ICTP SAIFR International Centre for Theoretical Physics
South American Institute for Fundamental Research

IFT unesp Universidade Estadual Paulista "Júlio de Mesquita Filho"

Physics Beyond the Standard Model

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Oct. 21 – Nov. 6, 2014

School on "New Trends on High-Energy Physics and QCD"

Disclaimers

I will assume that the students have little or no familiarity with BSM scenarios

The emphasis will be on overviewing the problems and some of the possible solutions. I will not be able to go over many interesting details, but will try to explain the main ideas.

These lectures are intended as a roadmap (with illustrations), so that students can better appreciate the discussions/expectations in the field.

- Lecture 1: The Standard Model
  - Why the SM cannot be a complete description of Nature?
  - Why do we think we could find new physics at the TeV scale?
- Lecture 2: Supersymmetry as an example for new Physics at the TeV scale.
  - Motivations and virtues.
  - Assessment of the present status.
- Lecture 3: Elementary or composite Higgs?
  - Strong dynamics as the origin of EWSB.
  - The connection to extra spatial dimensions.

Three Lectures on BSM Physics

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Table of contents: Lecture 1

The Standard Model Field Content

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

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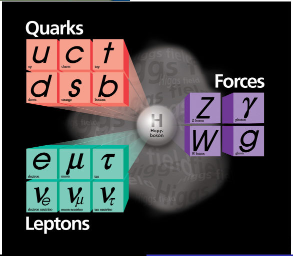

Local Symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y$

The Standard Model describes

$$(6 \times 3 \text{ [quark]} + 6 \text{ [lepton]}) \times 3 \text{ [generations]} = 72 \text{ fermionic d.o.f.}$$

$$8 \times 2 \text{ [gluon]} + 3 \times 3 \text{ [massive } W^{\pm}, Z] + 1 \times 2 \text{ [massless } \gamma] + 1 \text{ [Higgs]} = 28 \text{ real bosonic d.o.f.}$$

arranged into multiplets of $[\underbrace{SU(3)_C}_{G^A} \times \underbrace{SU(2)_L \times U(1)_Y}_{\{W^{\pm},Z,\gamma\} \leftrightarrow \{W^a,B\}}]^{local}$:

$$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \qquad \begin{matrix} u_R^i \\ d_R^i \end{matrix} \qquad L_L^i = \begin{pmatrix} \nu_L^i \\ l_L^i \end{pmatrix} \qquad l_R^i \qquad (i = 1, 2, 3)$$

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The Lagrangian (up to terms of dimension four) reads:

$$\mathcal{L}_{\rm SM} = \sum_{\Psi = Q, L} i \overline{\Psi}_L^i \not{D} \Psi_L^i + \sum_{\psi = u, d, l} i \overline{\psi}_R^i \not{D} \psi_R^i - \frac{1}{4} G_{\mu\nu}^A G_A^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^a W_a^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \mathcal{L}_{\rm Yuk}$$

with the covariant derivative $D_\mu = \partial_\mu - i g_s G_\mu^A T_C^A - i g W_\mu^a T_L^a - i g' Y B_\mu$

Local Symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y$

With the Higgs field doublet, $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$, $\tilde{H} \equiv i\sigma^2 H^* = \begin{pmatrix} H^{0*} \\ -H^- \end{pmatrix}$

we can also write

$$\mathcal{L}_{\rm Yuk} = -\overline{Q}_L \tilde{H} \lambda_u u_R - \overline{Q}_L H \lambda_d d_R - \overline{L}_L H \lambda_e l_R + \text{h.c.}$$

where the λ_i are 3×3 matrices in **"Flavor Space"**.

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Given the field content, the above is (almost) the most general Lagrangian invariant under the local (or gauge) symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$.

Note that there are no mass terms (i.e. bilinears, without derivatives) for any of the fields . . .

Global Symmetries

The SM Lagrangian has the following "accidental" global symmetries:

$$U(1)_B \times \underbrace{U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}}_{\to\, U(1)_L \text{ [due to non-zero neutrino masses (e.g. oscillations)]}} \longrightarrow U(1)_{B-L} \text{ [due to a quantum anomaly]}$$

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It is also very useful to notice that if the Yukawa couplings, λ_i, are set to zero then the theory has a much larger global *flavor* symmetry group

$$U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_l$$

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$\longrightarrow U(1)_{B-L}$ [due to a quantum anomaly]

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$$U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_l$$

One can use these flavor transformations to write

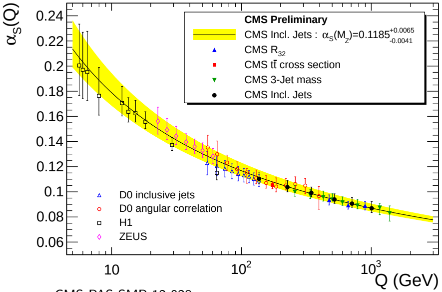
$$\mathcal{L}_{\rm Yuk} = -\overline{Q}'_L \tilde{H} \lambda_u^{\rm diag} u'_R - \overline{Q}'_L H\, U^\dagger_{\rm CKM} \lambda_d^{\rm diag} d'_R - \overline{L}'_L H \lambda_e^{\rm diag} l'_R + {\rm h.c.}$$

where the $\lambda_i^{\rm diag}$ are now real and diagonal, and $U_{\rm CKM} = U_{d_L} U^\dagger_{u_L}$ is unitary.

Parameters so far: $(g_s, g, g') + 9\ [\lambda \text{ eigenvalues}] + 4\ [\text{CKM matrix}] = 16$

The Origin of Mass?

- Running of α_s: asymptotic freedom
- Strong dynamics in the infrared
  $(\Lambda_{\rm QCD} \sim 200\ {\rm MeV})$
- Bound states: hadrons (confinement)
- $m_{\rm nucleon} \sim 1\ {\rm GeV}$: essentially binding energy



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The bulk of the mass of ordinary matter arises dynamically due to the QCD interactions!

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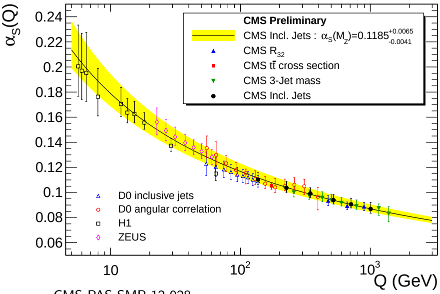


CMS-PAS-SMP-12-028

The bulk of the mass of ordinary matter arises dynamically due to the QCD interactions!

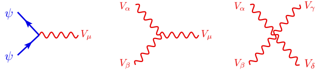
Electrons do not get mass from QCD. Even if comparatively tiny, it is certainly crucial that their mass is non-vanishing . . .

Why *most* Elementary Particles are not massless

- We have known for a while that the EW symmetry is *spontaneously broken*:

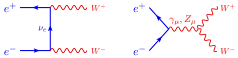
$$SU(2)_L \times U(1)_Y \to U(1)_Q$$

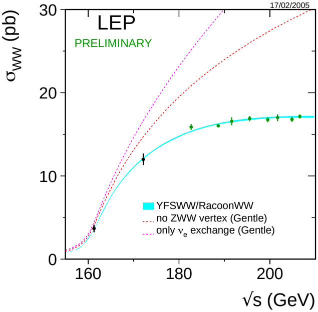
- This means that the dimensionless couplings satisfy the relations required by the symmetry



- However, the spectrum does not reflect the symmetry:

$$M_W \neq M_Z \neq M_\gamma = 0$$





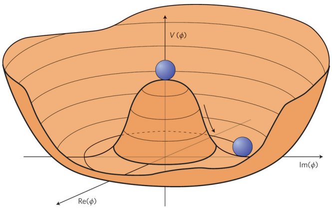
Why *most* Elementary Particles are not massless

The Higgs field (the only scalar in the SM!) has a potential (two more parameters)

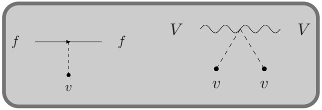
$$V(H) = \lambda(H^\dagger H - v^2)^2$$

so that

$$|\langle H \rangle| = v \approx 174 \text{ GeV}$$



By selecting a direction, e.g. $H = \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}} h^0 \end{pmatrix}$, the underlying symmetry is hidden [much as in a spontaneously magnetized ferromagnet the underlying rotational invariance is not immediately apparent]



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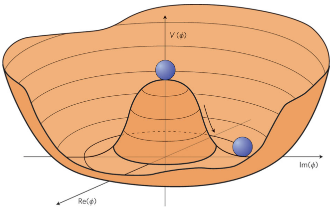

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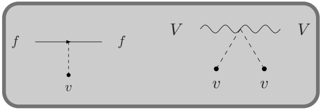
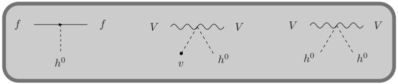


and also



[Interactions with the Higgs boson (h^0)] are fully determined]

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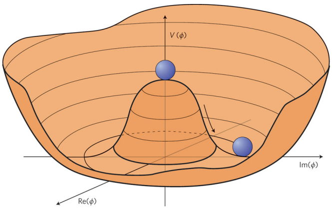

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Note that QCD, through the condensate $\langle \bar{q}_L^i q_R^j \rangle \sim \Lambda^3_{\text{QCD}} \delta^{ij}$, would give a mass to the $W^\pm, Z$ gauge bosons of several tens of $\text{MeV} \ll m_p \sim 1 \text{ GeV}$. It would not give (current) masses to the quarks and leptons.

A reason to celebrate!

Open Questions

In spite of its success, the SM leaves several questions unanswered!

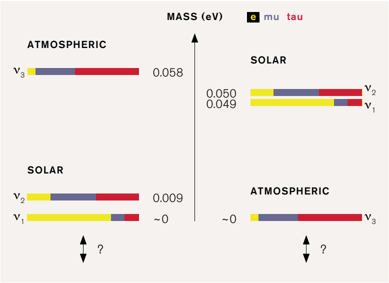
Neutrino Masses

- The observation of neutrino oscillations implies that the three neutrinos cannot be degenerate, hence at least two of them must have a (tiny) mass.
- Their mass could arise as for the rest of the fermions:

$$\mathcal{L}_{\rm Yuk} \supset -\overline{L}_L H \lambda_\nu \nu_R + \text{h.c.}$$

  by introducing an **unobserved** RH neutrino (a SM singlet!).
- For a singlet, one can write a (Majorana) mass term (unrelated to EWSB):

$$-M\bar{\nu}_R\nu_R^c + \text{h.c.}$$



See-saw mechanism for $M \gg \lambda_\nu v$:

$$\begin{pmatrix} 0 & \lambda_\nu v \\ \lambda_\nu v & M \end{pmatrix} \to \begin{cases} M_{\rm heavy} \approx M \\ M_{\rm light} \approx -\dfrac{(\lambda_\nu v)^2}{M} \end{cases}$$

Neutrino Masses

- Are neutrinos Majorana or Dirac fermions?
- What is the absolute mass scale?
- Is the hierarchy normal or inverted?
- What is the nature of CP-violation in the neutrino sector?
- Why are the mixing angles large, unlike those observed in the quark sector? (or perhaps one should pose the question the other way around?)
- What is the underlying physics that gives rise to the observations?

The Question of Flavor

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What is the underlying physics that gives rise to the observations?

By far, the most “arbitrary” sector of the SM is related to the Yukawa couplings (13 of the 18 parameters we have encountered).

We find Yukawa interactions between the Higgs and the fermions spanning $10^{-6} - 1$ (perhaps a larger range, depending on what is the correct description for neutrino masses).

In the quark sector, we find a pattern of mixing angles that is almost diagonal. In the lepton (neutrino sector), the mixing angles are order one.

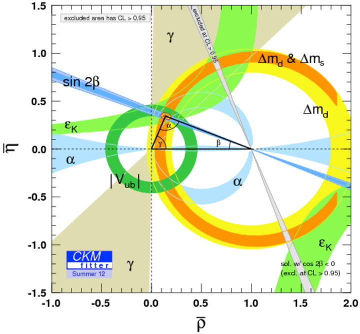
The Question of Flavor

- The quark flavor structure has been tested to great precision (at the quantum level)
- Higher-dimension operators such as

$$\frac{1}{\Lambda^2}(\bar{\psi}_i \Gamma \psi_j)(\bar{\psi}_k \Gamma \psi_l)$$

have to be suppressed by scales of order $100 - 1000$ TeV!

- The physics that gives rise to the flavor structure may be rather heavy.



This is because extensions of the SM typically destroy the flavor protection properties of the SM (e.g. the GIM mechanism)

Important constraints and guide for Physics Beyond the SM!

The CKM Phase and the Strong CP problem

- The CKM matrix has exactly one physical CP-violating phase. This accounts for all the $\not{CP}$ observations (which are at the level of 10^{-3}).
- However, in order to see that there is a single $\not{CP}$ phase in the quark sector, we need to redefine the phases of the quark fields (chirally).

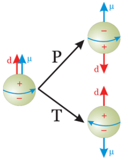
  This procedure generates the renormalizable operator

  $$\frac{n_f g_s^2 \theta}{32\pi^2} G^A_{\mu\nu} \tilde{G}^{\mu\nu}_A \quad \text{where} \quad \tilde{G}^{\mu\nu}_A = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} G^A_{\alpha\beta} \quad \text{and} \quad \theta = \text{Arg}[\text{Det}(\text{M}_\text{f})]$$

  This operator does not affect the EOM (it is a total derivative). However, it violates CP and can have an effect in the presence of gauge configurations with a non-trivial behavior at infinity.
- In fact, we should have written such an operator from the start, with a "bare" coefficient θ_0! Unless

  $$\bar{\theta} = \theta + \theta_0 \lesssim 10^{-10}$$

  a too large neutron electric dipole moment is induced!



The CKM Phase and the Strong CP problem

Summary

- The net theta-parameter is constrained to be very small ($\lesssim 10^{-10}$)
- It is the sum of two completely independent contributions, one of which is expected to be of order 10^{-3}
- This is the **Strong CP Problem**: the situation calls for a good reason why there should exist such a delicate cancellation, as opposed to being a fortuitous fine-tuning (recall that in QFT parameters are scale dependent)
- There exists several solutions, perhaps the most elegant of which requires the existence of a new pseudo-scalar particle: **the axion**.
- Other sources of $\not{C}\not{P}$ associated to BSM physics can also be rather constraining, and should be subdominant compared to the CKM CP-violation.

Why only matter and not anti-matter?

- The observable universe is dominated by matter, with only minuscule amounts of anti-matter
- In the early universe, at high temperatures, both existed in large quantities. We know from Big Bang Nucleosynthesis that

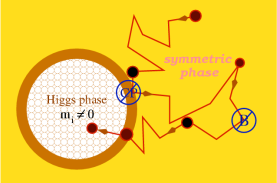
$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \equiv \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$$

- Can this very small difference simply be an initial condition? This would not be possible if, as is likely, the universe underwent a period of inflation at early times (that would have diluted any asymmetry).
- It turns out that a non-vanishing asymmetry can arise from a perfectly symmetric state, provided the three *Sakharov conditions* are satisfied
  1. There exists processes that violate Baryon number
  2. There is CP violation
  3. There existed departures from thermal equilibrium

Why only matter and not anti-matter?

- It turns out that the issue is non-trivial within the SM, and has been studied extensively. The conclusion is that the BAU cannot be generated within the SM, and our mere existence requires new physics!
- A couple of possibilities:

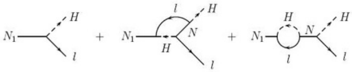
Electroweak Baryogenesis: the BAU could have been generated during the EW phase transition.



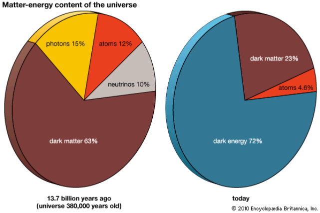
  - Closely connected to SM processes
  - Could in principle be probed in accelerators!

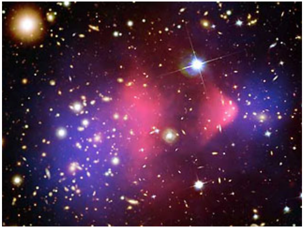
Leptogenesis: Produce a lepton asymmetry

  - E.g. in out-of-equilibrium decays of heavy RH Majorana neutrinos
  - B-L conservation: some lepton number converted to baryon number

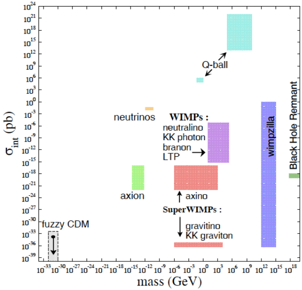


Dark Matter





- Baryonic Matter represents only 5% of the energy budget of the universe
- 27% is clumping **Dark Matter** of unknown nature (68% is non-clumping "Dark energy" with even more mysterious properties!)



Other Open Questions

There are still other questions that are made possible by our understanding of the Standard Models of Particle Physics and Cosmology, which nevertheless are not expected to have a resolution at the weak scale:

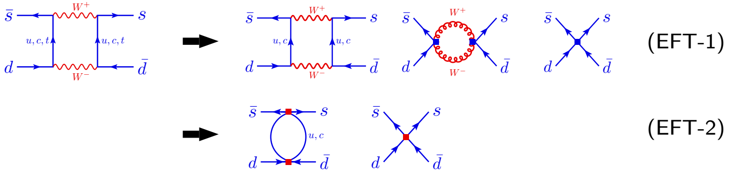
- What is the 70% of *Dark Energy*?
- What was the agent of inflation in the early Universe?
- What is the true nature of Quantum Gravity?

Assessment

- The SM, as the most general renormalizable theory with the observed d.o.f. (seen in lab. experiments), and the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge invariance is astonishingly successful.
- It is important that the exquisite agreement between theoretical calculations and the experimental observations validates not only the model, but also the more general framework of QFT (with detailed and non-trivial tests of the quantum aspects... more on this soon).
- Nevertheless, we have several reasons to believe that our current understanding of particle physics is incomplete: for sure there exist degrees of freedom in Nature that we have not (fully) identified.
- Theoretical ideas for addressing such open questions can suggest the possibly relevant scales, and whether/how we might be able to experimentally explore, test, and maybe eventually answer them.

Effective Field Theories (brief interlude)

- We have learned how to deal with multi-scale problems with **Effective Field Theory Methods**. (Also useful to include quantum subleading corrections.)
- Consider *as an illustrative example* the case of $K^0 - \bar{K}^0$ mixing (which often leads to the most severe constraints on new sources of flavor violation)



(Comment: this way of setting up the computation allows the inclusion of QCD corrections).

Effective Field Theories (brief interlude)

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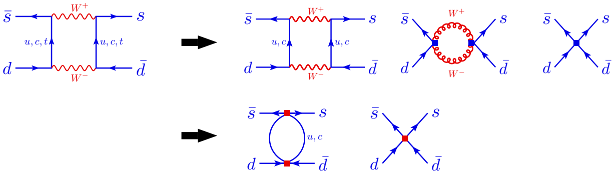


(EFT-1)

(EFT-2)

(Comment: this way of setting up the computation allows the inclusion of QCD corrections).

- In the same spirit, we are led to regard the (renormalizable) SM Lagrangian as the leading low energy limit of a more complete theory, with the effects of the heavy physics encoded in higher-dimension operators (as well as in the values of the measured low-energy couplings).

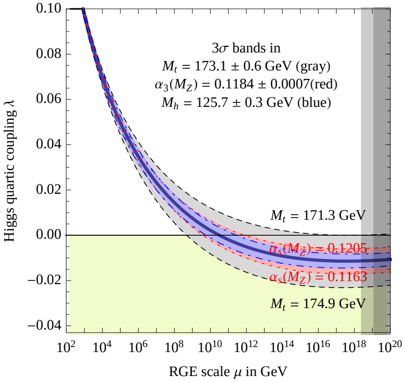
Extrapolating What We Know to Shorter Distances

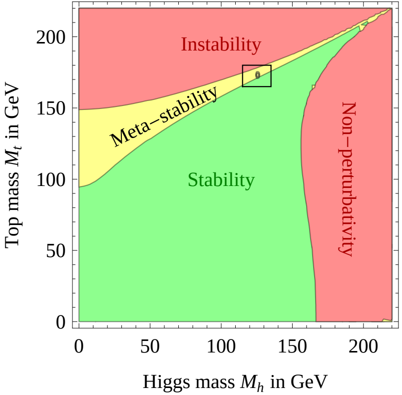
- Nevertheless, one possibly interesting question is: does the SM, as a QFT model, force upon us the existence of a new scale?

  (Much as the Fermi Theory forced upon us the weak scale?)
- The previous discussion shows that we know how to take into account the contributions of (virtual) momentum modes at least up to the EW scale, following our understanding of QFT as well as EFT methods
- Let us imagine that such a description is actually valid up to a certain scale Λ

  Note: Here Λ is a physical scale. Examples of its interpretation could be
  - The mass of a new particle that appears as a real external state at such energies
  - The onset of a UV conformal regime
  - A scale above which QFT breaks down, e.g. could get replaced by string theory
  - Other possibilities we have not thought about?

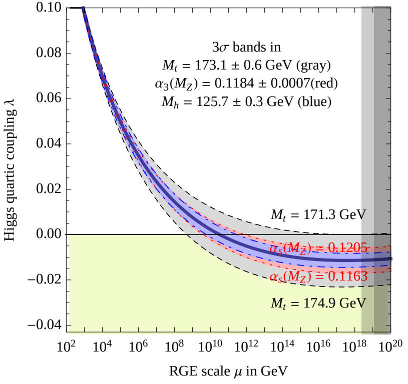
Extrapolating What We Know to Shorter Distances





From Degrassi et.al. arXiv:1205.6497

Extrapolating What We Know to Shorter Distances



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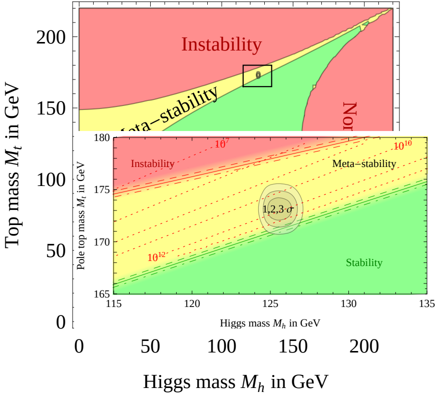
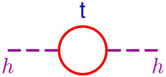


Higher Scales (Shorter Distances)

- But we are hiding something under the rug...
- Consider the 1-loop corrections to the Higgs mass parameter from the top quark:

$\Delta m_H^2 \sim$



$$\sim \; -N_c y_t^2 \int_0^\Lambda \frac{d^4k}{(2\pi)^4} \,\mathrm{Tr}\left[\frac{1}{\not{k}-m_t}\right]^2 \;\sim\; -\frac{N_c y_t^2}{8\pi^2}\,\Lambda^2$$

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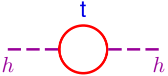

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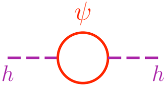
- If there are new, heavy particles that couple to the Higgs (e.g. a heavy fermion) we have:

$\Delta m_H^2 \sim$



$$\sim -\frac{y^2}{8\pi^2}\left[\Lambda^2 + M_\psi^2 \log(\Lambda^2/M_\psi^2)\right]$$

The weak scale is quadratically sensitive to ultrashort distances!

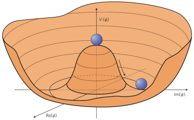
The Hierarchy Problem

- The bottom-line is that practically any physics that we can imagine to address any of the questions left open by the SM, will impact the weak scale, unless
  1. It lies rather close to the weak scale
  2. It has special properties that shield the weak scale from the high-momentum modes
- This is a fine-tuning problem: it is not logically impossible that all the actual high-energy contributions (including many loop orders) cancel out to an extraordinary degree, but as physicist we should explore robust mechanisms that lead to such an outcome!
- Note that the Planck scale most likely is associated to new degrees of freedom, or another deep change in our physical framework. Such unknown physics would push the weak scale close to the Planck scale, i.e. a weakless universe.

  (Comment: even if gravity was absent, the hypercharge gauge coupling presents a Landau pole –at an extremely large scale– that would force upon us a new physical scale).

Expectations for the Weak Scale

There is another unsatisfactory issue with our current picture of EWSB:



$$V(H) = -m_H^2 H^\dagger H + \lambda (H^\dagger H)^2$$

Not only is the scale $v^2 \sim |m_H^2|/\lambda$ chosen by hand, but the sign of m_H^2 is chosen in an adhoc manner as well! (quite apart from this being Nature's choice)

Is there some *microscopic dynamics* that leads to EWSB in a dynamical way?

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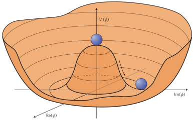

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Is there some *microscopic dynamics* that leads to EWSB in a dynamical way?

General EFT thinking, whereby widely different scales are expected to be decoupled, leads us to a simple expectation: the dynamics directly responsible for EWSB should be characterized by a scale not too different from the EW scale itself. In the context of QFT, the hierarchy problem makes such an intuition extremely sharp!

It seems difficult to expect that the "wine-bottle potential" is more than a phenomenological description, even if it turns out to work very well.

(Think of the Ginzburg-Landau description of superconductivity vs the BCS theory.)

Expectations for the Weak Scale

- It is important to appreciate that the central question remains unanswered: what is the origin of electroweak symmetry breaking? What is the underlying physics?
- We have known for decades that our vacuum breaks the EW symmetry ($v \neq 0$). The Higgs boson discovery sheds additional light (and excludes a few previously contemplated scenarios). But it does not explain **why** this phenomenon occurs in Nature.
- The Hierarchy Problem has led us to expect that the new physics responsible for EWSB may very well be discoverable at the LHC. This is the only argument that points unambiguously to new physics at the weak scale.

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- The Hierarchy Problem has led us to expect that the new physics responsible for EWSB may very well be discoverable at the LHC. This is the only argument that points unambiguously to new physics at the weak scale.
- Often the envisioned new physics scenarios have the potential for addressing one or more of the open questions reviewed earlier.
- In the next two lectures we will explore two such widely studied scenarios. Although it is not possible to do justice in the allotted time, hopefully the students will get a flavor of what could lie ahead, experimentally speaking...

End of First Lecture

Thank you!