Holography:
a tool for the LHC

Veronica Sanz

Boston University

What are you gonna do if dynamical symmetry breaking shows up at the LHC?

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Wait for lattice computations…

What are you gonna do if dynamical symmetry breaking shows up at the LHC?

Wait for lattice computations…

Use Holography

Holographic QCD

QCD and a holographic model of hadrons.
Erlich, Katz, Son and Stephanov. PRL95 (2005)

Chiral symmetry breaking from five dimensional spaces.

Da Rold and Pomarol. NPB721 (2005)

Interpolating between low and high energy QCD via a 5-D YM model.
Hirn and Sanz. JHEP 0512 (2005)

Holographic Technicolor

A Negative S parameter from holographic technicolor.
Hirn and Sanz. PRL973 (2006)

The Fifth dimension as an analogue computer for strong interactions at the LHC.
Hirn and Sanz. JHEP???

Summary

We know Holography works
for QCD

Summary

We know Holography works for QCD

We apply it to

EWSB

Summary

1. We know Holography works for QCD

2. We apply it to EWSB

3. Explore the pheno

We have checked that

Holography

Works for

QCD

Hum…let's see…

what do we know about 4D QCD?

many things, but in particular…

Hum…let's see…

what do we know about 4D QCD?

At high energies scale invariant, except NP dynamics, Condensates

$$\langle GG \rangle, \langle q\bar{q} \rangle \ldots \neq 0$$

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OPE expansion

$$\Pi_{OPE}(Q) \sim N_c \, log(Q), \frac{\alpha_s \langle GG \rangle}{Q^4}, \frac{\alpha_s \langle q\bar{q} \rangle^2}{Q^6} \ldots$$

Hum…let's see…

What do we know about 4D QCD?

At high energies scale invariant, except NP dynamics, Condensates

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Global symmetries of QCD? Chiral Symmetry

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

broken by $\langle q\bar{q}\rangle$

Let's try the simplest thing in 5D

Scale invariant AdS

Quark condensate bulk scalar

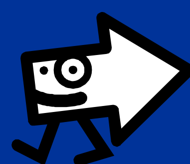
Let's try the simplest thing in 5D

Scale invariant $\rightarrow$ AdS

Quark condensate bulk scalar

$$ds^2 = w(z)^2(dx^2 - dz^2)$$

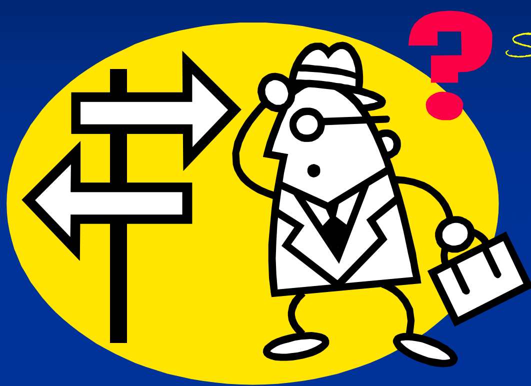
If $w(z) = \frac{l_0}{z}$ then $z \rightarrow \lambda z \quad Q \rightarrow Q/\lambda$

Scale invariance  Conformal invariance

$$\Pi(Q) \sim log(Q) \qquad AdS$$

$$Q \leftrightarrow 1/z$$

Let's try the simplest thing in 5D

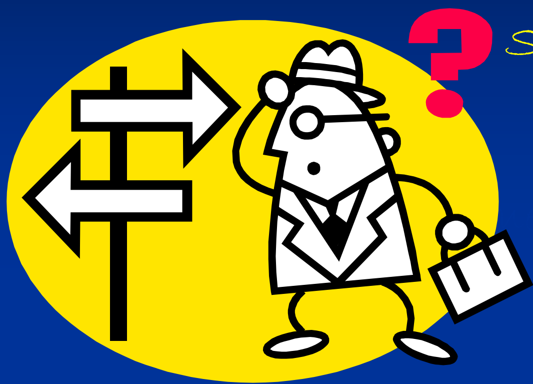


Scale invariant $\rightarrow$ AdS

But wait!

I thought the *dictionary* had an entry

Let's try the simplest thing in 5D



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"weak in 4D, strong in 5D"

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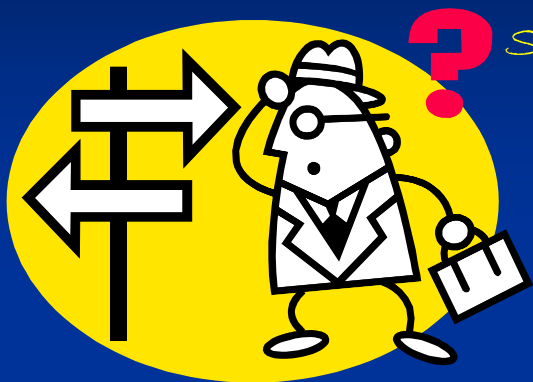

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QCD at high energies is weak, right?

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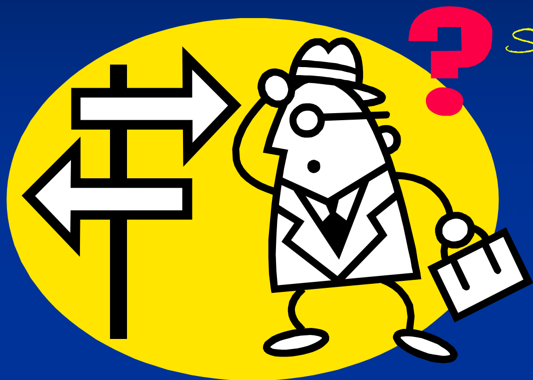

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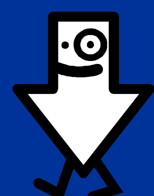

NO 5D weakly coupled description!

But before letting it go and going home…

We use the correspondence $$J_\mu = \bar{q}\gamma_\mu q \longleftrightarrow A_\mu$$

the action is 5D YM

$$\mathcal{S} = \int \sqrt{g}\, d^5x \,(F^2_{MN})$$

But before letting it go and going home…

We use the correspondence $J_\mu = \bar{q}\gamma_\mu q \longleftrightarrow A_\mu$

the action is 5D YM, and we lose control when h.o.

$$\mathcal{S} = \int \sqrt{g}\, d^5x \left(F_{MN}^2 + \frac{(DF)^2}{\Lambda^2} + \frac{FD^2F}{\Lambda^2} + \frac{FD^4F}{\Lambda^4} \ldots \right)$$

"weak in 4D, strong in 5D"

in reality, "at scales around Λ I'm stuck!"

All that goes for the 't Hooft coupling,

we're still in the large-N !

But before letting it go and going home…

BUT

In AdS/CFT all the computations are ON-SHELL

$$D^2 F \sim F$$

$$\mathcal{S} = \int \sqrt{g}\, d^5x\, a\, F_{MN}^2 + \int_{z=z_{IR}} d^4x\, b\, F_{\mu\nu}^2$$

In general A_μ fields may couple to other fields → They may see a different **effective** metric

Cubic terms DO receive corrections $\frac{F^3}{\Lambda^2} + \frac{(DF)^2}{\Lambda^4} F + \ldots$

Let's try the simplest thing in 5D

Scale invariant $\rightarrow$ AdS

Quark condensate bulk scalar

$$\frac{\alpha_s \langle q\bar{q}\rangle^2}{Q^6} \longrightarrow \alpha_s \langle q\bar{q}\rangle^2 \, z^6$$

Let's try the simplest thing in 5D

Scale invariant $\rightarrow$ AdS

Quark condensate $\longrightarrow$ bulk scalar

Let's try the simplest thing in 5D

Scale invariant $\rightarrow$ AdS

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Chiral symmetries

Let's try the simplest thing in 5D

Scale invariant $\rightarrow$ AdS

Quark condensate $\longrightarrow$ bulk scalar

Chiral symmetries $\longrightarrow$ Bulk gauge symmetries

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

$$V_M, A_M \propto L_M \pm R_M$$

Let's try the simplest thing in 5D

Scale invariant $\rightarrow$ AdS

Quark condensate $\longrightarrow$ bulk scalar

Chiral symmetries $\longrightarrow$ Bulk gauge symmetries

Chiral symmetry breaking

Let's try the simplest thing in 5D

Scale invariant $\rightarrow$ AdS

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Chiral symmetry breaking $\longrightarrow$ bulk scalar couplings

A_M Couples to $X(z) \sim z^3$

Let's try the simplest thing in 5D

Scale invariant $\rightarrow$ AdS

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5D model in AdS

$X(z)$ Charged under the bulk

YM $SU(N_f)_L \times SU(N_f)_R$

and M_X chosen to

$$X(z) = Az + Bz^3$$

Let's try the simplest thing in 5D

Scale invariant $\rightarrow$ AdS

Quark condensate $\longrightarrow$ bulk scalar

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5D parameters

(A, B, l_1)

4D parameters

$f_\pi, m_q, \langle q\bar{q} \rangle$

5D model in AdS

$X(z)$ Charged under the bulk

YM $SU(N_f)_L \times SU(N_f)_R$

and M_X chosen to

$$X(z) = Az + Bz^3$$

And the result is…

And the result is…

Agreement to the 10% !

Observable	Measured (MeV)	Model (MeV)
m_π	139.6±0.0004	141
m_ρ	775.8±0.5	832
m_{a_1}	1230±40	1220
f_π	92.4±0.35	84.0
$F_\rho^{1/2}$	345±8	353
$F_{a_1}^{1/2}$	433±13	440
$g_{\rho\pi\pi}$	6.03±0.07	5.29

Erlich et al PRL95 (05)

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Agreement to the 10% !

It is a 3pt function!

4%

Erlich et al PRL95 (05)

Even though QCD is NOT

Supersymmetric

(very) large N_c

Even though QCD is NOT

Supersymmetric

(very) large N_c

But seems to be quite conformal

Substitute $X(z)$ by Neumann, Dirichlet BCs

and the agreement is still

15%

Hirn & Sanz. **JHEP 0512**

News from last 2 years

You can apply Holography to QCD

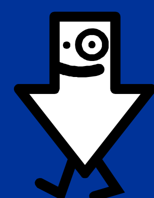
and it works!

Apply it

to EWSB

Apply it

to EWSB

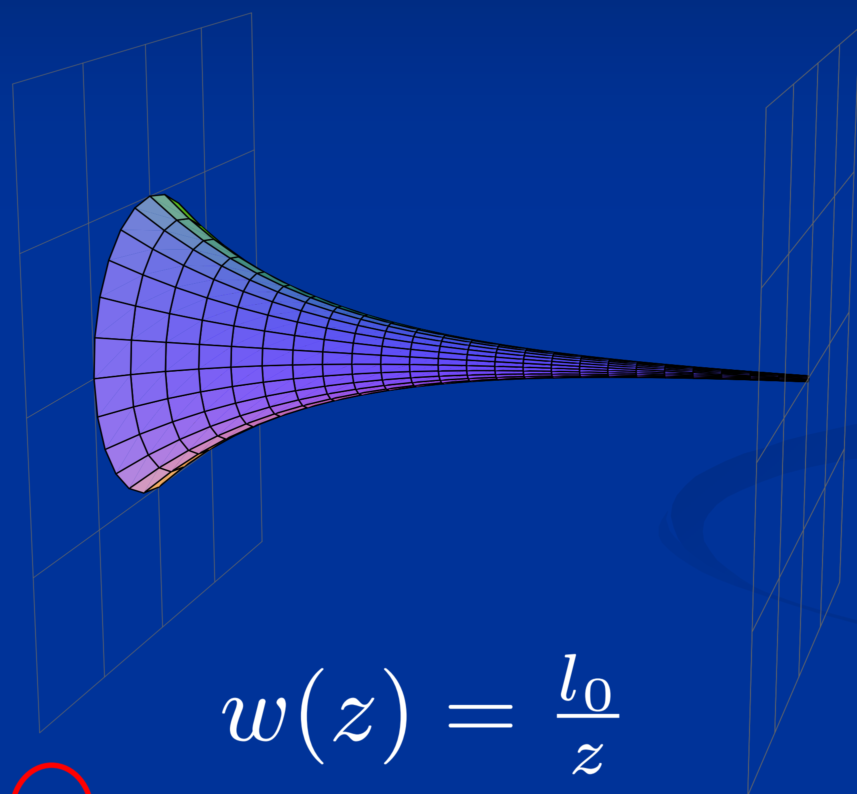


Holographic Technicolor

Hirn & Sanz. PRL95(06)

Let’s start again,

5D model in AdS, LR bulk, some ’s



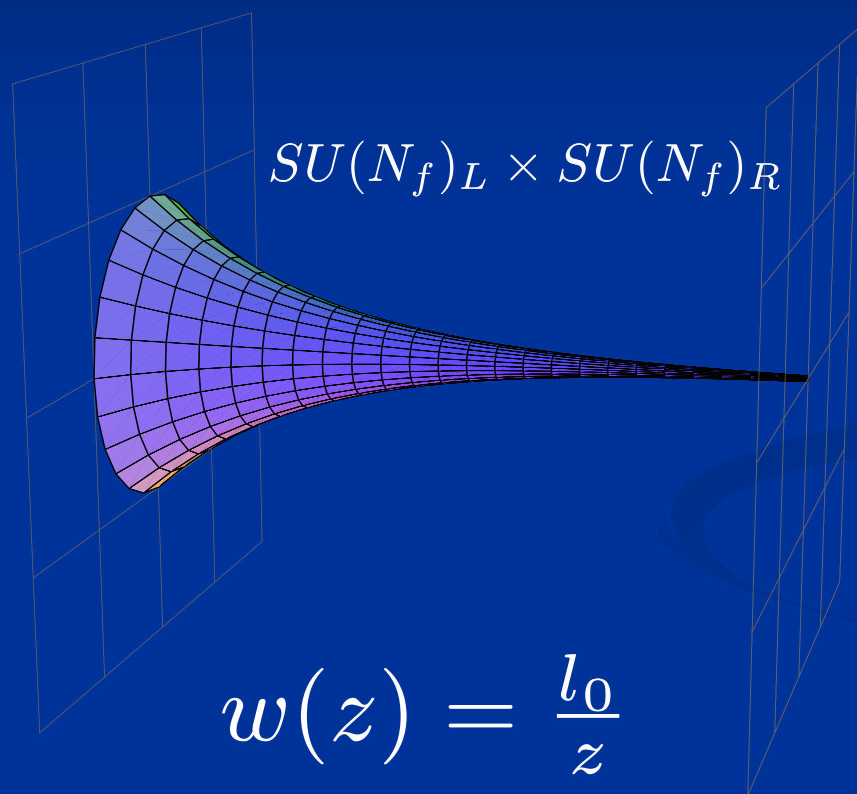
$$w(z) = \frac{l_0}{z}$$

UV brane l_0

l_1 IR brane

Let’s start again,

5D model in AdS, LR bulk, some ‘s



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

4D Custodial symmetry

$$w(z) = \frac{l_0}{z}$$

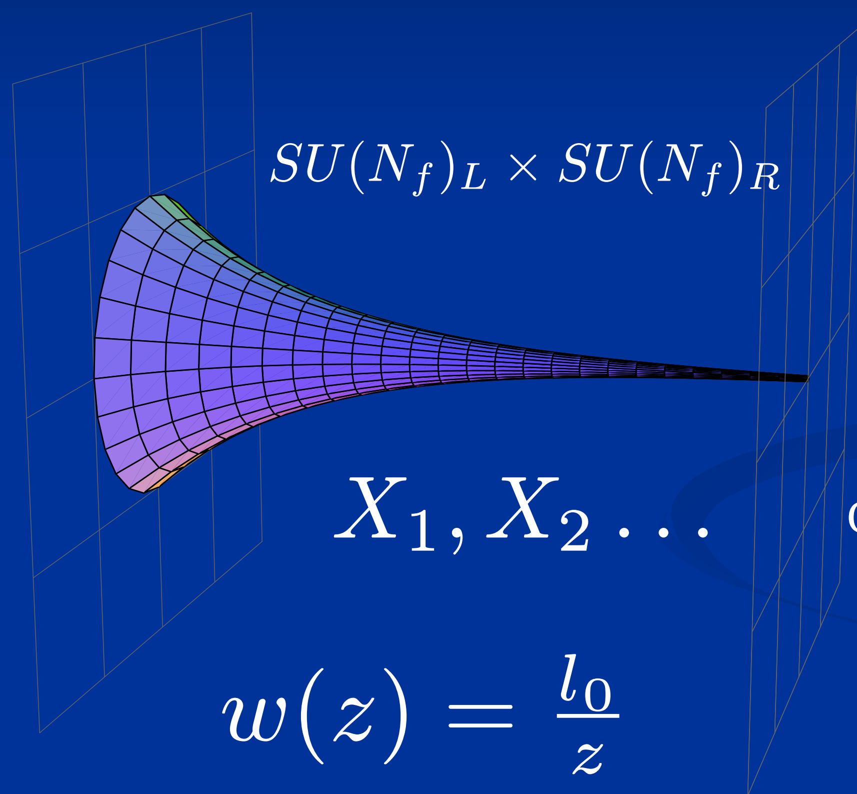
Higgsless

Agashe et al.

Csaki et al.

Let's start again,

5D model in AdS, LR bulk, some $X(z)$'s



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

As in QCD

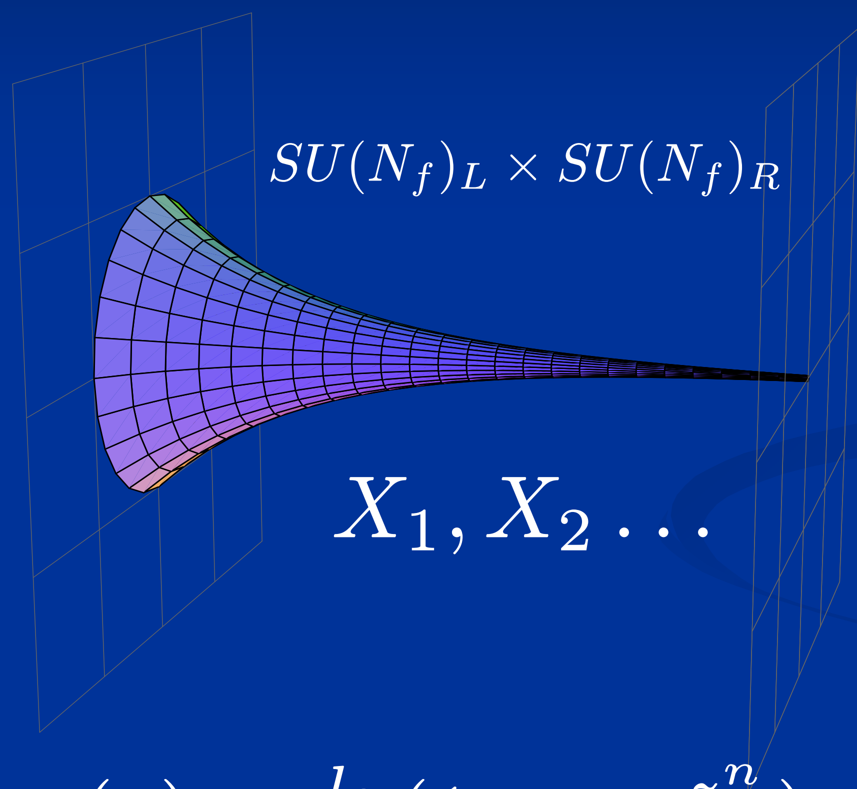
$$X_1, X_2 \ldots$$

Couple to A_M and V_M

$$w(z) = \frac{l_0}{z}$$

And here it is,

5D model in AdS, LR bulk, some $X(z)$'s

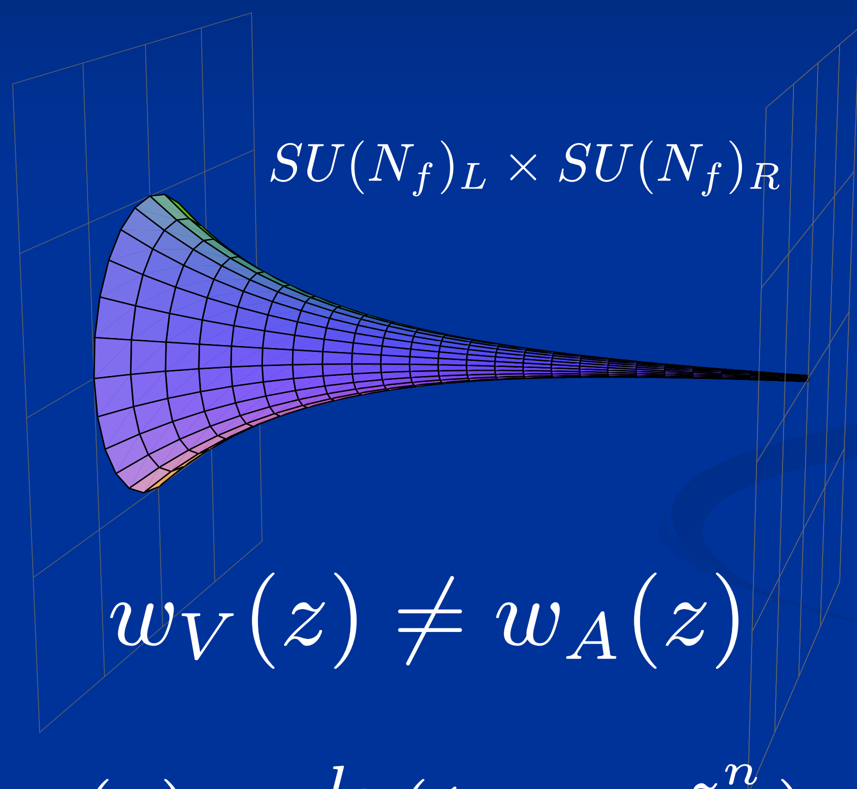


$SU(N_f)_L \times SU(N_f)_R$

$$X_1, X_2 \ldots$$

$$w(z) \sim \frac{l_0}{z}\left(1 + c_n \frac{z^n}{l_1^n}\right)$$

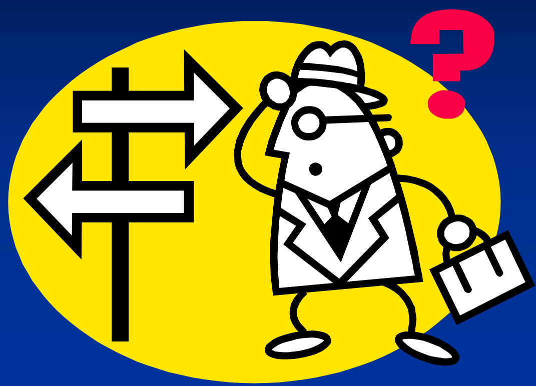
5D model in AdS, LR bulk, some $X(z)$'s



$$w_V(z) \neq w_A(z)$$

$$w(z) \sim \frac{l_0}{z}\left(1 + c_n \frac{z^n}{l_1^n}\right)$$

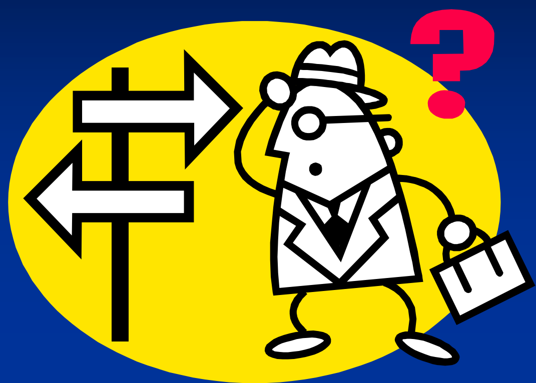
Does it mean we can do whatever, and get whatever?



Does it mean we can do whatever, and get whatever?

Apparently,

YES



Does it mean we can do whatever, and get whatever?

Apparently,

YES

In detail,

NOT really

What are the rules?

1. What's the valid approximation?

Always large-N

(weak coupling in 5D)

No localized kin terms to play with

What are the rules?

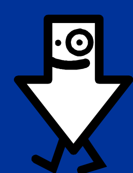
2. NDA for the condensates

NDA Background fields $\Longrightarrow$ Natural potential

$$X(l_0) \sim \frac{1}{l_0}$$

How many of these condensates X_i's we have to take into account?

$$X_d \sim z^d$$



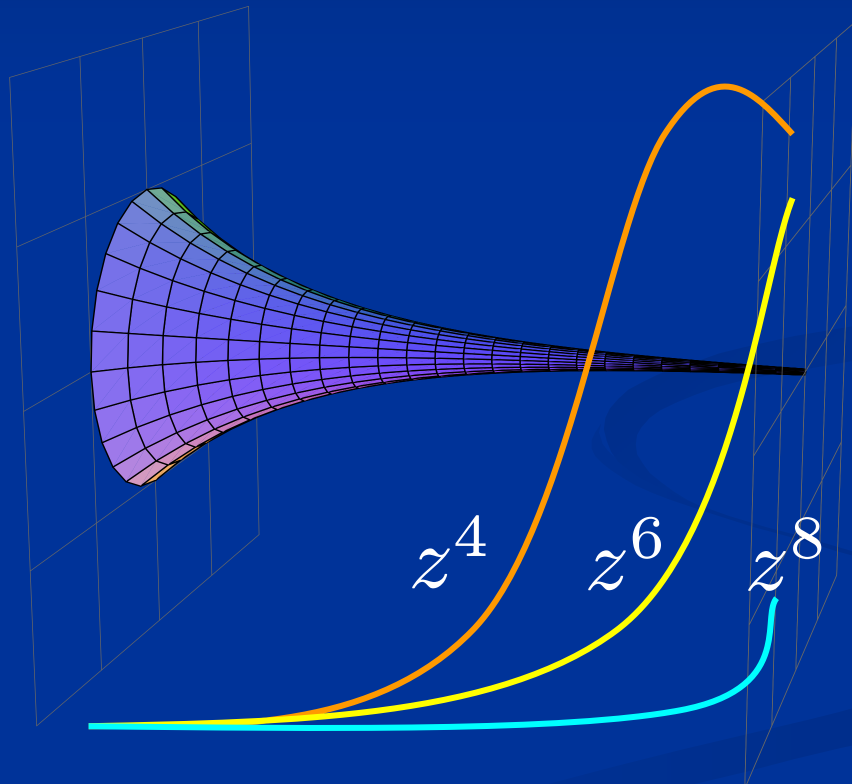
$$w(z) = \frac{l_0}{z}\left(1 + \frac{o_d}{2d(d-1)}\frac{z^{2d}}{l_1^{2d}}\right)$$

What are the rules?

$$w(z) = \frac{l_0}{z}\left(1 + \boxed{\frac{o_d}{2d(d-1)}\,\frac{z^{2d}}{l_1^{2d}}}\right)$$

1 . towards IR

2. Coefficient irrelevant as d grows



What are the rules? At the end of the day…

1. Large-N (5D weak coupling)

2. Pheno relevant condensates

just low d

$$o_2^V\,, o_2^A \sim \mathcal{O}(1)$$

Technical point

$$\Pi(Q^2)_{OPE} \sim \frac{1}{Q^{2d}}$$

NDA in $X(z)$

$$w(z) \sim \frac{1}{d(d-1)} z^{2d} \Rightarrow \Pi \sim \frac{d!^2}{Q^{2d}}$$

Technical point

$$\Pi(Q^2)_{OPE} \sim \frac{1}{Q^{2d}}$$

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Shifman

Now we know the rules,

Let's look at the phenomenology

5D model dual to Technicolor?

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Problem with the S parameter!

5D model dual to Technicolor?

Problem with the S parameter!

$$S = S_{tree} + \frac{1}{12\pi}\left(\log\left(\frac{\mu^2}{m_H^2} - \frac{1}{6}\right)\right) = -0.13 \pm 0.1\,(PDG)$$

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$$\sim 0.1 - 0.2$$

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≤ 0 $\qquad\qquad$ $\sim 0.1 - 0.2$

5D model dual to Technicolor?

Problem with the S parameter!

What's typical value for S in TC? (rescaled QCD)

$$S_{tree} \sim \frac{N}{4\pi}$$

5D model dual to Technicolor?

Problem with the S parameter!

What's typical value for S in TC?

$$S_{tree} \sim \frac{N}{4\pi}$$

What's the value in pure AdS?

$$S_{tree} = \frac{N}{4\pi}$$

as in QCD...

$$N = \frac{12\pi^2 l_0}{g_5^2}$$

5D model dual to Technicolor?

Problem with the S parameter!

What's typical value for S in TC?

$$S_{tree} \sim \frac{N}{4\pi}$$

What's the value in pure AdS?

$$S_{tree} = \frac{N}{4\pi} > 0$$

Csaki et al.

Barbieri et al.

as in QCD...

$$N = \frac{12\pi^2 l_0}{g_5^2}$$

5D model dual to Technicolor?

Problem with the S parameter!

Low N

$$S_{tree} = \frac{N}{4\pi} > 0$$

5D model dual to Technicolor?

Problem with the S parameter!

$$S_{tree} = \frac{N}{4\pi} > 0$$

Low N

1. S decreases
2. big IR kin terms

5D model dual to Technicolor?

Problem with the S parameter!

$$S_{tree} = \frac{N}{4\pi} > 0$$

~~Low N~~

1. Strong coupling
2. Tachyons
3. Low-N dual?

5D model dual to Technicolor?

Problem with the S parameter!

$$S_{tree} = \frac{N}{4\pi} > 0$$

~~Low N~~

"flat" fermions

5D model dual to Technicolor?

Problem with the S parameter!

$$S_{tree} = \frac{N}{4\pi} > 0$$

~~Low N~~

"flat" fermions Flavor $\Leftrightarrow$ S

5D model dual to Technicolor?

Problem with the S parameter!

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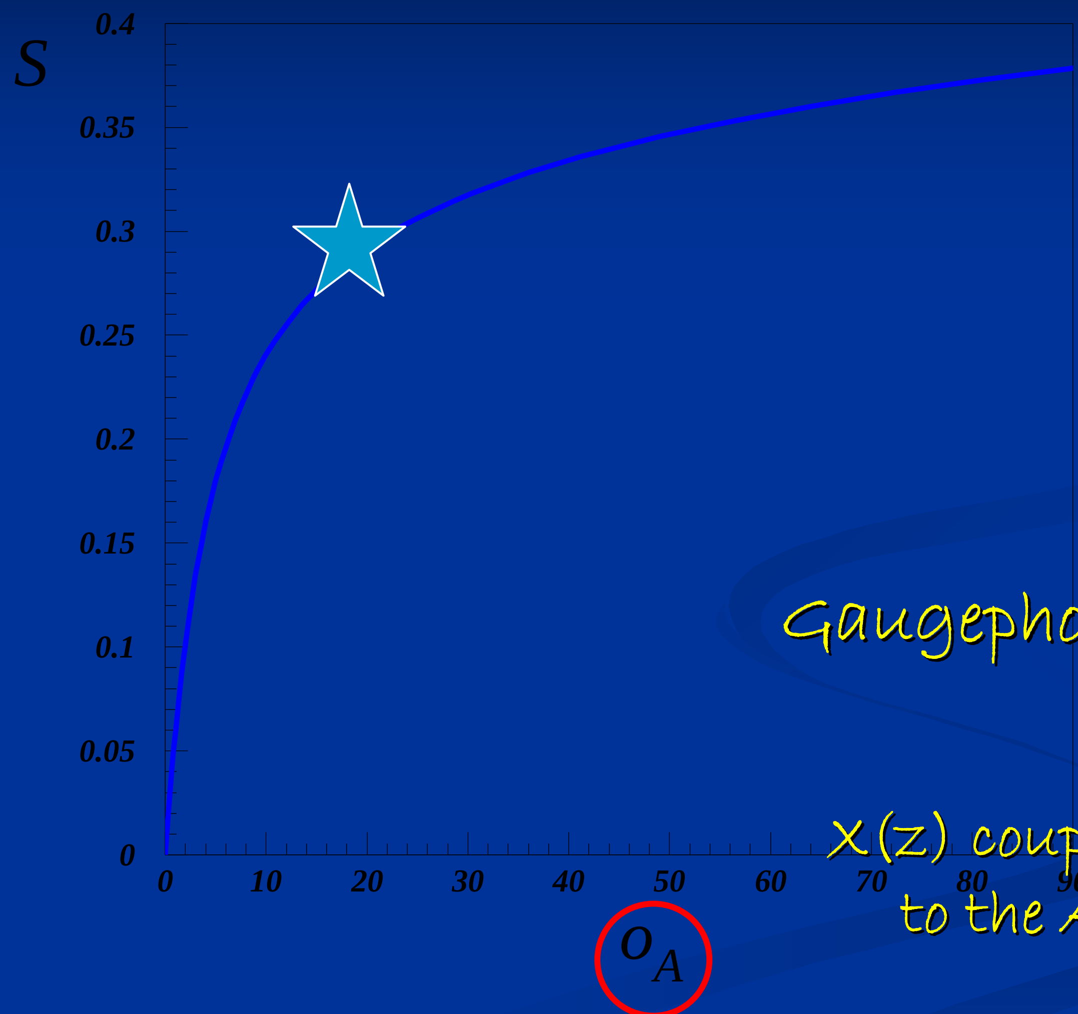
~~Low N~~

"flat" fermions

QCD-like answer?

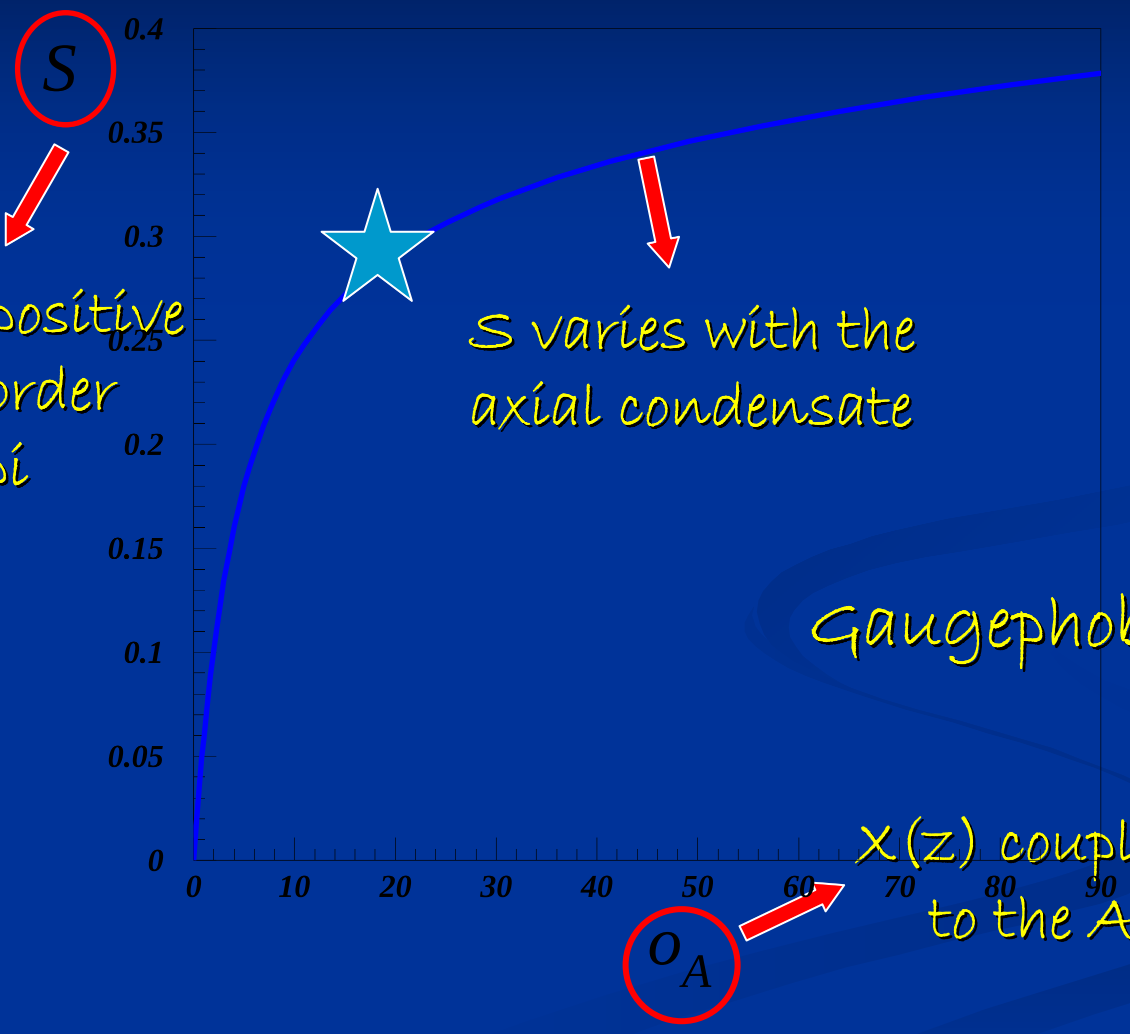
What's the value of S in HolQCD?



Gaugephobic Higgs

X(z) couples just to the Axial

What's the value of S in HolQCD?



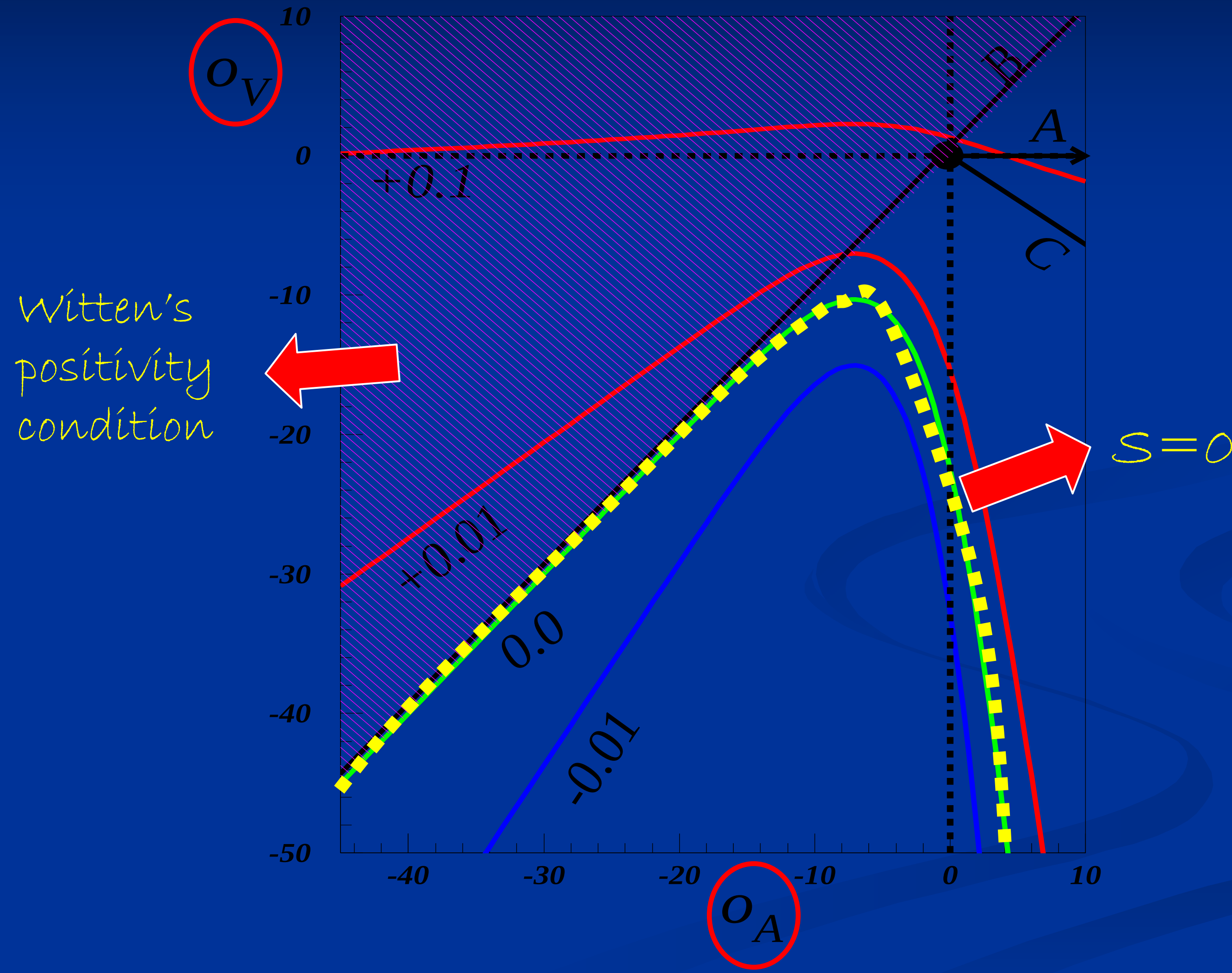
S is positive and order 3/4 pi

S varies with the axial condensate

Gaugephobic Higgs

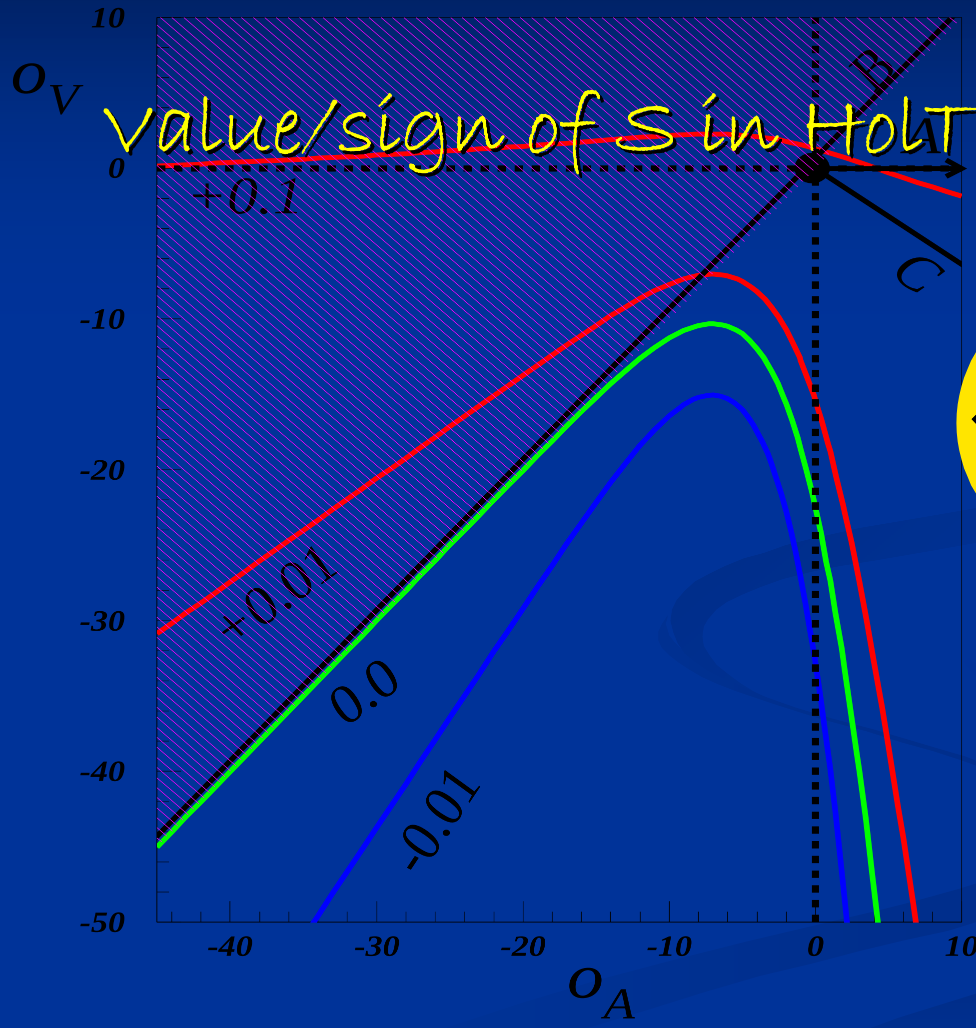
X(z) couples just to the Axial

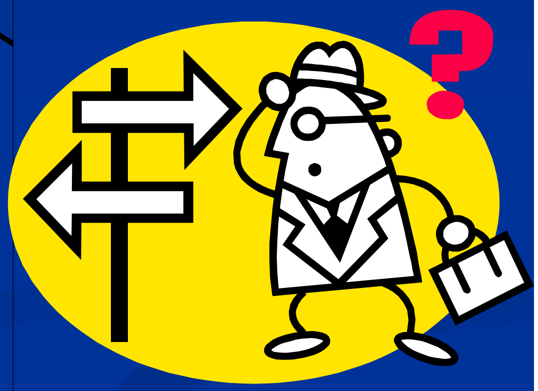
d=2



O_V
10
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
O_A
B
A
C
+0.1
+0.01
0.0
-0.01
Witten's positivity condition
S=0

Value/sign of S in HolTC?



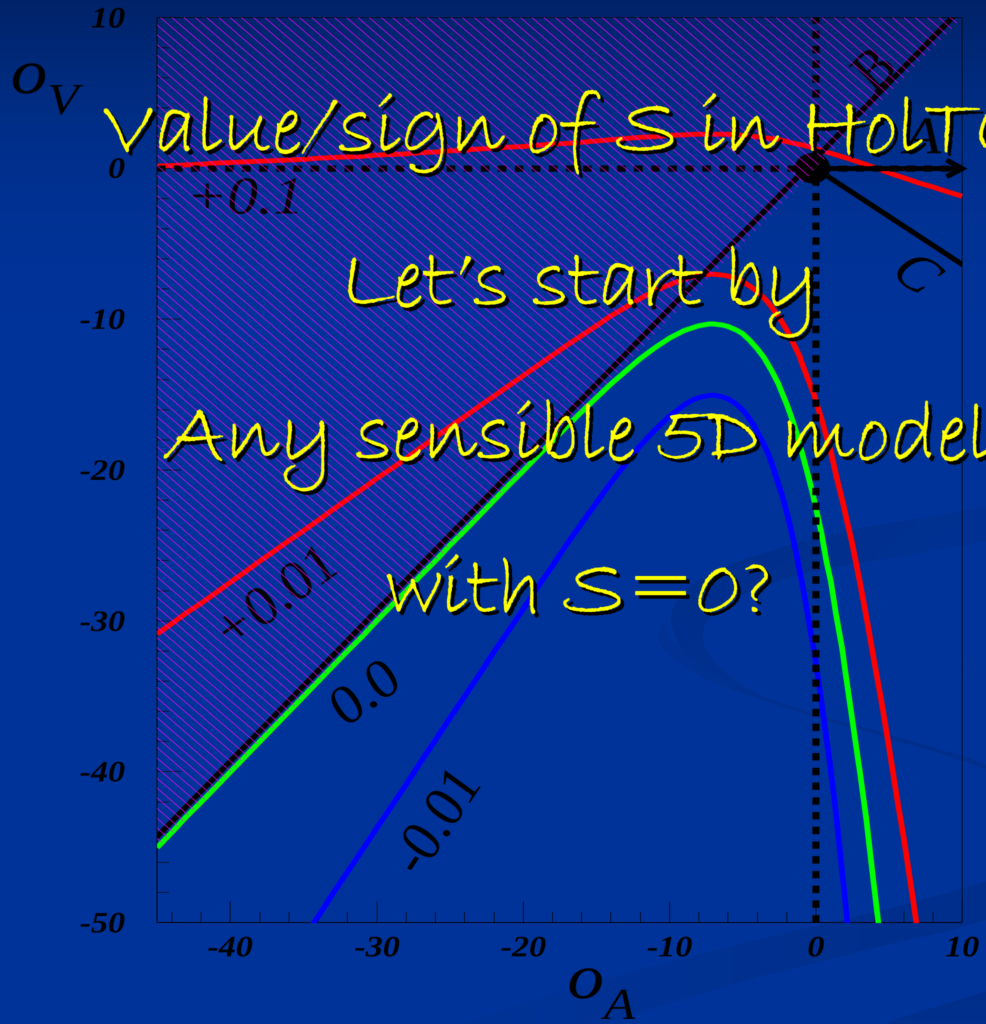


Value/sign of S in HolTC?

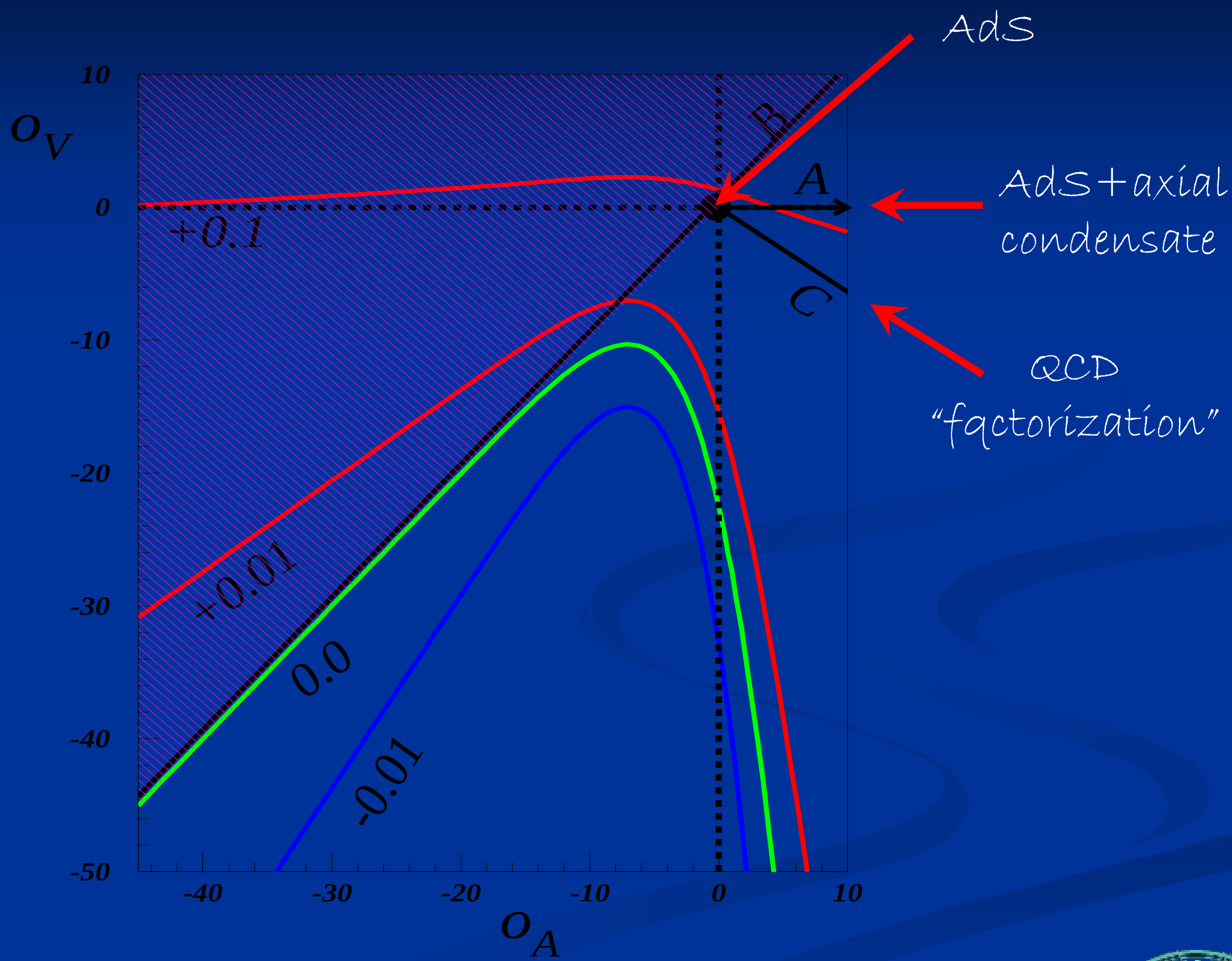
Let's start by

Any sensible 5D model

with S=0?

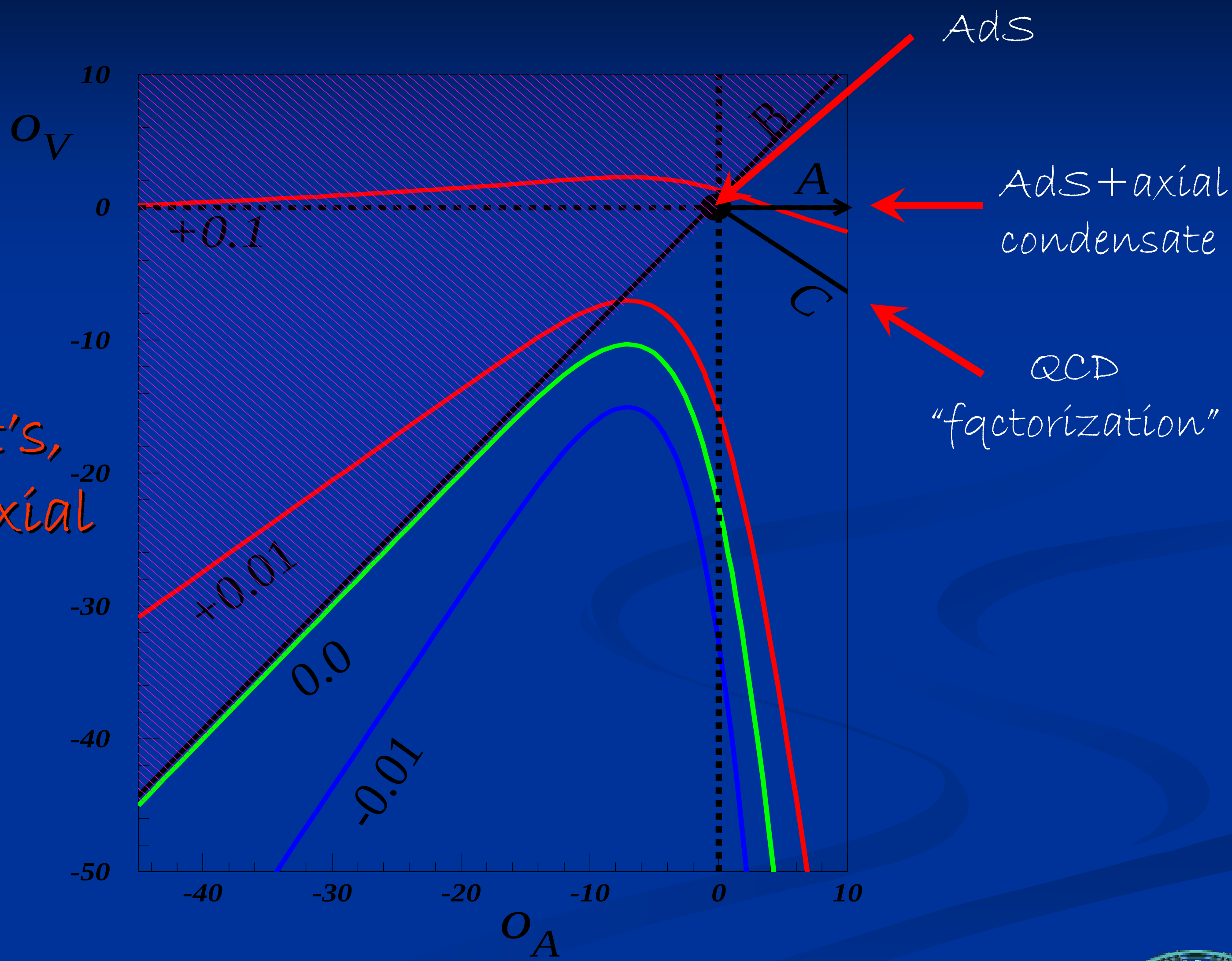


Things that DON'T work



Things that DON'T work

Whatever it's, vector and axial see it



A simple thing that DOES work

$$\phi(z) \qquad X(z)$$

Neutral, couples to gravity

Charged, EWSB

A simple thing that DOES work

$$\phi(z) \qquad X(z)$$

Neutral, couples to gravity

Charged, EWSB

Non-tachyonic

$$v^2 > 0$$

$$o_A^{\phi} = o_V^{\phi} < 0 \qquad o_A^{X} > 0$$

A simple thing that DOES work

$$\phi(z) \qquad X(z)$$

Neutral, couples to gravity

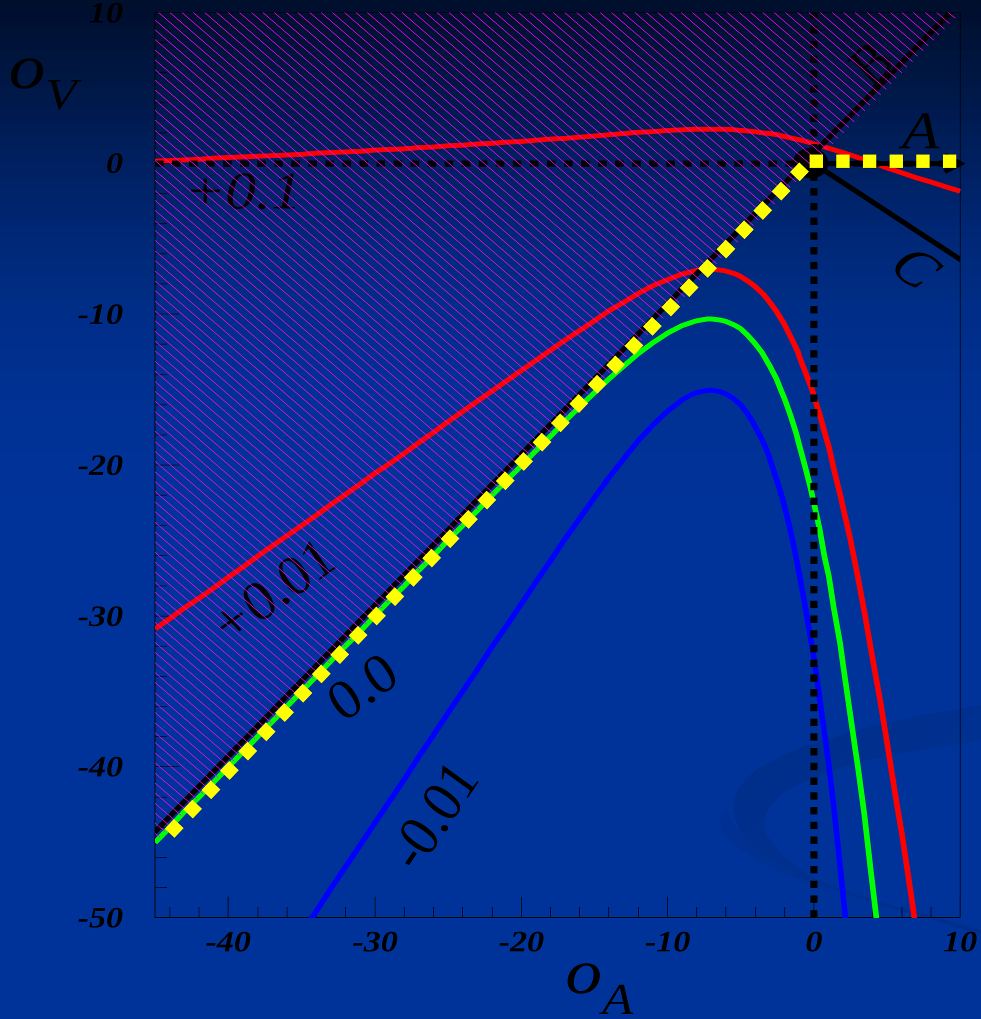
Charged, EWSB

Non-tachyonic

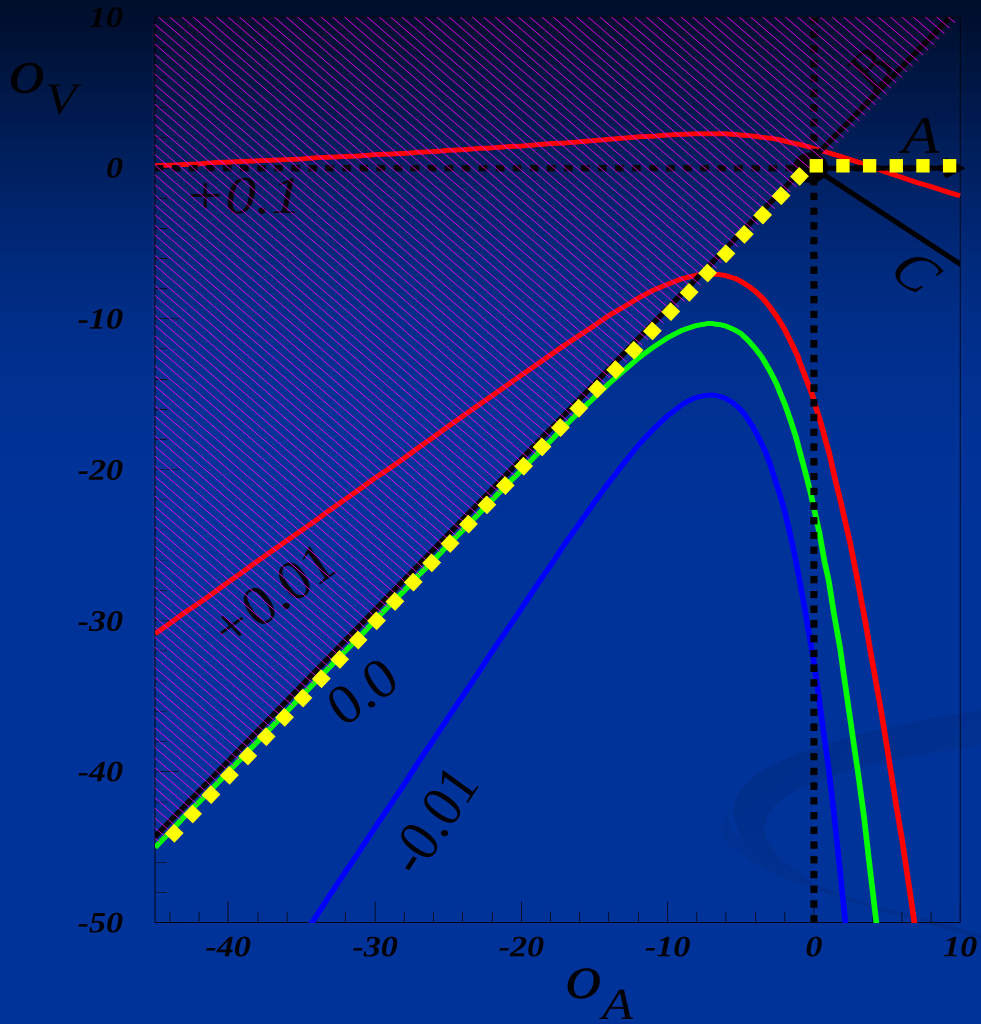
$$v^2 > 0$$

$$o_A^{\phi} = o_V^{\phi} < 0 \qquad o_A^X > 0$$

$$o_V < 0,\ o_A > o_V$$

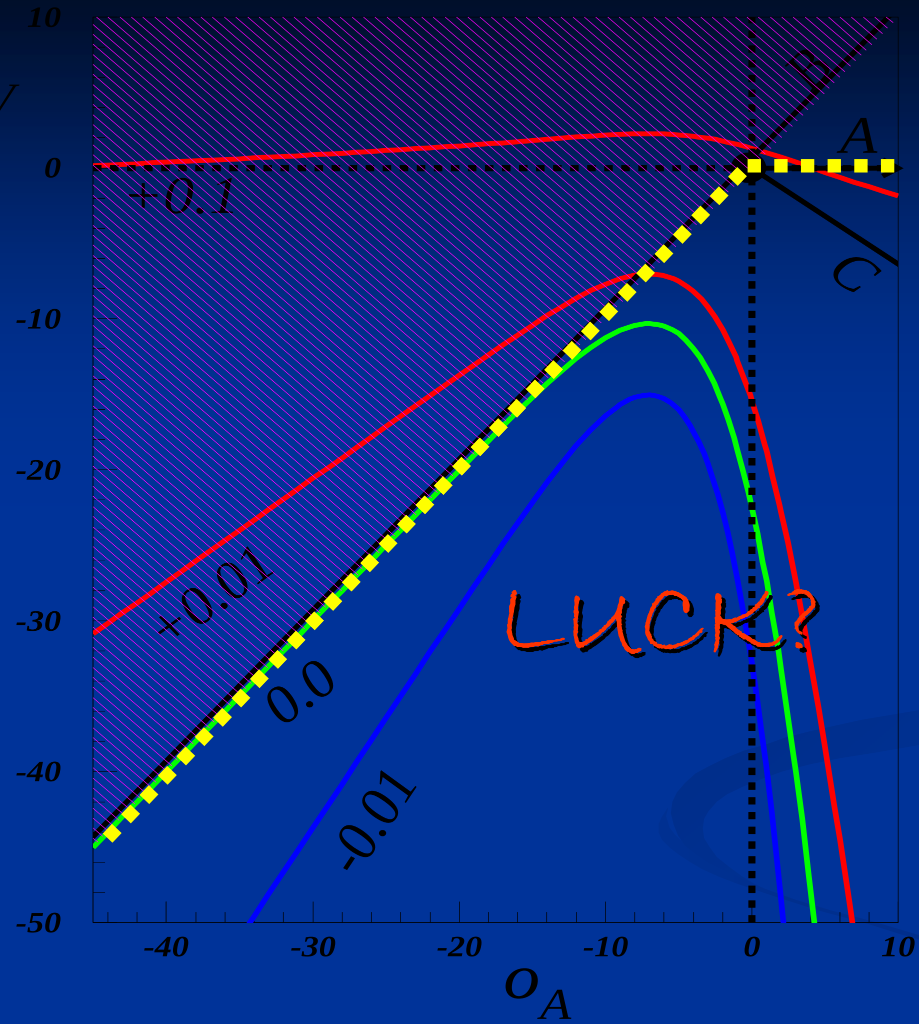


$$o_V < 0,\ o_A > o_V$$



Consistent with negative S and Witten's positivity condition

$$o_V < 0,\ o_A > o_V$$

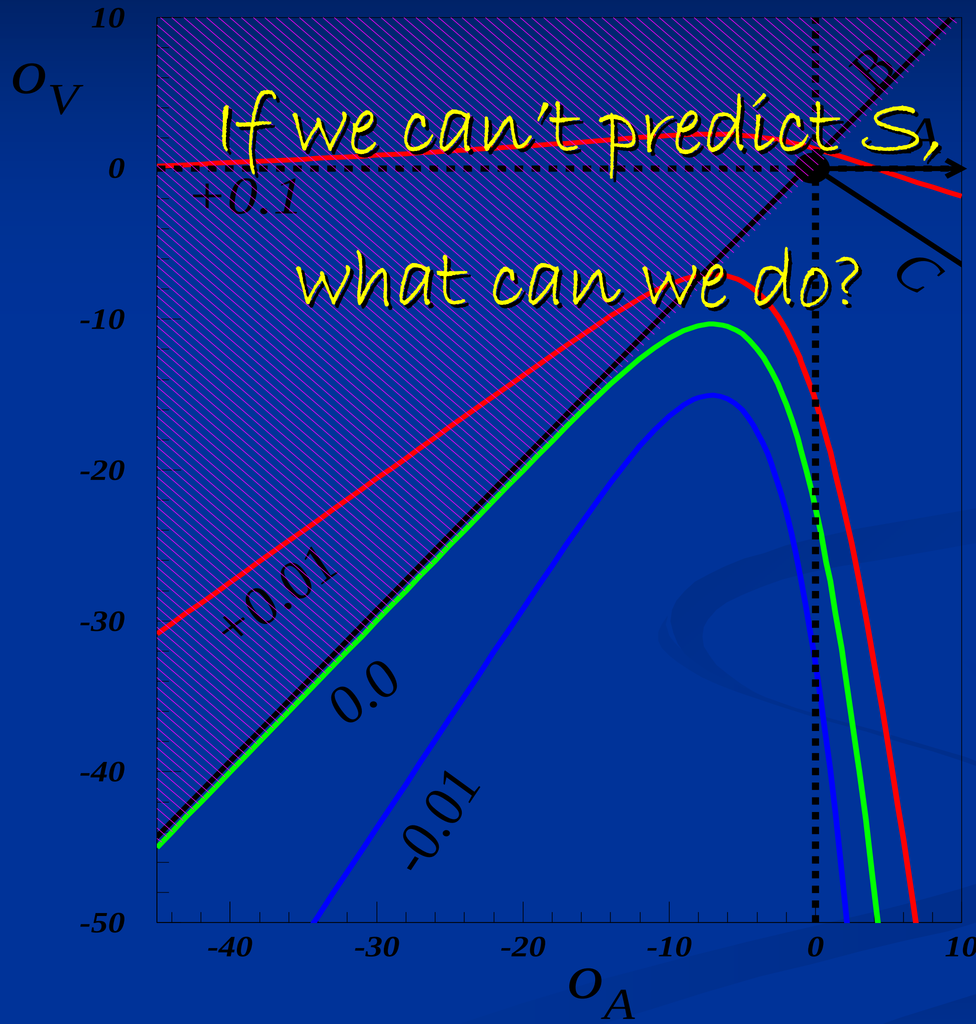


Consistent with negative S and Witten's positivity condition

$$o_V < 0, \; o_A > o_V$$

If we can't predict S,

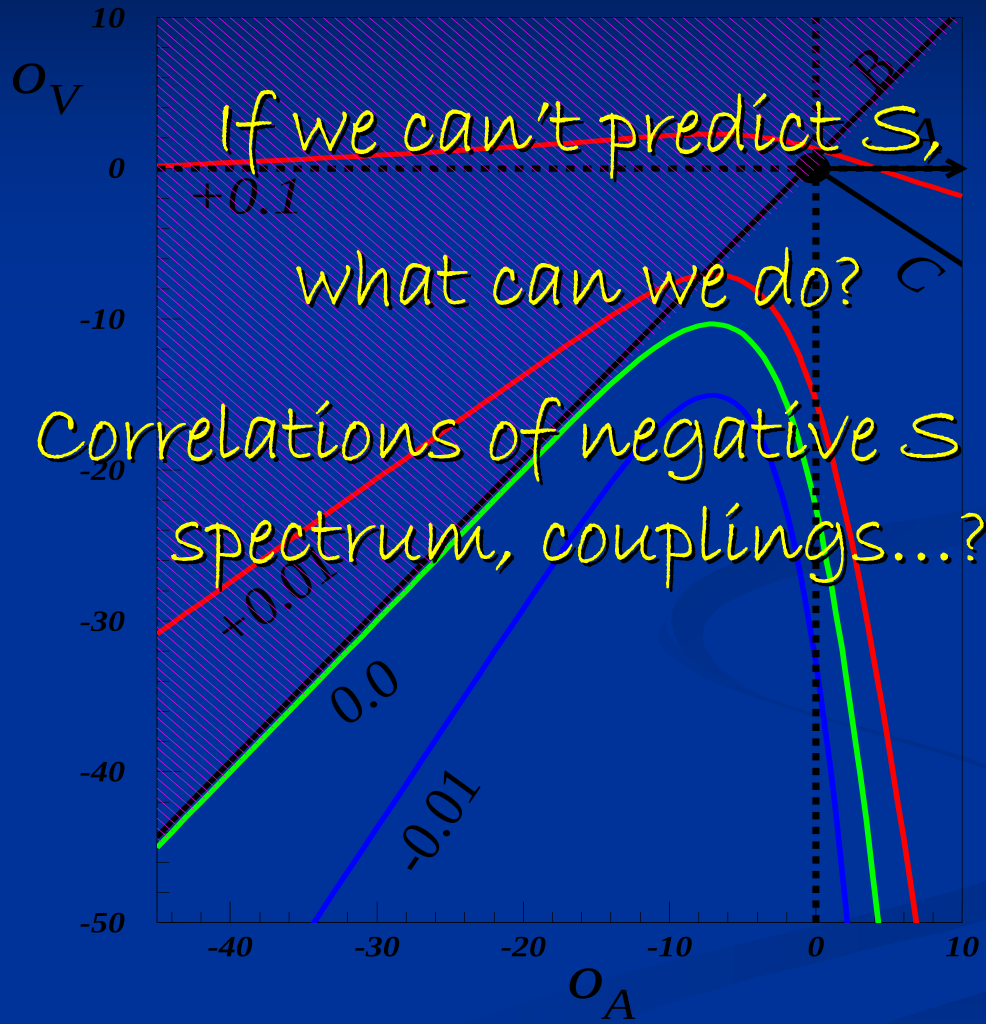
what can we do?



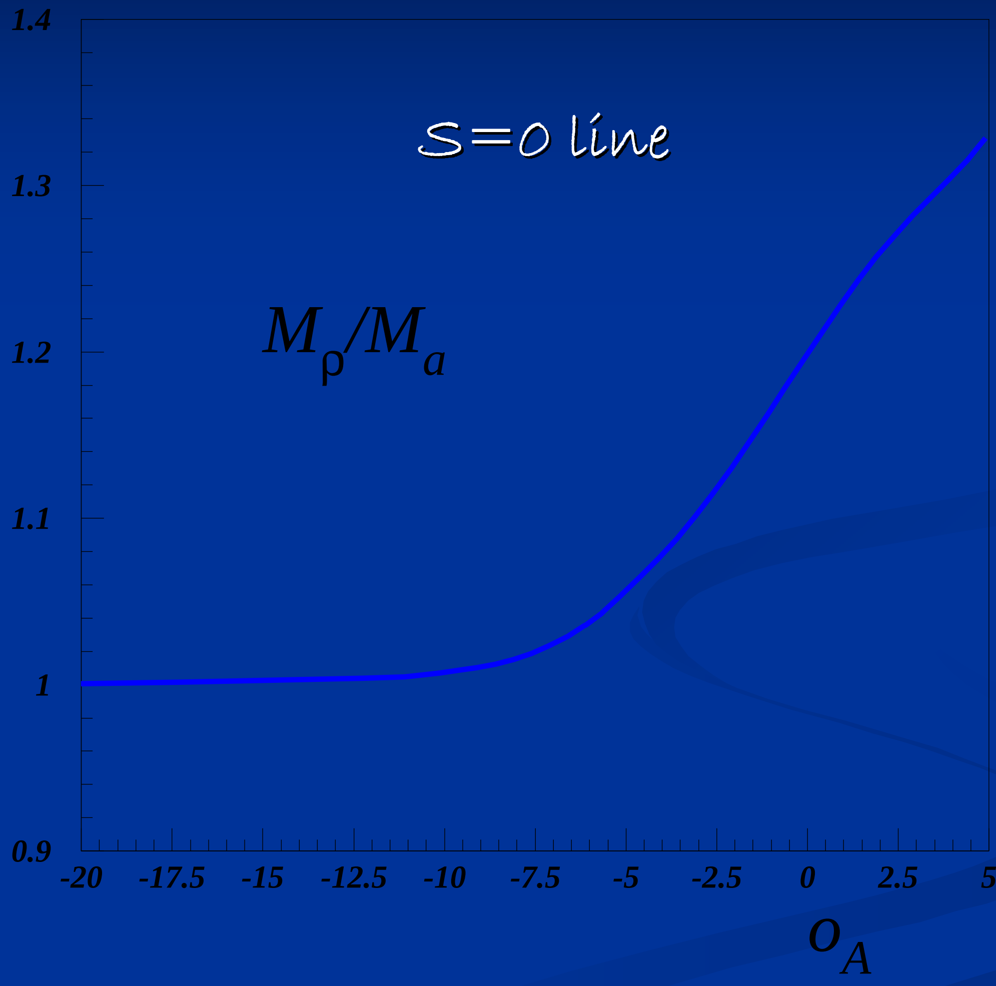
If we can't predict S,

what can we do?

Correlations of negative S and spectrum, couplings…?



For example,



Either degenerate or inverted (axial then vector)

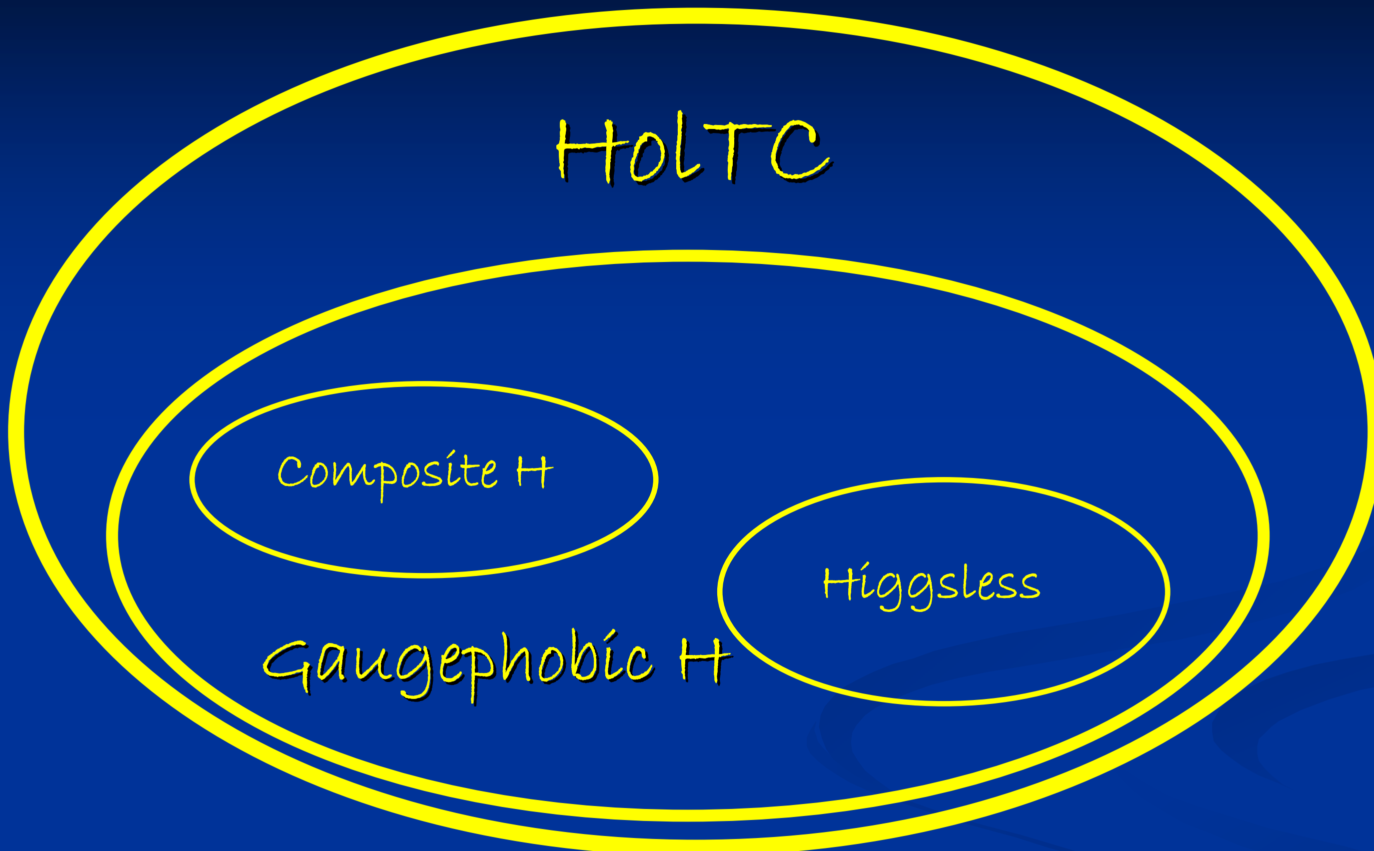
Conclusions

Holography tested on QCD

Rules of the game:

- Large-N
- NDA for condensates
- Quadratic quantities

Rich Pheno (weakly coupled 600 GeV-1 TeV resonances)


HolTC
Composite H
Higgsless
Gaugephobic H

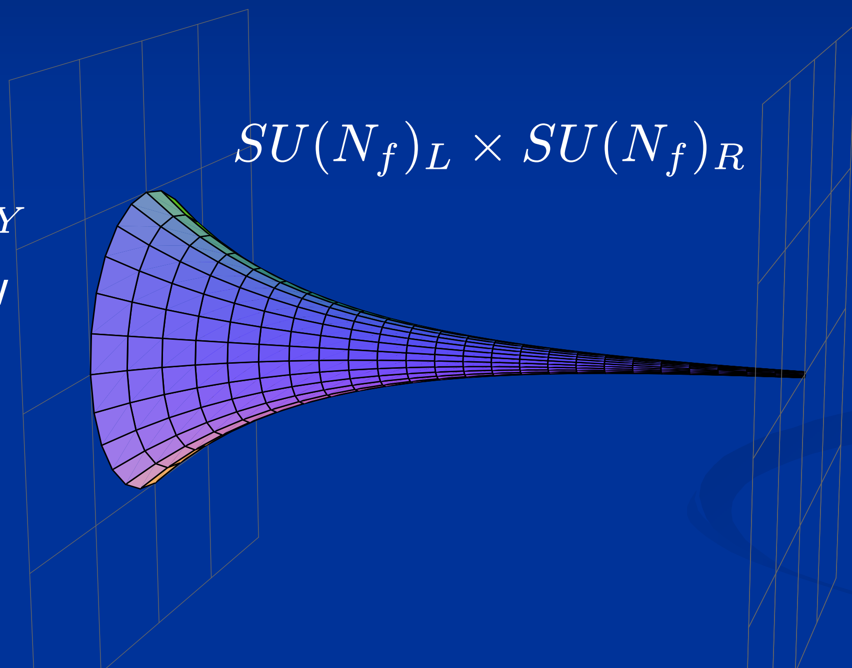
and a technical point

from QCD to TC...

$SU(2)_L \times U(1)_Y$

UV sources now DYNAMICAL!

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



In QCD no dependence on l_0

but TC different