Soft and Hard Pomeron in AdS/QCD

Marko Djurić

Robert Carcasses, Miguel Costa and Alfonso Ballon-Bayona

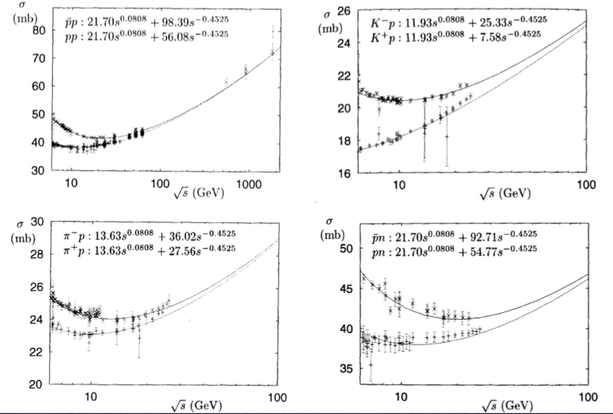
Iberian Strings 2015, Salamanca, Friday, May 29

U.PORTO
FC FACULDADE DE CIÊNCIAS UNIVERSIDADE DO PORTO

Outline

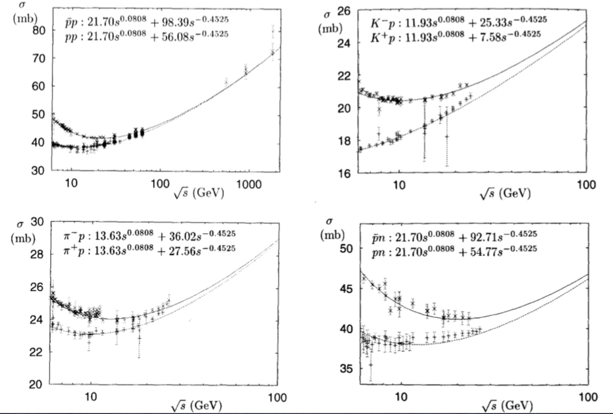
Outline

- Cross section data for a wide range of processes shows evidence for power law behaviour with *s* [Donnachie, Landshoff]



- This is evidence for so called soft Pomeron exchange, with the power $s^{0.08}$

- Cross section data for a wide range of processes shows evidence for power law behaviour with s [Donnachie, Landshoff]



- This is evidence for so called soft Pomeron exchange, with the power $s^{0.08}$

At the same time HERA, the largest electron - proton collider ever built, and operated from 1992-2007 collected a wealth of small x data. Two crucial (related) discoveries:

- Structure functions for many different processes (DIS, DVCS, VM production...) show a power growth with $1/x$.
- The same, universal gluon distribution functions describe these processes, and gluons dominate at small x.
- These point to a universal Pomeron exchange as the dominant process.
- 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 $Q^2 = 1 - 4GeV^2$.
- However the large Q^2 data shows evidence for a power closer to $s^{0.4}$, the so called hard Pomeron.

At the same time HERA, the largest electron - proton collider ever built, and operated from 1992-2007 collected a wealth of small x data. Two crucial (related) discoveries:

- Structure functions for many different processes (DIS, DVCS, VM production...) show a power growth with $1/x$.
- The same, universal gluon distribution functions describe these processes, and gluons dominate at small x.
- These point to a universal Pomeron exchange as the dominant process.
- 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 $Q^2 = 1 - 4GeV^2$.
- However the large Q^2 data shows evidence for a power closer to $s^{0.4}$, the so called hard Pomeron.

At the same time HERA, the largest electron - proton collider ever built, and operated from 1992-2007 collected a wealth of small x data. Two crucial (related) discoveries:

- Structure functions for many different processes (DIS, DVCS, VM production...) show a power growth with $1/x$.
- The same, universal gluon distribution functions describe these processes, and gluons dominate at small x.
- These point to a universal Pomeron exchange as the dominant process.
- 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 $Q^2 = 1 - 4 GeV^2$.
- However the large Q^2 data shows evidence for a power closer to $s^{0.4}$, the so called hard Pomeron.

At the same time HERA, the largest electron - proton collider ever built, and operated from 1992-2007 collected a wealth of small x data. Two crucial (related) discoveries:

- Structure functions for many different processes (DIS, DVCS, VM production...) show a power growth with $1/x$.
- The same, universal gluon distribution functions describe these processes, and gluons dominate at small x.
- These point to a universal Pomeron exchange as the dominant process.
- 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 $Q^2 = 1 - 4GeV^2$.
- However the large Q^2 data shows evidence for a power closer to $s^{0.4}$, the so called hard Pomeron.

At the same time HERA, the largest electron - proton collider ever built, and operated from 1992-2007 collected a wealth of small x data. Two crucial (related) discoveries:

- Structure functions for many different processes (DIS, DVCS, VM production...) show a power growth with $1/x$.
- The same, universal gluon distribution functions describe these processes, and gluons dominate at small x.
- These point to a universal Pomeron exchange as the dominant process.
- 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 $Q^2 = 1 - 4 GeV^2$.
- However the large Q^2 data shows evidence for a power closer to $s^{0.4}$, the so called hard Pomeron.

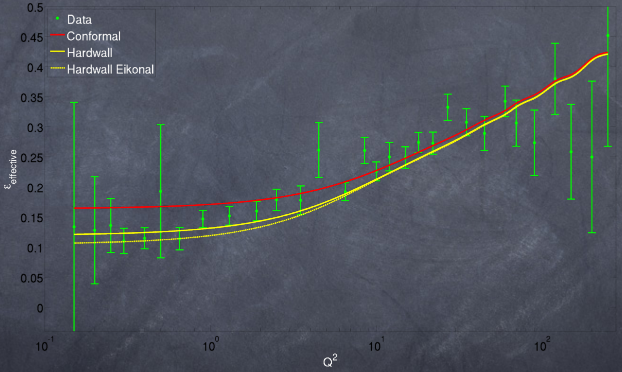
At the same time HERA, the largest electron - proton collider ever built, and operated from 1992-2007 collected a wealth of small x data. Two crucial (related) discoveries:

- Structure functions for many different processes (DIS, DVCS, VM production...) show a power growth with $1/x$.
- The same, universal gluon distribution functions describe these processes, and gluons dominate at small x.
- These point to a universal Pomeron exchange as the dominant process.
- 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 $Q^2 = 1 - 4 GeV^2$.
- However the large Q^2 data shows evidence for a power closer to $s^{0.4}$, the so called hard Pomeron.

At the same time HERA, the largest electron - proton collider ever built, and operated from 1992-2007 collected a wealth of small x data. Two crucial (related) discoveries:

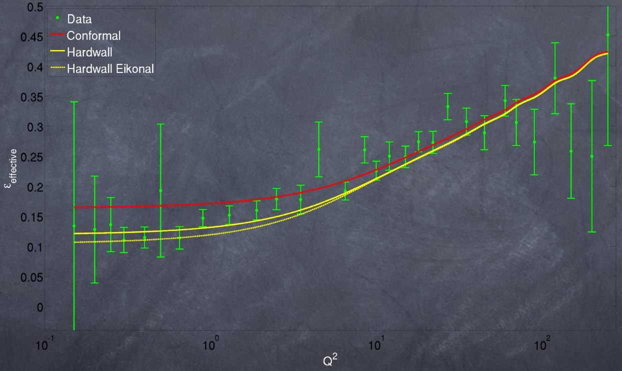
- Structure functions for many different processes (DIS, DVCS, VM production...) show a power growth with $1/x$.
- The same, universal gluon distribution functions describe these processes, and gluons dominate at small x.
- These point to a universal Pomeron exchange as the dominant process.
- The BFKL 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 $Q^2 = 1 - 4 GeV^2$.
- However the large Q^2 data shows evidence for a power closer to $s^{0.4}$, the so called hard Pomeron.

- Hence we have a long standing question, are these objects different or the same, and if the same what is the relation between them?



- We will attempt to answer this question using AdS/QCD

- Hence we have a long standing question, are these objects different or the same, and if the same what is the relation between them?



- We will attempt to answer this question using AdS/QCD

Outline

- So what is the Pomeron?
- We start by expanding the $2 \to 2$ amplitude in a partial wave expansion

$$A(s,t) = 16\pi \sum_{j=0}^{\infty} (2j+1) A_j(t) P_j(\cos\theta_t),$$

- In the Regge limit, $s \gg t$,

$$P_j(1 + \frac{2s}{t}) \to \frac{\Gamma(2j+1)}{\Gamma^2(j+1)} (\frac{s}{2t})^j \sim f(t) s^j.$$

- Giving us for the exchange of a spin j particle

$$A(s,t) \sim s^j, \;\; \sigma_{tot} \sim s^{j-1}.$$

- Each term is more and more divergent, we need to sum all of them to get a finite result.

- So what is the Pomeron?
- We start by expanding the $2 \to 2$ amplitude in a partial wave expansion

$$A(s,t) = 16\pi \sum_{j=0}^{\infty} (2j+1) A_j(t) P_j(\cos\theta_t),$$

- In the Regge limit, $s \gg t$,

$$P_j(1 + \frac{2s}{t}) \to \frac{\Gamma(2j+1)}{\Gamma^2(j+1)} (\frac{s}{2t})^j \sim f(t) s^j.$$

- Giving us for the exchange of a spin j particle

$$A(s,t) \sim s^j, \;\; \sigma_{tot} \sim s^{j-1}.$$

- Each term is more and more divergent, we need to sum all of them to get a finite result.

- So what is the Pomeron?
- We start by expanding the $2 \to 2$ amplitude in a partial wave expansion

$$A(s,t) = 16\pi \sum_{j=0}^{\infty} (2j+1) A_j(t) P_j(\cos\theta_t),$$

- In the Regge limit, $s \gg t$,

$$P_j(1 + \frac{2s}{t}) \to \frac{\Gamma(2j+1)}{\Gamma^2(j+1)} (\frac{s}{2t})^j \sim f(t) s^j.$$

- Giving us for the exchange of a spin j particle

$$A(s,t) \sim s^j, \;\; \sigma_{tot} \sim s^{j-1}.$$

- Each term is more and more divergent, we need to sum all of them to get a finite result.

- So what is the Pomeron?
- We start by expanding the $2 \to 2$ amplitude in a partial wave expansion

$$A(s,t) = 16\pi \sum_{j=0}^{\infty} (2j+1) A_j(t) P_j(\cos\theta_t),$$

- In the Regge limit, $s \gg t$,

$$P_j(1 + \frac{2s}{t}) \to \frac{\Gamma(2j+1)}{\Gamma^2(j+1)} (\frac{s}{2t})^j \sim f(t) s^j.$$

- Giving us for the exchange of a spin j particle

$$A(s,t) \sim s^j, \;\; \sigma_{tot} \sim s^{j-1}.$$

- Each term is more and more divergent, we need to sum all of them to get a finite result.

- So what is the Pomeron?
- We start by expanding the $2 \to 2$ amplitude in a partial wave expansion

$$A(s,t) = 16\pi \sum_{j=0}^{\infty} (2j+1) A_j(t) P_j(\cos\theta_t),$$

- In the Regge limit, $s \gg t$,

$$P_j(1+\frac{2s}{t}) \to \frac{\Gamma(2j+1)}{\Gamma^2(j+1)} (\frac{s}{2t})^j \sim f(t) s^j.$$

- Giving us for the exchange of a spin j particle

$$A(s,t) \sim s^j, \;\; \sigma_{tot} \sim s^{j-1}.$$

- Each term is more and more divergent, we need to sum all of them to get a finite result.

- We need to start where the sum is well defined, $t > 4m^2, s < 0, |\cos\theta| \leq 1$, and analytically continue.
- However, it turns out that $A_j(t)$ does not have a unique analytic continuation.
- Hence

$$A(s,t) = 8\pi\Big[\sum_{j=0}^{\infty}(2j+1)A_j^+(t)(P_j(z_t)+P_j(-z_t)) + \sum_{j=0}^{\infty}(2j+1)A_j^-(t)(P_j(z_t)-P_j(-z_t))\Big]$$

- This is the origin of the even and odd signature amplitudes.

- We need to start where the sum is well defined, $t > 4m^2, s < 0, |\cos\theta| \leq 1$, and analytically continue.
- However, it turns out that $A_j(t)$ does not have a unique analytic continuation.
- Hence

$$A(s,t) = 8\pi\Big[\sum_{j=0}^{\infty}(2j+1)A_j^{+}(t)(P_j(z_t)+P_j(-z_t)) + \sum_{j=0}^{\infty}(2j+1)A_j^{-}(t)(P_j(z_t)-P_j(-z_t))\Big]$$

- This is the origin of the even and odd signature amplitudes.

- We need to start where the sum is well defined, $t > 4m^2, s < 0, |\cos\theta| \leq 1$, and analytically continue.
- However, it turns out that $A_j(t)$ does not have a unique analytic continuation.
- Hence

$$A(s,t) = 8\pi\Big[\sum_{j=0}^{\infty}(2j+1)A_j^+(t)(P_j(z_t) + P_j(-z_t)) + \sum_{j=0}^{\infty}(2j+1)A_j^-(t)(P_j(z_t) - P_j(-z_t))\Big]$$

- This is the origin of the even and odd signature amplitudes.

- We need to start where the sum is well defined, $t > 4m^2, s < 0, |\cos\theta| \leq 1$, and analytically continue.
- However, it turns out that $A_j(t)$ does not have a unique analytic continuation.
- Hence

$$A(s,t) = 8\pi\Big[\sum_{j=0}^{\infty}(2j+1)A_j^{+}(t)(P_j(z_t)+P_j(-z_t)) + \sum_{j=0}^{\infty}(2j+1)A_j^{-}(t)(P_j(z_t)-P_j(-z_t))\Big]$$

- This is the origin of the even and odd signature amplitudes.

- We can now analytically continue. After performing the Sommerfeld-Watson transform we would get

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

- $\alpha(t)$ is the term with the largest value of $\Re\alpha_i(t)$
- Amplitude corresponds to an exchange of a whole trajectory of particles $\alpha^{\pm}(t)$.
- Equivalently, we are exchanging a ‘Regge trajectory’ - object with spin $\alpha^{\pm}(t)$.

- We can now analytically continue. After performing the Sommerfeld-Watson transform we would get

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

- $\alpha(t)$ is the term with the largest value of $\Re\alpha_i(t)$
- Amplitude corresponds to an exchange of a whole trajectory of particles $\alpha^{\pm}(t)$.
- Equivalently, we are exchanging a ‘Regge trajectory’ - object with spin $\alpha^{\pm}(t)$.

- We can now analytically continue. After performing the Sommerfeld-Watson transform we would get

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

- $\alpha(t)$ is the term with the largest value of $\Re\alpha_i(t)$
- Amplitude corresponds to an exchange of a whole trajectory of particles $\alpha^{\pm}(t)$.
- Equivalently, we are exchanging a ‘Regge trajectory’ - object with spin $\alpha^{\pm}(t)$.

- We can now analytically continue. After performing the Sommerfeld-Watson transform we would get

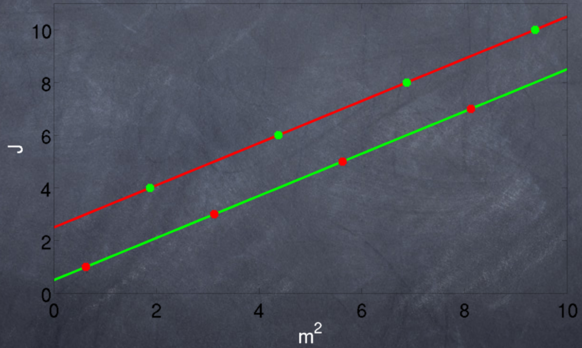
$$A^{\pm}(s,t) \sim (1 \pm e^{-i\pi\alpha^{\pm}(t)})\beta(t)(\frac{s}{s_0})^{\alpha^{\pm}(t)}.$$

- $\alpha(t)$ is the term with the largest value of $\Re\alpha_i(t)$
- Amplitude corresponds to an exchange of a whole trajectory of particles $\alpha^{\pm}(t)$.
- Equivalently, we are exchanging a 'Regge trajectory' - object with spin $\alpha^{\pm}(t)$.

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

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

- Equivalently, we are exchanging a 'Regge trajectory' - object with spin $\alpha^{\pm}(t)$.



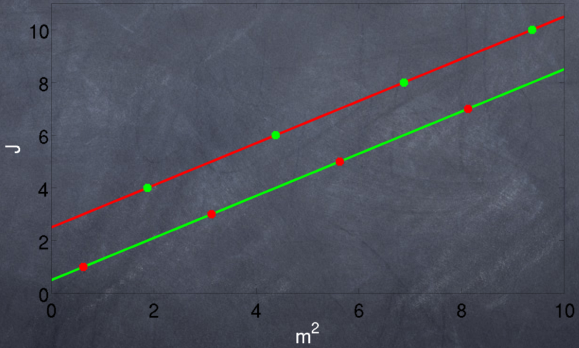
- The trajectories are (approximately) linear, and for the soft Pomeron we have (from experiment)

$$\alpha(t) = j_0 + \alpha' t, \;\; j_0 = 1.08, \;\; \alpha' = 0.25 GeV^{-2}.$$

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

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

- Equivalently, we are exchanging a ‘Regge trajectory’ - object with spin $\alpha^{\pm}(t)$.



-

- The trajectories are (approximately) linear, and for the soft Pomeron we have (from experiment)

$$\alpha(t) = j_0 + \alpha' t, \ \ j_0 = 1.08, \ \ \alpha' = 0.25 GeV^{-2}.$$

Outline

1. Introduction
2. Pomeron
3. Pomeron at Strong Coupling
4. Applications
5. More Similar to QCD

BPST Pomeron

At strong coupling the Pomeron was first introduced by Brower, Polchinski, Strassler and Tan, 2006.

- They show that the Pomeron emerges as the Regge trajectory of the graviton. We can introduce a vertex operator

$$\mathcal{V}_P(j,\pm) = (\partial X^{\pm}\bar{\partial}X^{\pm})^{\frac{j}{2}} e^{\mp ik\cdot X}\phi_{\pm j}(r).$$

- This operator must satisfy the on-shell condition.

$$[\frac{j-2}{2} - \frac{\alpha'}{4}\Delta_j]e^{\mp ik\cdot X}\phi_{\pm j}(r) = 0$$

- where $\Delta_j = (r/R)^j(\Delta_0)(r/R)^{-j}$. And Δ_0 is the scalar Laplacian in curved space.
- This leads to the propagator of the Pomeron with intercept

$$j_0 = 2 - \frac{2}{\sqrt{\lambda}}$$

BPST Pomeron

At strong coupling the Pomeron was first introduced by Brower, Polchinski, Strassler and Tan, 2006.

- They show that the Pomeron emerges as the Regge trajectory of the graviton. We can introduce a vertex operator

$$\mathcal{V}_P(j, \pm) = (\partial X^{\pm}\bar{\partial} X^{\pm})^{\frac{j}{2}} e^{\mp ik\cdot X} \phi_{\pm j}(r).$$

- This operator must satisfy the on-shell condition.

$$[\frac{j-2}{2} - \frac{\alpha'}{4}\Delta_j] e^{\mp ik\cdot X} \phi_{\pm j}(r) = 0$$

- where $\Delta_j = (r/R)^j (\Delta_0)(r/R)^{-j}$. And Δ_0 is the scalar Laplacian in curved space.
- This leads to the propagator of the Pomeron with intercept

$$j_0 = 2 - \frac{2}{\sqrt{\lambda}}$$

BPST Pomeron

At strong coupling the Pomeron was first introduced by Brower, Polchinski, Strassler and Tan, 2006.

- They show that the Pomeron emerges as the Regge trajectory of the graviton. We can introduce a vertex operator

$$\mathcal{V}_P(j,\pm) = (\partial X^{\pm}\bar{\partial}X^{\pm})^{\frac{j}{2}} e^{\mp ik\cdot X}\phi_{\pm j}(r).$$

- This operator must satisfy the on-shell condition.

$$[\frac{j-2}{2} - \frac{\alpha'}{4}\Delta_j]e^{\mp ik\cdot X}\phi_{\pm j}(r) = 0$$

- where $\Delta_j = (r/R)^j(\Delta_0)(r/R)^{-j}$. And Δ_0 is the scalar Laplacian in curved space.
- This leads to the propagator of the Pomeron with intercept

$$j_0 = 2 - \frac{2}{\sqrt{\lambda}}$$

BPST Pomeron

At strong coupling the Pomeron was first introduced by Brower, Polchinski, Strassler and Tan, 2006.

- They show that the Pomeron emerges as the Regge trajectory of the graviton. We can introduce a vertex operator

$$\mathcal{V}_P(j, \pm) = (\partial X^{\pm} \bar{\partial} X^{\pm})^{\frac{j}{2}} e^{\mp ik \cdot X} \phi_{\pm j}(r).$$

- This operator must satisfy the on-shell condition.

$$[\frac{j-2}{2} - \frac{\alpha'}{4} \Delta_j] e^{\mp ik \cdot X} \phi_{\pm j}(r) = 0$$

- where $\Delta_j = (r/R)^j (\Delta_0)(r/R)^{-j}$. And Δ_0 is the scalar Laplacian in curved space.
- This leads to the propagator of the Pomeron with intercept

$$j_0 = 2 - \frac{2}{\sqrt{\lambda}}$$

- Can also be applied to other Regge trajectories, e.g. Odderon [Brower, MD, Tan 2008; Brower, Costa, MD, Raben, Tan 2014].
- The weak and strong coupling Pomeron exchange kernels have a remarkably similar form.
- At $t = 0$
  Weak coupling:

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

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

  Strong coupling:

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

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

- Can also be applied to other Regge trajectories, e.g. Odderon [Brower, MD, Tan 2008; Brower, Costa, MD, Raben, Tan 2014].
- The weak and strong coupling Pomeron exchange kernels have a remarkably similar form.
- At $t = 0$
  Weak coupling:

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

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

  Strong coupling:

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

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

- Can also be applied to other Regge trajectories, e.g. Odderon [Brower, MD, Tan 2008; Brower, Costa, MD, Raben, Tan 2014].
- The weak and strong coupling Pomeron exchange kernels have a remarkably similar form.
- At $t = 0$
  Weak coupling:

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

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

  Strong coupling:

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

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

Outline

We can apply these methods to calculate the amplitude for any process where Pomeron exchange dominates.

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

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

- Single Pomeron exchange would correspond to expanding the above to first order in χ.
- To study different processes, we just provide different wavefunction for the external states.
- Already applied to DIS [Brower, MD, Sarcevic, Tan], DVCS [Costa, MD] and vector meson production [Costa, MD, Evans].

We can apply these methods to calculate the amplitude for any process where Pomeron exchange dominates.

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

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

- Single Pomeron exchange would correspond to expanding the above to first order in χ.
- To study different processes, we just provide different wavefunction for the external states.
- Already applied to DIS [Brower, MD, Sarcevic, Tan], DVCS [Costa, MD] and vector meson production [Costa, MD, Evans].

We can apply these methods to calculate the amplitude for any process where Pomeron exchange dominates.

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

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

- Single Pomeron exchange would correspond to expanding the above to first order in χ.
- To study different processes, we just provide different wavefunction for the external states.
- Already applied to DIS [Brower, MD, Sarcevic, Tan], DVCS [Costa, MD] and vector meson production [Costa, MD, Evans].

We can apply these methods to calculate the amplitude for any process where Pomeron exchange dominates.

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

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

- Single Pomeron exchange would correspond to expanding the above to first order in χ.
- To study different processes, we just provide different wavefunction for the external states.
- Already applied to DIS [Brower, MD, Sarcevic, Tan], DVCS [Costa, MD] and vector meson production [Costa, MD, Evans].

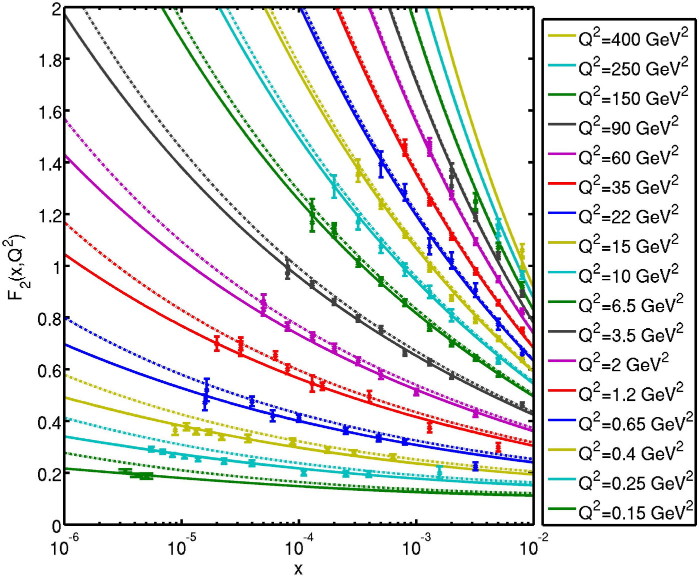
We can apply these methods to calculate the amplitude for any process where Pomeron exchange dominates.

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

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

- Single Pomeron exchange would correspond to expanding the above to first order in χ.
- To study different processes, we just provide different wavefunction for the external states.
- Already applied to DIS [Brower, MD, Sarcevic, Tan], DVCS [Costa, MD] and vector meson production [Costa, MD, Evans].

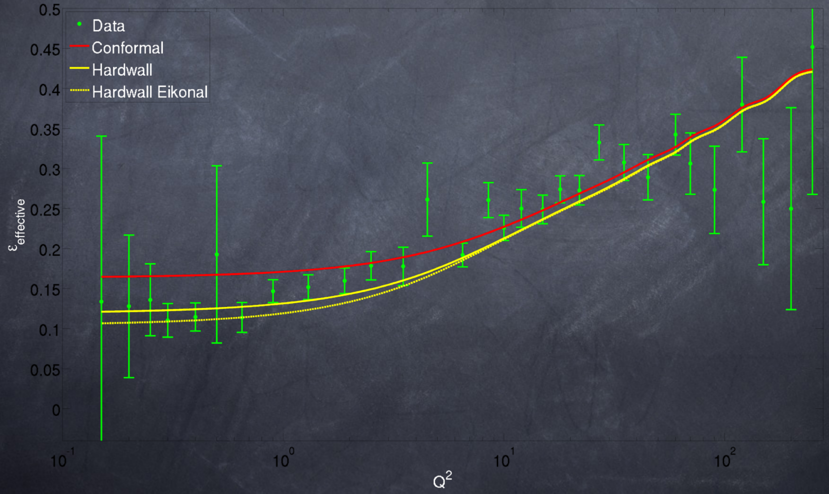
F_2



F2(x,Q2)
x
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10-6
10-5
10-4
10-3
10-2
Q2=400 GeV2
Q2=250 GeV2
Q2=150 GeV2
Q2=90 GeV2
Q2=60 GeV2
Q2=35 GeV2
Q2=22 GeV2
Q2=15 GeV2
Q2=10 GeV2
Q2=6.5 GeV2
Q2=3.5 GeV2
Q2=2 GeV2
Q2=1.2 GeV2
Q2=0.65 GeV2
Q2=0.4 GeV2
Q2=0.25 GeV2
Q2=0.15 GeV2

Effective Pomeron Intercept

$$F_2 \sim \left(\frac{1}{x}\right)^{\epsilon_{eff}}$$



Outline

We have a very good agreement with experiment, but the hard-wall model has some problems as well, for example no running coupling. Hence we will try to use the Gursoy-Kiritsis-Nitti model, which is more similar to real world QCD.

- This is a phenomenologica 5D dilaton-gravity model starting from the action

$$S = 2\kappa^2 \int d^5x \sqrt{-g} \left[R - \frac{4}{3}(\partial\phi)^2 + V(\phi) \right]$$

- The potential $V(\phi)$ contains two free parameters and is constructed to match the perturbative QCD β function.
- It reproduces the heavy quark-antiquark linear potential,
- the glueball spectrum from lattice simulations
- thermodynamic properties of QGP (bulk viscosity, drag force and jet quenching parameters).

We have a very good agreement with experiment, but the hard-wall model has some problems as well, for example no running coupling. Hence we will try to use the Gursoy-Kiritsis-Nitti model, which is more similar to real world QCD.

- This is a phenomenologica 5D dilaton-gravity model starting from the action

$$S = 2\kappa^2 \int d^5x \sqrt{-g} \left[R - \frac{4}{3}(\partial\phi)^2 + V(\phi) \right]$$

- The potential $V(\phi)$ contains two free parameters and is constructed to match the perturbative QCD β function.
- It reproduces the heavy quark-antiquark linear potential,
- the glueball spectrum from lattice simulations
- thermodynamic properties of QGP (bulk viscosity, drag force and jet quenching parameters).

We have a very good agreement with experiment, but the hard-wall model has some problems as well, for example no running coupling. Hence we will try to use the Gursoy-Kiritsis-Nitti model, which is more similar to real world QCD.

- This is a phenomenologica 5D dilaton-gravity model starting from the action

$$S = 2\kappa^2 \int d^5x\,\sqrt{-g}\,\left[R - \frac{4}{3}(\partial\phi)^2 + V(\phi)\right]$$

- The potential $V(\phi)$ contains two free parameters and is constructed to match the perturbative QCD β function.
- It reproduces the heavy quark-antiquark linear potential,
- the glueball spectrum from lattice simulations
- thermodynamic properties of QGP (bulk viscosity, drag force and jet quenching parameters).

We have a very good agreement with experiment, but the hard-wall model has some problems as well, for example no running coupling. Hence we will try to use the Gursoy-Kiritsis-Nitti model, which is more similar to real world QCD.

- This is a phenomenologica 5D dilaton-gravity model starting from the action

$$S = 2\kappa^2 \int d^5x \sqrt{-g} \left[R - \frac{4}{3}(\partial\phi)^2 + V(\phi) \right]$$

- The potential $V(\phi)$ contains two free parameters and is constructed to match the perturbative QCD β function.
- It reproduces the heavy quark-antiquark linear potential,
- the glueball spectrum from lattice simulations
- thermodynamic properties of QGP (bulk viscosity, drag force and jet quenching parameters).

We have a very good agreement with experiment, but the hard-wall model has some problems as well, for example no running coupling. Hence we will try to use the Gursoy-Kiritsis-Nitti model, which is more similar to real world QCD.

- This is a phenomenologica 5D dilaton-gravity model starting from the action

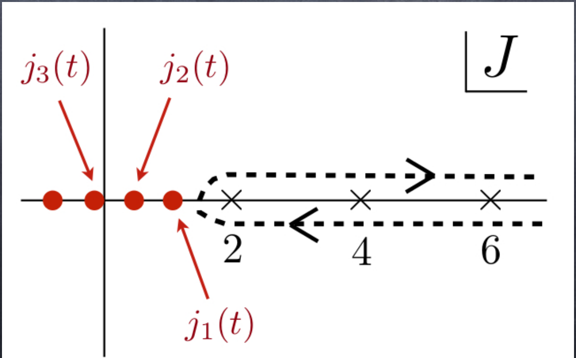
$$S = 2\kappa^2 \int d^5x \sqrt{-g} \left[R - \frac{4}{3}(\partial\phi)^2 + V(\phi) \right]$$

- The potential $V(\phi)$ contains two free parameters and is constructed to match the perturbative QCD β function.
- It reproduces the heavy quark-antiquark linear potential,
- the glueball spectrum from lattice simulations
- thermodynamic properties of QGP (bulk viscosity, drag force and jet quenching parameters).

- We construct the Pomeron propagator in this model by starting from the spin J equation of motion

$$\left[(D^2 - 2\partial^b \phi D_b - \frac{2}{\alpha'}(J-2))g_{a_1 b} g_{a_2 c} + J R_{a_1 b a_2 c}\right] h^{bc}_{a_3 \ldots a_J} = 0$$

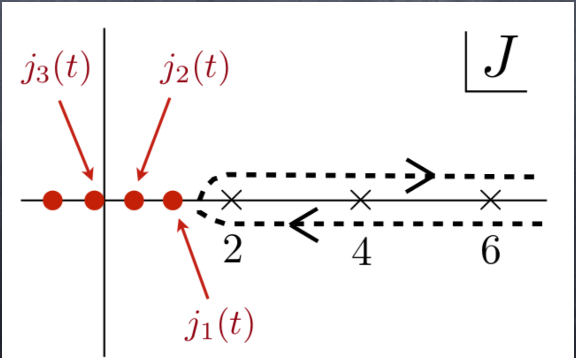
- This is an approximation for even spin states lying on the trajectory of the graviton. We only need the leading component in the Regge limit, which is either the $++$ or the $--$.
- We then sum over all even J and perform the Sommerfeld-Watson transformation from Regge theory



- We construct the Pomeron propagator in this model by starting from the spin J equation of motion

$$\left[(D^2 - 2\partial^b \phi D_b - \frac{2}{\alpha'}(J-2))g_{a_1 b} g_{a_2 c} + J R_{a_1 b a_2 c}\right] h^{bc}_{a_3 \ldots a_J} = 0$$

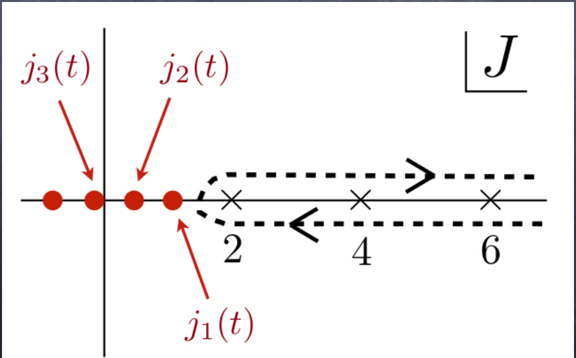
- This is an approximation for even spin states lying on the trajectory of the graviton. We only need the leading component in the Regge limit, which is either the $++$ or the $--$.
- We then sum over all even J and perform the Sommerfeld-Watson transformation from Regge theory



- We construct the Pomeron propagator in this model by starting from the spin J equation of motion

$$\left[(D^2 - 2\partial^b \phi D_b - \frac{2}{\alpha'}(J-2)) g_{a_1 b} g_{a_2 c} + J R_{a_1 b a_2 c} \right] h^{bc}_{a_3 \ldots a_J} = 0$$

- This is an approximation for even spin states lying on the trajectory of the graviton. We only need the leading component in the Regge limit, which is either the $++$ or the $--$.
- We then sum over all even J and perform the Sommerfeld-Watson transformation from Regge theory



- Problem reduces to a J dependent Schrodinger potential. There are poles in the J plane at

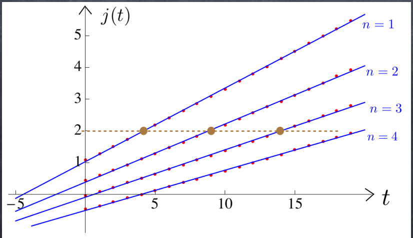
$$t = t_n(J) \Longrightarrow J = j_n(t)$$

- The propagator is expressed as a sum of eigenfunctions

$$T(s,t) \sim \sum_n \left(e^{-A(z)-A(z')}s\right)^{j_n(t)} \psi_n(z)\psi_n^*(z')$$

- We obtained approximately linear Regge trajectories. We adjust one parameter to fix the intercept of the first trajectory, and we get the slope as well as the intercepts and slopes of all the other trajectories:

$$j_1(t) = 1.08+0.21t,\ j_2(t) = 0.433+0.17t,\ j_3(t) = -0.471+0.13t \ldots$$



- Problem reduces to a J dependent Schrodinger potential. There are poles in the J plane at

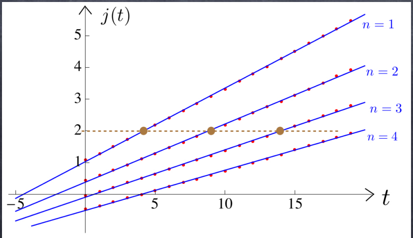
$$t = t_n(J) \Longrightarrow J = j_n(t)$$

- The propagator is expressed as a sum of eigenfunctions

$$T(s,t) \sim \sum_n \left(e^{-A(z)-A(z')}s\right)^{j_n(t)} \psi_n(z)\psi_n^*(z')$$

- We obtained approximately linear Regge trajectories. We adjust one parameter to fix the intercept of the first trajectory, and we get the slope as well as the intercepts and slopes of all the other trajectories:

$j_1(t) = 1.08+0.21t$, $j_2(t) = 0.433+0.17t$, $j_3(t) = -0.471+0.13t\ldots$



- Problem reduces to a J dependent Schrodinger potential. There are poles in the J plane at

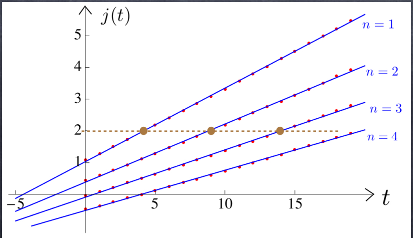
$$t = t_n(J) \implies J = j_n(t)$$

- The propagator is expressed as a sum of eigenfunctions

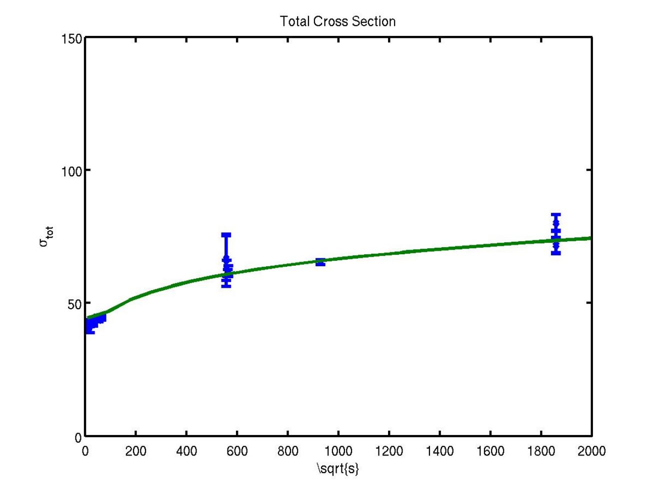
$$T(s,t) \sim \sum_n \left(e^{-A(z)-A(z')}s\right)^{j_n(t)} \psi_n(z)\psi_n^*(z')$$

- We obtained approximately linear Regge trajectories. We adjust one parameter to fix the intercept of the first trajectory, and we get the slope as well as the intercepts and slopes of all the other trajectories:

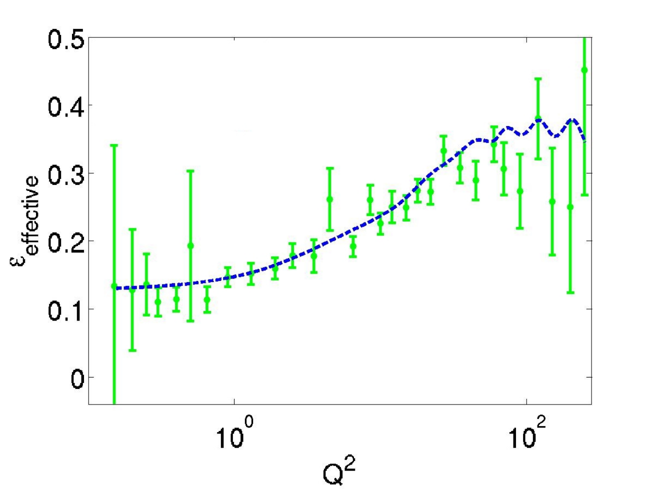
$$j_1(t) = 1.08+0.21t,\ j_2(t) = 0.433+0.17t,\ j_3(t) = -0.471+0.13t\ldots$$



This matches well with the soft Pomeron seen in total cross sections



Is the running between the soft and the hard pomeron the effect of adding the subleading Regge trajectories?



Possible, but still work in progress...

Thank You!