STRING-GAUGE DUAL (ADS/CFT) DESCRIPTION OF DEEP-INELASTIC SCATTERING

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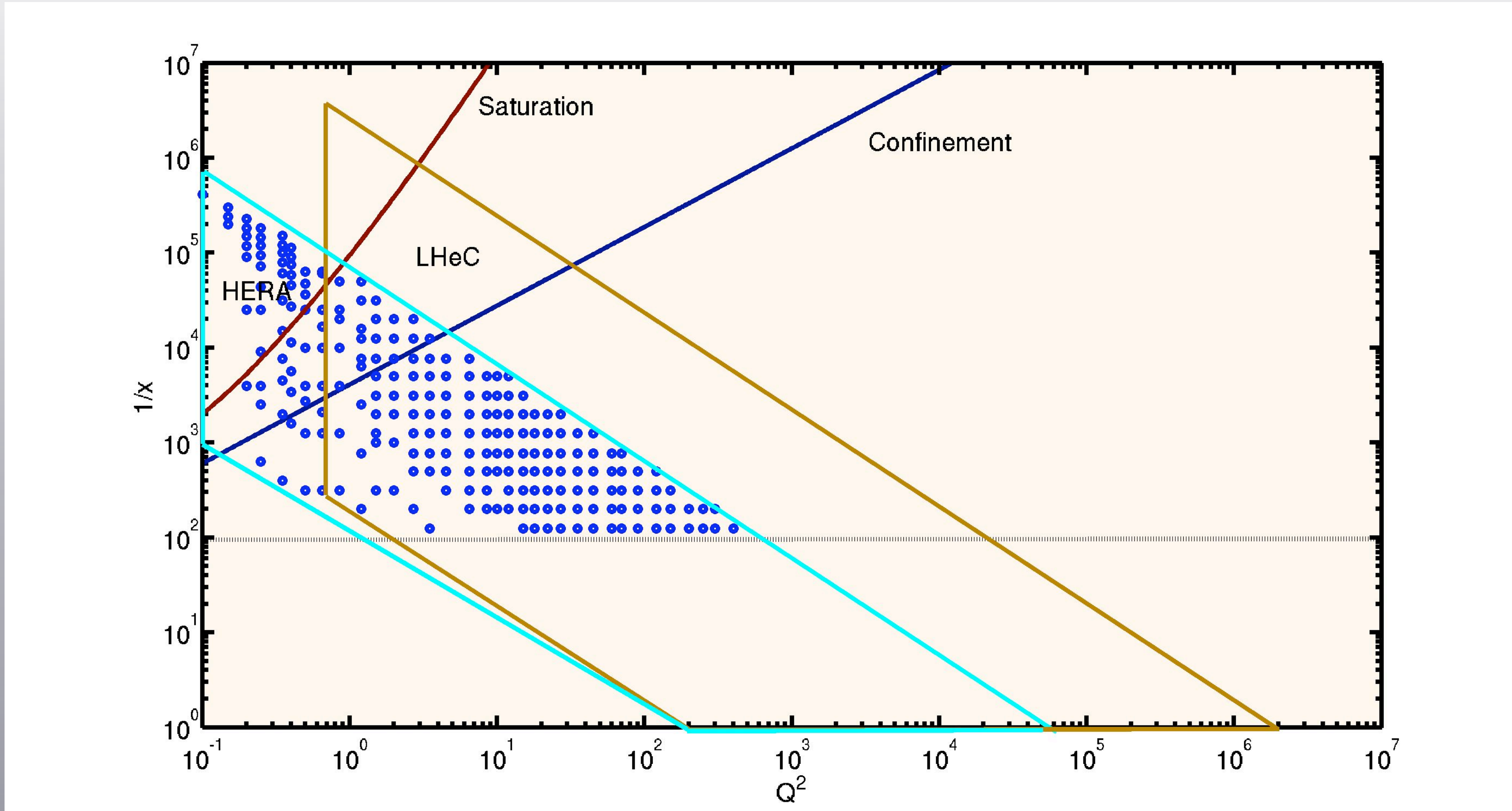
Low-x Workshop, Paphos, Cyprus
June 27 - July 1, 2012

Richard Brower, Marko Djurić, Ina Sarcević and Chung-I Tan: *String-Gauge Dual Description of DIS and Small-x*, 10.1007/JHEP 11(2010)051, arXiv:1007.2259

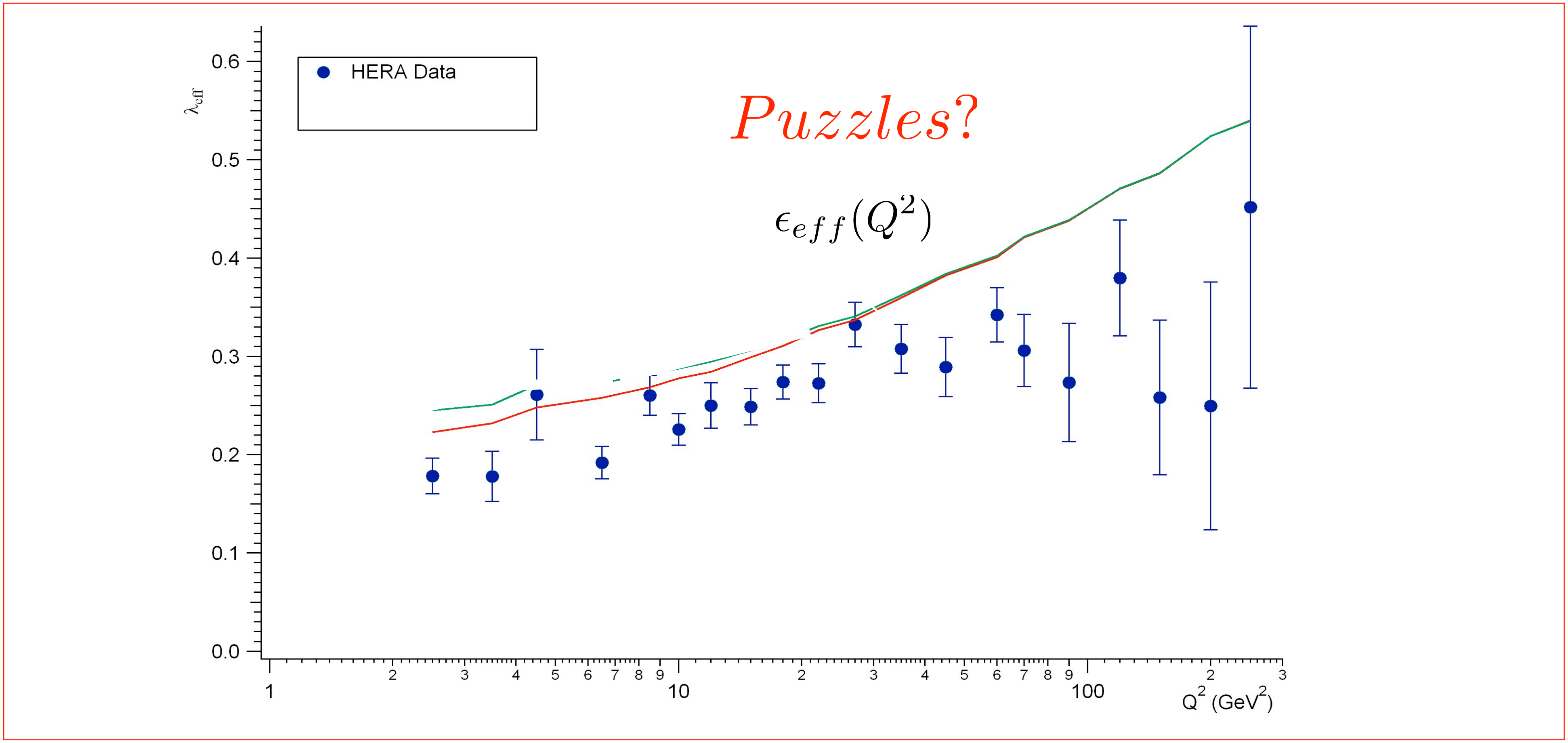
Brower, Polchinski, Strassler, Tan (BPST) The Pomeron and Gauge/String Duality (2006)

HERA vs LHeC region: dots are H1-ZEUS small-x data points



Effective Pomeron Intercept from HERA data:

$$F_2 \simeq C(Q^2)\; x^{-\epsilon_{eff}}$$



Executive Summary:

Gauge/String Duality (AdS/CFT) → 2-GLUONS $\simeq$ GRAVITON

Status Report:

- Establishing "Pomeron" in QCD non-perturbatively,
- Unification of Soft and Hard Physics in High Energy Collision
- New phenomenology based on "Large Pomeron intercept", e.g., DIS at small-x: (DGLAP vs Pomeron); Central Diffractive Higgs Production.

Outline

- QCD High Energy Scattering with AdS/CFT
- Deep Inelastic Scattering at Small-x: (universality)
- Higher Order Effects: Saturation, Confinement, etc.
- Summary and Outlook

I. Gauge-String Duality: AdS/CFT

Weak Coupling:

Gluons and Quarks: $A_\mu^{ab}(x), \psi_f^a(x)$

Gauge Invariant Operators: $\bar{\psi}(x)\psi(x), \ \bar{\psi}(x)D_\mu\psi(x)$

$S(x) = TrF_{\mu\nu}^2(x), \ \ O(x) = TrF^3(x)$

$T_{\mu\nu}(x) = TrF_{\mu\lambda}(x)F_{\lambda\nu}(x), \ \ etc.$

$$\mathcal{L}(x) = -TrF^2 + \bar{\psi}\not{D}\psi + \cdots$$

Strong Coupling:

Metric tensor: $G_{mn}(x) = g_{mn}^{(0)}(x) + h_{mn}(x)$

Anti-symmetric tensor (Kalb-Ramond fields): $b_{mn}(x)$

Dilaton, Axion, etc. $\phi(x), \ a(x), \ etc.$

Other differential forms: $C_{mn\cdots}(x)$

$$\mathcal{L}(x) = \mathcal{L}(G(x), b(x), C(x), \cdots)$$

$\mathcal{N} = 4$ SYM Scattering at High Energy

$$\langle e^{\int d^4x \phi_i(x) \mathcal{O}_i(x)} \rangle_{CFT} = \mathcal{Z}_{string}\left[\phi_i(x,z)|_{z\sim 0} \to \phi_i(x)\right]$$

Bulk Degrees of Freedom from type-IIB Supergravity on AdS_5:

- metric tensor: G_{MN}
- Kalb-Ramond 2 Forms: B_{MN}, C_{MN}
- Dilaton and zero form: ϕ and C_0

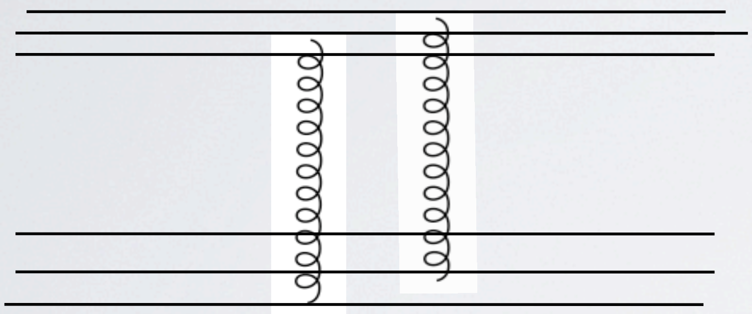
$$\lambda = g^2 N_c \to \infty$$

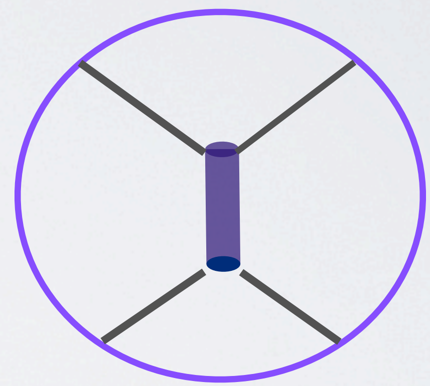
Supergravity limit

- Strong coupling
- Conformal
- Pomeron as Graviton in AdS

WHAT IS THE BARE POMERON ? LEADING 1/N TERM CYLINDER EXCHANGE

WEAK: TWO GLUON <=> STRONG: ADS GRAVITON





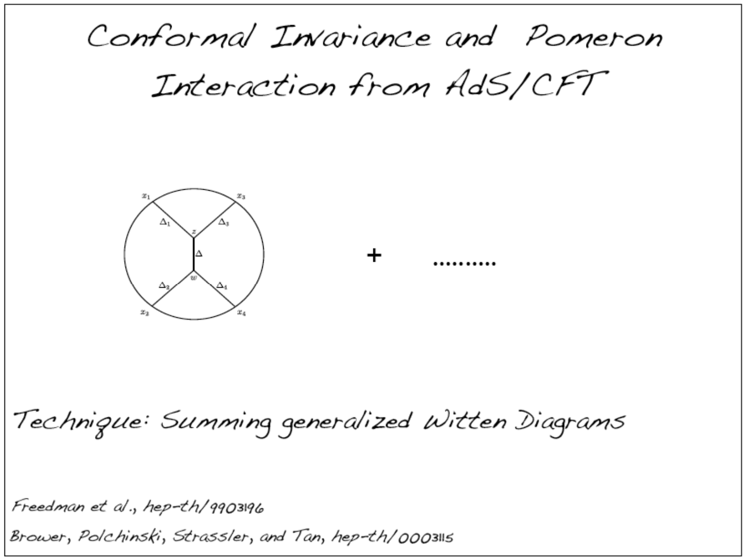
$$J = 2$$

$$J_{cut} = 1 + 1 - 1 = 1$$

$$S = \frac{1}{2\kappa^2}\int d^4x dz \sqrt{-g(z)}\Big(- \mathcal{R} + \frac{12}{R^2} + \frac{1}{2} g^{MN}\partial_M\phi\partial_N\phi\Big)$$

F.E. Low. Phys. Rev. D 12 (1975), p. 163.
S. Nussinov. Phys. Rev. Lett. 34 (1975), p. 1286.

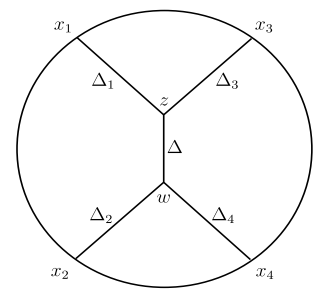
AdS Witten Diagram: Adv. Theor. Math. Physics 2 (1998)253



- Draw all "Witten-Feynman" Diagrams in AdS_5,
- High Energy Dominated by Spin-2 Exchanges:

One Graviton Exchange at High Energy

$$p_1 + p_2 \to p_3 + p_4$$



$$T^{(1)}(p_1,p_2,p_3,p_4) = g_s^2 \int \frac{dz}{z^5} \int \frac{dz'}{z'^5}\, \tilde{\Phi}_\Delta(p_1^2,z)\tilde{\Phi}_\Delta(p_3^2,z)\mathcal{T}^{(1)}(p_i,z,z')\tilde{\Phi}_\Delta(p_2^2,z')\tilde{\Phi}_\Delta(p_4^2,z')$$

$$\mathcal{T}^{(1)}(p_i,z,z') = (z^2 z'^2 s)^2 G_{++,--}(q,z,z') = (zz's)^2 G^{(5)}_{\Delta=4}(q,z,z')$$

Additional Steps for QCD:

◆ Spin-2 leads to too rapid an increase for cross sections

Need to consider $\lambda = g^2 N$ finite.

◆Confinement:

Conformal, therefore no scale and no particles, etc.

◆Short-distance: Running Coupling

Brower, Polchinski, Strassler, and Tan: "The Pomeron and Gauge/String Duality," hep-th/063115

Diffusion in AdS: $(\lambda < \infty)$

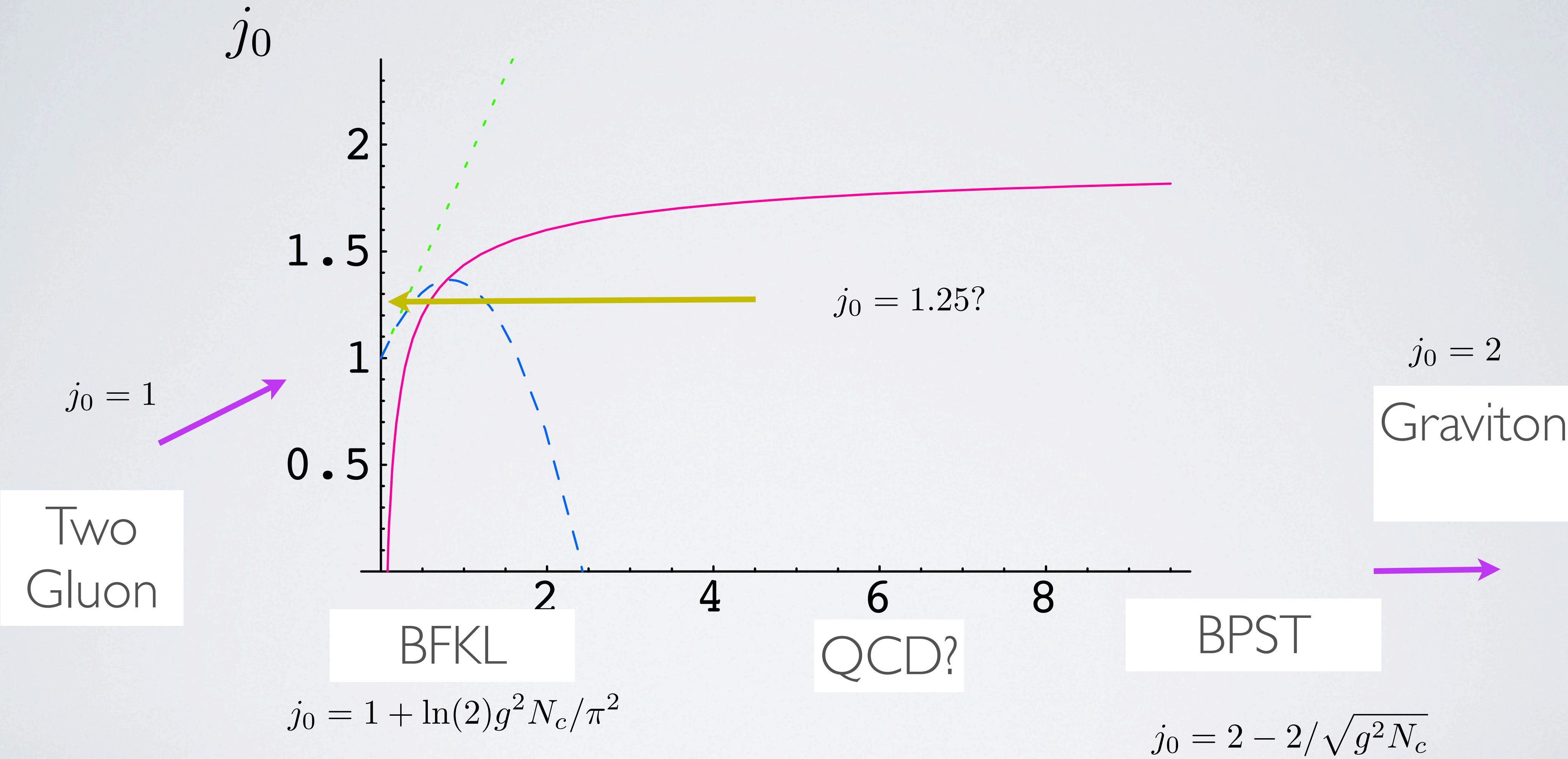
At finite λ, due to Diffusion in AdS

- Graviton (Pomeron) becomes j-plane singularity at

$$j_0 : \quad 2 \to 2 - 2/\sqrt{\lambda}$$

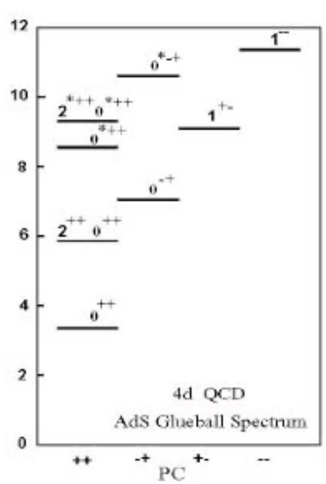
- Conformal: No scale and it is a branch cut, not a Regge trajectory

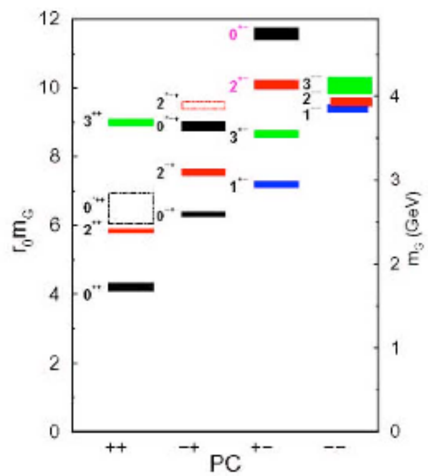
$\mathcal{N} = 4$ Strong vs Weak $g^2 N_c$

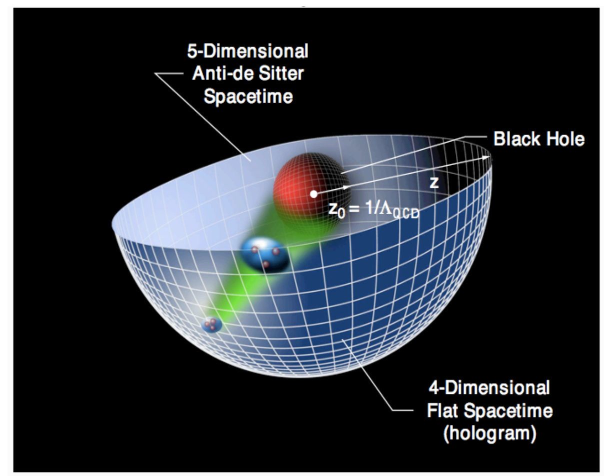


Confinement Deformation: Glueball Spectrum

$(\lambda = \infty)$







Four-Dimensional Mass:

$$E^2 = (p_1^2 + p_2^2 + p_3^2) + M^2$$

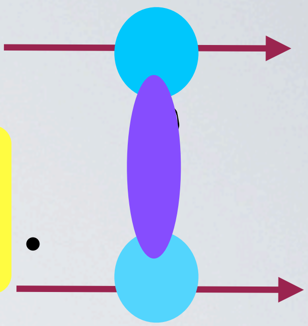
5-Dim Massless Mode:

$$0 = E^2 - (p_1^2 + p_2^2 + p_3^{\,2} + p_r^2)$$

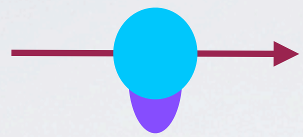
ADS BUILDING BLOCKS BLOCKS

For 2-to-2

$$A(s,t) = \Phi_{13} * \widetilde{\mathcal{K}}_P * \Phi_{24} .$$



BASIC BUILDING BLOCK

- Elastic Vertex: 
- Pomeron/Graviton Propagator: 

$$\mathcal{K}(s,b,z,z') = -\left(\frac{(zz')^2}{R^4}\right)\int \frac{dj}{2\pi i}\left(\frac{1+e^{-i\pi j}}{\sin \pi j}\right)\widehat{s}^{j}\, G_j(z,x^{\perp},z',x'^{\perp};j)$$

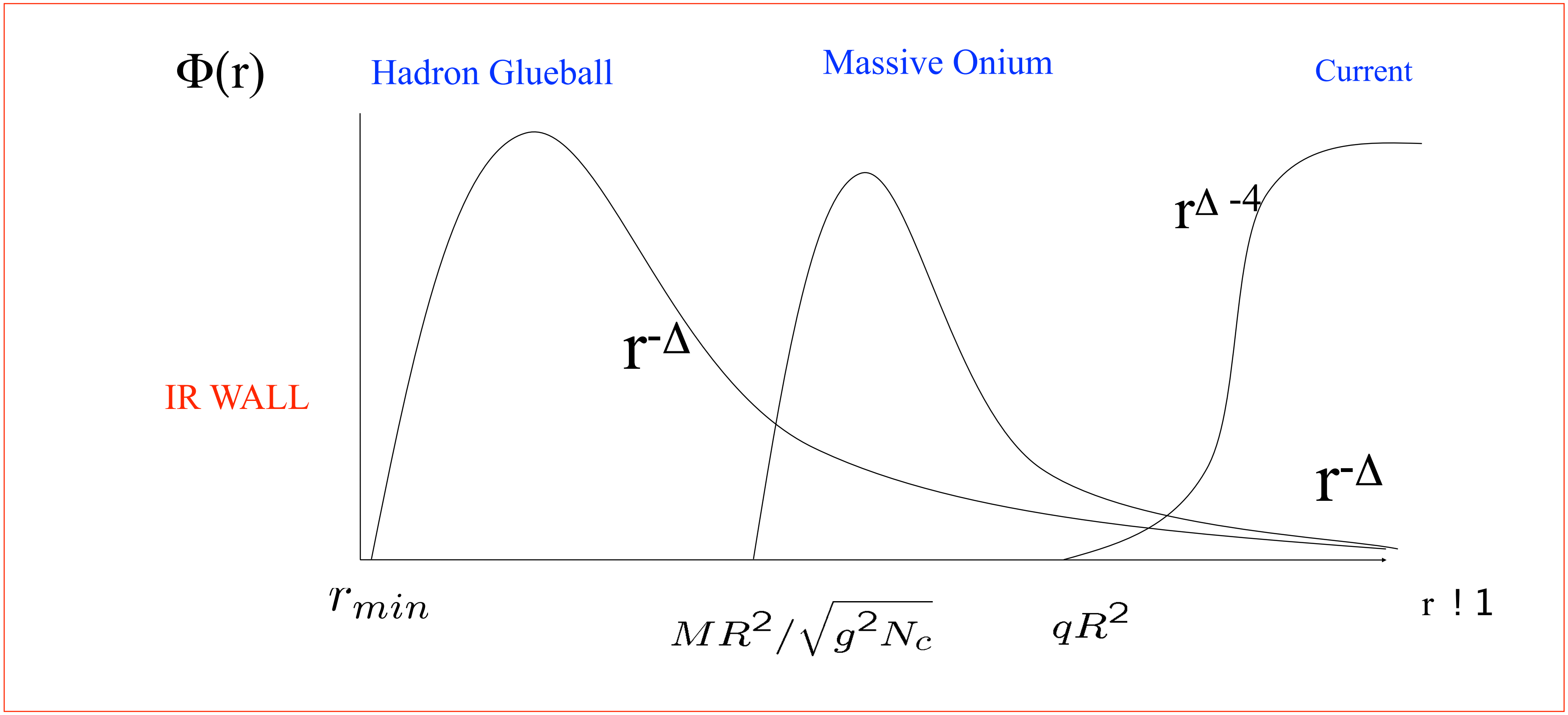
conformal: $$G_j(z,x^{\perp},z',x'^{\perp}) = \frac{1}{4\pi z z'}\frac{e^{(2-\Delta(j))\xi}}{\sinh \xi},$$

$$\Delta(j) = 2 + \sqrt{2}\,\lambda^{1/4}\sqrt{(j-j_0)}$$

confinement: $G_j(z,x^{\perp},z',x'^{\perp};j)$ → discrete sum

- Universality and Holographic:

  By choosing wave functions, Φ, can treat
  DIS, Higgs Production, Proton-Proton, etc., on equal footing.



Comparison of strong vs weak coupling kernel at t=0

Strong Coupling:

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

Diffusion in "warped co-ordinate"

$$j_0 = 2 - \frac{2}{\sqrt{g^2N}} + O(1/g^2N)$$

$$\mathcal{D} = \frac{1}{2\sqrt{g^2N}} + O(1/g^2N) \quad .$$

Weak Coupling:

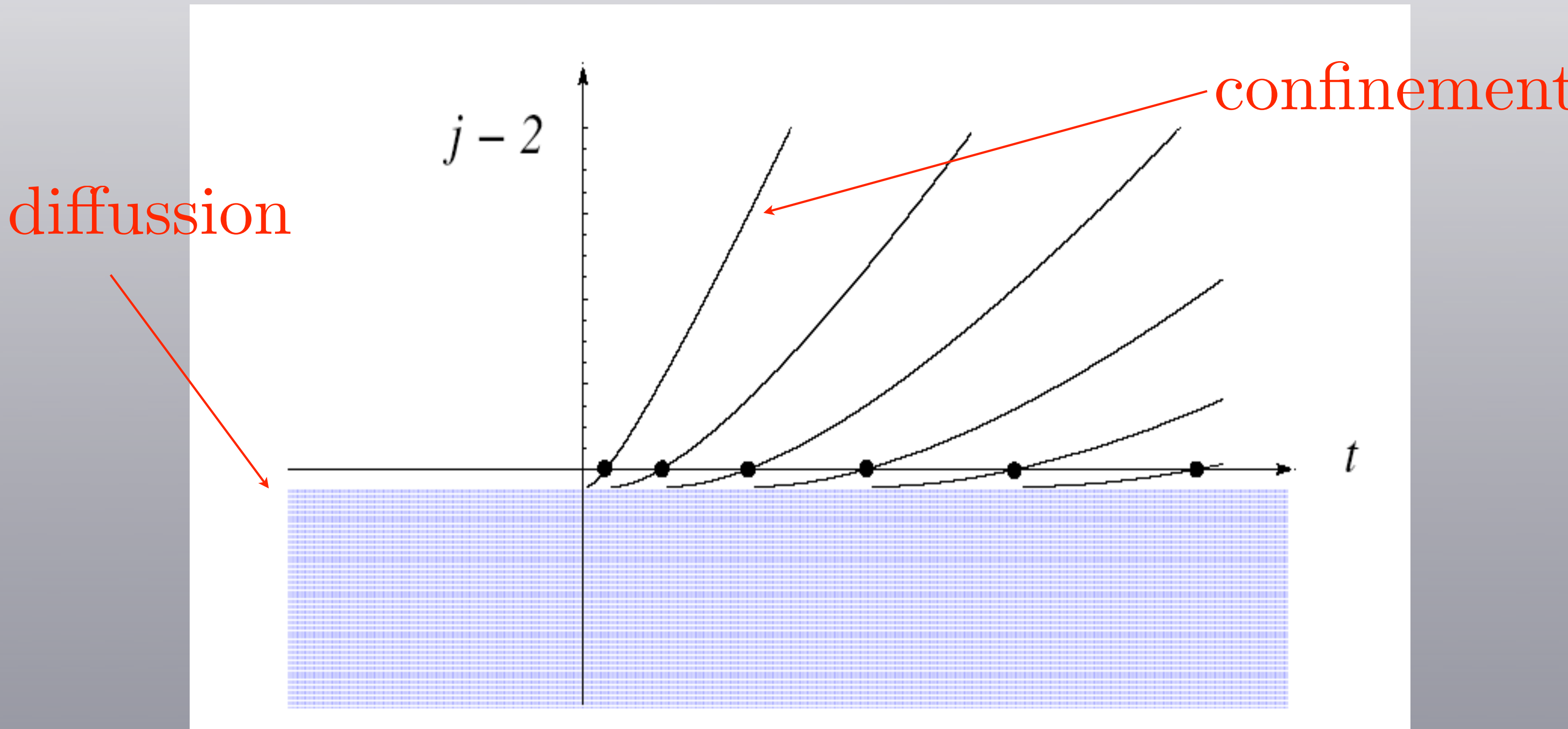
$$K(s,k_\perp,k'_\perp) \approx \frac{s^{\alpha(0)-1}}{\sqrt{\pi\ln s}} e^{-[(\ln k'_\perp - \ln k_\perp)^2/4\mathcal{D}\ln s]}$$

$$j_0 = 1 + \ln(2) g^2N/\pi^2$$

$$\mathcal{D} = \frac{14\zeta(3)}{\pi} g^2N/4\pi^2.$$

Unified Hard (conformal) and Soft (confining) Pomeron

At finite λ, due to Confinement in AdS, *at* $t > 0$ aymptotical linear Regge trajectories



AdS/CFT ===>

In gauge theories with string-theoretical dual descriptions, the Pomeron emerges unambiguously.

Pomeron can be associated with a Reggeized Graviton.

Both the IR (soft) Pomeron and the UV (BFKL) Pomeron are dealt in a unified single step.

R. Brower, J. Polchinski, M. Strassler, and C-I Tan, "The Pomeron and Gauge/String Duality", (hep-th/0603115.)

BFKL vs Soft Pomeron

- Perturbative QCD
- Short-Distance
- $\alpha_{BFKL}(0) \sim 1.4$
- Increasing Virtuality
- No Shrinkage of elastic peak
- Fixed-cut in t
- Diffusion in Virtuality
-
-

- Non-Perturbative
- Long-distance: Confinement
- $\alpha_P(0) \sim 1.08$
- Fixed trans. Momenta
- Shrinkage of Elastic Peak: $<|t|> \sim 1/\log s$
- $\alpha'(0) \sim 0.3\ \text{Gev}^{-2}$
- Diffusion in impact space

Note: Slide from 1990

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Unified treatment in terms of diffusion

-- in Impact Space and in Virtuality

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"Heterotic Pomeron"--Levin-CIT (hep-ph/9302308)

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Unified treatment in terms of diffusion in AdS with confinement deformation

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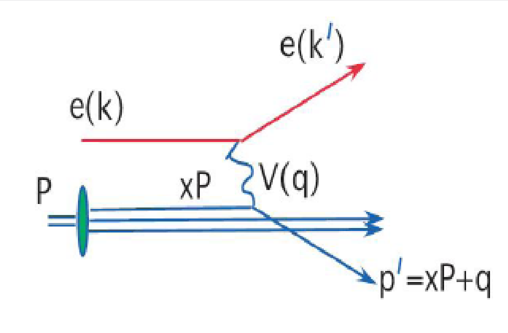
Brower, Polchinski, Strassler, CIT (hep-th/0603115)

II. Deep Inelastic Scattering (DIS) at small-x

$$Deep\ Inelastic\ Scattering\ (DIS)$$



$$F_2(x, Q2) = \frac{Q^2}{4\pi^2\alpha_{em}}\left[\sigma_T(\gamma^* p) +_L (\gamma^* p)\right]$$

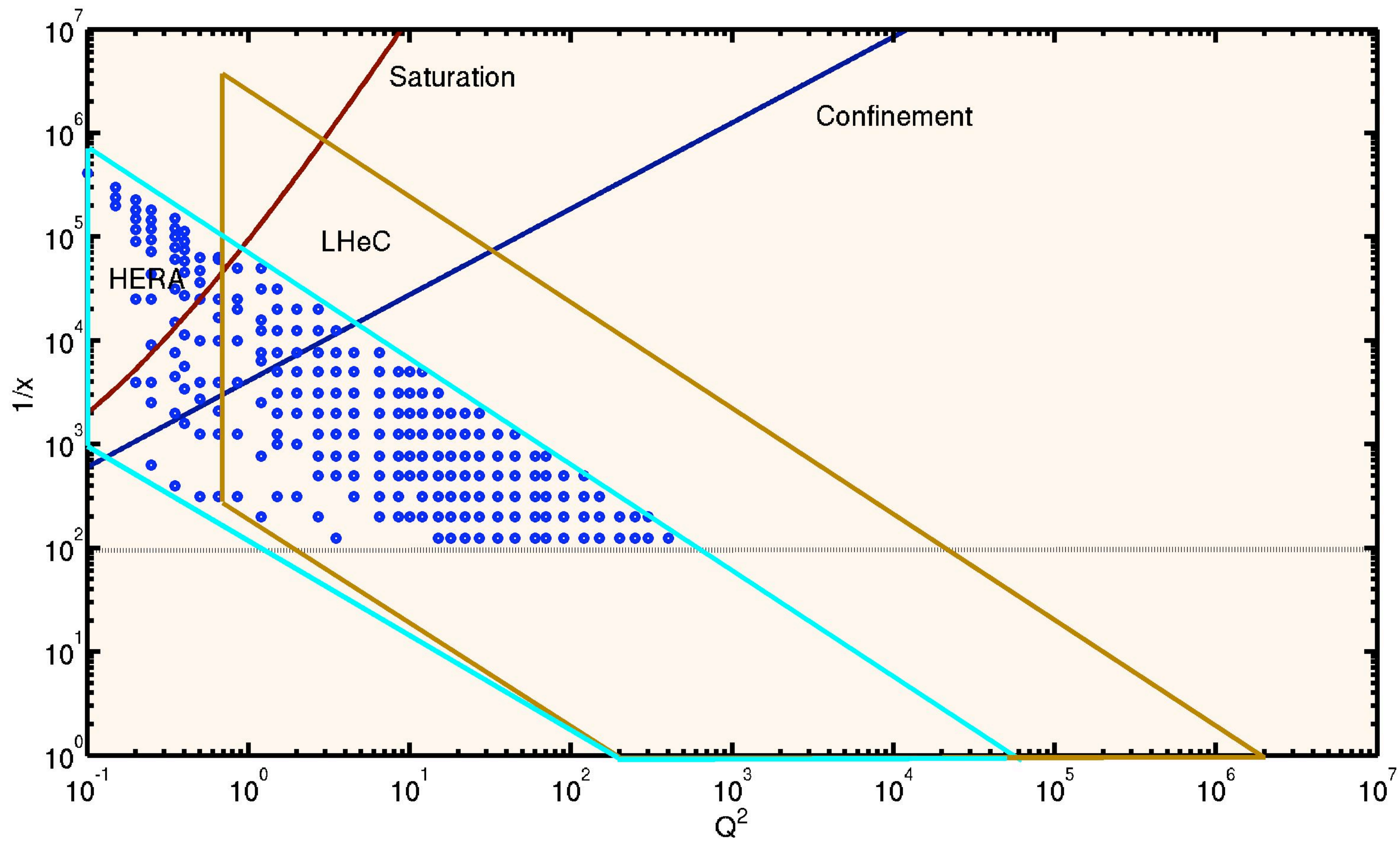
$$x \equiv \frac{Q^2}{s}$$

$$Small\ x: \ \frac{Q^2}{s} \to 0$$

$$Optical\ Theorem$$

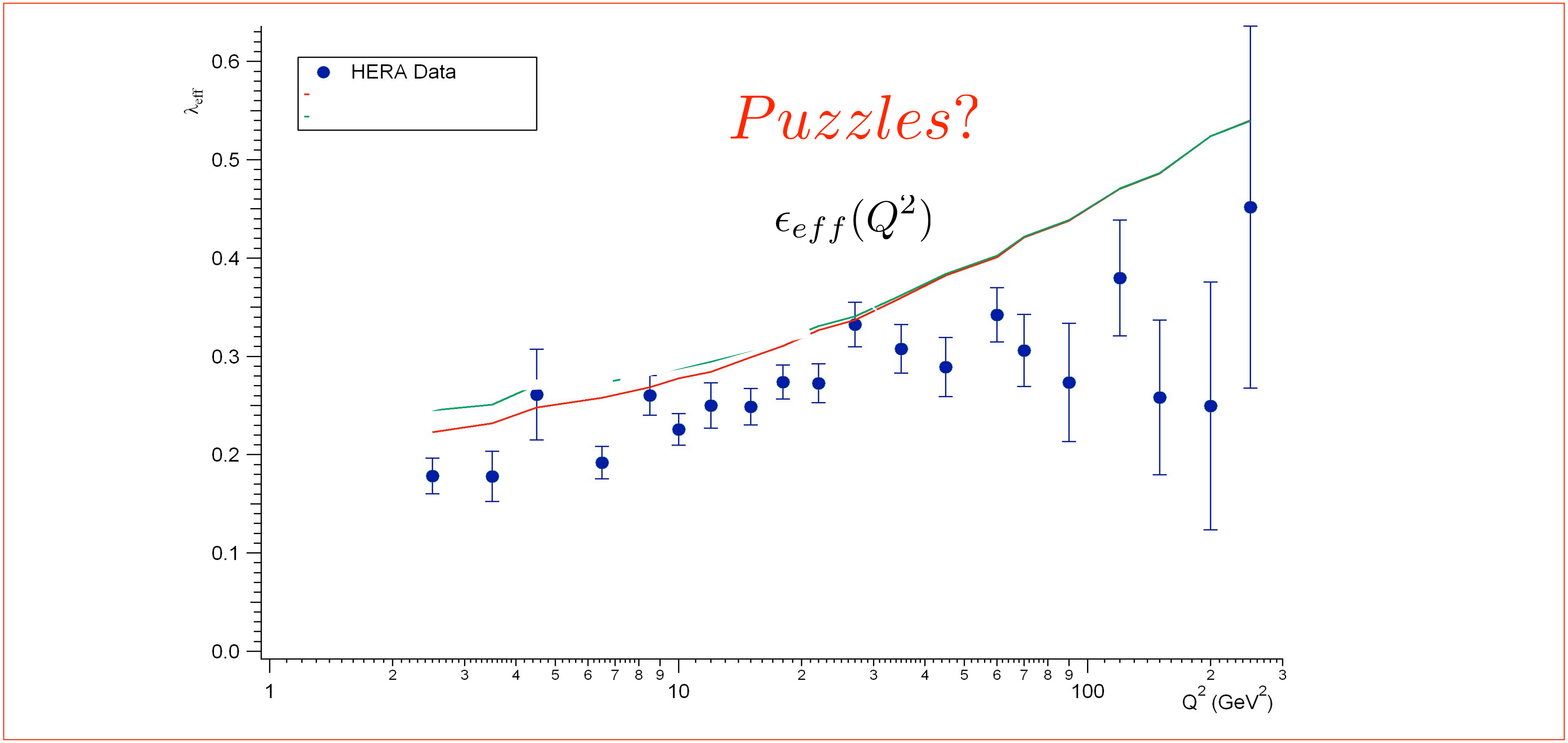
$$\sigma_{total}(s, Q^2) = (1/s)\mathrm{Im}\ A(s, t=0; Q^2)$$

HERA vs LHeC region: dots are H1-ZEUS small-x data points



Effective Pomeron Intercept from HERA data:

$$F_2 \simeq C(Q^2)\ x^{-\epsilon_{eff}}$$



Questions on HERA DIS small-x data:

- Why $\alpha_{eff} = 1 + \epsilon_{eff}(Q^2)$?
- Confinement? (Perturbative vs. Non-perturbative?)
- Saturation? (evolution vs. non-linear evolution?)

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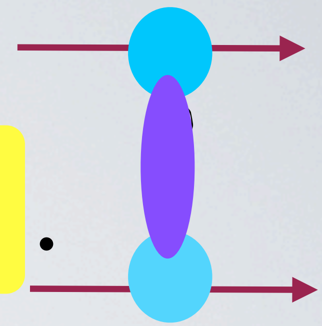
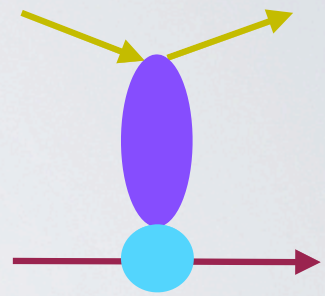


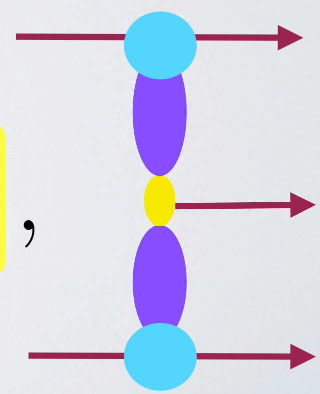
$$A(s,t) = g_0^2 \int d^3\mathbf{b} d^3\mathbf{b}' \; e^{i\mathbf{q}_\perp \cdot (\mathbf{x}-\mathbf{x}')} \; \Phi_{13}(z) \; \mathcal{K}(s, \mathbf{x}-\mathbf{x}', z, z') \; \Phi_{24}(z')$$

$$d^3\mathbf{b} \equiv dz d^2 x_\perp \sqrt{-g(z)} \quad \text{where} \quad g(z) = \det[g_{nm}] = -e^{5A(z)}$$



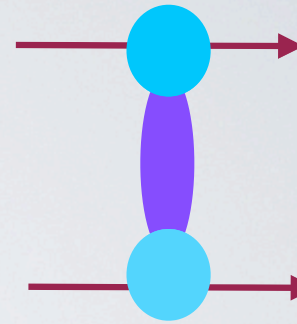
For 2-to-3

$$A(s, s_1, s_2, t_1, t_2) = \Phi_{13} * \widetilde{\mathcal{K}}_P * V * \widetilde{\mathcal{K}}_P * \Phi_{24} \,,$$



ELASTIC VS DIS ADS BUILDING BLOCKS

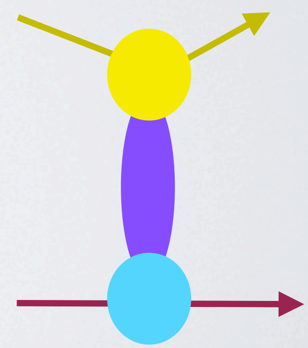
$$A(s, x_\perp - x'_\perp) = g_0^2 \int d^3\mathbf{b} d^3\mathbf{b}' \Phi_{12}(z) G(s, x_\perp - x'_\perp, z, z') \Phi_{34}(z')$$



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

for $\quad F_2(x, Q)$

$$\Phi_{13}(z) \to \Phi_{\gamma^*\gamma^*}(z, Q) = \frac{1}{z}[Qz)^4 (K_0^2(Qz) + K_1^2(Qz)]$$



$$d^3\mathbf{b} \equiv dz d^2 x_\perp \sqrt{-g(z)} \quad \text{where} \quad g(z) = \det[g_{nm}] = -e^{5A(z)}$$

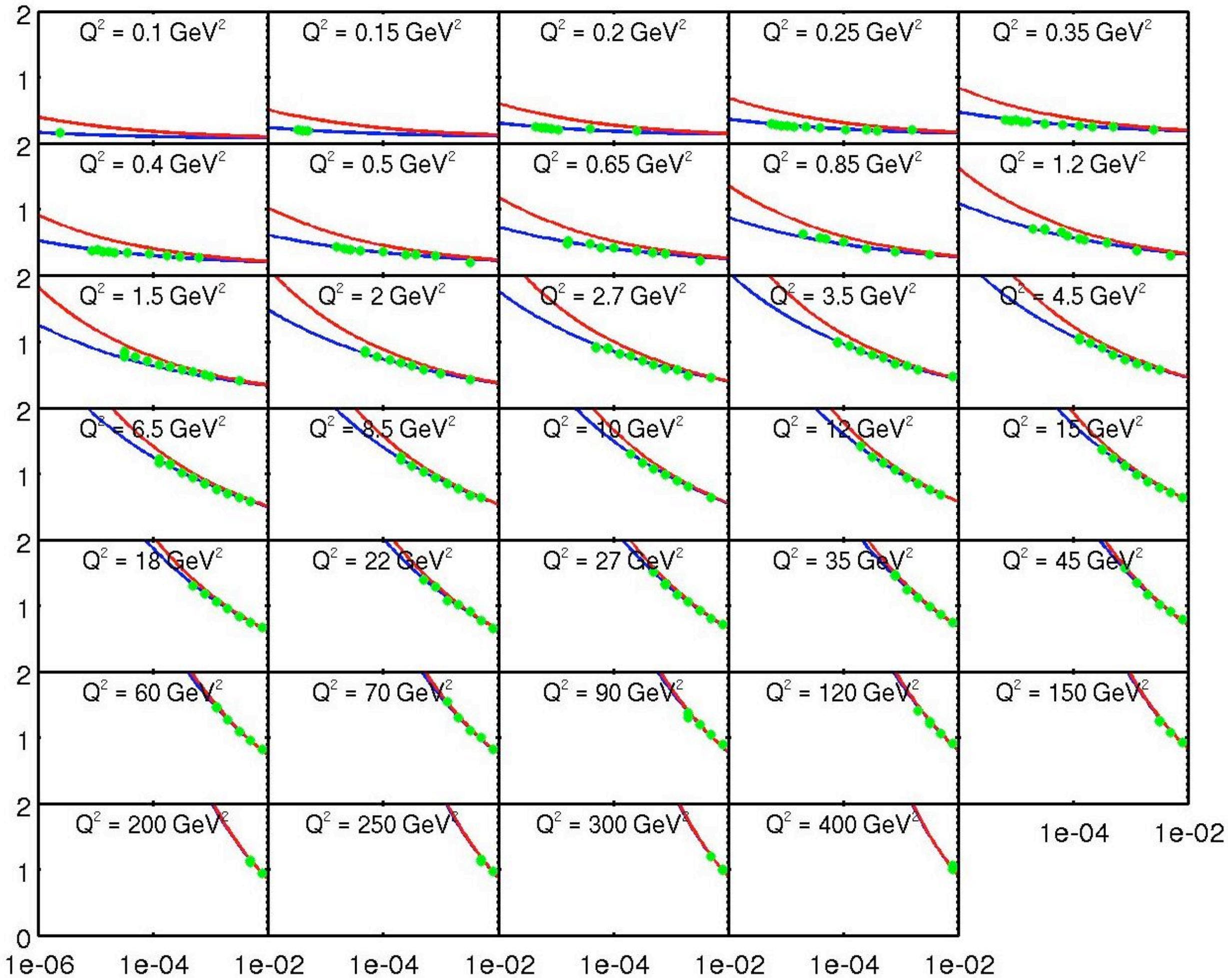
DIS in String Theory

continued

$F_2(x, Q^2)$ from AdS/CFT

$$F_2 = c\frac{Q}{Q'}\frac{(Q_0^2\frac{Q}{Q'}\frac{1}{x})^{1-\rho}}{\sqrt{\log(Q_0^2\frac{Q}{Q'}\frac{1}{x})}}\exp\left(-\frac{\log^2(\frac{Q}{Q'})}{\rho\log(Q_0^2\frac{Q}{Q'}\frac{1}{x})}\right)$$

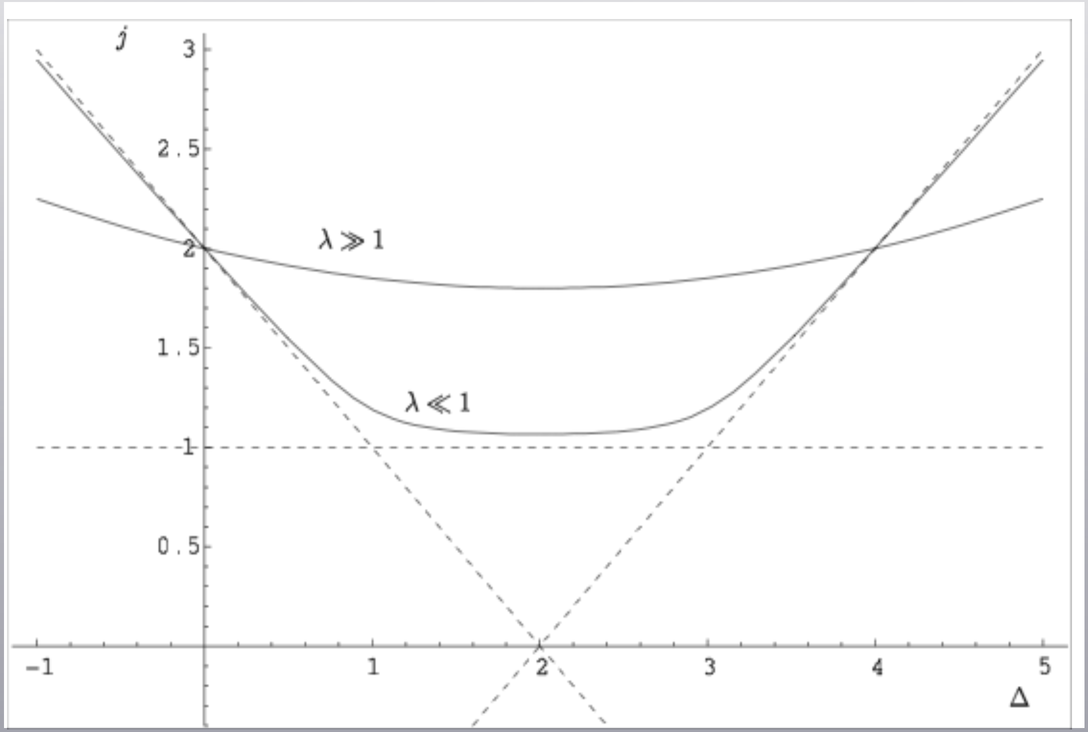
- This is the expression we will use later for comparing to data. Let's make a few comments about this function.
- c is a dimensionless normalization constant. I have grouped here all the constants the multiply F_2, including the coupling constant that comes from χ, and only appears as product together with normalization.
- At any Q^2 fixed, we see that at small x the term $(\frac{1}{x})^{(1-\rho)}$ dominates. This leads to a violation of the Froissart bound.



red – Conformal kernel, green – Hard-Wall kernel

MOMENTS AND ANOMALOUS DIMENSION

$$M_n(Q^2) = \int_0^1 dx\; x^{n-2} F_2(x, Q^2) \to Q^{-\gamma_n}$$



$$\gamma_2 = 0$$

Simultaneous compatible large Q^2 and small x evolutions!

Energy-Momentum Conservation

MOMENTS AND ANOMALOUS DIMENSION

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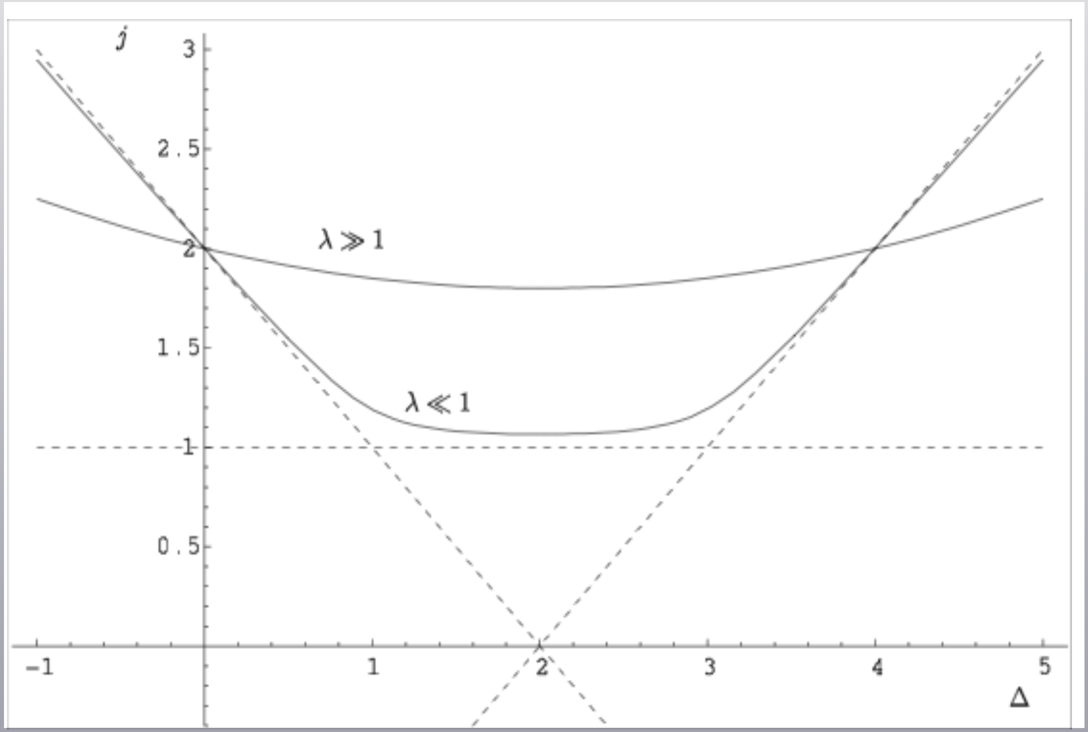


$$\gamma_2 = 0$$

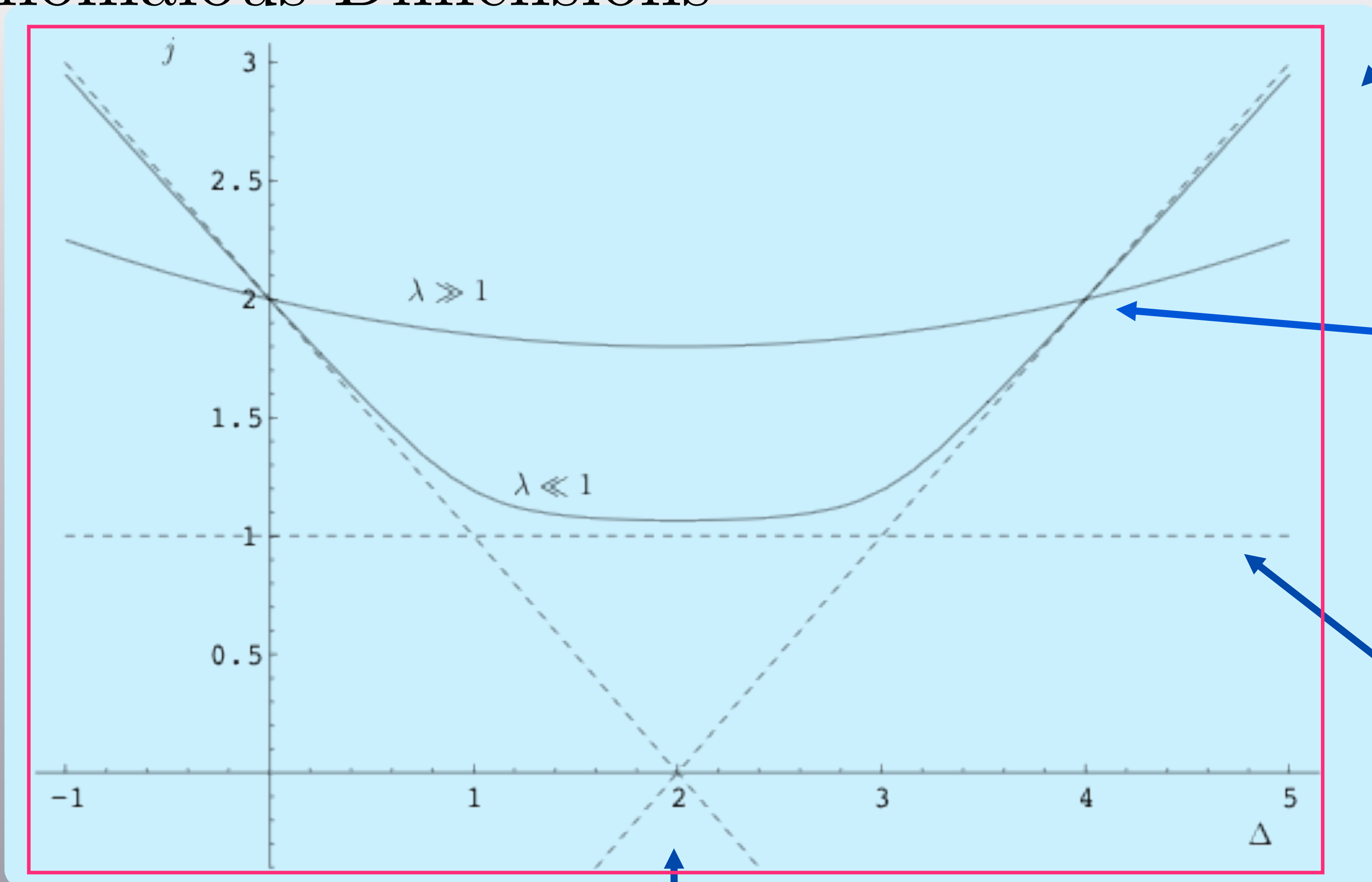
$$\Delta(j) = 2 + \sqrt{2}\sqrt{\sqrt{g^2 N_c}(j - j_0)}$$

$$\gamma_n = 2\sqrt{1 + \sqrt{g^2 N}(n-2)/2} - n$$

Simultaneous compatible large Q^2 and small x evolutions!

Energy-Momentum Conservation built-in automatically.

$\mathcal{N} = 4$ SYM Leading Twist $\Delta(J)$ vs J: Anomalous Dimensions



λ = 0 DGLAP (DIS moments)

$Tr[F_{+\mu} D_+^{j-2} F_+^{\mu}]$

(0,2) $T_{\mu\nu}$ $\gamma = 0$

λ = 0, BFKL

$\lambda = g^2 N = 0$

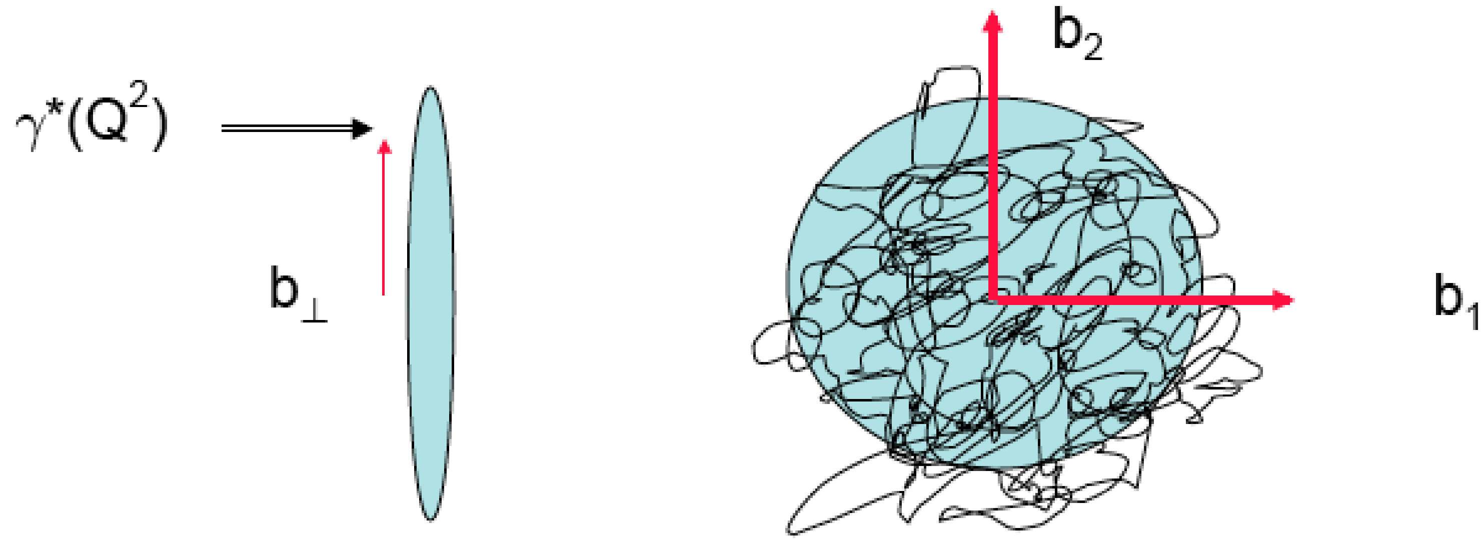
$j = j_0$ @ min Δ

II-b. Deep Inelastic Scattering (DIS) at small-x:

Confinement !!!

QCD: EMERGENCE OF 5-DIM: ADS

"Fifth" co-ordinate is size z / z' of proj/target



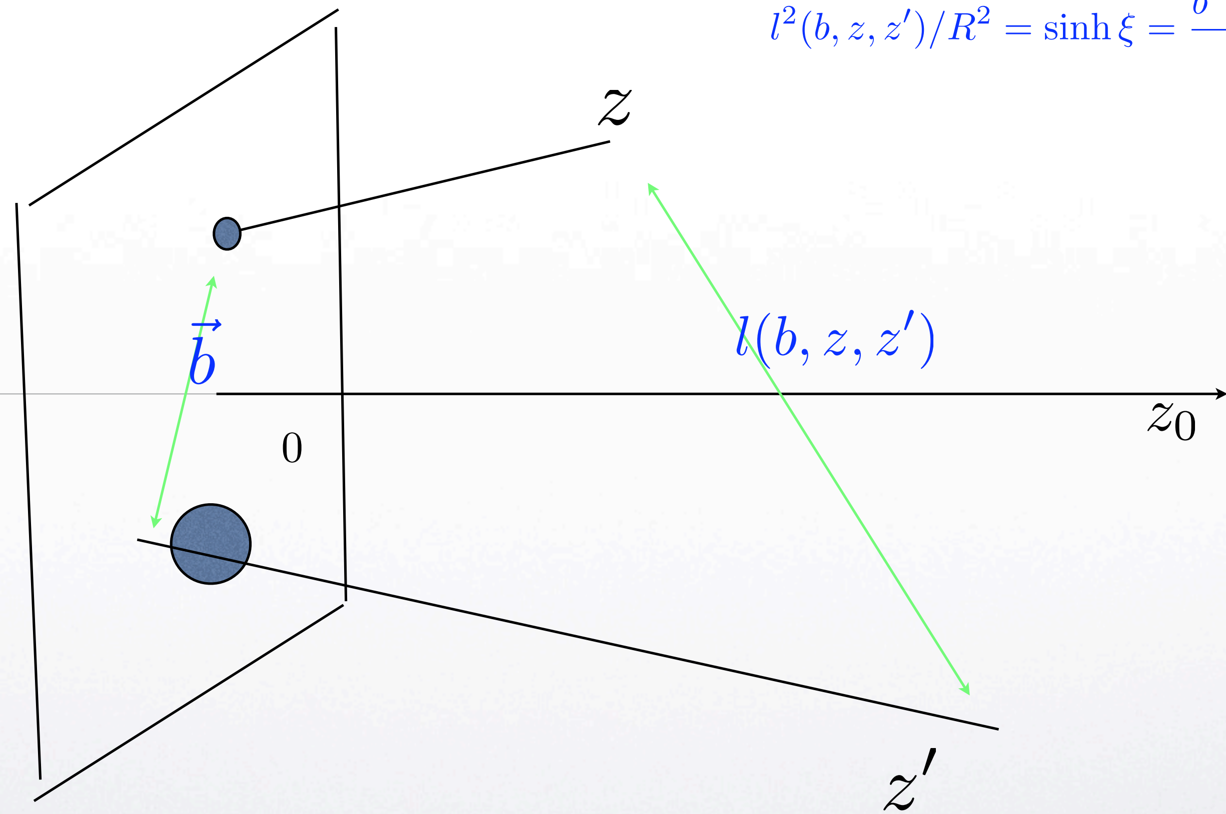
5 kinematical Parameters:

2-d Longitudinal	$p^\pm = p^0 \pm p^3 \simeq \exp[\pm \log(s/\Lambda_{qcd})]$
2-d Transverse space:	$x'_\perp - x_\perp = b_\perp$
1-d Resolution:	$z = 1/Q$ (or $z' = 1/Q'$)

Geometry of Transverse AdS-3

chordal distance: $l(b, z, z')$

$$l^2(b, z, z')/R^2 = \sinh \xi = \frac{b^2 + (z - z')^2}{2zz'}$$



DIS in String Theory

The Hard-wall Model continued

We will take over the structure function formula we had before, and just replace the Pomeron exchange kernel with the new version.

$F_2(x, Q^2)$ from hard-wall AdS/CFT

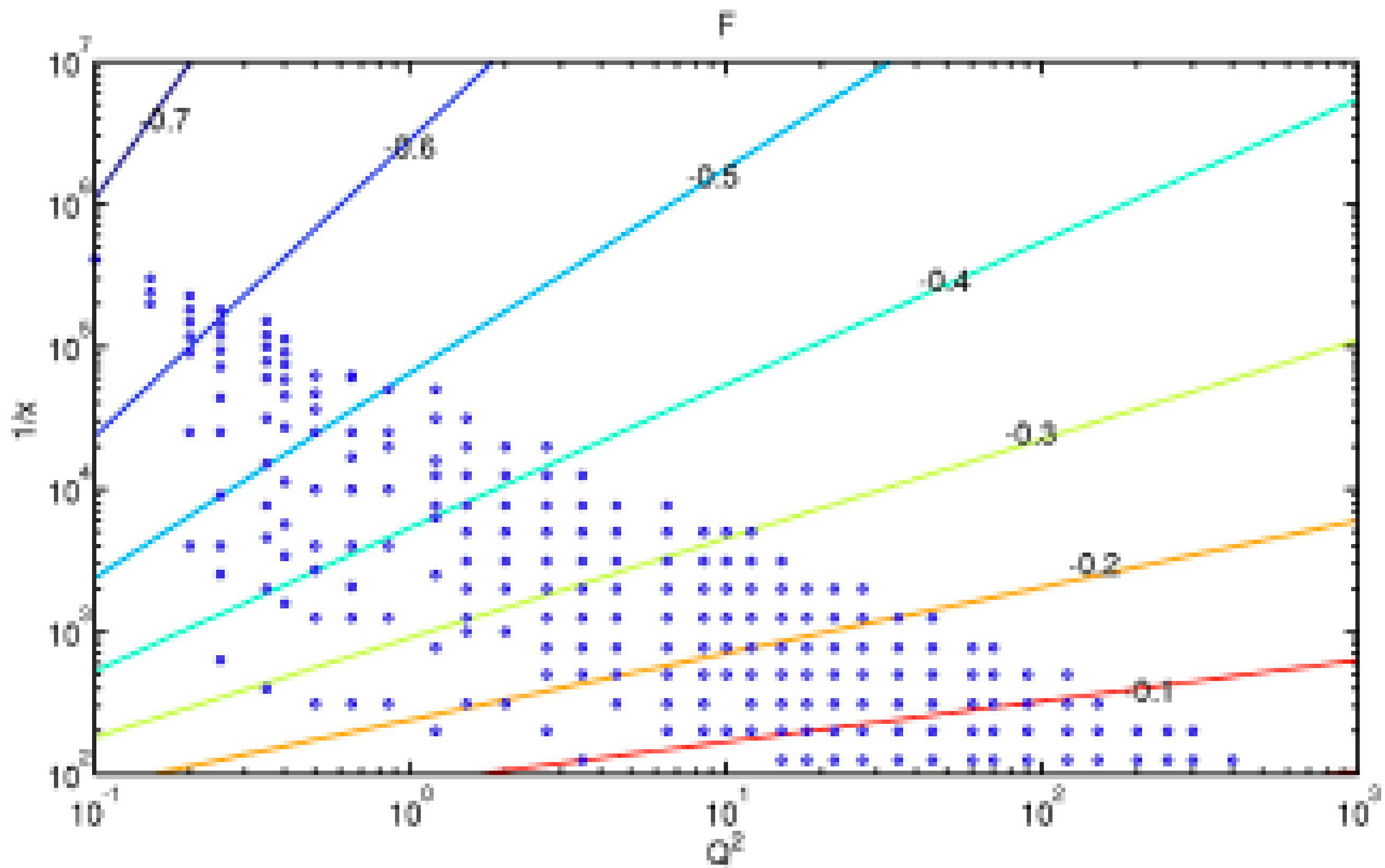
$$F_2 = c\frac{Q}{Q'}\frac{(Q_0^2\frac{Q}{Q'}\frac{1}{x})^{1-\rho}}{\sqrt{\log(Q_0^2\frac{Q}{Q'}\frac{1}{x})}}(\exp(-\frac{\log^2(\frac{Q}{Q'})}{\rho\log(Q_0^2\frac{Q}{Q'}\frac{1}{x})}) + \mathcal{F}\exp(-\frac{\log(\frac{Q_0^2}{QQ'})^2}{\rho\log(Q_0^2\frac{Q}{Q'}\frac{1}{x})}))$$

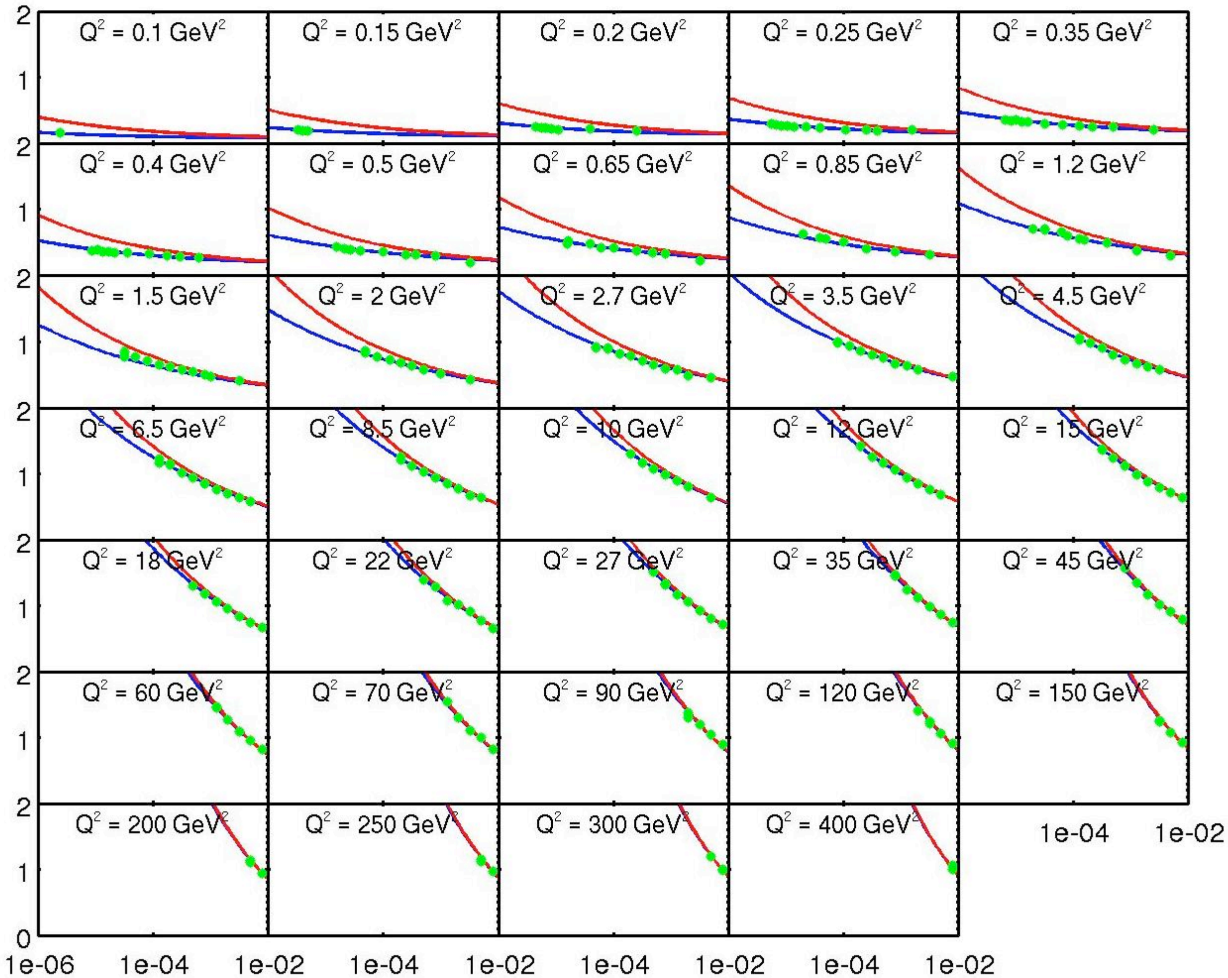
we see that this part is the same as before, while this part is new. The function $\mathcal{F}$ is given by

$$\mathcal{F}(x, Q, Q') = 1 - 4\sqrt{\pi\log(Q_0^2\frac{Q}{Q'}\frac{1}{x})}e^{\eta^2}erfc(\eta)$$

where

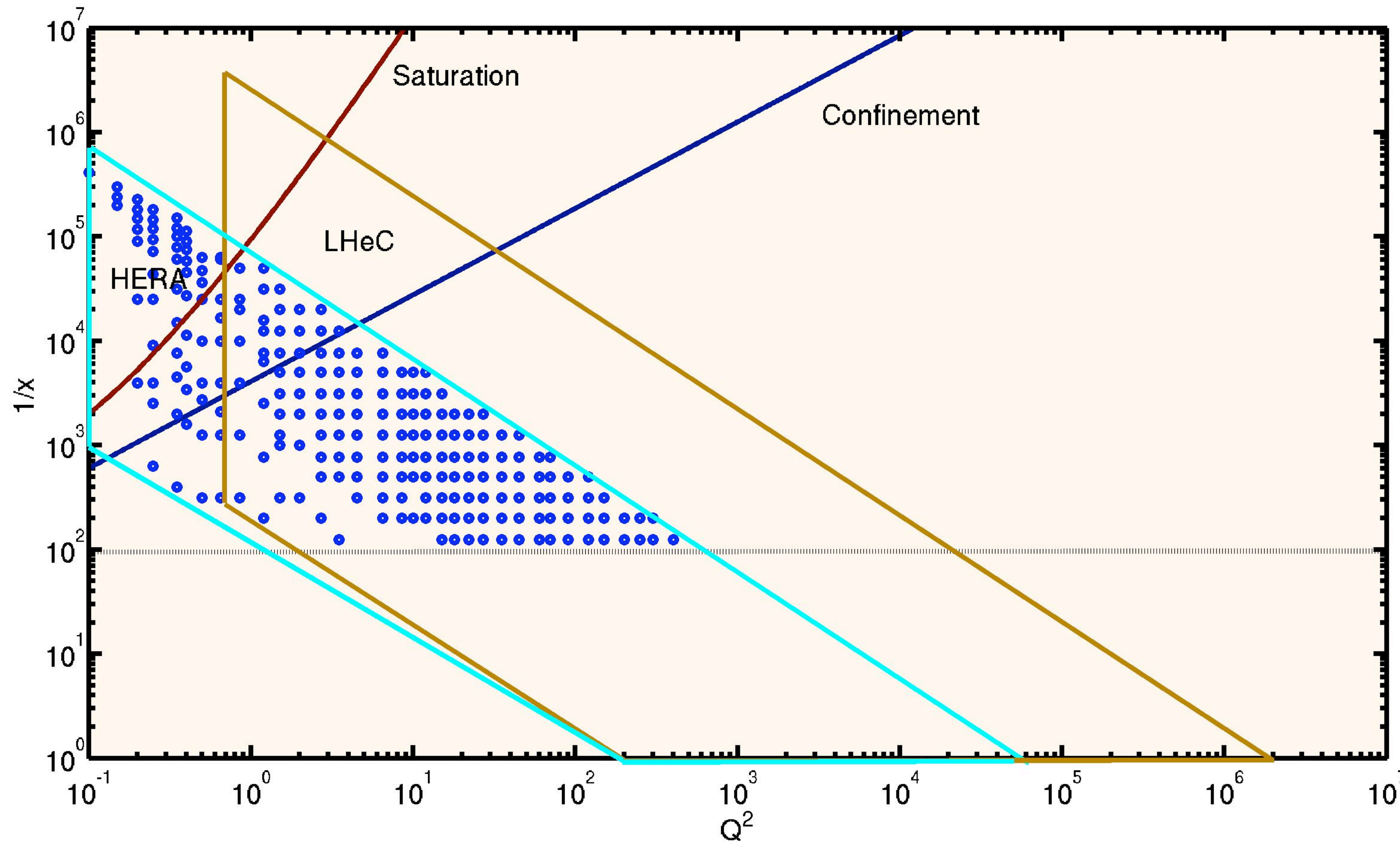
$$\eta = \frac{\log(\frac{x}{Q^2}(Q_0^2\frac{Q}{Q'}\frac{1}{x})^{1-\rho})}{\sqrt{\rho\log(Q_0^2\frac{Q}{Q'}\frac{1}{x})}}$$


F
1/x
Q^2
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1



red – Conformal kernel, green – Hard-Wall kernel

Confining Pomeron: $\chi^2 = 1.07$

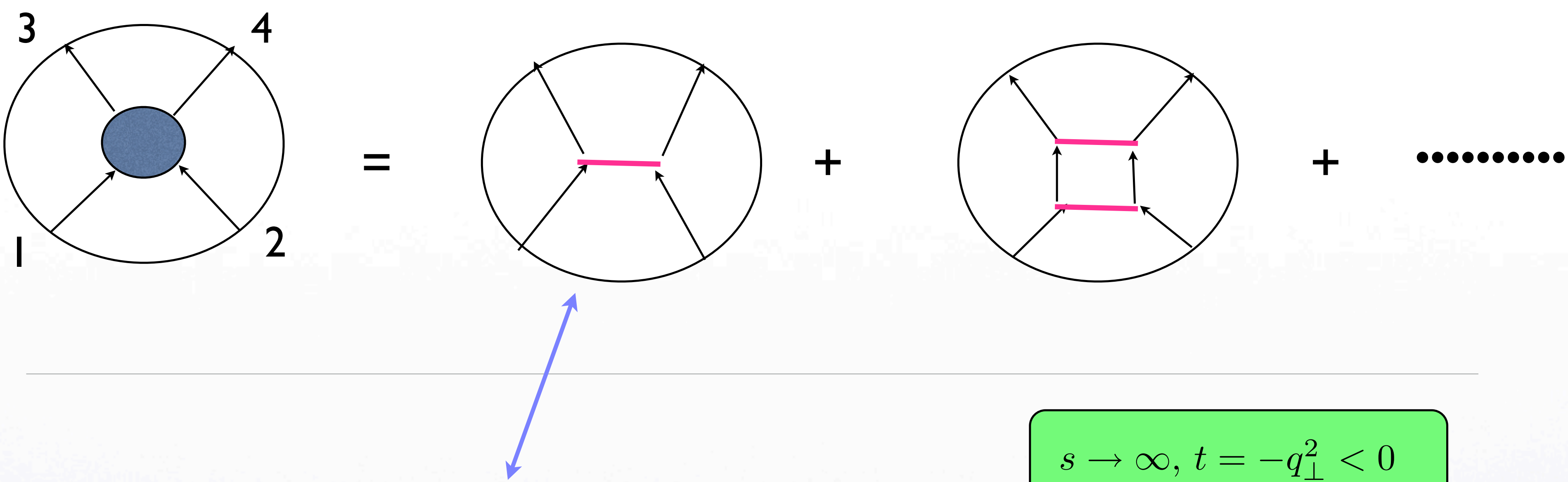


Saturation
Confinement
LHeC
HERA
1/x
Q^2

III. Beyond Pomeron

- Sum over all Pomeron graph (string perturbative, $1/N^2$)
- Eikonal summation in AdS_3
- Constraints from Conformal Invariance, Unitarity, Analyticity, Confinement, Universality, etc.
- Froissart Bound?
- "non-perturbative" (e.g., blackhole production)

Higher Orders Witten Diagrams:



$$s \to \infty, \; t = -q_\perp^2 < 0$$

$$A_4(s,t) \simeq \int d^2b \, e^{-i\mathbf{b}\cdot\mathbf{q}_\perp} \int d\mu(z) \int d\mu(z')$$

$$\times \quad \phi_1(z,\mathbf{b})\phi_3(z,\mathbf{b})\mathcal{K}(s,\mathbf{b}-\mathbf{b}',z,z')\phi_2(z',\mathbf{b}')\phi_4(z',\mathbf{b}')$$

- # Eikonal Sum: derived both via Cheng-Wu or by Shock-wave method

$$A_{2\to 2}(s,t) \simeq -2is \int d^2b\, e^{-ib^\perp q_\perp} \int dz dz' P_{13}(z) P_{24}(z') \left[e^{i\chi(s,b^\perp,z,z')} - 1\right]$$

$$P_{13}(z) = (z/R)^2 \sqrt{g(z)} \Phi_1(z)\Phi_3(z) \qquad P_{24}(z) = (z'/R)^2 \sqrt{g(z')} \Phi_2(z')\Phi_4(z')$$

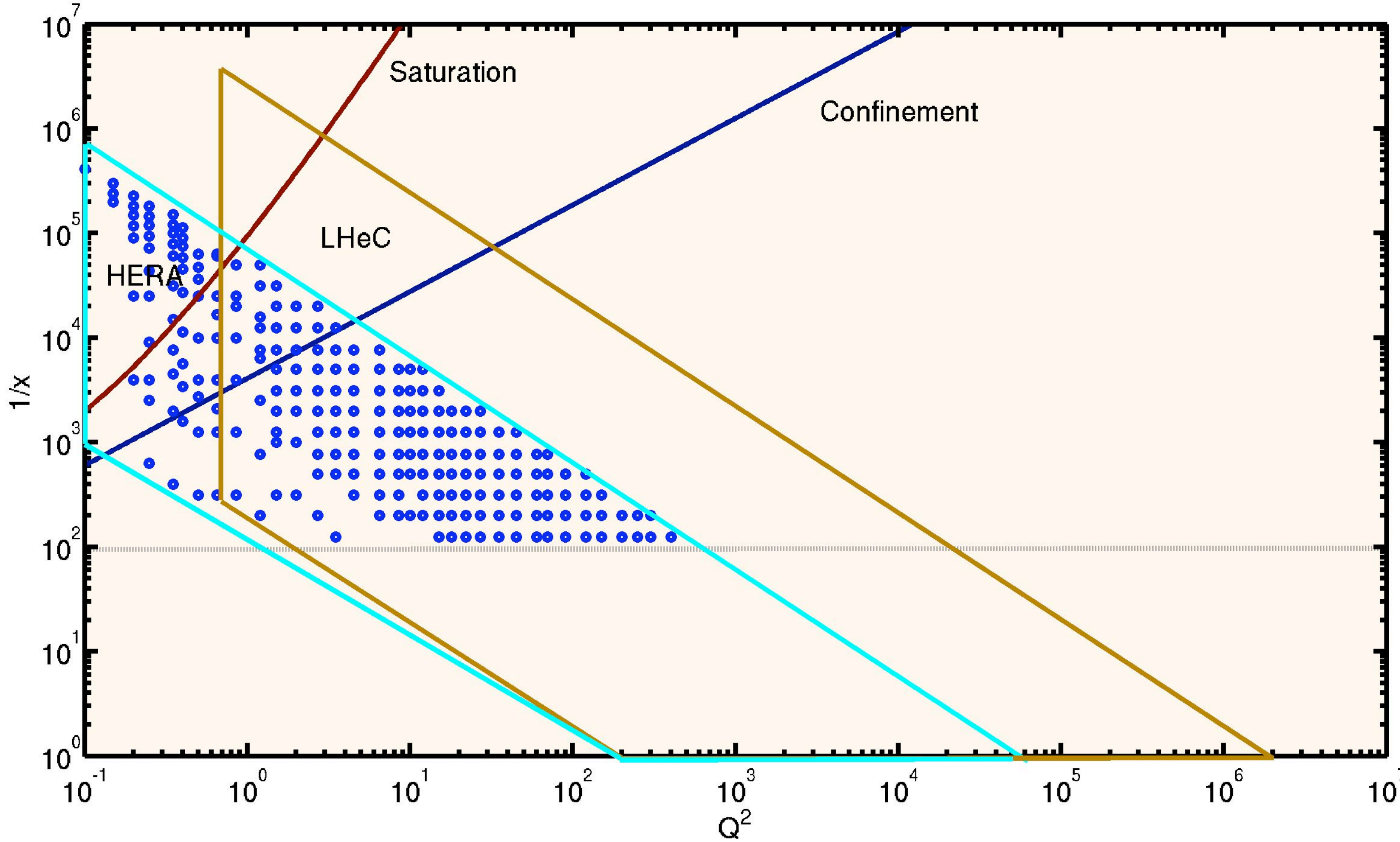
transverse AdS_3 space !!

$$\chi(s, x^\perp - x'^\perp, z, z') = \frac{g_0^2 R^4}{2(zz')^2 s} \mathcal{K}(s, x^\perp - x'^\perp, z, z')$$

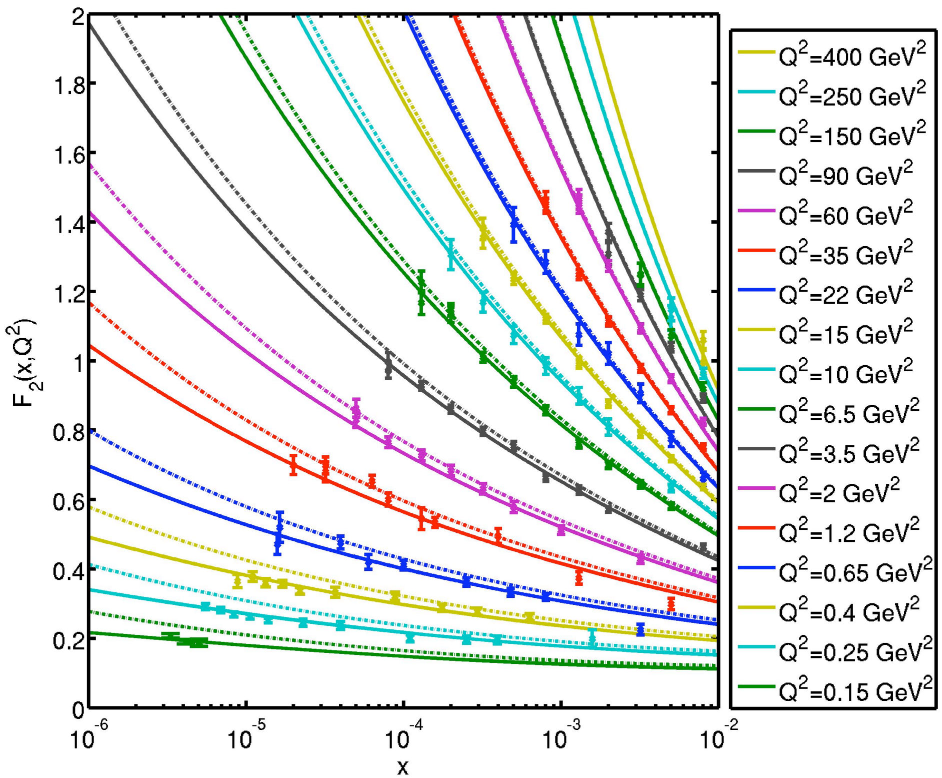
- Saturation:

$$\chi(s, x^\perp - x'^\perp, z, z') \ = \ O(1)$$

- Universality: e.g., Choose Φ_1 and Φ_3 for DIS.

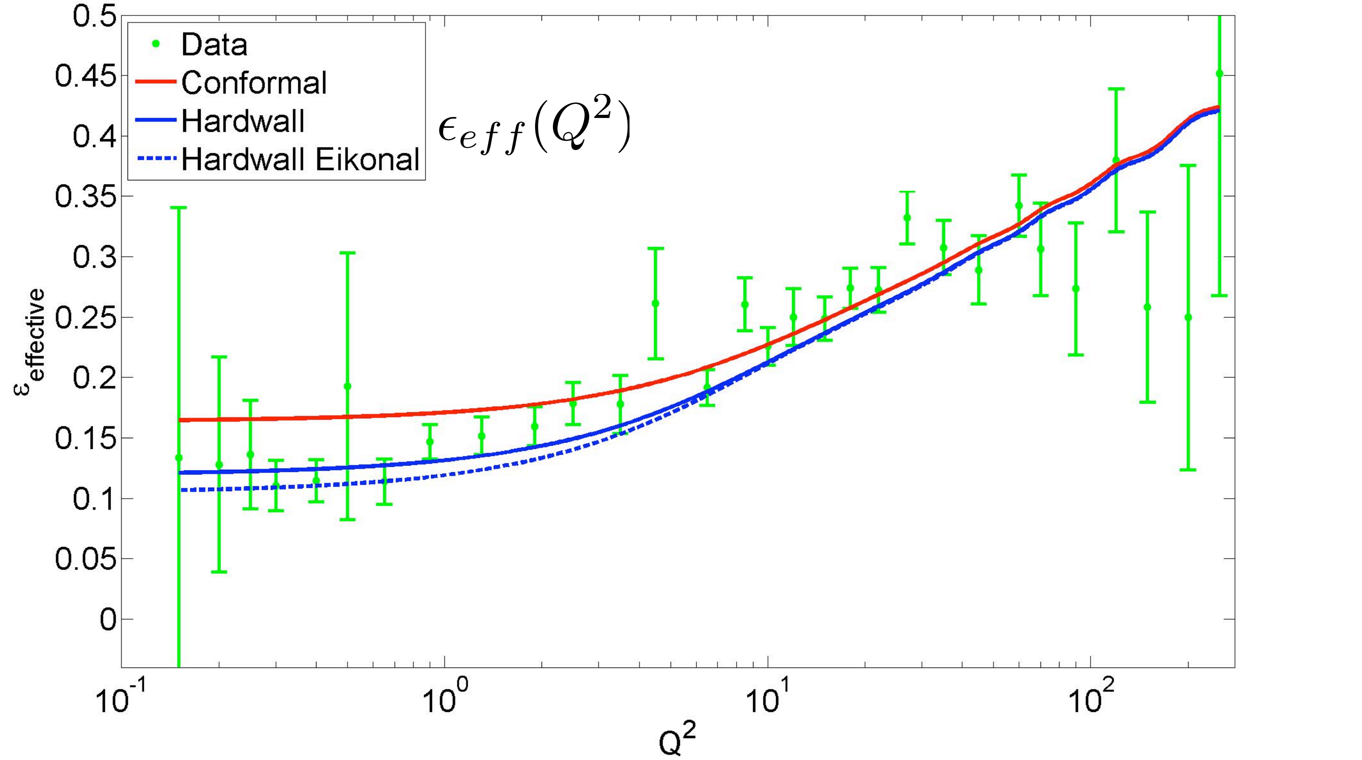


Saturation
Confinement
LHeC
HERA
1/x
Q^2

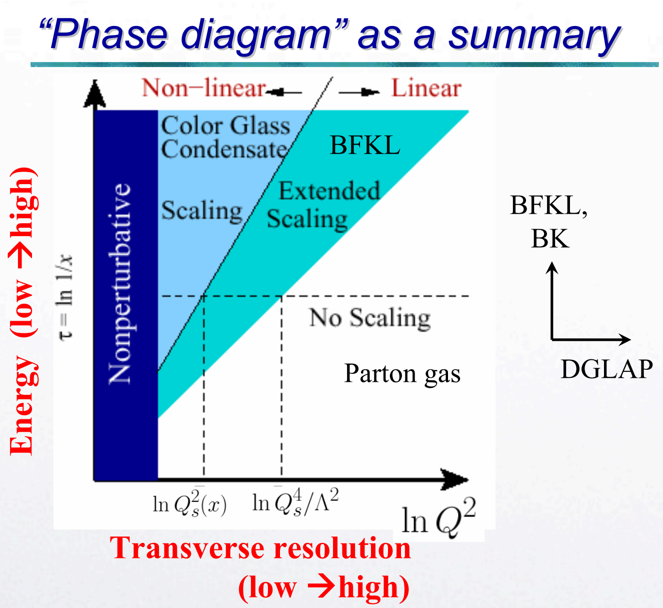


F2(x,Q2)
x
Q2=400 GeV2
Q2=250 GeV2
Q2=150 GeV2
Q2=90 GeV2
Q2=60 GeV2
Q2=35 GeV2
Q2=22 GeV2
Q2=15 GeV2
Q2=10 GeV2
Q2=6.5 GeV2
Q2=3.5 GeV2
Q2=2 GeV2
Q2=1.2 GeV2
Q2=0.65 GeV2
Q2=0.4 GeV2
Q2=0.25 GeV2
Q2=0.15 GeV2

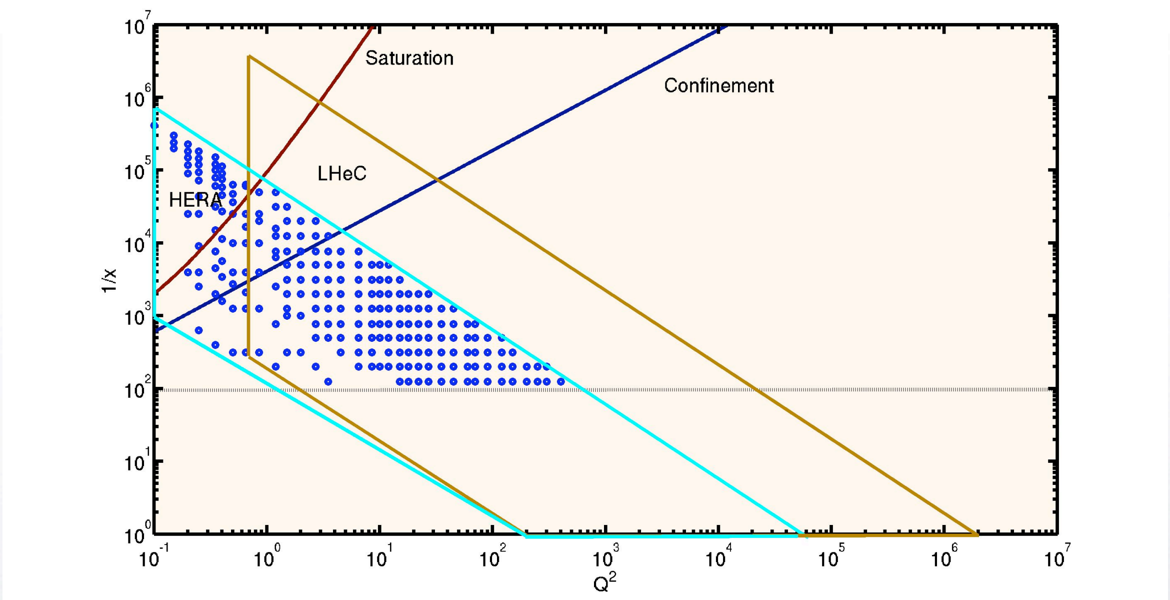
$F_2(x, Q^2) \sim (1/x)^{\epsilon_{effecti}}$



Standard expectation
(from Itakura's RIKEN lectures)



AdS/CFT expectation
(from BDST: hep-ph/1007.2259)



Scattering in Conformal Limit:

Use the condition: $\chi(s, x^\perp - x'^\perp, z, z') = O(1)$

Elastic Ring: $b_{\rm diff} \sim \sqrt{zz'}\,(zz's/N^2)^{1/6}$

No Froissart $\sigma_{total} \sim s^{1/3}$

Inner Absorptive Disc:

$$b_{\rm black} \sim \sqrt{zz'}\;\frac{(zz's)^{(j_0-1)/2}}{\lambda^{1/4}N} \qquad b_{\rm black} \sim \sqrt{zz'}\left(\frac{(zz's)^{j_0-1}}{\lambda^{1/4}N}\right)^{1/\sqrt{2\sqrt{\lambda}}(j_0-1)}$$

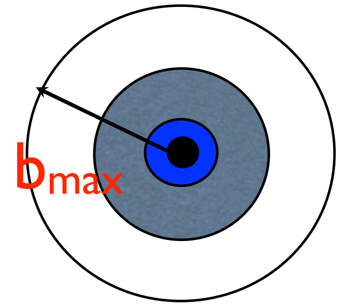
Inner Core: “black hole” production ?

Saturation of Froissart Bound

- The Confinement deformation gives an exponential cutoff for $b > b_{max} \sim c \log(s/s_0)$,
- Coefficient $c \sim 1/m_0$, m_0 being the mass of lightest tensor glueball.
- Froissart is respected and saturated.

$$\Delta b \sim \log(s/s_0)$$

Disk picture



b_{max} determined by confinement.

IV. Summary and Outlook

Executive Summary:

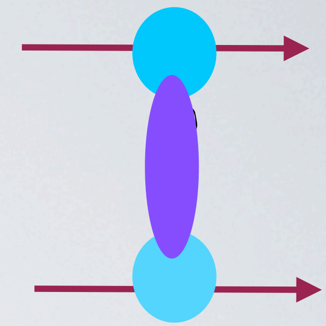
Gauge/String Duality (AdS/CFT) $\longrightarrow$ 2-GLUONS $\simeq$ GRAVITON

Status Report:

- Establishing "Pomeron" in QCD non-perturbatively,
- Unification of Soft and Hard Physics in High Energy Collision
- New phenomenology based on "Large Pomeron intercept", e.g., DIS at small-x: (DGLAP vs Pomeron); Central Diffractive Higgs Production.

ELASTIC, DIS, DOUBLE HIGGS: ADS BUILDING BLOCKS

$$A(s,t) = g_0^2 \int d^3\mathbf{b} d^3\mathbf{b}' \; e^{i\mathbf{q}_\perp \cdot (\mathbf{x}-\mathbf{x}')} \; \Phi_{13}(z) \; \mathcal{K}(s, \mathbf{x}-\mathbf{x}', z, z') \; \Phi_{24}(z')$$



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

$$d^3\mathbf{b} \equiv dz d^2 x_\perp \sqrt{-g(z)} \quad \text{where} \quad g(z) = \det[g_{nm}] = -e^{5A(z)}$$

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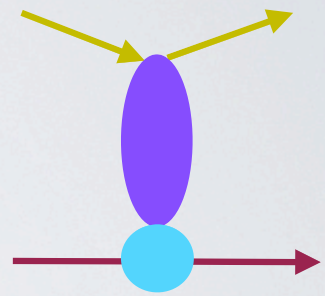
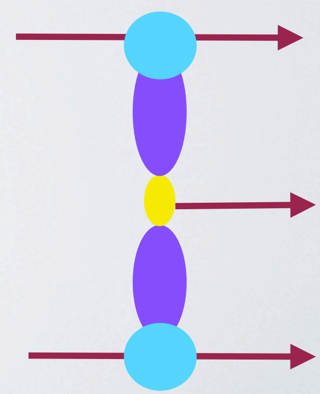
for $\quad F_2(x,Q)$



$$\Phi_{13}(z) \to \Phi_{\gamma^*\gamma^*}(z,Q) = \frac{1}{z}[Qz)^4 (K_0^2(Qz) + K_1^2(Qz)]$$

For Double Diffractive Higgs



$$A(s_1, s_2, s, t_1, t_2) = \Phi_{13} * \mathcal{K}_1 * \mathcal{V}_H * \mathcal{K}_2 * \Phi_{24}$$