Beyond the Standard Model

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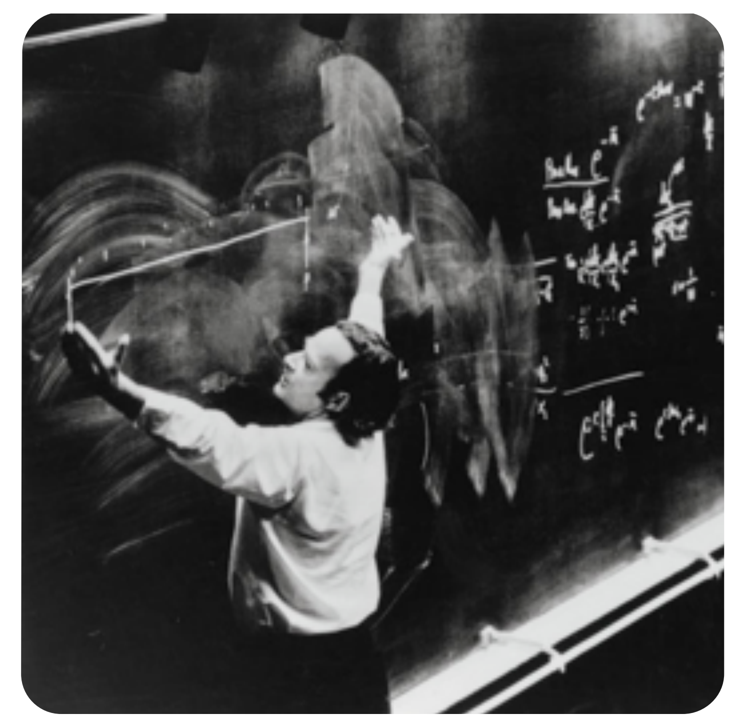
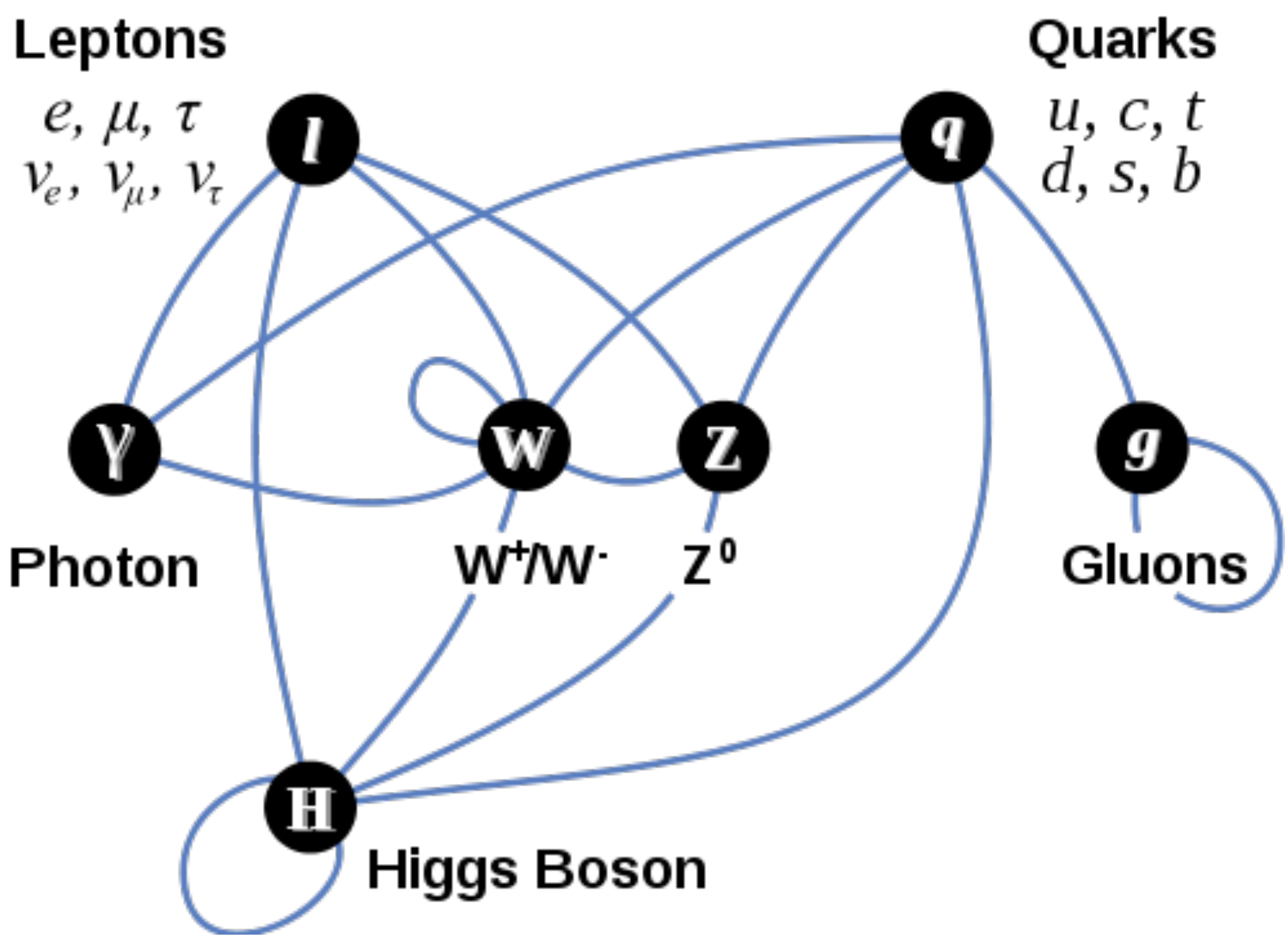
(DESY&CERN)



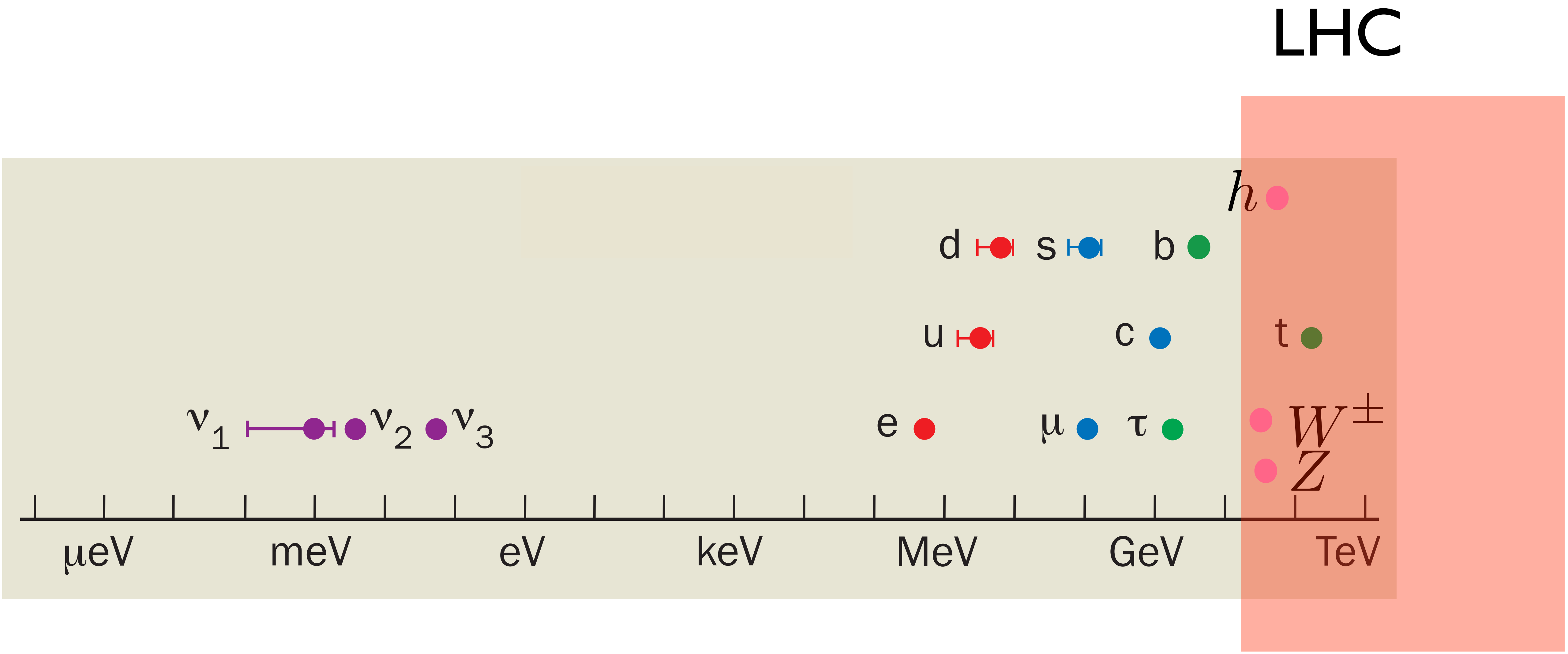
CERN school
2014/6/29

The SM



Leptons
e, μ, τ
νe, νμ, ντ
Quarks
u, c, t
d, s, b
l
q
γ
W
Z
g
Photon
W+/W-
Z0
Gluons
H
Higgs Boson

The energy frontier



What can we expect to discover?

Before $LHC_{7/8}$

theorists' statements

Susy is right around
the corner

Dark matter is a WIMP
and we'll produce it at LHC

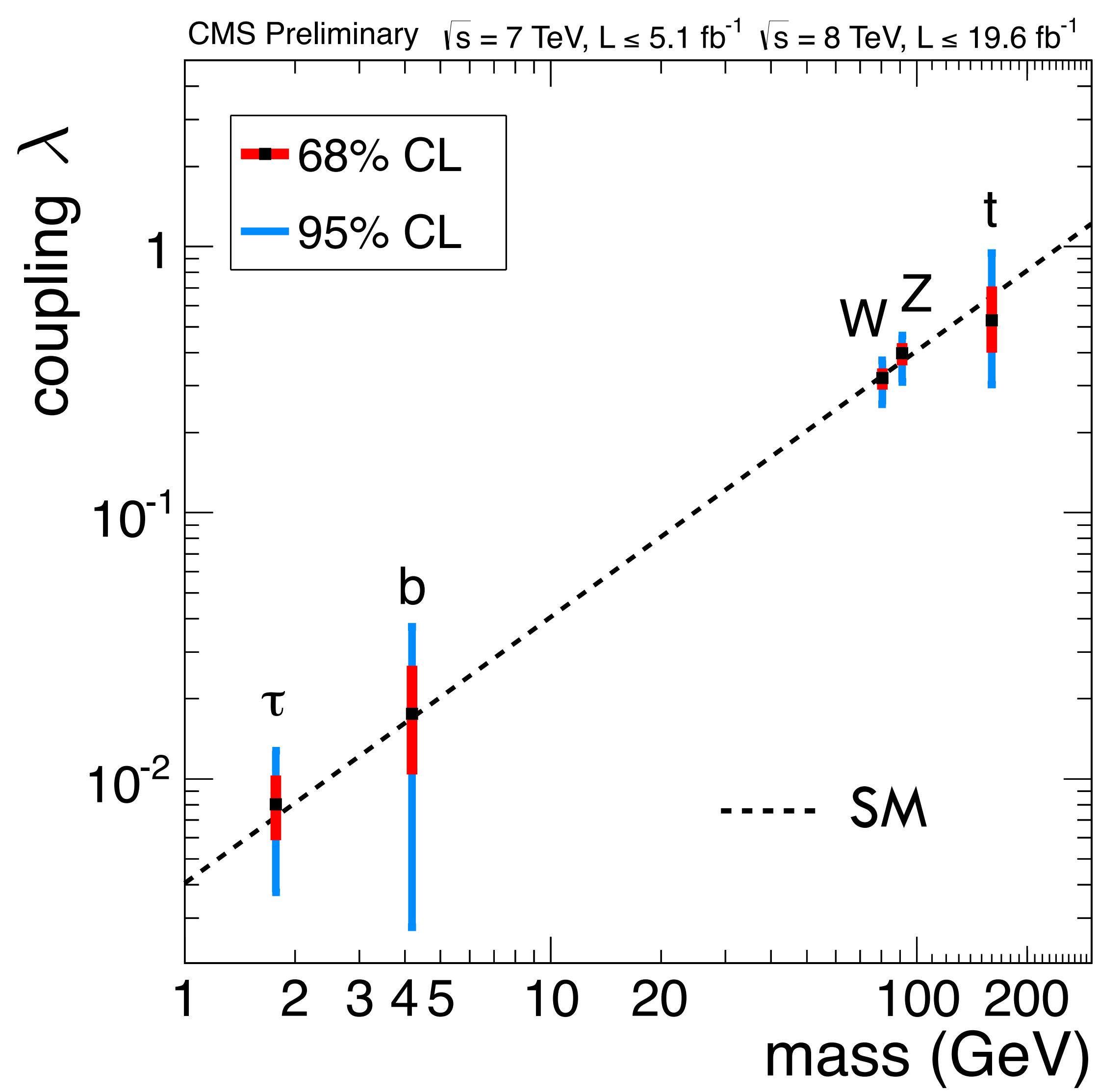
We'll see non-SM CP and
flavor violation

Extra-dimensions will
manifest itself through KK-states

We'll have a portal
to hidden sectors

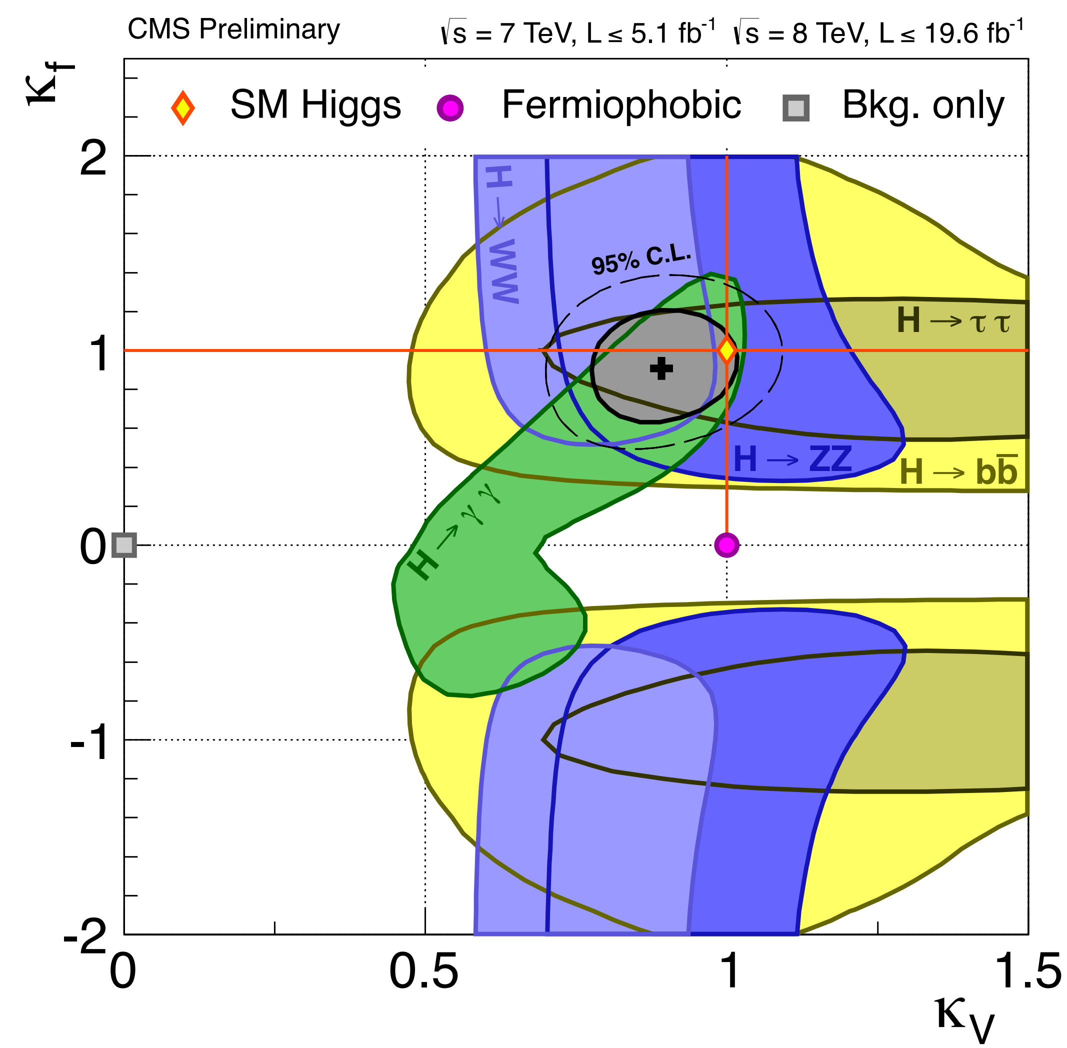
Higgs

Related to EWSB



$$\lambda_\psi \propto \frac{m_\psi}{v}, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

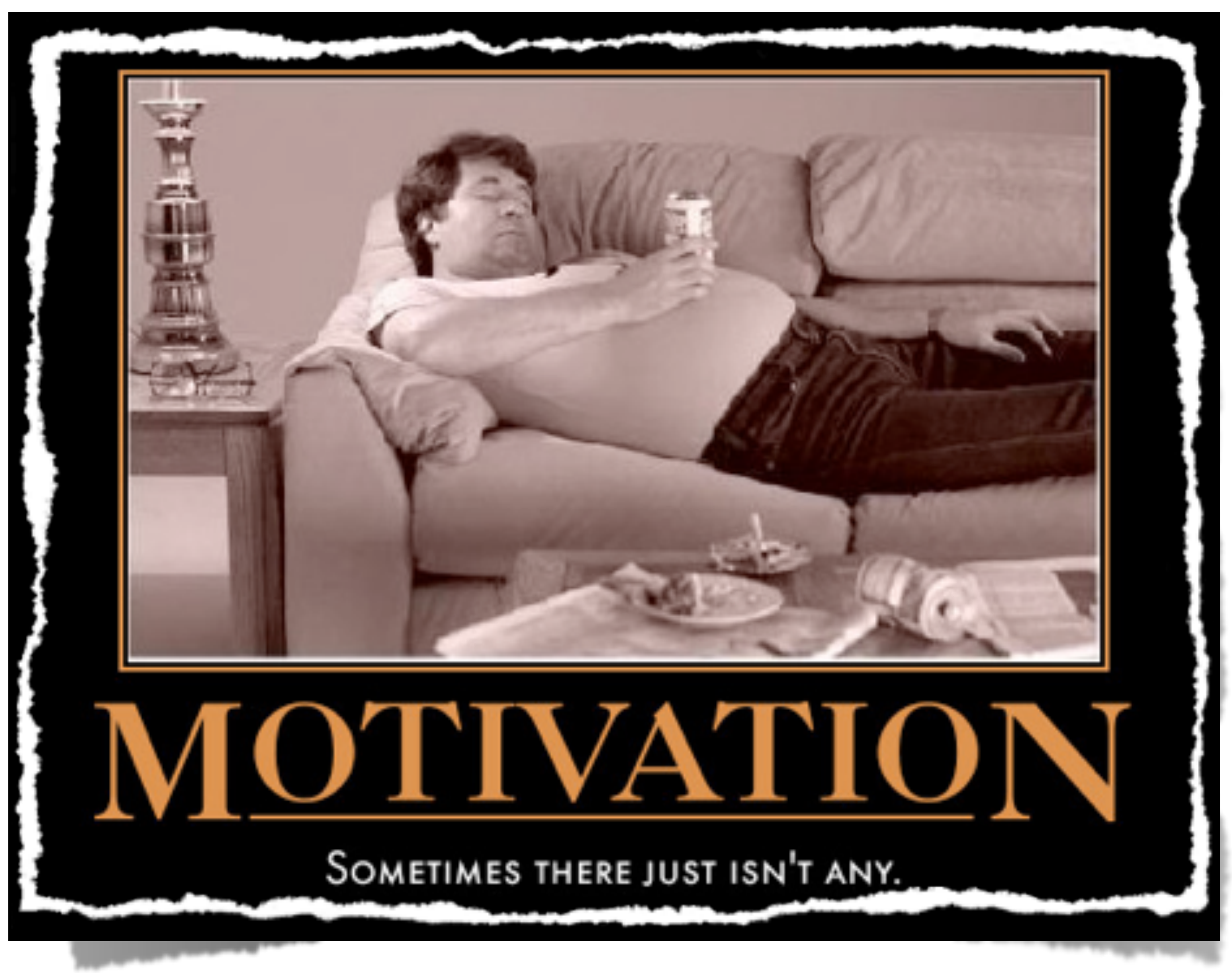
overall compatible w/ SM



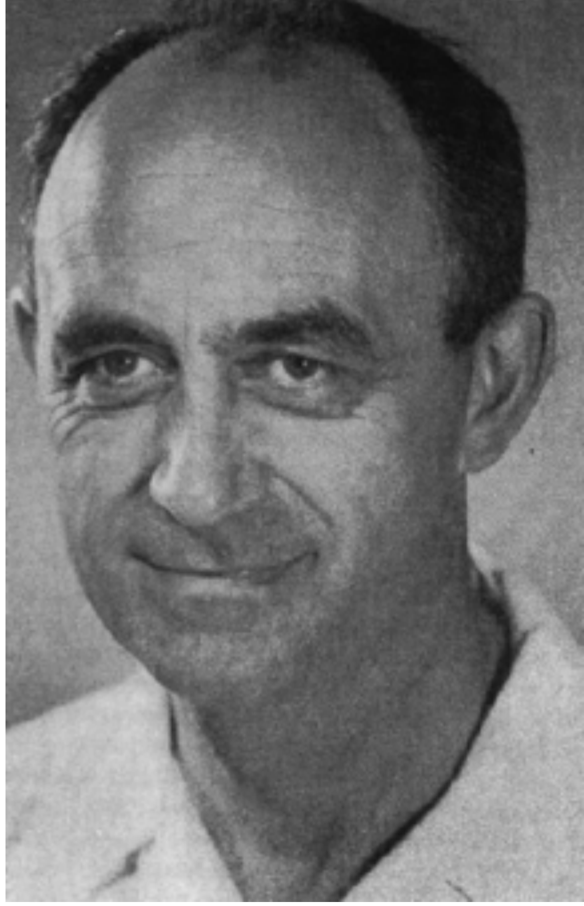
Good time for BSM?

- Fundamental scalars abound (Higgs, inflation)
- Are we done?

Why still expect new physics at the LHC?



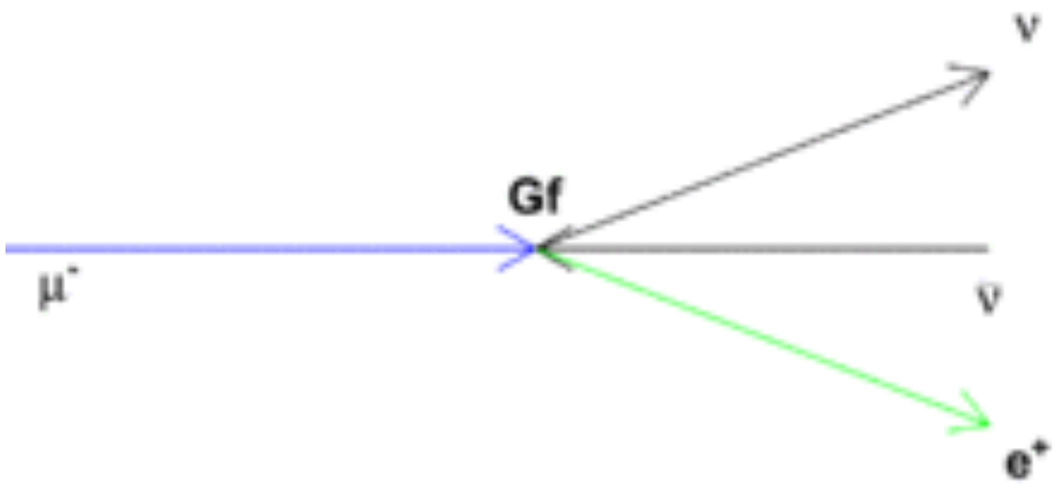
Fermi theory



G_F

$$\frac{g^2}{M_W^2}(\bar{\nu}_\mu \gamma_L^\alpha \mu)(\bar{e}\gamma_L^\alpha \nu_e)$$

scale!

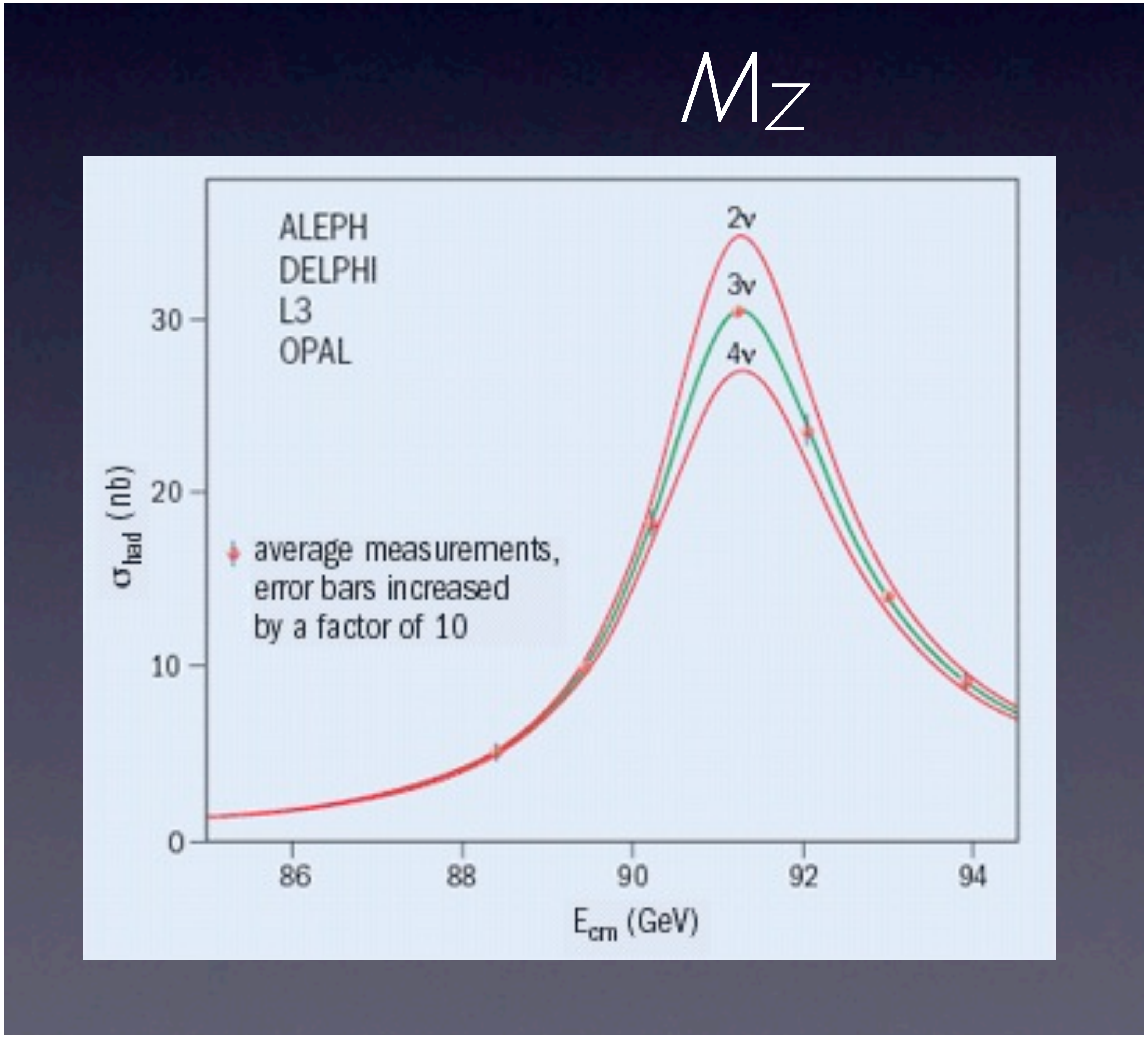


dimensional analysis

$$\sigma \propto \frac{g^4}{M_W^4} E^2$$

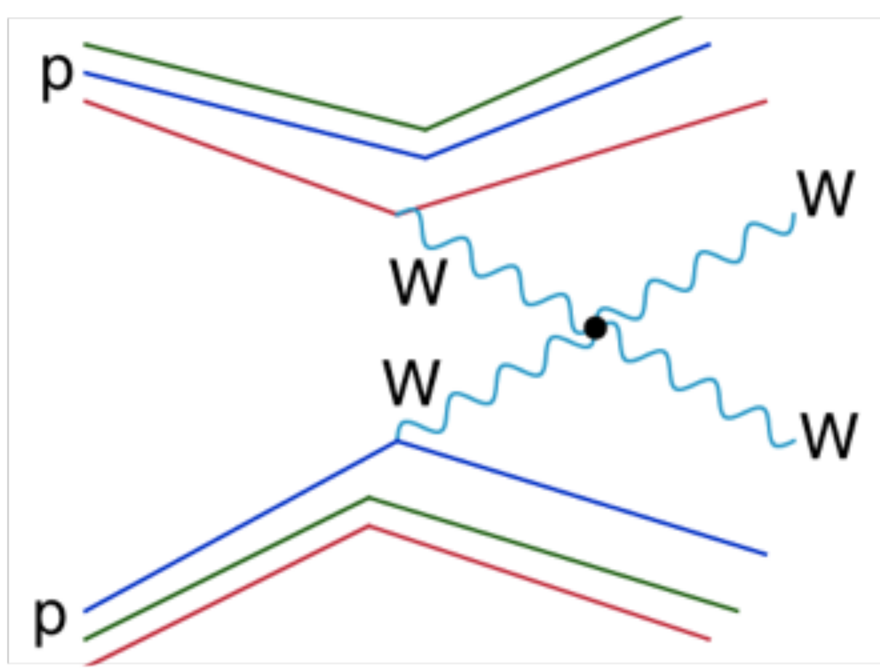
something interesting will happen around ***E ~ M***

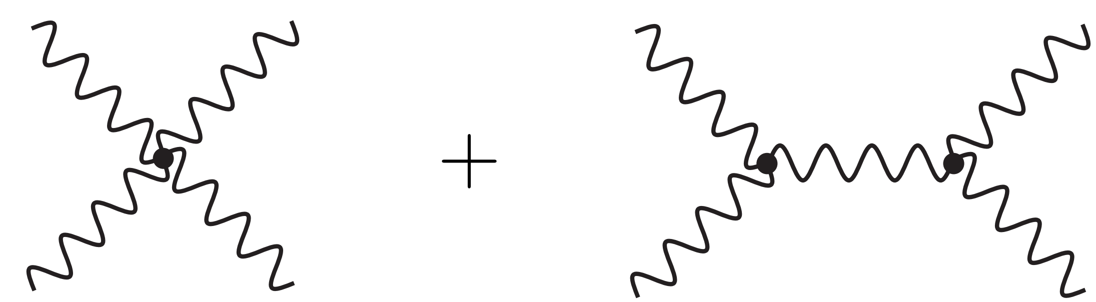
LEP


M_Z
ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements,
error bars increased
by a factor of 10
σ_{had} (nb)
E_{cm} (GeV)
0
10
20
30
86
88
90
92
94

SM without the Higgs

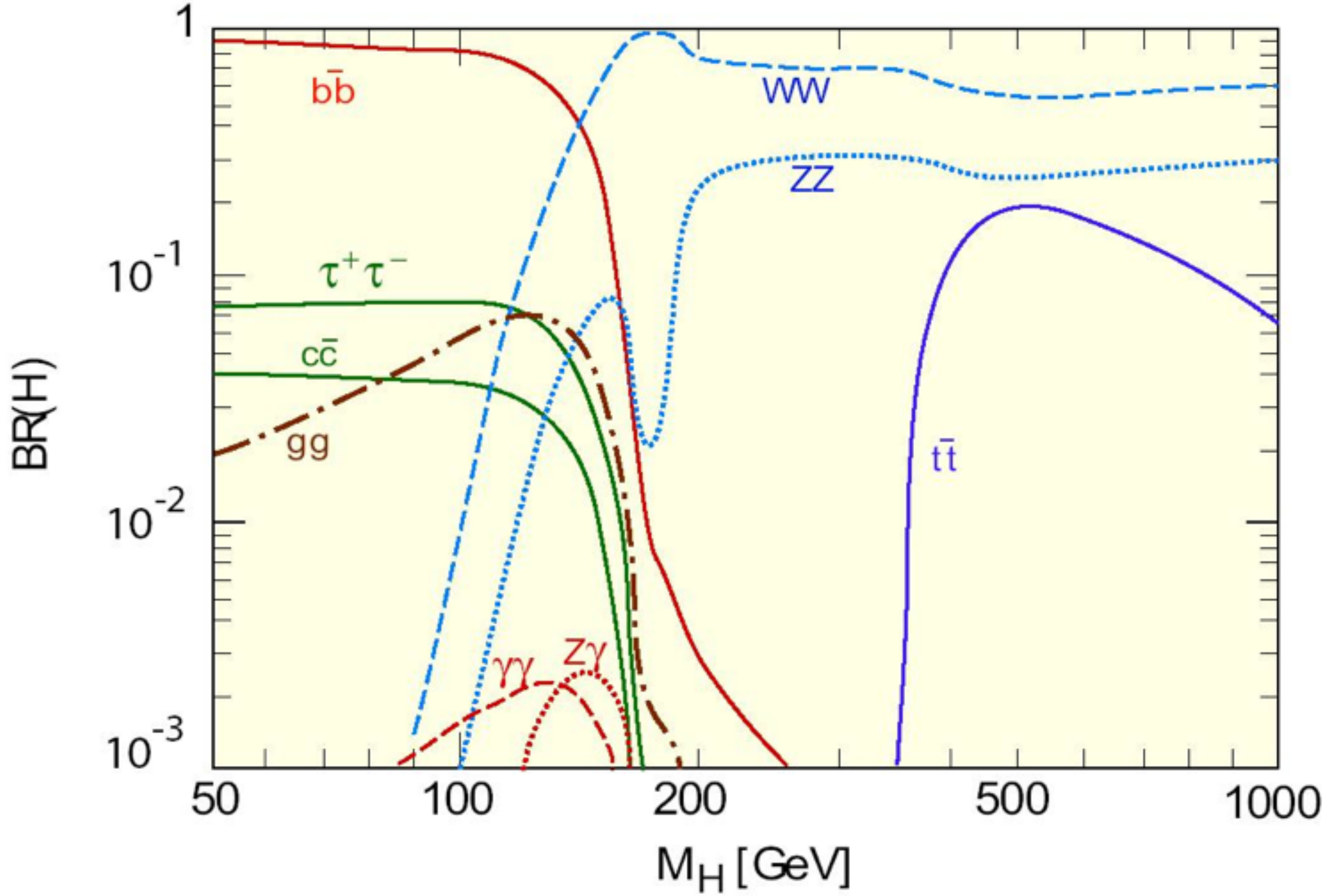
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM}(\cancel{h^0}, A_\mu, W_\mu^\pm, Z_\mu, G_\mu, q, \ell) \qquad \text{(unitary gauge)}$$





$$\sim E^2$$

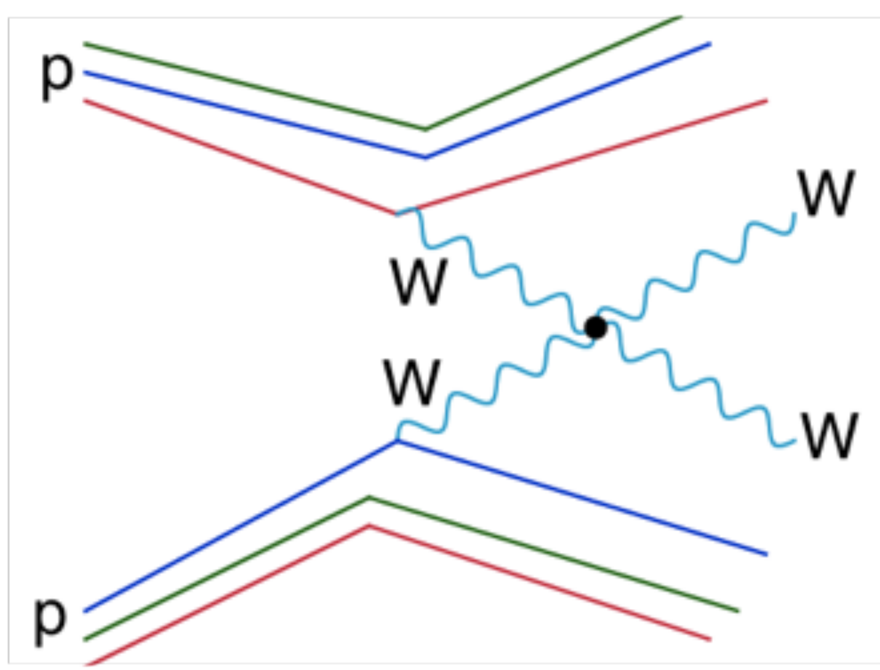
$$\sim \cancel{E^4} + E^2 + \cdots \qquad \sim \cancel{E^4} + E^2 + \cdots$$

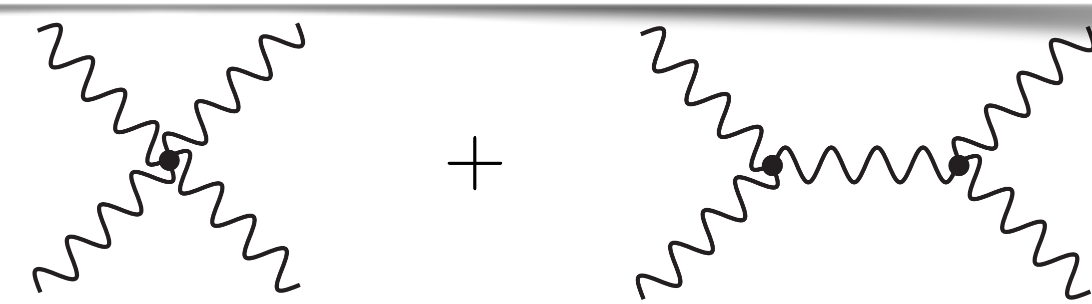


1
10^{-1}
10^{-2}
10^{-3}
BR(H)
$b\bar{b}$
WW
ZZ
$\tau^+\tau^-$
$c\bar{c}$
gg
$t\bar{t}$
γγ
Zγ
50
100
200
500
1000
M_H [GeV]

SM without the Higgs

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM}(\cancel{h^0}, A_\mu, W^\pm_\mu, Z_\mu, G_\mu, q, \ell) \qquad \text{(unitary gauge)}$$



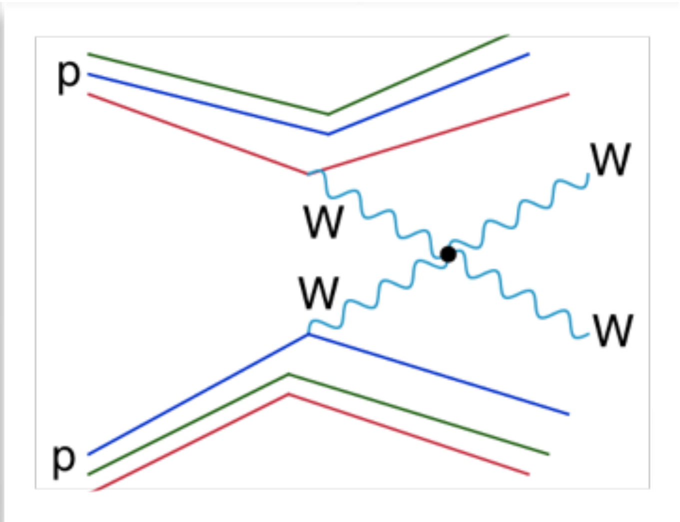
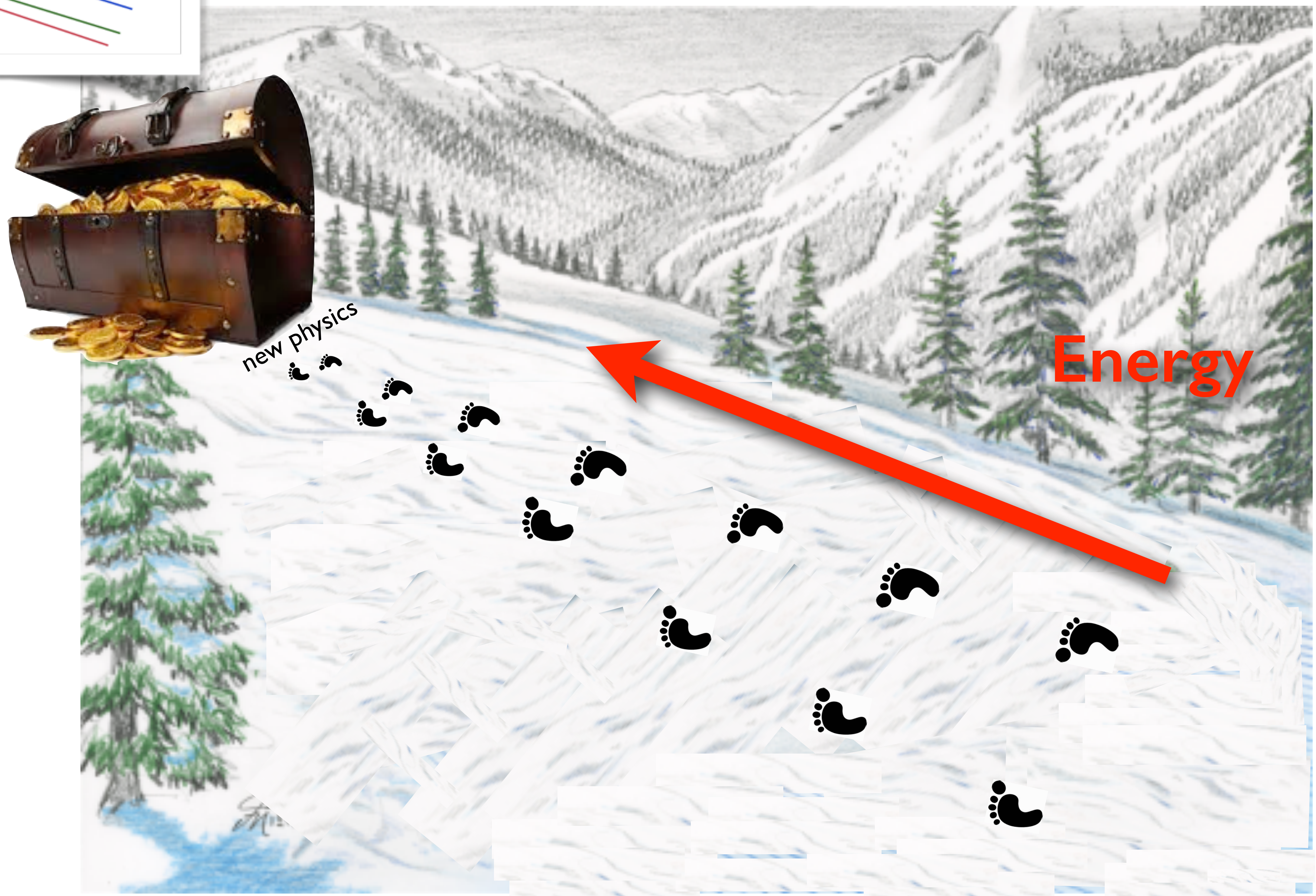


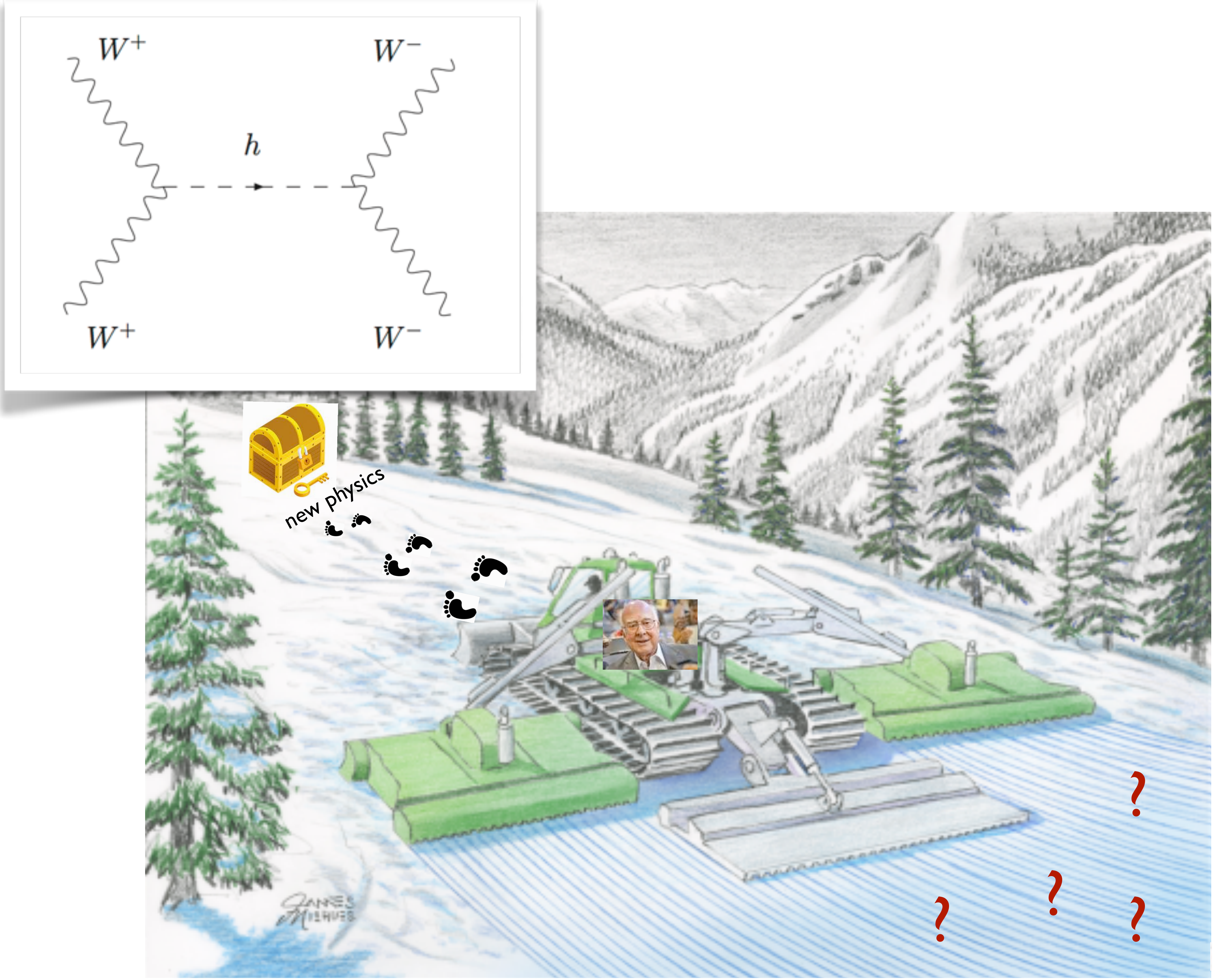
$$\sim E^2$$

$$\sim \cancel{E^4} + E^2 + \cdots \qquad \sim \cancel{E^4} + E^2 + \cdots$$

$$\Lambda \approx 4\pi v \approx 3\,\text{TeV}$$

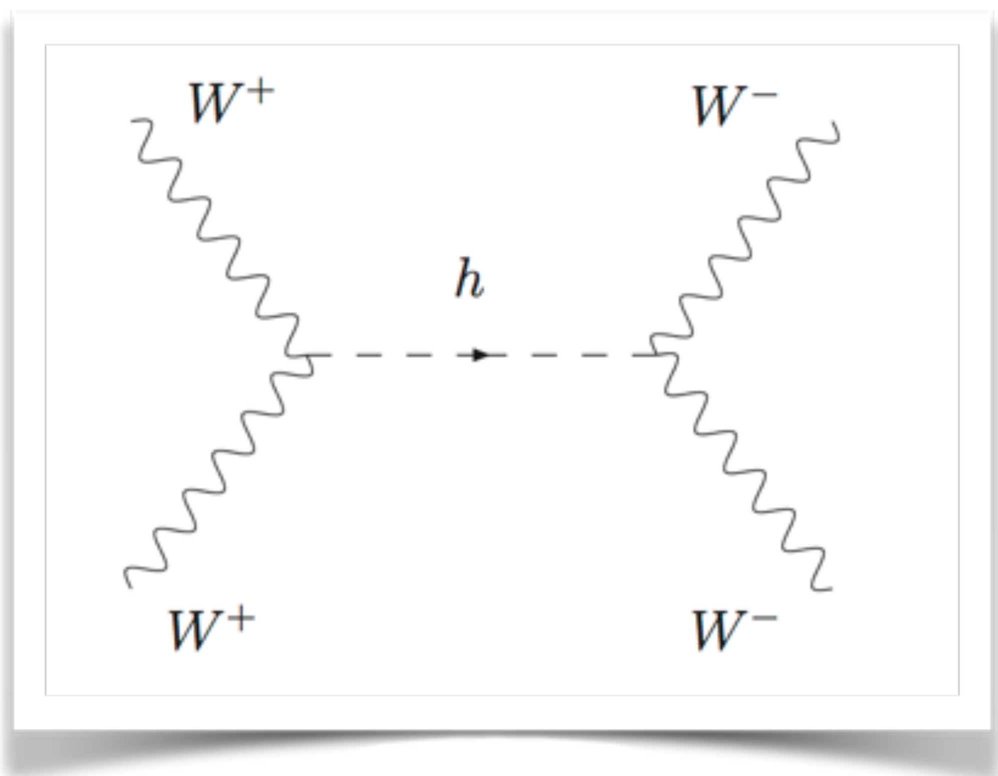
New physics to show up below this scale


p
W
W
W
W
p

new physics
Energy


W^+
W^-
h
W^+
W^-
new physics
?
?
?
?

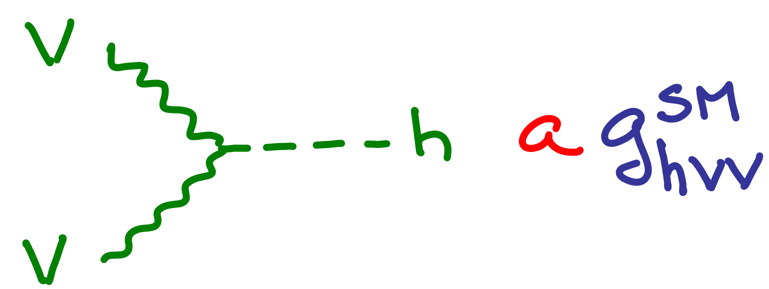
SM-like Higgs

What if it couples only approximately like the SM?

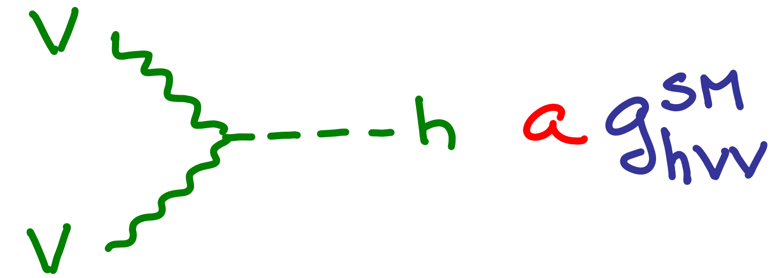


$W_L W_L$ -> $W_L W_L$

fully unitarized?



$$\Lambda \approx 4\pi v \longrightarrow \frac{4\pi v}{\sqrt{1-a^2}}$$



$$\Lambda \approx 4\pi v \longrightarrow \frac{4\pi v}{\sqrt{1-a^2}}$$

Even if we measure $a < 1$, current limits do not guarantee new physics in reach of LHC.

Example: composite pseudo-Goldstone Higgs:

$$a = \sqrt{1-(v/f)^2} \approx 0.8 \ldots 0.9$$

$$\Lambda > 6 \ldots 8\,\mathrm{TeV}$$

Where is the next scale?

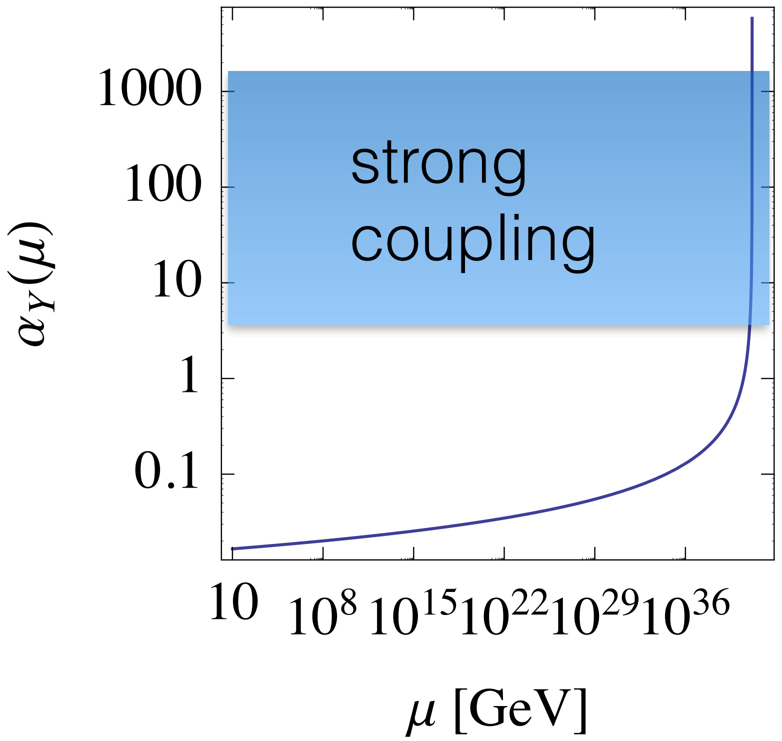
- 13/14 TeV enough to reveal fundamental physics?
- First time in history without nearby new scale: all couplings dimensionless (marginal) or of positive mass dimension (relevant)
- Remaining hopes?
    - Landau pole of hyper charge $U(1)_Y$
    - Gravity scale (M_{Planck})

SM Hyper-charge

Hyper-charge is not asymptotically free, will blow up at (very) high energies — Landau Pole

$$1/\alpha_Y(M_Z) = 1/\alpha_Y(\Lambda) + \frac{b_Y}{2\pi} \ln \frac{\Lambda}{M_Z} \qquad b_Y = \frac{41}{10}$$

$$\Lambda \sim M_Z\, e^{2\pi/\alpha_Y b_Y} \sim 10^{41}\ \mathrm{GeV}$$



Gravity

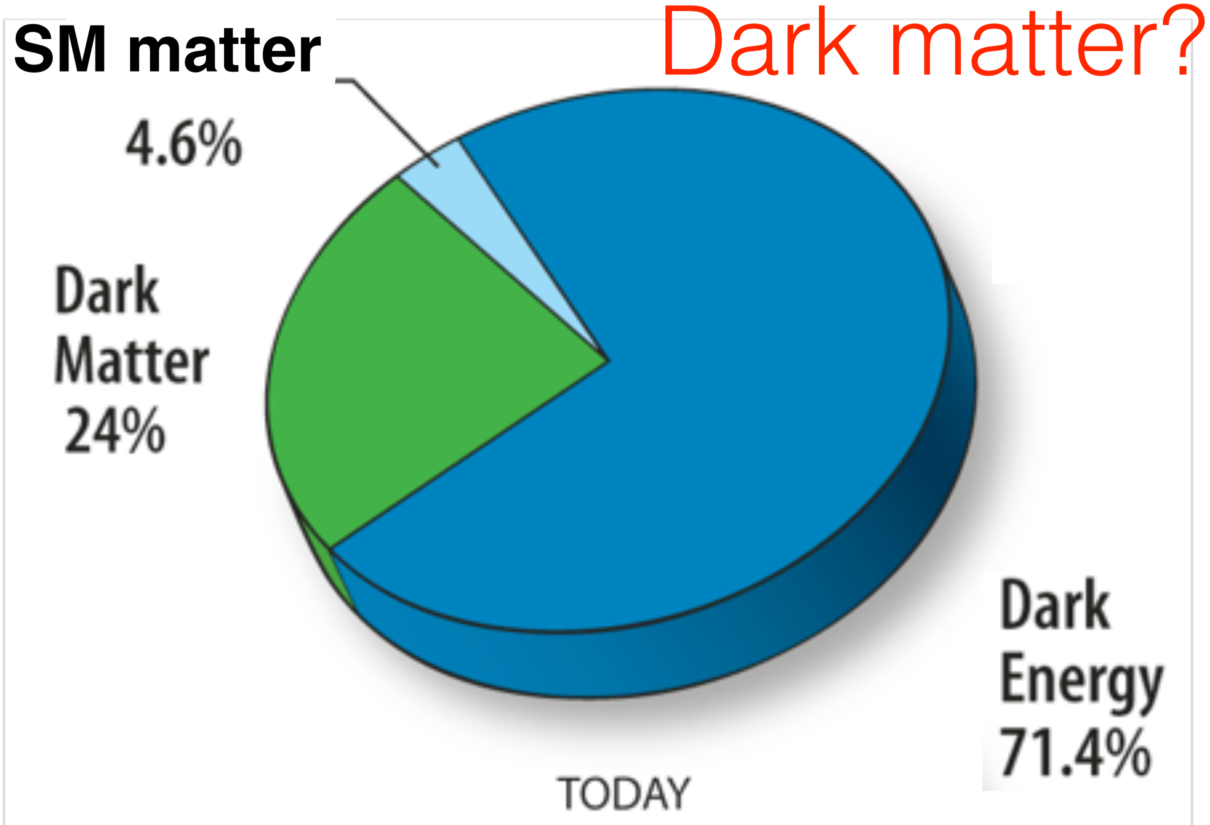
- Strong coupling problem, e.g. graviton-graviton scattering

$$\sigma \sim \frac{E^n}{M_{pl}^{n+2}} \qquad M_{pl} \simeq 10^{19} \text{ GeV}$$

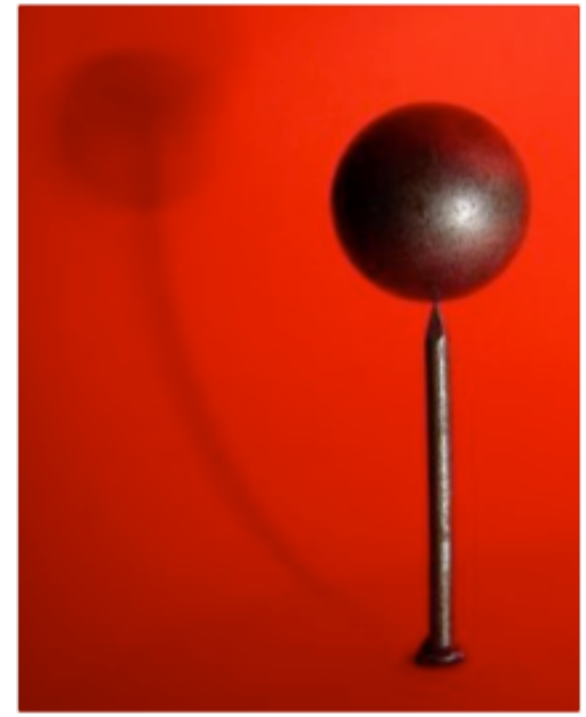
Open questions of the SM

The SM is incomplete

Dark matter?

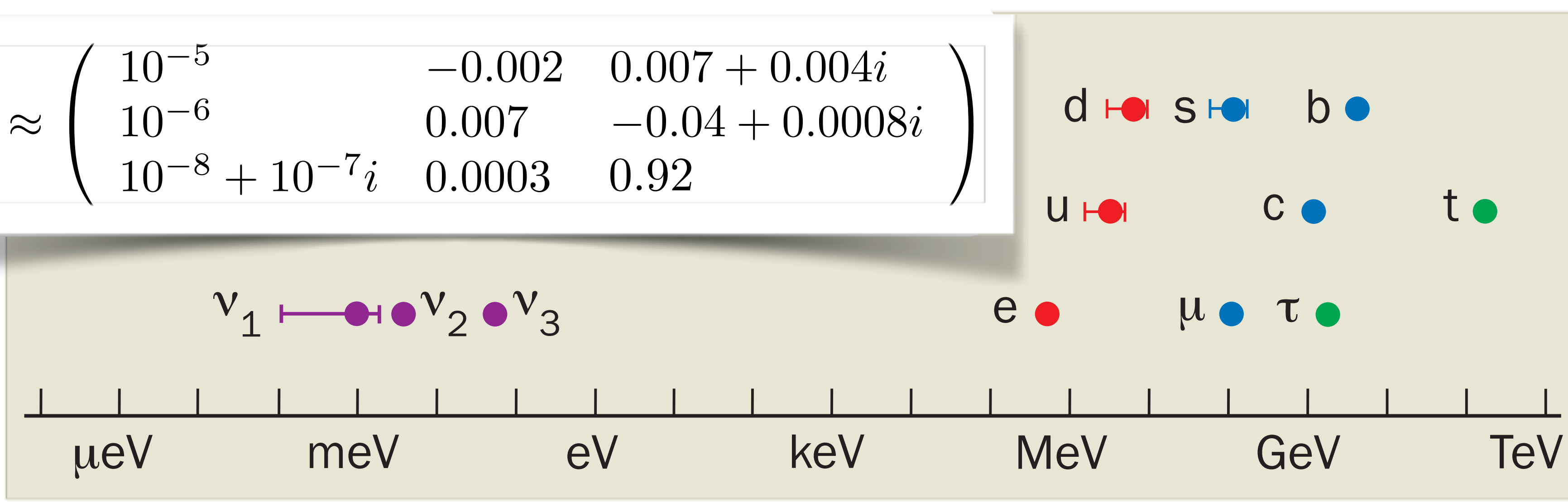


Fine-tuning?

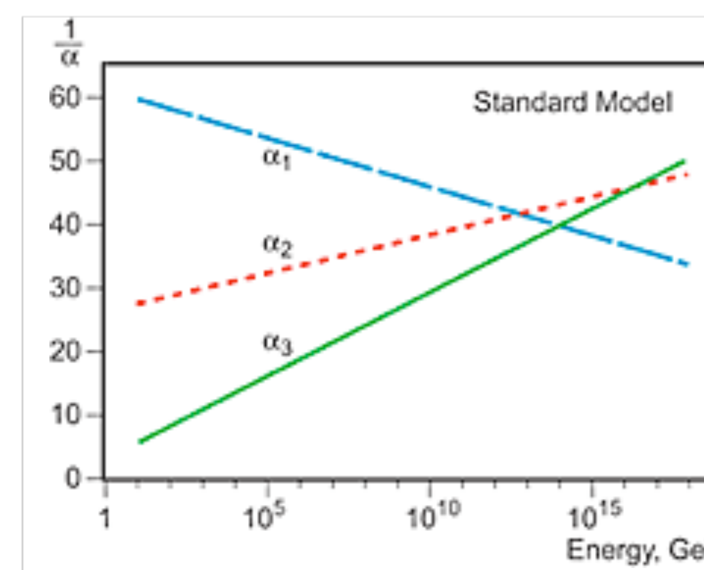


Origin of SM flavor and mass hierarchies?

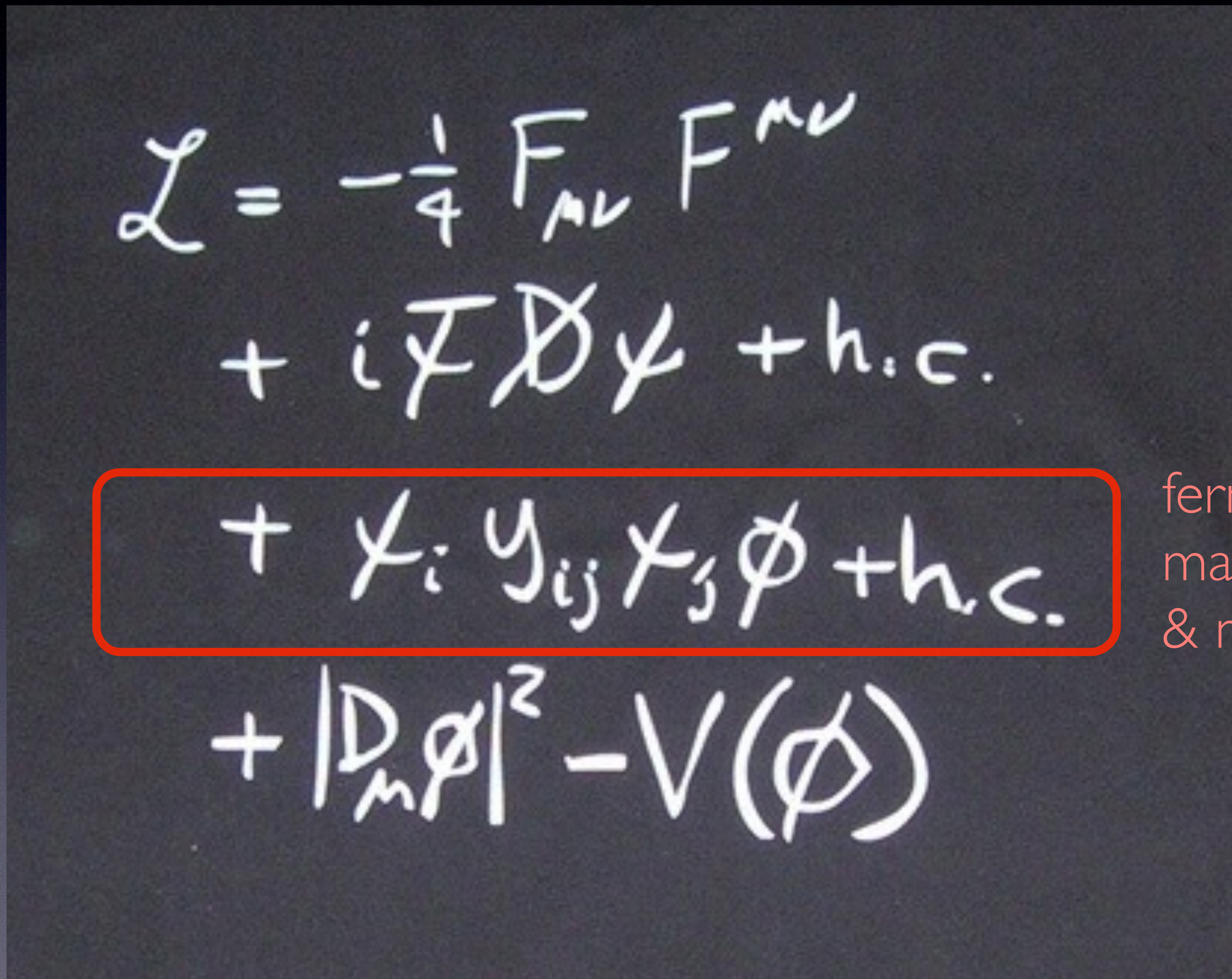
$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.92 \end{pmatrix}$$



Unity of forces?

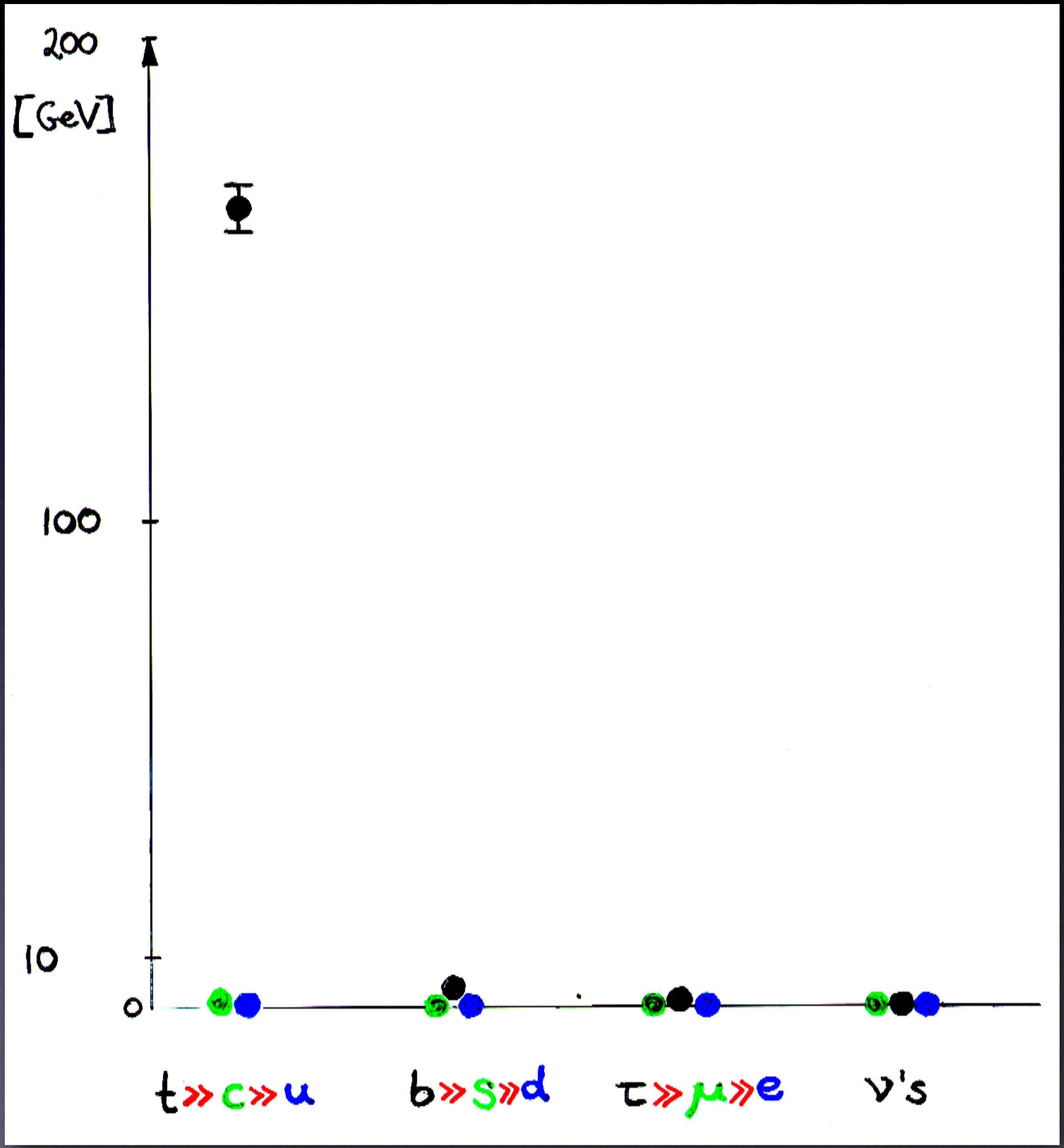


The SM

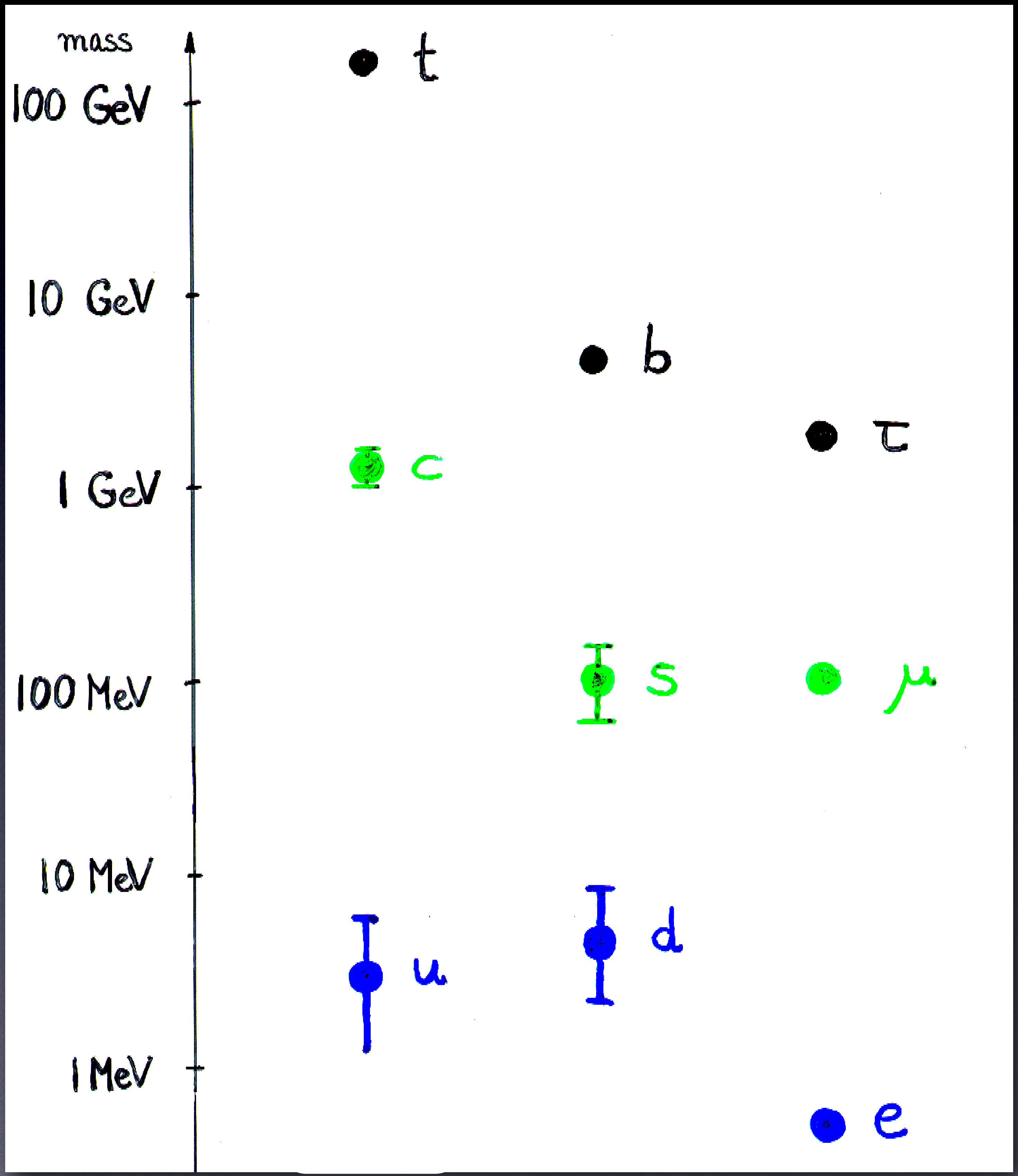


fermion
masses
& mixings

Quark and Lepton mass hierarchy



Masses on a Log-scale



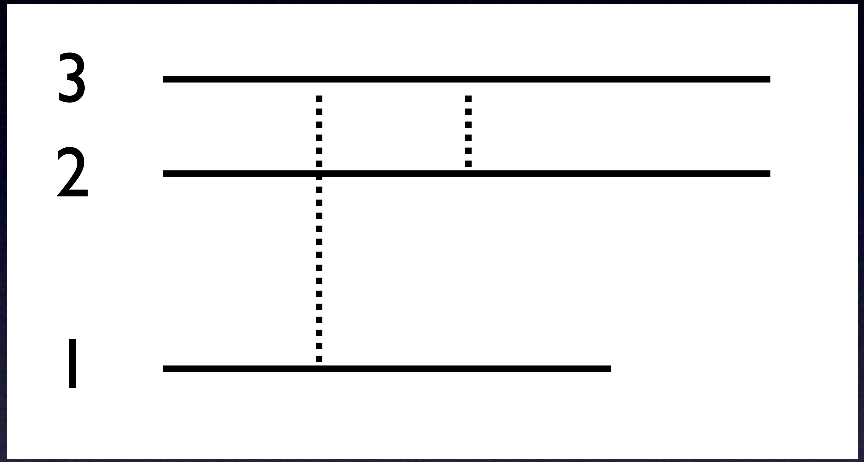
$$Y_D = (m_d, m_s, m_b)/v$$
$$Y_U = V^\dagger_{\rm CKM}(m_u, m_c, m_t)/v$$

$$Y_D \approx (10^{-5}, 0.0005, 0.026)$$
$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.96 \end{pmatrix}$$

SM quark masses: mostly small & hierarchical.
Origin of this structure?

Compare to: $g_s \sim 1$, $g \sim 0.6$, $g' \sim 0.3$, $\lambda_{\rm Higgs} \sim 1$

Analog to mysterious spectral lines before QM



$$\nu = \left(\frac{1}{n^2} - \frac{1}{m^2}\right) R$$

Explained by Bohr

$$E_n = -\frac{2\pi^2 e^4 m_e}{h^2 n^2}$$

Is there an analogue to the Bohr atom, we might discover at the LHC?

Flavor dynamics @ LHC ?

Possible, but ...

TeV? 10^3 TeV? 10^{16} GeV?

1) Lack of scale

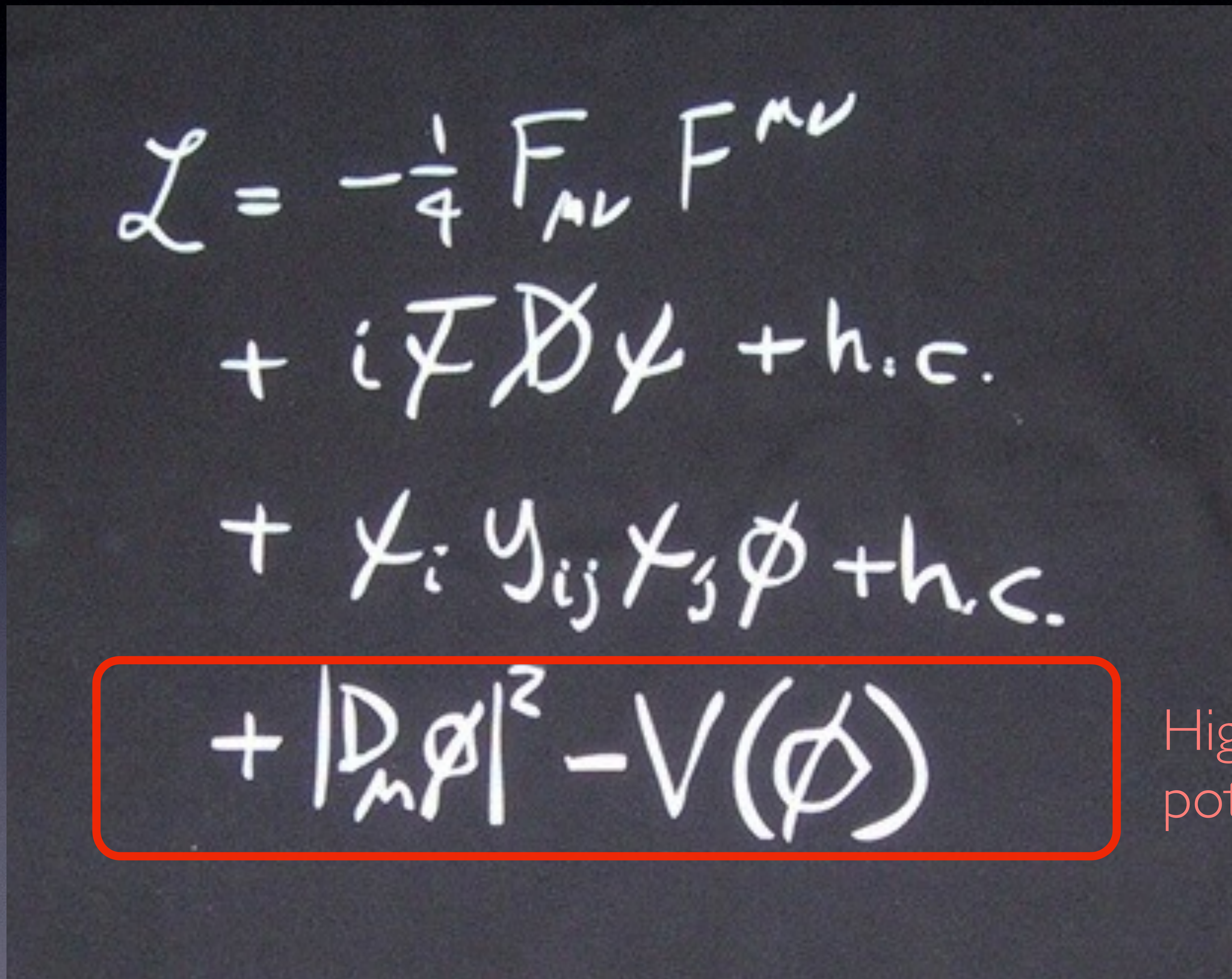
$$\mathcal{L}_{\text{flavor}} = [Y^U]_{ij}\, \bar{Q}_i H_c u_j + \ldots$$

dim 0 + 3/2+1+3/2 = 4

→ Jernej's lecture

2) Very strong constraints from flavor physics:
Generic flavor dynamics >> 100 TeV

The SM



Higgs potential

Top as a destabilizing agent

Stability and meta-stability

Cabibbo, Maiani, Parisi, Petronzio, '79;
Hung '79; Lindner 86; Sher '89; …

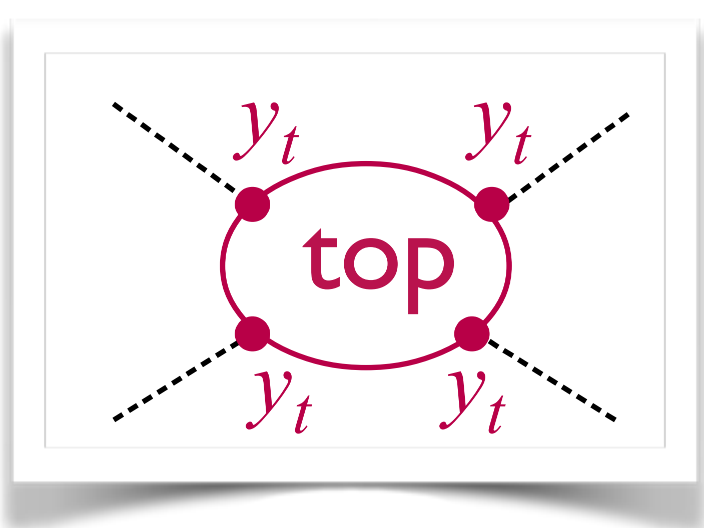
Tree-level

$$V(\phi) = -\mu^2|\phi|^2 + \boxed{\lambda|\phi|^4}$$

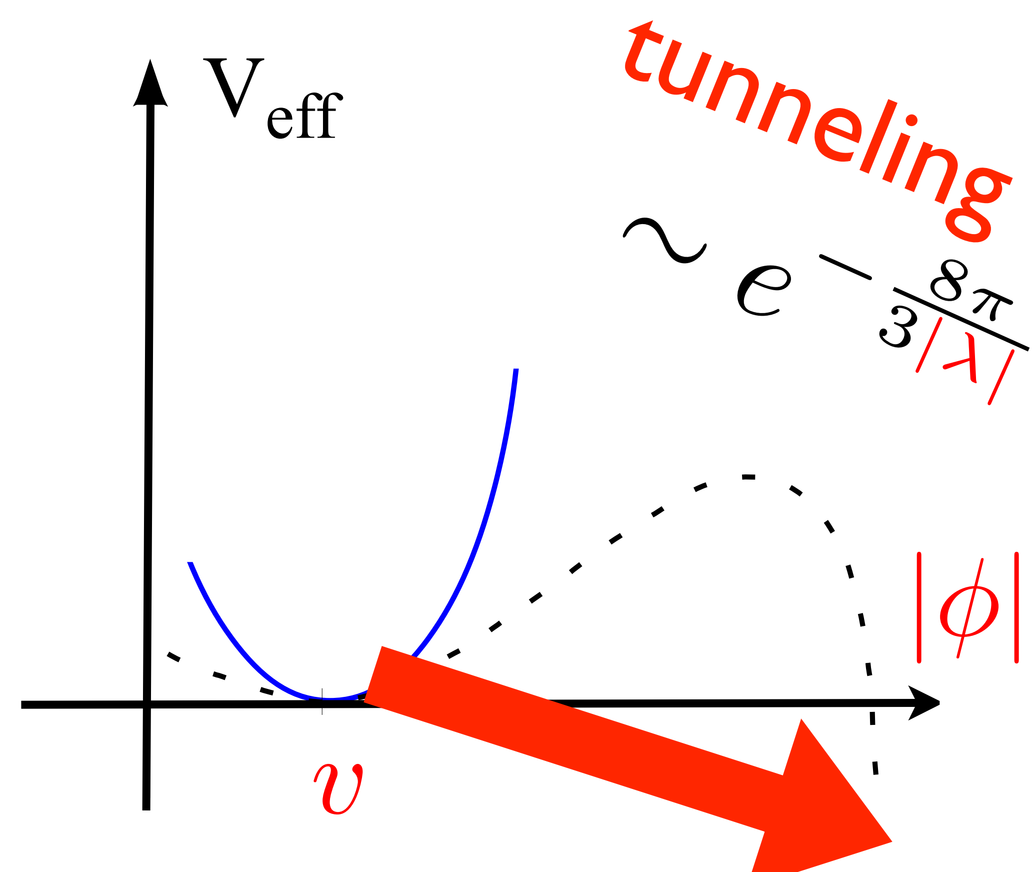
What happens at $|\phi| \gg v$? Focus on λ, $\mu^2 \ll |\phi|^2$

Quantum fluctuations change potential

$$V \simeq \lambda(|\phi|)\,|\phi|^4$$



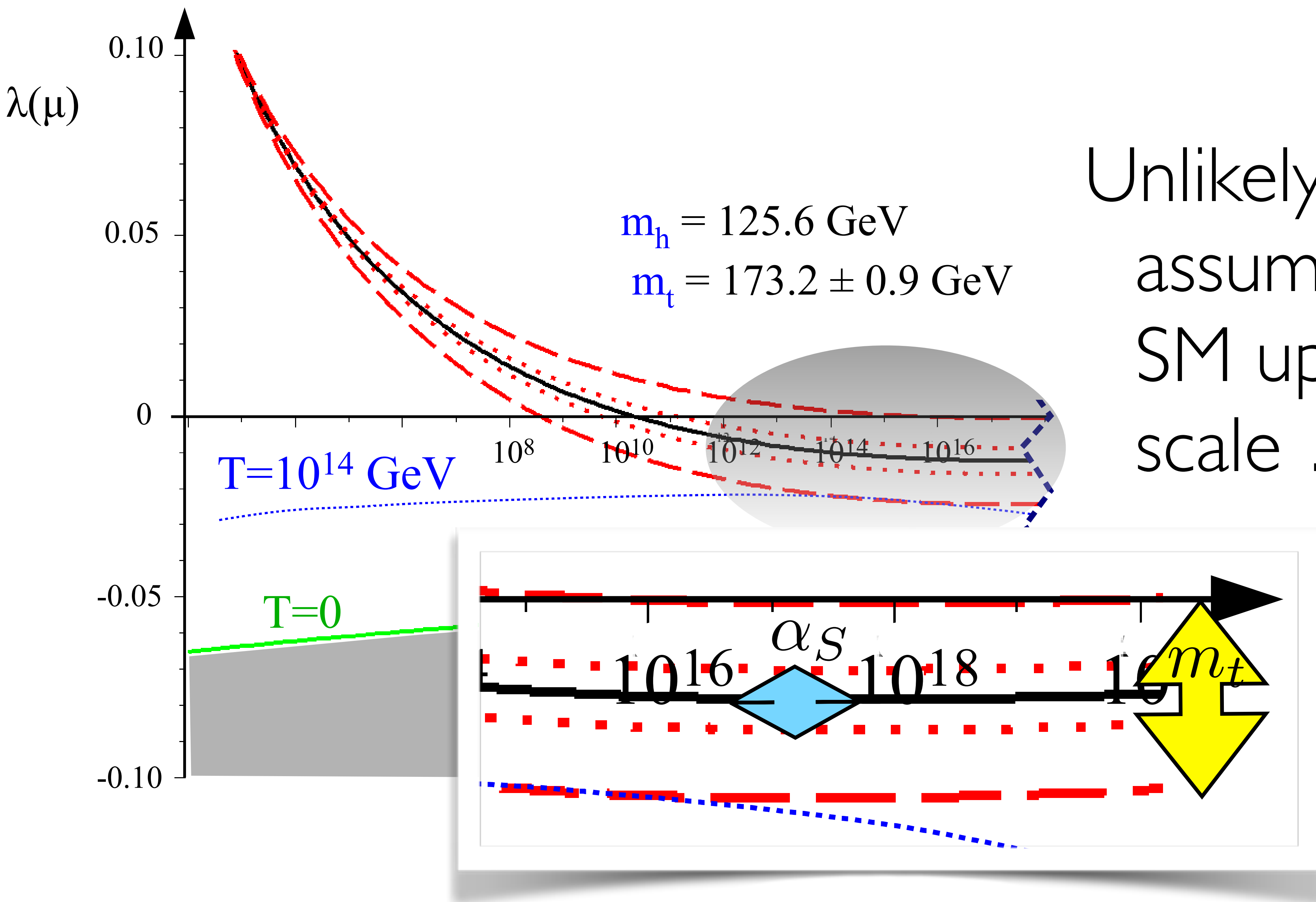
decreasing
at large
Energies
=>



Stability and meta-stability

SM vacuum is unstable but sufficiently long-lived,
(depends on m_{top}, m_{Higgs})

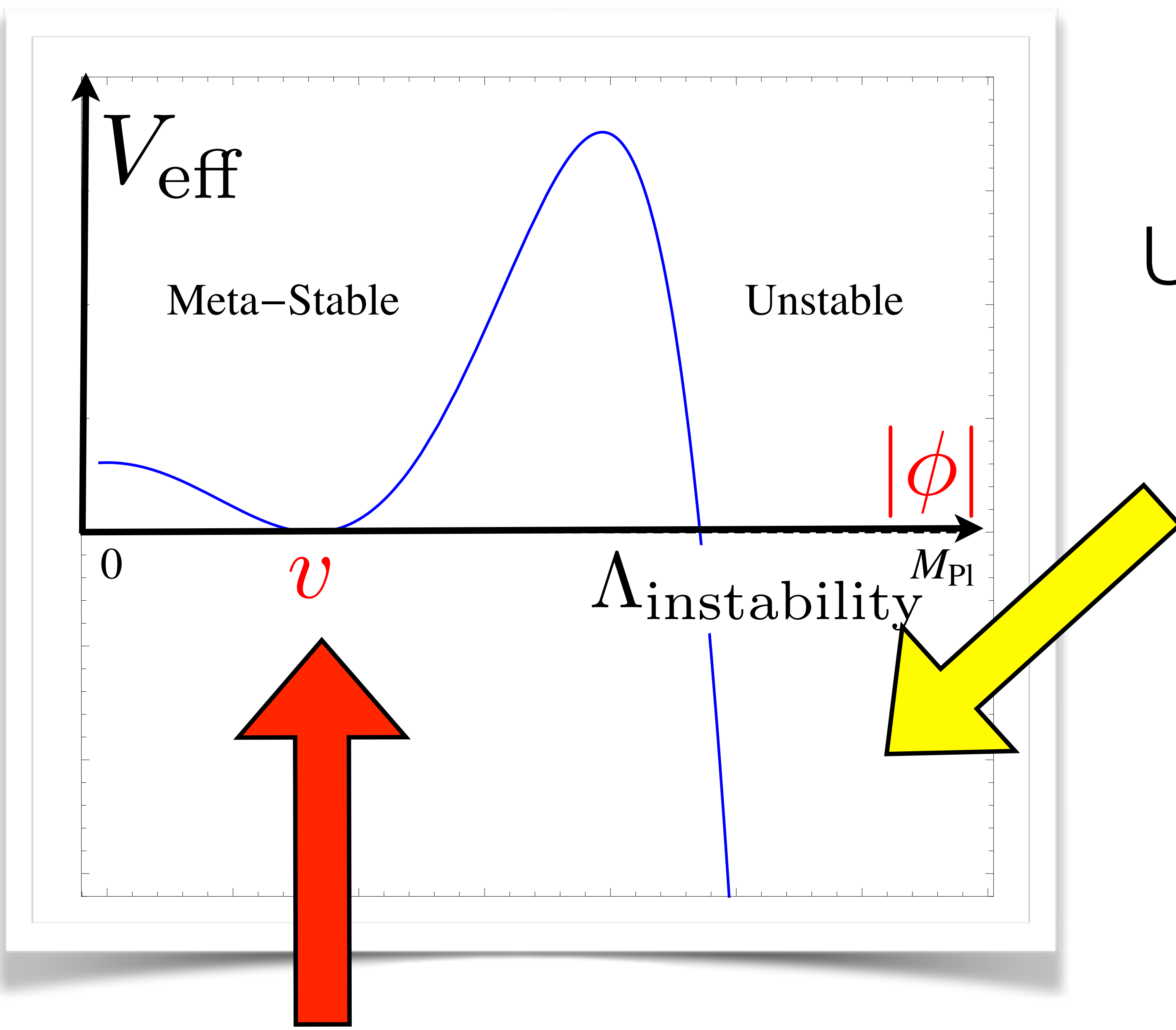
cf Elias-Miro et al. '12
Degrassi et al. '12
Buttazzo et al. '12



Unlikely the full story, assumes nothing but SM up to the Planck scale …

decisive uncertainty
m_{top}

If metastable: How did we end up in the energetically disfavoured vacuum?



You are here?!

Universe is overwhelmingly likely to evolve to wrong minimum

Fine-tuning of initial conditions?

$$\sim \Lambda_{\text{instability}}/M_{\text{Planck}}$$

For $\Lambda_{\text{instability}} \sim 10^{10}\,\text{GeV} \to 10^{-8}$ tuning

Higgs potential

$$V(\phi) = \boxed{-\mu^2|\phi|^2} + \lambda|\phi|^4$$

quantum fluctuations
destabilise Higgs mass^2

Effective Field Theory

An approximate field theory which works up to a certain energy scale (Λ), using only degrees of freedom with $m \ll \Lambda$.

Example: QED (e, γ), for E << M_W

Is the SM an EFT?

Yes! Breaks down latest at the gravity scale (details unknown).

Principle: UV insensitivity

Naturalness : absence of special conspiracies between phenomena occurring at very different length scales.

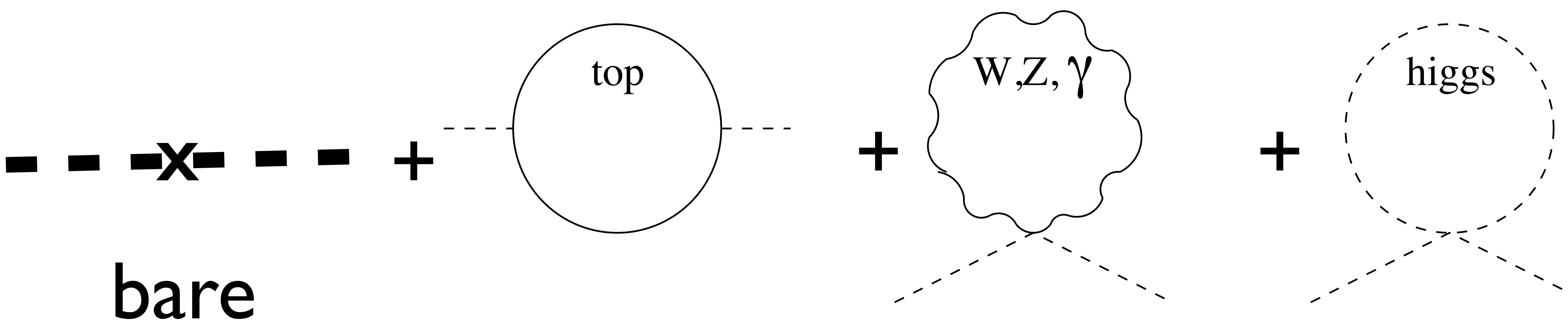
Planets do not care about QED.

QED at $E \sim m_e$ does not care about the Higgs.

See e.g. G. Giudice: 1307.7879

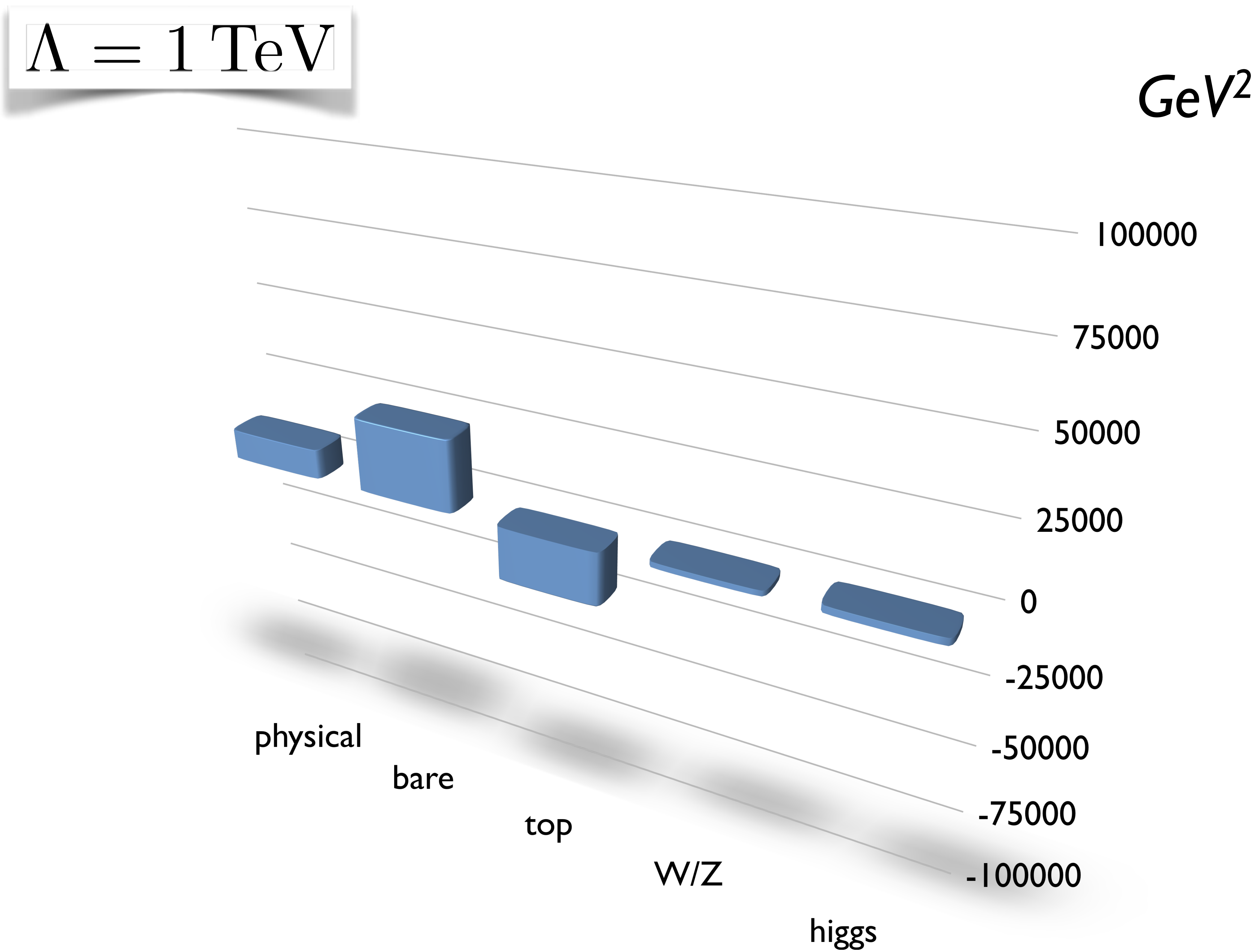
Hierarchy problem

- Higgs mass sensitive to thresholds (GUT, gravity)
- Enormous quantum corrections $\mathcal{O}(\text{highest scale})$ exceed Higgs mass physical value, need to fine-tune parameters

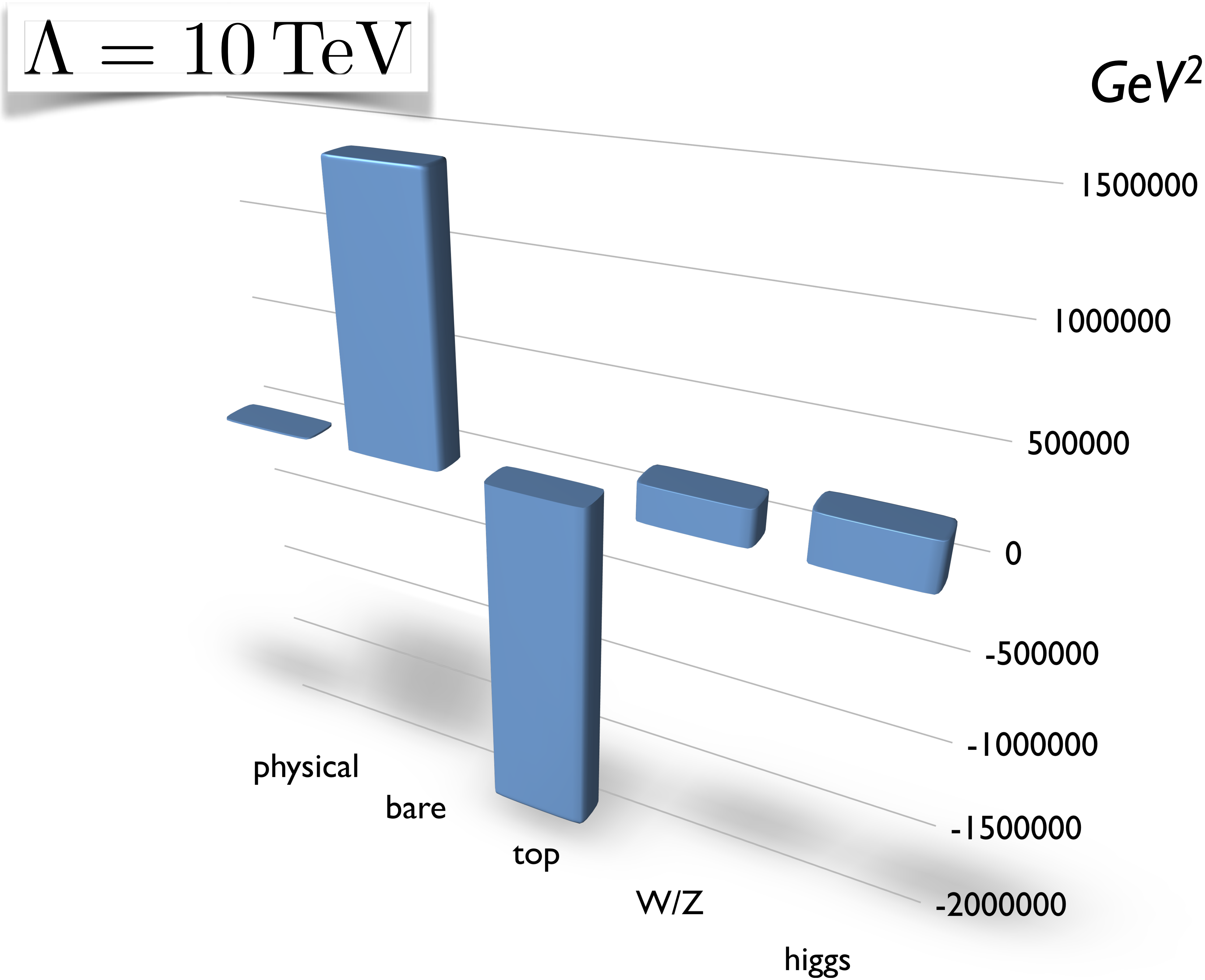


$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$ $\quad \frac{9}{64\pi^2}g^2\Lambda^2$ $\quad \frac{1}{16\pi^2}\lambda^2\Lambda^2$

$$m_h^2(\text{physical}) = m_h^2(\text{bare}) + \sum_i a_i \Lambda^2$$



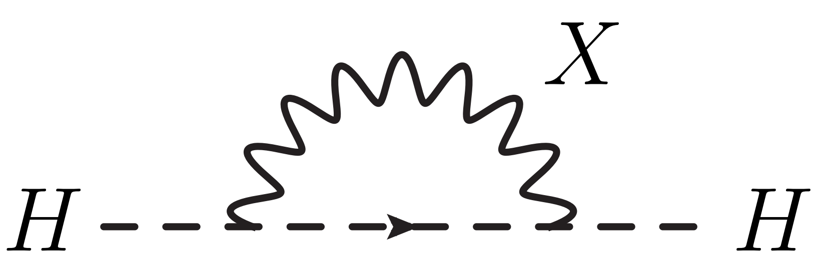
$\Lambda = 1\,\text{TeV}$
GeV^2
100000
75000
50000
25000
0
-25000
-50000
-75000
-100000
physical
bare
top
W/Z
higgs


$\Lambda = 10\,\mathrm{TeV}$
GeV²
1500000
1000000
500000
0
-500000
-1000000
-1500000
-2000000
physical
bare
top
W/Z
higgs

Comments

- The ‘cancelation of divergencies’ is not the question
- Rather: parameters in the effective theory are strongly sensitive to fundamental ones

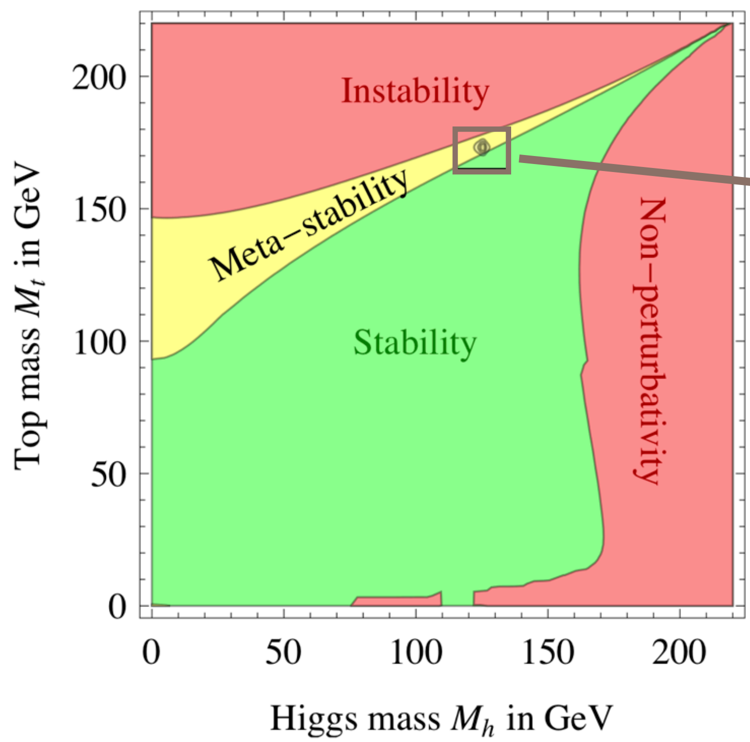
e.g. GUT

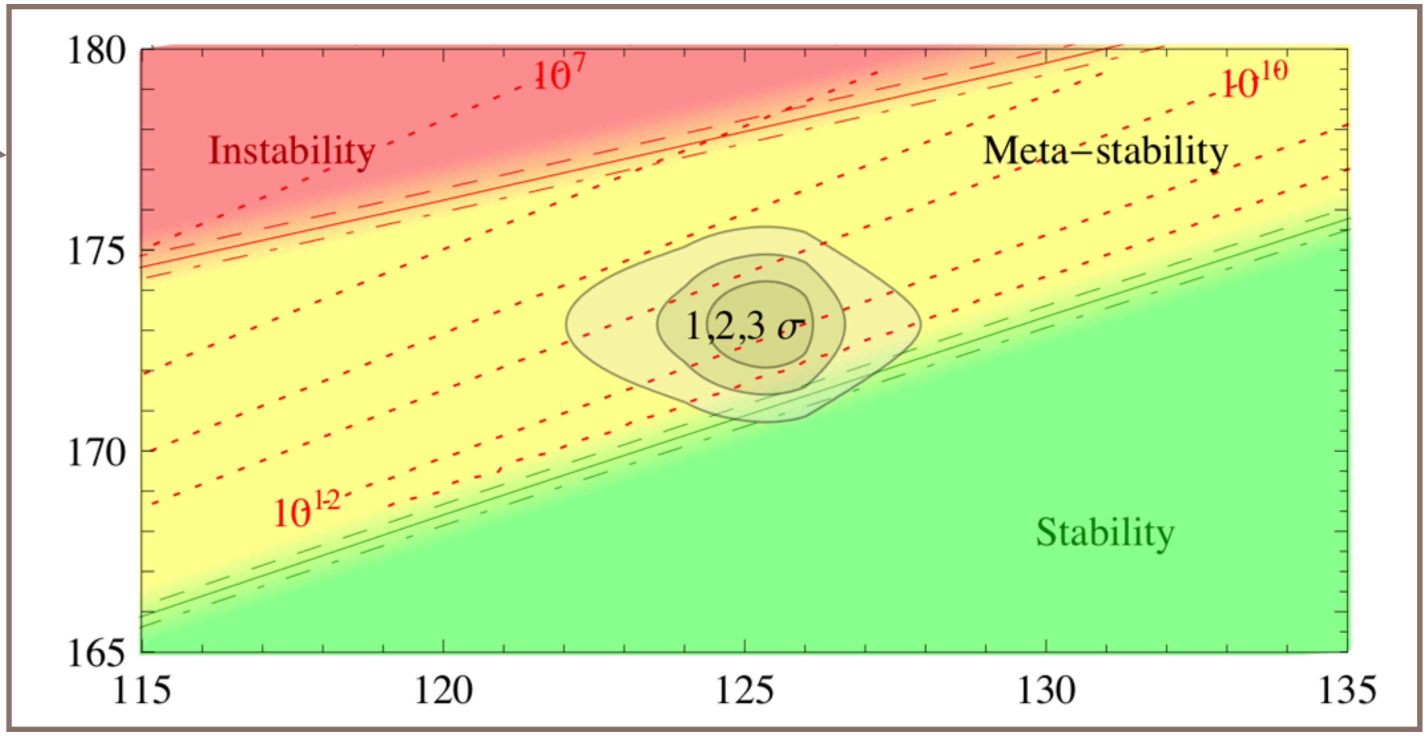


$$\Rightarrow \Delta m_H^2 \sim \frac{g_{\mathrm{GUT}}^2}{16\pi^2} M_X^2 \sim (10^{15}\ \mathrm{GeV})^2$$

- The hierarchy problem needs a ‘hierarchy of scales’. The SM alone (no gravity, nothing else) if fine → no hierarchy, no problem!

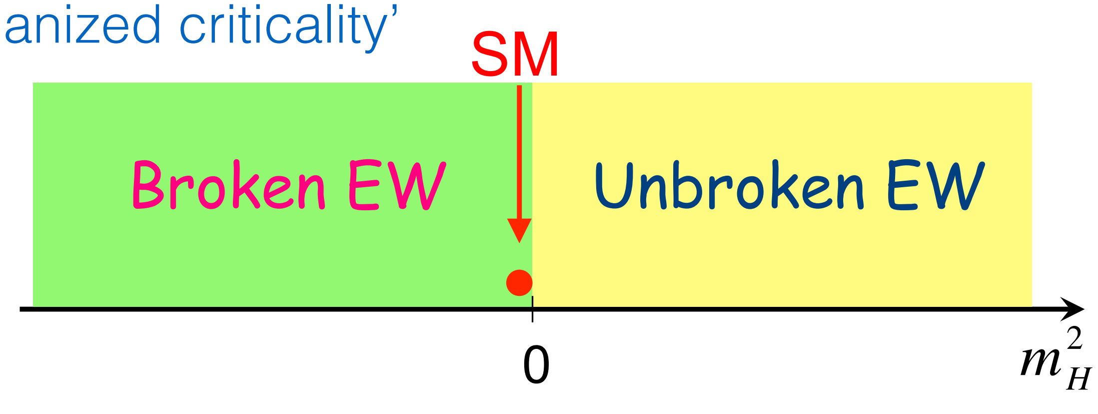
Only the SM?

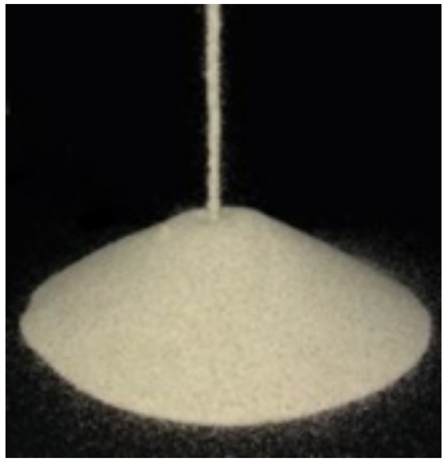




We seem to be living close to a critical condition,
similar to Planck-Weak hierarchy …

Giudice, Rattazzi, 'Self-organized criticality'

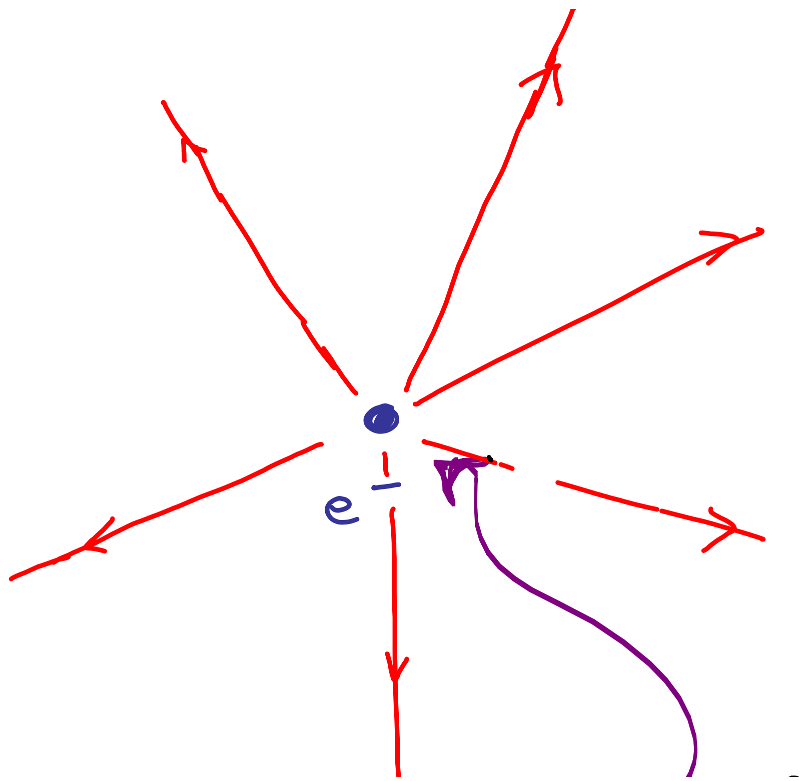




Fine-tuning not an inconsistency of physics since we can always cancel bare vs. quantum. However, it might help us understand where new physics could set in.

Example: Electron Mass

Ex1 : divergent self energy of electric field



New physics expected at

$\Lambda \sim m_e/\alpha$

Classically:

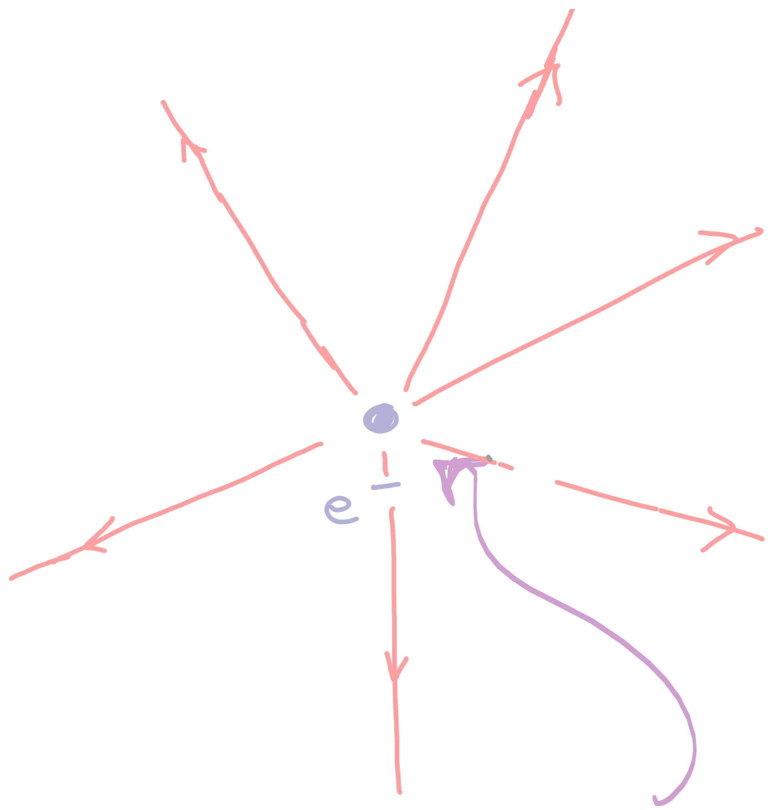
$$\int_{r=\Lambda^{-1}} d^3r \vec{E}^2 \simeq \alpha\Lambda \quad \text{vs.} \quad m_e$$

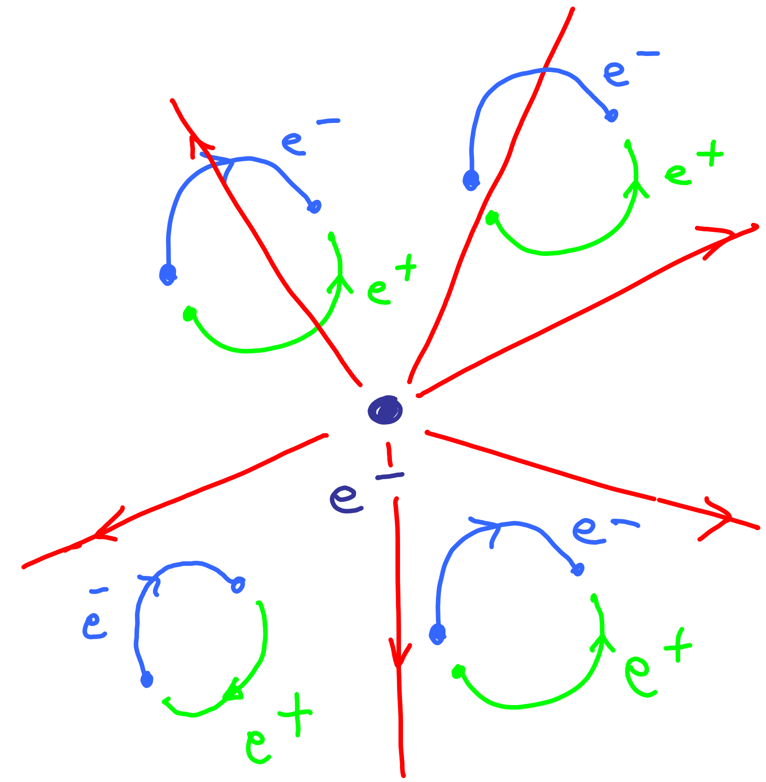
$\vec{E} \sim \vec{n}/r^2$ Coulomb

Electron Mass

Ex1 : divergent energy of electric field

+positron





Classically:

$$\int_{r=\Lambda^{-1}} d^3 r \vec{E}^2 \simeq \alpha\Lambda$$

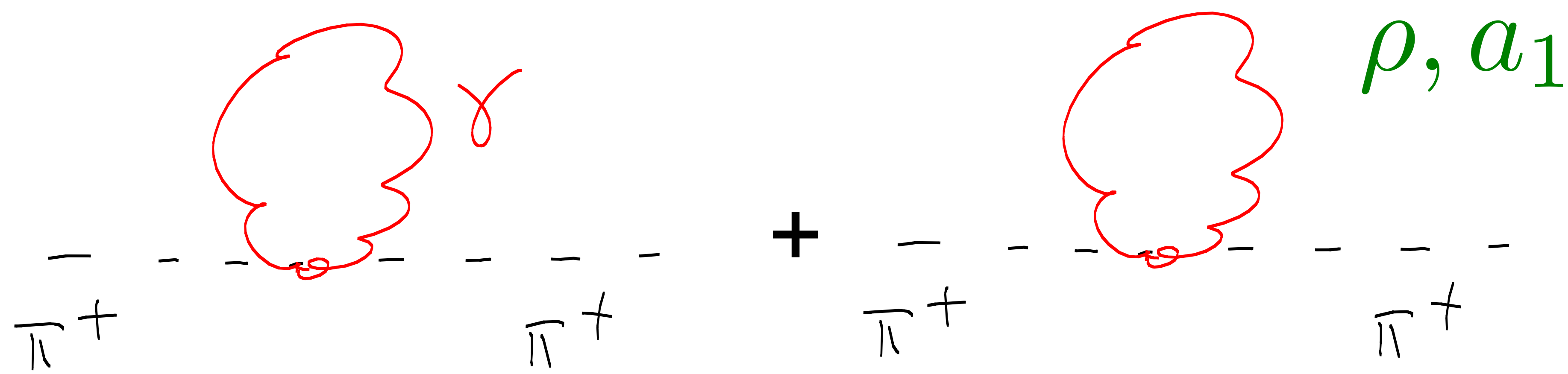
Extend space-time symmetry, relativity + QM: predict positron

$$\delta m_e \simeq \frac{\alpha}{\pi} m_e \log\left(\frac{\Lambda}{m_e}\right)$$

→ natural electron mass.

Another example: Pion mass

Ex2 Neutral-charged pion mass difference



$$\delta m^2_{\pi^+} \sim \frac{3\alpha}{4\pi}\Lambda^2 < (m^2_{\pi^+} - m^2_{\pi^0})_{\rm exp} \approx (4\,\mathrm{MeV})^2$$

Expect $\rightarrow \Lambda < 850\,\mathrm{MeV}$

'New physics': comes in at $m_\rho = 770\,\mathrm{MeV}$

Das et al '67

$$m^2_{\pi^\pm} - m^2_{\pi_0} \simeq \frac{3\,\alpha_{em}}{4\pi}\frac{m^2_\rho m^2_{a_1}}{m^2_{a_1} - m^2_\rho}\log\left(\frac{m^2_{a_1}}{m^2_\rho}\right)$$

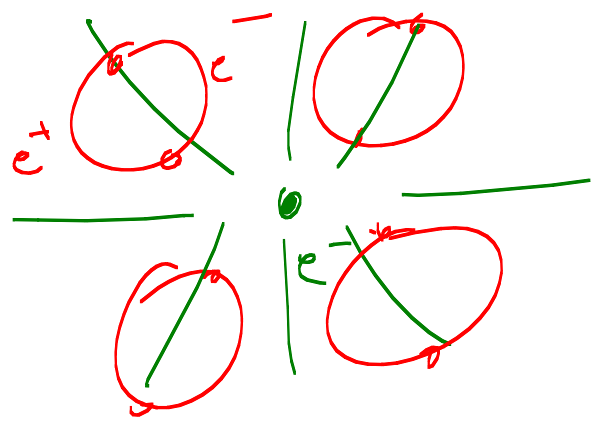
$$(m_{\pi^\pm} - m_{\pi_0})|_{\rm TH} \simeq 5.8\,\mathrm{MeV}\ !$$

Famous naturalness disaster

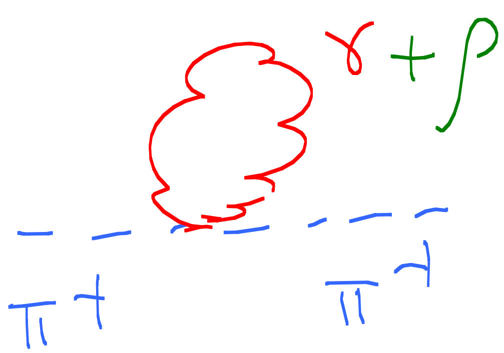
- We don't understand the cosmological constant $CC = \Lambda_0 \approx (10^{-3}\,\mathrm{eV})^4$

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,(R - \Lambda_0)$$

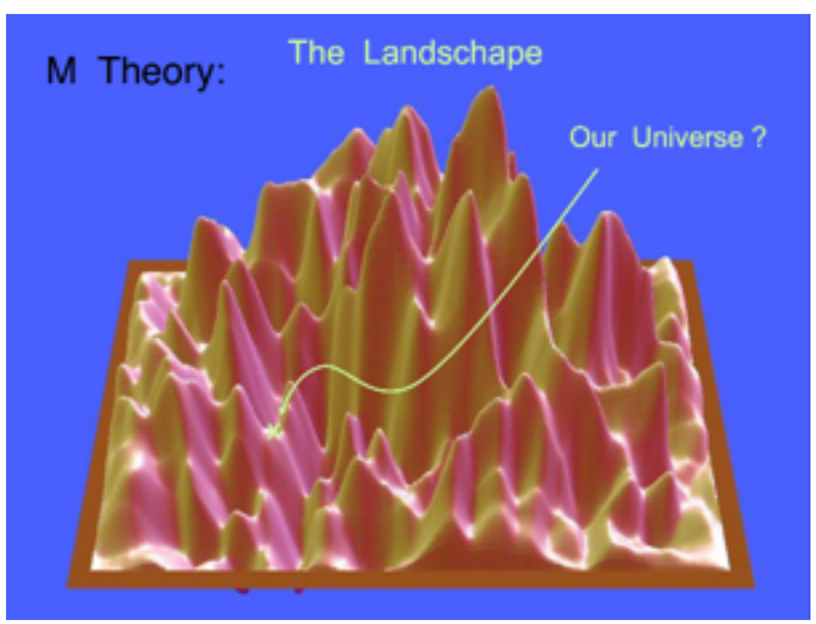
$\delta\Lambda_0 \approx \Lambda^4$ → new physics at $10^{-3}\,\mathrm{eV}$ or ~ few mm !?!



Supersymmetry (new space-time symmetry)



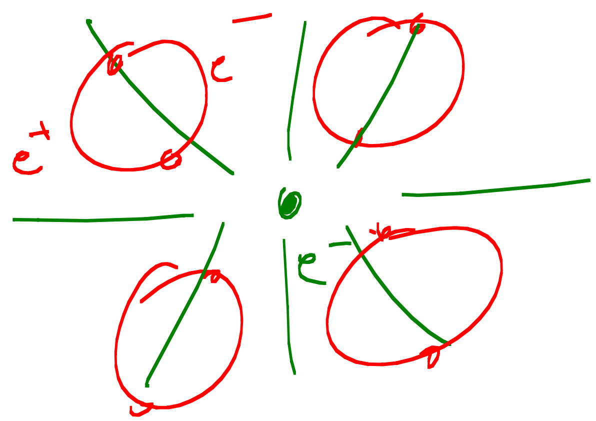
Composite Higgs



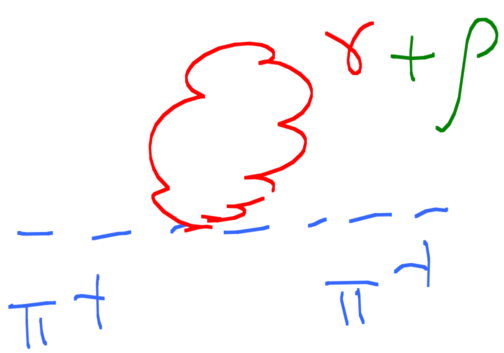
anthropic principle?

Multiverse

-> Yael's lectures

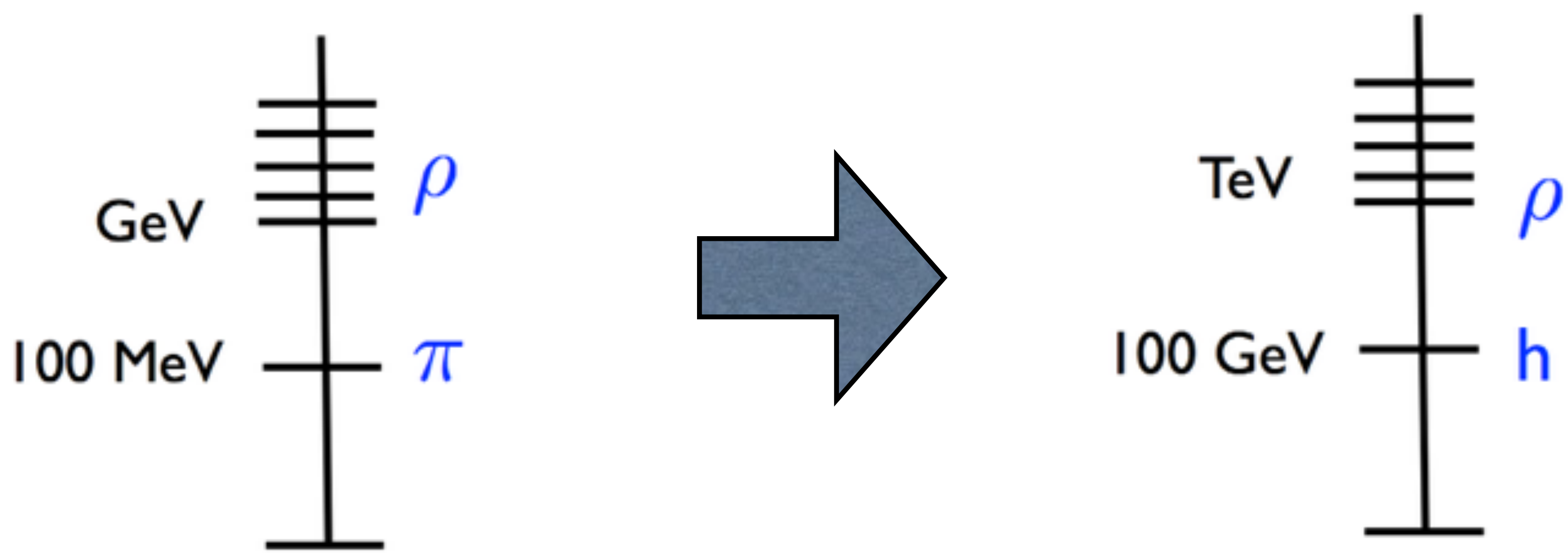


Supersymmetry
(new space-time symmetry)



Composite Higgs

Strong EWSB (Composite Higgs)



QCD

Higgs as a pGB

Why is the Higgs light?

Kaplan; Agashe et. al

Inspired by QCD: (pseudo) scalar pion is the lightest state

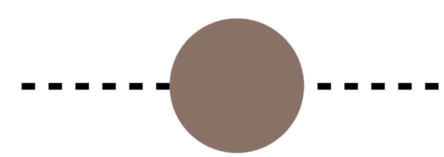
Shift symmetry…

$$\pi \to \pi + c$$

… protects its mass.

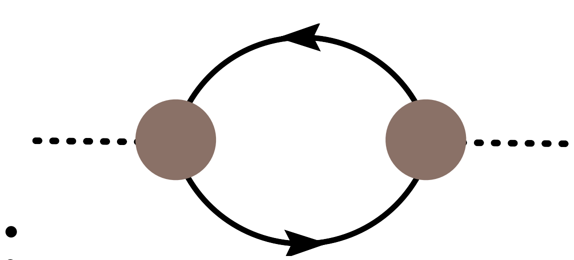
Interactions are perturbative for $E \ll 4\pi f$

No pure composite effects due to Goldstone symmetry



= 0

Shift symmetry broken by elementary-composite couplings:



$$m_h^2 \sim \frac{\lambda^2}{16\pi^2} \Lambda_{comp}^2$$

$$\lambda \ll 4\pi$$

Supersymmetry is a weakly coupled solution to the hierarchy problem. We can extrapolate physics to the Planck scale, complete the MSSM in a GUT.

There is another way and it's already in use. Nature already employs a strongly coupled mechanism to explain why

$$\Lambda_{\mathrm{QCD}} \ll M_{\mathrm{Planck}}$$

$$\sim 1\,\mathrm{GeV} \qquad 10^{19}\,\mathrm{GeV}$$

QCD


David J. Gross

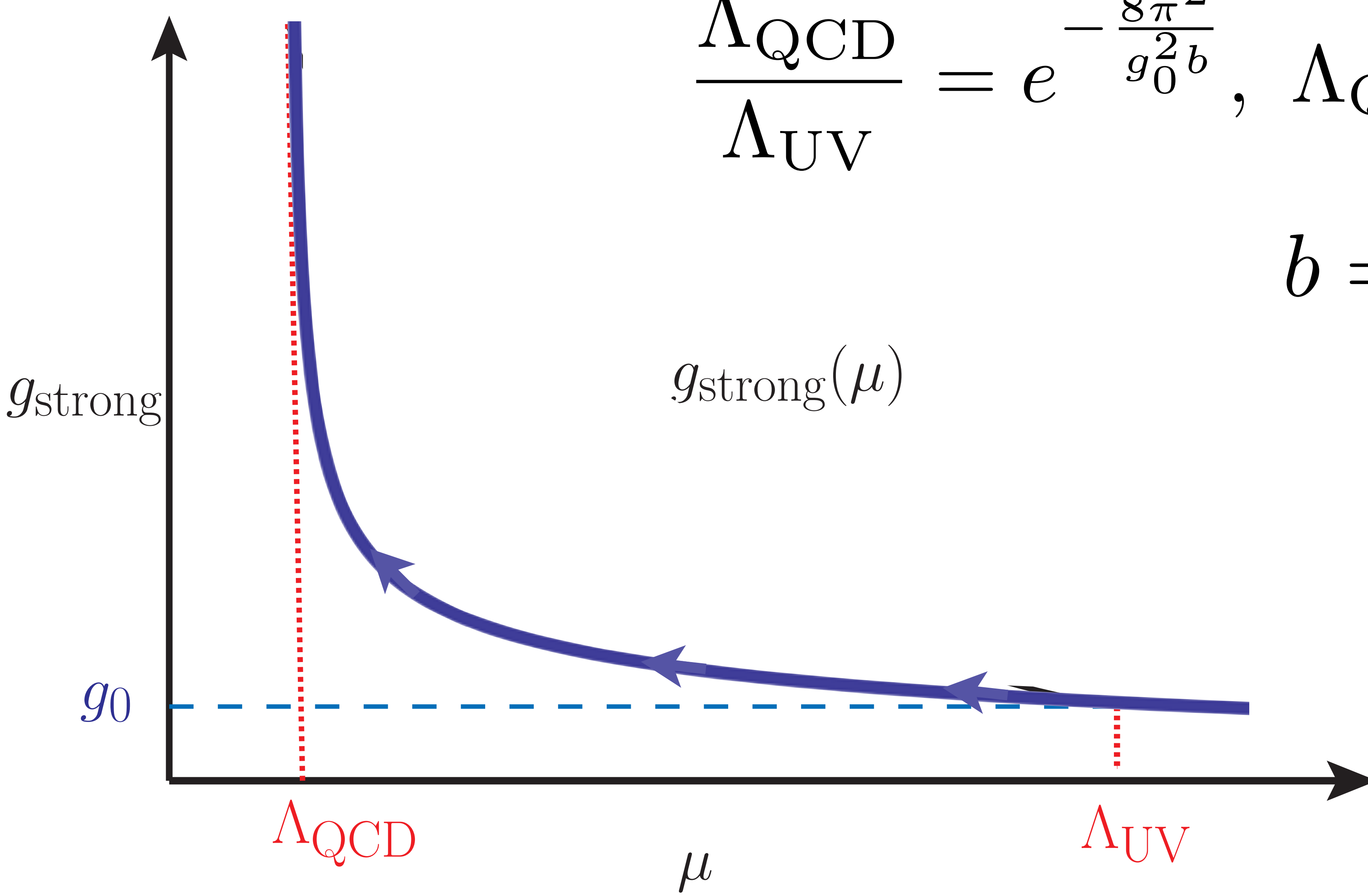

H. David Politzer


Frank Wilczek

Fix QCD coupling at some high scale
→ exponential hierarchy generated dynamically

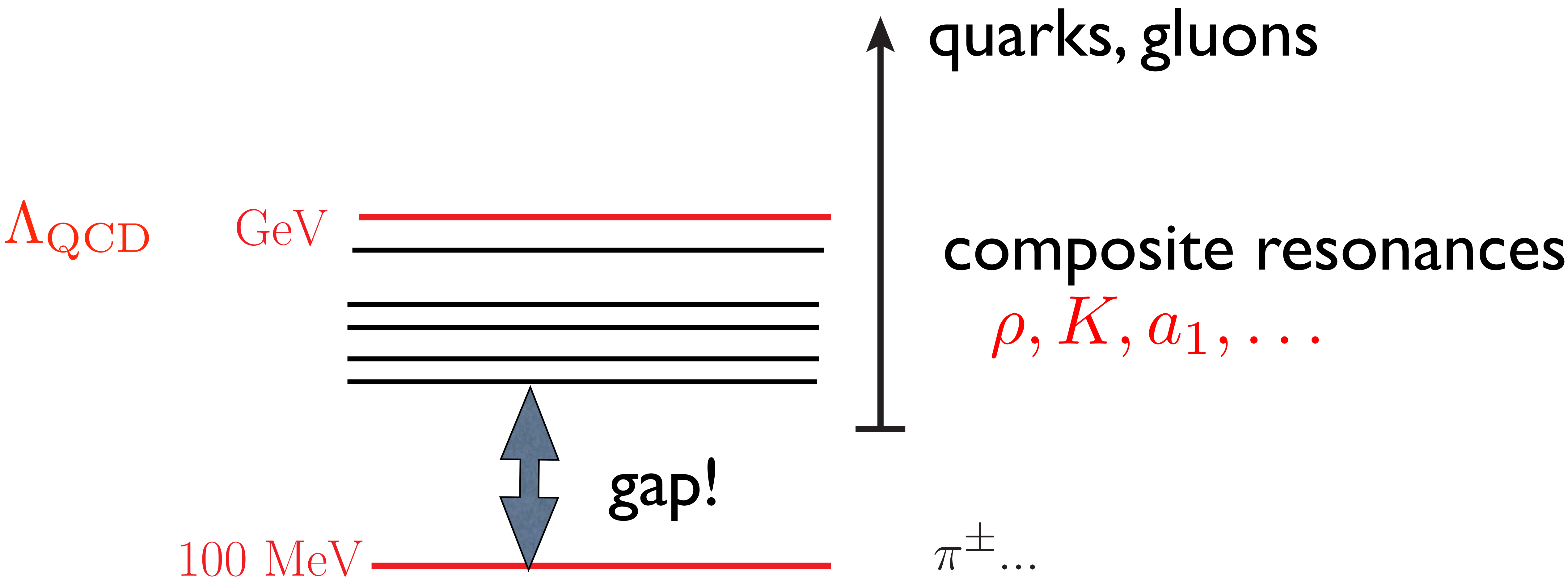
$$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm UV}} = e^{-\frac{8\pi^2}{g_0^2 b}}, \;\; \Lambda_{\rm QCD} \leq \;\; {\rm GeV}$$

$$b = 7$$



Asymptotic freedom

QCD: composite bound states



At strong coupling, new resonances are generated

QCD vs. EWSB

QCD dynamically breaks SM gauge symmetry

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$\langle \bar{q}_L q_R \rangle \simeq \Lambda^3_{\mathrm{QCD}} \sim \ (\mathrm{GeV})^3$$

The QCD masses of W/Z are small

$$m_{\mathrm{W,Z}} \sim \frac{g}{4\pi} \Lambda_{\mathrm{QCD}} \sim 100 \ \mathrm{MeV}$$

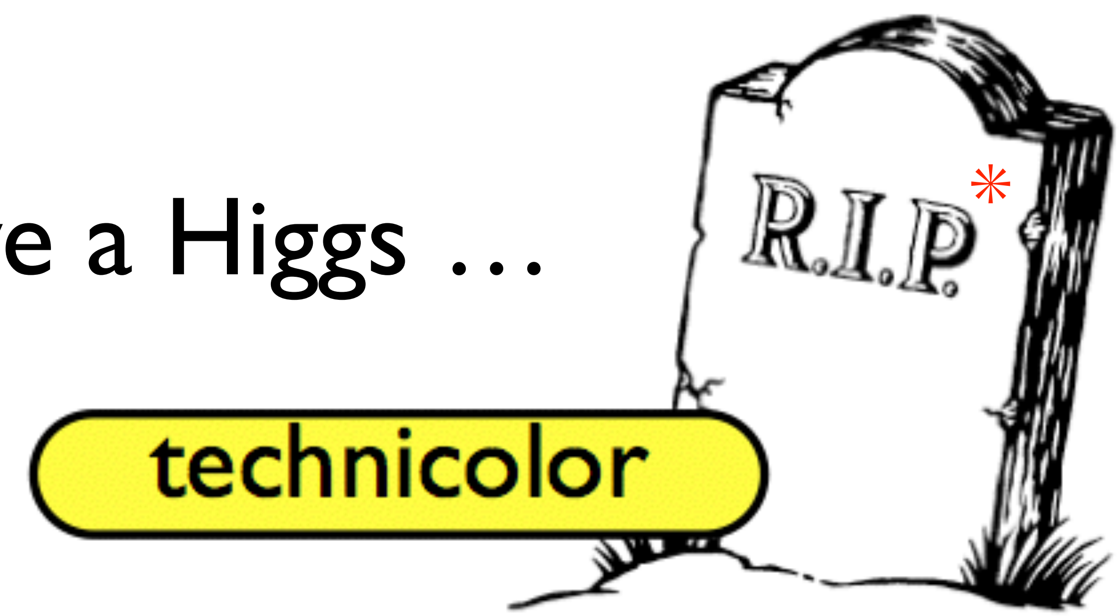
Longitudinal components of W & Z have tiny admixture of pions…

Technicolor

Scaled up version of QCD mechanism

$$\langle \bar{q}'_L q'_R \rangle \sim \Lambda^3_{\rm TC}, \quad \Lambda_{\rm TC} \sim \;{\rm TeV}$$

Technicolor, doesn't have a Higgs …



* the Higgs as the dilaton
as the last bastion …

Composite Higgs

- Want to copy QCD, but extend pion sector (QCD: $\pi^0, \pi^\pm$)
- Higgs as a (pseudo) Goldstone boson

Need to learn about goldstone bosons…

Quantum Protection

Symmetries can soften quantum behaviour

$$\mathcal{L} = |\partial_\mu \phi|^2 + \boxed{\mu^2 |\phi|^2} - \lambda |\phi|^4 + \ldots$$

breaks susy → corrections must be proportional to susy breaking

Shift symmetry

Higgs mass term can be forbidden

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots$$

$\phi \to e^{i\alpha}\phi$ does not forbid the mass^2

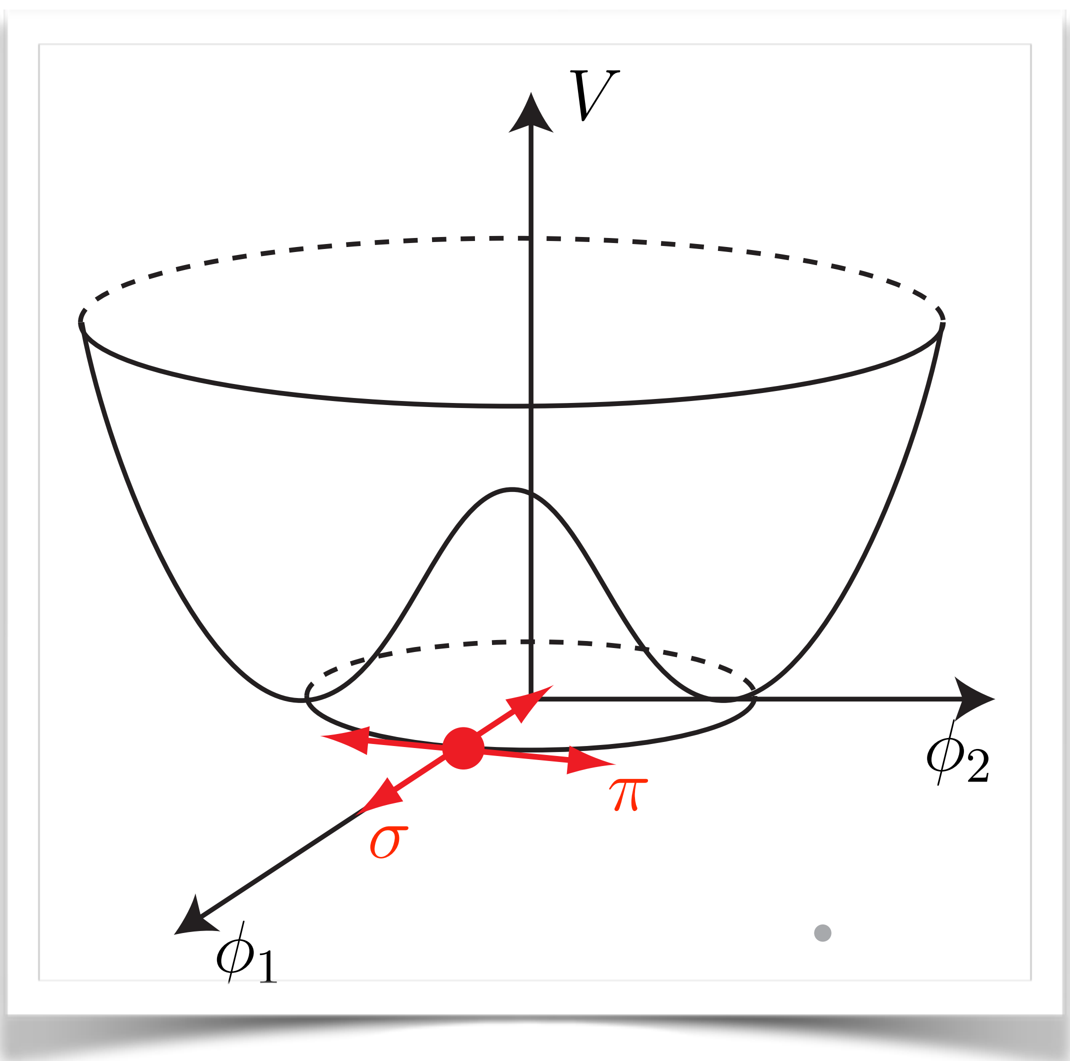
$\phi \to \phi + \alpha$ works!

Can we make the Higgs transform this way?

Spontaneous breaking of U(1)

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}}$$

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots$$



Instead using complex field

$$\phi = \phi_1 + i\phi_2$$

use real parametrisation

$$\phi(x) = \frac{1}{2} e^{i\pi(x)/f} (f + \sigma(x))$$

'phase' 'modulos'

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2|\phi|^2 - \lambda|\phi|^4 + \ldots$$

$V(|\phi(x)|^2)$

use $\phi(x) = \frac{1}{2} e^{i\pi(x)/f}(f + \sigma(x))$

$$\partial^\mu \phi^\dagger \partial_\mu \phi = \frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma + \frac{1}{2}(1 + \sigma/f)^2 \frac{1}{2}\partial^\mu \pi \partial_\mu \pi$$

no mass term

$$V(|\phi(x)|^2) = V(\sigma(x))$$

no dependence on $\pi(x)$

$$\frac{1}{2}\left(1+\sigma(x)/f\right)^2\frac{1}{2}\partial^\mu\pi\partial_\mu\pi+\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma-V(\sigma(x))$$

Using this parameterization a new symmetry is visible:

$$\pi(x)\rightarrow\pi(x)+\alpha$$

because $\pi(x)$ has only ‘derivative interactions’

$$\partial_\mu(\pi(x)+\alpha)=\partial_\mu\pi(x)$$

But what happened to the U(1) symmetry ?

$\pi(x),\sigma(x)$ are real…

But what happened to the U(1) symmetry ?

$$\phi \to e^{i\alpha}\phi$$

$$e^{i\pi(x)/f}(f+\sigma(x)) \to e^{i\alpha}e^{i\pi(x)/f}(f+\sigma(x))$$

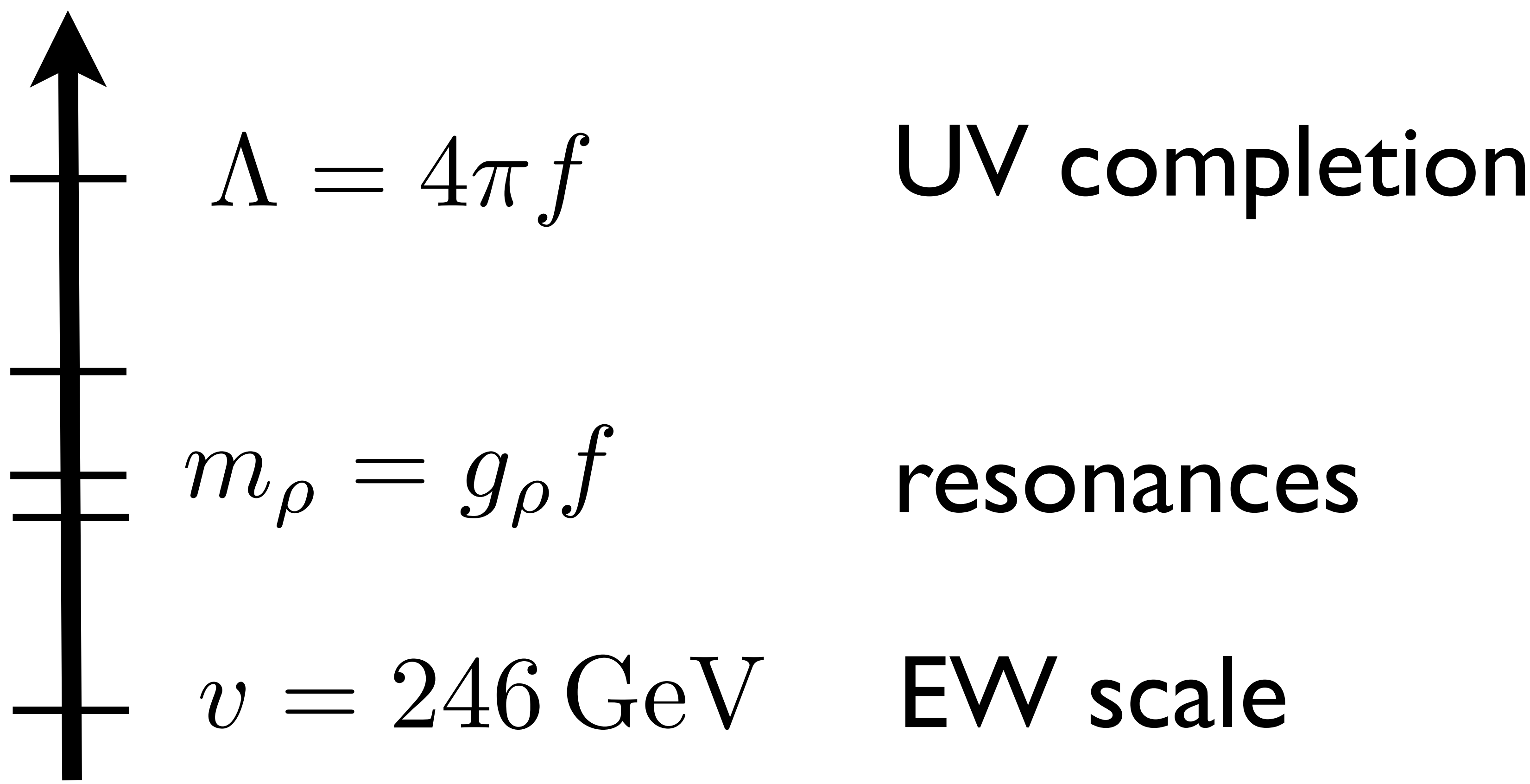
$$\sigma(x) \to \sigma(x)$$
$$\pi(x) \to \pi(x) + \alpha$$

Phase rotation becomes shift symmetry

$\pi(x)$ is massless **but** also no

- gauge couplings
- potential
- yukawas

Semi-realistic model


$\Lambda = 4\pi f$
UV completion
$m_\rho = g_\rho f$
resonances
$v = 246\,\mathrm{GeV}$
EW scale

pGB Higgs

$SU(3) \to SU(2)$

Break symmetry using $\langle \Phi \rangle = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$

Goldstone bosons = # broken generators

$$\Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f + \sigma \end{pmatrix} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2 \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix}$$

$$\Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f+\sigma \end{pmatrix} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2 \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix}$$

Expand

$$\Phi(x) = \begin{pmatrix} H_1(x) \\ H_2(x) \\ -\frac{2}{\sqrt{2}}\eta(x) \end{pmatrix} + \ldots$$

Contains a Higgs: $H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = SU(2)$ doublet

$SU(3) \to SU(2)$

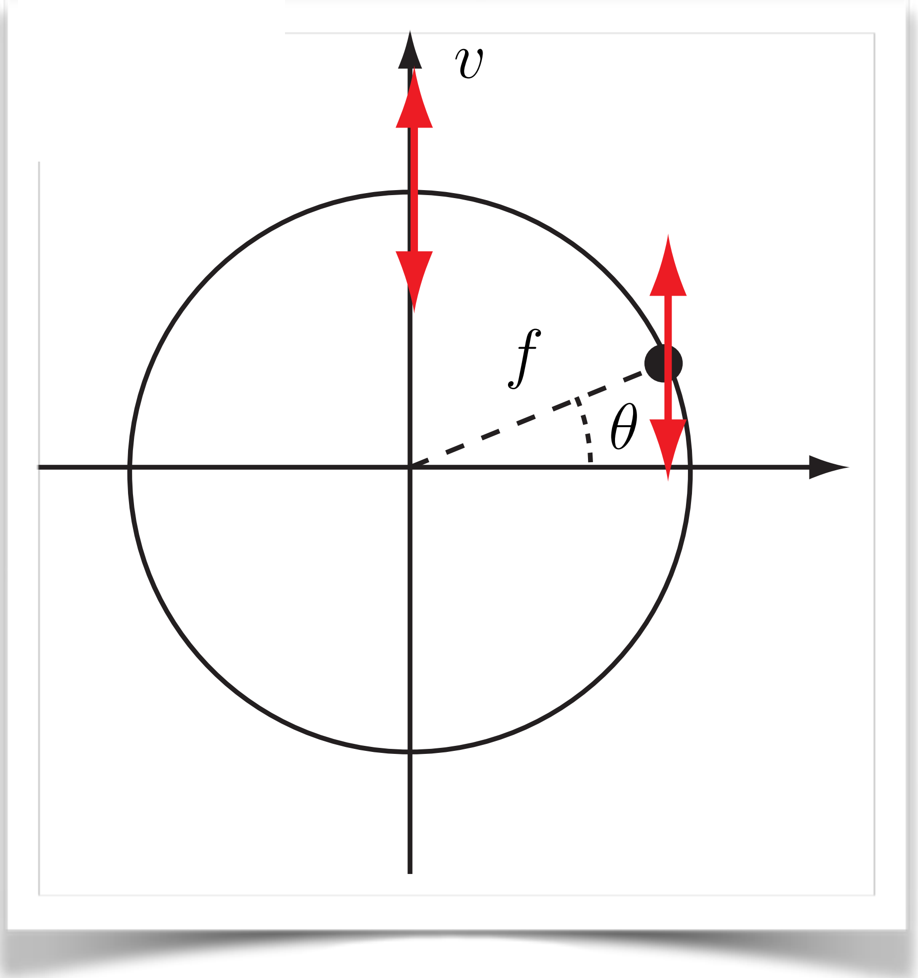
pGB Higgs

Unbroken gauge symmetry in global SU(2), dynamics generates 'vacuum misalignment'

$SU(2)_L$ vs. SU(2)

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} 0 \\ \sin\theta \\ \cos\theta \end{pmatrix} \quad SU(2)_L$$

EW symmetry broken



vacuum misalignment

pGB Higgs

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} 0 \\ \sin\theta \\ \cos\theta \end{pmatrix}$$

SU(2)$_L$

Electro-weak scale $v = f \sin\theta$

$f \sim$ scale of new physics

$\sin\theta \ll 1 \Leftrightarrow f \gg v$ (SM limit)

$$\Rightarrow \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Collective Breaking

We now want to add a yukawa coupling to give mass to the top quark

$$\lambda_t \bar{Q}_i H_i^c t_R$$ i: sum over SU(2)

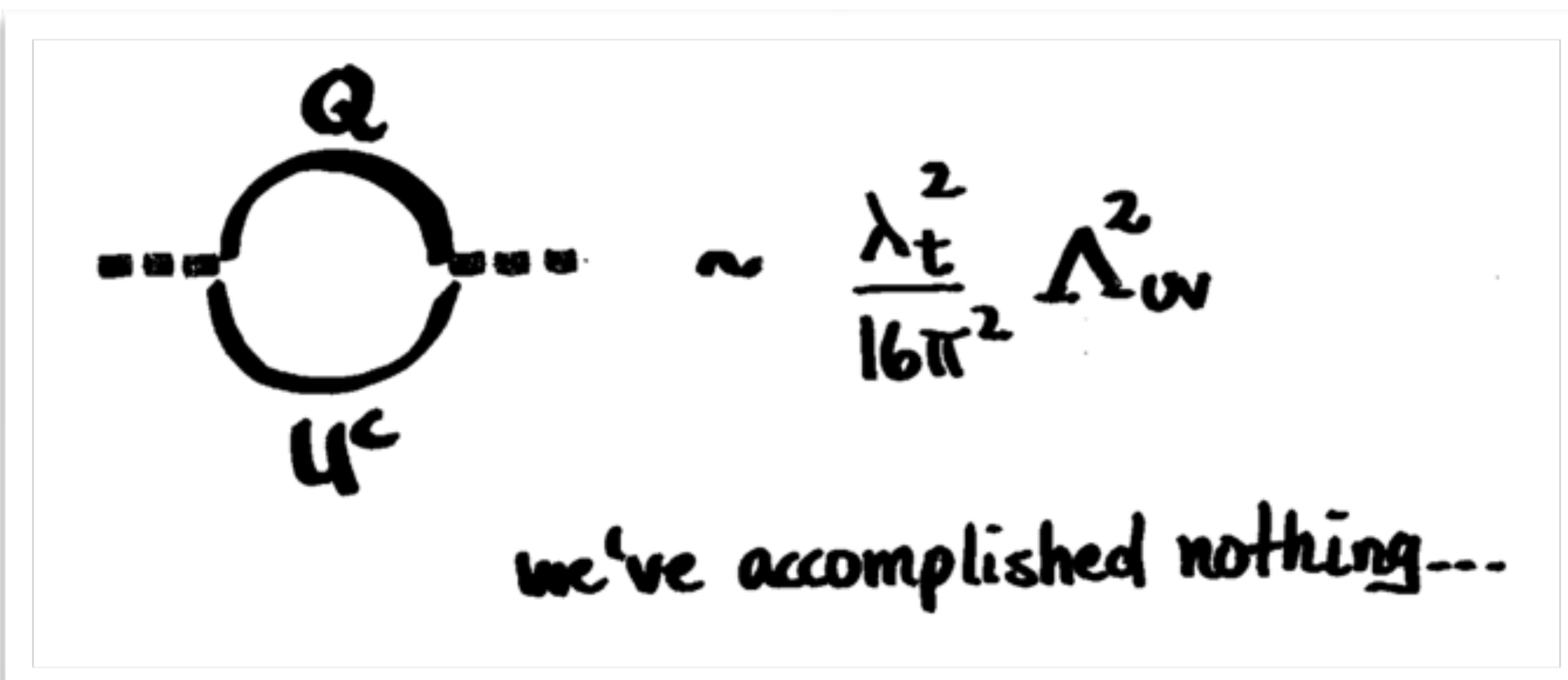
Fundamental field is a triplet

$$\phi = \exp\left\{ i \begin{pmatrix} & & h_1 \\ & & h_2 \\ h_1^* & h_2^* & \end{pmatrix} \right\} \begin{pmatrix} \\ \\ f \end{pmatrix}$$

Top yukawa: 1st try

$$\sum_i^{2} \lambda_t \phi_i^c \bar{Q}_i t_R$$ works, gives mass to the top

… but breaks SU(3) structure explicitly, does not respect Goldstone symmetry protecting the Higgs mass:



2nd try: Collective breaking

Example: $SU(3) \to SU(2)$ (ignore $U(1)_Y$ again)

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ {}_{2} \end{pmatrix}$$

Gauge full $SU(3)$ ⇒ exact symmetry

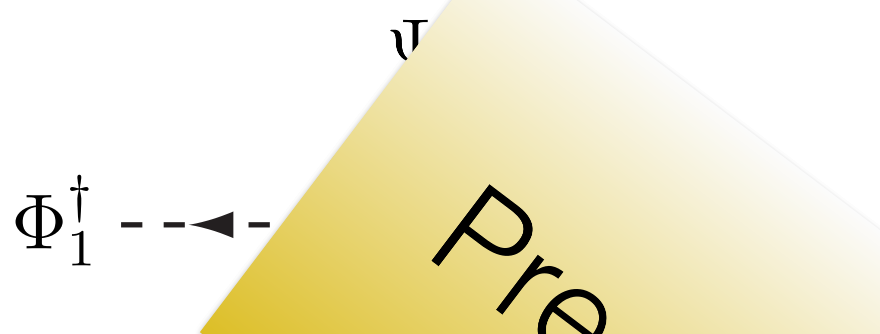
$$\Psi_L = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} \qquad t_{1R},\, t_{2R},\, b_R$$

$$\mathcal{L}_{\text{Yukawa}} = y_1 \bar{\Psi}_L \Phi_1 t_{1R} + y_2 \bar{\Psi}_L \Phi_2 t_{2R}$$

$y_1 \to 0$ ⇒ exact $SU(3)_2 \to SU(2)_2$ and *vice versa*

Both $y_1, y_2 \neq 0$ required for non-derivative couplings of PNGB Higgs

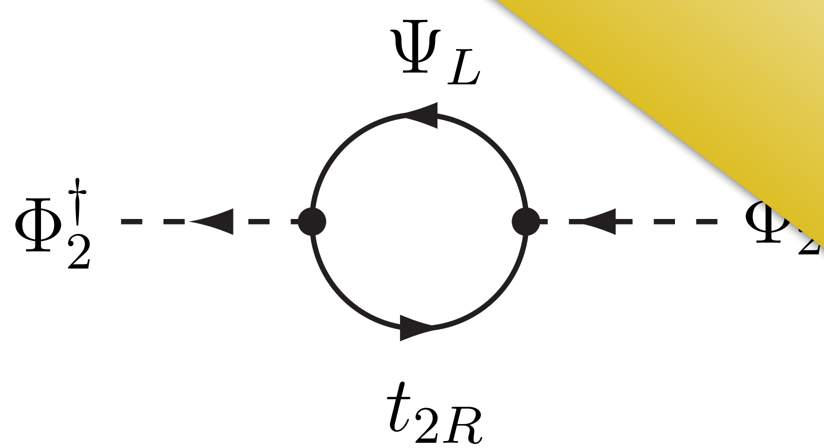
Predicts top-partners



$\sim \underbrace{\frac{y_1^2}{16\pi^2}\Lambda^2}$

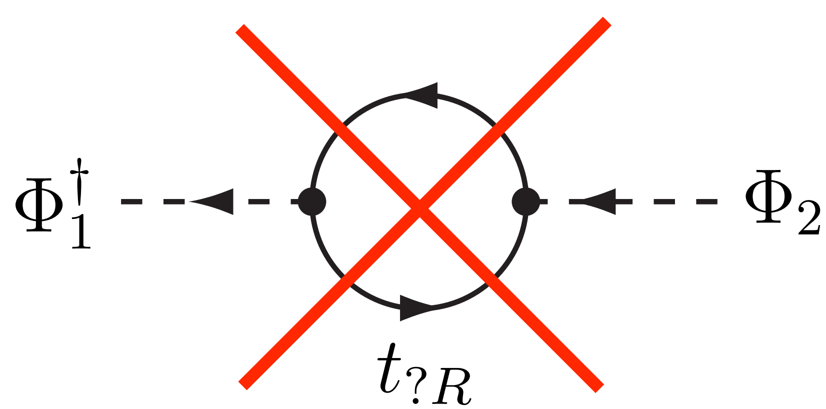
...erves $SU(3)_2 \to SU(2)_2$

...GB Higgs mass



pr... $\to SU(2)_1$

⇒ no ... gs mass

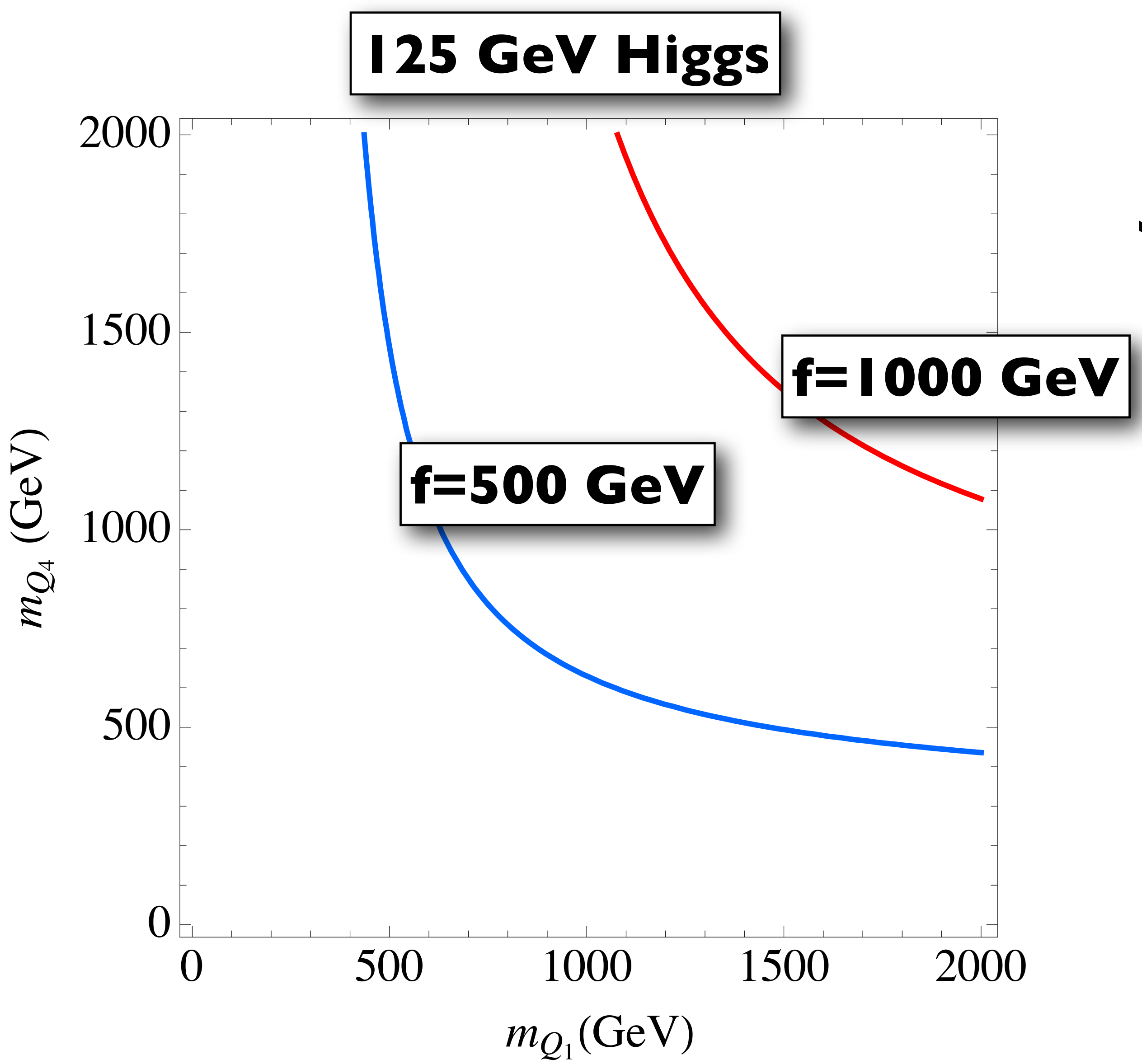


Not allowed

Light Higgs implies light fermionic top partners

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

Pomarol et al; Marzocca



5 = 4 + 1

Q_4 Q_1

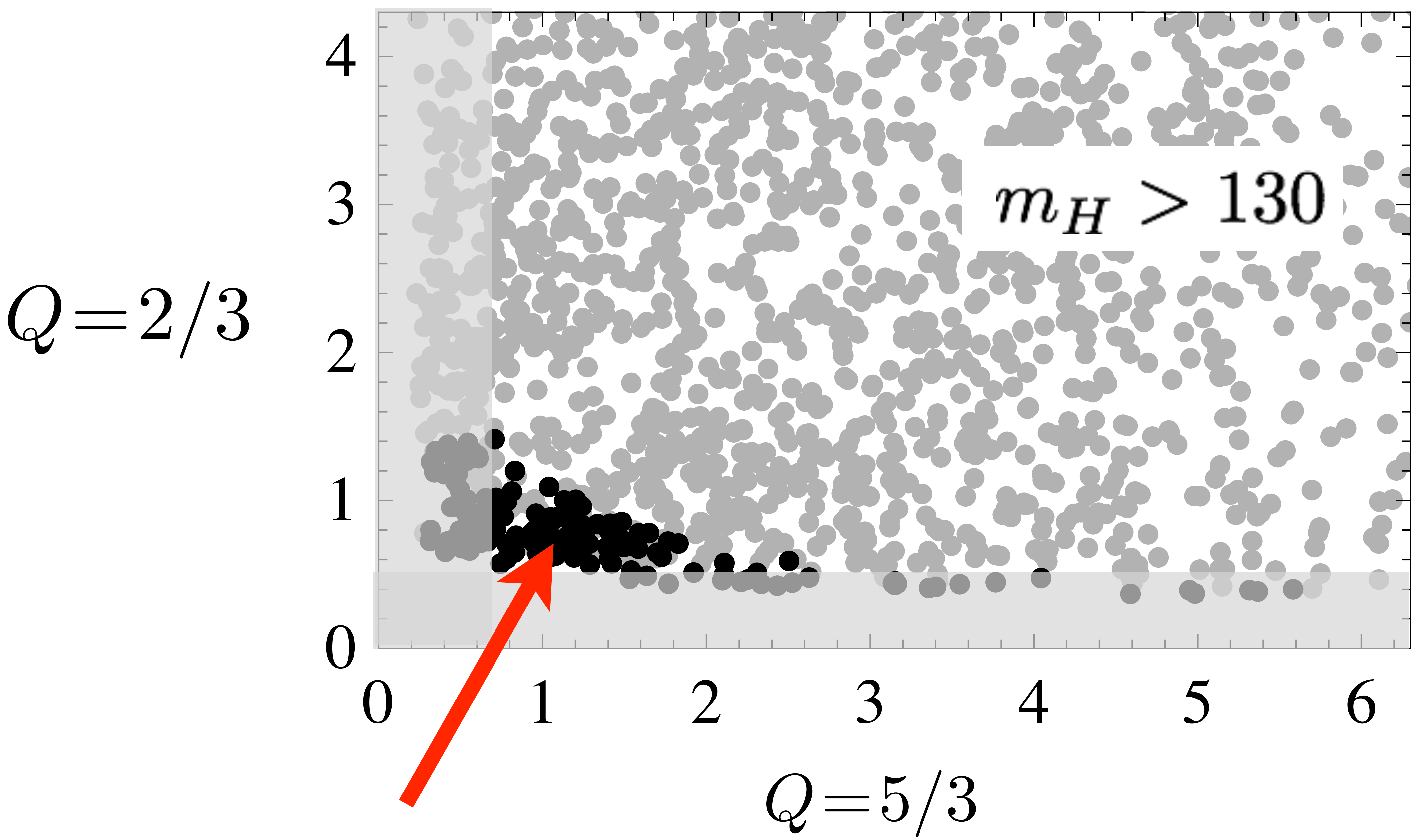
with EM charges 5/3, 2/3,-1/3

Contino et al; Pomarol, Riva; Matsedonskyi,Panico,Wulzer; Redi,Tesi; Marzocca,Serone,Shu;

Scan over composite Higgs parameter space

$\xi = 0.2$

from 1204.6333

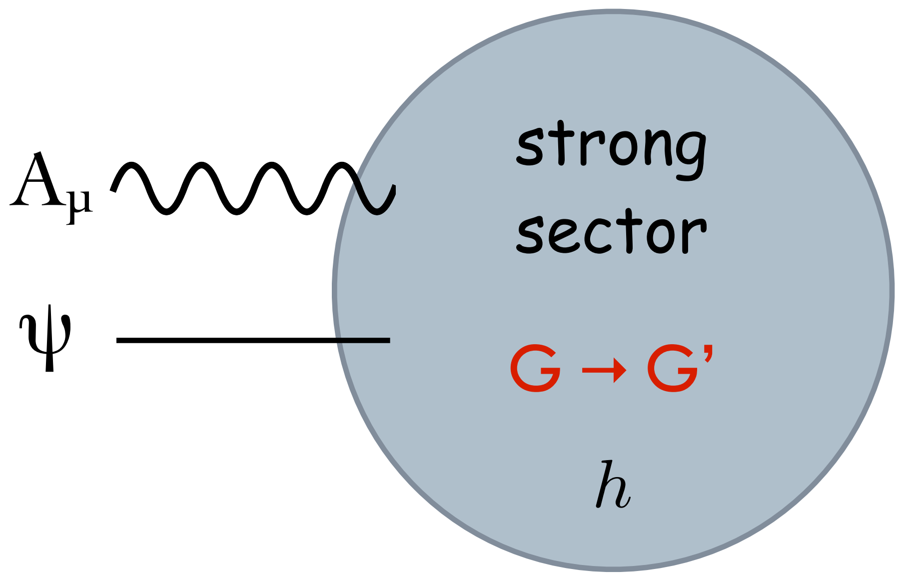


m_H = 115 … 130 GeV

see e.g. ATLAS-CONF-2013-051

Minimal composite Higgs

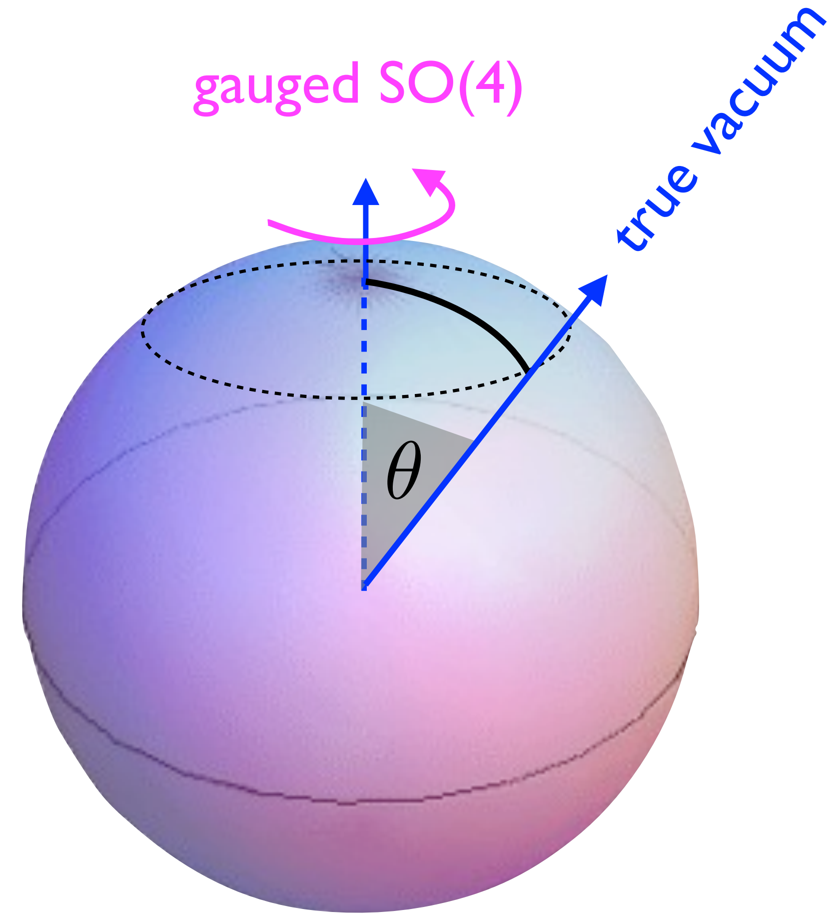
Agashe et. al



Minimal bottom up construction

$$SO(5) \rightarrow SO(4) \sim SU(2)_L \times SU(2)_R$$

$SO(5)/SO(4)$



Tree level: gauge SO(4) aligned

Higgs

$$\phi = e^{i\pi^{\hat{a}} T^{\hat{a}}/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \sin(\pi/f) \times \begin{pmatrix} \hat{\pi}^1 \\ \hat{\pi}^2 \\ \hat{\pi}^3 \\ \hat{\pi}^4 \end{pmatrix} \\ \cos(\pi/f) \end{pmatrix} = \begin{pmatrix} \sin(\theta + h(x)/f) \;\; e^{i\chi^i(x) A^i/v} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \\ \cos(\theta + h(x)/f) \end{pmatrix}$$

1-loop $\langle \phi(x) \rangle = \theta \cdot f$

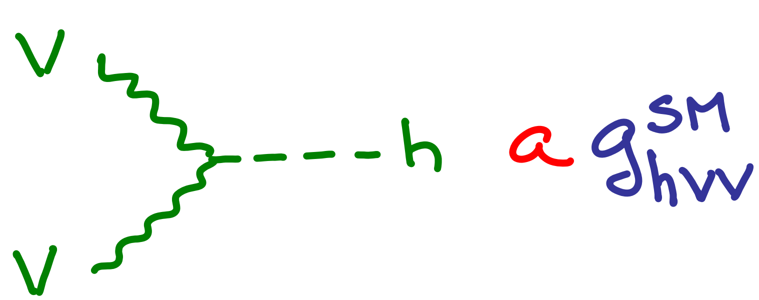
eaten by W_L, Z_L

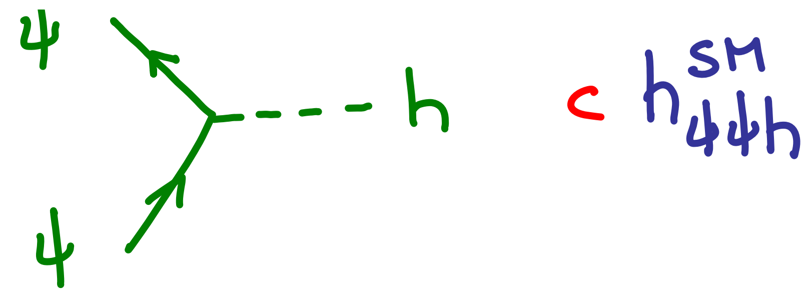
Deviations from SM Higgs

Goldstone boson nature

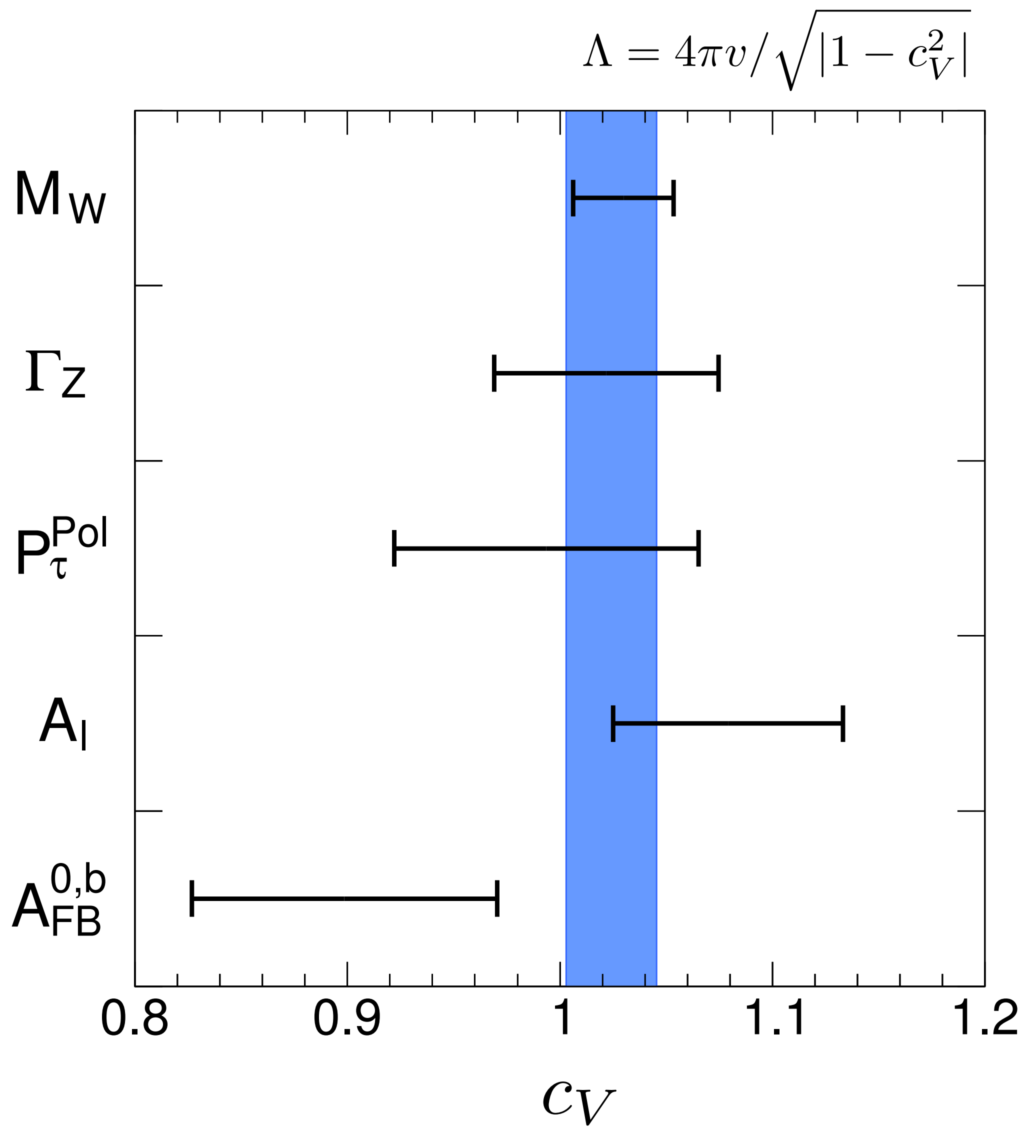
$$f^2 \left| \partial_\mu \, e^{i\pi/f} \right|^2 = |D_\mu H|^2 + \frac{c_H}{2f^2} \left[\partial_\mu (H^\dagger H) \right]^2 + \frac{c'_H}{2f^4} (H^\dagger H) \left[\partial_\mu (H^\dagger H) \right]^2 + \ldots$$

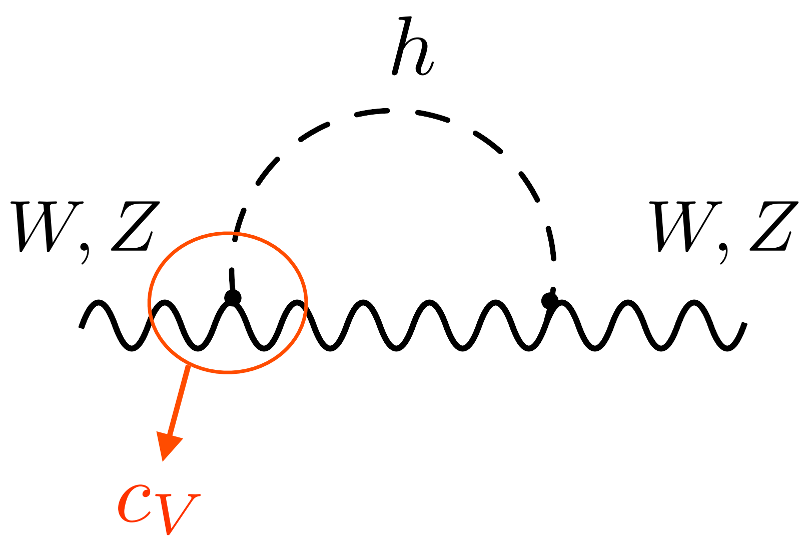
Giudice et al. JHEP 0706 (2007) 045





EW precision tests

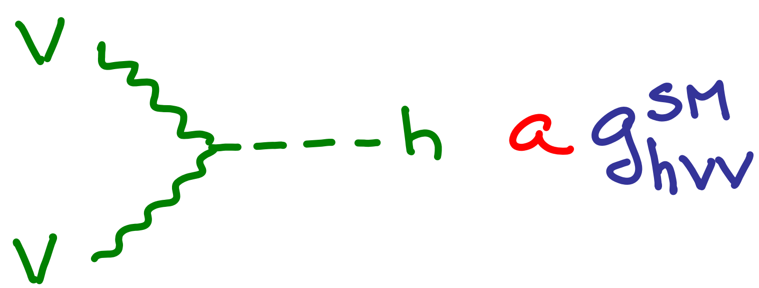


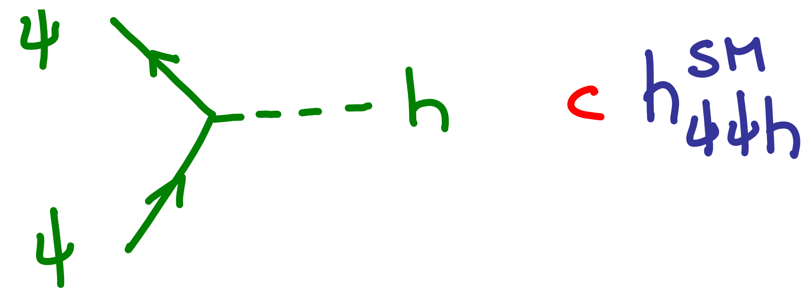


Ciuchini, Franco, Silvestrini, Mishima, arXiv:1306.4644

Higgs couplings

Have been measured to 20-30% precision





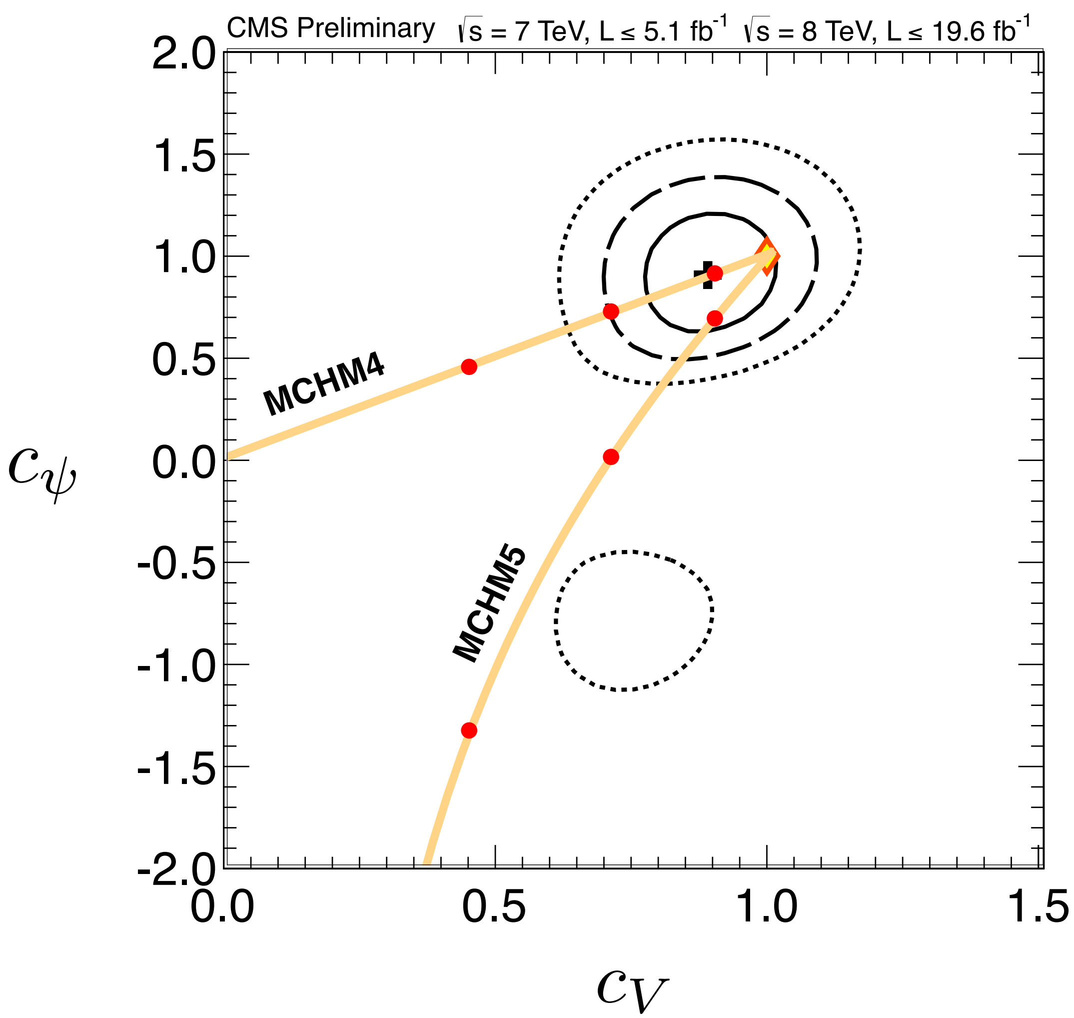
Expect deviations ~ $(v/f)^2$

$$\xi \equiv \frac{v^2}{f^2}$$

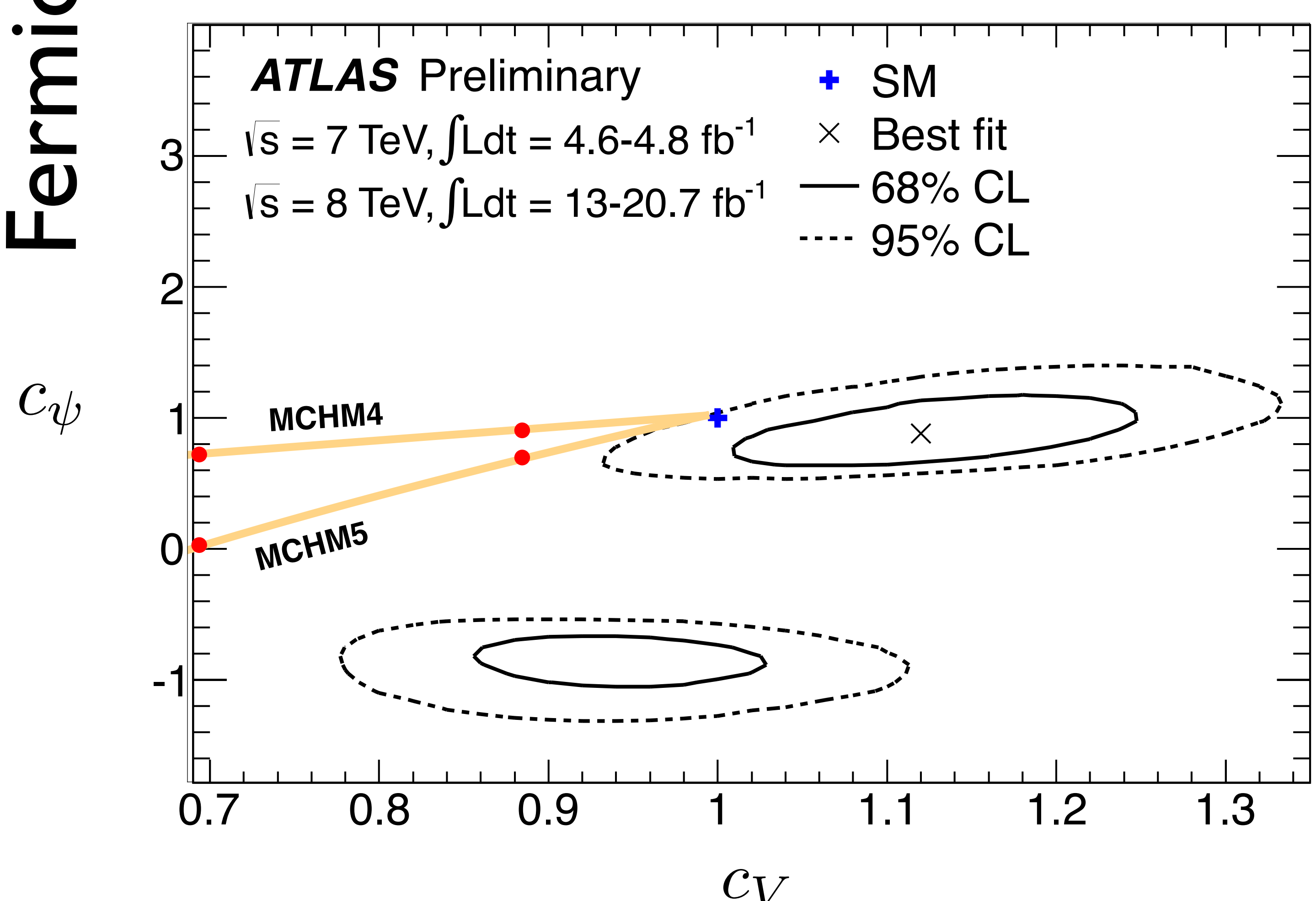
$$a = \sqrt{1-\xi}$$

$$c_f = \frac{1-(1+n)\xi}{1-\xi}$$

Higgs couplings



Fermion



Vector

Red points at $\xi \equiv (v/f)^2 = 0.2,\ 0.5,\ 0.8$