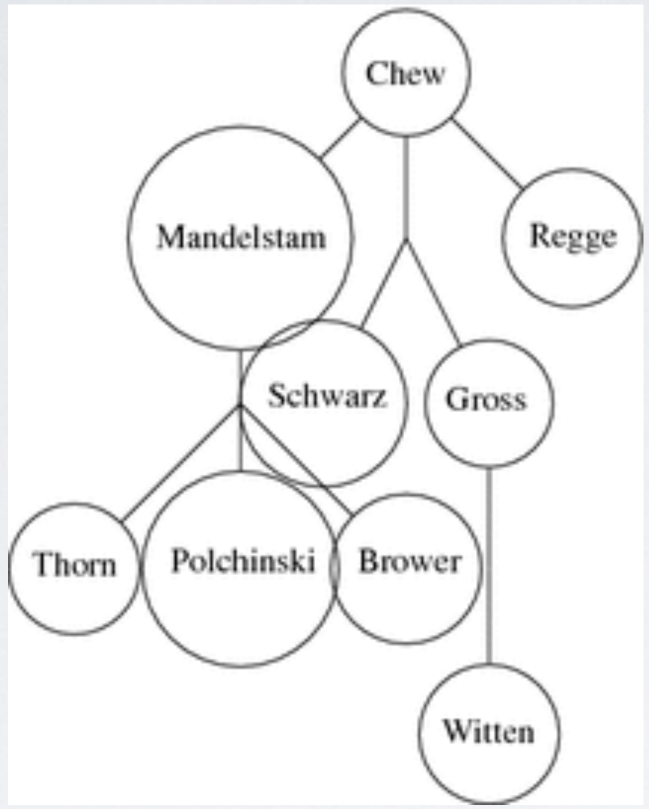
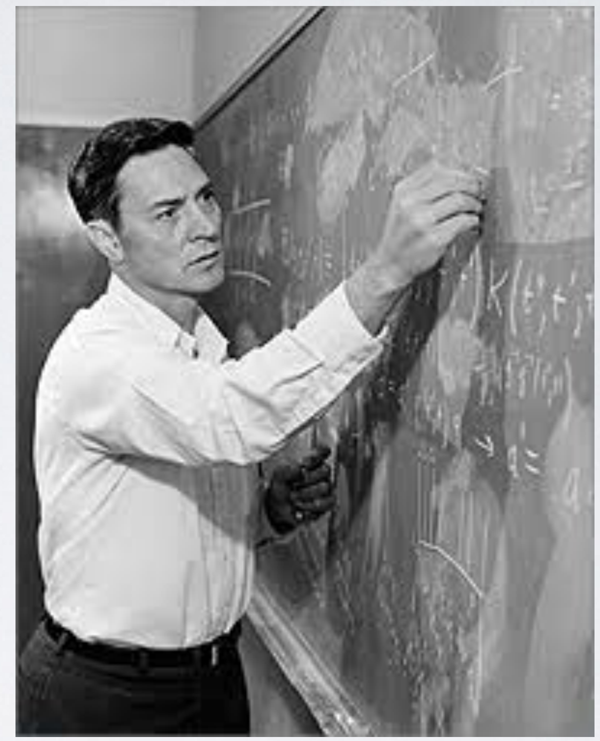
THE NO-GHOST THEOREM
&
BACK TO THE FUTURE

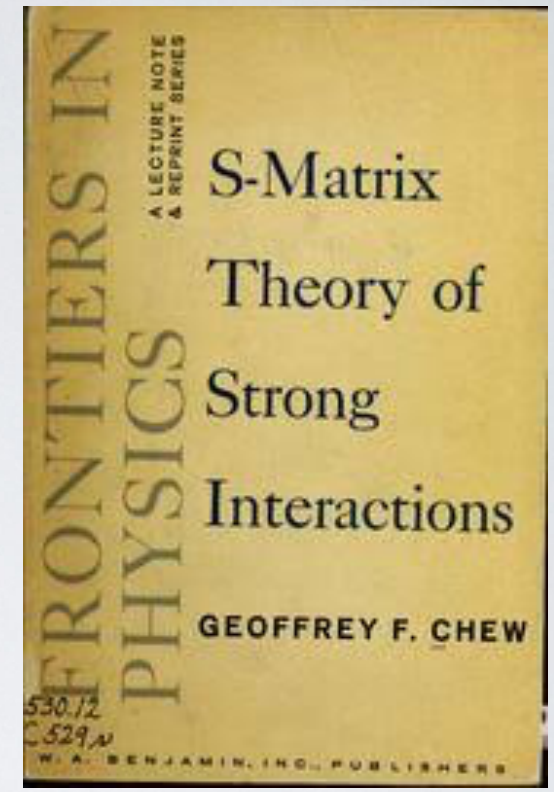
50 Years of the Veneziano Model:
From Dual Models to Strings, M-theory and Beyond

Rich Brower, Boston University:
Galileo Galilei Institute (GGI), May 11, 2018

The 60s Berkeley Bootstrap Scene







REMARKS

1. *Zero Width Bootstrap (aka leading 1/N)*

2. *The No Ghost Theorem**

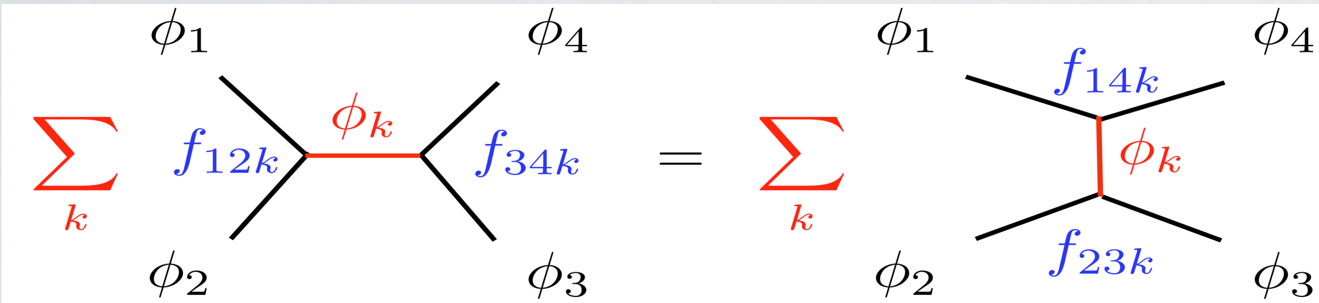
3. *Maldacena's "Counter Revolution"*

   - *Graviton/Pomeron & Wide Angle ?*

   - *Truncating SUSY: Glueballs & NS string?*

(*) See Brower's & Goddard's chapter in ***The Birth of String Theory*** for more details and the crucial collaborations with CharlesThorn

HADRONIC BOOTSTRAP



* **Kinematic Constraints on Infinitely Rising Regge Trajectories**

Brower & Harte: received 13 June 1967 (WRONG!)

Dynamics based on rising Regge trajectories*

Mandelstam: received 5 Sept 1967 (Amazing)

$$\alpha_\rho(t) = \alpha' t + 0.5$$

$$A(s,t) = \sum_{k,l} \frac{g_{kl}^2 P_l(cos\theta)}{s - m_{k.l}^2} \to \beta_0 \Gamma(1-\alpha_\rho(t))(-\alpha' s)^{\alpha_\rho(t)}$$

Construction of a crossing symmetric, Reggeon behaved amplitude for linearly rising trajectories (Wow!)

Veneziano: ricevuto 29 Luglio 1968

$$A(s,t) = \beta_0 \frac{\Gamma(1-\alpha_\rho(t))\Gamma(1-\alpha_\rho(s))}{\Gamma(2-\alpha_\rho(t)-\alpha_\rho(s))}$$

GHOST BUSTING

- The Problem of Ghosts: Minkowski metric $g^{00} = -1$

The on-shell covariant oscillator basis, $[a_n^\mu, a_m^{\dagger\nu}] = g^{\mu\nu}\delta_{n,m}$

$$|\{N_{i,\mu}\}, p\rangle = [(a_1^{\mu_1\dagger})^{N_{1,\mu}}(a_2^{\mu_2\dagger})^{N_{2,\mu}}\cdots]|0,p\rangle\ ,$$

$$[L_n, L_m] = (n-m)L_{n+m} + \frac{D-2}{12}n(n^2-1)\delta_{n,-m}\ ,$$

Virasoro

Joe Weis

$$(L_0 - 1)|\mathrm{Phys}\rangle = L_n|\mathrm{Phys}\rangle = 0 \quad \text{for} \quad n > 0\ ,$$

$$|\mathrm{Spurious}\rangle = [(L_1^\dagger)^{n_1}(L_2^\dagger)^{n_2}(L_3^\dagger)^{n_3}\cdots]|\mathrm{Phys}\rangle$$

Brower/Thorn “Verma Module”?

PHYSICAL STATE ALGEBRA

How do we find the Physical subspace?

$$\vec{A}_n = \frac{1}{2\pi i}\oint \frac{dz}{z}\vec{P}\, e^{inX_-} \equiv \langle \vec{P}\, e^{inX_-}\rangle$$

(DDF) Del Giudice, Di Vecchia and Fubini

These beautiful Physical operators $[A^i_m, A^j_n] = m\delta^{ij}\delta_{m.-n} \quad , \quad [L_m, \vec{A}_n] = 0$

$$|\text{Phys}, \{n_i\}, p\rangle = [(\vec{A}^\dagger_1)^{n_1}(\vec{A}^\dagger_2)^{n_2}\cdots]|0,p\rangle \ .$$

D-2 Transverse tensor products

Problem: DDF gives a D-2 dim physical space but Virasoro kills 1-dim space

For D > 26 there are Ghost states!

At D =26 like the "photon" with D-2 transverse "polarizations" and 2 null states.

Very elegant solution of Goldstone, Goddard, Rebbi and Thorn (GGRT)
using light-cone gauge quantization. Restoring LI only for 24 transverse modes

† $P^\mu(z) = z\partial_z X^\mu(z)$

SEARCH FOR LONGITUDINAL

Need Physical Longitudinal modes:

$$A_n^{(-)} = \langle \, P_- e^{inX_-} \, \rangle = 0 \qquad \text{and} \qquad A_n^{(+)} = \langle \, : P_+ e^{inX_-} \, : \rangle + \frac{n^2}{2} \langle P_- log(P_-) e^{inX_-} \rangle$$

$$[A_m^{(+)}, A_n^{(+)}] = (m-n) A_{m+n}^{(+)} + m^3 \delta_{m,-n} \qquad , \qquad [L_m, A_n^{(+)}] = 0$$

$$[A_m^{(+)}, A_n^i] = -n A_{m+n}^i$$

Off-Shell Derivation $\quad k^\mu = n\hat{e}_+^\mu + (k^2/2n)\hat{e}_-^\mu \quad \text{and} \quad e^\mu(k) = n\hat{e}_+^\mu - (k^2/2n)\hat{e}_-^\mu$

Expand $\langle : (\epsilon P)^{1-k^2/2} \, e^{ikX} \, : \rangle$ as $k^2 \to 0$

$$\Longrightarrow \; n \langle P_- e^{inX_-} \rangle + k^2 \langle : [-P_+/2n - (n/2) P_- ln(P_-) + n P_- i X_+ /2n] e^{inX_-} \, : \rangle$$

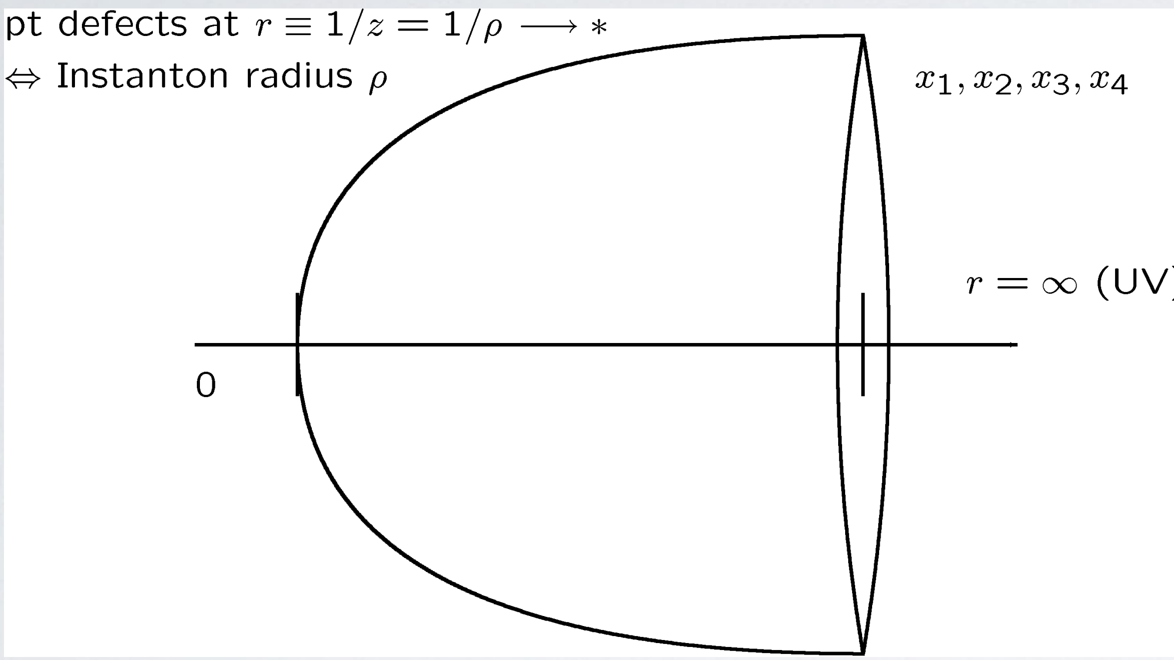
$$\Longrightarrow \; -(k^2/n)[\langle : P_+ e^{inX_-} \, : \rangle + \frac{n^2}{2} \langle P_- ln(P_-) e^{inX_-} \rangle]$$

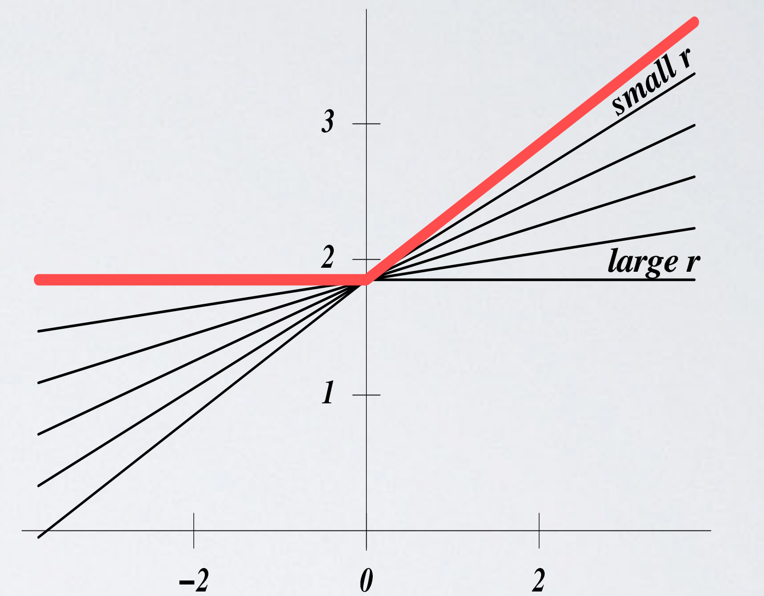
after integration by parts

ADS GRAVITON/POMERON

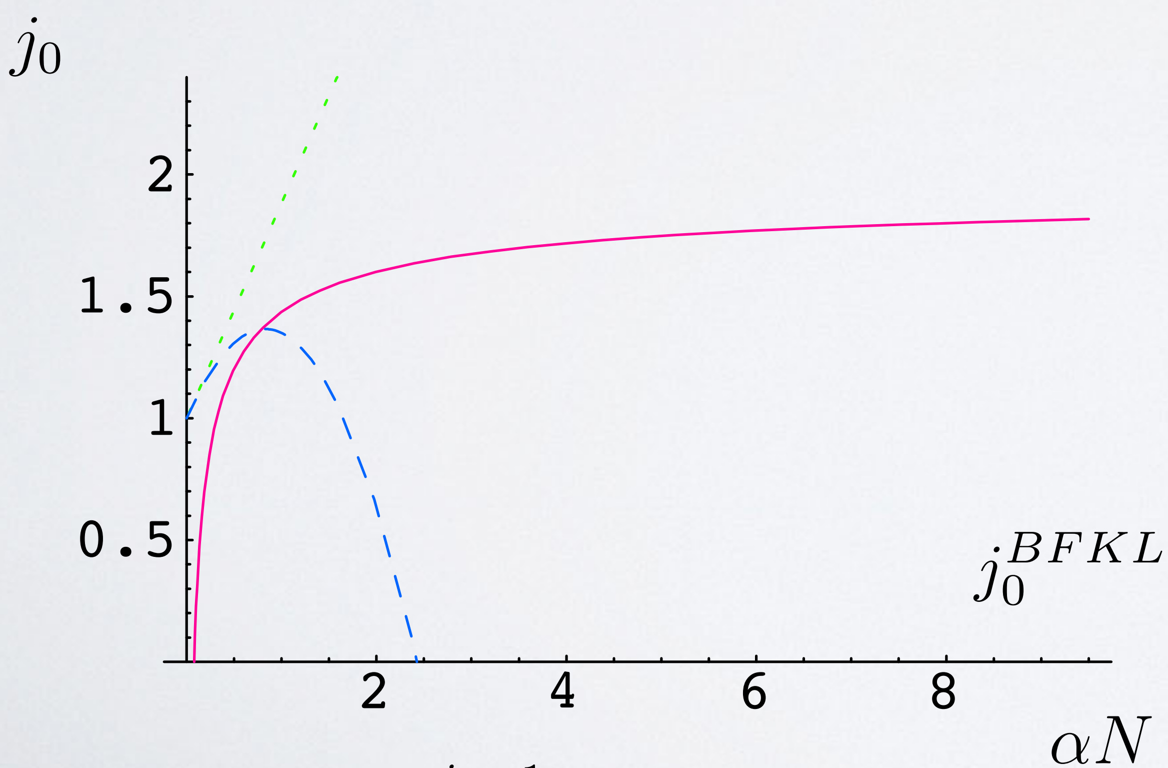
$\alpha'_{eff}(r) = \alpha' R^2/r^2$

Wide angle has naive $_j$conformal scaling





ultra Local Approximation



$$j_0^{AdS} = 2 - 2/\sqrt{\lambda} + O(1/\lambda)$$

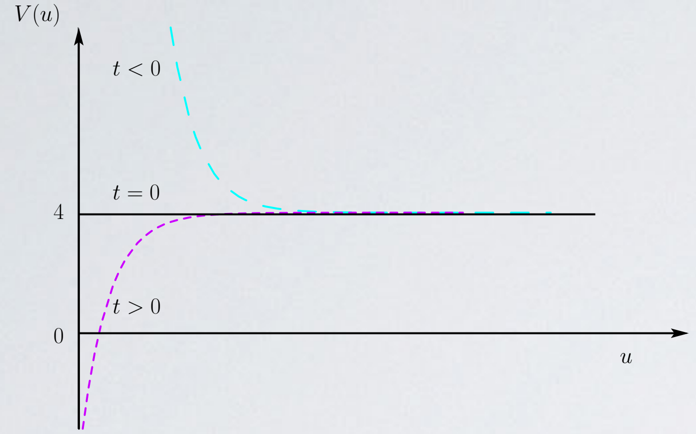
$$j_0^{BFKL} = 1 + 4\ln 2\ \frac{\lambda}{\pi^2}\left(1 - 7.58\ \frac{\lambda}{16\pi^2}\right)$$

$\sigma_{Tot} \sim s^{j_0 - 1}$

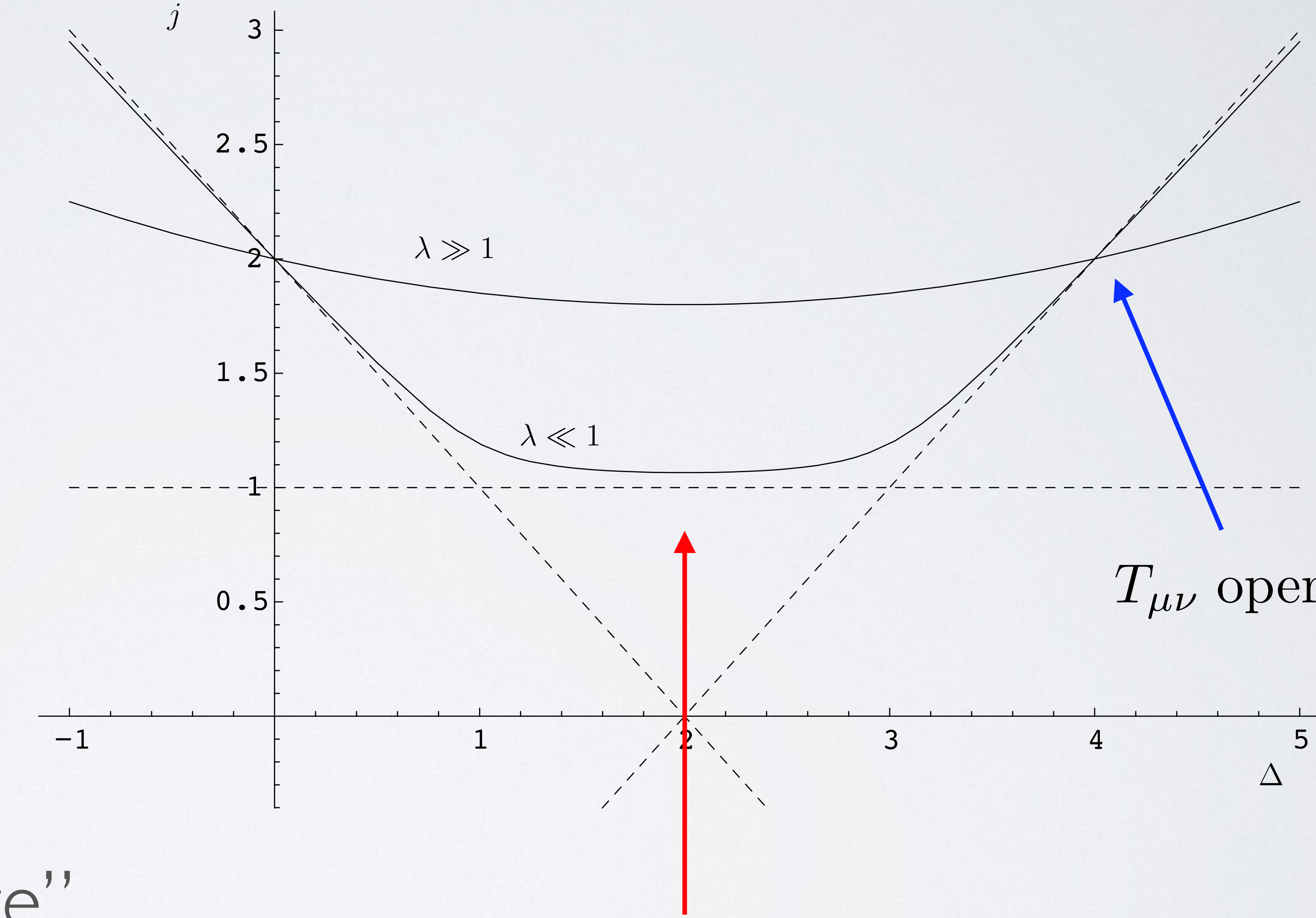
$\lambda = g_{YM}^2 N$

ADS POMERON VERTEX*

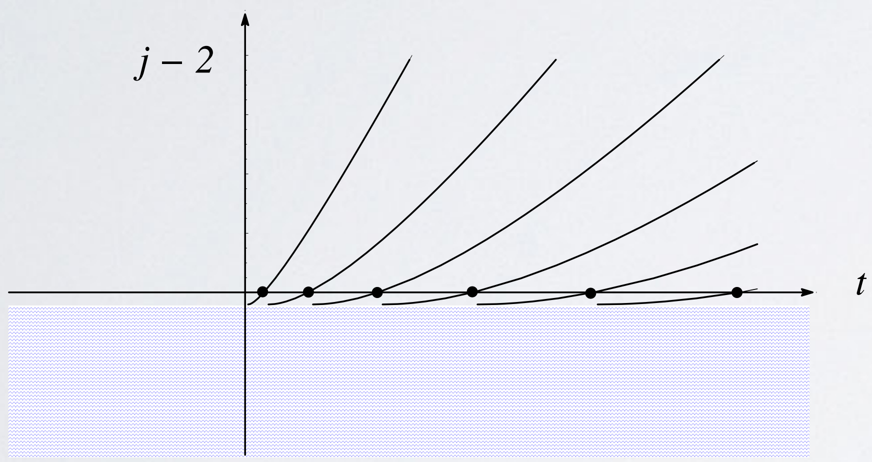
$$V^{Pomeron} = [\epsilon^\mu(k)\epsilon^\nu(k)\ P_\mu \overline{P}_\nu]^{1-k^2/4}\ :e^{ik^\mu(X_\mu+\overline{X}_\mu)}:$$



Δ plane meromorphy



$T_{\mu\nu}$ operator



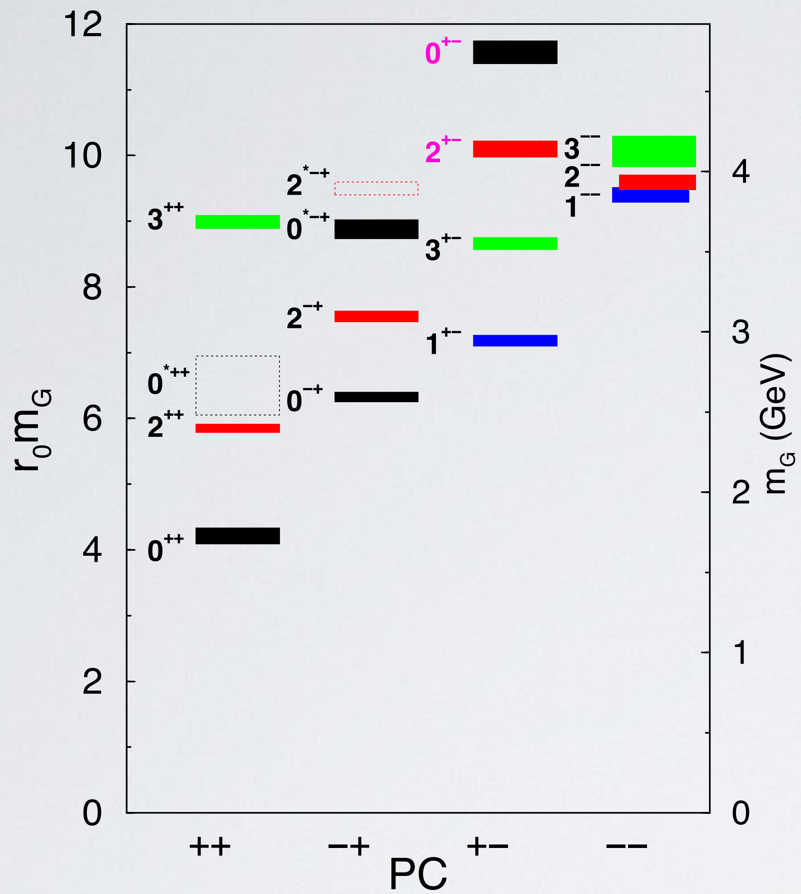
AdS/CFT "Regge"

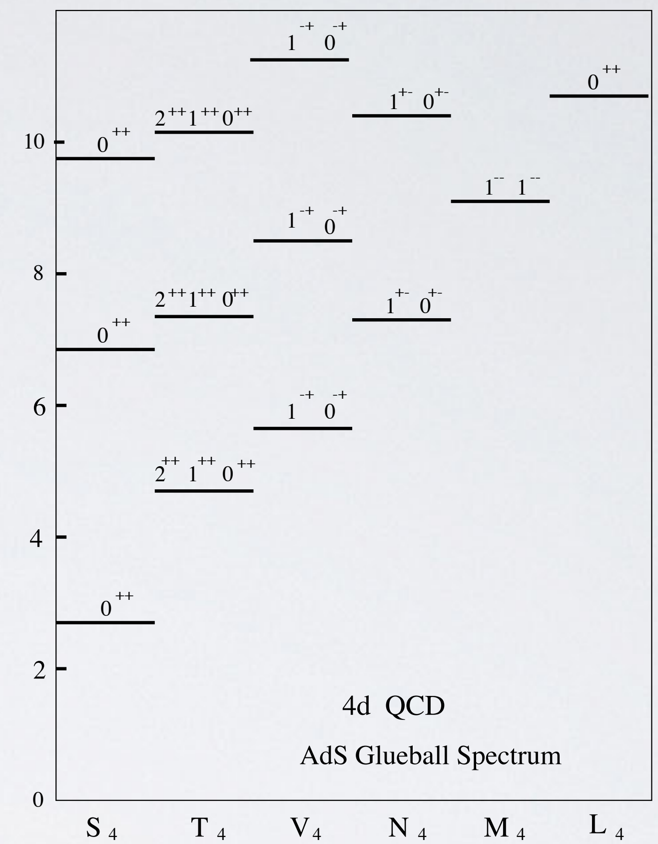
pole Δ- plan but a cut in the **J**-plane

$j_0 = Min[\Delta(\lambda)]$

*The Pomeron and Gauge/String Duality, Brower, Polchinski, Strassler, Tan received 2006

VESTIGIAL SUSY ? : I GLUEBALLS





States from 11-d G_{MN}				States from 11-d A_{MNL}		
$G_{\mu\nu}$	$G_{\mu,11}$	$G_{11,11}$	m_0 (Eq.)	$A_{\mu\nu,11}$	$A_{\mu\nu\rho}$	m_0 (Eq.)
G_{ij} 2^{++}	C_i $1^{++}_{(-)}$	ϕ 0^{++}	4.7007 (T_4)	B_{ij} 1^{+-}	C_{123} $0^{+-}_{(-)}$	7.3059 (N_4)
$G_{i\tau}$ $1^{-+}_{(-)}$	C_τ 0^{-+}		5.6555 (V_4)	$B_{i\tau}$ $1^{--}_{(-)}$	$C_{ij\tau}$ 1^{--}	9.1129 (M_4)
$G_{\tau\tau}$ 0^{++}			2.7034 (S_4)	G^α_α State 0^{++}		10.7239 (L_4)

Table 1: IIA Classification for QCD_4. Subscripts to J^{PC} designate $P_\tau = -1$.

Ramond-Ramond 2-form $C_{\mu\nu}$, NS NS 2-form field $B_{\mu\nu}$.

Glueball Spectrum for QCD for AdS Supergravity Dual,

IS NEVEU-SCHWARZ SUPER STRING
A N EFFECTIVE STRING THEORY (EST*) FOR QCD?

Factorizable Dual Model Of Pions,

Neveu and J. H. Schwarz, Nucl. Phys. B 31, 86 (1971)

Phenomenological six-pion amplitude,

R. Brower and G. Chu,,Phys. Rev. D 7, 56 (1973). Phys. Rev. D 7, 56 (1973).

For $p_i^\mu \to 0$ has soft pion Adler zeros

$$A_{\pi^+\pi^-\to\pi^+\pi^-}(s,t) = g_0^2 \frac{\Gamma[1-\alpha_\rho((t)]\Gamma[1-\alpha_\rho(s)]}{\Gamma[1-\alpha_\rho((t)-\alpha_\rho((s)]}$$

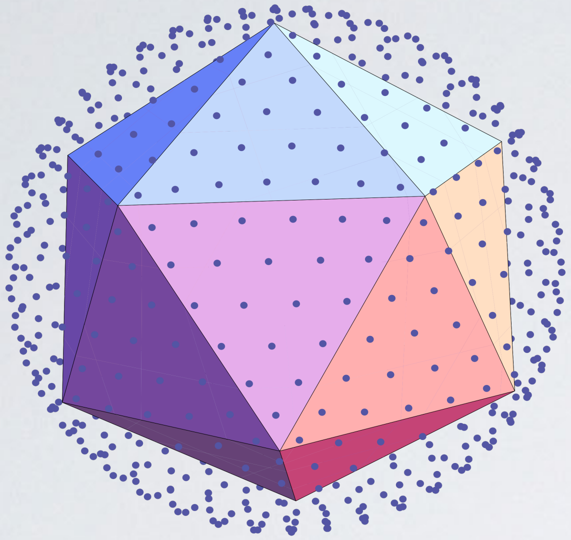
$$\sim g_0^2(s+t) \sim 0$$

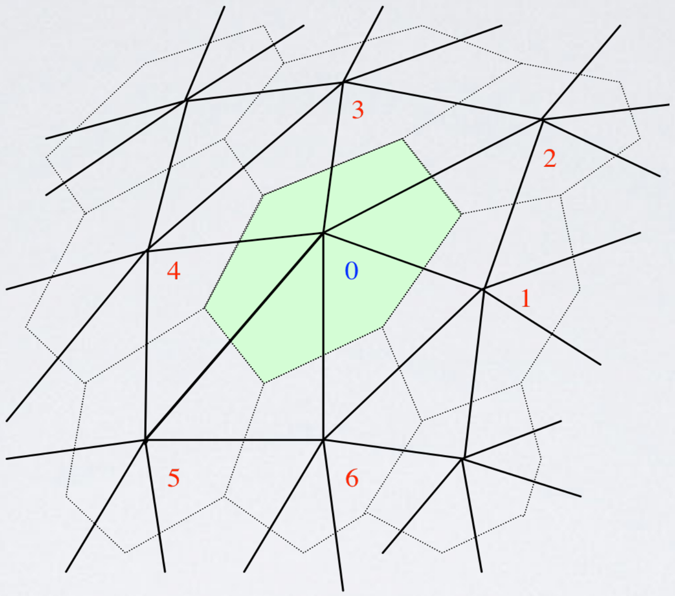
*

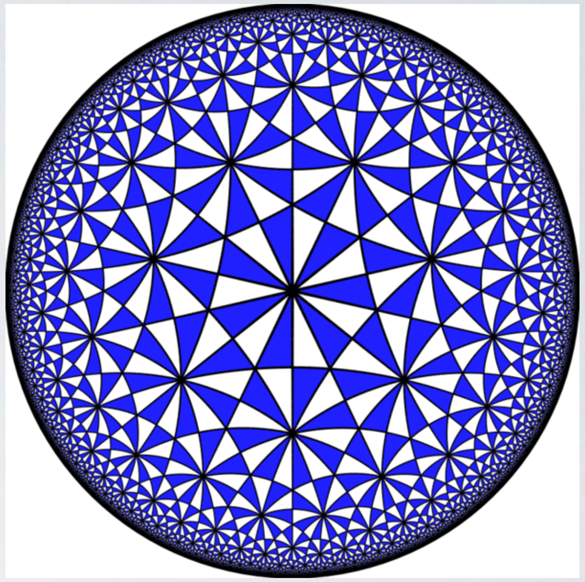
TABLE I. Meson spectrum. The experimental masses and widths are in square brackets, and are taken from the Review of Particle Properties.$^{\rm a}$

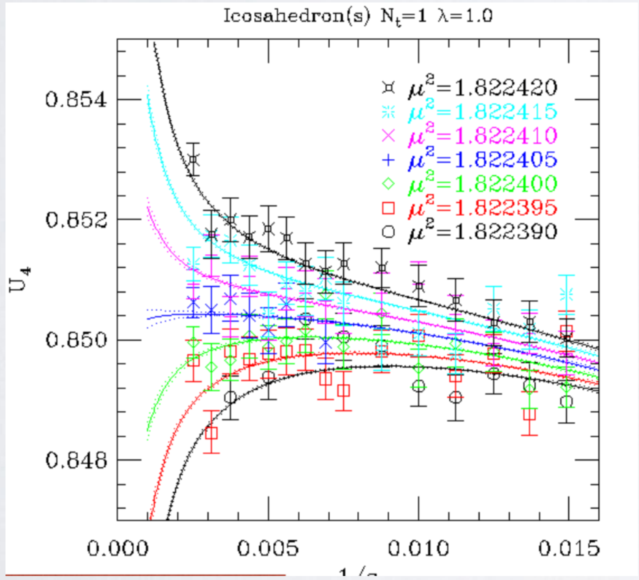
Name	$I^G(J^P)$	Mass M (MeV)	Partial width Γ (MeV)	Mode
π	$1^-(0^-)$	$137^{\rm b}$[137]		
σ	$0^+(0^+)$	760 [~800]	756[>>100]	2π
ρ	$1^+(1^-)$	760 [765]	$145^{\rm b}$[145]	2π
ω	$0^-(1^-)$	$784^{\rm b}$[784]	6[9]	3π
π'	$1^-(0^-)$	1060[NE]$^{\rm c}$	1100[NE]	3π
H	$0^-(1^+)$	1060[990]	180[?]	3π
A_1	$1^-(1^+)$	1060[1070]	154	$\rho\pi$
			2	$\sigma\pi$
			165[100–200]	$3\pi$$^{\rm d}$
σ'	$0^+(0^+)$	$1300^{\rm e}$	$-17^{\rm e}$	2π
ρ'	$1^+(1^-)$	1300[NE]	145[NE]	2π
f	$0^+(2^+)$	1300[1269]	124[125]	2π
			[12]$^{\rm f}$	4π
A_2	$1^+(2^+)$	1315[1310]	7.5[75]	$\rho\pi$
π_A	$1^-(2^-)$	1500[1640]	[108]$^{\rm f}$	3π
g	$1^+(3^-)$	1670[1680]	48[64]	2π
			[80]$^{\rm f}$	4π

QUESTIONS?




3
2
4
0
1
5
6




Icosahedron(s) N_t=1 λ=1.0
μ^2=1.822420
μ^2=1.822415
μ^2=1.822410
μ^2=1.822405
μ^2=1.822400
μ^2=1.822395
μ^2=1.822390
U_4
0.854
0.852
0.850
0.848
0.000
0.005
0.010
0.015