Deeply Virtual Compton Scattering from Gauge/Gravity Duality

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work with Miguel S. Costa

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Outline

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Pomeron in AdS

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The strong interaction is one of the fundamental interactions between particles.
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▶ The coupling constant in QCD runs in the opposite way to QED.

\[ \alpha(\mu_1) = 4\pi b_0 \ln(\mu_2 / \Lambda_{QCD}) \]

\[ b_0 = \frac{11}{3} N - \frac{2}{3} n_f (= 7) \]

▶ We see that at high energies the coupling is weak and we can study the theory perturbatively.

▶ However, at lower energies, once it is of order \( \Lambda_{QCD} \) the coupling is very strong and we cannot use pQCD.

▶ Our goal is to study the strong interaction at strong coupling.

▶ More specifically, a recent conjecture by Maldacena relating string theory on \( AdS_5 \times S_5 \) to \( N=4 \) SYM allows us to study QCD at strong coupling.
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- More specifically, a recent conjecture by Maldacena relating string theory on \( AdS_5 \times S_5 \) to \( \mathcal{N} = 4SYM \) allows us to study QCD at strong coupling.
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The Pomeron

The Pomeron is the leading order exchange in all total cross sections, and in $2 \to 2$ amplitudes with the quantum numbers of the vacuum, in the Regge limit $s \gg t$. It is the sum of an infinite number of states with the quantum numbers of the vacuum. It leads to an amplitude that as $s \to \infty$ goes as $A(s,t) \sim s^{\alpha(t)}$, $\alpha(t) = \alpha(0) + \alpha'(t^2)$, at weak coupling, the propagation of the Pomeron is given by the BFKL equation.
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The AdS/CFT Correspondence

The conjectured exact duality between type IIB string theory on AdS$_5 \times S^5$, and $N=4$ SYM, on the boundary.

The duality relates states in string theory to operators in the field theory through the relation

$$
\langle e^{\int d^4x \phi_i(x)} O_i(x) \rangle_{\text{CFT}} = \mathcal{Z}_{\text{string}}[\phi_i(x, z) | z \sim 0]
$$

The metric we will use

$$
ds^2 = e^{2A(z)} [-dx + dx - + dx_{\perp} dx_{\perp} + dz dz] + R^2 d^2 \Omega^5.
$$

In the hard-wall model up to a sharp cutoff $z_0 \approx 1/\Lambda_{\text{QCD}}$

$$
e^{2A(z)} = R^2 / z^2.
$$

Correspondence works in the limit $N_C \rightarrow \infty$, $\lambda = g^2 N_C = R^4 / \alpha' \gg 1$, fixed.
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Pomeron in AdS string theory

What is the Pomeron in AdS String theory? (Brower, Polchinski, Strassler, Tan 2006)

It is the Regge trajectory of the graviton.

In flat space, the Pomeron vertex operator

\[ V_P \] \nonumber = (2\alpha' \partial X + \bar{\partial} X + t^4 \exp(-ik \cdot X))^{1+\alpha'}

The Pomeron exchange propagator in AdS is given by

\[ K = 2(zz')^2 s g^2 R^4 \chi(s,b,z,z') \] \nonumber

where

\[ \chi(\tau,L) = (\cot(\pi\rho^2) + i) g^2 e^{(1-\rho)\tau} L \sinh L \exp(-L^2 \rho \tau)^{3/2} \]
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The weak and strong coupling Pomeron exchange kernels have a remarkably similar form.
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At $t = 0$

Weak coupling:

$$K(k_\perp, k'_\perp, s) = \frac{s^j_0}{\sqrt{4\pi D \log s}} e^{-\left(\log k_\perp - \log k'_\perp\right)^2 / 4D \log s}$$

$$j_0 = 1 + \frac{\log 2}{\pi^2} \lambda, \quad D = \frac{14\zeta(3)}{\pi} \lambda / 4\pi^2$$

Strong coupling:

$$K(z, z', s) = \frac{s^j_0}{\sqrt{4\pi D \log s}} e^{-\left(\log z - \log z'\right)^2 / 4D \log s}$$

$$j_0 = 2 - \frac{2}{\sqrt{\lambda}}, \quad D = \frac{1}{2\sqrt{\lambda}}$$
Pomeron and the Eikonal Approximation

According to the Froissart bound

\[ \sigma_{\text{tot}} \leq \pi c \log (s/s_0) \]

Hence the Pomeron exchange violates this bound.

Eventually effects beyond one Pomeron exchange become important.

Eikonal approximation in AdS space (Brower, Strassler, Tan; Cornalba, Costa, Penedones)

\[ A(s,t) = 2 \int d^2 l e^{-i l \cdot q} \int dz d\bar{z} P_{13}(z) P_{24}(\bar{z})(1 - e^{i\chi(s,b,z,\bar{z})}) \]

We can study different scattering processes by supplying \( P_{13} \) and \( P_{24} \).

For example, already applied to DIS [Brower, MD, Sarcevic, Tan].
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What is DVCS?

Deeply Virtual Compton Scattering is the scattering between an offshell photon and a proton.
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\[
\begin{align*}
\gamma^* & \rightarrow e^- + e^- \\
k_1 & \rightarrow k_2 + p \\
k_3 & \rightarrow \gamma + k_4 \\
\gamma & \rightarrow p \\
\end{align*}
\]
What is DVCS?

**Deeply Virtual Compton Scattering** is the scattering between an offshell photon and a proton.

The basic kinematical variables we need for describing this process are

- the center of mass energy $s = (p + k_1)^2$
- the photon virtuality $Q^2 = -k_1 \cdot k_1 > 0$
- the scaling variable $x \approx Q^2/s$
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![Diagram of Deeply Virtual Compton Scattering]

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- the scaling variable
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We are interested in calculating the differential and exclusive cross sections

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\frac{d\sigma}{dt}(x, Q^2, t) = \frac{|W|^2}{16\pi s^2},
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and

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\sigma(x, Q^2) = \frac{1}{16\pi s^2} \int dt |W|^2.
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Here \( W \) is the scattering amplitude

\[ W = 2isQQ' \int dl_\perp e^{iq_\perp \cdot l_\perp} \int \frac{dz}{z^3} \frac{d\bar{z}}{\bar{z}^3} \Psi(z) \Phi(\bar{z}) \left[ 1 - e^{i\chi(S,L)} \right]. \]
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This has the previously mentioned form, we just need to supply the wavefunctions \( \Psi(z) \) and \( \Phi(\bar{z}) \) for the photon and the proton.
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This has the previously mentioned form, we just need to supply the wavefunctions $\Psi(z)$ and $\Phi(\bar{z})$ for the photon and the proton.

In this analysis we use

$$\Psi(z) = -C \frac{\pi^2}{6} z^3 K_1(Qz), \quad \Phi(\bar{z}) = \bar{z}^3 \delta(\bar{z} - z_*)$$
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Conformal Pomeron

- In the paper we first consider the AdS black disk model [Cornalba, Costa, Penedones], but there is no time in this talk.

$$1 - e^{i\chi} \approx -i\chi = -i\left(\cot(\frac{\pi \rho}{2}) + i\right) g_2^0 e^{(1 - \rho \tau)} \sinh L \exp(-L^2 \rho \tau) \left(\frac{\rho \tau}{2}\right)^3/2$$

- Depends on 3 parameters: $z^* \rho = 2 - j^0 = 2\sqrt{\lambda}$.

- $C$ is the aforementioned normalization, and $g_2^0$ is related to the coupling of the external states to the pomeron.
Conformal Pomeron

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$$C \ g_0^2$$.

- $C$ is the aforementioned normalization, and $g_0^2$ is related to the coupling of the external states to the pomeron.
Hard wall pomeron

- Obtained by placing a sharp cut-off on the radial AdS coordinate at $z = z_0$. 

\begin{equation*}
\chi_{\text{hw}}(\tau, t = 0, z, \bar{z}) = \chi(\tau, 0, z, \bar{z}) + F(\tau, z, \bar{z}) \chi(0)_{\text{hw}}(\tau, l, z, \bar{z})
\end{equation*}

- When $t \neq 0$, we will use an approximation

\begin{equation*}
\chi_{\text{hw}}(\tau, l, z, \bar{z}) = C(\tau, z, \bar{z}) D(\tau, l) \chi(0)_{\text{hw}}(\tau, l, z, \bar{z})
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- First notice that at $t = 0$ $\chi$ for conformal pomeron exchange can be integrated in impact parameter

$$\chi(\tau, t = 0, z, \bar{z}) = i\pi g_0^2 \left( \cot \left( \frac{\pi \rho}{2} \right) + i \right) (z \bar{z}) e^{(1-\rho)\tau} e^{-\frac{(\ln(\bar{z}/z))^2}{\rho \tau}} \frac{e^{-\frac{(\ln(\bar{z}/z))^2}{\rho \tau}}}{(\rho \tau)^{1/2}}$$
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$$\chi(\tau, t = 0, z, \bar{z}) = i\pi g_0^2 \left( \cot \left( \frac{\pi \rho}{2} \right) + i \right) (z \bar{z}) e^{(1-\rho)\tau} \frac{e^{-\left(\frac{(\ln(\bar{z}/z))^2}{\rho \tau}\right)}}{(\rho \tau)^{1/2}}$$

- Similarly, the $t = 0$ result for the hard-wall model can also be written explicitly

$$\chi_{hw}(\tau, t = 0, z, \bar{z}) = \chi(\tau, 0, z, \bar{z}) + \mathcal{F}(\tau, z, \bar{z}) \chi(\tau, 0, z, z_0^2/\bar{z})$$
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- When $t \neq 0$, we will use an approximation

$$\chi_{hw}(\tau, l, z, \bar{z}) = C(\tau, z, \bar{z}) D(\tau, l) \chi_{hw}^{(0)}(\tau, l, z, \bar{z})$$
The function

\[ F(\tau, z, \bar{z}) = 1 - 4\sqrt{\pi \tau} e^{\eta^2} \text{erfc}(\eta), \quad \eta = \frac{-\log(z\bar{z}/z_0^2) + 4\tau}{\sqrt{4\tau}} \]

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- For the data here analysed, the size of \(F\) will roughly vary between \(-0.1\) and \(-0.4\).
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- We will look at both the differential and total exclusive cross sections.
- We have 52 points for the differential and 44 points for the cross section.
Note that the same formalism has been applied before to DIS with good results ($\chi^2 = 1.04$ for the best model) [Brower, MD, Sarčević, Tan, 2010].
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Fitting the differential cross section to the data, we get

\[ g_0^2 = 1.95 \pm 0.85, \quad z_* = 3.12 \pm 0.160 \text{GeV}^{-1}, \quad \rho = 0.667 \pm 0.048. \]

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Outline

Introduction

Pomeron in AdS

Deeply Virtual Compton Scattering

Models

Data Analysis

Conclusions
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- We have seen that we now have 2 processes (DIS and DVCS) where the AdS black disk and the AdS (BPST) pomeron exchange give excellent agreement with experiment in the strong coupling region.
- Hence string theory on AdS is giving us interesting insights into non-perturbative scattering.
- The value of the pomeron intercept is in the region $1.2 - 1.3$ which is in the crossover region between strong and weak coupling, and a lot of the equations have a form which is very similar both at weak and at strong coupling (but $\chi$ is different).
- It might therefore be possible to extend some of the insights we gain even into the weak coupling regime.
- The hard wall model, although a simple modification of AdS, seems to capture effects of confinement well. Interesting to repeat some of the calculations using a different confinement model to identify precisely what features are model independent.
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- It is also interesting to extend these methods beyond $2 \rightarrow 2$ scattering.
- Recent paper by Brower, MD and Tan applies double pomeron exchange to Higgs production - see the talk by Rich Brower on Friday.
Thank you!