Small x Scattering using Gauge/Gravity Duality

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Holography and QCD - Recent progress and challenges
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Outline

Introduction

Pomeron in AdS

Deep Inelastic Scattering

Deeply Virtual Compton Scattering

Vector Meson Production

Conclusions

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- The BFKL equation sums the leading $\log \frac{1}{x}$ diagrams for interaction of gluon on gluon, and leads to power behaviour for the cross section - QCD Pomeron.
- This perturbative QCD approach works at high Q^2, and the goal is to extend it as much as possible into the low Q^2 region, typically up to somewhere of the order $Q^2 = 1 - 4GeV^2$.

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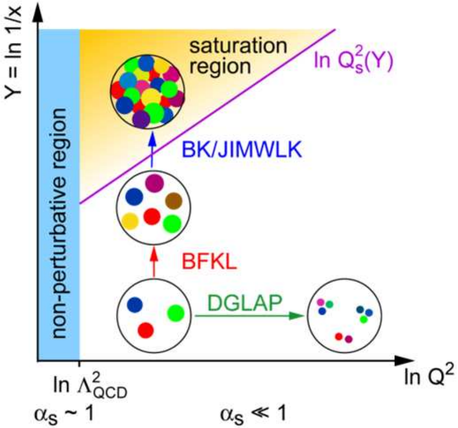

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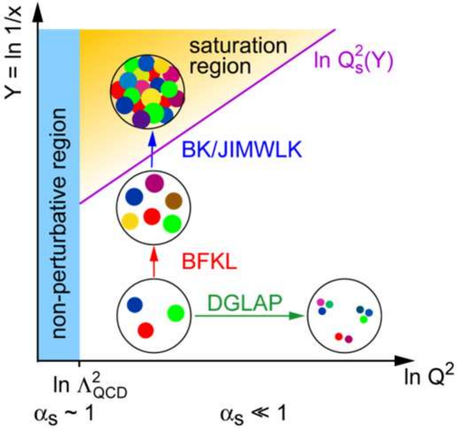

- Our goal is to apply an alternative method to study the non-perturbative and saturation regions, and also see how much can they be applied to the higher Q^2 region as well.

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- If exchanged particle has spin j

$$A(s,t) \sim s^j$$

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$$\sigma_{tot} = \frac{1}{s} \Im A(s, 0)$$

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- $A(j,t)$ will have as singularities poles at integer j for fixed t. As we change t, the position of the pole will change, leading to a trajectory

$$j = \alpha(t)$$

- We can write $A(s,t)$ as a contour integral in the complex plane

$$A^{\pm}(s,t) = 8\pi \sum_{j=0}^{\infty} (2j+1)\, A_j^{\pm}(t)(P_j(z_t) \pm P_j(-z_t))$$
$$= 8\pi i \int_C dj(2j+1)A^{\pm}(j,t)\frac{P(j,-z_t) \pm P(j,z_t)}{\sin(\pi j)}$$

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- We next deform the contour C to a contour C' parallel to imaginary axis and real part $-1/2$

$$A^{\pm}(s,t) = -16\pi^2 \sum_i \frac{(2\alpha_i^{\pm}(t)+1)\beta_i^{\pm}(t)}{\sin(\pi\alpha_i^{\pm}(t))} (P(\alpha_i^{\pm}(t),-z_t) \pm P(\alpha_i^{\pm}(t),z_t))$$

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- $\alpha_i^{\pm}(t)$ is the position of the pole in the j plane.
- Take advantage of the asymptotic form of the Legendre polynomials

$$\sqrt{\pi} P(j,z) \sim \frac{\Gamma(j+1/2)}{\Gamma(j+1)} (2z)^j \qquad \Re j \geq -1/2$$

- This will give us a sum in powers of s. At high energy, we can keep just the leading term

$$A^{\pm}(s,t) \sim (1 \pm e^{-i\pi\alpha^{\pm}(t)})\beta(t)(\frac{s}{s_0})^{\alpha^{\pm}(t)}.$$

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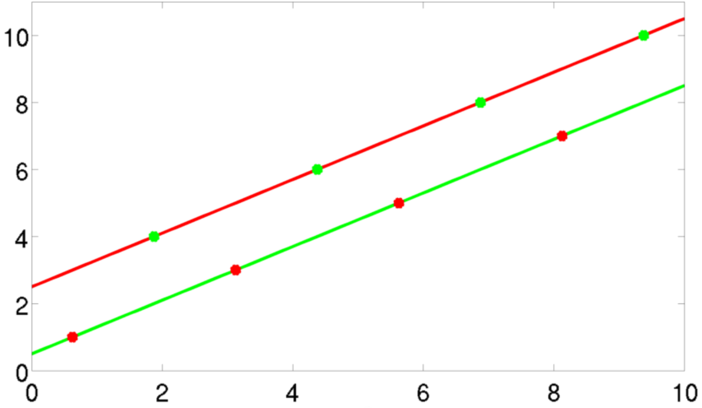

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- The leading Reggeon which has the quantum numbers of the vacuum, $C = +1$ and $I = 0$, is known as the Pomeron.
- The intercept $\alpha(0) > 1$ leading to non-vanishing

$$\sigma_{tot} \sim s^{\alpha(0)-1}$$

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- We can expand the exponential to get

$$A(s, -\mathbf{q_\perp}^2) = -2is \int d^2b e^{-i\mathbf{b}_\perp \cdot \mathbf{q}_\perp} (i\chi + \frac{(i\chi)^2}{2} + \cdots) \, .$$

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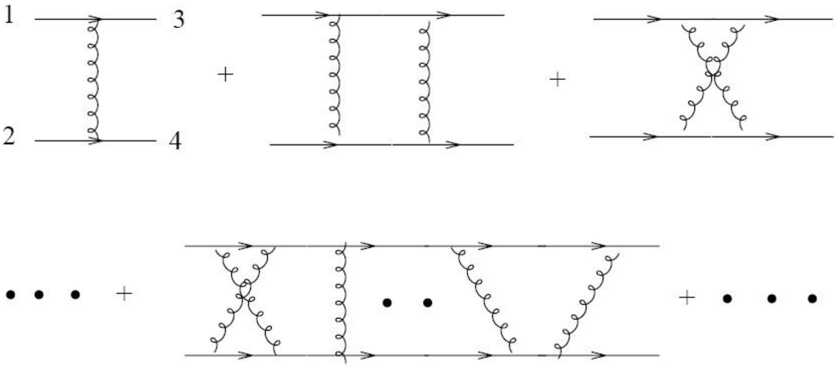

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- The cutoff position will roughly correspond to

$$z_0 \simeq \frac{1}{\Lambda_{QCD}}.$$

- Let us write the scattering amplitude [Brower, Polchinski, Strassler, Tan, 2006]

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- We can show that this would lead to amplitudes

$$A(s,t) \sim (\alpha' s)^{\alpha(t)}$$

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- where $\Delta_j = (r/R)^j(\Delta_0)(r/R)^{-j}$. And Δ_0 is the scalar Laplacian in curved space.

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- and for the amplitude we would have

$$\mathcal{T}^{(+)}\sim\int\frac{dj}{2\pi i}\int\frac{d\nu\nu\sinh 2\pi\nu}{\pi}\frac{\Pi(j)\ s^j}{j-j_0^{(+)}+\mathcal{D}\nu^2}$$
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- with $j_0^{(+)}$ given by

$$j_0^{(+)}=2-2/\sqrt{\lambda}+O(1/\lambda)\ .$$

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- Due to conformal invariance, χ is a function of only two variables

$$L = \log(1 + v + \sqrt{v(2+v)})$$
$$\tau = \log(\frac{\rho}{2} z z' s)$$

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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

$$\mathcal{F}(\tau, z, \bar{z}) = 1 - 4\sqrt{\pi\tau}\, e^{\eta^2}\,\mathrm{erfc}(\eta)\,, \qquad \eta = \frac{-\log(z\bar{z}/z_0^2) + 4\tau}{\sqrt{4\tau}}$$

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- Note that these methods can be generalized to Odderon exchange as well [Brower, MD, Tan, 2008].

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

  Strong coupling:

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

$$j_0 = 2 - \frac{2}{\sqrt{\lambda}}, \quad \mathcal{D} = \frac{1}{2\sqrt{\lambda}}$$

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- $z_0 \simeq \frac{1}{\Lambda_{QCD}}$, the position of the hard wall in AdS space, intuitively should be related to Λ_{QCD}
- Only three parameters for the conformal model, and 4 for the hard wall.

Outline

Introduction

Pomeron in AdS

Deep Inelastic Scattering

Deeply Virtual Compton Scattering

Vector Meson Production

Conclusions

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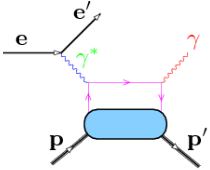

Figure: DIS in dipole picture (Mueller 1990)

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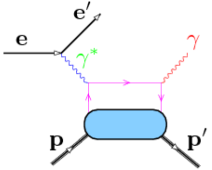

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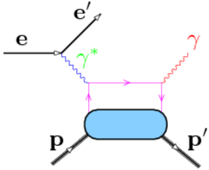

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The basic kinematical variables we need for describing this process are

- center of mass energy s, the virtuality Q^2 and the scaling variable x

$$
\begin{aligned}
s &= -(P+k)^2 \\
Q^2 &= -q^\mu q_\mu = -(k-k')^2 > 0 \\
x &\approx \frac{Q^2}{s}
\end{aligned}
$$

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$$\sigma_{tot} = \frac{1}{s} \Im A(s, t = 0)$$

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- We will look at $0.10GeV^2 < Q^2 < 400GeV^2$.
- At lower or higher Q^2 there is no experimental data with $x < 0.01$.

As we saw, we are going to calculate F_2 by relating it to the total cross section. This in turn we will calculate using the optical theorem, for which we need the forward scattering amplitude at $t = 0$. Putting it all together, using the eikonal approximation we get [Brower, MD, Sarcevic, Tan, 2010]

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We need to supply the wavefunctions for the photon and the proton. For the photon we will consider an R boson propagating through the bulk that couples to leptons on the boundary (Polchinski, Strassler 2003)

$$P_{13}(z, Q^2) = \frac{1}{z}(Qz)^2(K_0^2(Qz) + K_1^2(Qz)),$$

We would also need a wavefunction associated to the proton $\phi_p(z)$. For the current analysis, we will assume that the wave function is sharply peaked near the IR boundary z_0, with $1/Q' \leq z_0$, with Q' of the order of the proton mass. For simplicity, we will simply replace P_{24} by a sharp delta-function

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- The structure function F_2 can be expressed as

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- The difference between the conformal and confinement depends on the size of the function $\mathcal{F}$.
- $\mathcal{F}$ at fixed z, z', goes to 1 as $\tau \to 0$ and to -1 as $\tau \to \infty$. Hence, at small x, $\mathcal{F} \to -1$ and confinement leads to a partial cancelation for the growth rate. Since $\mathcal{F}$ is continuous, there will be a region over which $\mathcal{F} \sim 0$, and, in this region, there is little difference between the hard-wall and the conformal results.

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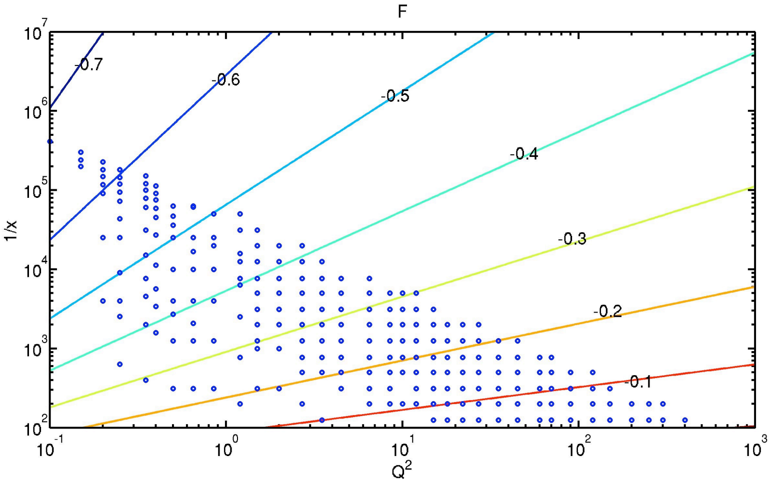

Figure: Contour plot for coefficient function $\mathcal{F}$ as a function of $log(1/z)$ and $\log(1/x)$, with $z' \simeq z_0$ fixed, $z_0 \sim \Lambda_{QCD}^{-1}$.

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$$\chi^2_{d.o.f.} = 11.7$$

- For the hard-wall model we get a much better fit. Parameters are:

$$\rho = 0.7792 \pm 0.0034,\ g_0^2 = 103.14 \pm 1.68,$$
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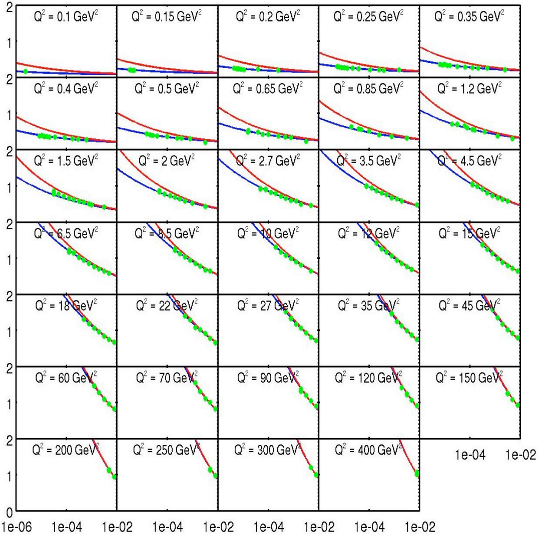
Plots


Q^2 = 0.1 GeV^2
Q^2 = 0.15 GeV^2
Q^2 = 0.2 GeV^2
Q^2 = 0.25 GeV^2
Q^2 = 0.35 GeV^2
Q^2 = 0.4 GeV^2
Q^2 = 0.5 GeV^2
Q^2 = 0.65 GeV^2
Q^2 = 0.85 GeV^2
Q^2 = 1.2 GeV^2
Q^2 = 1.5 GeV^2
Q^2 = 2 GeV^2
Q^2 = 2.7 GeV^2
Q^2 = 3.5 GeV^2
Q^2 = 4.5 GeV^2
Q^2 = 6.5 GeV^2
Q^2 = 8.5 GeV^2
Q^2 = 10 GeV^2
Q^2 = 12 GeV^2
Q^2 = 15 GeV^2
Q^2 = 18 GeV^2
Q^2 = 22 GeV^2
Q^2 = 27 GeV^2
Q^2 = 35 GeV^2
Q^2 = 45 GeV^2
Q^2 = 60 GeV^2
Q^2 = 70 GeV^2
Q^2 = 90 GeV^2
Q^2 = 120 GeV^2
Q^2 = 150 GeV^2
Q^2 = 200 GeV^2
Q^2 = 250 GeV^2
Q^2 = 300 GeV^2
Q^2 = 400 GeV^2
0
1
2
1e-06
1e-04
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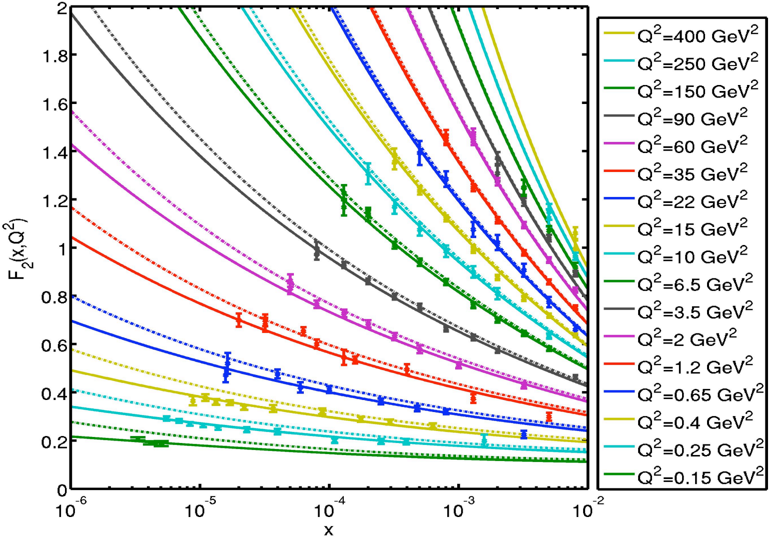
Fitting this expression we get the parameters:

$$\rho = 0.7833 \pm 0.0035,\ g_0^2 = 104.81 \pm 1.41,$$

$$z_0 = 6.04 \pm 0.15\, GeV^{-1},\ Q' = 0.4439 \pm 0.0177\, GeV$$

Plots



$F_2(x,Q^2)$
x
Q^2=400 GeV^2
Q^2=250 GeV^2
Q^2=150 GeV^2
Q^2=90 GeV^2
Q^2=60 GeV^2
Q^2=35 GeV^2
Q^2=22 GeV^2
Q^2=15 GeV^2
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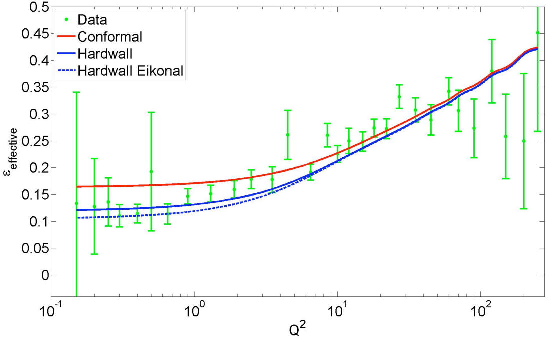

Figure: Q^2-dependence for effective Pomeron intercept, $\alpha_P = 1 + \epsilon_{eff}$.

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- Comparable number of parameters and χ^2 (Kowalski et al $\chi^2 \sim 1.2$), but the advantage of our approach is we can go to low Q^2 (the data with lowest Q^2 is at $0.10 GeV^2$) whereas their approach stops at $Q^2 = 4 GeV^2$.

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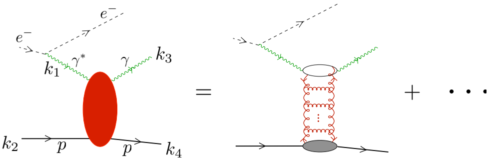

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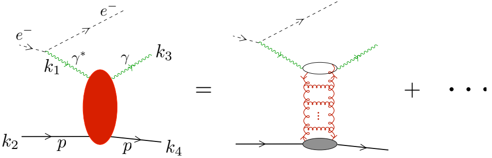

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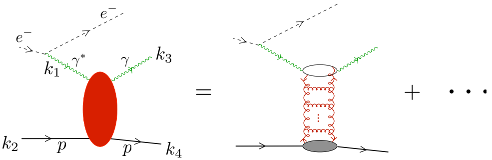

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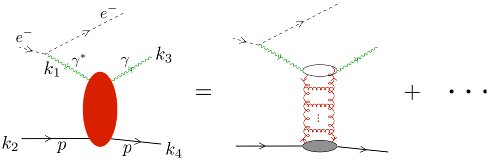

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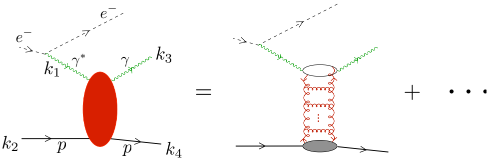

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- the scaling variable

$$x \approx \frac{Q^2}{s}$$

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- In this analysis we use

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

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- We have 52 points for the differential and 44 points for the cross section.

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- Fitting the differential cross section to the data, we get [Costa, MD, 2012]

  $$g_0^2 = 1.95 \pm 0.85\,, \qquad z_* = 3.12 \pm 0.160\mathrm{GeV}^{-1}\,, \qquad \rho = 0.667 \pm 0.048\,.$$

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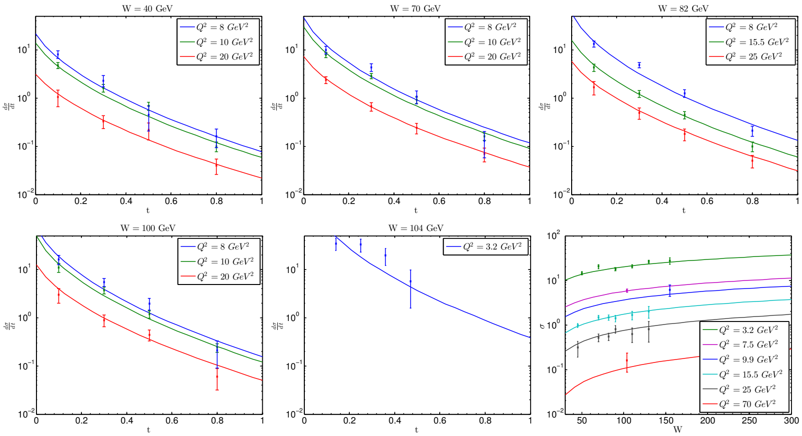
W = 40 GeV
W = 70 GeV
W = 82 GeV
W = 100 GeV
W = 104 GeV
$Q^2 = 8\ GeV^2$
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$Q^2 = 20\ GeV^2$
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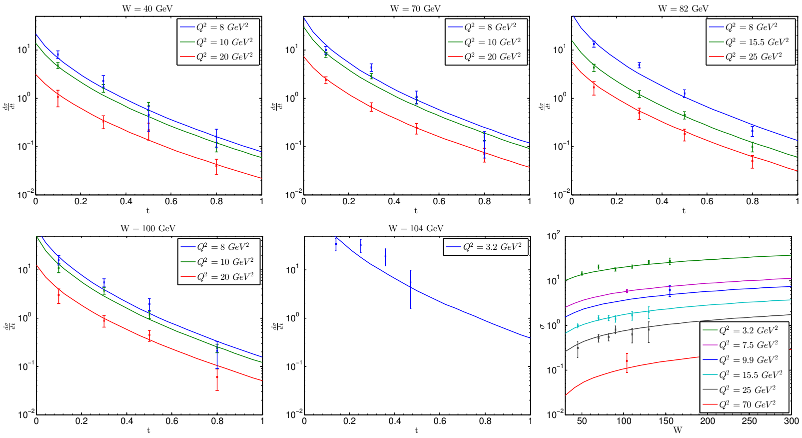
$\frac{d\sigma}{dt}$
σ
t
W



Running the same fit using the eikonal approximation, instead of just keeping single pomeron exchange, does not improve the fits, due to the fact that the size of χ is small in this kinematical region.

Hard wall pomeron

- The parameters we obtain by fitting are

$$g_0^2 = 2.46 \pm 0.70\,, \quad z_* = 3.35 \pm 0.41 \text{ GeV}^{-1}, \quad \rho = 0.712 \pm 0.038\,,$$
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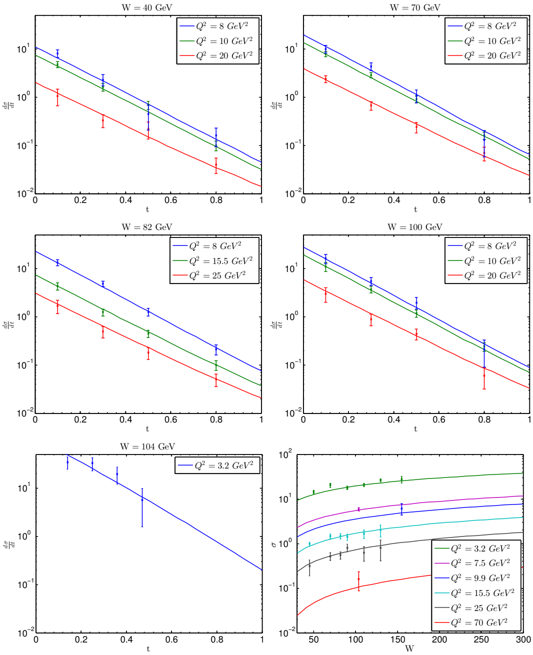
W = 40 GeV
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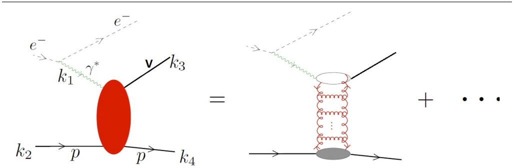

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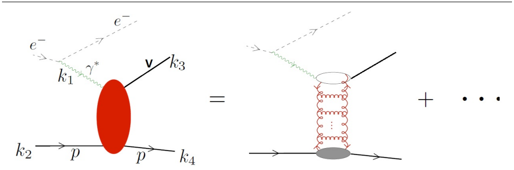

The vector mesons consist of a quark-antiquark pair, and have the same quantum numbers as the photon, $J^{PC} = 1^{--}$. The production of the ρ^0, ω, ϕ and J/Ψ was measured at HERA.

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- In this analysis we use [Costa, MD, Evans, 2013]

$$\Psi_n(z) = -(\sqrt{C\,\frac{\pi^2}{6}}\,z^2\,K_n(Qz))(\frac{\sqrt{2}}{\xi J_1(\xi)}z^2 J_n(mz)),\;\; \Phi(\bar{z}) = \bar{z}^3\,\delta(\bar{z}-z_\star)$$

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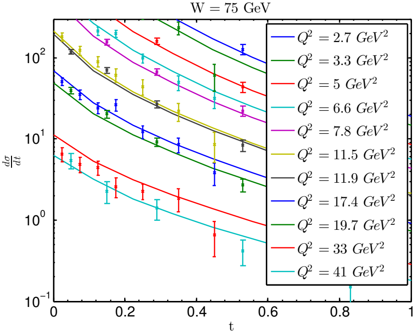
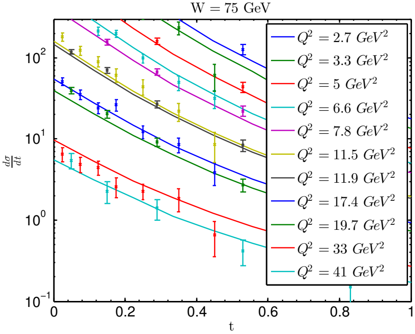
- We will look at both the differential and total exclusive cross sections.

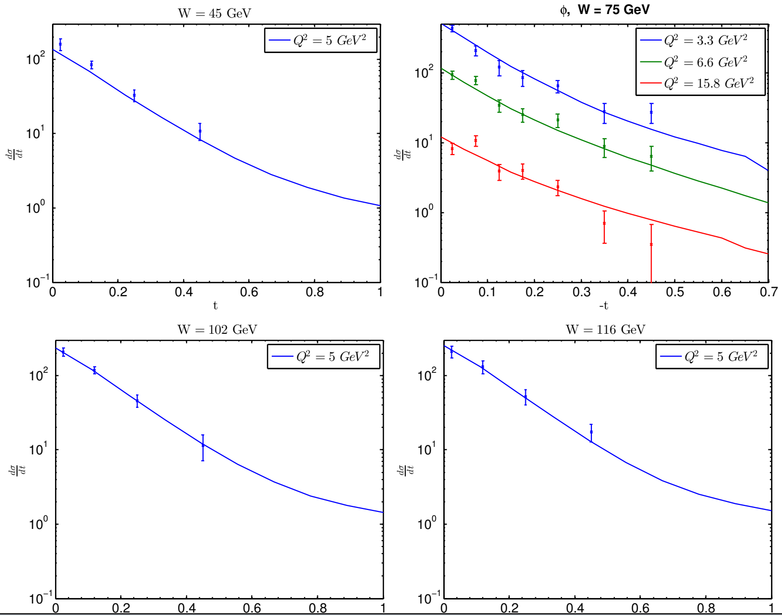
		σ [nb]				dσ/dt [nb/GeV²]		
		ρ	φ	Ω	J/ψ	ρ	φ	J/ψ
	m [GeV]	0.77549	1.019445	0.78265	3.096916	0.77549	1.019445	3.096916
	N	48	27	6	38	35	21	84
Conformal	χ^2	0.92	0.60	0.0099	0.28	1.7	1.3	2.9
	g_0^2	4.6	1.8	0.53	0.62	1.6	0.25	0.56
	ρ	0.76	0.73	0.64	0.70	0.65	0.54	0.72
	z* [GeV^{-1}]	3.4	3.0	1.8	0.98	2.1	2.5	2.2
Hardwall	χ^2	0.88	0.61	0.015	0.30	1.7	1.4	1.8
	g_0^2	4.1	1.8	0.67	0.75	2.2	0.38	0.69
	ρ	0.76	0.73	0.66	0.71	0.69	0.59	0.75
	z* [GeV^{-1}]	3.6	3.6	1.5	0.87	2.2	2.5	2.4
	z_0 [GeV^{-1}]	4.8	4.4	7.3	5.3	7.7	8.6	4.6

Differential cross section for the ρ meson:

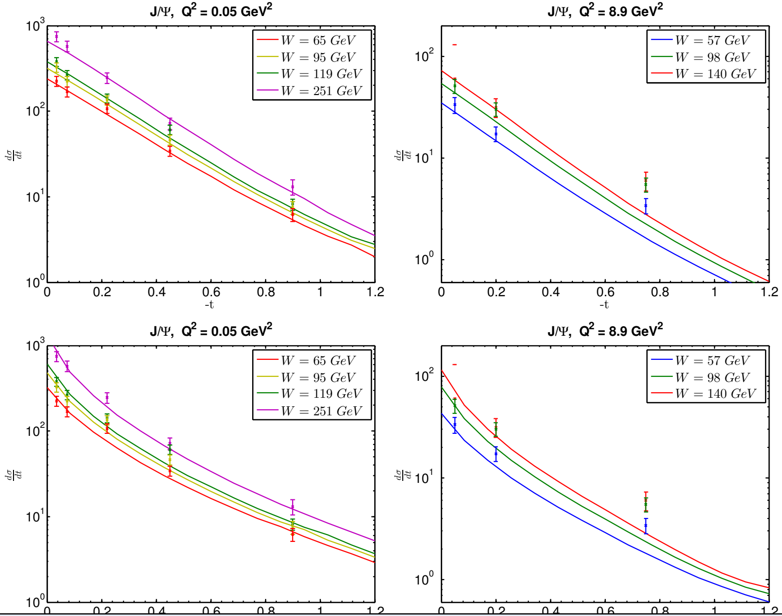




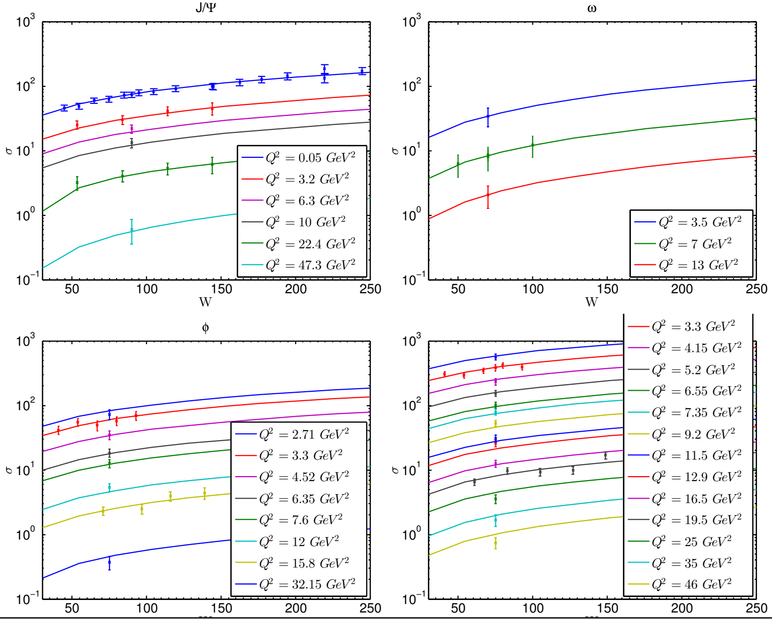
Differential cross section for the ϕ meson (hardwall model):



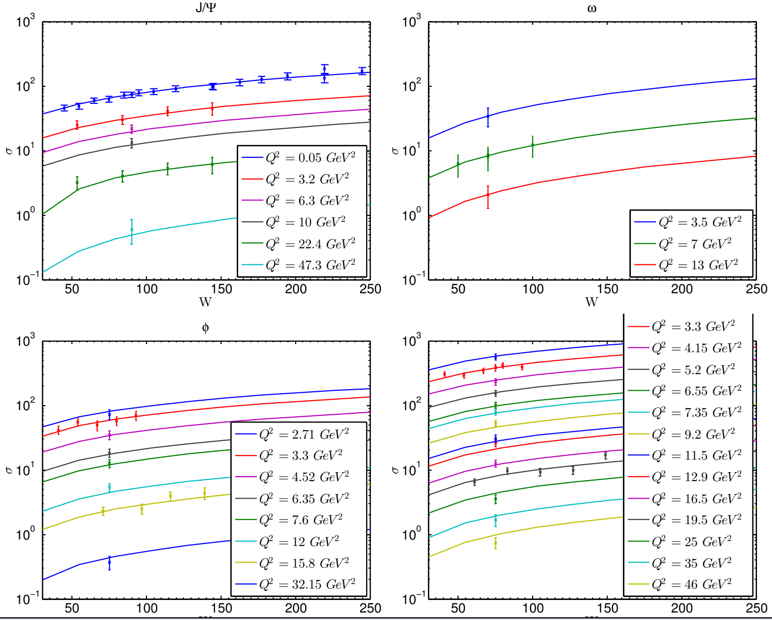
Differential cross section for the J/Ψ meson (hardwall model):



Cross sections for the conformal model:



Cross sections for the hardwall model:



Outline

Introduction

Pomeron in AdS

Deep Inelastic Scattering

Deeply Virtual Compton Scattering

Vector Meson Production

Conclusions

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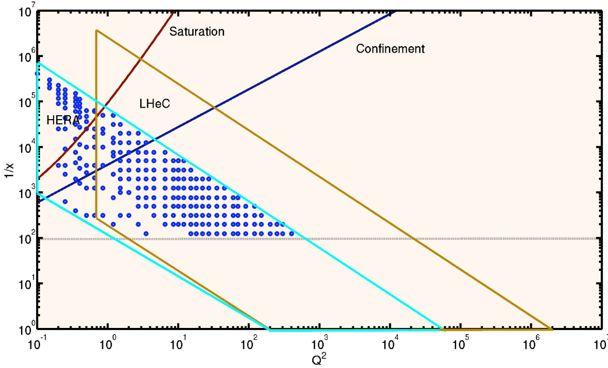

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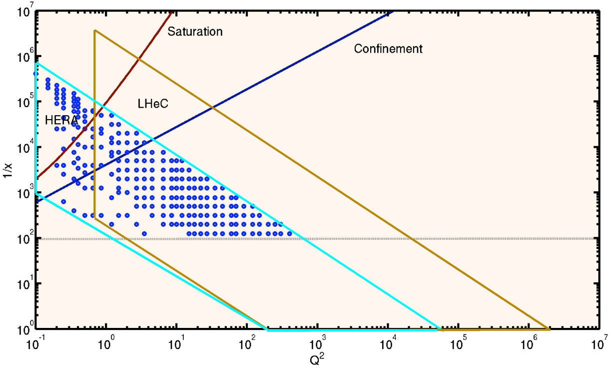

The above order of lines is the opposite of what is generally thought. Is it an artifact of our model?

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- 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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- Recent paper by Brower, MD and Tan applies double pomeron exchange to Higgs production [JHEP 1209 (2012) 097]
- Eventually it would be good to have a single set of parameters that fits several different processes.
- We can also try to use a different AdS model of confinement (for example the soft wall model [Brower, MD, Raben, Tan, in preparation]) and combine our methods with work by others (for example on the vector meson wavefunctions).

Thank you!