Maiani-70

Symposium in Honor of Luciano Maiani on the Occasion of his 70th Birthday

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Dipartimento di Fisica, Universita' degli Studi "Sapienza"

Chiral Symmetry in QCD and super-QCD and its implications

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PART I. History

1974, infancy of QCD, doubts in everything, everything is NEW ✎ ✎ ✎ Epic, legendary times ☺

First Application was deep inelastic scattering;
Neither theory nor data were good enough!

Second QCD application: ΔI = 1/2 Rule:

$$\frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K^+ \to \pi^+\pi^0)} = 450$$

Expected ~ 9/4

Guido Altarelli, L. Maiani, Octet Enhancement of Nonleptonic Weak Interactions in Asymptotically Free Gauge Theories, Phys.Lett. B52 (1974) 351-354;

M.K. Gaillard, Benjamin W. Lee , Δ I = 1/2 Rule for Nonleptonic Decays in Asymptotically Free Field Theories, Phys.Rev.Lett. 33 (1974) 108.

$$\mathcal{O}_1 = \bar{s}_L\gamma_\mu d_L\,\bar{u}_L\gamma^\mu u_L - \bar{s}_L\gamma_\mu u_L\,\bar{u}_L\gamma^\mu d_L, \qquad (\mathbf{8_f},\ \Delta I = 1/2)$$

$$\mathcal{O}_+ = \bar{s}_L\gamma_\mu d_L\,\bar{u}_L\gamma^\mu u_L + \bar{s}_L\gamma_\mu u_L\,\bar{u}_L\gamma^\mu d_L$$

includes $\Delta I = 3/2$

J. Schwinger, 1964 → 9/4

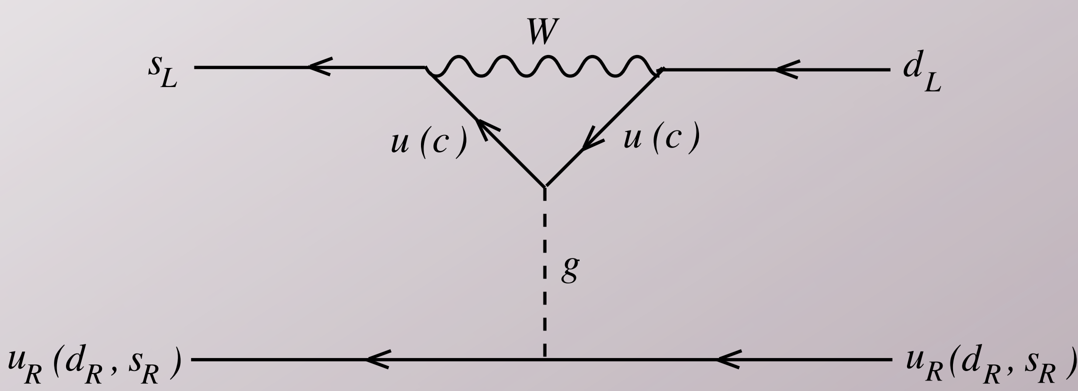
K. Wilson, 1969, → $(M_W)^\kappa$ enhancement/suppression

AMGL, 1974 → $\ln(M_W/\Lambda)$ enhancement/suppression

AMGL: Good news - ✌ ✌ ✌ Inspirational, O_1 enhanced O_+ suppressed;

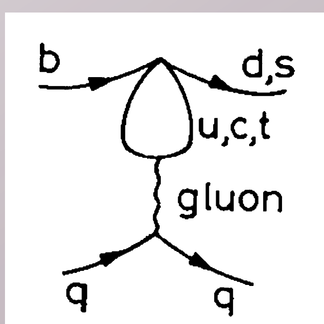
Bad news: 9/4 ~ 10 rather than 450 ☹ ☹ ☹

SVZ, penguins, 1974 (Heavy Quarks Enter the Game)



GIM cancellation: believed $(m_c^2 - m_u^2)/\Lambda^2$

actual $\ln\,(m_c^2/\Lambda^2)$ ✈ ✈ ✈



← J. Ellis et al.

$\bar{s}_L \gamma_\mu t^a d_L$ D_μ $G^{\mu\nu a}$ →

$$\mathcal{O}_5 = \bar{s}_L \gamma_\mu t^a d_L \left(\bar{u}_R \gamma^\mu t^a u_R + \bar{d}_R \gamma^\mu t^a d_R + \bar{s}_R \gamma^\mu t^a s_R \right), \quad (\mathbf{8}, \ \Delta I = 1/2).$$

One of two penguins, coefficient is rather small,

BUT

LR chiral structure. Chiral enhancement:

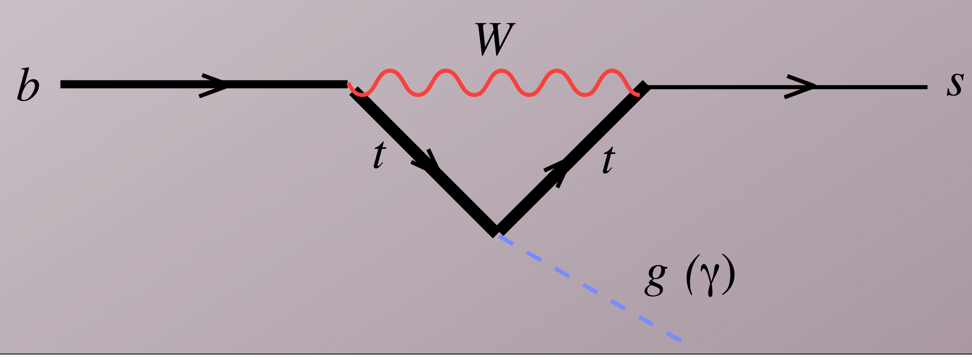
$$\frac{m_\pi^2}{m_u + m_d} \sim 2\,\mathrm{GeV}$$ versus Λ~ 200 MeV; factor of 10 in ampl.

Leutwyler, Gell-Mann, Weinberg: $m_{u,d}$ quark mass terms very small

- ☞ Coleman-Witten, 1980: 'Proof' of χSB in large-N QCD
- ☞ Leutwyler and many others: Development of χPT ☞
- ☞ Matrix elements in lattice QCD (Martinelli and others)

Qualitatively and semi-quantitatively we are on the safe ground and in chartered waters, together with penguins. High precision theoretical predictions are still elusive because of the large-distance dynamics.

Penguins are much better off in heavier quark decays, bs→γ



PART II. Present

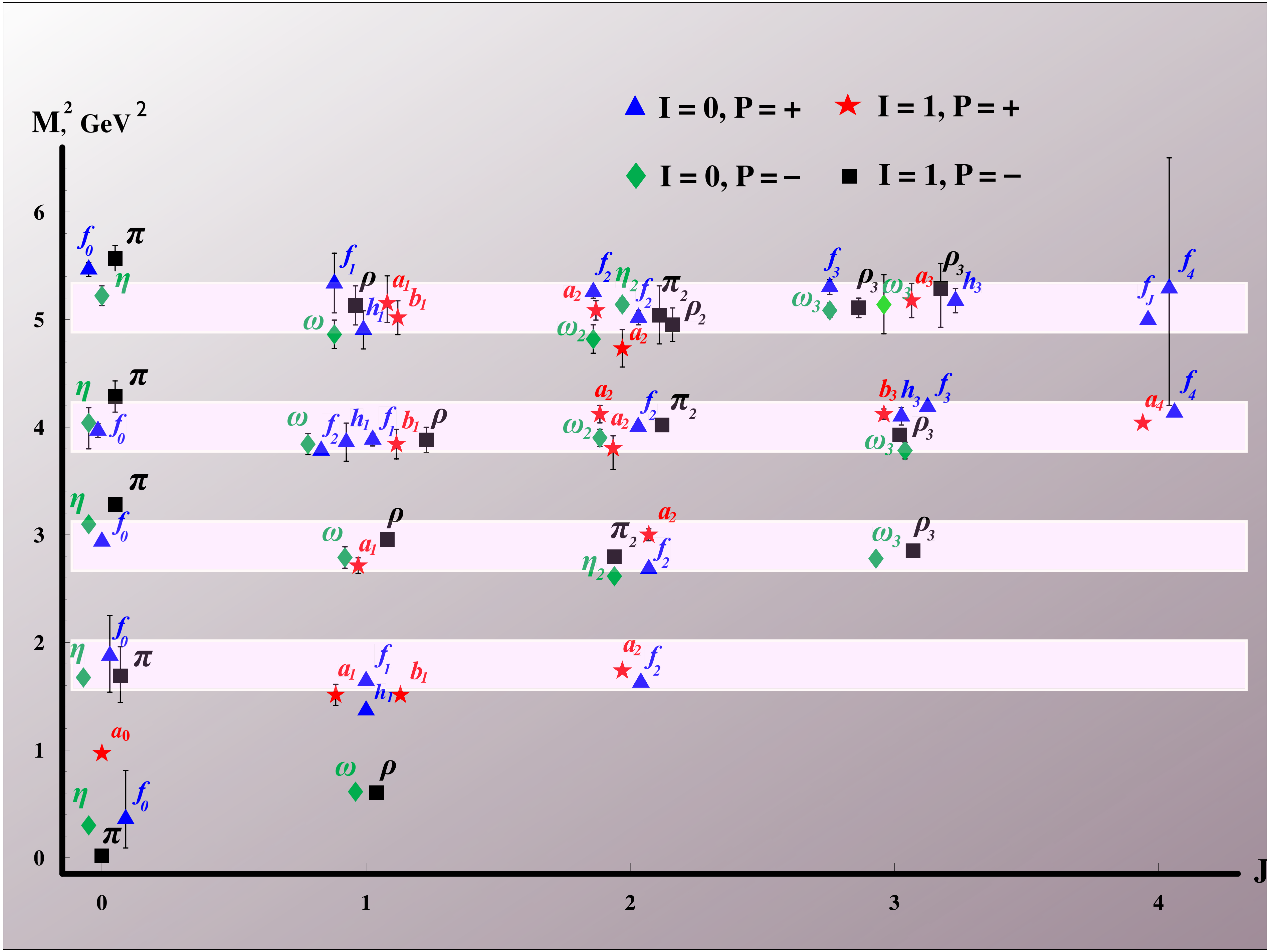
Chiral symmetry restoration versus nonrestoration in highly excited states

Outline

"Theory of QCD strings is hard to develop! For long strings (high excitations) it should be much easier."

Divine revelation/Common wisdom

- ✶ Nonlinear versus linear realization
- ✶ Regge phenomenology
- ✶ Quasiclassical long string
- ✶ AdS/CFT and related approaches
- ✶ ✶ ✶ Conclusions



M², GeV²
I = 0, P = +
I = 1, P = +
I = 0, P = −
I = 1, P = −
J
0
1
2
3
4
5
6

Chiral Symmetry→Goldstone vs. Linear:

$SU(N_f)_L \times SU(N_f)_R \rightarrow SU(N_f)_V$

If $|\pm\rangle$ are opposite parity states, the axial current a^μ

$$\langle +|a^\mu|-\rangle = g(q^2)(p_+ + p_-)_\nu \left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)$$

$$= g(q^2)\left[(p_+ + p_-)_\mu - q_\mu \frac{M_+^2 - M_-^2}{q^2}\right]$$

- Linear realization:

$$M_+^2 = M_-^2 \qquad g_A = g(0) = 1$$

- Nonlinear realization:

$$g_{\pi+-} = f_\pi^{-1} g_A (M_+^2 - M_-^2)$$

← generalized Goldberger-Treiman relation

- No constraints on g_A, the axial charge vanishes!

Glozman et al conjectured: At high energies the chiral condensate becomes less important. Pions decouple → Asymptotically linear realization,

$$g_A \to 1, \quad \Delta M \equiv M_+ - M_- \to 0$$

inside the given representation
while $g_A \to 0$ for "outside" transitions

How fast?

✶ If the distance $\Delta M^2_{chiral} \ll \Delta M^2_{radial} \sim n^0$

A natural scaling law would be:

$$\Delta M^2_{chiral} \sim M^{-2} \sim (n^{-1}, J^{-1})$$

We will argue (from linearity of Regge trajectories, quasiclassical picture, etc.):

For highly excited states

$$M_+^2 - M_-^2 = \Delta J_0/\alpha' \sim \Lambda^2$$

a_1 ρ

and $g_A \sim n^{-1/2}$ for all axial transition amplitudes.

The Nambu-Goldstone mode persists!

Two-dimensional 't Hooft model presents a (primitive) example of this type: no asymptotic restoration.

Regge Phenomenology

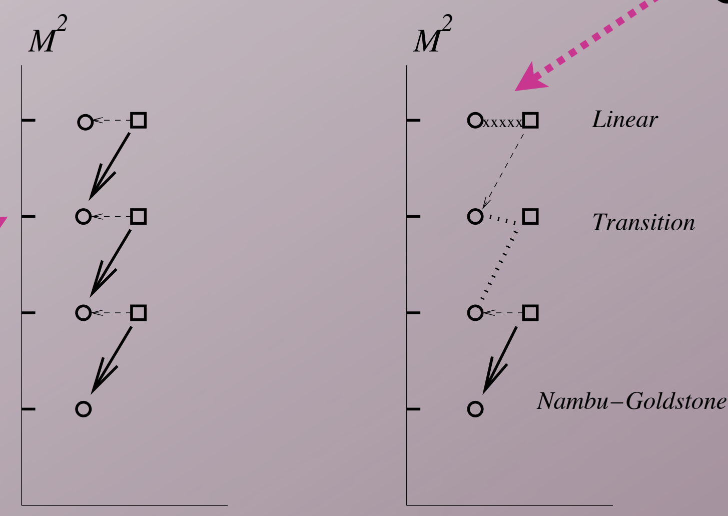
- Linear equidistant quark-meson trajectories (except M^2, J=0, 0);
- No parity degeneracy on the leading trajectory

If the trajectories do not start converging "later" → asymptotic linear realization is not restored ...

$g_A \approx 1$

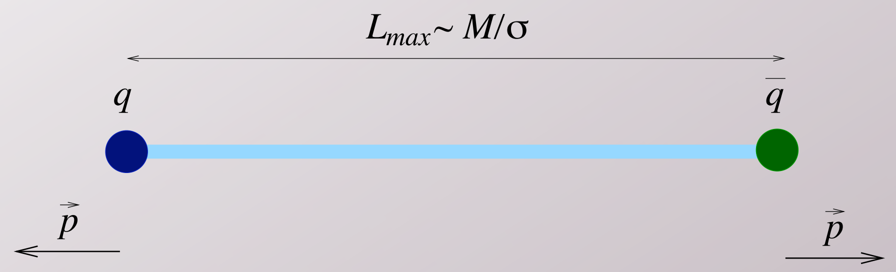
Contrived scenario (not realized in the quasiclassical picture) →

All g_A's different, ≠ 1



a) Nambu–Goldstone mode b)

Quasiclassical (long) string



The mass M_n

$$M_n = 2p + \sigma r$$

Quantization

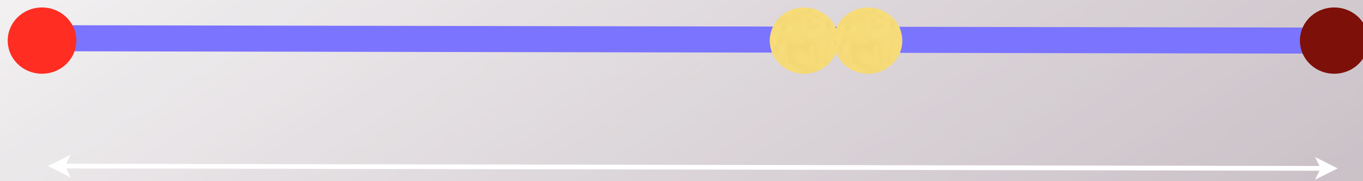
$$\int_0^{\ell_*} p(r)\,dr = \pi n \qquad p(r) = (M_n - \sigma r)/2 \qquad \ell_* = \frac{M_n}{\sigma}$$

gives

$$M_n^2 = 4\pi\sigma n \sim \Lambda^2\, n$$

When $L \neq 0$

$$n \to n_r + L$$



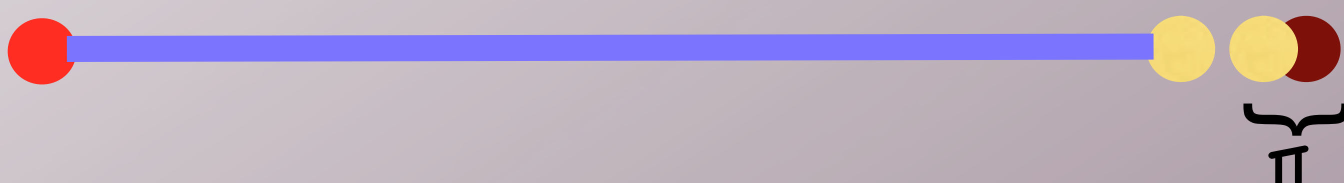
$L \sim M$

$\Gamma_{tot} \sim (1/N)\, M \sim (1/N)\, \Lambda\, n^{1/2}$ (CNN, 1979)

(PSZ '05)

The # of channels ~ n; each has $\Gamma \sim (1/N)\, \Lambda\, n^{-1/2}$

$A \rightarrow V\pi$ amplitude $\sim (\varepsilon_i \varepsilon_f) |\vec{p}_\pi| / N^{1/2} \sim (\varepsilon_i \varepsilon_f)\, \Delta M^2 g_A / f_\pi$



At maximum $g_A \sim \Lambda / M \sim n^{-1/2}$

A part of the spectral degeneracy comes from spin independence.
(Chromo)magntic charges are screened in the vacuum!

An upper bound on spin-spin

$\sim \Lambda^{-2} L^{-3} \sim \Lambda\, n^{-3/2}$; $\Delta M^2 \sim 1/n$

✷ String degeneracy:

$$M = F(L+n_r)[1+O(1/n,\ 1/L)]$$

↑

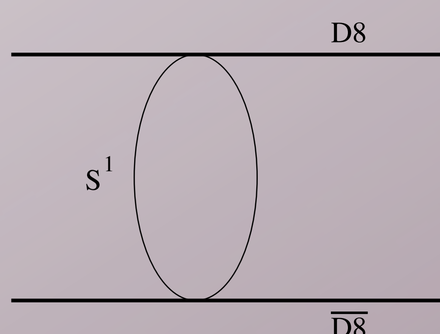
$(L+n_r)^{1/2}$

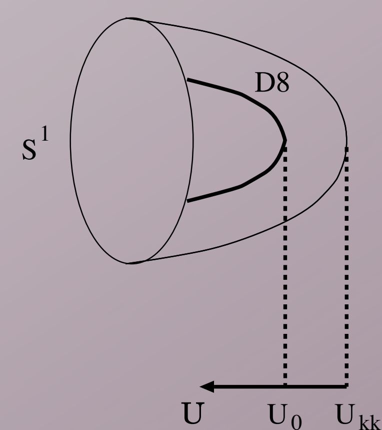
$\Delta M^2 \sim 1/n$

AdS/CFT & AdS/QCD

(a) Sakai & Sugimoto (top-down)
(b) Karch, Katz, Son & Stephanov (bottom-up)
(c) Casero, Kiritsis, Paredes (mixed)

Holographic description of hadrons with the fifth coordinate z is used.
SS placed N_f test D8 - D8 brane pairs in the background of N_c D4 branes compactified on SUSY breaking S_1.





$$S^{\mathrm{SS}} = \kappa \int d^4x\, dz\, \mathrm{Tr}\left[K^{-1/3}\,\frac{1}{2}\,F_{\mu\nu}^2 + K\,F_{\mu z}^2\right]$$

$$K = 1 + z^2\,, \qquad \kappa = \frac{\lambda\,N_c}{108\pi^3}\,.$$

The massless pion is built in and does not decouple from high excitations.

Nambu-Goldstone mode

$$S^{\rm KKSS} = \int d^4x dz \, e^{\Phi(z)} \sqrt{g} \left[-|DX|^2 + 3|X|^2 - \frac{1}{4g_5^2}(F_L^2 + F_R^2) \right]$$

$$\Phi = z^2 \qquad\qquad g_5^2 = 12\pi^2/N_c$$

QM eigenvalues of the hologhaphic coordinate z give M^2 in 4D. Characteristic $z \sim n^{1/2}$.

"ρ-a_1" splittings in KKSS are due to the X field (containing pion and its scalar partner).

KKSS: X→ const. ⇨M^2_+-M^2_- ~1/n BUT trajectories NONlinear

CKP: X→ z, ⇨M^2_+-M^2_- ~const.
Trajectories are linear & equidistant
BUT⇨Nambu-Goldstone mode

Conclusions

✷ Linearity of the Regge trajectories & quasiclassical picture of long strings imply persistence of the Nambu-Goldstone mode of the chiral symmetry realization for high excitations.

Happy Birthday, Luchano! Many happy returns of the day!