Odderons at the EIC

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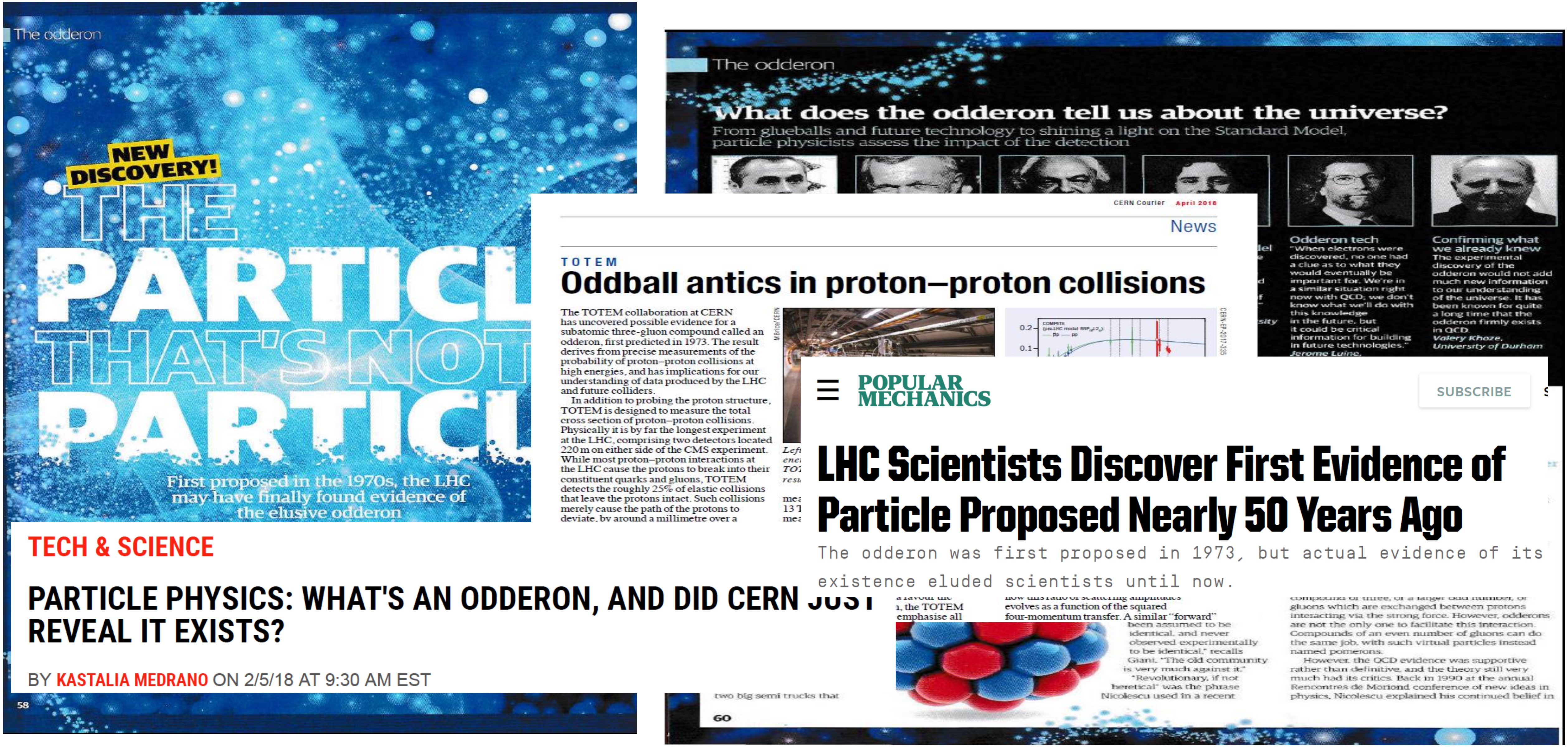
“Saturation and diffraction at the LHC and the EIC” ECT workshop, June 29-July 1, 2021.

Contents

- Odderons in DIS
- Odderons as generalized TMDs (GTMD)
- Connection to Odderons at the LHC
- Odderons in AdS/CFT

Odderon at the LHC

→ Talk by Tim Raben



The odderon

NEW DISCOVERY!

THE PARTICLE THAT'S NOT A PARTICLE

First proposed in the 1970s, the LHC may have finally found evidence of the elusive odderon

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The odderon

What does the odderon tell us about the universe?

From glueballs and future technology to shining a light on the Standard Model, particle physicists assess the impact of the detection

Odderon tech
"When electrons were discovered, no one had a clue as to what they would eventually be important for. We're in a similar situation right now with QCD; we don't know what we'll do with this knowledge in the future, but it could be critical information for building in future technologies."
Jerome Luine,

Confirming what we already knew
The experimental discovery of the odderon would not add much new information to our understanding of the universe. It has been known for quite a long time that the odderon firmly exists in QCD.
Valery Khoze, University of Durham

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CERN Courier April 2018

News

TOTEM

Oddball antics in proton–proton collisions

The TOTEM collaboration at CERN has uncovered possible evidence for a subatomic three-gluon compound called an odderon, first predicted in 1973. The result derives from precise measurements of the probability of proton–proton collisions at high energies, and has implications for our understanding of data produced by the LHC and future colliders.

In addition to probing the proton structure, TOTEM is designed to measure the total cross section of proton–proton collisions. Physically it is by far the longest experiment at the LHC, comprising two detectors located 220 m on either side of the CMS experiment. While most proton–proton interactions at the LHC cause the protons to break into their constituent quarks and gluons, TOTEM detects the roughly 25% of elastic collisions that leave the protons intact. Such collisions merely cause the path of the protons to deviate, by around a millimetre over a

POPULAR MECHANICS

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LHC Scientists Discover First Evidence of Particle Proposed Nearly 50 Years Ago

The odderon was first proposed in 1973, but actual evidence of its existence eluded scientists until now.

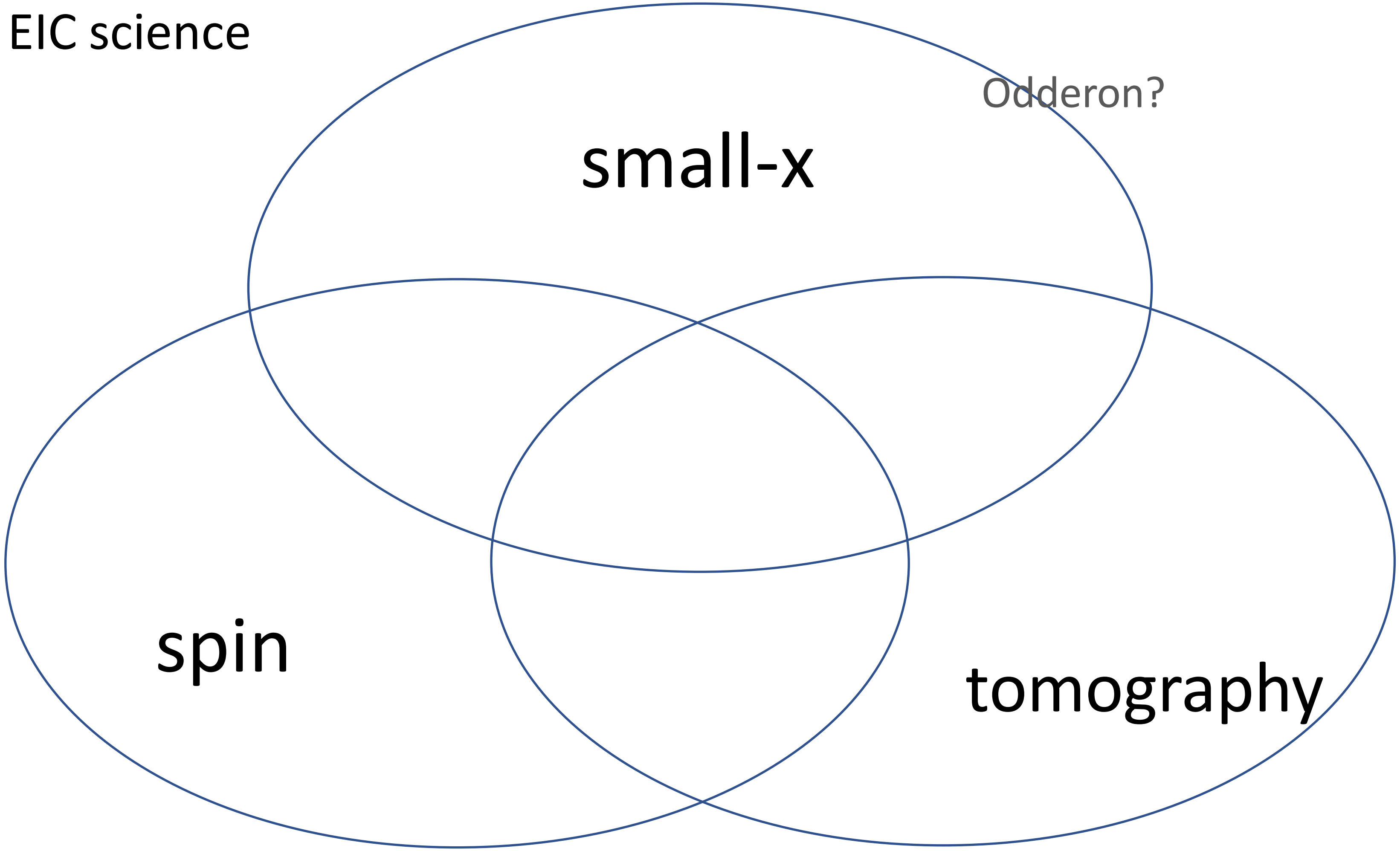
TECH & SCIENCE

PARTICLE PHYSICS: WHAT'S AN ODDERON, AND DID CERN JUST REVEAL IT EXISTS?

BY KASTALIA MEDRANO ON 2/5/18 AT 9:30 AM EST

Odderon at the EIC?

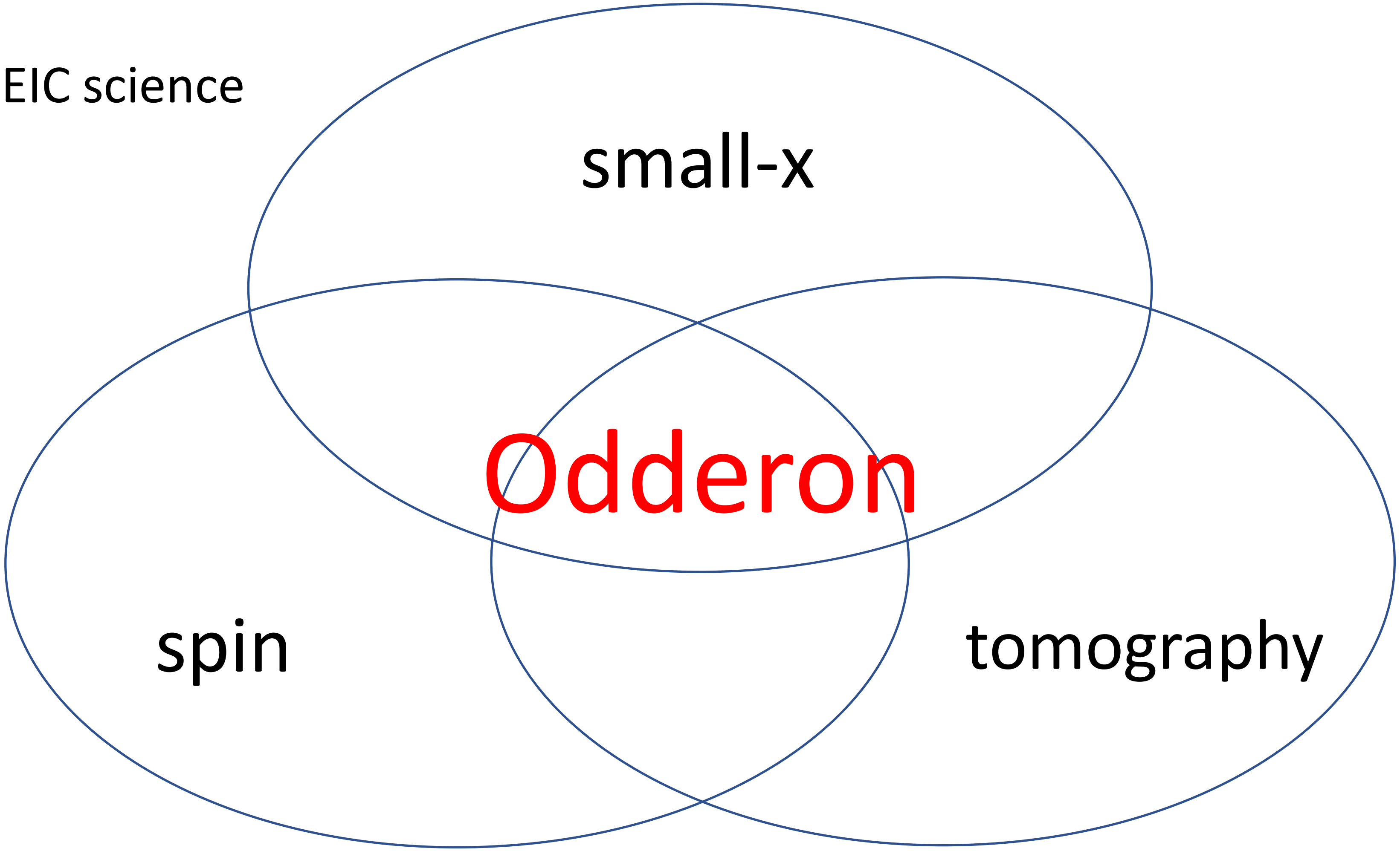
Three pillars of EIC science



No mention of Odderon in the 2012 EIC white paper…

Odderon at the EIC!

Three pillars of EIC science

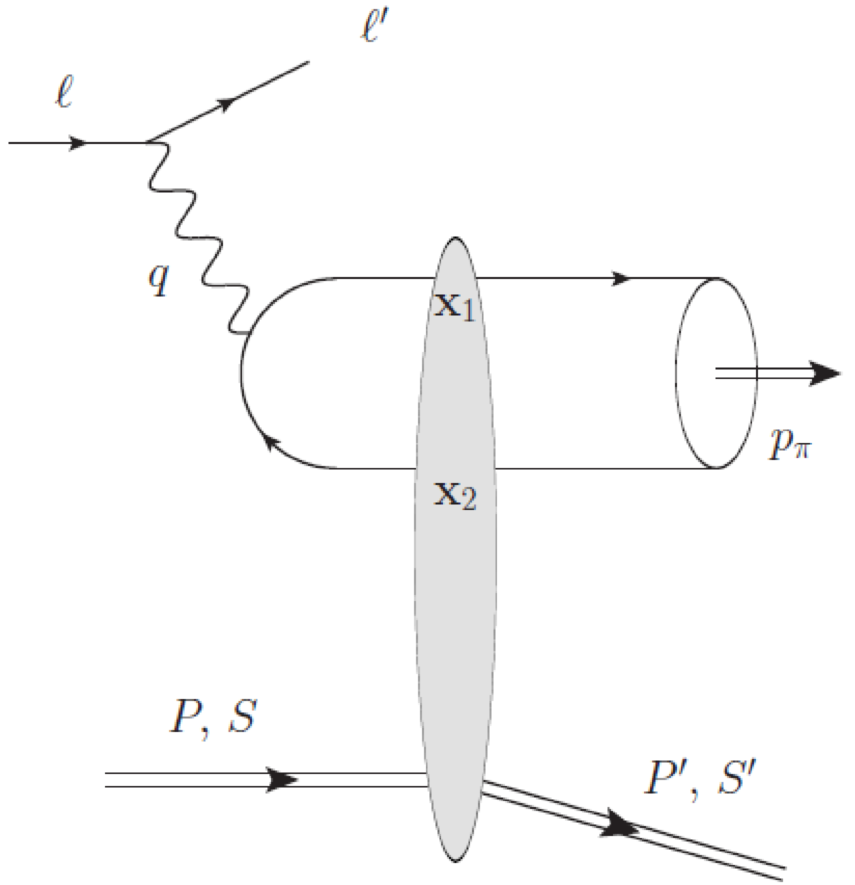


Odderon is the quintessence of EIC science!

Odderon in DIS

Classic discovery channel of Odderon in DIS: Exclusive π^0, η_c production

Czyzewski, Kwiecinski, Motyka, Sadzikowski (1996)



photon C-odd

Odderon C-odd

→ π^0, η_c C-even

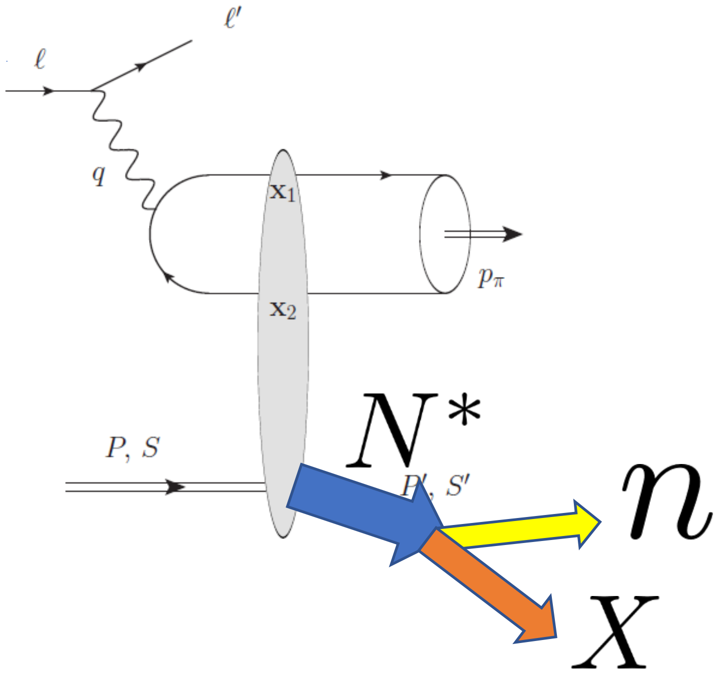
Exclusive two-pion production also proposed.

$ep \to e'p'\pi^+\pi^-$ Hagler, Pire, Szymanowski, Teryaev (2002)

Need a large scale to justify perturbative approaches

Either large $Q^2 = -q^2$ or large meson mass

π^0 photoproduction previously measured by the H1 collaboration at HERA



hep-ex/0206073

Search for Odderon-Induced Contributions to Exclusive π° Photoproduction at HERA

H1 Collaboration

Abstract

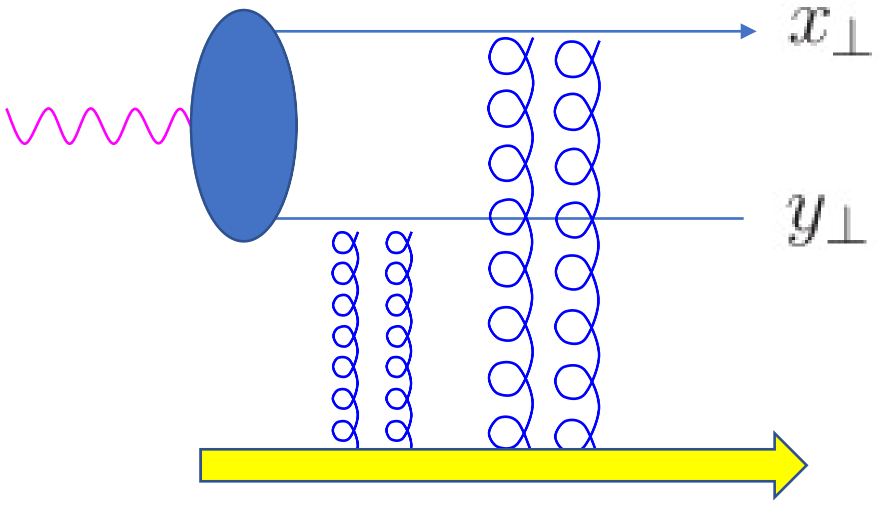
A search for contributions to the reaction $ep \to e\pi^\circ N^*$ from photon-Odderon fusion in the photoproduction regime at HERA is reported, at an average photon-proton centre-of-mass energy $\langle W \rangle = 215$ GeV. The measurement proceeds via detection of the π° decay photons, a leading neutron from the N^* decay, and the scattered electron. No π° signal is observed and an upper limit on the cross section for the photon-Odderon fusion process of $\sigma(\gamma p \to \pi^\circ N^*) < 49$ nb at the 95 % confidence level is derived, integrated over the experimentally accessible range of the squared four-momentum transfer at the nucleon vertex $0.02 < |t| < 0.3$ GeV^2. This excludes a recent prediction from a calculation based on a non-pert[...]b.

The community was traumatized by this null result…

Modern theory of Odderon in QCD

→ Talk by Leszek Motyka

Small-x limit of QCD → Effective theory of Wilson lines



\`\`Dipole S-matrix”

$$S \sim \frac{1}{N_c} \mathrm{tr}\left[U(x_\perp) U^\dagger(y_\perp)\right]$$

$$U(x_\perp) = P \exp\left(ig \int_{-\infty}^{\infty} dx^- A^+(x^-, x_\perp)\right)$$

Odderon as the imaginary part of dipole S-matrix

YH, Iancu, Itakura, McLerran (2004)

$$S \sim \frac{1}{N_c}\mathrm{tr}\left[U(x_\perp)U^\dagger(y_\perp)\right] = P(x_\perp, y_\perp) + iO(x_\perp, y_\perp)$$

Pomeron Odderon

Flips signs under $x_\perp \leftrightarrow y_\perp$ ← charge conjugation

Satisfies a non-linear evolution equation in rapidity $Y = \ln 1/x$

Kovchegov, Szymanowski, Wallon (2003) (large-Nc)
YH, Iancu, Itakura, McLerran (2004) (finite-Nc)

$$\partial_Y O(x_\perp, y_\perp) = \frac{\alpha_s}{2\pi}\int d^2 z_\perp \frac{(x_\perp - y_\perp)^2}{(x_\perp - z_\perp)^2 (z_\perp - y_\perp)^2}\Big[O(x_\perp, z_\perp) + O(z_\perp, y_\perp) - O(x_\perp, y_\perp)$$
$$- O(x_\perp, z_\perp)N(z_\perp, y_\perp) - N(x_\perp, z_\perp)O(z_\perp, y_\perp)\Big] \qquad (N = 1 - P)$$

Odderon brothers

$O(x_\perp, y_\perp)$ proportional to the transverse vector $r_\perp = x_\perp - y_\perp$

However, O is a scalar, so there must be another 2D vector to contract indices.

There are two possibilities

impact parameter $b_\perp = \frac{x_\perp + y_\perp}{2}$ $O \propto r_\perp \cdot b_\perp$ ➡ tomography

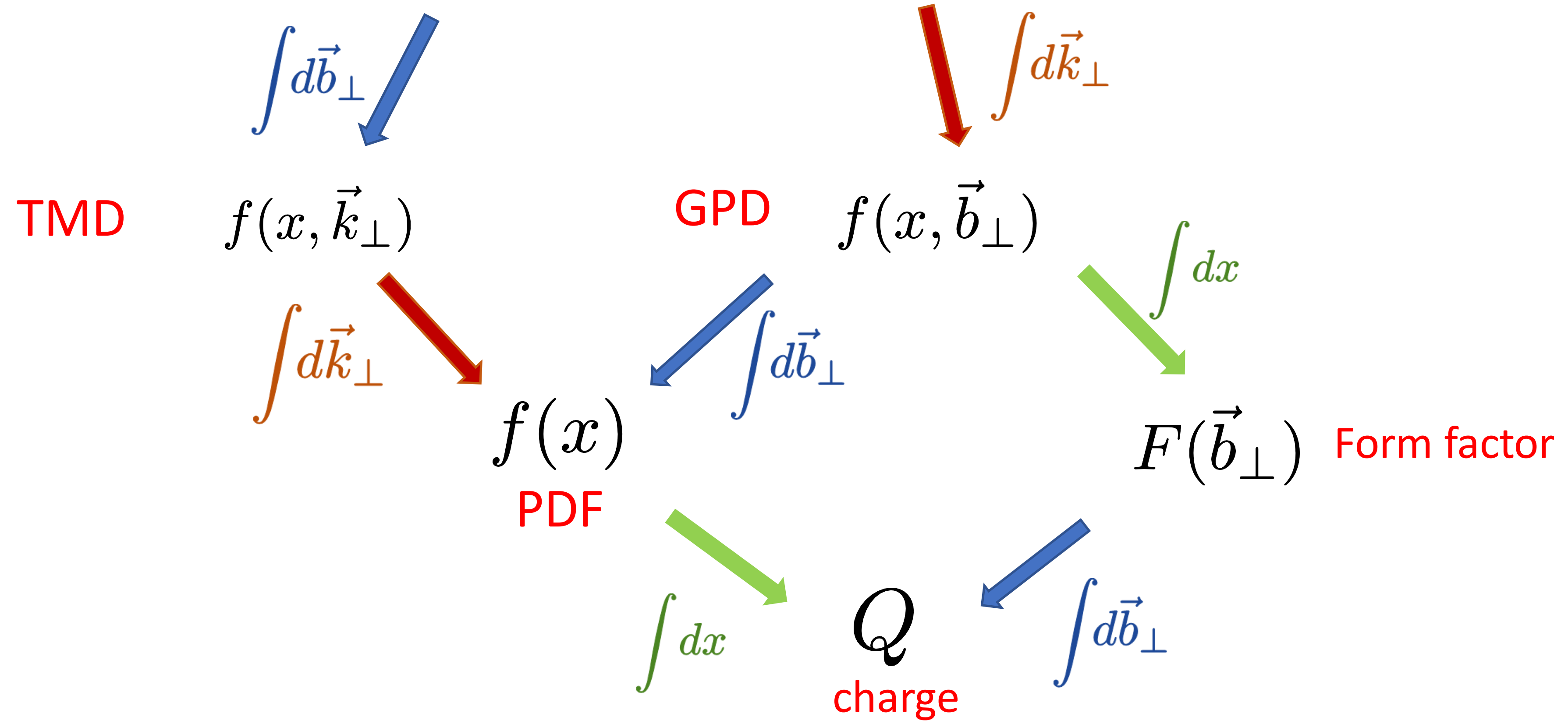
transversely polarized proton spin $S_\perp$ $O \propto r_\perp \times S_\perp$ ➡ spin

Complete description of Odderon requires transverse momentum $\leftrightarrow r_\perp$, impact parameter $b_\perp$, and spin $S_\perp$ → Wigner distribution

QCD Wigner distribution, the `mother’ distribution

Belitsky, Ji, Yuan (2003)

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



Odderons as GTMDs

GTMD = generalized TMD

$$f(x, k_\perp, \Delta_\perp)$$

Fourier transform

Wigner distribution

$$f(x, k_\perp, b_\perp)$$

Most general parametrization of Odderon matrix element in terms of GTMDs

Boussarie, YH, Szymanowski, Wallon (2020)

$$\int d^2 r_\perp e^{-ik_\perp \cdot r_\perp} \langle P'S' | iO(r_\perp) | PS \rangle$$

$$\propto k_\perp^j \bar{u}(P'S') \left[i \frac{\Delta^j}{M^2} g_{1,1} - \frac{\sigma^{i+}}{P^+} \left(\delta^{ij} g_{1,2} + \frac{\Delta^i \Delta^j}{M^2} g_{1,3} \right) \right] u(PS)$$

Take-home message: There are three independent Odderons $g_{1,1}, g_{1,2}, g_{1,3}$

Spin-dependent Odderon $g_{1,2}$

Only one that survives in the limit $t \to 0$. Sensitive to the proton's spin state.

For a transversely polarized proton, $k_\perp^i \bar{u}(PS_\perp)\sigma^{i+}u(PS_\perp) \propto k_\perp \times S_\perp$

Compare this with the definition of the Sivers function

$$f(x, k_\perp) = f_0(x, |k_\perp|) + k_\perp \times S_\perp f_{1T}^\perp(x, k_\perp)$$

$$g_{1,2}(x, k_\perp) \propto f_{1T}^{g\perp}(x, k_\perp)$$

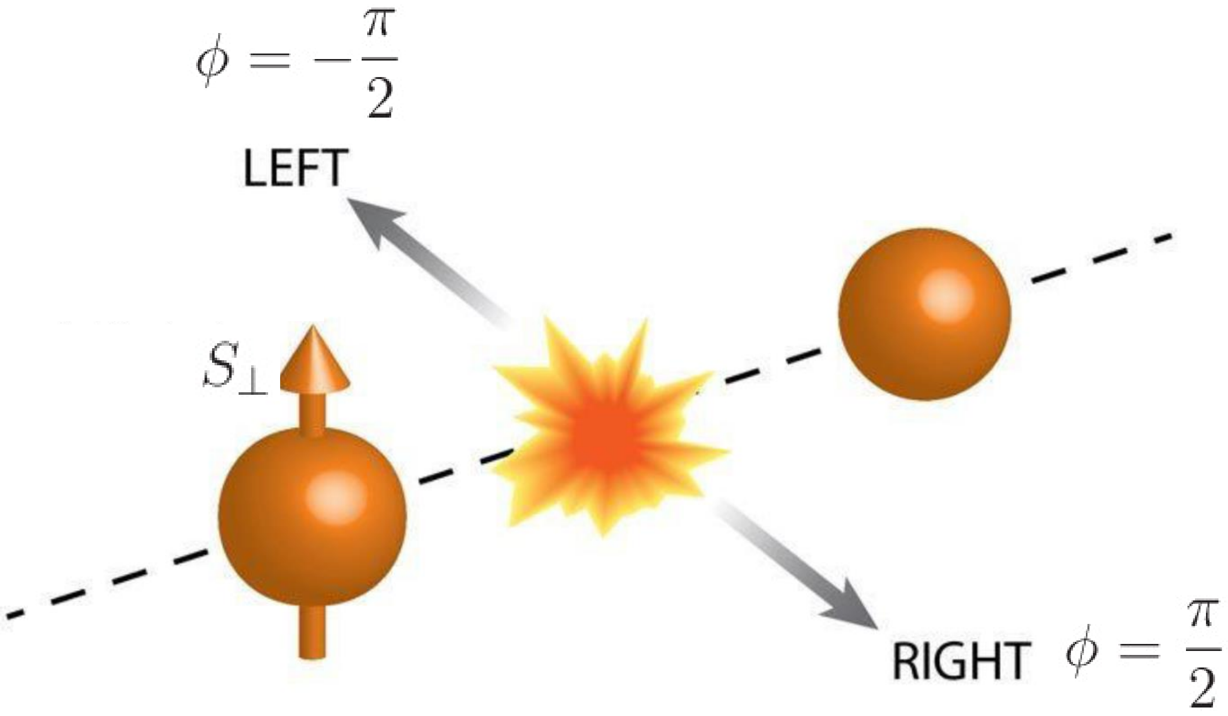
Spin-dependent Odderon = gluon Sivers function at small-x

Zhou (2013)

Sivers function

Introduced by Sivers in 1990 to explain the observed large Single Spin Asymmetry (SSA)

$$\frac{d\sigma}{d\phi} \sim k_\perp \times S_\perp \sim \sin\phi$$



Long history, many measurements, but so far most of the studies have been focused on the quark Sivers function.

Much interest in the possibility to access the gluon Sivers function at EIC

c.f., Zheng, Aschenauer, Lee, Xiao, Yin (2018)

Novel connection between Odderon and SSA!

Computing Odderon=gluon Sivers at small-x

Yao, Hagiwara, YH (2018)

Numerically solve the nonlinear-evolution equation in the form

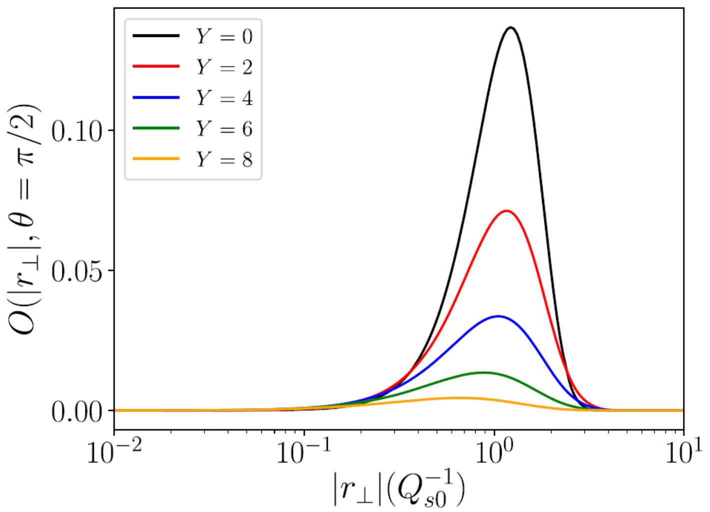
$$O(x,y) = \sin\phi\, f(|x-y|)$$

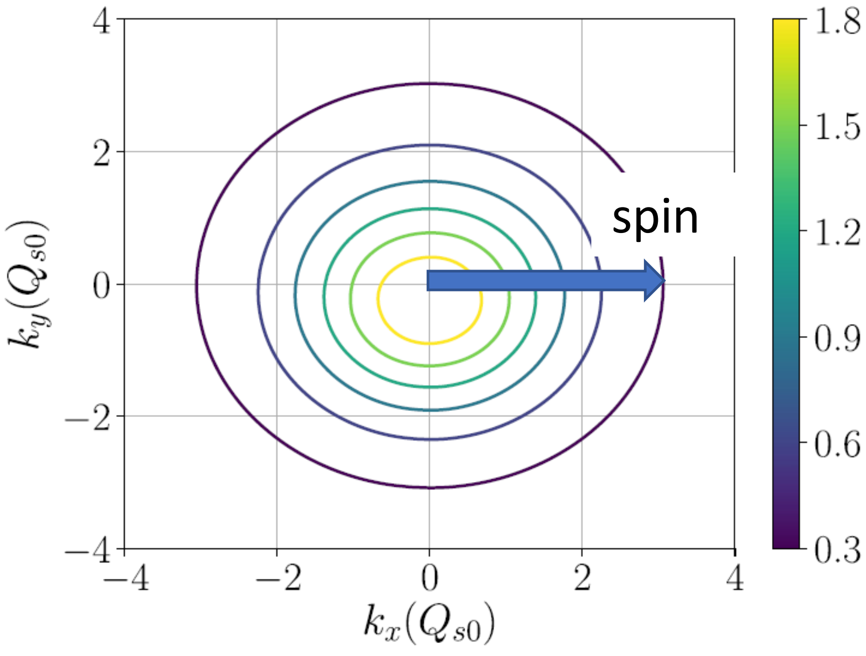
See also,
Motyka (2005)
Lappi, Ramnath, Rummukainen, Weigert (2016)
Contreras, Levin, Meneses, Sanhueza (2020)

In the linear regime, Odderon intercept=1 (Bartels-Lipatov-Vacca solution)

Saturation effects tend to suppress Odderon

No geometric scaling





The `flip' side of $g_{1,2}$

The same spinor product also nonvanishing if longitudinally polarized and if helicity flips

c.f. $k_\perp^i \bar{u}(PS_\perp)\sigma^{i+}u(PS_\perp) \propto k_\perp \times S_\perp$

$$k_\perp^i \bar{u}(P,-S_L)\sigma^{i+}u(PS_L) = \pm ik^x - k^y$$

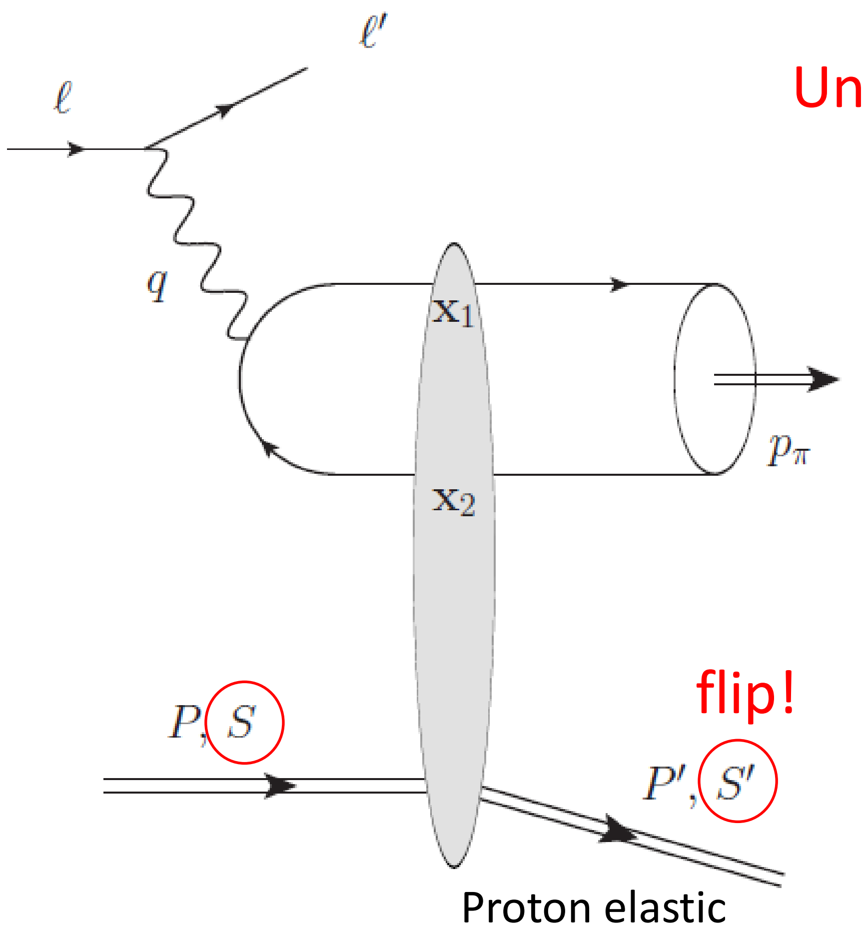
proton helicity

Spin-dependent Odderon can also be probed in processes which involve spin-flips. Does not necessarily require polarized beams.

Contrary to prevailing belief, spin-flip amplitudes may survive at high energy because Odderon intercept =1. (sans saturation)

Exclusive π^0 production at EIC

Boussarie, YH, Szymanowski, Wallon (2020)



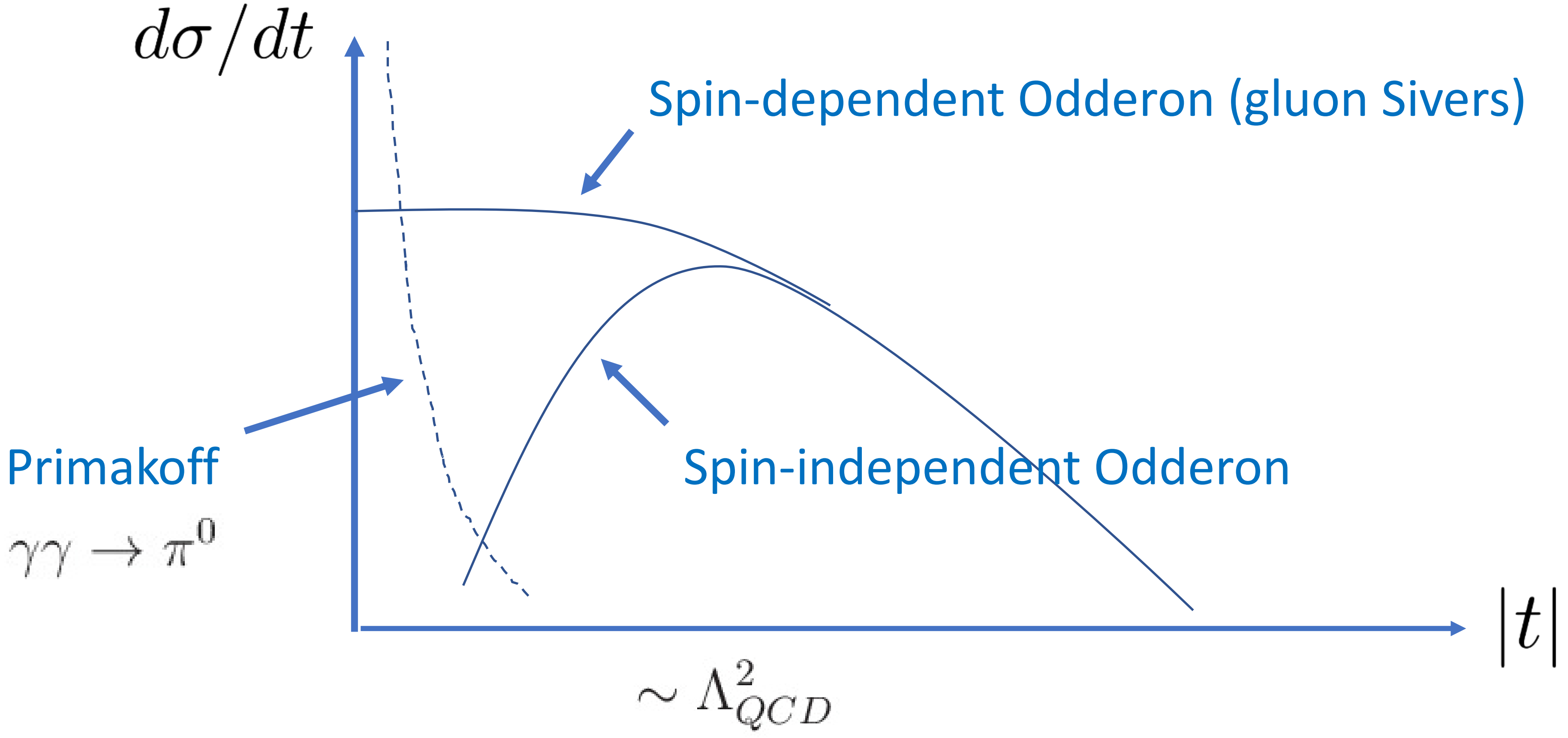
Unpolarized cross section at small-x, $t \approx 0$

$$\frac{d\sigma}{dt} = \sum_{SS'=\pm} \frac{d\sigma_{SS'}}{dt} \approx \frac{d\sigma_{+-}}{dt} + \frac{d\sigma_{-+}}{dt}$$

$$\frac{d\sigma}{dx_B dQ^2 d|t|} = \frac{\pi^5 \alpha_{\rm em}^2 \alpha_s^2 f_\pi^2}{2^3 x_B N_c^2 M^2 Q^6} (1 - y + \frac{y^2}{2})$$
$$\times \left[\int_0^1 dz \frac{\phi_\pi(z)}{z\bar{z}} \int d\boldsymbol{k}^2 \frac{\boldsymbol{k}^2}{\boldsymbol{k}^2 + z\bar{z}Q^2} x f_{1T}^{\perp g}(x, \boldsymbol{k}^2) \right]^2$$

Cross section in the forward limit dominated by Odderon=gluon Sivers!

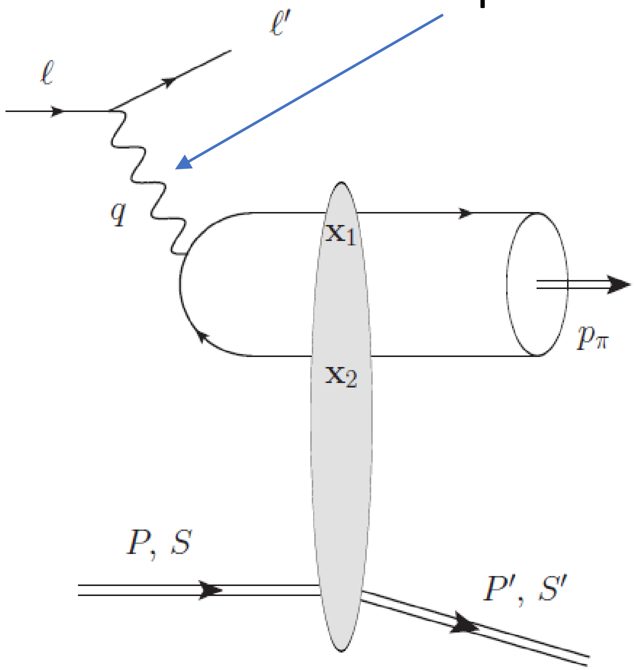
Exclusive π^0 at the EIC: where to look for



Nonvanishing in the limit $t \to 0$: highly nontrivial

Why H1 measured neutrons (and why we don't)

Only the transversely polarized photon can contribute



Transverse polarization vector $\vec{\epsilon}_\perp$ has to be contracted by another transverse vector.

Naively, the only available vector is momentum transfer $\vec{\Delta}_\perp$

→ $d\sigma/dt$ vanishes as $t \to 0$

Theorists suggested to excite proton. Berger et al. (1999)
(P-wave wavefunction contains a transverse vector.)
This is why H1 measured neutrons from the decay $p \to N^* \to n$

Don't forget proton is a spin-1/2 particle. We get a transverse vector when helicity flips

$$k_\perp^i \bar{u}(P, -S_L)\sigma^{i+}u(PS_L) = \pm ik^x - k^y$$

$d\sigma/dt$ finite as $t \to 0$ without exciting proton!

Discussion: H1 kinematics

Integrated luminosity $30.6\ \mathrm{pb}^{-1}$

Theory prediction $300\ \mathrm{nb}$

H1 upper limit $< 49\ \mathrm{nb}$

$\langle W \rangle = 215\ \mathrm{GeV}.$

$Q^2 < 0.01\ \mathrm{GeV}^2$ Photoproduction

$0.02 < |t| < 0.3\ \mathrm{GeV}^2$

Background: Primakoff process $\gamma^{(*)}\gamma \to \pi^0$

H1 says `negligible' according to Pythia

(because the predicted cross section is large?)

My comments

We don't have a prediction for the magnitude of the cross section…

Top EIC ep energy, top $\gamma^* p$ energy desirable

Theorists are more comfortable with $Q^2 > 1\mathrm{GeV}^2$ ….

Larger $|t|$ is also interesting, probe spin-independent Odderons

Could be a serious background if the Odderon cross section is very small.

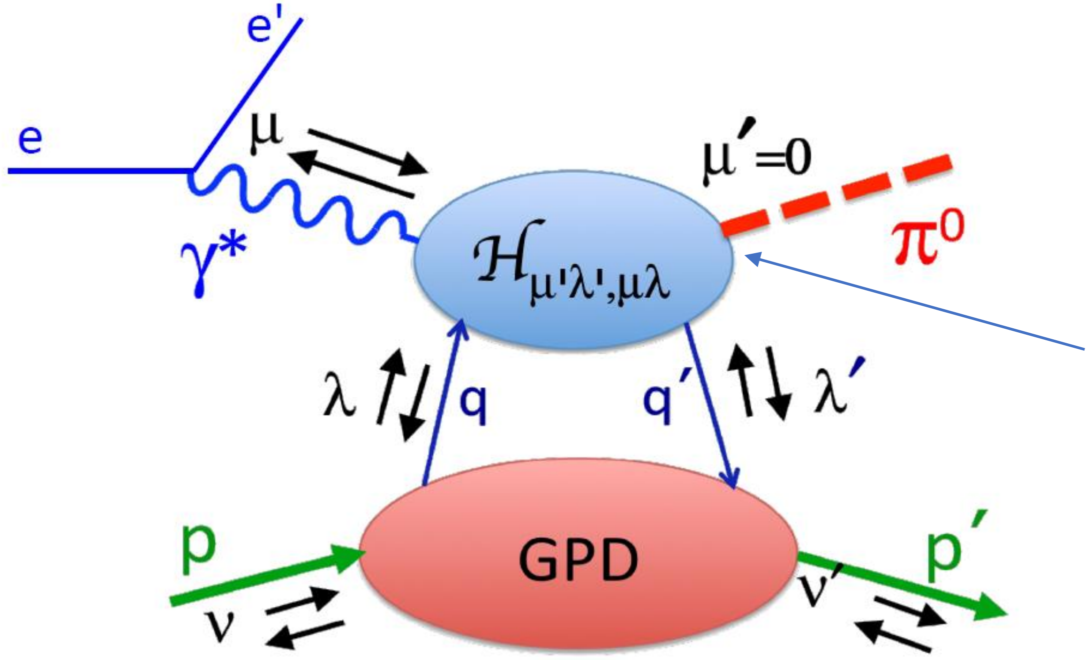
cf. Dumitru, Stebel (2019) (η_c production)

Exclusive π^0 production at low energy

Probe of chiral-odd quark GPD $H_T,\ \tilde{H}_T,\ E_T,\ \tilde{E}_T$ → tensor charge

Ahmad, Goldstein, Liuti (2009)
Goloskokov, Kroll (2011)

Ongoing experiments at JLab



twist-3 pion distribution amplitude

At high energy, quark contribution dies away, and Odderon takes over.

Can we see this transition at the EIC?

Connection to Odderons at the LHC

Five helicity amplitudes in elastic pp

$$(t \to 0)$$

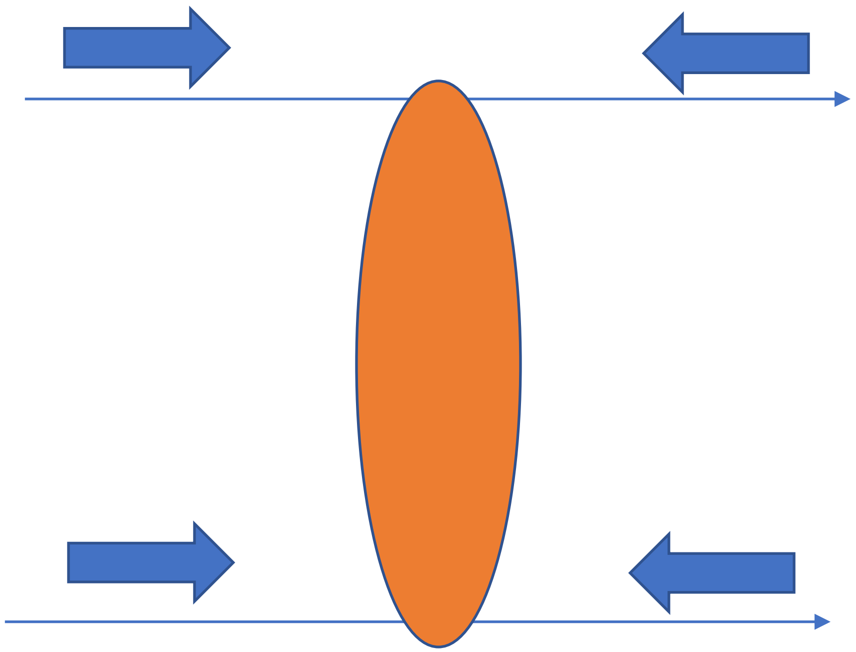
$$8\pi\phi_1(s,t) = \langle ++|\tilde{T}|++\rangle \quad \to const.$$

$$8\pi\phi_2(s,t) = \langle ++|\tilde{T}|--\rangle \quad \to const.$$

$$8\pi\phi_3(s,t) = \langle +-|\tilde{T}|+-\rangle \quad \to const.$$

$$8\pi\phi_4(s,t) = \langle +-|\tilde{T}|-+\rangle \quad \propto t$$

$$8\pi\phi_5(s,t) = \langle ++|\tilde{T}|+-\rangle \quad \propto \sqrt{-t}$$



Elastic cross section at the LHC

Elastic pp scattering, unpolarized

$$\frac{d\sigma}{dt} = \sum_{S_1 S_2 S_3 S_4 = \pm} \frac{d\sigma_{S_1 S_2 \to S_3 S_4}}{dt}$$

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\sigma_{\text{tot}}^2}{16\pi}\left(1 + \rho^2 + 2|r_2|^2\right)$$

double helicity-flip

rho-parameter (spin non-flip)

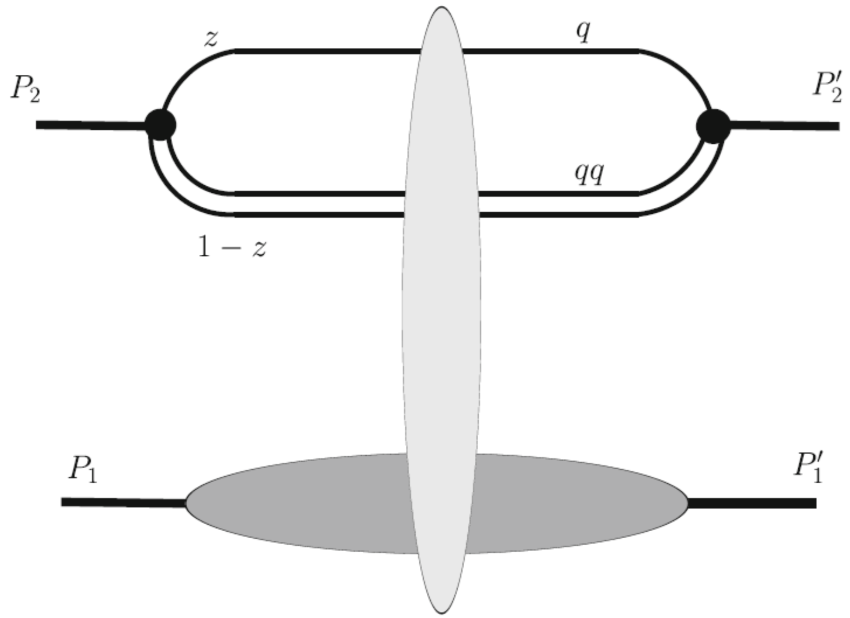
$$r_2(s,t) = \frac{\phi_2(s,t)}{2\mathrm{Im}\phi_+(s,t)}$$

$$\rho(s,t) = \frac{\mathrm{Re}T(s,t)}{\mathrm{Im}T(s,t)} \quad \sim \phi_{1,3}$$

Quark-diquark model for pp

Hagiwara, YH, Pasechnik, Zhou (2020)

Work in an asymmetric frame. Proton splits into a “dipole” consisting of a quark and a scalar diquark.



$$\phi_1 = \phi_3 = -\frac{isg^2c_s^2}{8N_cM}\int_0^1 dz\bar{z}\int\frac{d^2r_\perp}{4\pi}\Phi_n \times\left[\tilde{H}\left(1-\frac{z_*^2}{4}\Delta_\perp^2 r_\perp^2\right)-\delta^{(2)}(\Delta_\perp)\frac{2N_c}{g^2\pi}+\frac{iz_*\Delta_\perp^2}{2M^2}\tilde{g}_{1,1}\right]$$

$$\phi_2 = -\frac{sg^2c_s^2}{4N_cM}\int_0^1 dz\bar{z}\int\frac{d^2r_\perp}{4\pi}\Phi_f \times\left[\tilde{g}_{1,2}+\frac{\Delta_\perp^2}{4M^2}(2\tilde{g}_{1,3}-\tilde{g}_{1,1}-z_*^2M^2r_\perp^2\tilde{g}_{1,2})+i\frac{z_*^2}{4}\Delta_\perp^2 r_\perp^2\tilde{E}\right]$$

$\mathrm{Re}\,\phi_1 \sim g_{1,1}$ (spin-independent Odderon)

at work in the \`dip’ region?

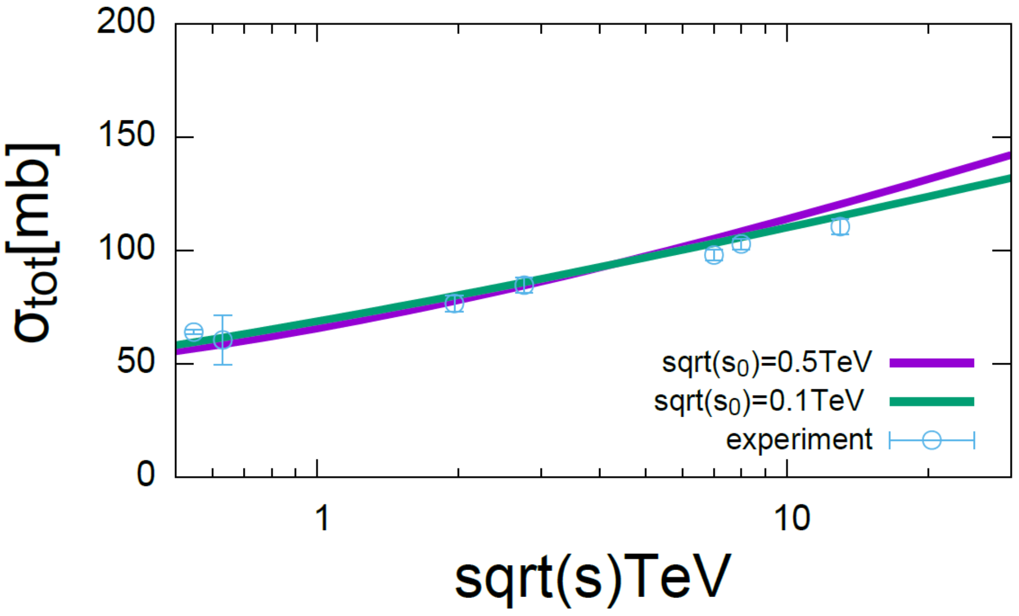
$\mathrm{Re}\,\phi_2 \sim g_{1,2}$ (spin-dependent Odderon)

Dominates ϕ_2 in the limit $t \to 0$

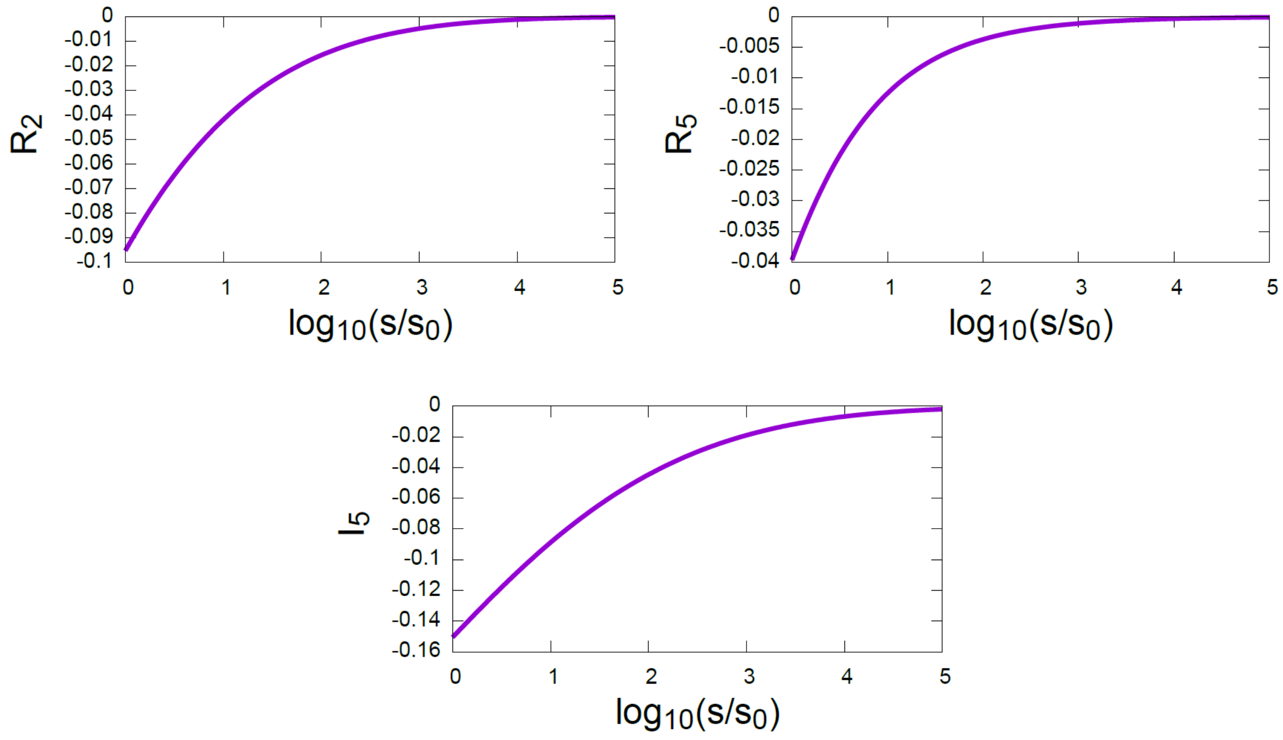
Energy dependence of helicity amplitudes from nonlinear evolution equations

Hagiwara, YH, Pasechnik, Zhou (2020)

Total cross section



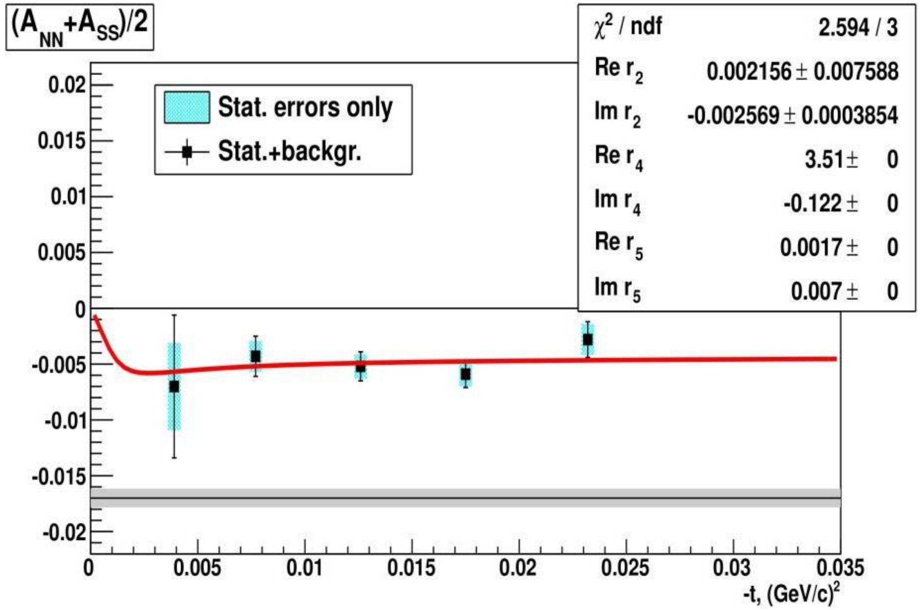
Single and double spin flip



Discussion: Spin-flip amplitudes in pp at RHIC and LHC

$r_2 \propto \phi_2$ can be measured from double transverse spin asymmetry A_{NN}

Preliminary results from STAR at RHIC $\sqrt{s} = 200\ \mathrm{GeV}$ suggest small values, consistent with zero for the real part.
(There may be room for debate in the fitting method…)



CNI analysis to extract the rho-parameter usually ignores spin-flip amplitudes.
Can this be generalized to include r_2 ?

$$\frac{d\sigma}{dt}^{C+N} = \frac{\pi(\hbar c)^2}{sp^2}\left|\frac{\alpha s}{t}\mathcal{F}^2 + \mathcal{A}^N\left[1 - i\alpha G(t)\right]\right|^2 ,$$

$$G(t) = \int_{-4p^2}^{0} dt' \log\frac{t'}{t}\frac{d}{dt'}\mathcal{F}^2(t') - \int_{-4p^2}^{0} dt' \left(\frac{\mathcal{A}^N(t')}{\mathcal{A}^N(t)} - 1\right)\frac{I(t,t')}{2\pi} ,$$

1812.04732 [TOTEM collaboration]

Odderon in AdS/CFT

type IIB superstring theory on $AdS_5 \times S^5$ dual to N=4 super YM at strong coupling

Odderon = antisymmetric B-field in 10D SUGRA Brower, Djuric, Tan (2009)

$$B_{\alpha\beta} = \begin{pmatrix} \overbrace{B_{mn}}^{AdS_5} & \overbrace{B_{ma}}^{S^5} \\ B_{an} & B_{ab} \end{pmatrix}$$

Diagonal $j = 1 - \frac{k^2}{2\sqrt{\lambda}}$ $j = 1 - \frac{(k+4)^2}{2\sqrt{\lambda}}$

Brower, Djuric, Tan (2009); Brower, Costa, Djuric, Raben, Tan (2014)

Off-diagonal $j = 1 - \frac{(k+2)^2}{2\sqrt{\lambda}}$ $k = 0, 1, 2, \cdots$

Avsar, YH, Matsuo (2010)

Caveat: The leading Odderon with $j = 1$ is a gauge artifact.
No corresponding operator in SYM. → Becomes physical after Regegization

Total cross section difference

Avsar, YH, Matsuo (2010)

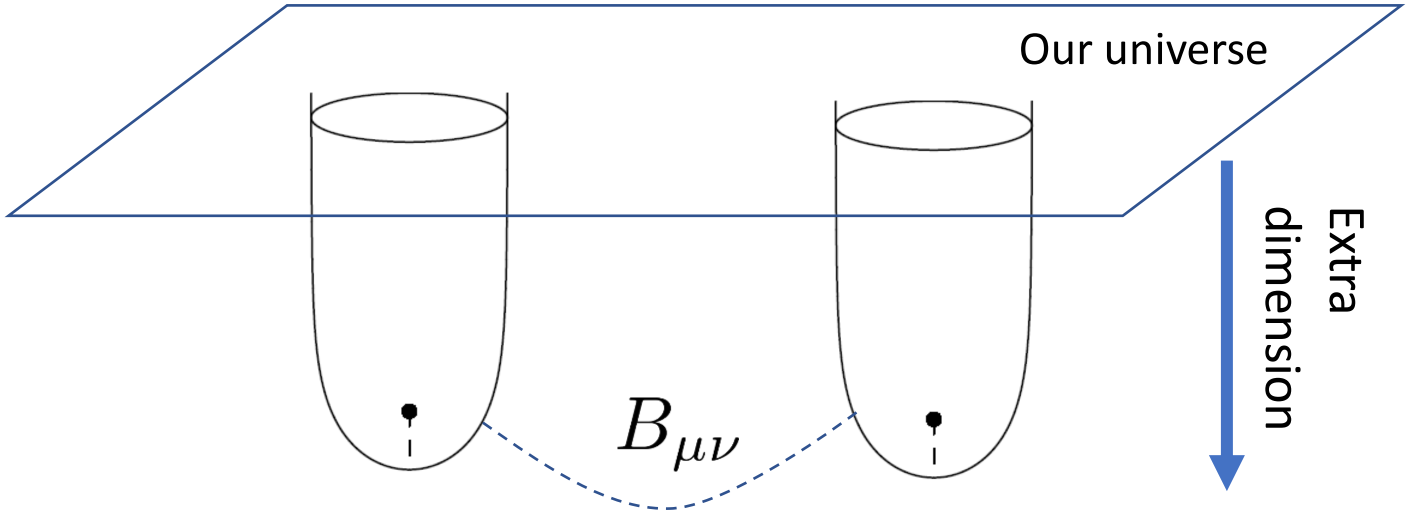
Baryon = D-brane in string theory Witten (1998)

Exchange Reggeized B-field and compute the imaginary part.

$j = 1$ Odderon decouples
Use the first subleading Odderon

Intercept shifted after integrating over $b_\perp$

$$j = 1 - \frac{1}{2\sqrt{\lambda}} \to j = 1$$



Our prediction $\sigma^{tot}_{pp} > \sigma^{tot}_{p\bar{p}}$ (attraction between like charges!)

in agreement with the original prediction by Lukaszuk and Nicolescu in 1973!

Summary

- Take-home message: There are different types of Odderons, spin-dependent and spin-indepedent, classified by GTMDs.
- Odderon fits perfectly with the scope of EIC
- Fresh look at exclusive pi0 production with improved theory
- Complementary to the study of Odderons at the LHC