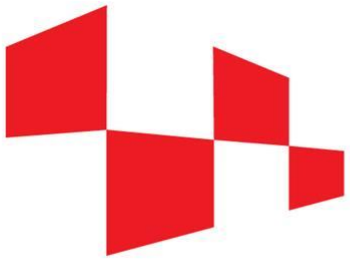
QCD theory overview

Sanjin Benić (University of Zagreb)

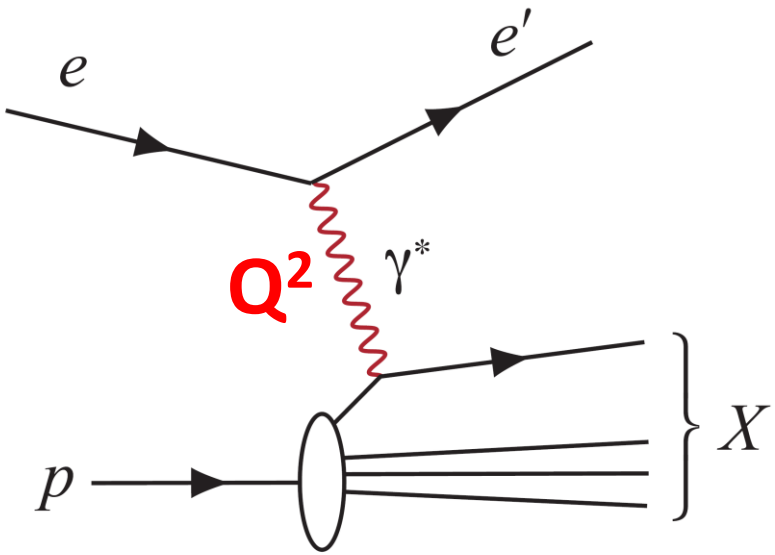
LHC days in Split, Sep 8- Oct 14, 2024



HrZZ
Croatian Science Foundation

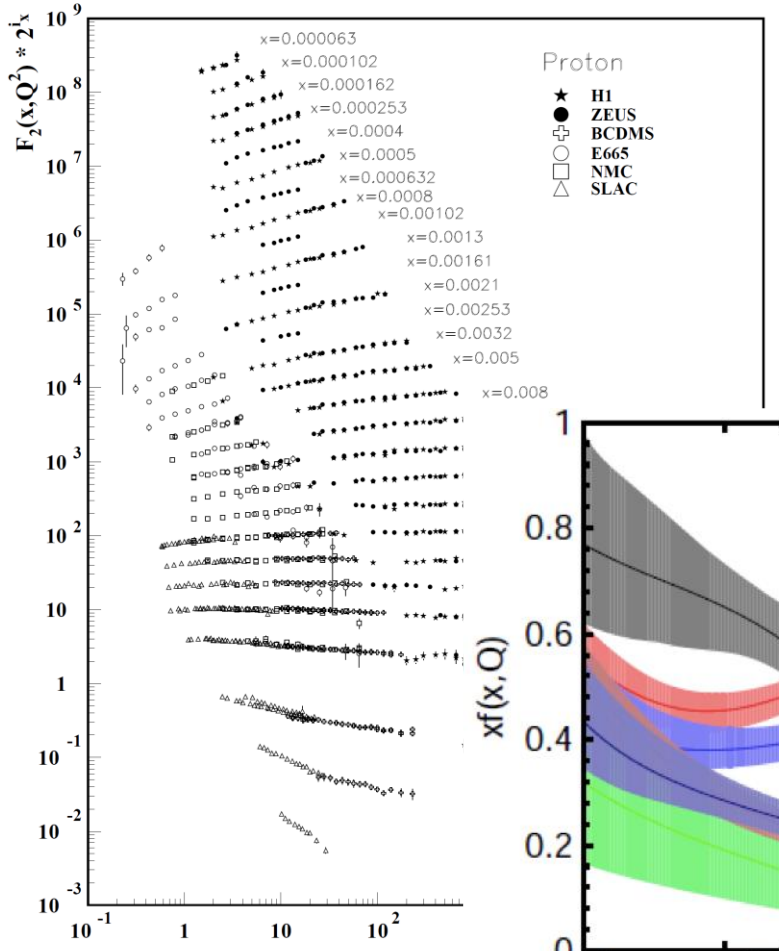
Structure of the proton

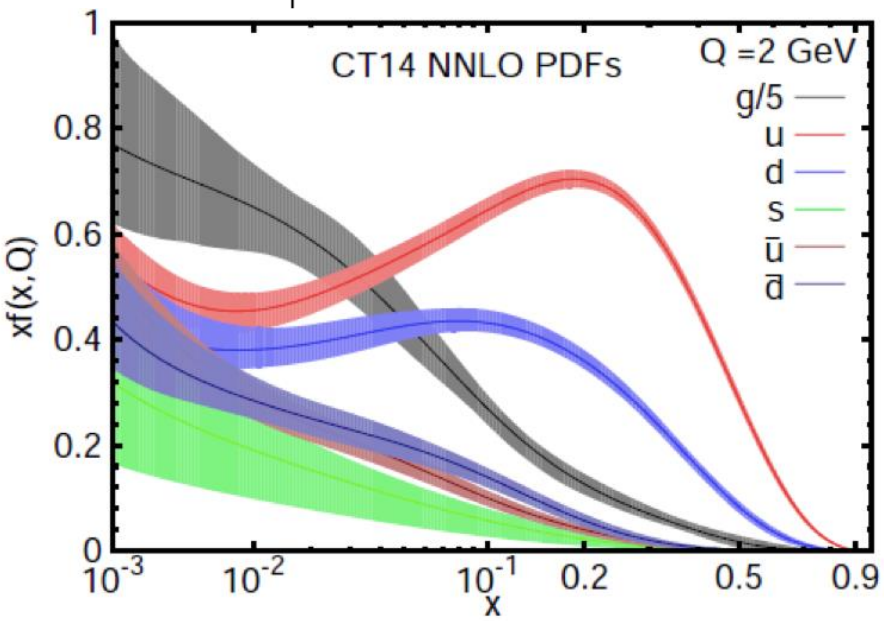
. DIS – a paradigm for probing the proton



$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} \sim f(x) \otimes H(x)$$

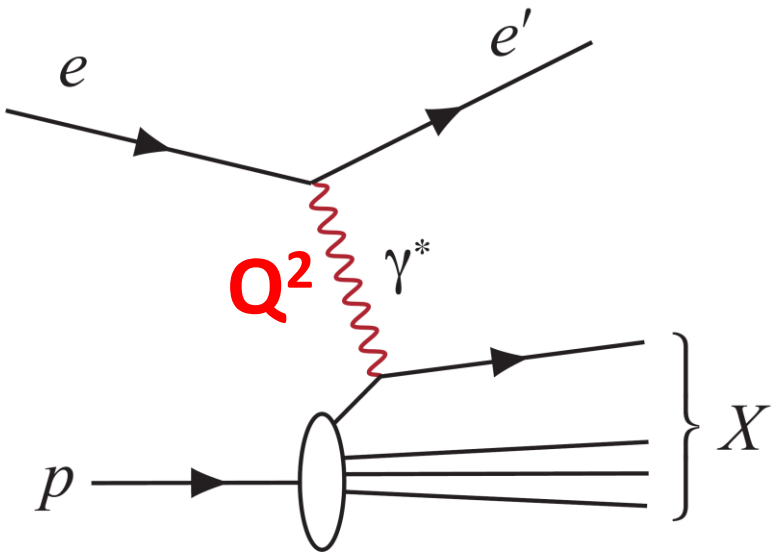
. the legacy of HERA..





Structure of the proton

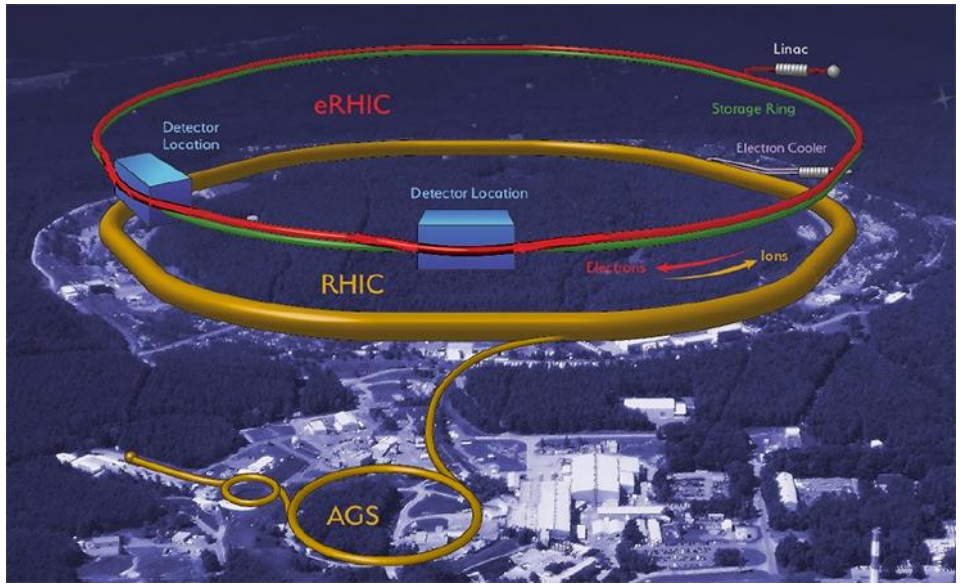
. DIS – a paradigm for probing the proton



$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} \sim f(x) \otimes H(x)$$

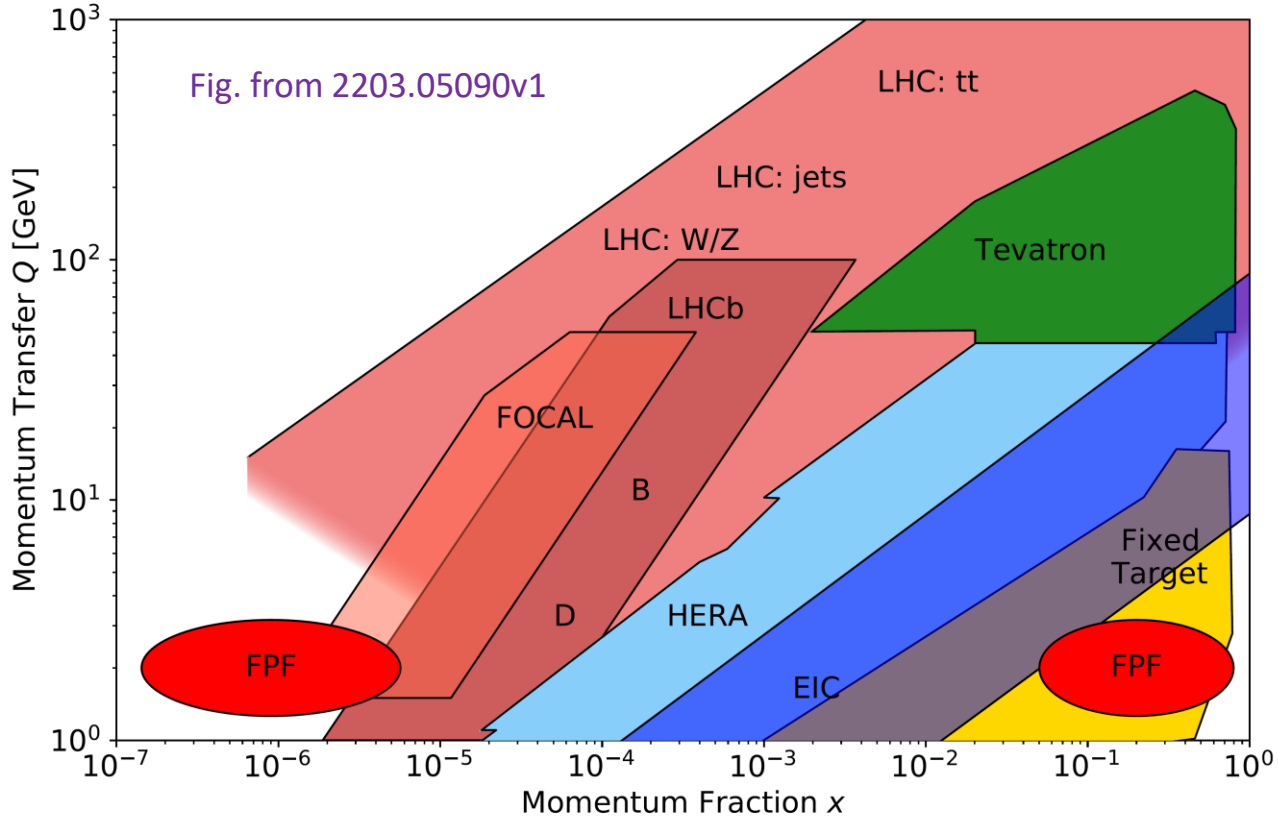
. and the future:

Electron-Ion Collider (EIC)

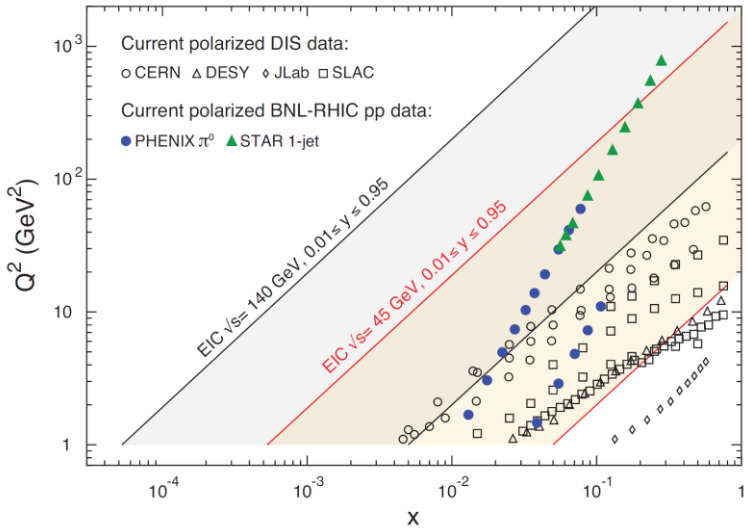


. 10^2 increase in luminosity from HERA
. < 140 GeV collision energy
. polarized electrons/protons/light ions
. different ion species
. tomography, spin, gluon saturation,…

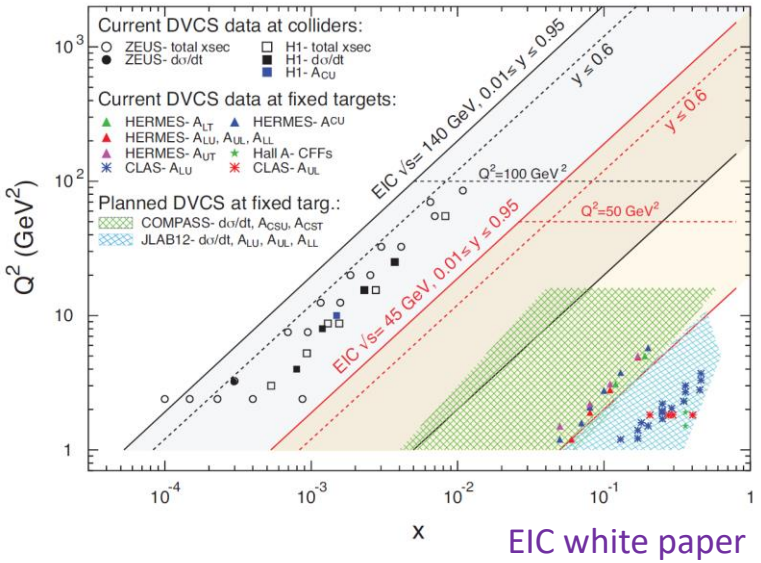
LHC vs EIC kinematics



spin



tomography



EIC white paper

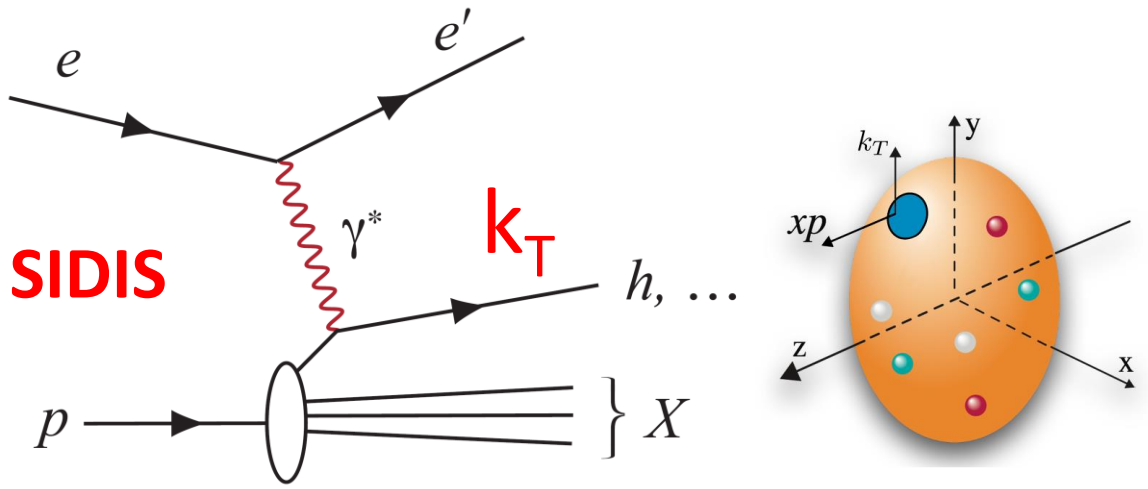
. LHC: unmatched kinematics reach in x-Q^2

. EIC: dedicated QCD studies such as spin, tomography, etc..

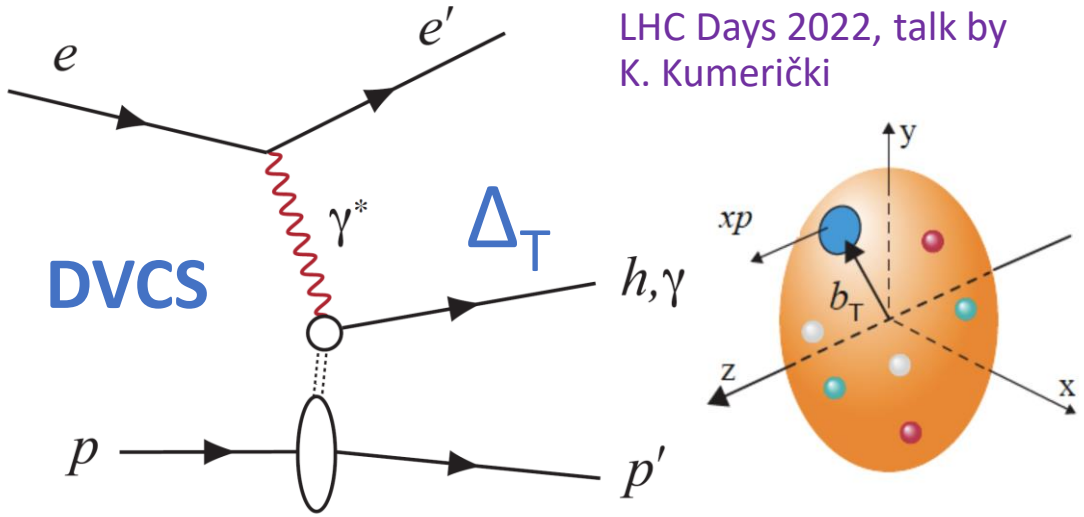
Tomography

Figs. from EIC Yellow Report

. **expand** the scope of the QCD processes -> enter the world of **multidimensional parton structure**



LHC Days 2022, talk by K. Kumerički



TMD = transverse momentum dependent PDF

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}^2\boldsymbol{k}_\perp} \sim f(x,\boldsymbol{k}_\perp) \otimes H(x,\boldsymbol{k}_\perp)$$

transverse confined motion inside the proton

GPD = generalized parton distribution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}^2\boldsymbol{\Delta}_\perp} \sim \left| f(x,\boldsymbol{\Delta}_\perp) \otimes H(x,\boldsymbol{\Delta}_\perp) \right|^2$$

spatial imaging (via Fourier transform)

TMDs

$$f(x, \boldsymbol{k}_\perp) \sim \int \frac{\mathrm{d}\xi^- \mathrm{d}^2\boldsymbol{\xi}_\perp}{(2\pi)^3} \mathrm{e}^{\mathrm{i}k\cdot\xi} \langle P|\bar{\psi}(0) V[0,\xi]\psi(\xi)|P\rangle_{\xi^+=0}$$

. relies on 2 scales: $Q \gg k_T$ ➡ assumed to work down to $k_T \sim \Lambda_{QCD}$

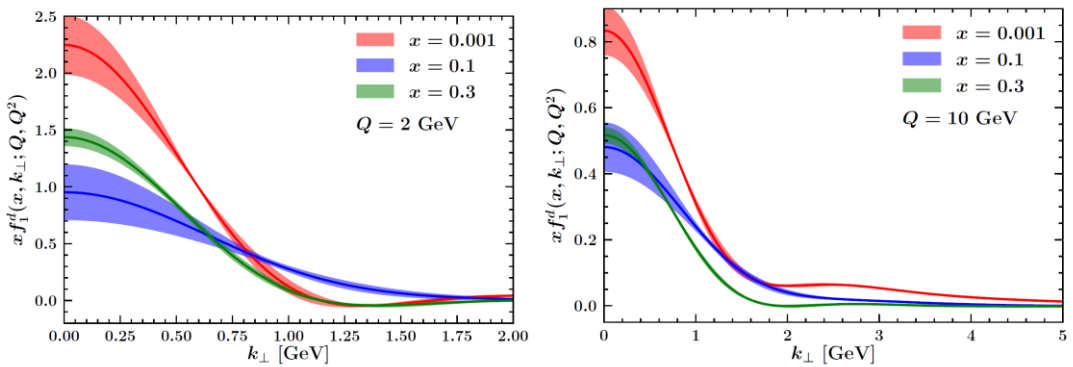
. complicated QCD evolution: soft+collinear gluons (Sudakov logs: $\log^2(k_T/Q)$), two scales, non-perturbative part of the evolution kernel

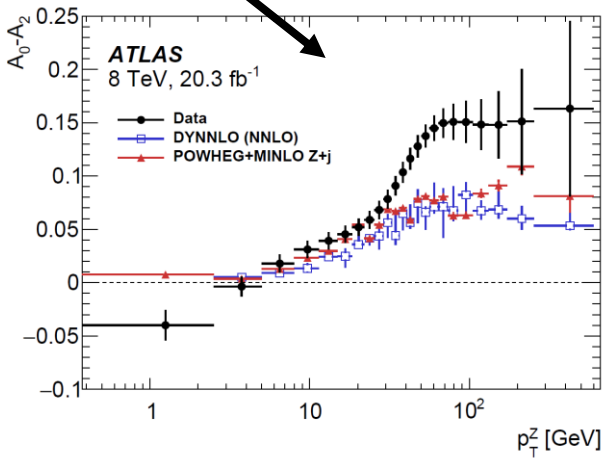
Collins, Soper, Sterman (1985)

. traditionally used to describe **k_T-distributions in Drell-Yan** (e. g. Z-boson at the LHC)

➡ global analysis of DY data

Bacchetta etal. (2020)





intrinsic-k_T violates the Lam-Tung relation

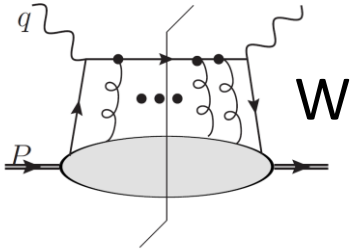
Boer, Vogelsang (2006)

Motyka, Sadzikowski, Stebel (2017)

Piloneta, Vladimirov (2024)

TMDs

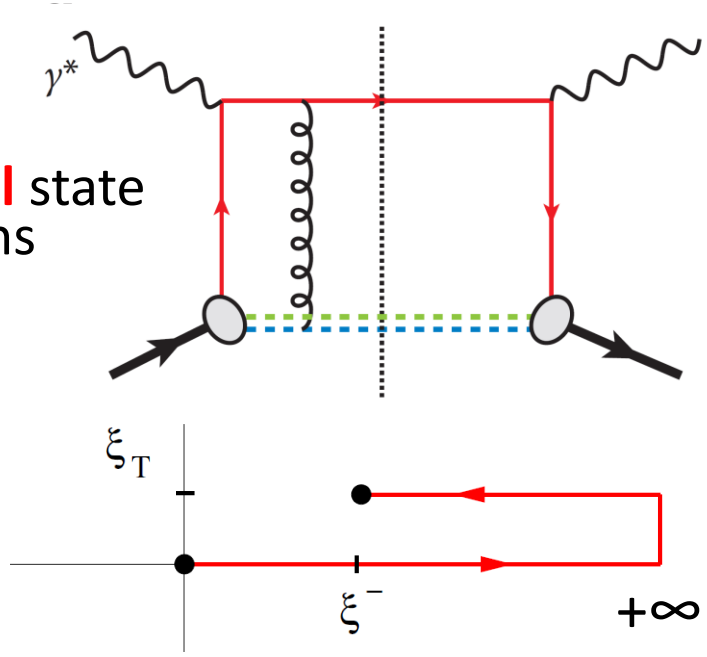
$$f(x,\boldsymbol{k}_\perp) \sim \int \frac{\mathrm{d}\xi^- \mathrm{d}^2\boldsymbol{\xi}_\perp}{(2\pi)^3} \mathrm{e}^{\mathrm{i}k\cdot\xi} \langle P|\bar{\psi}(0)V[0,\xi]\psi(\xi)|P\rangle_{\xi^+=0}$$



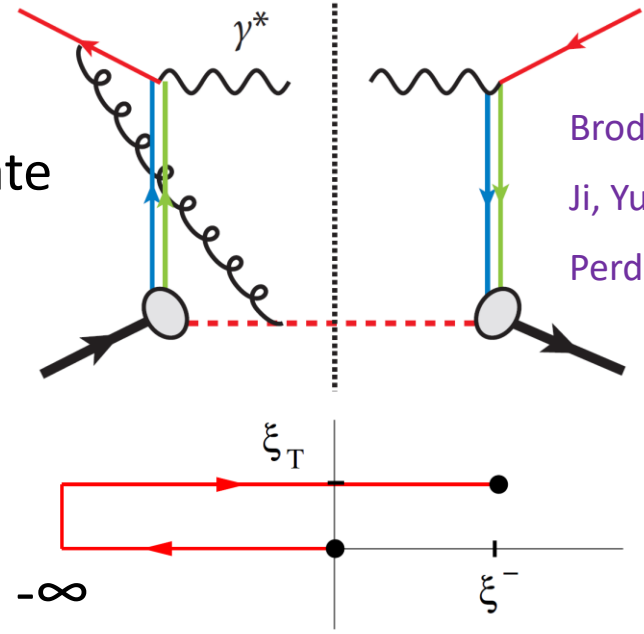
Wilson line

. modified universality (up to phases/gauge links)

SIDIS: **final** state interactions



DY: **initial** state interactions



Brodsky, Hwang, Schmidt (2002)

Ji, Yuan (2002)

Perdekamp, Yuan (2015)

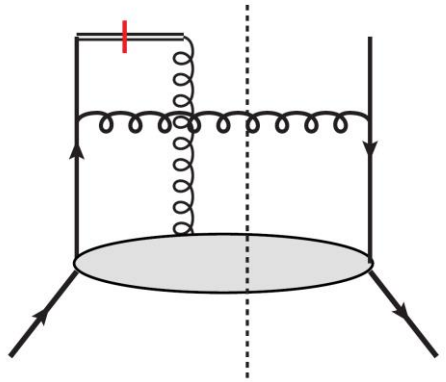
. disappears for usual collinear PDFs

$$f(x) \sim \int \mathrm{d}^2\boldsymbol{k}_\perp f(x,\boldsymbol{k}_\perp) \sim \int \frac{\mathrm{d}\xi^-}{2\pi} \mathrm{e}^{\mathrm{i}k^+\xi^-} \langle P|\bar{\psi}(0)V[0,\xi^-]\psi(\xi^-)|P\rangle$$

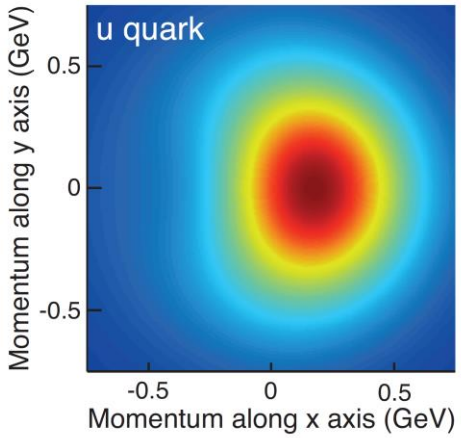
TMDs with spin: the Sivers function

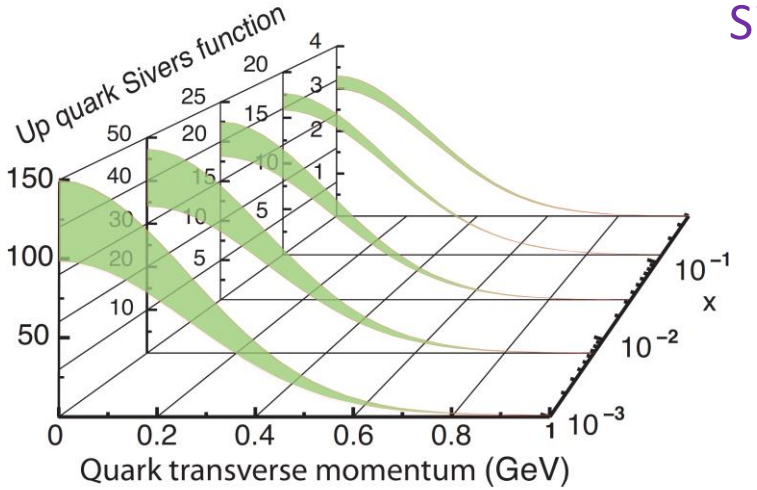
$$f(x, \boldsymbol{k}_\perp) = f_1(x, \boldsymbol{k}_\perp) + (\boldsymbol{k}_\perp \times \boldsymbol{S}_\perp) f_{1T}(x, \boldsymbol{k}_\perp)$$

Sivers (1989)



Ji, Qiu, Vogelsang, Yuan (2006)





. for a (transversely) spinning proton the quark TMD is distorted in the transverse plane

. rich pheno at RHIC, Jlab and COMPASS,..

. future experiments: LHCSpin, EIC,..

. physics of the gauge links: sign change of the Sivers function

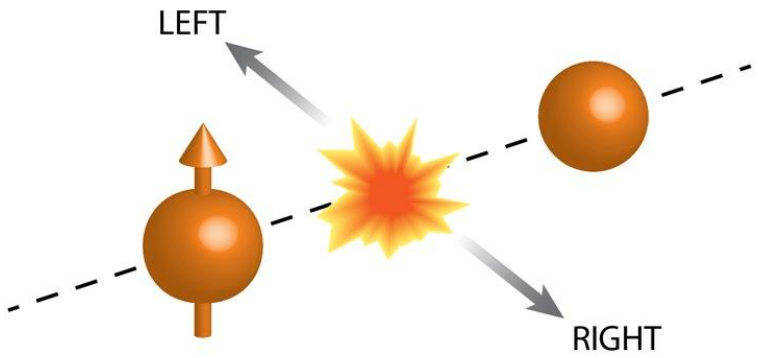
$$f_{1T}^{\mathrm{SIDIS}}(x, \boldsymbol{k}_\perp) = -f_{1T}^{\mathrm{DY}}(x, \boldsymbol{k}_\perp)$$

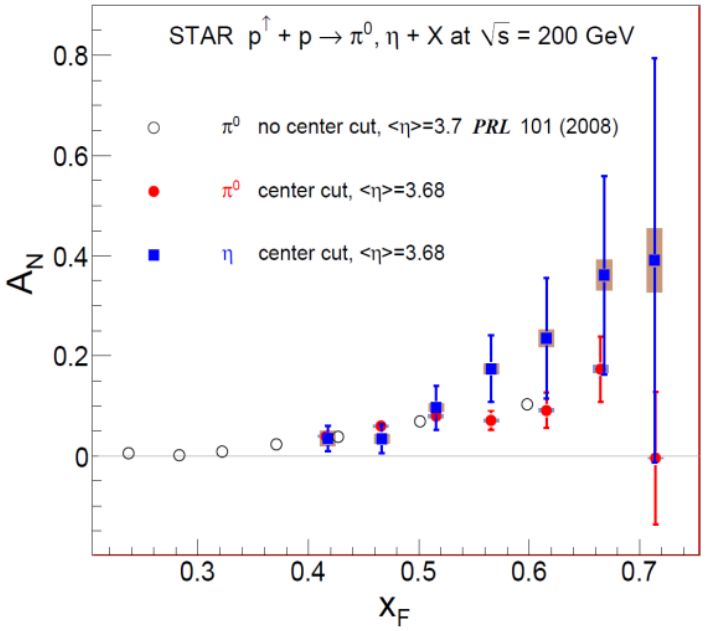
(from time reversal of Wilson line)

-> experimental results scarce, no decisive claim yet

Spin asymmetries

$$A_N = \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)} \sim \boldsymbol{k}_\perp \times \boldsymbol{S}_\perp$$

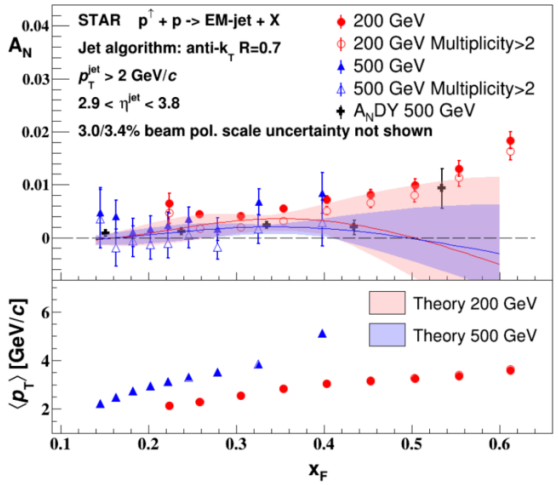


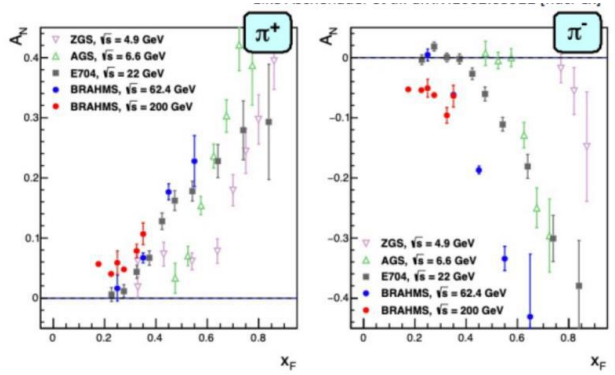


. production of hadrons in polarized pp is left-right asymmetric

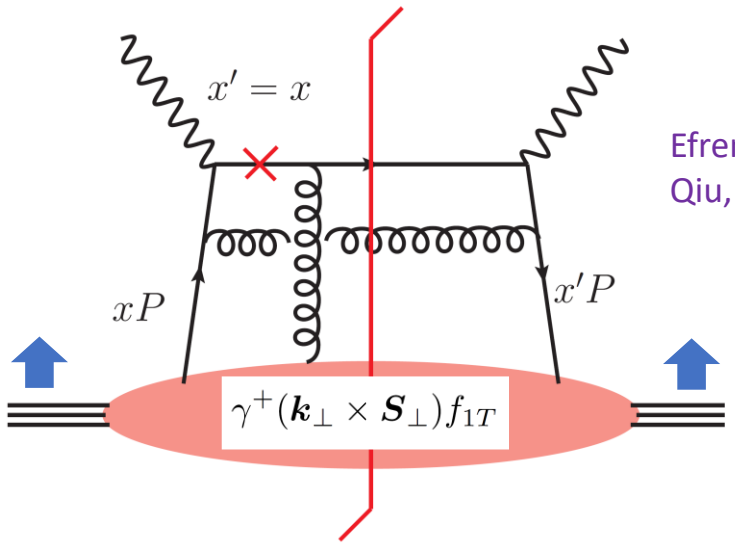
$$A_N \sim \alpha_S \frac{m_q}{k_\perp}$$

Kane, Pumplin, Repko (1978)





„transverse spin puzzle”: experimentally large -> **origin??**



Efremov, Teryaev (1982)
Qiu, Sterman (1999)

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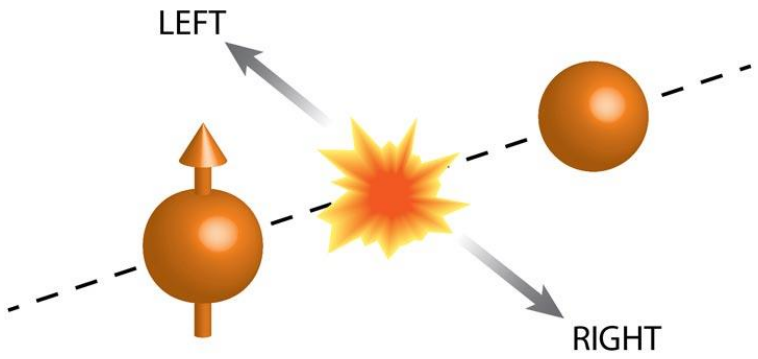

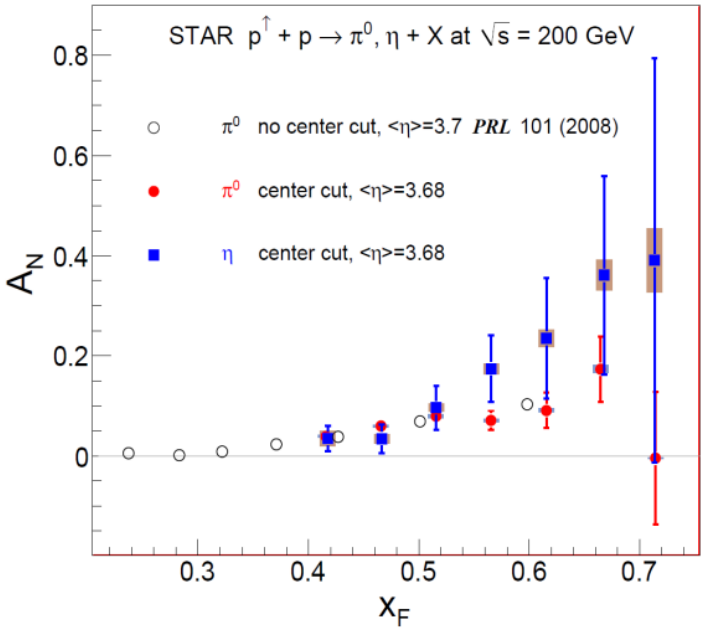

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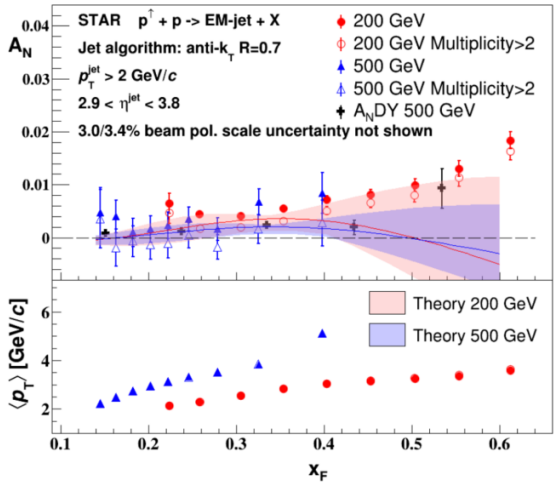

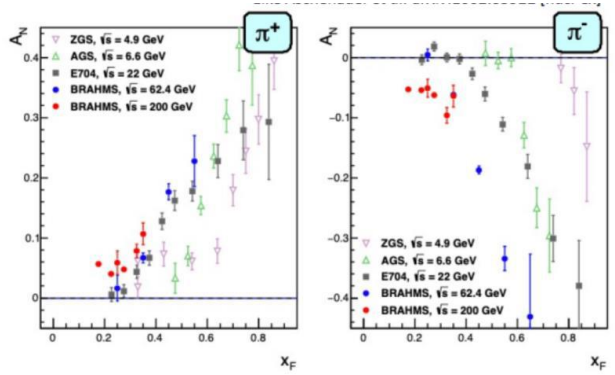

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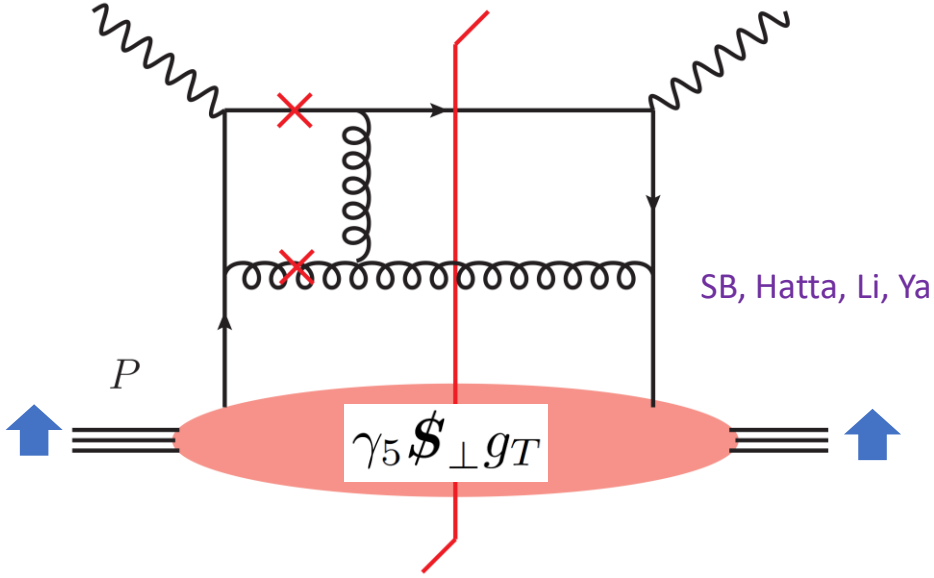
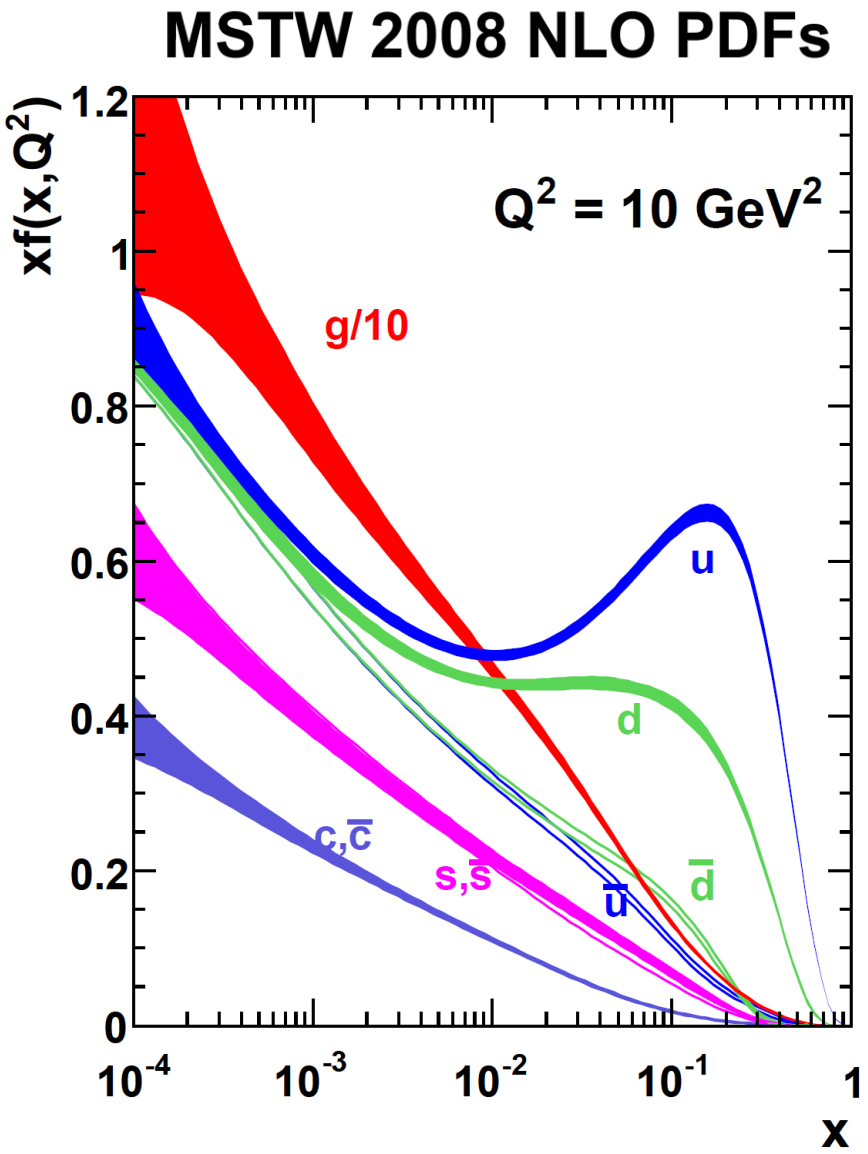
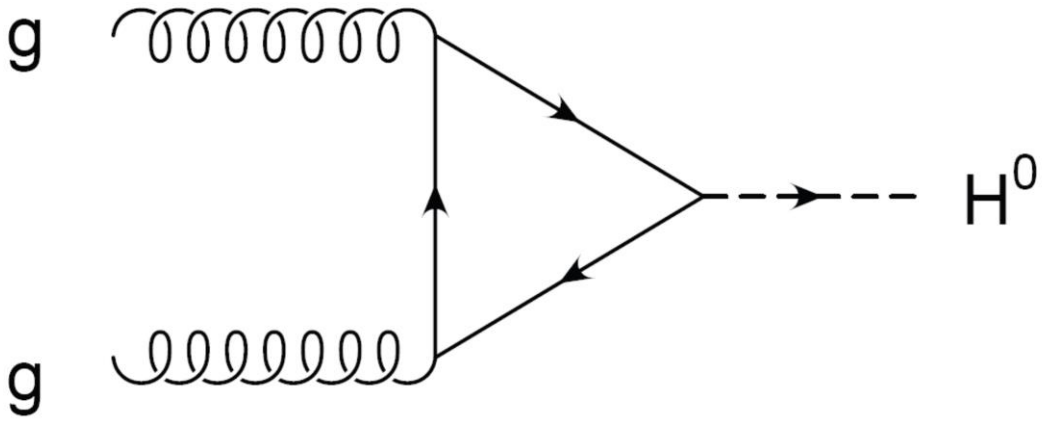


SB, Hatta, Li, Yang (2019)

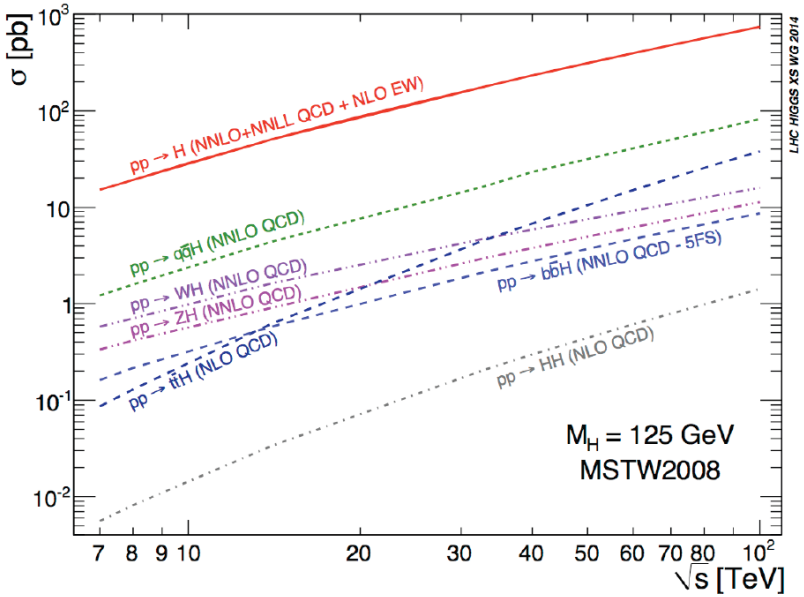
The LHC is a gluon factory

Figs. from T. Gehrmann





-> gg fusion as dominant mechanism for Higgs production

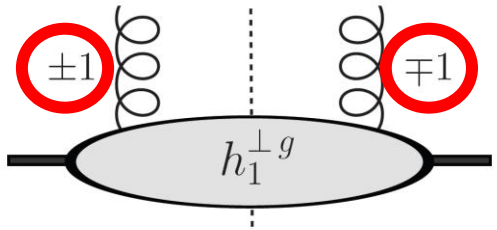


Gluon TMDs

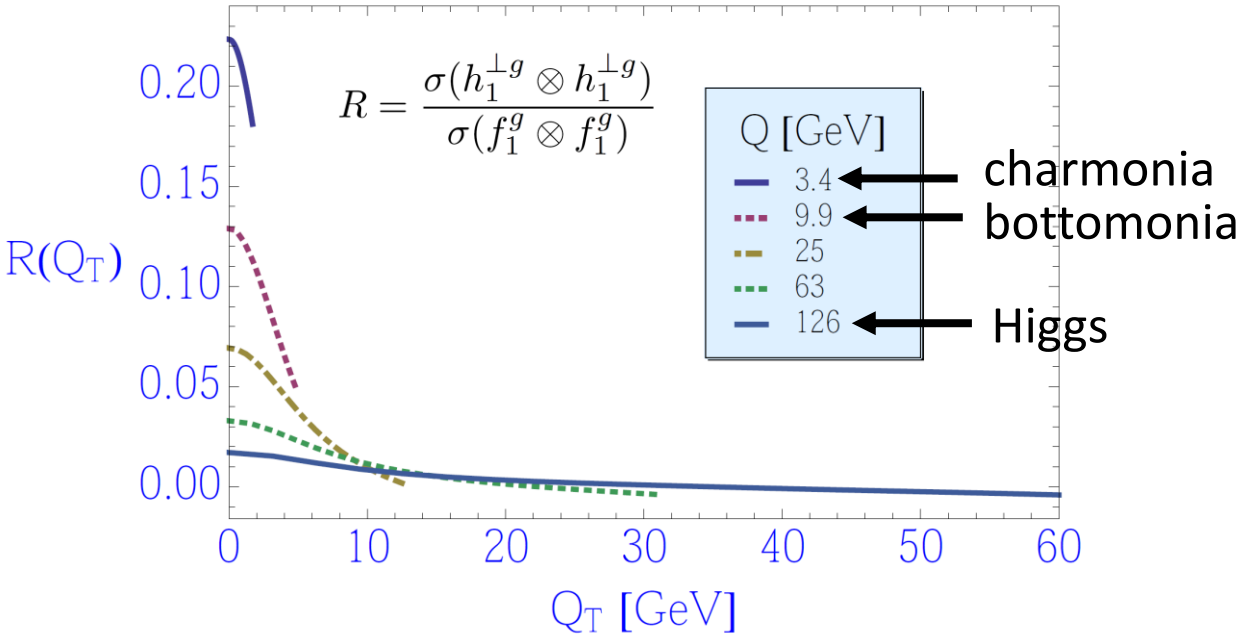
Mulders, Rodrigues (2001)

$$\int \frac{\mathrm{d}\xi^- \mathrm{d}^2\boldsymbol{\xi}_\perp}{(2\pi)^3} e^{\mathrm{i}k\cdot\xi} \langle P|F^{+i}(0)F^{+j}(\xi)|P\rangle_{\xi^+=0} \sim \delta^{ij} f_1^g(x,\boldsymbol{k}_\perp) + \left(\delta^{ij} - \frac{k_\perp^i k_\perp^j}{\boldsymbol{k}_\perp^2}\right) h_1^{\perp g}(x,\boldsymbol{k}_\perp)$$

-> with finite k_T gluons can be linearly polarized even in unpolarized proton



-> turns up in e. g. Higgs production at small k_T



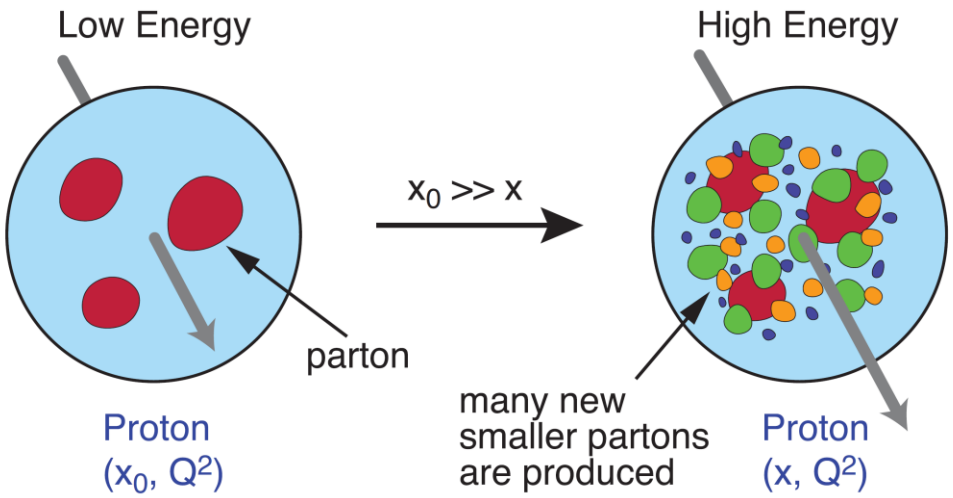
interference between + and - helicity!

Boer, den Dunnen (2014)

. for lighter scalar particle can be substantial, while for Higgs is a few percent effect

Physics at small-x

. gluons dominate at low-x (high energy)



"Color Glass Condensate"

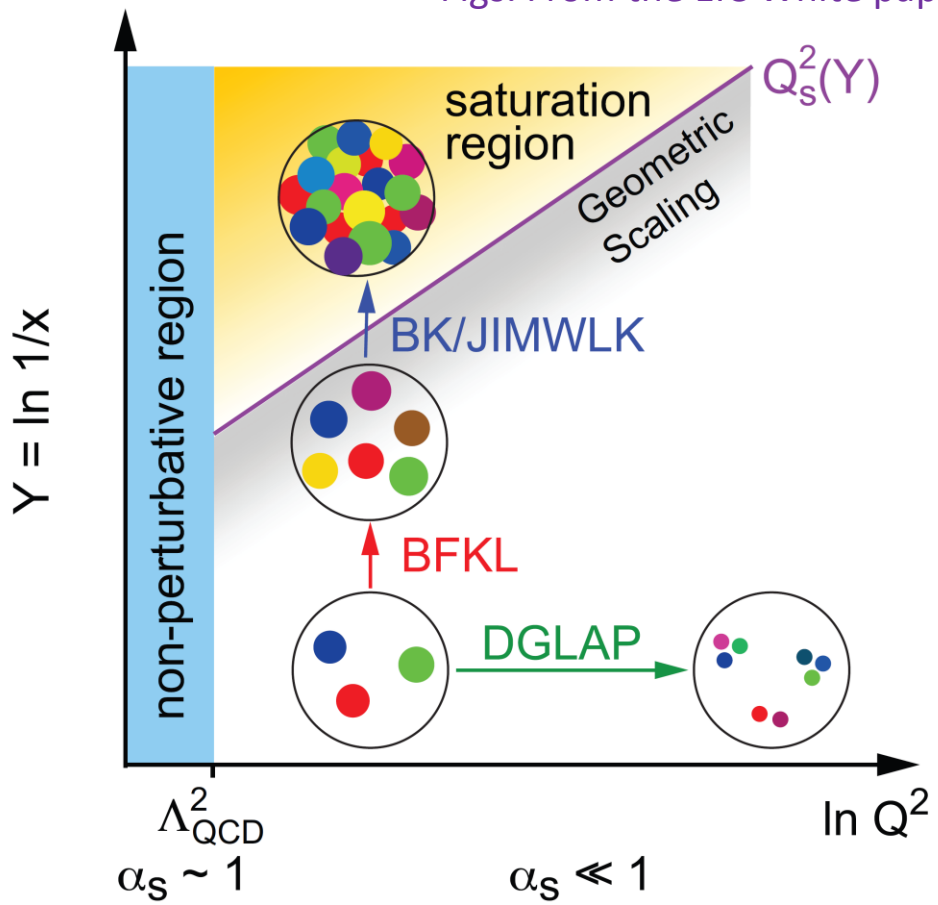
Dominguez, Xiao, Yuan (2011)

dipole S-matrix: $N(x, \boldsymbol{\xi}_\perp)$

$$\frac{f(x,\boldsymbol{k}_\perp)}{\boldsymbol{k}_\perp^2} \sim \int \frac{d^2\boldsymbol{\xi}_\perp}{(2\pi)^2} \mathrm{e}^{-\mathrm{i}\boldsymbol{k}_\perp\cdot\boldsymbol{\xi}_\perp} \langle P|V(0)V^\dagger(\boldsymbol{\xi}_\perp)|P\rangle$$

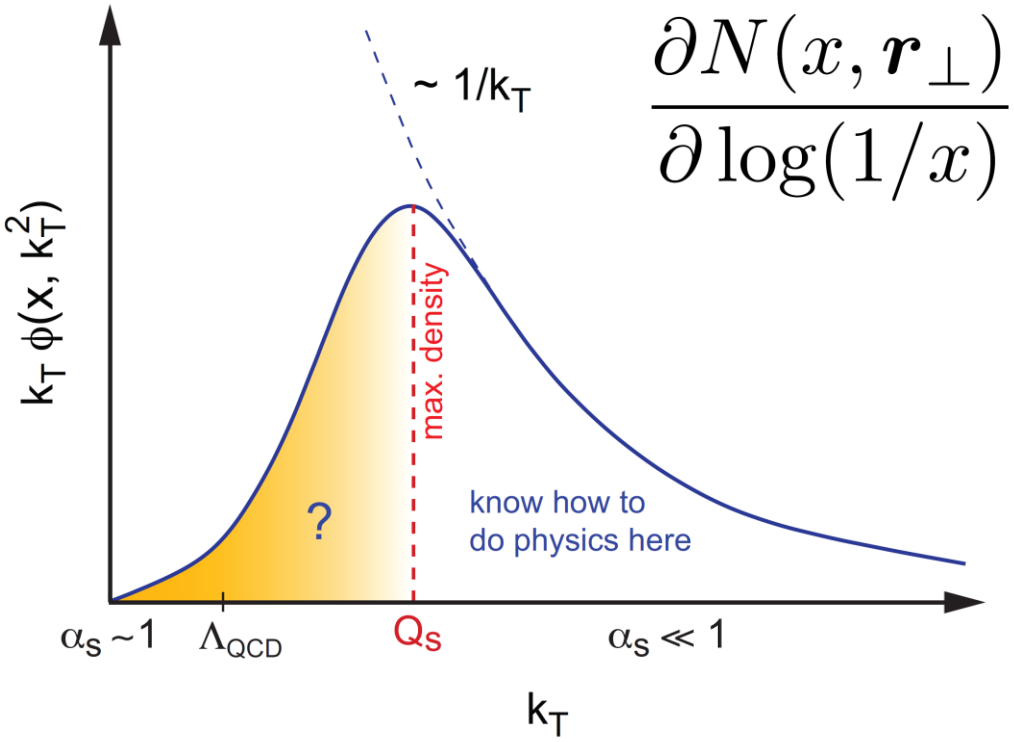
constructed entirely from Wilson lines: includes all-twists..

Figs. From the EIC White paper



. "orthogonal" to DGLAP we find evolution in x (gluons ordered in light-cone momenta): **BFKL** (linear), **BK/JIMWLK** (non-linear)

Gluon saturation



Balitsky-Kovchegov equation

$$\frac{\partial N(x,\boldsymbol{r}_\perp)}{\partial \log(1/x)} = \alpha_S K_{\mathrm{BFKL}} \otimes N(x,\boldsymbol{r}_\perp) - \alpha_S (N(x,\boldsymbol{r}_\perp))^2$$

. at large densities, gluon recombination balances gluon splitting

saturation scale $Q_s^2 \sim x^{-0.3} A^{1/3}$

nuclear oomph!

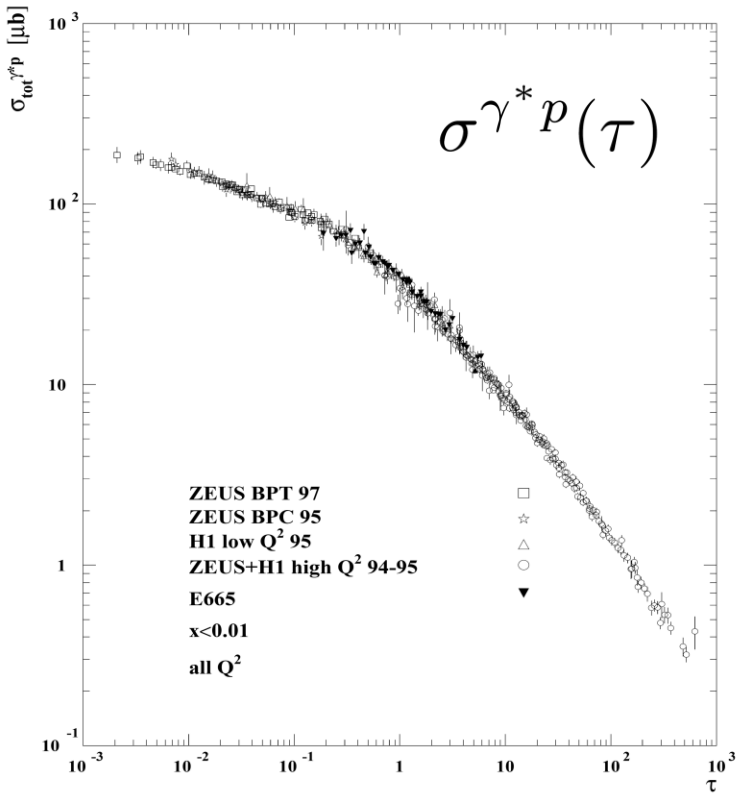
. saturated glue is maximally polarized: $f_1^g(x,\boldsymbol{k}_\perp) \sim h_1^{\perp g}(x,\boldsymbol{k}_\perp)$ Metz, Zhou (2011)

. large densities source large fields -> tree level, classical description

McLerran, Venugopalan (1994)

. **signals, precision** (NLO)?

Signals of gluon saturation



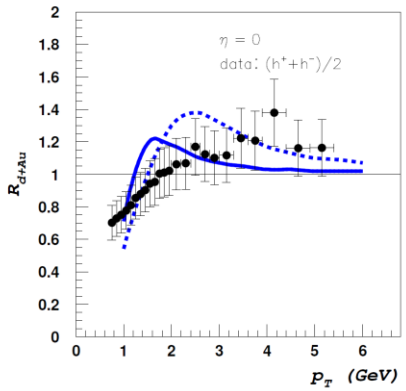
. geometric scaling @HERA

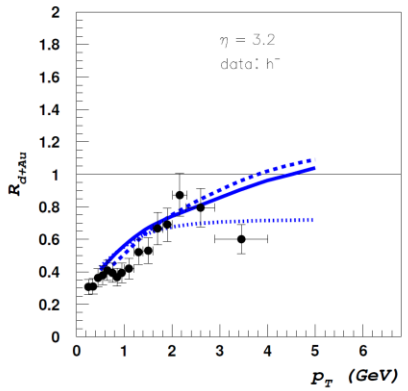
$$\tau = Q^2/Q_S^2(x)$$

Stasto, Golec-Biernat, Kwiecinski (2000)

. nuclear modifications

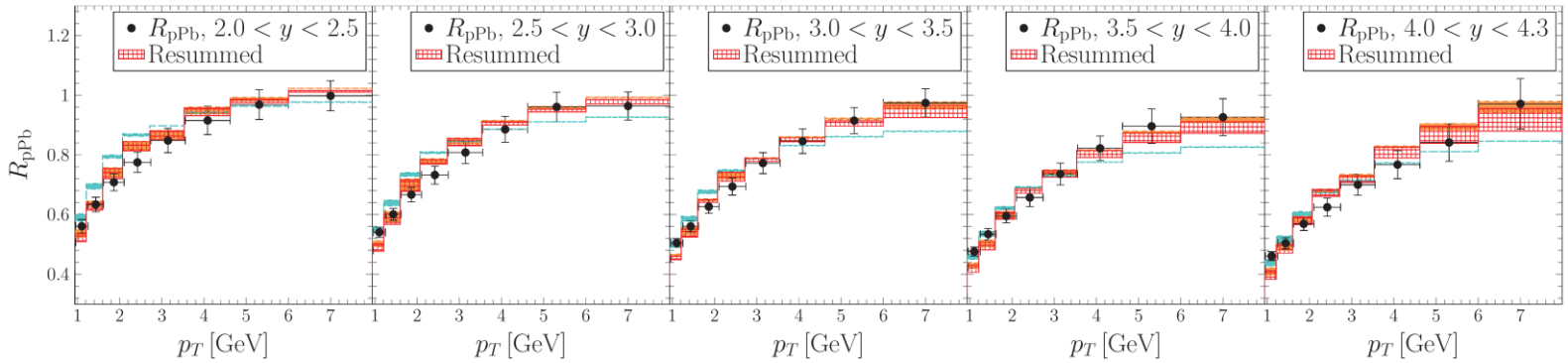
$$R_{pA} = \frac{\sigma(pA \to hX)}{A\sigma(pp \to hX)}$$





. CGC@LO vs RHIC data (BRAHMS)

Kharzeev, Kovchegov, Tuchin (2004)



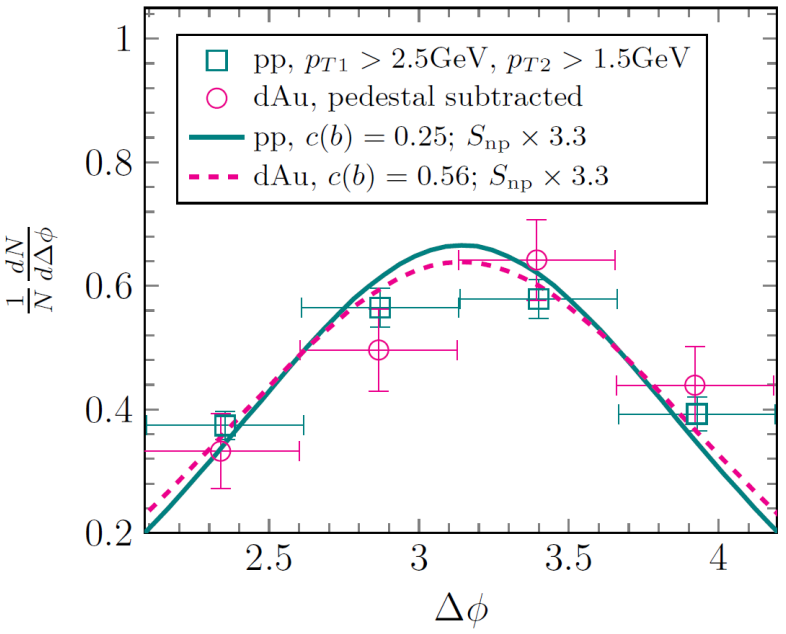
. state-of-the-art: CGC@NLO vs LHCb data

Shi, Wang, Wei, Xiao (2022)

Signals of gluon saturation

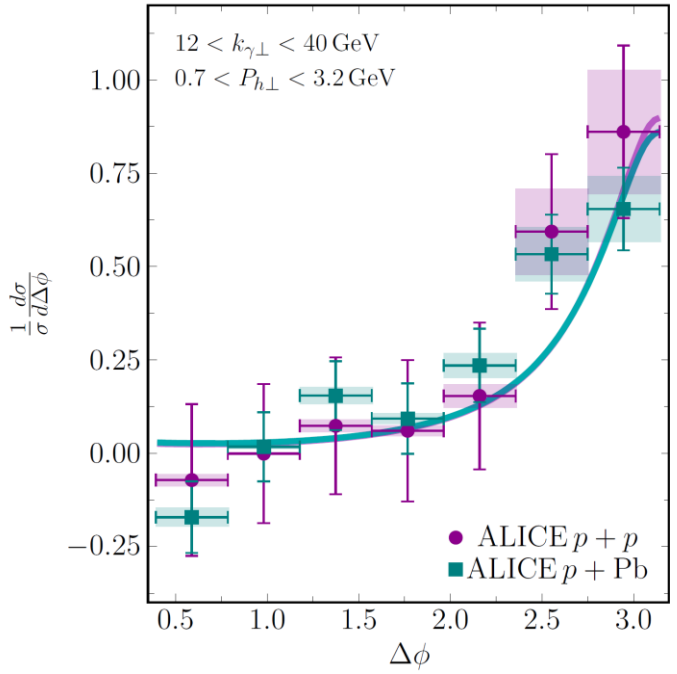
. decoherence of the back-to-back peak in angular correlations

Stasto, Wei, Xiao, Yuan (2018)



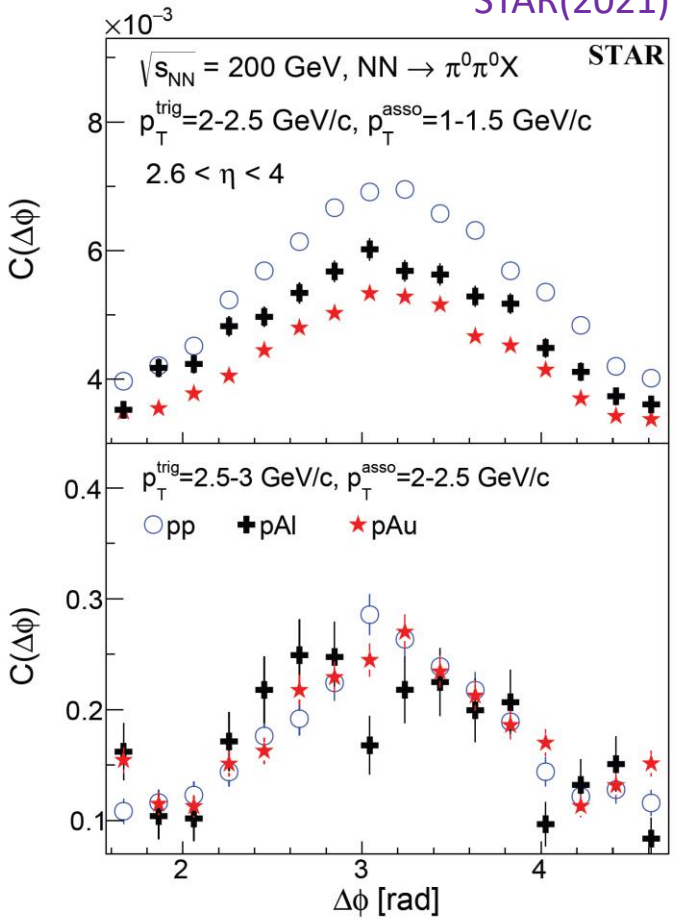
di-hadrons@RHIC

SB, Garcia-Montero, Perkov (2022)



γ+hadron@LHC

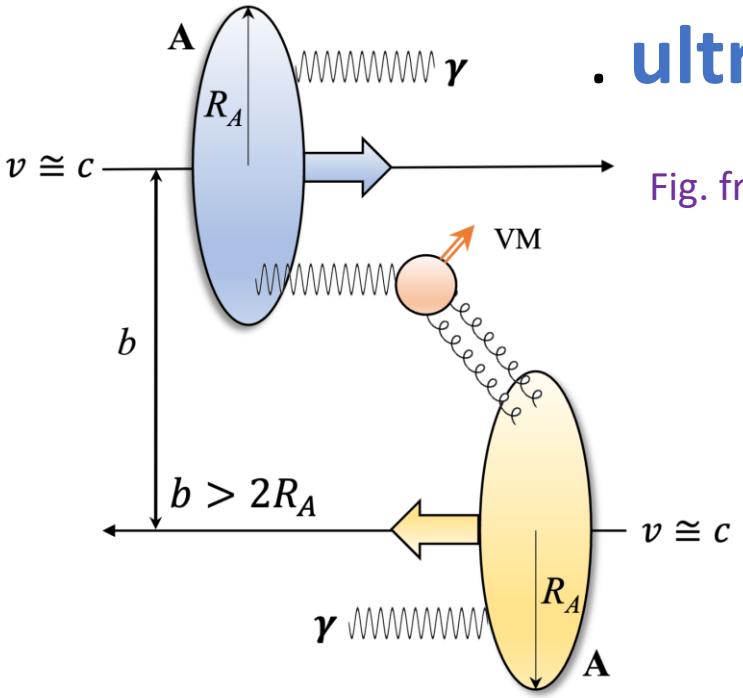
STAR(2021)



. joint Sudakov+small-x resummation

. LHCb + forward upgrades (Focal) + EIC

Further signals: diffractive vector meson



. **ultra-peripheral AA collisions** as DIS in the Q^2->0 limit

Fig. from Kovchegov, Sun, Tu (2024)

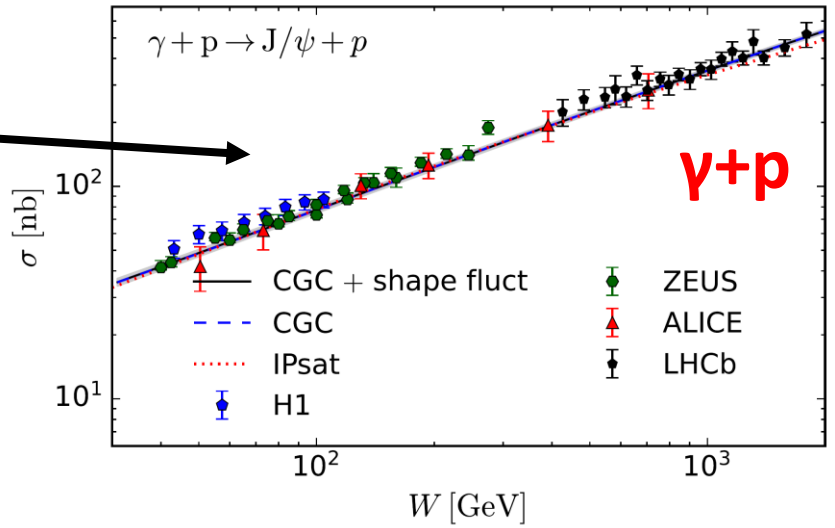
Pomeron exchange

-> used in tomography studies -> implications for GPDs at small-x..

. energy (W) dependence in γ+p follows a power law (BFKL)

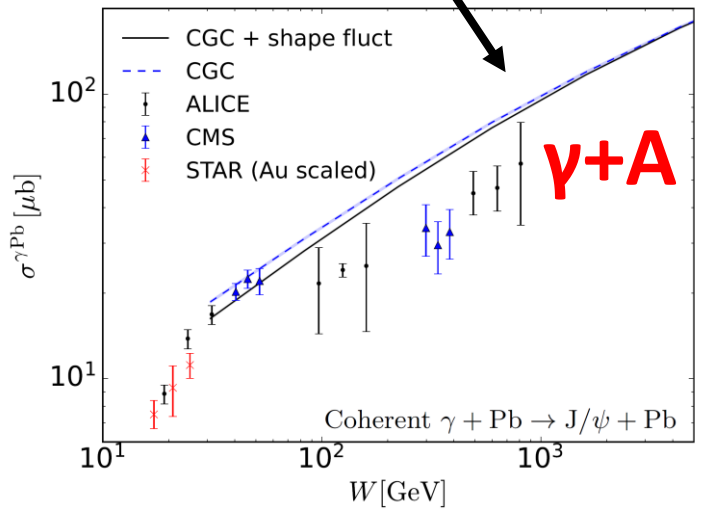
. NLO computations ongoing..

Mantysaari, Salazar, Schenke (2022)



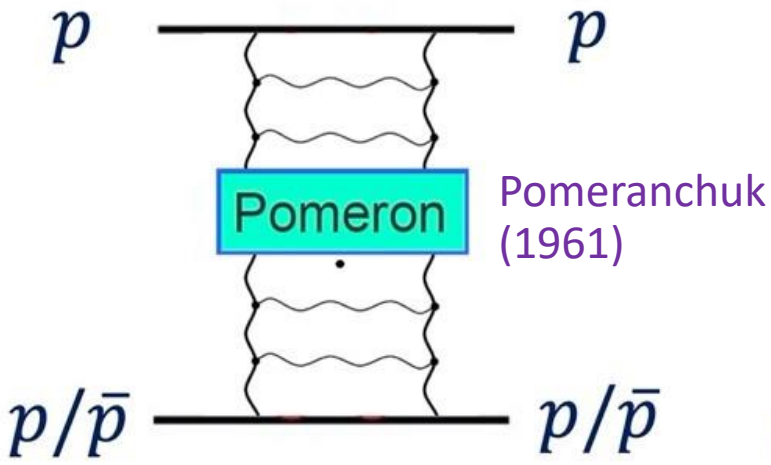
. deviations in γ+A? saturation?

Mantysaari, Salazar, Schenke (2023)

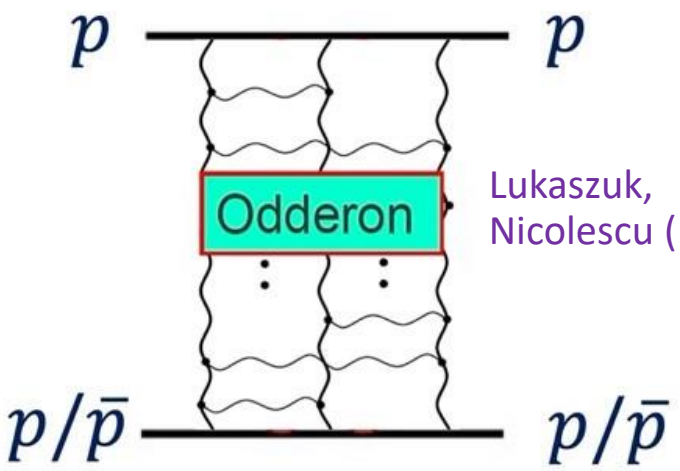


Pomeron brother: the elusive Odderon

. **colorless propagators** to control the total cross section asymptotics



Pomeranchuk (1961)



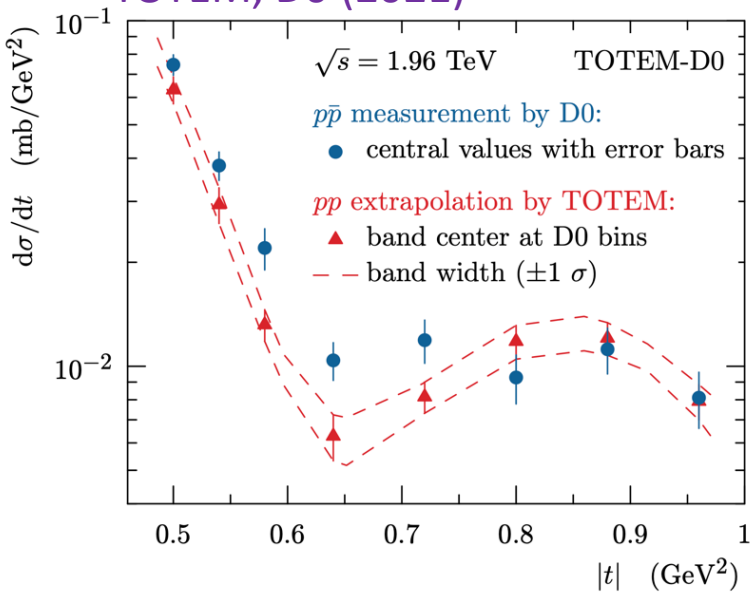
Lukaszuk, Nicolescu (1973)

$$\sigma_{\rm tot} \sim s^{\alpha_{\mathcal{P}}-1}$$

$$\sigma_{\rm tot}^{pp} - \sigma_{\rm tot}^{p\bar{p}} \sim s^{\alpha_{\mathcal{O}}-1}$$

subtle effect ->
elusive for decades..

TOTEM, D0 (2021)



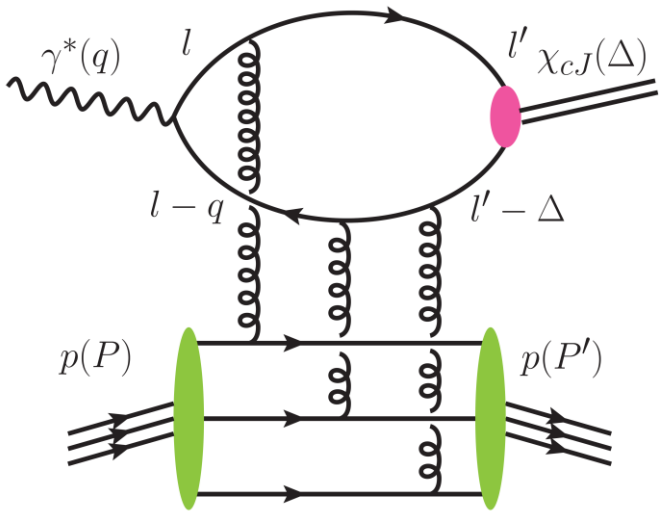
. TOTEM and D0: **discovery of the Odderon**

. not just a 3-gluon exch. -> insight into proton non-Gaussianities at small-x, spin physics, etc..

Zhou (2013)
Dumitru, Miller, Venugopalan (2018)

Odderon in the DIS?

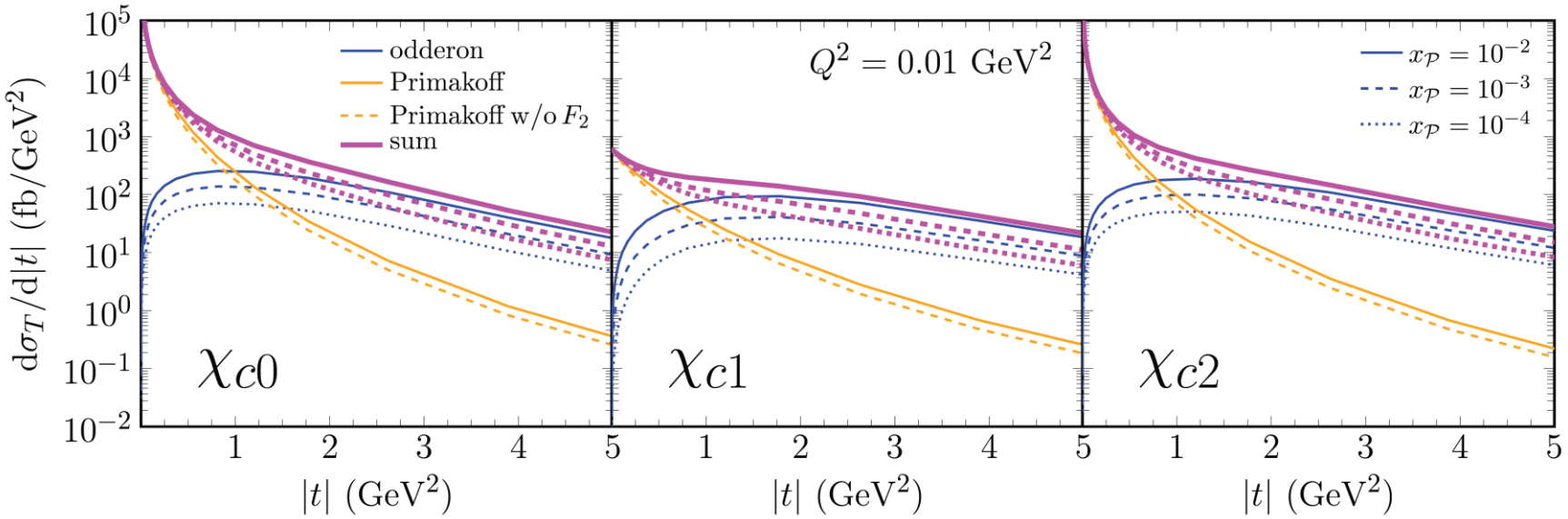
SB, Dumitru, Kaushik, Stebel Motyka (2024)



$$\mathcal{O}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp) \sim \int \frac{d^2\boldsymbol{\xi}_\perp}{(2\pi)^2} \mathrm{e}^{-\mathrm{i}\boldsymbol{k}_\perp\cdot\boldsymbol{\xi}_\perp} \mathrm{Im}\left[\langle P'|V(0)V^\dagger(\boldsymbol{\xi}_\perp)|P\rangle\right]$$

. **exclusive χ_c-quarkonia production**

. rare events: about a dozen of χ_c's/month@EIC



signal: almost flat t-distribution