SIZE AND SHAPE OF HADRONS: FROM PION CLOUD TO POMERON/ODDERON AND HOLOGRAPHY

QCD - Old Challenges
and New Opportunities

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BROWN

Goals of this Talk

A Non-perturbative Approach to QCD at High Energy

Two-step Procedure:

*Theoretical basis for Pomeron/Odderon via AdS/CFT,

*Fixing relevant Scales for QCD at high energy,

e.g., scale for Froissart bound,

role of pion mass, constituent quarks, etc.

partonic interpretation, etc.

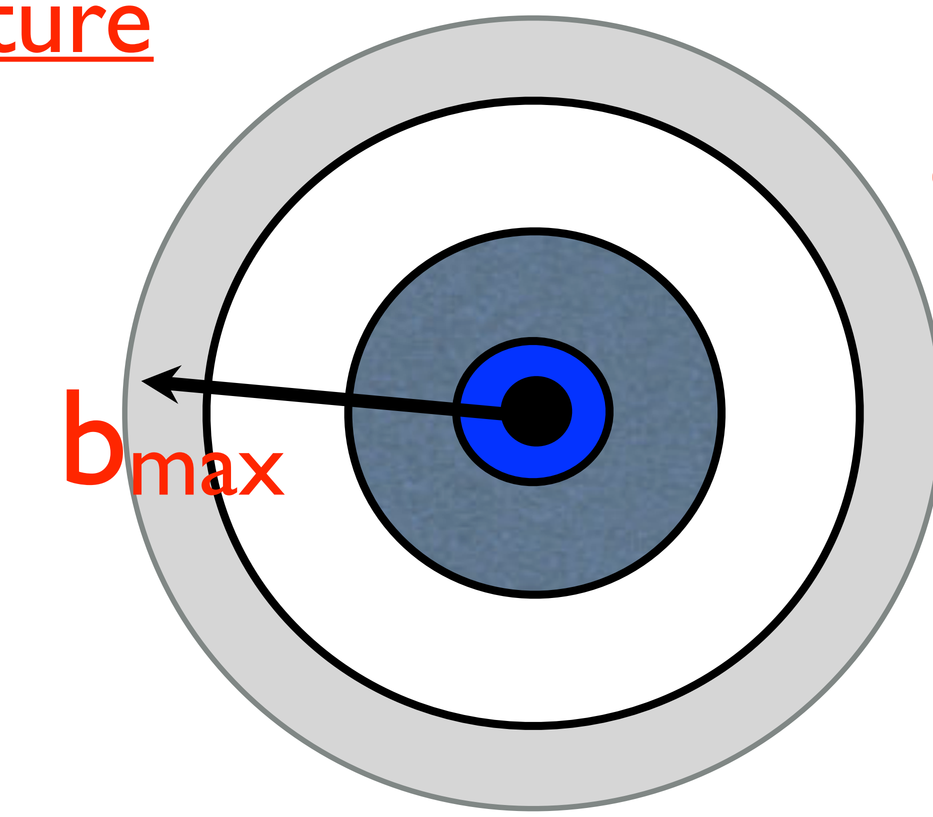
Shape, Size and Froissart Bound

- 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.
- There is a shell of "conformal region" of width: $\Delta b \sim \log(s/s_0)$

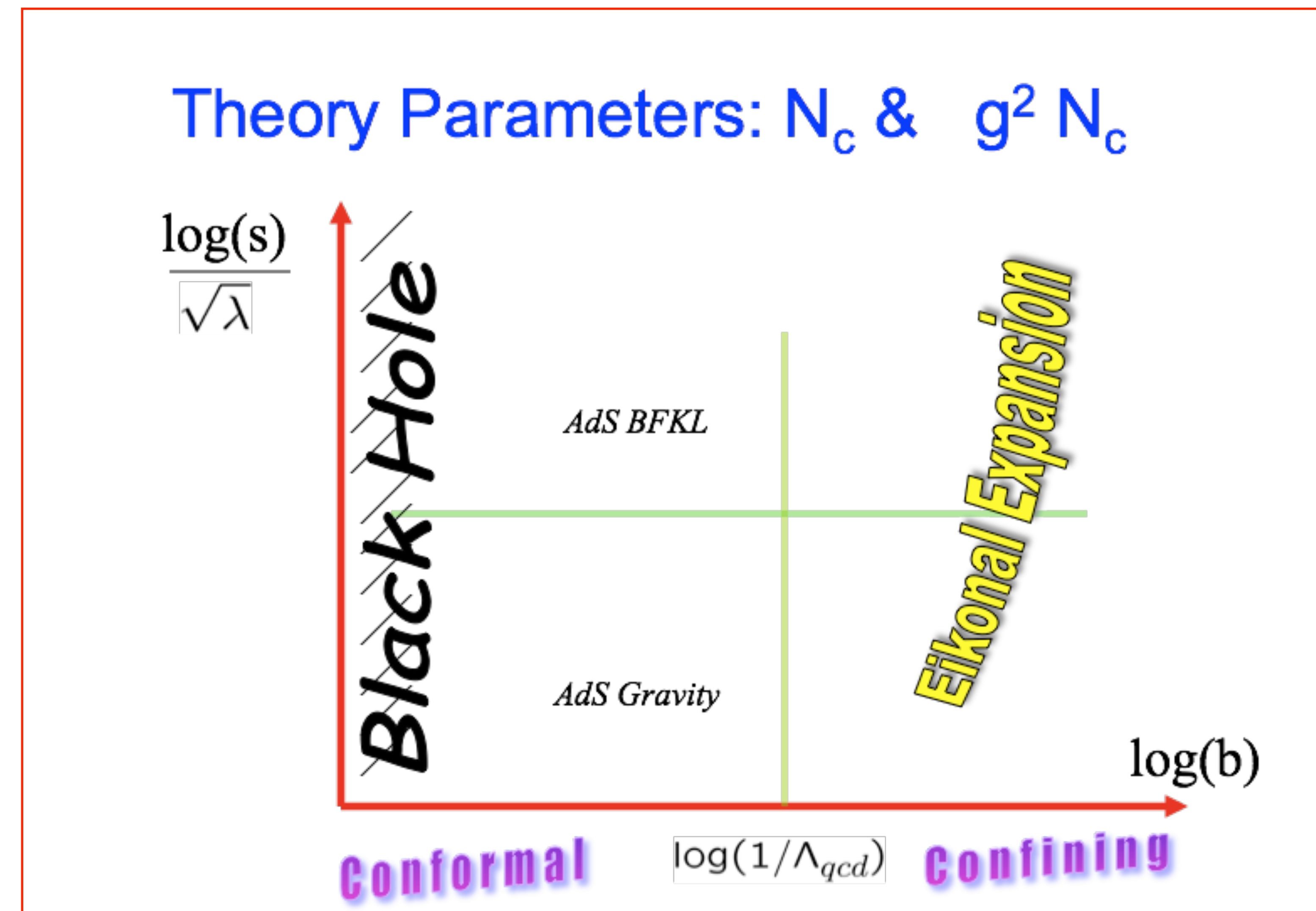
b_{max} determined by confinement.

- pion mass, constituents, etc.

Disk picture



Partonic structure



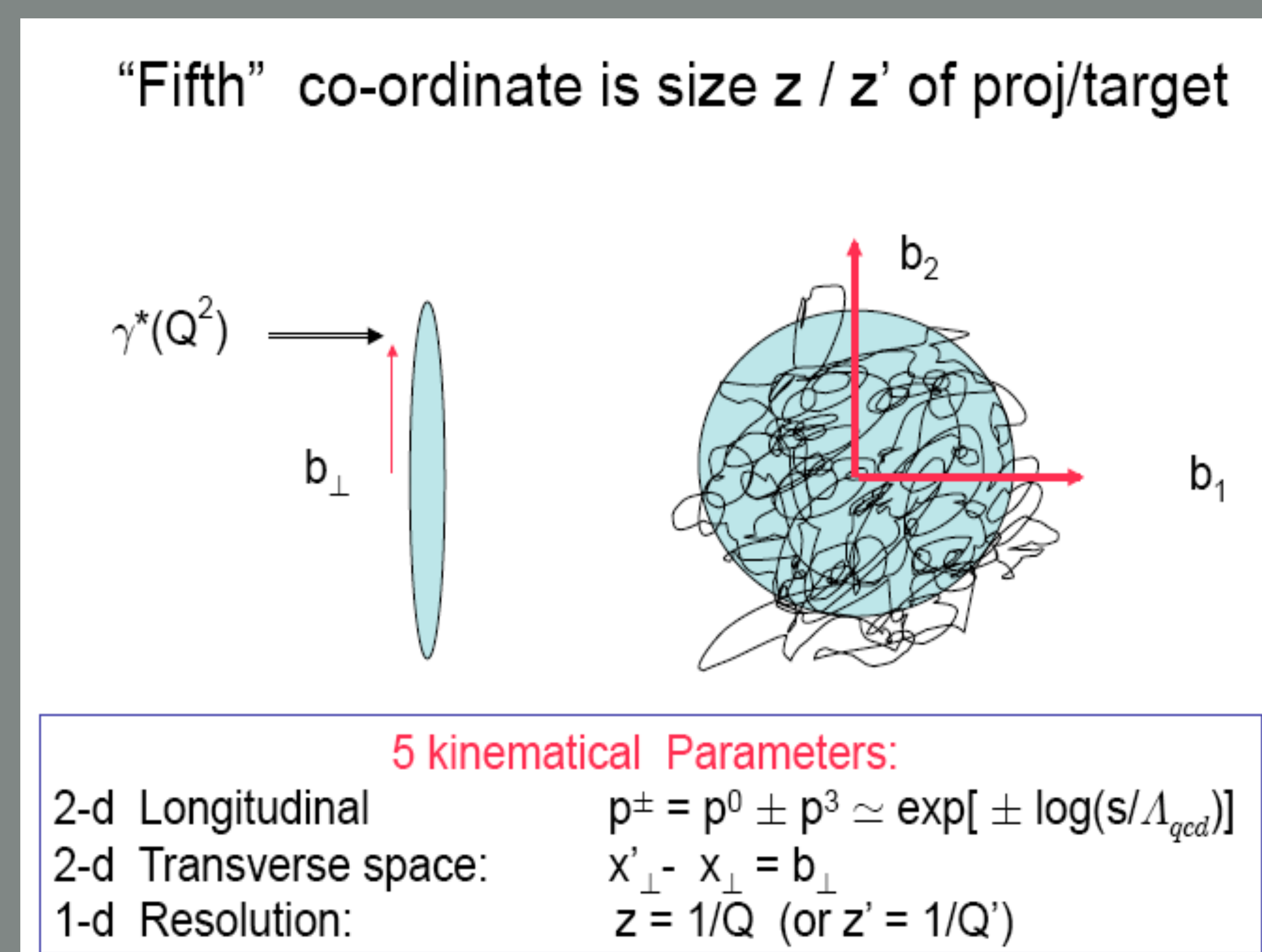
Outline

- Introduction:
  - Size and Shape of Proton; Lessons from earlier period
- Holography and AdS/CFT Duality
  - Dualities in physics, Holography, String-Gauge Duality and AdS Graviton
- Gauge/String Duality and QCD at Hgh Energy:
  - "AdS Graviton" as Quasi-Particle in HE Scattering in QCD - Pomeron
  - Confinement, Saturation, Glueballs, Inclusive Production, etc.
- Size and Shape of Proton at LHC
  - Pomeron and Odderon
  - Expanding Disk

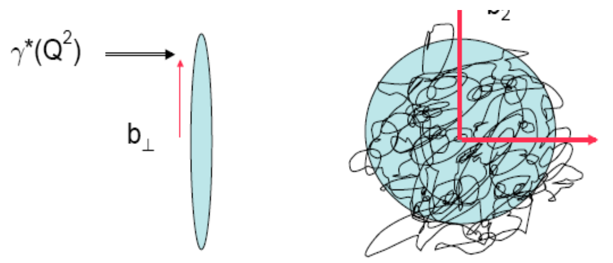
Outline

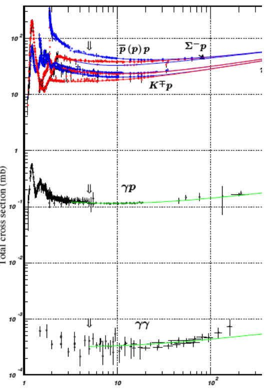
- Introduction:
  - Size and Shape of Proton; Lessons from earlier period

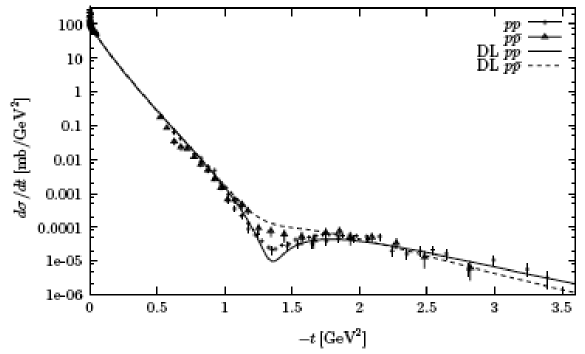
Geometry of High Energy Scattering and Naive Expectation



Geometry of High Energy Scattering and Naive Expectation







Near constant Size:

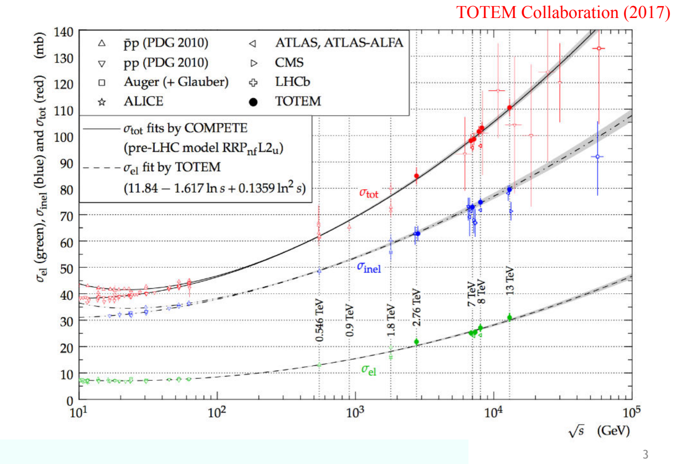
Diffraction Peak:

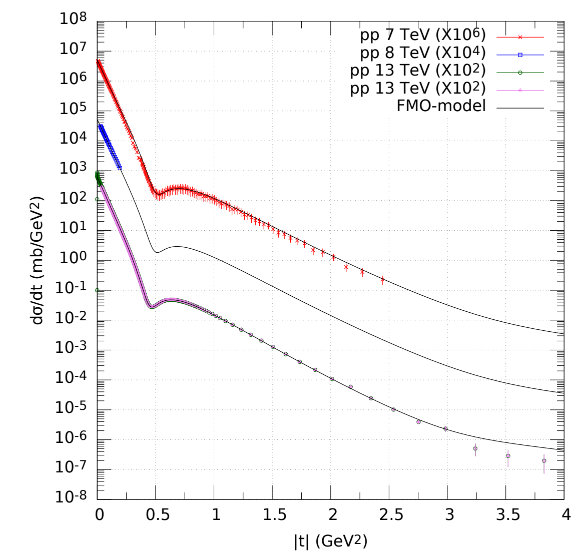
Size and Shape of Hadrons

should be calculable in QCD

Size and Shape of Proton in LHC Era

13TeV data from TOTEM





Interesting new non-perturbative physics in QCD?

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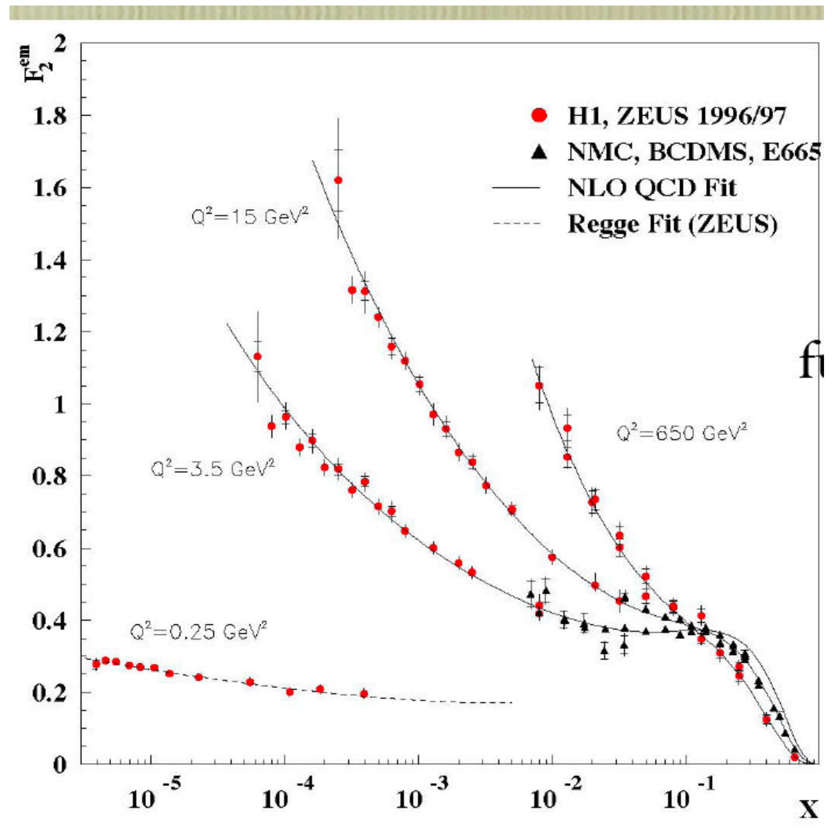
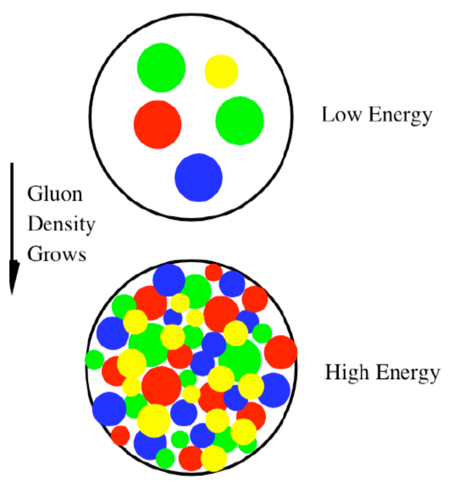
Deep Inelastic Scattering (DIS)





Size and Shape of Hadrons

Partonic Structure of hadrons: Scaling for DIS

Rising of total cross sections with total energy

Shape of differential cross section

Calculate in QCD as emergent phenomena?

Correlations in particle production

Dimensional scaling

Diffractive production at LHC

QCD

Fundamental Theory for the Strong Interactions.

It is a non-Abelian Gauge Theory,

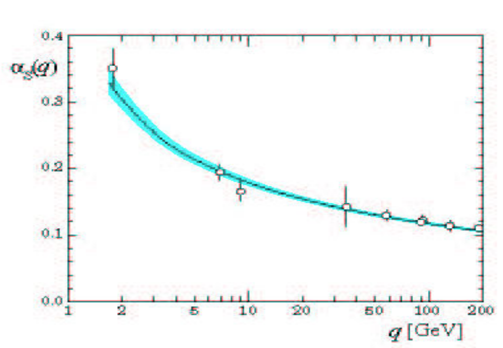
Elementary degrees of freedom:

Gluons and Quarks

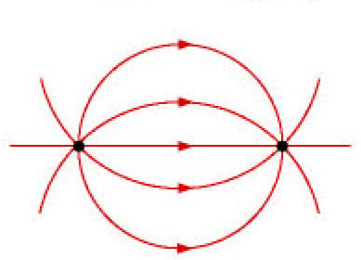
$$\mathcal{L}(x) = -TrF^2 + \bar{\psi}\not{D}\psi + \cdots$$

Asymptotic Freedom

perturbative



$$\alpha_s(q) \equiv \frac{\bar{g}(q)^2}{4\pi} = \frac{c}{\ln(q/\Lambda)} + \ldots$$



r < 0.1 fm

Confinement

non-perturbative

r >> 1 fm

Force at Long Distance--Constant Tension/Linear Potential, Coupling increasing, Quarks and Gluons strongly bound <==> "Stringy Behavior"

strong coupling, non-perturbative

Why does Total Cross Section increase with Energy?

Brief Review of Yukawa Picture:

$$V(r) = g^2 \frac{e^{-\mu r}}{r} \to \frac{g^2}{\mu^2 - t} \qquad \mu \neq 0 \leftrightarrow \text{"}short - range\text{"}$$

$$A = V + V * V + V * V * V + \cdots$$

"Relativistic kinematics"

scalar exchange : $\hat{V}(s,t) \sim \frac{1}{\mu^2 - t}$ $\qquad \sigma_{total} \sim \frac{1}{s}$

vector exchange : $J_\mu J^\mu \to \hat{V}(s,t) \sim \frac{s}{\mu^2 - t}$ $\qquad \sigma_{total} \sim$ constant

tensor exchange : $T_{\mu\nu} T^{\mu\nu} \to \hat{V}(s,t) \sim \frac{s^2}{\mu^2 - t}$ $\qquad \sigma_{total} \sim s$

Need "Vector $\sim$ Tensor" exchange:

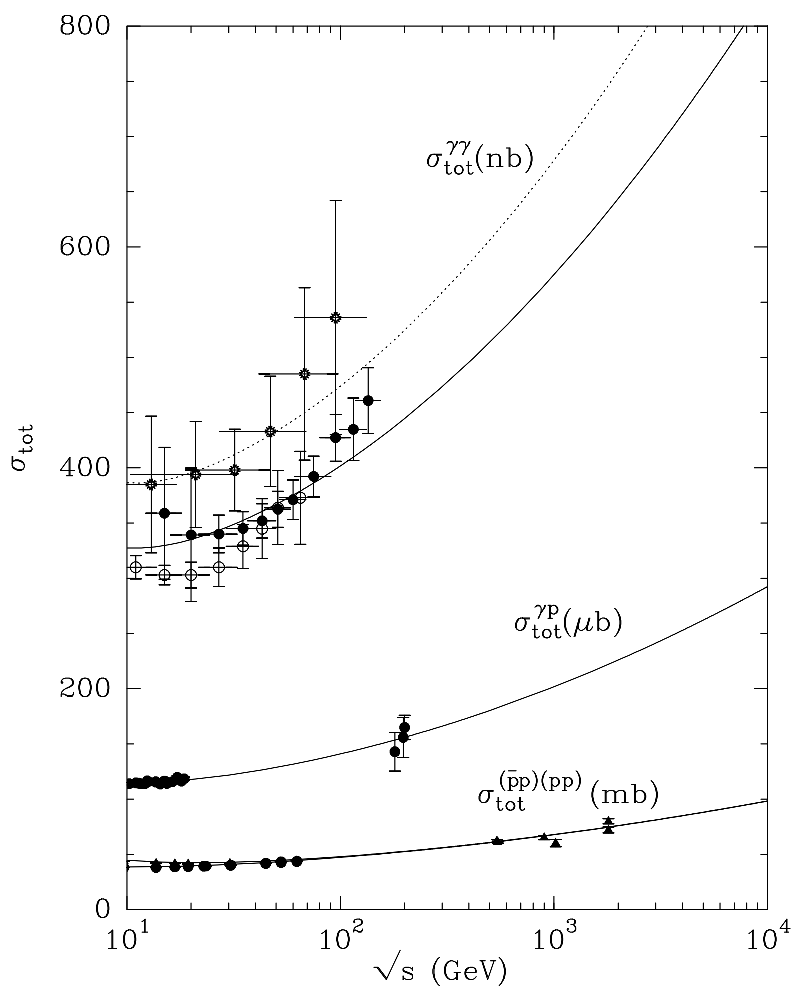
Need "none-zero Mass":

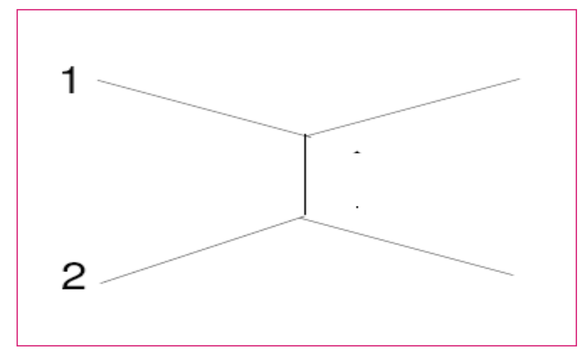
Size and Shape: Dynamics of QCD

Parton Interpretation

quarks and gluons $\quad \sim 2005$

Non-integral Effective Spin - Regge Behavior
Stringy Effect





$$\mathcal{A} \sim s^{J(t)} = s^{\alpha(0)+\alpha' t}$$

$$\sigma_{total} \sim \mathcal{A}(s,0)/s \sim S^{J(0)-1} \sim s^{\alpha(0)-1}$$

$$\alpha(0) > 1$$

effective spin exchange:
vector $\sim$ tensor

"String Theory for QCD"

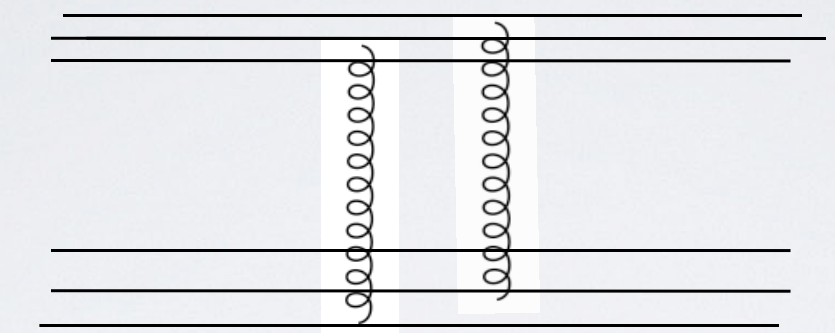
Need "Vector $\sim$ Tensor" exchange:

Need "none-zero Mass":

quarks and gluons ~ 2005

HIGH ENERGY SCATTERING

WEAK COUPLING EXPANSION: TWO-GLUON EXCHANGE



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

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

Require Non-Perturbative Treatment

Outline

- **AdS/CFT: Holographic Duality**
  - CFT: Conformal Field Theories (enlarged symmetry)
  - AdS: Anti-de Sitter
  - Gauge/String Duality
  - Weak coupling to Strong coupling Duality

Duality:

"High-Low Temperature Duality:"

"Ising Model:"

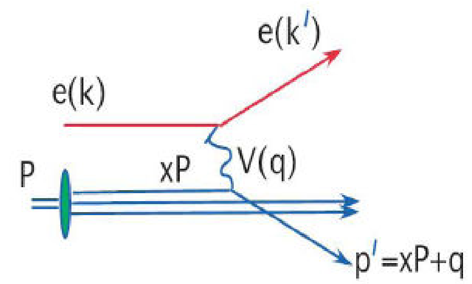
$$Z(\beta) = \sum_{\sigma=\pm1} e^{-\beta\sigma_i\sigma_{i+1}}$$

$$Z(\beta) \quad \Leftrightarrow \quad Z(1/\beta)$$

Understanding of symmetry, etc.,
leading to changed description of ground state,
new effective degrees of freedom.

Dynamical-Symmetry

Deep Inelastic Scattering (DIS)

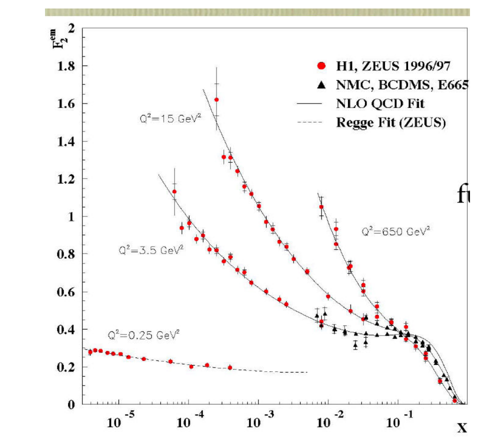


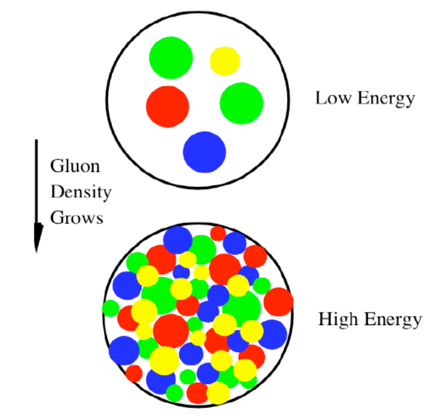
$$F_2(x, Q2) = \frac{Q^2}{4\pi^2\alpha_{em}}\left[\sigma_T(\gamma^* p) +_L (\gamma^* p)\right]$$

Scaling: $F(x, Q^2) \to F(x)$

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

CFT at work!





HIGH ENERGY SCATTERING AND SCALE INVARIANCE

Lagrangian for QED and QCD is scale invariant:

α_{qed}, α_{qcd}, etc., are dimensionless.

exceptions: mass for fermions.

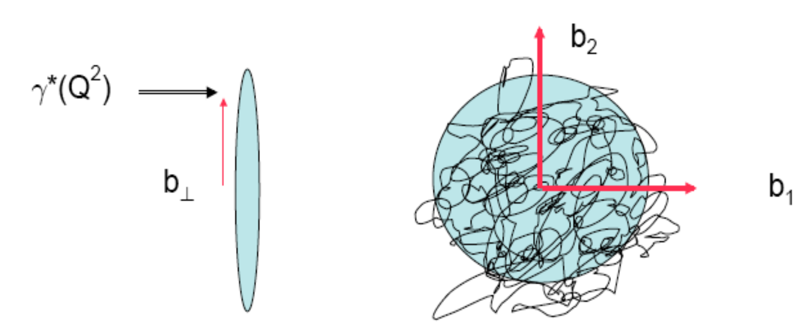
$$\frac{E}{pc} = \frac{\sqrt{(pc)^2 + m_0^2c^4}}{pc} \simeq 1, \qquad p \to \infty$$

Modern approaches to fundamental physics begins with massless fermions, and masses are generated dynamically.

Lorentz + Scale invariance lead to large symmetry: Conformal Symmetry.

CFT: Conformal Invariant Field Theory

Larger Symmetry



5 kinematical Parameters:

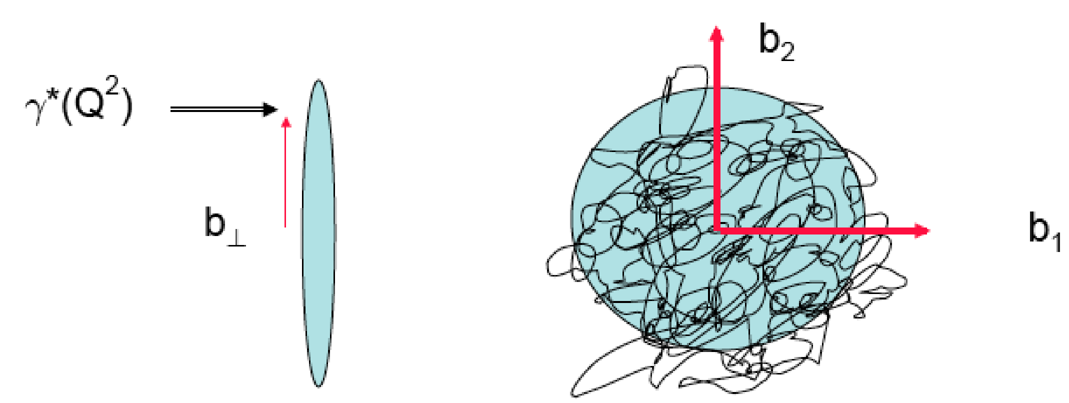
2-d Longitudinal	$p^\pm = p^0 \pm p^3 \simeq \exp[\pm \log(s/\Lambda_{qcd})]$
2-d Transverse space:	$x'_\perp - x_\perp = b_\perp$
1-d Resolution:	$z = 1/Q$ (or $z' = 1/Q'$)

Conformal Symmetry

$$O(1,1) \times O(1,3) \quad \Rightarrow \quad O(2,4)$$

QCD EMERGENCE OF 5-DIM

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



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2-d	Transverse space:	$x'_{\perp} - x_{\perp} = b_{\perp}$
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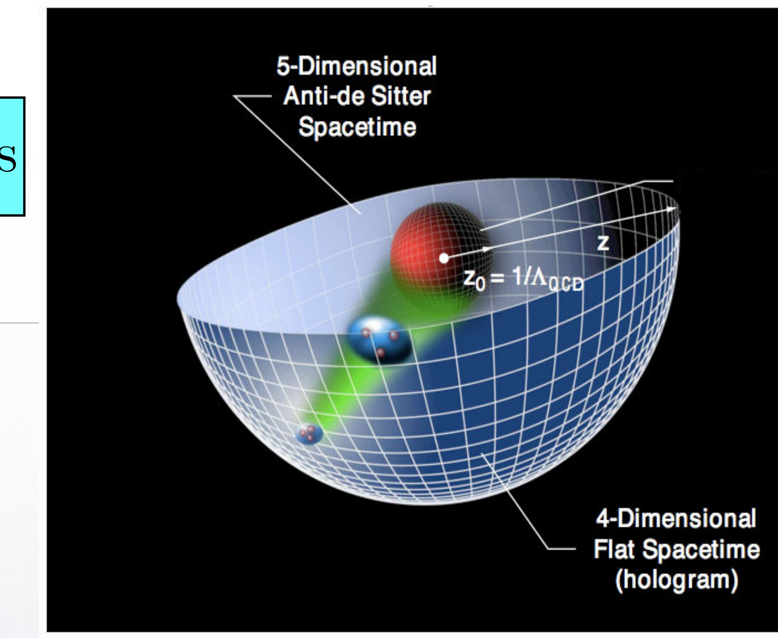
Holographic Duality:

"Holographic Duality:

AdS/CFT Correspondence for Gauge Theories



Understanding of symmetry, etc.,
leading to changed description of ground state,
new effective degrees of freedom.

Physics at D dimension ⇔ Equivalent Physics at (D+1) dimension

Symmetry and Geometrization:

- Symmetry: Conformal Invariance:

$$O(1,1) \times O(1,3) \quad \Rightarrow \quad O(2,4)$$

- Geometrization:

symmetry as isometry of geometry of extended space-time.

$$(t, \vec{x}) \oplus r \quad \Rightarrow \quad (t, \vec{x}, r)$$

Gauge-String Duality: AdS/CFT

Weak Coupling:

Gluons and Quarks: $A^{ab}_{\mu}(x), \psi^a_f(x)$

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

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

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

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

Strong Coupling:

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

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

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

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

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

Outline

- Gauge/String Duality and QCD at Hgh Energy:
    - "AdS Graviton" as Quasi-Particle in HE Scattering in QCD - Pomeron
    - Confinement, Saturation, Glueballs, Inclusive Production, etc.

$\mathcal{N} = 4$ 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

Witten Diagram and One-Graviton Exchange

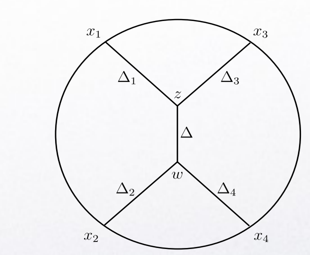
Scalar-exchange witten diagram

$$T(s,t;p_i^2) \sim \int d\mu(z)d\mu(z')K(z,p_1^2)K(z,p_2^2)G_0(t,z,z')K(z',p_3^2)K(z',p_4^2)$$

Graviton-exchange witten diagram

$$T(s,t;p_i^2) = t^{mn}(12) * G_{mn,m'n'} * t^{m'n'}(3,4)$$

$$\sim t^{++}(12) * G_{++,--} * t^{--}(3,4)$$

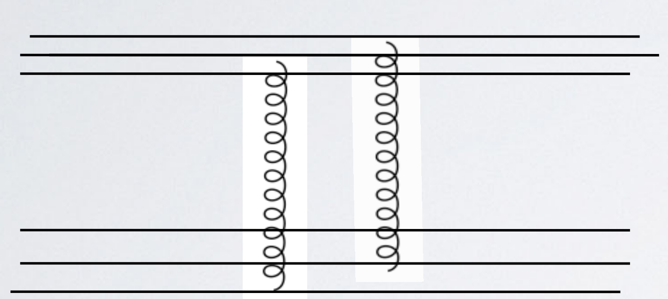


$$T(s,t;p_i^2) \sim s^2 \int d\mu(z)d\mu(z')K(z,p_1^2)K(z,p_2^2)(zz')^2G_0(t,z,z')K(z',p_3^2)K(z',p_4^2)$$

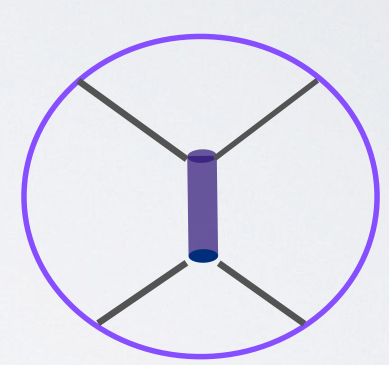
HIGH ENERGY SCATTERING <=> POMERON

WHAT IS THE POMERON ?

WEAK: TWO-GLUON <=> STRONG: ADS GRAVITON



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



$J = 2$

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

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

Challenge for AdS/CFT for QCD

- Spin-2 leads to too rapid an increase for cross sections
  - Need to consider $\lambda = g^2 N$ finite. (stringy corrections)
- 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

Outline

- Gauge/String Duality and QCD at Hgh Energy:
  - “AdS Graviton” as Quasi-Particle in HE Scattering in QCD - Pomeron
  - “AdS Odderon” in Strong Coupling

PHYSICS AT HIGH ENERGY

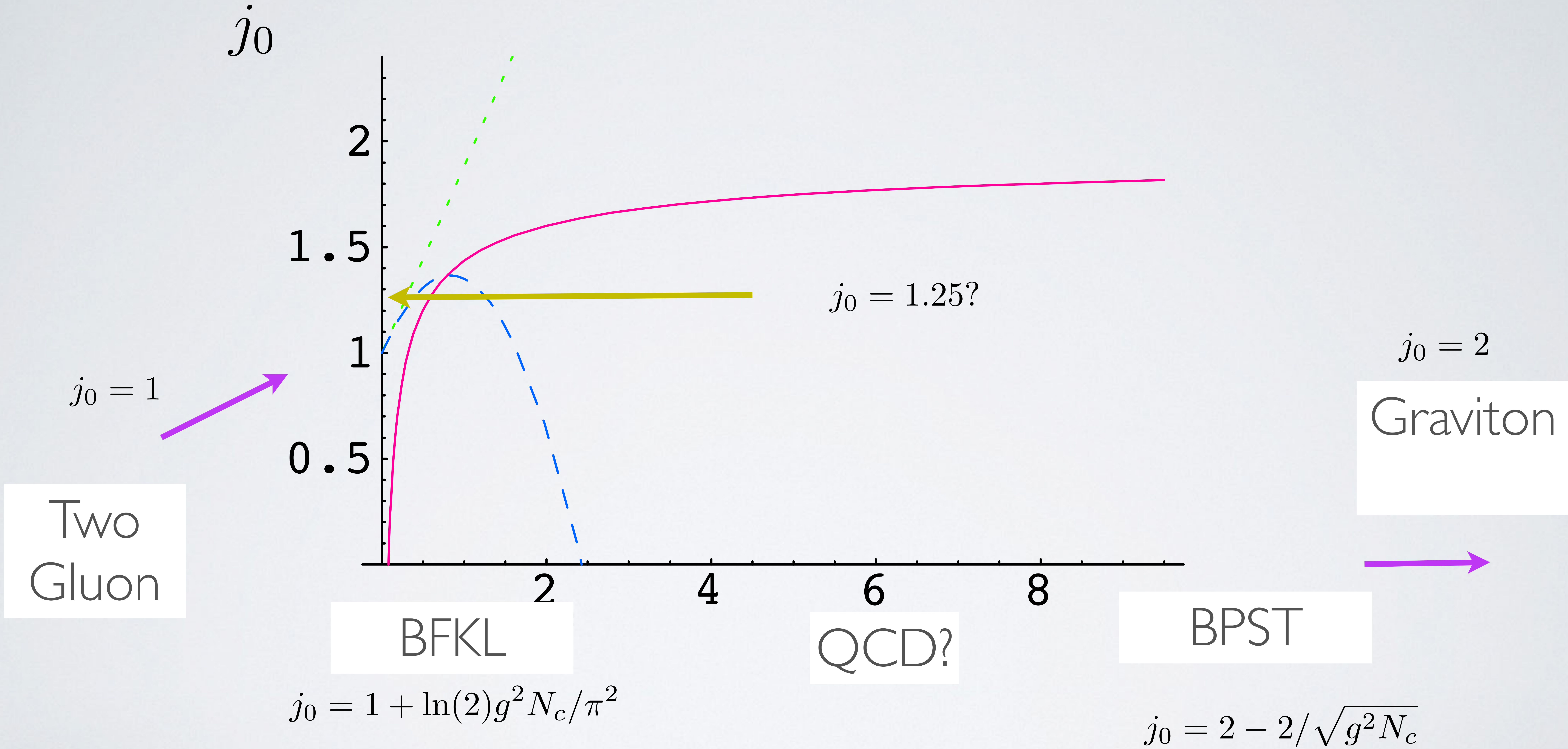
Summing higher spin modes interpolating graviton

◆leading to effective Regge trajectory

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

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

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



Pomeron and Odderon in conformal Limit

$$\text{Crossing Even } (C=+): \text{ Pomeron} \leftrightarrow (\sigma_{ab}+\sigma_{\bar{a}b})/2$$

$$\text{Crossing Odd } (C=-): \text{ Odderon} \leftrightarrow (\sigma_{ab}-\sigma_{\bar{a}b})/2$$

Massless modes of a closed string theory:
metric tensor,
Kolb-Ramond anti-sym. tensor,
dilaton, etc.

$$G_{mn} = g^0_{mn} + h_{mn}$$

$$b_{mn} = -b_{nm}$$

Pomeron/Odderon

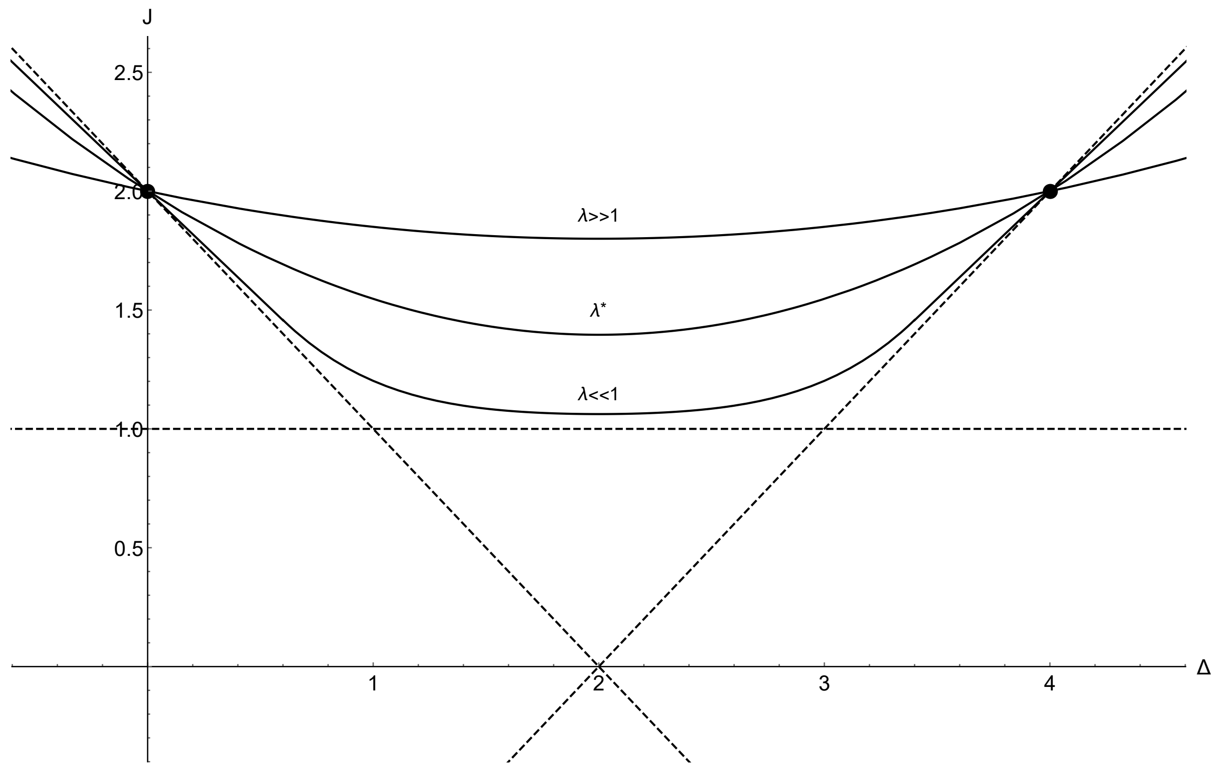
In gauge theories, non-perturbative Pomeron/ Odderon emerge unambiguously.

Conformal Invariance - - - Holographic.

Pomeron can be identified as Massive Graviton.

Odderons can be identified with Anti-symmetric Kalb-Ramond tensor.

Spin-Dimension Curves: Anomalous Dimensions



POMERON AND ODDERON IN STRONG COUPLING:

$$\widetilde{\Delta}(S)^2 = \tau^2 + a_1(\tau,\lambda)S + a_2(\tau,\lambda)S^2 + \cdots$$

B.Basso, 1109.3154v2

POMERON

$$\alpha_p = 2 - \frac{2}{\lambda^{1/2}} - \frac{1}{\lambda} + \frac{1}{4\lambda^{3/2}} + \frac{6\zeta(3)+2}{\lambda^2} + \frac{18\zeta(3)+\frac{361}{64}}{\lambda^{5/2}} + \frac{39\zeta(3)+\frac{447}{32}}{\lambda^3} + \cdots$$

Brower, Polchinski, Strassler, Tan

Gromov et al.

ODDERON

Kotikov, Lipatov, et al.

Costa, Goncalves, Penedones (1209.4355)

Kotikov, Lipatov (1301.0882)

Solution-a:

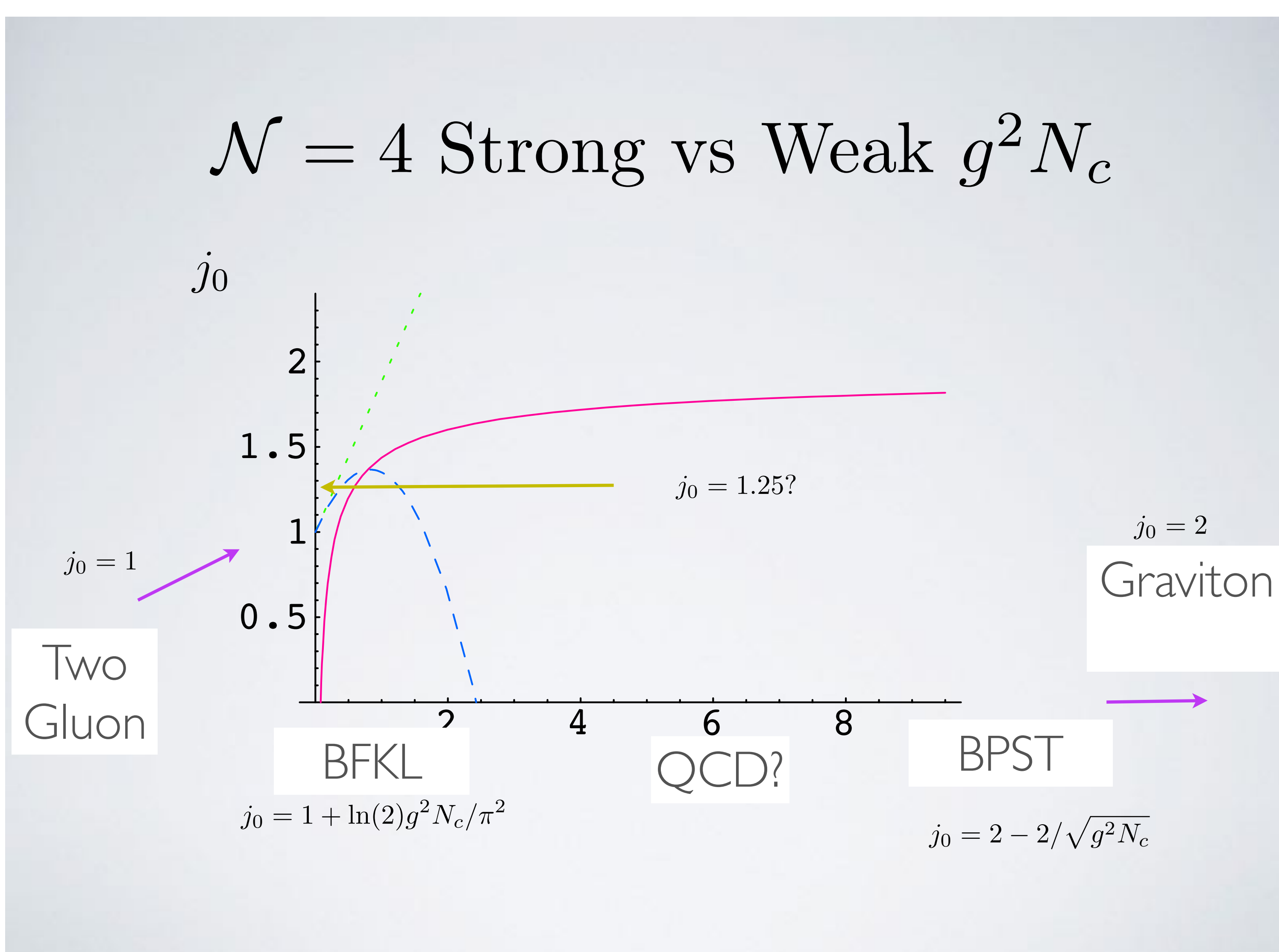
$$\alpha_O = 1 - \frac{8}{\lambda^{1/2}} - \frac{4}{\lambda} + \frac{13}{\lambda^{3/2}} + \frac{96\zeta(3)+41}{\lambda^2} + \frac{288\zeta(3)+\frac{1823}{16}}{\lambda^{5/2}} + \frac{720\zeta(5)+1344\zeta(3)-\frac{3585}{4}}{\lambda^3}$$

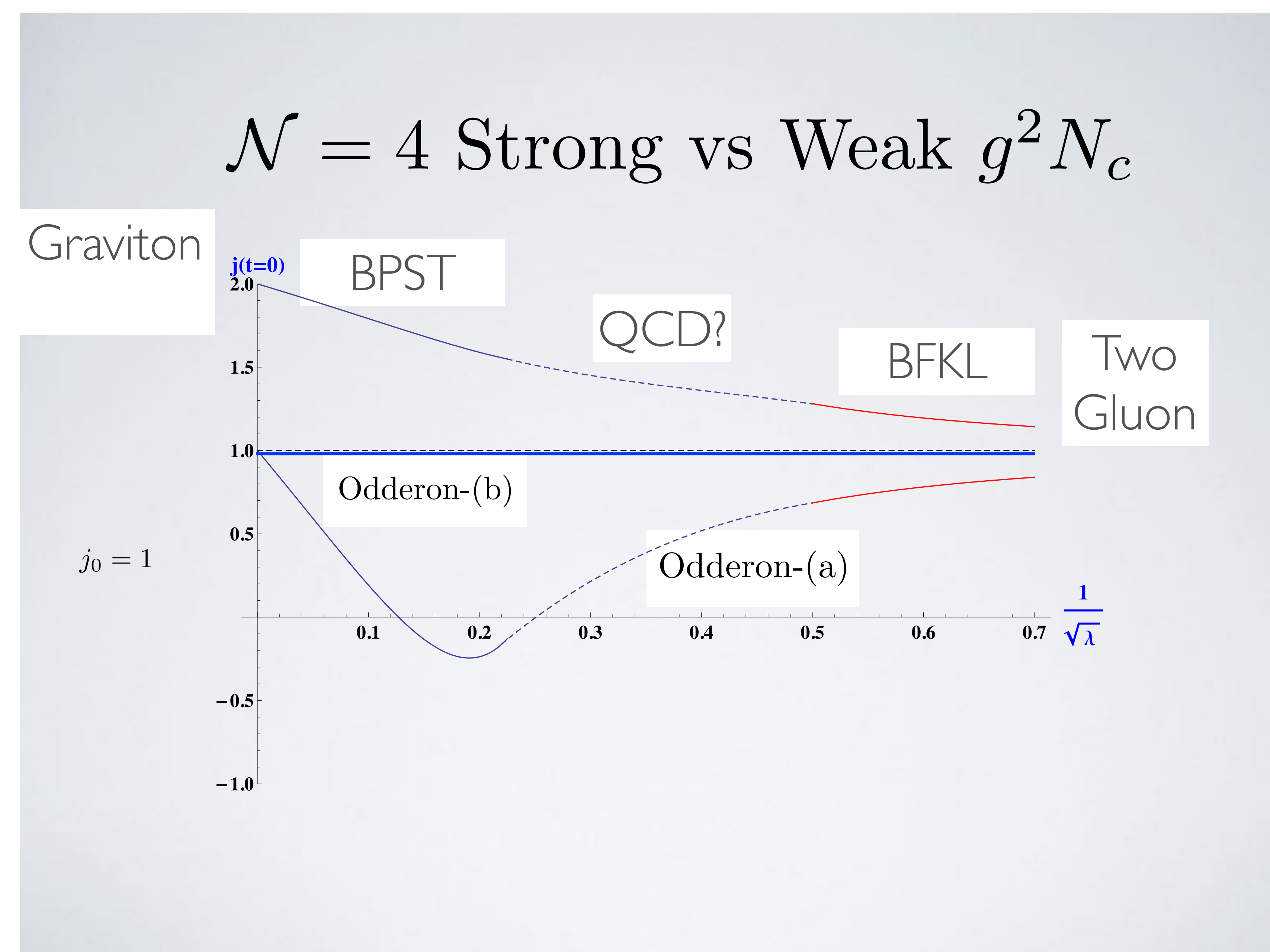
Solution-b:

$$\alpha_O = 1 - \frac{0}{\lambda^{1/2}} - \frac{0}{\lambda} + \frac{0}{\lambda^{3/2}} + \frac{0}{\lambda^2} + \frac{0}{\lambda^{5/2}} + \frac{0}{\lambda^3} + \cdots$$

Brower, Djuric, Tan

Brower, Costa, Djuric, Raben, Tan





$\mathcal{N}=4$ SYM Operators and String Modes:

Dimension	State J^{PC}	Operator	Supergravity
$\Delta=4$	0^{++}	$Tr(FF)=\vec{E}^a\cdot\vec{E}^a-\vec{B}^a\cdot\vec{B}^a$	ϕ
$\Delta=4$	2^{++}	$Tr(F_{\mu\rho}F^{\rho}_{\nu})\leftrightarrow T_{\mu\nu}$	G_{ij}
$\Delta=4$	0^{-+}	$Tr(F\tilde{F})=\vec{E}^a\cdot\vec{B}^a$	C_0
$\Delta=6$	1^{+-}	$Tr(F_{\mu\nu}\{F_{\rho\sigma},F_{\lambda\eta}\})\sim d^{abc}F^aF^bF^c$	B_{ij}
$\Delta=6$	1^{--}	$Tr(\tilde{F}_{\mu\nu}\{F_{\rho\sigma},F_{\lambda\eta}\})\sim d^{abc}\tilde{F}^aF^bF^c$	$C_{2,ij}$
$\Delta=4+S+\gamma$	S^{++}	$Tr(D^S_\lambda FF)+\cdots$	absent
$\Delta=4+(J-2)+\gamma$	J^{++}	$Tr(F_{\mu\rho}D^S_\lambda F^\rho_\nu)+\cdots, J=S+2$	absent
$\Delta=6+(J-1)+\gamma$	J^{+-}	$Tr(FD^SFF)+\cdots, J=S+1$	absent
$\Delta=2+(J-1)+\gamma$	J^{+-}	$Tr(D^SF)+\cdots, J=S+1$	absent

Anomalous Dimension:

$\mathcal{O}_{(\Delta,j)_k}(x)$ $\gamma=O(\lambda^{1/4})$ Conformal Dimension, Spin

Status of Pomeron and Odderon

	Weak Coupling	Strong Coupling
$C=+1$	$j_{0_+}=1+(\ln 2)\,\lambda/\pi^2+O(\lambda^2)$	$j_{0_+}=2-2/\sqrt{\lambda}+O(1/\lambda)$
$C=-1$	$j^{(a)}_{0_-}\simeq 1-0.24717\,\lambda/\pi+O(\lambda^2)$ $j^{(b)}_{0_-}=1+O(\lambda^3)$	$j^{(a)}_{0_-}=1-8/\sqrt{\lambda}+O(1/\lambda)$ $j^{(b)}_{0_-}=1+O(1/\lambda)$

Dimension	State J^{PC}	Operator	Supergravity
$\Delta=4$	0^{++}	$Tr(FF)=\vec{E}^a\cdot\vec{E}^a-\vec{B}^a\cdot\vec{B}^a$	ϕ
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$\Delta=6$	1^{--}	$Tr(\tilde{F}_{\mu\nu}\{F_{\rho\sigma},F_{\lambda\eta}\})\sim d^{abc}\tilde{F}^aF^bF^c$	$C_{2,ij}$
$\Delta=4+(J-2)+\gamma$	J^{++}, J even	$Tr(F_{\mu\rho}D^S_\lambda F^\rho_\nu)+\cdots, J=S+2$	absent
$\Delta=6+(J-1)+\gamma$	J^{+-} J odd	$Tr(FD^SFF)+\cdots, J=S+1$	absent
$\Delta=2+(J-1)+\gamma$	J^{+-} J odd	$Tr(D^SF)+\cdots, J=S+1$	absent

Pomeron as a sum over string modes

$$\mathcal{K}_P\sim\int dj\left[\frac{(-s)^j+(s)^j}{\sin\pi j}\right]G_P(z,z';j,0)\sim\frac{(-s)^{j_0}+(s)^{j_0}}{\sin\pi j_0}$$

$$\mathcal{K}_P\sim\int dj\left[\frac{(-s)^j+(s)^j}{\sin\pi j}\right]G_P(z,z';j)\sim(zz')\sum_{j_n=2n}\frac{\tilde{s}^{j_n}e^{-(\Delta(j_n)-2)\xi}}{\sinh\xi}$$

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

$$j=2,4,6,\cdots$$

Conformal Dimension for Reggeized Graviton

$$G(z,z';j,0)=\frac{1}{2\sqrt{\lambda}}\int_{-\infty}^{\infty}d\nu\frac{e^{i\nu(u-u')}}{j-j_0+\mathcal{D}\nu^2}$$
$$=\int_{-\infty}^{\infty}d\nu\frac{e^{i\nu(u-u')}}{(\Delta(j)-2)^2+\nu^2}$$
$$=\frac{2\pi}{\Delta(j)-2}e^{-(\Delta(j)-2)|u-u'|}$$

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

$$\mathcal{K}_P\sim\int dj\left[\frac{(-s)^j+(s)^j}{\sin\pi j}\right]G_P(z,z';j,0)\sim\frac{(-s)^{j_0}+(s)^{j_0}}{\sin\pi j_0}$$

Consequence of Conformal Invariance plus Confinement deformation for Holographic QCD

$$G_{mn} = g^0_{mn} + h_{mn}$$

Universality, Confinement, etc.

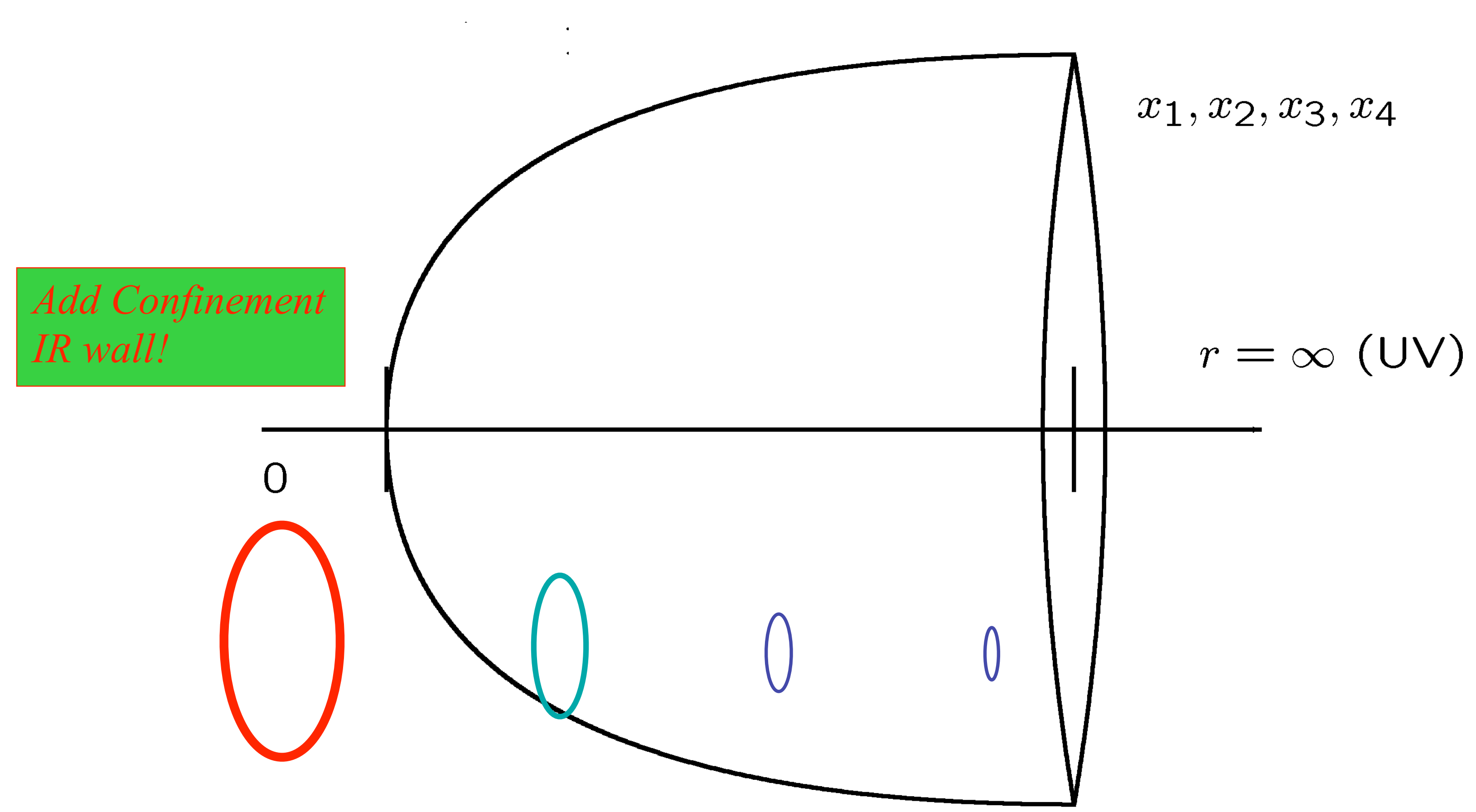
PHYSICS AT HIGH ENERGY

Confinement

- If strictly Conformal, therefore no scale and no particles,

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

Cutoff AdS_5



Scale Invariance and AdS

What is the curved space?

Maldacena: UV (large r) is (almost) an $AdS_5 \times X$ space

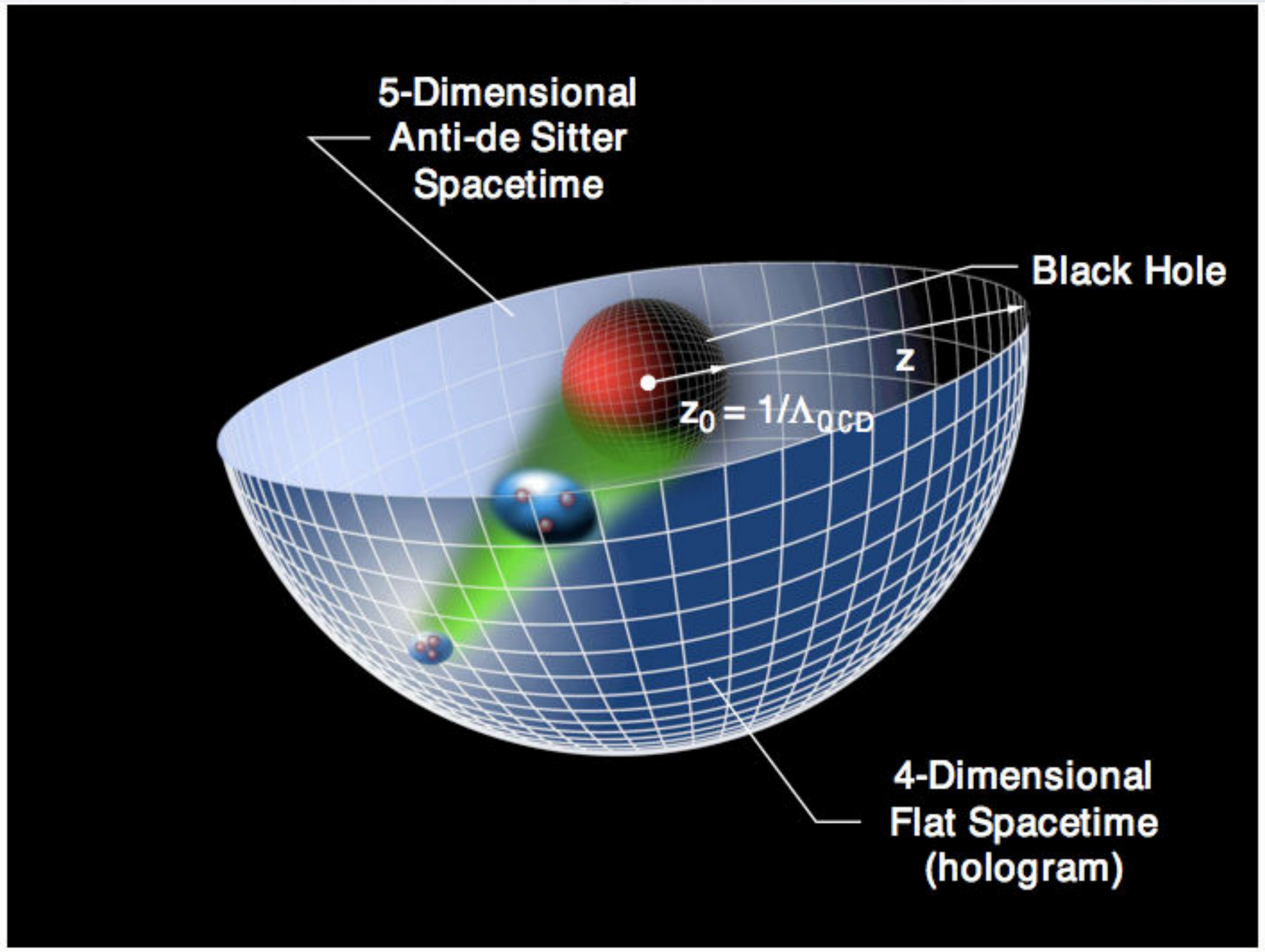
$$ds^2 = r^2 dx_\mu dx^\mu + \frac{dr^2}{r^2}$$

Captures QCD's approximate UV conformal invariance

$$x \to \zeta x \ , \ r \to \frac{r}{\zeta} \qquad \text{(recall } r \sim \mu\text{)}$$

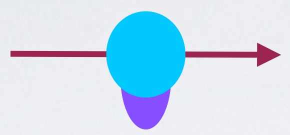
Confinement: IR (small r) is cut off in some way

$$r \sim \mu > r_{min} \sim \Lambda_{QCD}$$

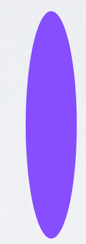


BASIC BUILDING BLOCK

- 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: $G_j(z,x^\perp,z',x'^\perp;j) \longrightarrow$ discrete sum

ADS BUILDING BLOCKS BLOCKS

For 2-to-2

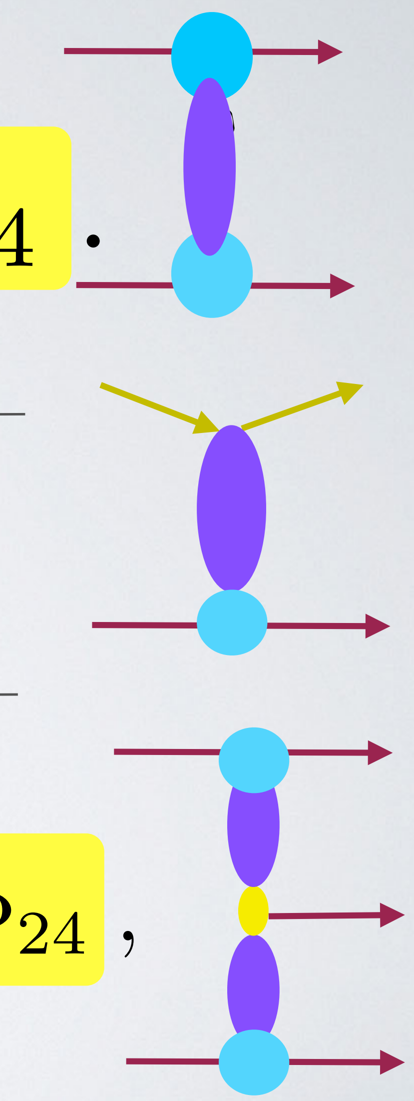
$$A(s,t) = \Phi_{13} * \widetilde{\mathcal{K}}_P * \Phi_{24}\,.$$

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

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

For 2-to-3

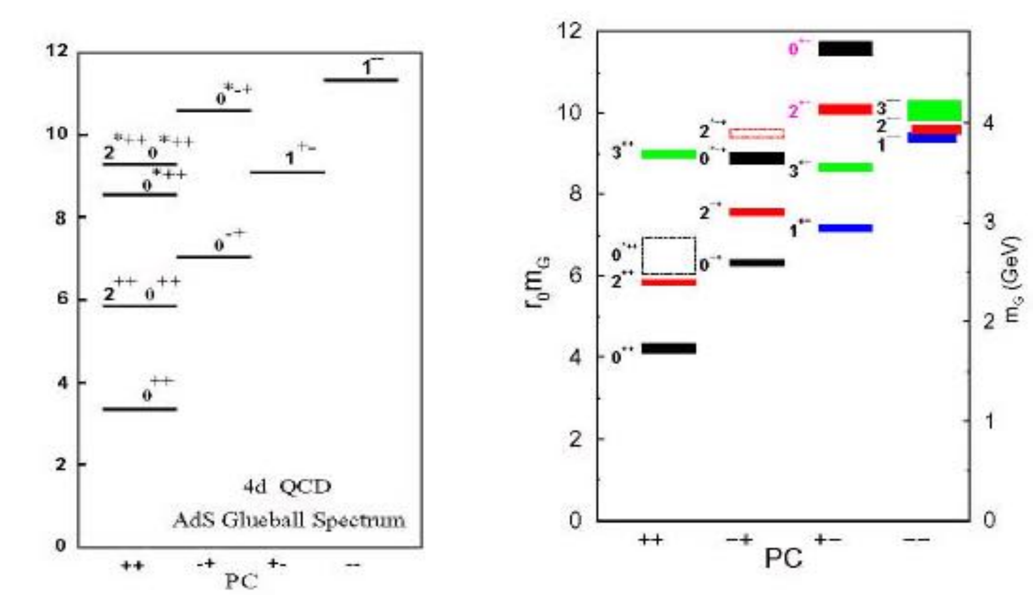
$$A(s,s_1,s_2,t_1,t_2) = \Phi_{13} * \widetilde{\mathcal{K}}_P * V * \widetilde{\mathcal{K}}_P * \Phi_{24}\,,$$



Applications

- Glueball Masses
- DIS at Small-x
- Inclusive Distribution at large P_t
- Size and Shape of Proton at LHC

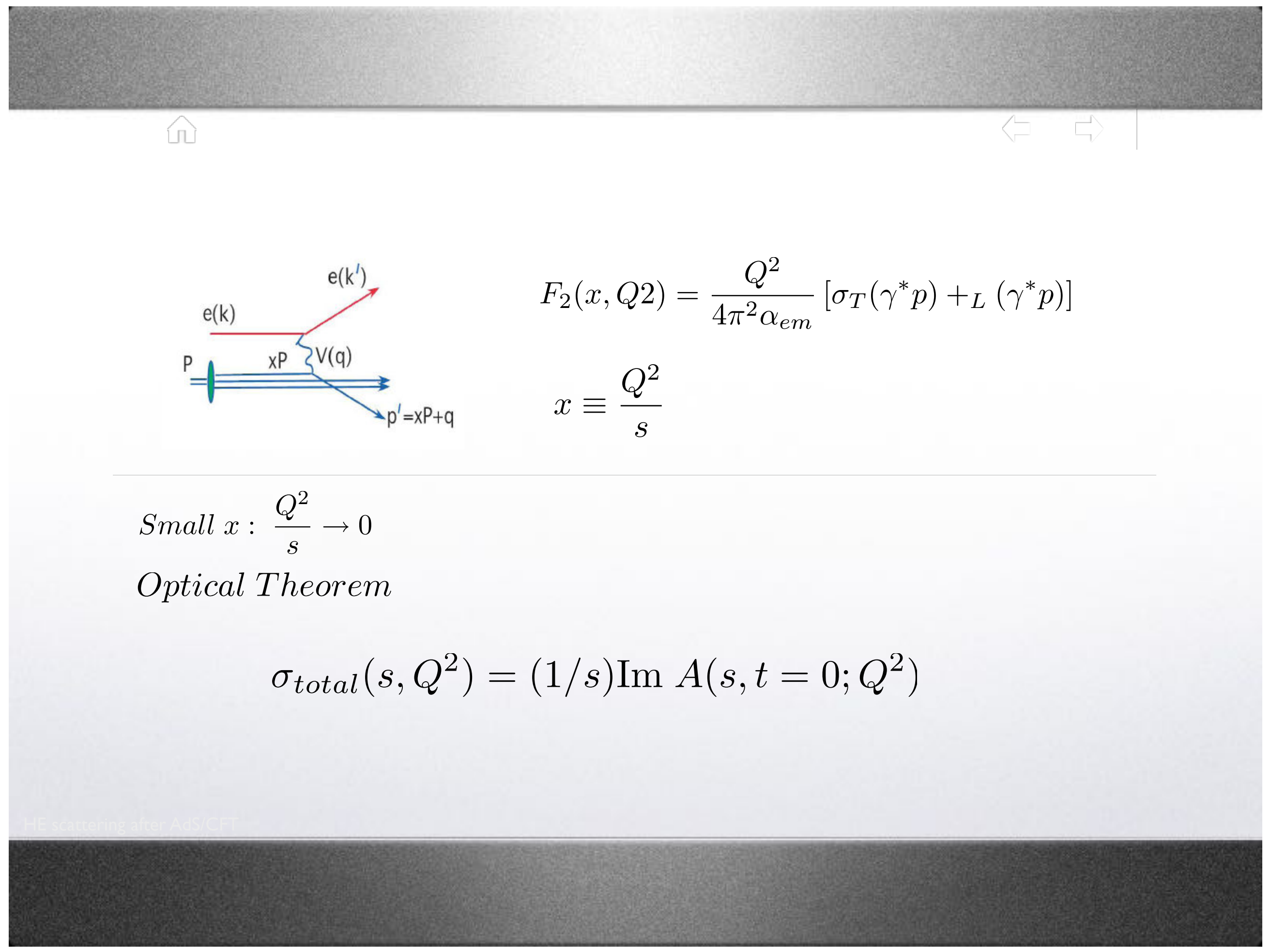
Glueball Spectrum

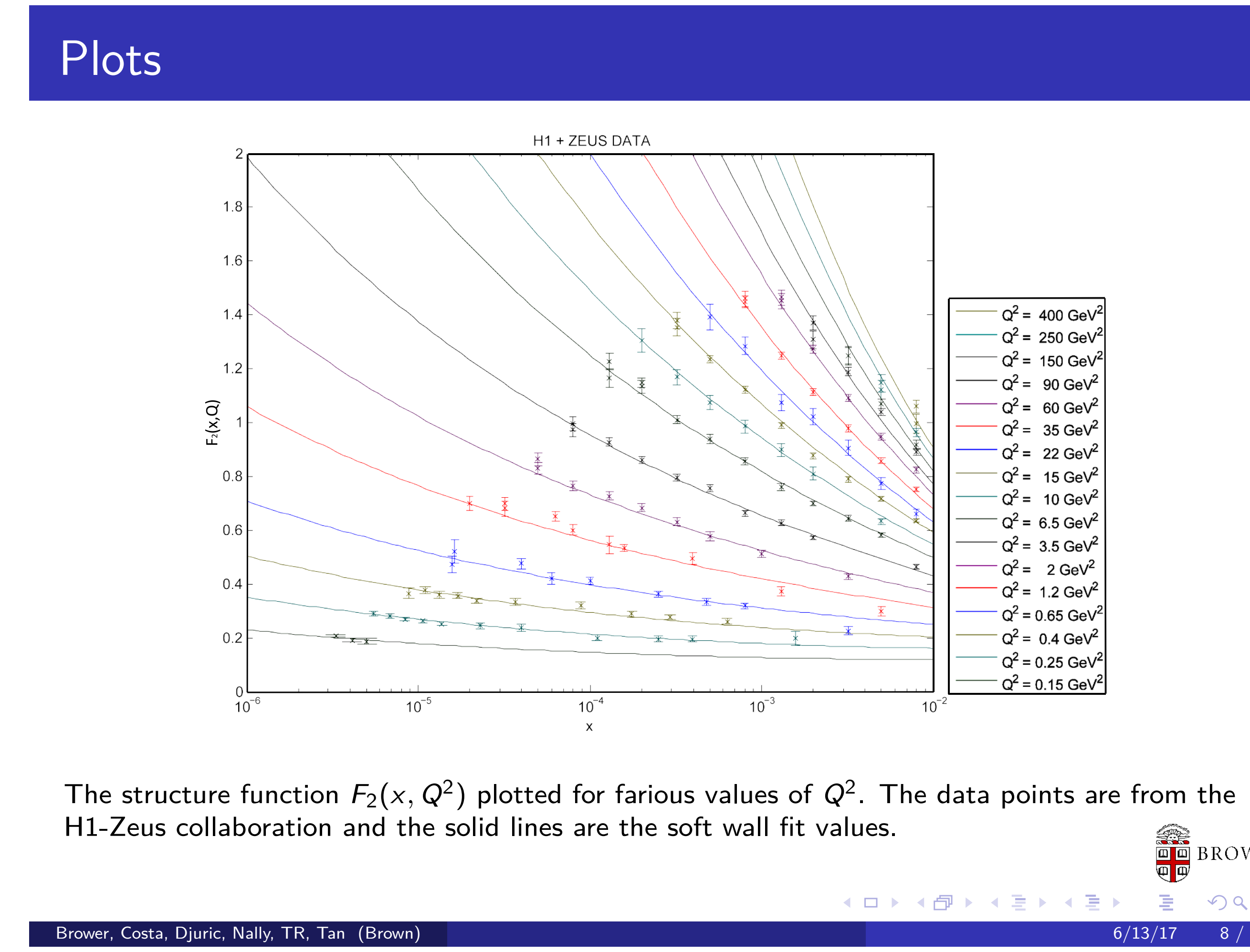


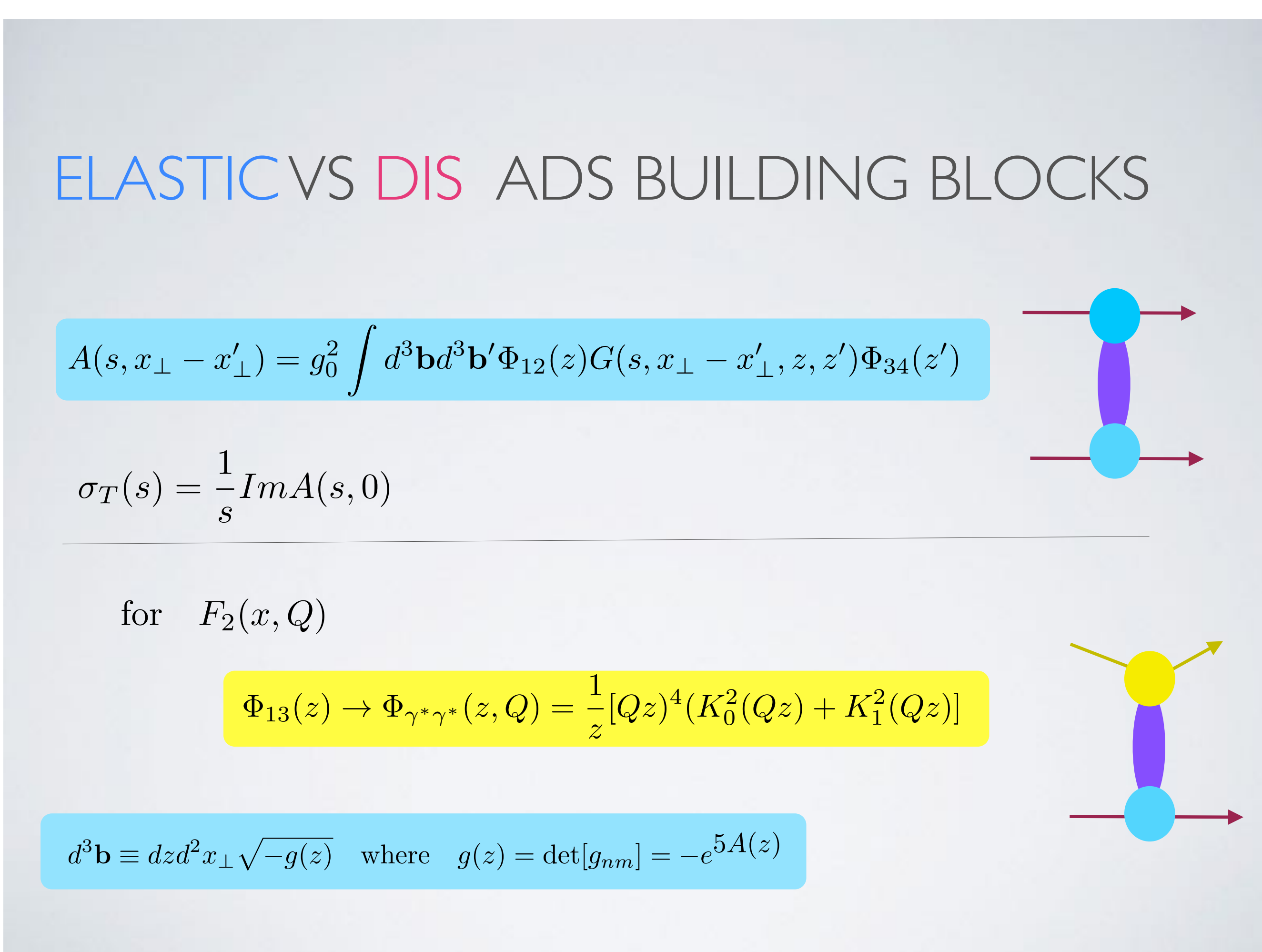
The AdS^7 glueball spectrum for QCD_4 in strong coupling (left) compared with the Morningstar/Peardon lattice spectrum for pure SU(3) QCD (right) with $1/r_0 = 410$ Mev.

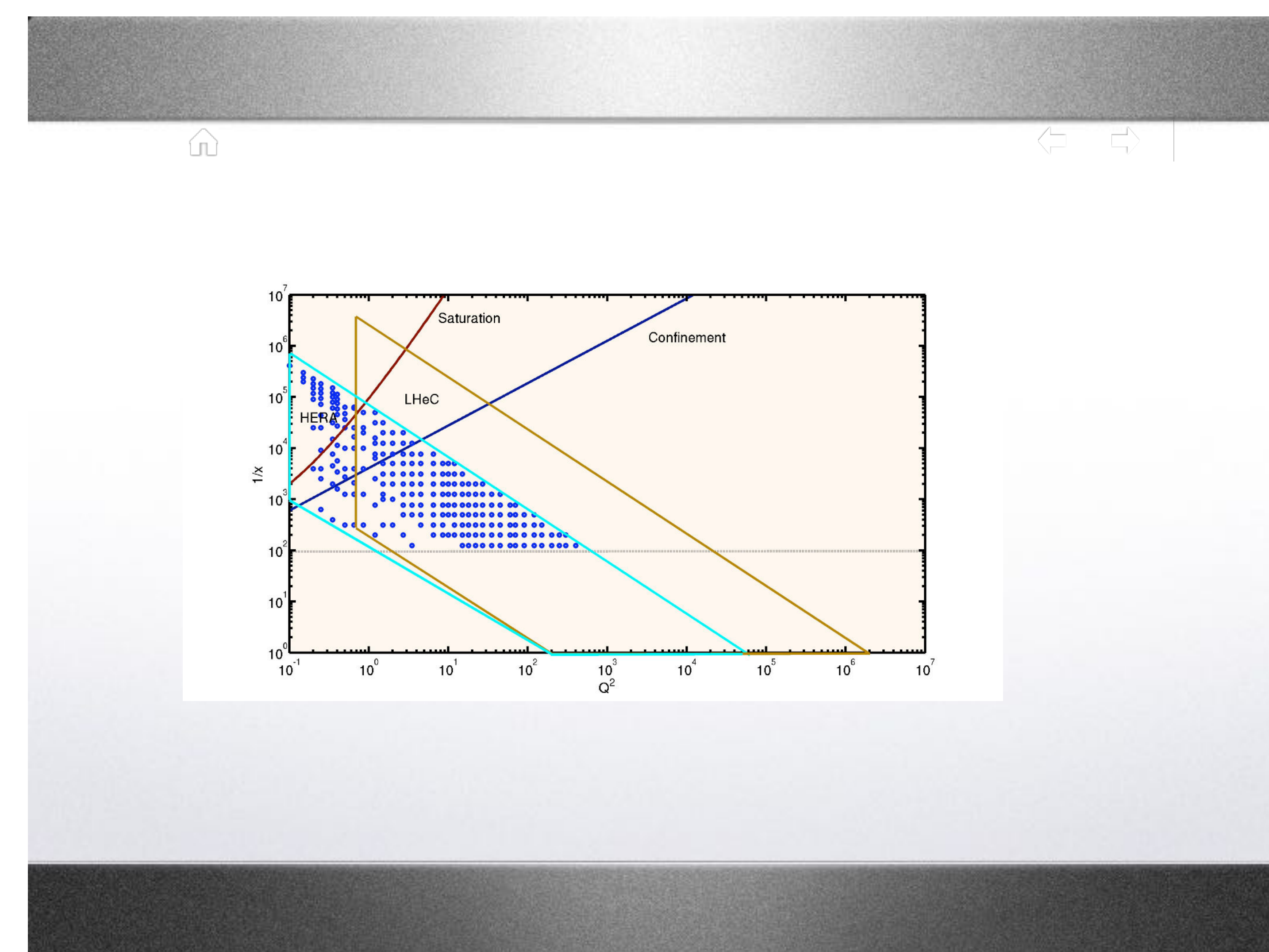
R. Brower, S. Mathur, and C-I Tan, hep-th/0003115, "Glueball Spectrum of QCD from AdS Supergravity Duality".

DIS at Small-x

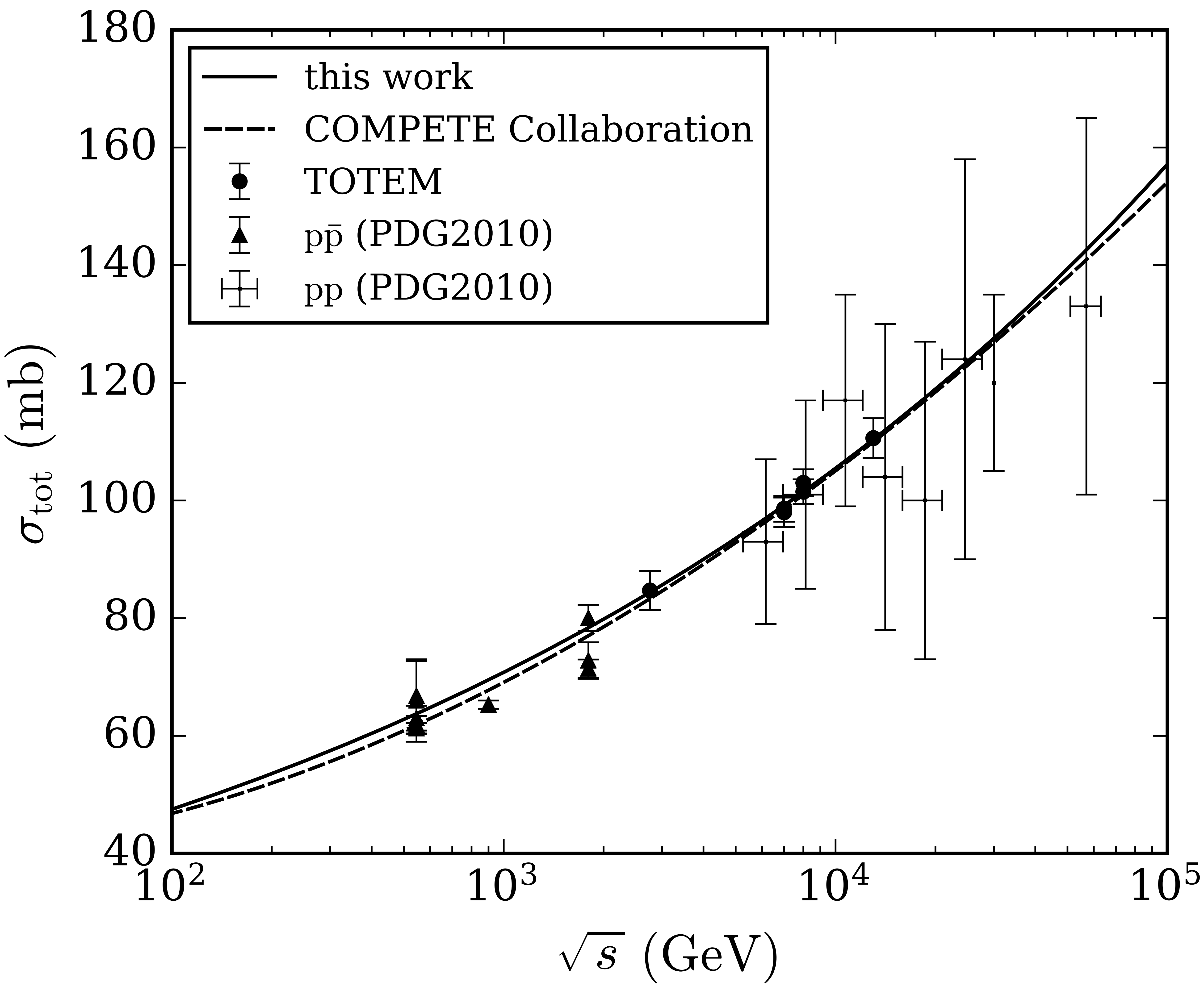








Total cross section



V. Higher order effects and Expanding Disk picture

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

$$A_{2\to2}(s,t) \simeq -2is \int d^2b\, e^{-ib^\perp q_\perp} \int dz dz' P_{13}(z) P_{24}(z') \left[e^{i\chi(s,b^\perp,z,z')} - 1\right]$$

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

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:

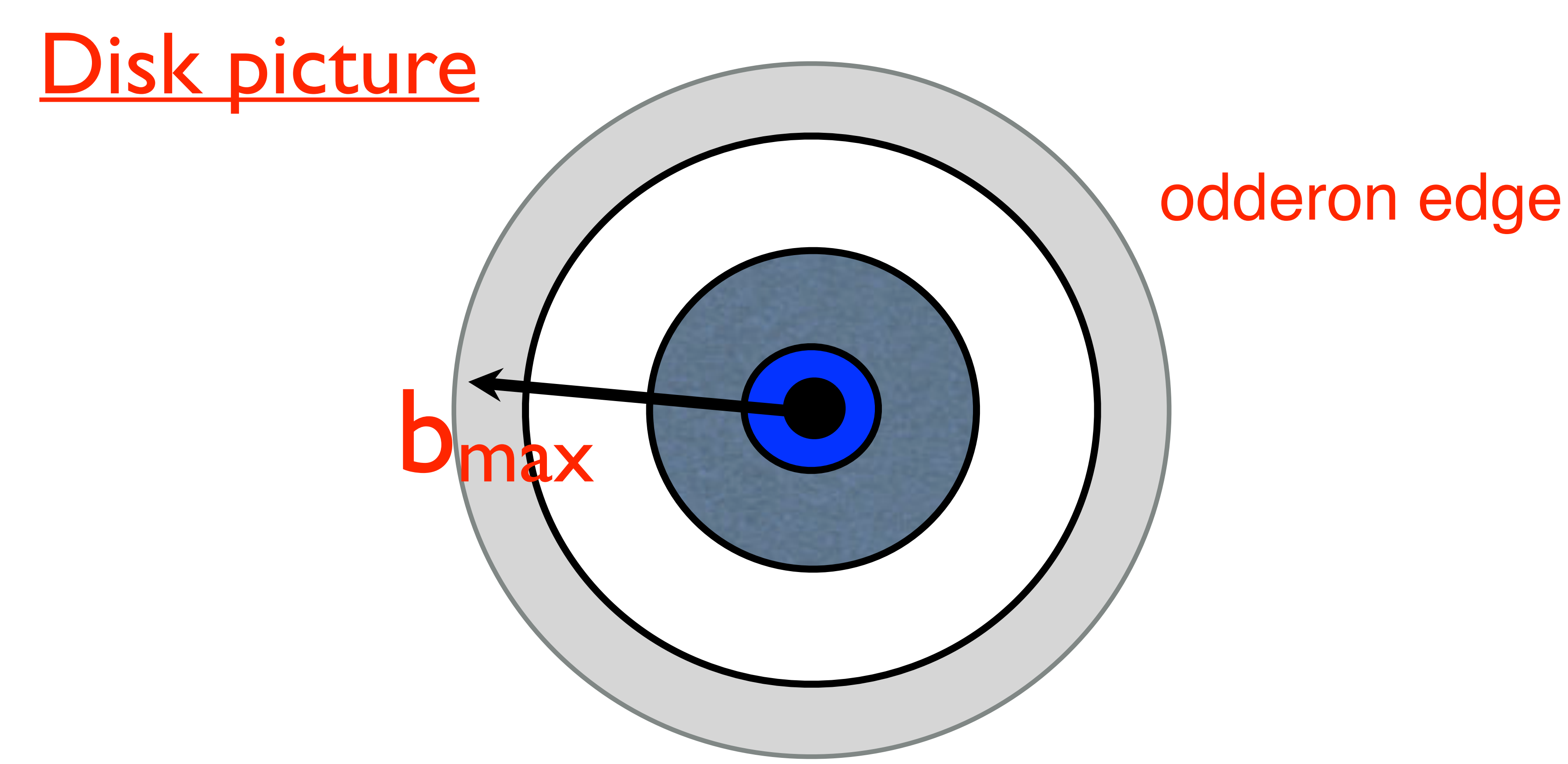
$$\chi(s, x^\perp - x'^\perp, z, z') \;=\; O(1)$$

Saturation of Froissart Bound

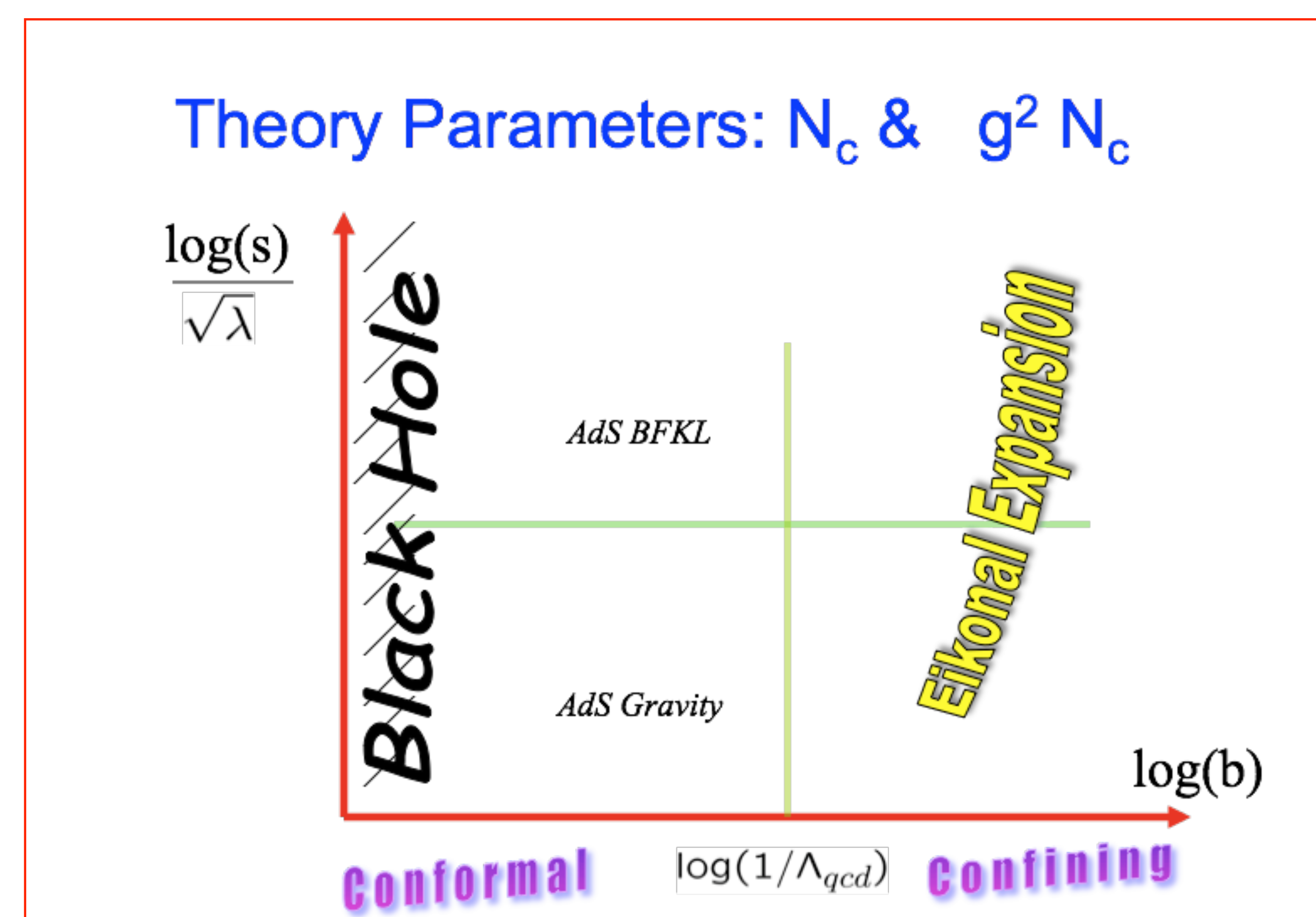
- The Confinement deformation gives an exponential cutoff for $b > b_{max} \sim c \log(s/s_0)$,
- Coefficient $c \sim 1/m_0$, m_0 being the mass of lightest tensor glueball.
- There is a shell of "conformal region" of width: $\Delta b \sim \log(s/s_0)$

b_{max} determined by confinement.

- pion mass, constituents, etc.



Partonic structure

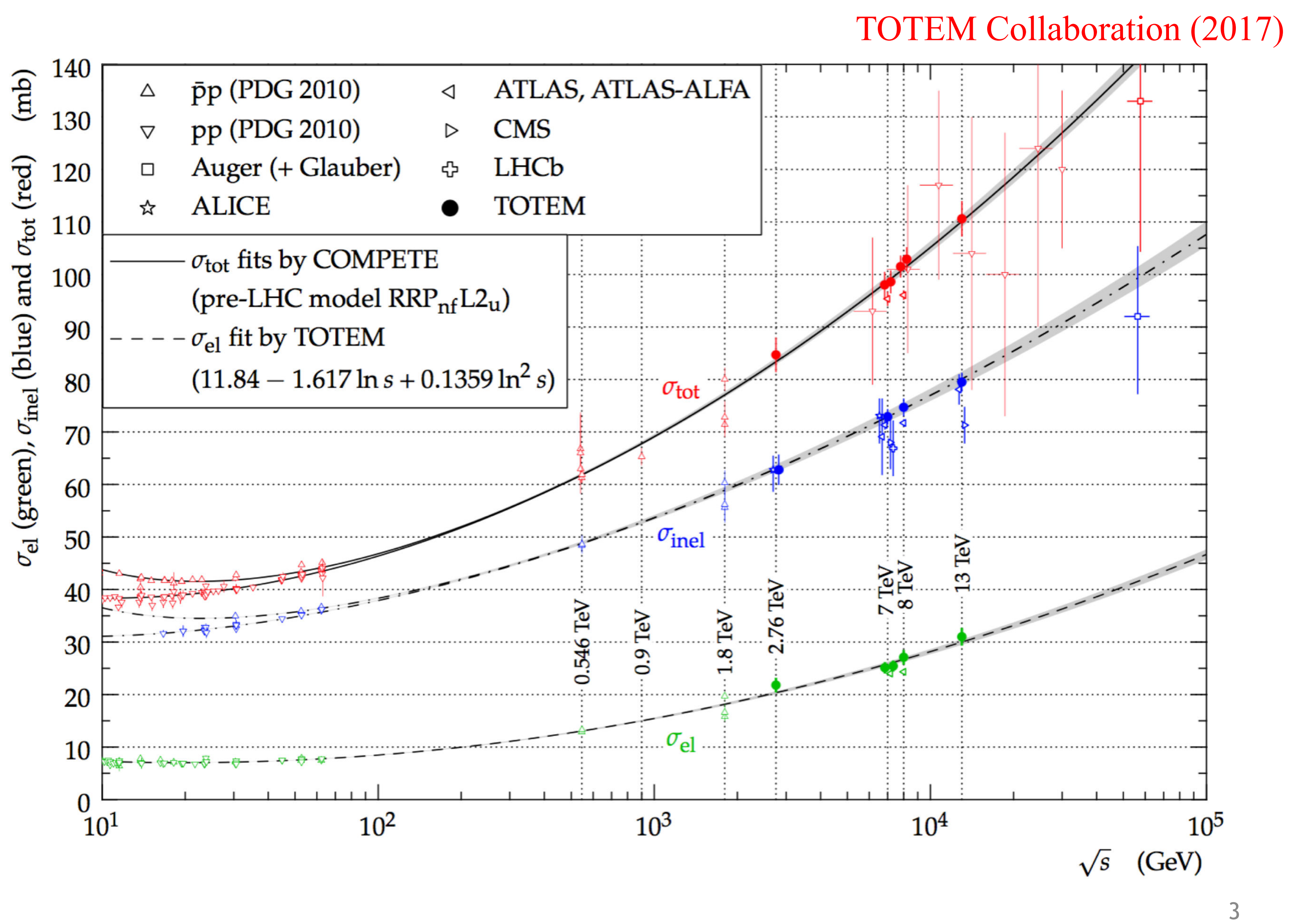


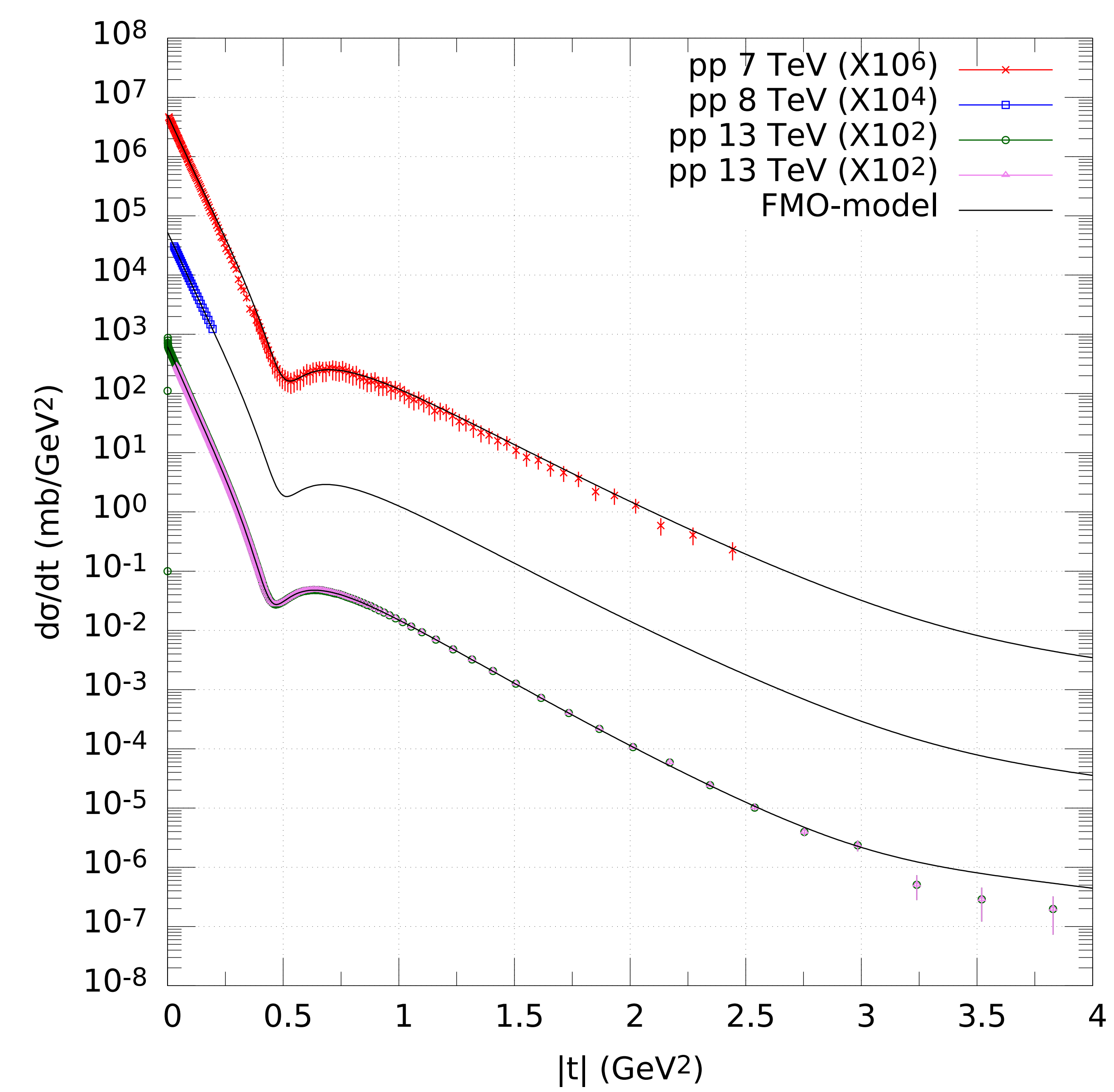
Outline

- Size and Shape of Proton at LHC
  - Pomeron and Odderon
  - Expanding Disk

Size and Shape of Proton at LHC Era

13TeV data from TOTEM

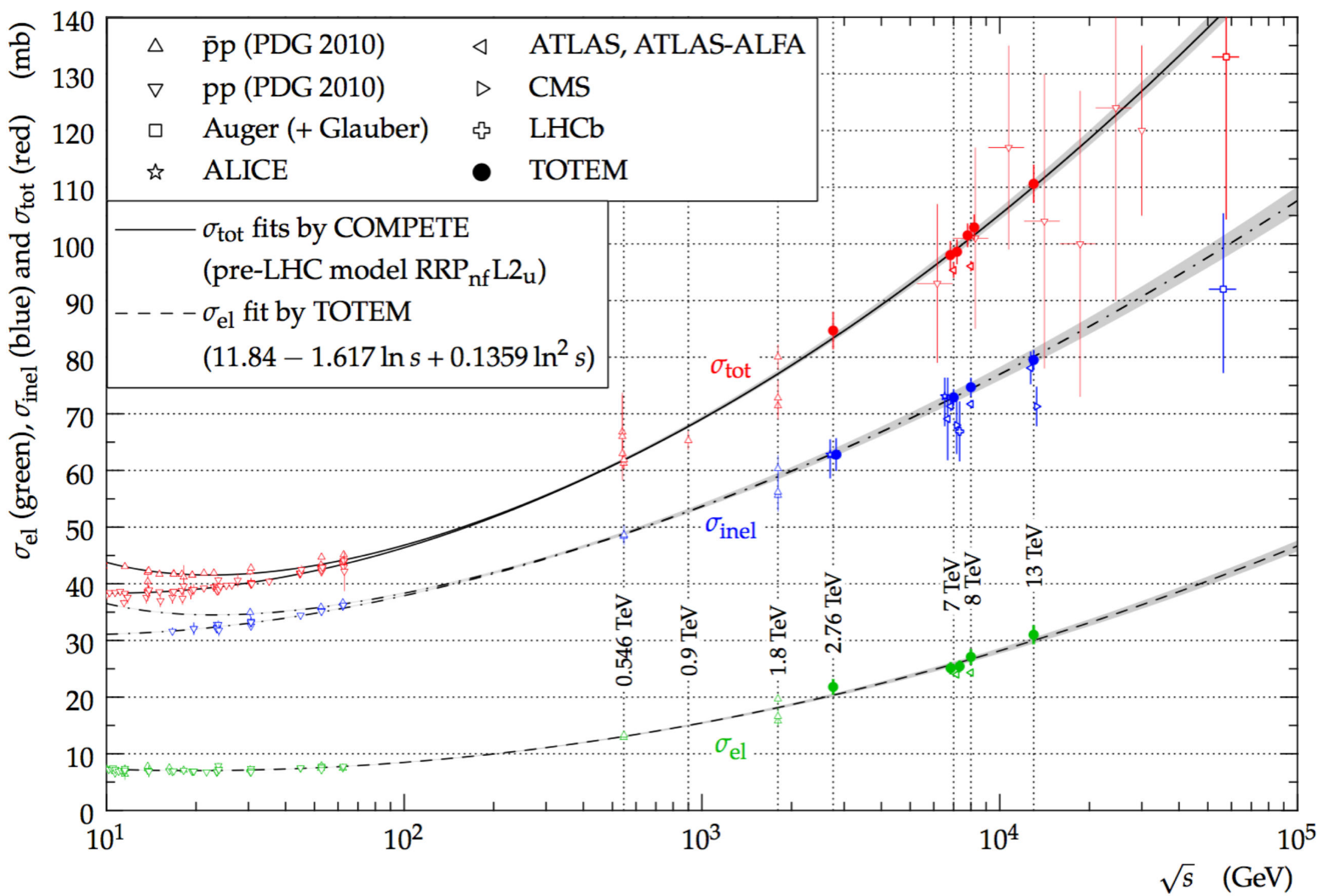




Interesting new non-perturbative physics in QCD?

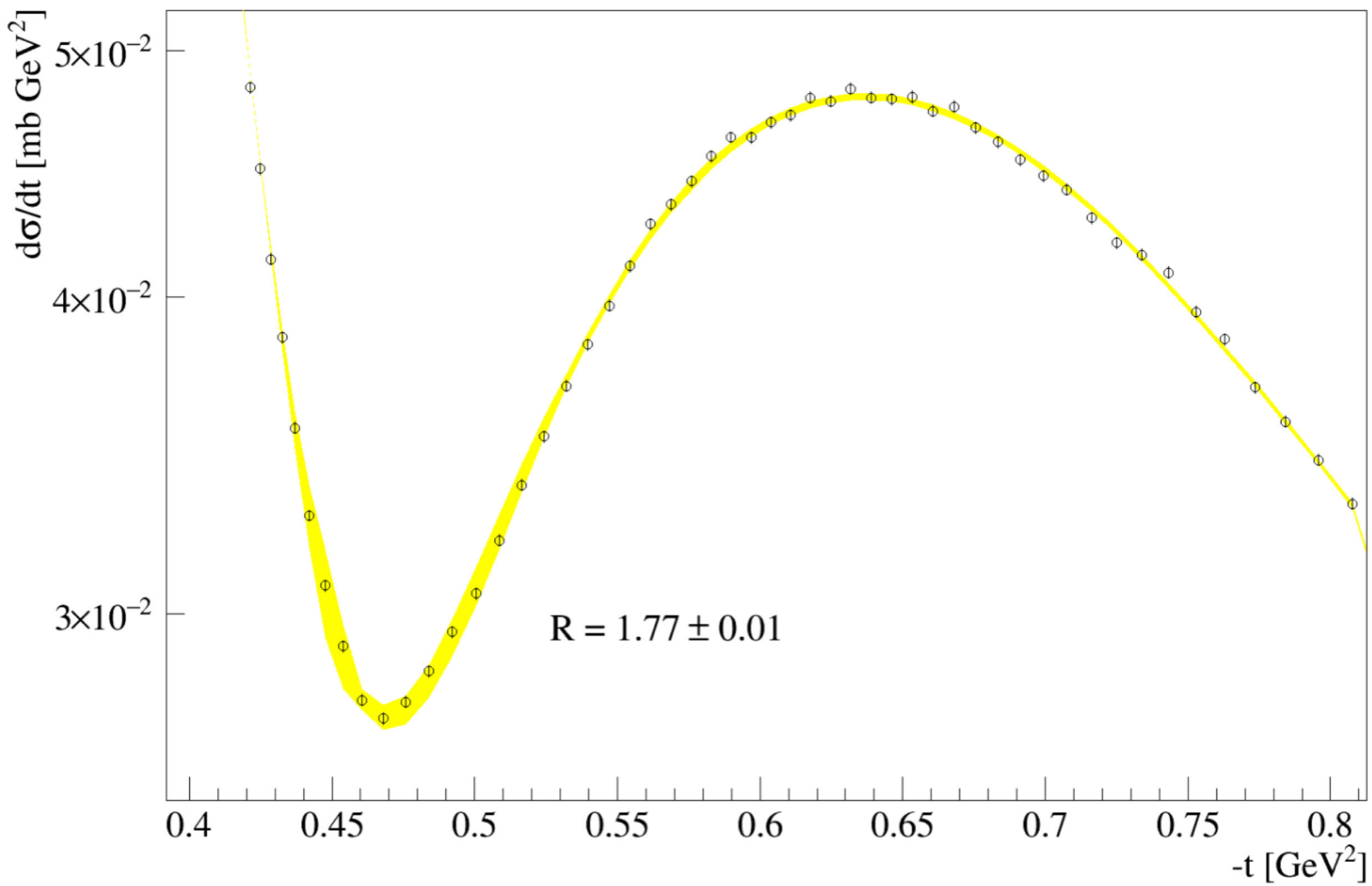
13TeV data from TOTEM

TOTEM Collaboration (2017)



Diffractive minimum (dip)

TOTEM collaboration (2018)



Noticeable Features

- Dip moved towards smaller t.
- Comparing with pp and ppbar at ISR and FNAL indicating the existence of “Odderon”

Maximal Odderon?

Lukaskuk and Nicolescu, Nuovo Cimento Lett 8 (1973) 405.

Finkelstein, Fried, Kang and Tan, “Froward Scattering at Collider Energies and Eikonal Unitarization of Odderon”, Phys. Lett. B232 (1989) 257-262.

Khoze, Martin and Ryakin, arXiv: 1806.05970v2.

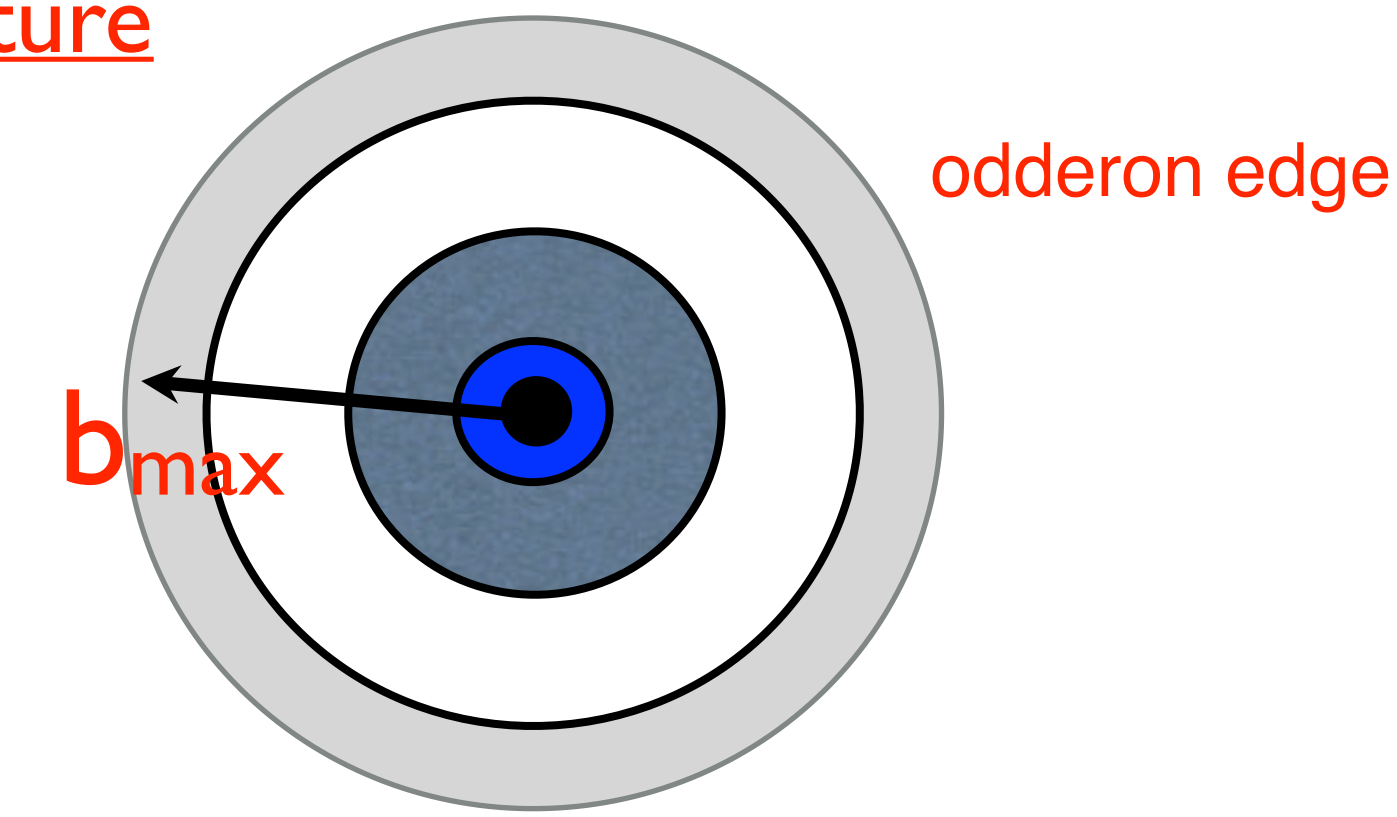
Saturation of Froissart Bound

- 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.
- There is a shell of "conformal region" of width: $\Delta b \sim \log(s/s_0)$

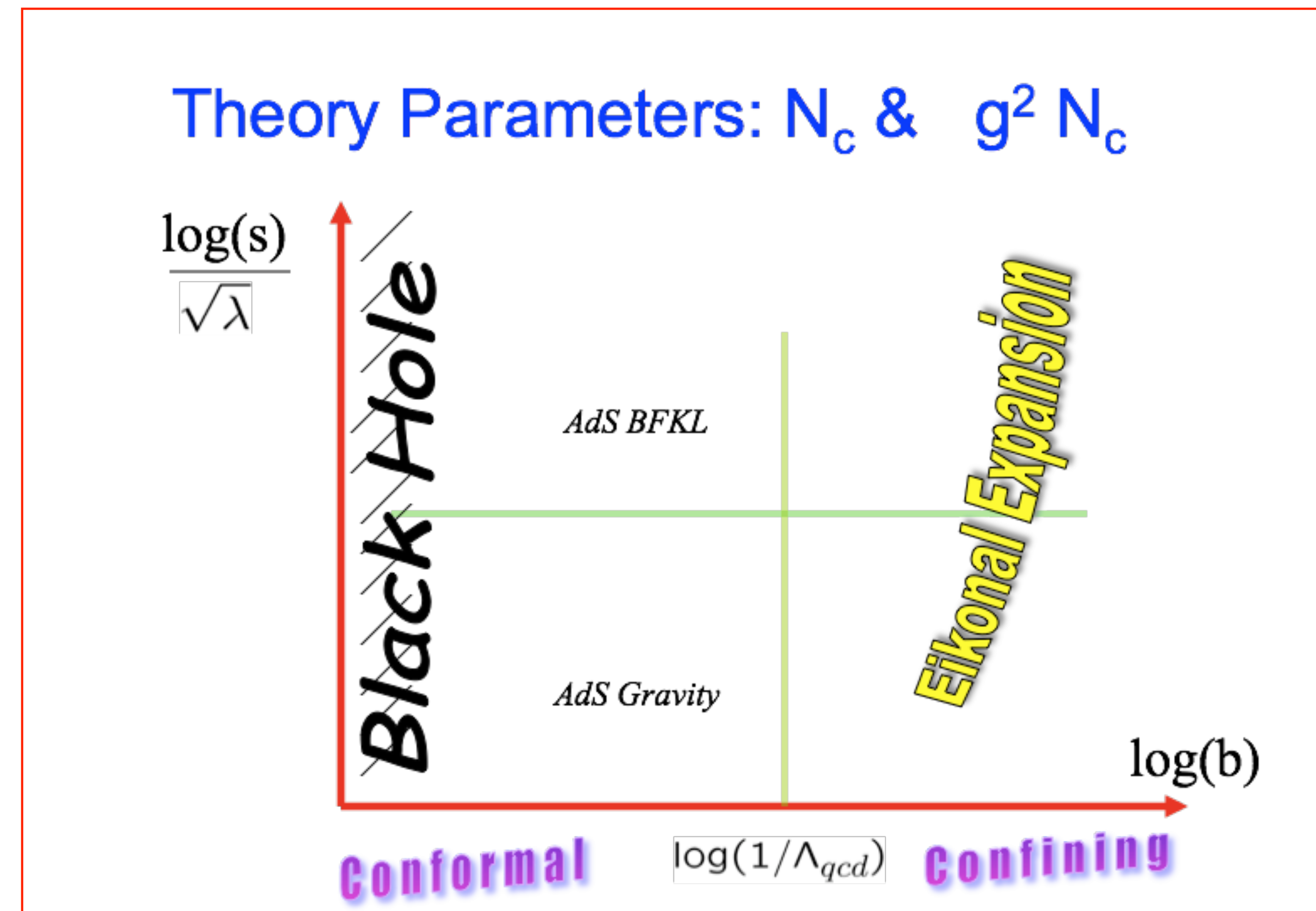
b_{max} determined by confinement.

- pion mass, constituents, etc.

Disk picture



Partonic structure

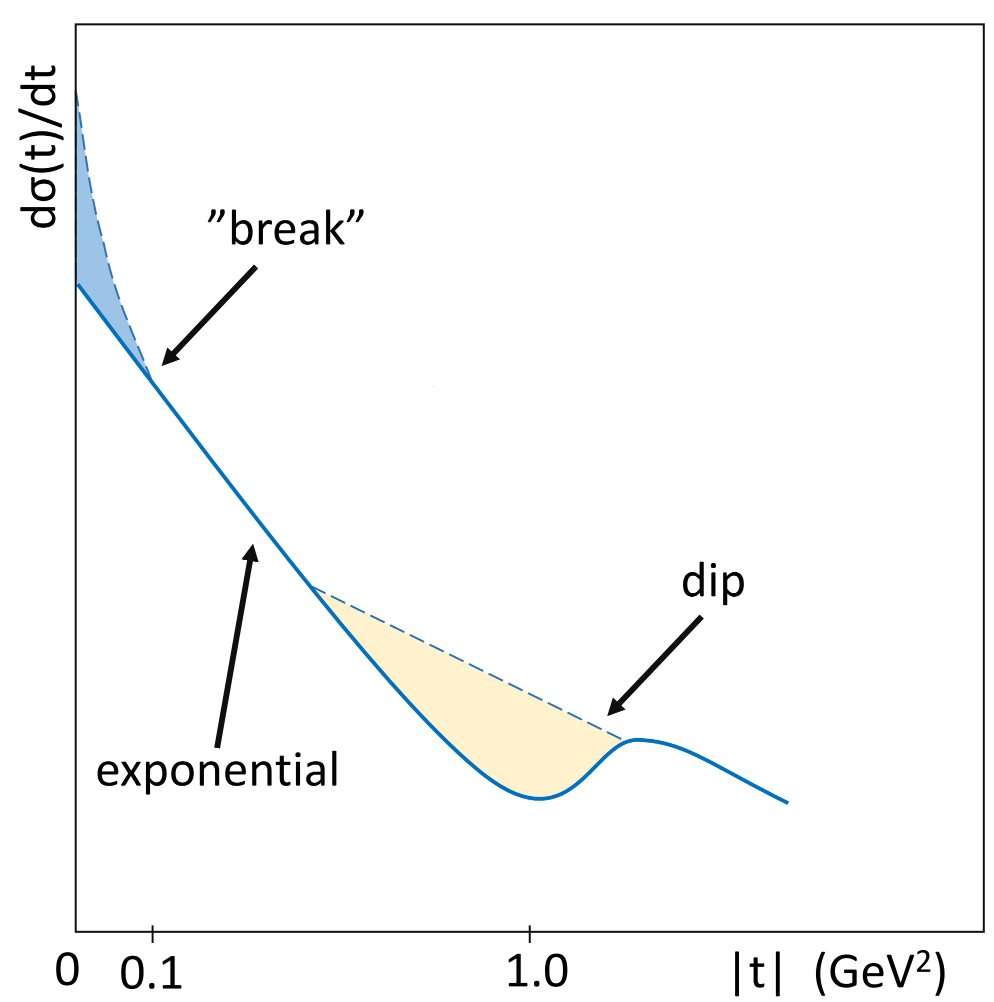


Noticeable Features

- Diffraction peak/dip persists.
- More noticeable break at very small t.
- Dip moved towards smaller t.
- Comparing with pp and ppbar at Fermi-Lab, indicating the existence of "Odderon"

Noticeable Features

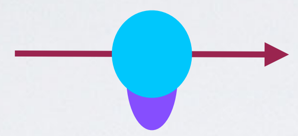
- More noticeable break at very small t.



Expected increasing importance at larger impact parameter due to 2-pion exchange

L.Jenkovszky, I. Szanyi, C-I Tan, "Shape of Proton and the Pion Cloud", EJPA, (2018) 54: 116

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

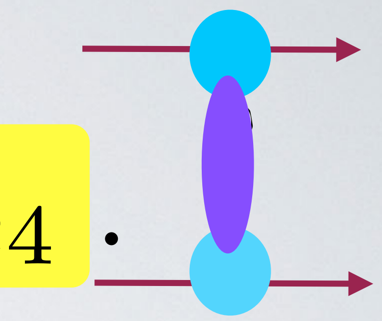
$$\Delta(j) = 2+\sqrt{2}\,\lambda^{1/4}\sqrt{(j-j_0)}$$

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

ADS BUILDING BLOCKS BLOCKS

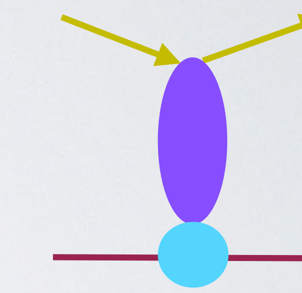
For 2-to-2

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



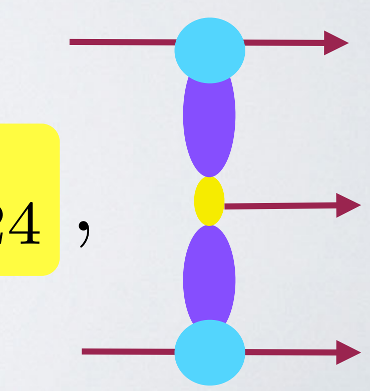
$$A(s,t) = g_0^2\int d^3\mathbf{b}d^3\mathbf{b}'\; e^{i\mathbf{q}_\perp\cdot(\mathbf{x}-\mathbf{x}')}\;\Phi_{13}(z)\;\mathcal{K}(s,\mathbf{x}-\mathbf{x}',z,z')\;\Phi_{24}(z')$$

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



For 2-to-3

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



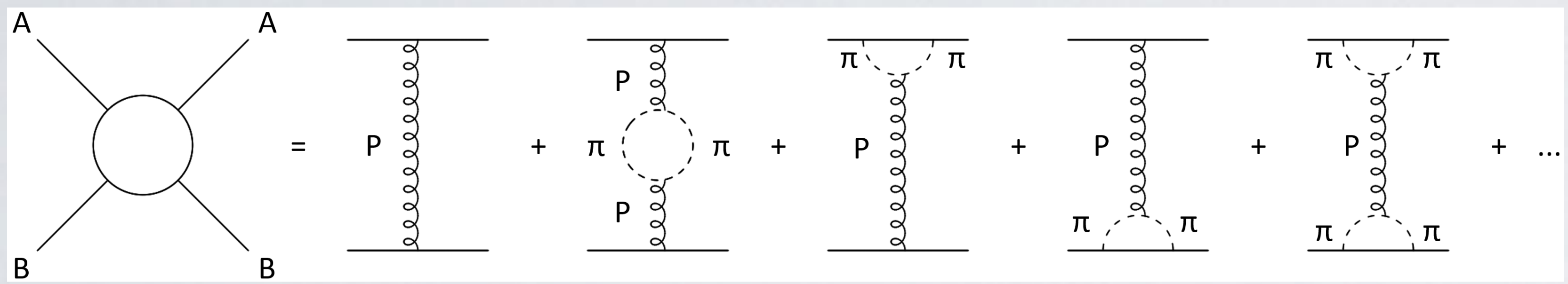


Fig. 2 Diagram for elastic scattering with t-channel exchange containing a branch point at $t = 4m_\pi^2$.

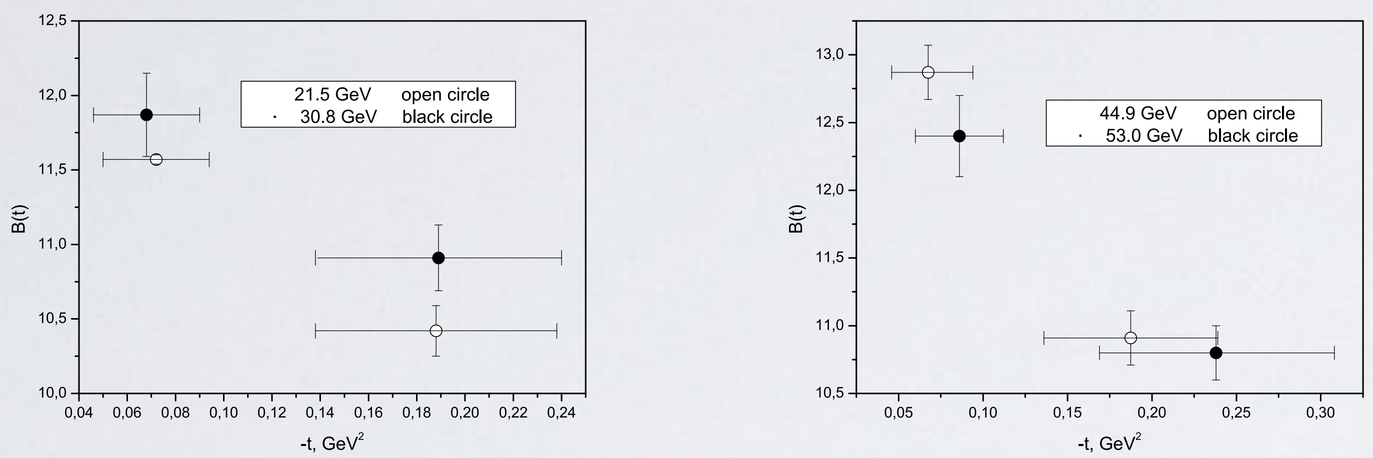


Fig. 3 Local slopes $B(t)$ calculated for the ISR data at 21 and 30 GeV (left) and 45 and 53 GeV (right) [11].

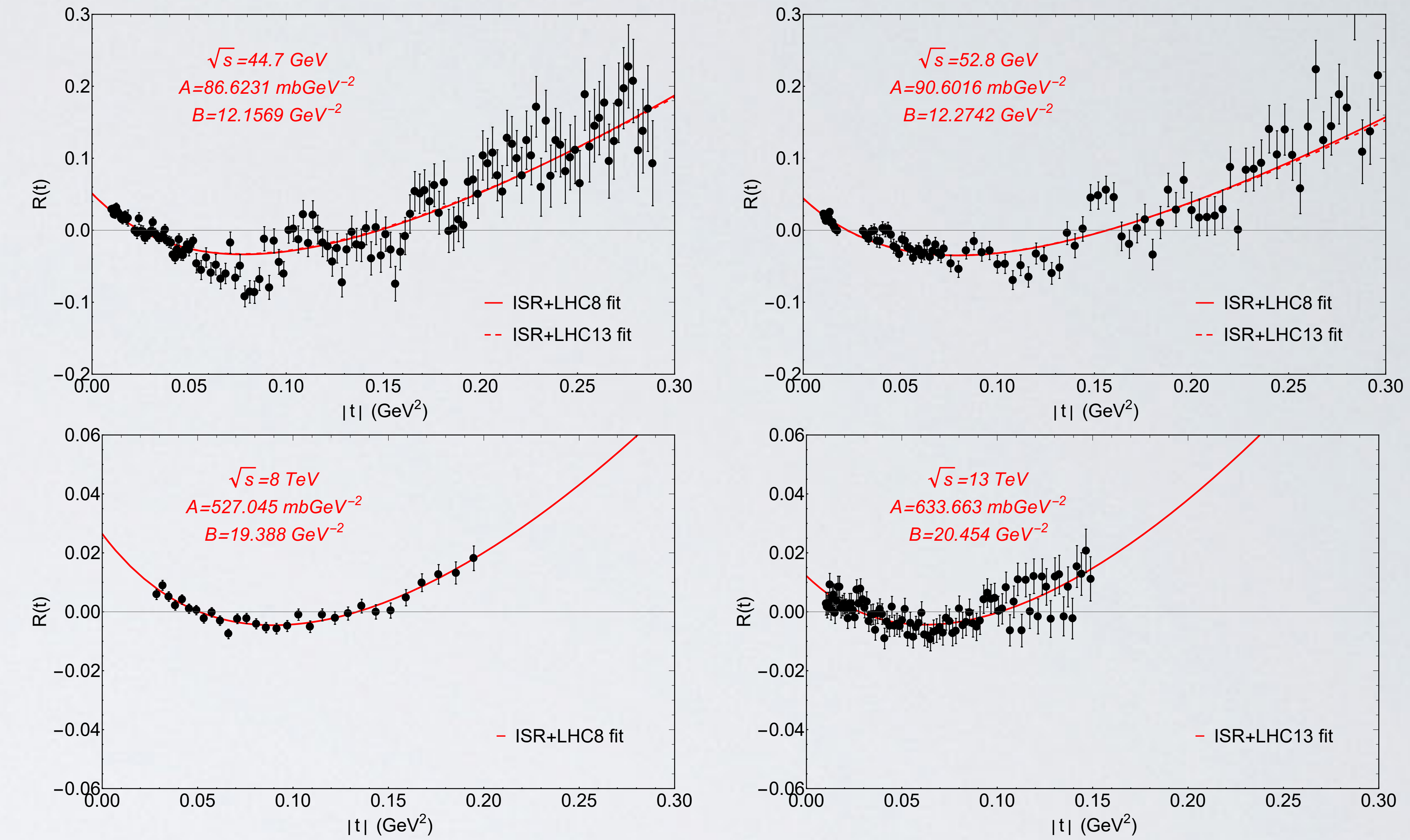


Fig. 6 $R(t)$ ratios.

4

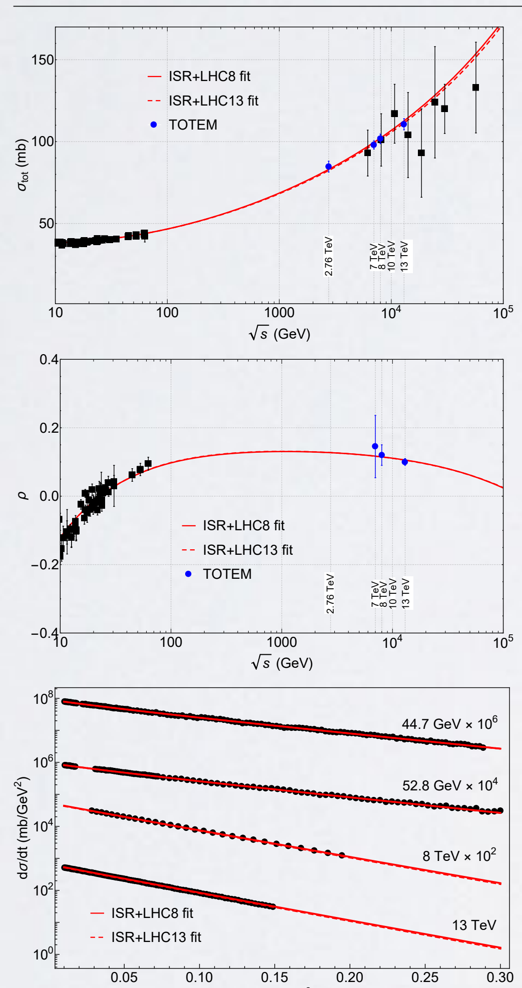


Fig. 4 Fit to pp total cross section (top), ρ-parameter (middle) and low-$|t|$ differential cross section data (bottom).

The best fits are shown in Figure 4 with the values of the fitted parameters quoted in Table 1. Aiming at a better fit, the number of the ISR data points on the differential cross section was restricted to the chosen t interval, furthermore the LHC 13 TeV data were fitted up to $|t_{max}| = 0.15$, as it was done by TOTEM in Ref. [2].

Table 1 Values of the parameters fitted to the pp data on the ρ-parameter, total and differential cross section.

Parameter	Value	Error
a_P	-1.62206	0.00723783
α_{0P}	1.09505	0.000507519
α'_P	0.350352	0.000807463
α_{1P}	0.0418504	0.000894104
β_{0P}	0.825955	0.00283623
β'_P	2.52918	0.0290946
β_{1P}	-0.036672	0.00831786
a_O	0.00113782	0.000135669
b_O	2	fixed
α_{0O}	1.36284	0.00461602
α'_O	0.4	fixed
a_f	-11.6528	0.257487
b_f	13.8938	0.868578
a_ω	9.92422	1.14544
b_ω	10	fixed
s_0	1	fixed
	χ^2/DOF	1.3
	DOF	183

(a) ISR + LHC 8 TeV

Parameter	Value	Error
a_P	-1.63005	0.00719853
α_{0P}	1.09385	0.000548782
α'_P	0.361809	0.00149993
α_{1P}	0.0372772	0.000761573
β_{0P}	0.832661	0.00282508
β'_P	2.49077	0.0282044
β_{1P}	-0.0364331	0.00852847
a_O	0.000860881	0.000126785
b_O	2	fixed
α_{0O}	1.37452	0.00331293
α'_O	0.4	fixed
a_f	-11.486	0.259798
b_f	14.3807	0.907834
a_ω	10.1825	1.12135
b_ω	10	fixed
s_0	1	fixed
	χ^2/DOF	1.2
	DOF	246

(b) ISR + LHC 13 TeV

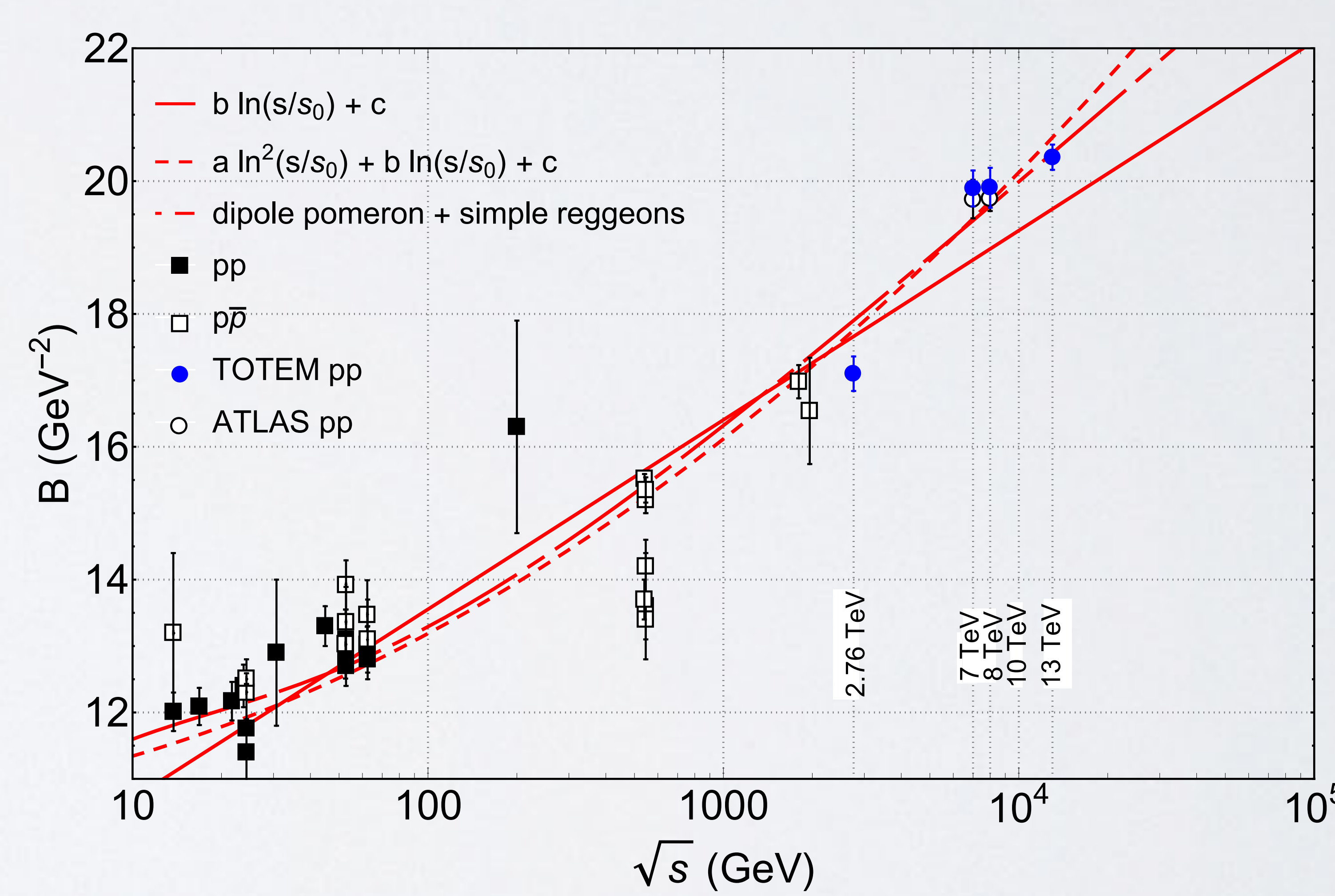


Fig. 7 Fits [27] to the pp and $p\bar{p}$ elastic slope data [18–22, 25].

Phenomenological Applications:

String-Gauge Dual Description of Deep Inelastic Scattering at Small-x, Richard C. Brower (Boston U.), Marko Djuric (Brown U.), Ina Sarcevic (Arizona U.), Chung-I Tan (Brown U.), arXiv:1007.2259.

Holographic Approach to Deep Inelastic Scattering at Small-x at High Energy, Richard C. Brower (Boston U.), Marko Djurić (Porto U.), Timothy Raben, Chung-I Tan (Brown U.), arXiv:1508.05063

Inclusive Production Through AdS/CFT, Richard Nally (Stanford U.), Timothy G. Raben (Kansas U.), Chung-I Tan (Brown U.), arXiv:1702.05502

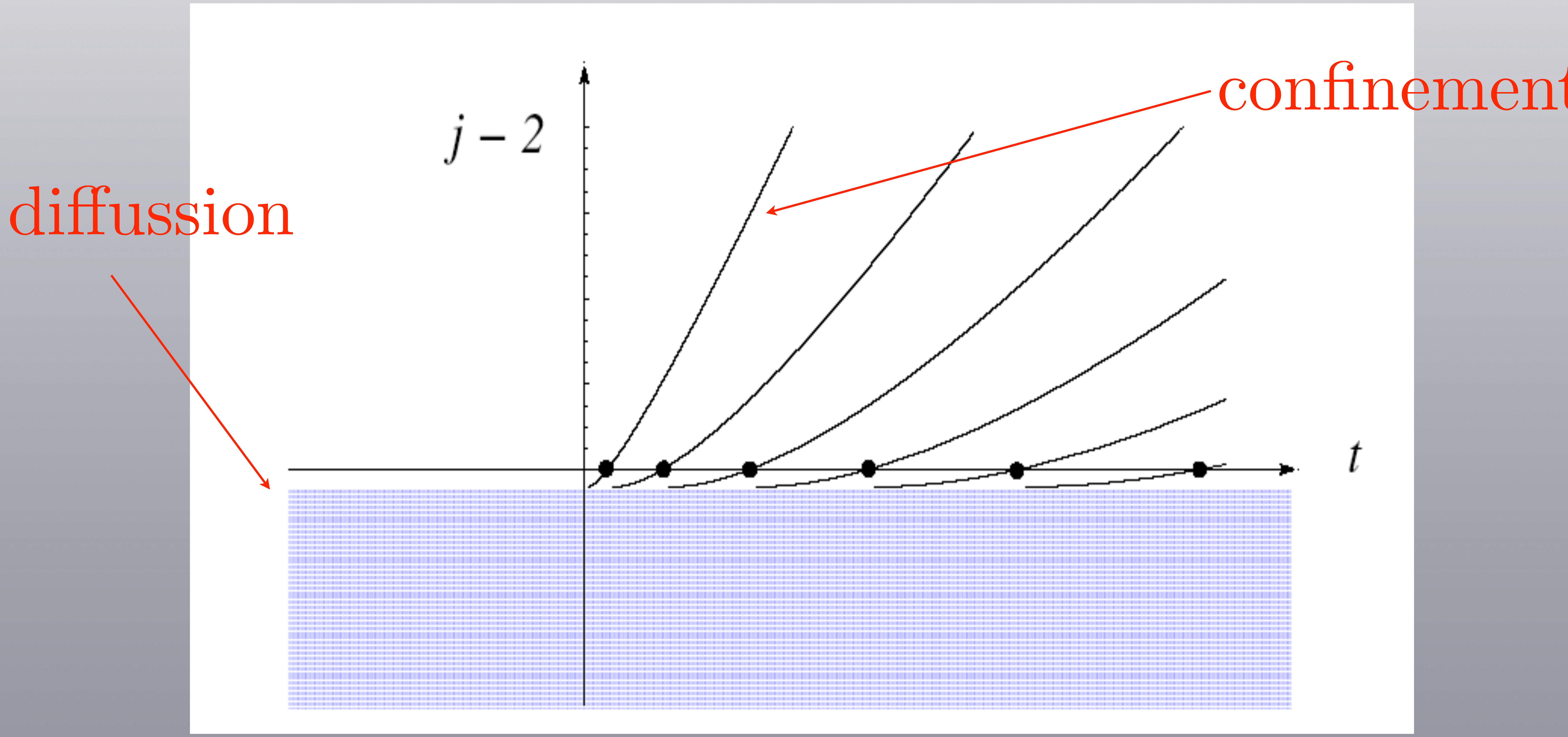
- **Applications to pp Elastic and Total Cross Section**

Total Hadronic Cross Sections via the Holographic Pomeron Exchange, Akira Watanabe (Beijing, Inst. High Energy Phys., TPCSF, Beijing, GUCAS), arXiv:1901.09564

Elastic proton-proton scattering at LHC energies in holographic QCD, Wei Xie (Three Gorges U., Beijing, Inst. High Energy Phys. and TPCSF, Beijing), Akira Watanabe (Beijing, Inst. High Energy Phys. and TPCSF, Beijing, GUCAS), Mei Huang (Beijing, GUCAS), arXiv:1901.09564

Unified Hard (conformal) and Soft (confining) Pomeron

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



Glueball Mass

4-Dim Massive Graviton

5-Dim Massless Mode:

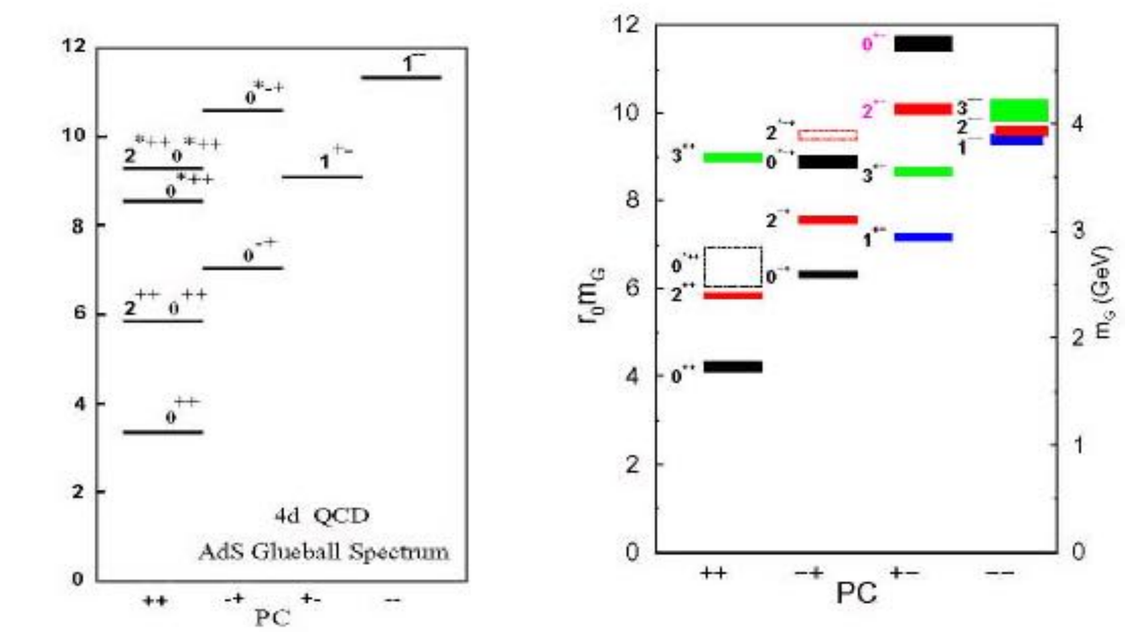
$$0 = E^2 - (p_1^2 + p_2^2 + p_3^2 + p_r^2)$$

If, due to Curvature in fifth-dim, $p_r^2 \neq 0$,

Four-Dimensional Mass:

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

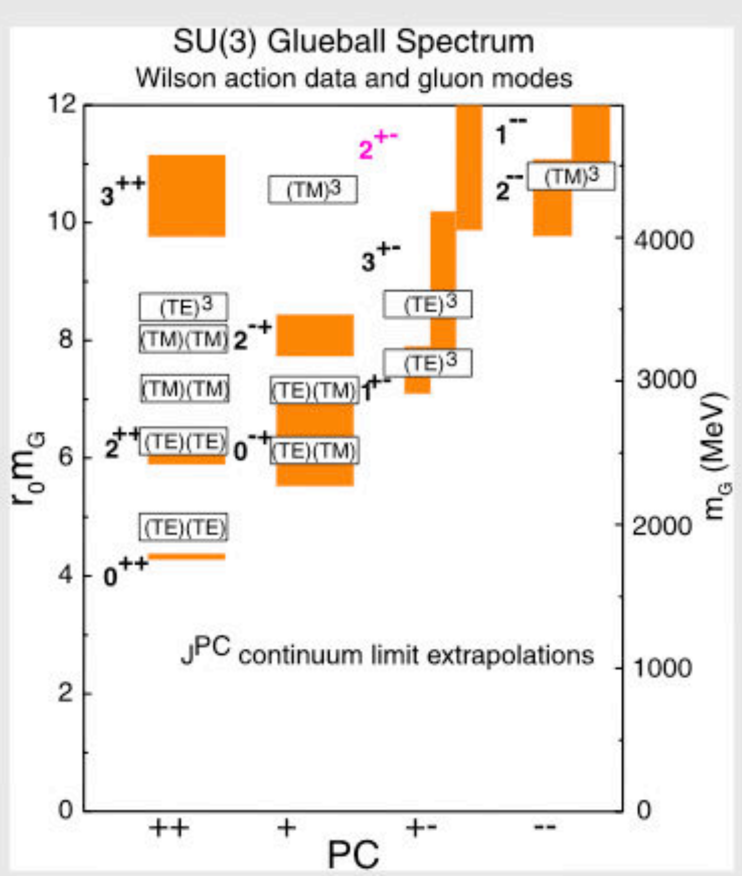
Glueball Spectrum



The AdS^7 glueball spectrum for QCD_4 in strong coupling (left) compared with the Morningstar/Peardon lattice spectrum for pure SU(3) QCD (right) with $1/r_0 = 410$ Mev.

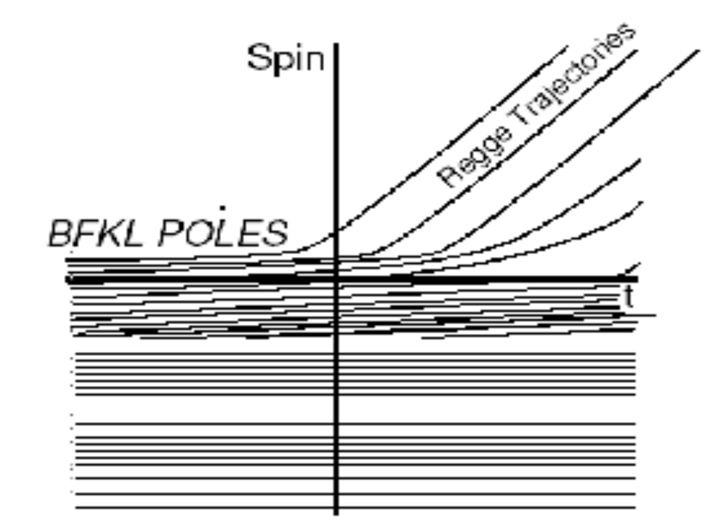
R. Brower, S. Mathur, and C-I Tan, hep-th/0003115, "Glueball Spectrum of QCD from AdS Supergravity Duality".

Comparison with MIT Bag Calculation



Pomeron in QCD

Running UV, Confining IR (large N)



The hadronic spectrum is little changed, as expected.

The BFKL cut turns into a set of poles, as expected.

Summary and Outlook

- Provide meaning for Pomeron/Odderon non-perturbatively from first principles.
- Realization of conformal invariance beyond perturbative QCD
- New starting point for unitarization, saturation, etc.
- First principle description of elastic/total cross sections, DIS at small-x, Central Diffractive Glueball production at LHC, etc.
- Inclusive Production and Dimensional Scalings.