3y^2)\, \mathcal{O}_8^P / M_Q^2}{26 - 26y + 9y^2}$$

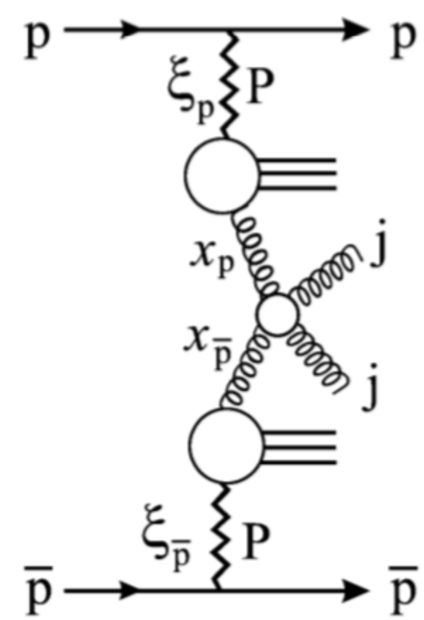
[Bacchetta, Boer, Pisano, Taels, arXiv:1809.02056]

Plus similar (but different) equations for *polarized* quarkonium production

Multi-dimensional parton distributions

Diffractive dijet production indicates **non-factorization** in pp and $p\bar{p}$ collisions [SPS, Tevatron, LHC] compared to ep [HERA]

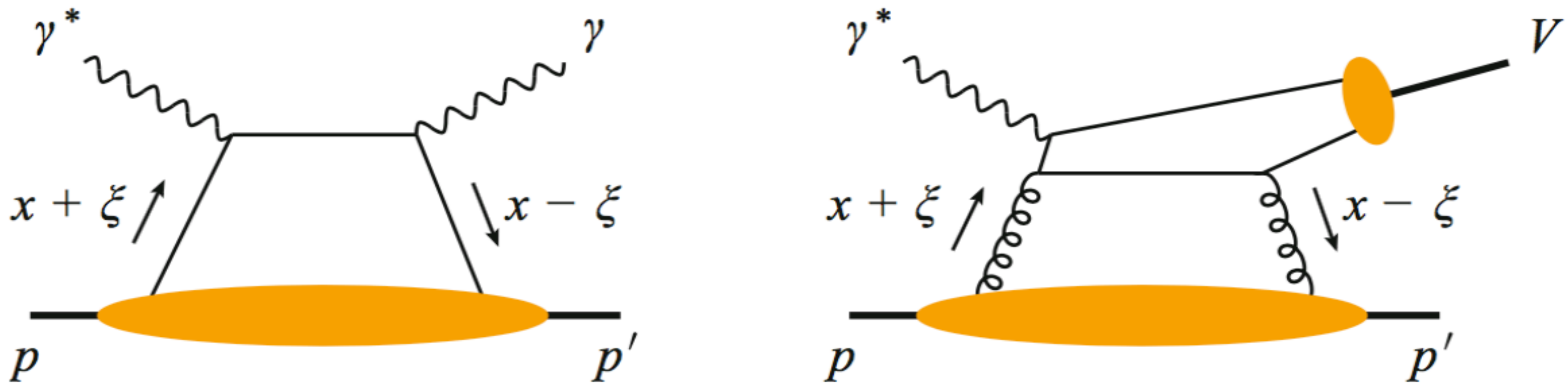




Inclusive dijet observables in pp that probe TMDs (transverse momentum dependent PDFs) are also expected to be **non-factorizing**

New knowledge on the origin and magnitude of the **non-factorization** is expected and is needed for global analyses of multi-dimensional PDFs

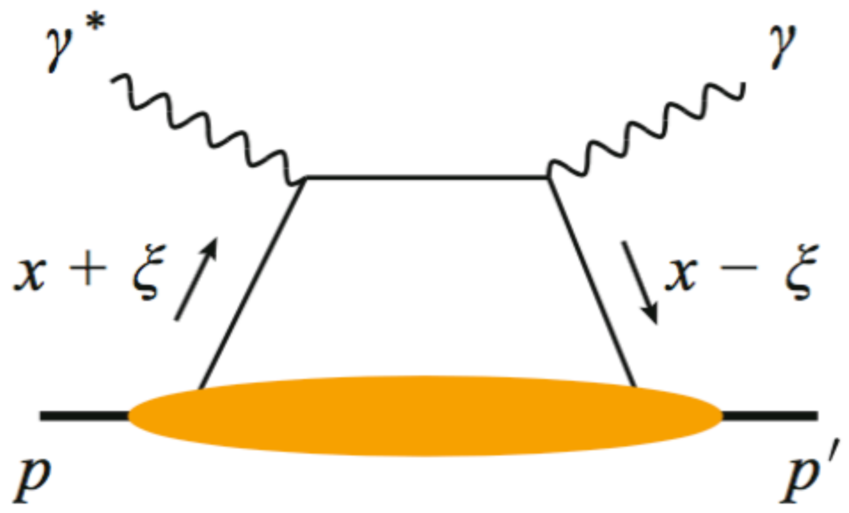
GDPs

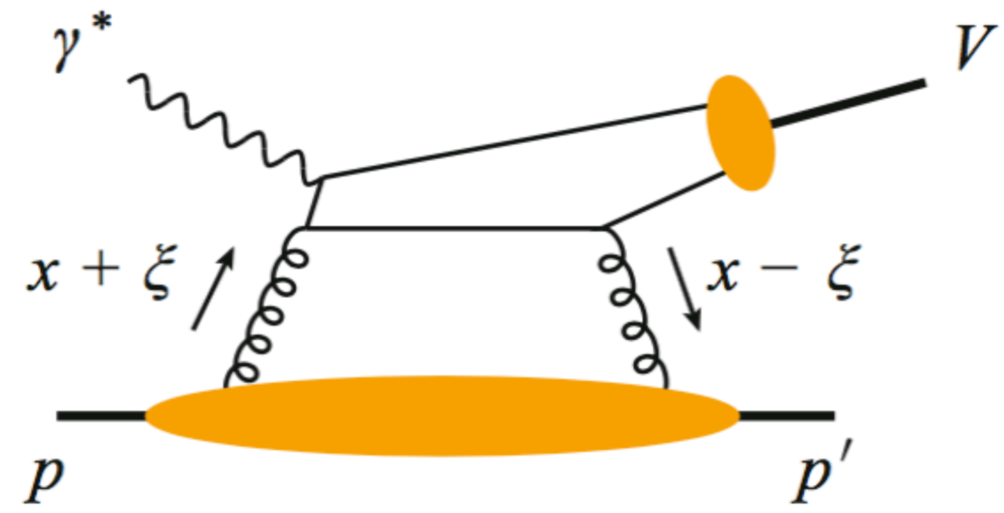


At EIC quark GPDs will be extracted in order to study quark OAM

$$J^q = \frac{1}{2}\int \mathrm{d}x\, x\, \left[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right]$$

GDPs





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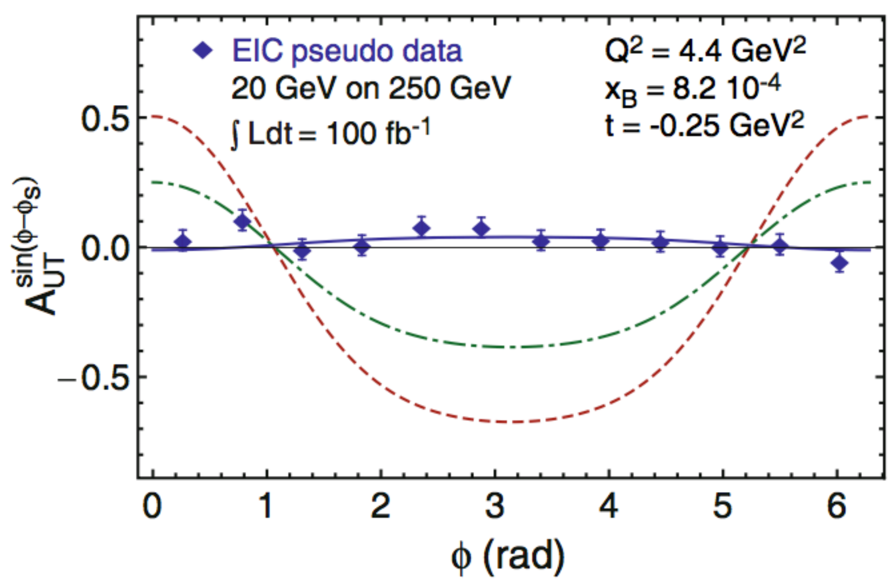
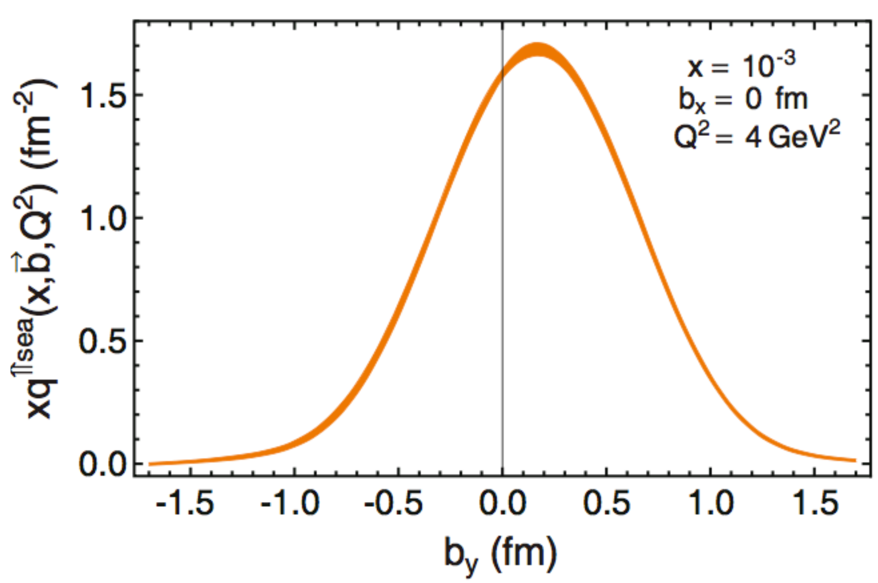
$$J^q = \frac{1}{2}\int \mathrm{d}x\, x\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

Sivers-like distortions ($b_T \times S_T$) and transversity GPDs can also be studied via transverse spin asymmetries





See Boer et al., arXiv:1108.1713; Accardi *et al.*, Understanding the glue that binds us all, EPJA (2016)