The holographic Pomeron and low-x physics

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Regge behaviour in QCD

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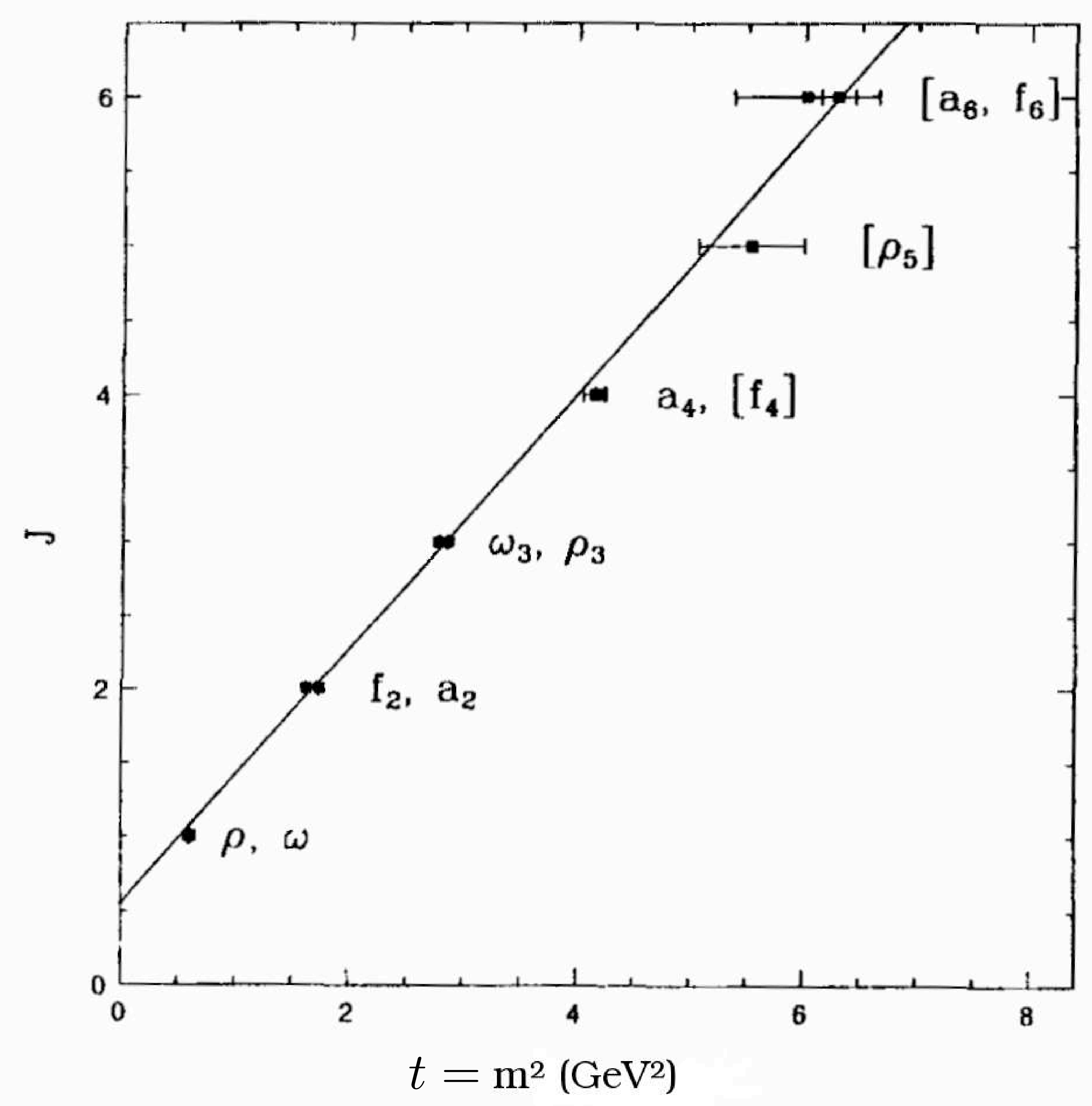
- Hadronic resonances fall in linear trajectories



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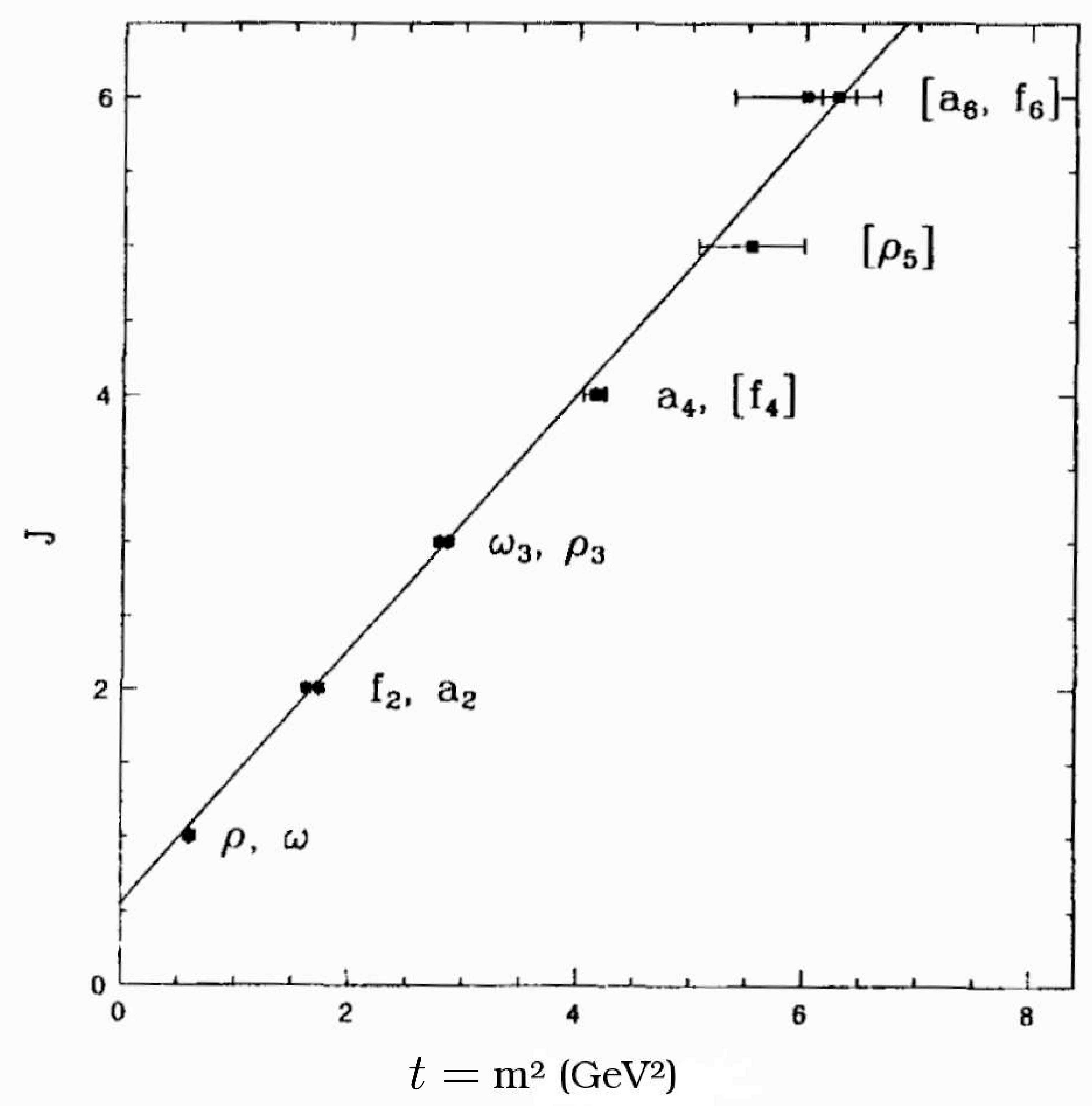

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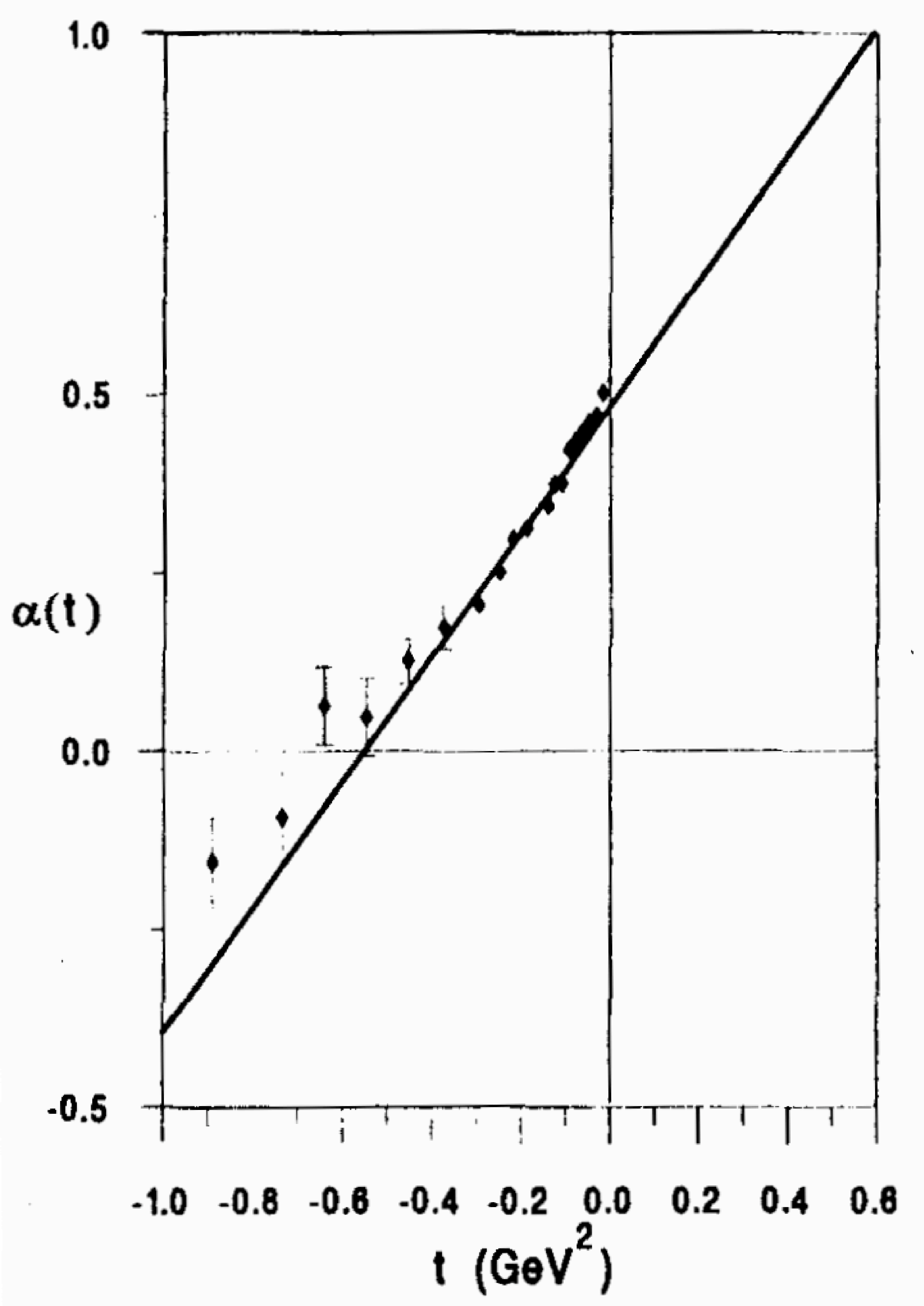

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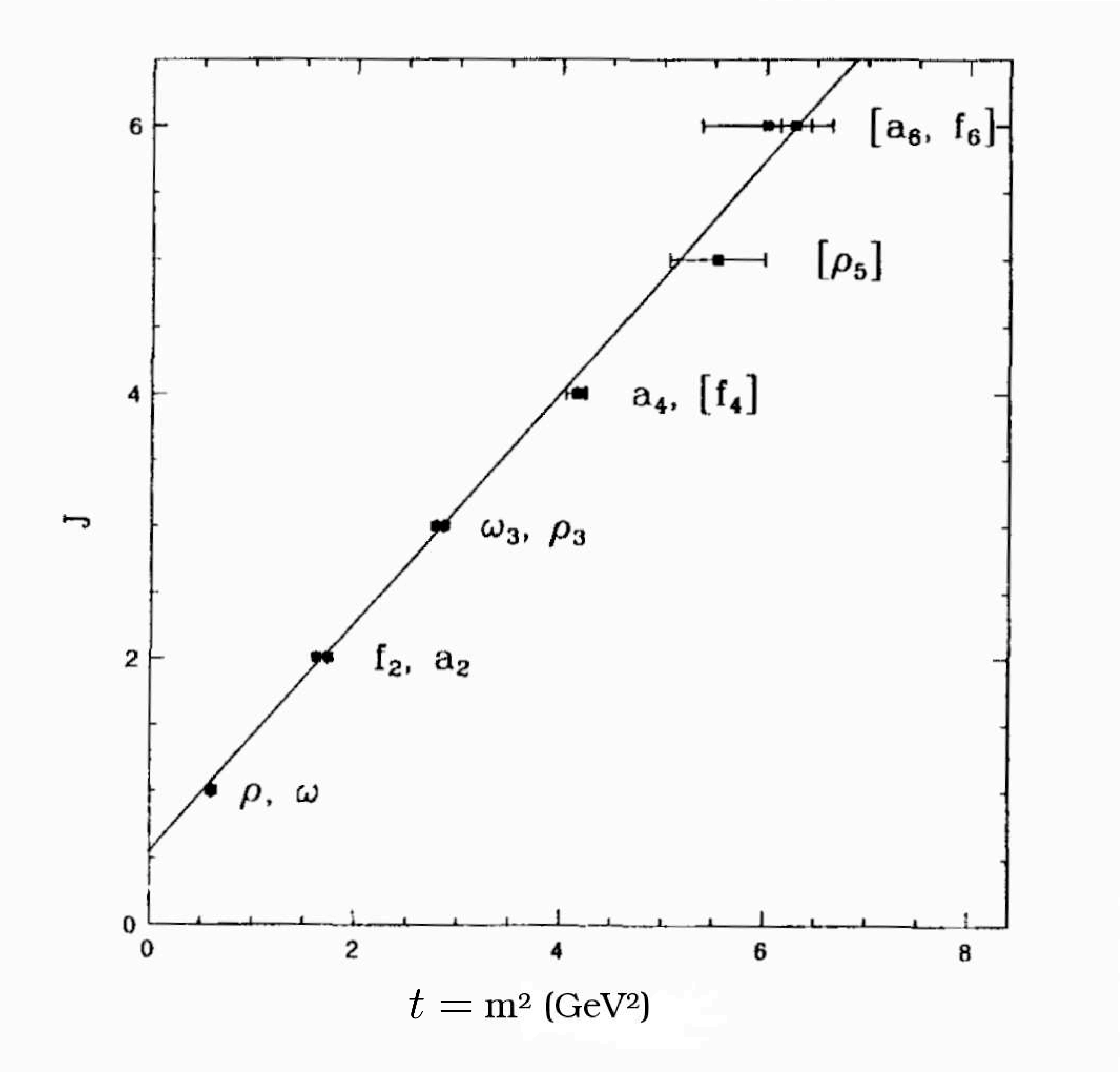

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Total cross section

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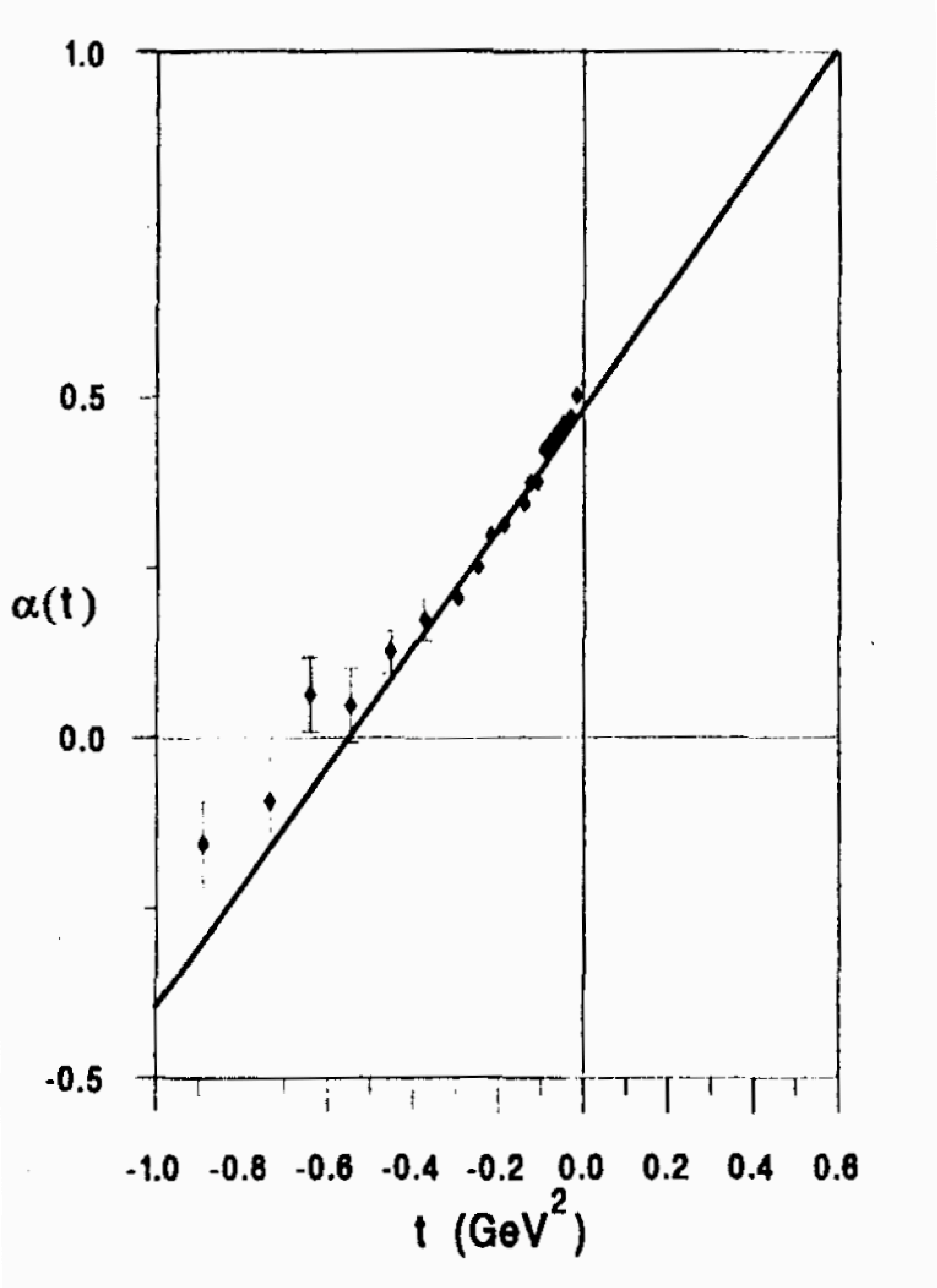

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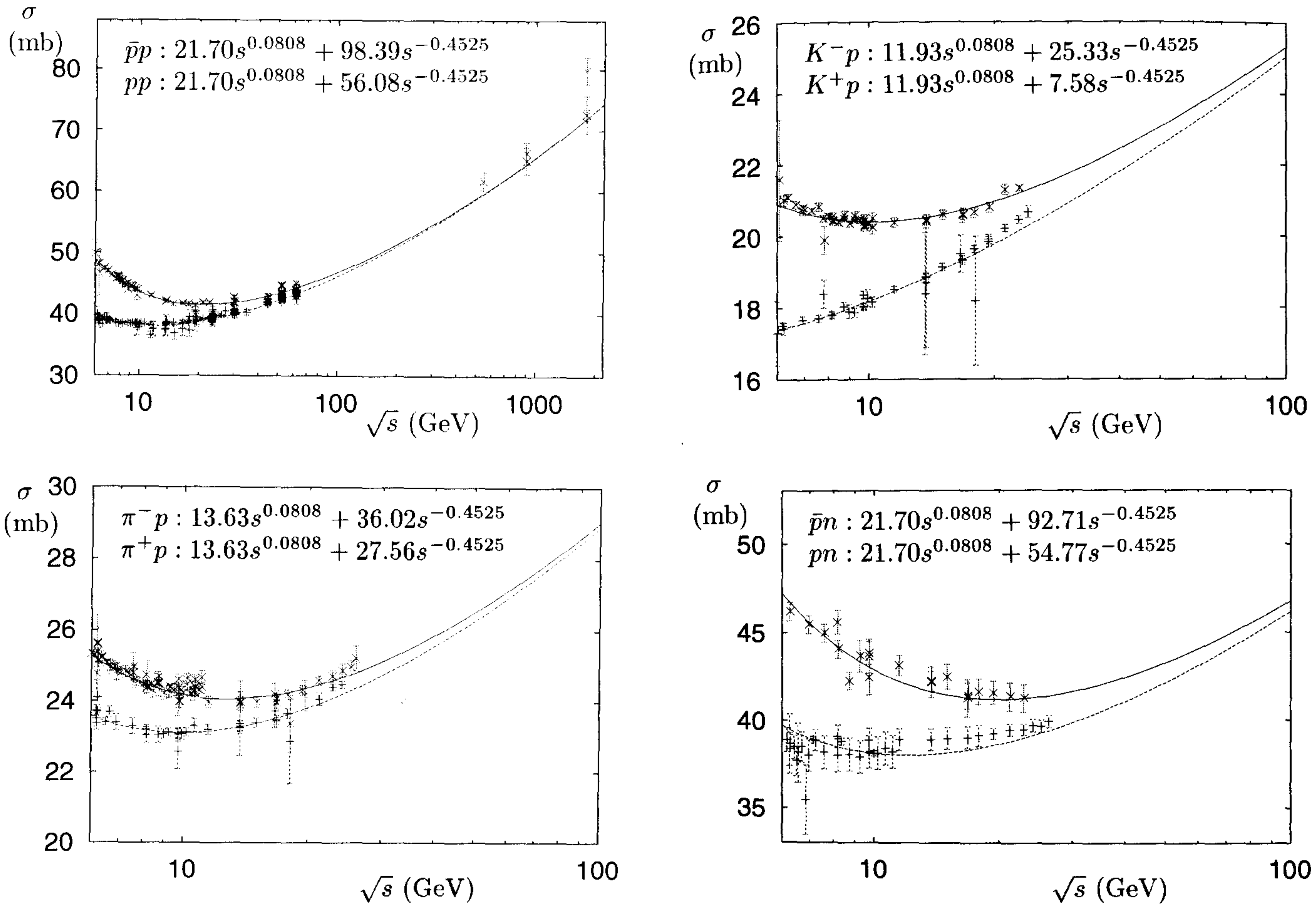

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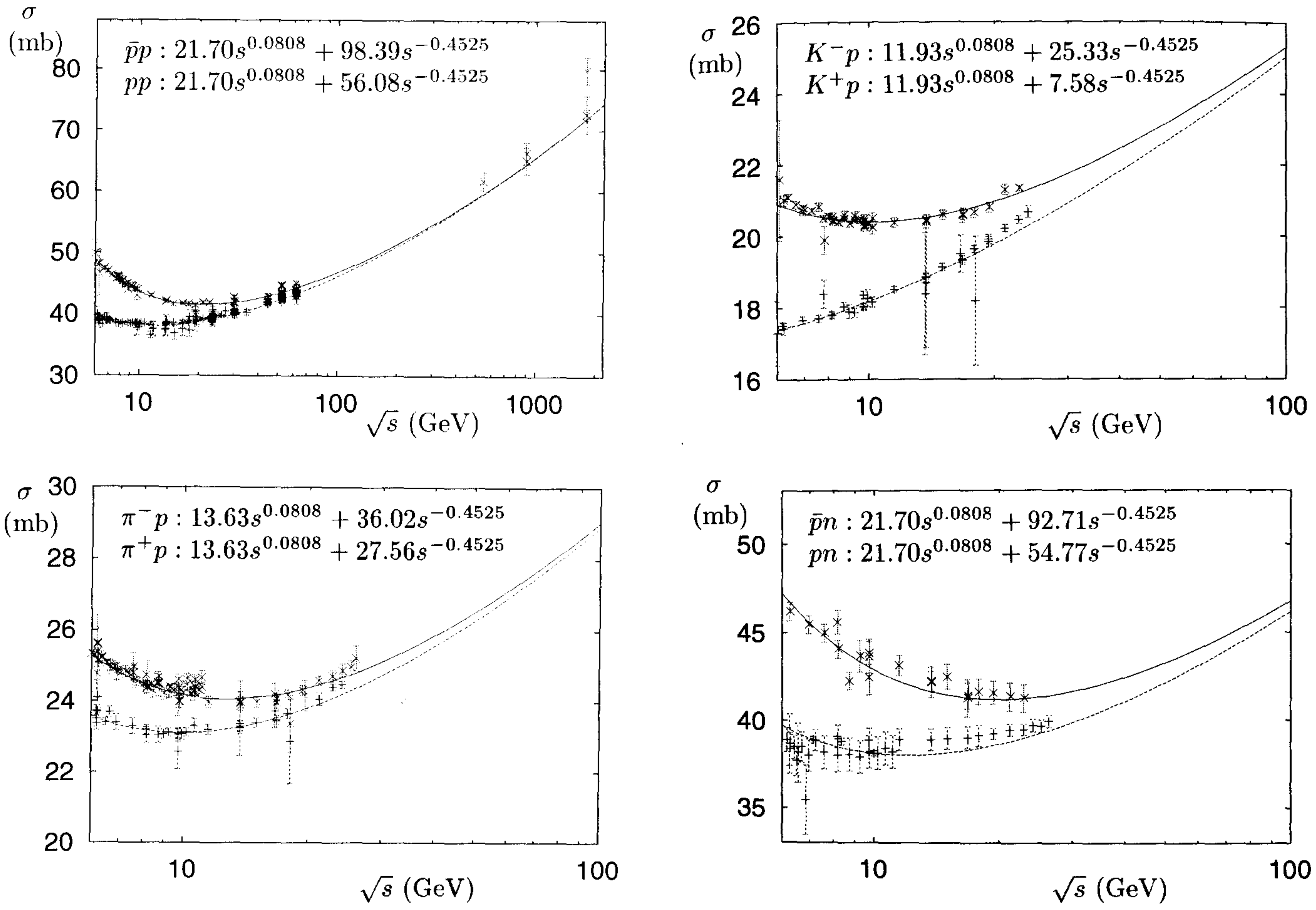

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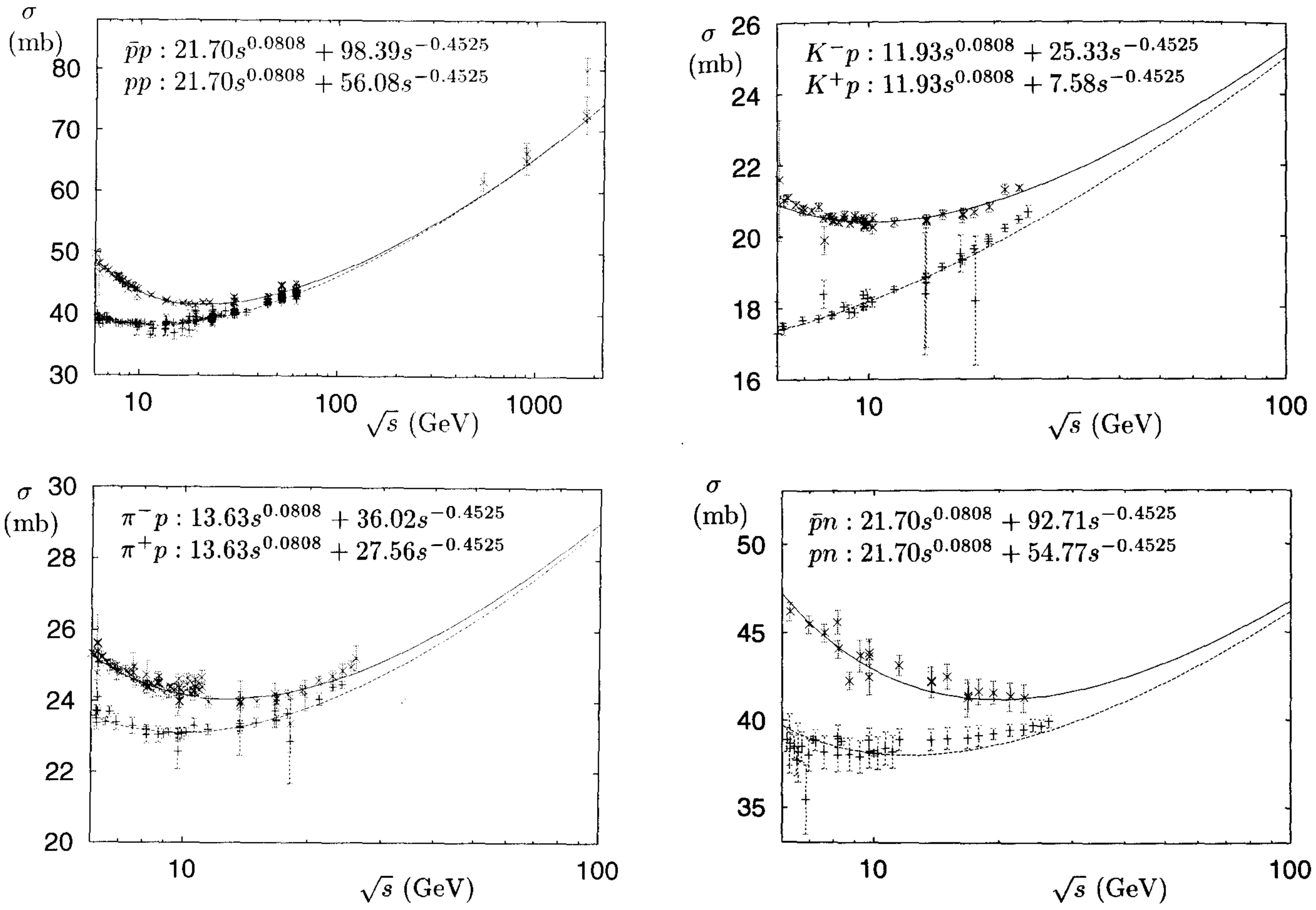
Evidence from lattice QCD that there are glueballs on this trajectory with $J \geq 2$.



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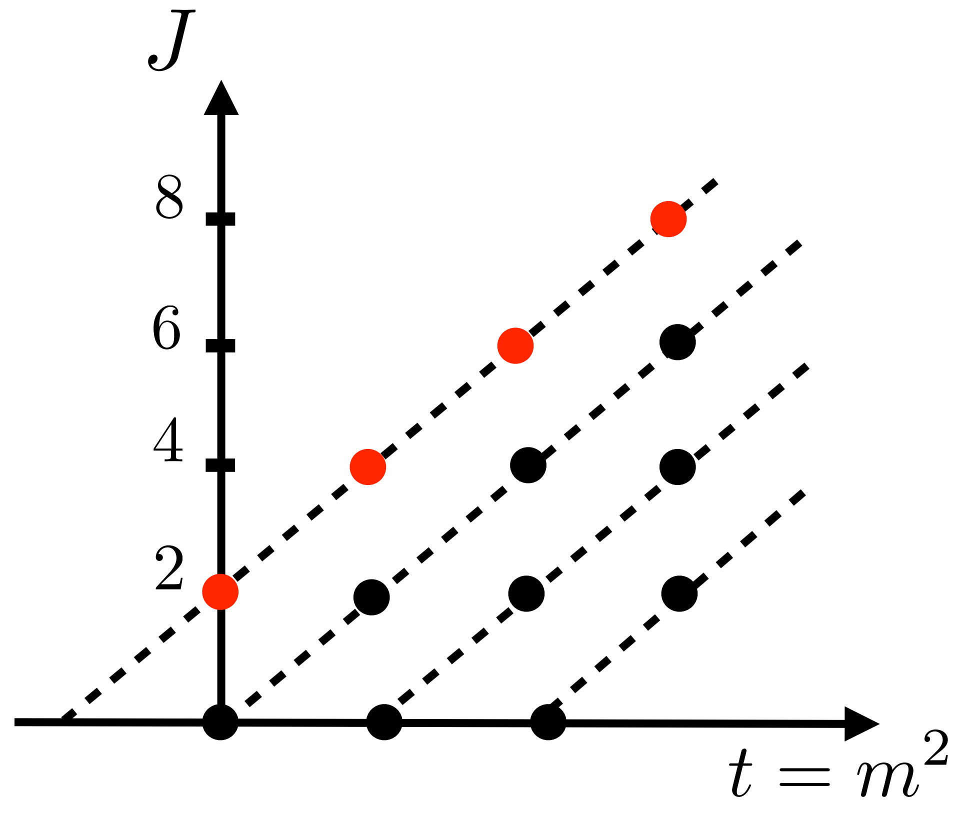
$$\sum_J \to \int_C \frac{dJ}{2\pi i} \frac{\pi}{\sin(\pi J)}$$



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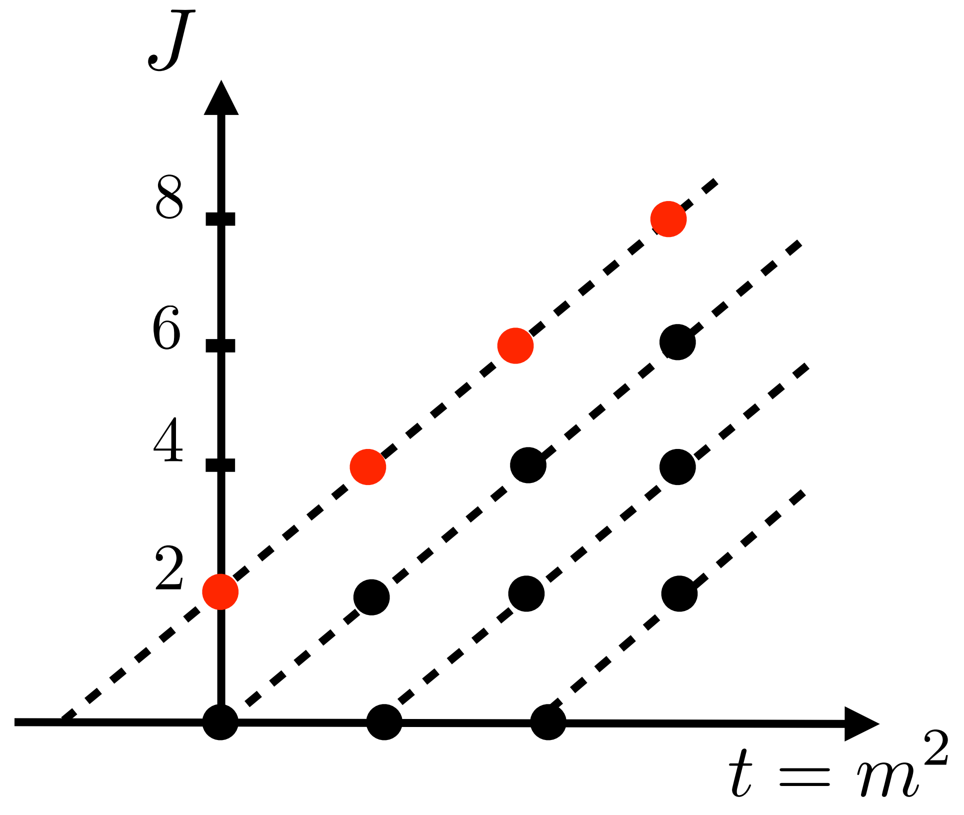
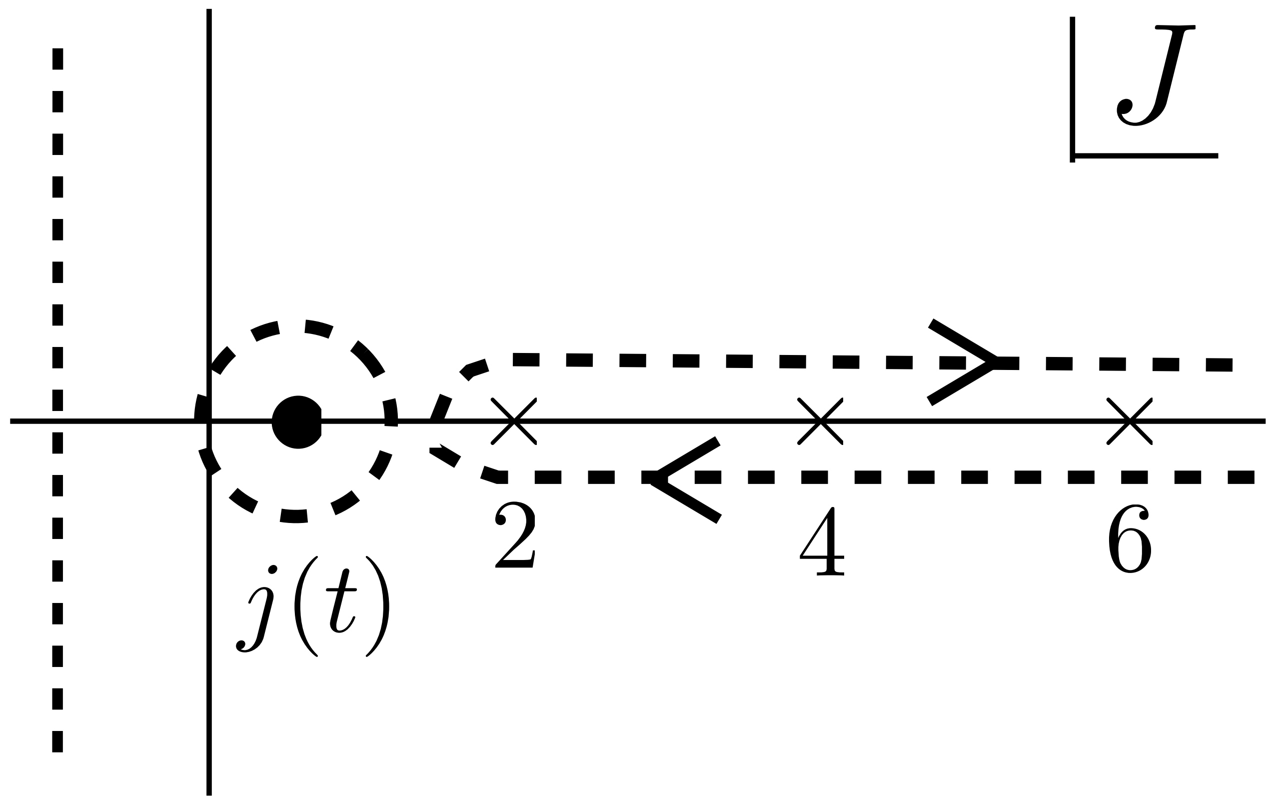


- Pick leading pole

$$a_J(t) \approx -\frac{j'(t)\, r(j(t))}{J - j(t)}$$



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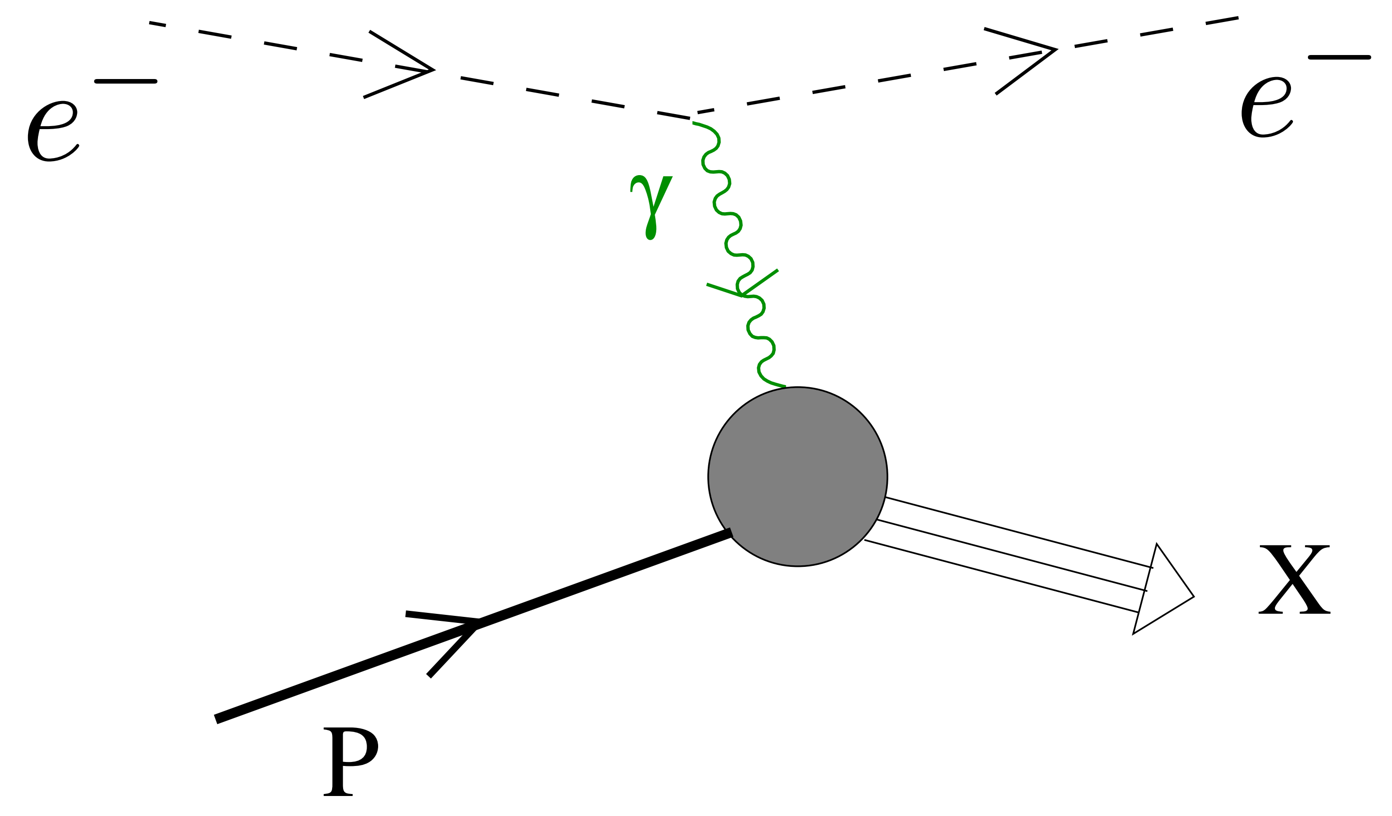
Deep Inelastic Scattering (DIS)

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



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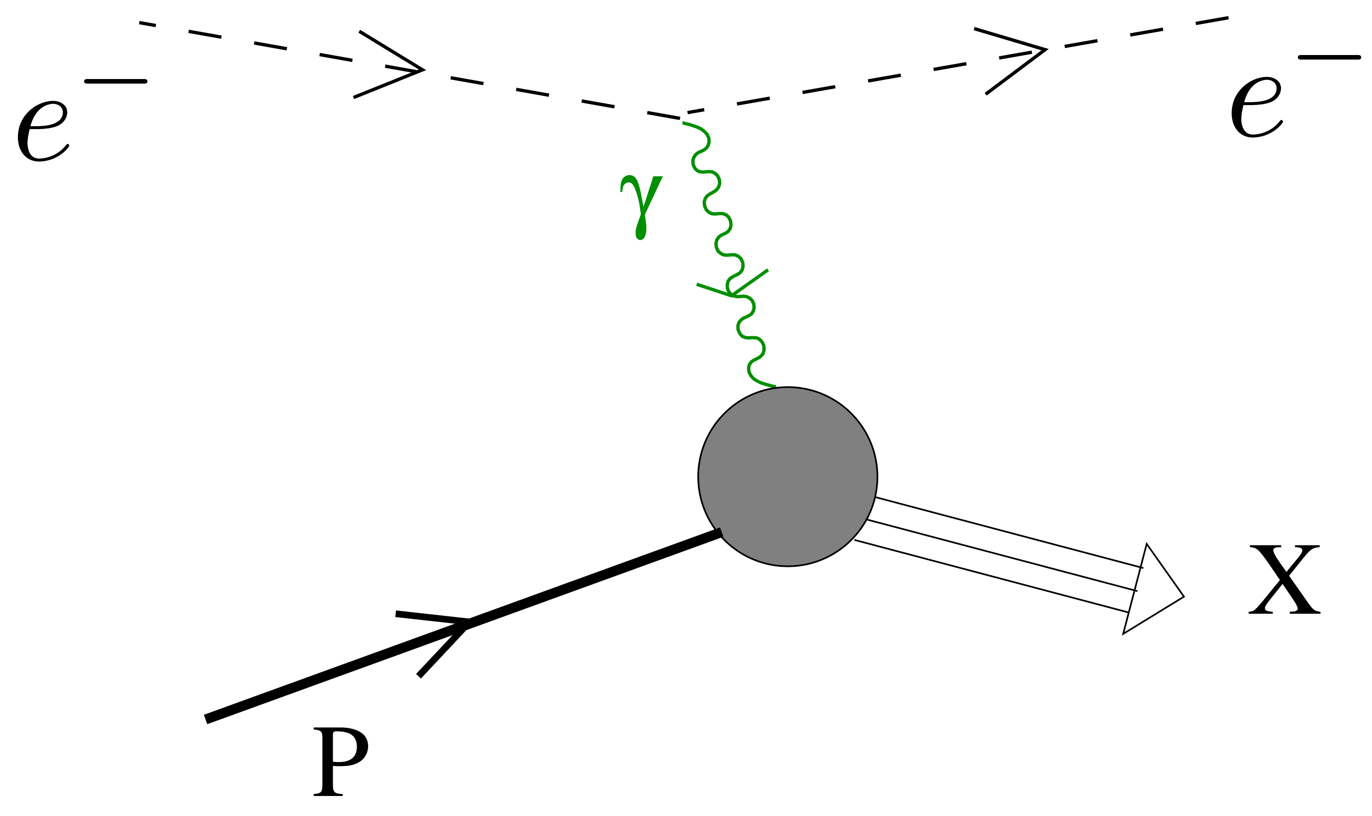

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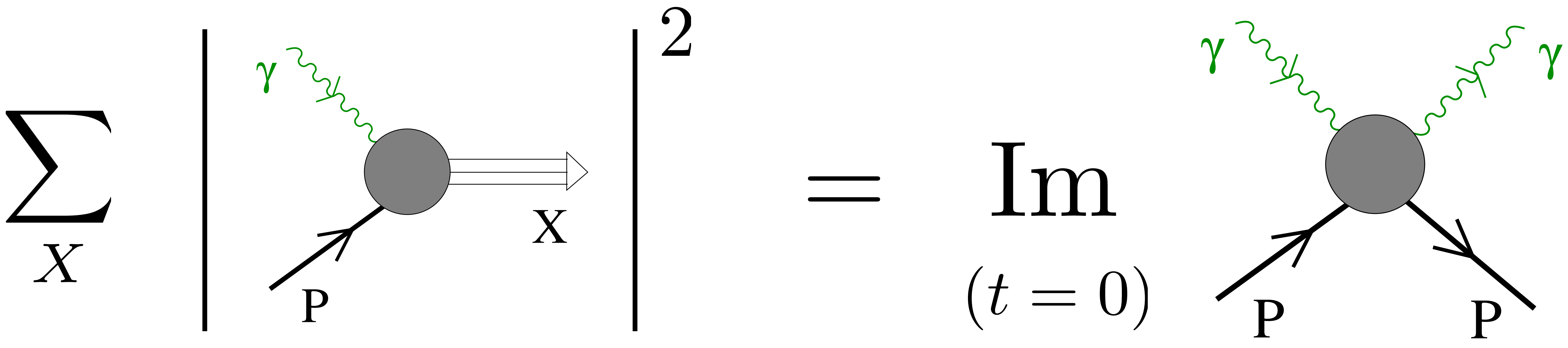

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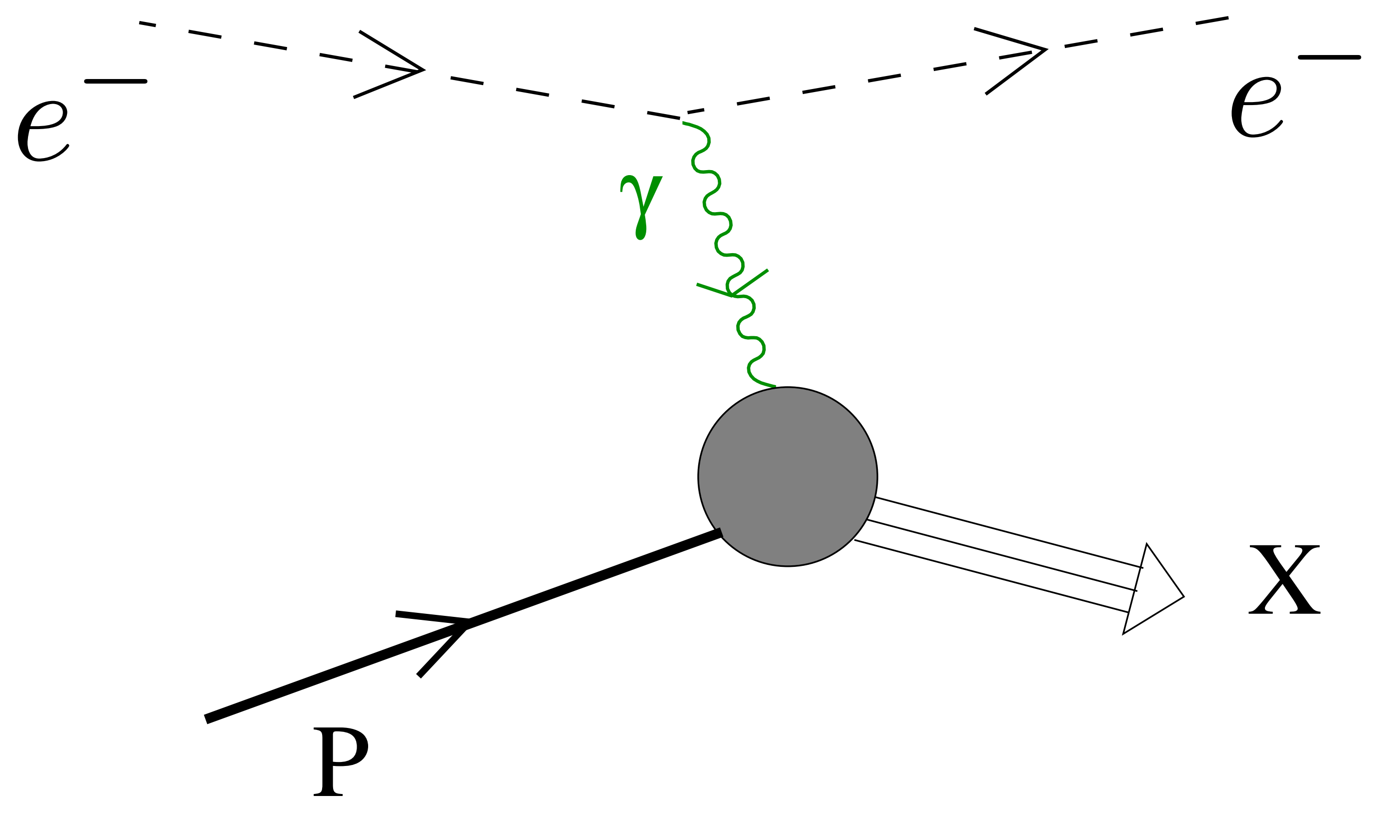

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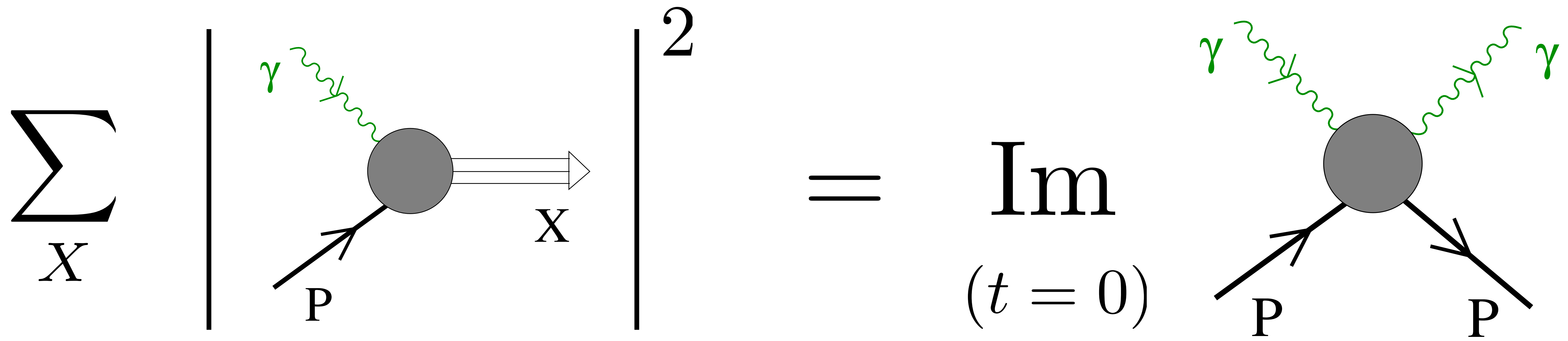
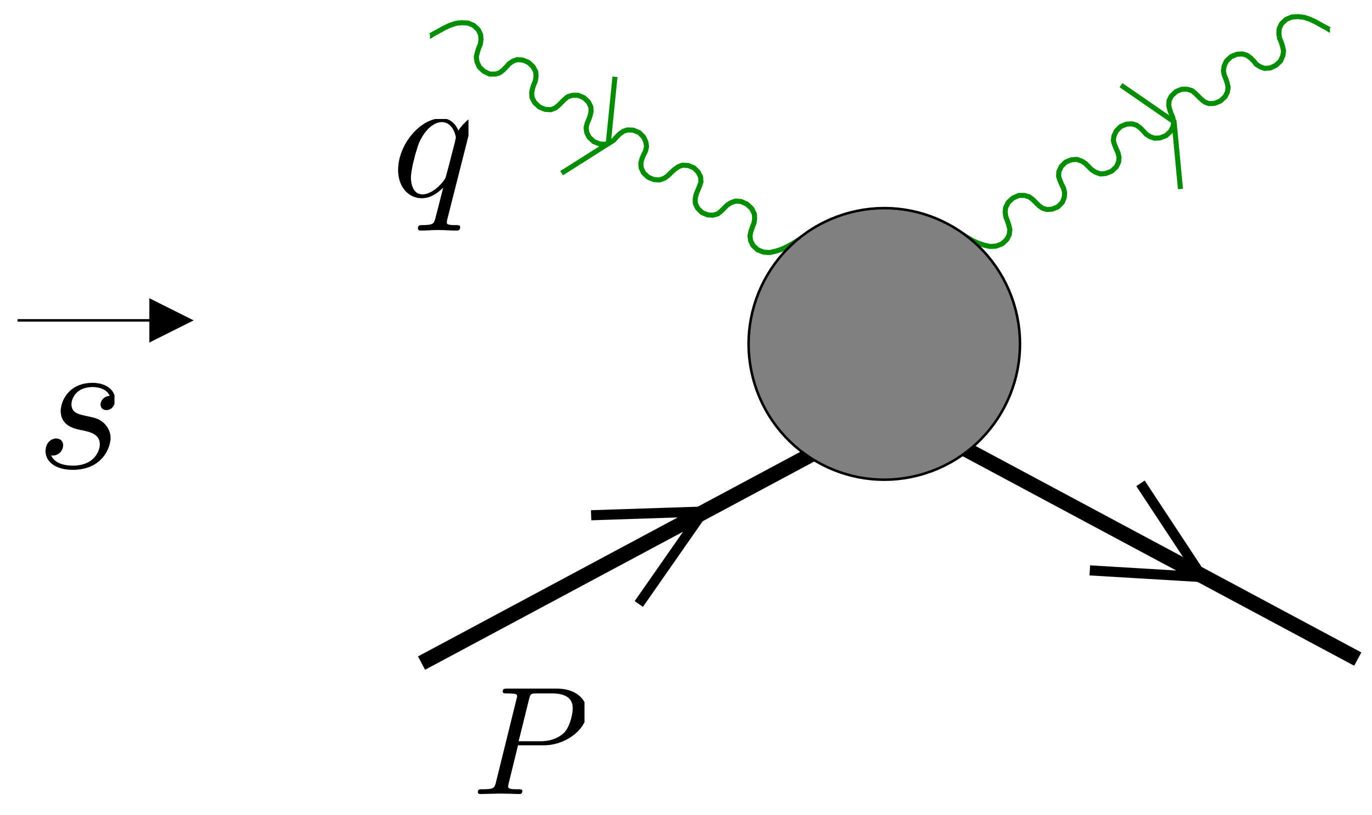


- Hadronic tensor

$$W^{ab}(x, Q, t) = i \int d^4y\, e^{iq\cdot y} \langle P | T\{ j^a(y)\, j^b(0) \} | P' \rangle$$



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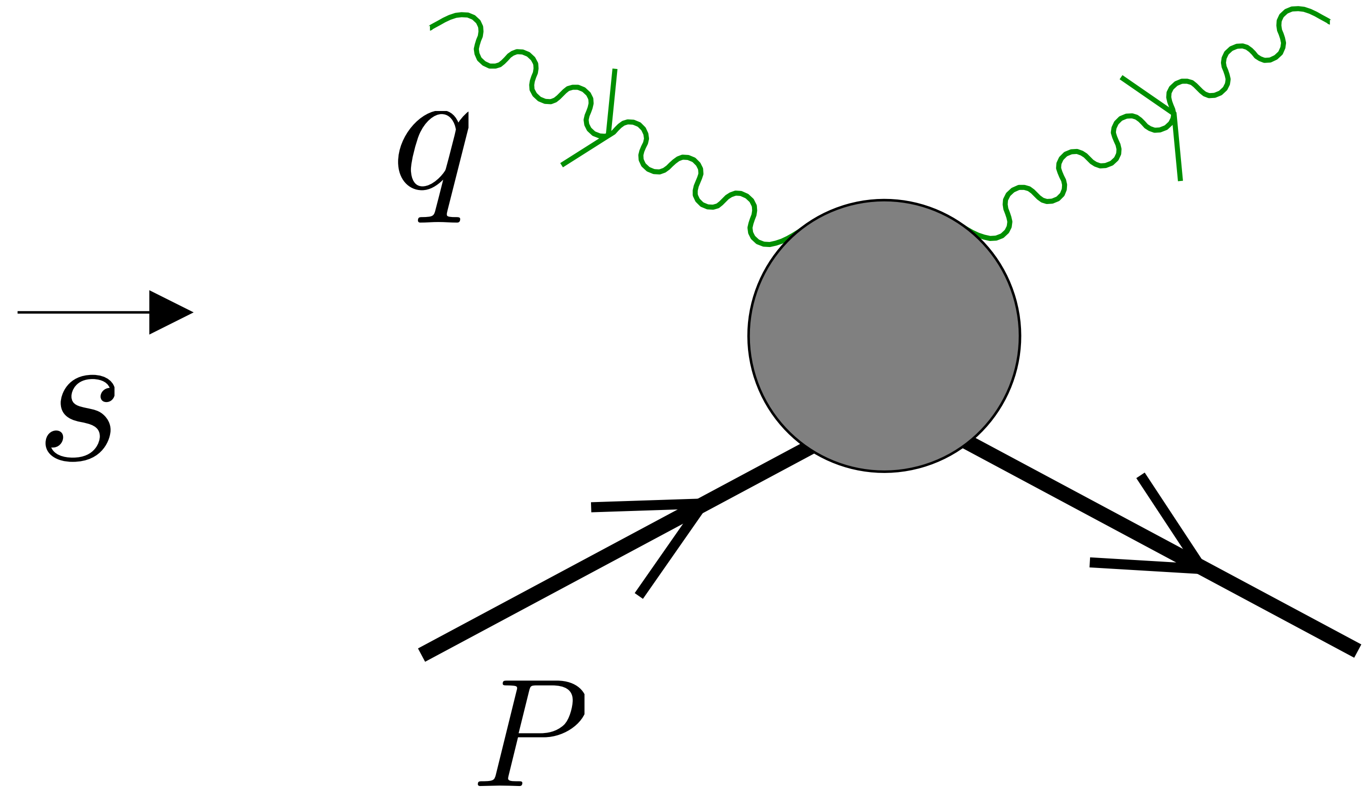

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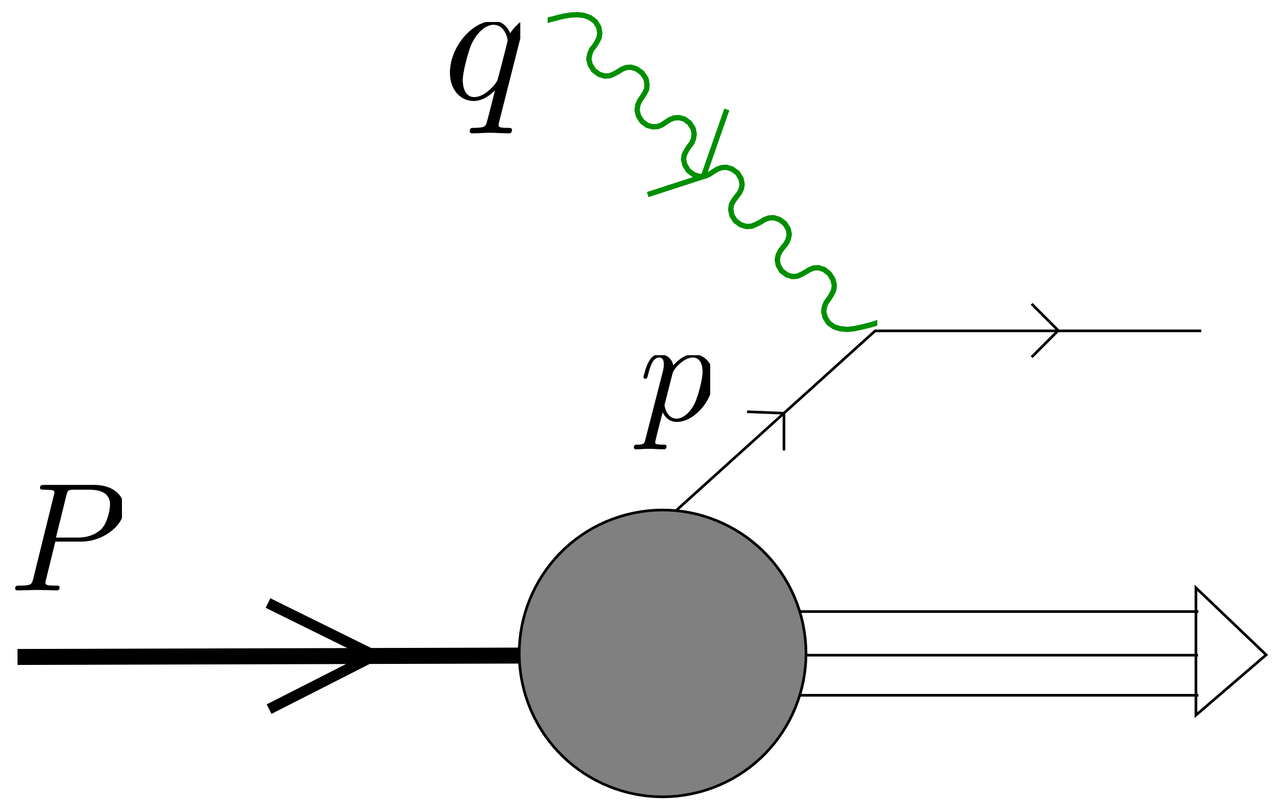

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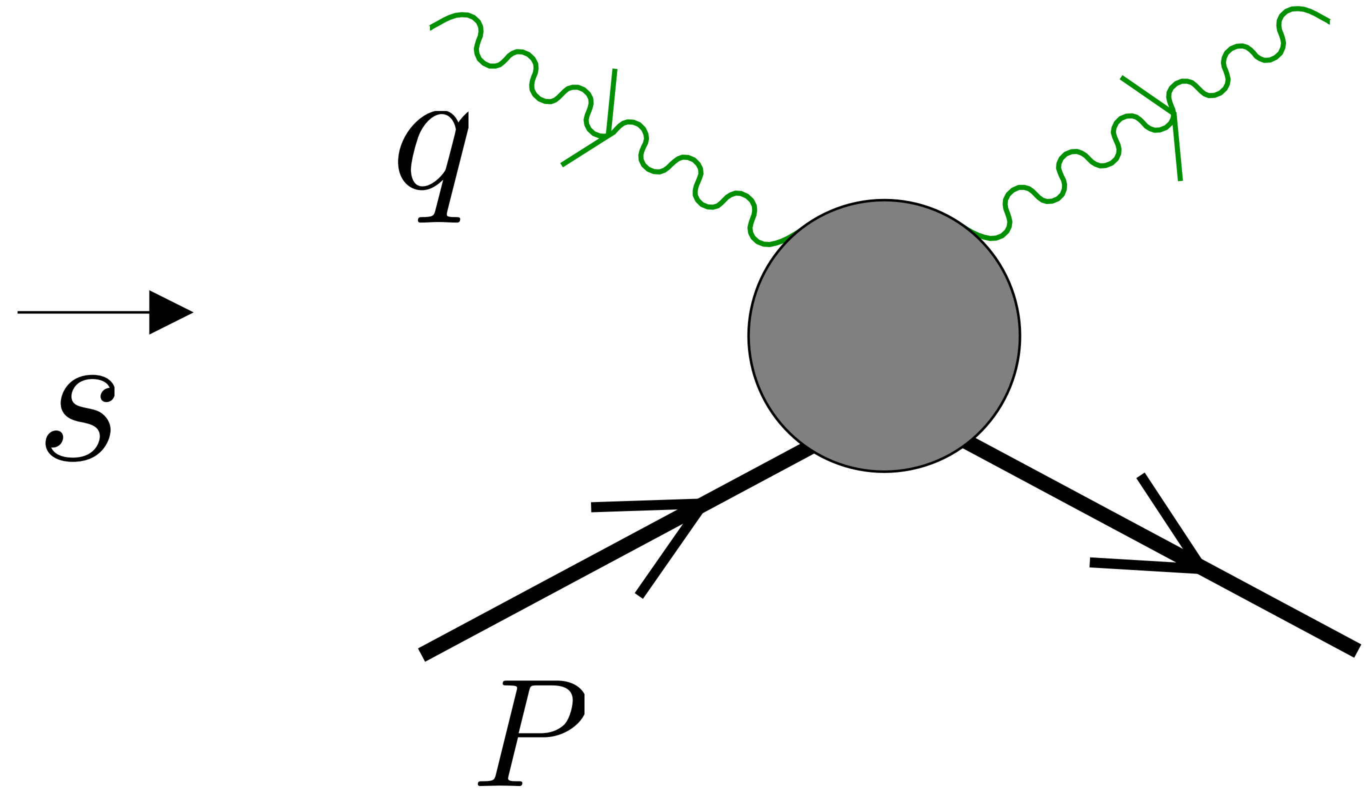

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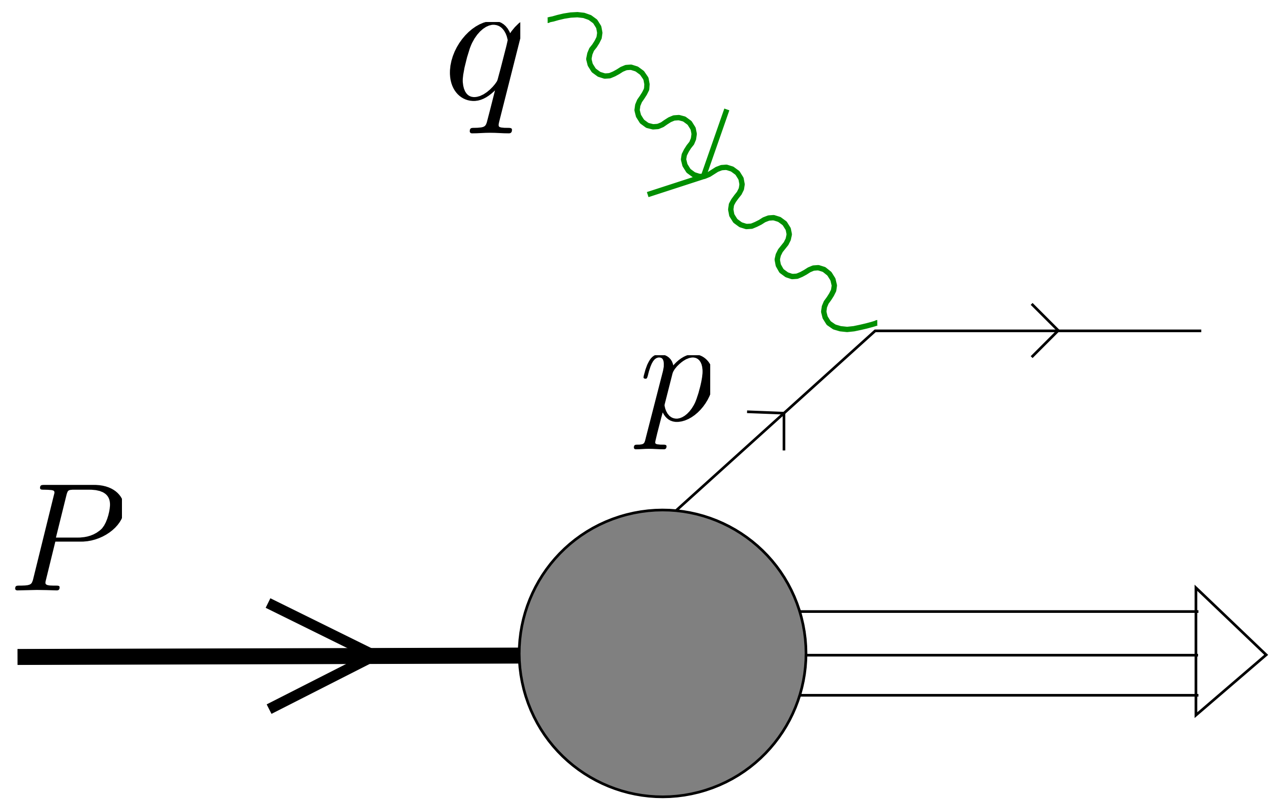

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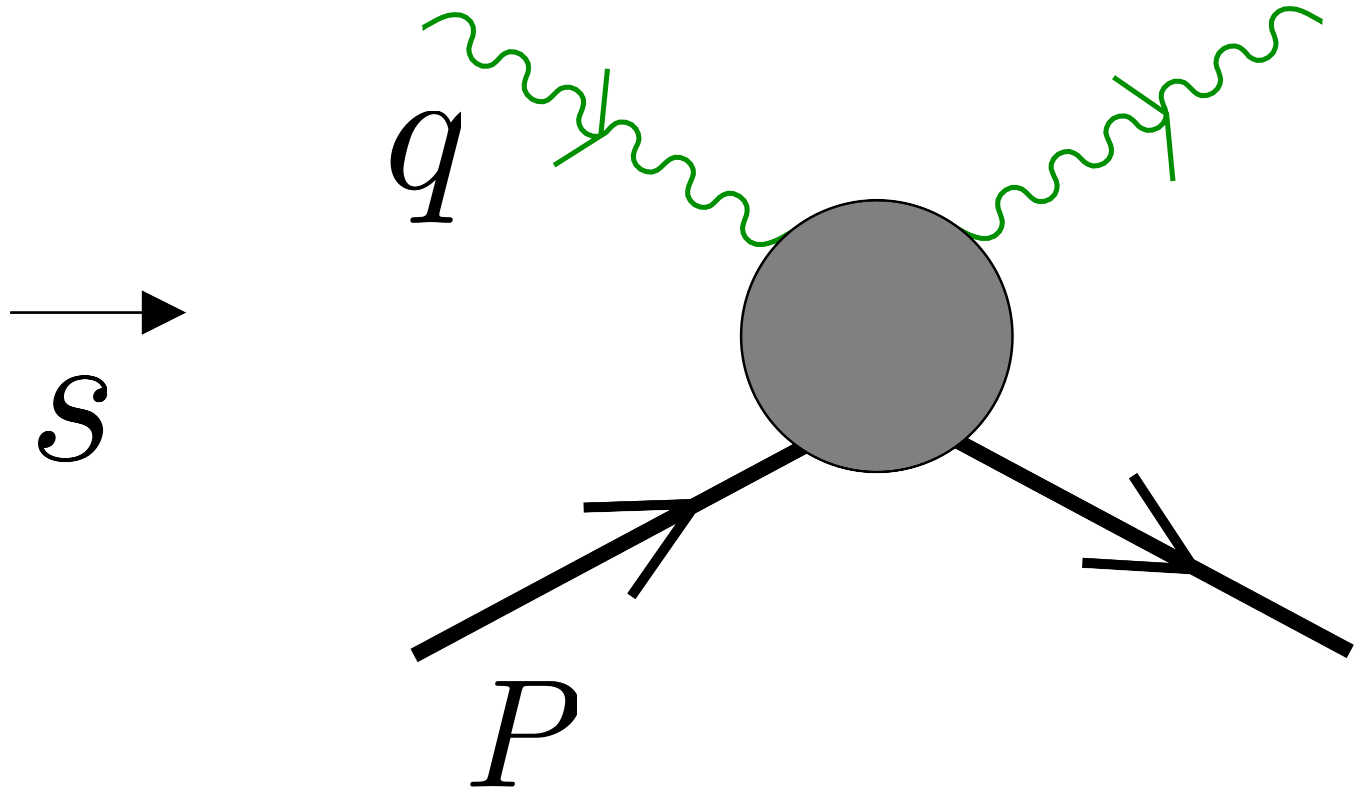
large s $\Rightarrow$ small x



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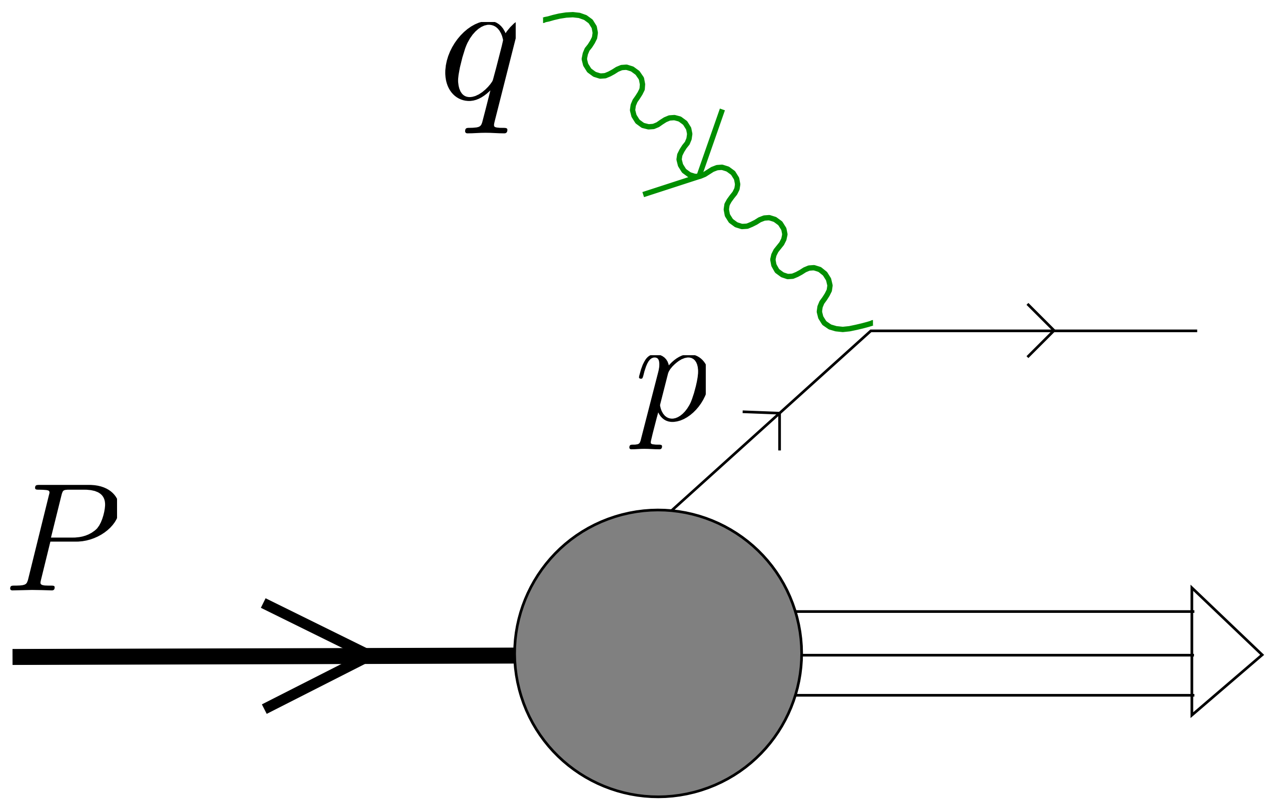
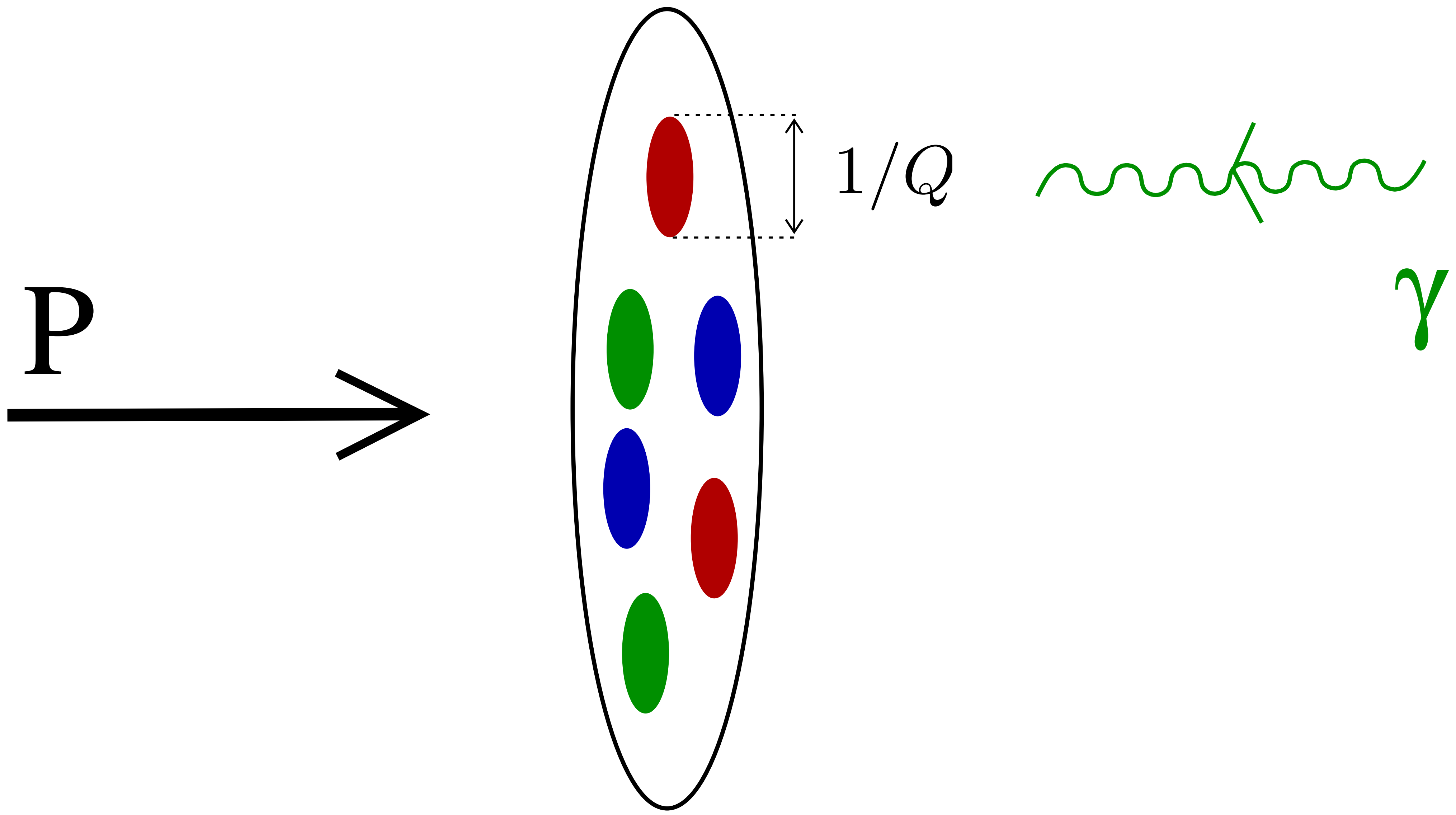
- Bjorken x
- Transverse resolution $1/Q$





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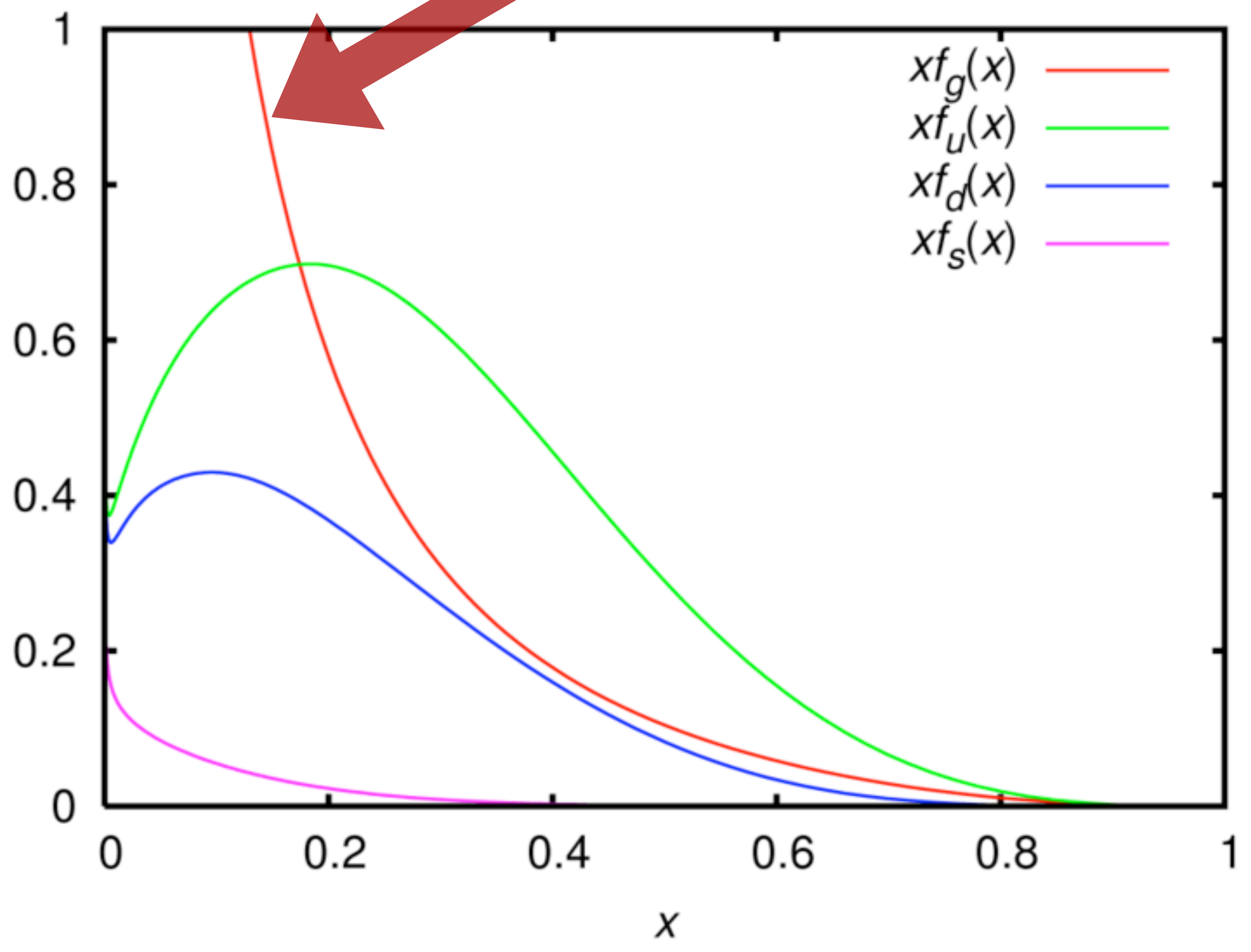
$f_i\left(x, Q^2\right)$

Gluons dominate at small x



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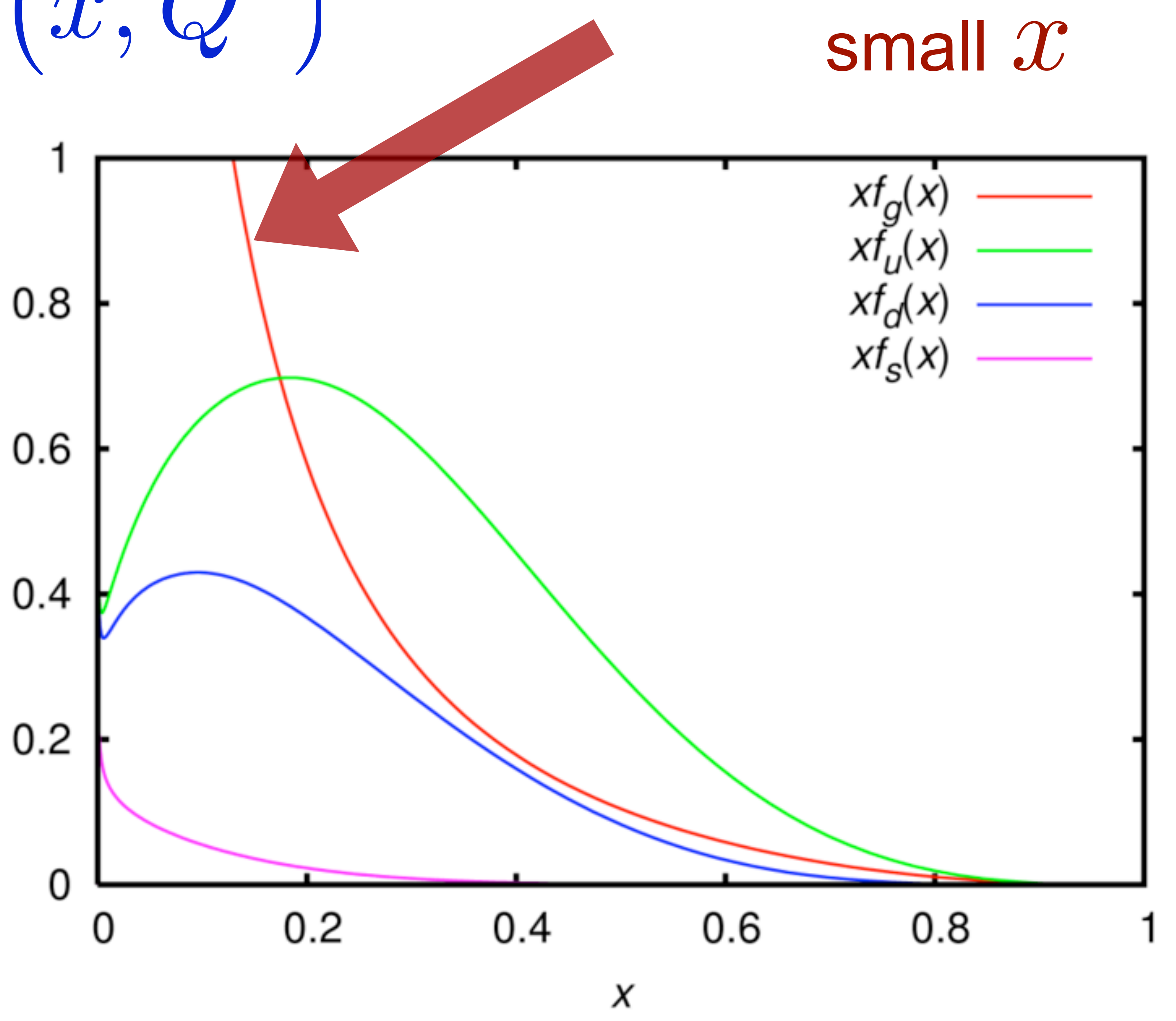
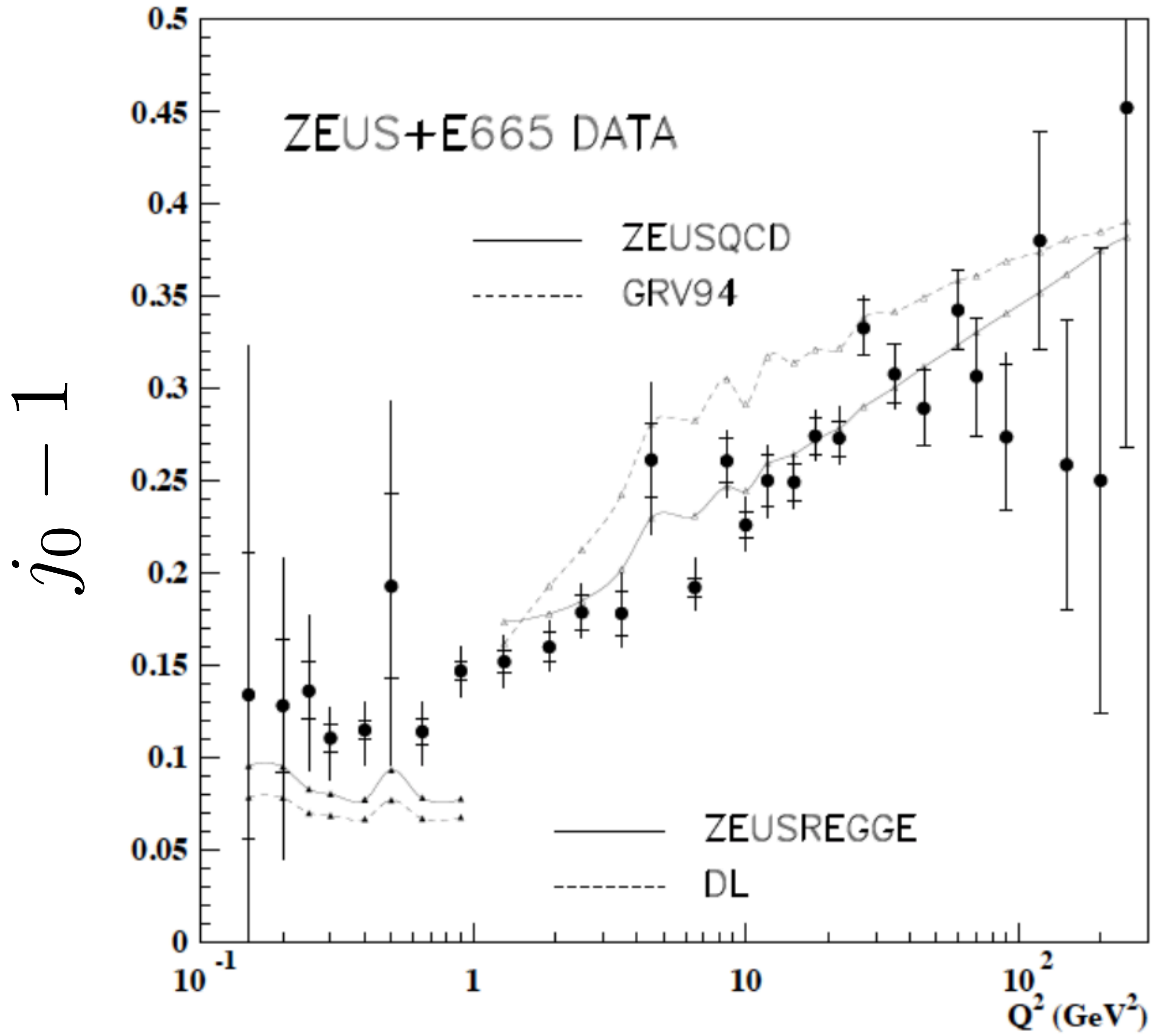


Effective slop varies with Q



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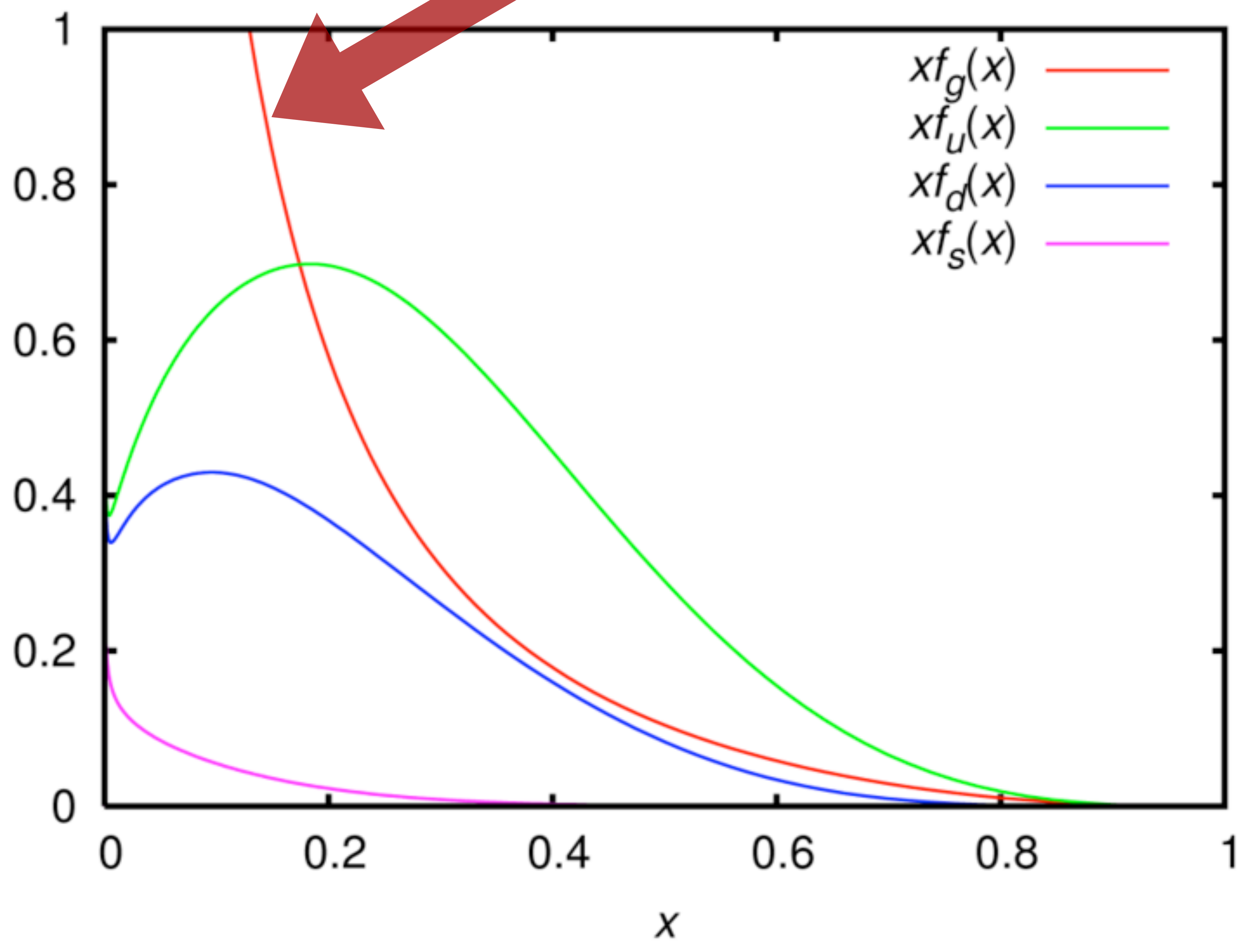

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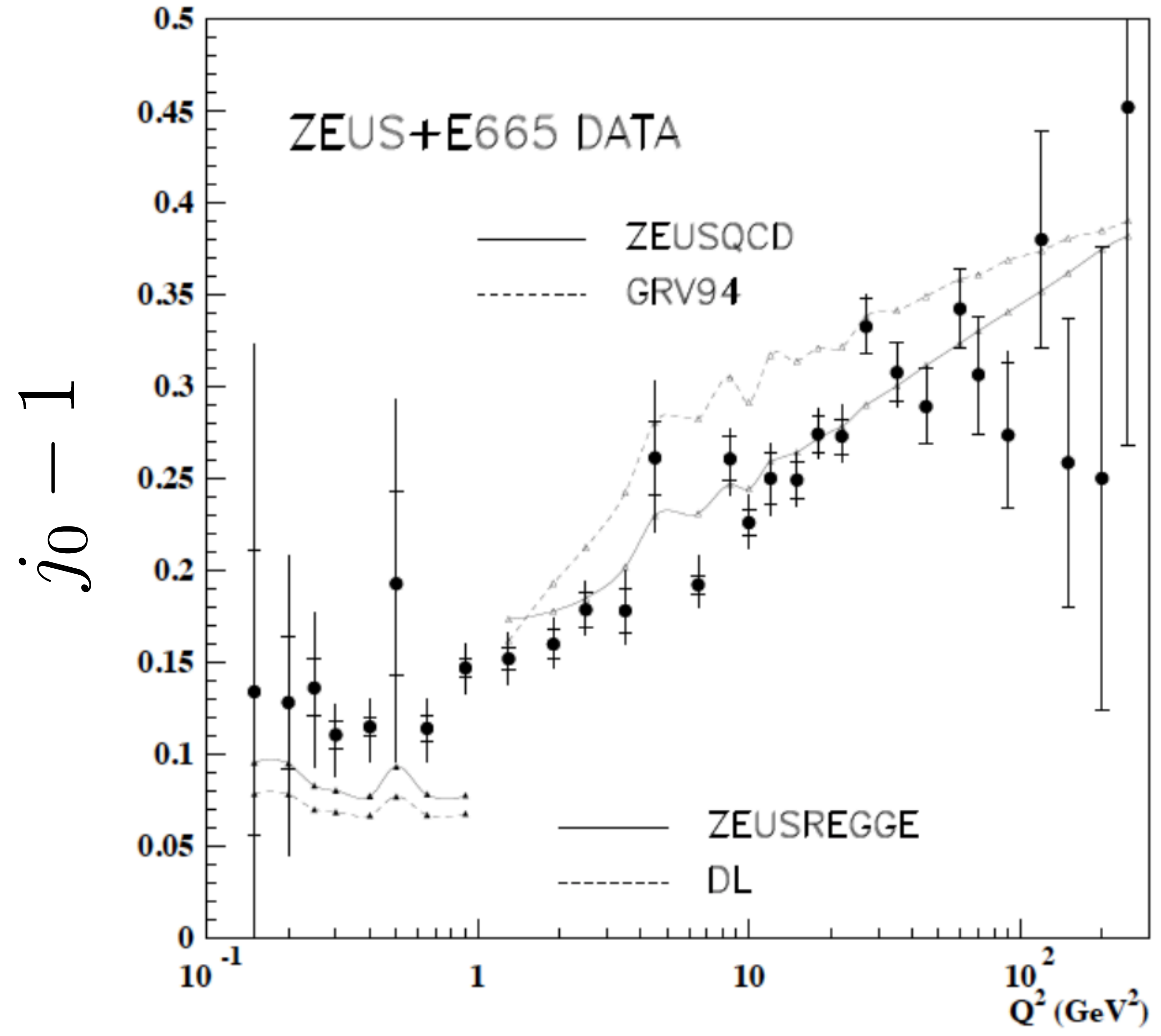

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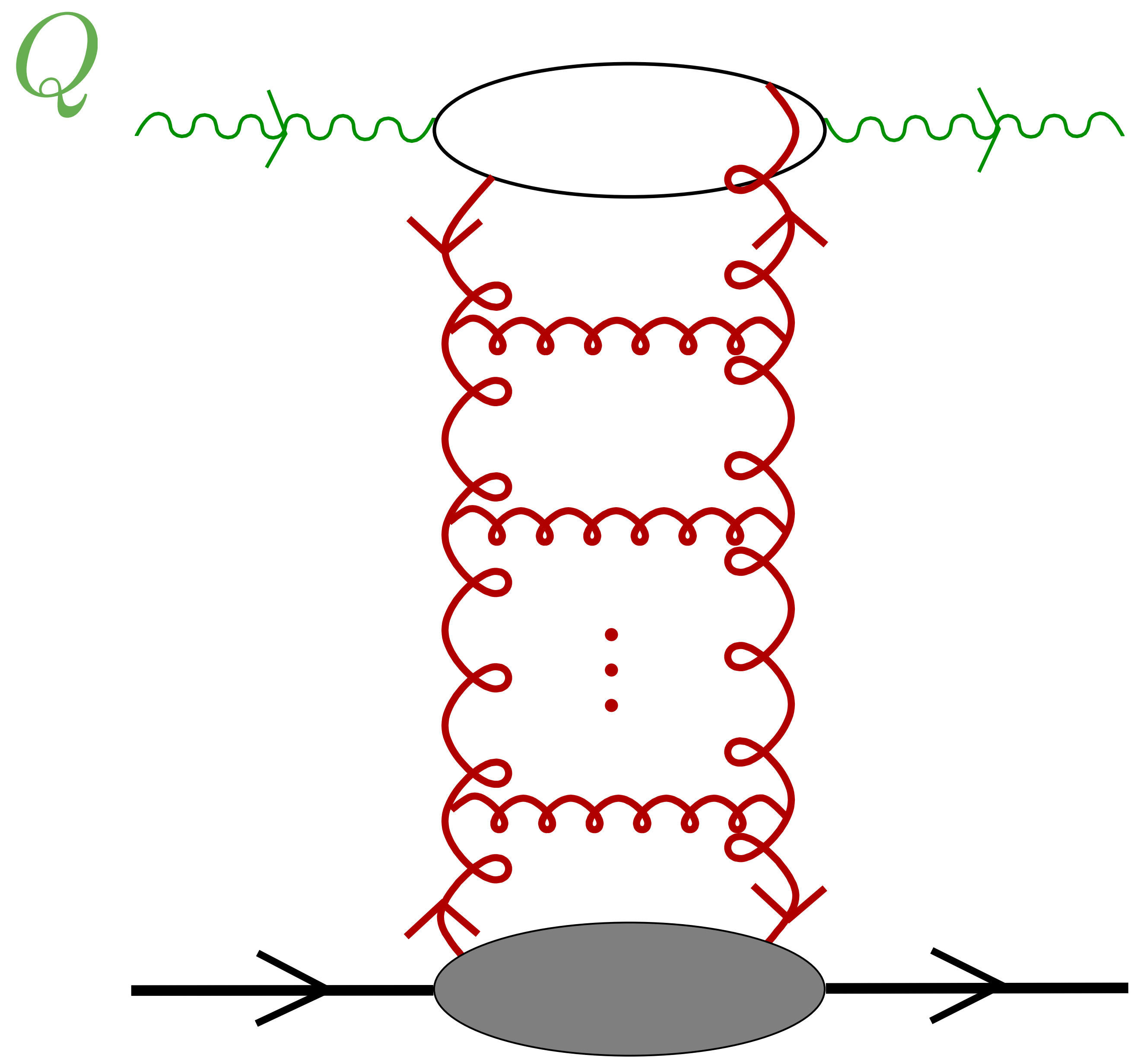
Is it the same Regge trajectory? One or two pomerons (soft and hard)?

Hard Pomeron [BFKL - Balitsky, Fadin, Kuraev & Lipatov]

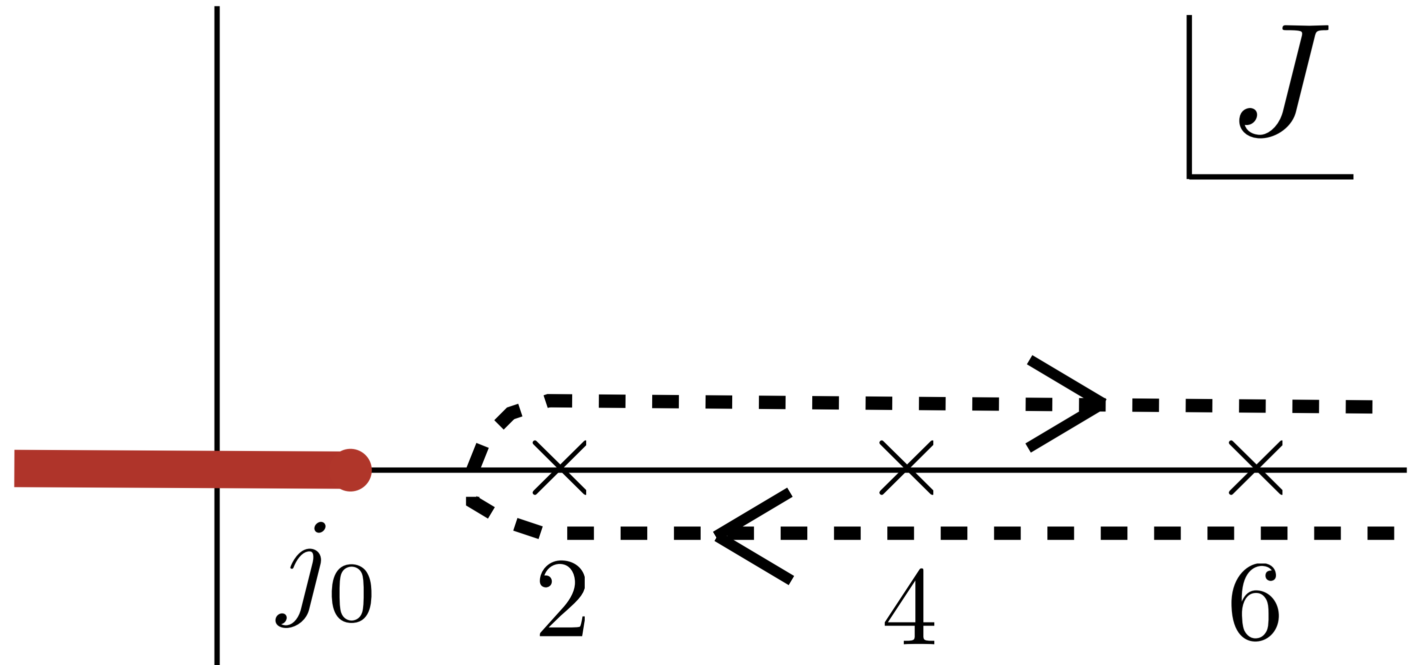


Two gluon exchange with ladder interactions

Resums $(\alpha_s \ln 1/x)^n$ contributions

Valid for hard probes $Q \gg \Lambda_{QCD}$ (conformal limit)

Hard pomeron is a cut in J-plane



$$j_0 = 1 + \frac{12 \ln 2}{\pi} \alpha_s = 1 + 2.65\, \alpha_s$$

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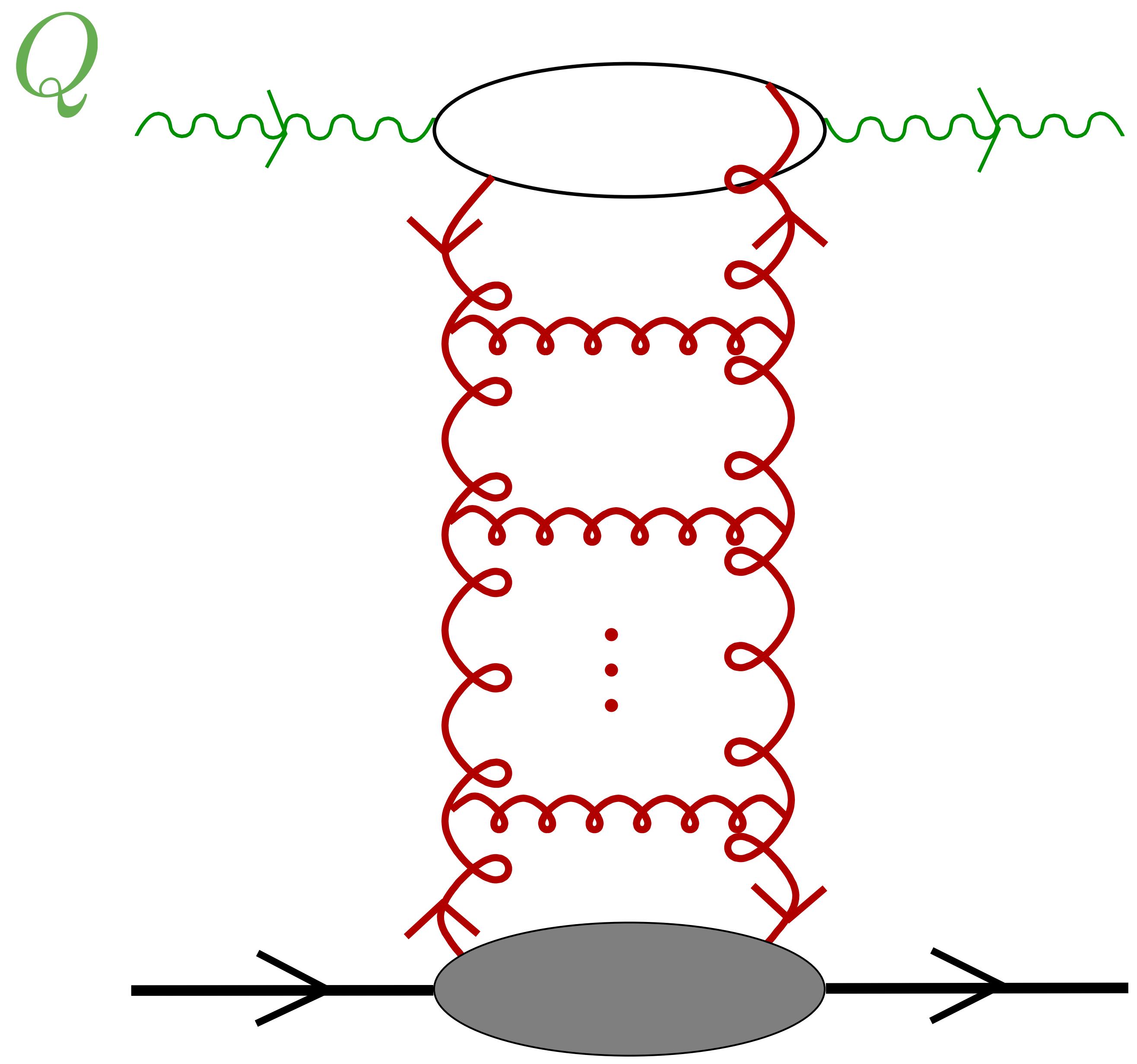

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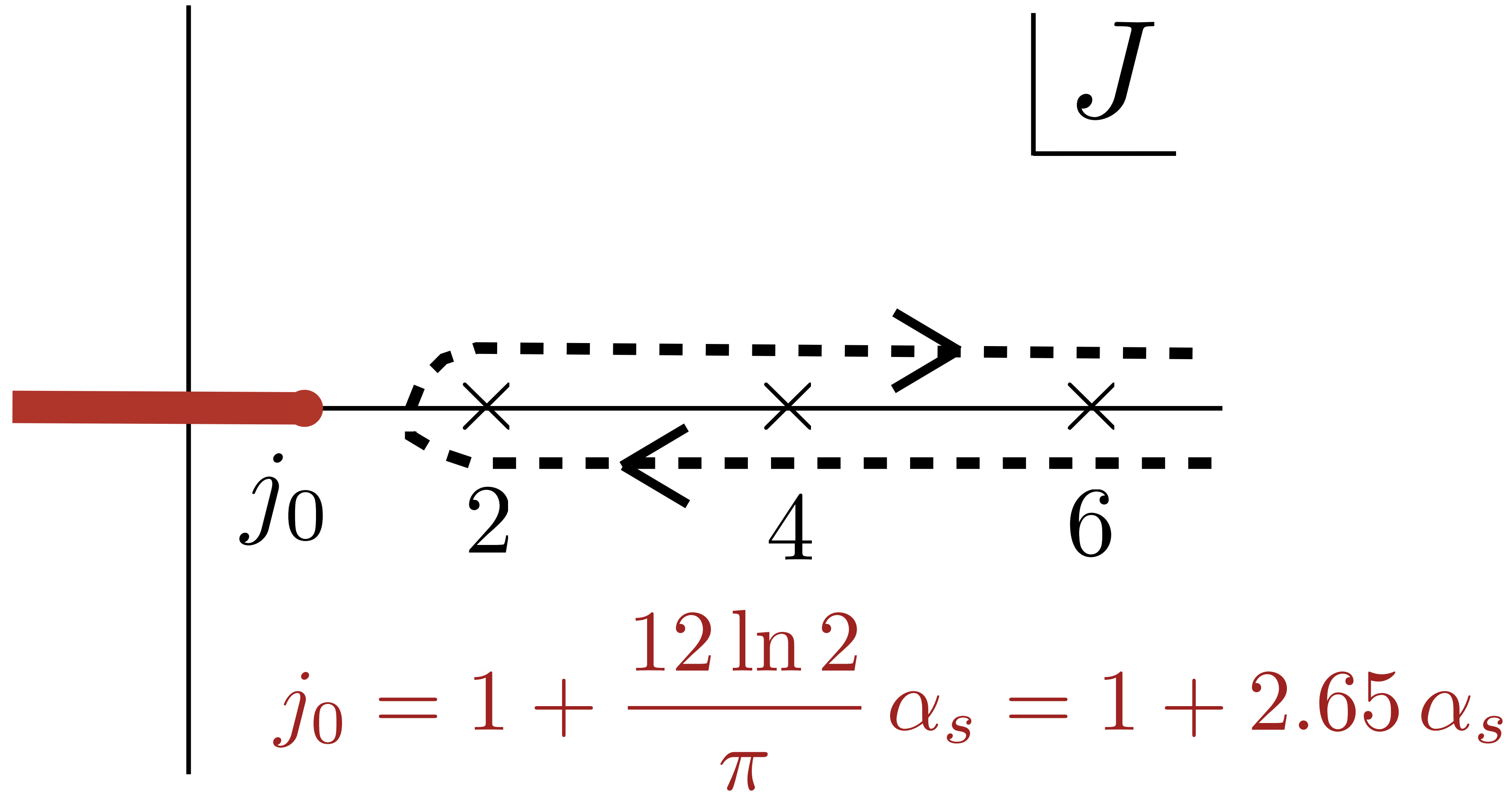

- Breaking conformal symmetry, explains well DIS data outside the confining region $Q > \Lambda_{QCD}$ [Kowalski, Lipatov, Ross, Watt 10]

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Eventually growth slows down (multi-pomeron, eikonal resummation)

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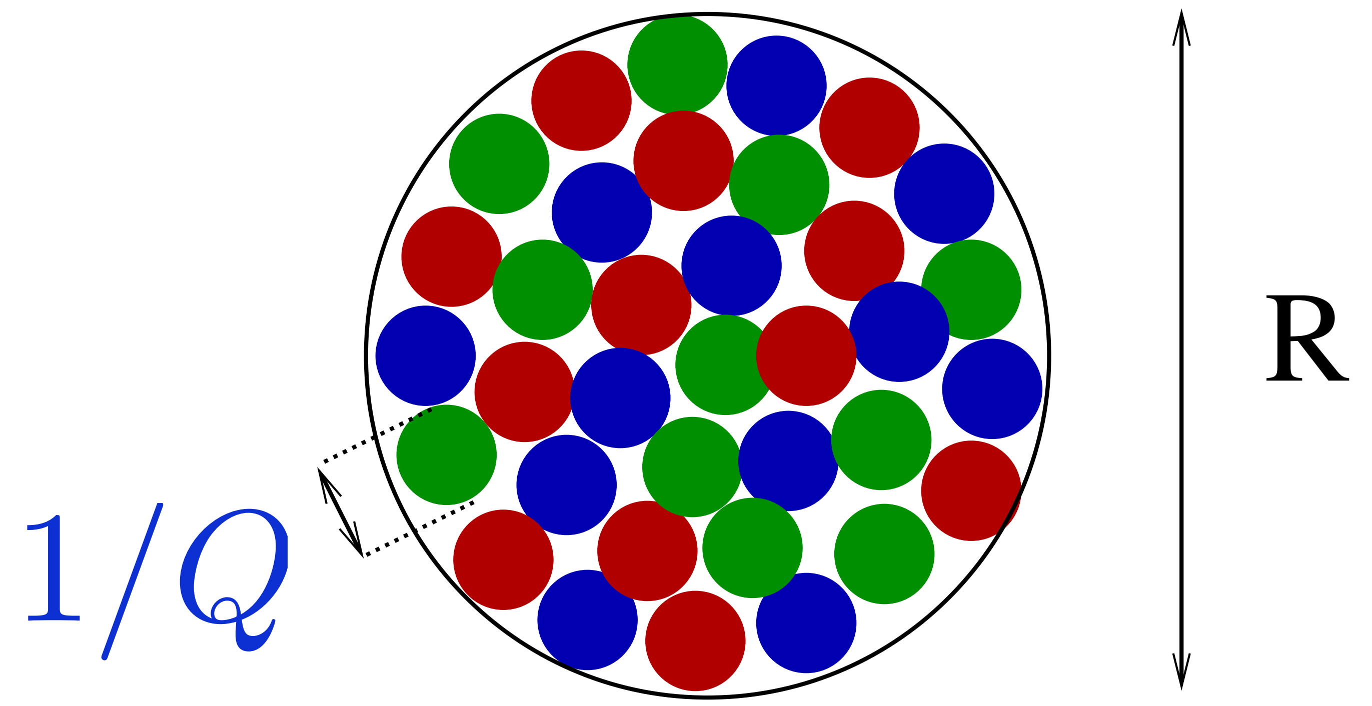

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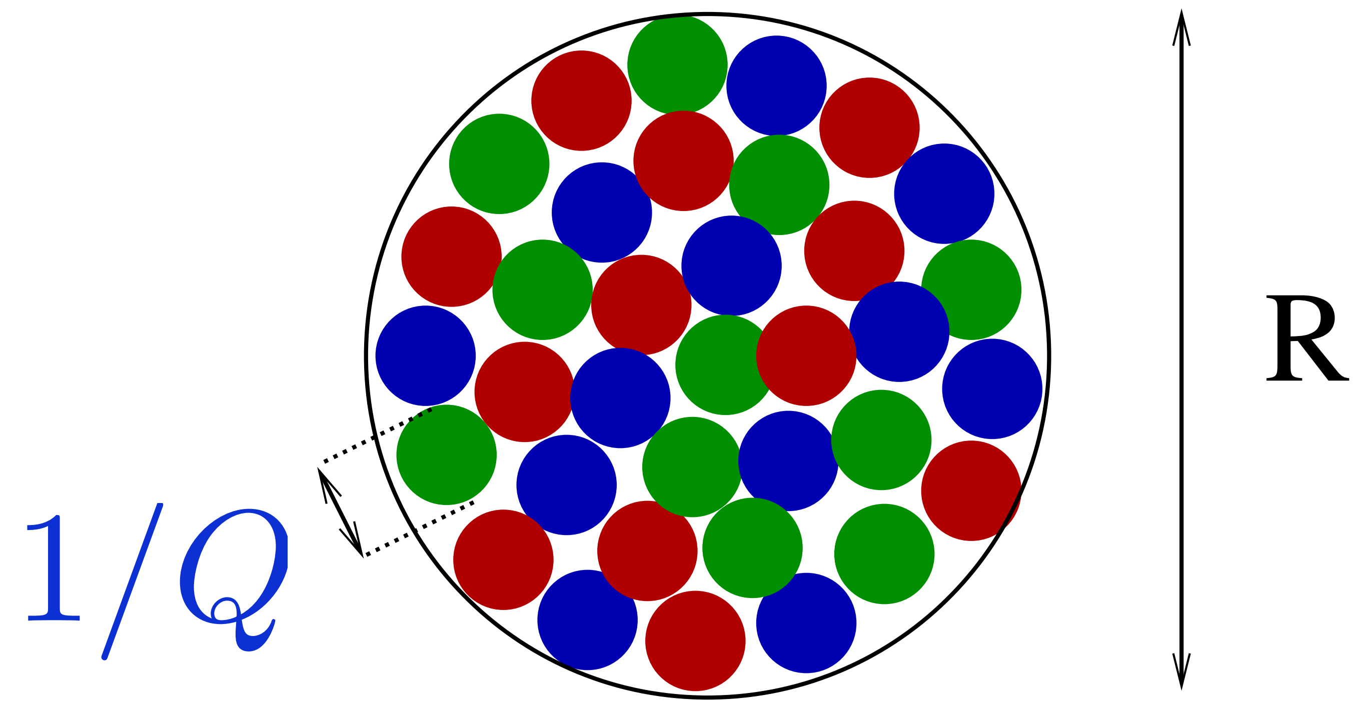

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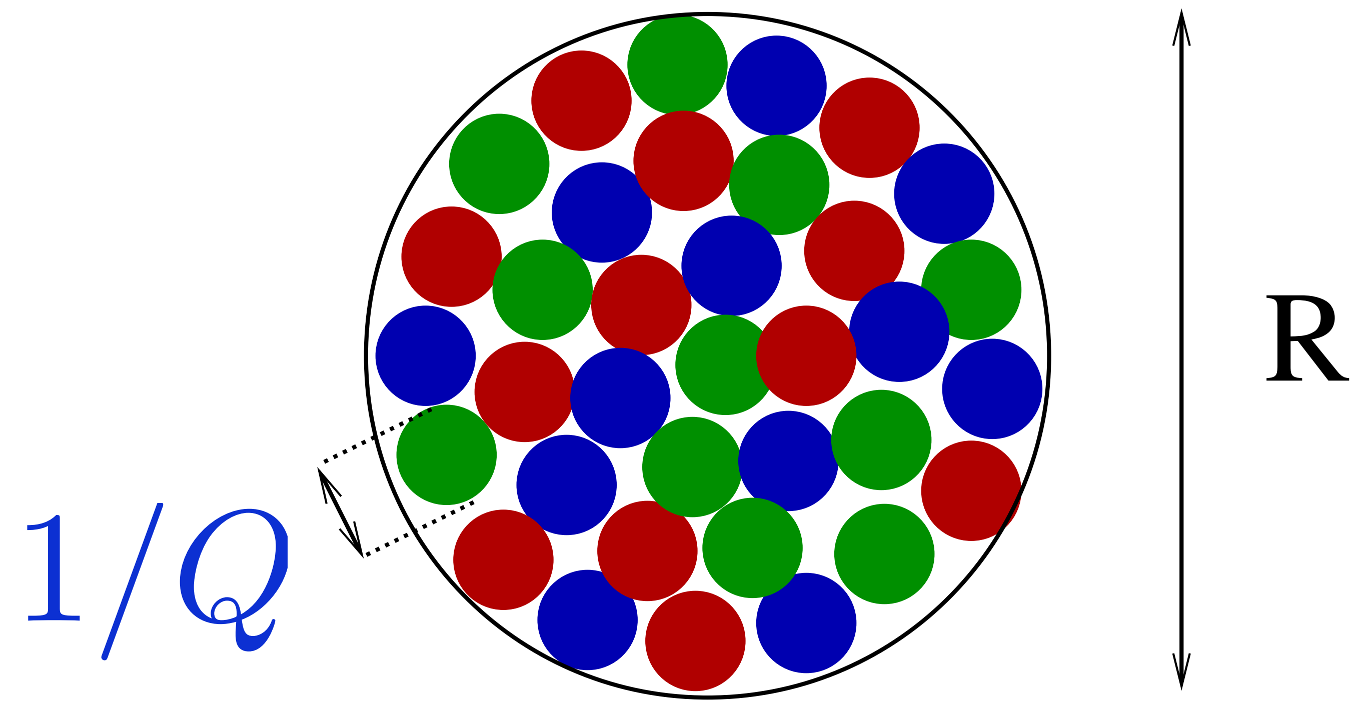

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Graviton Regge trajectory dual to pomeron trajectory

[Brower, Polchinski, Strassler, Tan 06]

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- Once dual description of pomeron well understood, can apply to low x physics in QCD starting from holographic QCD description, including confining region.

Regge Kinematics in CFTs [Cornalba, MSC, Penedones, Schiappa 06]

- Consider correlator with EMG current $j^a = \bar{\psi}\gamma^a\psi$ and scalar operator $\mathcal{O}$

$$A^{ab}(y_i) = \langle j^a(y_1)\, \mathcal{O}(y_2)\, j^b(y_3)\, \mathcal{O}(y_4)\rangle$$

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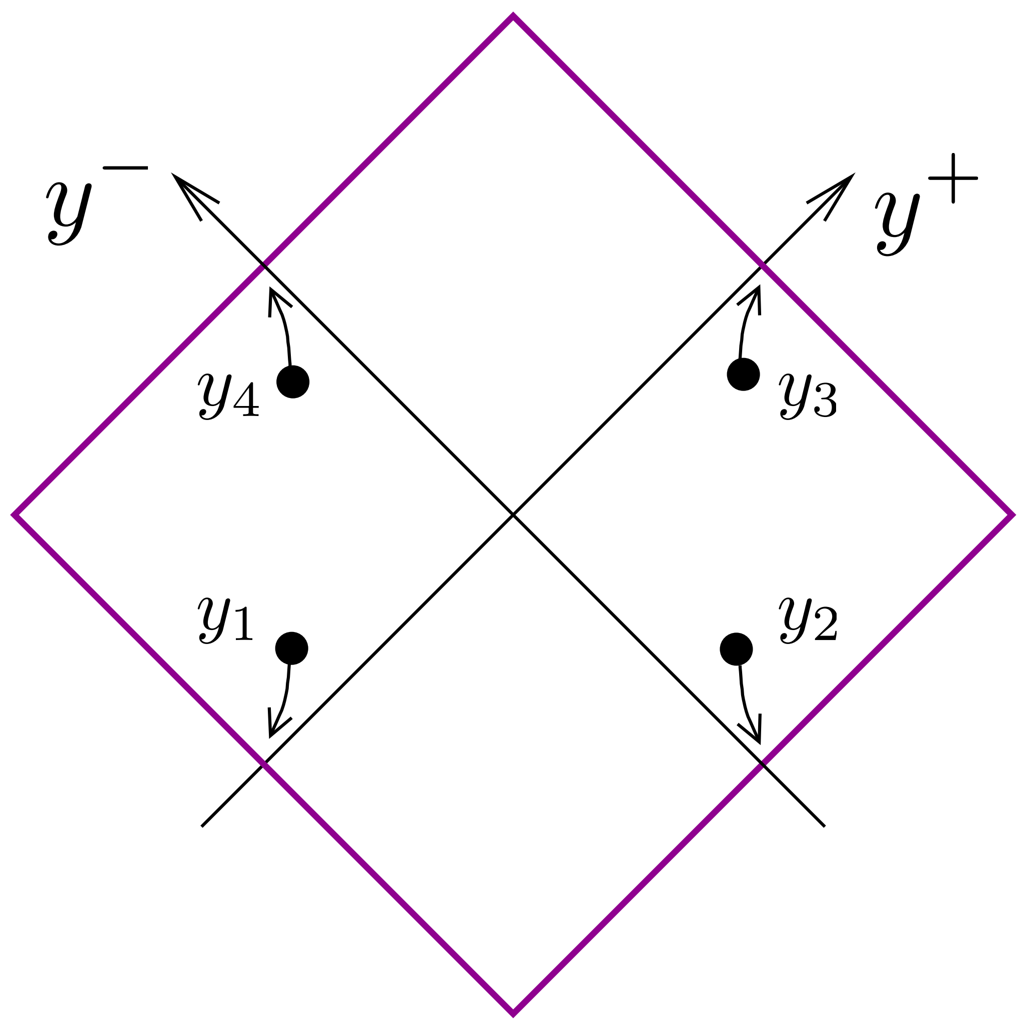
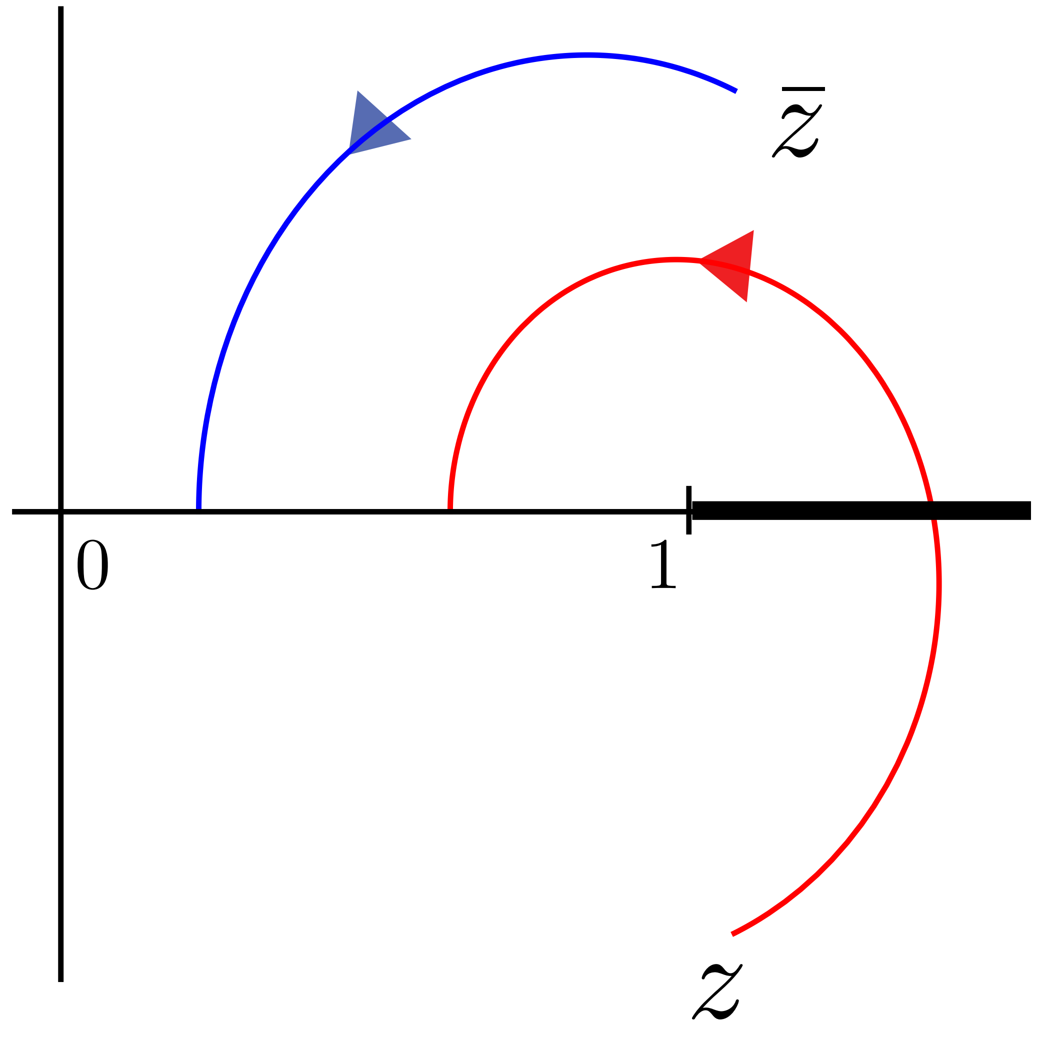
- Regge kinematics is Lorentzian. Analytically continue from Euclidean theory ($\bar{z} = z^*$) to $z, \bar{z}$ on real axis.





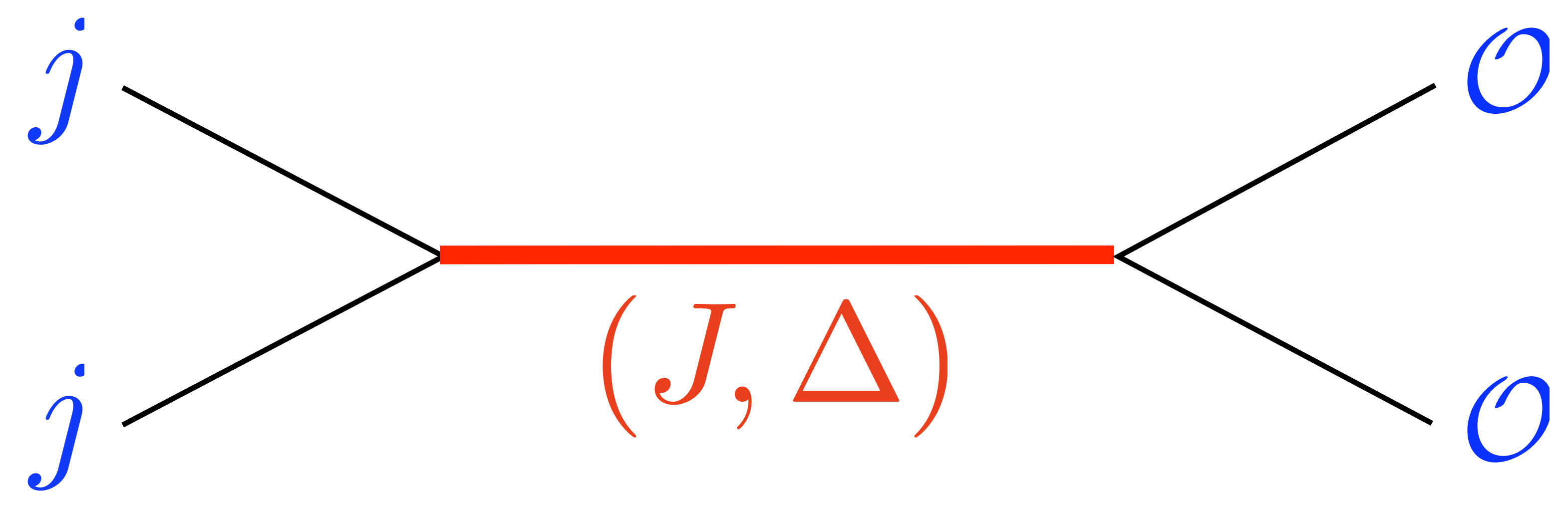
- Regge limit

$$z, \bar{z} \to 0 \quad \text{with} \quad \frac{z}{\bar{z}} \quad \text{fixed}$$

Conformal Regge Theory [Cornalba 07; MSC, Penedones, Gonçalves 12]

- Expand in t-channel conformal partial waves

$$\mathcal{A}(z,\bar{z}) = \sum_k C_{13k} C_{24k}\, G_{\Delta_k, J_k}(z,\bar{z})$$



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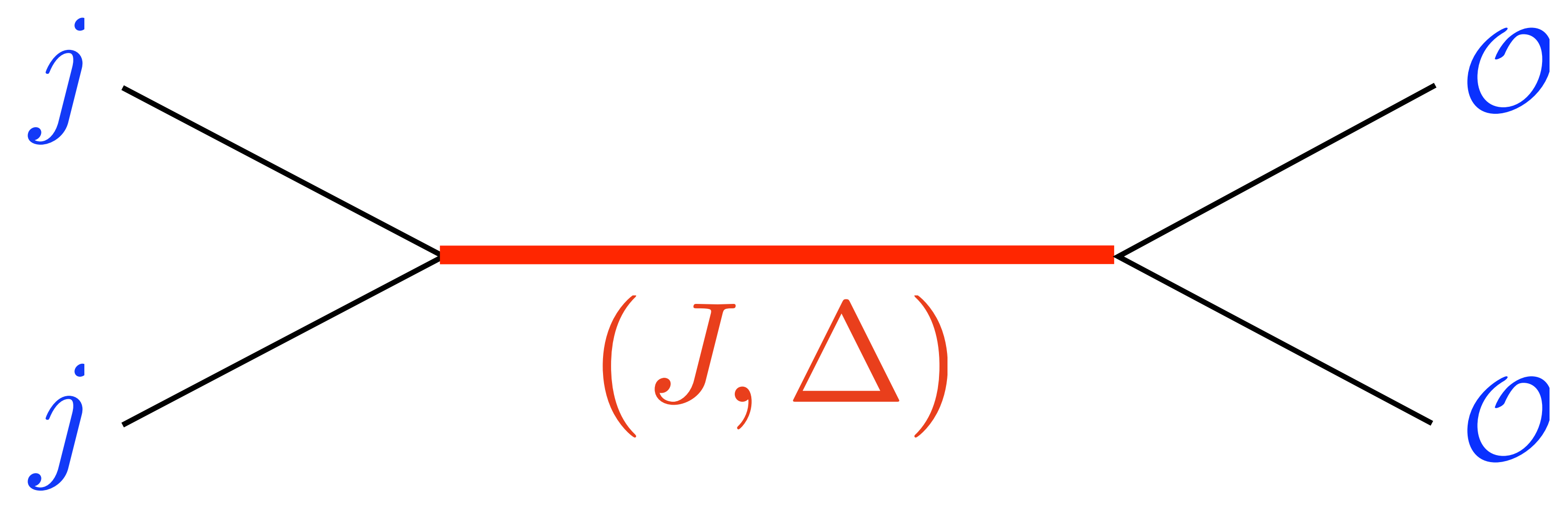

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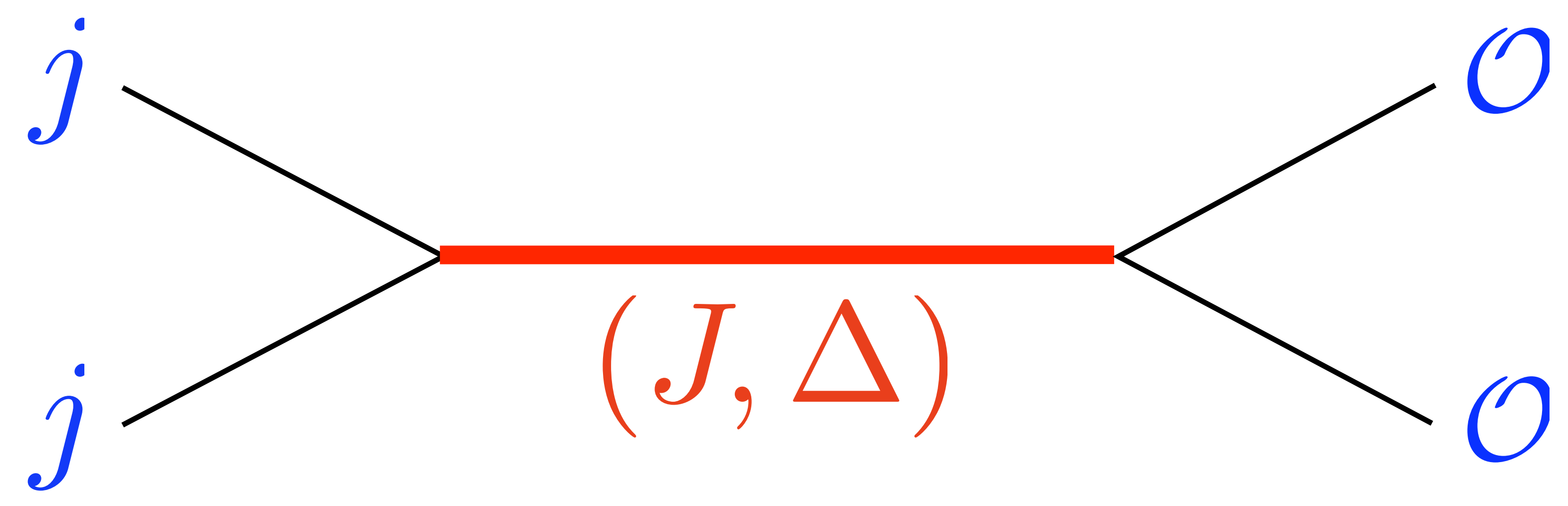

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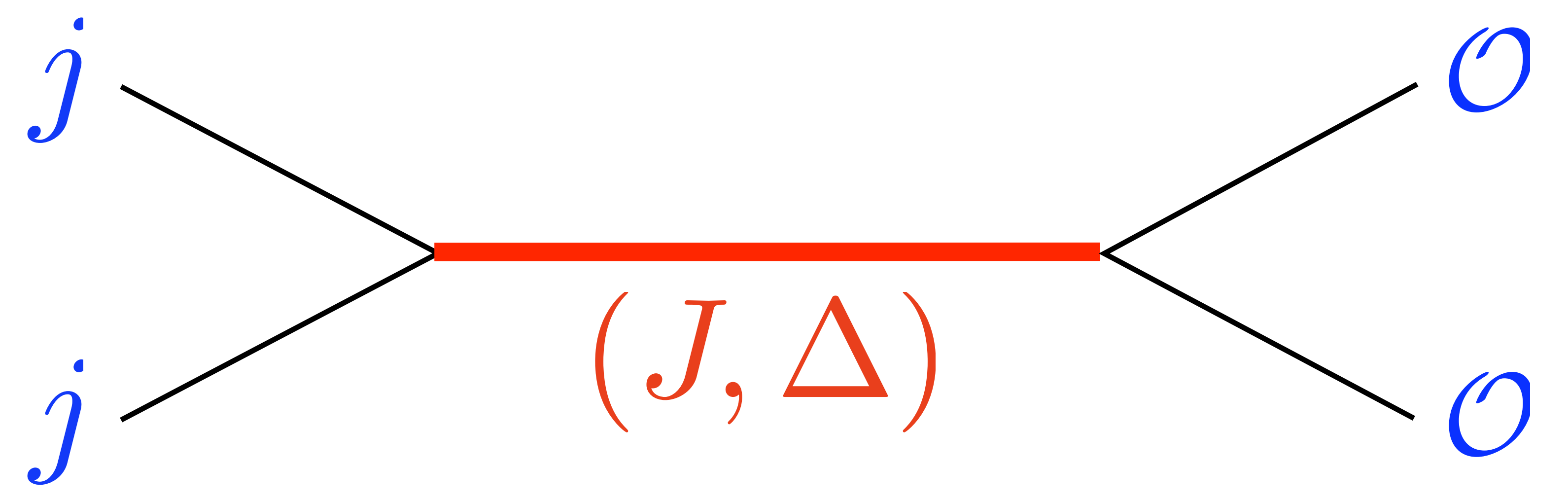
- Euclidean OPE dominated by lowest dimension $\lim_{z,\bar{z}\to 0} G_{\Delta,J} \sim (z\bar{z})^{\frac{\Delta}{2}} f_E(z/\bar{z})$

but after analytic continuation highest spin dominates $\lim_{z,\bar{z}\to 0} G_{\Delta,J} \sim (z\bar{z})^{\frac{1-J}{2}} f_L(z/\bar{z})$

Conformal Regge Theory

[Cornalba 07; MSC, Penedones, Gonçalves 12]



- Expand in t-channel conformal partial waves

$$\mathcal{A}(z,\bar{z}) = \sum_k C_{13k} C_{24k}\, G_{\Delta_k,J_k}(z,\bar{z})$$

- Euclidean OPE dominated by lowest dimension $\lim_{z,\bar{z}\to 0} G_{\Delta,J} \sim (z\bar{z})^{\frac{\Delta}{2}} f_E(z/\bar{z})$

but after analytic continuation highest spin dominates $\lim_{z,\bar{z}\to 0} G_{\Delta,J} \sim (z\bar{z})^{\frac{1-J}{2}} f_L(z/\bar{z})$

- Spectral representation $(h = d/2)$

$$\mathcal{A}(z,\bar{z}) = \sum_J \int_{-\infty}^{\infty} d\nu\, \frac{C_{13J} C_{24J}}{\nu^2 + (\Delta(J) - h)^2}\, F_{\nu,J}(z,\bar{z})$$

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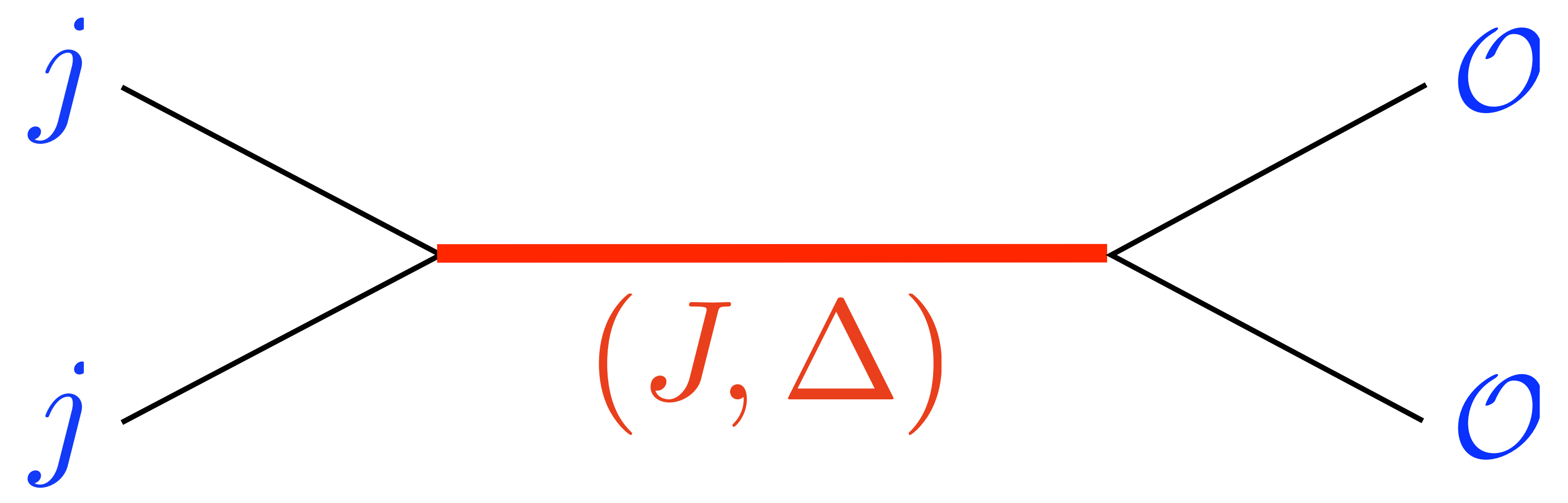

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$$\sigma^2 = z\bar{z}\,, \quad e^{2\rho} = \frac{z}{\bar{z}}$$

Regge limit $\sigma \to 0\,, \quad \rho$ fixed

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$$\sim \sum_J \sigma^{1-J} \int d\nu\, \alpha_J(\nu)\, \Omega_{i\nu}(\rho)$$

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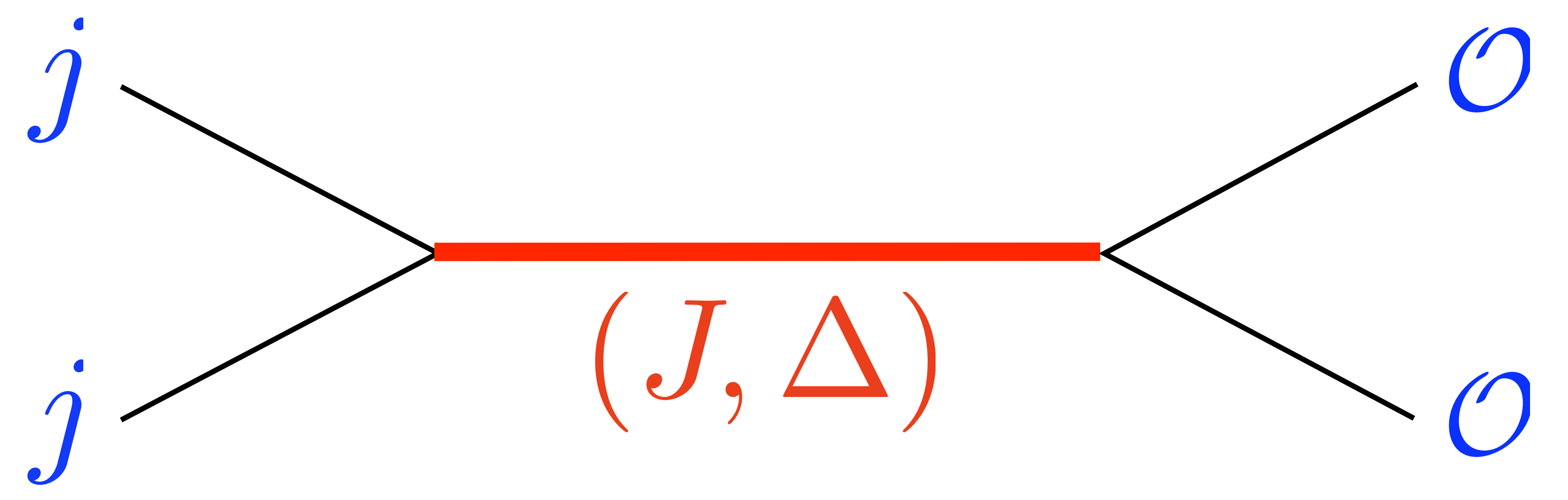

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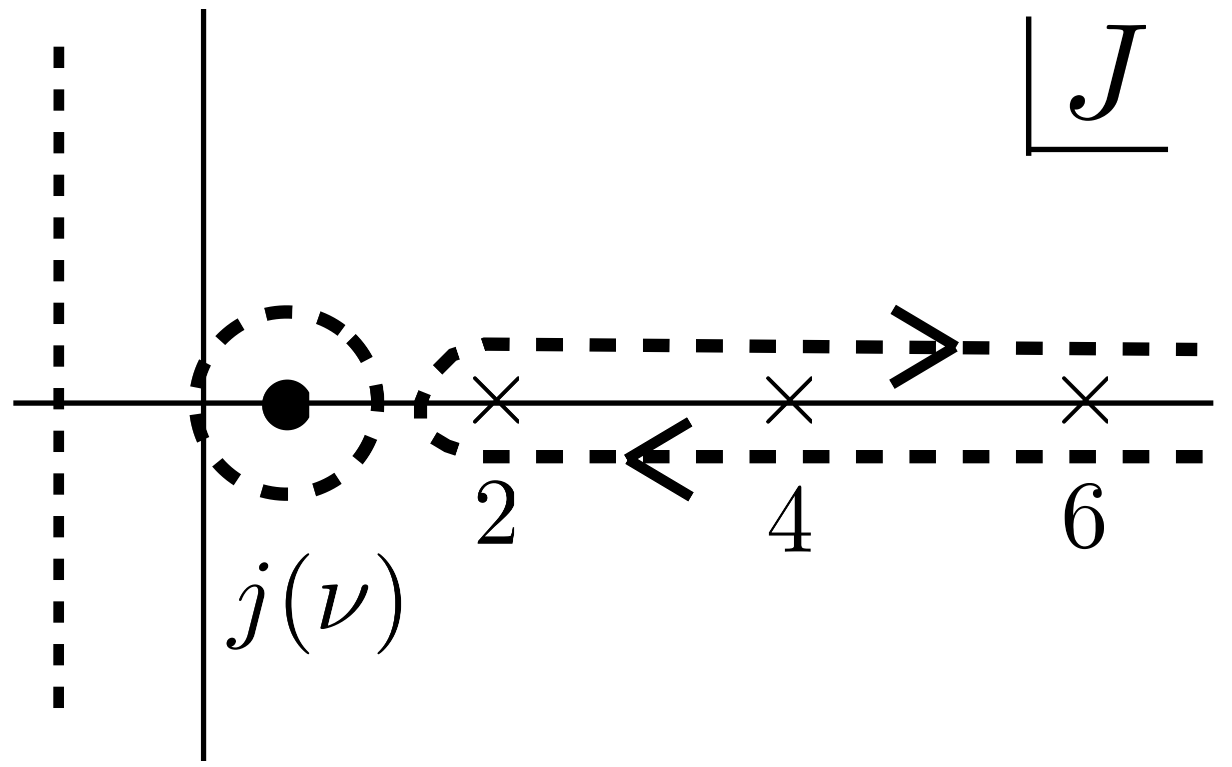
$$\sim \sum_J \sigma^{1-J} \int d\nu\, \alpha_J(\nu)\, \Omega_{i\nu}(\rho)$$

→ Harmonic function on $\mathbb{H}_{d-1}$ $\left(\nabla^2 \Omega_{i\nu} = -(\nu^2 + h - 1)\,\Omega_{i\nu}\right)$

- Sum over spin using Sommerfeld-Watson transform

$$\mathcal{A}(\sigma,\rho) = \sigma \int d\nu \int_C \frac{dJ}{2\pi i}\,\frac{\pi}{2\sin(\pi J)}\left(\sigma^{-J} + (-\sigma)^{-J}\right)\alpha_J(\nu)\,\Omega_{i\nu}(\rho)$$



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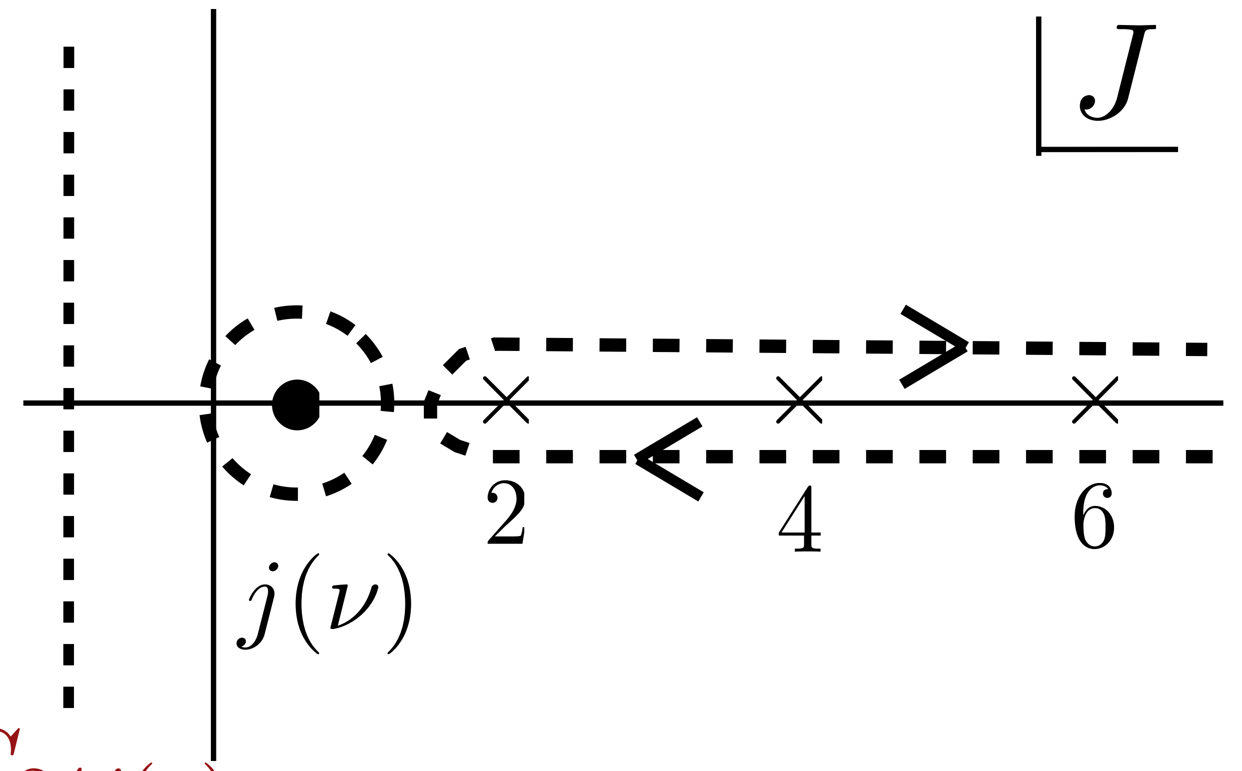
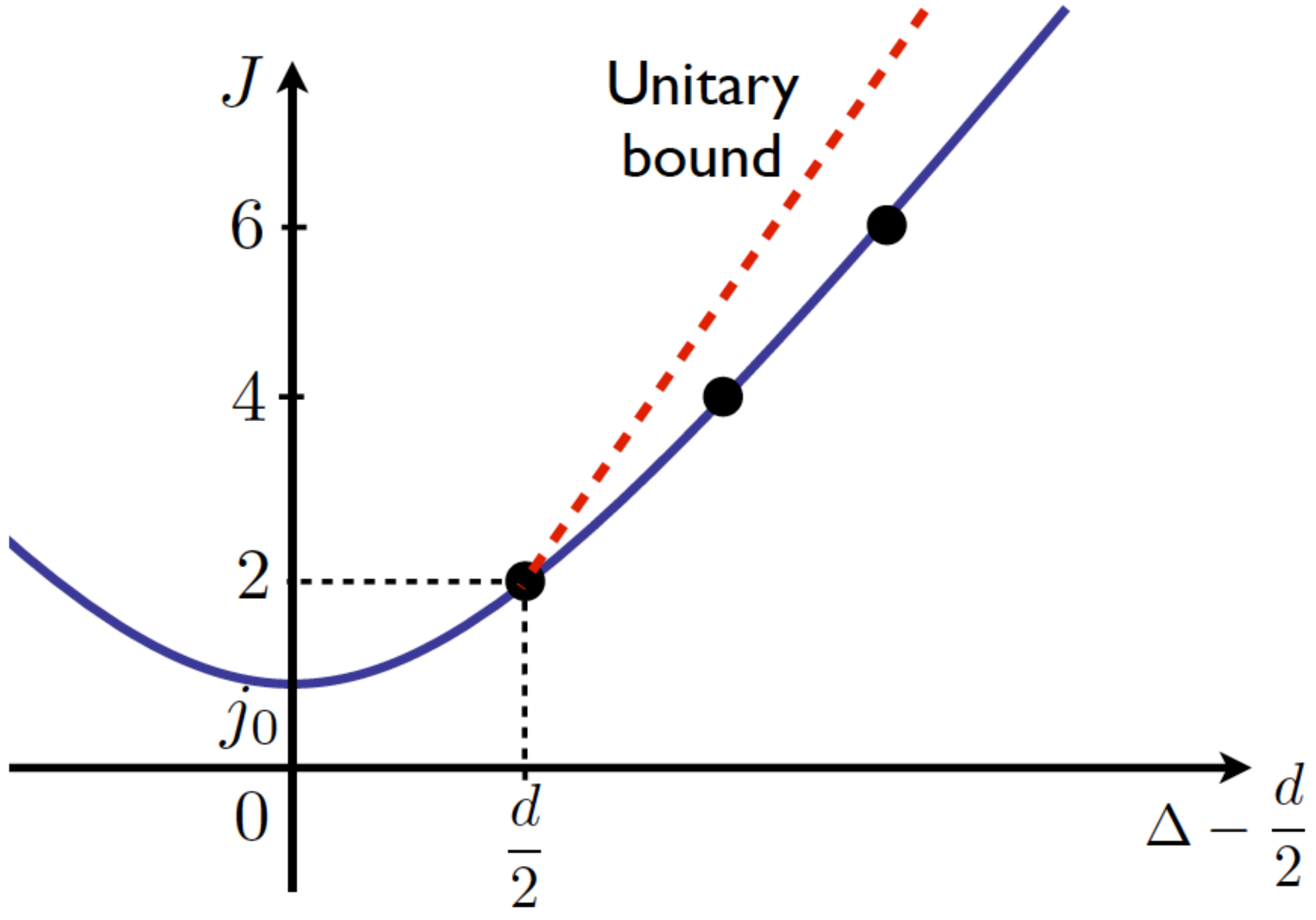


$$\alpha_J(\nu) = \frac{C_{13J}C_{24J}}{\nu^2 + (\Delta(J)-h)^2} \approx -\frac{j'(\nu)C_{13j(\nu)}C_{24j(\nu)}}{2\nu\big(J-j(\nu)\big)}$$

Regge pole for $J = j(\nu)$ **such that**

$$\nu^2 + \big(\Delta(j(\nu)) - h\big)^2 = 0$$



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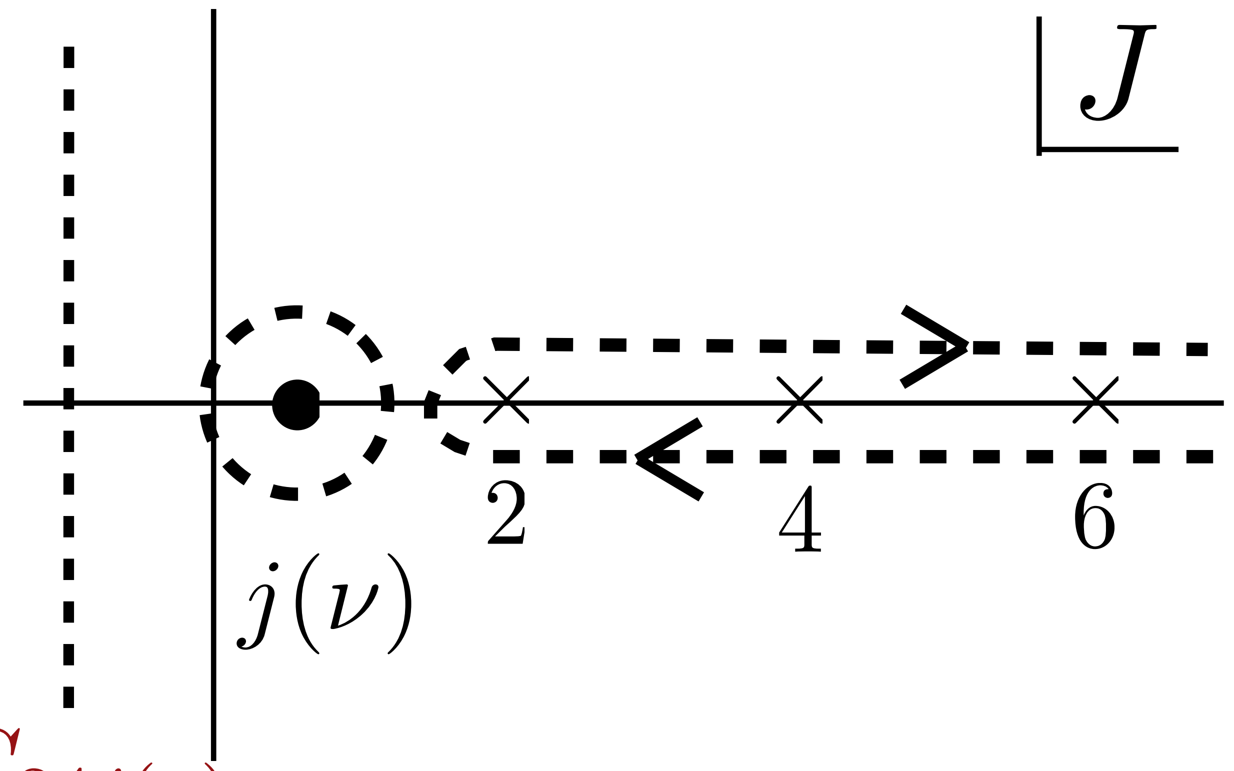

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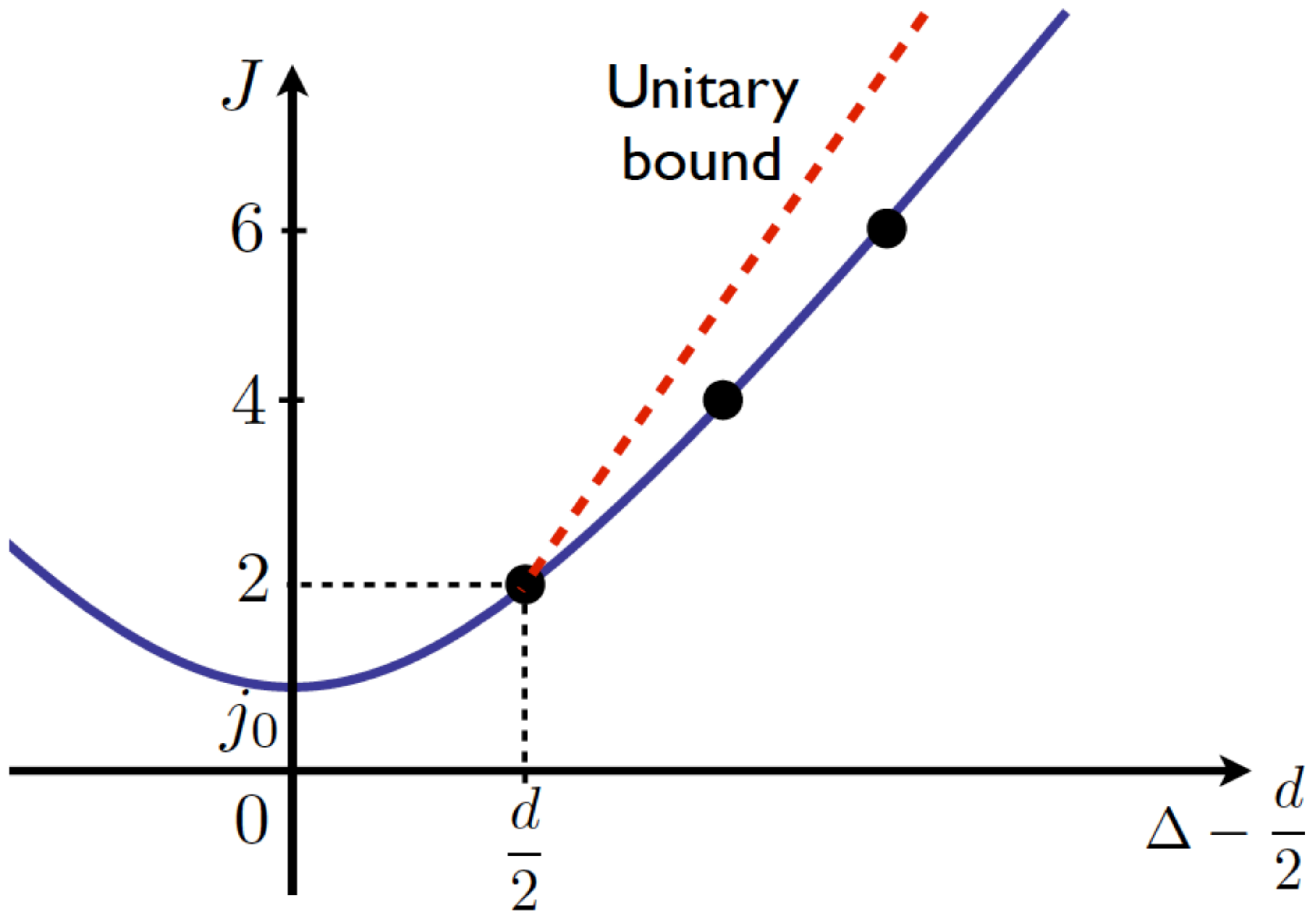


$$\mathcal{A}(\sigma,\rho) = \int_{-\infty}^{\infty} d\nu\,\alpha(\nu)\,\sigma^{1-j(\nu)}\,\Omega_{i\nu}(\rho)$$

N=4 Super Yang Mills

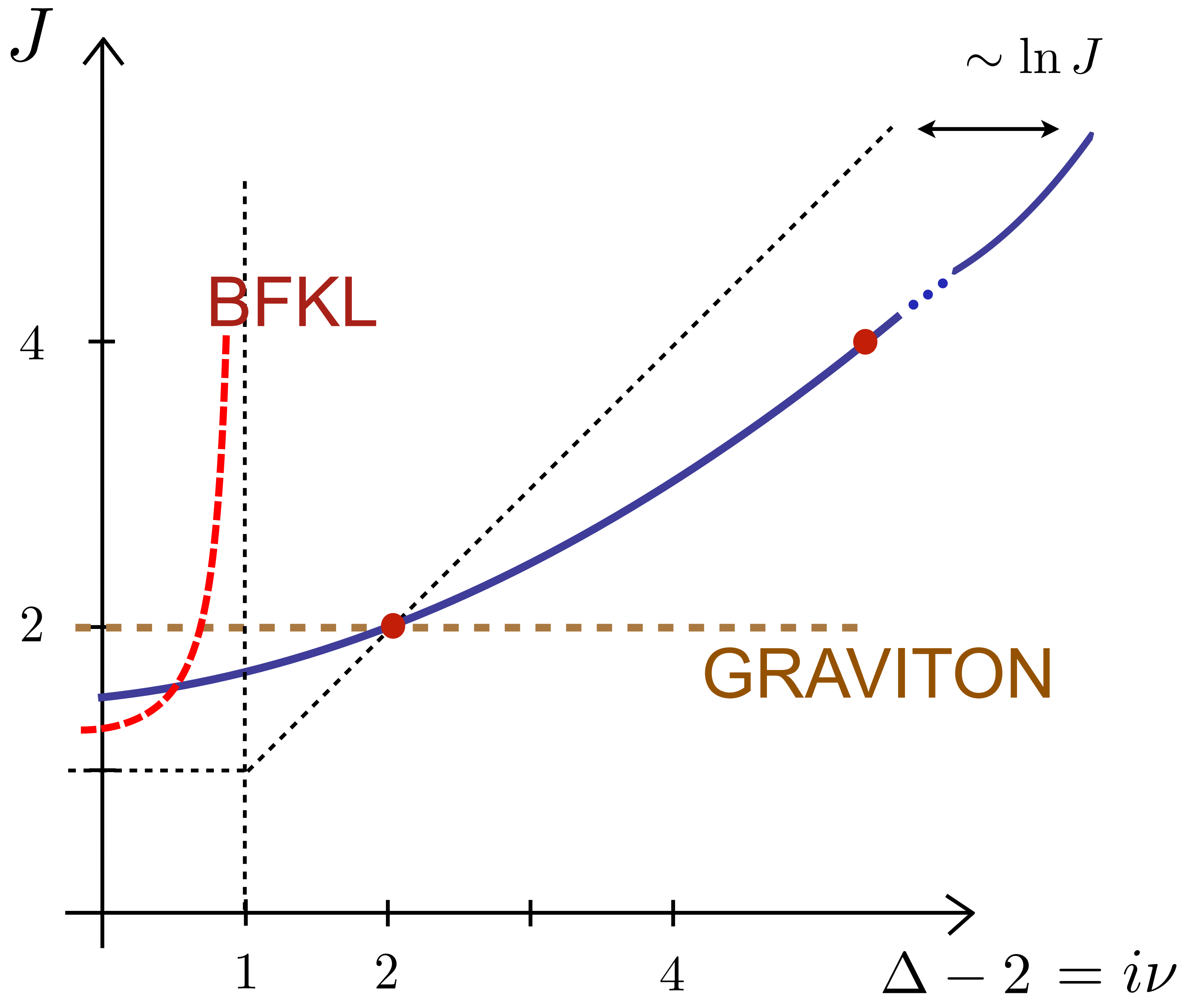
- Correlation functions that exchange vacuum quantum numbers are dominated in Regge limit by exchange of pomeron/graviton Regge trajectory (twist 2)

$$\mathcal{A}(\sigma,\rho) = \int d\nu\, \alpha(\nu,\lambda)\, \sigma^{1-j(\nu,\lambda)}\, \Omega_{i\nu}(\rho)$$

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

$$J = j(\nu,\lambda) = j_0(\lambda) - \mathcal{D}(\lambda)\,\nu^2 + \cdots$$

$$\Delta = \Delta(J) \quad \text{or} \quad J = j(\nu)$$



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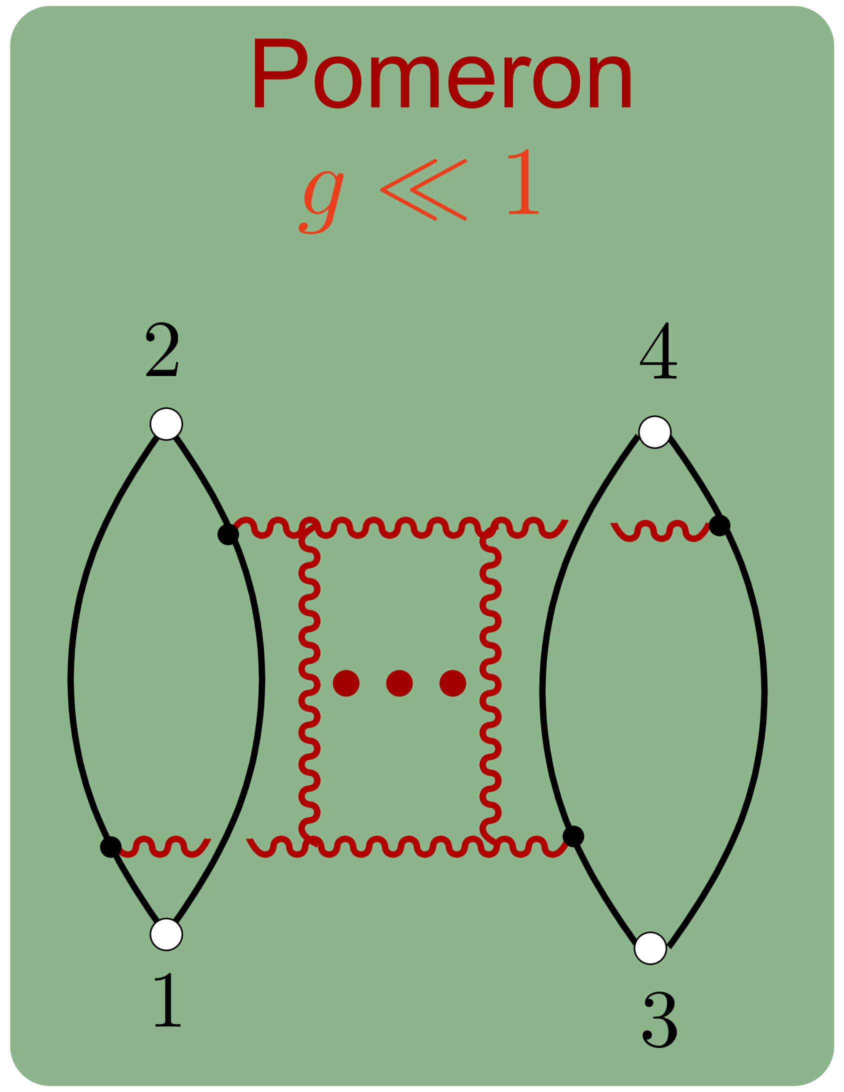
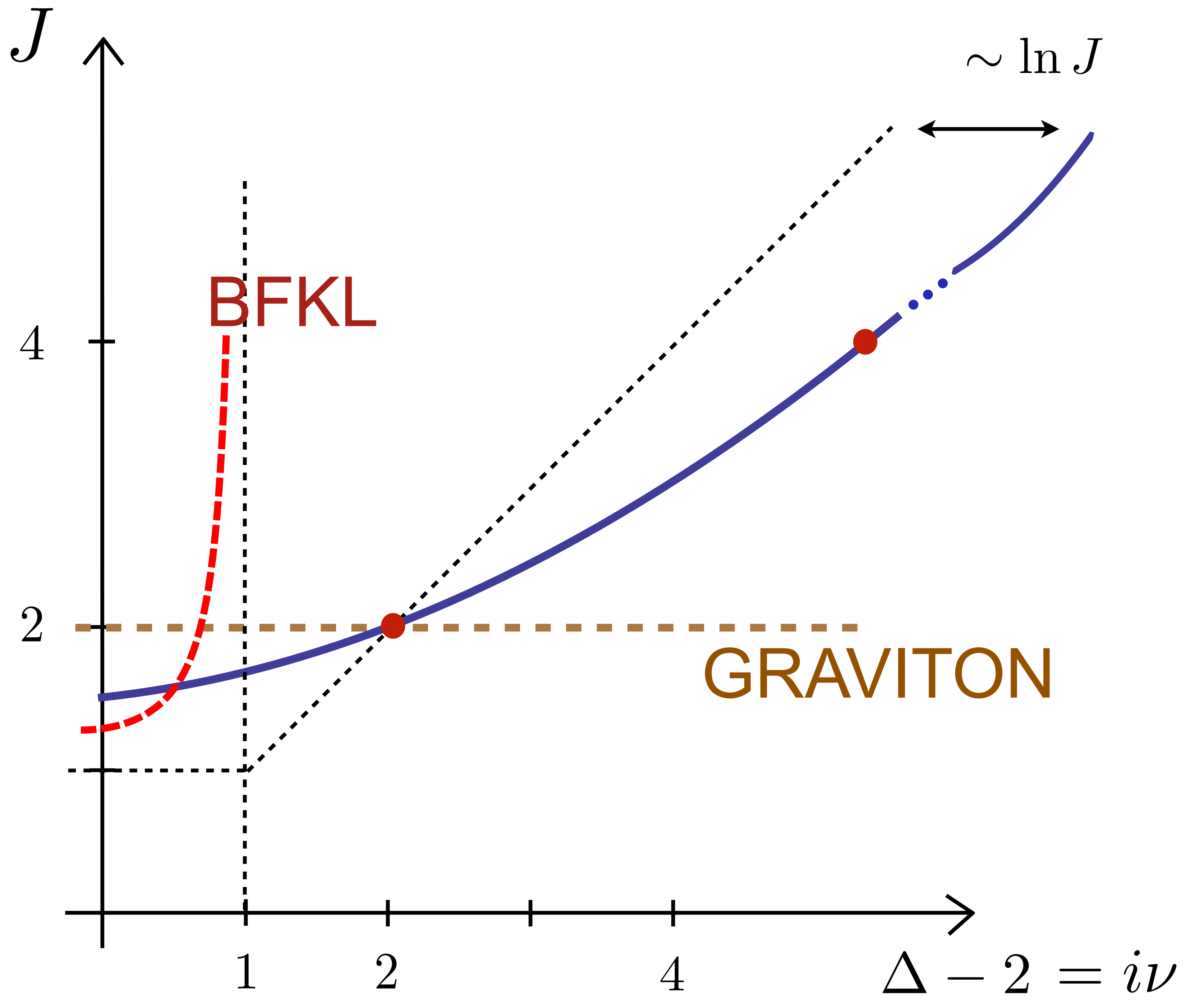
- Weak coupling





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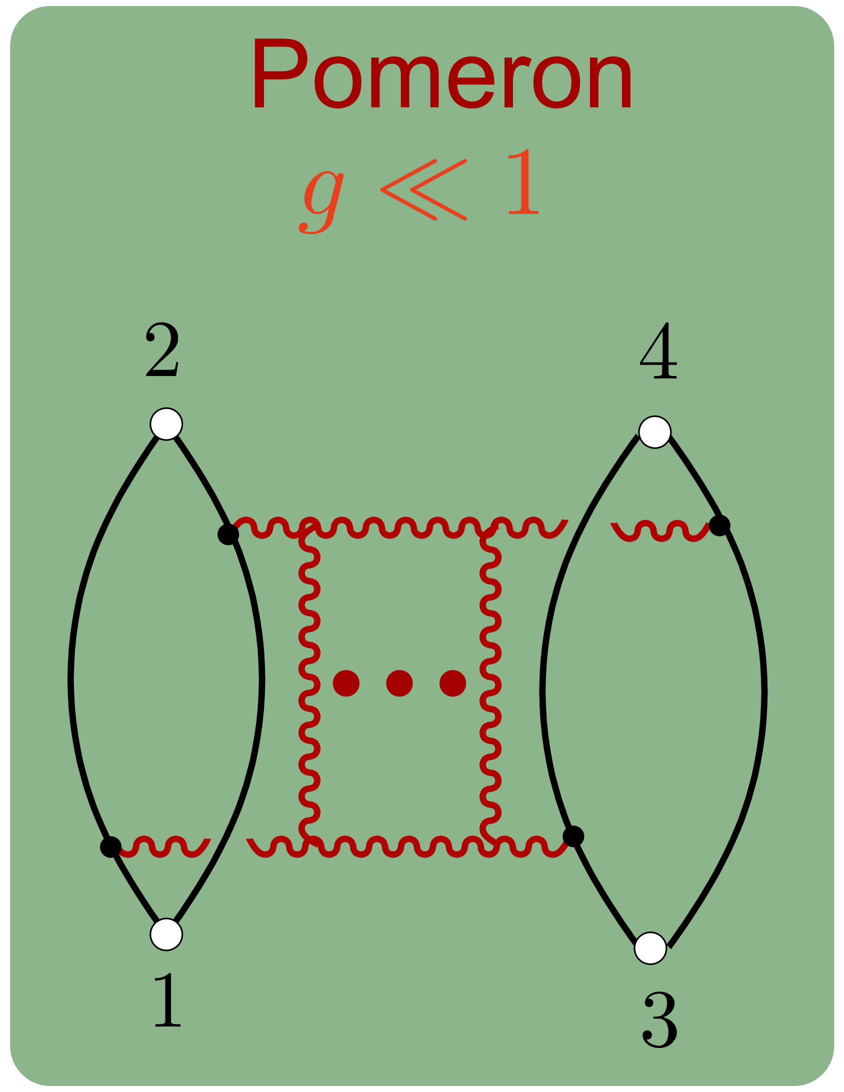
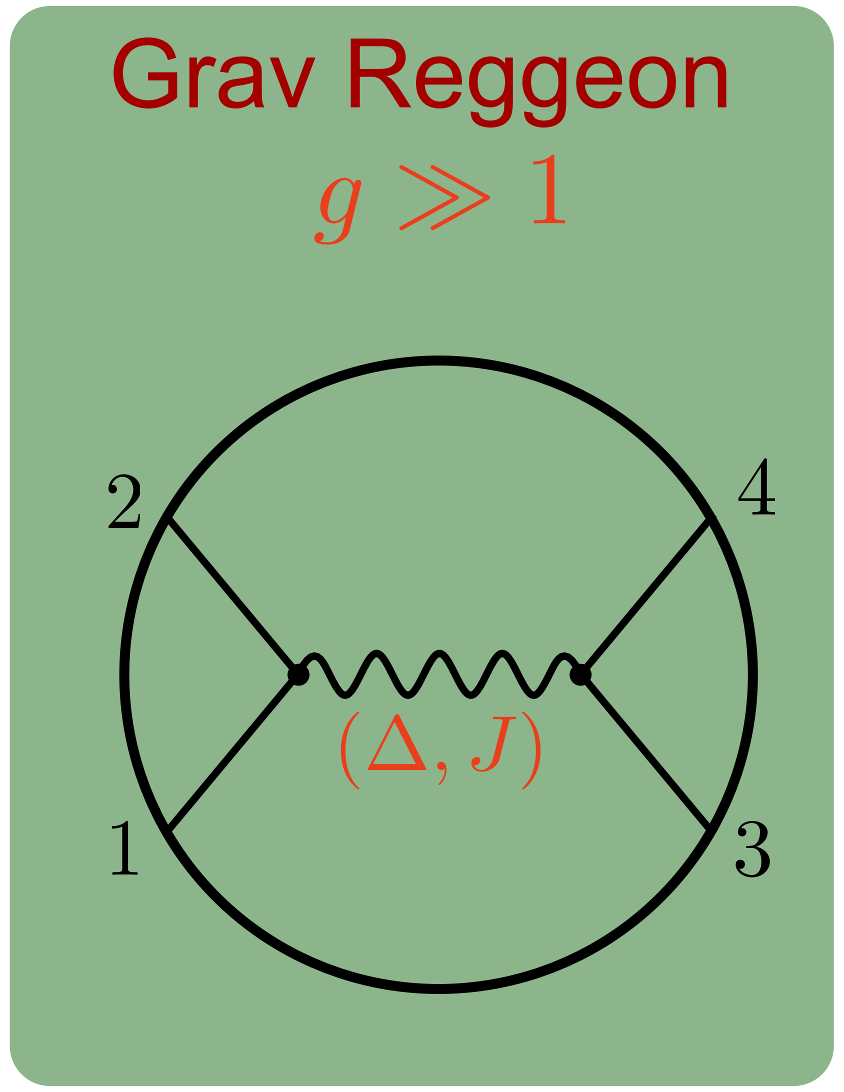
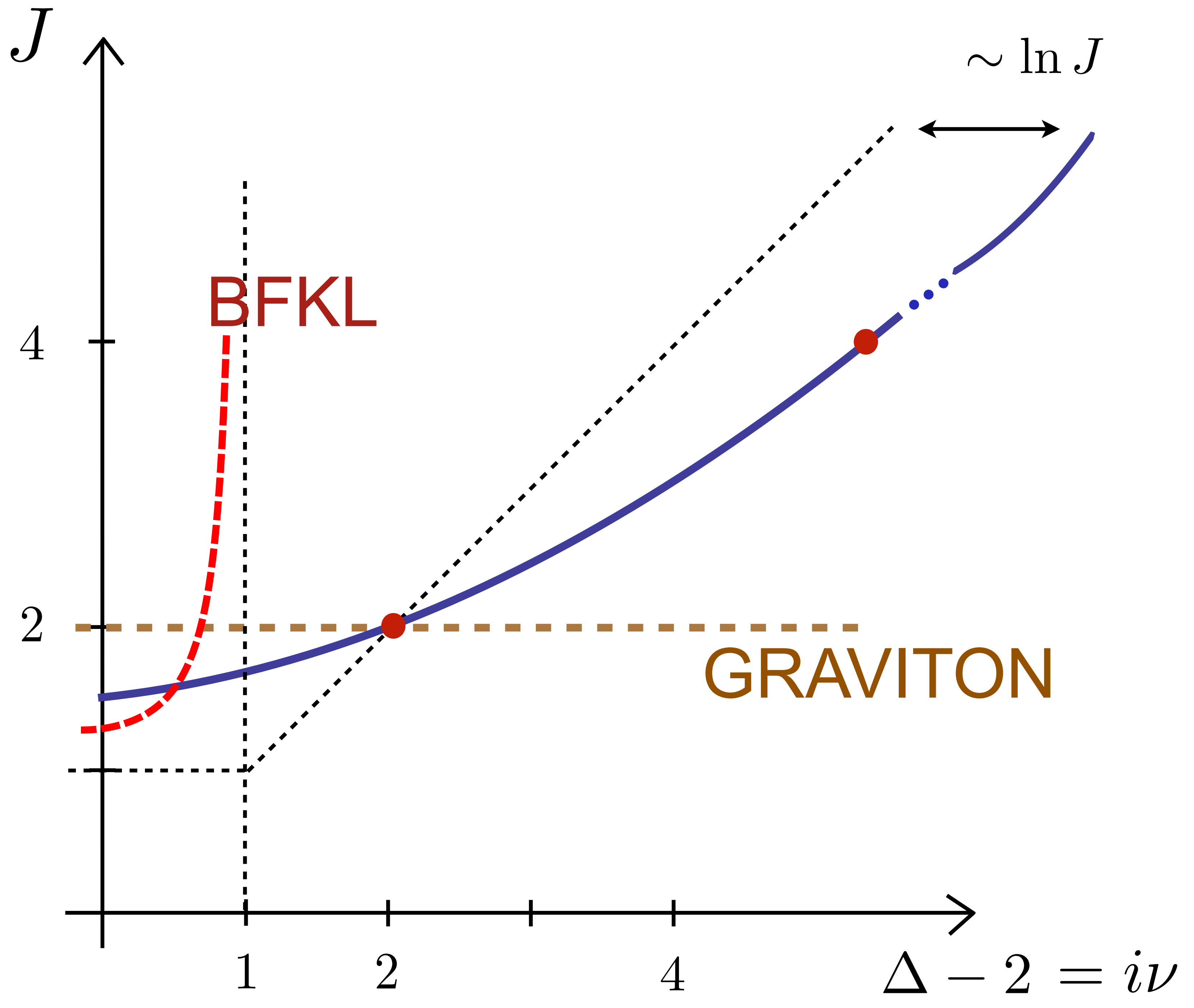
- Weak coupling
- Strong coupling







Graviton/Pomeron Regge trajectory at strong coupling [BPST 06]

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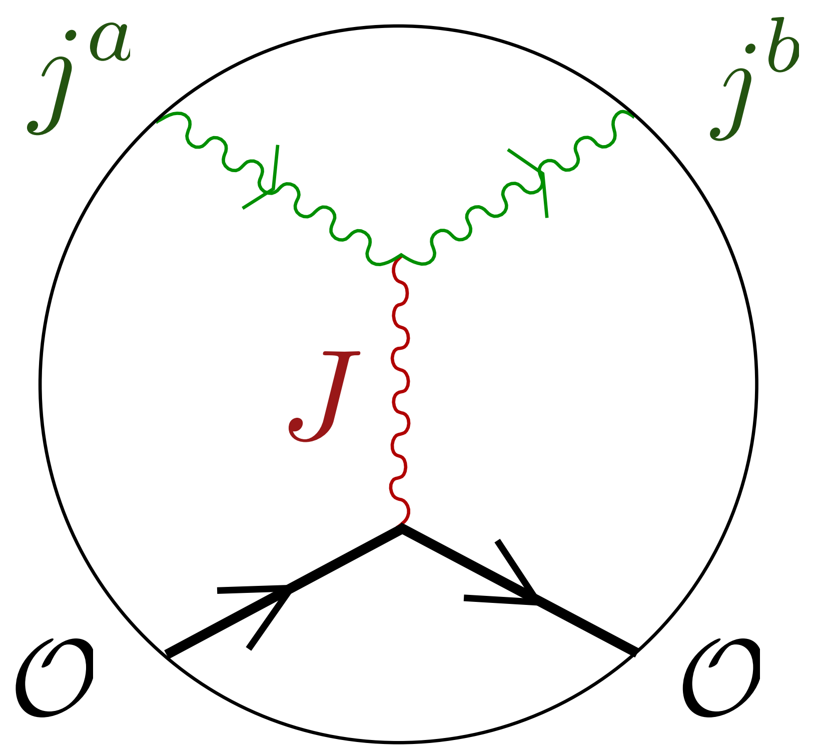
• At strong coupling pomeron trajectory described by graviton Regge trajectory of string theory in AdS (large N, conformal theory)

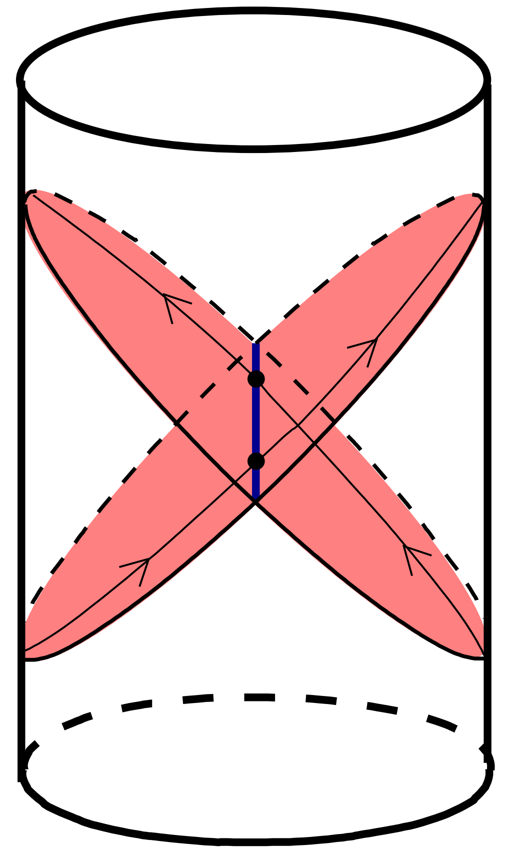
Exchange of spin J field in AdS
(symmetric, traceless and transverse)

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

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



AdS scattering process



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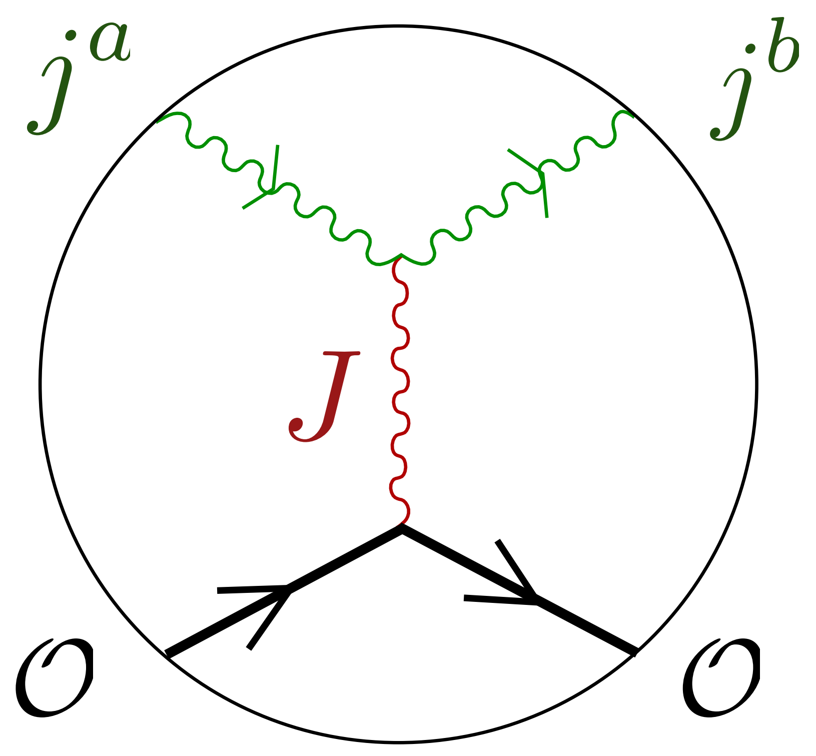

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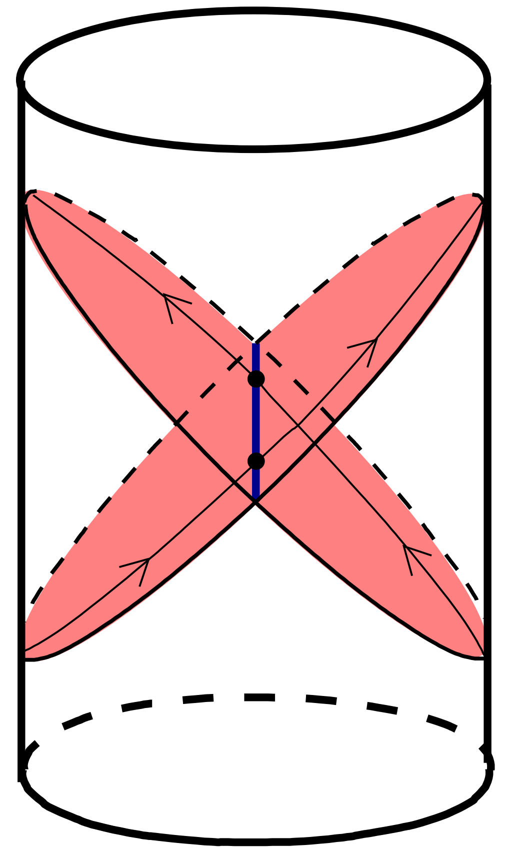
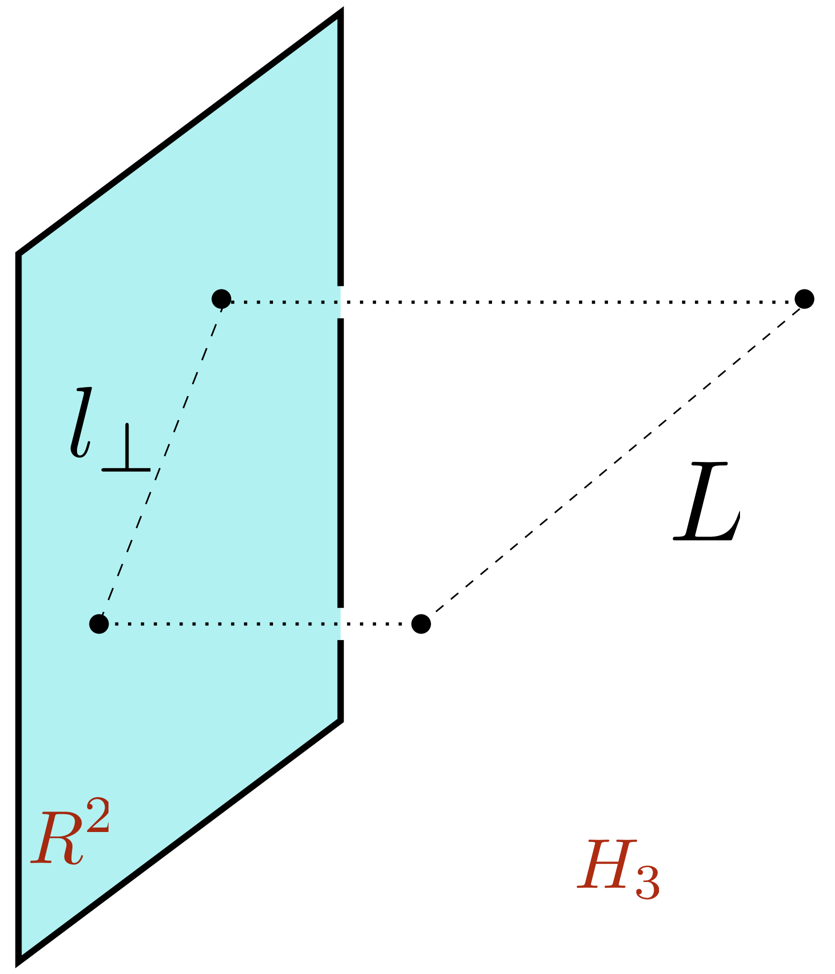


- AdS impact parameter representation. In Regge limit

[Cornalba, MSC, Penedones, Schiappa 07]

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



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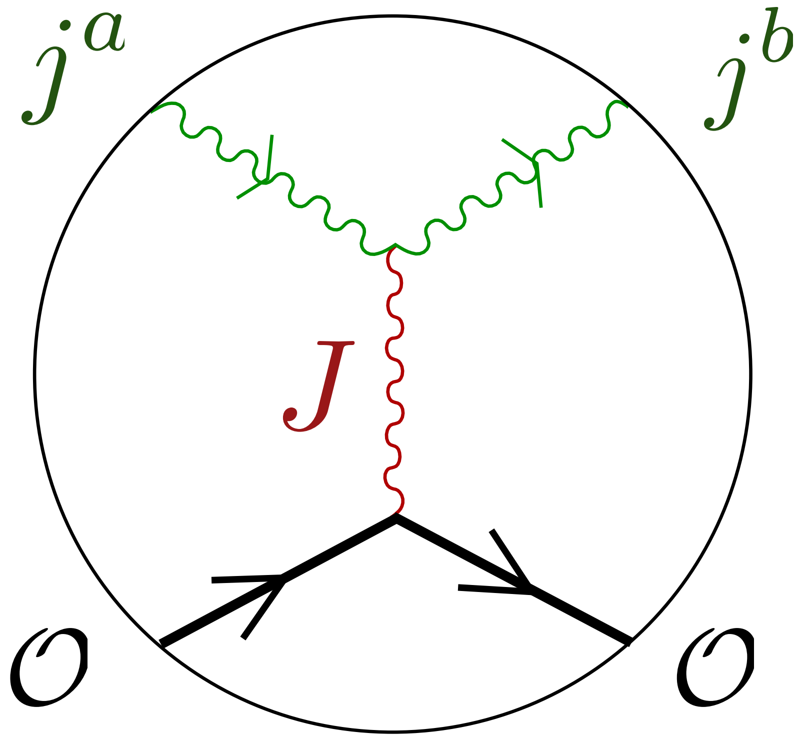

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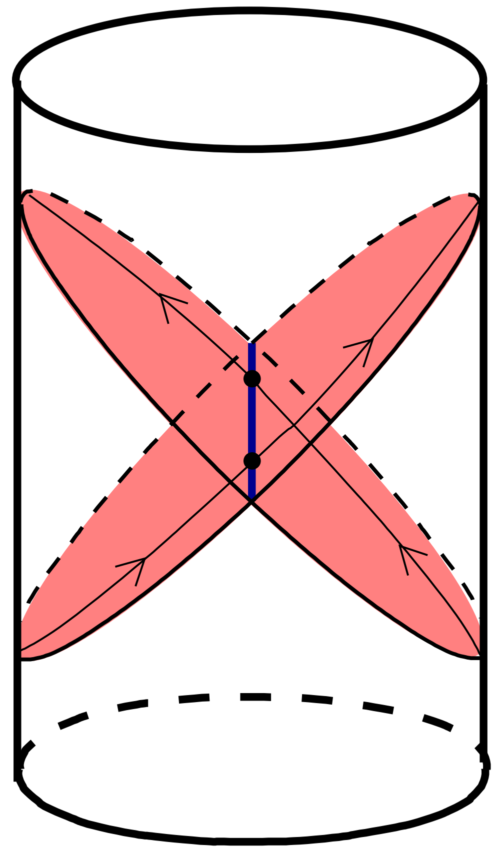

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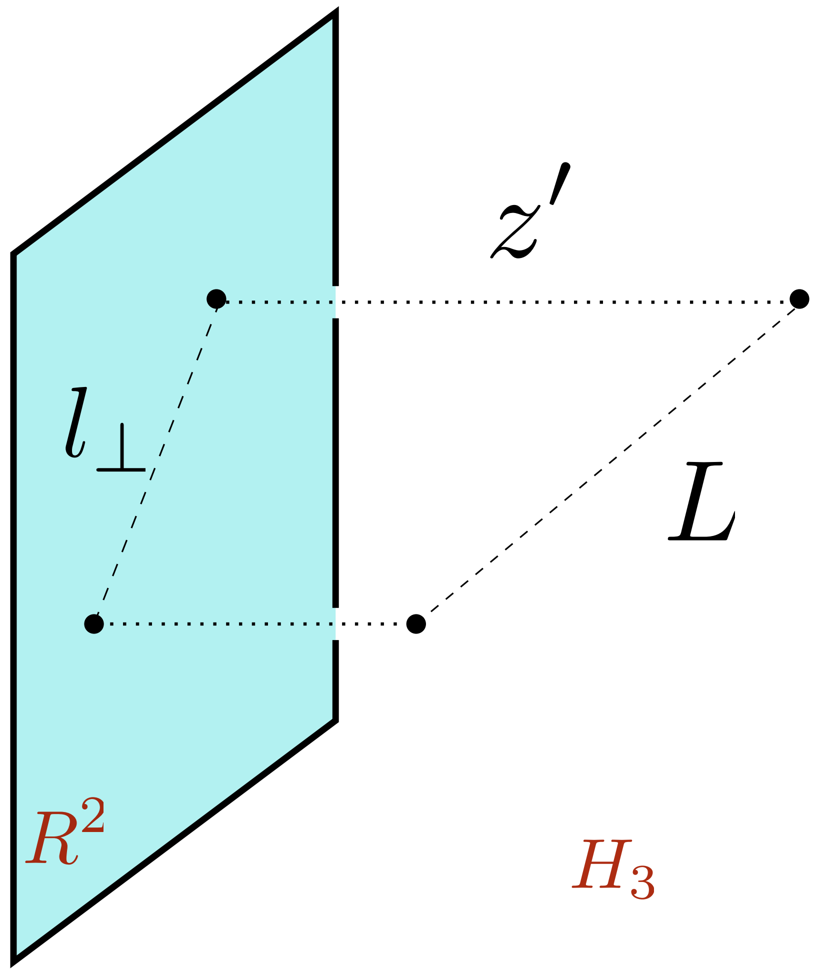

$S = zz's$, AdS energy squared

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

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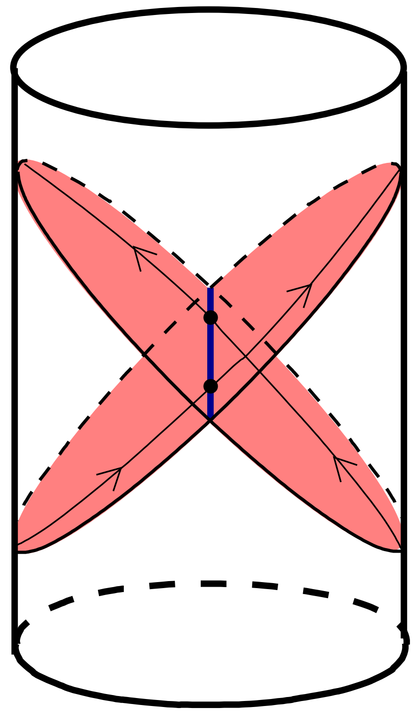

- $G_J(L)$ is the integrated propagator ($w = x - x' = (w^+, w^-, l_\perp)$)

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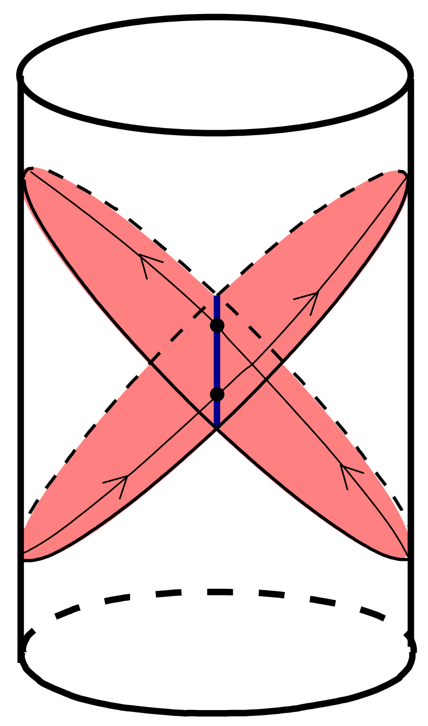

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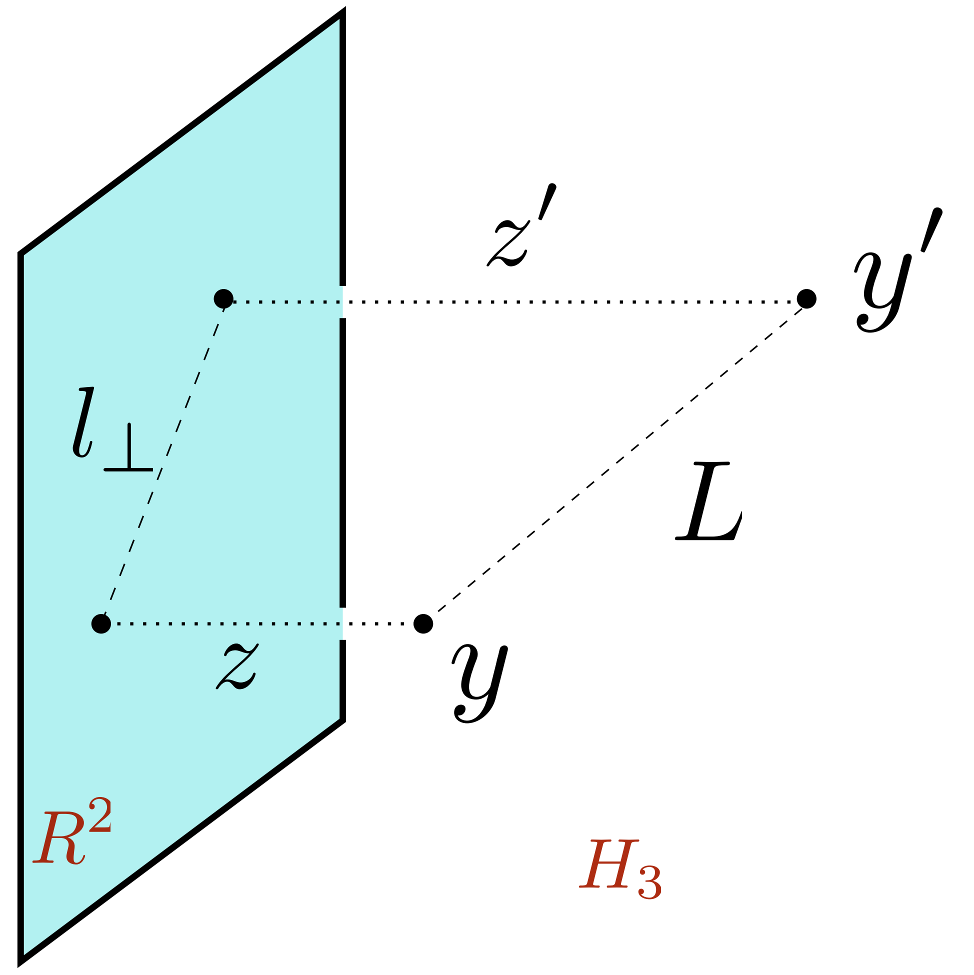
and obeys scalar propagator equation in transverse space

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



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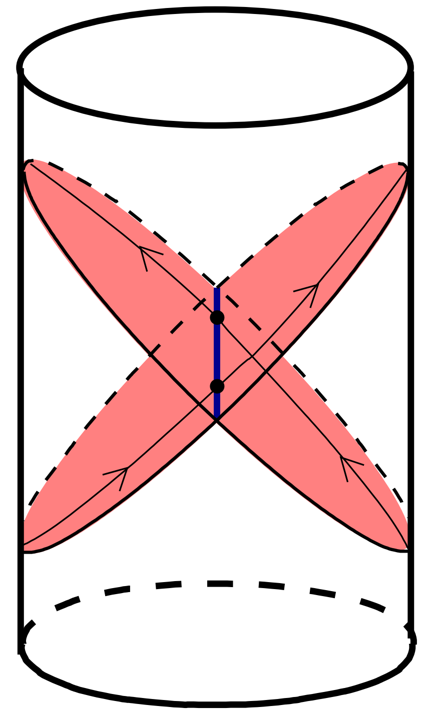

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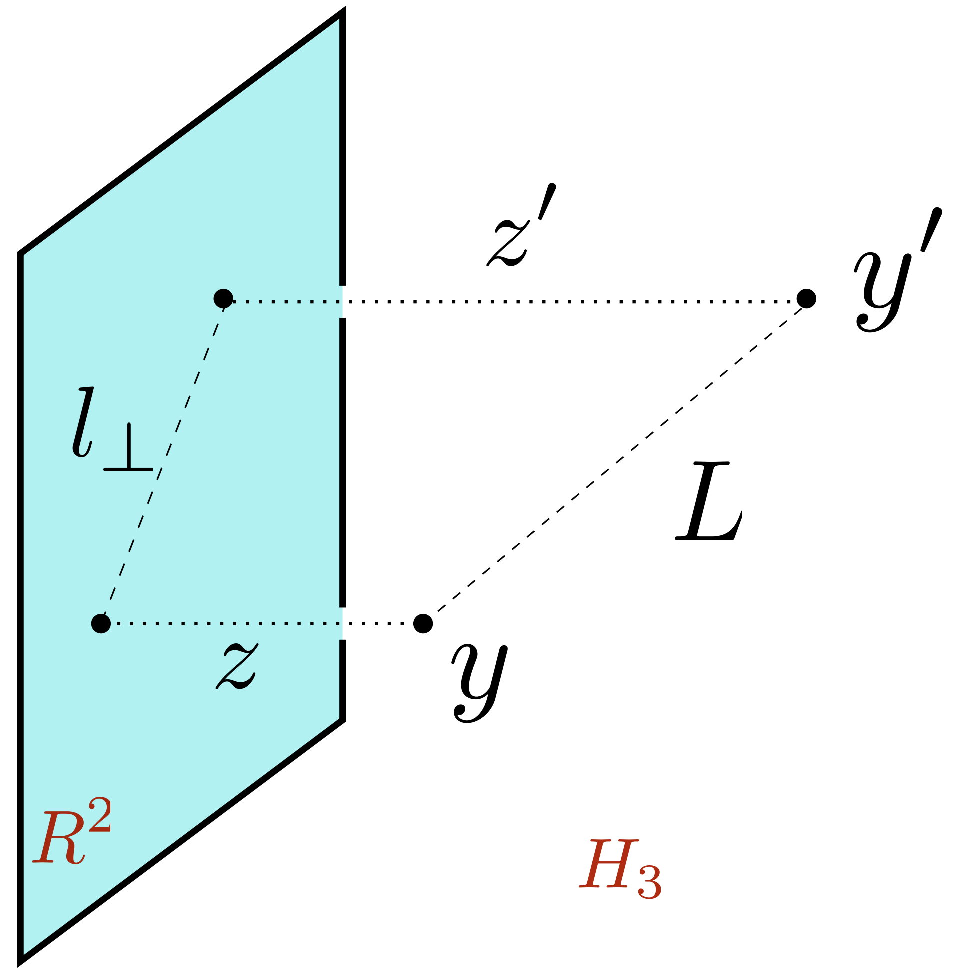
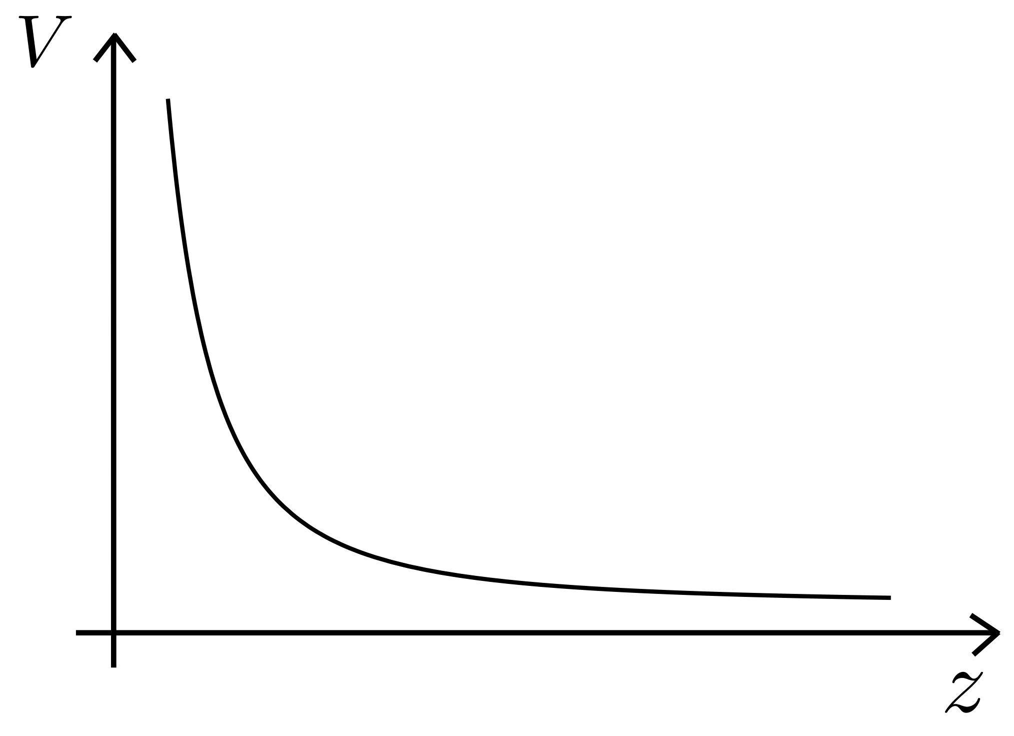


$G_J(L) = e^{iq_\perp\cdot l_\perp}\sqrt{z}\,\psi(z)$, reduces to Schrodinger problem

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



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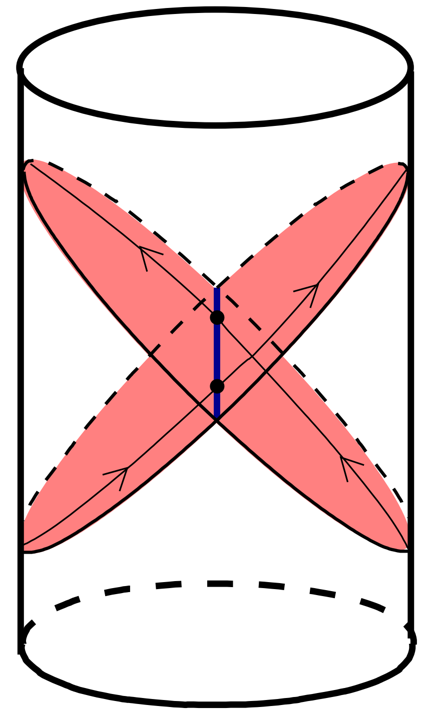

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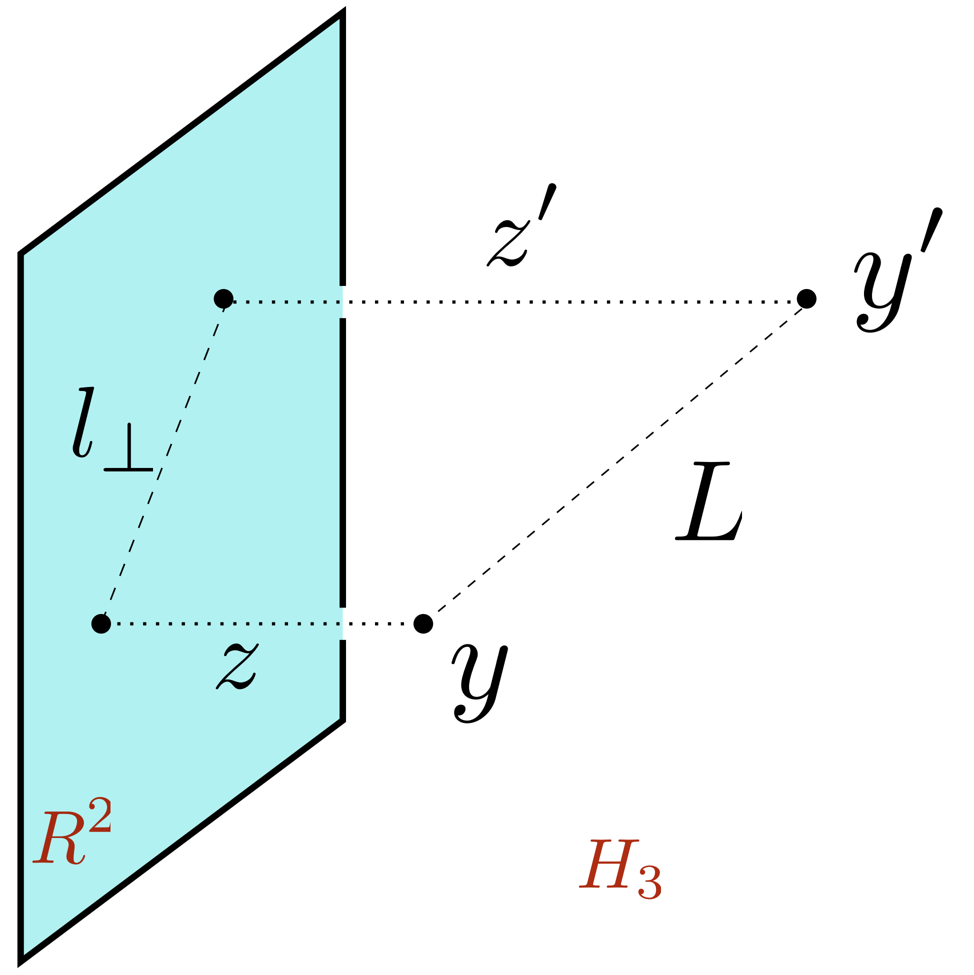

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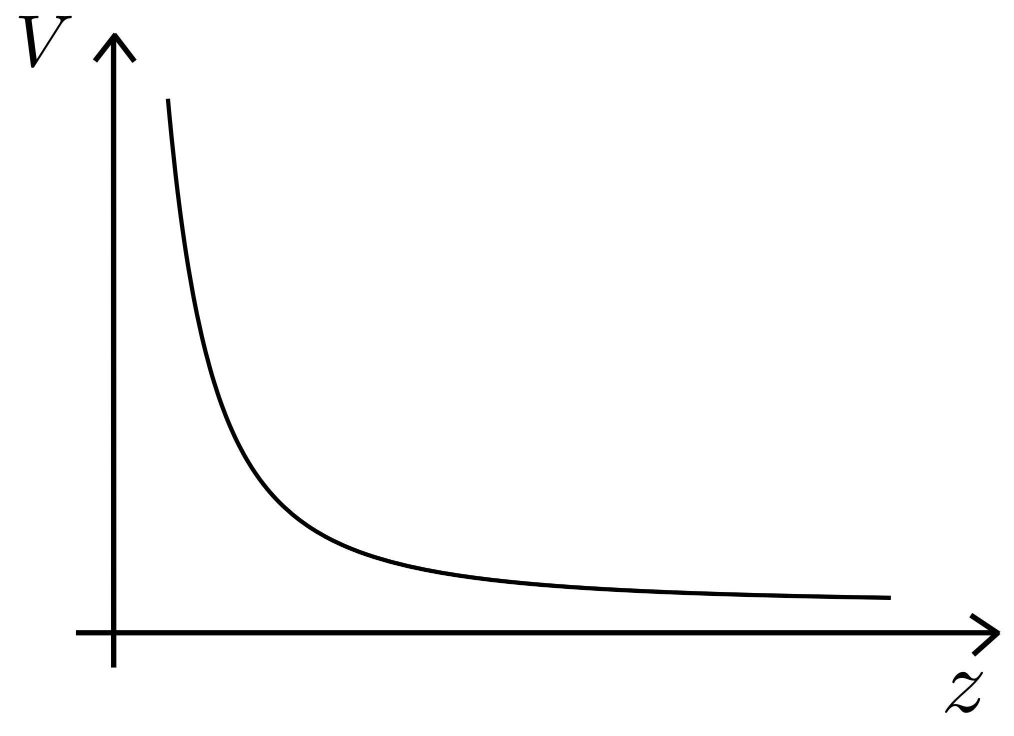
$\Delta = \Delta(J)$



Application to low x physics in QCD

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- Deep inelastic scattering (DIS)

[Hatta, Iancu, Mueller 07;
Cornalba, MSC 08;
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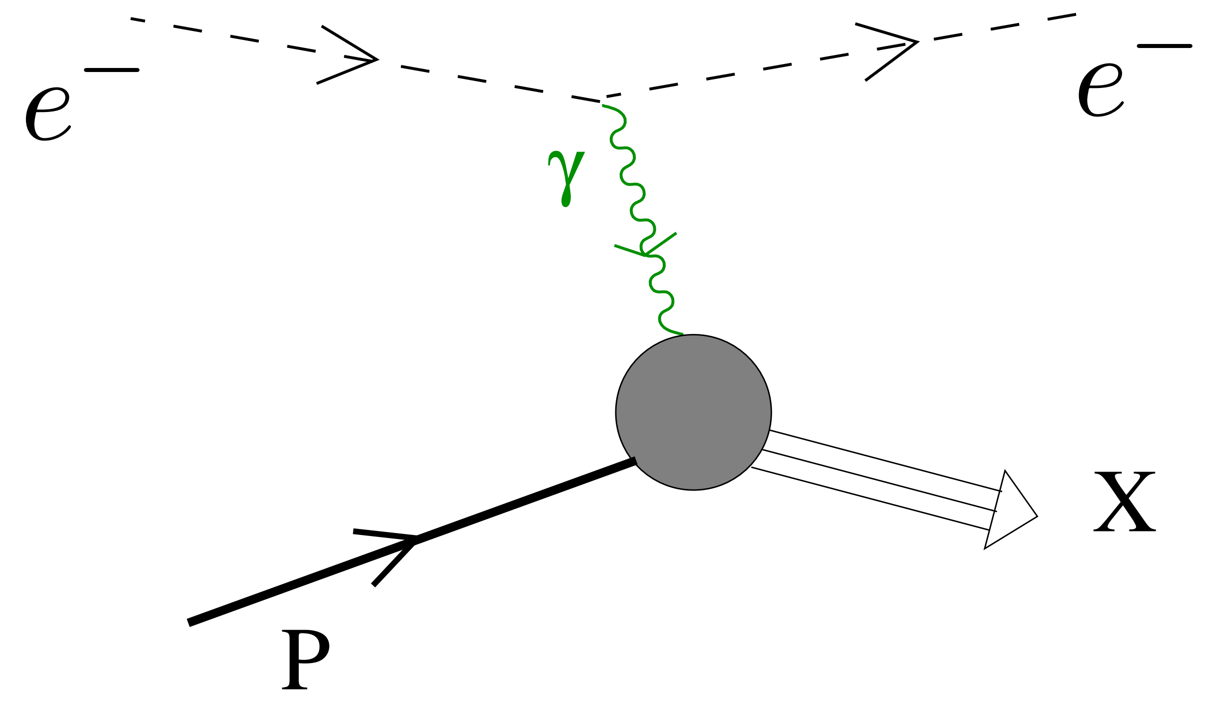

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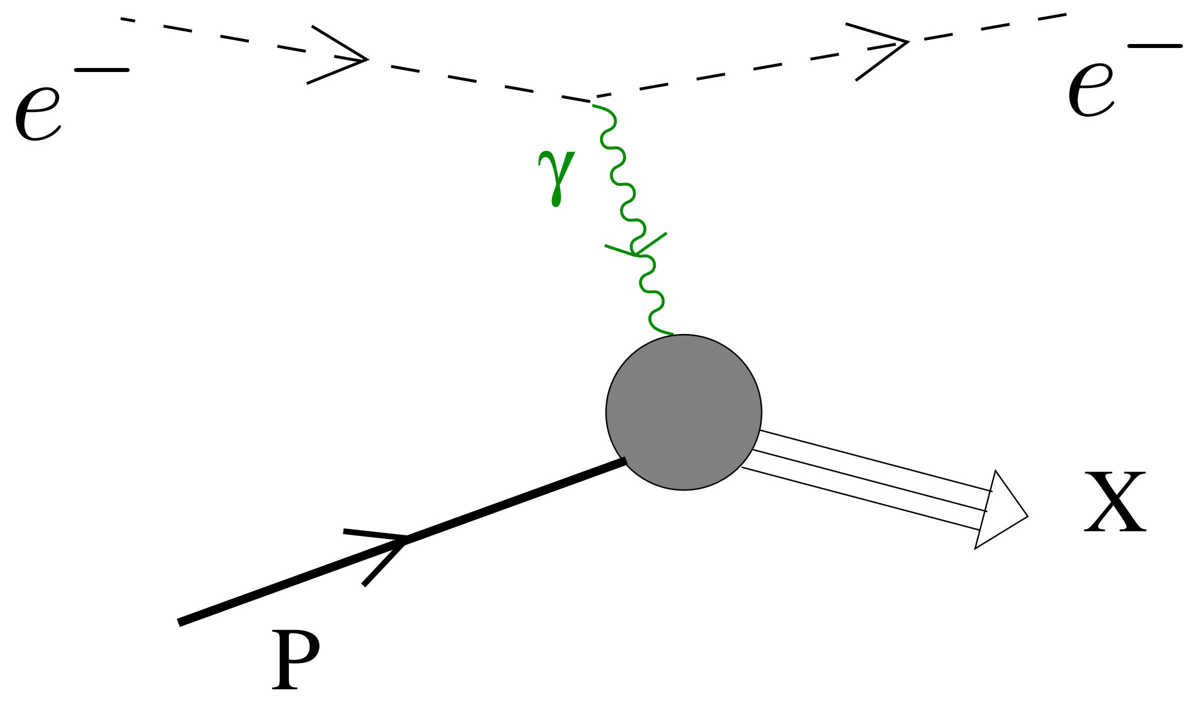
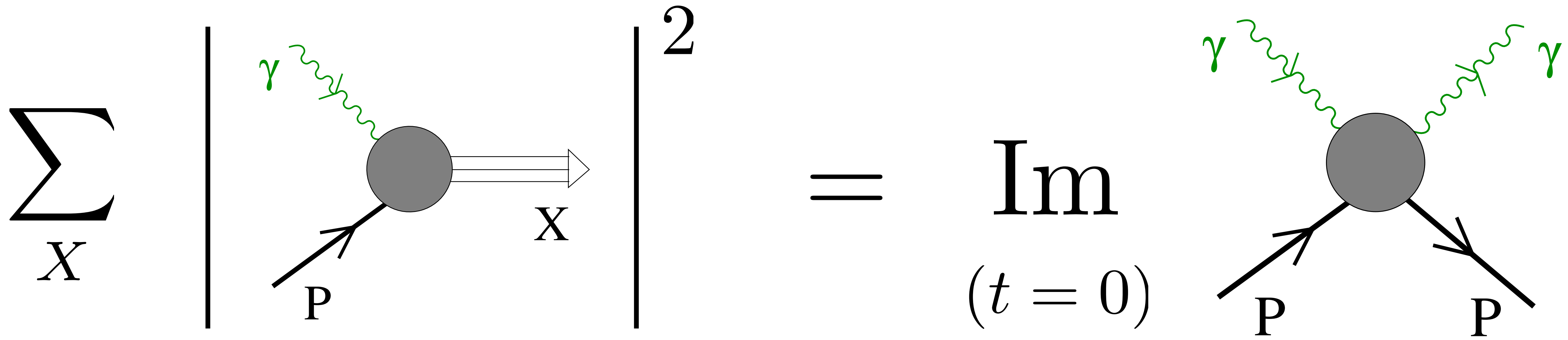


Optical theorem



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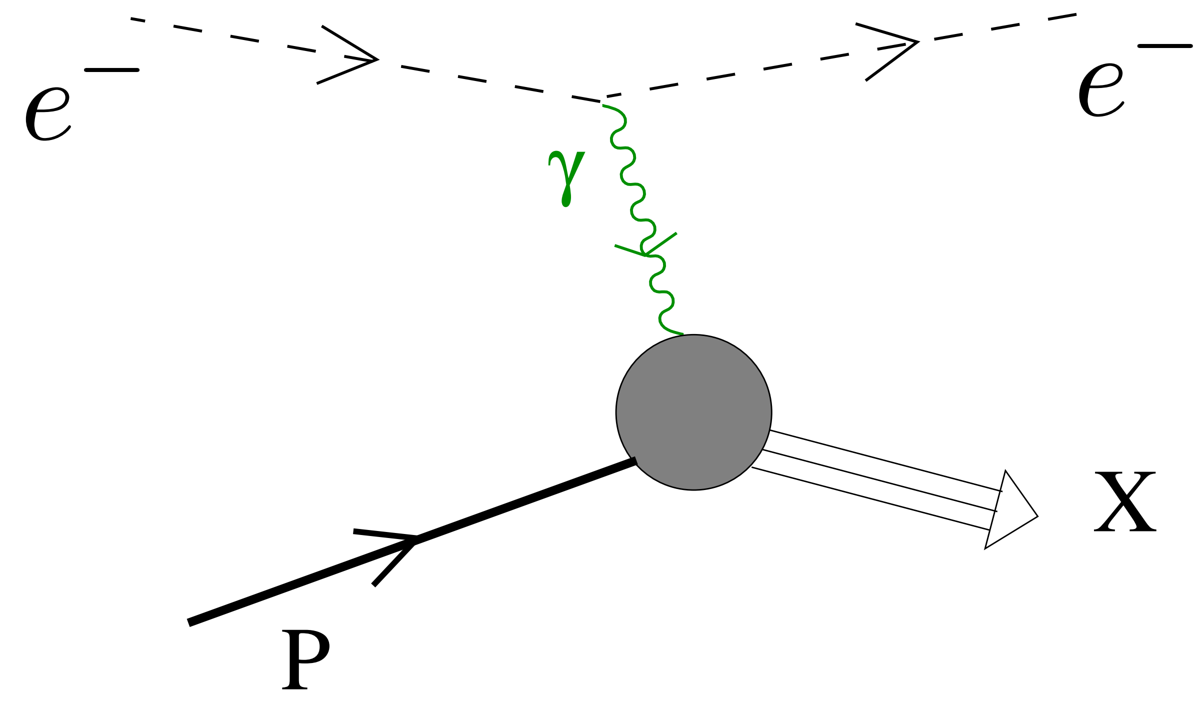

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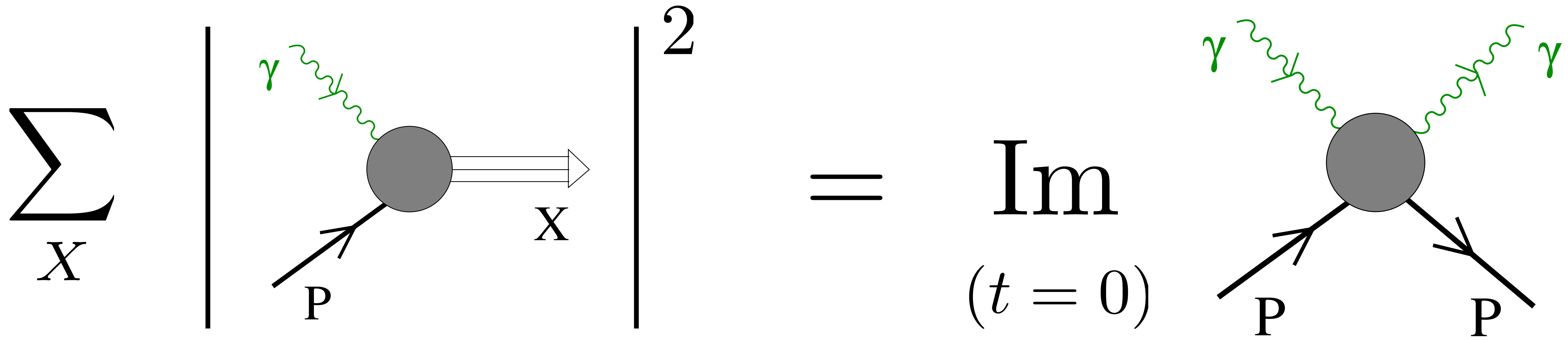

- DVCS & VMP

[MSC, Djuric 12;
MSC, Djuric, Evans 13]

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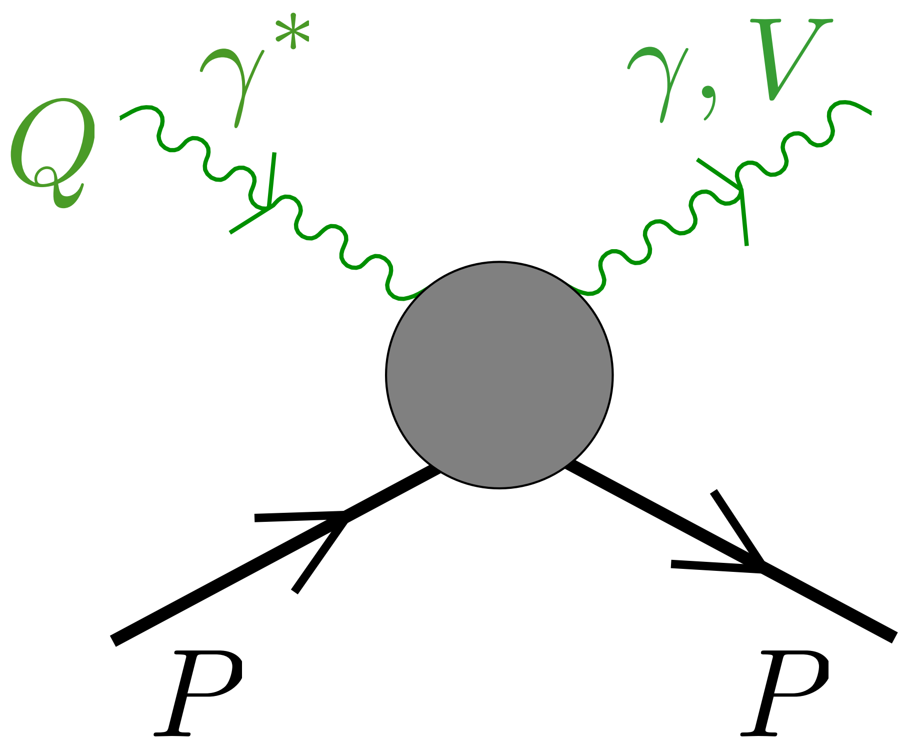


$$\frac{d\sigma}{dt}(Q,x,t) \propto |W|^2$$

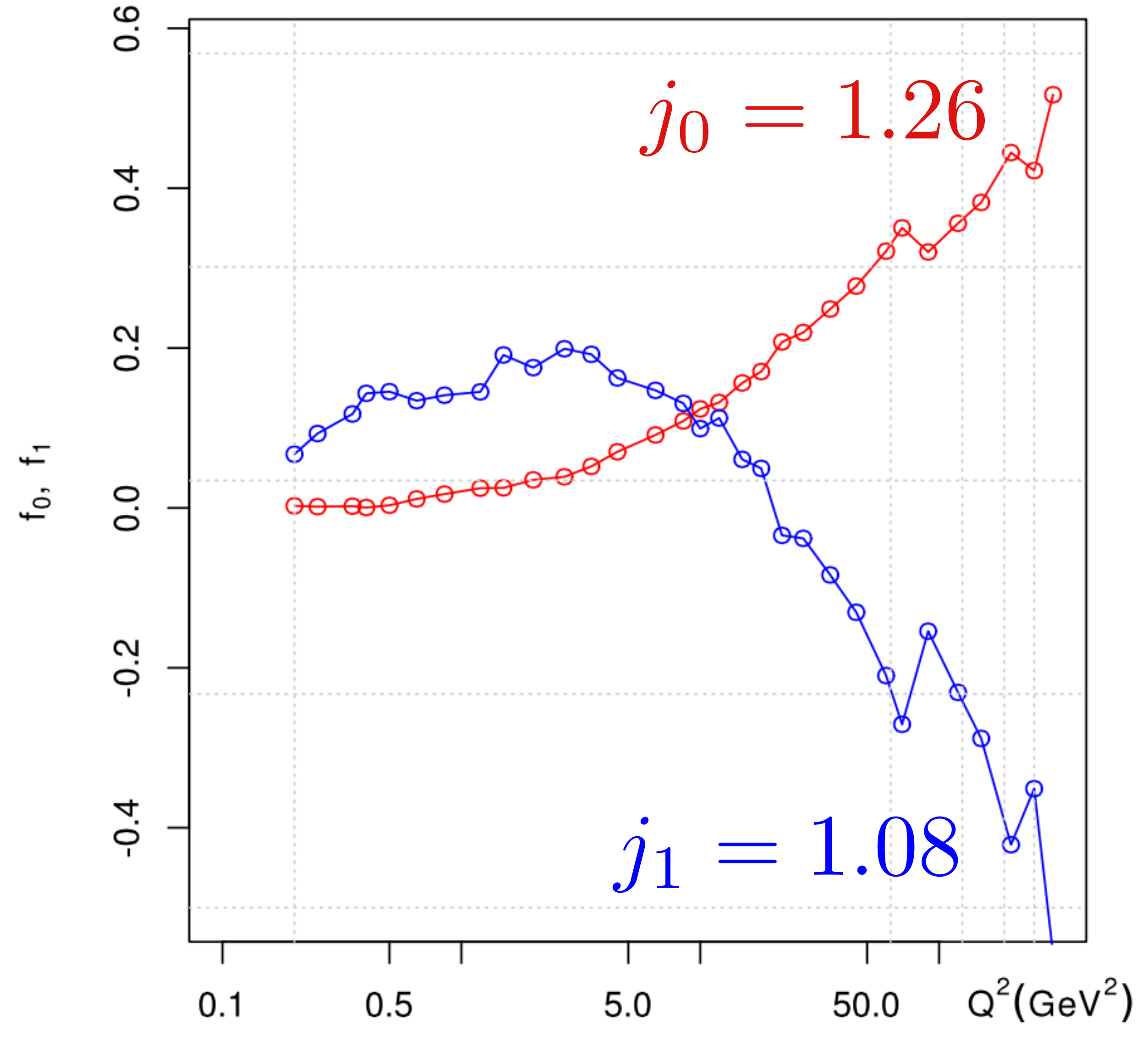
$$\sigma_{tot}(Q,x)$$

Hard and soft pomeron are distinct Regge trajectories [Donnachie, Landshoff]

Hard and soft pomeron are distinct Regge trajectories [Donnachie, Landshoff]

- Explain DIS data with two Regge trajectories

$$\sigma(Q^2, x) \propto f_0(Q^2)\, x^{-j_0} + f_1(Q^2)\, x^{-j_1}$$



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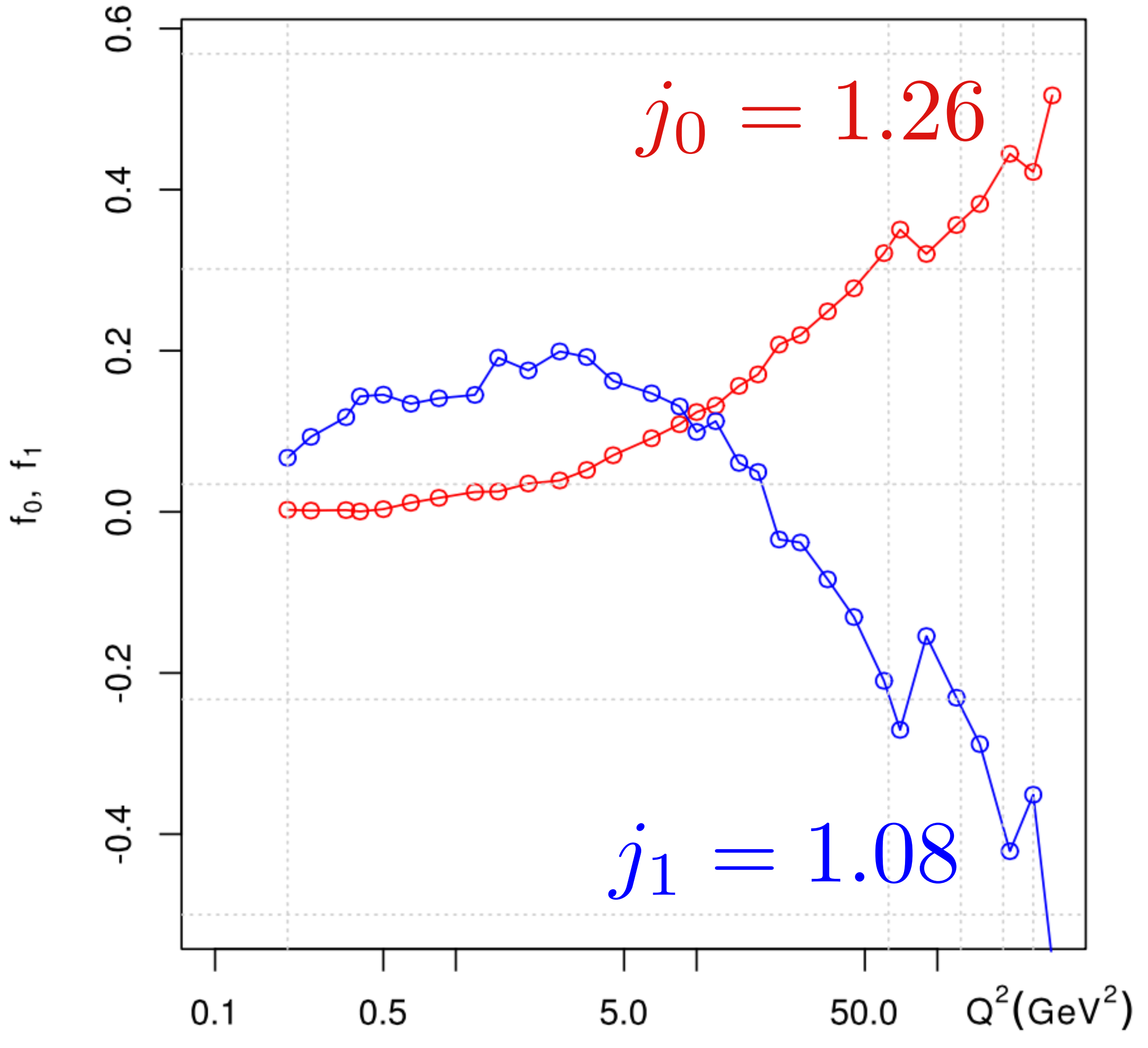

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  [Bayona, MSC, Quevedo 17]

Holographic direction $z \sim 1/Q$

$$f_k(Q^2) = P_k(Q^2)\, \varphi_k(Q^2)$$

Known function of Q^2 and j_k

Wave function of a 1D Schrodinger problem in holographic direction

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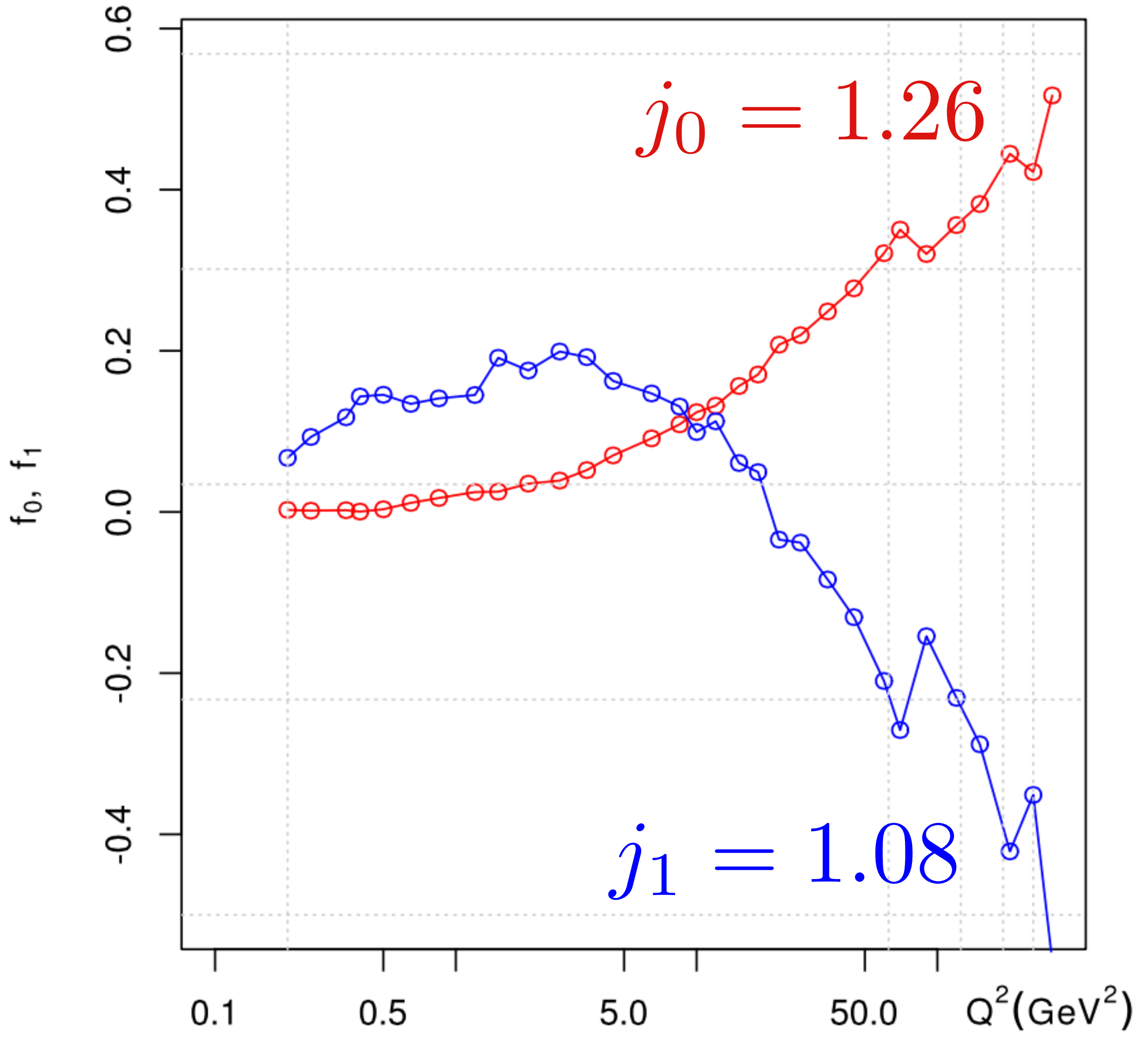
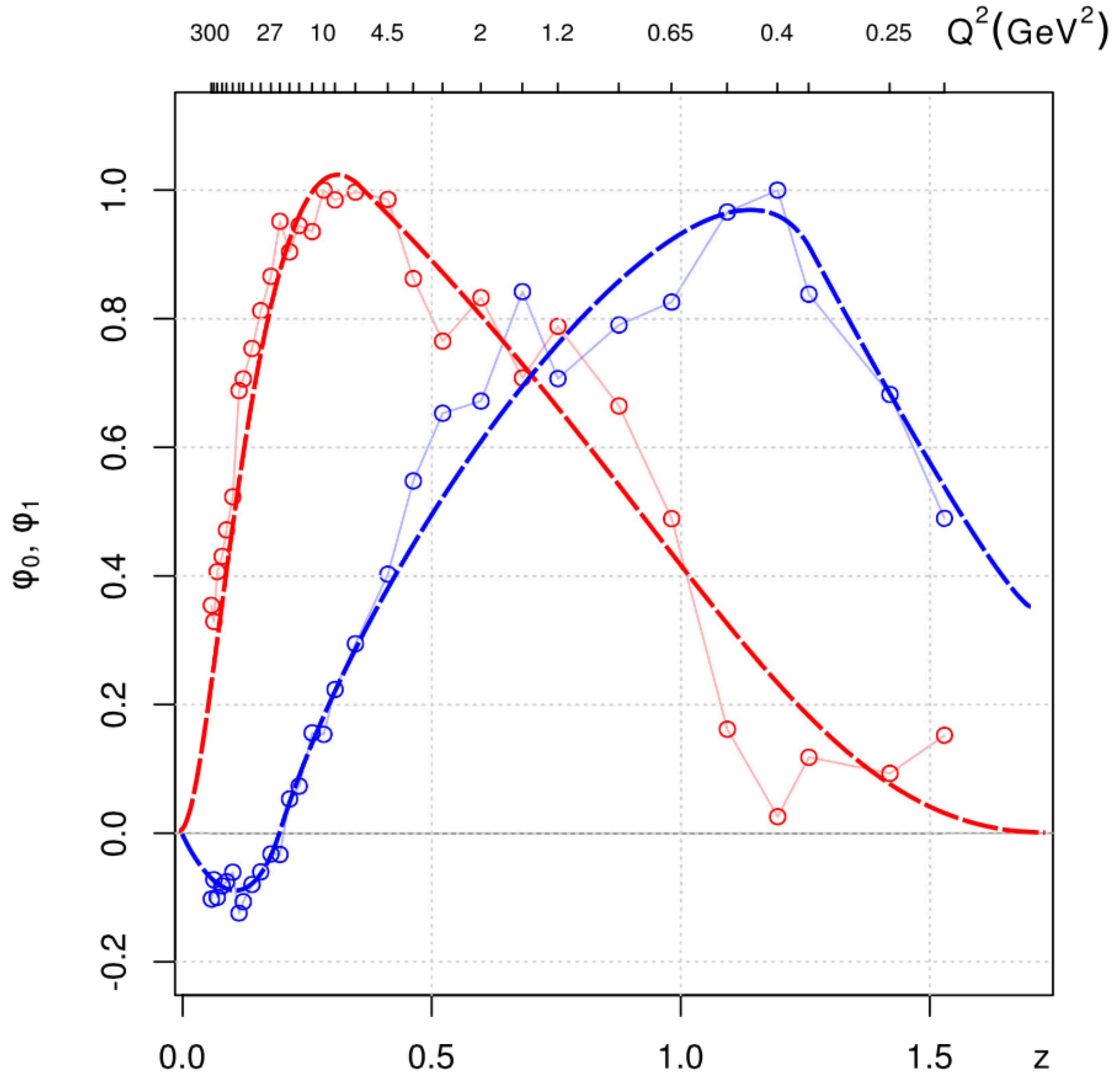
It seems data "knows" about holographic QCD!!





DIS from gauge/string duality

- Hadronic tensor $$W^{ab}(x, Q, t) = i \int d^4y \, e^{iq\cdot y} \langle P | T\{ j^a(y) \, j^b(0)\} | P' \rangle$$

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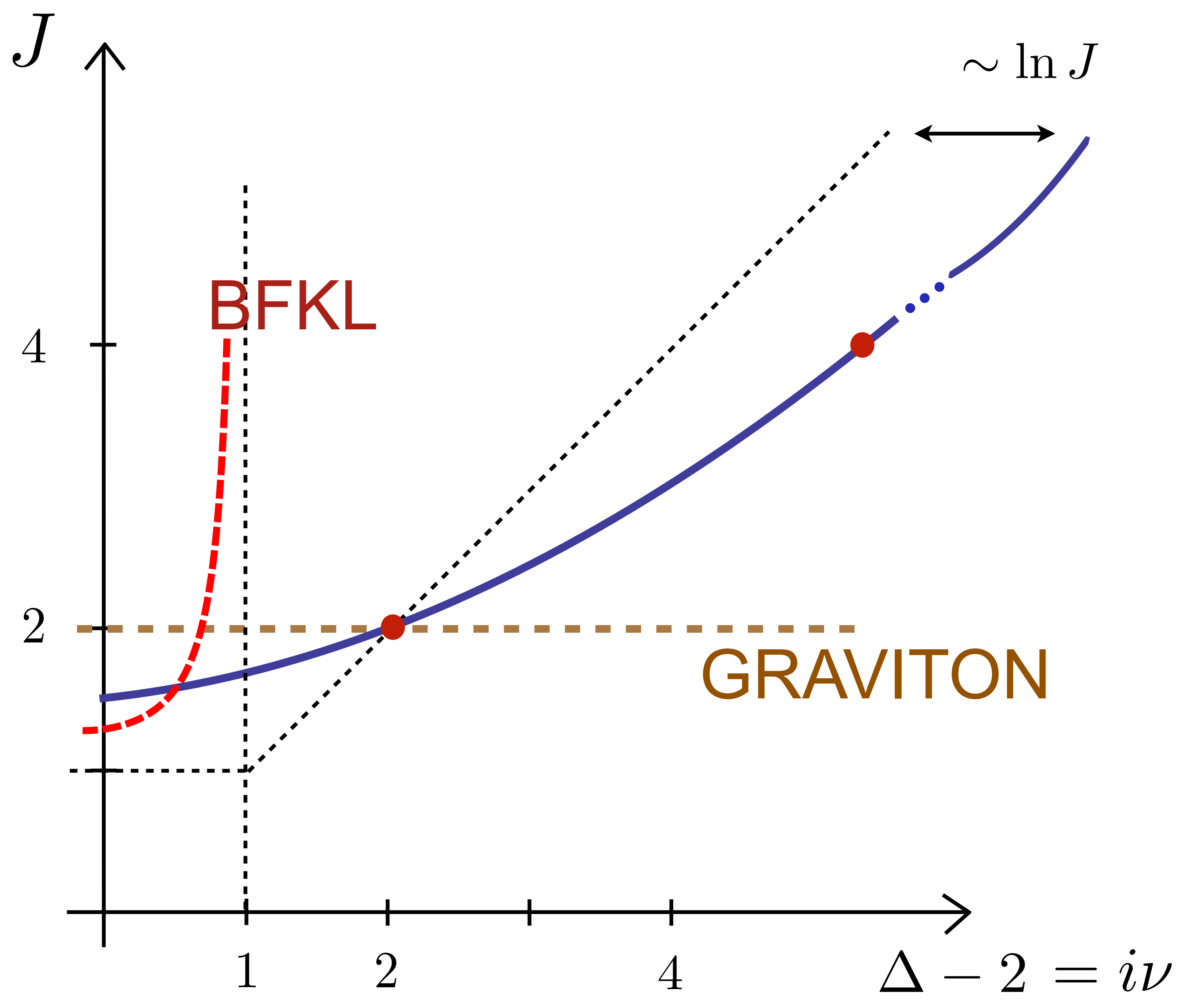

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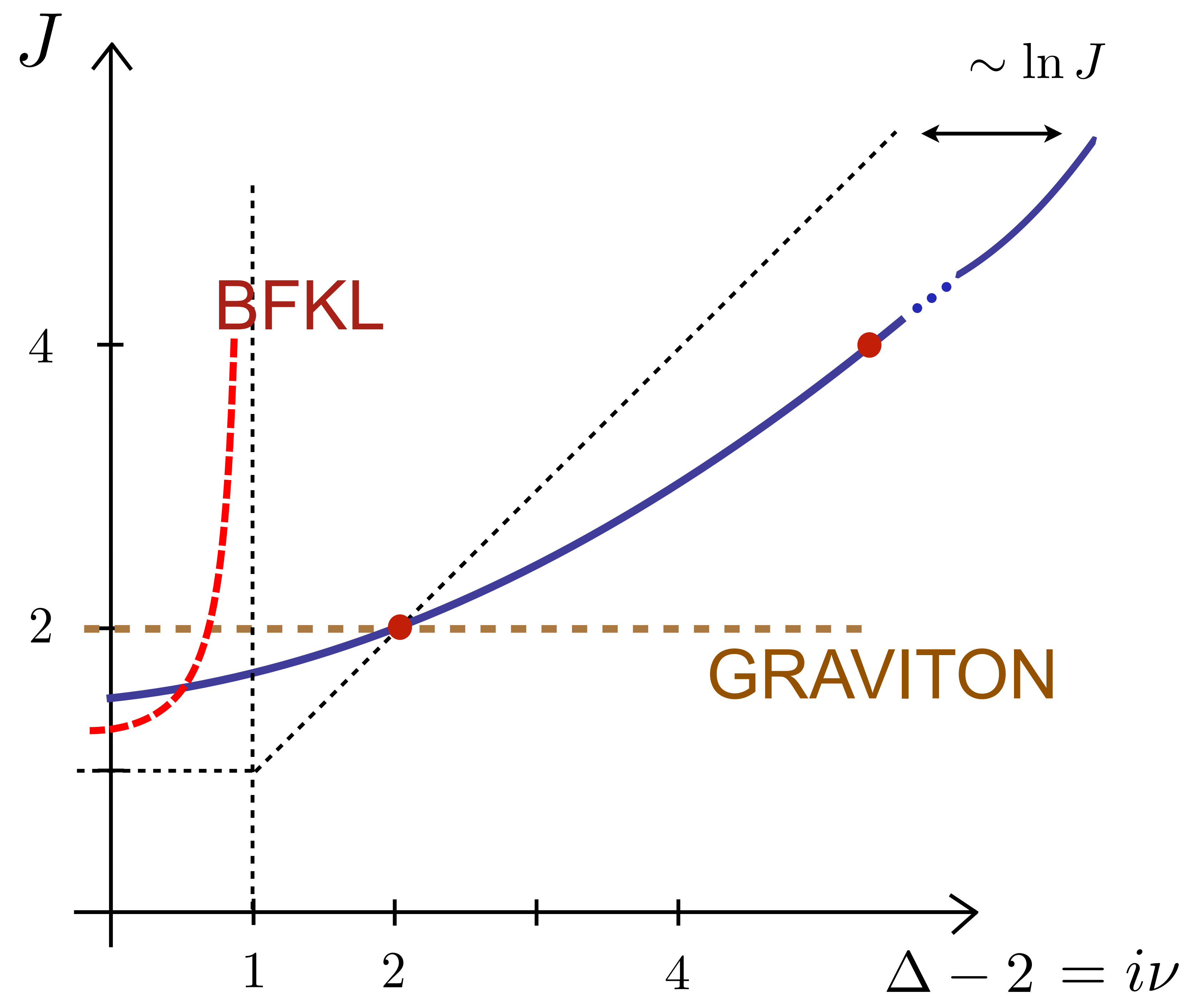

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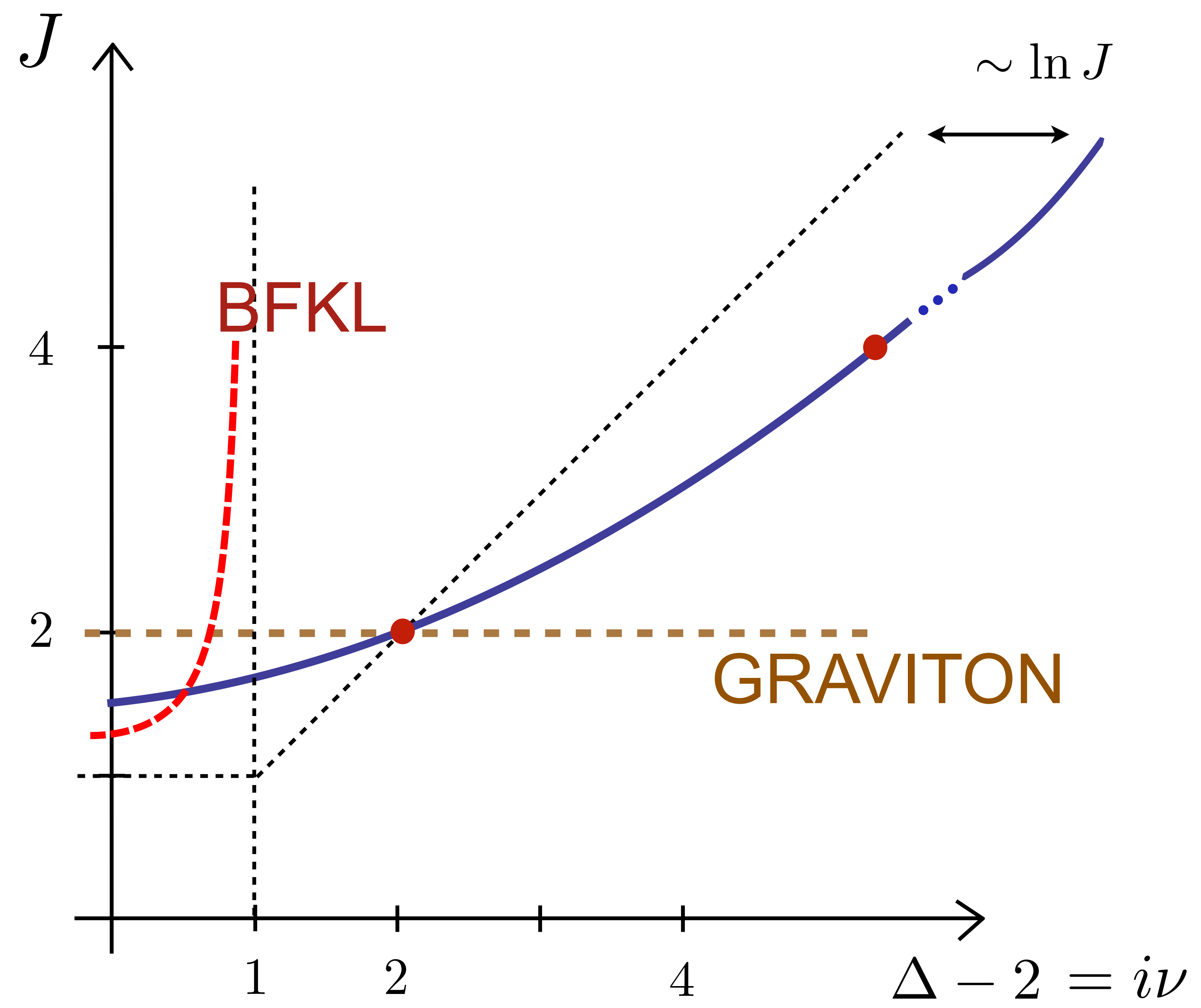

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Pomeron Kernel

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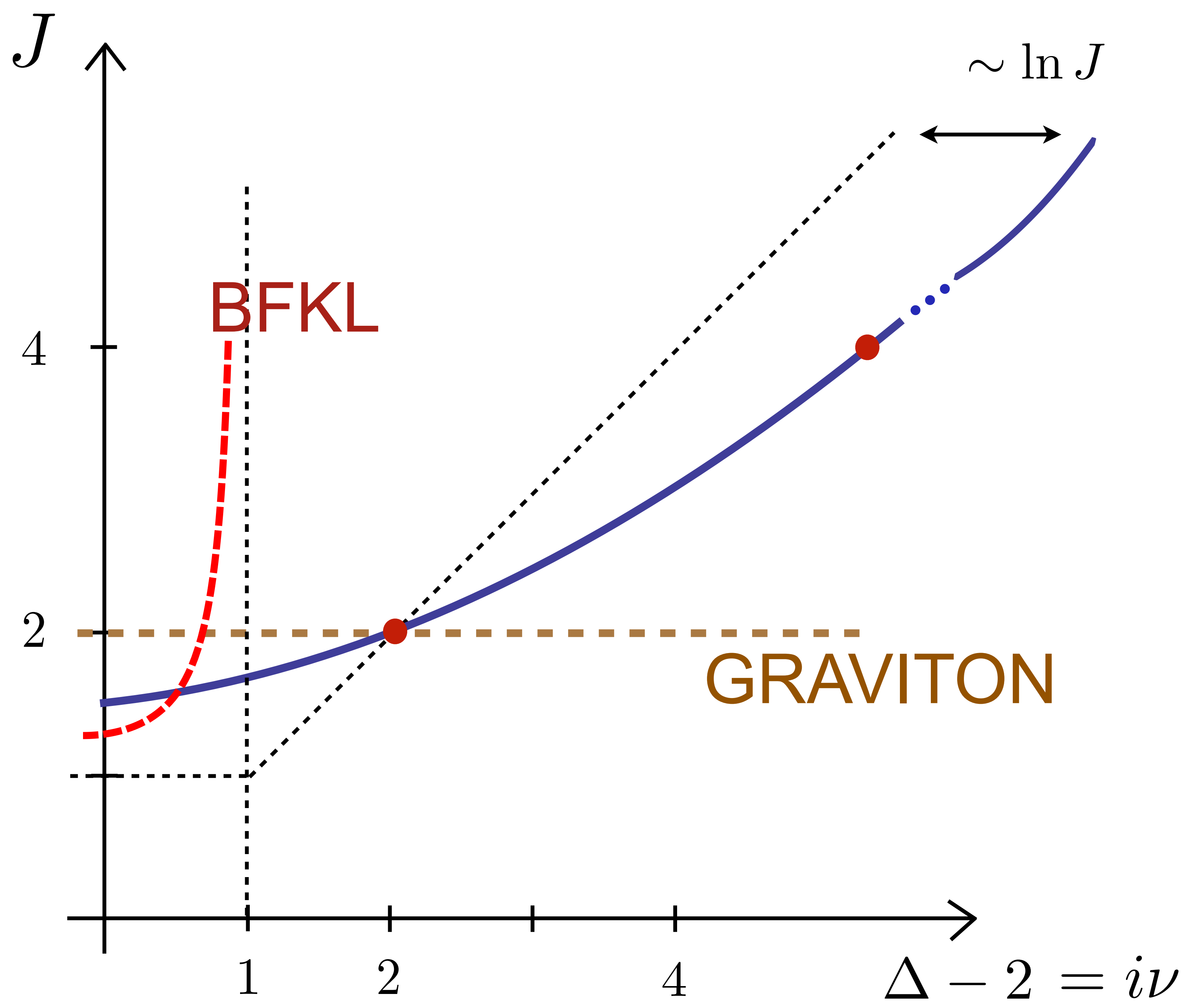

Holographic QCD

- QCD dual is a 5D theory with a graviton and a dilaton

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

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

AdS fields $\longleftrightarrow$ single trace operators

$$g_{ab} \leftrightarrow T_{\alpha\beta}$$

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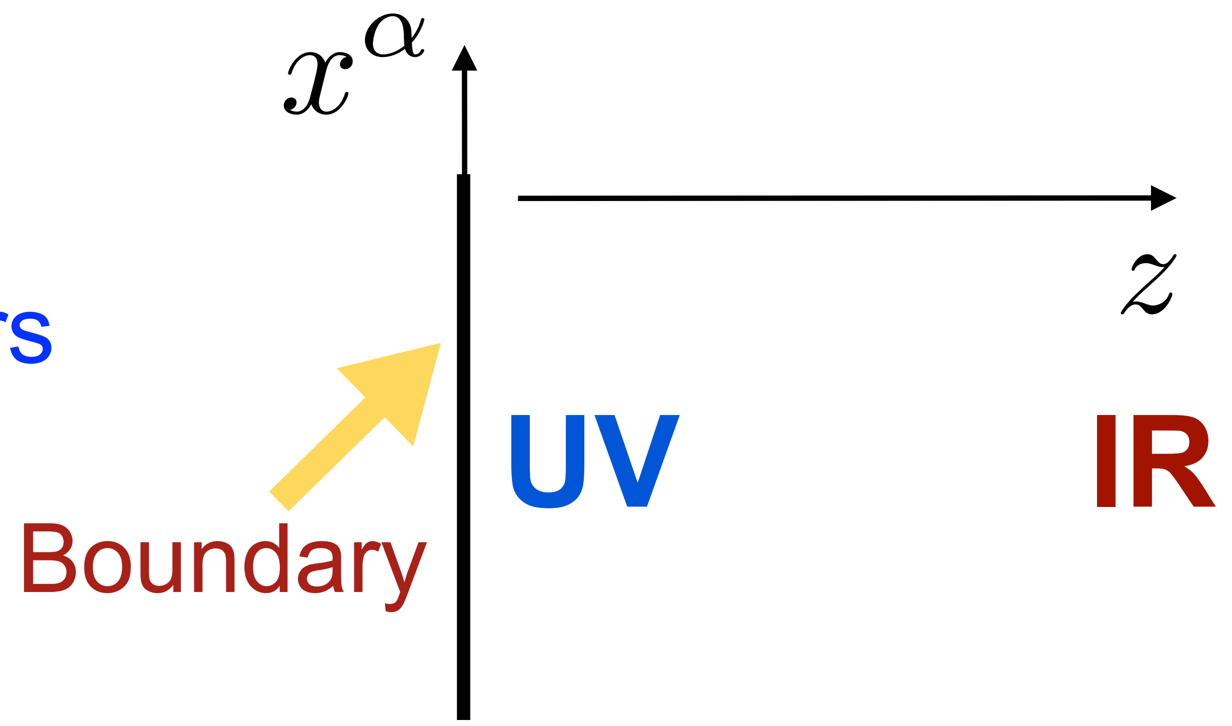

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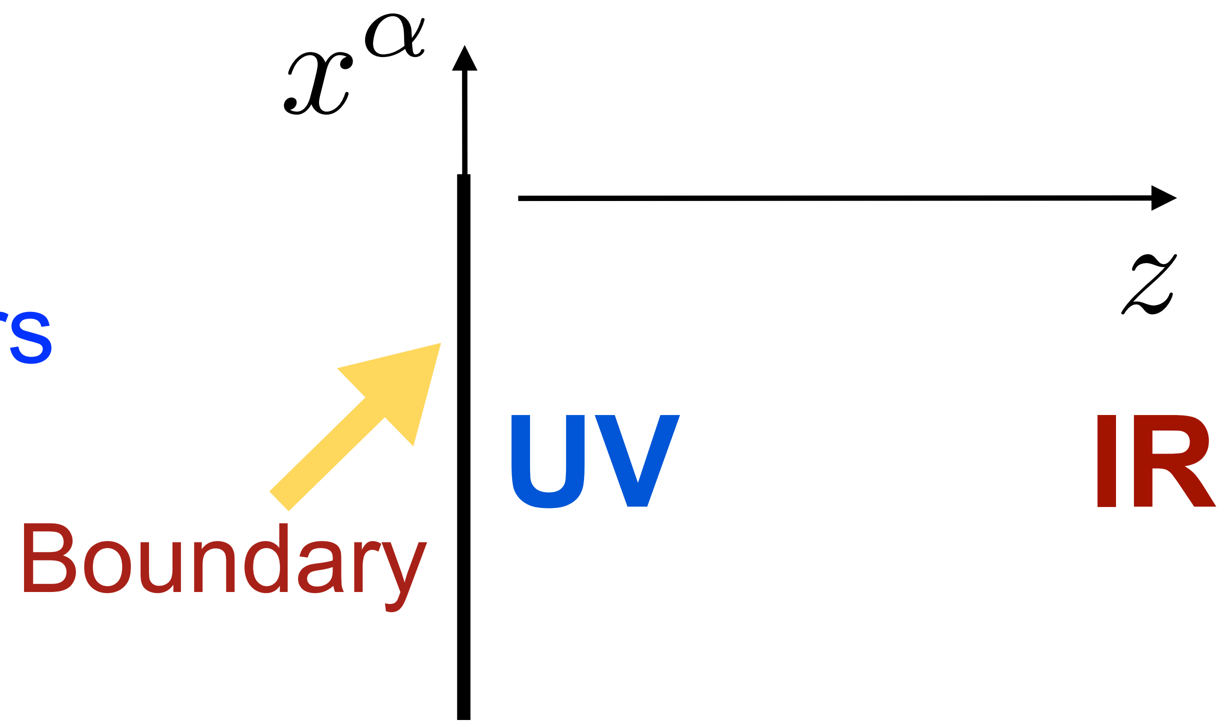

- Test our ideas with a 5D dilaton-gravity model [Gursoy, Kiritsis, Nitti 07]

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

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)

Spin J field in holographic QCD [Bayona, MSC, Djuric, Quevedo 15]

- 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, 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 $\left(D^2 - m^2\right) h_{a_1 \dots a_J} = 0 \qquad m^2 = \Delta(\Delta - 4) - J\,, \quad \Delta = \Delta(J)$
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Equation for propagating mode in effective field theory

$$\Big(\nabla^2 - 2\dot{\Phi}\nabla_z + J\dot{A}^2 e^{-2A} - \Delta(\Delta - 4) +$$
$$+ (J-2)e^{-2A}\left[a\ddot{\Phi} + b\dot{\Phi}^2 + c\left(\ddot{A} - \dot{A}^2\right)\right]\Big) h_{\alpha_1 \dots \alpha_J} = 0$$

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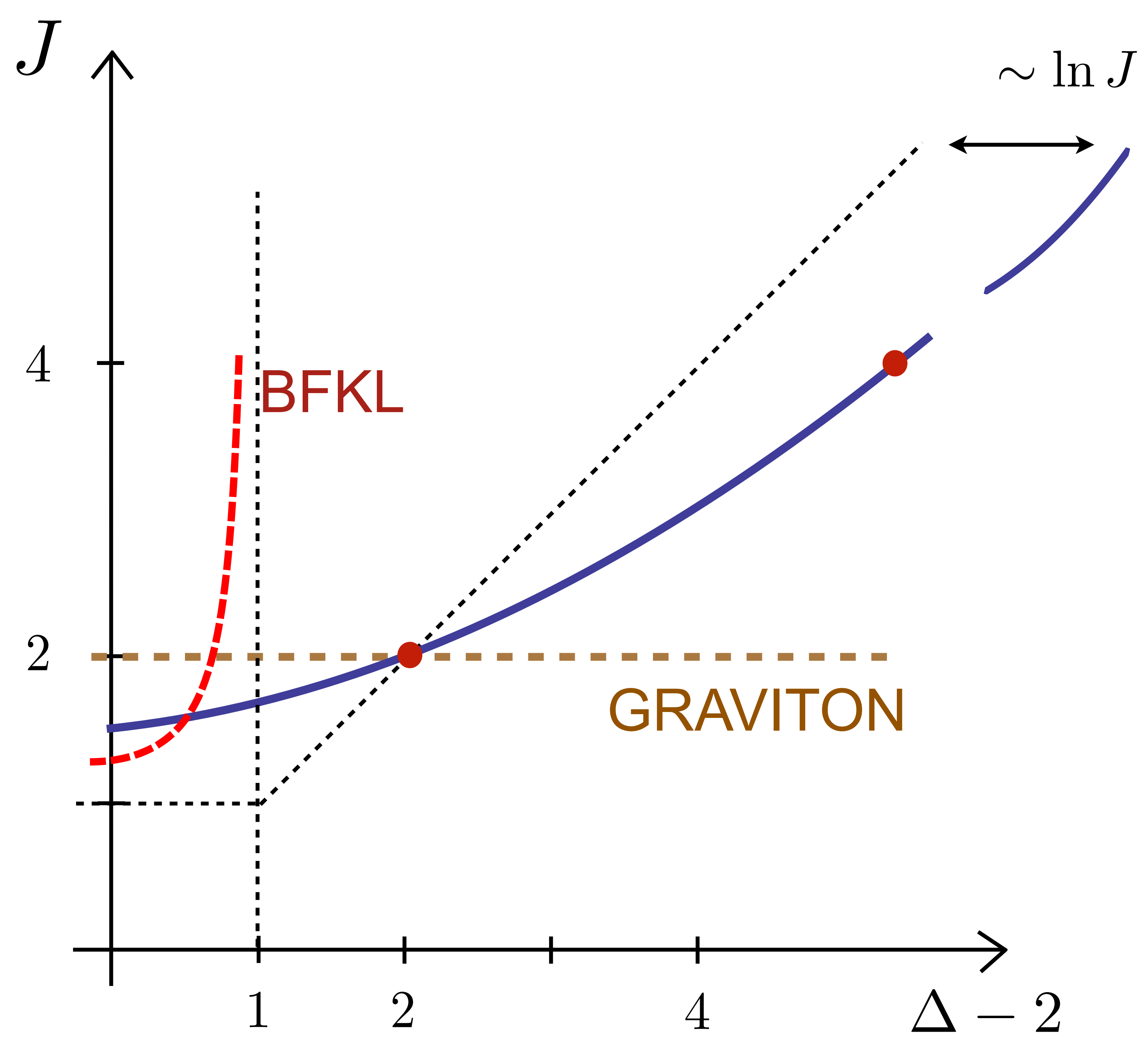
$$\Delta(\Delta - 4) \approx \frac{2}{l_s^2}(J-2)\left(1 + d\, e^{-\Phi/2}\right) + e^{-4\Phi/3}\left(J^2 - 4\right)$$

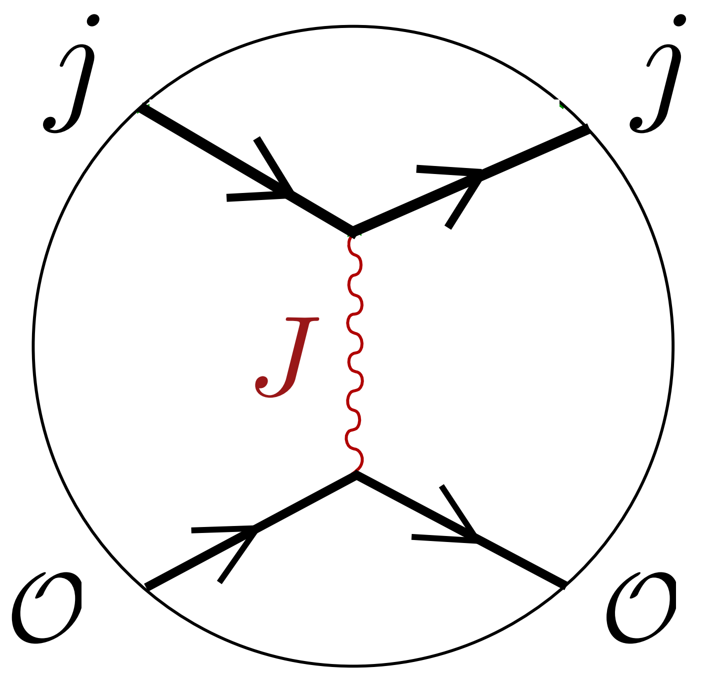
IR described by graviton trajectory

UV free theory unitarity bound



Many Regge trajectories

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



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

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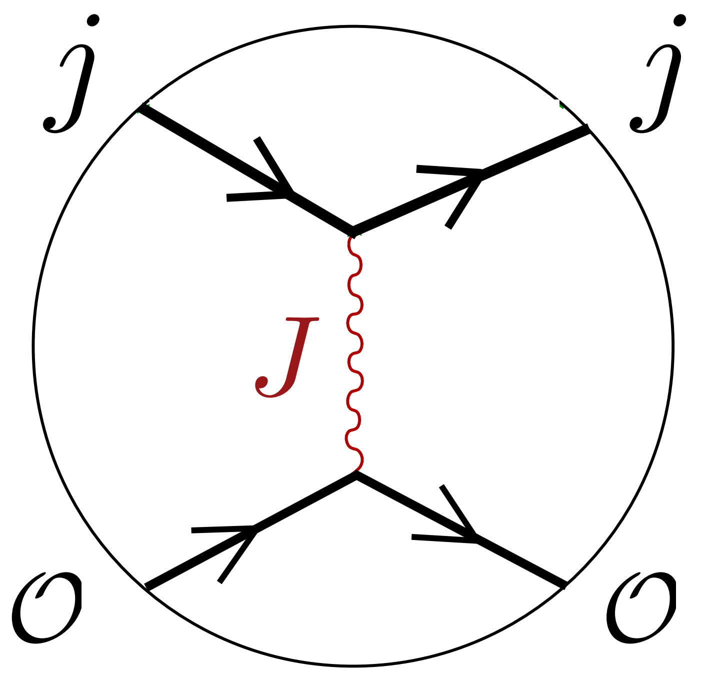

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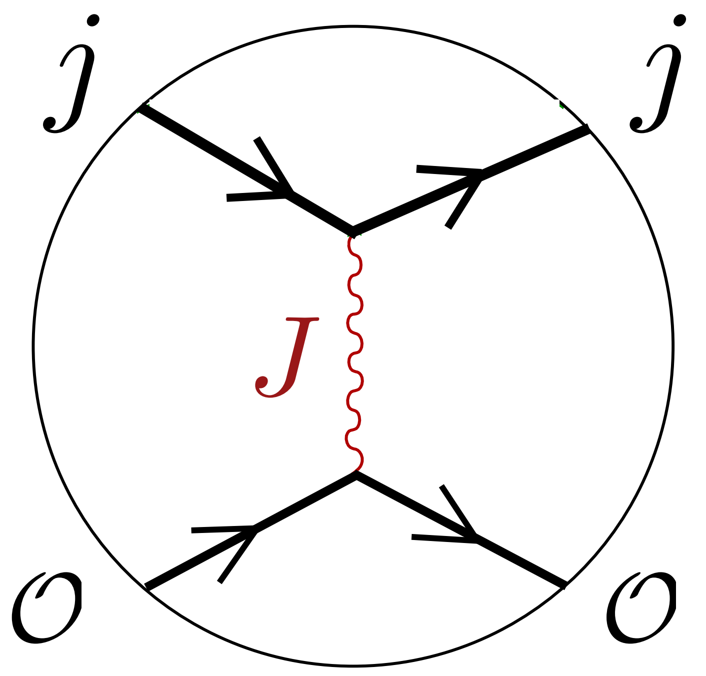

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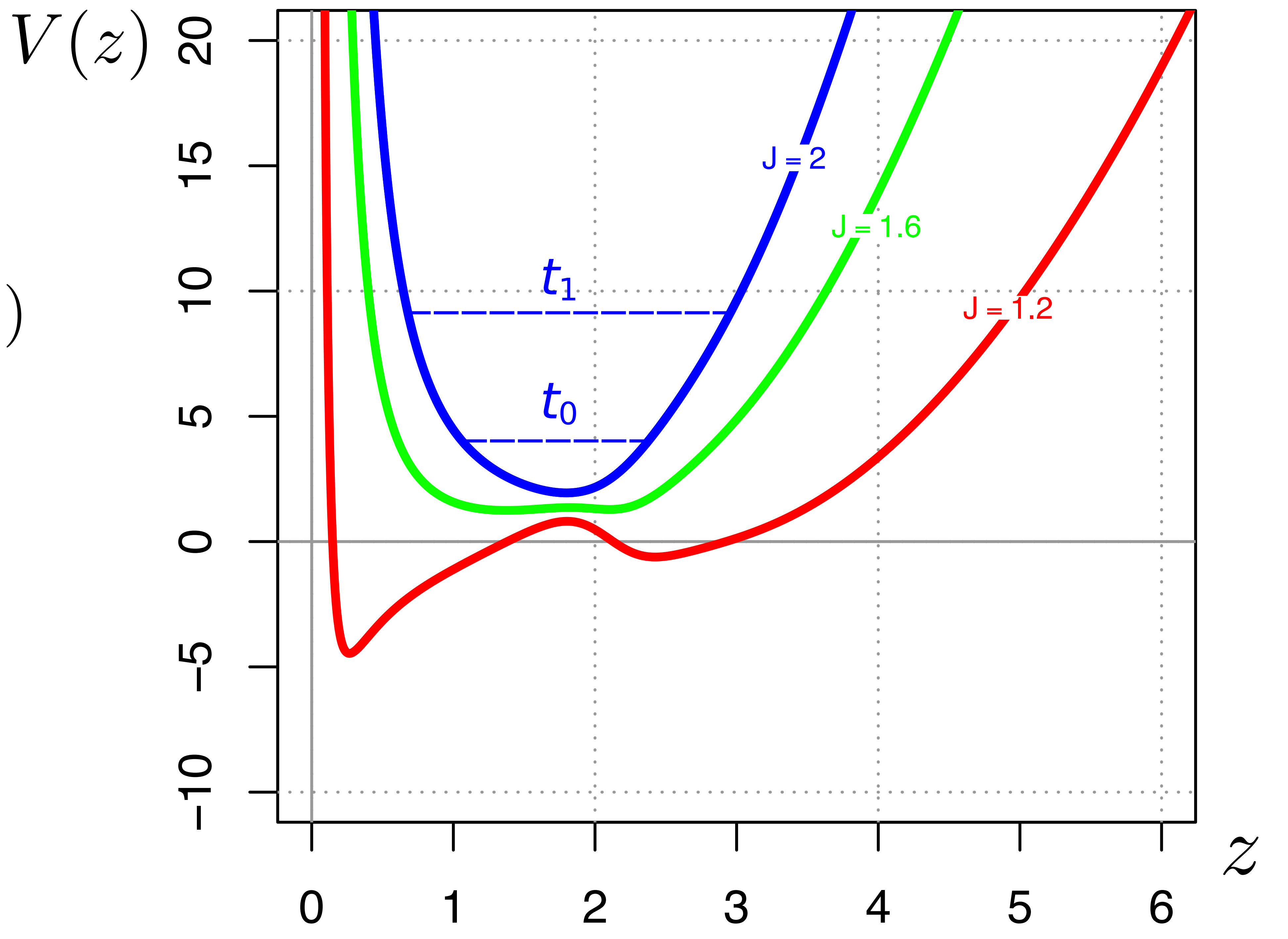
Reduces to a Schrodinger problem (spectral representation)

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



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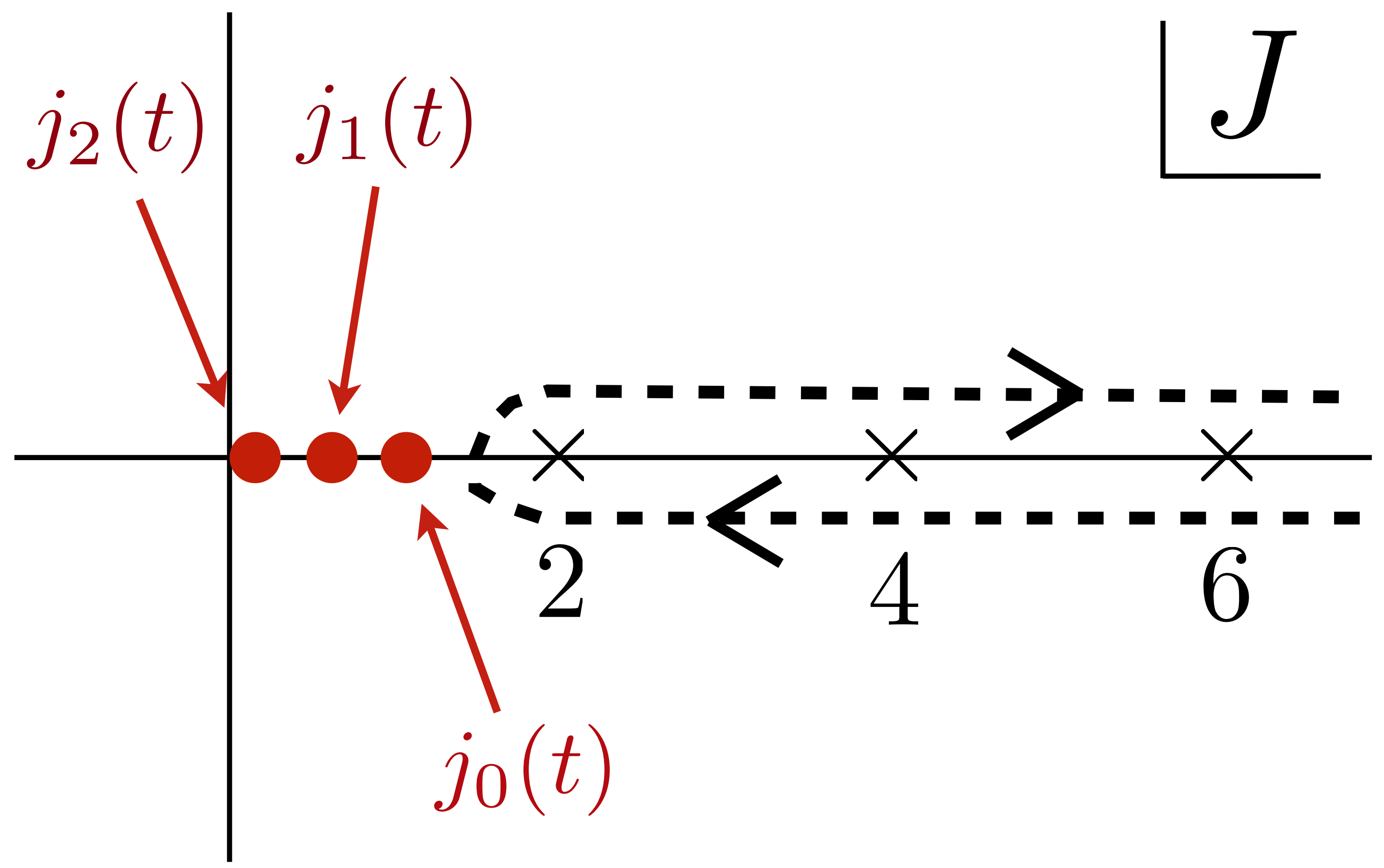

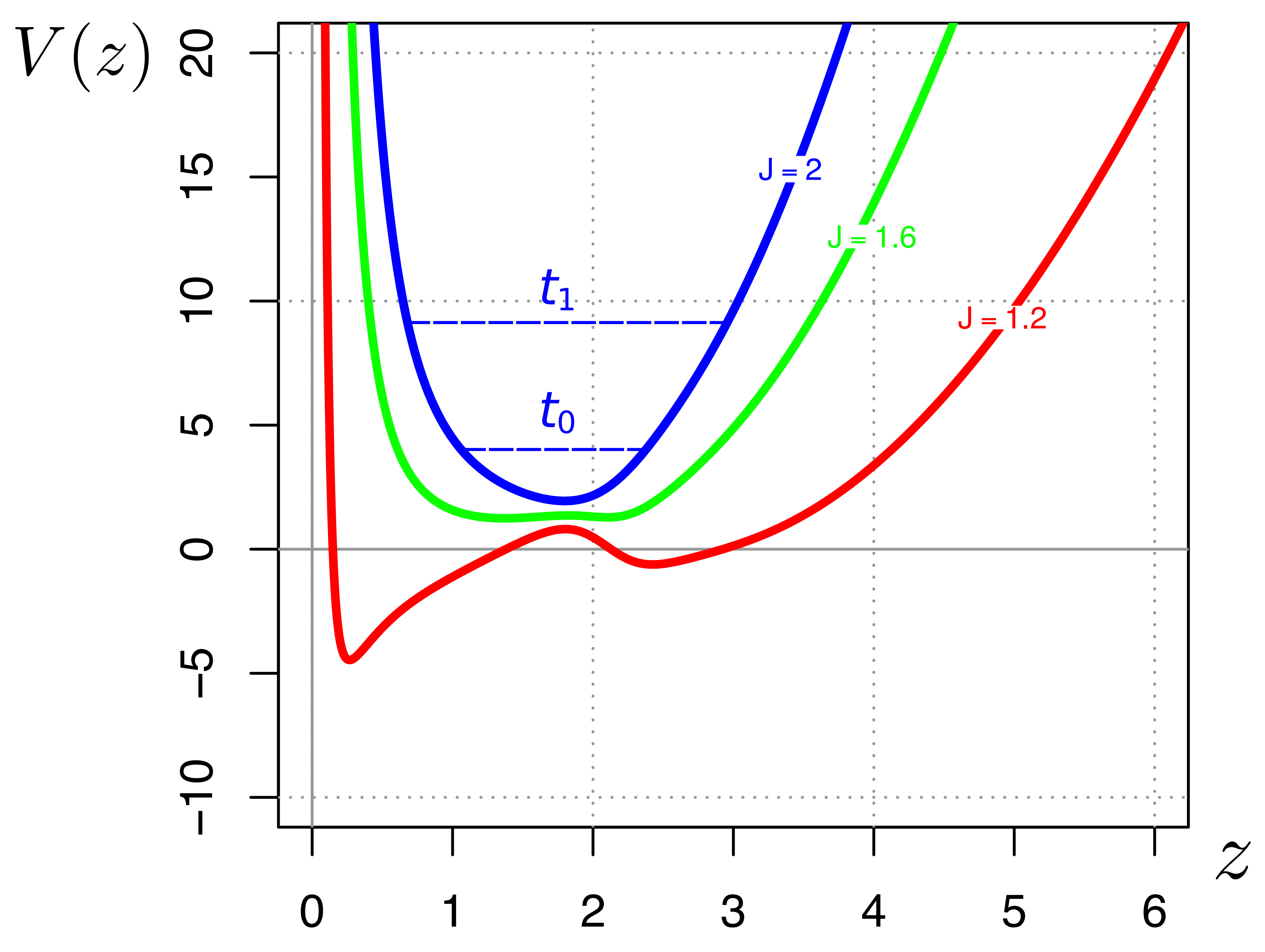

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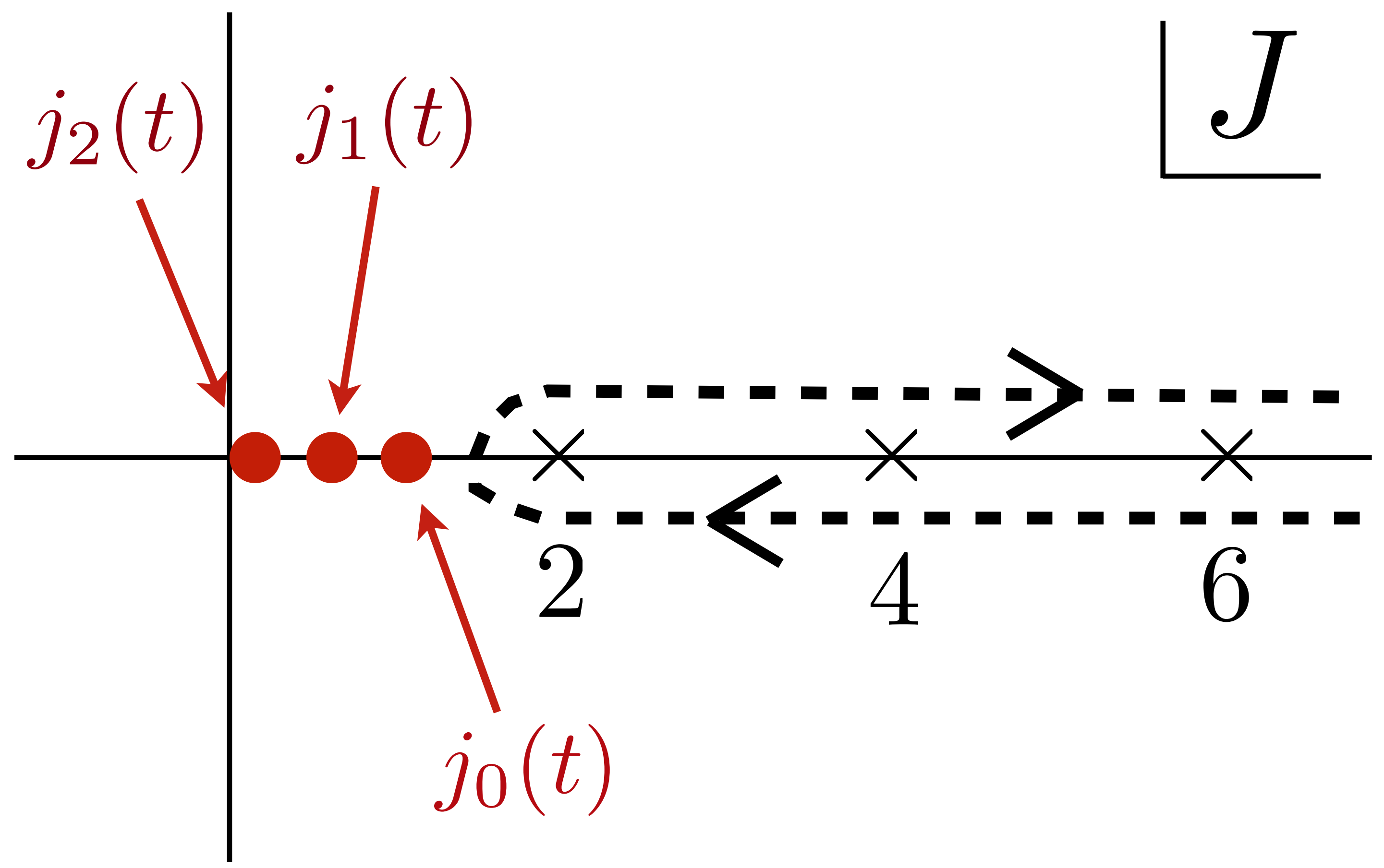

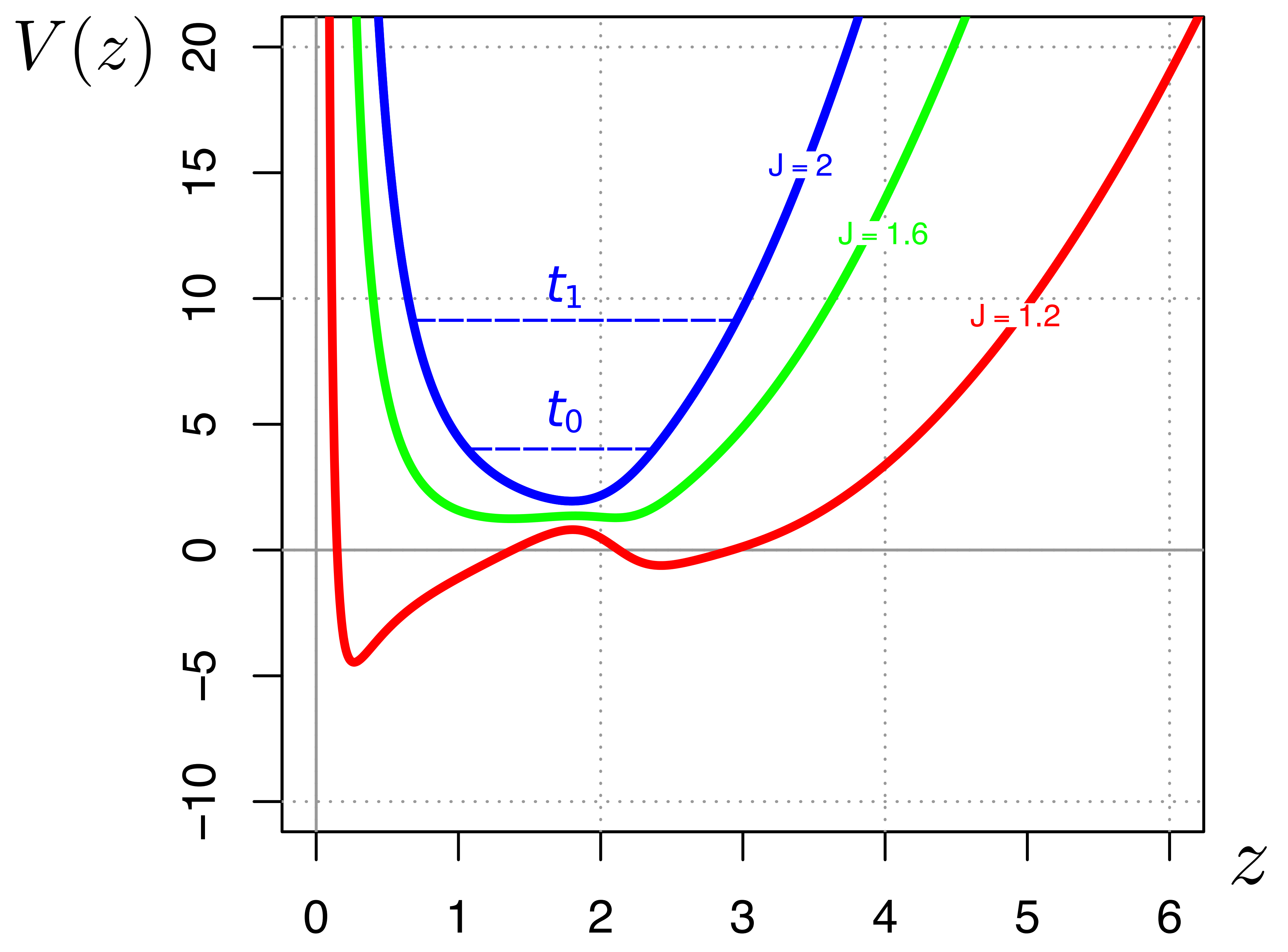

- At the end of the day, structure function is of the form

$$F_2(x, Q^2) = \sum_n g_n \, Q^{2 j_n(0)} \bar{P}_{13}(Q^2) \, x^{1 - j_n(0)}$$

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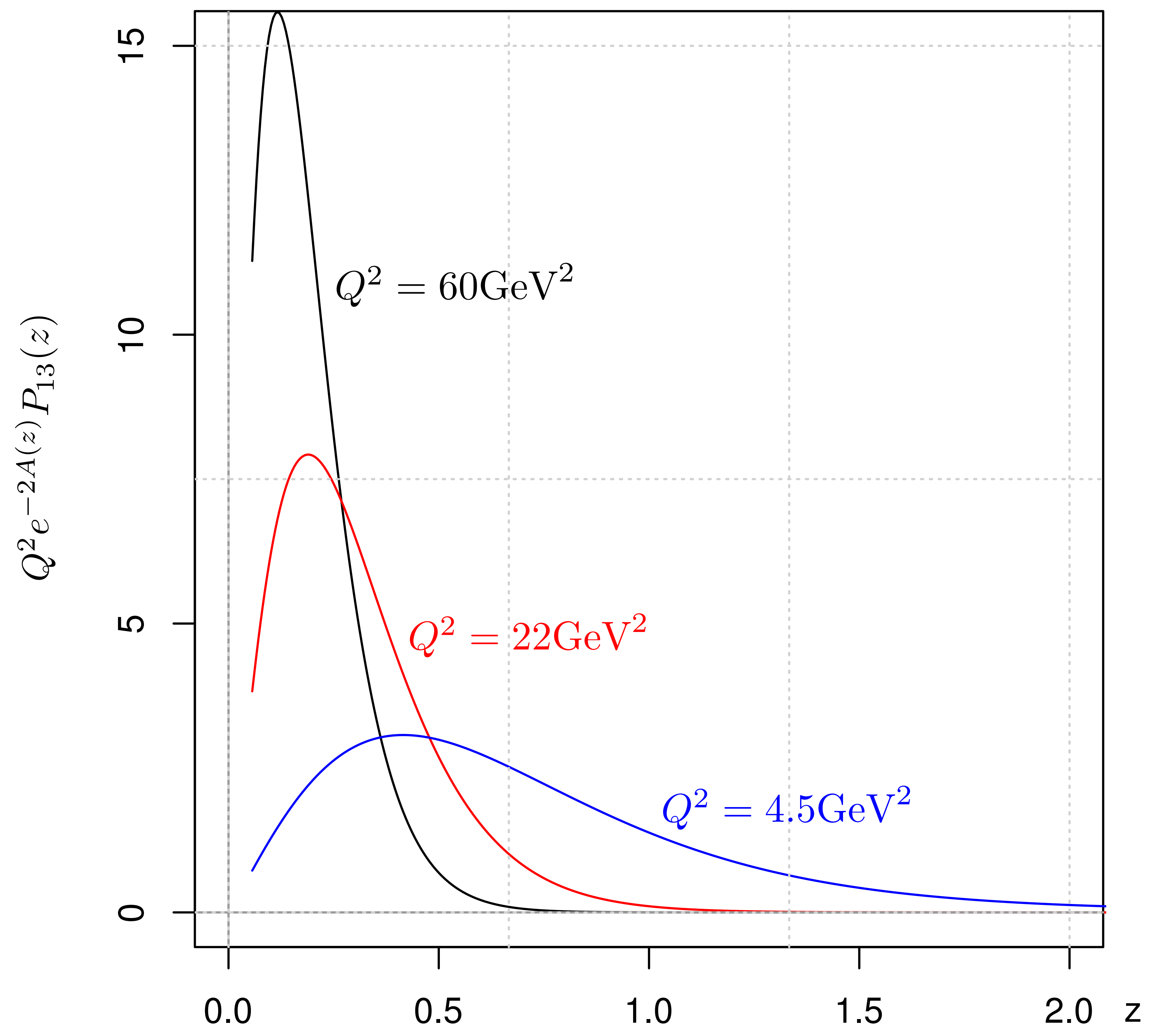
- Dependence on virtual photon wave function

$$\bar{P}_{13}(Q^2) = \int dz\, P_{13}(Q^2,z)\, e^{(1-j_n(0))A(z)} e^{B(z)} \psi_n(j_n(0),z)$$



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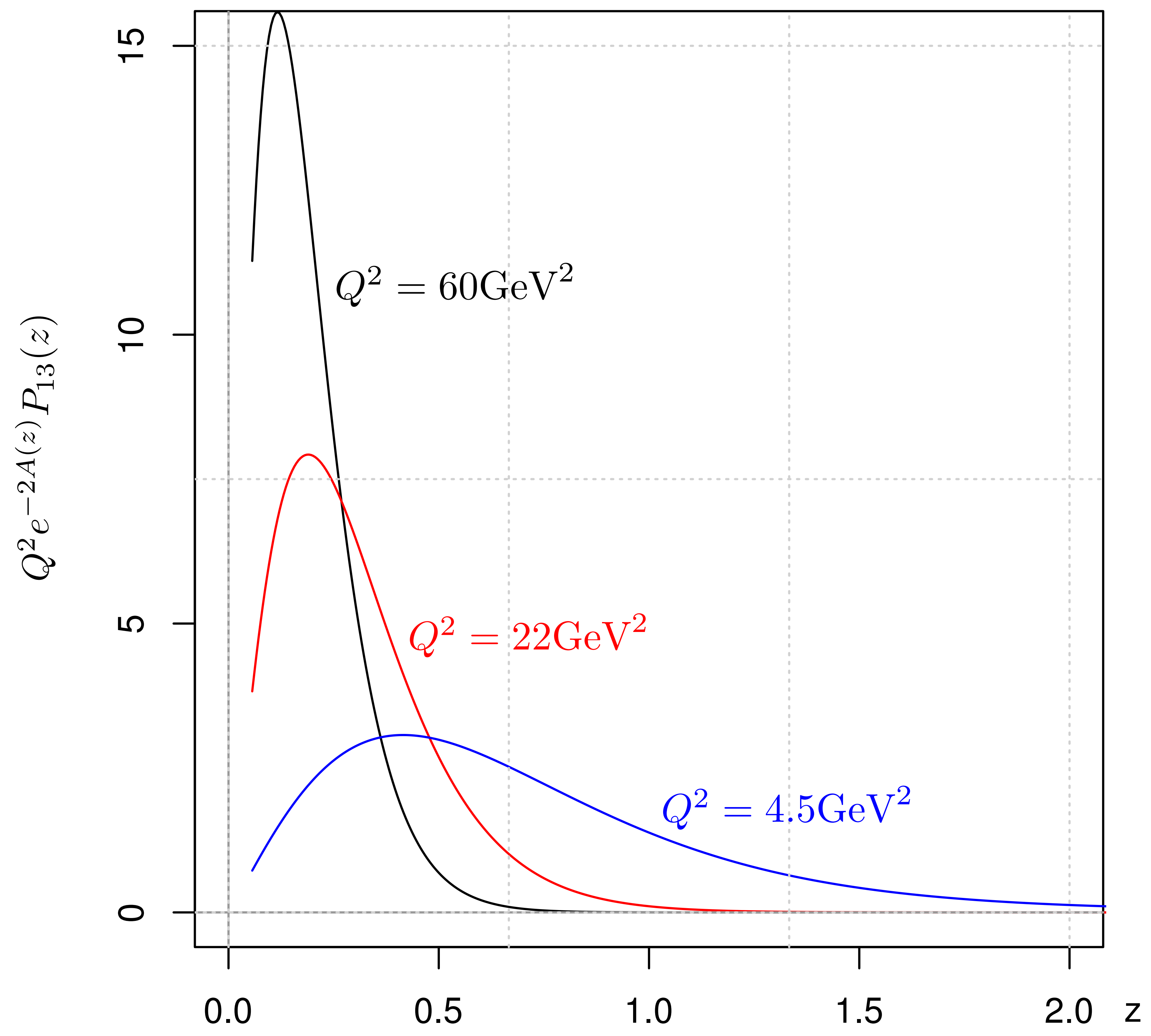
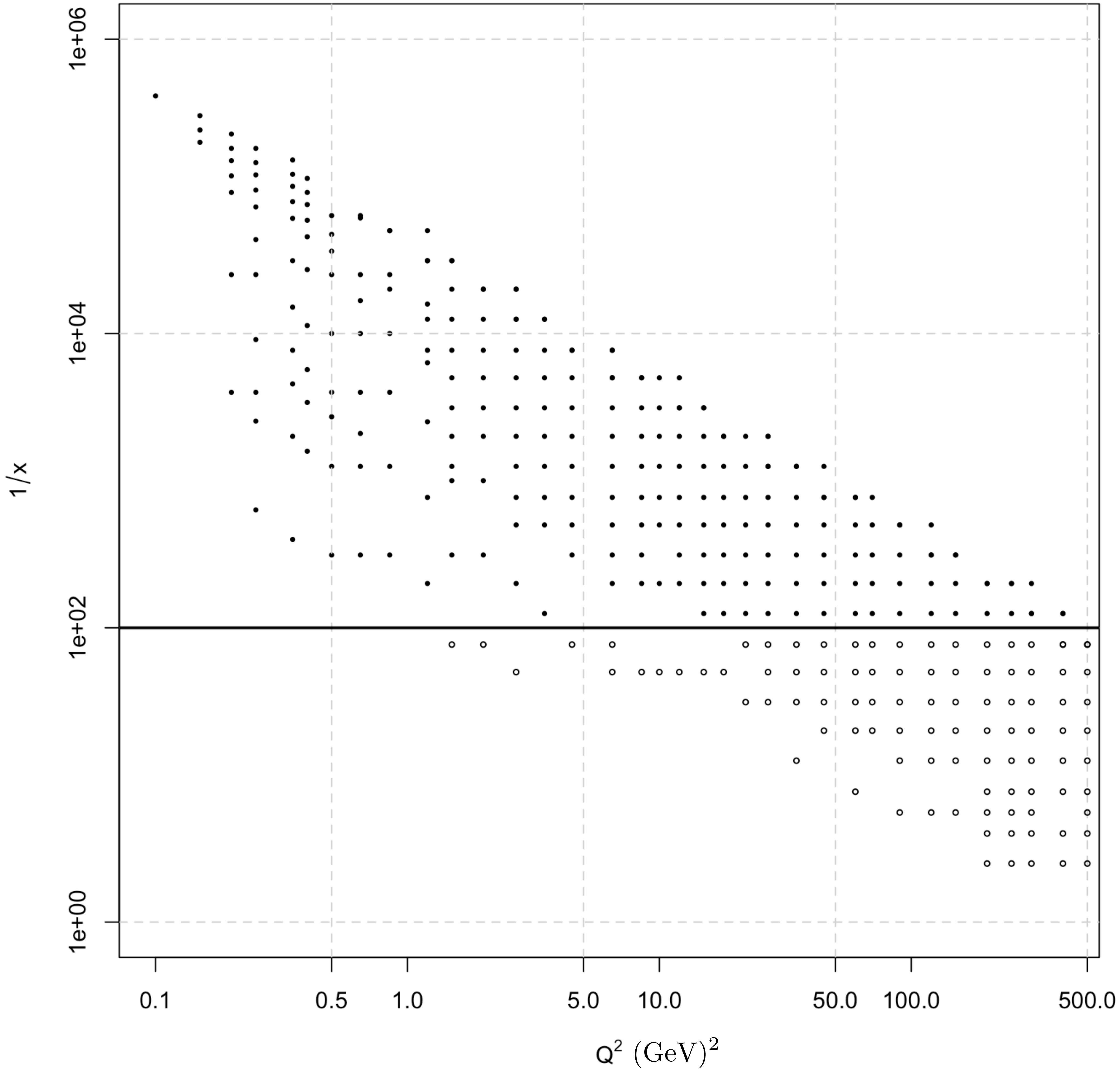


- Dependence on fixed target absorbed in coupling

$$g_n = -2\pi^2 \frac{\kappa_{j_n(0)} \bar{\kappa}_{j_n(0)}}{2^{j_n(0)}}\, j_n'(0) \int dz\, P_{24}(P^2,z)\, e^{(1-j_n(0))A(z)} e^{B(z)} \psi_n^*(j_n(0),z)$$

Test model agains low x DIS data from HERA



Truncated data to $x < 0.01$ region.
Has 249 data points and large range in Q

$$\left(0.1 < Q^2 < 400 \text{ GeV}^2\right)$$

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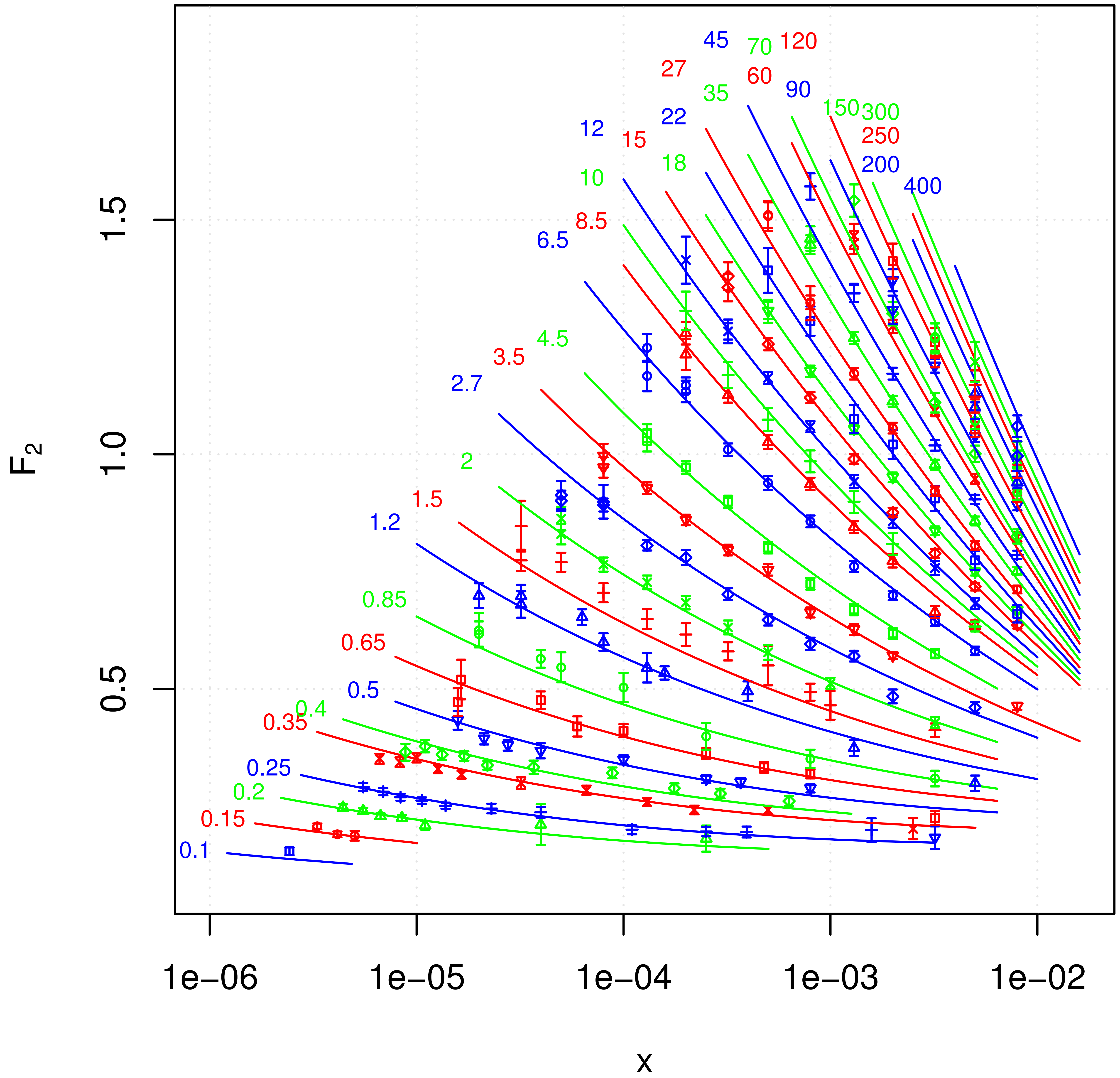

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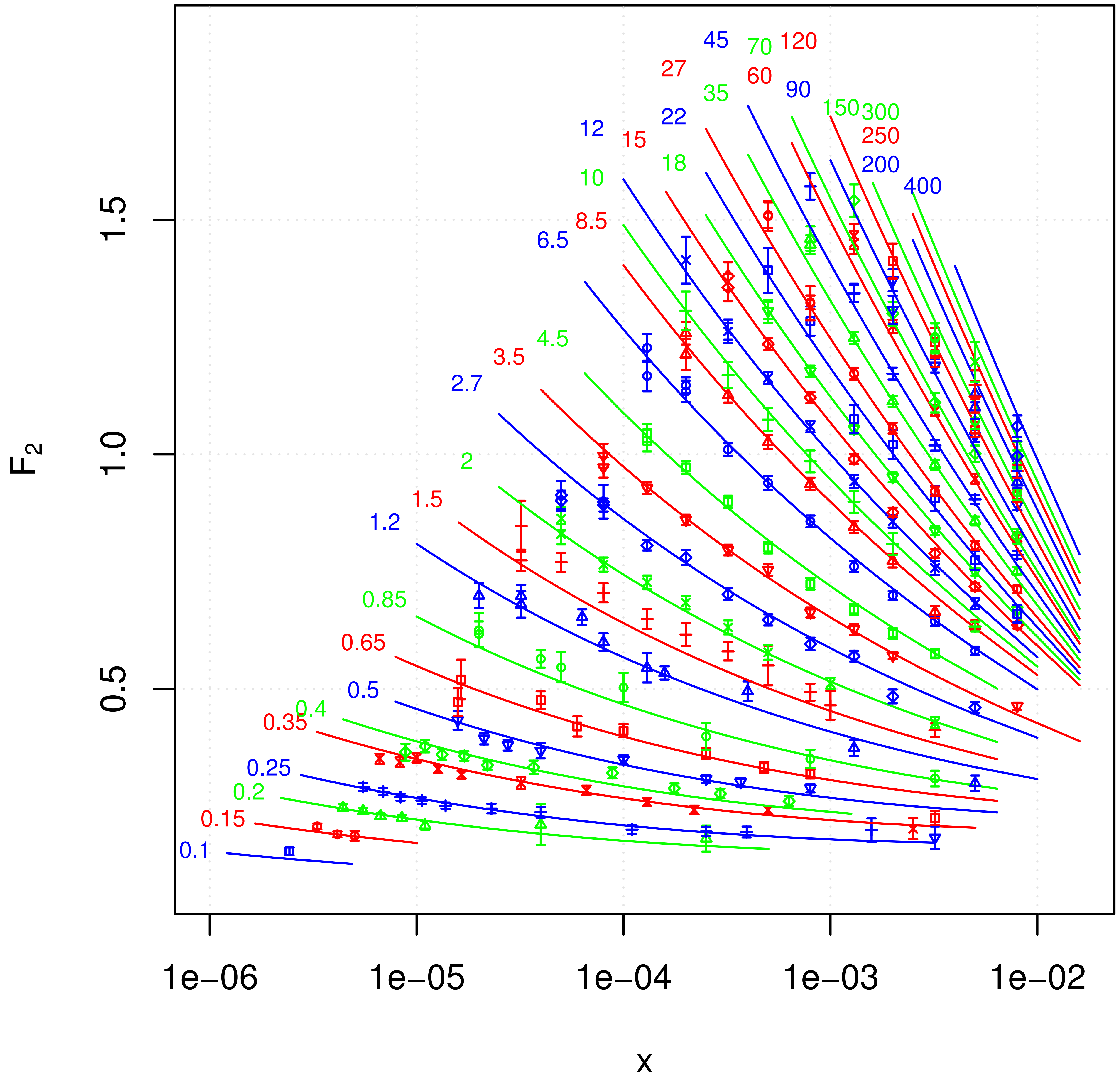

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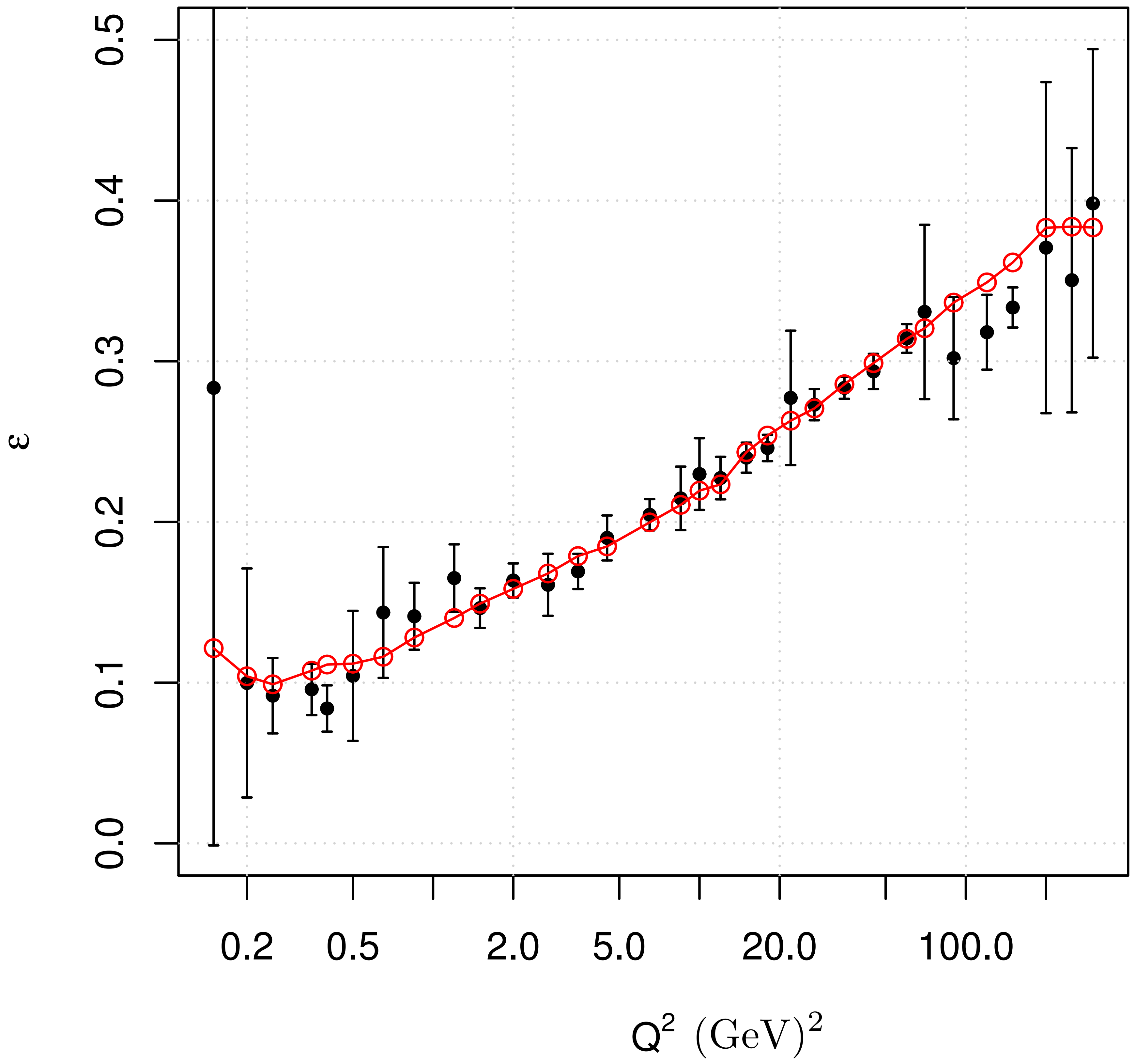
Parameters fixed with $\chi^2 = 1.7$

Pomeron equation coefficients	coupling	Intercept
$a = -4.35$	$g_0 = 0.175$	$j_0 = 1.17$
$b = 1.41$	$g_1 = 0.121$	$j_1 = 1.09$
$c = 0.626$	$g_2 = 0.297$	$j_2 = 0.969$
$d = -0.117$	$g_3 = -1.63$	$j_3 = 0.900$
$l_s = 0.153 \text{ GeV}^{-1}$	–	–

• Reproduced long sought running of effective exponent

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



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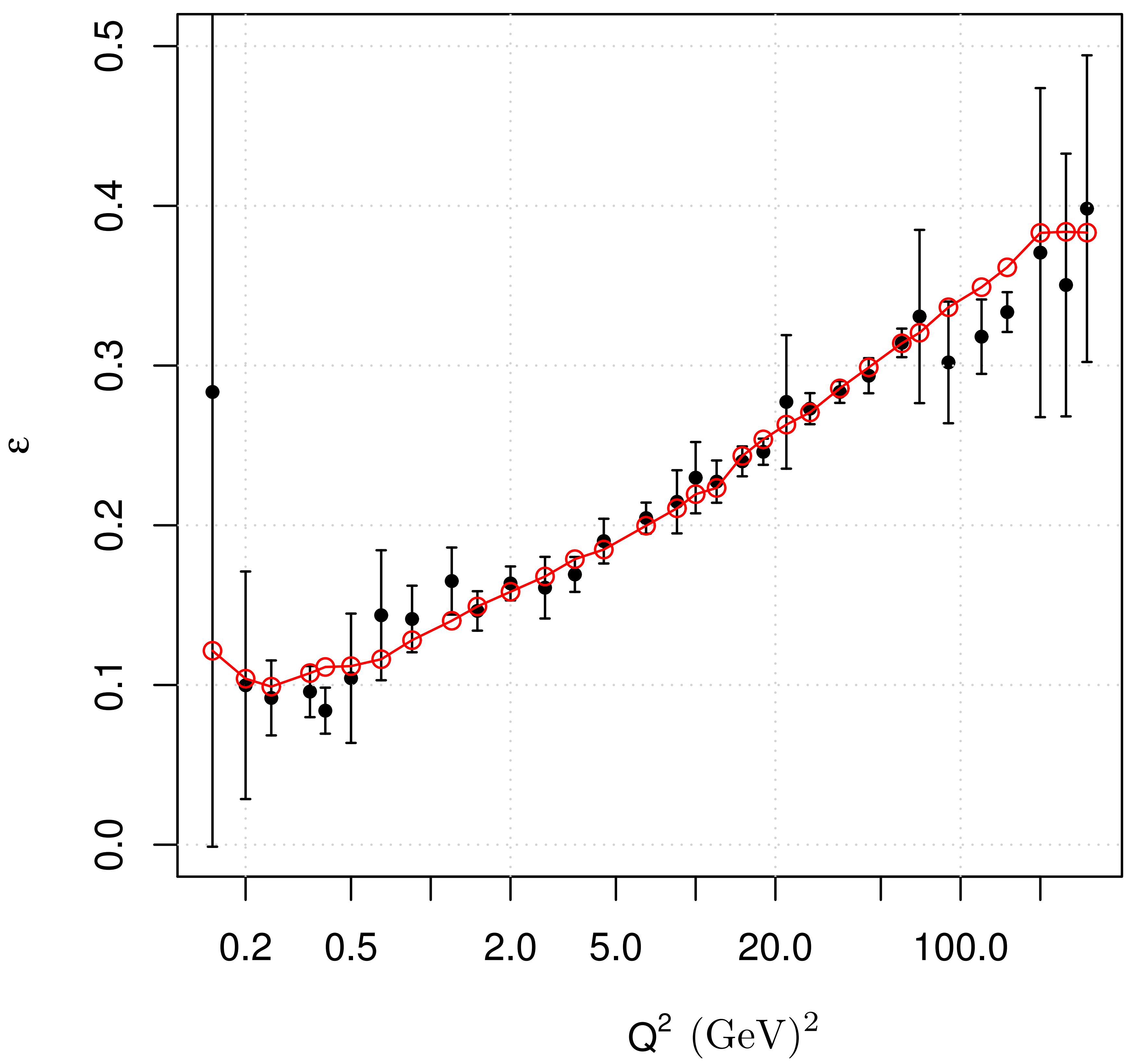

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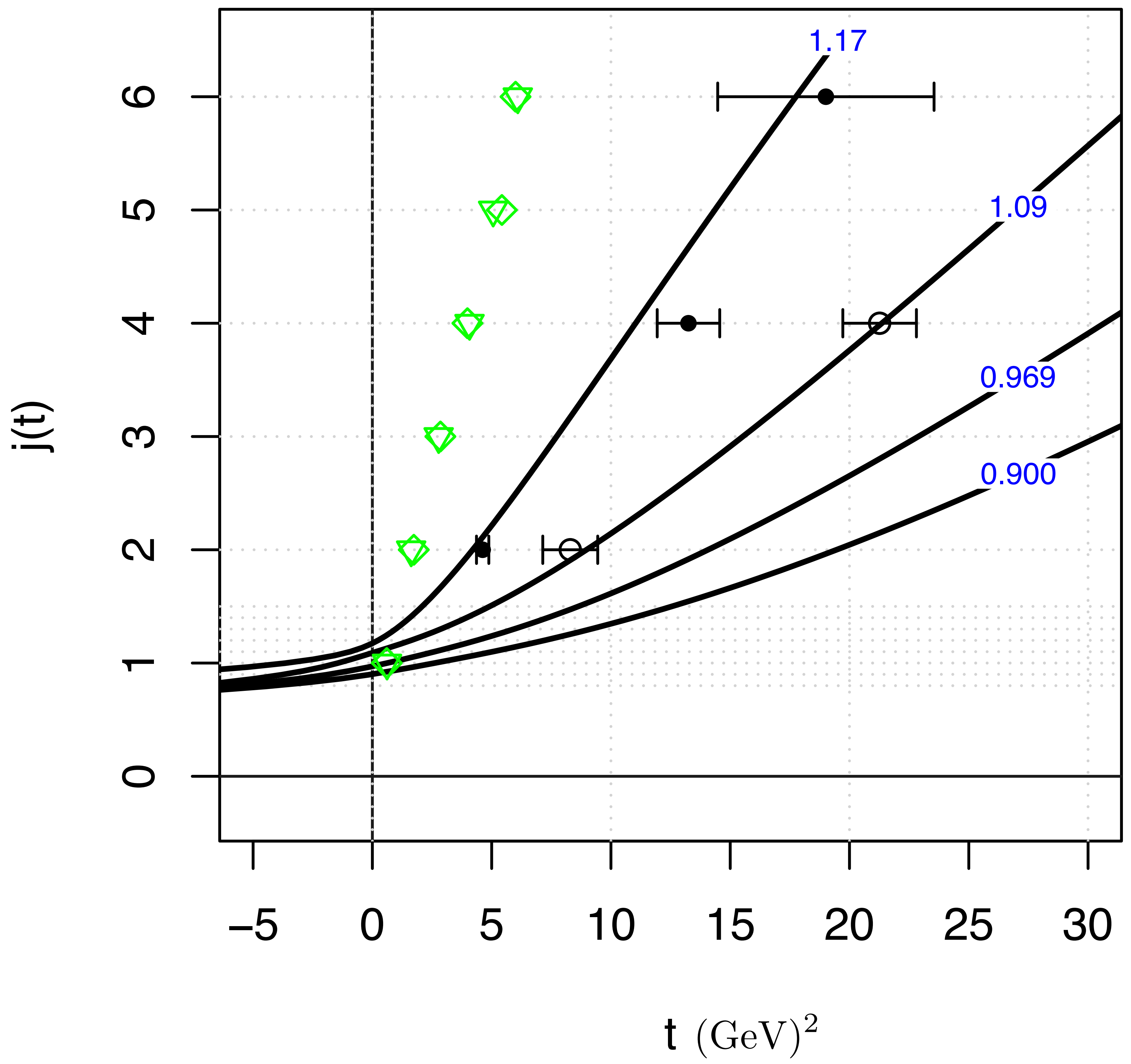
- Regge trajectories consistent with lattice [Meyer 05] QCD glueball spectrum!



In green meson trajectories

Shape matches [Caron-Huot, Komargodski, Sever, Zhiboedov et al 16]

EMG current and Reggeon non-minimal coupling [Amorim, MSC, Quevedo 18]

• So far considered minimal coupling between U(1) gauge field and graviton trajectory. But for graviton perturbations in AdS there are two possible couplings

$$\int d^5X\sqrt{-g}\,e^{-\Phi}\left(F_{ab}F^{ab}+\beta R_{abcd}F^{ab}F^{cd}\right) \longrightarrow \quad F^{ac}F^{b}{}_{c}h_{ab}\,, \quad F^{ac}F^{bd}\nabla_c\nabla_d h_{ab}$$

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- Generalized to spin J field in graviton Regge trajectory [Robert talk]

$$F_2(x,Q^2)=\sum_n\Big(f_n^{\rm MC}(Q^2)+f_n^{\rm NMC}(Q^2)\Big)x^{1-j_n}$$

$$f_n^{\rm MC}(Q^2)=g_nQ^{2j_n}\int dz\,e^{-(j_n-\frac{3}{2})A}\left(f_Q^2+\frac{\dot f_Q^2}{Q^2}\right)\psi_n$$

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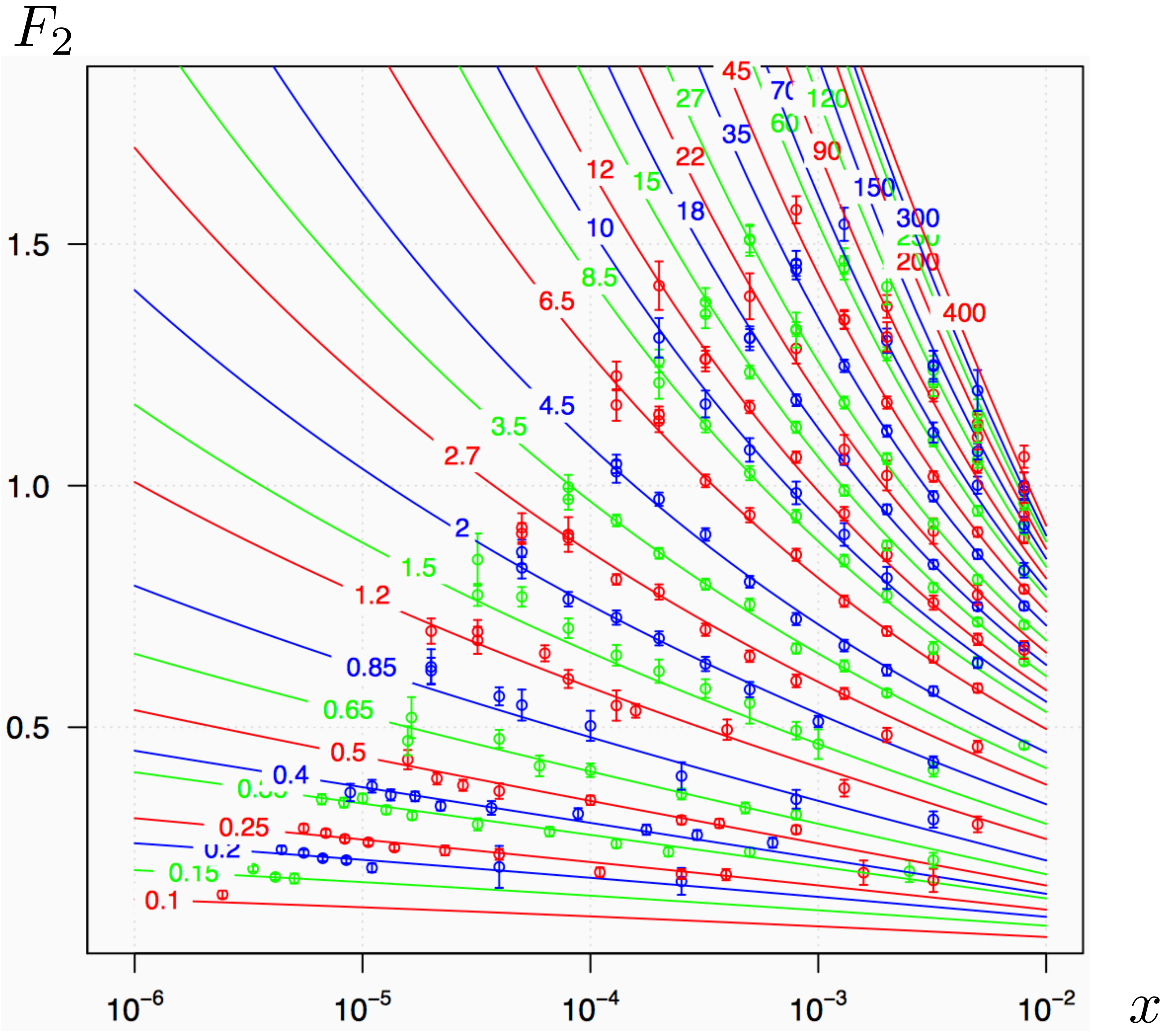
$$A_\mu^\lambda\,(X;k)=n_\mu^\lambda\,f_k(z)\,e^{ik\cdot x}$$

$$\tilde{\mathcal{D}}_\perp=e^{-2A}\left(\dot A\partial_z+\dot A^2+\dot A\dot B\right)$$

$$\tilde{\mathcal{D}}_\parallel=e^{-2A}\left(\partial_z^2-(\dot A-2\dot B)\partial_z+\ddot B+\ddot A+\dot B^2-\dot A\dot B\right)$$

- Quality of fit improved significantly!

$$\chi^2_{\mathrm{d.o.f.}} = 1.1$$



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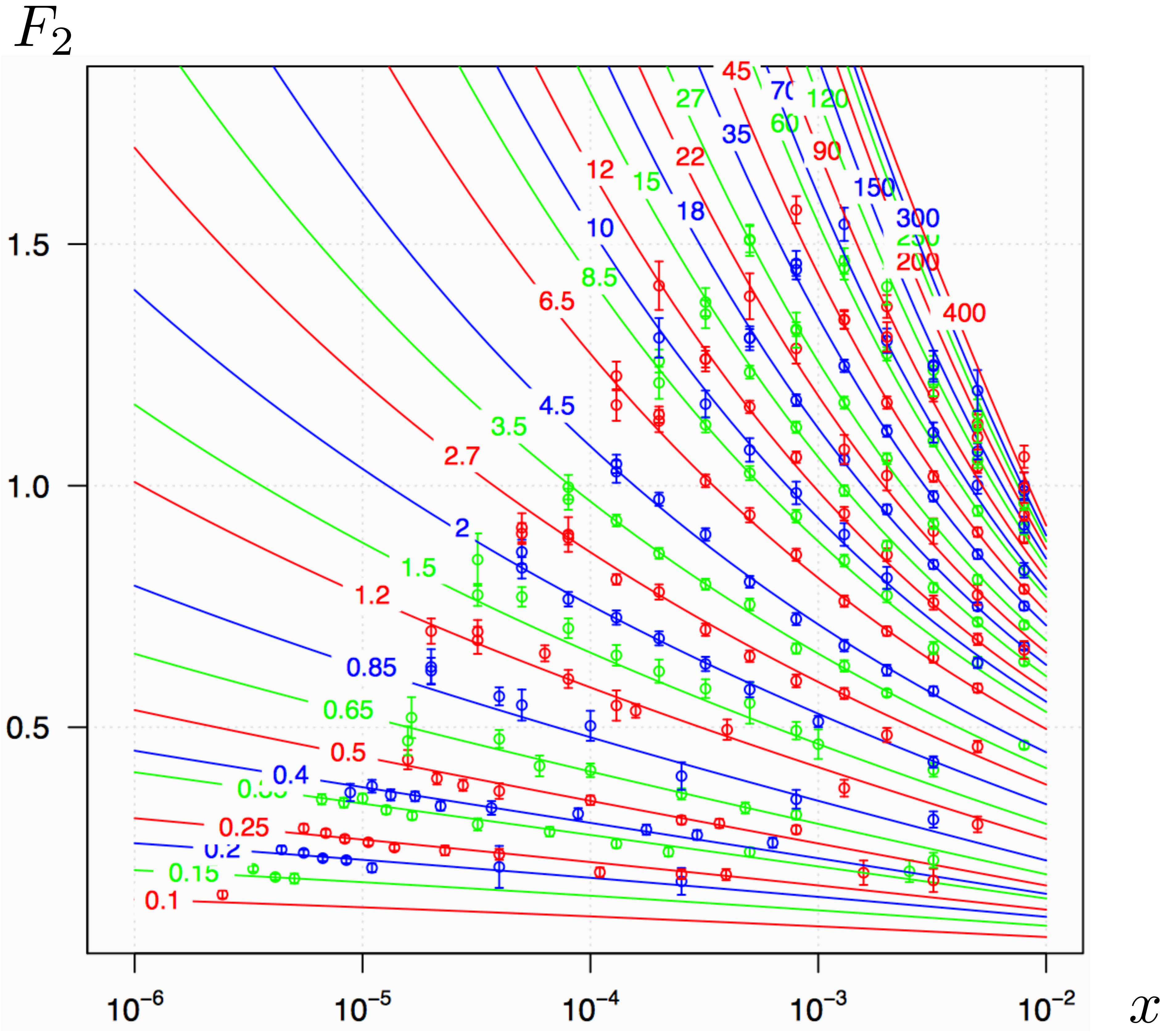
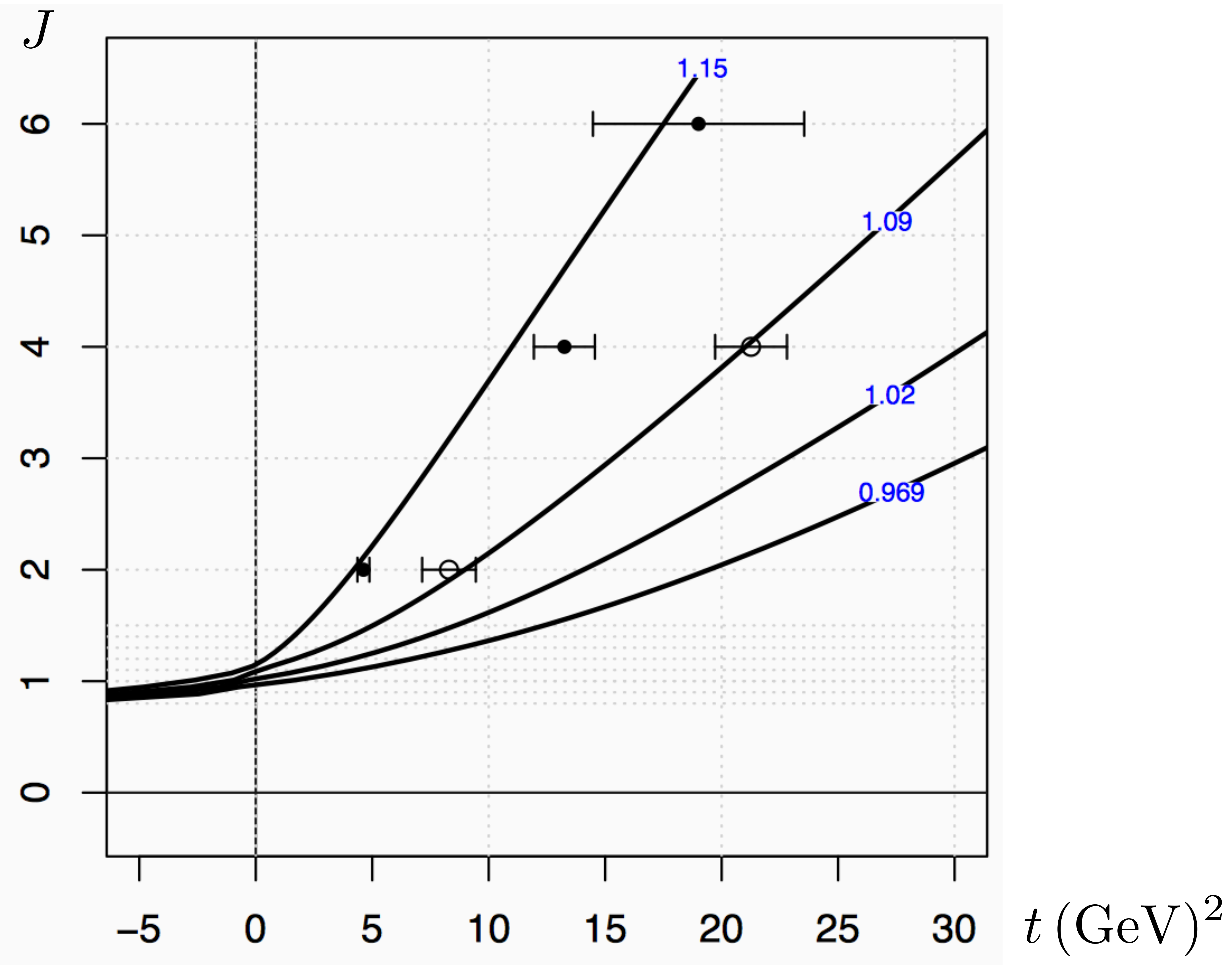


- Non-minimal coupling has dimensions and defines scale of 1-10 GeV. Matches order of magnitude of gap between spin 4 and 2 glueballs [CEMZ 14]



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- How generic are our results? Should try other holographic QCD models...

THANK YOU