DIFFRACTION: FROM ADS/CFT TO POMERON/ ODDERON IN QCD

Saturation and Diffrction
at LHC and EIC

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BROWN

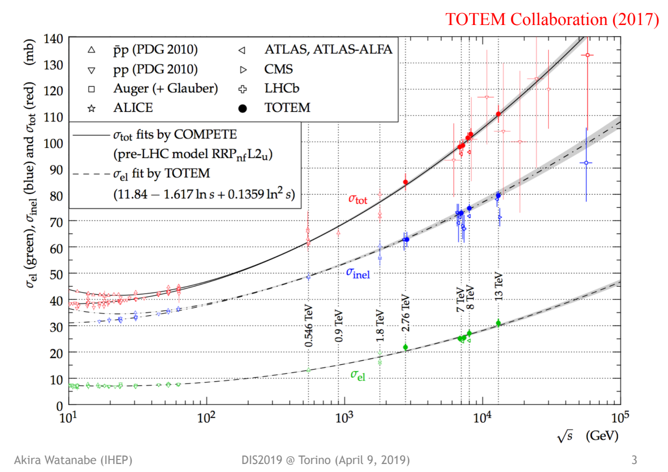
Outline

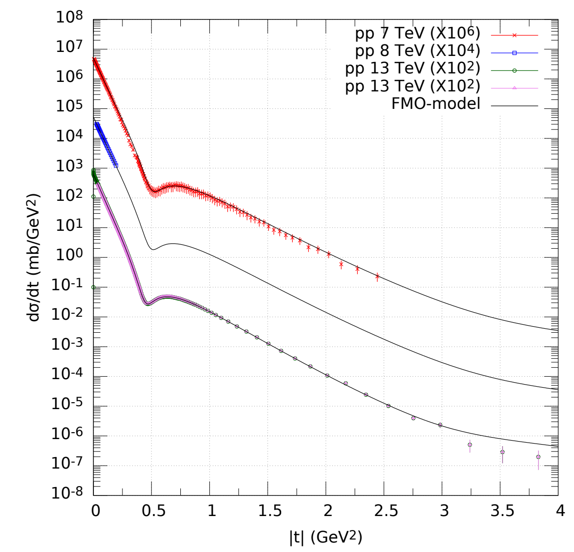
- Introduction:
  - Size and Shape of Proton
  - From ISR-LHC
- High Energy Scattering:
  - Characture for QCD: Conformal Invariance
  - Non-perturbative QCD and Holography
- AdS/CFT and Gauge/String Duality:
  - “Anomalous Dimensions”: Pomeron and Odderon Intercepts
  - Confinement, Glueballs, Saturation, etc.
  - Odderon at LHC and beyond

- Introduction:
    - Size and Shape of Proton
    - From ISR-LHC

Size and Shape of Proton at LHC

13TeV data from TOTEM



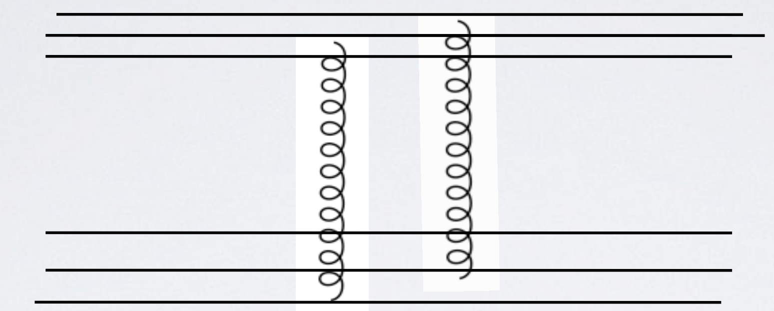


Interesting new non-perturbative physics in QCD?

4

HIGH ENERGY SCATTERING

WEAK COUPLING EXPANSION: TWO-GLUON EXCHANGE

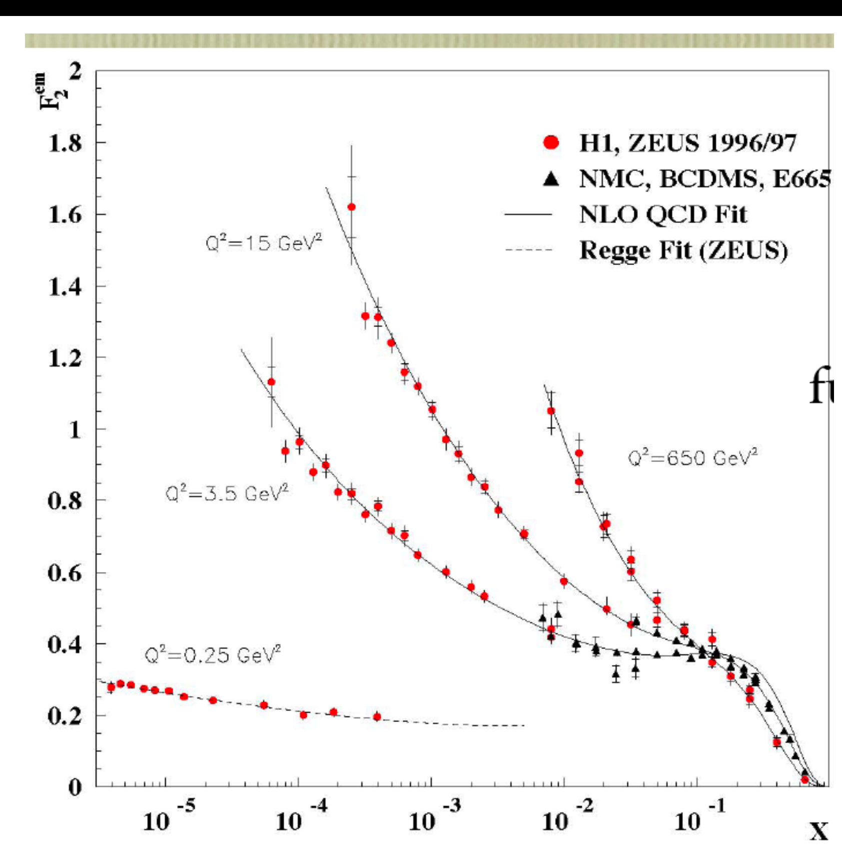


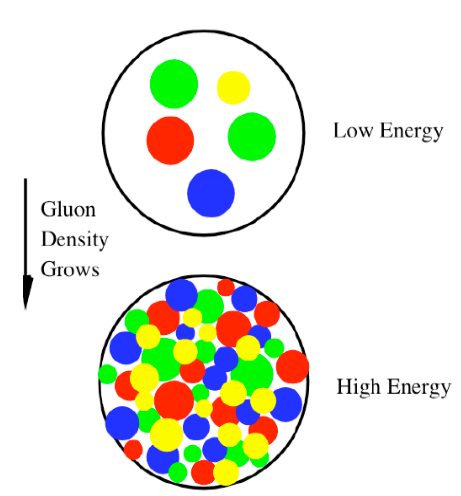
$$J_{cut} = 1 + 1 - 1 = 1$$

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

Require Non-Perturbative Treatment

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

- High Energy Scattering:
  - Characture for QCD: Conformal Invariance
  - Non-perturbative QCD and Holography

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.

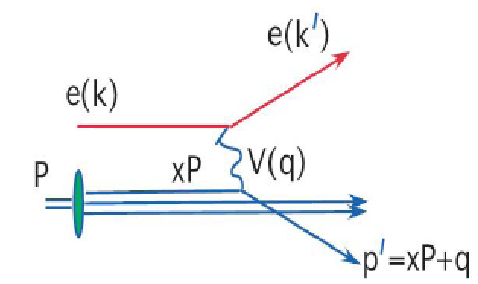
$$\frac{E}{pc} = \frac{\sqrt{(pc)^2 + m_0^2 c^4}}{pc} \simeq 1, \qquad p \to \infty$$

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

Deep Inelastic Scattering (DIS)

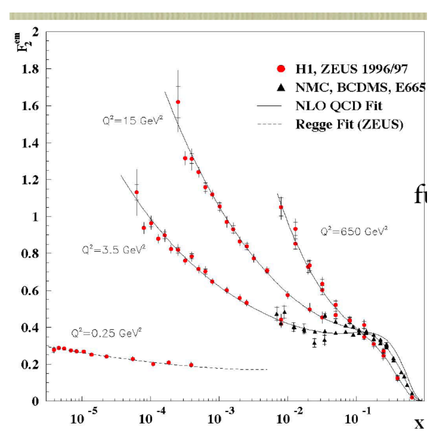


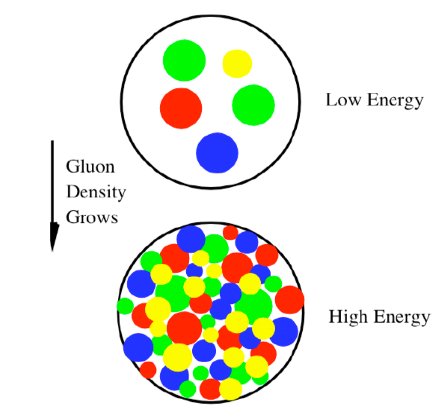
$$F_2(x, Q2) = \frac{Q^2}{4\pi^2 \alpha_{em}} [\sigma_T(\gamma^* p) +_L (\gamma^* p)]$$

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

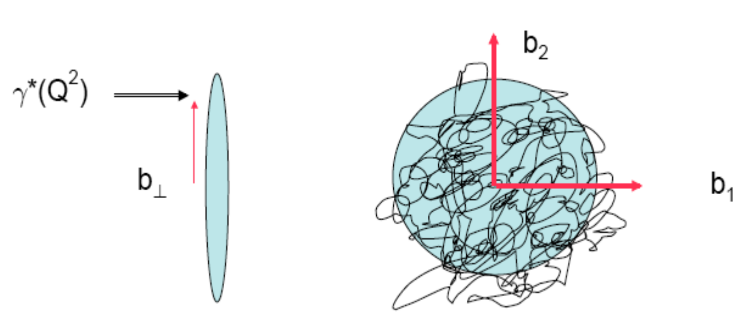
Small x : $\frac{Q^2}{s} \to 0$

CFT at work!





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

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

Poincare Group SO(3,1) x T(4) :

Generators: Lorentz $J_{\mu\nu}$ — 6, Tranlations P_μ – 4

Conformal Group SO(4,2):

Generators: Lorentz $J_{\mu\nu}$ – 6, Tranlations P_μ – 4,
Dilatation D – 1, Inversion K_μ – 4

Quadratic Casimir: $C_2 = -\Delta(\Delta - d) - \ell(\ell + d - 2)$

$d^2/4 < -\Delta(\Delta - d), \quad \Leftrightarrow \quad \Delta = d/2 + is$

$(d-2)^2/4 < -\ell(\ell + d - 2), \quad \Leftrightarrow \quad \ell = -\frac{d-2}{2} + is$

Euclidean Conformal Group SO(5,1):

$d^2/4 < -\Delta(\Delta - d), \quad \Leftrightarrow \quad \Delta = d/2 + is$

$\ell = 0, 1, 2, \cdots$

Kinematics of High Energy Scattering in CFT

$SO(1,1)\times SO(1,1)\subset SO(4,2)$ $\gamma^*(1)+\gamma^*(3)\to\gamma^*(2)+\gamma^*(4)$

$$\langle 0|T(\mathcal{J}_1(x_1)\mathcal{J}_2(x_2)\mathcal{J}_4(x_4)\mathcal{J}_3(x_3))|0\rangle=\frac{1}{(x_{12}^2)^{\Delta_1}(x_{34}^2)^{\Delta_3}}F^{(M)}(u,v)$$

$$u=\frac{x_{12}^2x_{34}^2}{x_{13}^2x_{24}^2}\,,\qquad v=\frac{x_{23}^2x_{14}^2}{x_{13}^2x_{24}^2}\qquad\qquad u\to 0,\quad v\to 1$$

For both Euclidean and Minkowski settings, the limit corresponds to $x_{12}^2\to 0$ and $x_{34}^2\to 0$ and $x_i^2\to 0$, $i=1,2,3,4$, with other invariants between left- and right-movers fixed:

$$L^2\simeq x_{13}^2\simeq x_{23}^2\simeq x_{24}^2\simeq x_{14}^2=O(1)$$

Due to scale invariance, this is equivalent to increasing the left-right separation,

$$L^2\simeq x_{ij}^2\to\infty,\quad i=1,2,\quad\text{and}\quad j=3,4\,,$$

while keeping fixed x_{12}^2, x_{34}^2, and x_i^2, $i=1,2,3,4$.

In Euclidean, a single scale, L, corresponding dilatation under $O(5,1)$

Induced Representation

Iwasawa Decomposition: $G=K\otimes P=K\otimes A\otimes N^+$

Maximal Abelian Subgroup: A
Maximal Compact Subgroup: K

For $SO(4,2)$: $A=SO(1,1)\times SO(1,1)$, $K=SO(4)\times SO(2)$

Timothy Raben and Chung-I Tan,
"Minkowski Conformal Blocks and the Regge Limit for SYK-like Models", Phys. Rev. D98, 086009 (2018).

Pulkit Agarwal, Richard Brower, Timothy Raben and Chung-I Tan,
"CFT in Lorentzian Limit and Principal Series Representation", (to appear).

Minkowski CFT

$SO(4,2)\supset SO(1,1)\otimes SO(3,1)\otimes T(4)\otimes K(4)$

$$\mathcal{A}(u,v)\leftrightarrow\int_{d/2-i\infty}^{d/2+i\infty}\frac{d\Delta}{2\pi i}\int_{-\frac{(d-2)}{2}-i\infty}^{-\frac{(d-2)}{2}+i\infty}\frac{d\ell}{2\pi i}a(\Delta,j)\mathcal{G}(u,v;\Delta,j)$$

Euclidean CFT

$SO(5,1)\supset SO(1,1)\otimes SO(4)\otimes T(4)\otimes K(4)$

$$\mathcal{A}(u,v)\leftrightarrow\int_{d/2-i\infty}^{d/2+i\infty}\frac{d\Delta}{2\pi i}\sum_j\;a_j(\Delta)\,G_{\Delta,j}(u,v)$$

Dynamics

$$a_j(\Delta)\sim\frac{1}{\Delta-\Delta_j}\quad\to\quad\frac{1}{\Delta-\Delta(j)}$$

Dynamics

$$a_j(\Delta)\sim\frac{1}{\Delta-\Delta_j}\quad\to\quad\frac{1}{\Delta-\Delta(j)}$$

Single Trace Gauge Invariant Operators of $\mathcal{N}=4$ SYM,

$$Tr[F^2],\quad Tr[F_{\mu\rho}F_{\rho\nu}],\quad Tr[F_{\mu\rho}D_\pm^S F_{\rho\nu}],\quad Tr[Z^\tau],\quad Tr[D_\pm^S Z^\tau],\cdots$$

Super-gravity in the $\lambda\to\infty$:

$$Tr[F^2]\leftrightarrow\phi,\quad Tr[F_{\mu\rho}F_{\rho\nu}]\leftrightarrow G_{\mu\nu},\quad\cdots$$

Symmetry of Spectral Curve:

$$\Delta(j)\leftrightarrow 4-\Delta(j)$$

Spectral Curve:

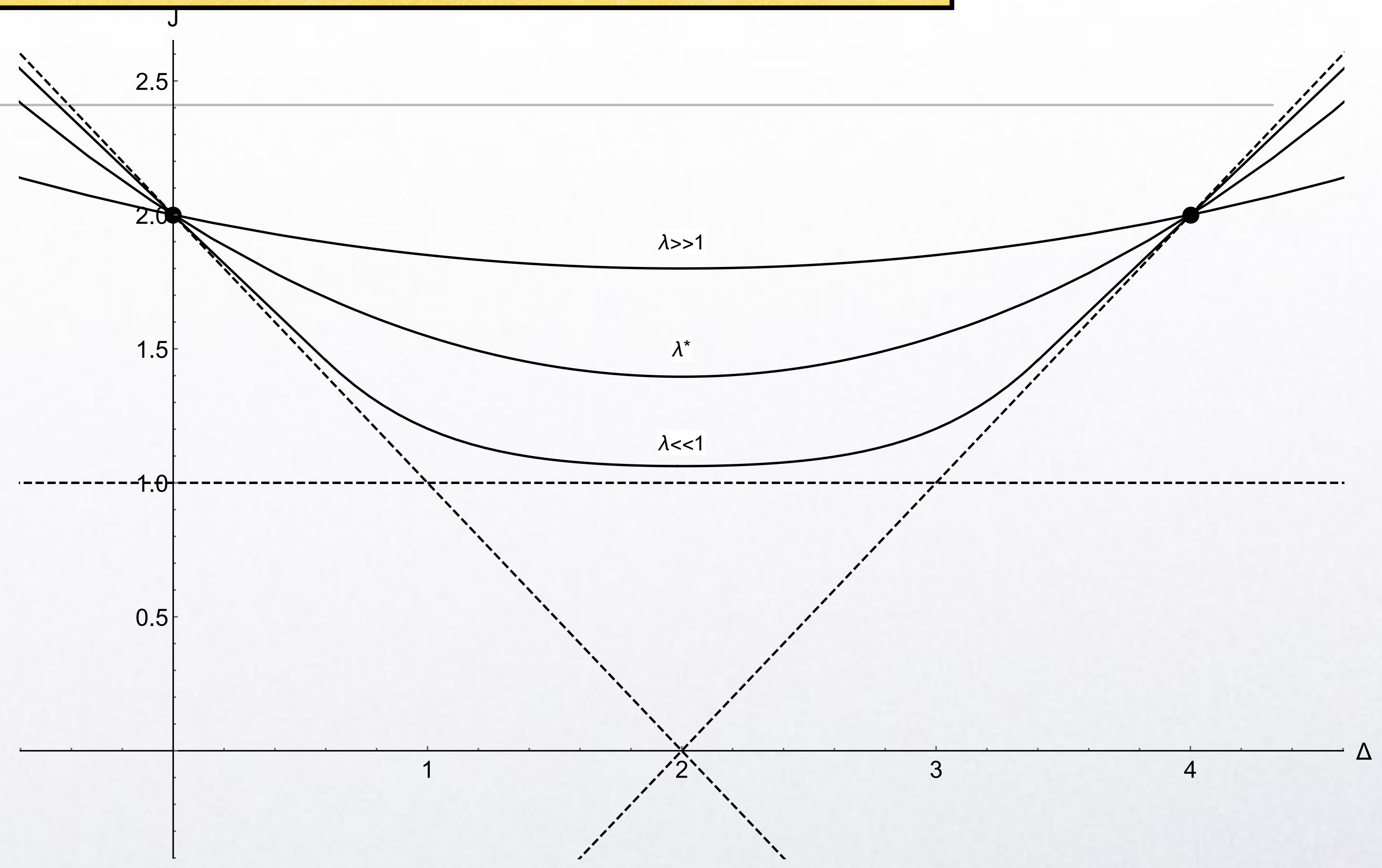
$$Im\, F(w,\sigma) = \pm \sum_{\alpha} \int_{L_0 - i\infty}^{L_0 + i\infty} \frac{d\ell}{2i} a^{(12),(34)}(\ell, \Delta_\alpha(\ell)) G(w,\sigma;\ell,\Delta_\alpha(\ell))$$

$$\Delta(\ell)(\Delta(\ell) - d) = m^2_{AdS}(\ell)$$

$$d = 4, \quad m^2_{AdS}(\ell) = \sum_{n=1} \beta_n (\ell - 2)^n$$

$$\Delta_P(\ell) \simeq 2 + B(\ell)\sqrt{\ell - \ell_{eff}}$$

$$\text{Im}\, F(w,\sigma) \sim \frac{w^{\ell_{eff}-1}}{|\ln w|^{3/2}}$$



Minkowski OPE and Scattering

$$F(w,\sigma) = \sum_\alpha \sum_\ell a^{(12),(34)}_{\ell,\alpha}\, G(w,\sigma;\ell,\Delta_{\ell,\alpha})$$

$$\sum_{\ell=2n} \to \sum_{\ell=2n<L_0} - \int_{L_0-i\infty}^{L_0+i\infty} \frac{d\ell}{2i} \frac{1-e^{i\pi(1-\ell)}}{\sin \pi\ell}$$

Sommerfeld-Watson Transform:

$$Im\, F(w,\sigma) = \pm \sum_\alpha \int_{L_0-i\infty}^{L_0+i\infty} \frac{d\ell}{2i} a^{(12),(34)}(\ell,\Delta_\alpha(\ell))G(w,\sigma;\ell,\Delta_\alpha(\ell))$$

Singularity at j_0 $\qquad$ $\mathcal{A} \sim u^{(1-j_0)/2}$

- AdS/CFT and Gauge/String Duality:
  - “Anomalous Dimensions”: Pomeron and Odderon Intercepts
  - Confinement, Glueballs, Saturation
  - Odderon at LHC and beyond

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: $C_{mn\cdots}(x)$

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

$\mathcal{N} = 4$ 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

Pomeron/Odderon

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

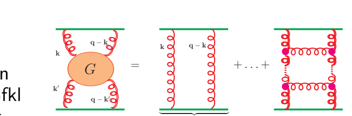
Conformal Invariance - - - Holographic.

Pomeron can be identified as Massive Graviton.

Both the IR Pomeron and the UV Pomeron are dealt in a unified single step.

BFKL

Balitsky, Fadin, Kuraev, Lipatov (BFKL): perturbative Pomeron. Large logs get in the way of usual perturabtion theory: resum $\alpha_s\, log(s)$ to all orders. Bfkl equation – integral equation for Green's function in Mellin space



$$G(\mathbf{k},\mathbf{k}',\mathbf{q},Y) = \int_{-i\infty}^{+i\infty} \frac{d\omega}{2\pi i} e^{Y\omega} f_\omega(\mathbf{k},\mathbf{k}',\mathbf{q}) \to \int_{-i\infty}^{+i\infty} \frac{d\omega}{2\pi i} e^{Y\omega} \sum_{n\in\mathcal{Z}} \int_{\frac12 - i\infty}^{\frac12 + i\infty} \frac{d\gamma}{2\pi\, i} \frac{E_{\gamma,n}(k)E^*_{\gamma,n}(k')}{\omega - \bar\alpha_s\chi(\gamma,n)}$$

where in Leading Log (LL)

$$\chi(\gamma,n) = 2\psi(1) - \psi(\gamma + \frac{|n|}{2}) - \psi(1-\gamma+\frac{|n|}{2}) \quad and \quad \omega_0 = \frac{4\alpha_s N_c}{\pi} ln(2)$$

Surprising conformal symmetry greatly simplifies things in coordinate space

Brower, Costa, Djuric, Nally, TR, Tan (KU) 9/15/17 4 / 19

Full $O(4,2)$ Conformal Group

$SO(4,2) = SO(1,1) \times SO(3,1)$

Anomalous dimensions

$$\gamma(j) = \Delta(j) - j - \tau_{twist}$$

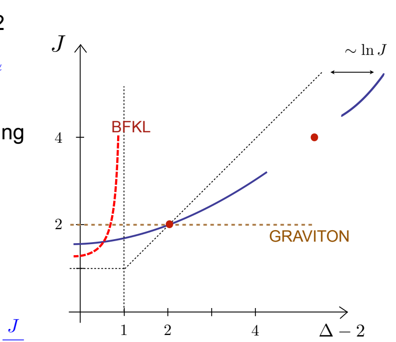
DGLAPP

BFKL

BPST Pomeron

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

- Operators that contribute are the twist 2 operators
$\mathcal{O}_J \sim F_{\alpha[\beta_1}D_{\beta_2}\ldots D_{\beta_{J-1}}F_{\beta_J]}{}^\alpha$
- Dual to string theory spin J field in leading Regge trajectory
$(D^2 - m^2)\, h_{a_1\ldots a_J} = 0$
$m^2 = \Delta(\Delta-4) - J\,, \quad \Delta = \Delta(J)$
- Diffusion limit
$J(\Delta) = J_0 + \mathcal{D}(\Delta-2)^2 \Rightarrow m^2 = \frac{2}{\alpha'}(J-2) - \frac{J}{L^2}$



Status of Pomeron

	Weak Coupling	Strong Coupling
$C = +1$	$j_{0_+} = 1 + (\ln 2)\ \lambda/\pi^2 + O(\lambda^2)$	$j_{0_+} = 2 - 2/\sqrt{\lambda} + O(1/\lambda)$

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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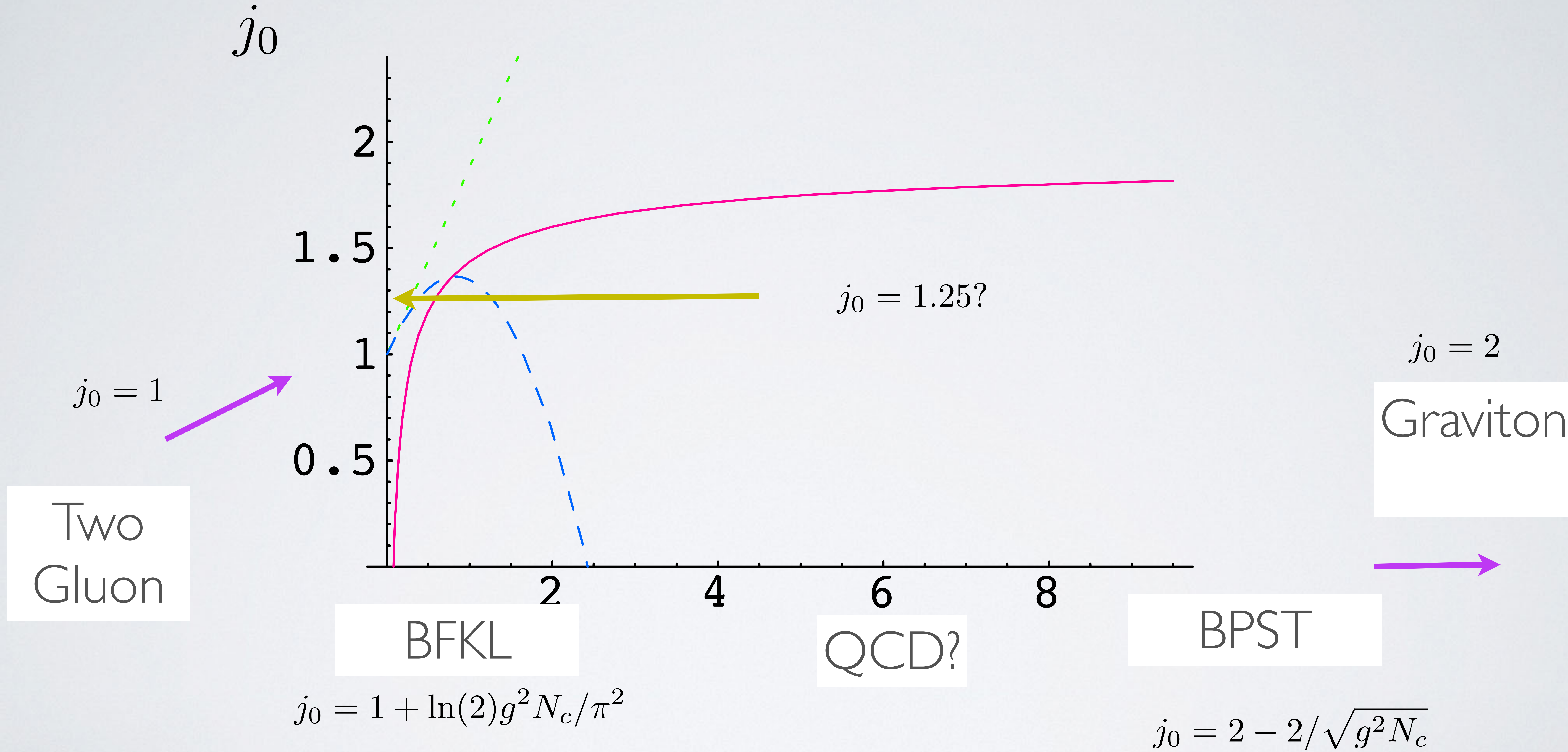
$\Delta = 4$	0^{-+}	$Tr(F\tilde{F}) = \vec{E}^a \cdot \vec{B}^a$	C_0
$\Delta = 6$	1^{+-}	$Tr(F_{\mu\nu}\{F_{\rho\sigma}, F_{\lambda\eta}\}) \sim d^{abc} F^a F^b F^c$	B_{ij}
$\Delta = 6$	1^{--}	$Tr(\tilde{F}_{\mu\nu}\{F_{\rho\sigma}, F_{\lambda\eta}\}) \sim d^{abc} \tilde{F}^a F^b F^c$	$C_{2,ij}$
$\Delta = 4 + (J-2) + \gamma$	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	$Tr(F D^S F F) + \cdots, J = S + 1$	absent
$\Delta = 2 + (J-1) + \gamma$	J^{+-} J odd	$Tr(D^S F) + \cdots, J = S + 1$	absent

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



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

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

$$\alpha_p = 2 - \frac{2}{\lambda^{1/2}}$$

Brower, Polchinski, Strassler, Tan

ODDERON

Solution-a: $\alpha_O = 1 - \frac{8}{\lambda^{1/2}}$

Solution-b: $\alpha_O = 1 - \frac{0}{\lambda^{1/2}}$

Brower, Djuric, Tan

Avsar, Hatta, Matsuo

Status of Pomeron and Odderon

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

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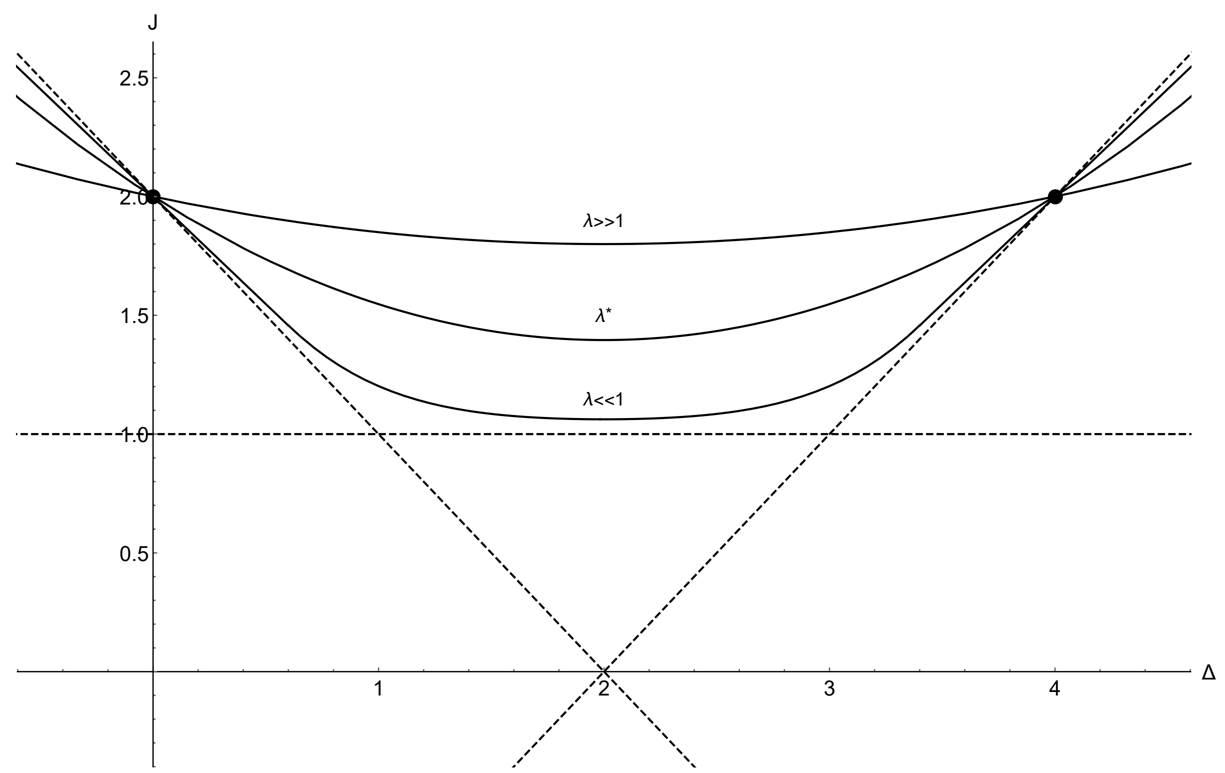
Spin-Dimension Curves: Anomalous Dimensions



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:

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

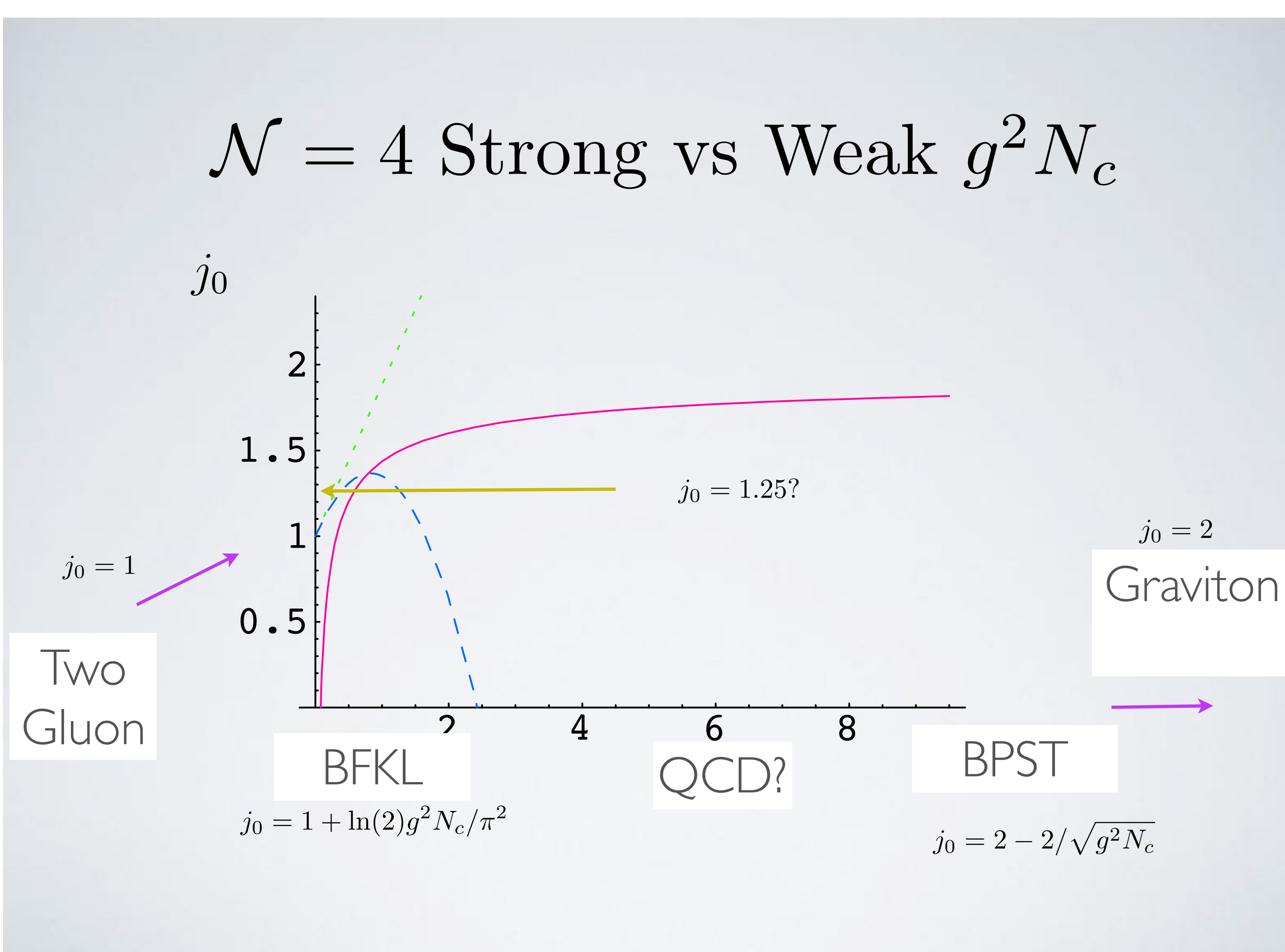
Solution-b:

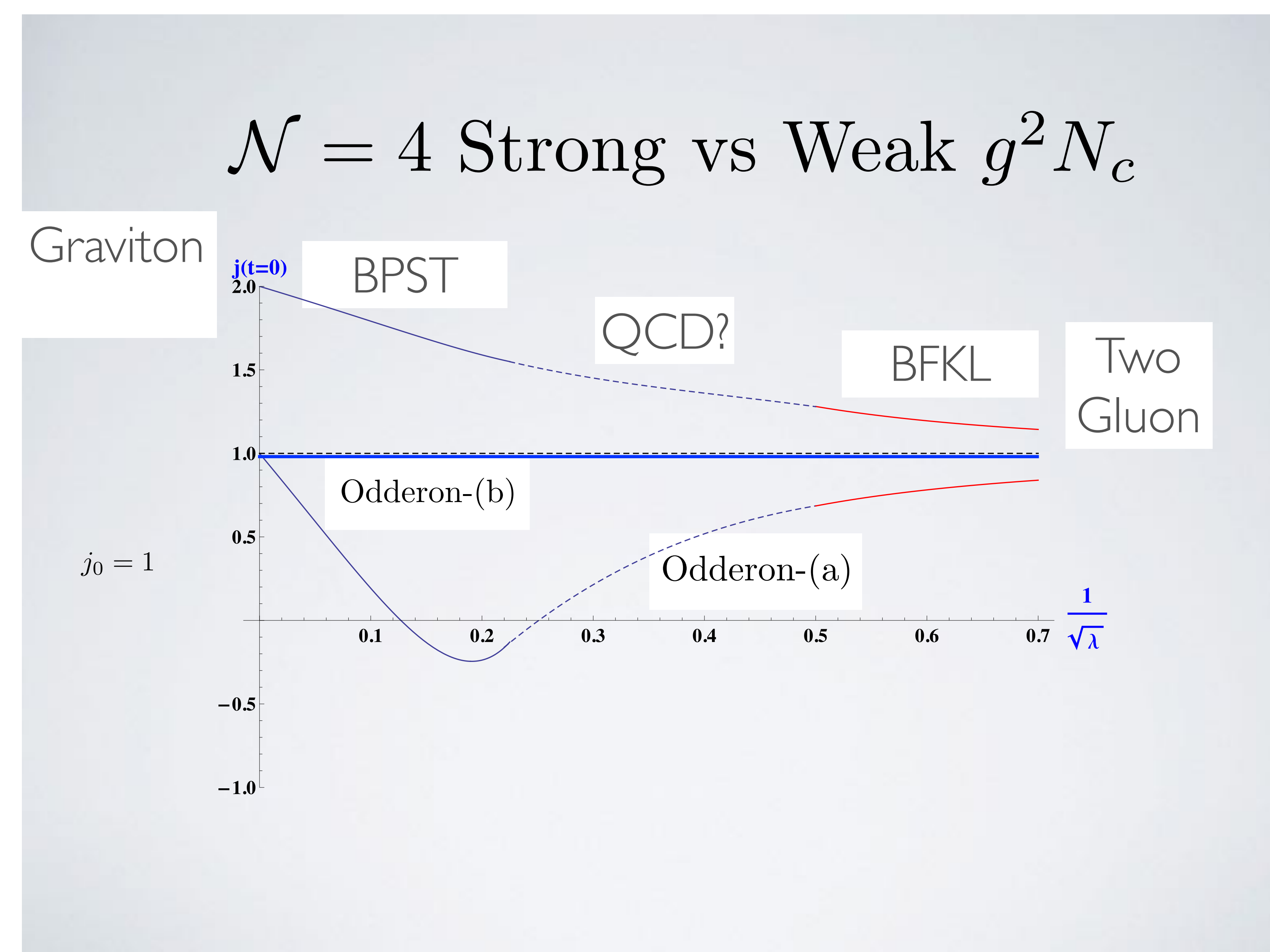
$$\alpha_O = 1 - \frac{0}{\lambda^{1/2}} - \frac{0}{\lambda} + \frac{0}{\lambda^{3/2}} + \frac{0}{\lambda^2} + \frac{0}{\lambda^{5/2}} + \frac{0}{\lambda^3} + \cdots$$

Brower, Djuric, Tan

Brower, Costa, Djuric, Raben, Tan

Avsar, Hatta, Matsuo





Coupling of Odderon:

$C = -1$ massless glueball does not exist.

$$\frac{\beta(t)(1-e^{-i\alpha(t)\pi})}{\sin\ \alpha(t)\pi}\ s^{\alpha(t)}$$

However, higher spin modes exists.

With confinement, leads to Odderon trajectory.

Regge residue must vanish at $t = 0$.

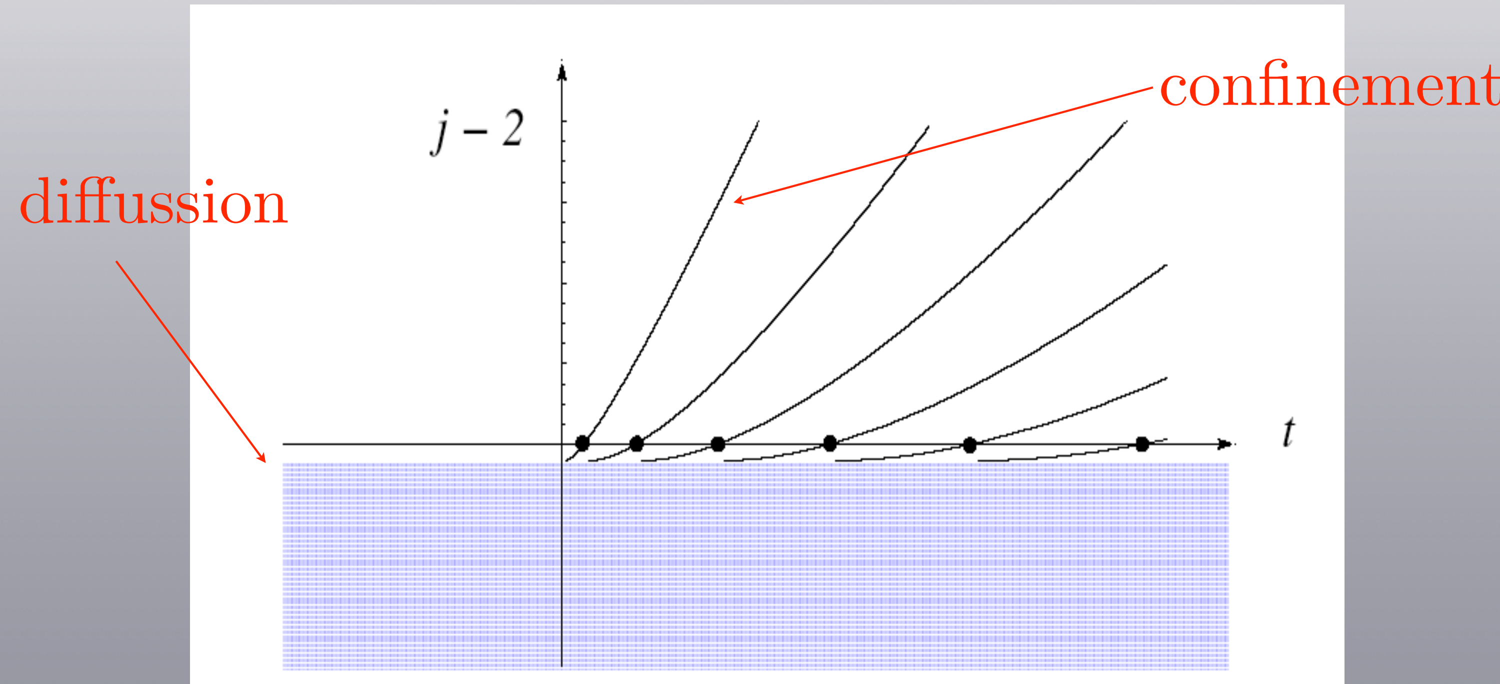
There is no physical pole at $t = 0$, but the Odderon contribution to cross section does not vanish at $t = 0$.

Need models for conventional hadrons to obtain couplings.

- AdS/CFT and Gauge/String Duality:
  - “Anomalous Dimensions”: Pomeron and Odderon Intercepts
  - Confinement, Glueballs, Saturation
  - Odderon at LHC and beyond

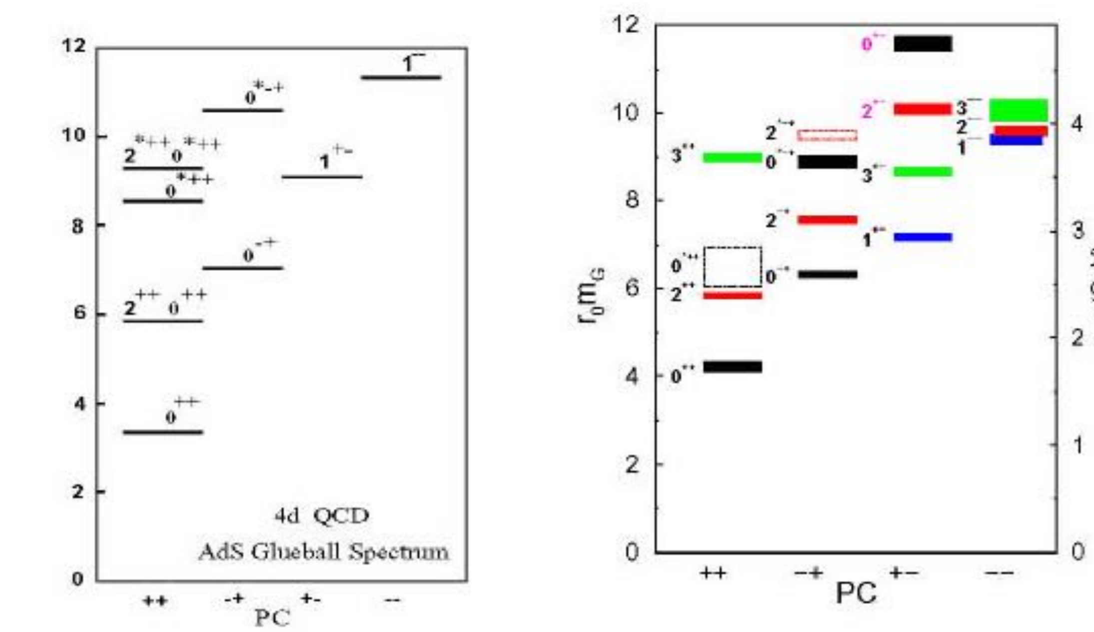
Unified Hard (conformal) and Soft (confining) Pomeron

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



HE scattering after AdS/CFT

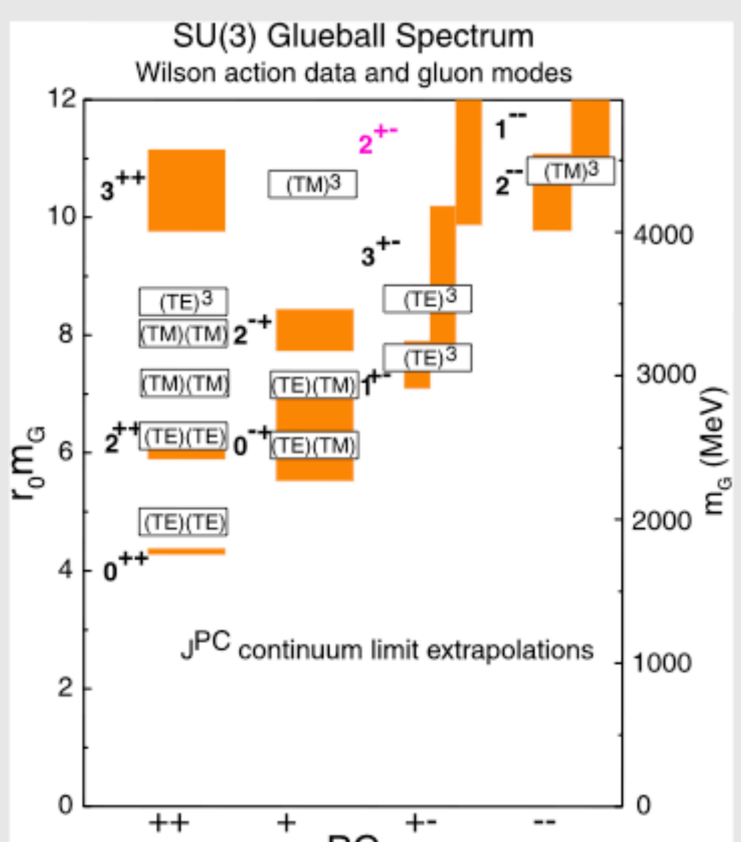
Glueball Spectrum



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.

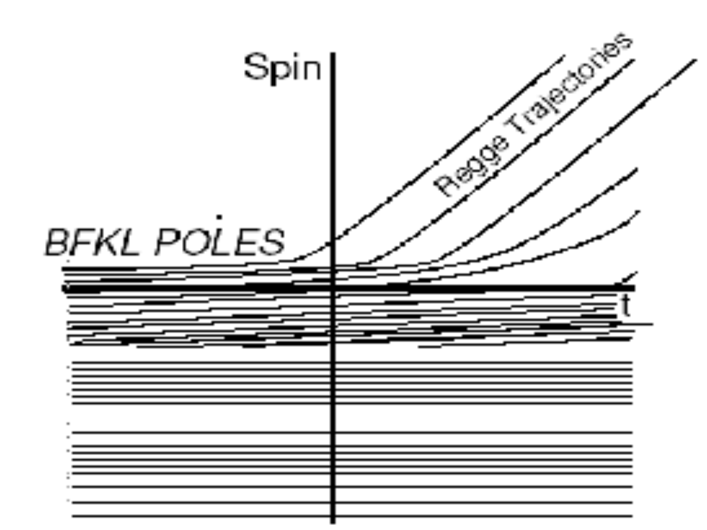
R. Brower, S. Mathur, and C-I Tan, hep-th/0003115, “Glueball Spectrum of QCD from AdS Supergravity Duality”.

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.

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

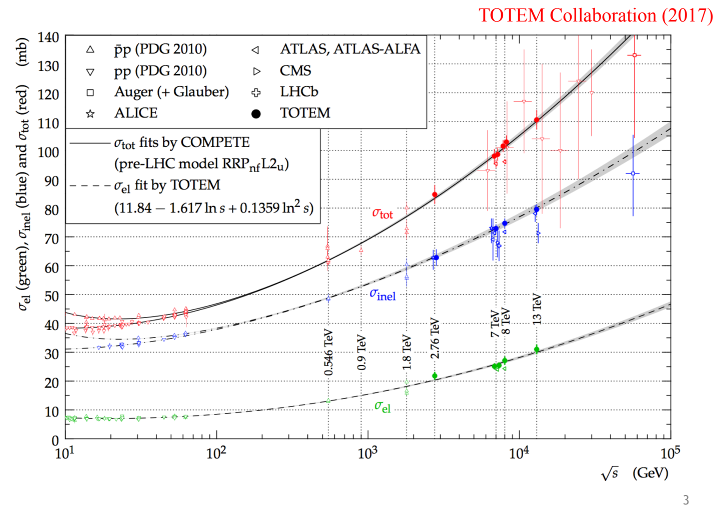
Total Hadronic Cross Sections via the Holographic Pomeron Exchange, Akira Watanabe (Beijing, Inst. High Energy Phys., TPCSF, Beijing, GUCAS), arXiv:1901.09564

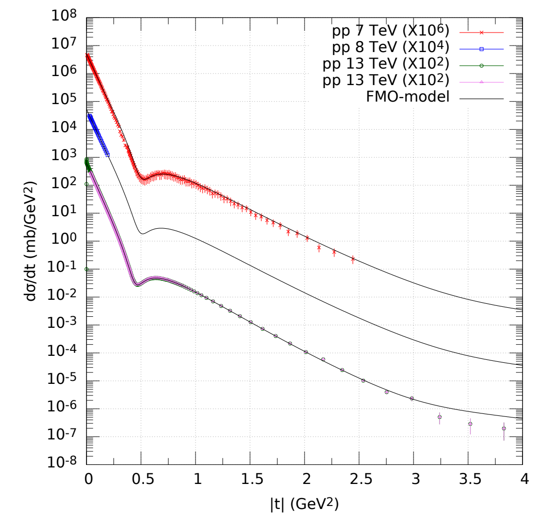
Elastic proton-proton scattering at LHC energies in holographic QCD, Wei Xie (Three Gorges U., Beijing, Inst. High Energy Phys. and TPCSF, Beijing), Akira Watanabe (Beijing, Inst. High Energy Phys. and TPCSF, Beijing, GUCAS), Mei Huang (Beijing, GUCAS), arXiv:1901.09564

- AdS/CFT and Gauge/String Duality:
  - “Anomalous Dimensions”: Pomeron and Odderon Intercepts
  - Confinement, Glueballs, Saturation
  - Odderon at LHC and beyond

Size and Shape of Proton at LHC Era

13TeV data from TOTEM





Interesting new non-perturbative physics in QCD?

Maximal Odderon?

Two concerns: (a) Theoretical, (b) Phenomenological.

Supression of Odderon due to Saturation

J. Finkelstein, H. M. Fried, K.Kang and C-I Tan, "Forward Scattering at Collider Energies and Eikonal Unitarization of Odderon", Phys. Lett. B232 (1989) 257.

V. A. Khoze, A.D.Martin, and M. G. Ryskin, "Elastic and diffractive scattering at the LHC", (arXiv: 1806.05970v2 [hep-ph]).

Noticeable Features

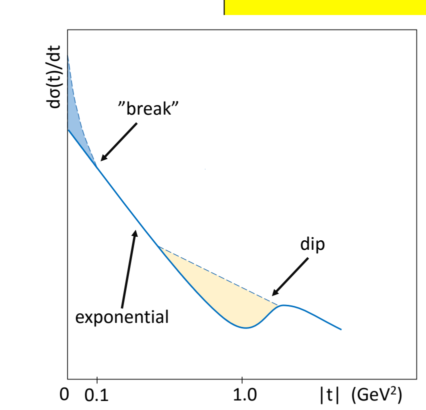
- Diffraction peak/dip persists.
- More noticeable break at very small t.
- Dip moved towards smaller t.

- Comparing with pp and ppbar at Fermi-Lab, indicating the existence of "Odderon"

Maximal Odderon?

Phenomenological Issue:

- 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

U. sukhatme, Chung-I Tan and Tran Thanh Van, "Size and Shape of Hadrons", Z. Phys. C, C, Particles and Fields, **1**, 95 (1979).

A. A. Anselm and V. N. Gribov, "Zero pion mass limit in interactions at very high energies", Phys. Lett. 40B (1972) 487.