Title: Physics of a 750 MeV Boson

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Abstract: <p>I will review recent progress in understanding the dynamics of confining strings in pure Yang-Mills theory.</p>

Physics of a 750 MeV Boson

Sergei Dubovsky
CCPP (NYU) & Perimeter Institute

w Victor Gorbenko, 1511.01908
w Raphael Flauger, Victor Gorbenko, 1203.1054, 1205.6805, 1301.2325, 1404.0037
w Victor Gorbenko, Mehrdad Mirbabayi 1305.6939
w Patrick Cooper, Victor Gorbenko, Ali Mohsen, Stefano Storace 1411.0703

and work in progress w Guzman Hernandez-Chifflet

The major underlying question:

What is $SU(\infty)$ Yang-Mills?

Old and famously hard. The main goal of this talk is to convince you it is an interesting one and worthwhile to revisit now.

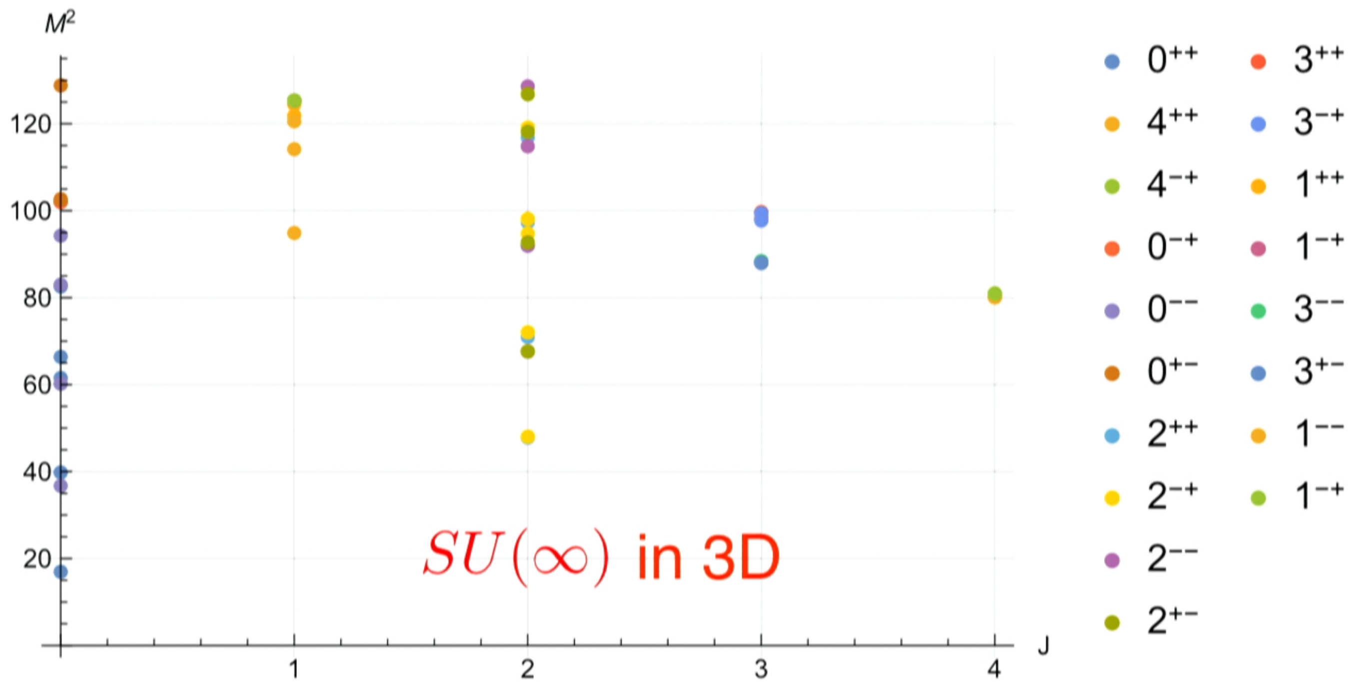
Somewhat restricted and ambitious definition of an interesting question:

1) One cares about the answer

2) Sufficiently sharply posed, so that the answer exists

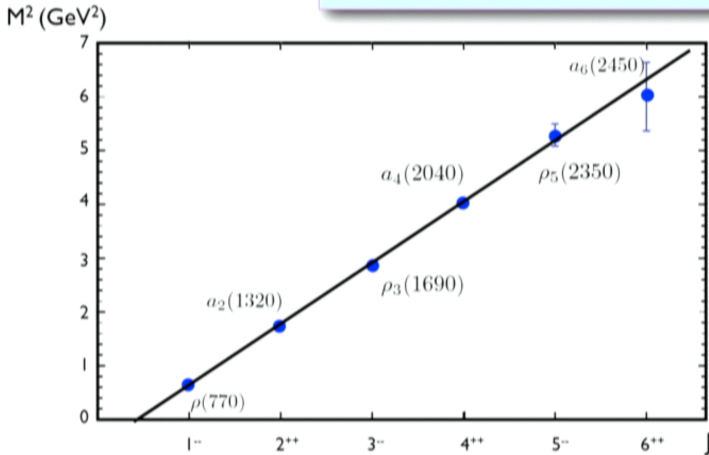
3) There is a path to find the answer, or at least to make progress

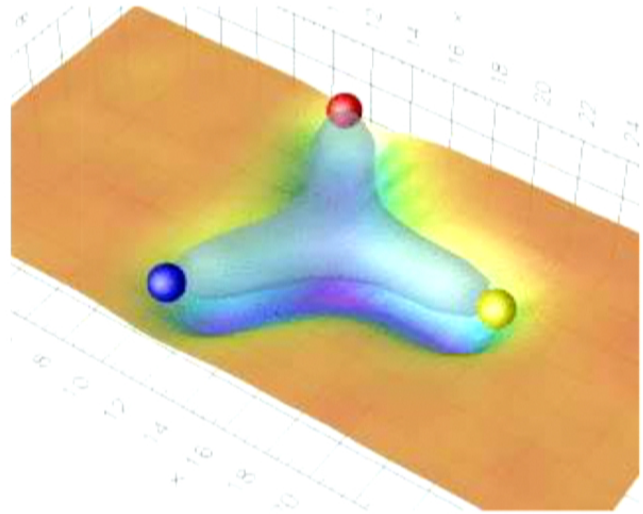
One sharp version of the question:
Calculate these masses and quantum numbers



Athenodorou, Teper 1609.03873

QCD is a theory of strings





Bissey et al, hep-lat/0606016

Large N QCD is a theory of free strings

Can we solve this free string theory?

Let's divide the question into two parts:

1)What is the worldsheet theory of an infinitely long string?

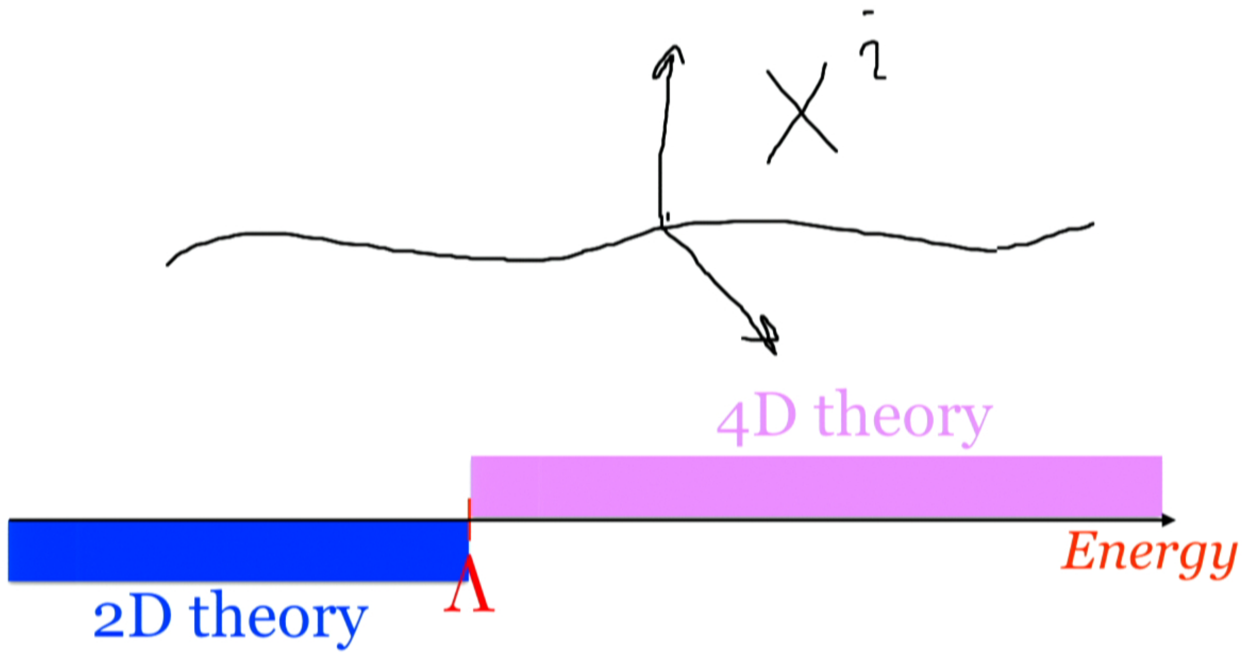
2)If we know the answer to 1) what can we say about short strings?

I will mostly talk about recent progress as far as 1) goes

SETUP

✓Confining gauge theory with a gap Λ

✓Unbroken center symmetry



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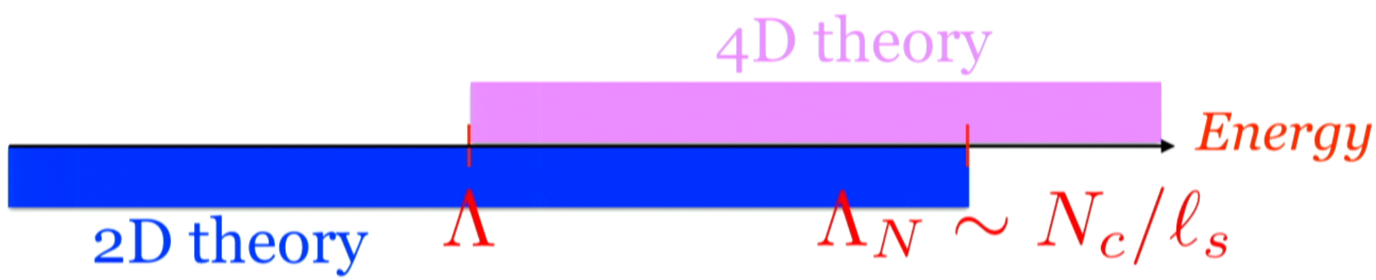

(Long) String as seen by an Effective Field Theorist

Lüscher '81
Lüscher, Weisz '04
Aharony et al '07-11
SD,Flauger, Gorbenko'12

Theory of Goldstone Bosons

$$ISO(1, D-1) \rightarrow ISO(1,1) \times SO(D-2)$$

$$\delta_\epsilon^{\alpha i} X^j = -\epsilon\left(\delta^{ij}\sigma^\alpha + X^i \partial^\alpha X^j\right)$$

Can a theory like that be integrable?

=no particle production

why this question?

- ✓To get an idea of what one might expect
- ✓By now we have a few examples of integrable higher dimensional conformal theories (N=4). This looks as a natural definition of an integrable confining theory
- ✓One may expect QCD string to be somewhat simple in the UV. Simple=Integrable?

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Can a theory like that be integrable?

Yes, at D=3 or 26

Ward identities of non-linearly realized Poincare plus integrability determine:

$$e^{2i\delta(s)} = e^{is\ell_s^2/4}$$

Finite volume spectrum from TBA

$$E(N,\tilde{N}) = \sqrt{\frac{4\pi^2(N-\tilde{N})^2}{R^2} + \frac{R^2}{\ell^4} + \frac{4\pi}{\ell^2}\left(N+\tilde{N}-\frac{D-2}{12}\right)}$$

At D=26 this a critical boson string

Integrable QG rather than QFT

Gravitational shock waves:

Dray,'t Hooft '85
Amati, Ciafaloni,Veneziano '88

Eikonal phase shift:

$$e^{i2\delta_{eik}(s)} = e^{i\ell^2 s/4}$$

$$\ell^2 \propto G_N b^{4-d}$$

Time Delay

$$\Delta t_{cms} = \frac{1}{2}\ell_s^2 E_{cms}$$

c.f. $\Delta t_H = \ell_{Pl}^4 E_{cms}^3$ for Hawking evaporation in 4d

Equivalence Principle at work

Δt is the same for a single hard particle and for a bunch of soft ones

String uncertainty principle

$$\Delta x_L \Delta x_R \geq \ell_s^2$$

for identical packets $\Delta x_{out}^2 = \Delta x_{in}^2 + \frac{\ell_s^4}{\Delta x_{in}^2}$

This is a *scaleful* theory:

No conformal/scale invariant fixed point in the UV.

Memory of ℓ_s stays forever.

Related to that no local observables.

New type of asymptotic behavior:

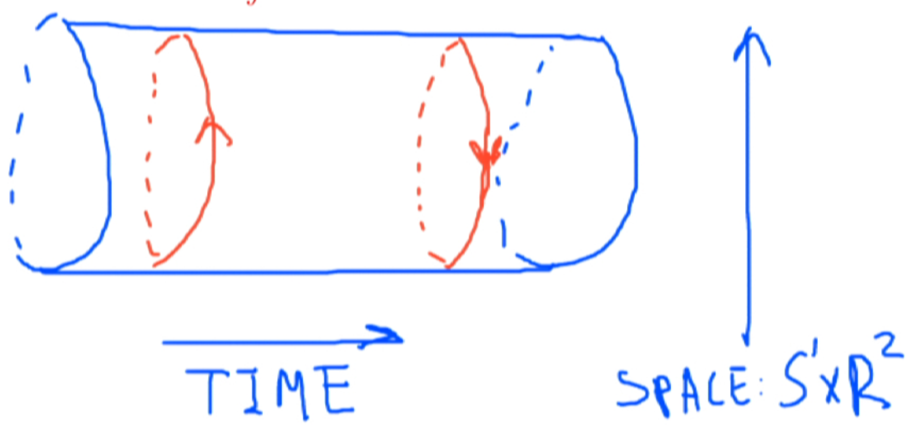
Asymptotic Fragility

QCD strings provides a good opportunity to study a non-integrable theory like that.

Looks hopeless to make progress without experimental data

all the data from the papers by Athenodorou, Bringoltz and Teper

$\mathcal{O} = P \exp\{i \oint A\}$



$$\int \mathcal{D}A e^{-S_{YM}} \mathcal{O}(0)\mathcal{O}^\dagger(t) \to e^{-E_{\mathcal{O}} t} + \ldots$$

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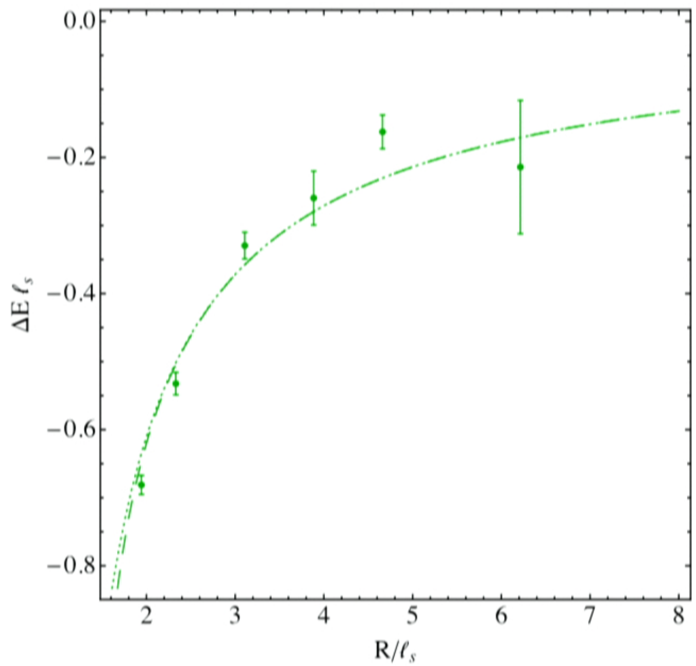
$$ISO(1, D-1) \to ISO(1,1) \times SO(D-2)$$

$$\delta_\epsilon^{\alpha i} X^j = -\epsilon(\delta^{ij}\sigma^\alpha + X^i \partial^\alpha X^j)$$

Huge amount of universality:

$$E_0(R) = \frac{R}{\ell_s^2} - \frac{(D-2)\pi}{6R} - \frac{(D-2)^2\pi^2\ell_s^2}{72R^3} - \frac{(D-2)^3\pi^3\ell_s^4}{432R^5} + \text{non-universal terms}$$



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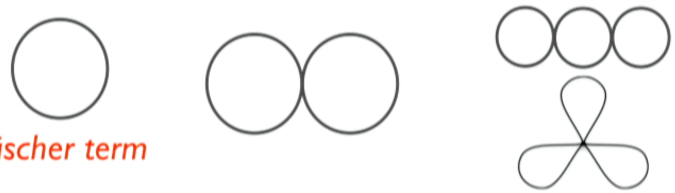
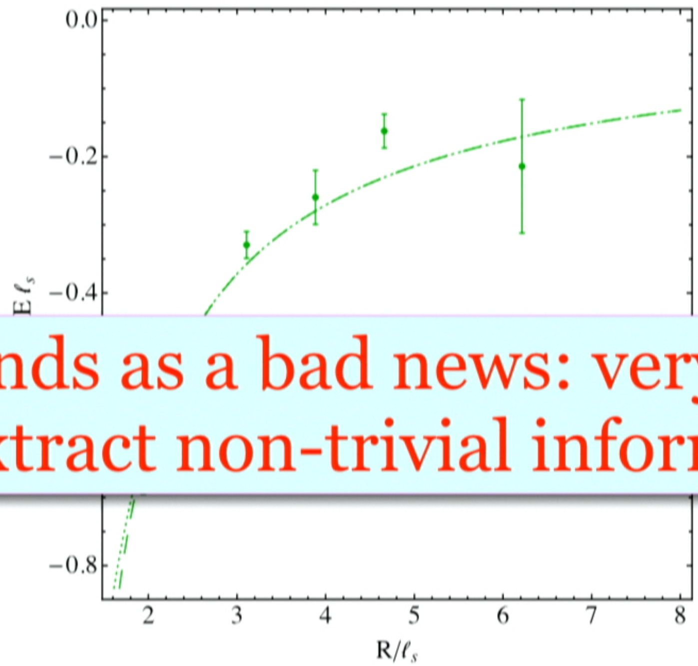
classical



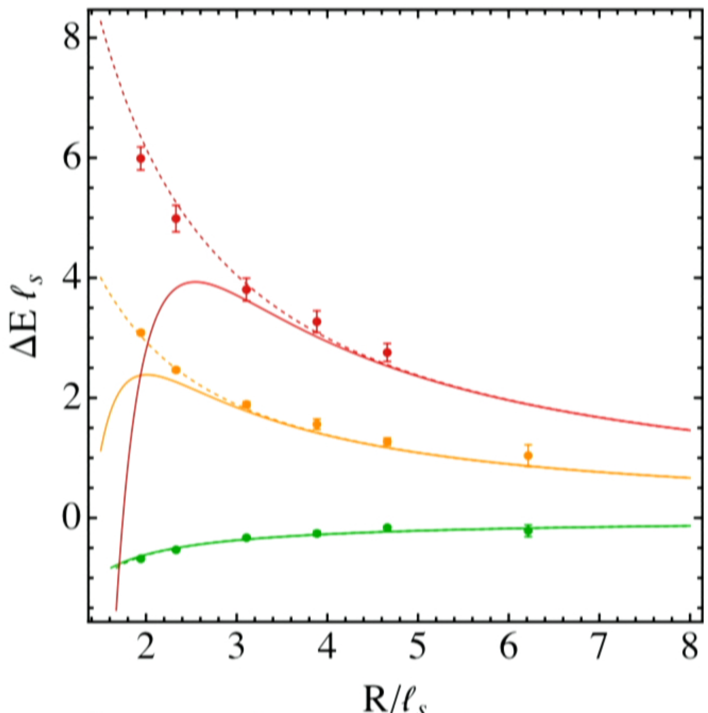
Lüscher term



sounds as a bad news: very hard to extract non-trivial information

Excited states are more promising

Left-movers only:

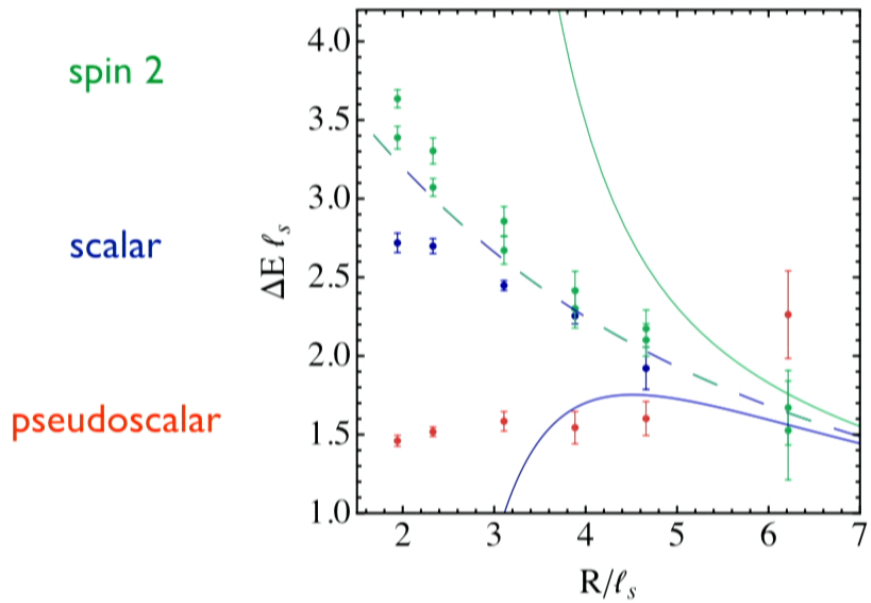


Solid --- universal terms in ℓ_s/R expansion

Dashed --- light cone quantized bosonic string

Excited states are more promising

Colliding left- and right-movers:



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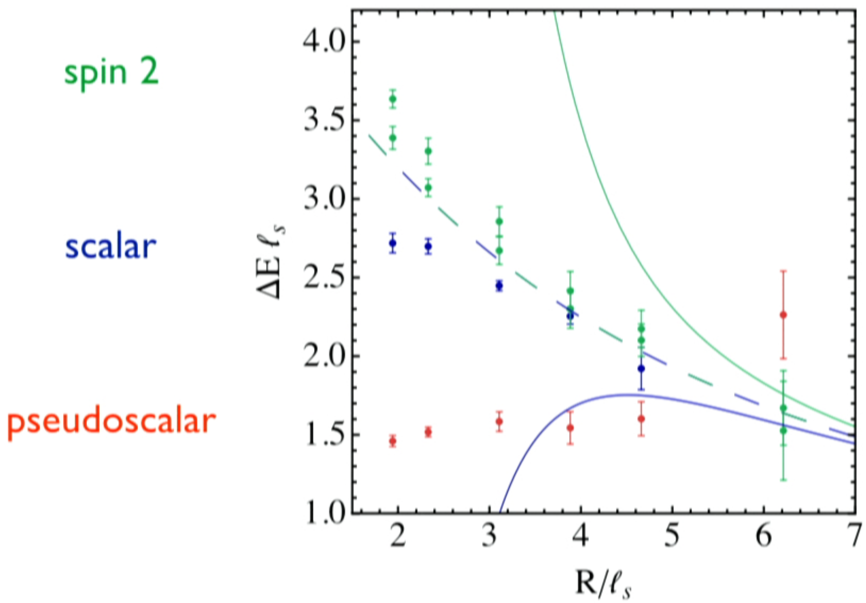

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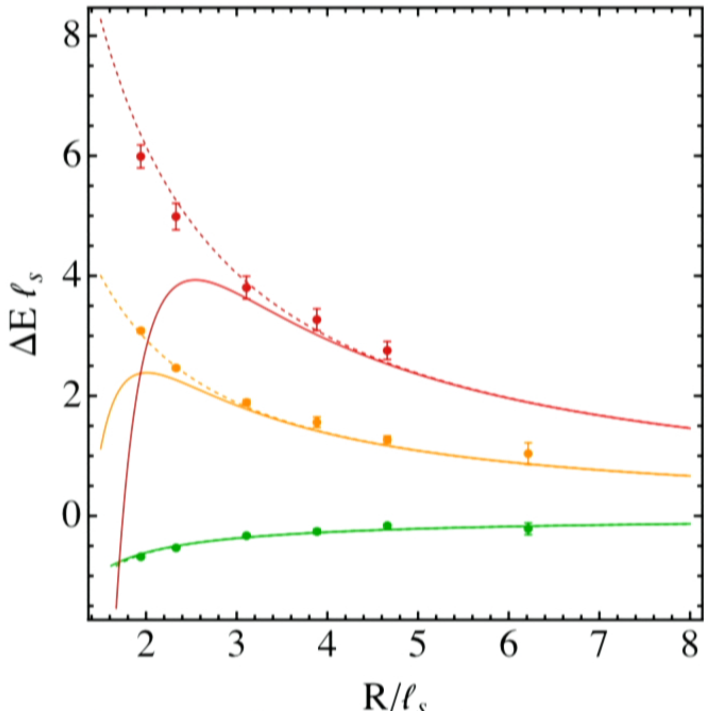

Solid --- universal terms in ℓ_s/R expansion

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critical string spectrum:

$$E_{LC}(N,\tilde{N}) = \sqrt{\frac{4\pi^2(N-\tilde{N})^2}{R^2} + \frac{R^2}{\ell_s^4} + \frac{4\pi}{\ell_s^2}\left(N+\tilde{N} - \frac{D-2}{12}\right)}$$

ℓ_s/R expansion breaks down for excited states because 2π is a large number!

for excited states:

$$E = \ell_s^{-1}\mathcal{E}(p_i\ell_s, \ell_s/R)$$

Let's try to disentangle these two expansions critical string spectrum:

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Let's try to disentangle these two expansions

Thermodynamic Bethe Ansatz

Zamolodchikov'91
Dorey, Tateo '96

$$\hat{p}^{(i)}_{k\,L} R + \sum_{j,m} 2\delta(\hat{p}^{(i)}_{k\,L}, \hat{p}^{(j)}_{m\,R}) N^{(j)}_{m\,R} - i \sum_{j=1}^{D-2} \int_0^\infty \frac{dp'}{2\pi} \frac{d\, 2\delta(i\hat{p}^{(i)}_{k\,L}, p')}{dp'} \ln\left(1 - e^{-R\epsilon^j_R(p')}\right) = 2\pi n^{(i)}_{k\,L}$$

$$\epsilon^i_L(p) = p + \frac{i}{R} \sum_{j,k} 2\delta(p, -i\hat{p}^{(j)}_{k\,R}) N^{(j)}_{k\,R} + \frac{1}{2\pi R} \sum_{j=1}^{D-2} \int_0^\infty dp' \frac{d\, 2\delta(p, p')}{dp'} \ln\left(1 - e^{-R\epsilon^j_R(p')}\right)$$

$$E(R) = R + \sum_{j,k} p^{(j)}_{k\,L} + \sum_{j=1}^{D-2} \int_0^\infty \frac{dp'}{2\pi} \ln\left(1 - e^{-R\epsilon^j_L(p')}\right)$$

+right-movers

Thermodynamic Bethe Ansatz

Zamolodchikov'91
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Asymptotic Bethe Ansatz
(~Lüscher's formula)

finite size corrections

$$\hat{p}^{(i)}_{k\,L} R + \sum_{j,m} 2\delta(\hat{p}^{(i)}_{k\,L}, \hat{p}^{(j)}_{m\,R}) N^{(j)}_{m\,R} - i \sum_{j=1}^{D-2} \int_0^\infty \frac{dp'}{2\pi} \frac{d\,2\delta(i\hat{p}^{(i)}_{k\,L}, p')}{dp'} \ln\left(1 - e^{-R\epsilon^j_R(p')}\right) = 2\pi n^{(i)}_{k\,L}$$

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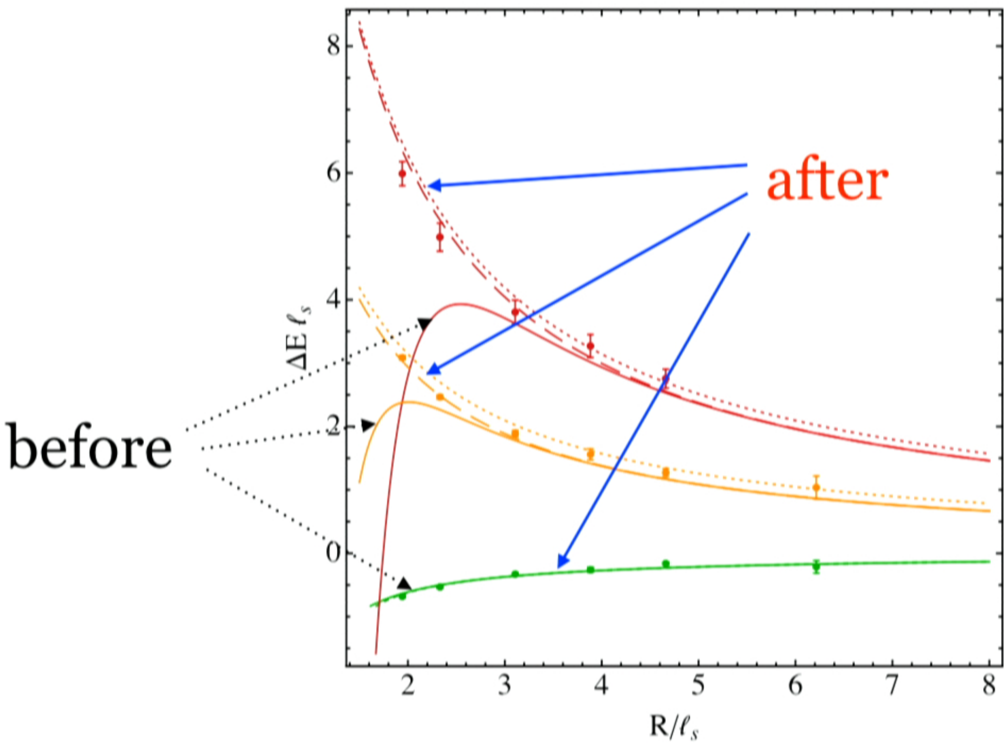
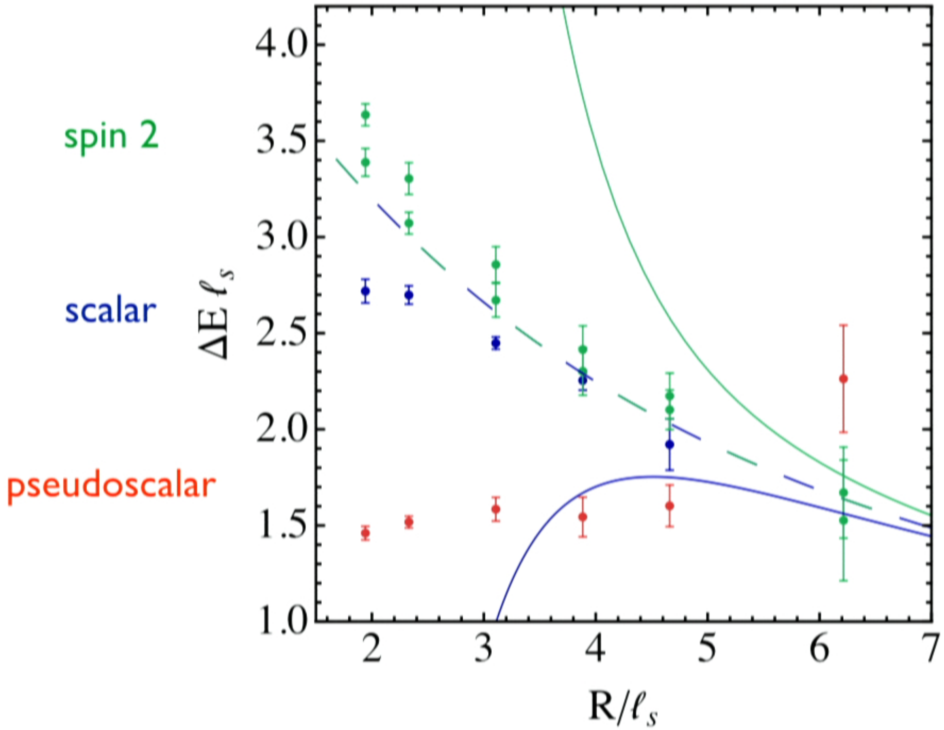
+right-movers

Improve your appearance with TBA:

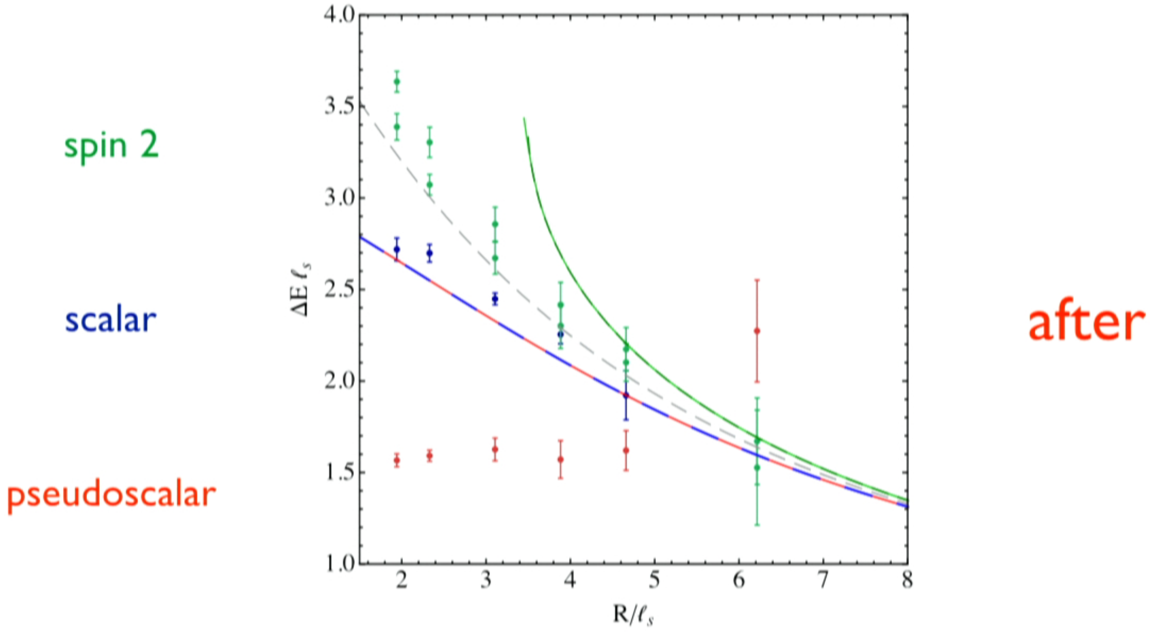


Colliding left- and right-movers



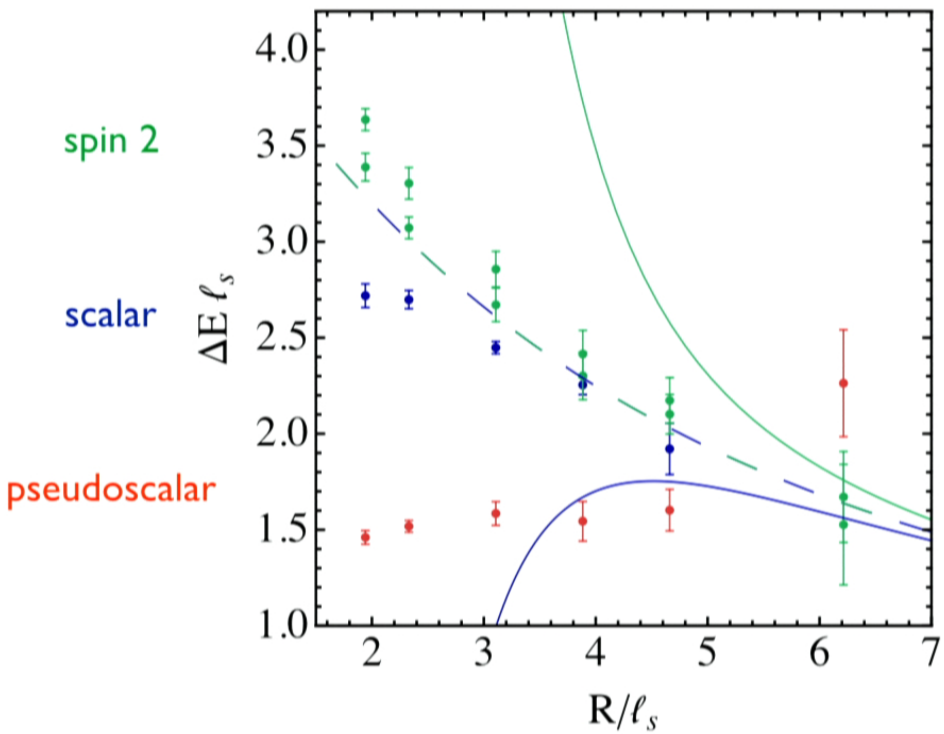
before

Colliding left- and right-movers



Red points:
A new massive state appearing as a resonance in the pseudoscalar channel!

Colliding left- and right-movers



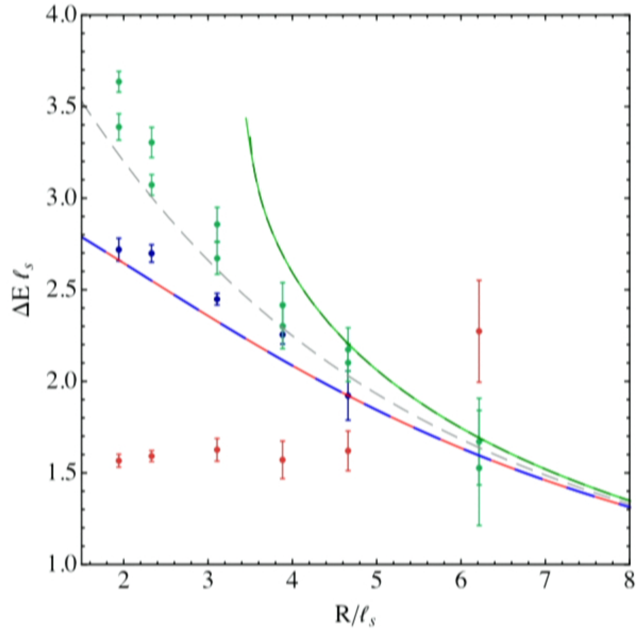
before

Colliding left- and right-movers

spin 2

scalar

pseudoscalar

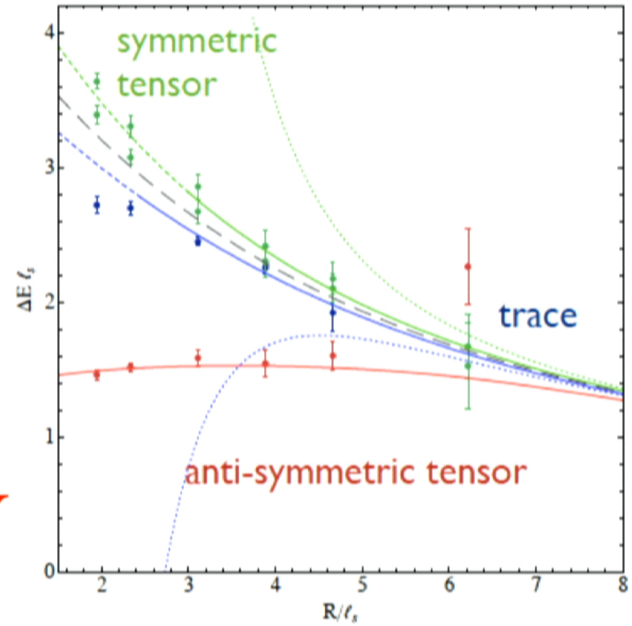


after

Red points:

A new massive state appearing as a resonance in the pseudoscalar channel!

$$S = \int d^2\sigma \frac{1}{2}\partial_\alpha\phi\partial^\alpha\phi - \frac{1}{2}m^2\phi^2 + Q\phi\epsilon^{\alpha\beta}\epsilon_{ij}K^i_{\alpha\gamma}K^{j\gamma}_\beta$$



~750 MeV

$$m\ell_s \approx 1.85^{+0.02}_{-0.03} \qquad Q \approx 0.382 \pm 0.004$$

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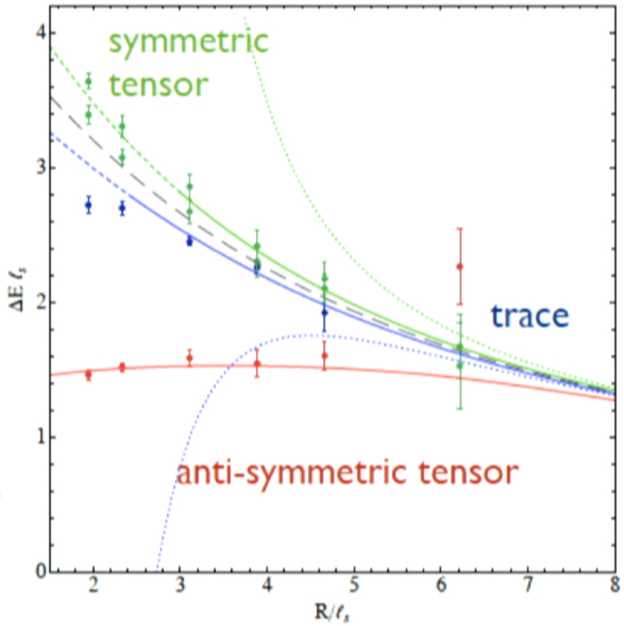


~750 MeV

$$m\ell_s \approx 1.85^{+0.02}_{-0.03} \qquad Q \approx 0.382 \pm 0.004$$

A simple option to restore integrability:

$$S_{string} = -\ell_s^{-2} \int d^2\sigma \sqrt{-det(\eta_{\alpha\beta} + \partial_\alpha X^i \partial_\beta X^i + \partial_\alpha \phi \partial_\beta \phi)} + Q \int d^2\sigma \phi R[X] + \ldots$$

$$Q = \sqrt{\frac{25 - D}{48\pi}}$$

$$e^{2i\delta(s)} = e^{is\ell^2/4}$$

This is also known as a linear dilaton background

Another simple option to restore integrability:

$$S_{string} = -\ell_s^{-2} \int d^2\sigma \sqrt{-det(\eta_{\alpha\beta} + \partial_\alpha X^i \partial_\beta X^i + \partial_\alpha \phi \partial_\beta \phi)} + Q \int d^2\sigma \phi K \tilde{K} + \ldots$$

$$Q = \sqrt{\frac{25 - D}{48\pi}} = \sqrt{\frac{7}{16\pi}} \approx 0.373176\ldots$$

$$e^{2i\delta(s)} = e^{is\ell^2/4}$$

Compare to

$$Q_{lattice} \approx 0.382 \pm 0.004$$

???

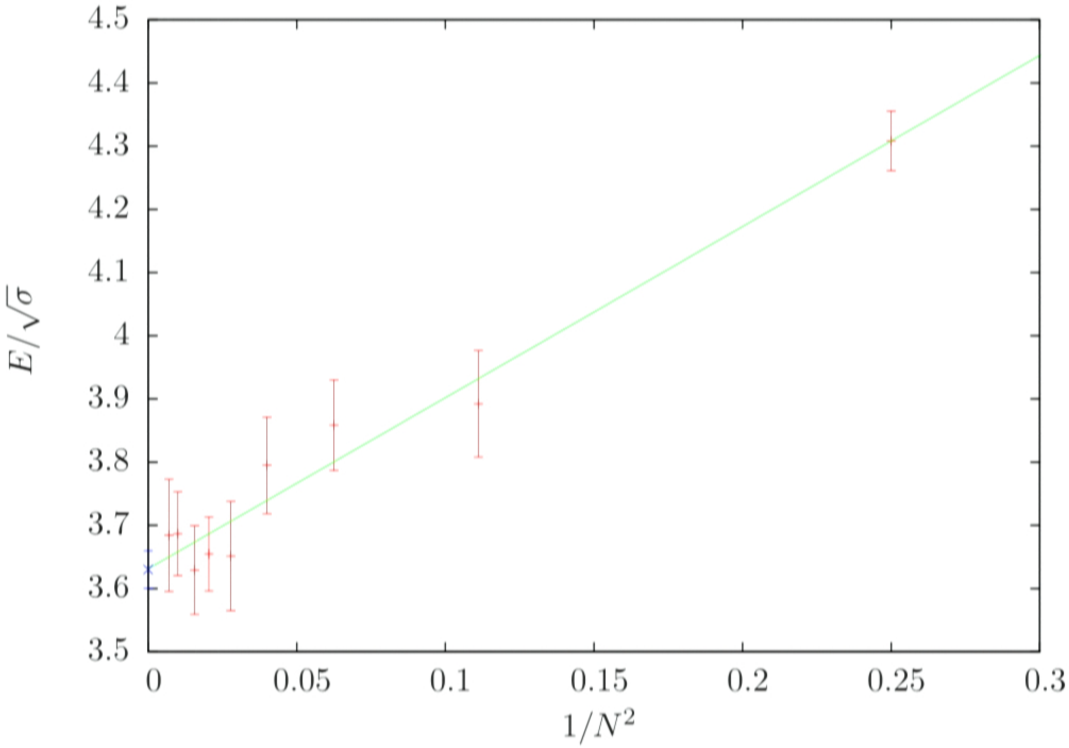
What could this mean?

* Numerology

* In the planar limit axion becomes massless and the planar QCD string is integrable

* This tells us about UV asymptotics of a planar QCD string

Athenodorou, Teper, to appear



the second option is excluded

(Strawman) proposal for the structure of the QCD string in D=3,4:

✶Matter content:

Goldstones+massive antisymmetric O(D-2) tensor

✶Integrable UV asymptotics with

$$e^{2i\delta(s)} = e^{is\ell^2/4}$$

✶Future checks: confront with lattice data for longs strings and glueball spectra

Non-critical strings as the Higgs mechanism?

Two problems with bosonic strings:

1) Tachyon

2) Massless vector (open strings), graviton and B-field (closed strings)

$$Closed = Open_L \otimes Open_R$$

$\Box$ of O(D-2) should become a full O(D-1) multiplet

linear dilaton | axion

O(D-2) O(D-1) | O(D-2) O(D-1)

$$\Box + 1 = \Box \qquad\qquad \begin{smallmatrix}\Box\\\Box\end{smallmatrix} + \Box = \begin{smallmatrix}\Box\\\Box\end{smallmatrix}$$

Conclusions:

✶Being a phenomenologist, I'm somewhat disappointed by what happened to a 750 Gev boson (this still may change!).

✶Being a theorist, I always hoped that new physics at the LHC will bring in new interesting hard puzzles to solve.

✶Absence of this new physics definitely appears to be such a puzzle.

✶But there are existing puzzles at lower energies (such as a 750 MeV boson), which are also quite fundamental and may be easier to approach. I will feel ashamed if people will do it, say 20 years from now, while we don't even give it a fair try.

✶In the QCD string case, definitely people gave it a proper try in the past. Right now we have an additional advantage of having a massive amount of high quality data.