Soft pomeron in Holographic QCD

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arXiv:1508.00008 (with A. Bayona, M. Djuric, R. Quevedo)

Current Themes in Holography:
Exact results, applications, extensions and fundamentals

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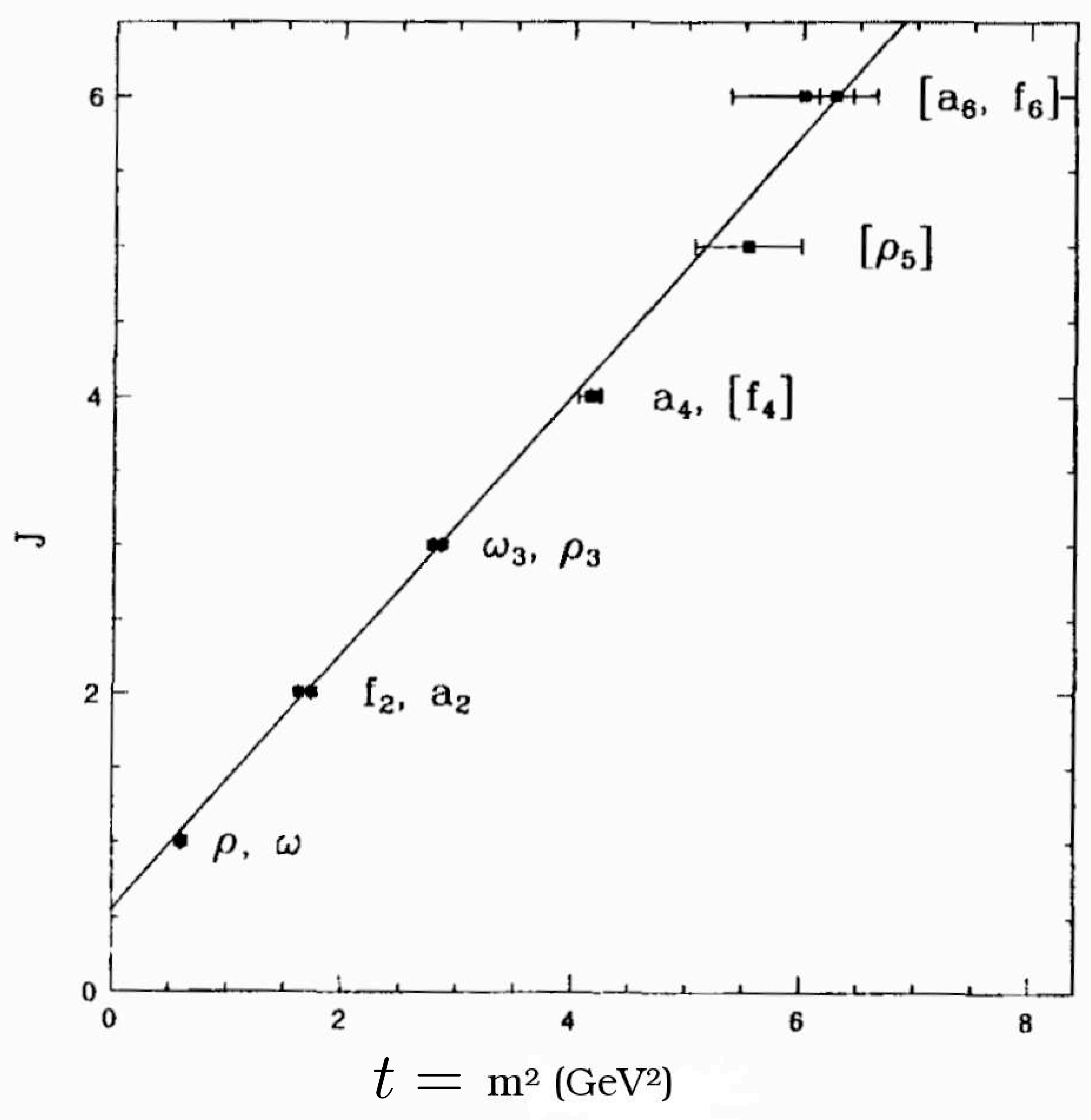
Regge behaviour in QCD

- Hadronic resonances fall in linear trajectories

$\pi^- + p \rightarrow \pi^0 + n$

$I = 1$ even parity mesons

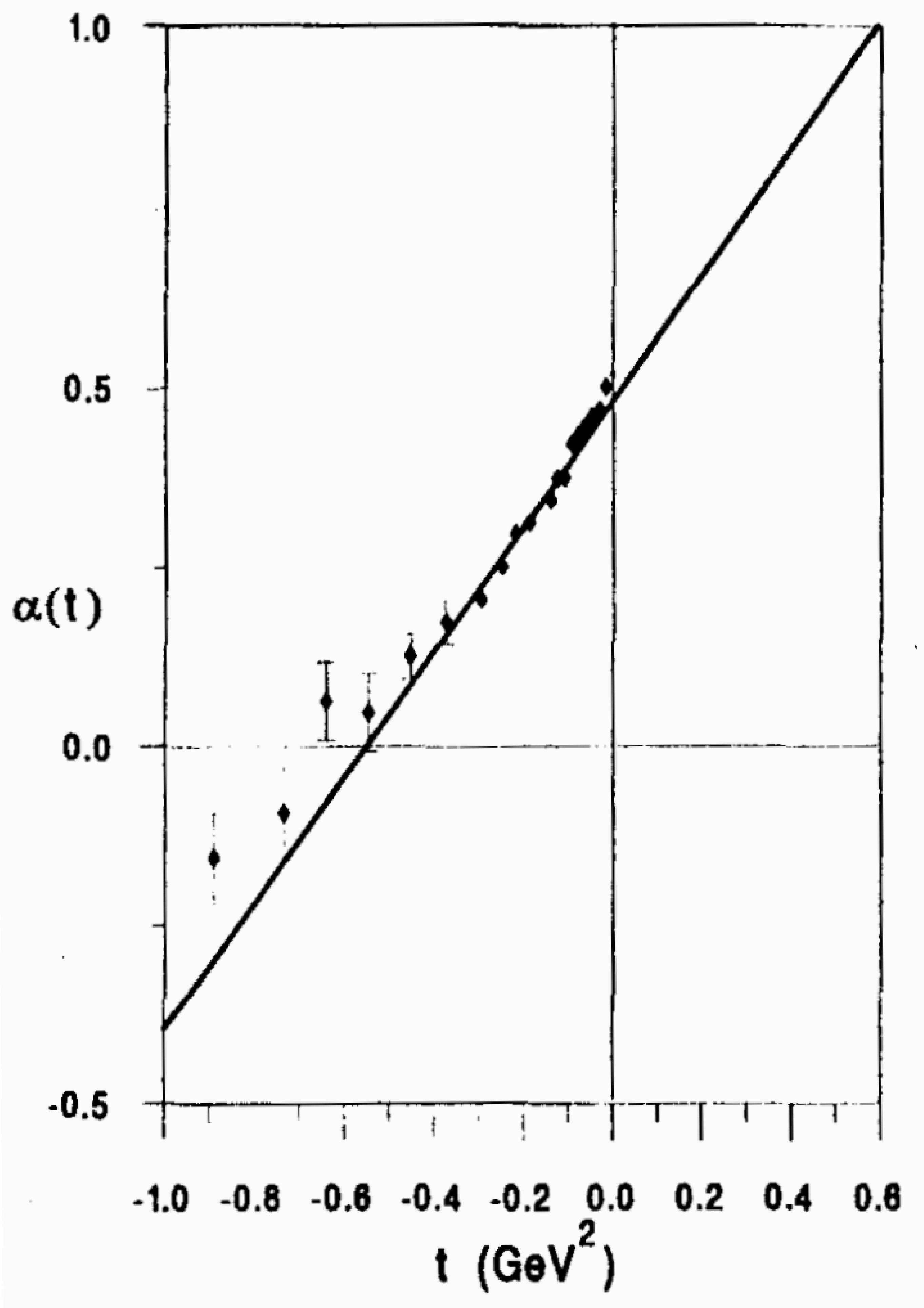


$$J = j(t) = j(0) + \alpha' t$$

$$A(s,t) \sim \beta(t) s^{j(t)}$$
$$(s \gg t)$$

Total cross section

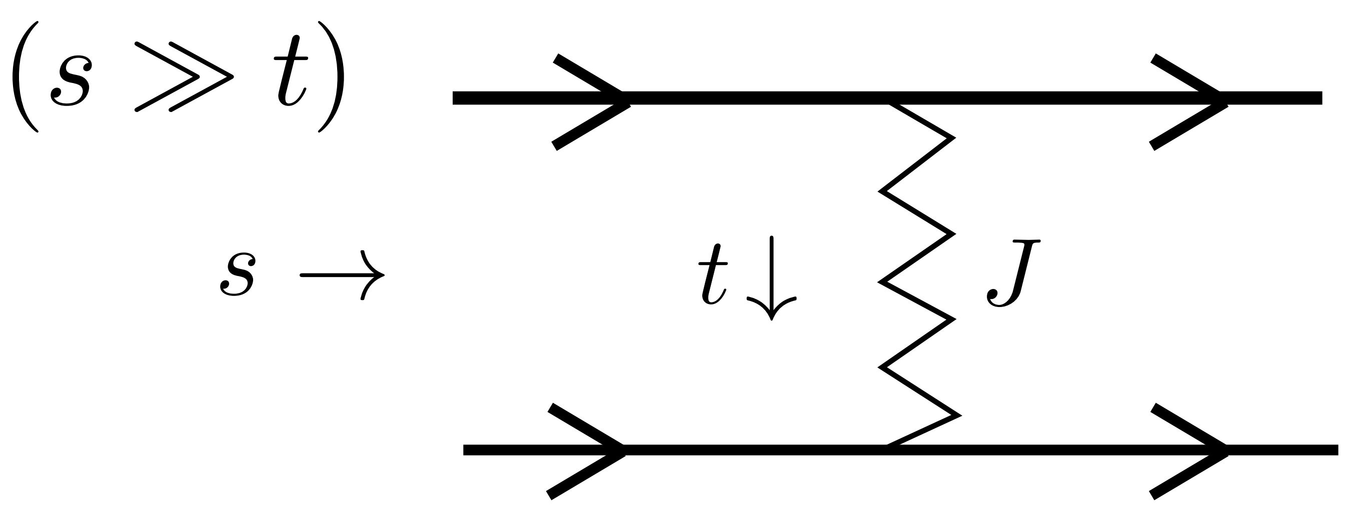
$$\sigma \sim s^{j(0)-1}$$



Regge theory

- Scattering dominated by t-channel exchange of a Regge trajectory

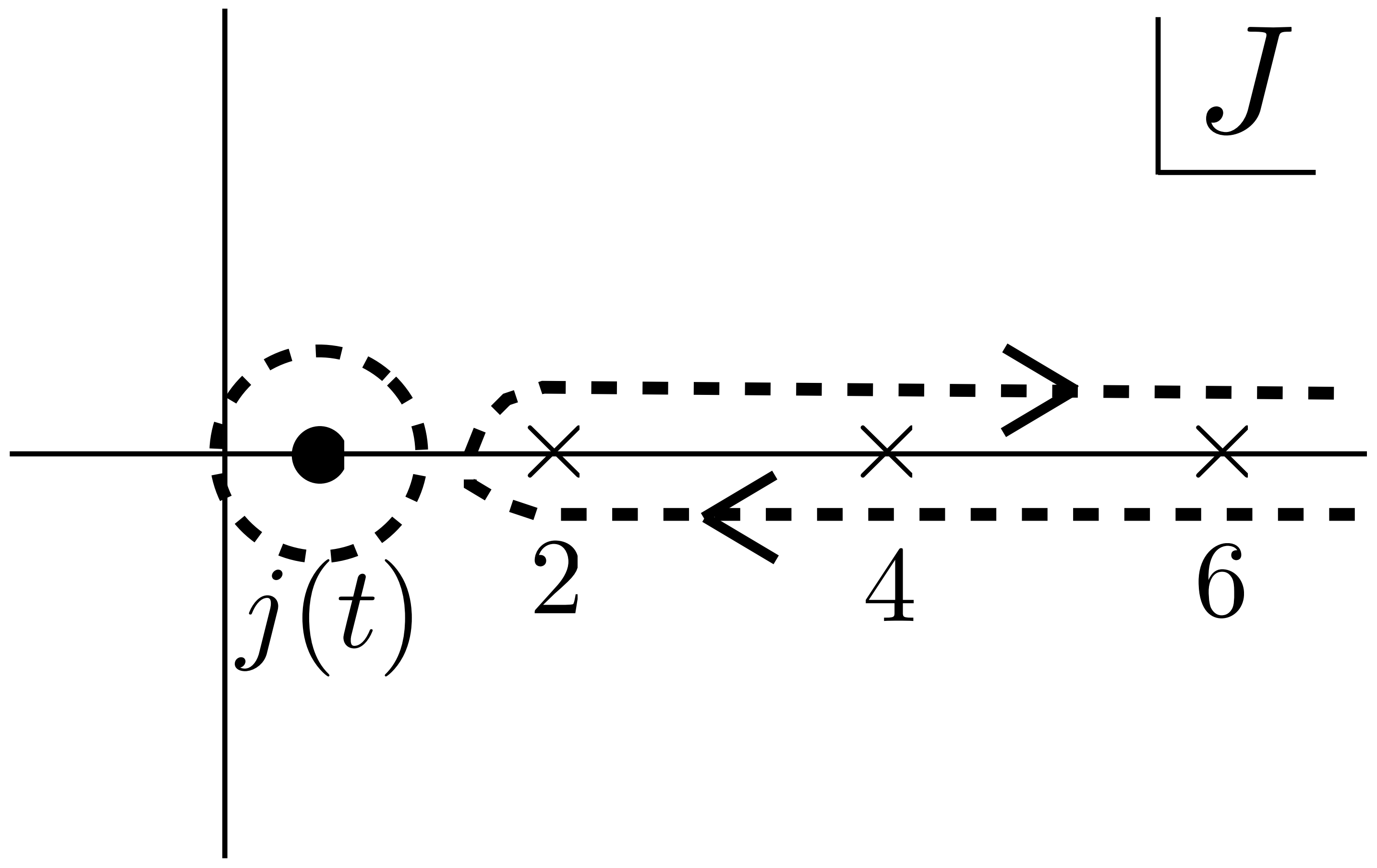
$$A(s,t) \approx \sum_J g_J \frac{s^J}{t - m^2(J)} \sim \sum_J g_J \frac{s^J}{J - j(t)}$$



- Sommerfeld-Watson transform:

$$\sum_J \rightarrow \int \frac{dJ}{\sin \pi J}$$

$$A(s,t) \sim \beta(t) s^{j(t)}$$



Soft Pomeron trajectory [Donnachie, Landshoff]

• Trajectory selected by exchanged quantum numbers. For elastic scattering these are the vacuum quantum numbers.

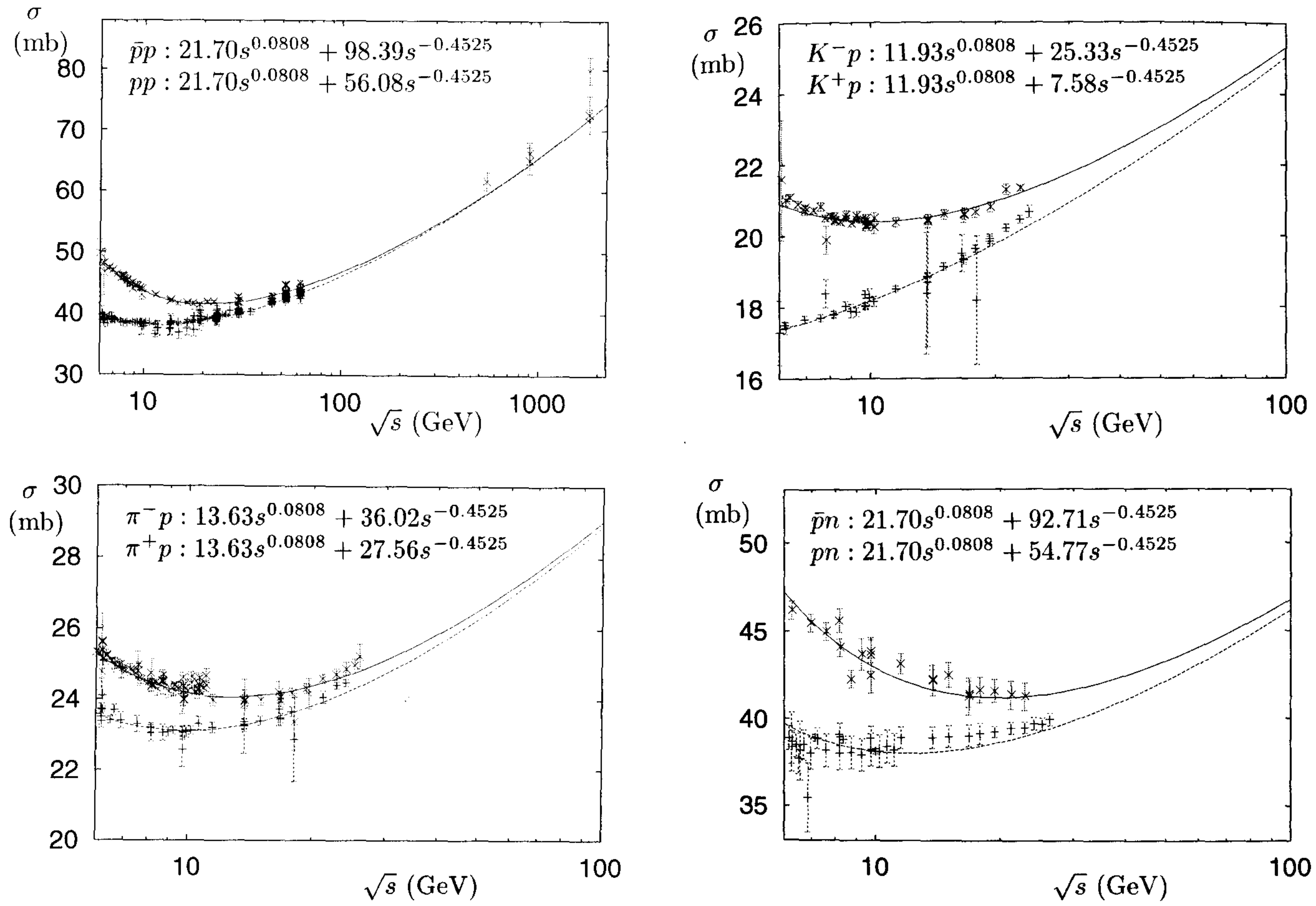
$$j_P(t) \approx 1.08 + 0.25t \quad \text{(GeV units)}$$

Total elastic cross sections

$$\sigma \sim s^{j_P(0)-1} \sim s^{0.08}$$

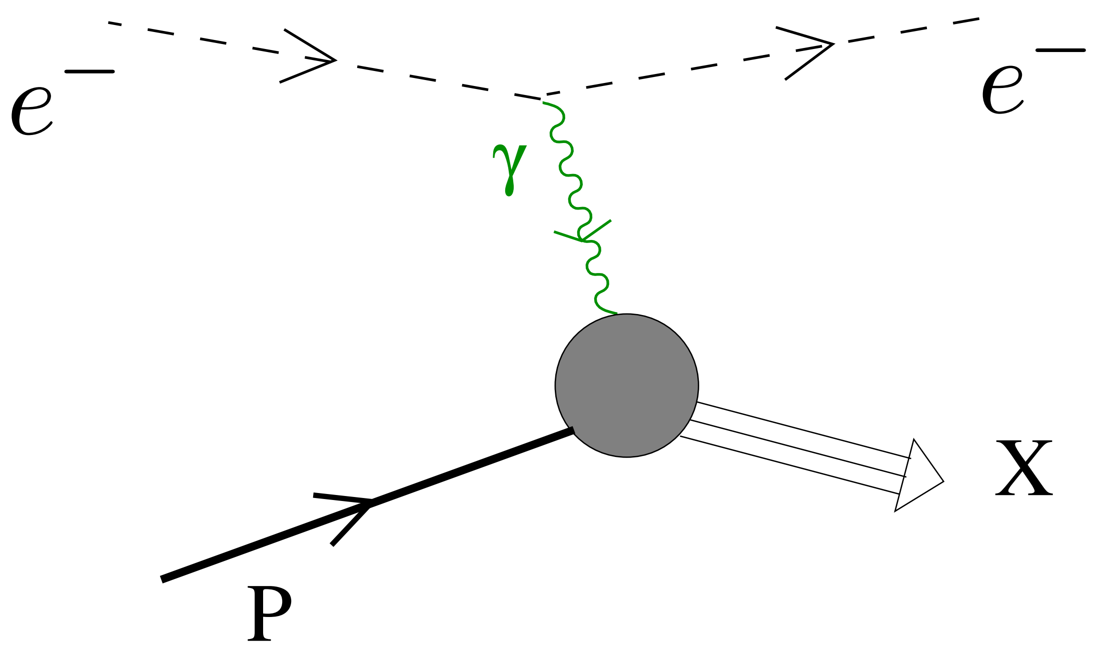
Exchange of even spin glueballs $(J \geq 2)$

$$\mathcal{O}_J \sim \mathrm{Tr}\left(F_{\alpha[\beta_1} D_{\beta_2} \ldots D_{\beta_{J-1}} F_{\beta_J]}{}^{\alpha}\right)$$

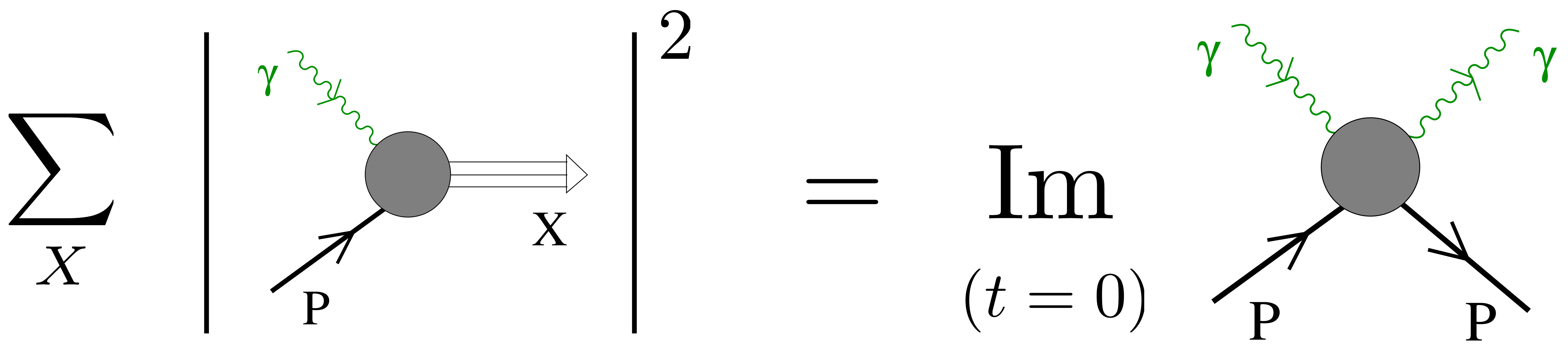


Deep Inelastic Scattering

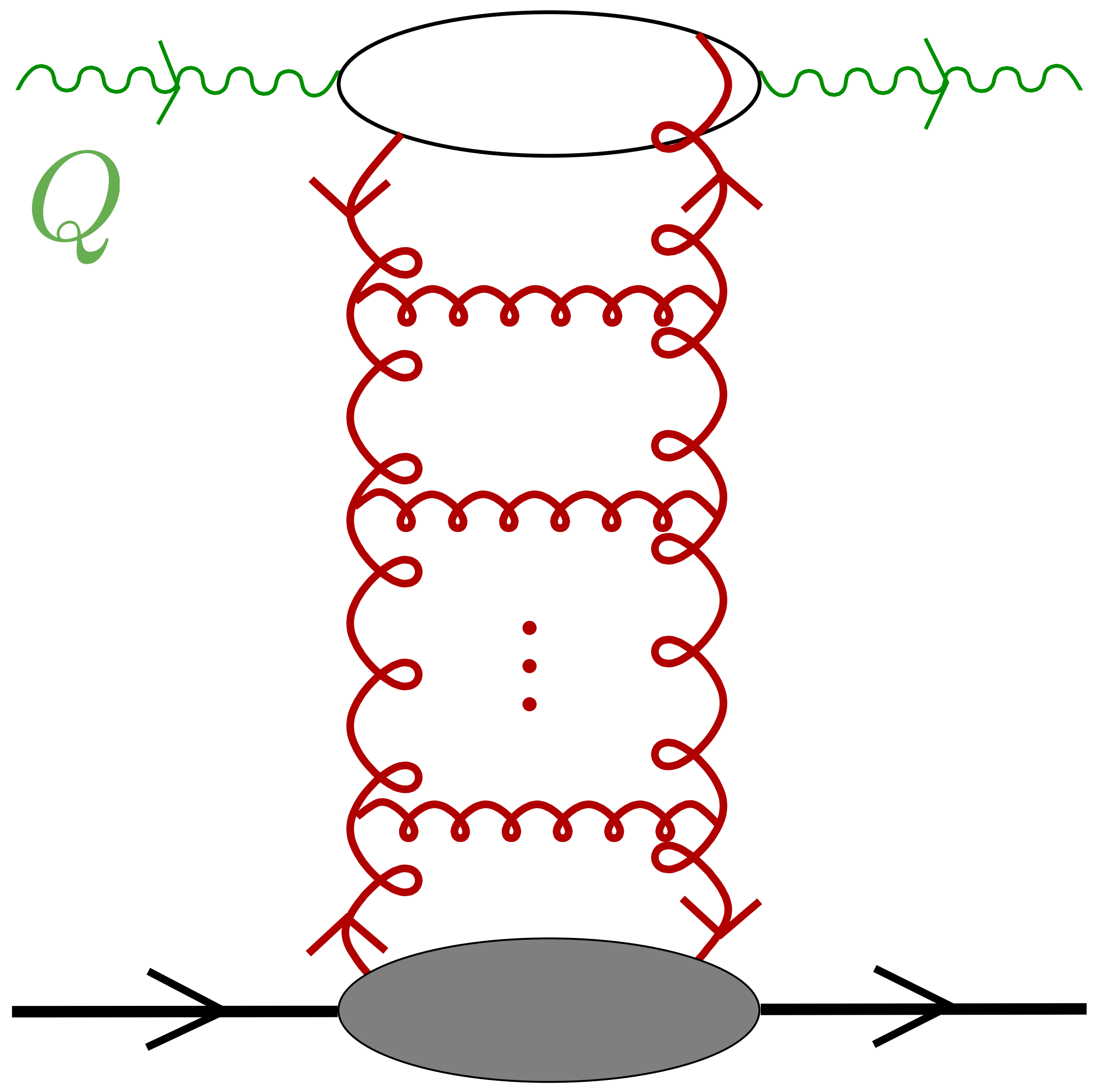
• Pomeron enters also in diffractive processes. For example DIS, where electron interacts with proton via exchange of off-shell photon



• Optical theorem



$j_0 \sim 1.1 - 1.4$



• Regge limit corresponds to low x $(s \sim Q^2/x)$

BFKL pomeron explains well DIS data outside the confining region $Q \sim \Lambda_{QCD}$
[Kowalski, Lipatov, Ross, Watt 10]

Is it the same Regge trajectory?
One or two pomerons (soft and hard)?

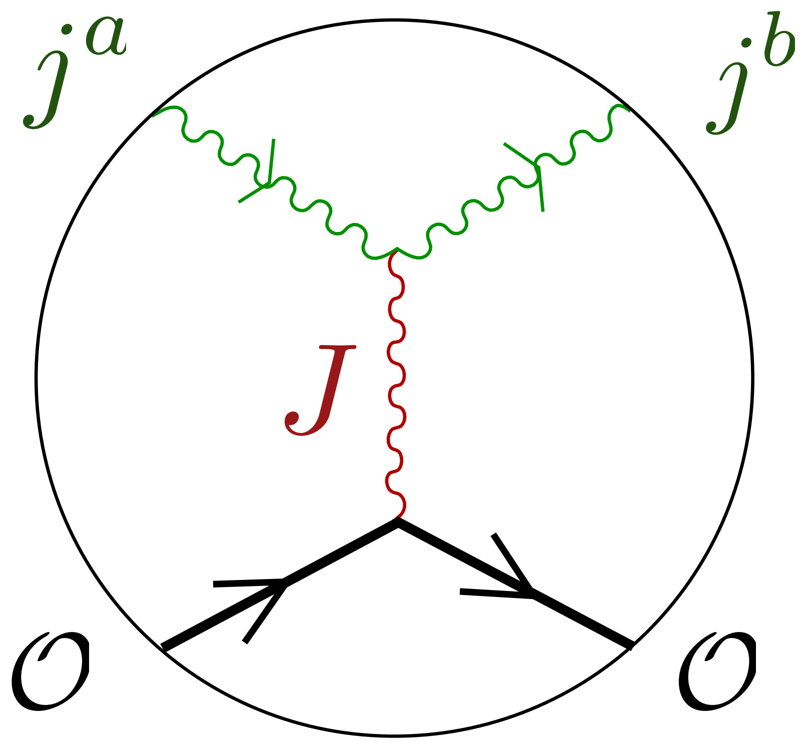
Graviton/Pomeron Regge trajectory [Brower, Polchinski, Strassler, Tan 06]

- At strong coupling pomeron trajectory described by graviton Regge trajectory of string theory in Anti-de Sitter space (large N, conformal theory $\mathcal{N}=4$ SYM)

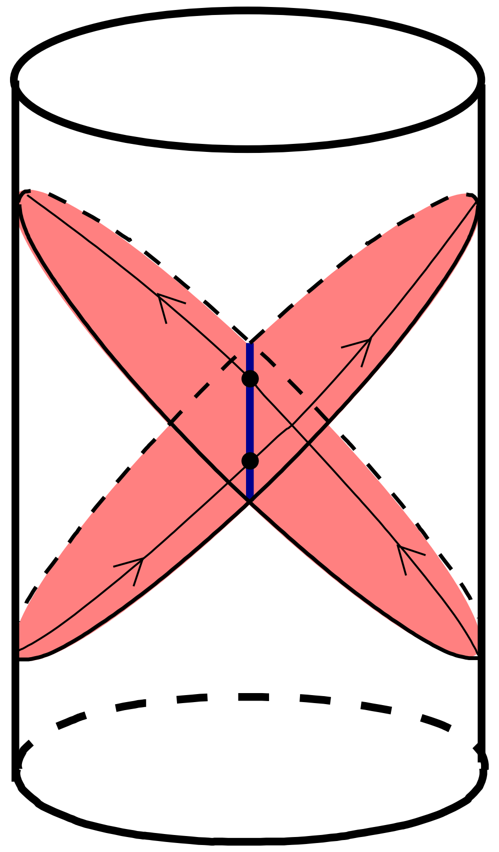
Exchange of spin J field in AdS (symmetric, traceless and transverse)

$$\left(D^2 - m^2\right) h_{a_1 \dots a_J} = 0$$

with $m^2 = \Delta(\Delta - 4) - J$



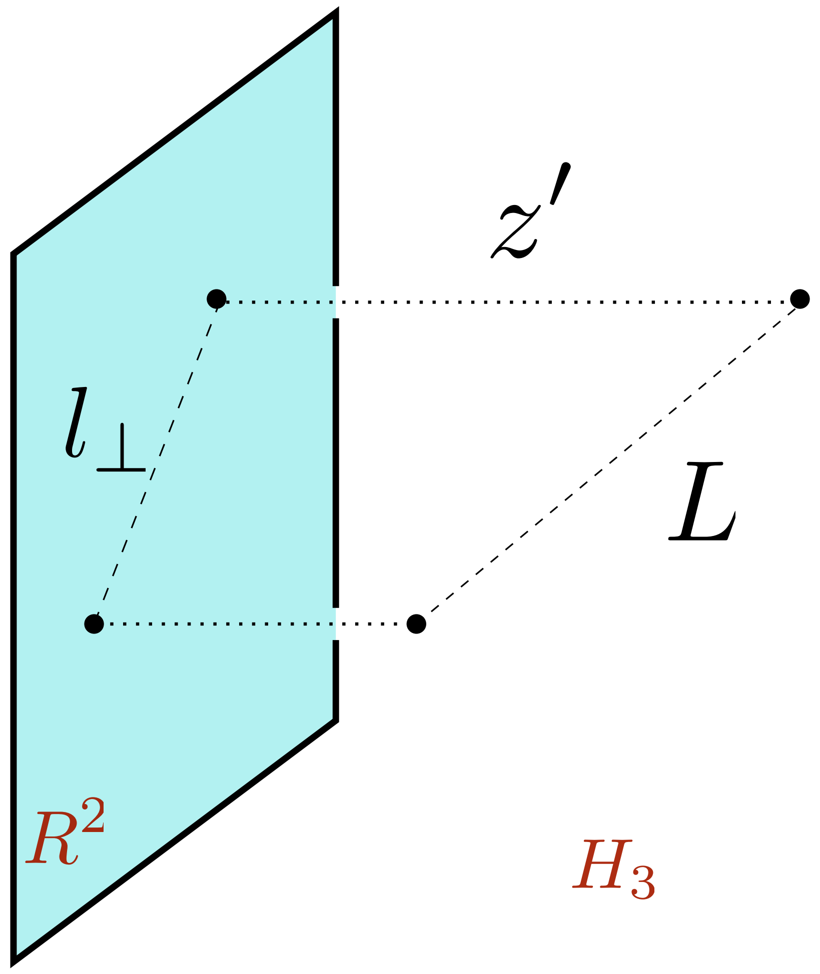
AdS scattering process



- AdS impact parameter representation. In Regge limit

[Cornalba, MSC, Penedones, Schiappa 07]

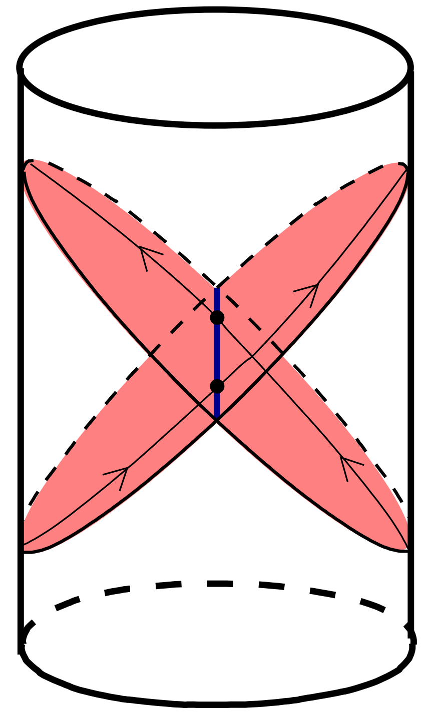
$$A_J(s,t) \approx i V \kappa_J \kappa'_J\, s \int dl_\perp e^{i q_\perp \cdot l_\perp} \int \frac{dz}{z^3}\frac{dz'}{z'^3} \Phi_1(z)\Phi_3(z)\Phi_2(z')\Phi_4(z')\, S^{J-1} G_J(L)$$



$S = z z' s$, AdS energy squared

$\cosh L = \dfrac{z^2 + z'^2 + l_\perp^2}{2 z z'}$, impact parameter

$$A_J(s,t) \approx iV\kappa_J\kappa'_J\, s \int dl_\perp e^{iq_\perp \cdot l_\perp} \int \frac{dz}{z^3}\frac{dz'}{z'^3}\Phi_1(z)\Phi_3(z)\Phi_2(z')\Phi_4(z)\, S^{J-1}G_J(L)$$

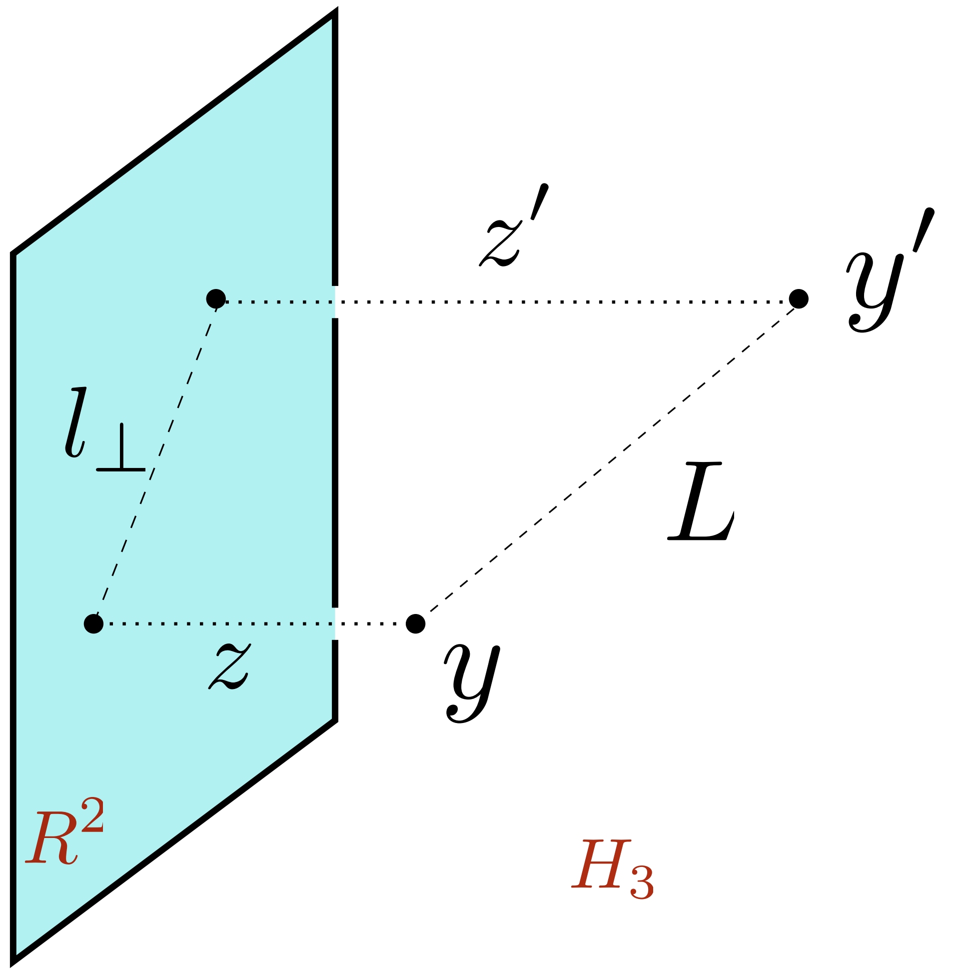


- $G_J(L)$ is the integrated propagator ($w = x - x' = (w^+, w^-, l_\perp)$)

$$G_J(L) \sim i\,(zz')^{(J-1)} \int dw^+ dw^- \Pi_{+\cdots+.-\cdots-}(z,z',w)$$

and obeys scalar propagator equation in transverse space

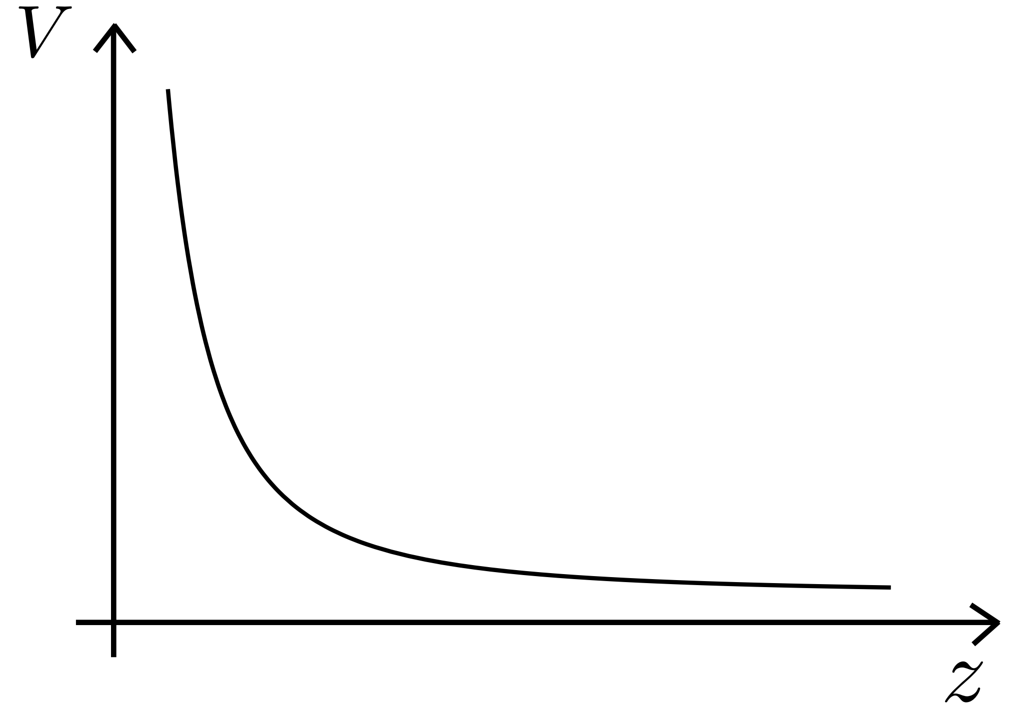
$$\Big[\Box_{H_3} - 3 - \Delta(\Delta-4)\Big] G_J(L) = -\delta_{H_3}(y,y')$$



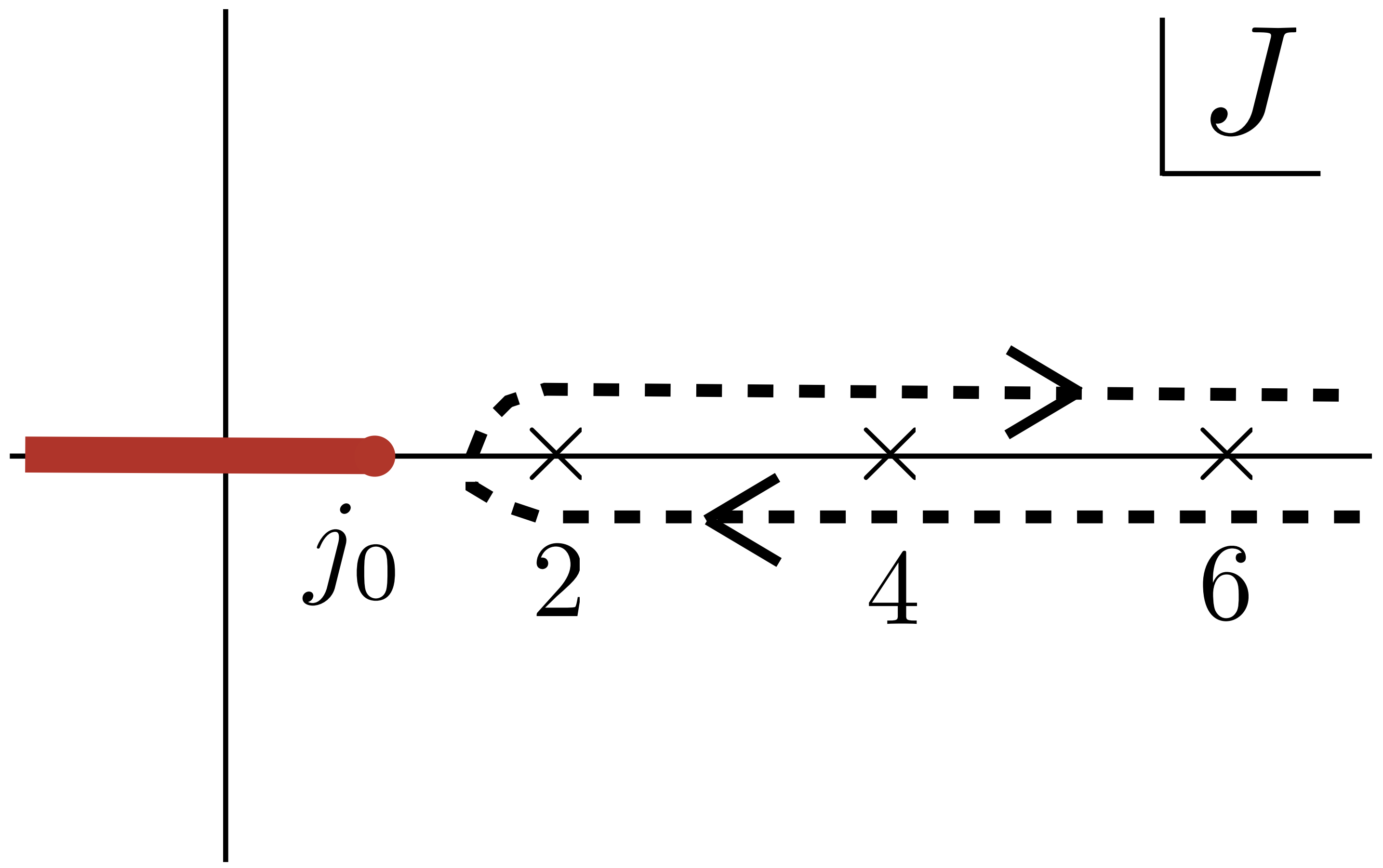
$G_J(L) = e^{iq_\perp \cdot l_\perp}\sqrt{z}\,\psi(z)$, reduces to Schrodinger problem

$$\left(-\frac{d}{dz^2} + V(z)\right) = t\,\psi(z)\,, \text{ with } V = \left(\frac{15}{4} + \Delta(\Delta-4)\right)\frac{1}{z^2}$$

$\Delta = \Delta(J)$

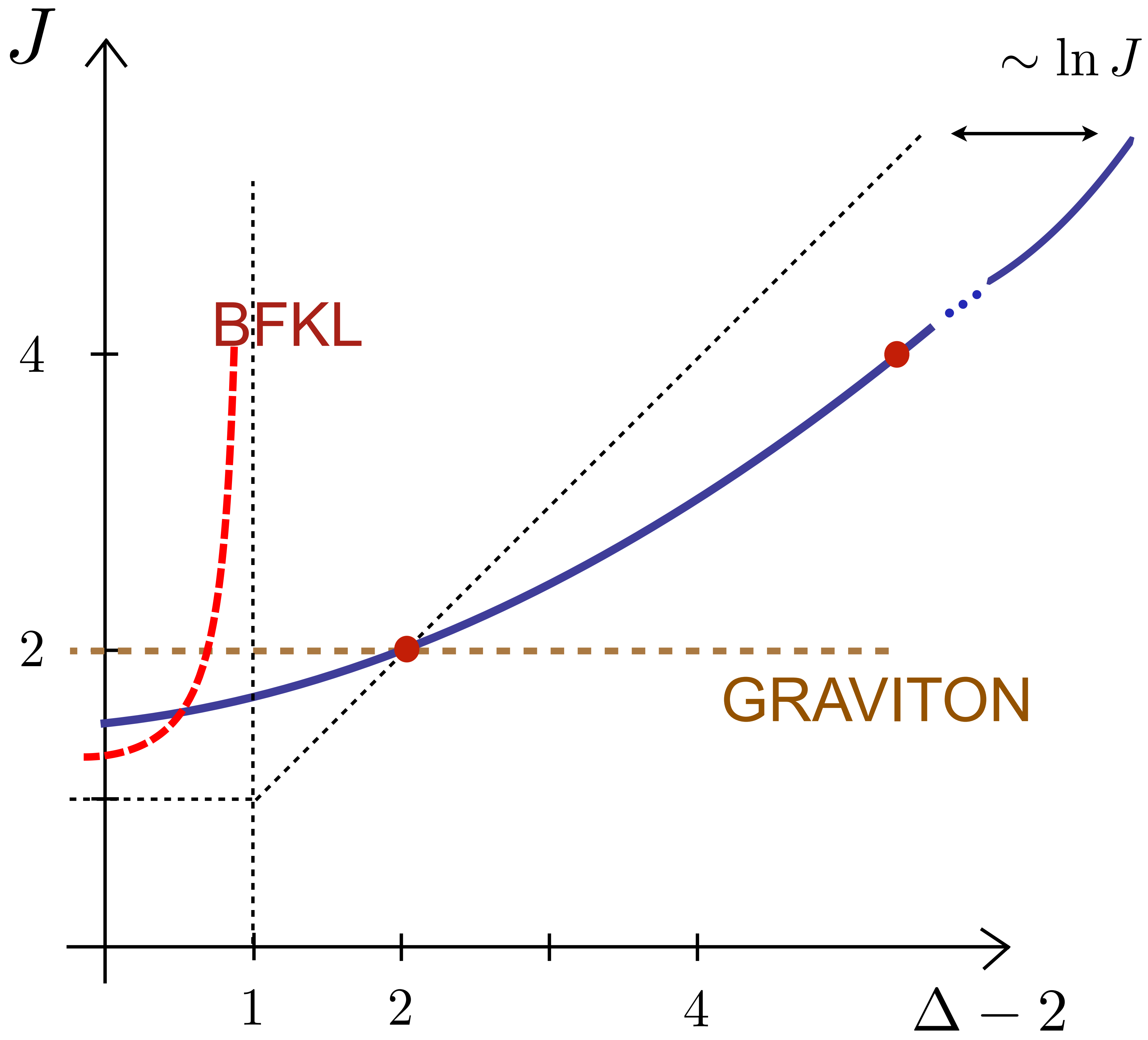


- Sommerfeld-Watson transform $\sum_J \to \int \frac{dJ}{\sin \pi J}$



Operators that contribute have twist 2 and even spin

$$\mathcal{O}_J \sim \mathrm{Tr}\left(F_{\alpha\beta_1} D_{\beta_2} \ldots D_{\beta_{J-1}} F_{\beta_J}{}^{\alpha}\right)$$



At strong coupling, $\sqrt{\lambda} = \frac{1}{\alpha'} \gg 1$, we have

$$\Delta(\Delta - 4) \approx \frac{2}{\alpha'}(J-2)$$

$$G_J(z, q_\perp) = \sqrt{zz'}\, I_\alpha(q_\perp z) K_\alpha(q_\perp z')$$

$$\alpha = \sqrt{4 + \Delta(\Delta - 4)}$$

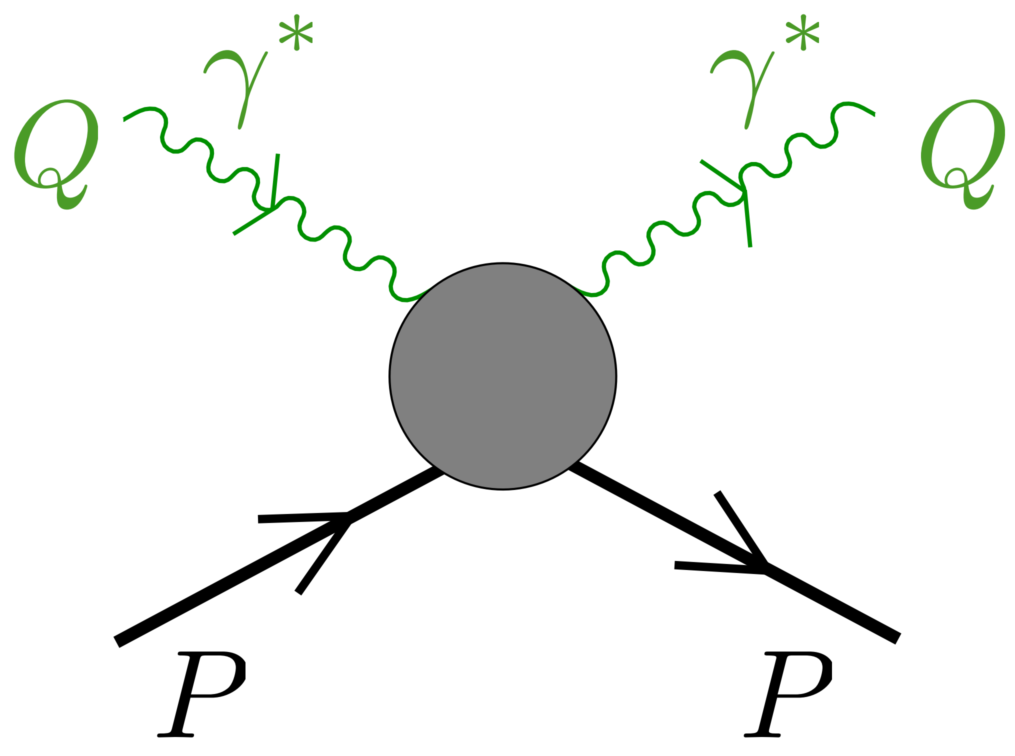
Branch cut starts for $J < j_0 = 2 - \frac{2}{\sqrt{\lambda}}$

Applications to low-x QCD

- Fits low x data for DIS, DVCS, VMP including confining region $Q \sim \Lambda_{QCD}$

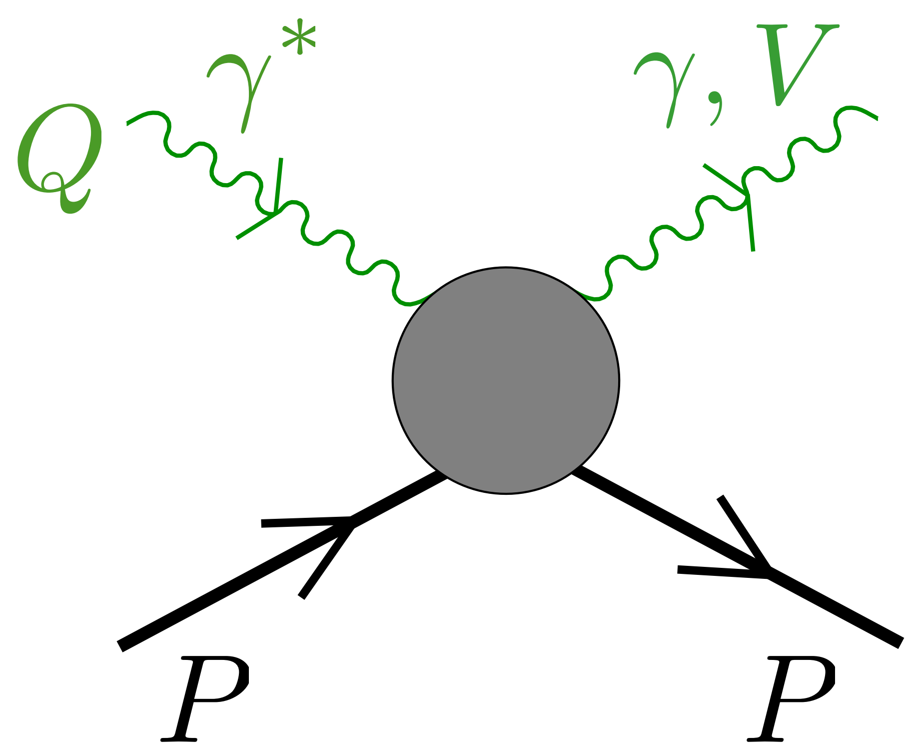
DIS [Cornalba, MSC 08; Levin, Potashnikova 10; Brower, Djuric, Sarcevic, Tan 10];
DVSC [MSC, Djuric 12]; VMP [MSC, Djuric, Evans 13]

- DIS



$$\sigma(Q,x) \propto \underset{(t=0)}{\mathrm{Im}\ W} \quad \rightarrow \quad F_2$$

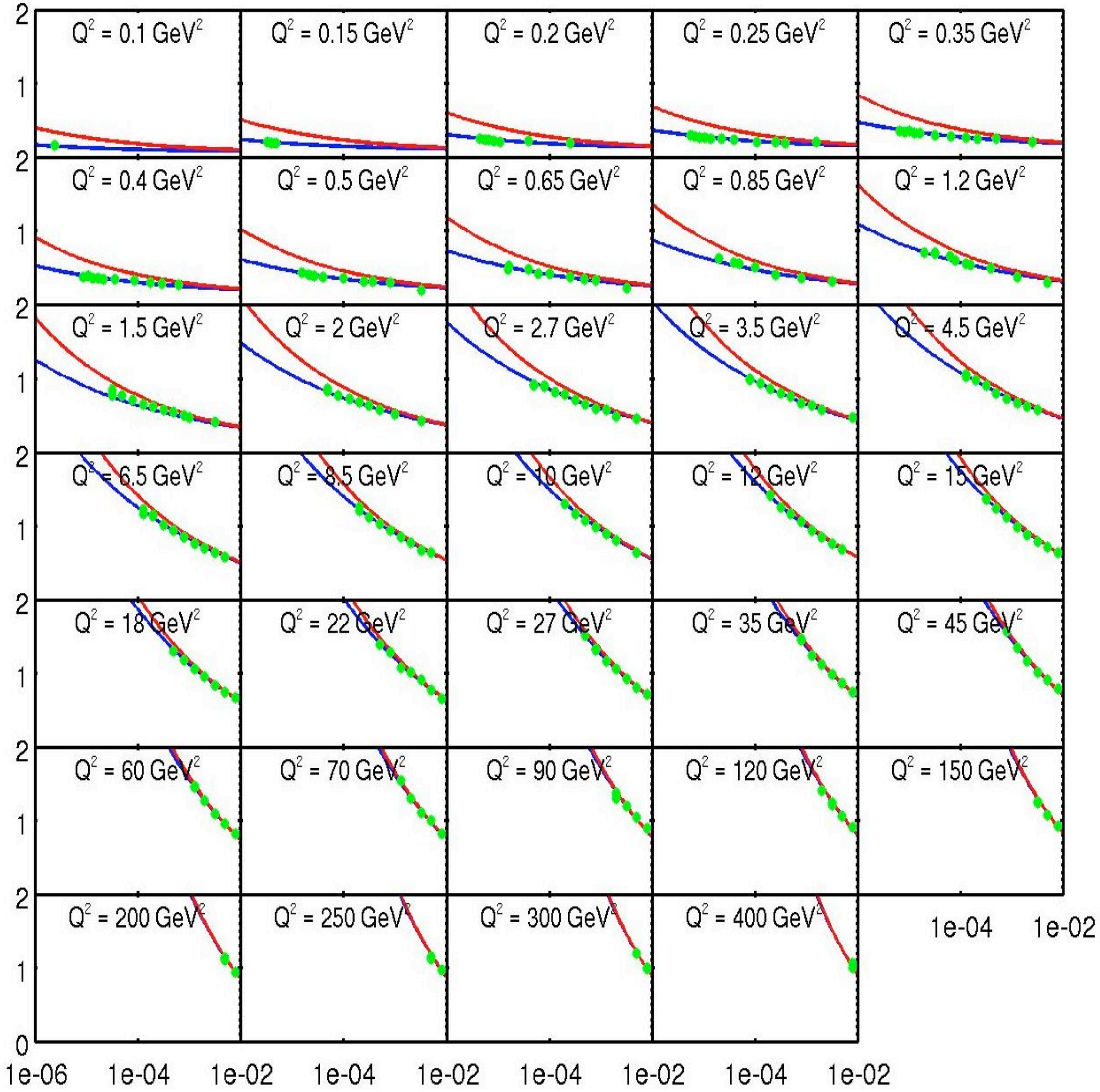
- DVCS & VMP



$$\frac{d\sigma}{dt}(Q,x,t) \propto |W|^2 \ \text{ and } \ \sigma_{tot}(Q,x)$$

- Fits for hard-wall model have 4 parameters $j_0\ ,\ \kappa^2\ ,\ z_*\ ,\ z_0$

DIS - AdS Pomeron [Brower, Djuric, Sarcevic, Tan 10]



HERA combined data by H1 and ZEUS experiments [Aaron et al 10] with

$$0.10 < Q^2 < 400\ GeV^2,\ x < 10^{-2}$$

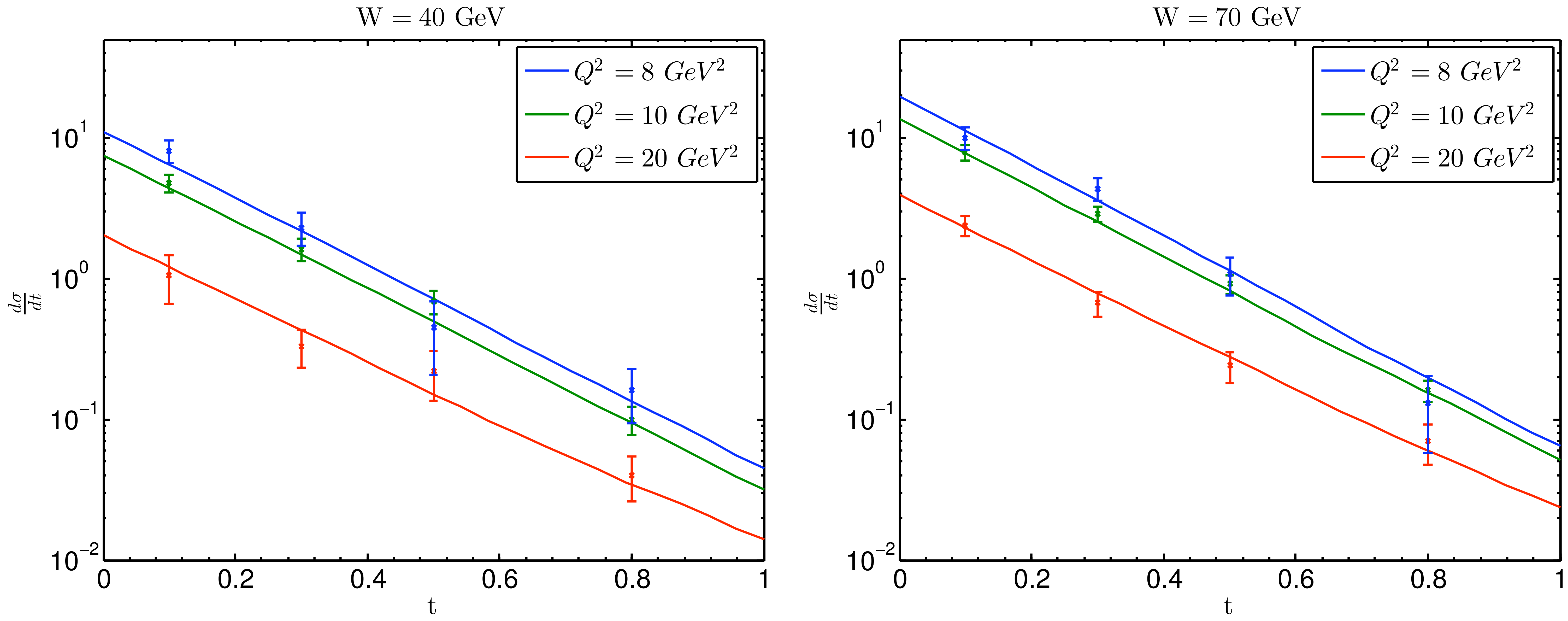
For hard wall model obtained excellent fit with (249 points)

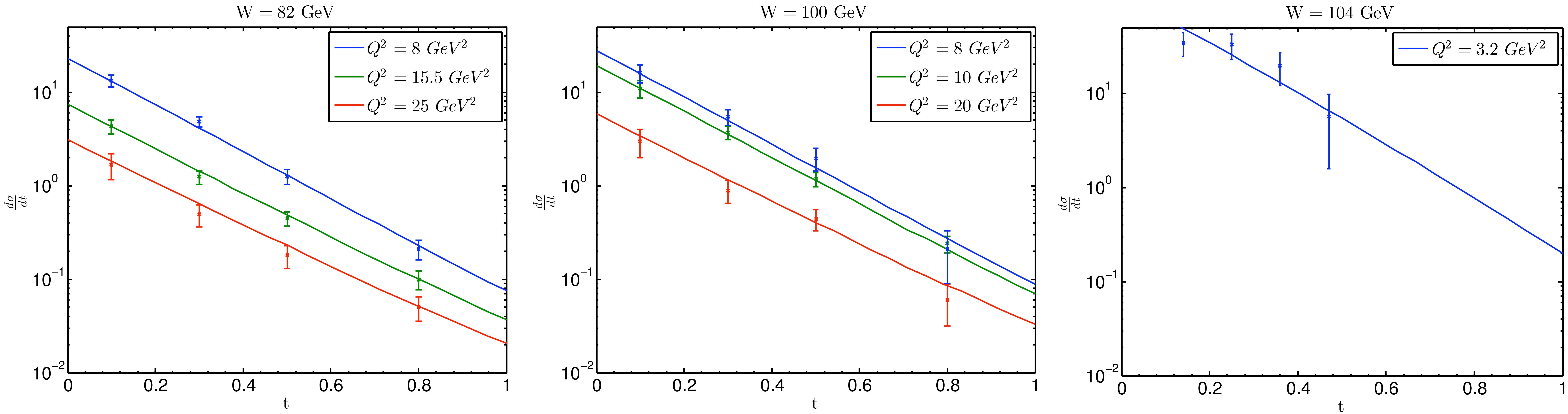
$$\chi^2_{d.o.f.} = 1.07$$

DVSC (differential cross section) [MSC, Djuric 12]

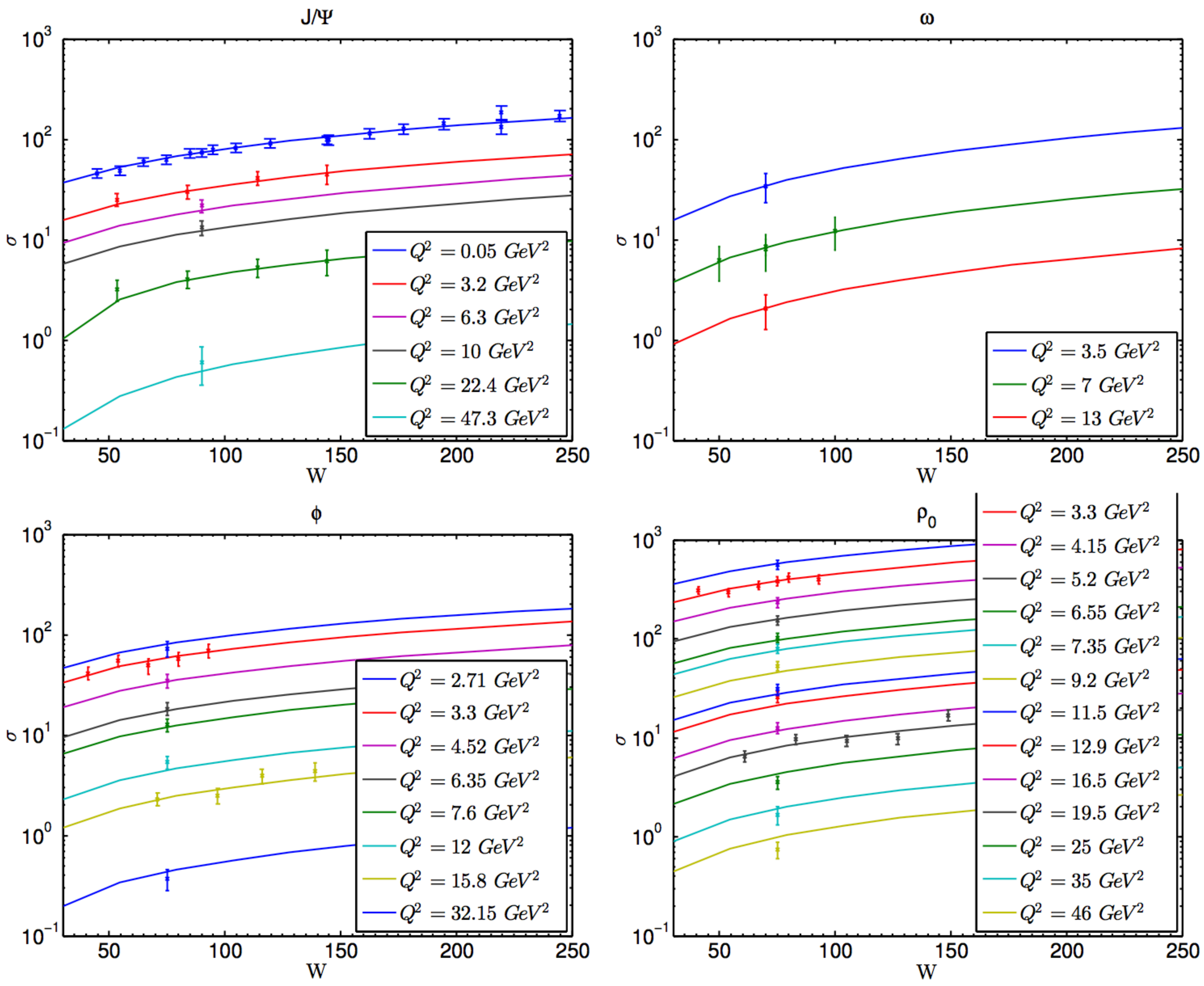
All data (52 points)

$$\chi^2_{d.o.f.} = 0.51$$





VMP (J/Ψ, ω, ϕ, ρ_0) [MSC, Djuric, Evans 13]

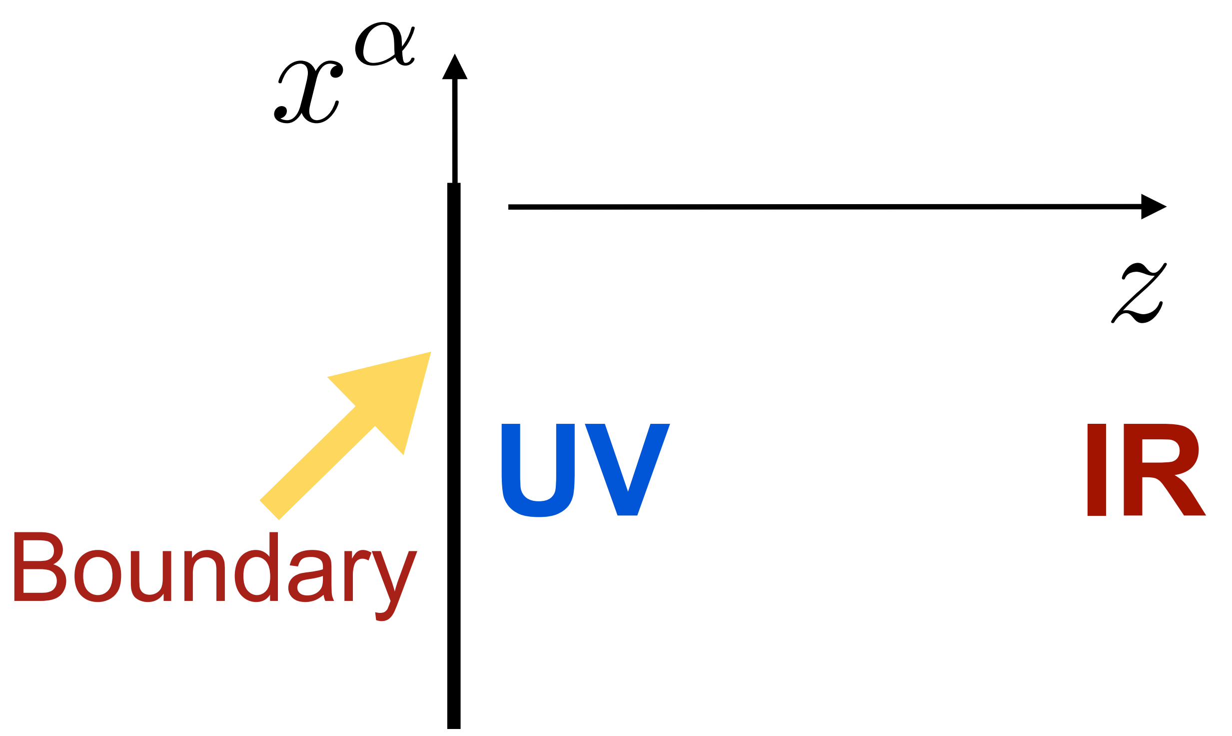


Soft pomeron in holographic QCD [Bayona, MSC, Djuric, Quevedo 15]

- 5D dilaton-gravity model constructed to reproduce QCD [Gursoy, Kiritsis, Nitti 07]

$$S = \frac{1}{2\kappa^2}\int d^5x\sqrt{-g}\,e^{-2\Phi}\Big[R + 4(\partial\phi)^2 + V(\phi)\Big]$$

Judicious choice of potential with only 2 free parameters



Constructed to match QCD perturbative beta function

Reproduces: - heavy quark-antiquark linear potential

- glueball spectrum from lattice simulations
- thermodynamic properties of QGP (bulk viscosity, drag force and jet quenching parameters)

$$ds^2 = e^{2A(z)}\left(dz^2 + \eta_{\alpha\beta}dx^\alpha dx^\beta\right)$$

$$\Phi = \Phi(z)$$

Spin J field in holographic QCD

- Construct spin J field dual to gluon operator $\mathcal{O}_J \sim \mathrm{Tr}\left(F_{\alpha\beta_1} D_{\beta_2} \dots D_{\beta_{J-1}} F_{\beta_J}{}^{\alpha}\right)$

Decompose symmetric, traceless and transverse field $h_{a_1 \dots a_J}$ with respect to global $SO(1,3)$ boundary symmetry. Propagating modes have boundary indices $h_{\alpha_1 \dots \alpha_J}$

Spin J equation must:

- In AdS limit reduce to $\left(D^2 - m^2\right) h_{a_1 \dots a_J} = 0$

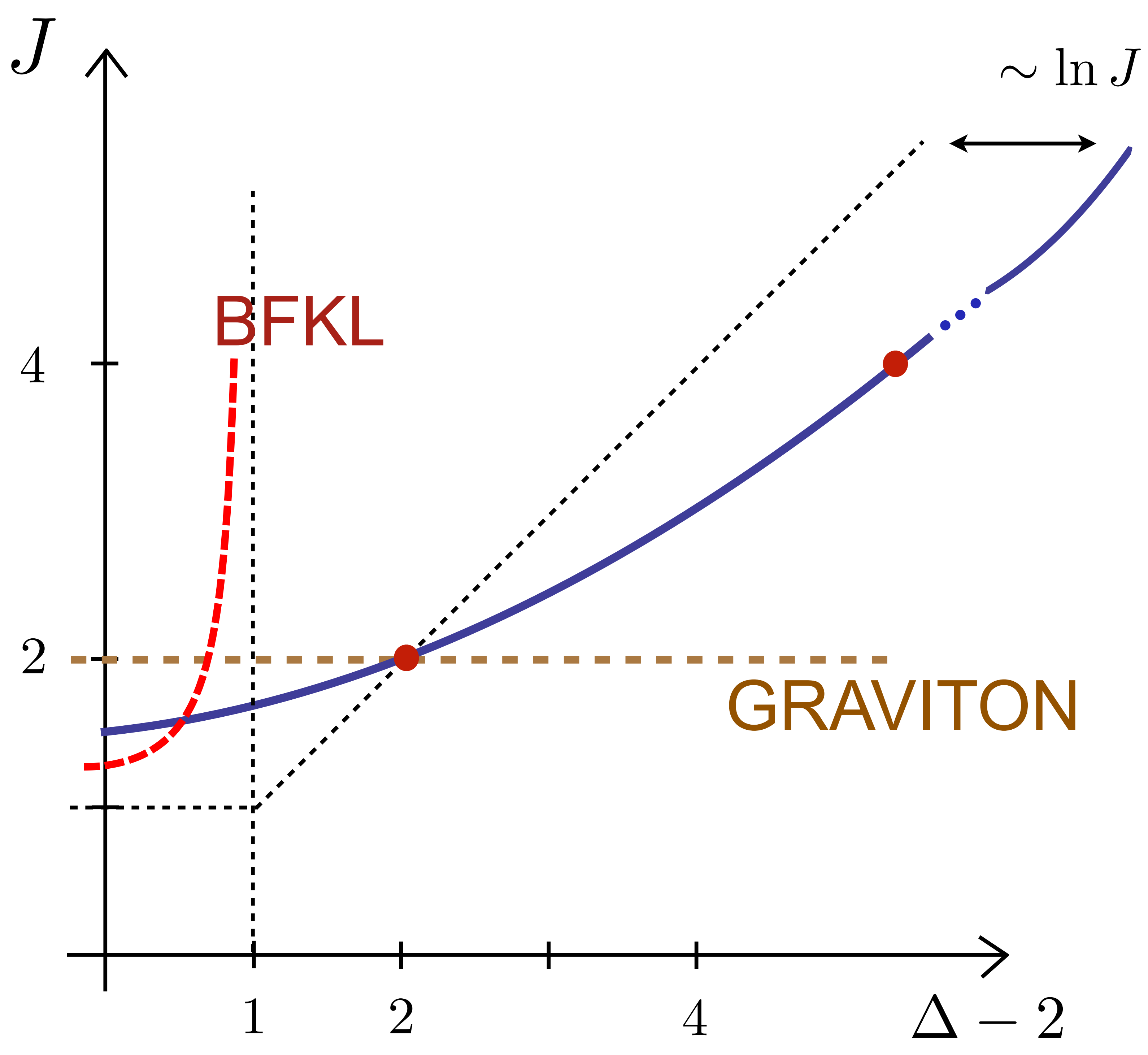
$$m^2 = \Delta(\Delta - 4) - J\,, \quad \Delta = \Delta(J)$$

- For $J = 2$ reproduce TT metric fluctuations

$$\left(\nabla^2 - 2\dot{\Phi}\nabla_z + 2\dot{A}^2 e^{-2A(z)}\right) h_{\alpha\beta} = 0$$

Proposed equation for propagating mode

$$\left(\nabla^2 - 2\dot{\Phi}\nabla_z - \Delta(\Delta - 4) + J\dot{A}^2 e^{-2A}\right) h_{\alpha_1 \dots \alpha_J} = 0$$

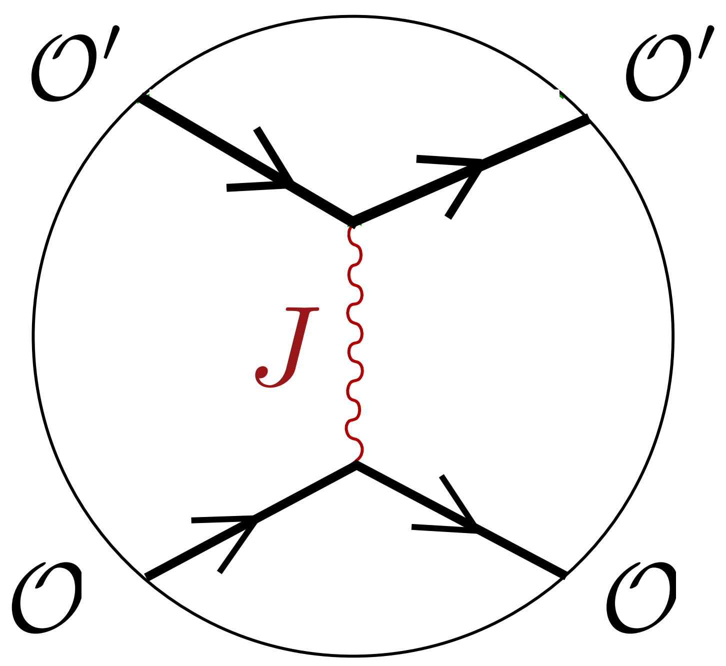


- In the region $J < 2$ we take

$$\Delta(\Delta - 4) \approx \frac{2}{l_s^2}(J - 2)$$

Soft pomeron Regge trajectories

- Consider 5D exchange of spin J field in the Regge limit

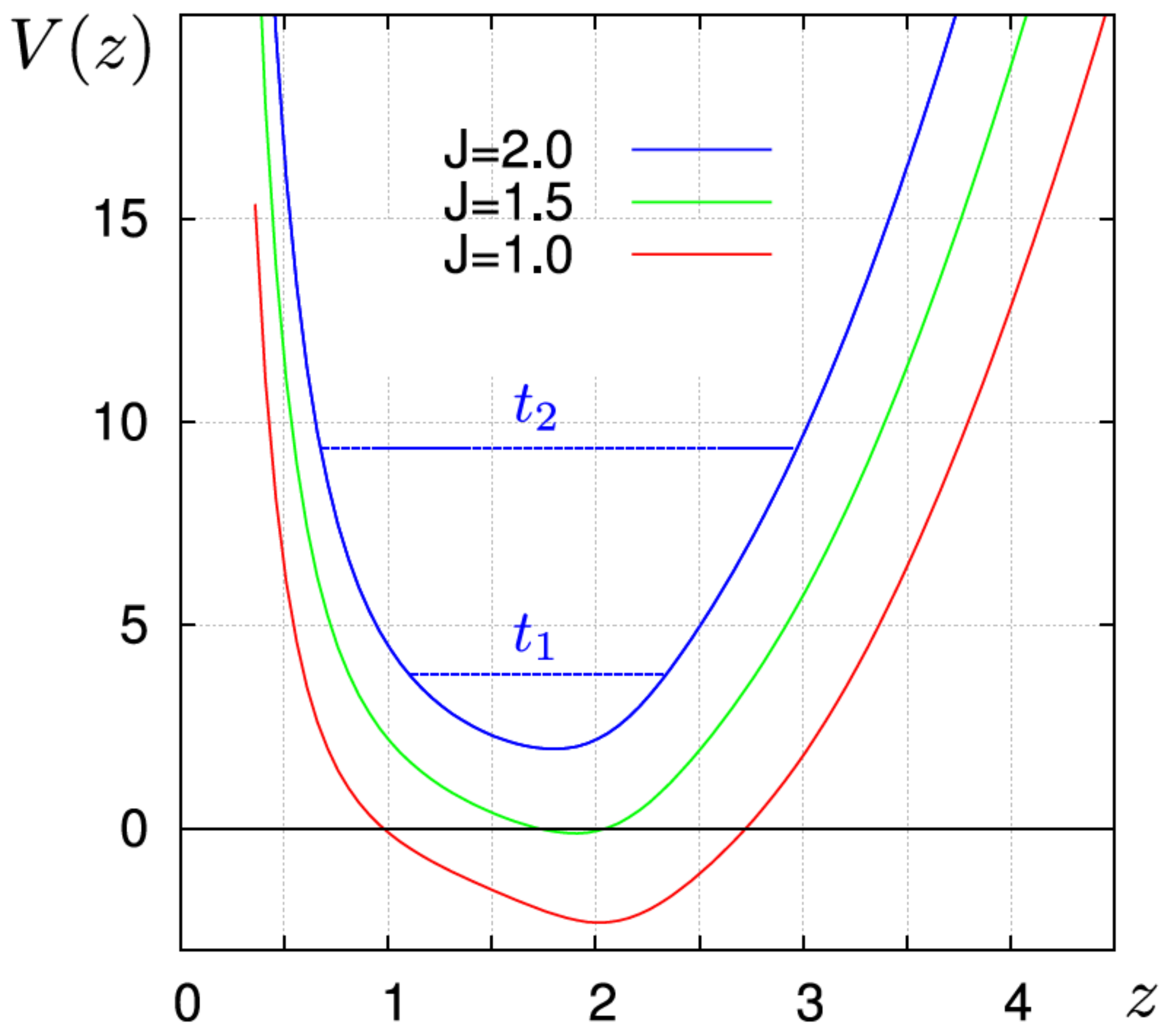


$$A_J(s,t) = iV \frac{\kappa_J \kappa'_J}{(-2)^J}\, s \int dz dz' e^{3A+3A'-\Phi-\Phi'} |v_1|^2 |v'_2|^2 \left(s e^{-A-A'}\right)^{J-1} G_J(z,z',t)$$

Problem reduces to a Schrodinger problem

$$G_J(z,z',t) = e^{\Phi-\frac{A}{2}+\Phi'-\frac{A'}{2}} \sum_n \frac{\psi_n(z)\psi_n^*(z')}{t_n(J)-t}$$

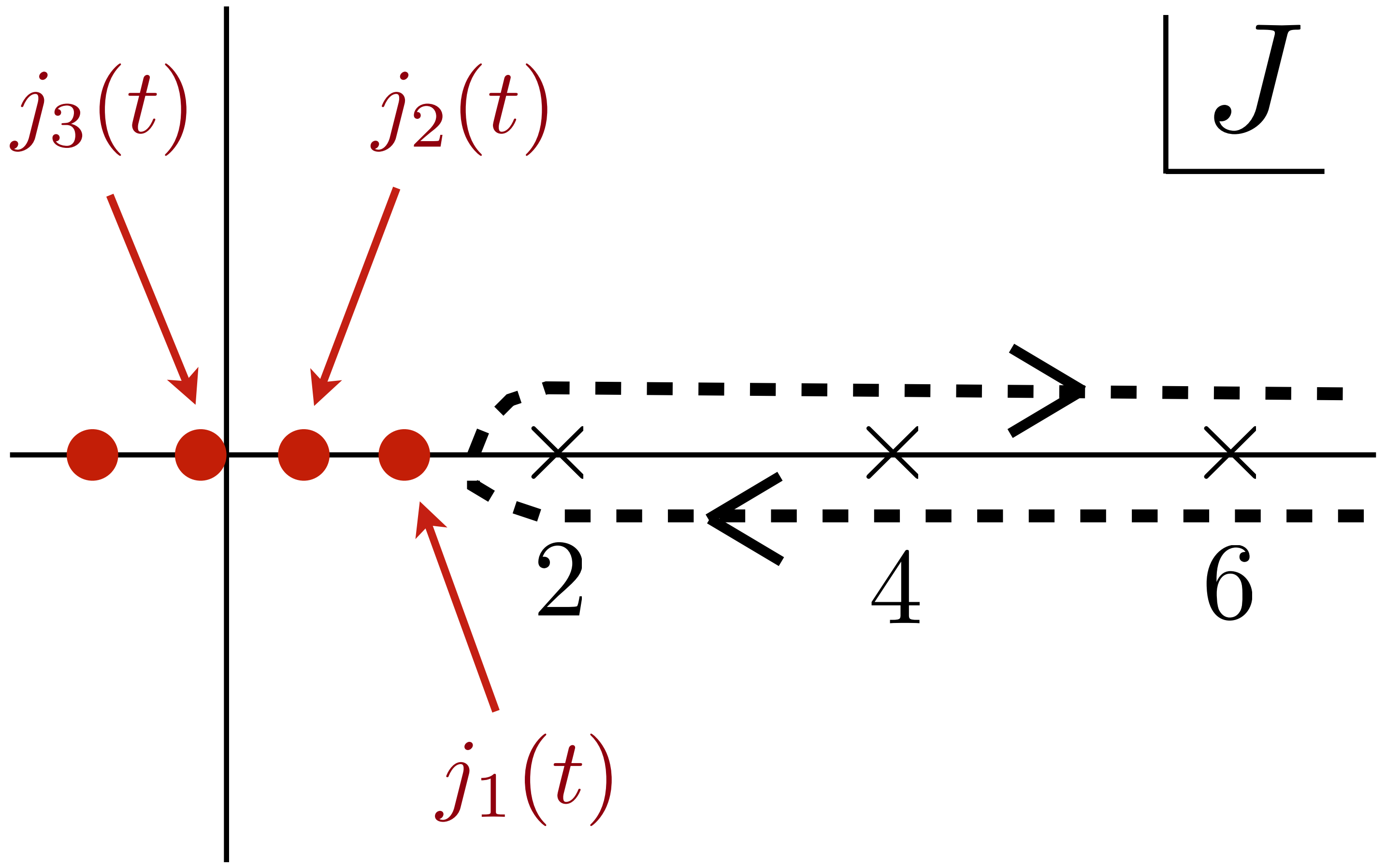
$$V(z) = \frac{15}{4}\dot{A}^2 - 5\dot{A}\dot{\Phi} + \dot{\Phi}^2 + \Delta(\Delta-4)\, e^{2A(z)}$$

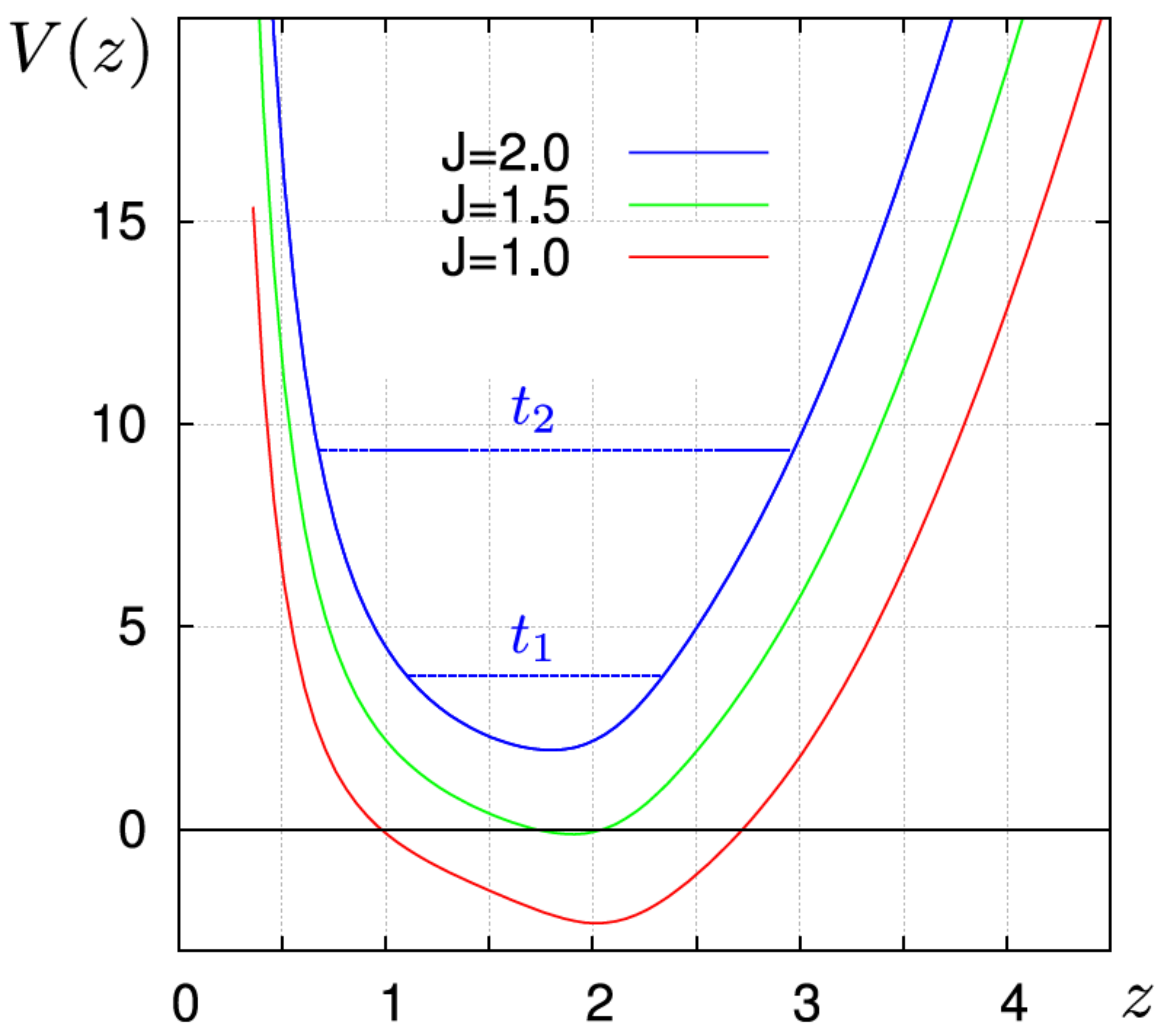


- Sum over spin J exchanges in 5D dual theory $\sum_J \rightarrow \int \frac{dJ}{\sin \pi J}$

$$G_J(z, z', t) = e^{\Phi - \frac{A}{2} + \Phi' - \frac{A'}{2}} \sum_n \frac{\psi_n(z)\psi_n^*(z')}{t_n(J) - t}$$

Poles in the J-plane at $t = t_n(J) \;\Rightarrow\; J = j_n(t)$

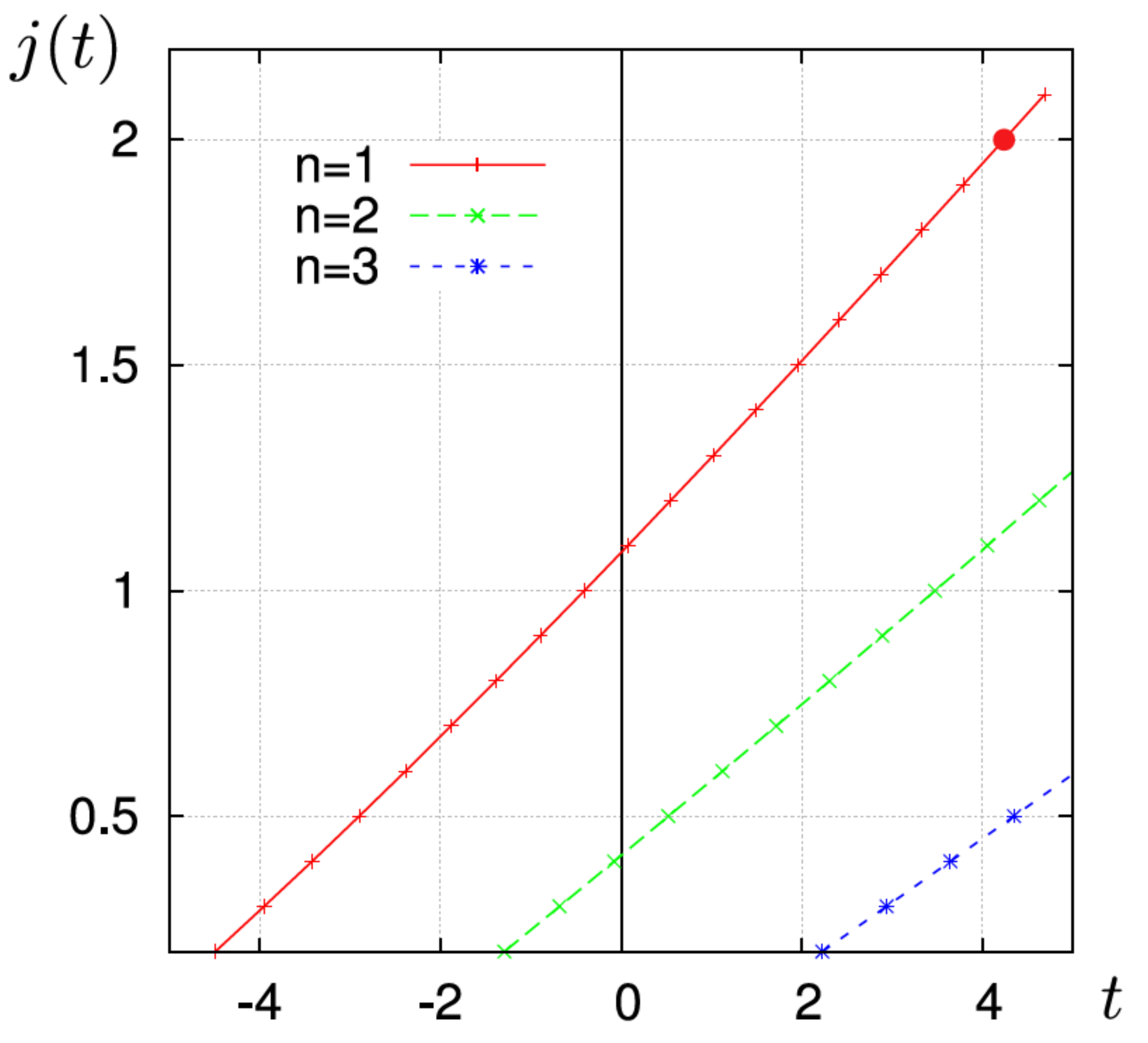




• Obtained approximate linear Regge trajectories. Spin J equation has one free parameter, l_s , to fit soft pomeron intercept and slop.

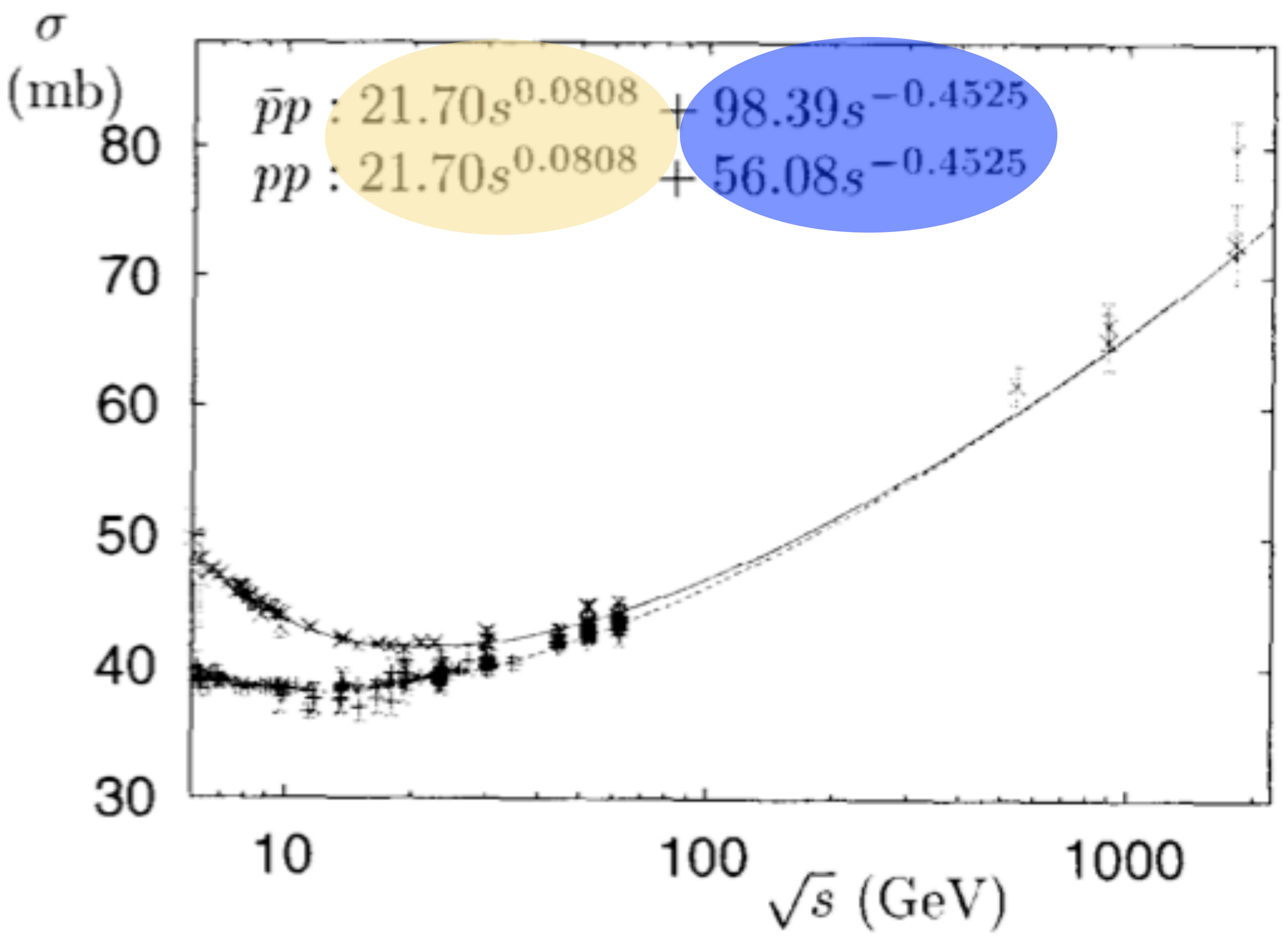
$$l_s = 0.178 \text{ GeV}^{-1} \;\Rightarrow\; \begin{array}{l} j_0 = 1.08 \\ \alpha' \Lambda_{QCD}^2 = 0.018 \end{array}$$

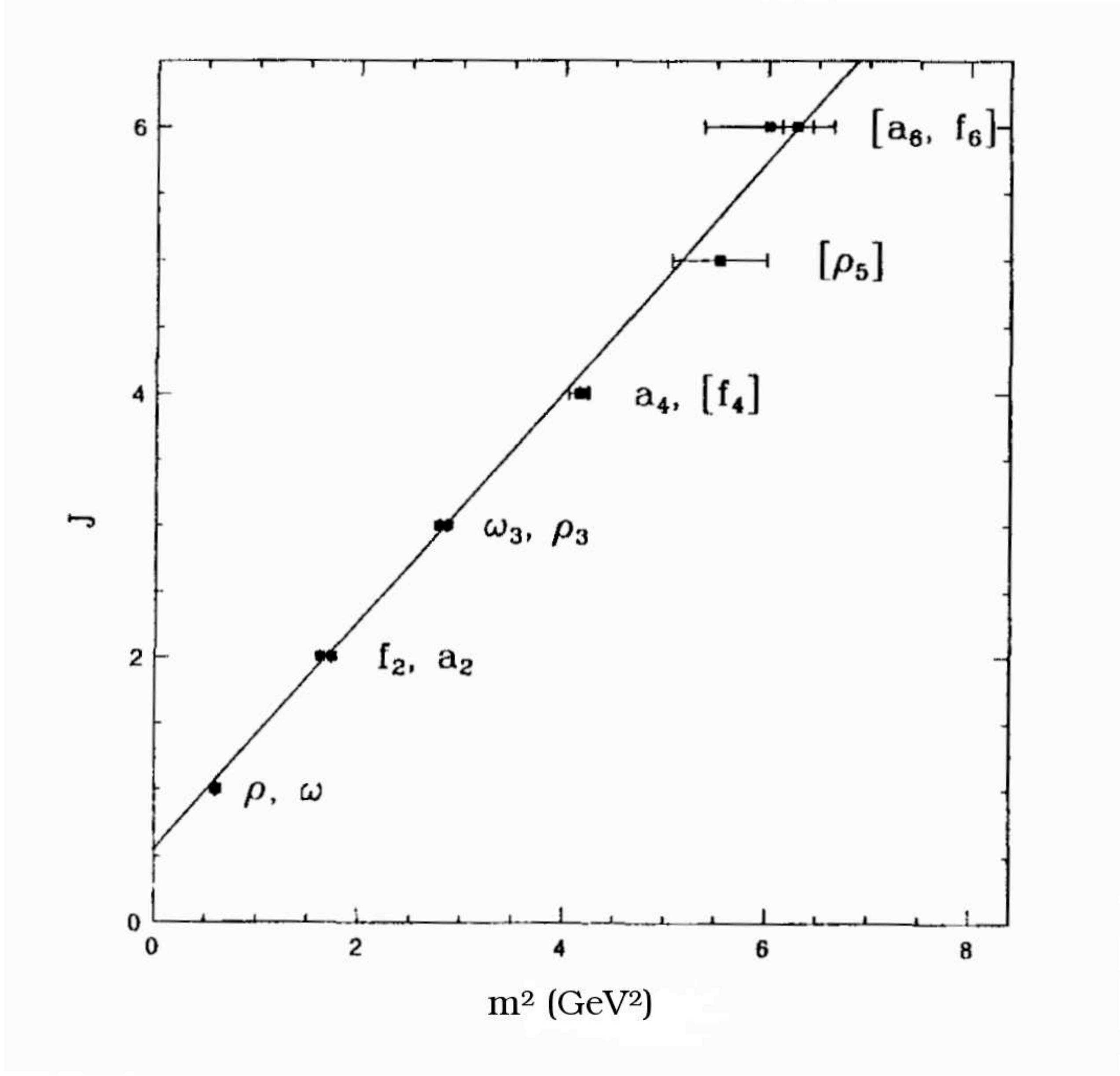
where Λ_{QCD} is a parameter of the holographic QCD model



- $\Lambda_{QCD} = 0.292$ GeV to match m_{0++} from lattice then $\alpha' = 0.21 \text{ GeV}^{-2}$
- $\Lambda_{QCD} = 0.265$ GeV to match possible value of m_{2++} at pomeron trajectory then $\alpha' = 0.25 \text{ GeV}^{-2}$

- Recall that Donnachie-Landshoff fits require the $\rho\,, \omega\,, f_2\,, a_2$ meson trajectories that are subleading

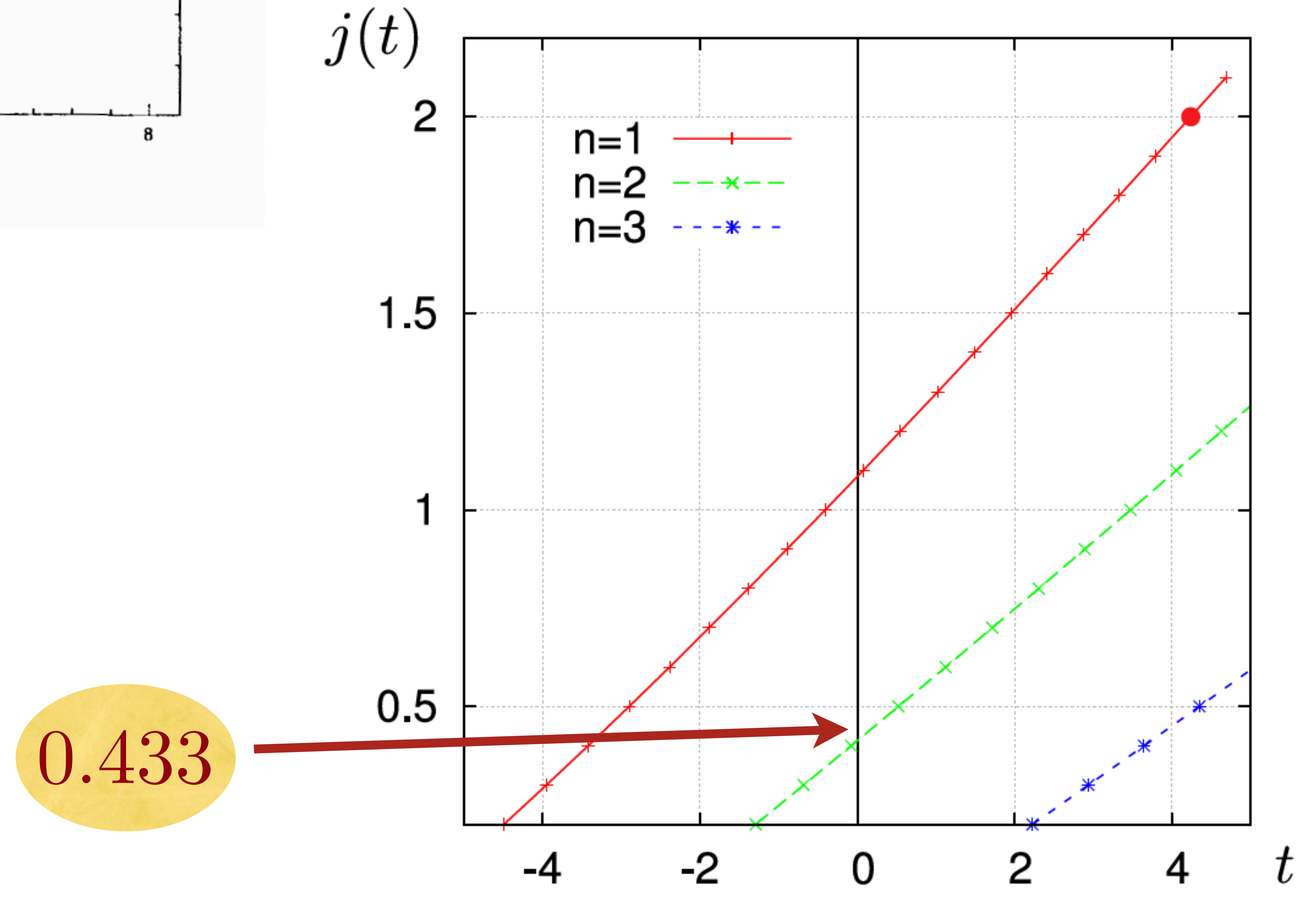




$$\sigma = X\, s^{\,j_0 - 1} + Y\, s^{\,j_0' - 1}$$

Fits allow for intercept j_0' in the range $0.35 - 0.55$

The second pomeron trajectory is precisely in this range!!

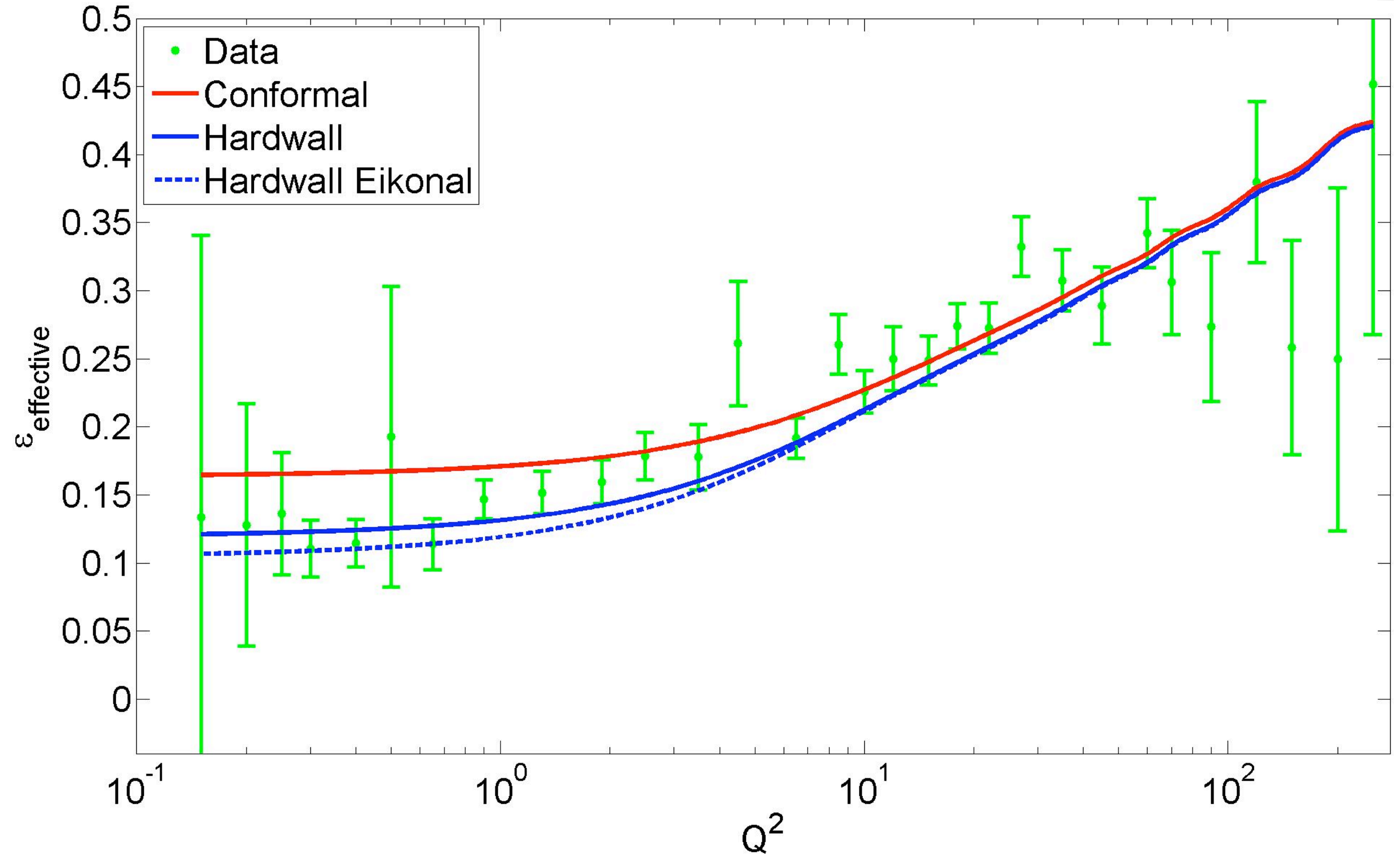


Concluding Remarks

• Holographic QCD model reproduces physics of Donnachie-Landshoff pomeron, with sensible results for intercept and slope.
Importance of second pomeron trajectory?

• Connection with hard-pomeron, i.e. **unify hard and soft pomerons**.
Understand running of effective exponent

[Brower, Djuric, Sarcevic, Tan 10]



$$\sigma \sim f(Q) \left(\frac{1}{x}\right)^{\epsilon_{eff}(Q)}$$

- Add next sub-leading poles and study behavior with a varying probe scale Q?

- Understand better asymptotics of spin J field near the boundary to reproduce QCD anomalous dimension. What is analytic structure in J-plane?

• Ultimate goal: a single holographic model for scattering of soft probes, as well as DIS, DVSC and VMP based, on the graviton Regge trajectory.

THANK YOU