Composite Higgs Models

Michele Redi

OUTLINE

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- Standard Model Higgs
- Physics Beyond the SM
- Composite Higgs

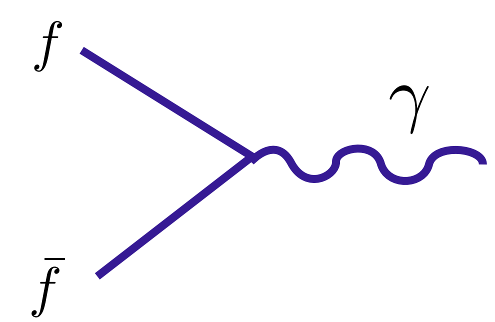
STANDARD MODEL

SM is built on the principle of gauge invariance

- U(1): Electromagnetism

$$A_\mu(x) \to A_\mu(x) + \partial_\mu \alpha(x)$$

$$\mathcal{L} = -\frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu}$$



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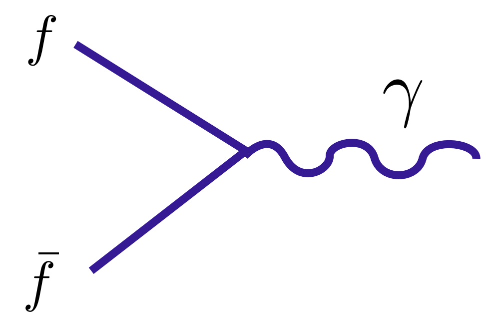
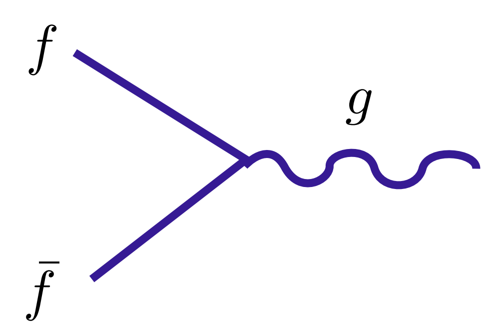
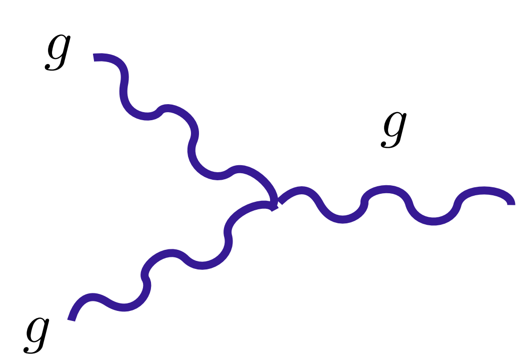


- SU(n): Yang-Mills theory



$$\delta A_\mu^a \to f^{abc} \alpha^b A_\mu^c + \partial_\mu \alpha^a$$

$$\mathcal{L} = -\frac{1}{4g^2} F_{\mu\nu}^a F^{a\mu\nu}$$



SM gauge group:

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$g_3 \simeq 1.2$$

$$g_2 \simeq 0.65$$

@ 100 GeV

$$g_3 \simeq 0.36$$

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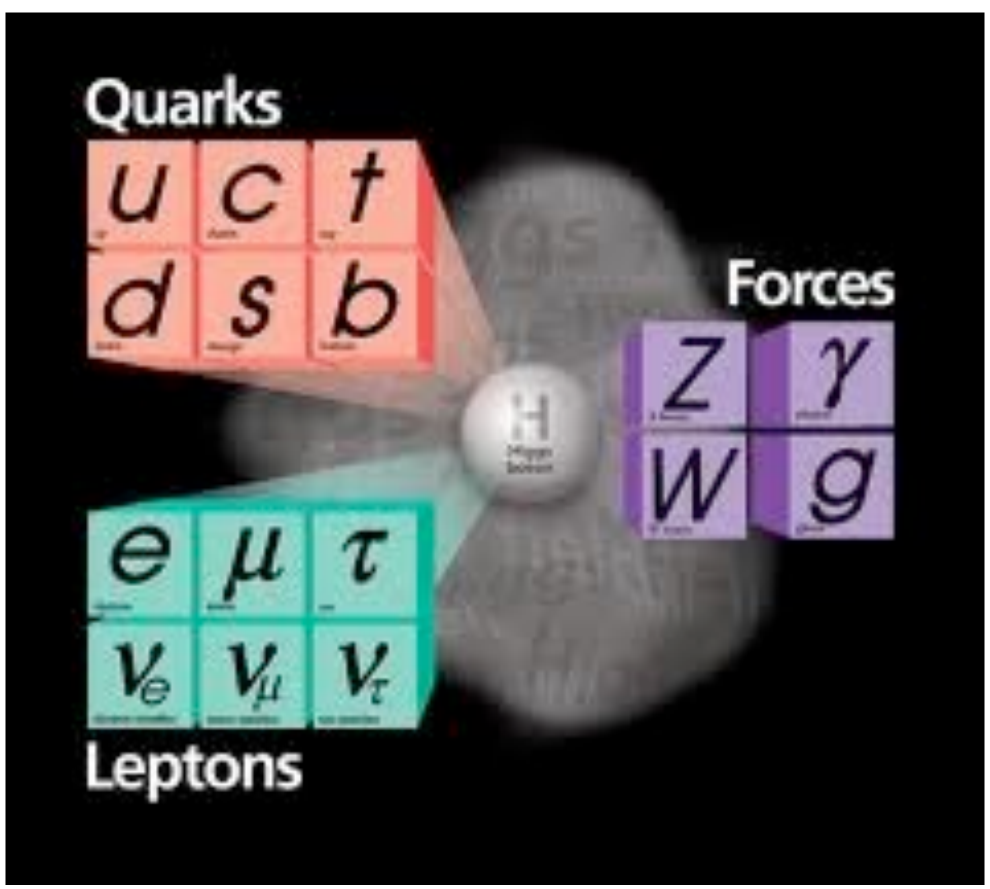

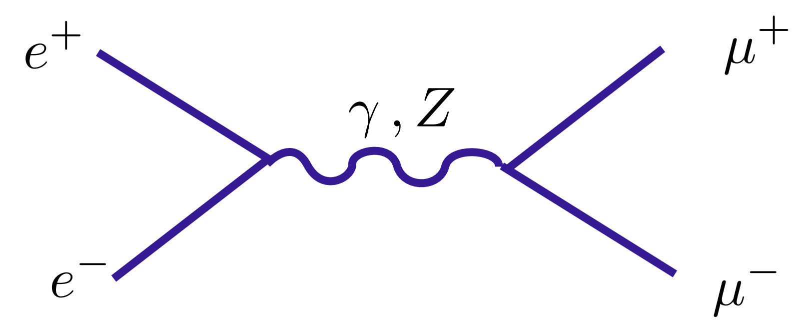

Unbroken symmetry forbids mass terms: vacuum must respect a smaller symmetry

$$SU(3)_c \otimes U(1)_Q \longrightarrow \frac{SU(2)_L \times U(1)_Y}{U(1)_Q}$$

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$$SU(3)_c \otimes U(1)_Q \longrightarrow \frac{SU(2)_L \times U(1)_Y}{U(1)_Q}$$

family \ type	ups	downs	leptons
3rd	$m_t = 175$	$m_b = 4.2$	$m_\tau = 1.7$
2nd	$m_c = 1.2$	$m_s = 0.1$	$m_\mu = 0.1$
1st	$m_u = 3 \times 10^{-3}$	$m_d = 5 \times 10^{-3}$	$m_e = 5 \times 10^{-4}$

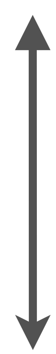
(GeV)

$$m_W = 80.4\,\text{GeV}$$

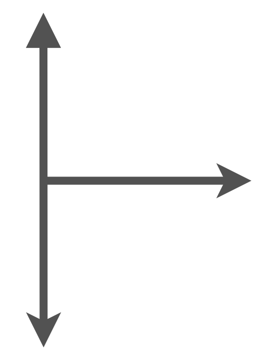
$$m_Z = 91.2\,\text{GeV}$$

Mass for spin-1 means new degrees of freedom

$m_1 = 0$



$m_1 \neq 0$



Mass for spin-1 means new degrees of freedom

$m_1 = 0$ $\qquad\qquad$ $m_1 \neq 0$

The extra degrees of freedom are Goldstone Bosons

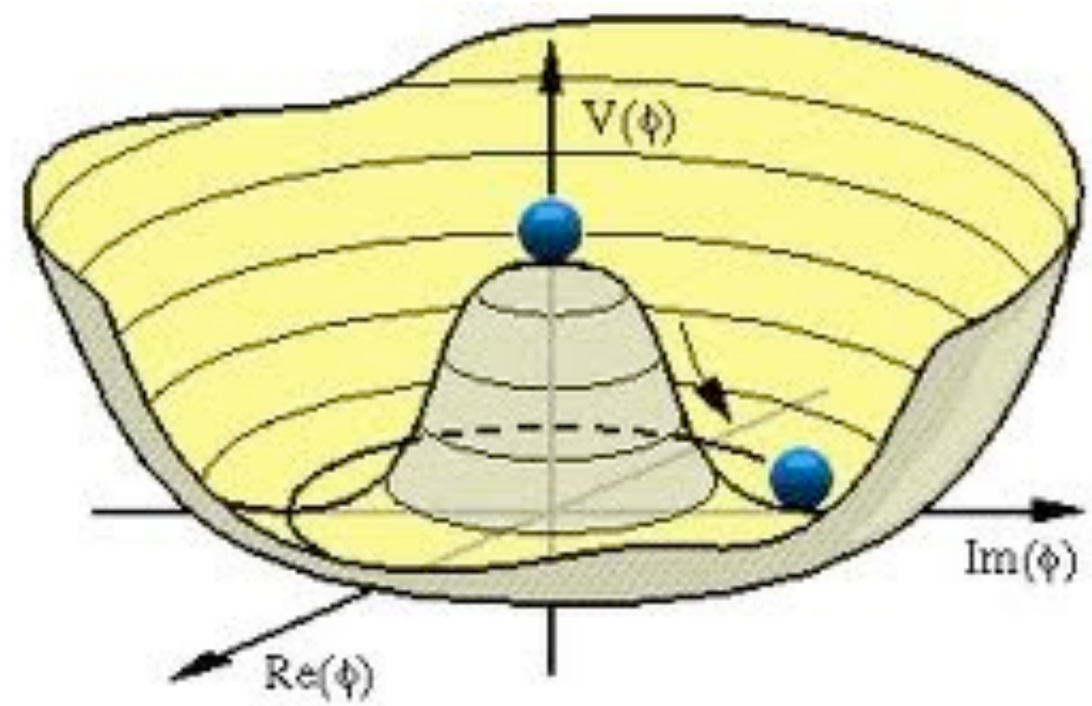
$$\frac{SU(2)_L \times U(1)_Y}{U(1)_Q} \longrightarrow \textbf{3 GB}$$

Conceptually identical to superconductivity.

In SM electro-weak symmetry broken by scalar doublet

$$H = \begin{pmatrix} h_1 + i h_2 \\ h_3 + i h_4 \end{pmatrix}$$

$$V(H) = \lambda \left(|H|^2 - v^2 \right)^2$$



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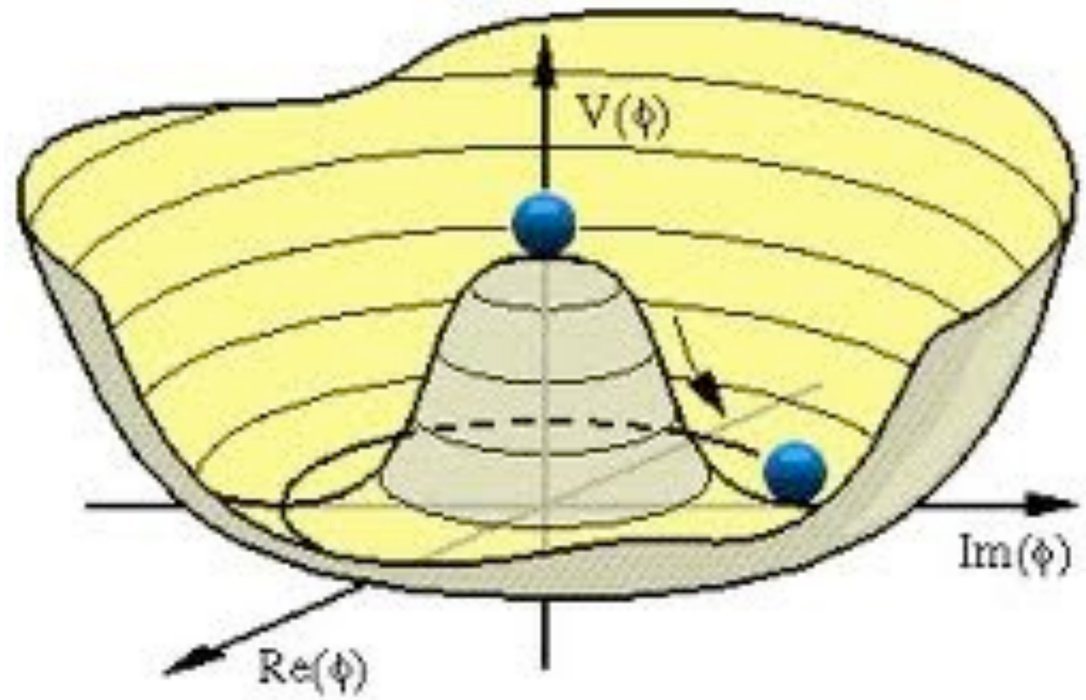
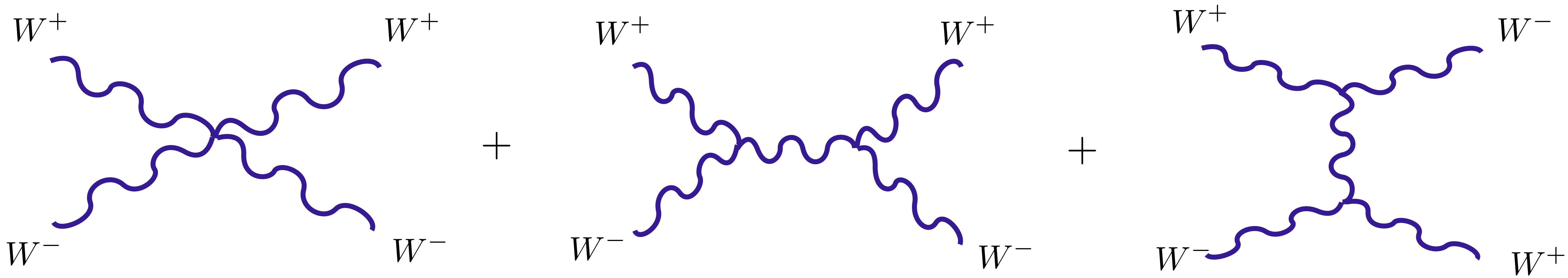


$$V(H) = \lambda \left(|H|^2 - v^2\right)^2$$

$$H(x) = U(x) \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \qquad v = 174\, GeV$$

Physical scalar is the Higgs boson $m_h = \sqrt{\lambda}\, v$

In principle Higgs scalar not even needed



$$A(W_L^+ W_L^- \to W_L^+ W_L^-) \sim \frac{E^2}{v^2}$$

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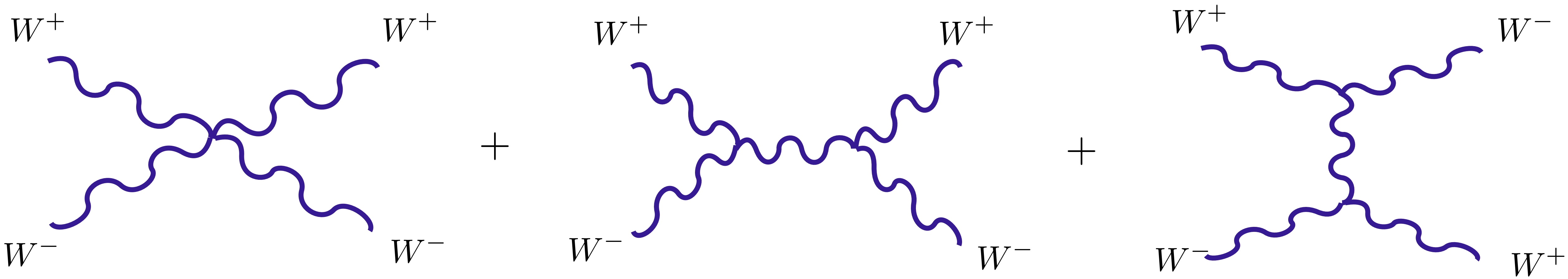


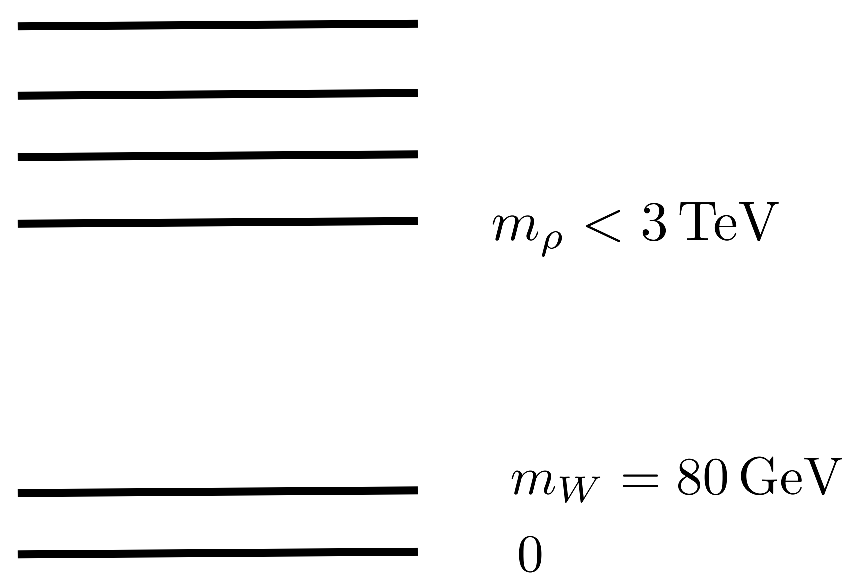
$$A(W_L^+ W_L^- \to W_L^+ W_L^-) \sim \frac{E^2}{v^2}$$

SM without Higgs does not make sense above

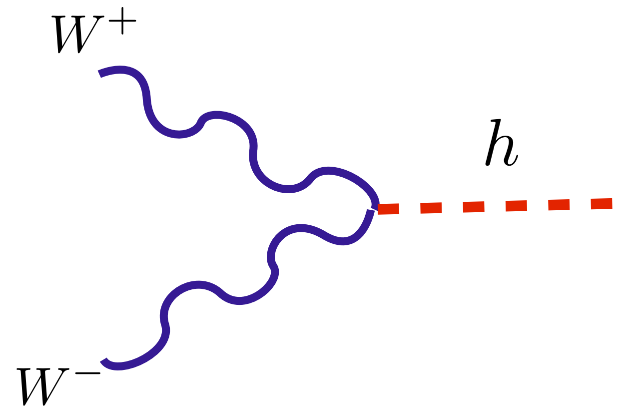
$$\Lambda = 4\pi v \sim 3\text{TeV}$$

New strong interactions could break the electro-weak symmetry. This is known as technicolor.

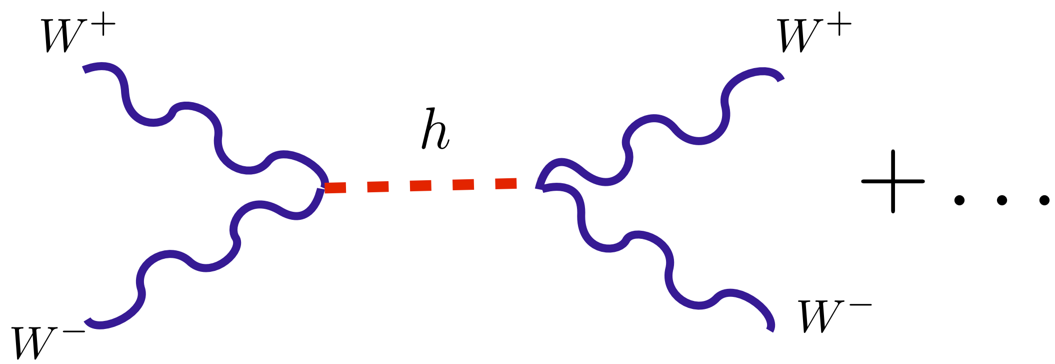
No Higgs scalar but techni-resonances (spin 0, 1/2, 1, ... etc.).



In the SM:



$$\sqrt{2} i \frac{m_W^2}{v}$$



$$A(W_L^+ W_L^- \to W_L^+ W_L^-) \sim m_h^2$$

$$(E \gg m_h)$$

SM with Higgs can be valid up to high scale.

Electro-weak scale is the analog the sea

$$m_W = 80\,\mathrm{GeV}$$

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Waves are the "Higgs"

SM sea is "calm"

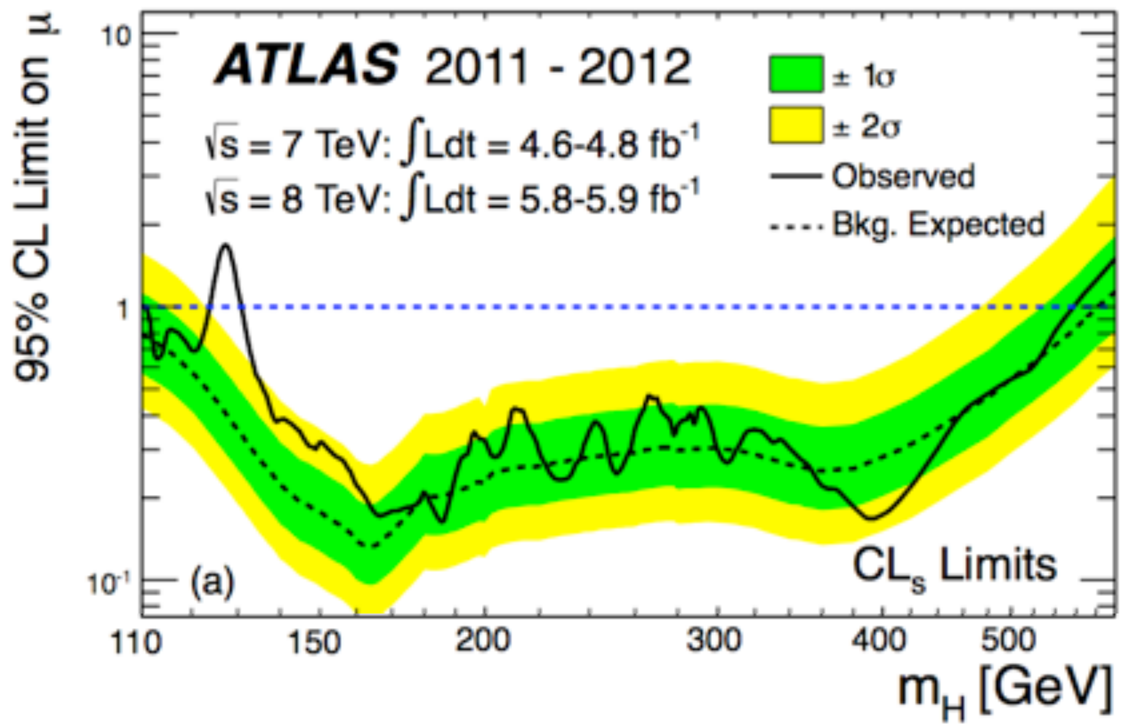
Electro-weak scale is the analog the sea

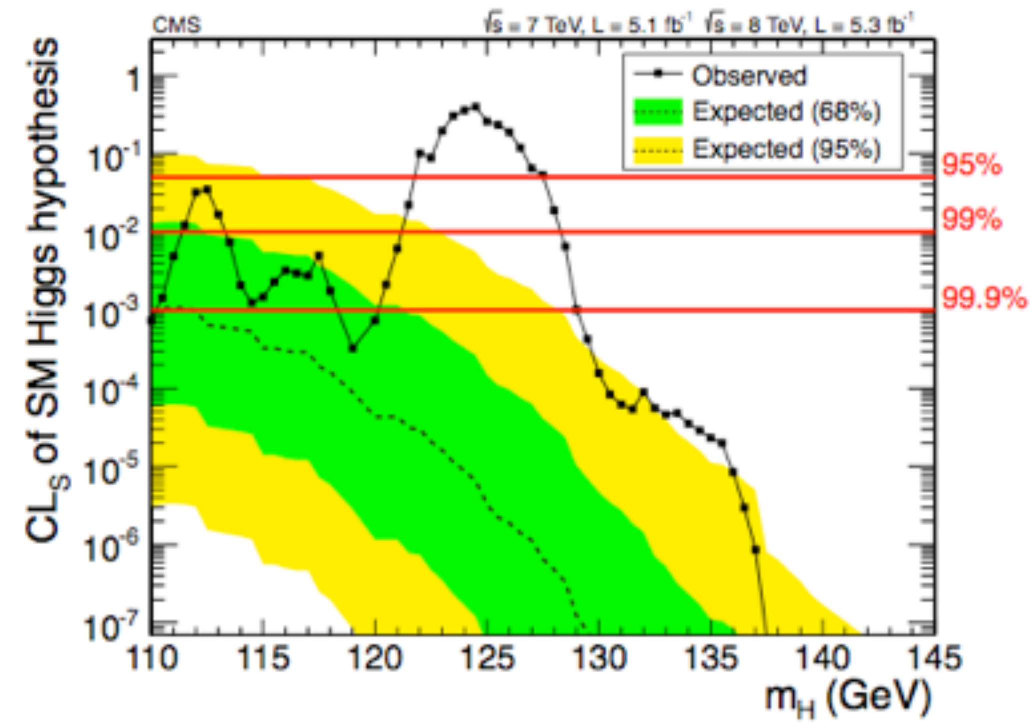
$$m_w = 80\,\mathrm{GeV}$$

Waves are the "Higgs"

Storms are can be unpredictable...

July 31, 2012 Phys. Lett. B716





$$m_h \approx 125\,\mathrm{GeV}$$

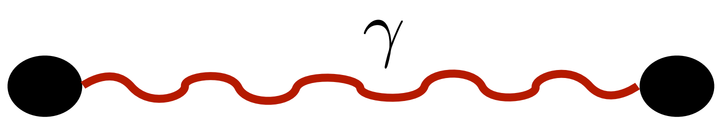
With 125 GeV Higgs SM can be valid up Mp.
SM sea is as calm as it can be!!!

BEYOND SM

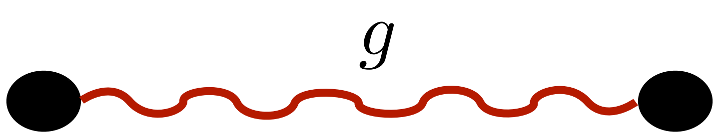
WHY?

- SM is incomplete: no quantum gravity, no dark matter
- Matter-anti-matter asymmetry
- Why 3 generations?
- Why fermion masses so different?
- Strong CP problem
- ....
- Hierarchy or naturalness problem

We don't understand why gravity is so weak:



$$F_{el} \sim \frac{e^2}{r^2}$$



$$F_{gr} \sim 8\pi G_N \frac{m_1 m_2}{r^2}$$

$$\frac{F^p_{GR}}{F^p_{el}} \sim 10^{-40}$$

Gravity and other forces unify at

$$M_p = (8\pi G_N)^{-\frac{1}{2}} = 10^{19}\,\mathrm{GeV}$$

Hierarchy (naturalness) problem:

$$\frac{m_h^2}{M_p^2} \sim 10^{-34}$$

?

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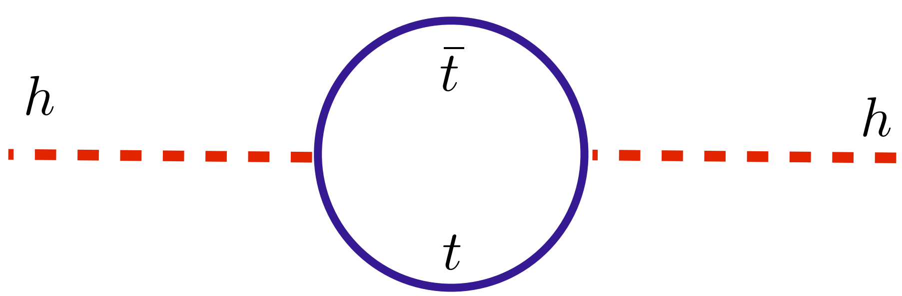
Hierarchy (naturalness) problem:

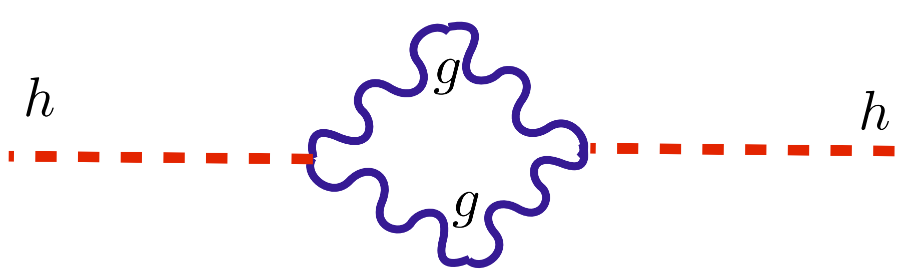
$$\frac{m_h^2}{M_p^2} \sim 10^{-34}$$

?

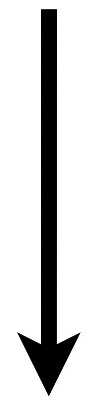
Electro-weak scale is unstable



$$\delta m_h^2 \sim \frac{g_{SM}^2}{16\pi^2}\Lambda^2$$



$$\Lambda \sim M_p$$



$$m_h^2 = 100000000000000000000000000000000.01\,\mathrm{TeV}^2$$
$$- \,100000000000000000000000000000000.00\,\mathrm{TeV}^2$$

$$\Lambda \sim M_p$$

↓

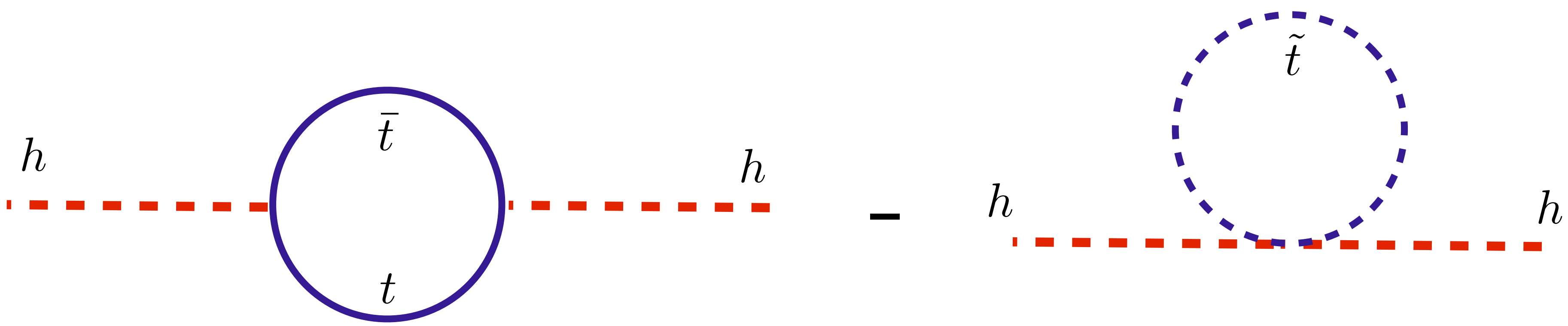
$$m_h^2 = 1000000000000000000000000000000.01 \,\mathrm{TeV}^2$$
$$- 1000000000000000000000000000000.00 \,\mathrm{TeV}^2$$

Natural theory:

$$\Lambda \sim \mathrm{TeV}$$

Two paradigms:

- Weak Coupling:
  Supersymmetry



$\sim 100\,\mathrm{GeV}$

Two paradigms:

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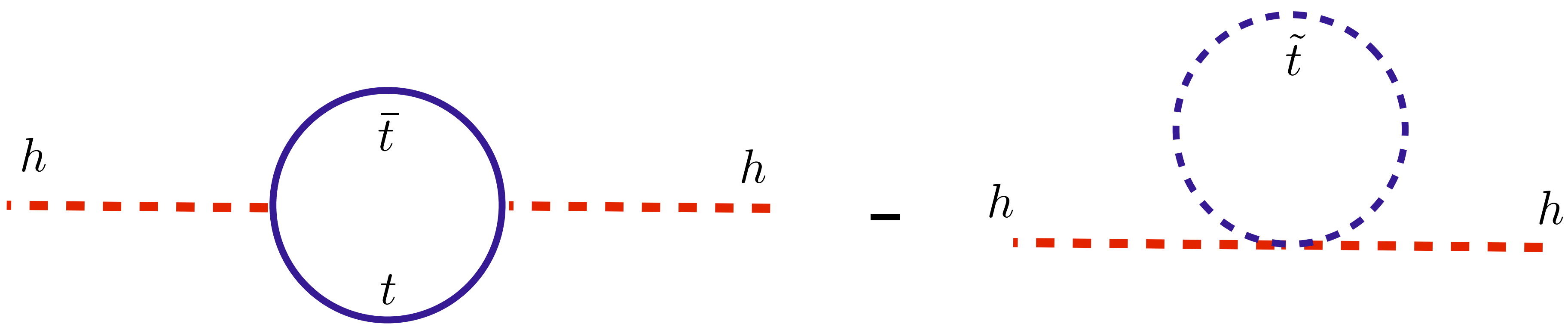
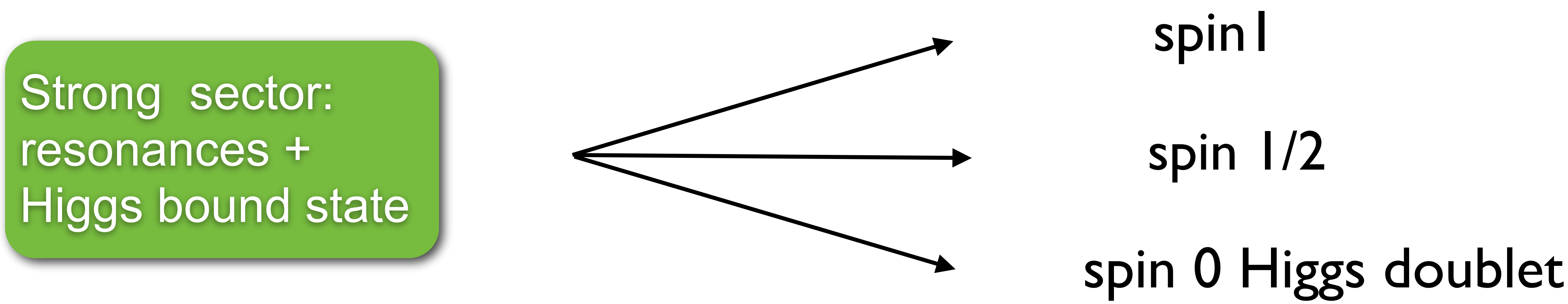


$\sim 100\,\mathrm{GeV}$

- Strong Coupling:
  ~~Technicolor~~, Composite Higgs, ~~Higgsless~~, ~~Extra-dimensions~~ ...

COMPOSITE HIGGS

Higgs doublet could be a bound state



Compositeness scale acts as cut-off

$$\delta m_h^2 \sim \frac{g_{SM}^2}{16\pi^2} m_\rho^2$$

Higgs doublet could be a bound state

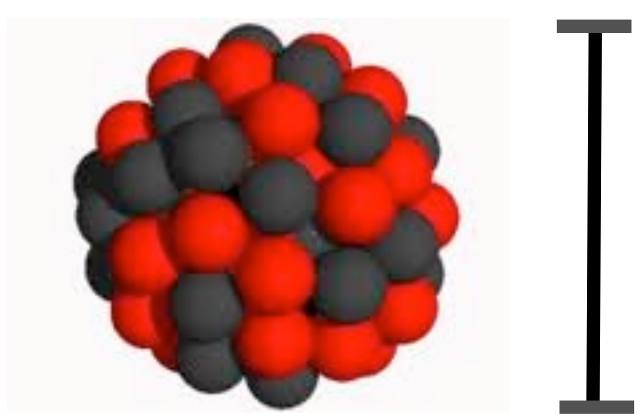
Strong sector:
resonances +
Higgs bound state

→ spin1
→ spin 1/2
→ spin 0 Higgs doublet

Compositeness scale acts as cut-off

$$\delta m_h^2 \sim \frac{g_{SM}^2}{16\pi^2} m_\rho^2$$

Natural theory

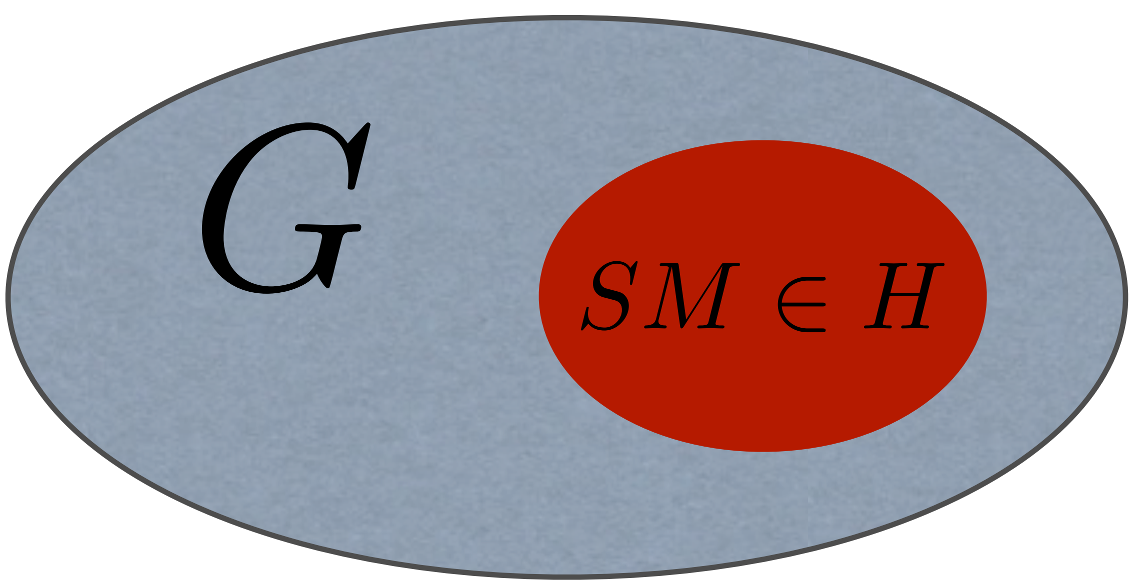


$$\sim \frac{1}{\mathrm{TeV}} = 10^{-18}\,\mathrm{m}$$

Scalars automatically massless if they are Goldstone bosons

$$\frac{G}{H} \longrightarrow \text{\# GB} = \text{Dim}[G] - \text{Dim}[H]$$

Higgs could be an approximate GB



Georgi, Kaplan '80s

Ex:

Agashe , Contino,
Pomarol, '04

$$\frac{SO(5)}{SO(4)} \longrightarrow \mathrm{GB} = 4$$

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Agashe , Contino, Pomarol, '04

$$\frac{SO(5)}{SO(4)} \longrightarrow \mathrm{GB} = 4$$

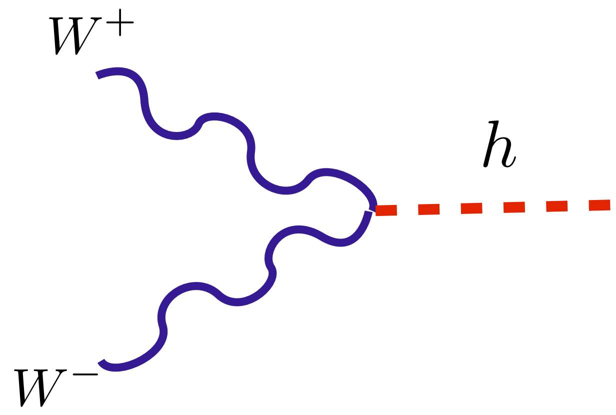
Many possibilities:

G	H	N_G	NGBs rep.$[H]$ = rep.[SU(2) × SU(2)]
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2 \times (\mathbf{2}, \mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \times (\mathbf{2}, \mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4}, \mathbf{2}) = 2 \times (\mathbf{2}, \mathbf{2}), (\mathbf{2}, \mathbf{2}) + 2 \times (\mathbf{2}, \mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4_{-5}} + \mathbf{\bar{4}_{+5}} = 2 \times (\mathbf{2}, \mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$

Mrazek et al., '11

Deviations from SM:

$$\mathcal{O}\left(\frac{v^2}{f^2}\right)$$



$$\sqrt{2}i\frac{m_W^2}{v}\left(1 + a\frac{v^2}{f^2}\right)$$

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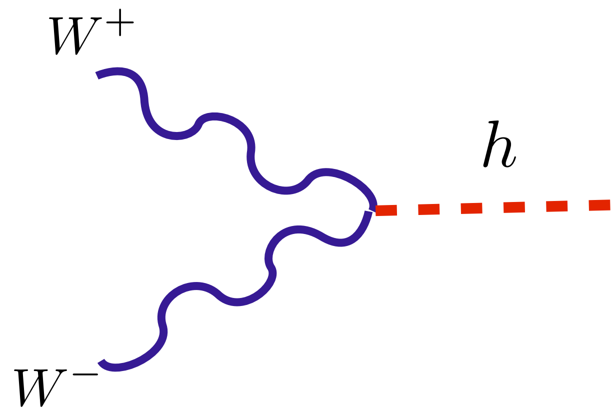
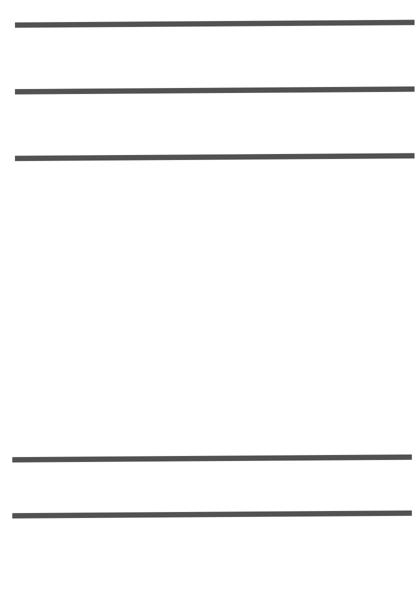
$$\mathcal{O}\left(\frac{v^2}{f^2}\right)$$



$$\sqrt{2}i\frac{m_W^2}{v}\left(1+a\frac{v^2}{f^2}\right)$$

Spectrum:



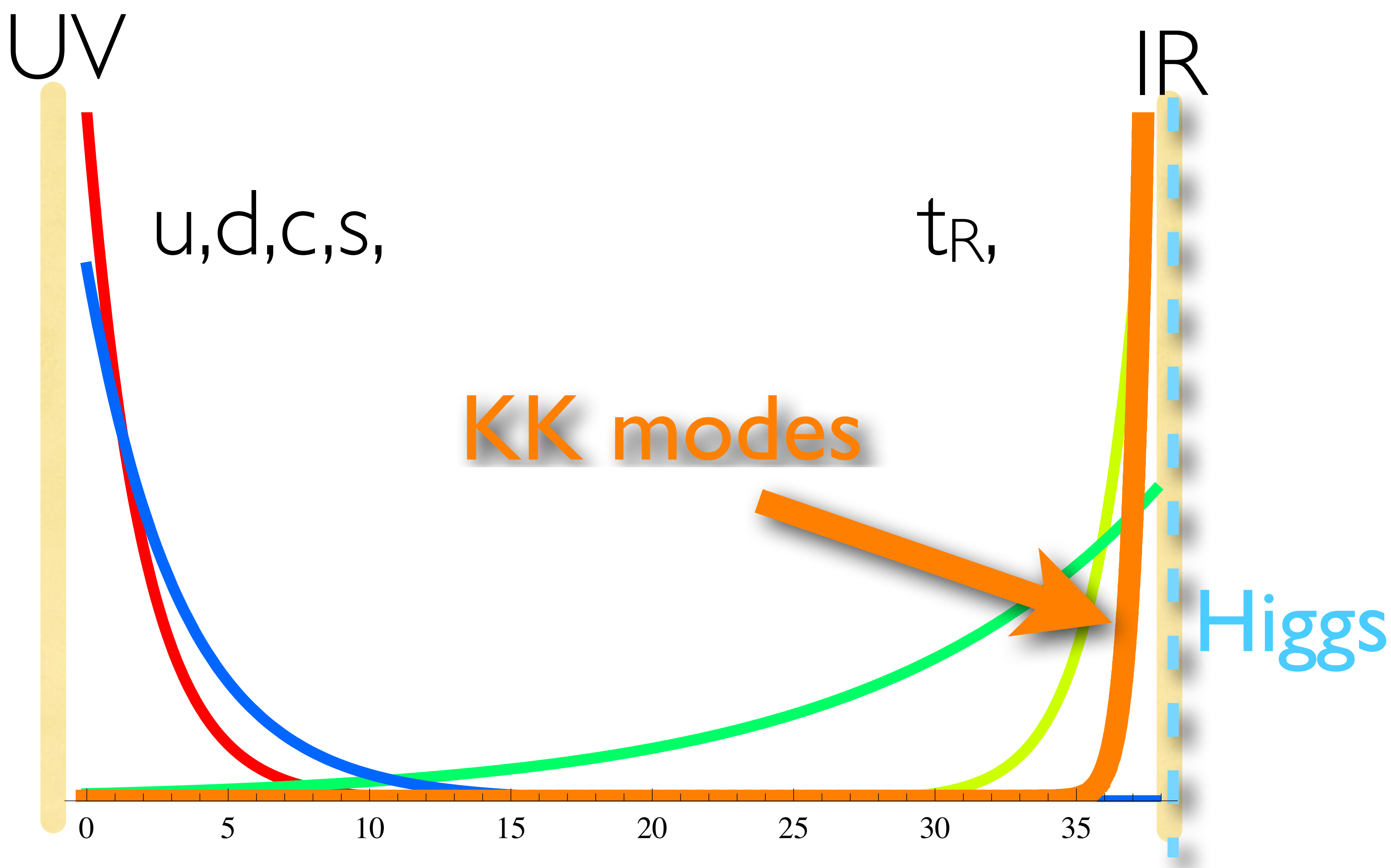
$m_\rho = g_\rho f$

$m_h = 125\,\mathrm{GeV}$

$m_W = 80\,\mathrm{GeV}$

0

- **5D Models**



(Randall-Sundrum '99)

$$ds^2 = e^{-2kry}(-dt^2 + dx^2) + dy^2$$

SM fields propagate in the extra dimension.
Different profiles generate hierarchies.

Ex:

Agashe , Contino,
Da Rold, Pomarol, '06

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

Neumann

$$SU(3)_c \times SO(5) \times U(1)_X$$

$\mathbf{5}^{\mathbf{t_L}}_{\frac{\mathbf{2}}{\mathbf{3}}}$ $\quad$ $\mathbf{5}^{\mathbf{t_R}}_{\frac{\mathbf{2}}{\mathbf{3}}}$

$\mathbf{5}^{\mathbf{b_L}}_{-\frac{\mathbf{1}}{\mathbf{3}}}$ $\quad$ $\mathbf{5}^{\mathbf{b_R}}_{-\frac{\mathbf{1}}{\mathbf{3}}}$

$A_\mu^{\hat{a}} = 0$ $\quad$ $\frac{SO(5)}{SO(4)}$

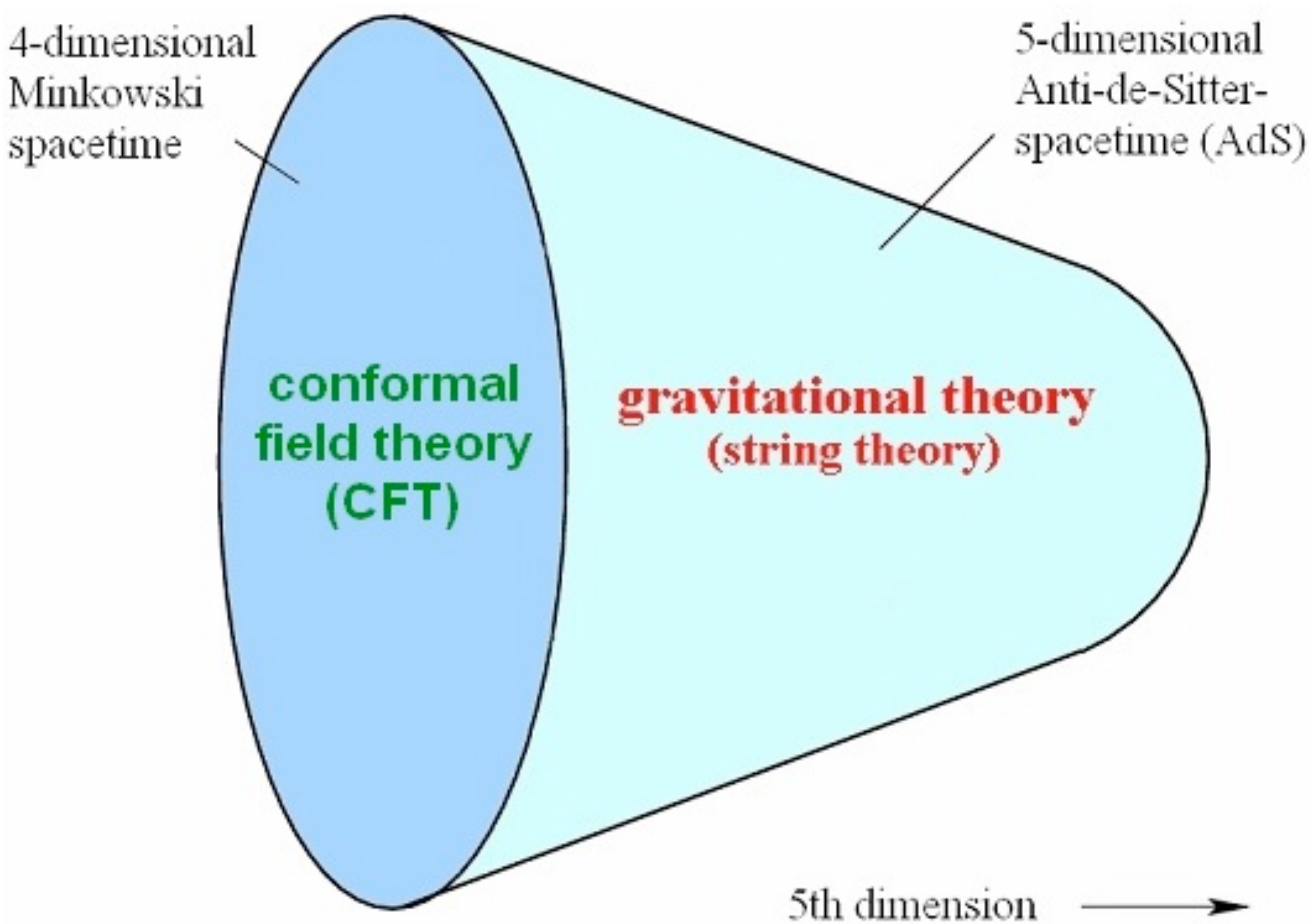
$\partial_z A_\mu^a = 0$ $\quad$ $SO(4)$

Each SM state correspond to a 5D field!

$$e_R(x) \longrightarrow e^i_R(x,y)$$

- **4D Models**

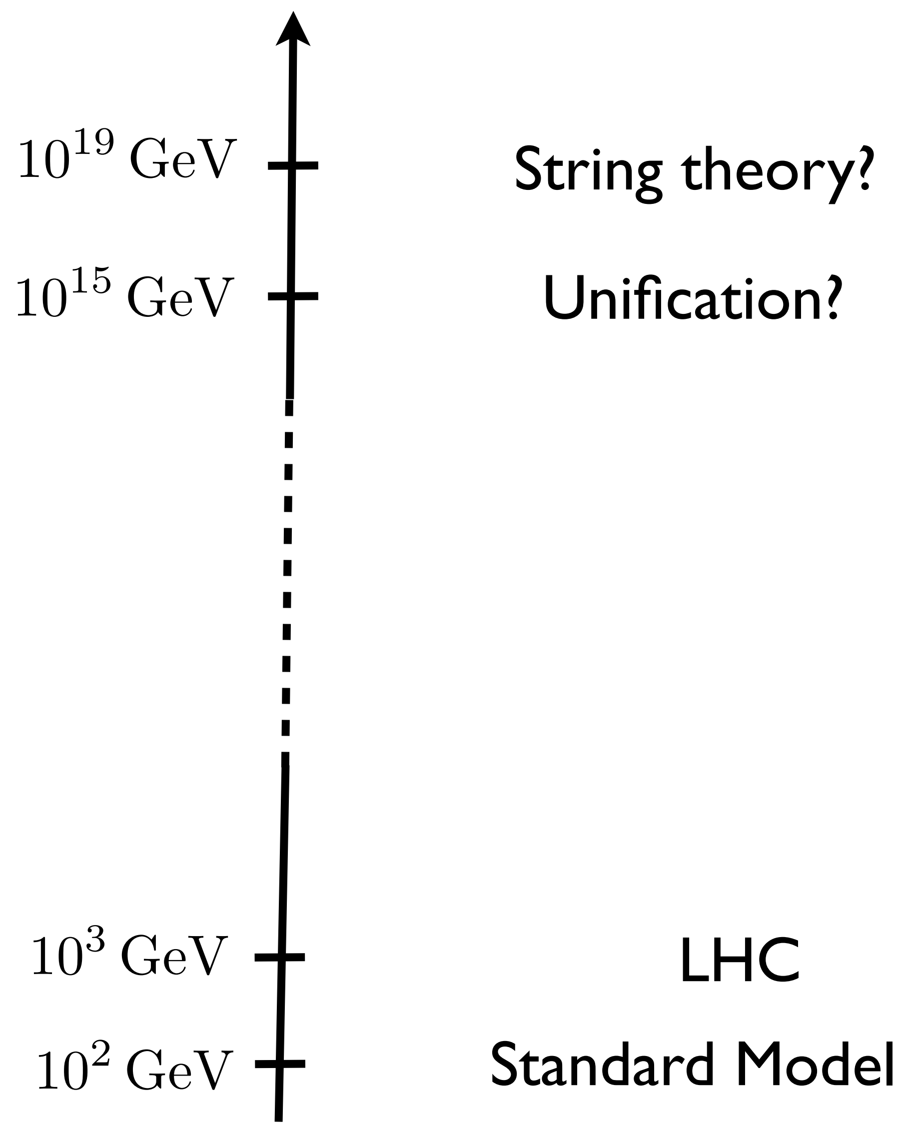
5D models are dual to 4D strongly coupled theories



5th dimension dual to energy scale

Effective field theory:
Physics at a scale Λ largely independent on shorter distances.

For LHC focus on the lightest degrees of freedom



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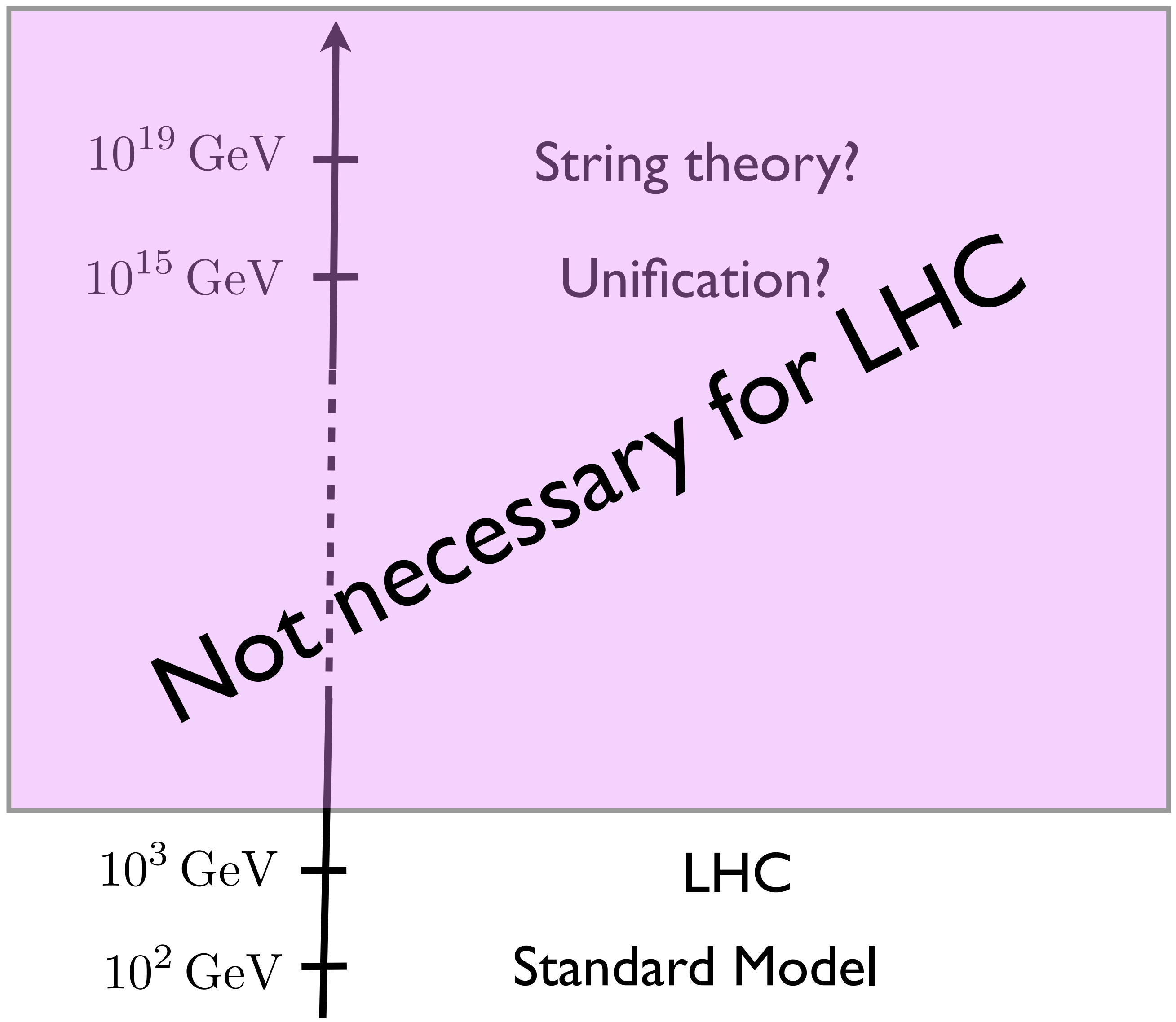
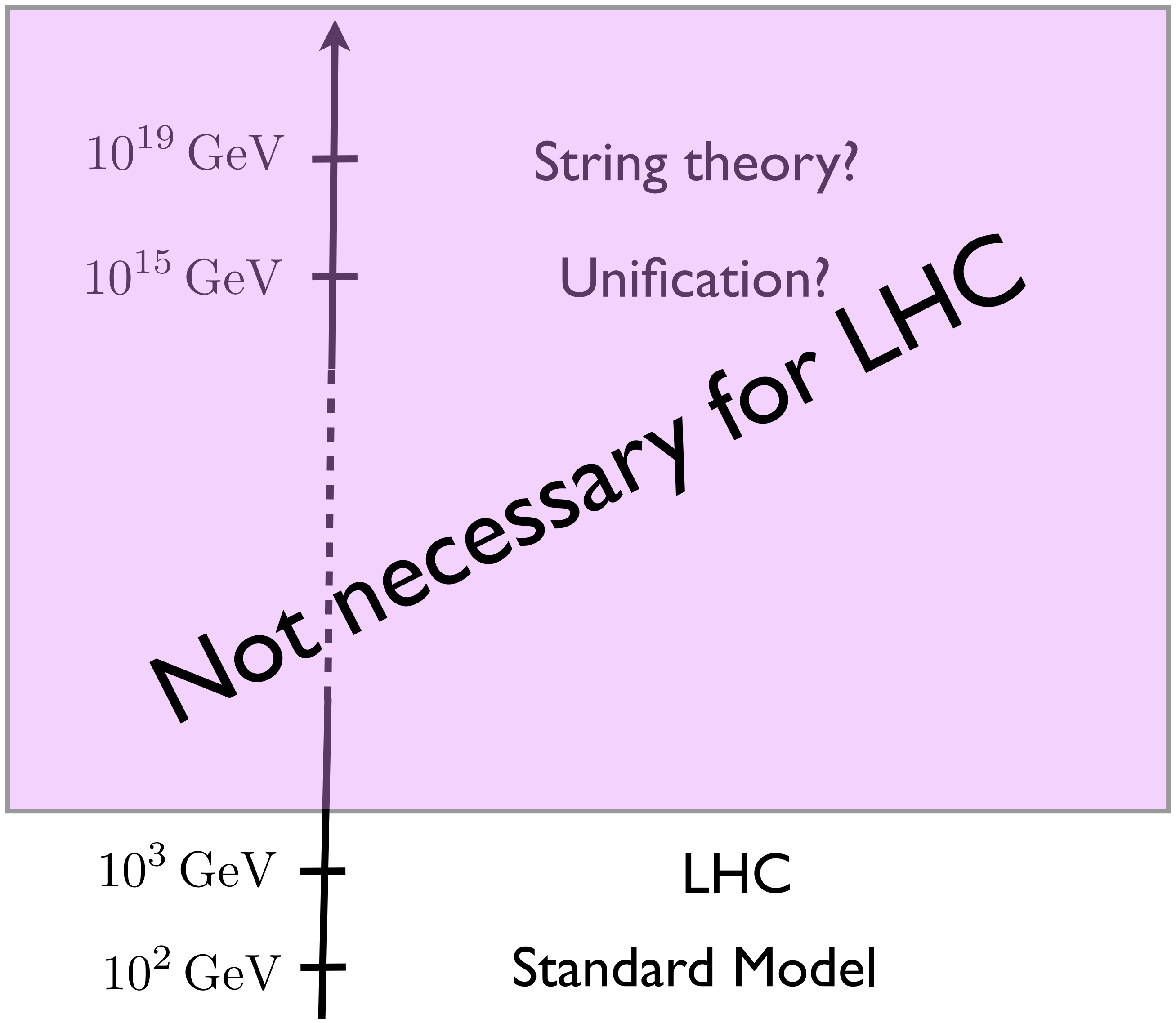


For LHC focus on the lightest degrees of freedom



GOAL: Find an effective theory compatible with experiments (and predicts new testable phenomena). Not the full theory!

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- Naturalness suggests presence of new physics at LHC energies. The Higgs particle could be composite.

- No full theory yet.
  For phenomenology effective description sufficient.

Without tuning:

$$m_h \sim \Lambda$$

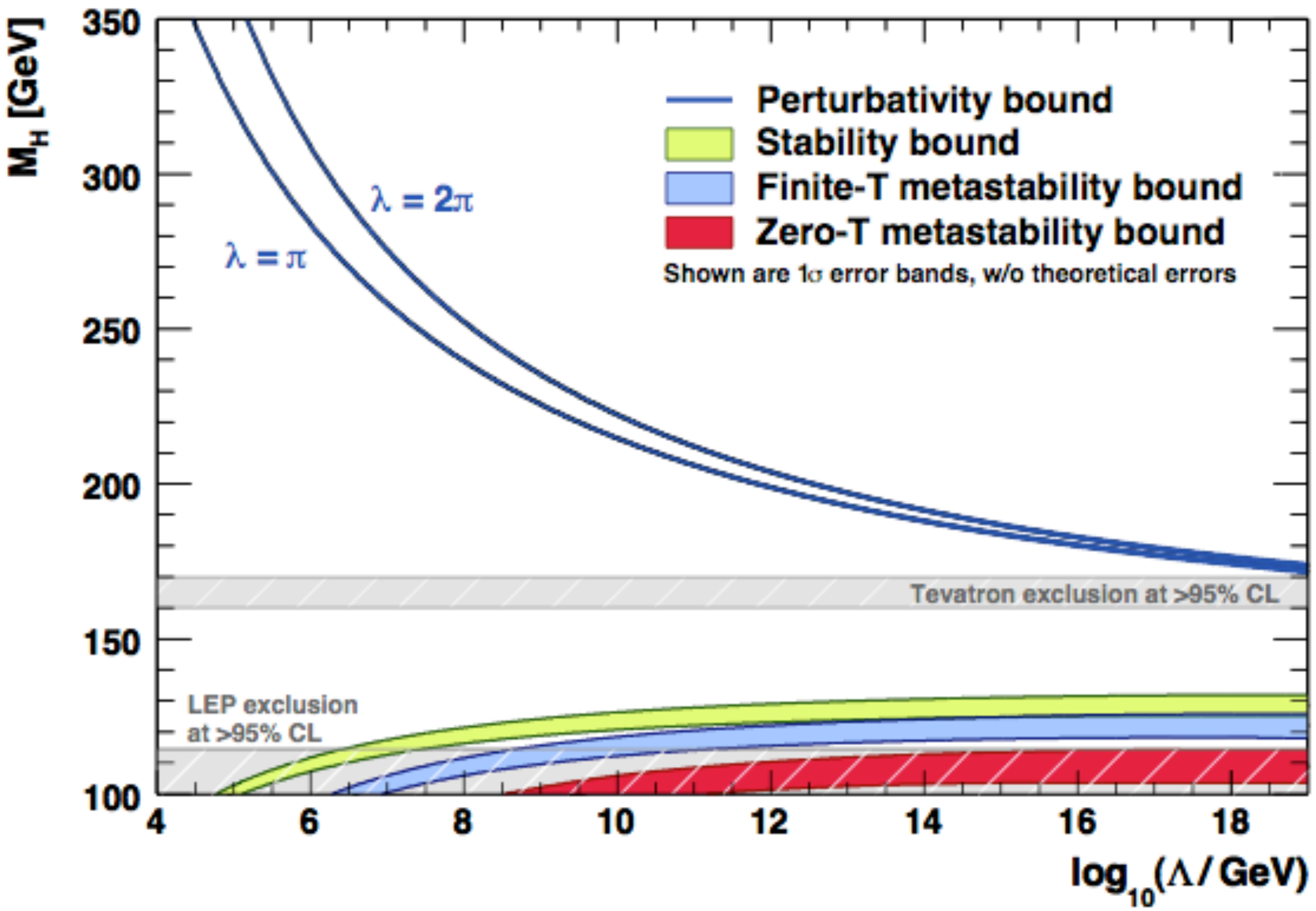
Without tuning:

$$m_h \sim \Lambda$$

No obvious experimentalist:

New physics will be seen at the LHC

$$\mu \frac{d\lambda}{d\mu} = \frac{1}{16\pi^2}(24\lambda^2 - 6y_t^4 + \dots)$$



Giudice et al.
1112.3022

$$115\,\mathrm{GeV} < m_h < 160\,\mathrm{GeV}$$

With 125 GeV Higgs SM can be valid up Mp.
SM sea is as calm as it can be!!!