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Doktoratskolleg Particles and Interactions

Holographic Odderon at TOTEM?

2311.05973 [hep-ph]

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FAKT Retreat

Februrary 22, 2024

Outline

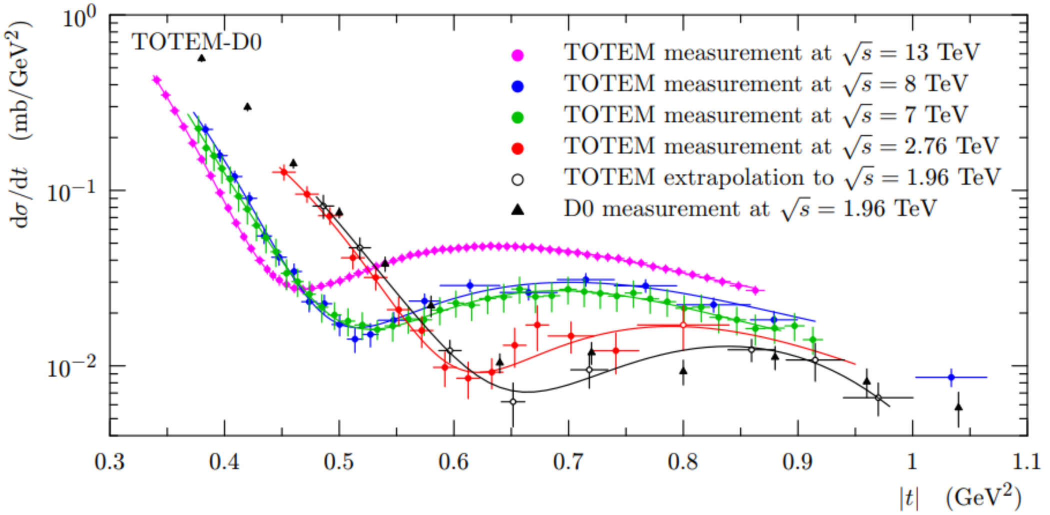
1. Introduction
2. Holographic principle
3. Holographic framework
4. Results
5. Conclusion and outlook

Outline

Introduction

- The Pomeron arose out of necessity to describe the slow rise of pp and $p\bar{p}$ total cross sections. Phenomenologically: $\sigma_{tot} \sim s^{j_{\mathbb{P}}(0)-1}$, $j_{\mathbb{P}}(0) \approx 1.08$
- No known meson trajectory fits the bill $\rightarrow$ Collective glueball phenomenon?
- In perturbative QCD, the Pomeron arises through the resummation of a C-even gluon ladder (BFKL).
- Similarly, the Odderon is obtained through a resummation of a C-odd gluon ladder (BKP).

TOTEM and DØ claimed the Odderon discovery in 2020



Phys. Rev. Lett. **127**, 062003

Outline

Holographic principle

Different forms of the AdS/CFT correspondence

	4d $\mathcal{N}=4$ Super Yang-Mills (SYM)	IIB String Theory on $AdS_5 \times S^5$
Strongest form	any N and λ	Quantum string theory, $g_s \neq 0$, $l_s/L \neq 0$
Strong form	$N \to \infty$, λ fixed but arbitray	Classical string theory, $g_s \to 0$, $l_s/L \neq 0$
Weak form	$\boldsymbol{N \to \infty, \lambda}$ **large**	**Classical supergravity,** $\boldsymbol{g_s \to 0, l_s/L \to 0}$

Pomeron and Odderon in gauge/gravity duality

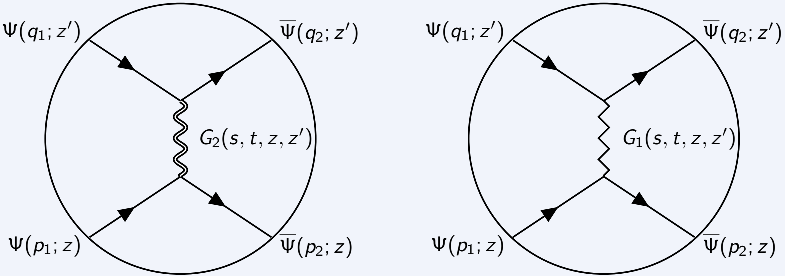
The Pomeron arises as a reggeized version of h_{MN}, while the Odderon is a mixture of reggeized B_2 and C_p fields. They are sourced by the QCD boundary operators

$$
\begin{aligned}
h^{\mu\nu}[2^{++}] &: \quad G^{a\mu\alpha} G^{a\nu}_{\alpha} \\
B^{\mu\nu}[1^{+-}] &: \quad d^{abc} G^{a\alpha\beta} G^{b}_{\alpha\beta} G^{c\mu\nu} \\
C^{\mu\nu}[1^{--}] &: \quad d^{abc} G^{a\alpha\beta} G^{b}_{\alpha\beta} \tilde{G}^{c\mu\nu}
\end{aligned}
\tag{1}
$$

Outline

The setup

Anatomy of scattering in AdS: Witten diagrams



The repulsive-wall model

$$\begin{aligned} ds^2 &= e^{2A(z)}(dz^2 + \eta_{\mu\nu}dx^\mu dx^\nu), \\ e^{2A(z)} &= \left(\frac{R}{z}\right)^2 e^{a_{c,o}\kappa^2 z^2}, \; a_c = a = 4, \; a_o = 1, \end{aligned} \tag{2}$$

Reggeized bulk-to-bulk propagator

We seek the scalar bulk-to-bulk propagator analytically continued to spin-j by the closed string quantized mass spectrum

$$\Delta_g(j) = 2 + \sqrt{4 + S_j}, \qquad S_j = m_5^2 R^2 + m_j^2 R^2 \tag{3}$$

$$\text{Pomeron}: \quad j = 2 + \frac{1}{2}\alpha' m_j^2, \qquad \text{Odderon}: \quad j = 1 + \frac{1}{2}\alpha' \tilde{m}_j^2 \tag{4}$$

Analytically continued scalar bulk-to-bulk propagator follows from

$$-\frac{1}{\sqrt{g}}\,\partial_z\left(\sqrt{g}\,e^{-2A(z)}\,\partial_z G_0(j,t,z,z')\right) + \left(S_j - e^{-2A(z)}\,t\right) G_0(j,t,z,z') = \frac{\delta(z-z')}{\sqrt{g}}. \tag{5}$$

Spin-1 and spin-2 are related to spin-0 via

$$G_{j_\pm}(j,t,z,z') = e^{-(A(z)+A(z'))(j-j_\pm)}\,G_0(j,t,z,z'), \quad j_+ = 2, \quad j_- = 1 \tag{6}$$

After certain field redefinitions and rescalings we arrive at the Whittaker equation

$$K_0(v,v') = \frac{1}{2}\mathcal{A}\, K_2(v_>)K_1(v_<), \quad \mathcal{A}^{-1} = -\frac{\sqrt{6}a\kappa\Gamma(1+2\alpha)}{\Gamma\left(\frac{1}{2}+\alpha-\beta\right)}. \tag{7}$$

$$\alpha = (\Delta_g(j)-2)/2, \quad \beta = (3 - S_j - m_5^2 + t/a\kappa^2)/6. \tag{8}$$

The branch cuts of $\mathcal{A}$ determine the Regge trajectories

$$j_{\mathbb{P}}(t) = 2 - \frac{3}{2\sqrt{\lambda}} + \frac{\alpha'}{2}t, \quad j_{\mathbb{O}}(t) = 1 - \frac{m_k^2-1}{2\sqrt{\lambda}} + \frac{\alpha'}{2}t. \tag{9}$$

Note:

- The diffusion in AdS shifts...
  - ...the Pomeron intercept from 2 to $2-3/2\sqrt{\lambda}$
  - ...the Odderon intercept from 1 to $1-(m_k^2-1)/2\sqrt{\lambda}$
- For $\lambda \to \infty$ we recover the spin-2 and spin-1 exchange

Sommerfeld-Watson transform

$$G_{j_\pm}(s,t,z,z') \;=\; \oint \frac{dj}{4\pi i} \frac{(\alpha' s)^{j-j_\pm} + (-\alpha' s)^{j-j_\pm}}{\sin \pi (j - j_\pm)} G_{j_\pm}(j,t,z,z') \tag{10}$$

- At large rapidities, the integral can be evaluated via saddlepoint approximation
- Odderon pole at $j = 1$ ("Maximal Odderon") not regulated $\rightarrow m_k = k = 2$

$$G_{j_\pm}(s,t,z,z') = -f^{\pm}(\lambda)\sqrt{\frac{3}{10\sqrt{\lambda}\pi \log s/s_0}} \left(\frac{s}{s_0}\right)^{j_{\mathbb{R}}(t)-j_\pm} \times \ldots\,,$$
$$f^{+}(\lambda) = i + \frac{4\sqrt{\lambda}}{3\pi} - \frac{\pi}{4\sqrt{\lambda}}, \qquad f^{-}(\lambda) = i + \frac{4\sqrt{\lambda}}{(m_k^2-1)\pi} - \frac{(m_k^2-1)\pi}{12\sqrt{\lambda}} \tag{11}$$

Note:

- The standard hard- and soft-wall fail to capture the Gribov diffusion

Eikonalization

The Pomeron violates unitarity, a simple remedy is eikonalization. In AdS this is achieved by

$$\begin{aligned} \mathcal{A}_{pp}(s,t,z,z') &= -2is \int d^2b_\perp \, e^{-iq_\perp \cdot b_\perp} \left(e^{i(\chi_{\mathbb{P}}+\chi_{\mathbb{O}})} - 1 \right) \\ \mathcal{A}_{p\bar{p}}(s,t,z,z') &= -2is \int d^2b_\perp \, e^{-iq_\perp \cdot b_\perp} \left(e^{i(\chi_{\mathbb{P}}-\chi_{\mathbb{O}})} - 1 \right), \end{aligned} \tag{12}$$

with the eikonal phase $\chi_{\mathbb{R}}(s,b_\perp,z,z') = s^{j_\pm - 1} G_{j_\pm}(j_{\mathbb{R}}, s, b_\perp, z, z')$.
The 4D amplitudes are then obtained via

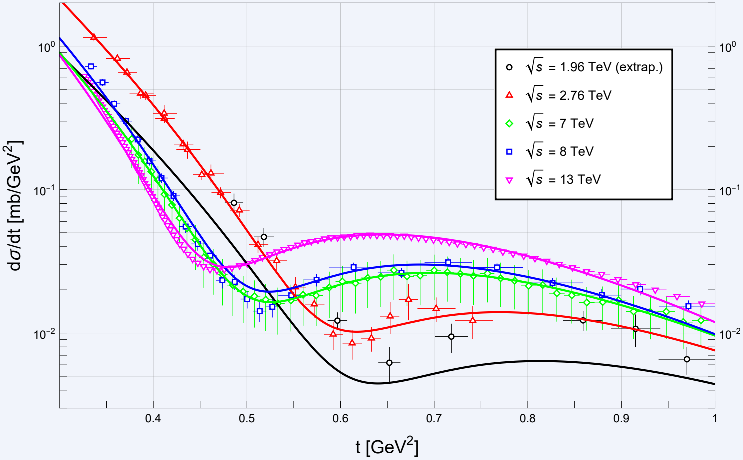
$$\mathcal{A}(s,t) = \int dzdz' \sqrt{g(z)}\, \Psi_{12}(z)\, \mathcal{A}(s,t,z,z')\, \sqrt{g(z')}\, \Psi_{34}(z'), \tag{13}$$

with vertex factors implicit.

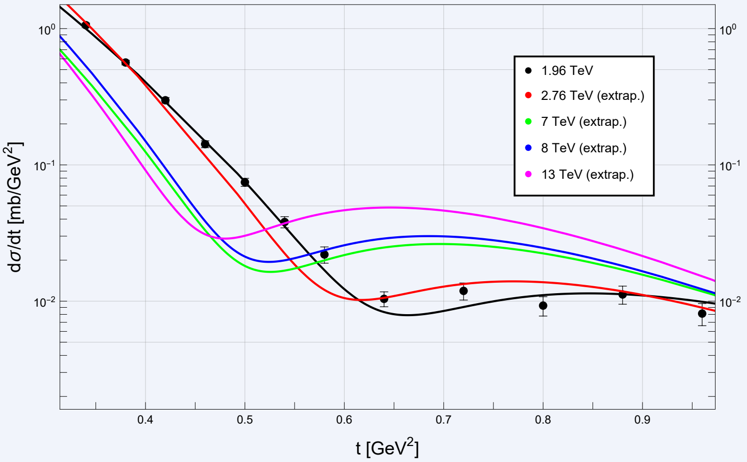
Outline

pp

- Dependence on Odderon subtle, since $j_{\mathbb{O}}(0) < 1 \rightarrow$ obtain upper bound for Odderon coupling from forward quantities $\sigma_{tot}(s)$, $\rho(s)$



$p\bar{p}$



1.96 TeV
2.76 TeV (extrap.)
7 TeV (extrap.)
8 TeV (extrap.)
13 TeV (extrap.)
dσ/dt [mb/GeV^2]
t [GeV^2]
0.4
0.5
0.6
0.7
0.8
0.9
10^0
10^{-1}
10^{-2}

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Conclusion and outlook

Conclusion

- Construction of a holographic model that captures the necessary forward as well as off-forward behaviour to describe the total and differential pp and $p\overline{p}$ cross section
- The data is well reproduced without an Odderon contribution with intercept < 1
- Unfortunately, in our model the pole of the maximal Odderon can not be regulated

Outlook

Our study suggest to look for (holographic) Odderon physics at lower energies:

- Threshold production of η_c and η_b (hep-ph/2401.121628)
- Nucleon structure via GPDs $\rightarrow$ Gluon helicity contribution to proton spin?
- Single-Spin asymmetry in semi-inclusive DIS due to Odderon?

All these processes can be studied at the future EIC at BNL!

For questions, comments, suggestions: florian.hechenberger@tuwien.ac.at

Backup Slides

Fit results

$g^{(2)}_{\mathbb{O}\overline{\Psi}\Psi}$	α' (GeV^{-2})	$g_{\mathbb{P}\overline{\Psi}\Psi}$	$\mathcal{N}_\sigma$	$\mathcal{N}_\rho$
0	1.098(2)	2.1856(40)	$4.6 \cdot 10^{-3}(07)$	0.787(190)
15	1.098(2)	2.1856(40)	$4.6 \cdot 10^{-3}(07)$	0.787(190)
25	1.098(2)	2.1857(40)	$4.6 \cdot 10^{-3}(07)$	0.787(190)

$\sqrt{s}$	α' [GeV^{-2}]	$g_{\mathbb{P}\overline{\Psi}\Psi}$	$\mathcal{N}_{d\sigma}$
1.96 TeV	0.640(21)	1.071(15)	0.003
2.76 TeV	0.715(27)	1.009(3)	0.007
7 TeV	0.607(5)	1.089(3)	0.002
8 TeV	0.626(15)	1.046(9)	0.003
13 TeV	0.587(5)	1.0782(3)	0.002

Homogeneous solution

The resulting mode equation is the Whittaker equation with homogeneous solutions

$$\begin{aligned} K_1(v) &= e^{-\frac{v}{2}} v^{\frac{1}{2}+\alpha}\,\mathbb{M}\left(\frac{1}{2}+\alpha-\beta, 1+2\alpha, v\right) \\ K_2(v) &= e^{-\frac{v}{2}} v^{\frac{1}{2}+\alpha}\,\mathbb{U}\left(\frac{1}{2}+\alpha-\beta, 1+2\alpha, v\right) \\ \alpha &= \frac{\Delta_g(j)-2}{2}, \;\; \beta = \frac{3-S_j-m_5^2+t/a\kappa^2}{6}. \end{aligned} \tag{14}$$

Inhomogeneous solution

$$K_0(v,v') = \frac{1}{2}\mathcal{A}\, K_2(v_>)K_1(v_<), \quad \mathcal{A}^{-1} = -\frac{\sqrt{6}a\kappa\Gamma(1+2\alpha)}{\Gamma\left(\frac{1}{2}+\alpha-\beta\right)}, \tag{15}$$

with the normalization fixed by the Wronskian.