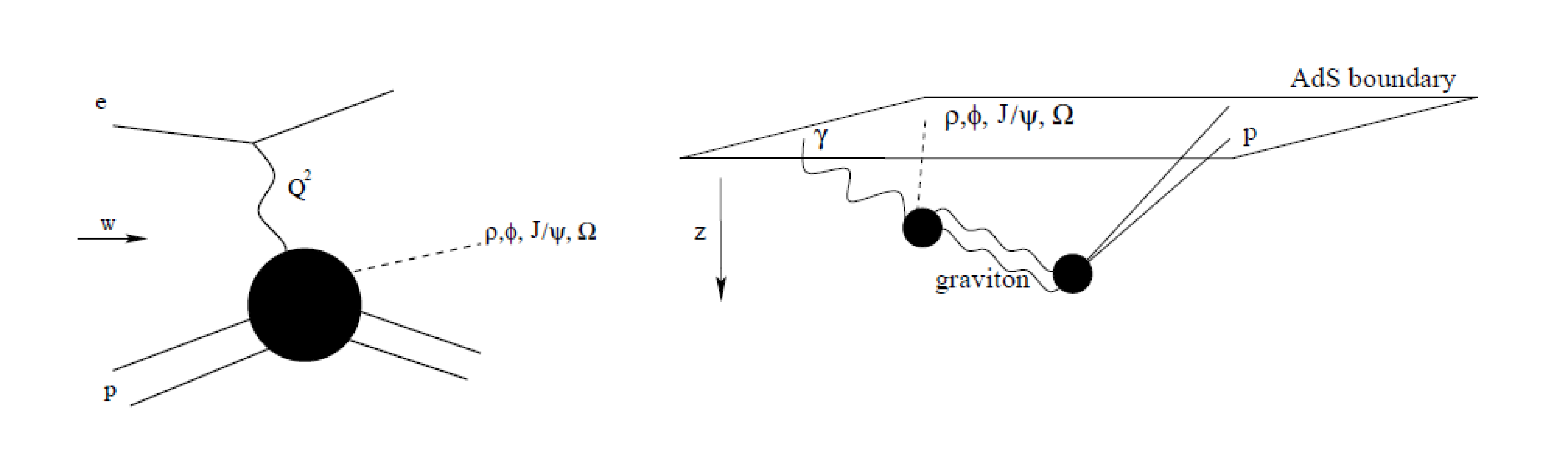
Holographic Vector Mesons and Low x Production



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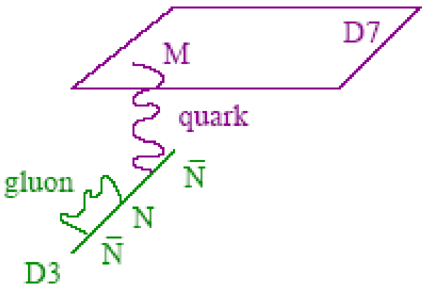
Holography of Quarks

AdS_5 is dual to the dynamics of a conformal strongly coupled gauge theory

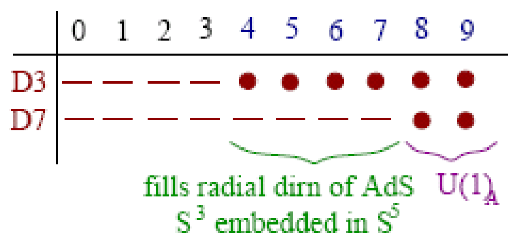
Adding Quarks

Bertolini, DiVecchia...; Polchinski, Grana; Karch, Katz...



Quarks can be introduced via D7 branes in AdS

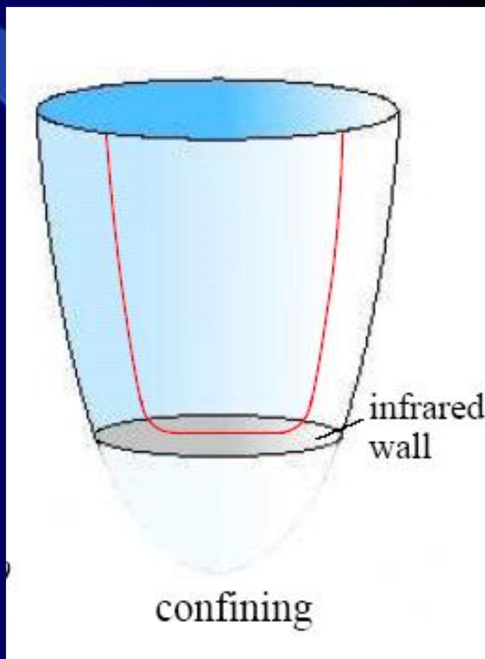
The brane set up is



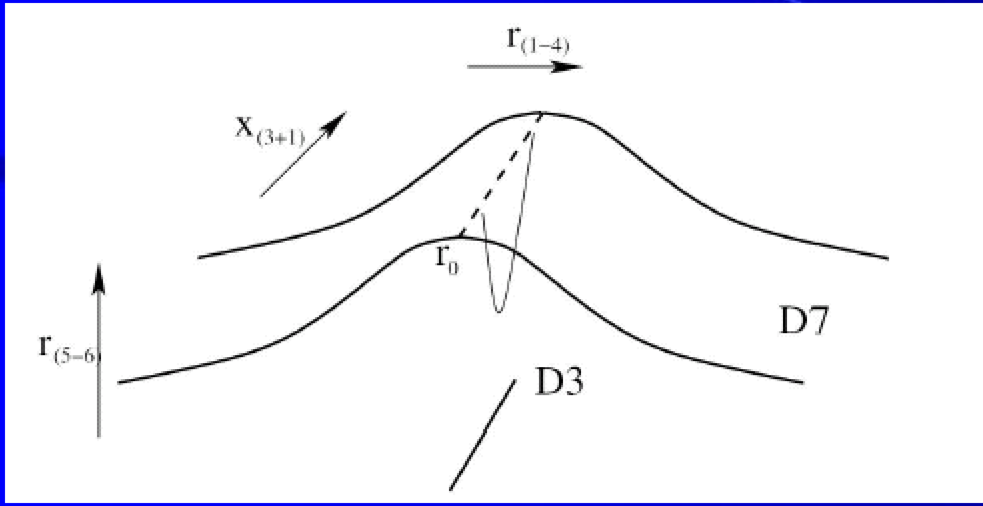
We will treat D7 as a probe - quenching in the gauge theory.

Minimize D7 world volume with DBI action

$$S_{D7} = -T_7 \int d\xi^8 \sqrt{P[G_{ab}]}, \qquad P[G_{ab}] = G_{MN} \frac{dx^M}{d\xi^a} \frac{dx^N}{d\xi^b}$$



Chiral Symmetry Breaking



A repulsive core to the geometry drives dynamical mass generation eg through an applied B field or running coupling/dilaton

BEEGK, Ghoroku..

Position of brane is a scalar in AdS – instability sets in when BF bound is violated

$$m^2 \geq -4$$

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

ie when the dimension of qq falls from 3 to 2… $\gamma = 1$

Mysteriously the same result as from truncated Schwinger-Dyson…

Evans, Kim

Mesons in AdS_5

Kruczenski,Myers, Mateos, Winters

The D7 lie flat in AdS. We can consider fluctuations that describe R-chargeless mesons

$$w_6 + i w_5 = d + \delta(\rho) e^{ik.x}$$

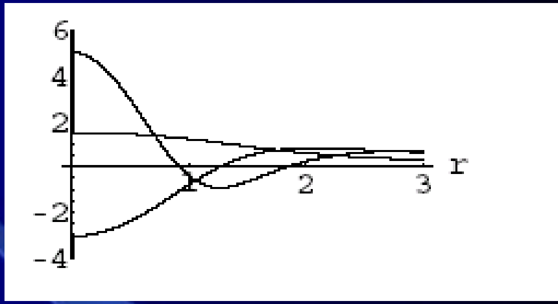
δ satisfies a linearized EoM

$$\partial_\rho^2 \delta + \frac{3}{\rho}\partial_\rho \delta + \frac{M^2}{(\rho^2+1)^2}\delta = 0$$

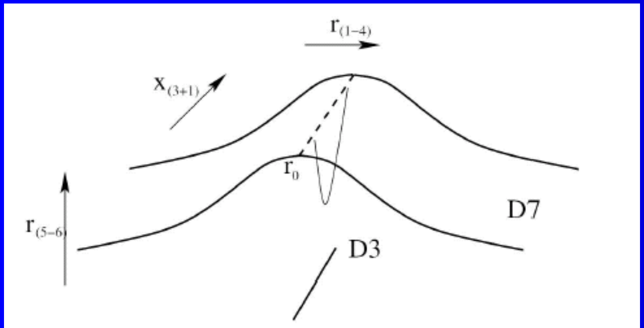
and the mass spectrum is

$$M = \frac{2d}{R^2}\sqrt{(n+1)(n+2)} \sim \frac{2m}{\sqrt{\lambda_{YM}}}$$

Tightly bound - meson masses suppressed relative to quark mass



Orthonormal wave functions

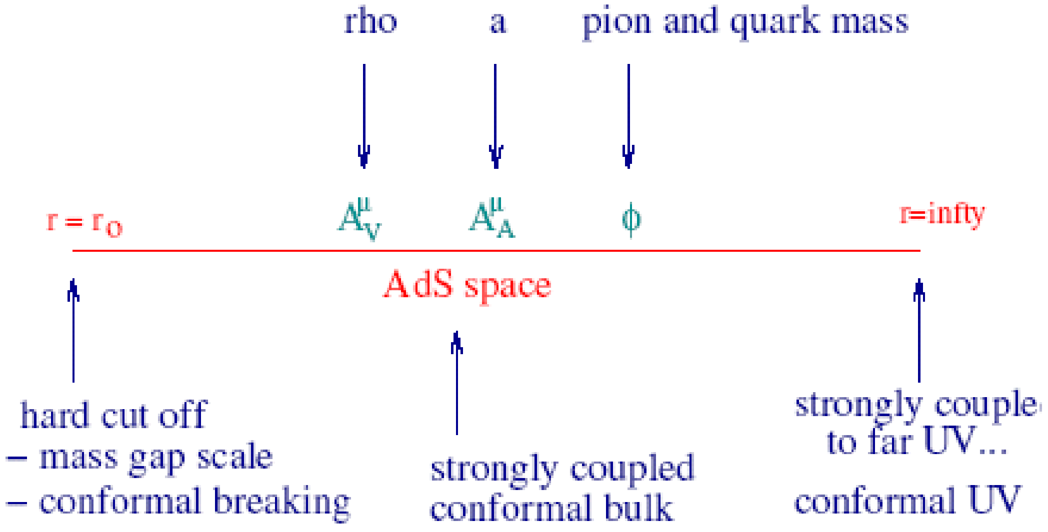


Generically the computation is similar with d replaced by the embedding function

ie the AdS space is cut off by the dynamical quark mass

AdS/QCD

$$S = \int_{r_0}^{\infty} d^5x \sqrt{-g}\, Tr \left\{ |DX|^2 + 3|X|^2 - \frac{1}{4g_5^2}(F_L^2 + F_R^2) \right\}$$



r_0 represents the dynamical light quark mass and is fixed phenomenologically by the ρ mass.

Mesons made from heavier quarks see a larger IR wall – again we fix by the Φ, J/ψ, Ω masses

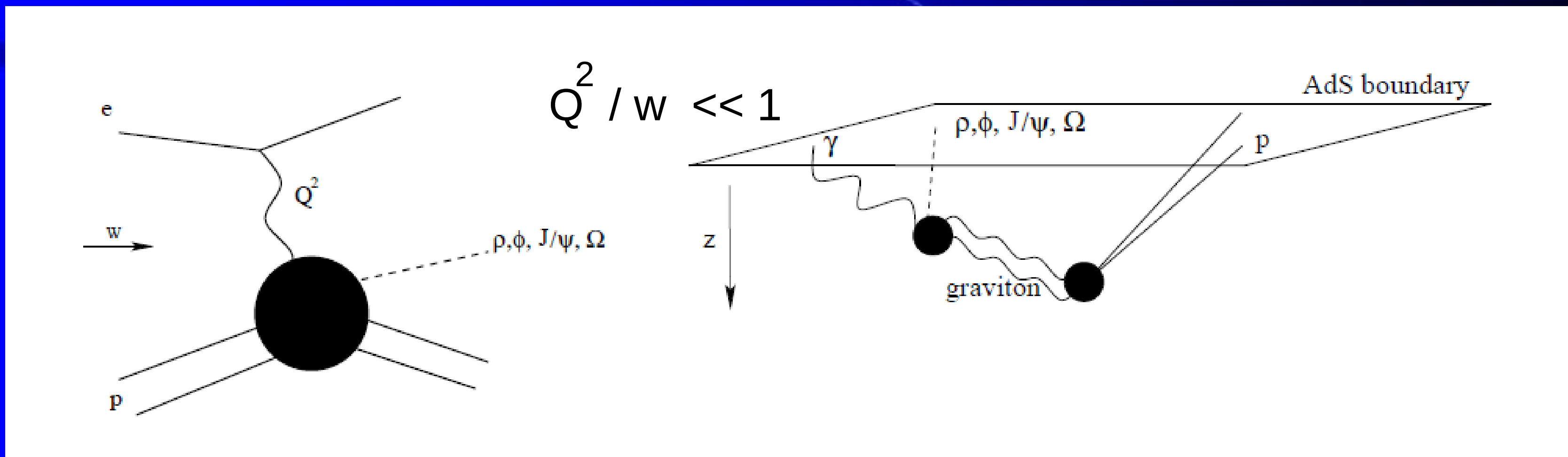
$$A(z,k) = \frac{\sqrt{2}}{\xi J_1(\xi)} mz J_1(mz)$$

$$\xi = 2.4048$$

The wave functions are then predicted…

Dynamic AdS/QCD – input more dynamics by inputting γ(x) – Evans, Tuominen

Holographic Vector Meson Production at Low x



A testing ground for our wave functions…

$$ds^2 = -dx^+dx^- + dx_\perp^2$$

$$k_1 = \left(\sqrt{s}, -\frac{Q^2}{\sqrt{s}}, 0\right), \qquad k_2 = \left(\frac{M^2}{\sqrt{s}}, \sqrt{s}, 0\right)$$

$$k_3 = -\left(\sqrt{s}, \frac{q_\perp^2 + m^2}{\sqrt{s}}, q_\perp\right), \qquad k_4 = -\left(\frac{M^2 + q_\perp^2}{\sqrt{s}}, \sqrt{s}, -q_\perp\right)$$

γ polarizations

$$n_\lambda = (0, 0, \epsilon_\lambda), \qquad (\lambda = 1, 2)$$

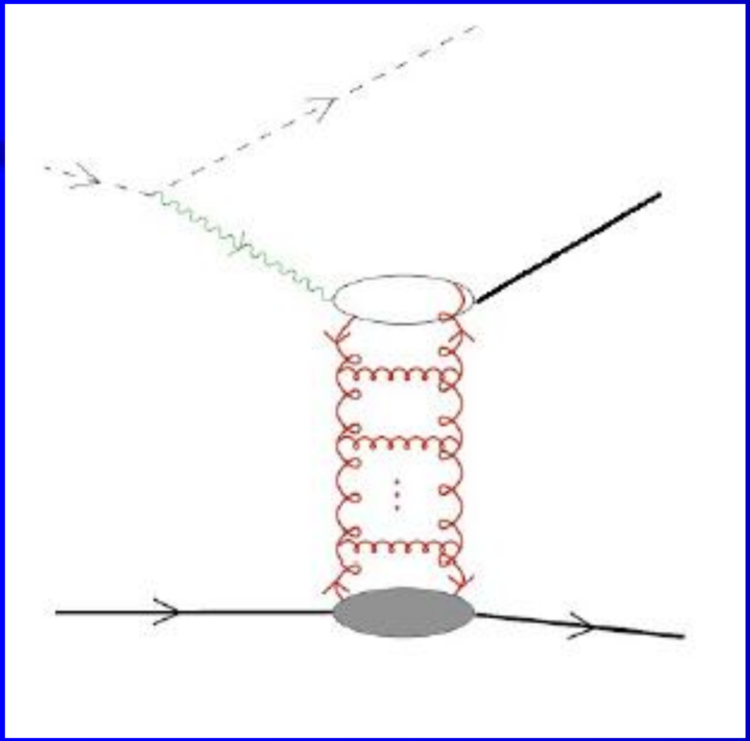
$$n_3 = \frac{1}{Q}\left(\sqrt{s}, \frac{Q^2}{\sqrt{s}}, 0\right)$$

ρ polarizations

$$n'_\lambda = \left(0, 2\frac{\epsilon'_\lambda \cdot q_\perp}{\sqrt{s}}, \epsilon'_\lambda\right), \qquad (\lambda = 1, 2)$$

$$n'_3 = \frac{1}{m}\left(\sqrt{s}, \frac{-m^2 + q_\perp^2}{\sqrt{s}}, q_\perp\right)$$

Approaches from Perturbation Theory



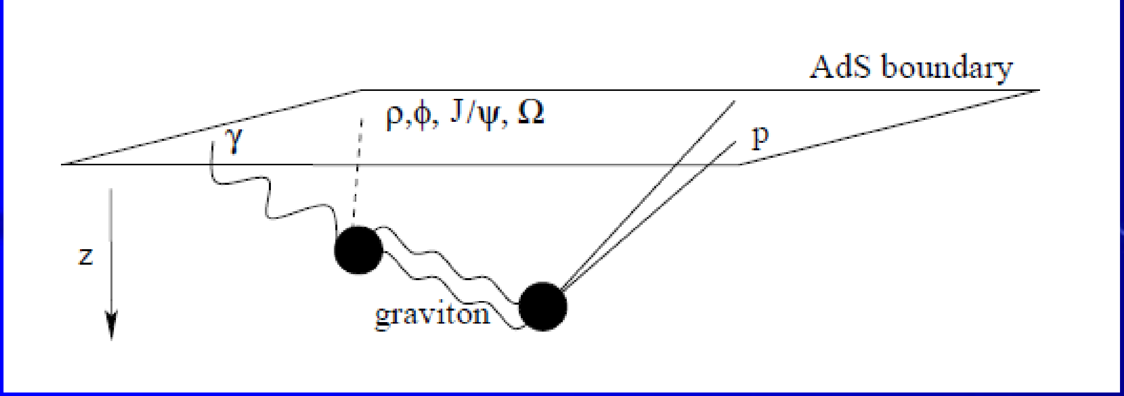
Perturbative exchange of a gluon plus ladders lead to a pomeron of spin >1

hep-ph/0709.4406
hep-ph/0610311
hep-ph/0702171
1109.6374
1212.2974

Forshaw and Sandapen (1203.6088) incorporate AdS wave functions…

These approaches seem to fit the data at the 1.5-2 χ^2 / dof level…

AdS/CFT Approach



At infinite ‘tHooft coupling the process is dominated by exchange of the spin 2 graviton

(Brower, Polchinski, Strassler and Tan)

At finite coupling the full graviton Regge trajectory is exchanged…

CONFORMAL symmetry ensures

$$\frac{d\sigma}{dt}(x, Q^2, t) = \frac{1}{16\pi s^2}\,\frac{1}{3}\sum_{\lambda,\lambda'=1}^{3} |W^{\lambda\lambda'}|^2$$

z = 1/r

After kinematics …

$$W_n = 2is \int dl_\perp\, e^{iq_\perp \cdot l_\perp} \int \frac{dz}{z^3}\,\frac{d\bar{z}}{\bar{z}^3}\,\Psi_n(z)\,\Phi(\bar{z})\,\mathcal{B}(S, L)\,.$$

$$W_n = 2is \int dl_\perp \, e^{iq_\perp \cdot l_\perp} \int \frac{dz}{z^3} \frac{d\bar{z}}{\bar{z}^3} \Psi_n(z) \, \Phi(\bar{z}) \, \mathcal{B}(S, L) \, .$$

$$\Psi_n(z) = -\left(\sqrt{\frac{C\pi^2}{6}} \, z^2 K_n(Qz) \right) \left(\frac{\sqrt{2}}{\xi J_1(\xi)} \, z^2 J_n(mz) \right)$$

External photon – non-normalizable solution for gauge field in AdS

External vector meson – normalizable solution for gauge field in AdS

$$\Phi(\bar{z}) = |\phi(\bar{z})|^2 = \bar{z}^3 \delta(\bar{z} - z_*) \, ,$$

Product of two proton AdS wave functions…

$m^2 = 9/4$

$$\phi(\bar{z}) \propto \bar{z}^{3/2} \left(-\sin \bar{z} - 3 \cos \bar{z}/\bar{z} + 3 \sin \bar{z}/\bar{z} \right).$$

But… this is essentially peaked at the IR “proton wall” – hence we use a delta function to eliminate a numerical integral…

$$W_n = 2is \int dl_\perp \, e^{iq_\perp \cdot l_\perp} \int \frac{dz}{z^3} \frac{d\bar{z}}{\bar{z}^3} \Psi_n(z)\, \Phi(\bar{z})\, \mathcal{B}(S, L) \, .$$

Regge graviton trajectory propagator post kinematics

Π_{++--} of the graviton propagator dominates the exchange,

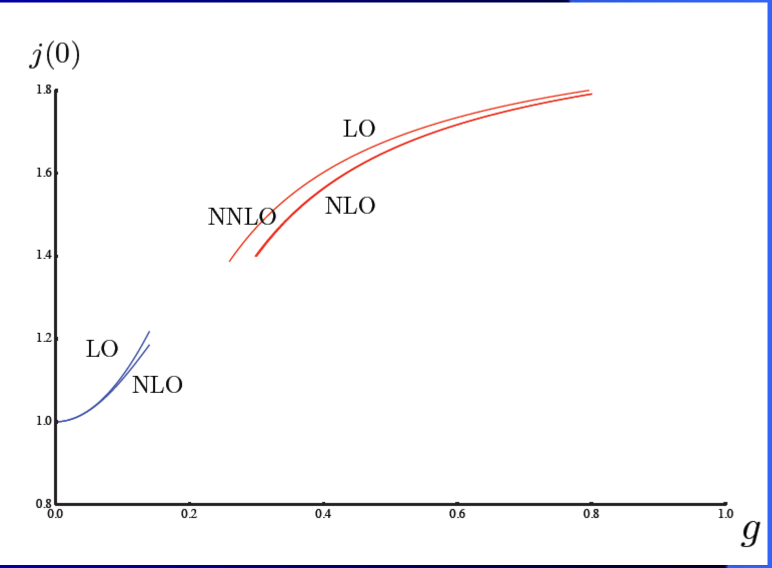
$$\cosh L = \frac{z^2 + \bar{z}^2 + l_\perp^2}{2z\bar{z}}$$

$$\mathcal{B}(S,L) = g_0^2 \left(1 + i \cot\left(\frac{\pi\rho}{2}\right)\right) (\alpha' S)^{1-\rho} \frac{e^{-\frac{L^2}{\rho \ln(\alpha' S)}}}{(\rho \ln(\alpha' S))^{3/2}} \frac{L}{\sinh L} \, ,$$

$$\alpha' S = \frac{z\bar{z}s}{\sqrt{\lambda}} \, , \qquad \rho = 2 - j_0 = \frac{2}{\sqrt{\lambda}} \, .$$

ρ marks the deviation of the pomeron spin from 2…

NB: there has been a huge amount of work at weak (BFKL etc) and strong coupling (integrability) to track the spin of the pomeron with gauge coupling… evidence is that QCD lies between the two regimes… our computation approaches QCD from strong coupling extreme…



Parameter Count

ρ – the strength of the gauge coupling

g0 x wave function normalizations - pomeron vector meson coupling

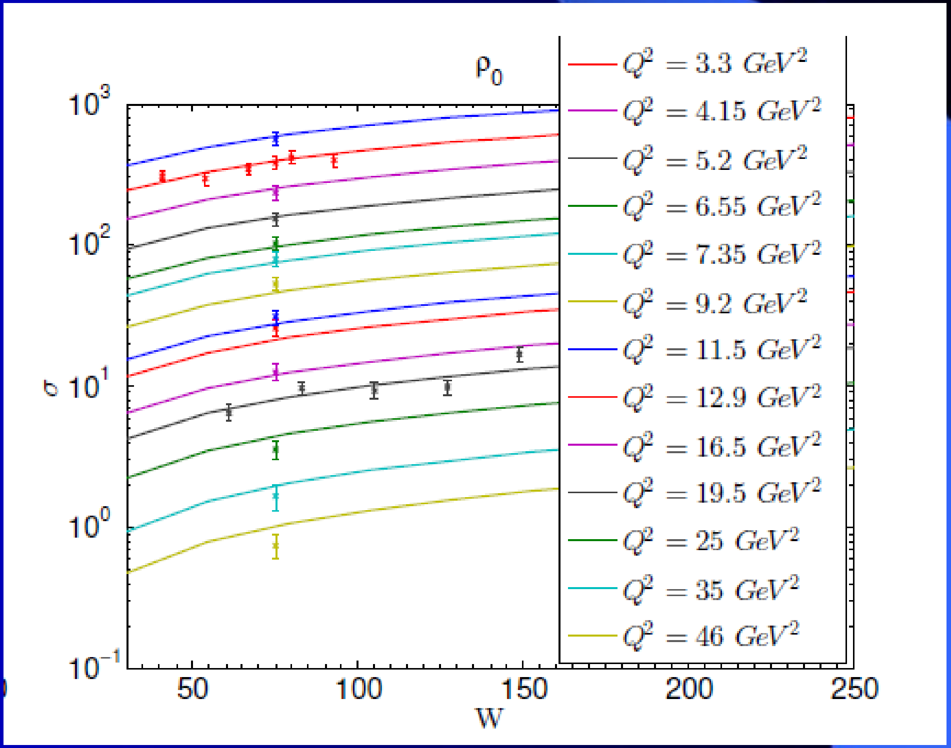
z* - the position of the proton IR wall

Now we can fit to the data…

eg H1 data for ρ –
48 points for σ – all x<0.01

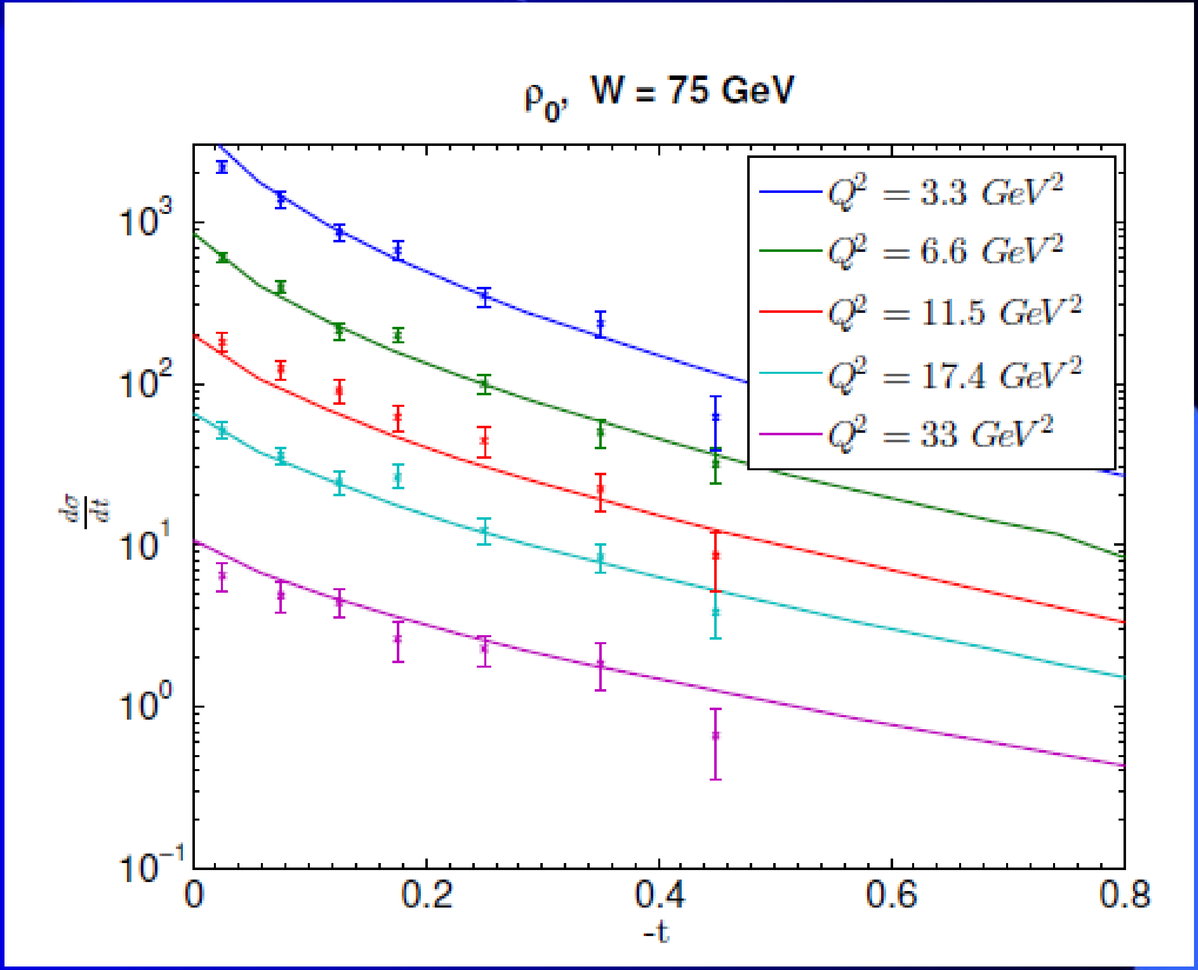
χ^2	0.9234
$g_0^{\,2}$	2.29
ρ	0.76
z*	3.4074

1/GeV

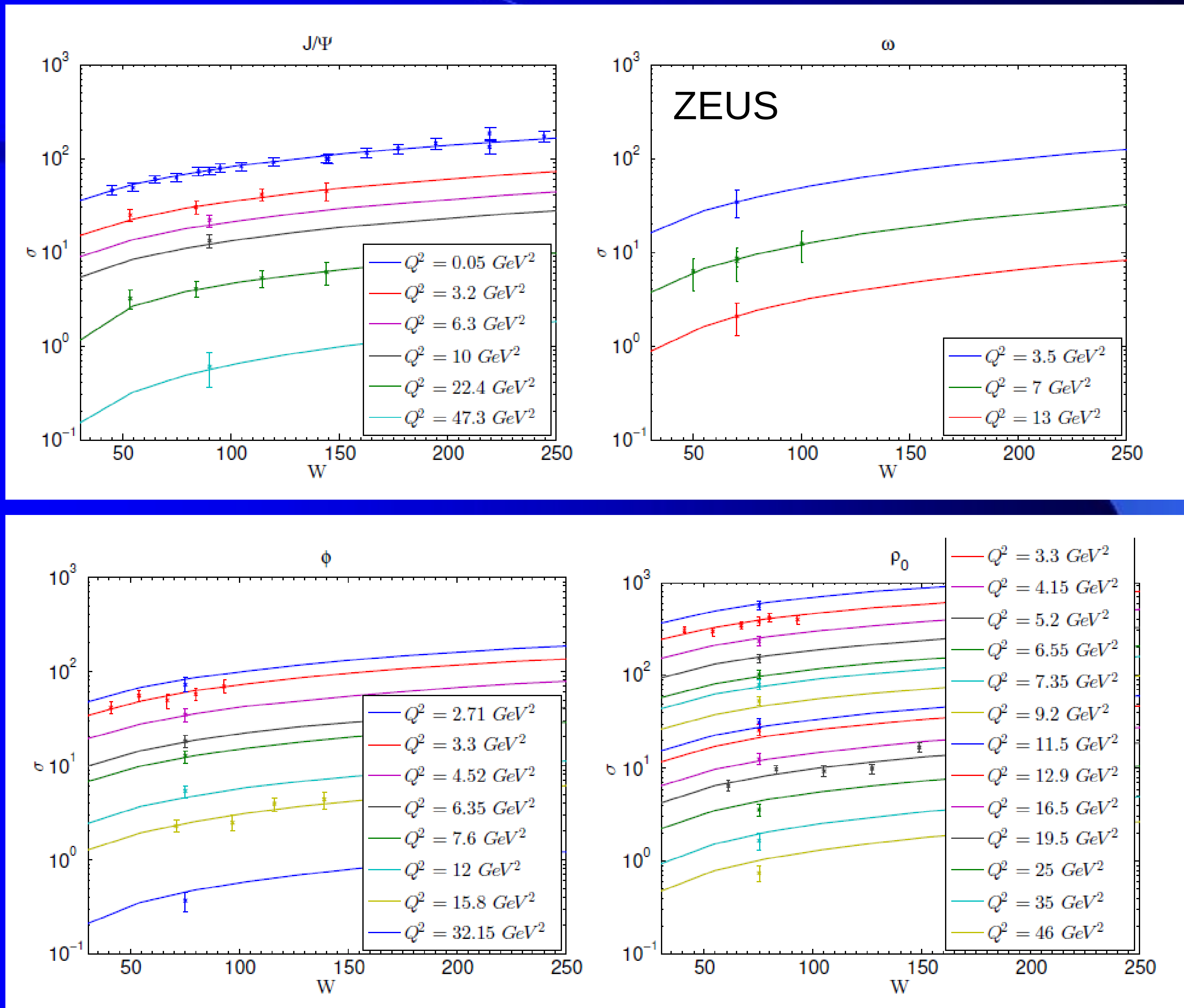


eg H1 data for ρ –
35 points for dσ/dt

χ^2	1.7387
$g_0^{\ 2}$	0.7814
ρ	0.6473
z*	2.1453



Total cross-sections



	σ				$d\sigma/dt$		
	ρ	ϕ	Ω	J/ψ	ρ	ϕ	J/ψ
m	0.77549	1.019445	0.78265	3.096916	0.77549	1.019445	3.096916
N	48	27	6	38	35	21	84
χ^2	0.9234	0.6002	0.0099	0.2844	1.7387	1.2732	2.8818
g_0^2	2.29	0.5742	0.2673	0.3946	0.7814	0.0805	0.3565
ρ	0.76	0.7339	0.6416	0.697	0.6473	0.5443	0.7165
z*	3.4074	3.0012	1.8355	0.9823	2.1453	2.5445	2.1536

The fits on σ are very good

Fits on differenential σ OK…

g0 is process dependent and this infects the ρ and z* stability a little…

Hard Wall Pomeron

So far we assumed a pomeron emerging from a conformal gauge theory… we can include a hard wall at z0 to represent the IR glue confinement scale… it changes the graviton AdS wave functions

$$\mathcal{B}(S,L) = -i\chi(S,L)$$

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

$$D(\tau,l) = \min\left(1, \frac{\exp[-m_1 l - (m_0-m_1)^2 l^2/4\rho\tau]}{\exp[-m_1 z_0 - (m_0-m_1)^2 z_0^2/4\rho\tau]}\right)$$

$$\chi^{(0)}_{hw}(\tau,l,z,\bar{z}) = \chi_c(\tau,l,z,\bar{z}) + \mathcal{F}(\tau,z,\bar{z})\,\chi_c(\tau,l,z,z_0^2/\bar{z}).$$

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

τ = log((ρ/2) z z' s)

m1 and m0 are the masses of the lightest spin 2 glueballs

		σ ρ	σ ϕ	σ Ω	σ J/ψ	dσ/dt ρ	dσ/dt ϕ	dσ/dt J/ψ
	m	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	0.9234	0.6002	0.0099	0.2844	1.7387	1.2732	2.8818
Conformal	g_0^2	2.29	0.5742	0.2673	0.3946	0.7814	0.0805	0.3565
Conformal	ρ	0.76	0.7339	0.6416	0.697	0.6473	0.5443	0.7165
Conformal	z*	3.4074	3.0012	1.8355	0.9823	2.1453	2.5445	2.1536
Hardwall	χ^2	0.8819	0.6131	0.015	0.2969	1.6574	1.3595	1.8442
Hardwall	g_0^2	2.0438	0.5559	0.3335	0.4758	1.0963	0.1196	0.4345
Hardwall	ρ	0.758	0.7321	0.6589	0.713	0.6946	0.5905	0.7539
Hardwall	z*	3.5947	3.6341	1.4668	0.8698	2.1847	2.5064	2.4172
Hardwall	z_0	4.8164	4.3625	7.2955	5.3429	7.6918	8.5684	4.6465

The J/ψ differential cross-section is improved.. Otherwise little change…

Summary

- Holographic modelling of QCD incorporates confinement and chiral symmetry breaking
- Vector meson AdS wave functions are predicted
- We've incorporated them into AdS computations of vector meson production at low x and matched to H1 data… (4 parameter fit)
- The pomeron is a Regge-ized graviton tower…
- The fits seem as good as any in the literature… ($\chi^2 < 1$) ... Not a bad first stab…
- In the future we'd like to fit all data with fewer free parameters, fixed zo, z*, ρ across all channels which may mean refining mesonic & pomeron wave functions…