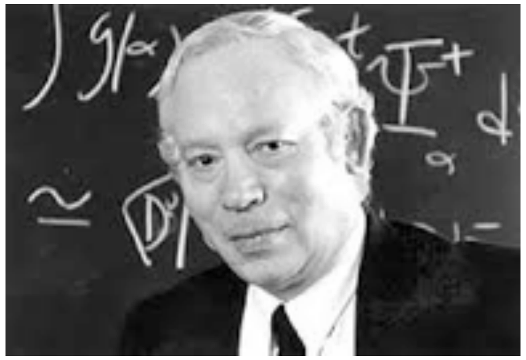
Beyond the SM 1/3

Andreas Weiler
CERN & DESY

Four Lessons

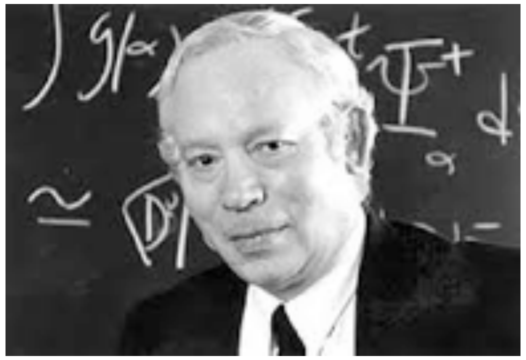


1) How could I do anything without knowing everything that had already been done? […] pick up what I needed to know as I went along. It was sink or swim. […] But I did learn one big thing: that no one knows everything, and you don't have to.

2) While you are swimming and not sinking you should aim for rough water. […] My advice is to go for the messes — that's where the action is.

Scientist: Four golden lessons
Steven Weinberg, Nature 426, 389 (27 November 2003)

Four Lessons



3) Forgive yourself for wasting time. […] in the real world, it's very hard to know which problems are important, and you never know whether at a given moment in history a problem is solvable [...] get used […] to being becalmed on the ocean of scientific knowledge.

4) Learn something about the history of science […] As a scientist, you're probably not going to get rich. […] But you can get great satisfaction by recognizing that your work in science is a part of history.

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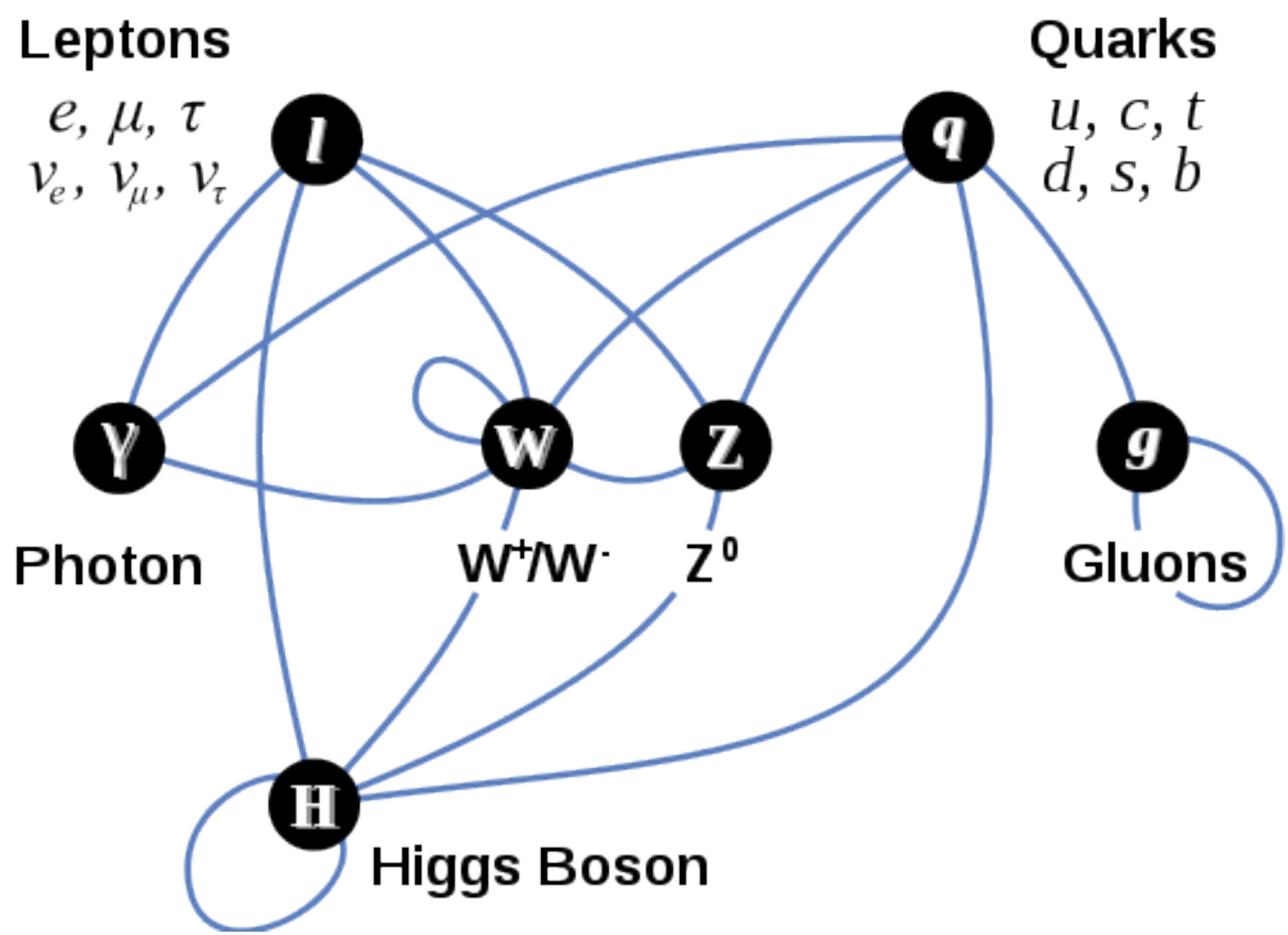
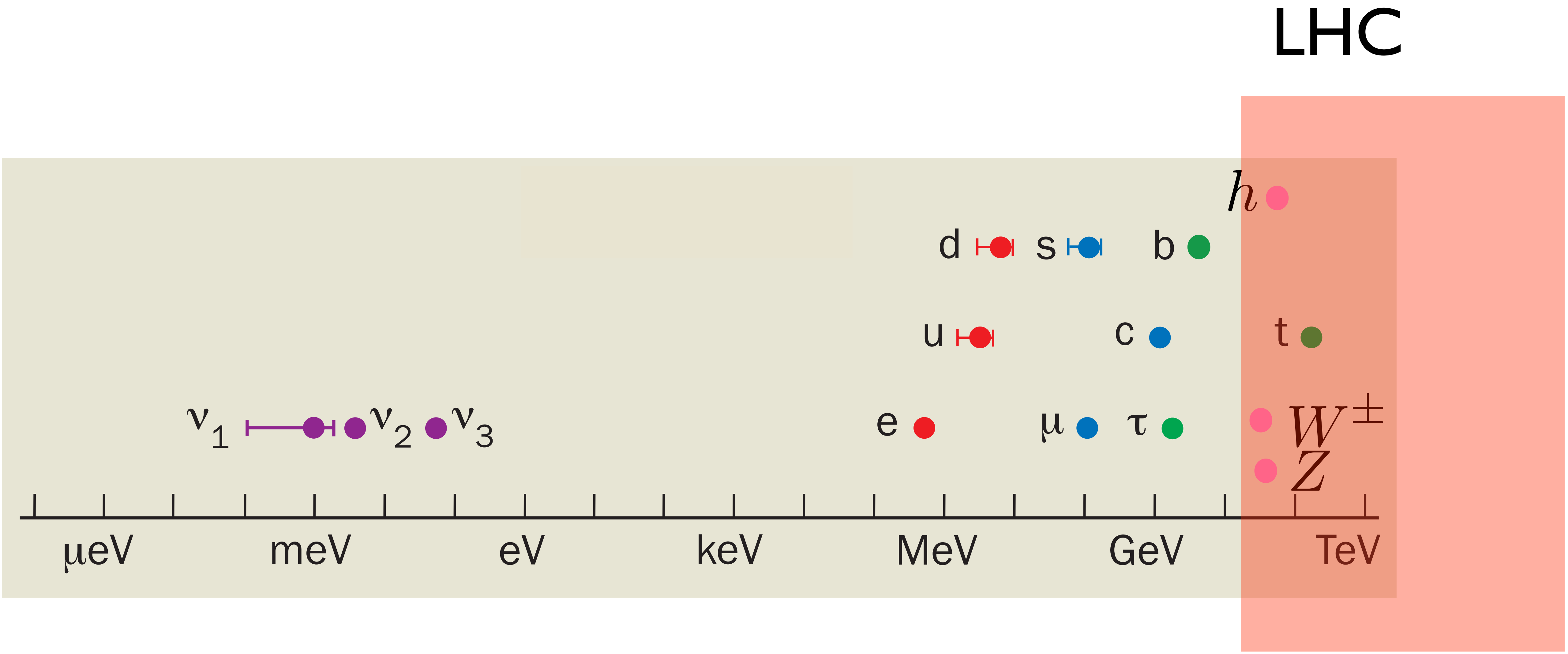
The SM



→ M. Schmaltz lecture

The energy frontier

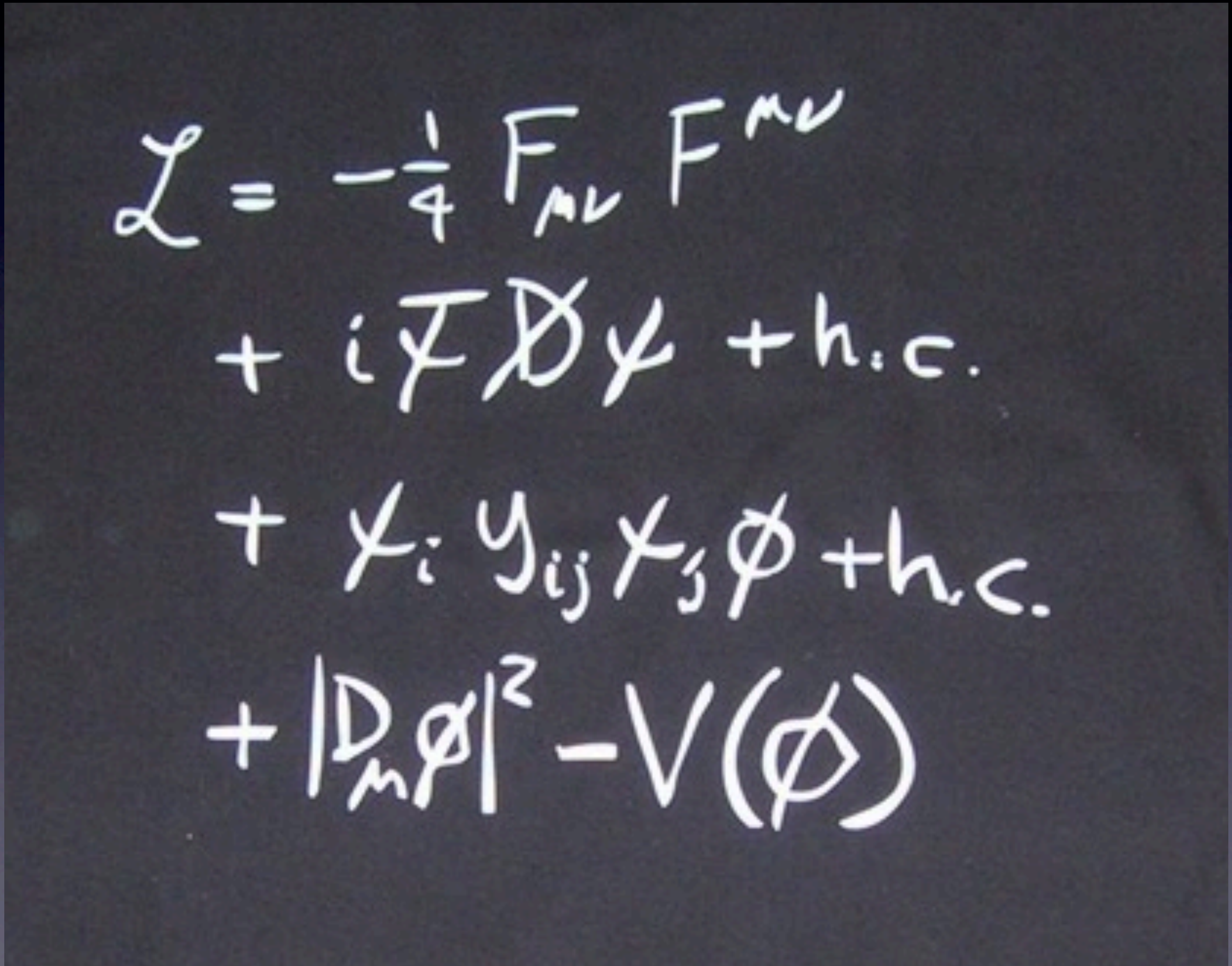


What can we expect to discover?

The SM


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

The SM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fermion masses & mixings

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Higgs potential

The SM

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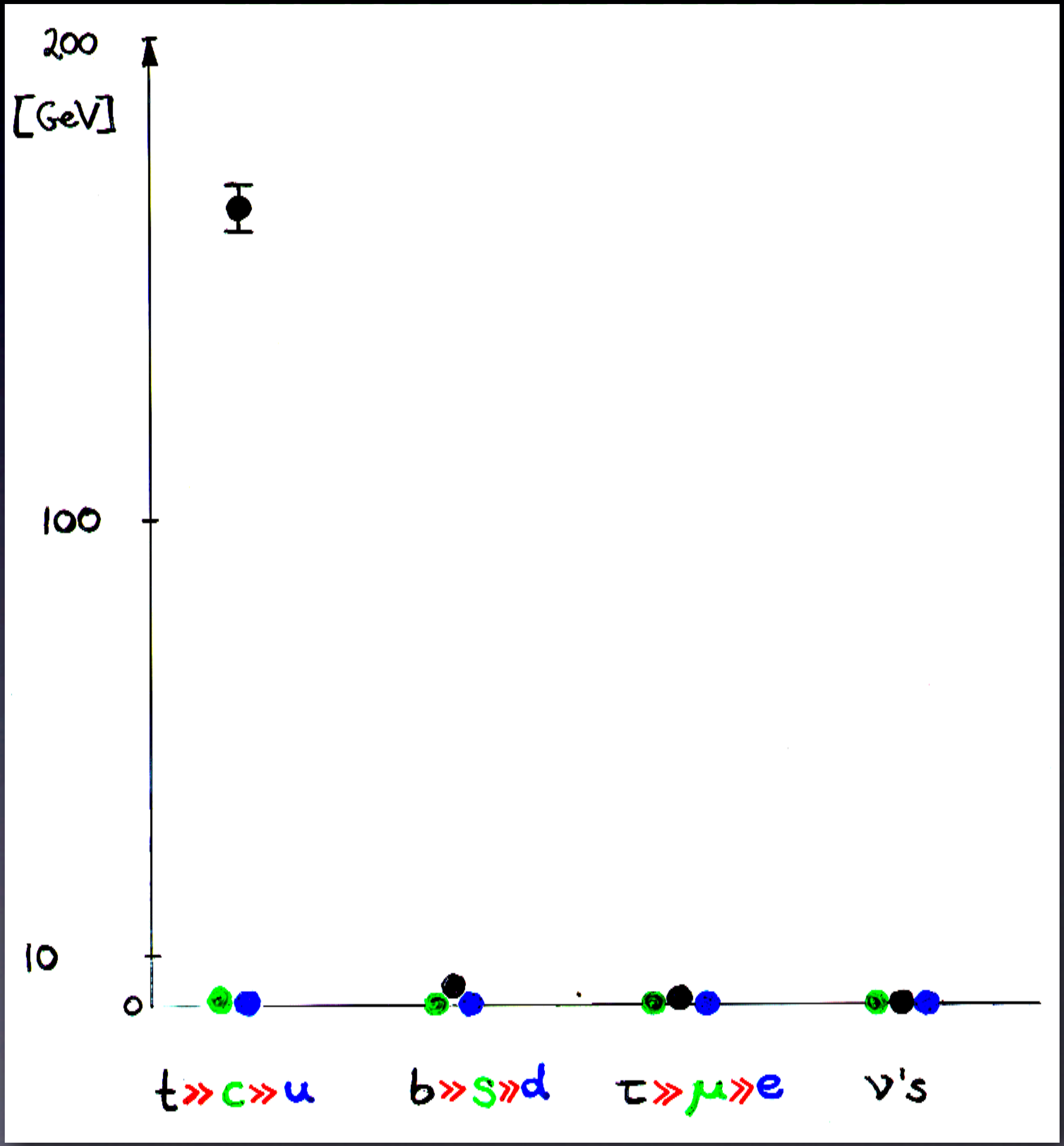
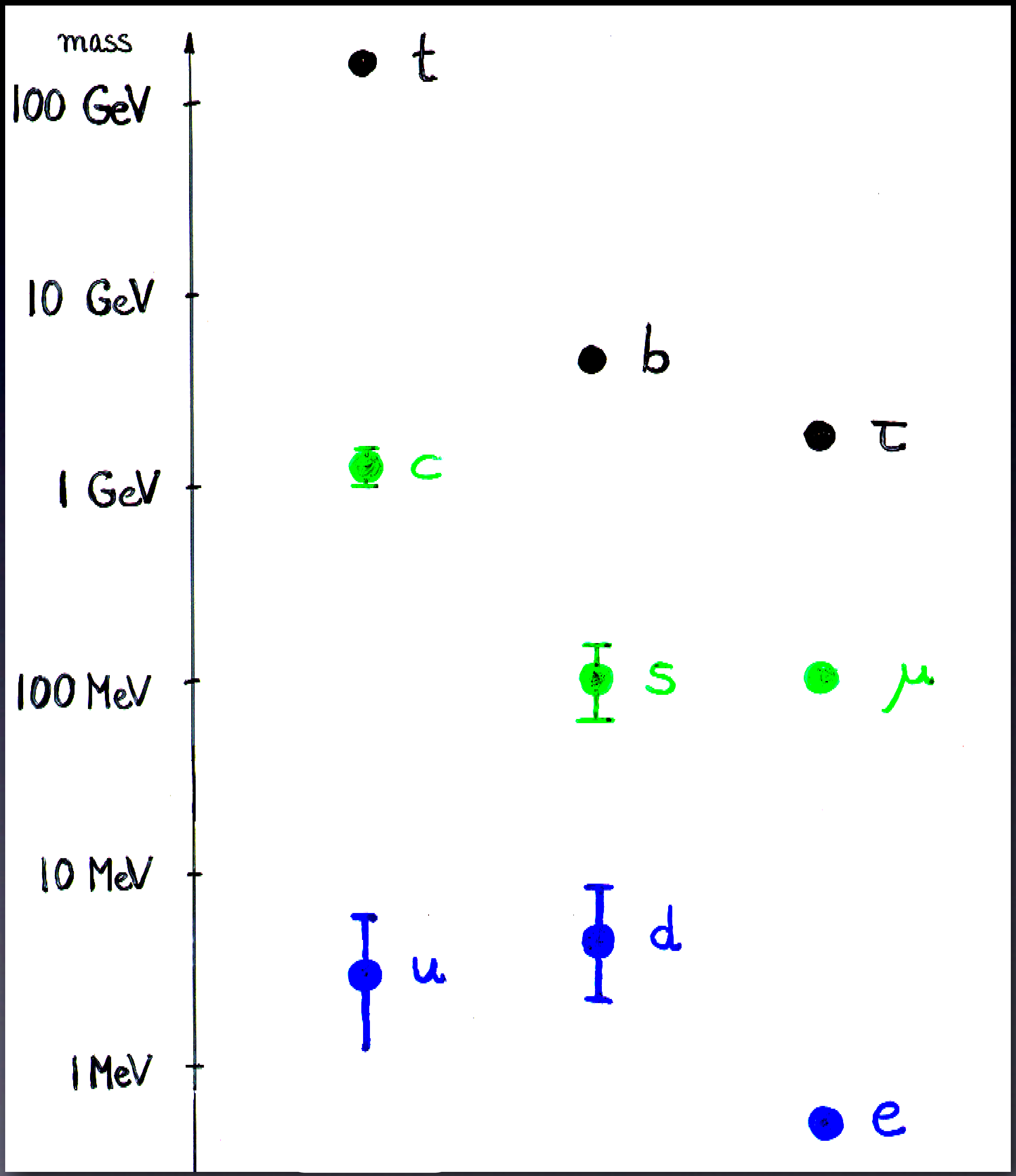
fermion masses & mixings

Quark and Lepton mass hierarchy



Masses on a Log-scale



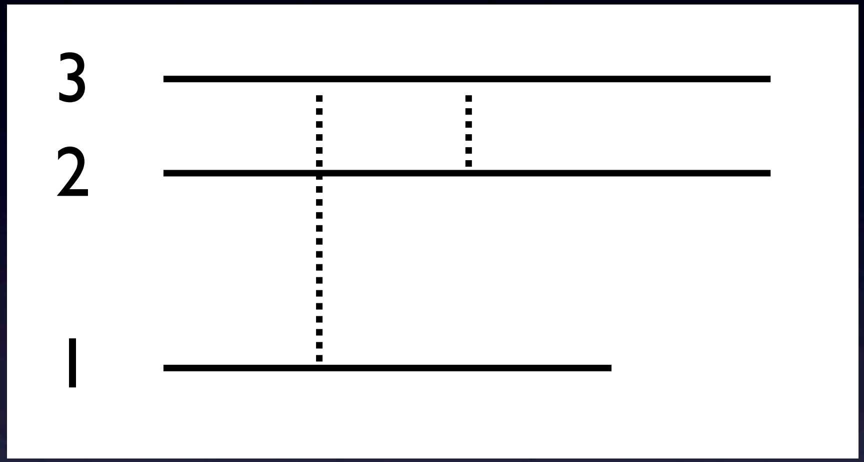
$$Y_D = (m_d, m_s, m_b)/v$$
$$Y_U = V_{\rm CKM}^\dagger (m_u, m_c, m_t)/v$$

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

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

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

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

→ D. Straub lecture

2) Very strong constraints from flavor physics:

Generic flavor dynamics >> 100 TeV

The SM

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Higgs potential

What's the problem?

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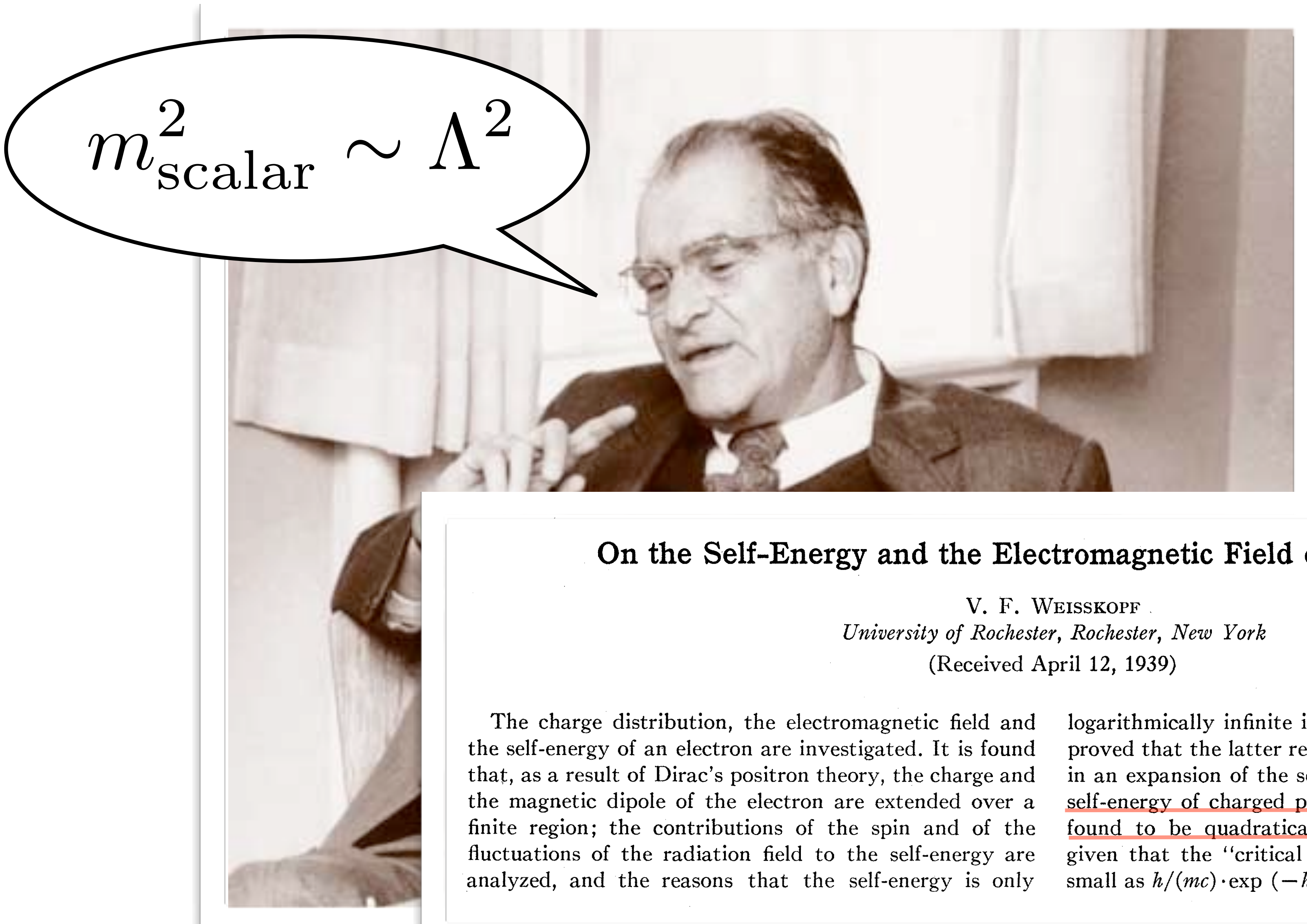


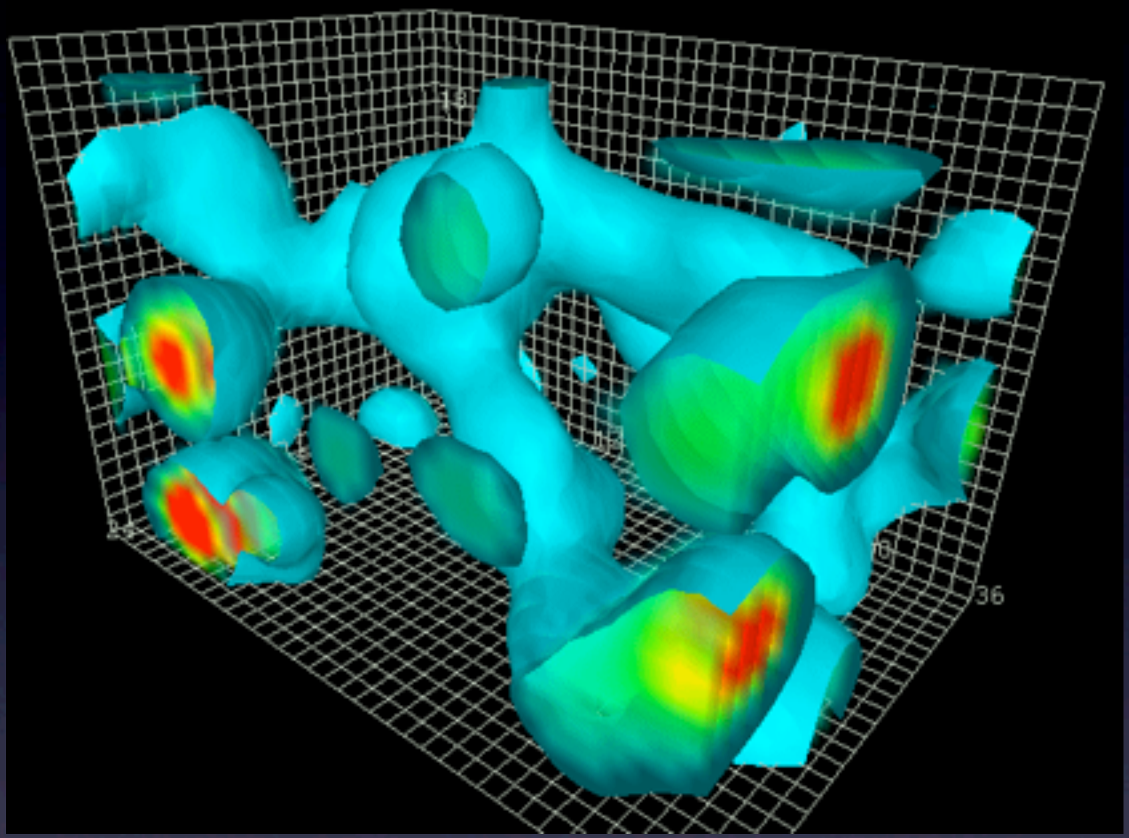
On the Self-Energy and the Electromagnetic Field of the Electron

V. F. Weisskopf
University of Rochester, Rochester, New York
(Received April 12, 1939)

The charge distribution, the electromagnetic field and the self-energy of an electron are investigated. It is found that, as a result of Dirac's positron theory, the charge and the magnetic dipole of the electron are extended over a finite region; the contributions of the spin and of the fluctuations of the radiation field to the self-energy are analyzed, and the reasons that the self-energy is only logarithmically infinite in positron theory are given. It is proved that the latter result holds to every approximation in an expansion of the self-energy in powers of e^2/hc. The self-energy of charged particles obeying Bose statistics is found to be quadratically divergent. Some evidence is given that the "critical length" of positron theory is as small as $h/(mc) \cdot \exp(-hc/e^2)$.

Weisskopf, Phys. Rev. 56 (**1939**) 72

Electro-weak scale unstable



Quantum fluctuations destabilize weak scale

$$E_n^{(2)} = \sum_{m \neq n} \frac{|\langle \psi_n | H^1 | \psi_m \rangle|^2}{E_n^0 - E_m^0}$$

sum over all available states

Sensitive to highest scale Λ

A light Higgs is unnatural

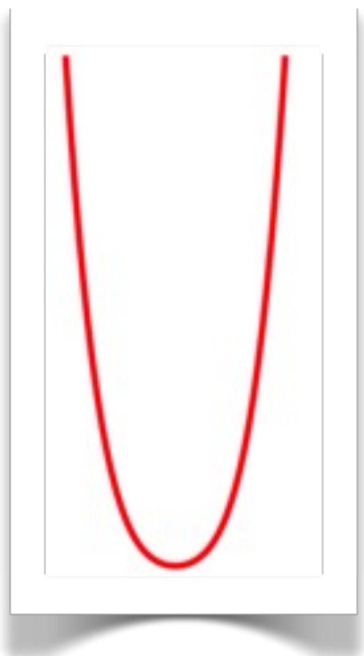
$$V(h) = \epsilon\Lambda^2 h^2 + \lambda h^4$$

$$\Lambda \gg m_W$$

No tuning:

$$\epsilon = \pm\,\mathcal{O}(1)$$

$$\langle h \rangle = 0$$



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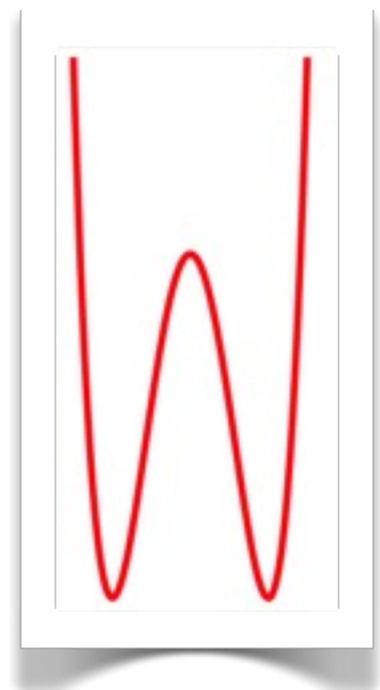

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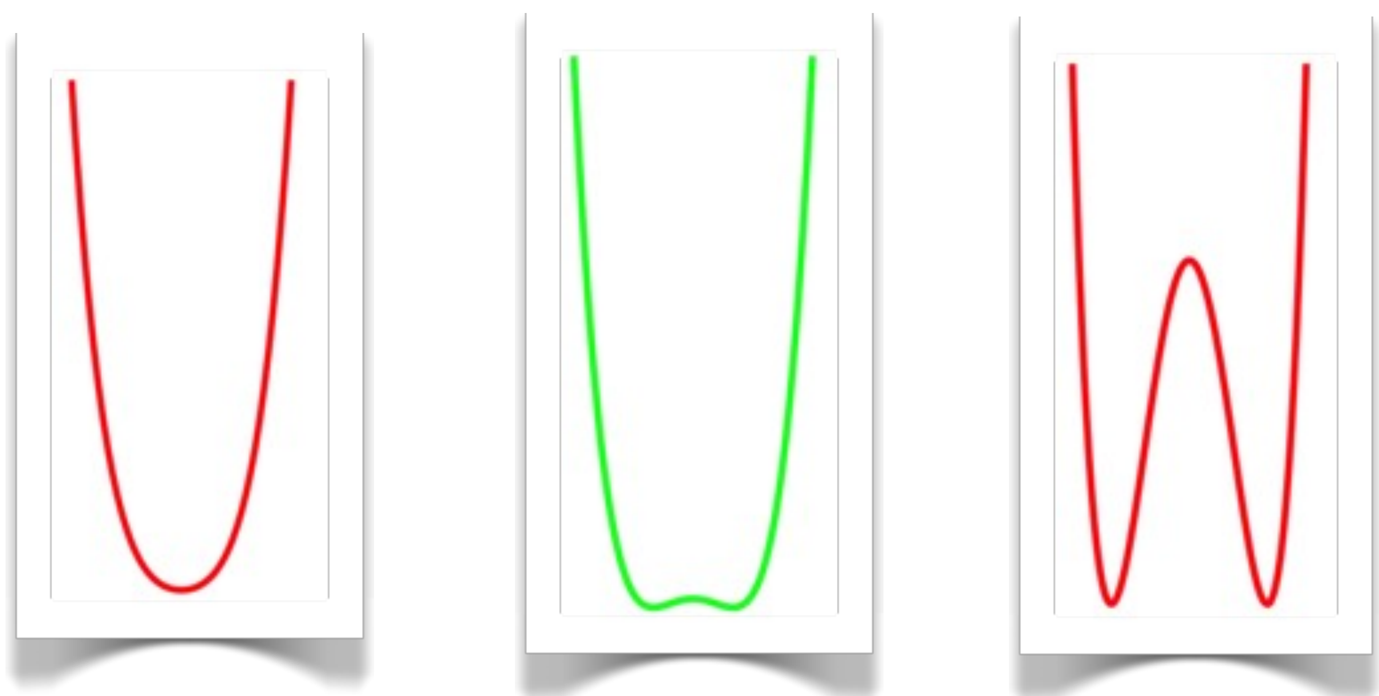


No tuning:

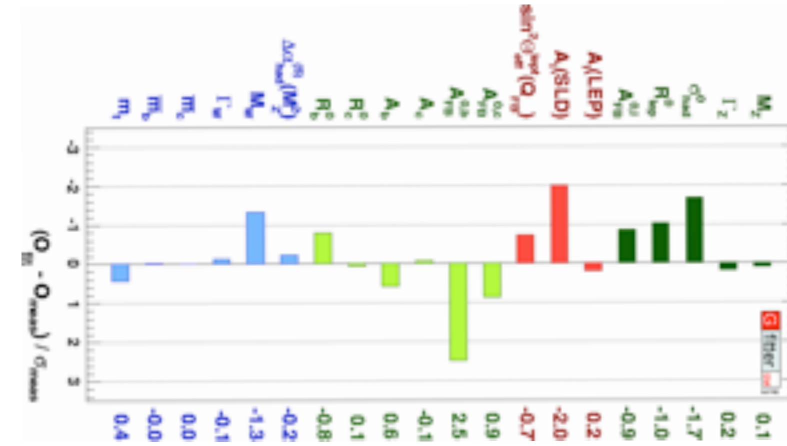
$\epsilon = \pm\, \mathcal{O}(1)$

Needs tuning or new physics close by

$\sqrt{\epsilon} \sim m_W / \Lambda$

$$\sim M_W / M_{\text{Planck}} \sim 80.4/10^{19} \approx 0.0000000000000000001$$

New physics in EW sector



Different to flavor ($M_{flavor} >> 10^3$ TeV), the Higgs constrains only ~ few TeV

$$\left((h^\dagger \sigma^a h) W^a_{\mu\nu} B^{\mu\nu}\right)/\Lambda^2 \qquad |h^\dagger D_\mu h|^2/\Lambda^2 \qquad \left(h^\dagger h\right)^3/\Lambda^2$$

New dynamics possible and required, promising for LHC!

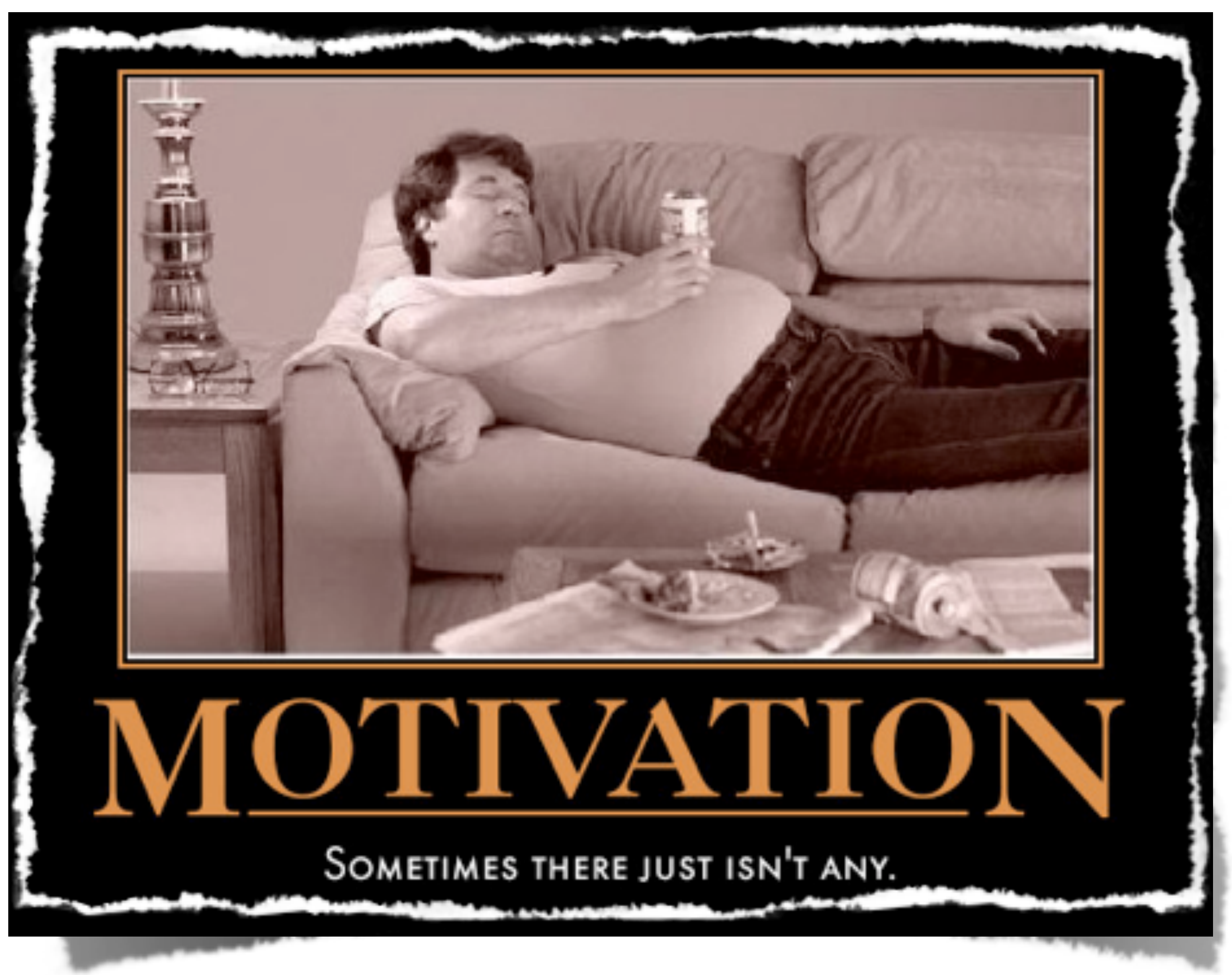
Overview

1. Motivation for new physics at the TeV scale
2. Supersymmetry
3. Composite/Little Higgs
4. Alternatives (if time allows)

Motivation

Dark matter?
Dark Energy?
Origin of quark mass and mixing hierarchies?
Strong CP?
EW strong coupling/unitarity problem?
Matter-Antimatter asymmetry?
Neutrino masses?
Inflation?
Quantum instability of Higgs mass?
Charge quantization (GUT?)?
Quantum Gravity?
. . .

Why expect new physics at the LHC?



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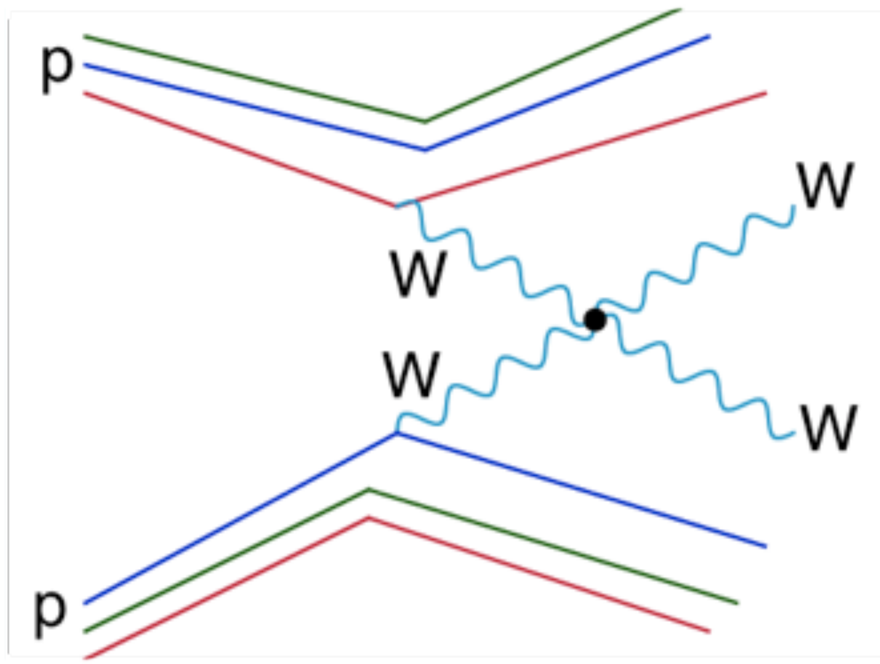
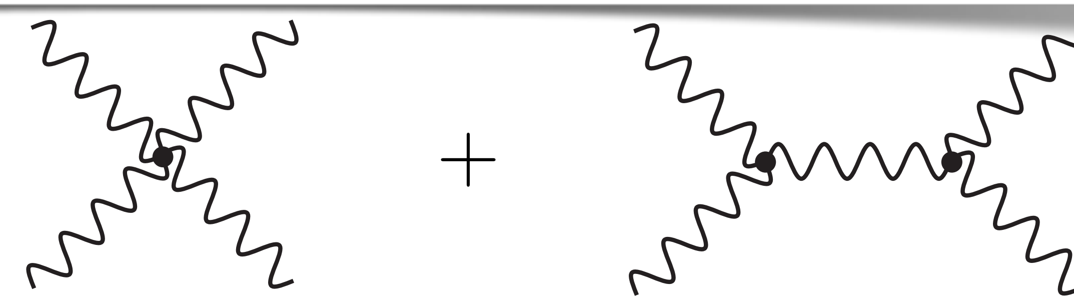
SM without the Higgs

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





$+$ $\sim E^2$

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

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

Energy

New physics has to show up below this scale

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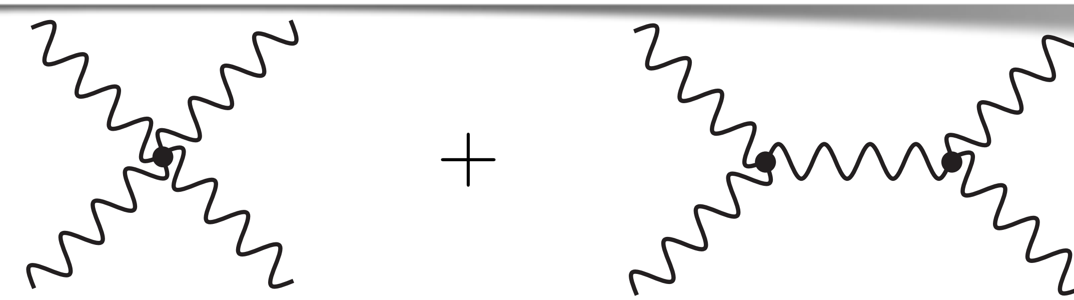
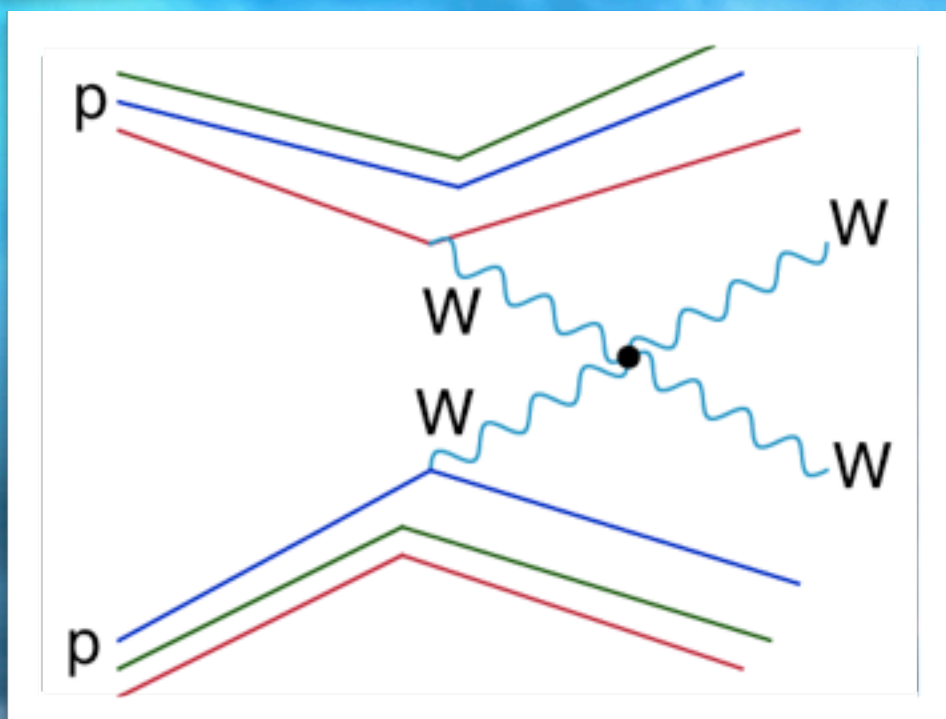
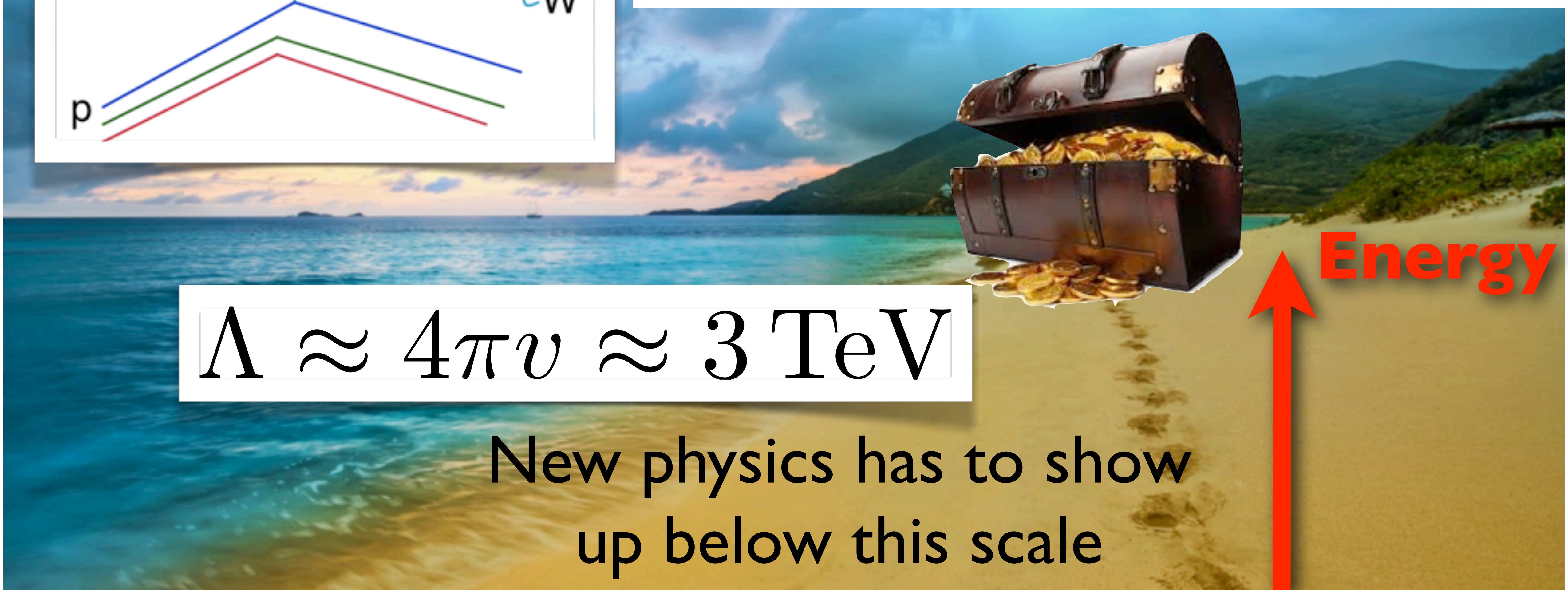


$$\sim E^2$$

$$\sim \not{E}^4 + E^2 + \cdots \qquad \sim \not{E}^4 + E^2 + \cdots$$





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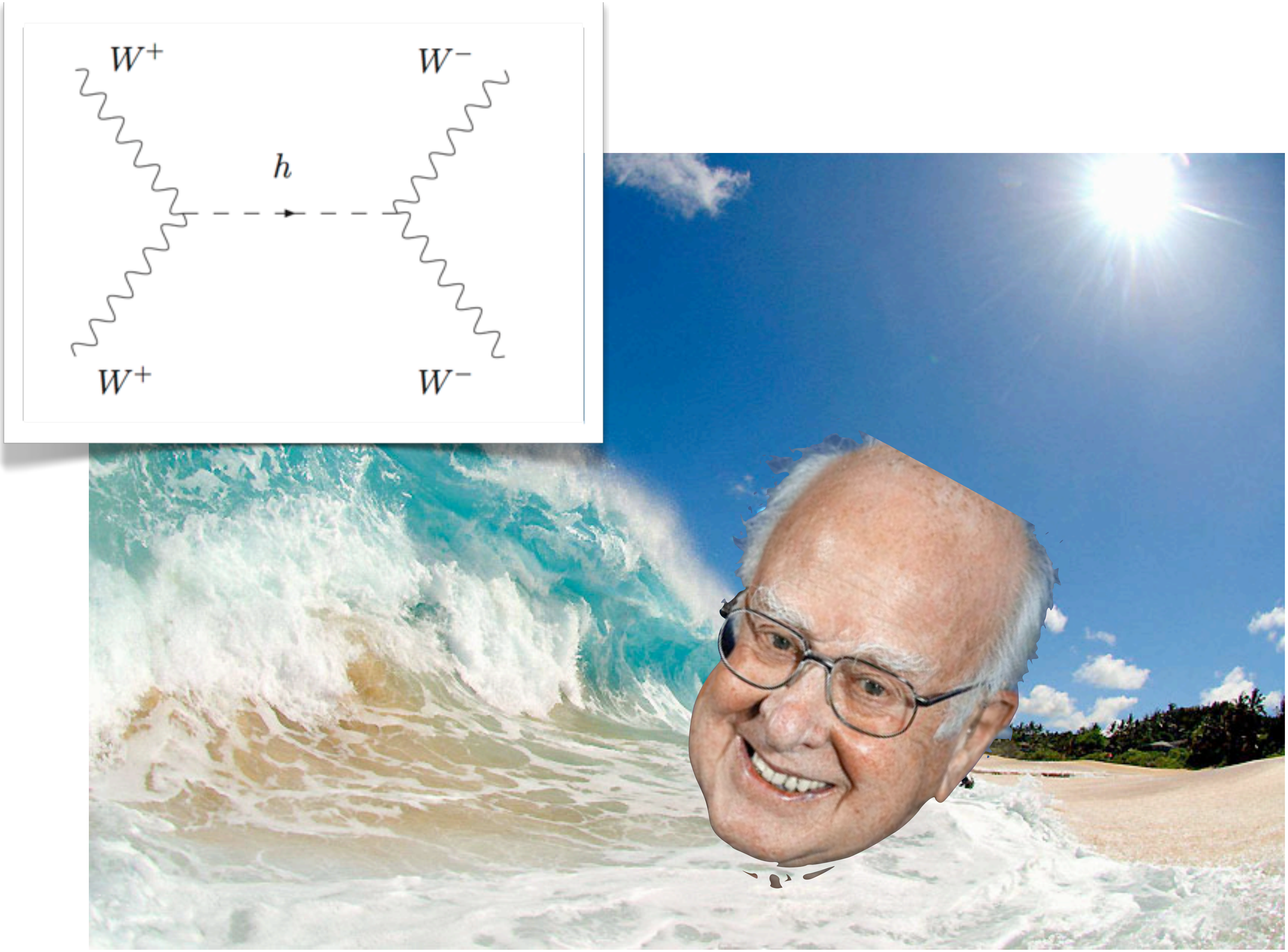
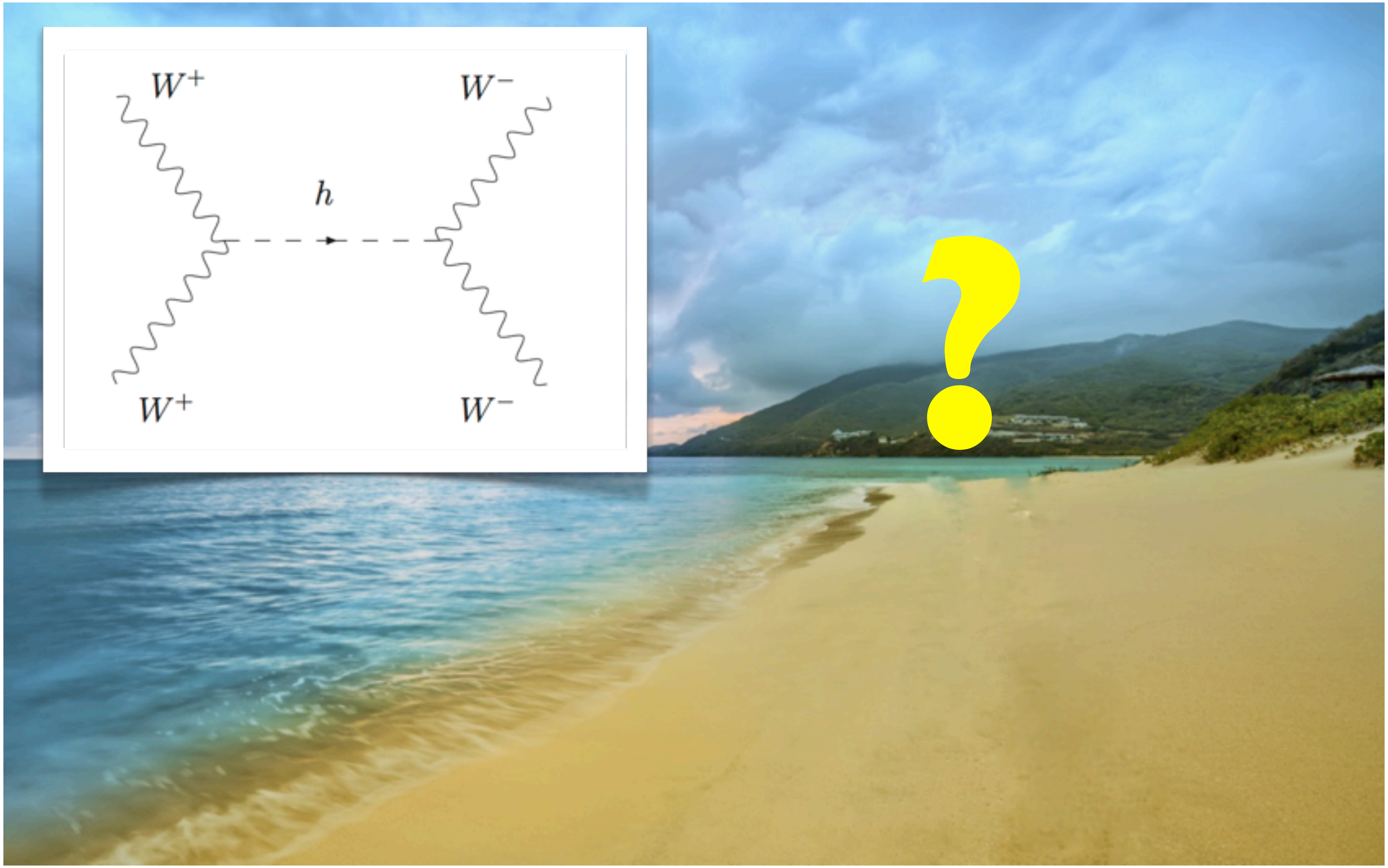

W^+
W^-
h
W^+
W^-

Adding SM-like Higgs

SM works up to $\Lambda \gg \mathrm{LHC}$



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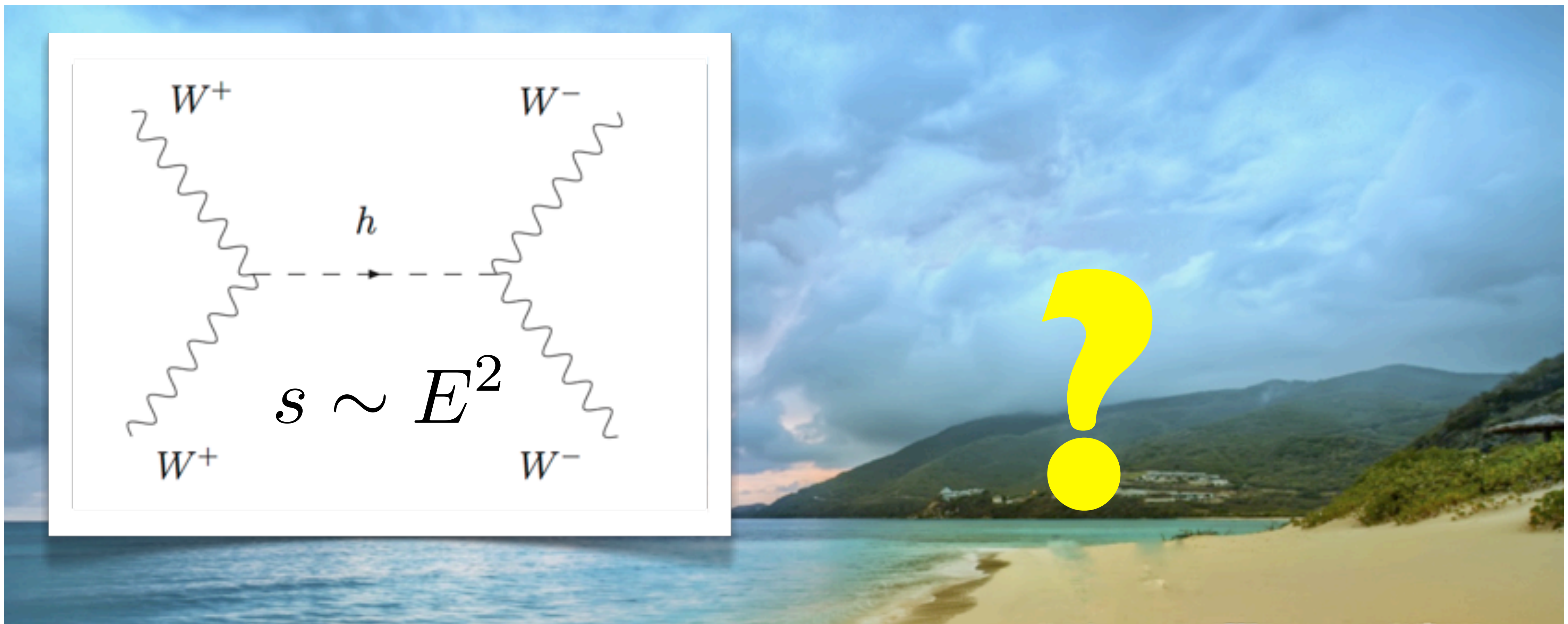

$$\mathcal{A} \simeq \frac{1}{v^2}\left[s - \frac{s^2}{s - m_h^2} + \ldots\right] \rightarrow \sqrt{s} \gg v$$

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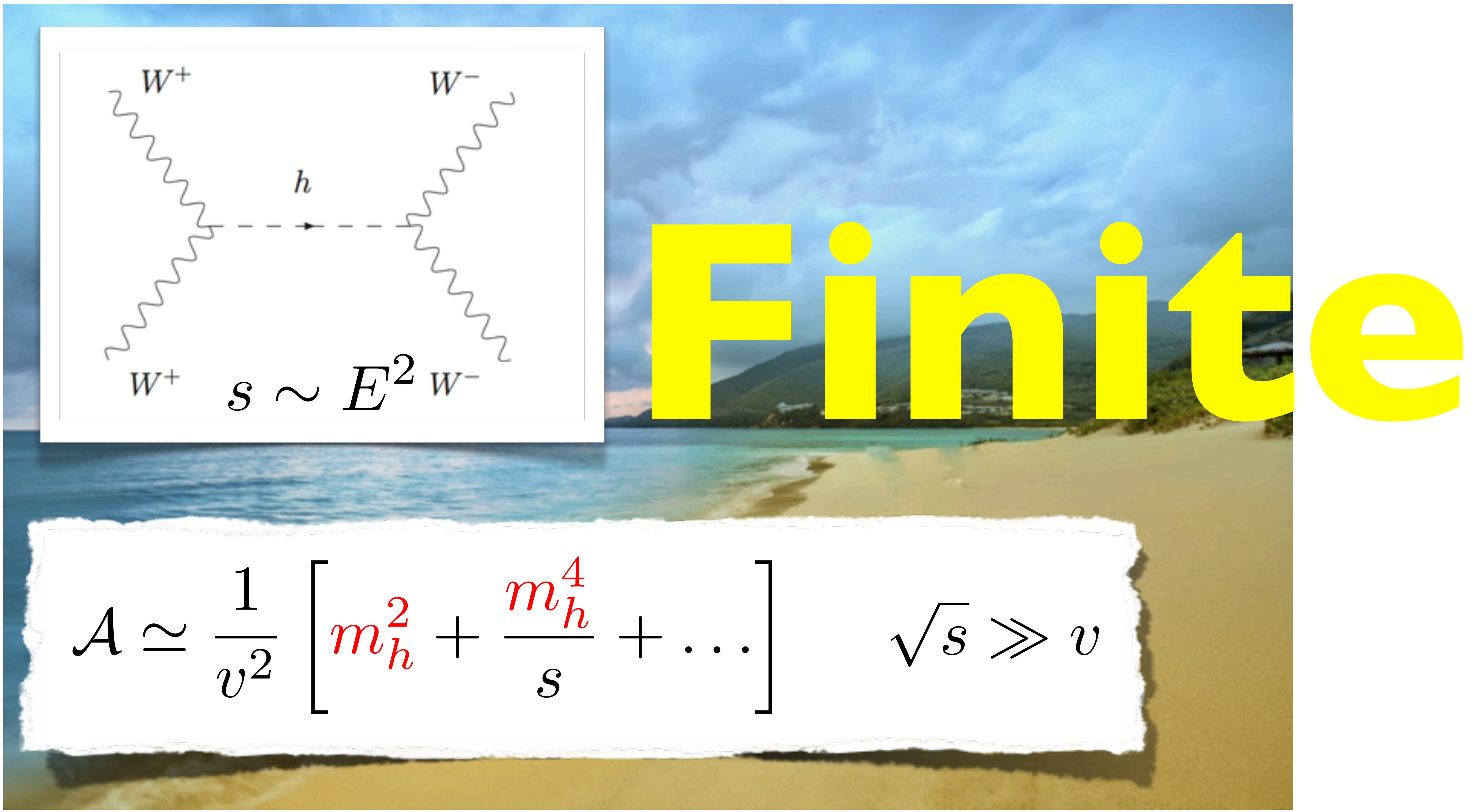
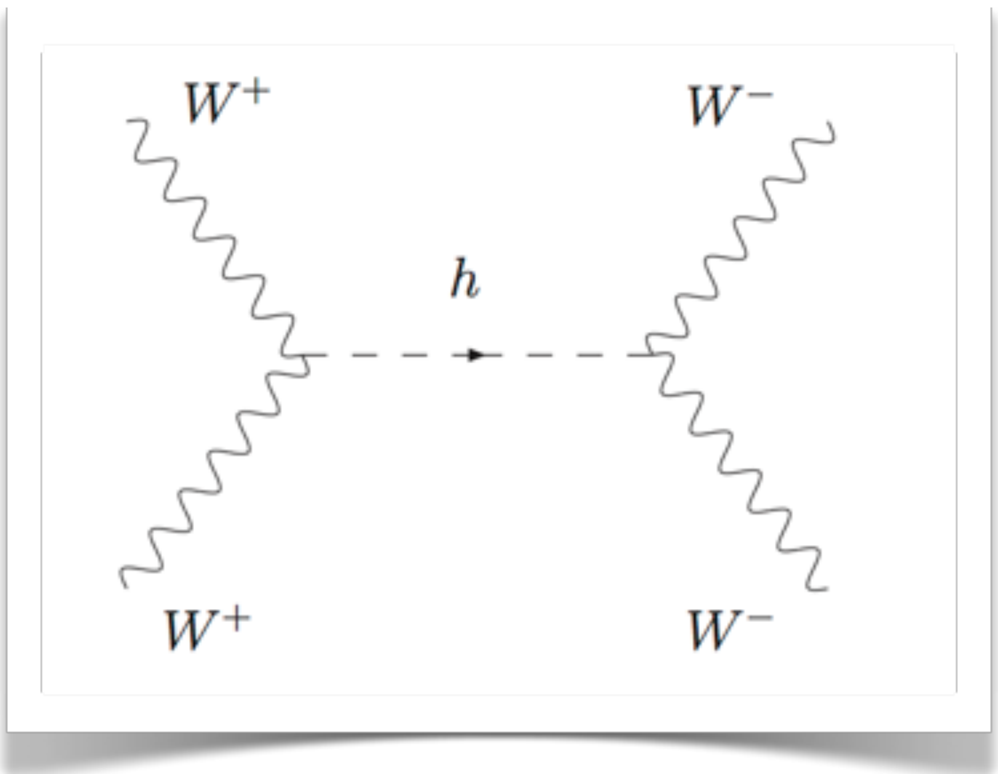
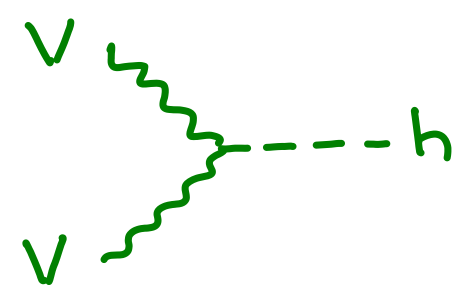


$$\mathcal{A} \simeq \frac{1}{v^2}\left[m_h^2 + \frac{m_h^4}{s} + \ldots\right] \qquad \sqrt{s} \gg v$$

Adding SM-like Higgs

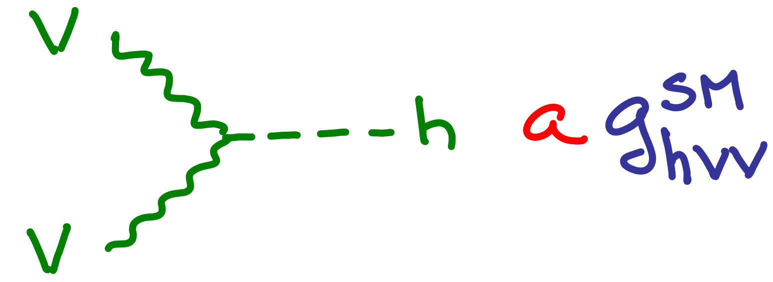
What if the coupling is not exactly like in the SM?





$a\, g_{hVV}^{SM}$

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



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

Even if we measure $a < 1$, no guarantee for new physics in reach of LHC.

Example: composite pseudo-Goldstone Higgs:

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

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

Stability and meta-stability

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

Tree-level

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

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What happens at $|\phi| \gg v$? Can ignore $\mu^2 \ll |\phi|^2$

Quantum fluctuations change potential

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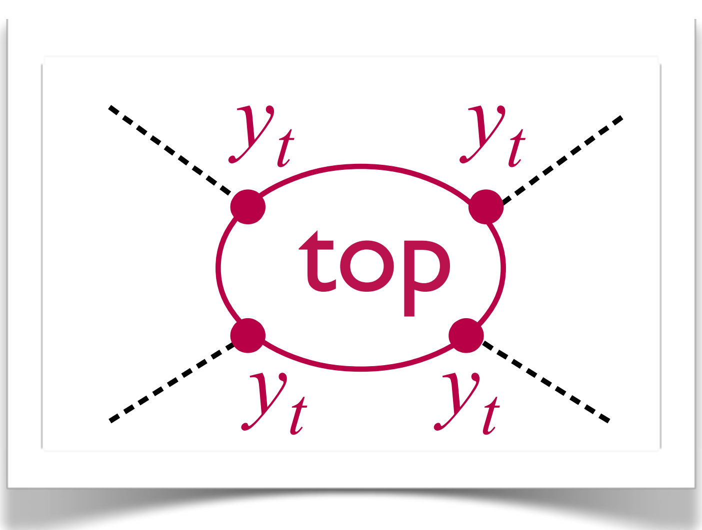
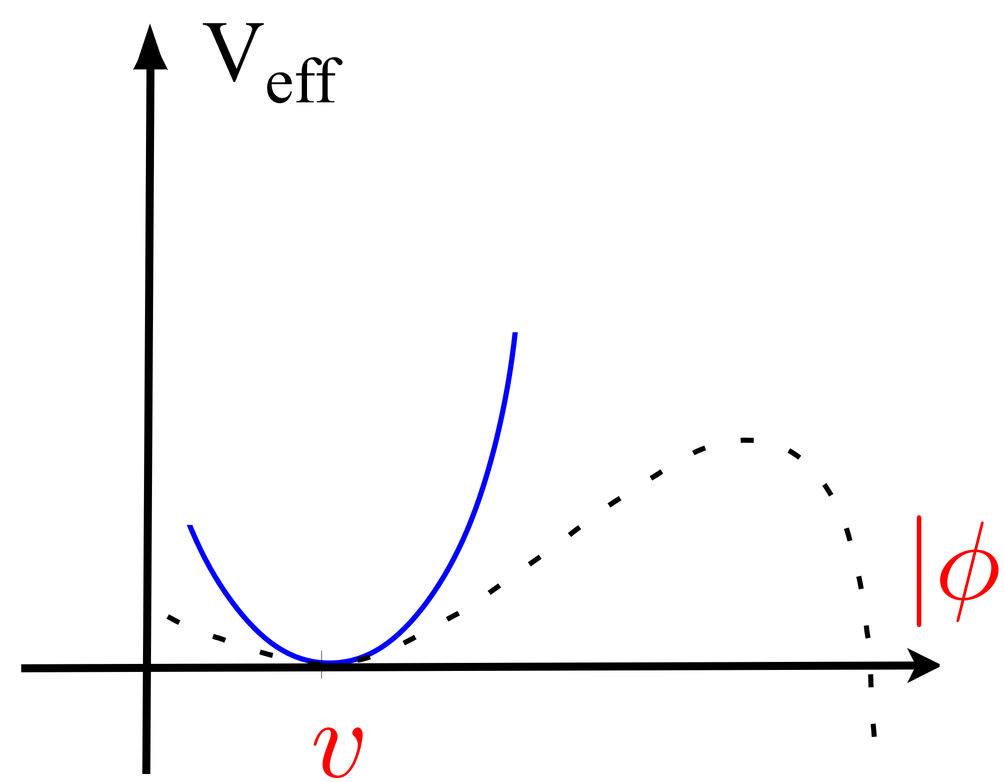
$$V \simeq \lambda(|\phi|)\,|\phi|^4$$



decreasing at large Energies =>



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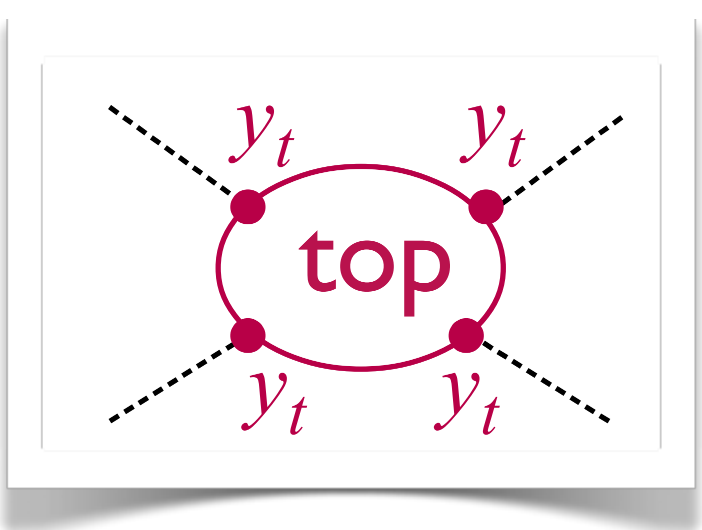
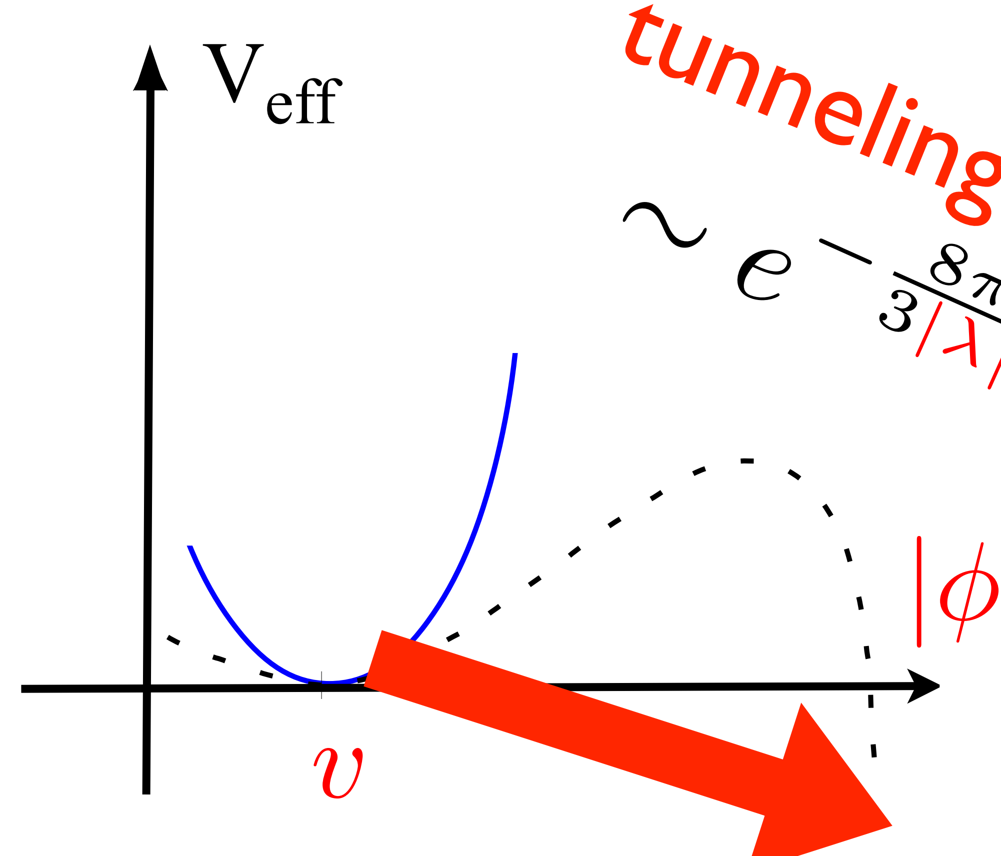


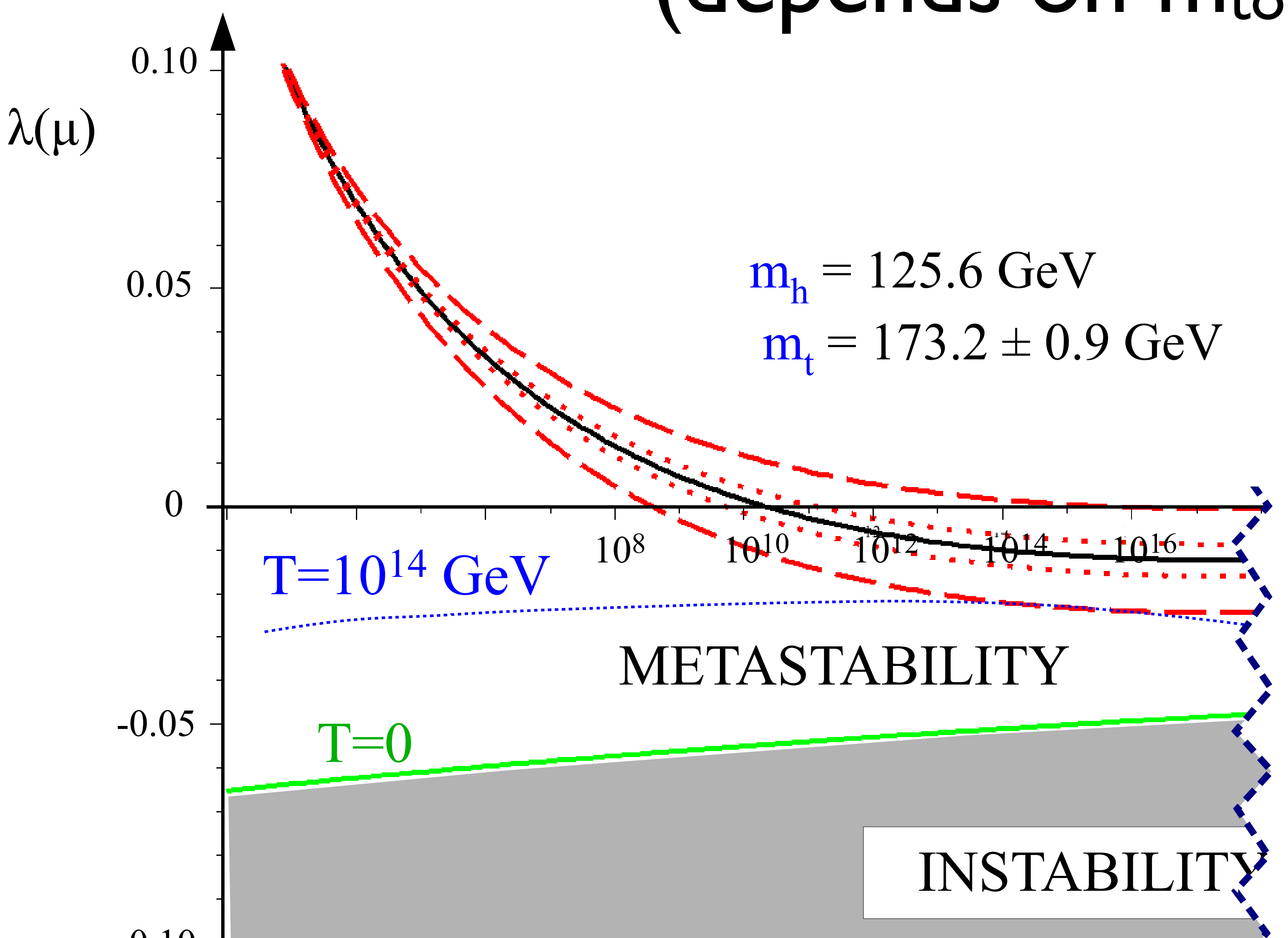
decreasing at large Energies =>

tunneling $\sim e^{-\frac{8\pi}{3|\lambda|}}$



Stability and meta-stability

SM vacuum is unstable but sufficiently long-lived, compared to the age of the Universe (depends on m_{top}, m_{higgs})



Planck scale

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

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

So what should be our guiding principle?

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

- - -x- - - - +

bare

See e.g. G. Giudice: 1307.7879

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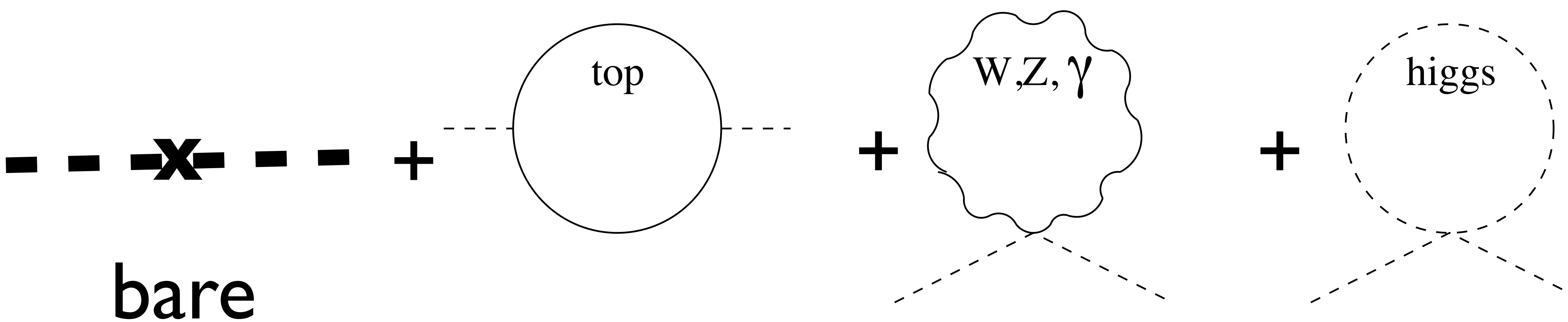
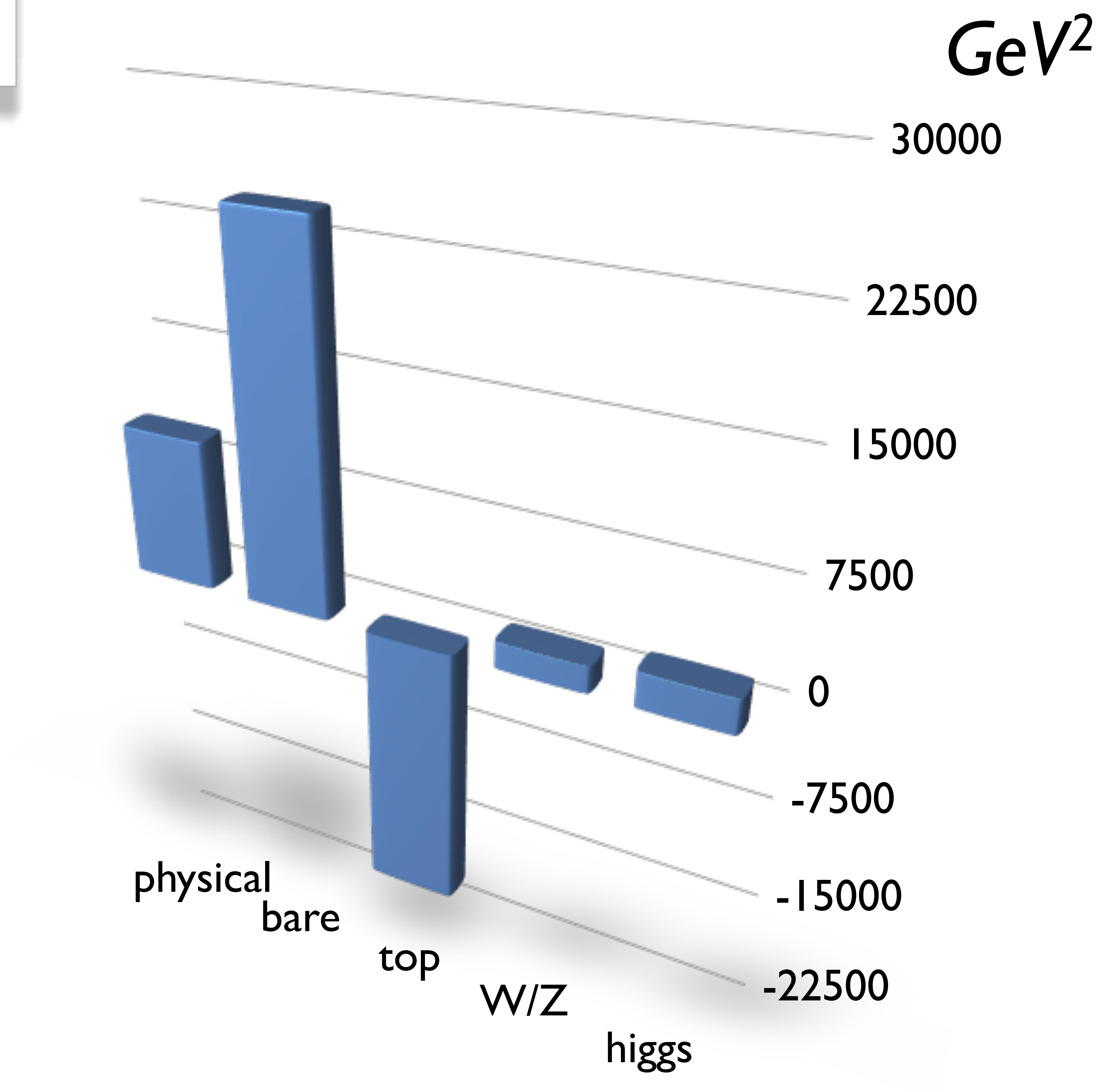


$$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \qquad \frac{9}{64\pi^2}g^2\Lambda^2 \qquad \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

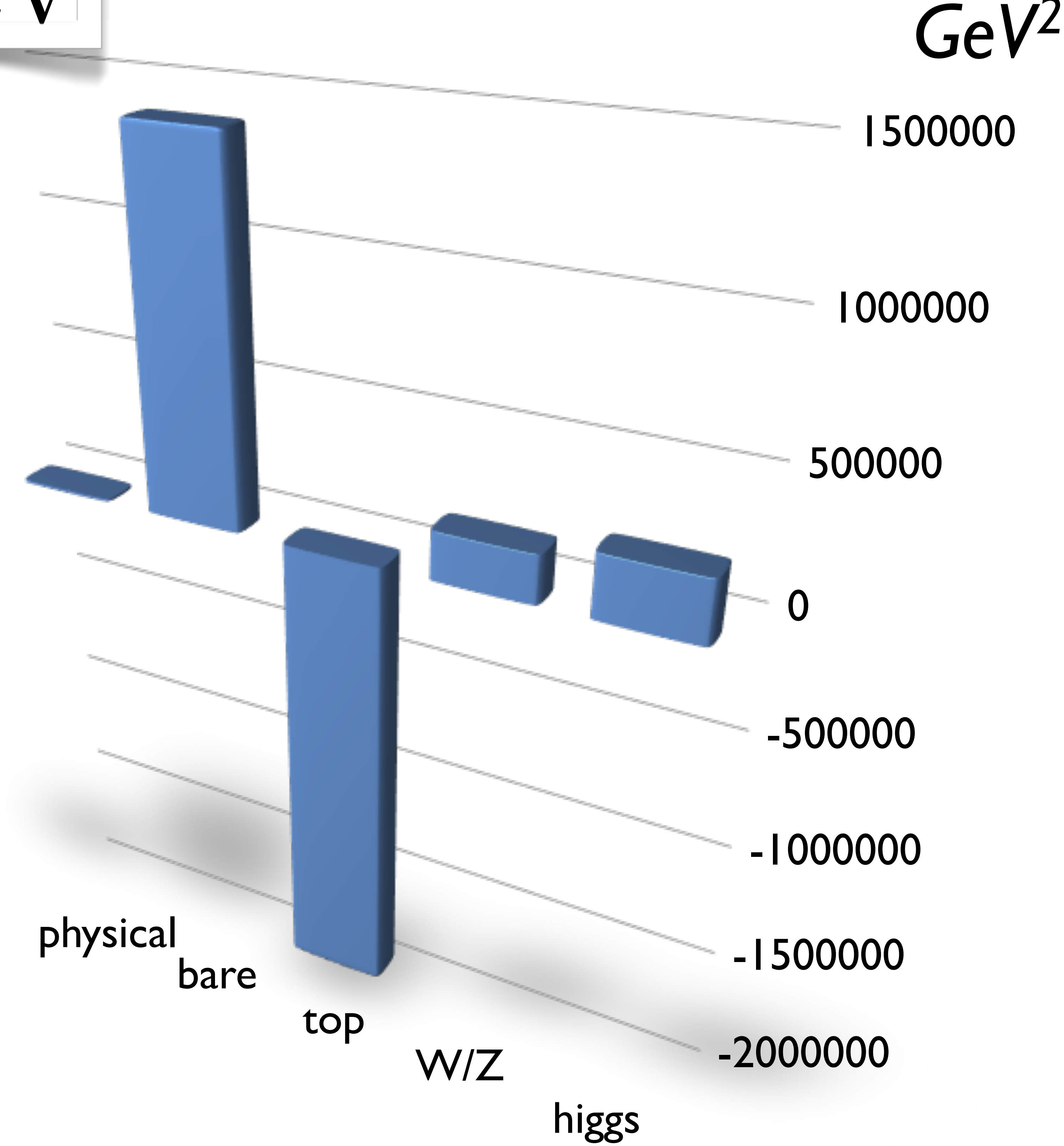
$$m_h^2(\text{physical}) = m_h^2(\text{bare}) + \sum_i a_i \Lambda^2$$

- Does the photon quantum correction matter?
- How about the other quarks (u,d,c,s,b)? Why did I only consider the top?

$\Lambda = 1\,\mathrm{TeV}$



$\Lambda = 10\,\text{TeV}$



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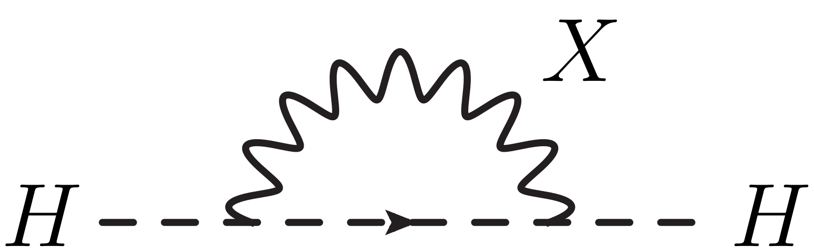
e.g. GUT

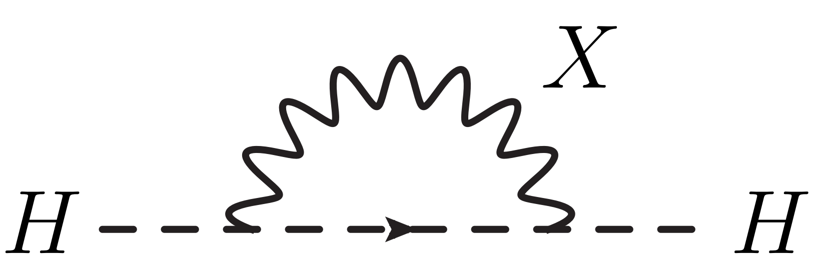


$$\Rightarrow \Delta m_H^2 \sim \frac{g_{\rm GUT}^2}{16\pi^2} M_X^2 \sim (10^{15}\ \mathrm{GeV})^2$$

Comments

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

e.g. GUT



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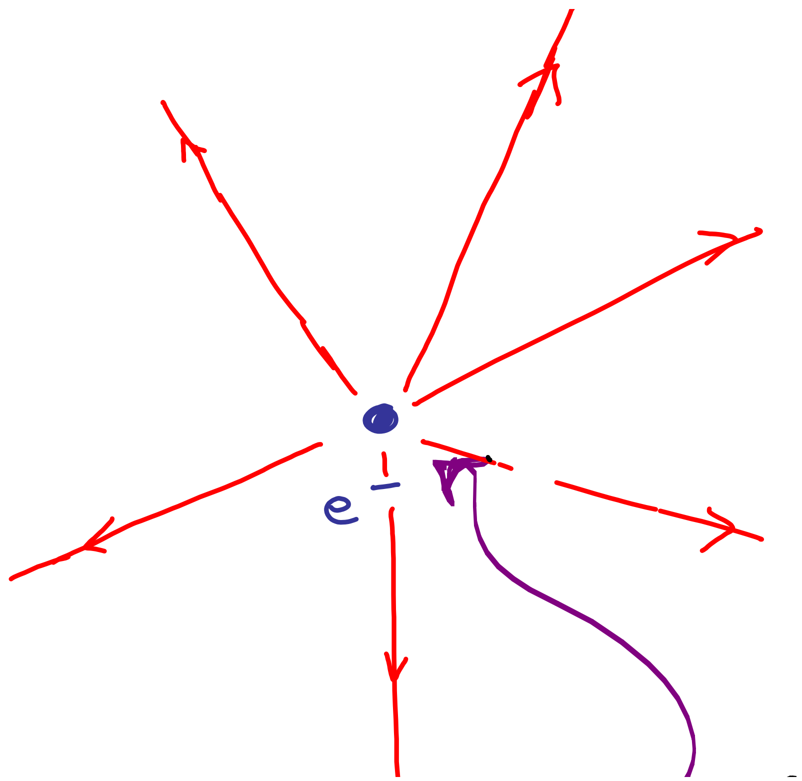
- The hierarchy problem needs a 'hierarchy of scales'. The SM alone (no gravity, nothing else): **no hierarchy, no problem**!

This is not an inconsistency of physics (can always cancel bare vs. quantum) rather it helps us understand where new physics might set in.

Electron Mass

Ex1 : divergent energy of electric field



New physics expected at

$$\Lambda \sim m_e/\alpha$$

Classically:

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

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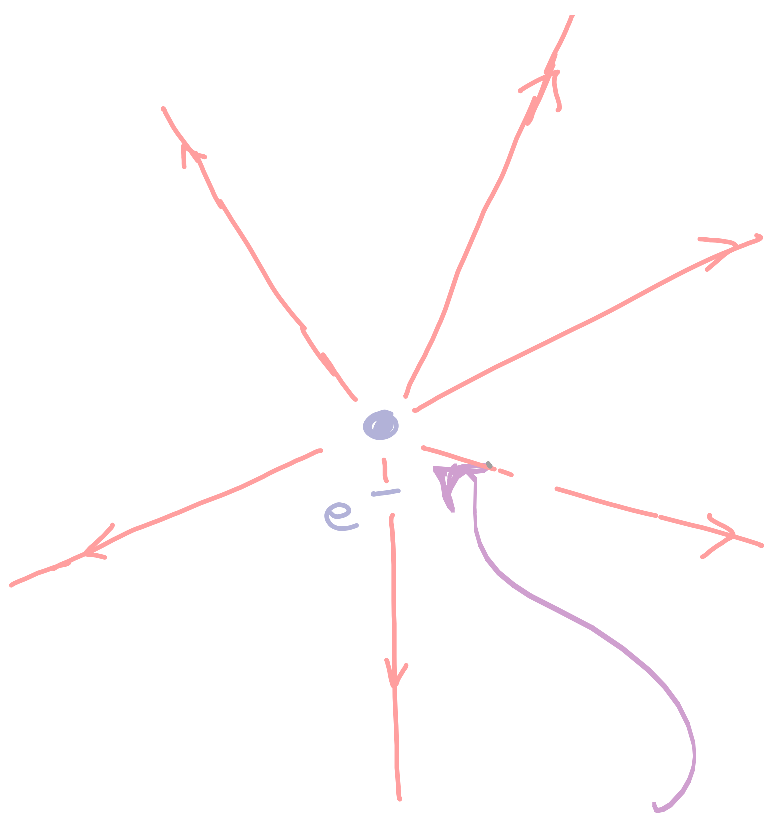
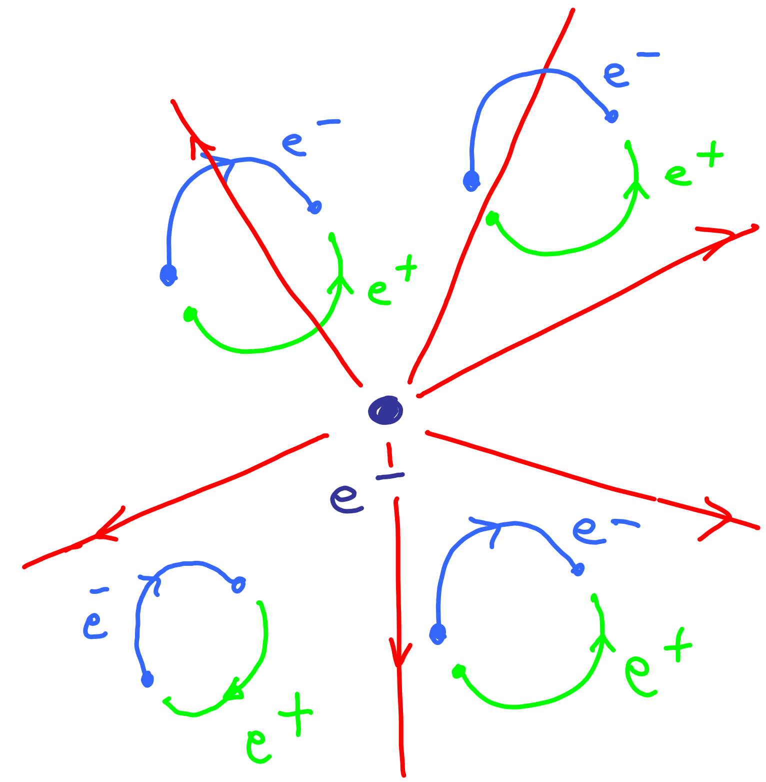


+positron



Classically:

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

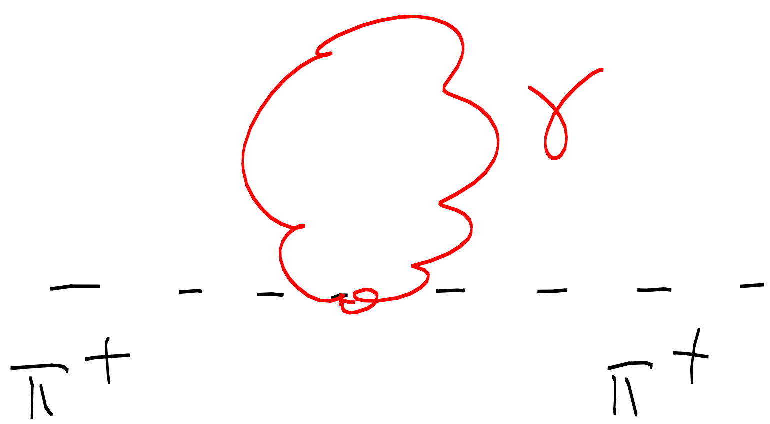
Extend space-time symmetry, relativity + QM: predict positron

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

→ natural electron mass.

Another example: Pion mass

Ex2 Neutral-charged pion mass difference



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

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

Das et al ‘67

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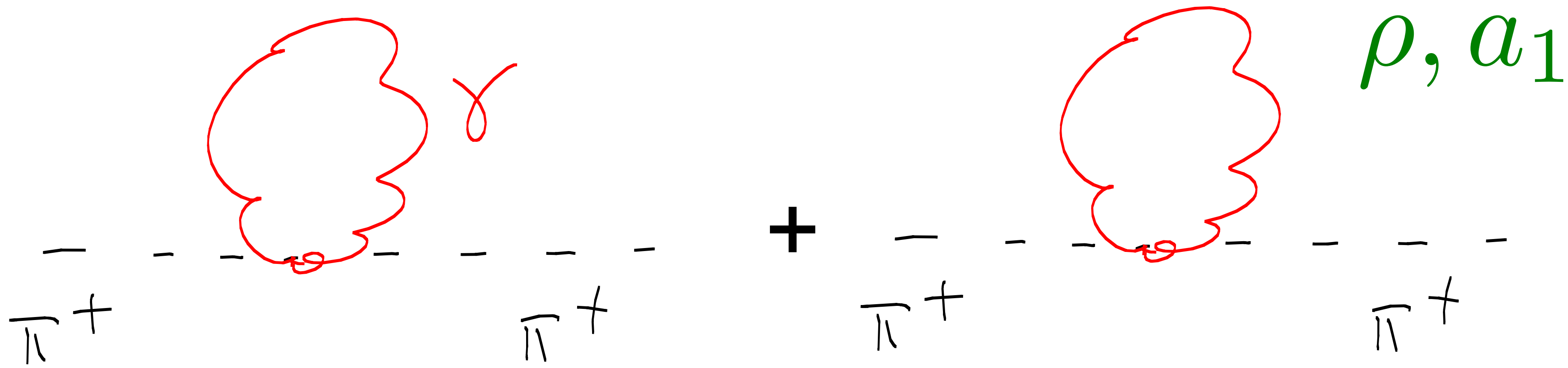

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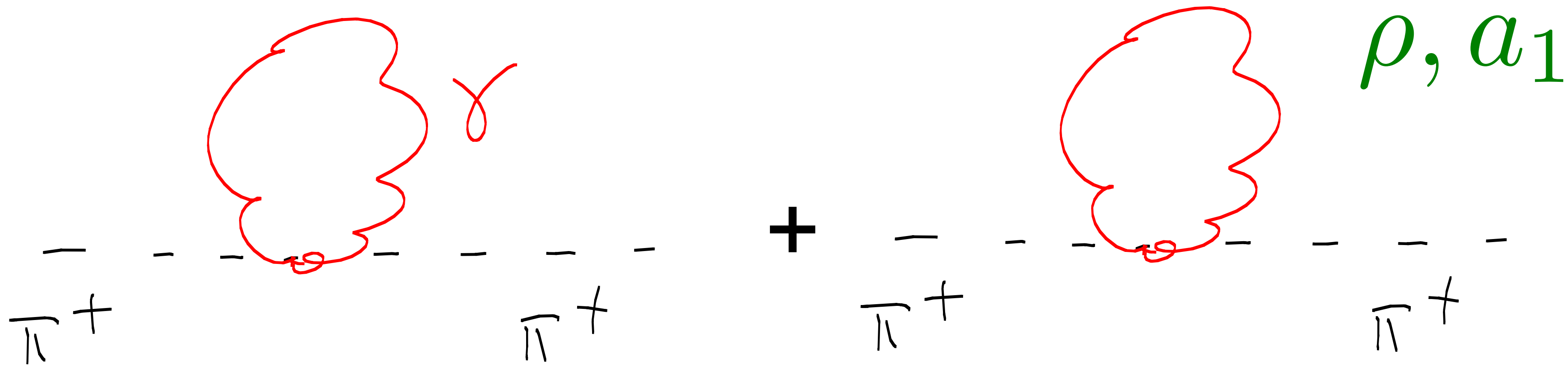

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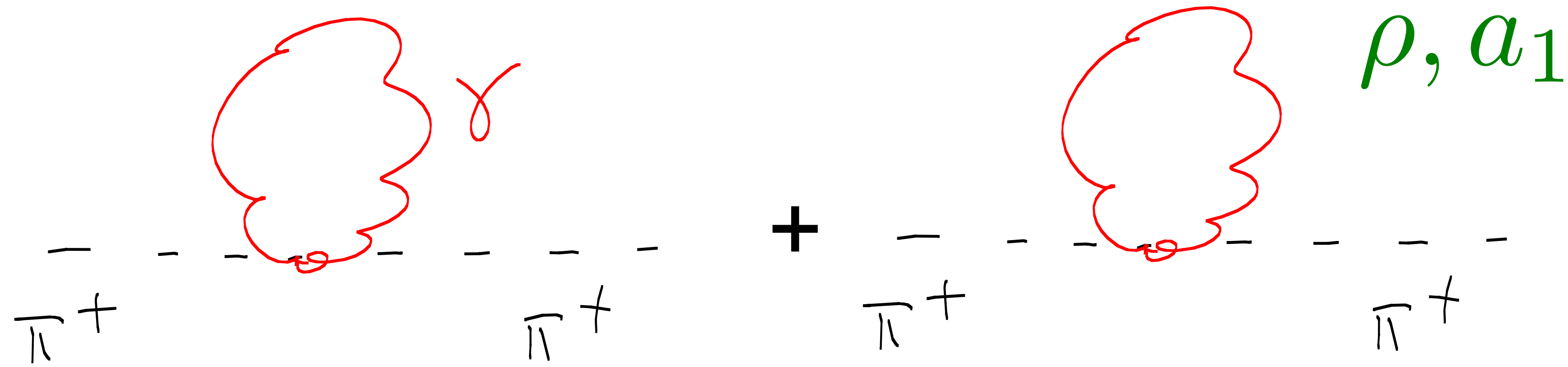

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Expect $\rightarrow \Lambda < 850\,\mathrm{MeV}$

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

Das et al '67

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

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

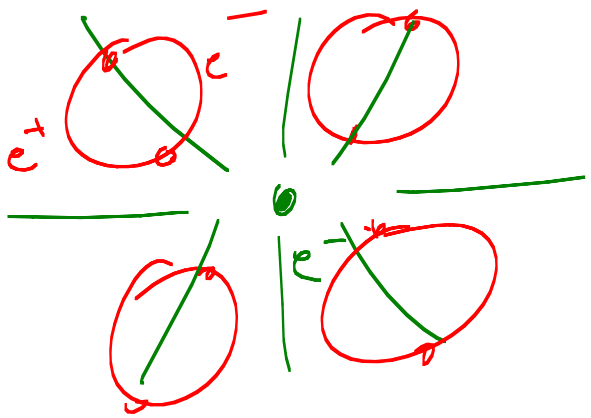
Naturalness disaster

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

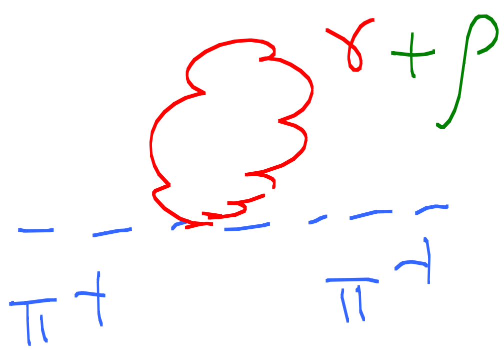
$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,(R - \Lambda_0)$$

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

Next



Supersymmetry (new space-time symmetry)



Composite Higgs