Gauge-Higgs Unification models: a reappraisal

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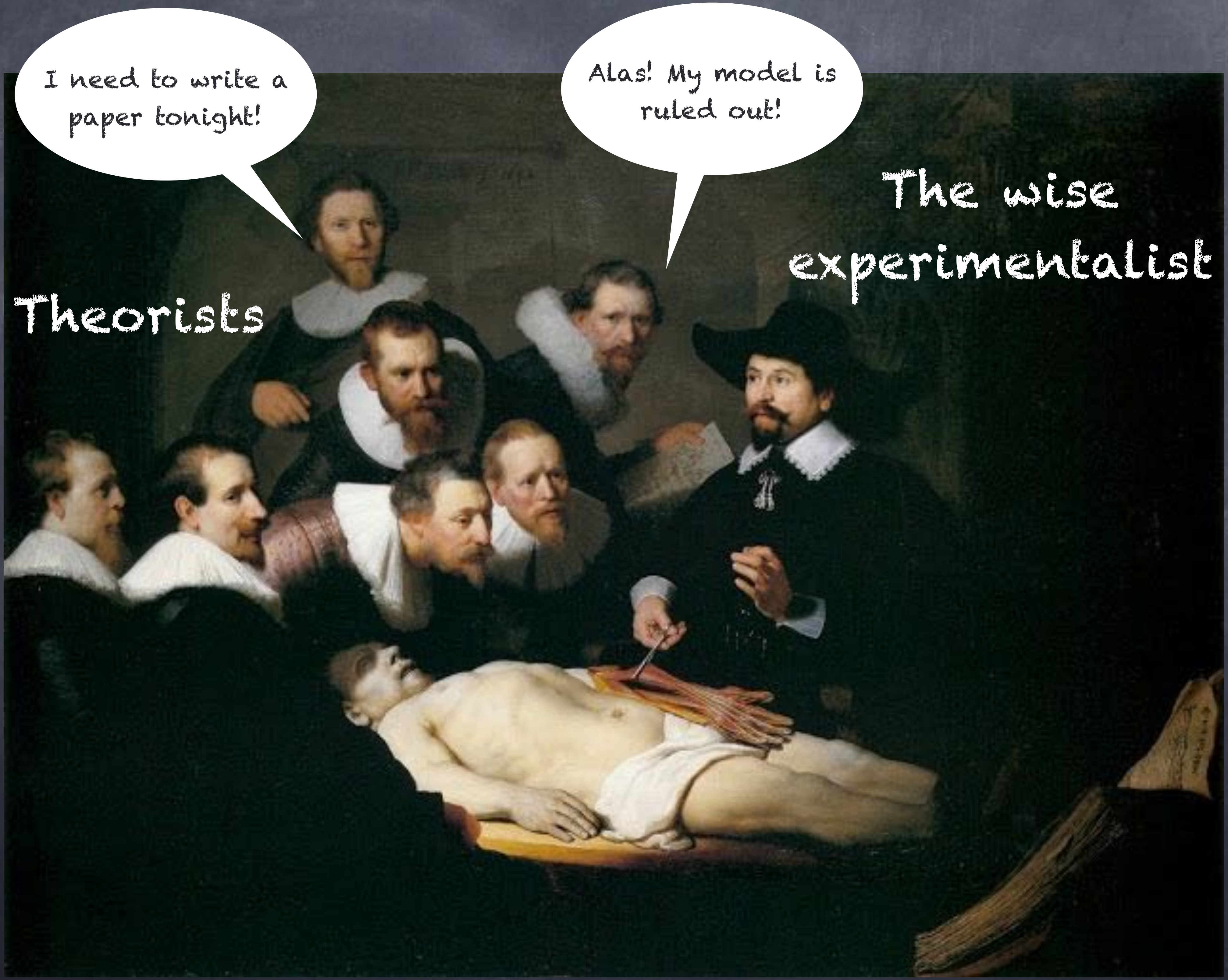
The ideal world:



The real world:

Higgs couplings!

Flavour!

No DM!

EWPTs!

Struggling to put together a model in the midst of "buzzers"!

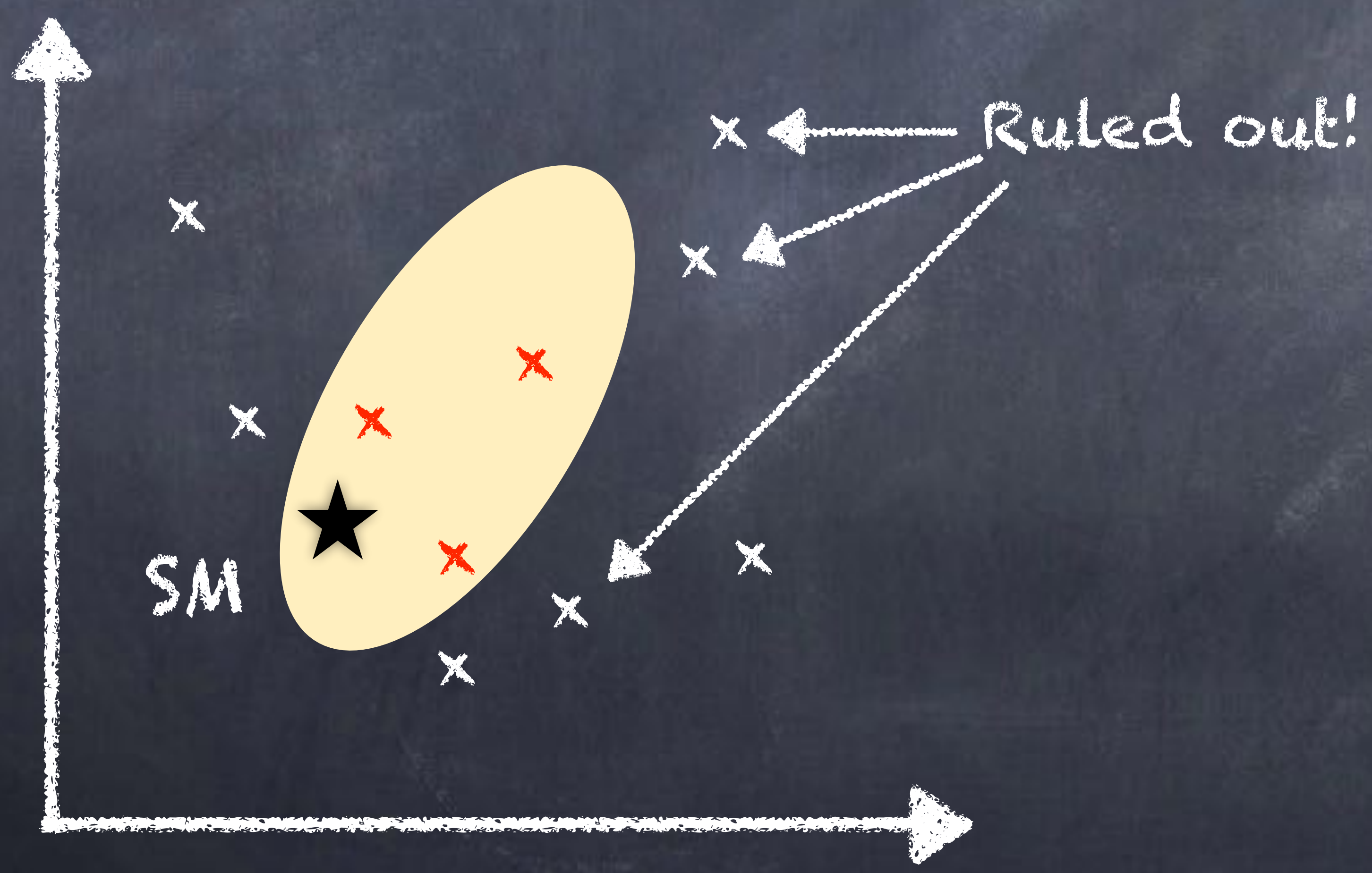
Top couplings!

No bumps!

Higgs mass!

What is our job?

- Models can be ruled out, but cannot be proven right!



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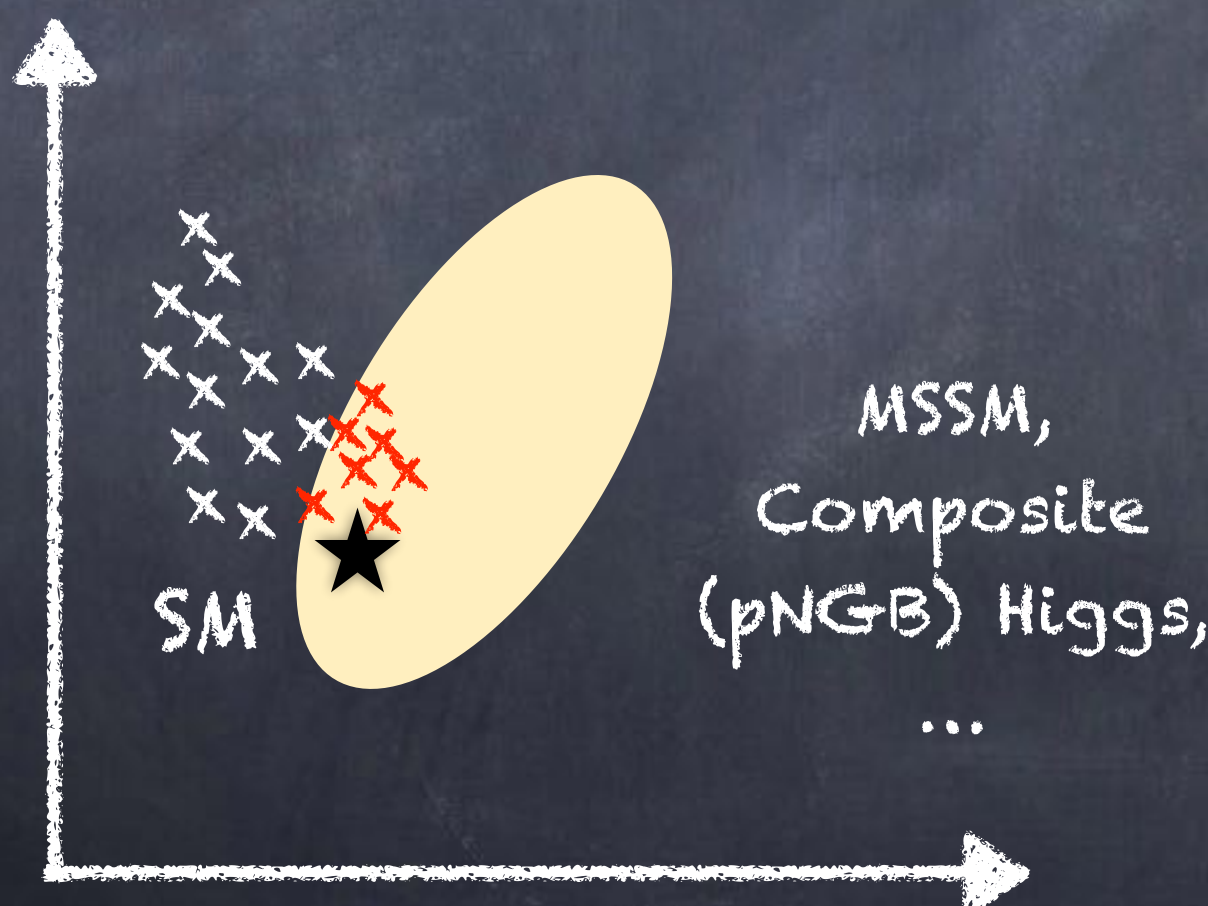

Class A:

Parameter space connected to the SM prediction

↓

Cannot be ruled out!

What is our job?

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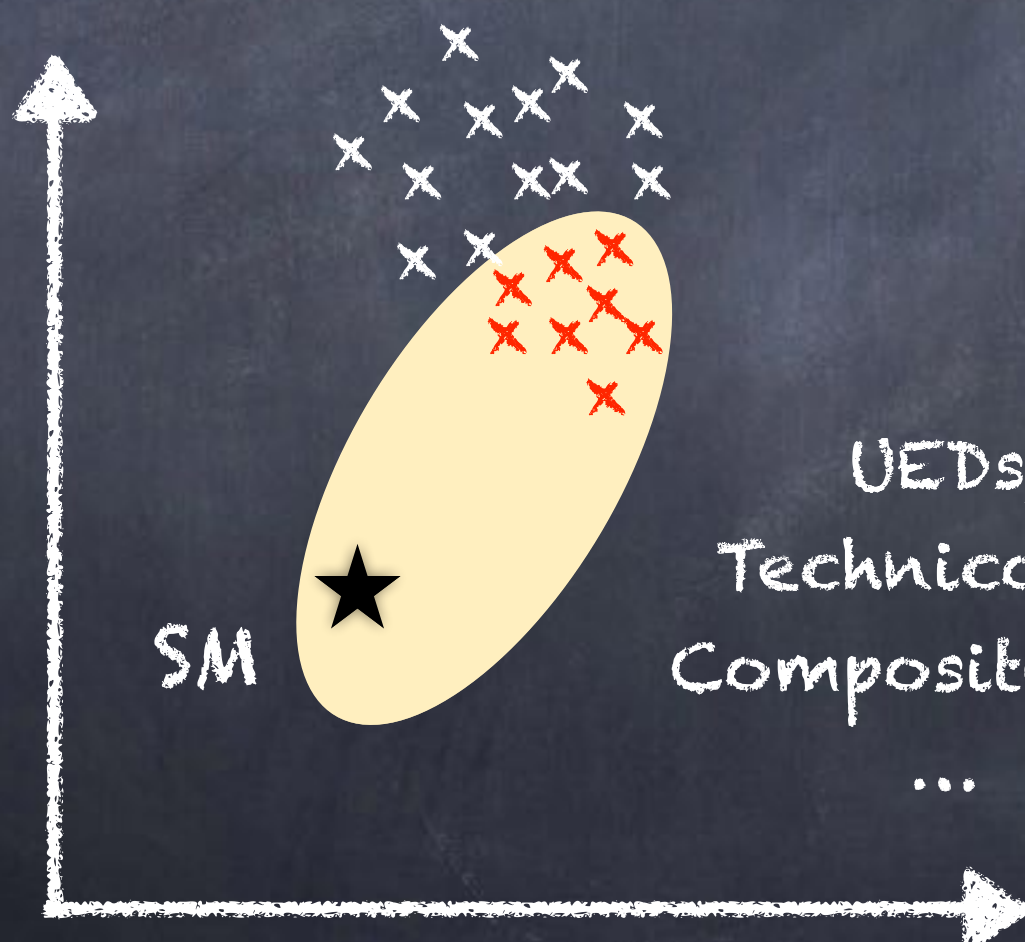

UEDs,
Technicolor,
Composite DM,
...

Class B:

Parameter space disconnected from SM prediction

↓

Can be ruled out!

What is our job?

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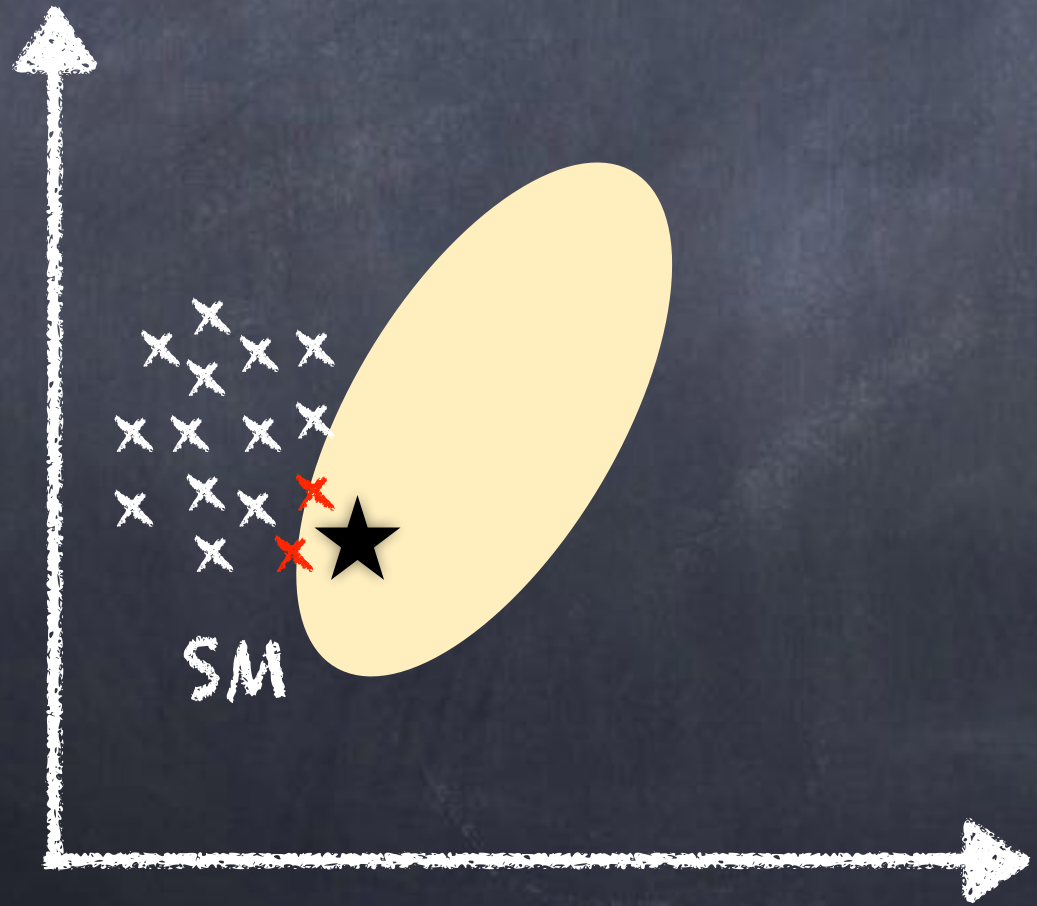


Grey zone:

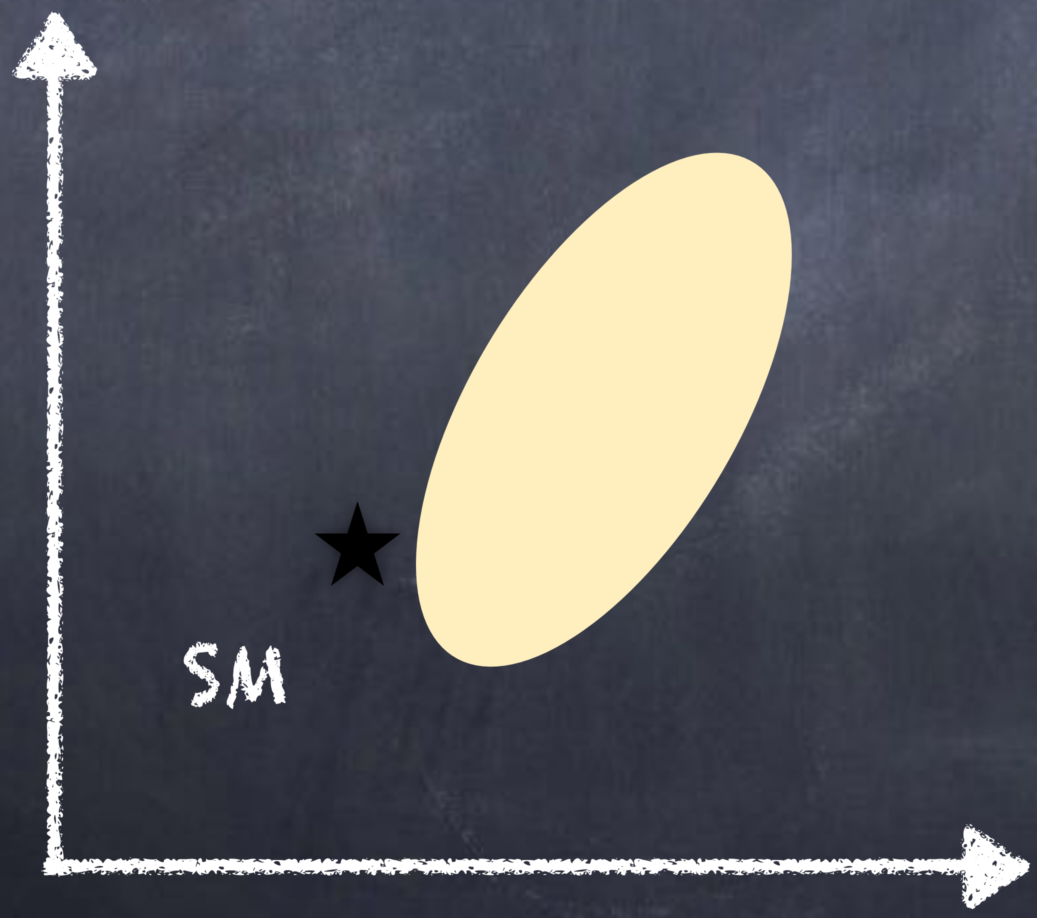
Fine tuning?

Personal taste?

How close to
the decoupling limit?

What is our job?

- Models can be ruled out, but cannot be proven right!



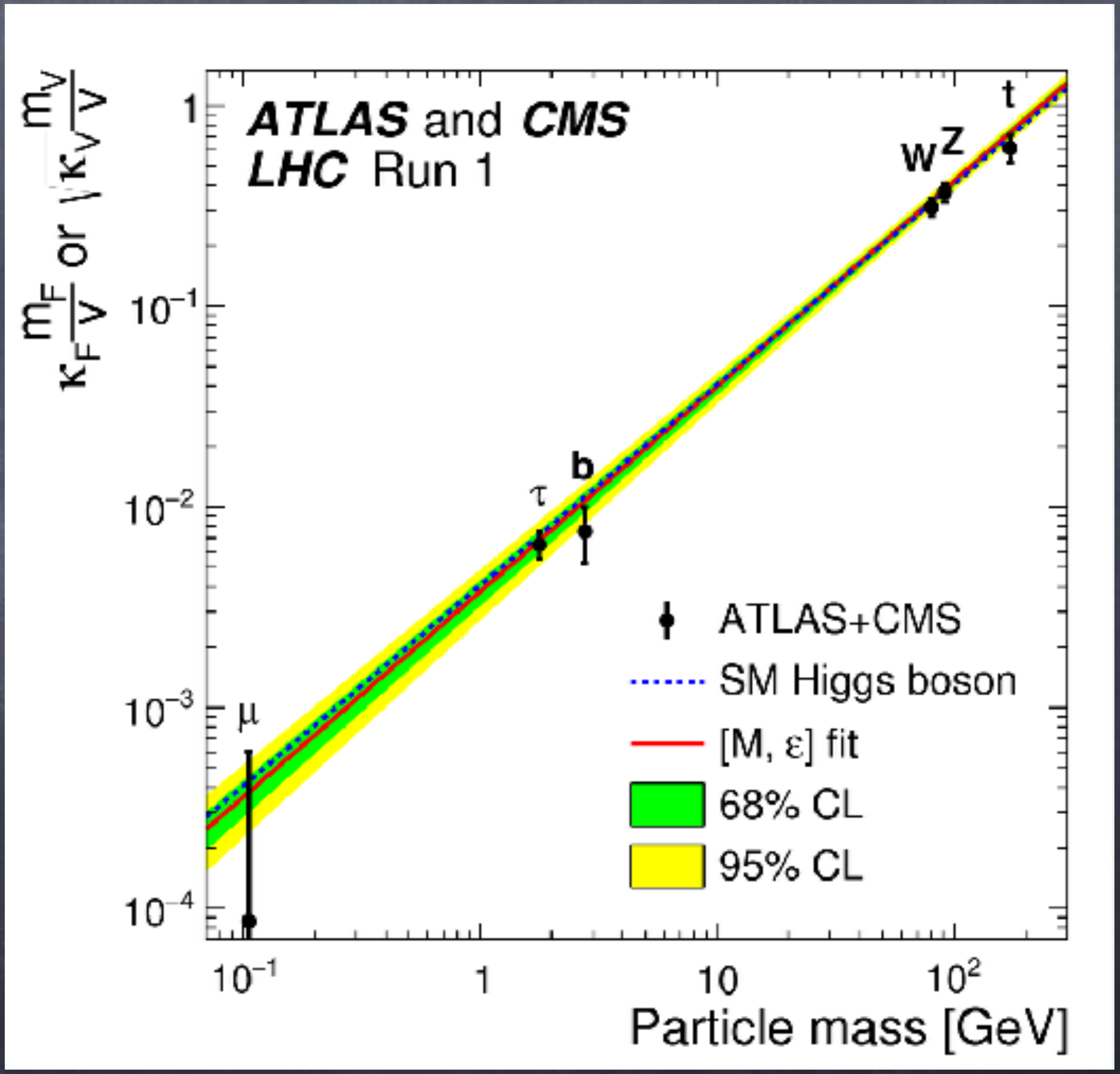
BSM dream:

The SM itself can be excluded!

Are we there yet? No...

What do we know about the Higgs?

- The mass has been precisely measured!
- The couplings follow the SM expectations: being proportional to mass.
- The uncertainties are still large!
- Coupling measurements are always subject to model assumptions!!!



What do we know about the Higgs?

- Theoretical Modelling, i.e. the Standard Model Higgs

$$\mathcal{L}_{\rm Higgs} = (D_\mu \phi)^\dagger (D^\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda\, (\phi^\dagger \phi)^2$$

"wrong sign"

It well describes the symmetry breaking, but no dynamical insight!

$$\tau^i = \frac{\sigma^i}{2}$$

Pauli matrices

$$\phi = e^{i\pi^i \tau^i} \cdot \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$$

$$v = \frac{\mu}{\sqrt{2\lambda}} \sim 246 \;\; \text{GeV}$$

Do we still need BSM?

We have a pretty good idea of the mechanism

But, we don't know how to protect it:

$$\delta m_h^2 \sim \frac{g^2}{16\pi^2} M_{\rm NPh}^2$$

Having measured a light Higgs brings the naturalness problems to the real world!

A natural Higgs = a special type of scalars!

Supersymmetry:

All scalars are special, associated to a fermion by a space-time symmetry!

Scalar <—> Fermion

$$\delta m_h^2 \sim \frac{g^2}{16\pi^2} M_{\cancel{SUSY}}^2 \log \frac{\Lambda}{M_{\cancel{SUSY}}}$$

A natural Higgs = a special type of scalars!

Compositeness:

Special scalars are bound states of more fundamental fermions!

$$\phi \sim \langle \psi\psi \rangle$$

$$\delta m_h^2 \sim \Lambda_{TC}^2 \qquad \Lambda_{TC} \sim 4\pi v_{SM} \sim 3\ TeV$$

A natural Higgs = a special type of scalars!

Goldstones:

Goldstone bosons are special massless scalars.
Masses generated by symmetry breaking spurions.

Usually in association with compositeness:

$$\phi \sim \langle \psi\psi \rangle$$

$$V(h)^{\text{tree}} = 0$$

No potential allowed at tree level!

$$\delta m_h^2 \sim \frac{g^2}{16\pi^2}\Lambda_{TC}^2 \sim v_{SM}^2$$

A natural Higgs = a special type of scalars!

Scalars as gauge bosons:

In extra dimensions, the extra polarisations of gauge bosons are special 4D scalars!

$$\phi \sim A_5\,, \quad A_6\,, \ldots A_D$$

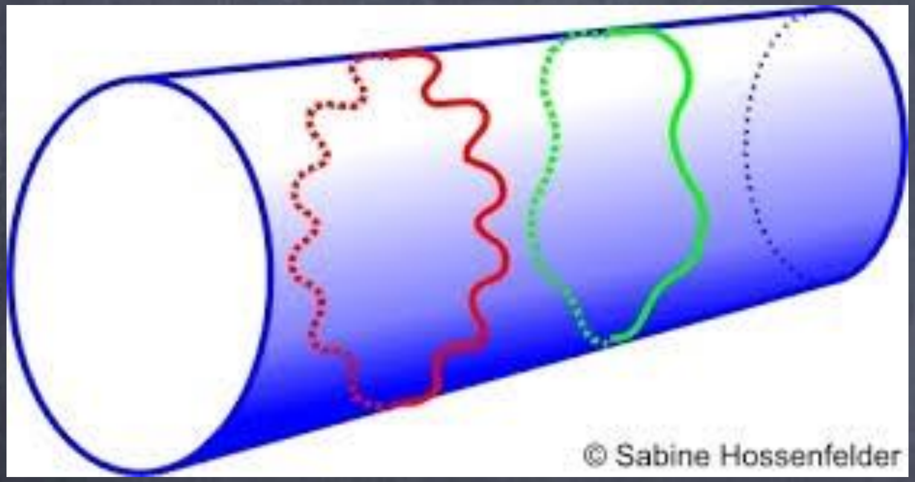
$$V(h)^{\text{tree}} = 0$$

No potential allowed at tree level!

$$\delta m_h^2 \sim \frac{g^2}{16\pi^2}\frac{1}{R^2}$$

Extra dimensions for dummies

- Think of an additional space dimension, wrapped on itself.

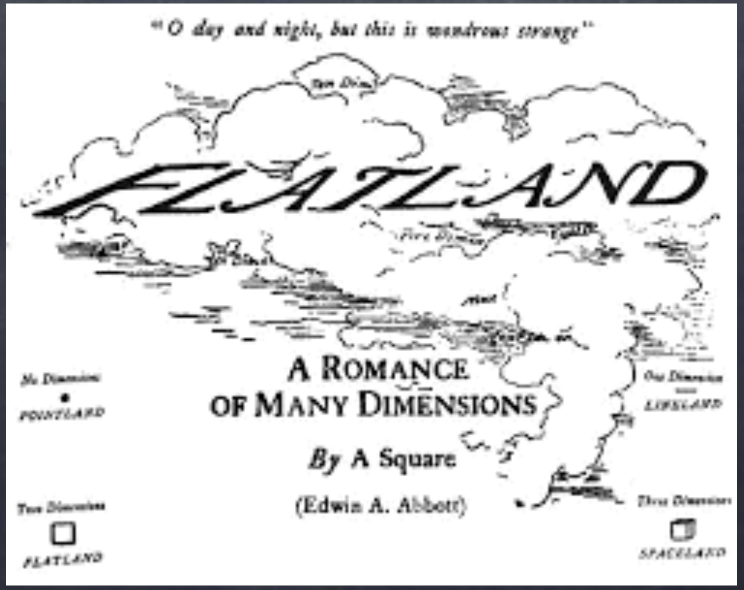


XD fields -> tower of KK states

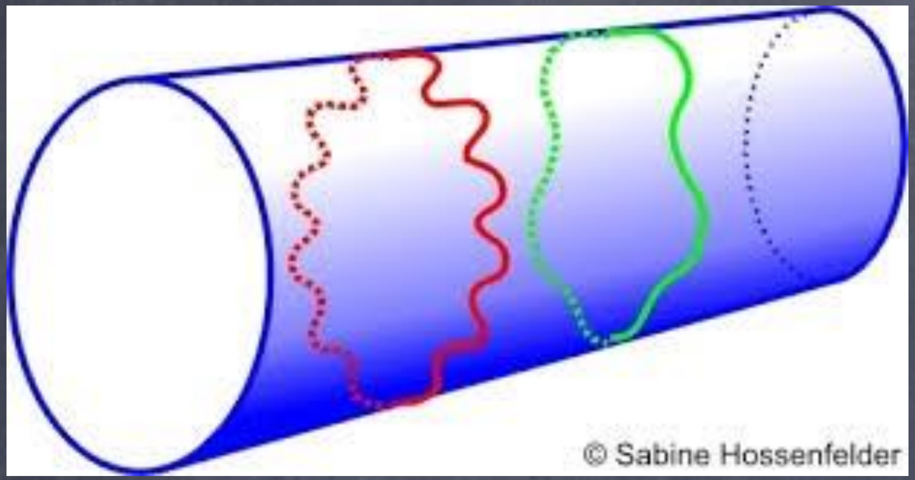
frequencies -> KK masses

geometry -> KK parities

- For us, 4D beings, the 5D fields appear as massive 4D fields!



Extra dimensions for dummies



$$\phi(x^\mu, y)$$

Periodicity condition:

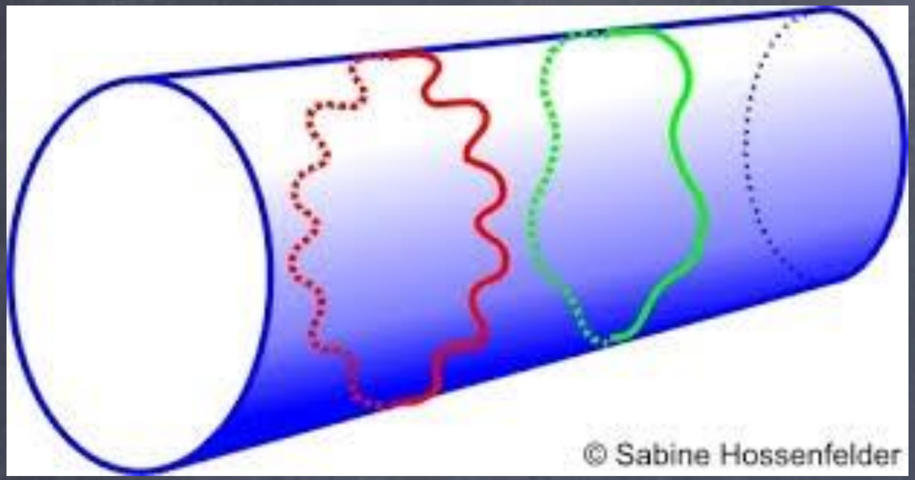
$$\phi(x^\mu, 2\pi R) = \phi(x^\mu, 0)$$

Fourier expansion: $$\phi(x^\mu, y) = \sum_{n\in\mathbb{Z}} \tilde{\phi}_n(x^\mu) e^{in/Ry}$$

$$[\partial_\mu\partial^\mu - \partial_y^2]\phi(x^\mu, y) = \sum_{n\in\mathbb{Z}} e^{in/Ry}[\partial_\mu\partial^\mu - \frac{n^2}{R^2}]\tilde{\phi}_n(x^\mu) = 0$$

5D EOM 4D EOM

Extra dimensions for dummies



Geometric parity can be imposed: orbifold projection

$$\phi(x^\mu, -y) = \pm\phi(x^\mu, y)$$

$$\phi(x^\mu, y) = \sum_{n=0}^{\infty} \cos\left(\frac{n}{R}y\right)\tilde{\phi}_n^+ + \sum_{n=1}^{\infty} \sin\left(\frac{n}{R}y\right)\tilde{\phi}_n^-$$

Parity even. Includes massless n=0 mode!

Parity odd.

XD gauge fields

$$A_M = (A_\mu, A_5)$$

Vector Scalar

$$S = \int d^4x \int_0^{2\pi R} dy \; -\frac{1}{4g_5^2} F_{MN}F^{MN}$$

dim 1 dim 4

$$\frac{2\pi R}{g_5^2} = \frac{1}{g^2}$$

For the zero mode

A generic loop factor will thus grow with the energy. Using Naive dimensional analysis:

$$\frac{g_5^2}{16\pi^2}\Lambda \sim 1 \Rightarrow \Lambda \sim \frac{8\pi}{g^2}\frac{1}{R}$$

An XD Higgs mechanism

$$F_{MN}F^{MN} = F_{\mu\nu}F^{\mu\nu} - 2F_{5\mu}F^{5\mu}$$

$$= F_{\mu\nu}F^{\mu\nu} - 2(\partial_5 A_\mu)^2 - 2(\partial_\mu A_5) + 4(\partial_5 A_\mu)(\partial^\mu A_5)$$

A mixing between (massive) vectors and scalars is present!

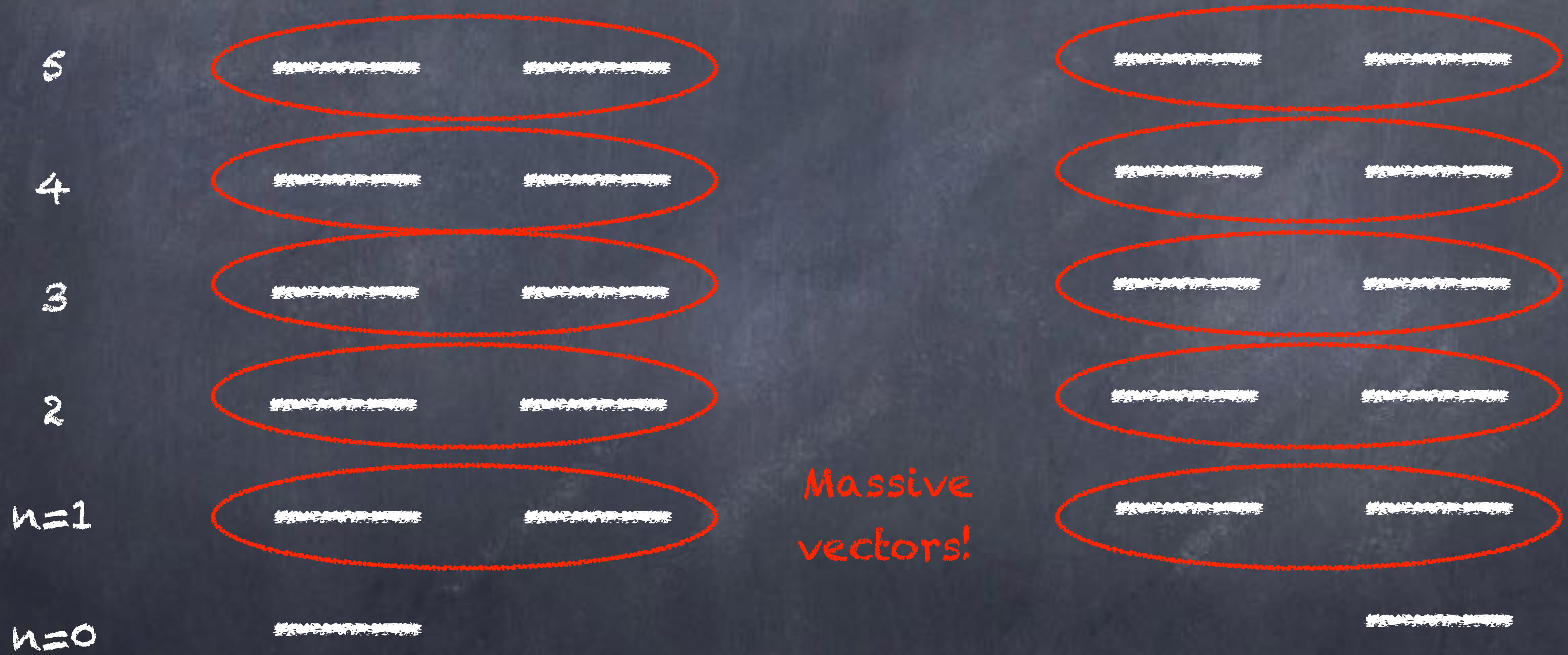
In the orbifold projection vector and scalar have opposite parities.

$$A_M^+ = (A_\mu^+, A_5^-)$$

$$A_M^- = (A_\mu^-, A_5^+)$$

An XD Higgs mechanism

$$A_M^+ = (A_\mu^+, A_5^-) \qquad\qquad A_M^- = (A_\mu^-, A_5^+)$$



An XD Higgs mechanism

$$F_{MN}F^{MN} = F_{\mu\nu}F^{\mu\nu} - 2F_{5\mu}F^{5\mu}$$

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A mixing between (massive) vectors and scalars is present!

In the orbifold projection vector and scalar have opposite parities.

$A_M^+ = (A_\mu^+, A_5^-)$ Massless vector + massive vectors

$A_M^- = (A_\mu^-, A_5^+)$ Massless scalar + massive vectors

- XD gauge theories have a built-in Higgs mechanism via special scalars!
- Gauge symmetries can be broken by orbifold projection (parity assignments)

An SU(3) toy model

$$A_M(-y) = P \cdot A_M(y) \cdot P \qquad P = \begin{pmatrix} -1 & & \\ & -1 & \\ & & 1 \end{pmatrix}$$

SU(2) U(1)

$$A_M^+ \ : \quad \begin{pmatrix} \frac{1}{2}W_3 & \frac{1}{\sqrt{2}}W^+ & 0 \\ \frac{1}{\sqrt{2}}W^- & -\frac{1}{2}W_3 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \frac{1}{2\sqrt{3}}\begin{pmatrix} B & 0 & 0 \\ 0 & B & 0 \\ 0 & 0 & -2B \end{pmatrix}$$

$$A_M^- \ : \qquad \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H_0 \\ H^- & H_0^* & 0 \end{pmatrix}$$

An SU(3) toy model

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H_0 \\ H^- & H_0^* & 0 \end{pmatrix}$$

Can we identify this with the Higgs doublet?

U(1) charge:

$$\frac{1}{2\sqrt{3}}(1-(-2)) = \frac{\sqrt{3}}{2}$$

$$g' = \sqrt{3}g \Rightarrow \sin^2\theta_W = \frac{3}{4}$$

Does not match the SM value!

An SU(3) toy model

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H_0 \\ H^- & H_0^* & 0 \end{pmatrix}$$

Can we identify this with the Higgs doublet?

Easy solution: add a bulk U(1)x gauge symmetry and tune the gx coupling.

U(1) charge:

$$\frac{1}{2}g' = \frac{\sqrt{3}}{2}g + \frac{1}{2}g_x$$

Antoniadis, Benakli, Quiros hep-th/0108005

The Hosotani mechanism

The Higgs VEV can be geometrised!

Hosotani 1983

EWSB induced by giving a VEV to the Higgs, which is a gauge boson.

The VEV can be removed by a suitable gauge transformation:

$$\Omega(y) = e^{i\alpha\ T_H\ y/R}$$

$$H_0 \to H_0 - \partial_y \left(\alpha \frac{y}{R}\right) = H_0 - \frac{\alpha}{R}$$

The periodicity condition is also affected:

$$\Omega(0)\phi(0) = \Omega(2\pi R)\phi(2\pi R)$$

$$\downarrow$$

$$\phi(0) = e^{i2\pi\alpha\ T_H}\ \phi(2\pi R)$$

$$\longrightarrow \quad \phi = \sum_n \tilde{\phi} e^{i(n+\alpha)y/R}$$

The Hosotani mechanism

The Higgs VEV can be geometrised!

$$\phi(0) = e^{i2\pi\alpha\ T_H}\ \phi(2\pi R) \longrightarrow \phi = \sum_n \tilde{\phi} e^{i(n+\alpha)y/R}$$

$$m_n = \frac{|n+\alpha|}{R}$$

The spectrum is shifted.

$$m_0 = \frac{|\alpha|}{R}$$

Zero modes pick up a mass!

How about fermions?

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & H^+ \\ 0 & 0 & H_0 \\ H^- & H_0^* & 0 \end{pmatrix}$$

We can identify this with the Higgs doublet!

Consider a fundamental of SU(3):

$$\psi = \begin{pmatrix} \psi_D \\ \psi_S \end{pmatrix}$$

U(1) charges: $\begin{pmatrix} 1/6 \\ -1/3 \end{pmatrix}$

$$\bar{\psi} D_5 \gamma^5 \psi \quad \Rightarrow \quad \frac{g}{\sqrt{2}} \bar{\psi}_D H \psi_S + h.c.$$

$$y_f = \frac{g}{\sqrt{2}}$$

Yukawa couplings are related to gauge couplings!

The SU(3) model fails!

- Incorrect prediction of the Weinberg angle! $\sin^2\theta_W = \frac{3}{4}$
- Yukawas related to the gauge couplings: $m_f = m_W$

Grossmann, Neubert hep-ph/9912408

It is easy to reduce the fermion masses by use of localisation, but hard to enhance.

The value of the top mass is a serious issue!

Many solutions attempted:

- Looking for other gauge groups: G2, ... Csaki, Grojean, Murayama hep-ph/0210133
- Embedding the top in higher representations. Cacciapaglia, Csaki, Park hep-ph/0510366
- Adding localised couplings/fields. Scrucca, Serone, Silvestrini hep-ph/0304220
- Changing the geometry of the space. Contino, Nomura, Pomarol hep-ph/0306259
- ...

Geometry at work

In flat space, gauge zero modes are constant:

Geometry at work

In flat space, gauge zero modes are constant:

$$\int dy\ H\bar{\psi}\psi = H\int dy\ \bar{\psi}\psi$$

Geometry at work

In warped space, gauge-scalar zero modes are NOT constant:

The overlap integral can give enhancement factors!

Geometry at work

In warped space, gauge-scalar zero modes are NOT constant:

$$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2)$$

Conformal invariant if

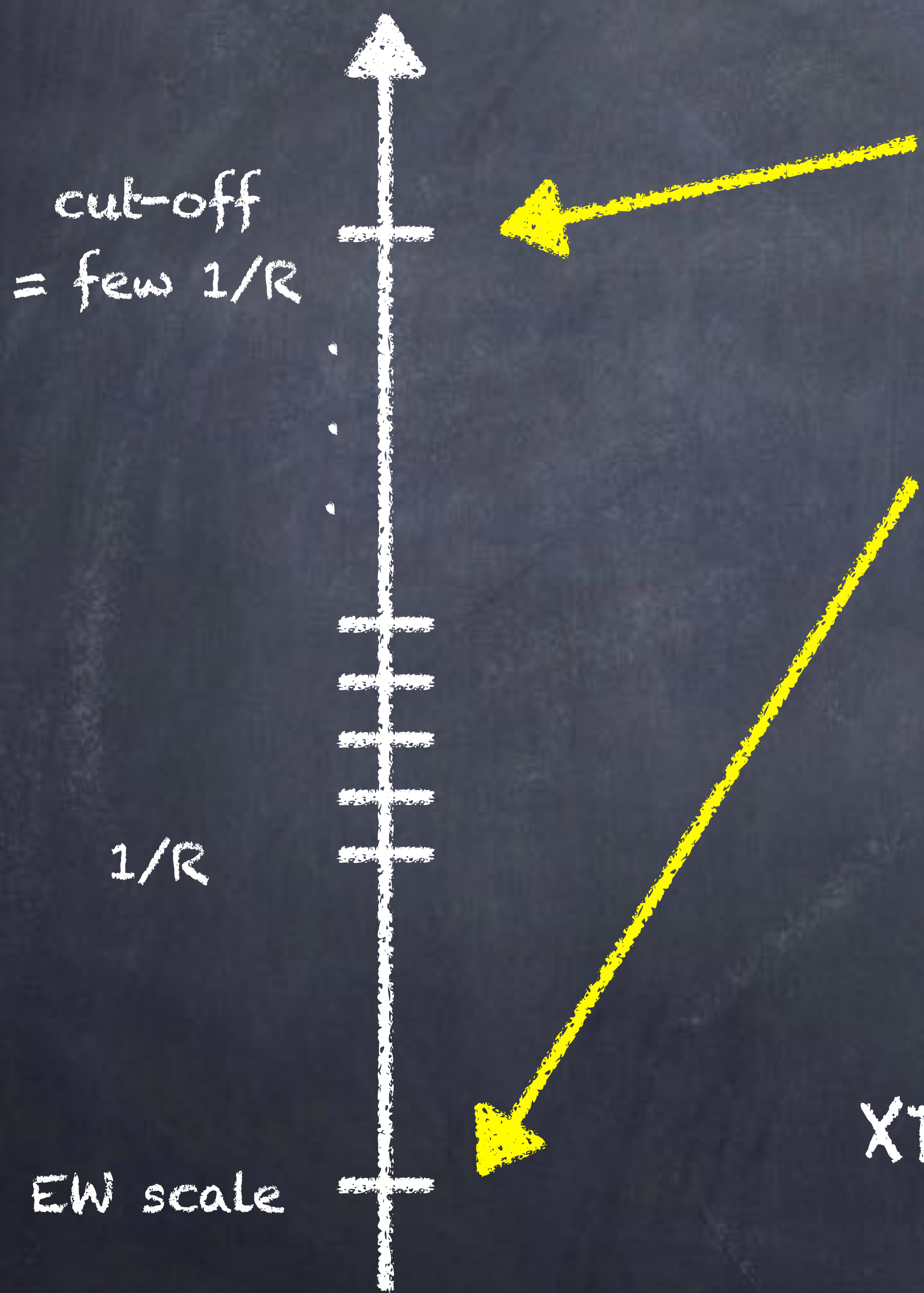
$$x \to \epsilon\, x \qquad z \to \epsilon\, z$$

Randall, sundrum hep-ph/9905221

The AdS/CFT duality (conjectured for supersymmetric models) suggests that the XD model may share the same features of (composite) conformal 4D models!

This observation lead to a revival of composite Higgs models.

One fact has been overlooked so far: couplings run!

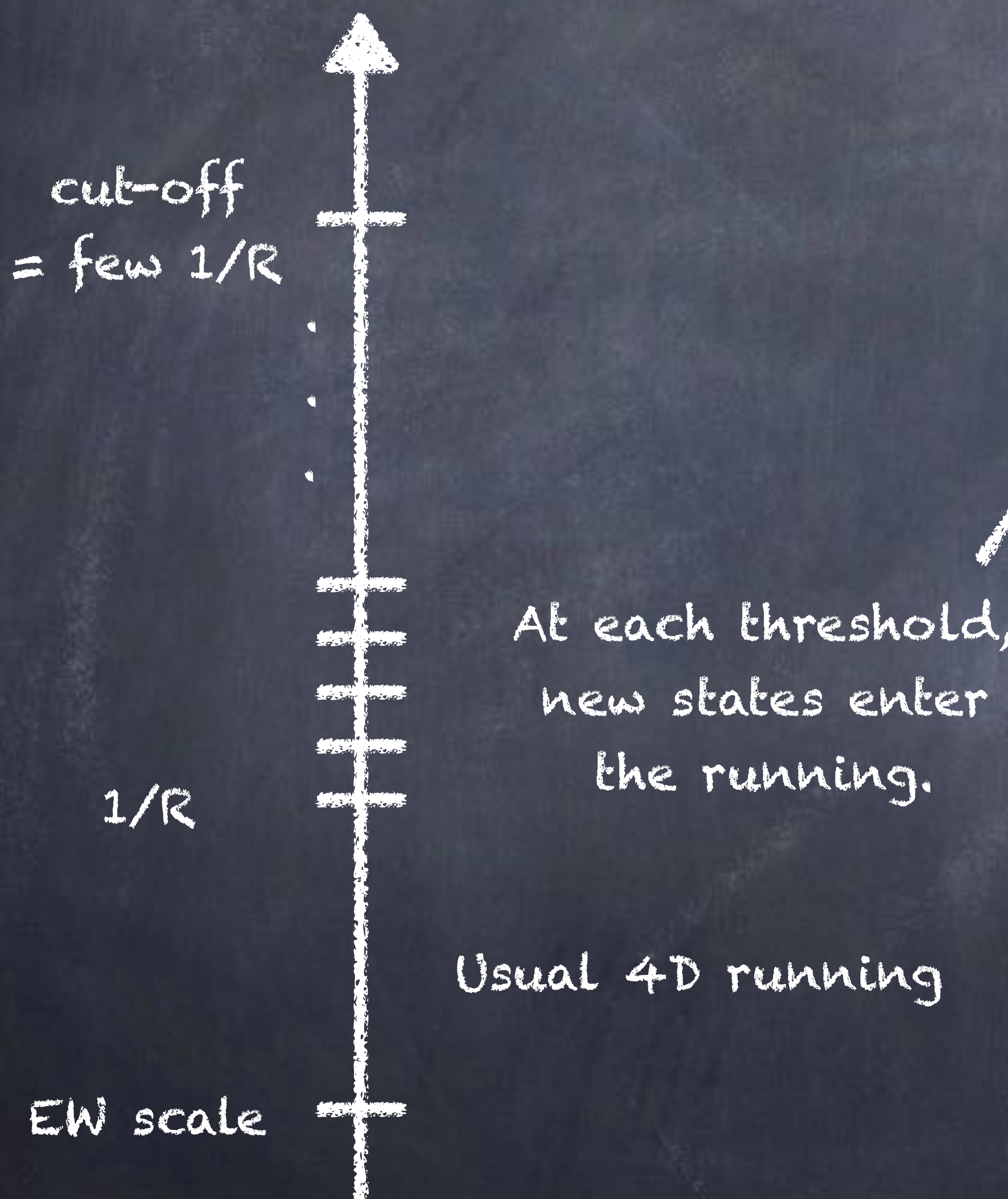


The Unified predictions are valid at this scale.

They need to be matched at the EW scale!

Even though the two scales may not be that far, XD features <u>accelerated running</u>!

One fact has been overlooked so far: couplings run!



The collective effect of the resonances produces a fast linear running vs. the 4D log one!

This fact is well known for the gauge couplings (see XD GUT models).

But, the Yukawas are also gauge couplings!

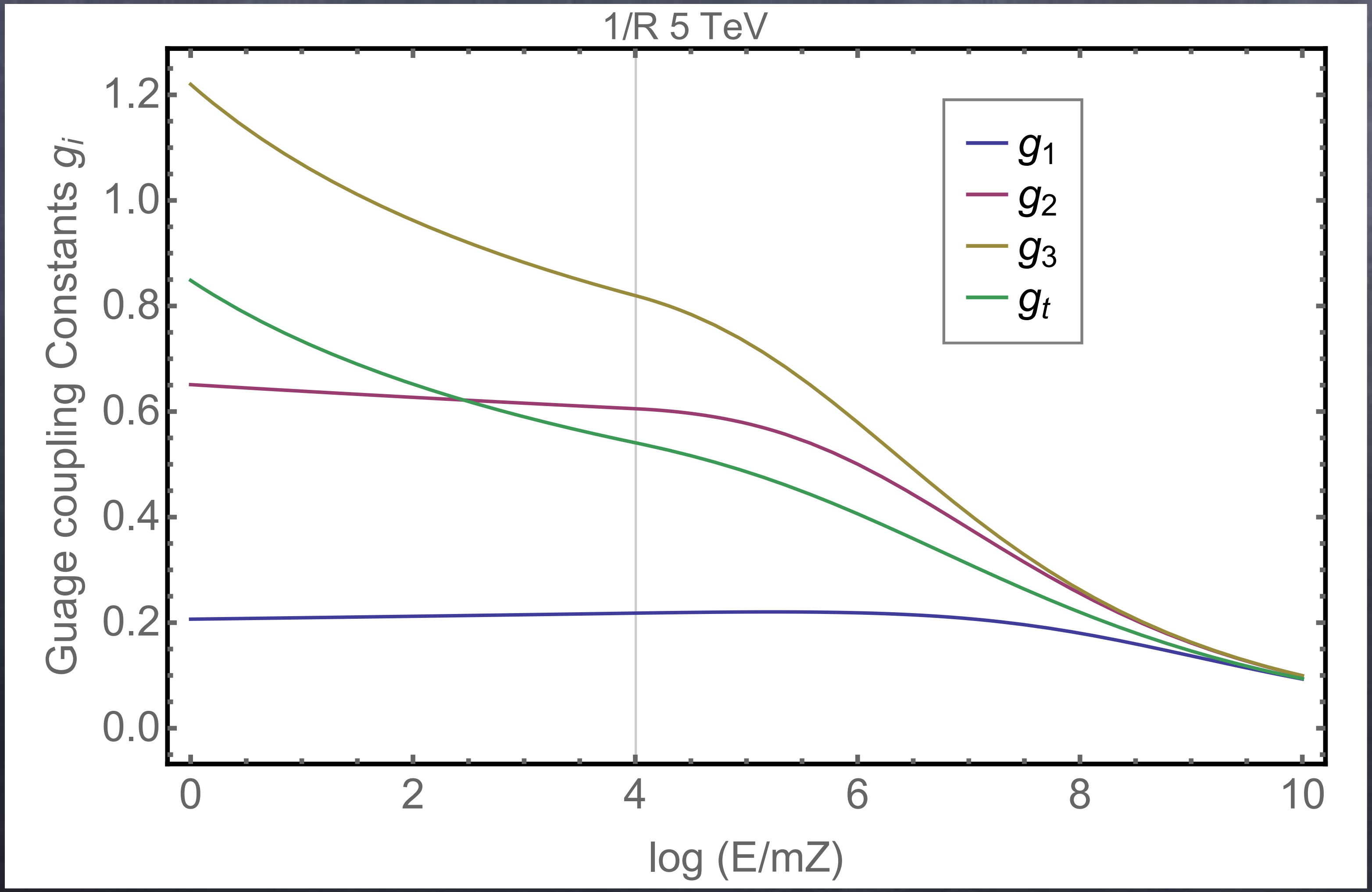
We reconsidered the simple SU(3) model

	$SU(2)_L$	$U(1)_Y$	Yuk.	$SU(3)_c$
	g	g'	y_t	g_s
SU(3) GHU	g_{GHU}	$\sqrt{3}\, g_{GHU}$	$g_{GHU}/\sqrt{2}$	-
SM	0.66	0.35	1.0	1.2

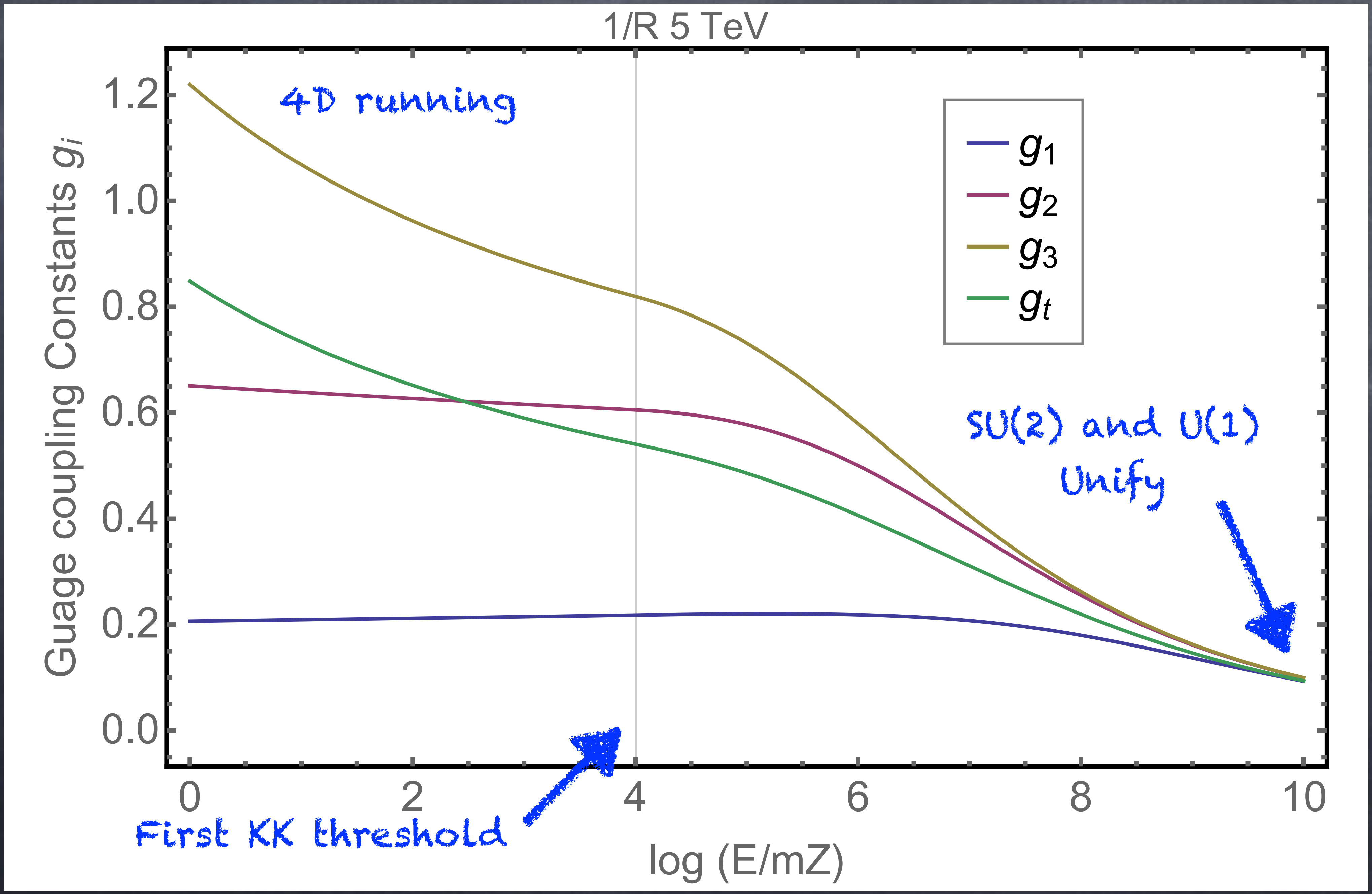
Rescaled couplings:

$$\{g_1, g_2, g_3, g_t\} = \{\frac{g'}{\sqrt{3}}, g, g_s, \sqrt{2}\, y_t\}\,.$$

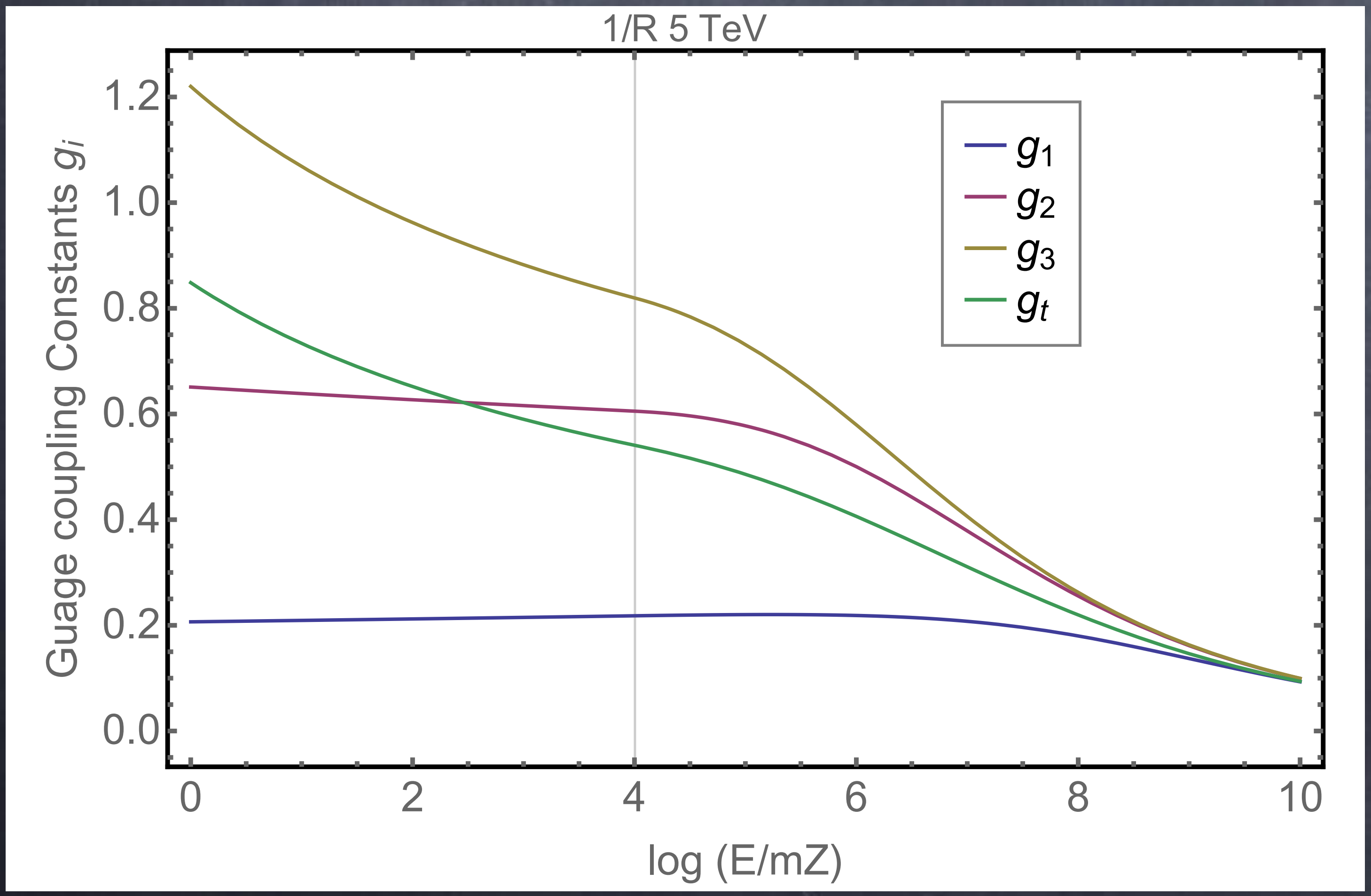
G.C., Cornell, Deandrea, Khogali,
1706.02313v2
to appear.



We reconsidered the simple SU(3) model



We reconsidered the simple SU(3) model



Value of the couplings at Unification:

$$g_2 \sim 0.1$$

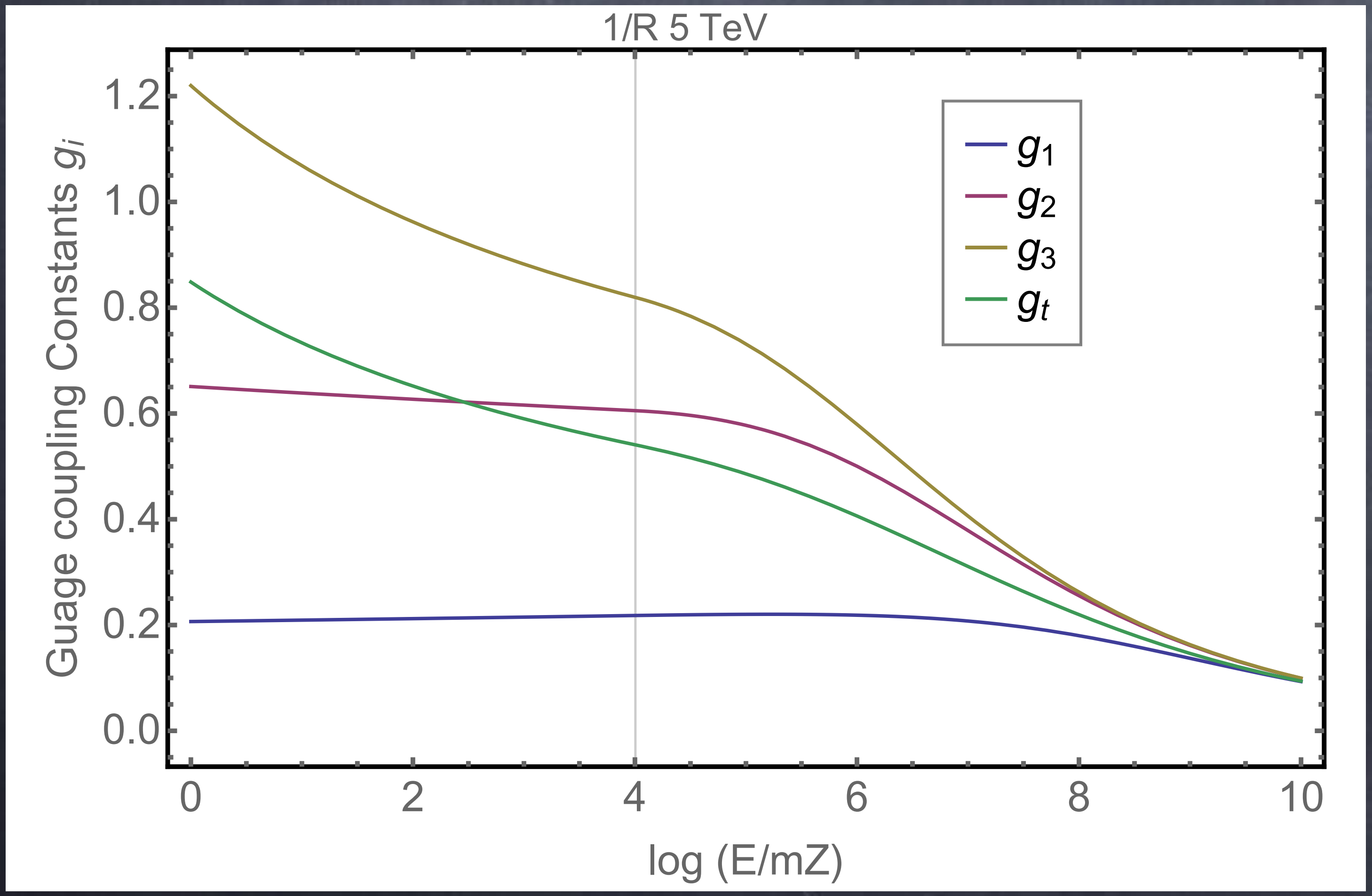
No. of KK modes below Unification.

$$n_{KK} \sim m_Z R e^{10} \sim 400$$

NDA cut=off :

$$\Lambda R \sim \frac{8\pi}{g^2_{\text{Uni.}}} \sim 2000$$

We reconsidered the simple SU(3) model



Value of the couplings at Unification:

$$g_2 \sim 0.1$$

"top" Yukawa at the EW scale:

$$y_t \sim 0.6$$

Running of the gauge couplings:

$$16\pi^2 \frac{dg_i}{dt} = b_i^{\rm SM}\, g_i^3 + (S(t)-1)\, b_i^{\rm GHU}\, g_i^3\,,$$

$$g_i = \{g'\,,\, g\,,\, g_s\}$$

Encodes linear 5D running:

$$S(t) = \begin{cases} \mu R = M_Z R\, e^t & \text{for} \quad \mu > 1/R\,, \\ 1 \quad \text{for} \quad M_Z < \mu < 1/R, \end{cases}$$

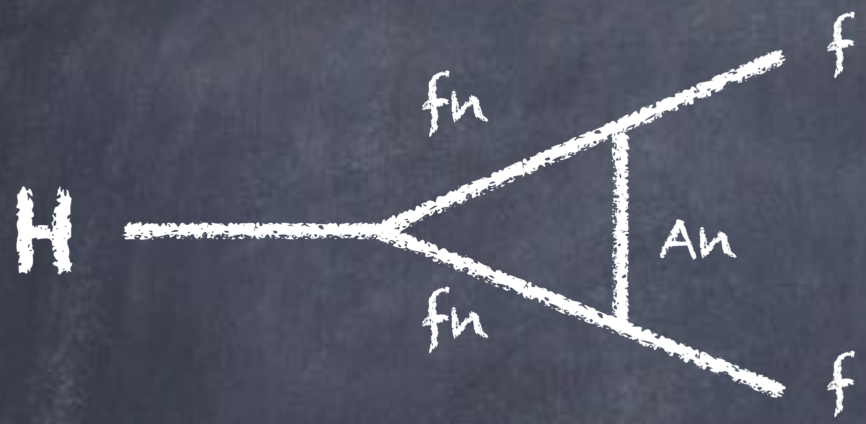
Contribution of KK modes:

$$b_i^{SM} = \left[\frac{41}{6}\,,\, -\frac{19}{6}\,,\, -7\right] \qquad b_i^{GHU} = \left[-\frac{17}{6}\,,\, -\frac{17}{2}\,,\, -\frac{17}{2}\right]$$

Check: same for all couplings!

Running of the Yukawa:

Complication: it depends on other couplings.



We simplify by assuming that couplings of the KK modes follow the running of the gauge/Yukawa couplings

$$16\pi^2 \, \frac{d\, y_t}{d\, t} = \beta_t^{SM} + \Big(S(t) - 1\Big)\, \beta_t^{\mathrm{GHU}},$$

$$\beta_t = y_t \left[c_t \; y_t^2 + \sum_i d_i \; g_i^2 \right]$$

Running of the Yukawa:

$$\beta_t = y_t \left[c_t \; y_t^2 + \sum_i d_i \; g_i^2 \right]$$

Numerical values:

$$c_t^{SM} = \frac{9}{2} \qquad d_i^{SM} = \left[-\frac{5}{12}, \; -\frac{9}{4}, \; -8 \right]$$

$$c_t^{GHU} = \frac{21}{2} \qquad d_i^{GHU} = \left[-\frac{35}{24}, \; -\frac{39}{8}, \; -4 \right]$$

Running of the Yukawa:

$$\beta_t = y_t \left[c_t \, y_t^2 + \sum_i d_i \, g_i^2 \right]$$

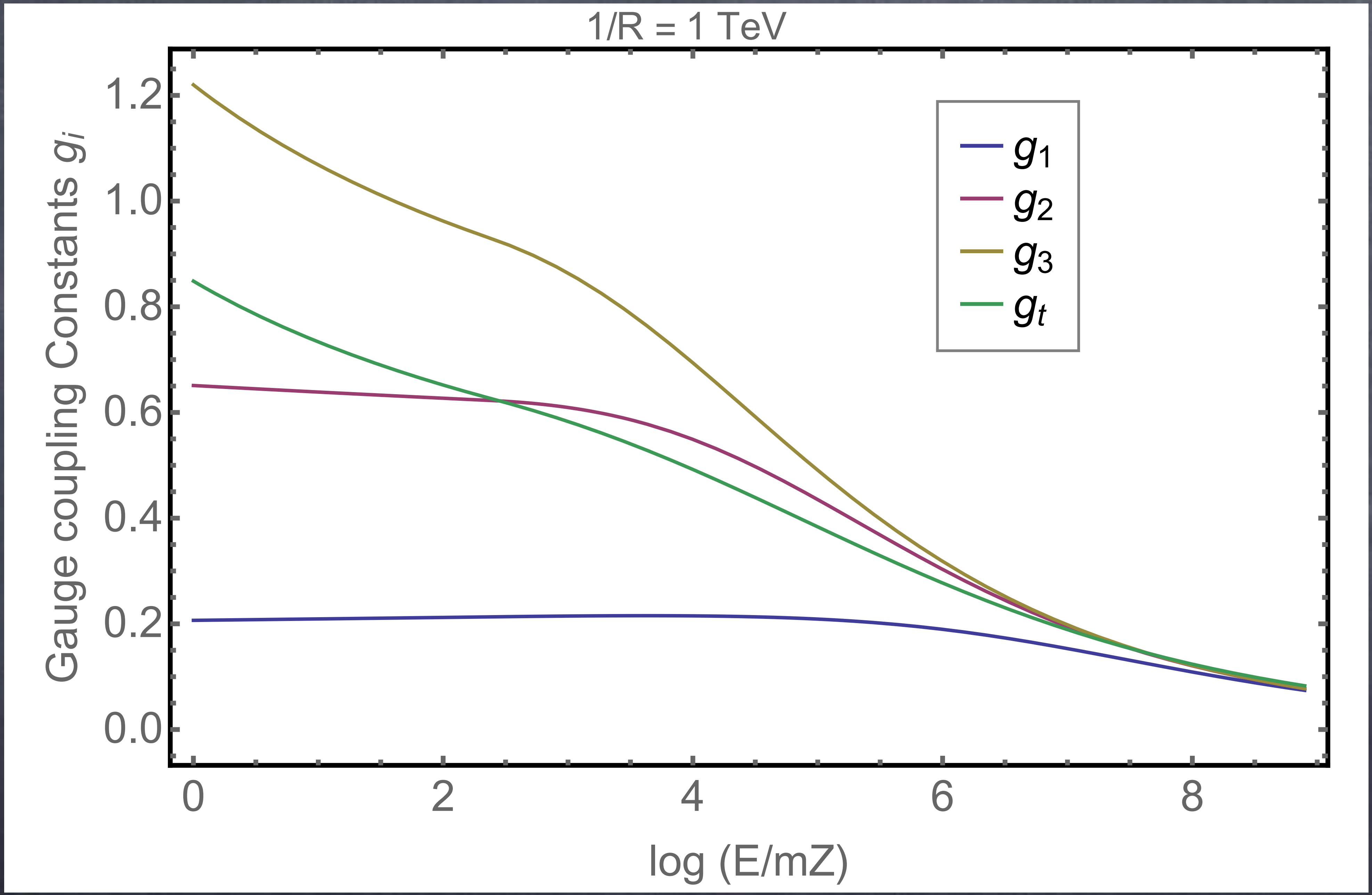
$$c_t^{GHU} = \frac{21}{2} \qquad d_i^{GHU} = \left[-\frac{35}{24}, \, -\frac{39}{8}, \, -4 \right]$$

Imposing the Unification relations $\quad g' = \sqrt{3}\, g \,, \; y_t = \frac{g}{\sqrt{2}} \,,$

$$\beta_t = \left(-4 \, g^2 - 4 \, g_s^2 \right) \frac{g}{\sqrt{2}}$$

Conclusions

- Gauge-Higgs Unification models have been prematurely abandoned
- Running of the gauge and Yukawa couplings <u>needed</u> to properly match the theory to the EW scale!
- We show in a SU(3) toy model that the tree level tensions can be softened by the running!
- More work needs to be done towards a realistic model: <u>Higgs mass</u>?



1/R = 1 TeV
Gauge coupling Constants g_i
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
log (E/mZ)
g_1
g_2
g_3
g_t