Exact Top Mass Determinations and BSM Physics

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High precision fundamental constants at the TeV scale; March 10-21, 2014

Introduction

- **Physics Beyond the Standard Model must exist**
  - …
  - neutrino masses
  - evidence for Dark Matter
  - evidence for Dark Energy
  - BAU (Baryon Asymmetry of the Universe)
  - hierarchy problem

- **But …. so far nothing seen**
  → only SM Higgs: ``nightmare scenario''
  ←→ a lot happened in the last 20 years: SM as gauge theory, W,Z,t, m_ν

- **Different ways to see (or guess) new physics:**
  - new particles and interactions (see neutrinos, DM, …)
  - indications from QFT effects: consistency, extrapolation, … ← this talk

Look very careful at the SM as QFT

- **The SM itself (without embedding) is a QFT like QED**
  - infinities, renormalization ➔ only differences are calculable
  - perfectly OK ➔ many things unexplained…
- **It has (like QED) a triviality problem (Landau poles)**
  - running U(1) coupling (pole well beyond Planck scale…)
  - running Higgs / top coupling ➔ upper bounds on m_H and m_t

  ➔ requires some scale Λ where the SM is embedded

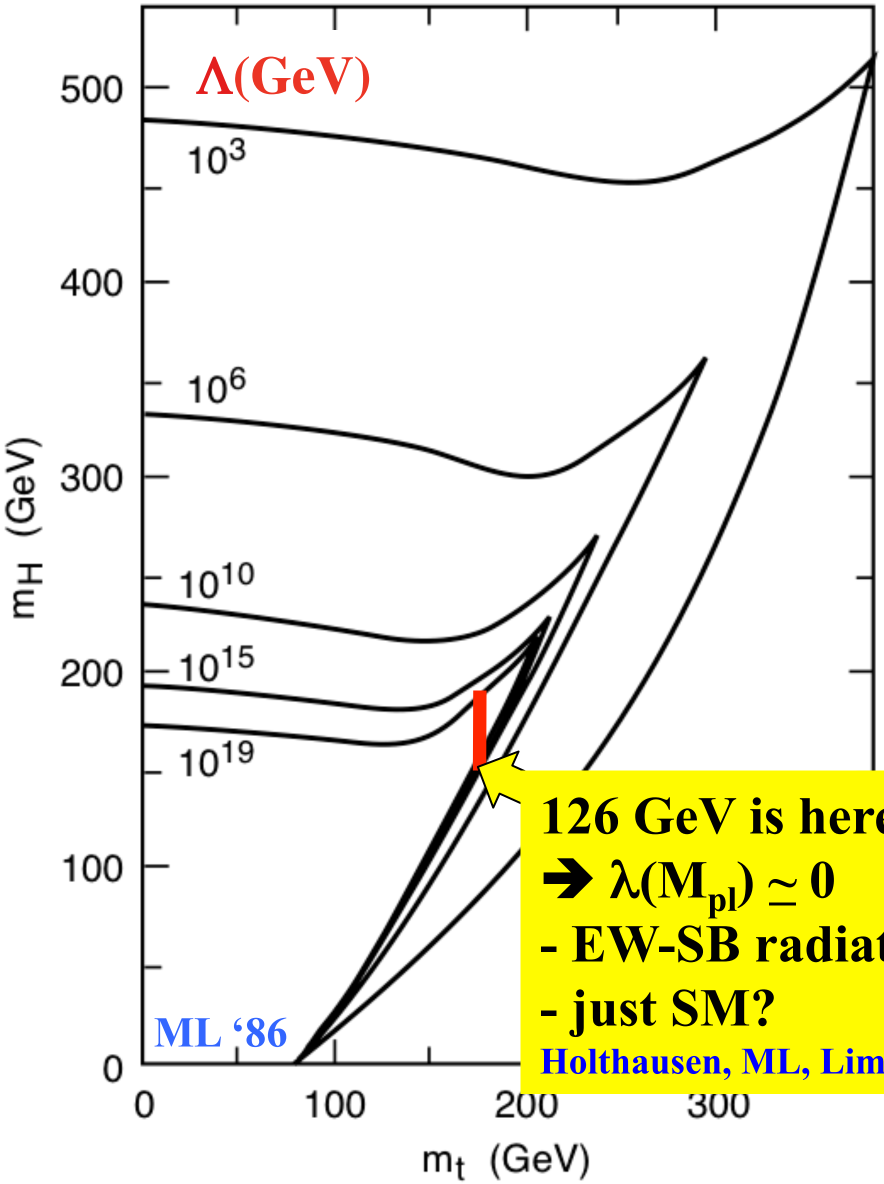
  ➔ the physics of this scale is unknown

  ➔ does not hurt SM QFT-calculations @ 0,1,2,.. loops
- **Another potential problem is vacuum instability (negative λ)**
  - does occur in SM for large top mass > 79 GeV ➔ lower bounds on m_H

SM as QFT: A hard cutoff and the sensitivity towards Λ has no meaning

⬄ The SM (without an embedding) is a renormalizable QFT just like QED

Triviality and Vacuum Stability



126 GeV is here!

➔ $\lambda(M_{pl}) \simeq 0$

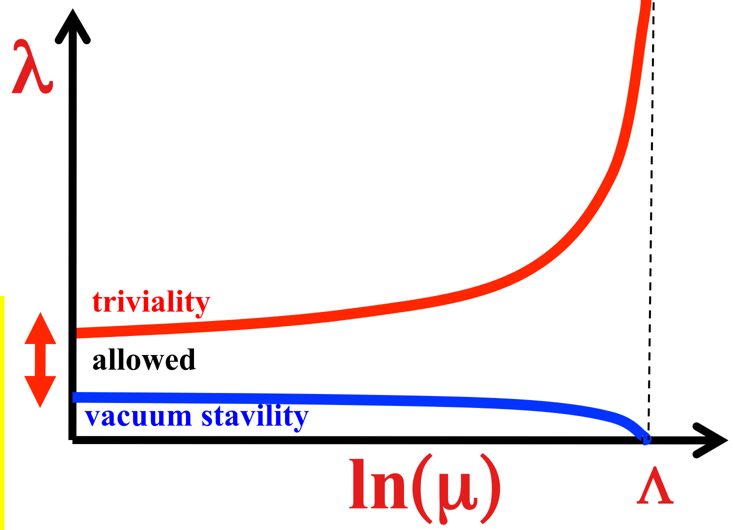
- EW-SB radiative

- just SM?

Holthausen, ML, Lim (2011)

$126\text{ GeV} < m_H < 174\text{ GeV}$

SM does not exist w/o embedding
- U(1) copling , Higgs self-coupling



➔ RGE arguments seem to work
➔ we need some embedding

The allowed Range ←→ Experiment

$$m_{\rm min} = [126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5]\ {\rm GeV}$$

$$m_{\rm max} = [173.5 + \frac{m_t - 171.2}{2.1} \times 1.1 - \frac{\alpha_s - 0.1176}{0.002} \times 0.3]\ {\rm GeV}$$

➔ interesting experimental cases (for $\Lambda = M_{Planck}$):

1) m_H < ca. 126 GeV ➔ instability ➔ new physics (or disaster)

2) 126 GeV – 135 GeV perfect: SM + MSSM range, …

3) 135 GeV – 157 GeV perfect: SM , non-minimal SUSY, …

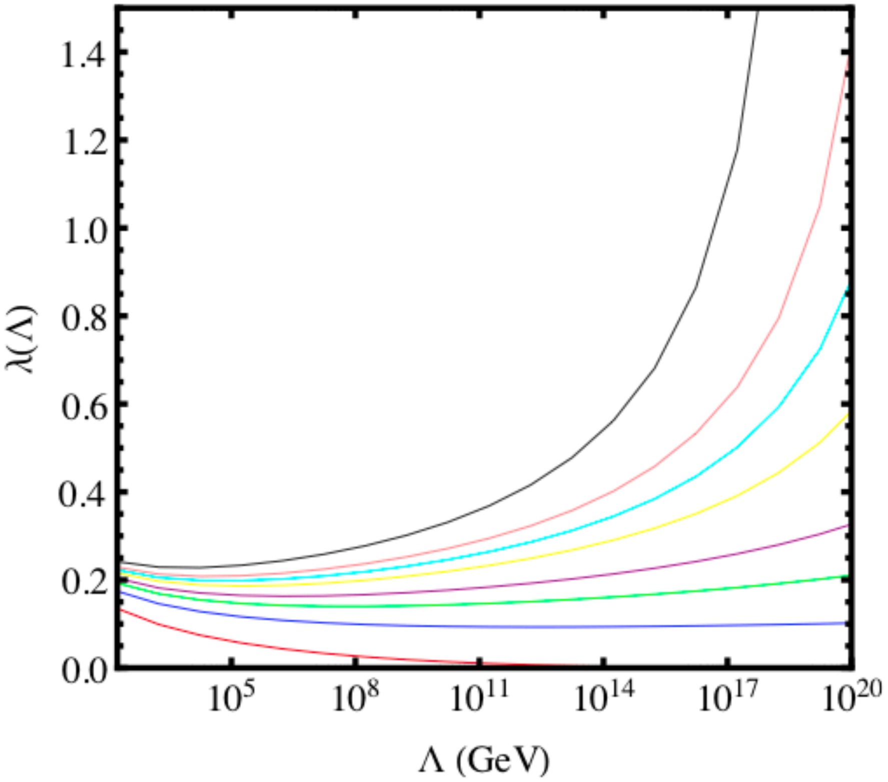
4) above 157 GeV – BSM

➔ Remarkable aspects:

- **SM parameters ←→ quantum corrections over large scales**
- **we seem to be very precisely at the transition between 1) and 2)**

A special Value of λ at M_{planck} ?

ML '86



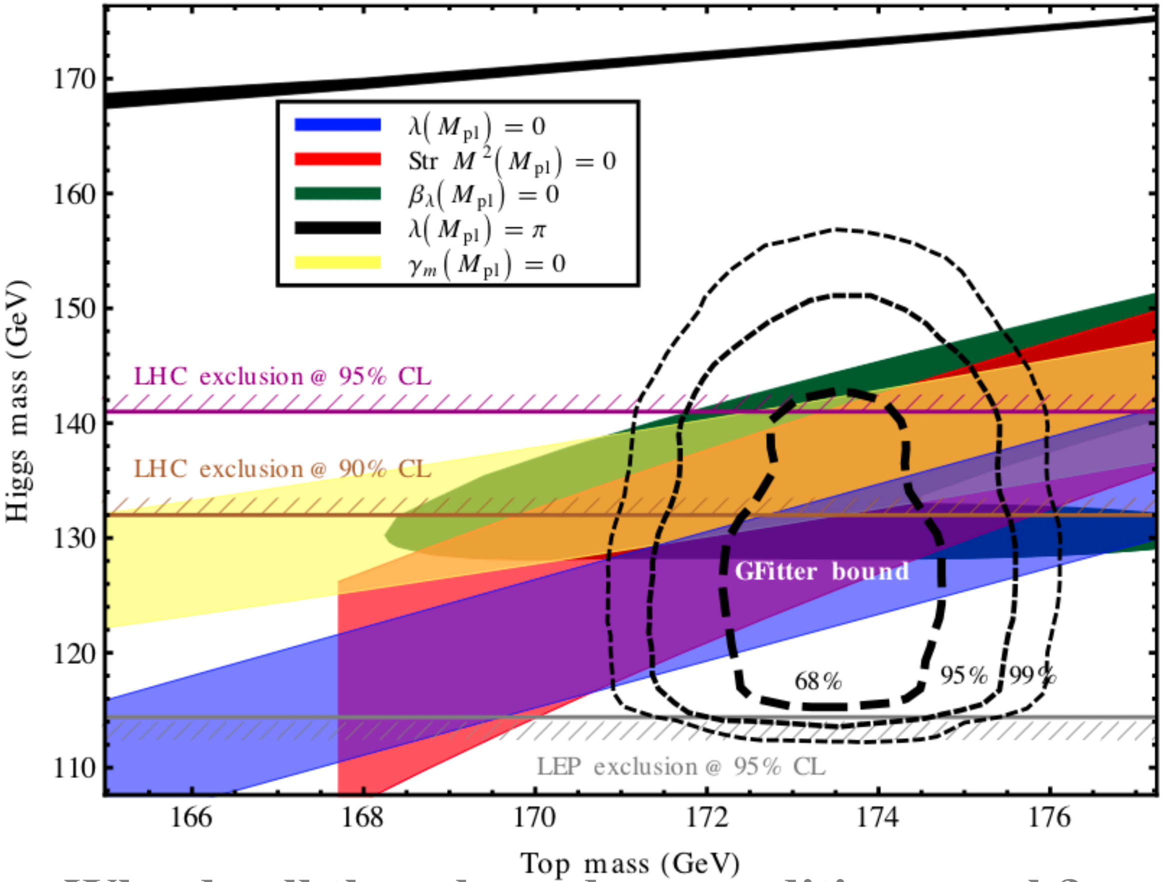
downward flow of RG trajectories
➔ IR QFP ➔ random λ flows to m_H > 150 GeV
➔ $m_H \simeq$ 126 GeV flows to tiny values at M_{Planck}…

Holthausen, ML Lim (2011)
Different conceivable special conditions:

- Vacuum stability
  $\lambda(M_{pl}) = 0$ [7–12]
- vanishing of the beta function of λ
  $\beta_\lambda(M_{pl}) = 0$ [9, 10]
- the Veltman condition [13–15] $\mathrm{Str}\mathcal{M}^2 = 0$,

$$\delta m^2 = \frac{\Lambda^2}{32\pi^2 v^2}\mathrm{Str}\mathcal{M}^2$$
$$= \frac{1}{32\pi^2}\left(\frac{9}{4}g_2^2 + \frac{3}{4}g_1^2 + 6\lambda - 6\lambda_t^2\right)\Lambda^2$$

- vanishing anomalous dimension of the Higgs mass parameter
  $\gamma_m(M_{pl}) = 0,\ m(M_{pl}) \neq 0$



$m_H < 150$ GeV
➔ random $\lambda = O(1)$ excluded

- **Why do all these boundary conditions work?**
  - suppression factors compared to random choice = O(1)
  - $\lambda = F(\lambda, g_i^2, \ldots)$ ➔ loop factors $1/16\pi^2$
  - top loops ➔ fermion loops ➔ factors of (-1)

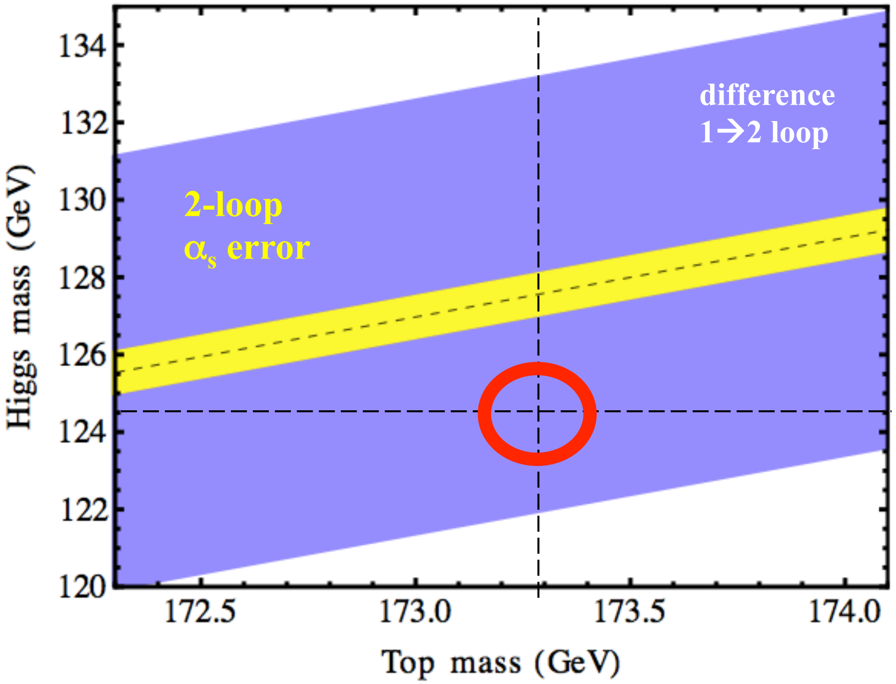
➔ any scenario which 'predicts' a suppressed (small/tiny) λ at M_{Planck} is OK

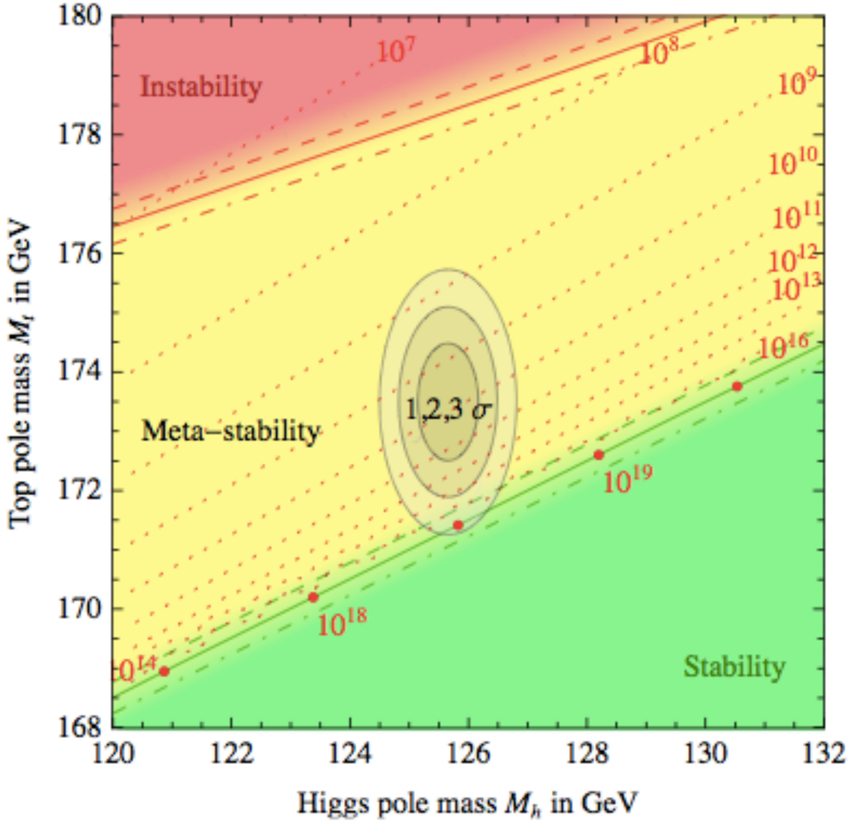
➔ more precision ➔ selects options ; e.g. $\gamma_m = 0$ now ruled out

Is the Higgs Potential at M_{Planck} flat?

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia

Holthausen, ML, Lim





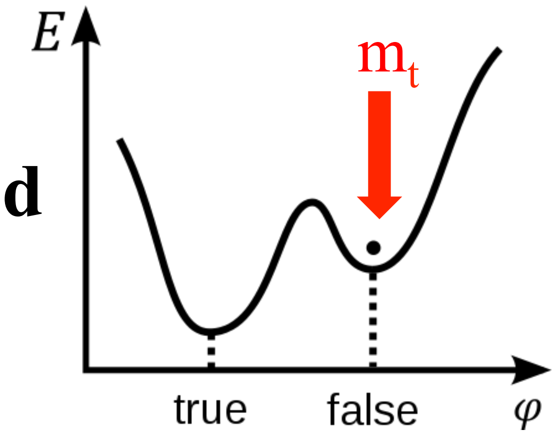
Notes:

- remarkable relation between weak scale, m_t, couplings and M_{Planck} ←→ precision
- strong cancellations between Higgs and top loops
  → very sensitive to exact value and error of m_H, m_t, $\alpha_s = 0.1184(7)$
- higher orders, other physics, … Planck scale thresholds… Lalak, Lewicki, Olszewski,
  → important: watch central values & errors

What if the SM were metastable?

➔ **for large m_t the Higgs potential has two minima. If m_t > stability bound**

- **EW (false, required, local, metastable)**
- **"true" (deeper, global minimum)**



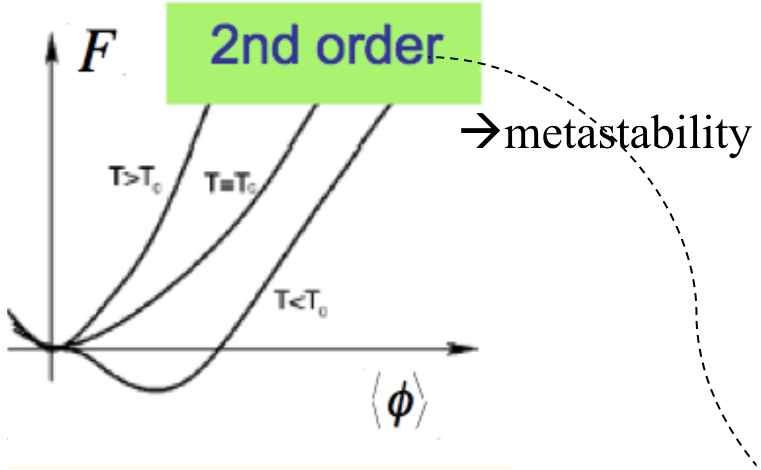
- 1^{st} bubble of true vacuum in U grows (surface vs. volume)
- mechanisms producing a 1^{st} bubble in the Universe: $r \sim 1/m_H$

  ➔ random CR collission / tunneling

  ➔ metastability (slightly negative λ) is OK (yellow region)
- do other (faster) mechanisms exist?

  ➔ maybe some intelligent form of life did already collide somewhere particles to form a critical bubble…?

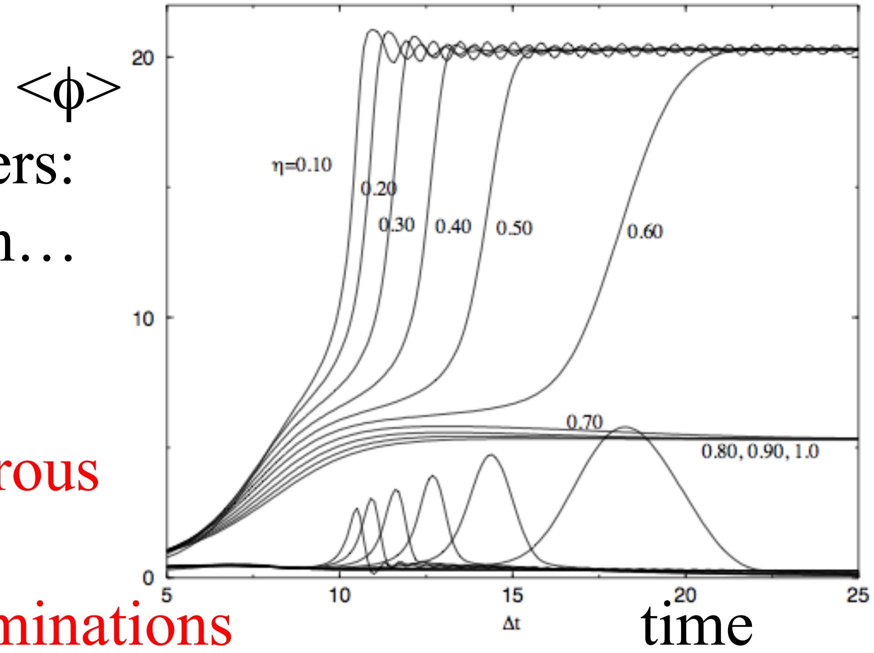
The dynamics of metastability:



- the bubble discussion ignores thermal cool-down, i.e. how/why we ended up in the (metastable) EW vacuum
- calculate thermal evolution of fluctuations and of field expectation value in cooling Universe ➔ Langevin eqs.

➔ does the fluctuating field fall into EW or global (wrong) vacuum?

Bergerhoff, ML, Weiser



The answer depends on exact parameters:
- correct vacuum ➔ bubble discussion…
- wrong vacuum ➔ always instable!

➔ SM metastability potentially dangerous

➔ or avoid it: embedding into…

➔ importance of precise m_H, m_t determinations

Interpretations of special Conditions: E.g. $\lambda(M_{Planck}) = 0$

$\lambda\phi^4$ → 0 at the Planck scale → no Higgs self-interaction (V is flat)
→ m_H at low E radiatively generated - value related to m_t and g_i
→ SM emdedded directly into gravity …!?

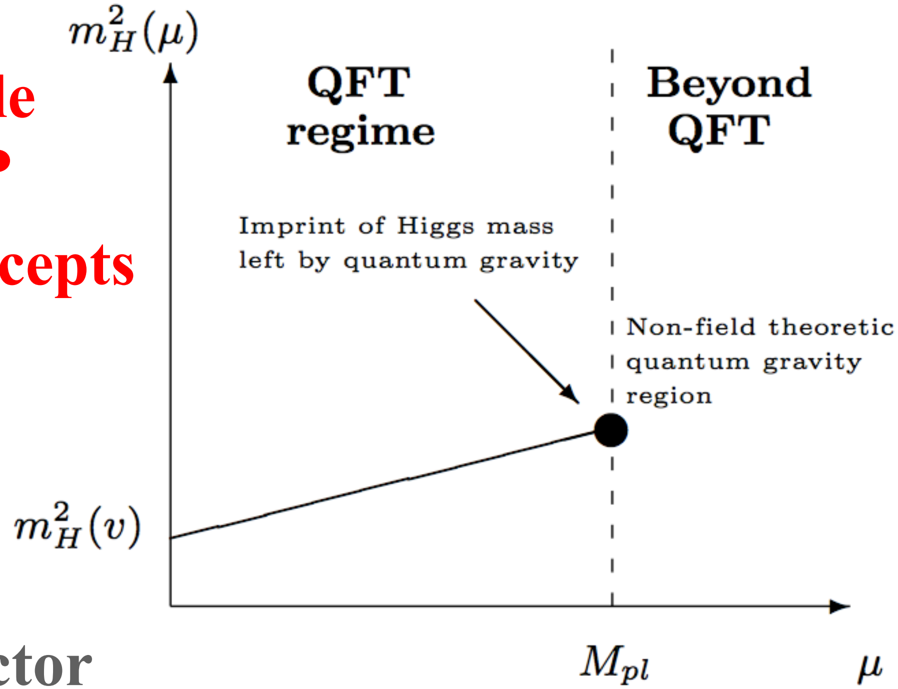
- **What about the hierarchy problem?**
  → GR is different: Non-renormalizable!
  → requires new concepts beyond QFT/gauge theories: … ?
  → BAD: We have no facts which concepts are realized by nature
  → Two GOOD aspects:

1) QFTs cannot explain absolute masses and couplings
   - QFT embeddings = shifting the problem only to the next level
   → new concepts beyond QFT might explain absolute values

2) Asymmetry SM←→Planck scale may allow new solutions of the HP

→ **new non-QFT Planck-scale concepts could have mechanism which explain hierarchies**

→ **lost in effective theory = SM**



Anaology: Type II superconductor
Ginzburg-Landau effective QFT ←→ BCS theory

$$E \approx \alpha|\phi|^2 + \beta|\phi|^4 + \ldots$$ ←→ **α, β, dynamical details lost**

➔ **Important consequence of this scenario:**
no intermediate QFT scales ←→ hierarchy problem back
(separation of two scalars unnatural in QFT)

Embedding the SM

Remember: The SM does not exist without some embedding triviality/vacuum stab. ➔ scale Λ required ➔ cannot be ignored!

Embedding into which concept? ➔ two options:

1) some new concept beyond d=4 QFT
2) some d=4 QFT

The $\lambda(M_{Planck})=0$ scenario above was along route #1
Most work over many years was along route #2:

- add representations
- extended gauge groups with and without GUTs
- include SUSY: MSSM, NMSSM, …, SUSY GUTs
- hidden (gauge) sectors, mirror symmetry, …

➔ Must face the gauge hierarchy problem

The Hierarchy Problem: Specify Λ

- Renormalizable QFTs with two scalars φ , Φ with masses m, M and a mass hierarchy **m << M**
- These scalars must interact since $\varphi^+\varphi$ and $\Phi^+\Phi$ are singlets
  ➔ $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$ **must exist** in addition to φ^4 and Φ^4
- **Quantum corrections ~M^2 drive both masses to the (heavy) scale**
  ➔ two vastly different scalar scales are generically unstable

Therefore: If (=since) the SM Higgs field exists

➔ problem: embedding with a 2nd scalar with much larger mass

➔ solutions:

a) new scale @TeV
b) protective symmetry (SUSY) @TeV

→ LHC !

Remark: SUSY & gauge unification → SUSY GUT →
→ doublet-triplet splitting problem → hierarchy problem back


STORY
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THIS WASN T PREDICTED IN OUR MODEL – WHAT SHOULD WE DO?
DON T SAY ANYTHING. MAYBE NO ONE WILL NOTICE.
LARGE HADRON COLLIDER
Flavour
LFV
DM, DE, …
CERN
CERN

Reconsider SM Embedding Directions

Recap.: Embedding options (and some examples) **at scale Λ**

1) some new concept beyond d=4 QFT

extra dimensions @TeV , $\lambda(M_{Planck})=0$, …

2) some d=4 QFT

a) new scale @TeV

LR symmetry, Z', composite, …

b) protective symmetry @TeV

SUSY: MSSM, …

BUT: no new physics @TeV observed???

BUT: Maybe there is another way out: **conformal symmetry (CS)**

The SM has almost CS

$$V(\Phi^+\Phi) = -\cancel{\mu^2}\Phi^+\Phi + \frac{\lambda}{2}\left(\Phi^+\Phi\right)^2$$

$\lambda \simeq 0$ @ M_{Planck}

Conformal Symmetry as Protective Symmetry

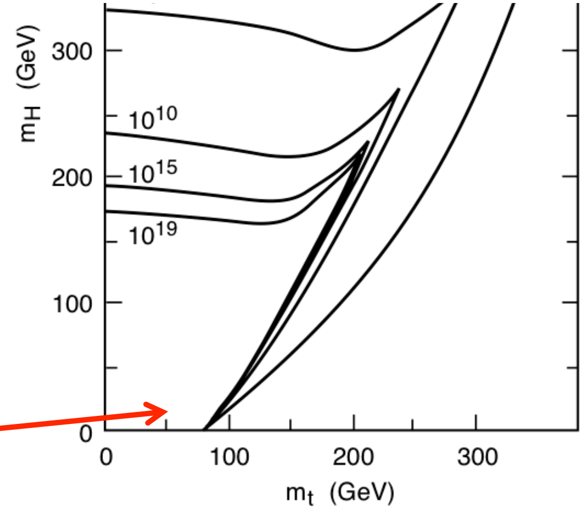
- **Exact (unbroken) CS**
  - → absence of Λ^2 and $\ln(\Lambda)$ divergences
  - → no preferred scale and therefore no scale problems

- **Conformal anomaly: Quantum effects break CS**
  - → explicit breaking of CS → anomaly induced spontaneous EWSB
  - → CS breaking ←→ β-functions ←→ $\ln(\Lambda)$ divergences
  - → BUT: maybe CS still forbids Λ^2 divergences **Bardeen**

Conformal anomaly → no symmetry preserving regularization
- cutoff → Λ^2 terms but violates CS explicitly → Ward Identity
- dimensional regularization gives no Λ^2 terms – only $\ln(\Lambda)$

IMPORTANT CONSEQUENCE: The conformal limit of the SM (or extensions) may have no hierarchy problem!

Realizing this Idea



Minimalistic: The Standard Model

choose $\mu = 0$ ←→ CS

Coleman Weinberg: effective potential

➔ CS breaking (dimensional transmutation)

➔ induces for $m_t < 79$ GeV
a Higgs mass $m_H = 8.9$ GeV

This would conceptually realize the idea, but:
Higgs too light and the idea does not work for $m_t > 79$ GeV
AND: We need neutrino masses, dark matter, …

➔ Other realizations:

A) new SM singlets
B) embeddings of the SM gauge group into larger groups
C) orthogonal (hidden) sectors
D) new scalar representations of QCD

Realizing this Idea: Left-Right Extension

M. Holthausen, ML, M. Schmidt

Radiative SB in conformal LR-extension of SM

(use isomorphism SU(2) × SU(2) $\simeq$ Spin(4) → representations)

particle	parity $\mathcal{P}$	$\mathbb{Z}_4$	$\mathrm{Spin}(1,3) \times (\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R) \times (\mathrm{SU}(3)_C \times \mathrm{U}(1)_{B-L})$
$\mathbb{L}_{1,2,3} = \begin{pmatrix} L_L \\ -\mathrm{i}L_R \end{pmatrix}$	$P\mathbb{P}\mathbb{L}(t,-x)$	$L_R \to \mathrm{i}L_R$	$\left[\left(\underline{\tfrac{1}{2}},\underline{\mathbf{0}}\right)(\underline{\mathbf{2}},\underline{\mathbf{1}}) + \left(\underline{\mathbf{0}},\underline{\tfrac{1}{2}}\right)(\underline{\mathbf{1}},\underline{\mathbf{2}})\right](\underline{\mathbf{1}},-1)$
$\mathbb{Q}_{1,2,3} = \begin{pmatrix} Q_L \\ -\mathrm{i}Q_R \end{pmatrix}$	$P\mathbb{P}\mathbb{Q}(t,-x)$	$Q_R \to -\mathrm{i}Q_R$	$\left[\left(\underline{\tfrac{1}{2}},\underline{\mathbf{0}}\right)(\underline{\mathbf{2}},\underline{\mathbf{1}}) + \left(\underline{\mathbf{0}},\underline{\tfrac{1}{2}}\right)(\underline{\mathbf{1}},\underline{\mathbf{2}})\right](\underline{\mathbf{3}},\tfrac{1}{3})$
$\Phi = \begin{pmatrix} 0 & \Phi \\ -\tilde{\Phi}^\dagger & 0 \end{pmatrix}$	$\mathbb{P}\Phi^\dagger\mathbb{P}(t,-x)$	$\Phi \to \mathrm{i}\Phi$	$(\underline{\mathbf{0}},\underline{\mathbf{0}})(\underline{\mathbf{2}},\underline{\mathbf{2}})(\underline{\mathbf{1}},0)$
$\Psi = \begin{pmatrix} \chi_L \\ -\mathrm{i}\chi_R \end{pmatrix}$	$\mathbb{P}\Psi(t,-x)$	$\chi_R \to -\mathrm{i}\chi_R$	$(\underline{\mathbf{0}},\underline{\mathbf{0}})\left[(\underline{\mathbf{2}},\underline{\mathbf{1}}) + (\underline{\mathbf{1}},\underline{\mathbf{2}})\right](\underline{\mathbf{1}},-1)$

→ **the usual fermions, one bi-doublet, two doublets**

→ **a Z_4 symmetry**

→ **no scalar mass terms ←→ CS**

➔ Most general gauge and scale invariant potential respecting Z4

$$\mathcal{V}(\Phi,\Psi) = \frac{\kappa_1}{2}\left(\overline{\Psi}\Psi\right)^2 + \frac{\kappa_2}{2}\left(\overline{\Psi}\Gamma\Psi\right)^2 + \lambda_1\left(\mathrm{tr}\Phi^\dagger\Phi\right)^2 + \lambda_2\left(\mathrm{tr}\Phi\Phi + \mathrm{tr}\Phi^\dagger\Phi^\dagger\right)^2 + \lambda_3\left(\mathrm{tr}\Phi\Phi - \mathrm{tr}\Phi^\dagger\Phi^\dagger\right)^2 + \beta_1\,\overline{\Psi}\Psi\mathrm{tr}\Phi^\dagger\Phi + f_1\,\overline{\Psi}\Gamma[\Phi^\dagger,\Phi]\Psi\,,$$

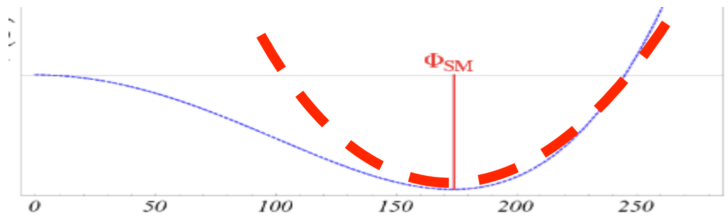
➔ calculate V_{eff}

➔ Gildner-Weinberg formalism (RG improvement of flat directions)

- anomaly breaks CS
- spontaneous breaking of parity, Z_4, LR and EW symmetry
- $m_H \ll v$; typically suppressed by 1-2 orders of magnitude

  Reason: V_{eff} flat around minimum

  $\leftrightarrow$ $m_H \sim$ loop factor $\sim 1/16\pi^2$
- everything works nicely…



➔ requires moderate parameter adjustment for the separation of the LR and EW scale… PGB…?

Realizing the Idea: Other Directions

SM + extra singlet: Φ, φ

Nicolai, Meissner
Farzinnia, He, Ren
Foot, Kobakhidze, Volkas

SM + extra SU(N) with new N-plet in a hidden sector

Ko
Carone, Ramos
Holthausen, Kubo, Lim, ML
…

SM + new QCD representation

Kubo, Lim, ML

Since the SM-only version does not work → observable effects:
- Higgs coupling to other scalars (singlet, hidden sector, …)
- dark matter candidates ←→ hidden sectors & Higgs portals
- consequences for neutrino masses

More Scalars + Conformal Symmetry

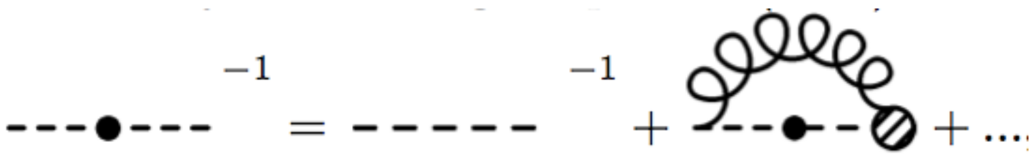
- SM scalar Φ plus some new scalar φ (or more scalars)
- CS → no scalar mass terms
- the scalars interact: $\lambda_{mix}(\varphi^{+}\varphi)(\Phi^{+}\Phi)$ must exist
  → a condensate in the φ direction can lead to $\langle\varphi^{+}\varphi\rangle > 0$
  λ_{mix} → effective mass term for Φ

- CS anomalous … → broken by quantum effects → only $\ln(\Lambda)$

- Note that this opens many other possibilities:
  - φ could be an effective field of some hidden sector DSB
  - further particles could exist in hidden sector; e.g. confining…
  - extra U(1) potentially problematic ←→ U(1) mixing
  - avoid Yukawas which couple visible and hidden sector
  → phenomenology safe since NP comes only via portal

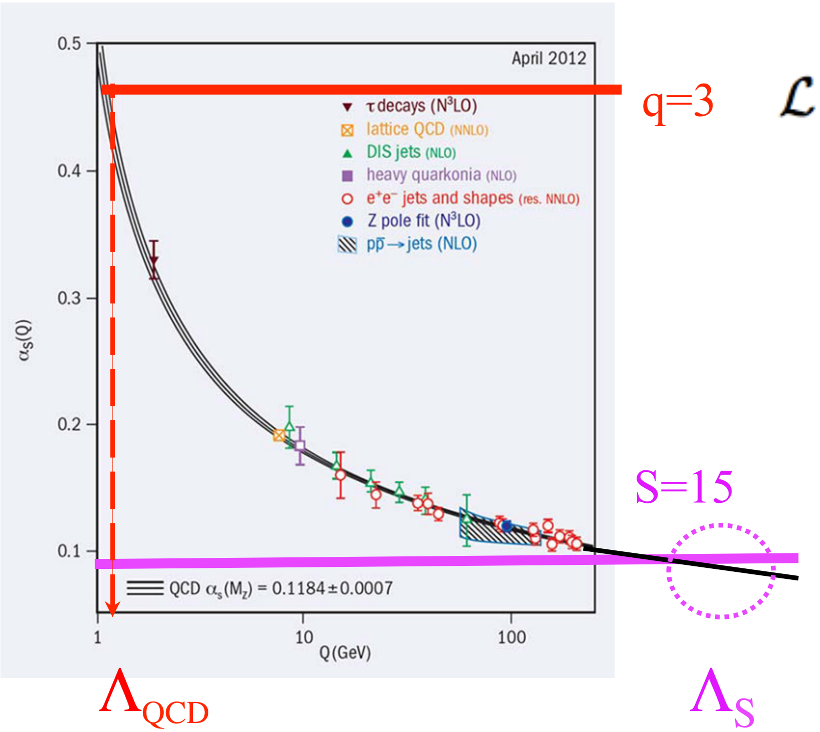
On the arXiv today: SM + QCD Scalar

New scalar representation S → QCD gap equation:



→ $C_2(S)\alpha(\Lambda) \gtrsim X$

$C_2(\Lambda)$ increases with larger representations
←→ condensation for smaller values of running α



$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + (D_{\mu,ij}S_j)^\dagger (D^\mu_{ik}S_k) + \lambda_{HS} H^\dagger H S^\dagger S - \lambda_{1_i}\left[\bar{\boldsymbol{S}}\times\boldsymbol{S}\times\bar{\boldsymbol{S}}\times\boldsymbol{S}\right]_{\boldsymbol{1}_i}$$

$$\lambda_{HS}\langle S^\dagger S\rangle H^\dagger H \to \lambda_{HS}\Lambda^2 H^\dagger H$$

$$m_h^2 = 2\lambda_{HS}\Lambda^2 \qquad \frac{\lambda_h}{\lambda_{HS}} = \frac{\Lambda^2}{v^2}$$

Phenomenology

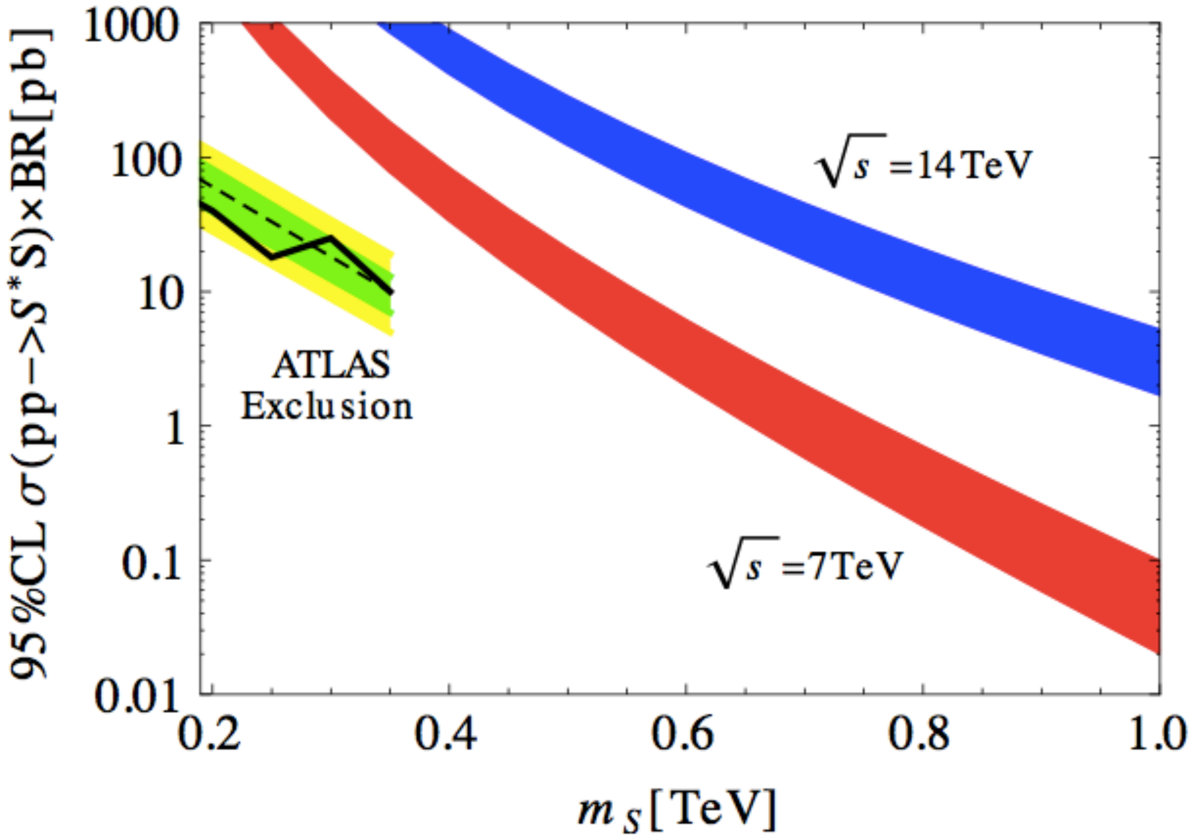


Figure 3. The S pair production cross section from gluon fusion channel is calculated for different value of m_S. The 95% confidence level exclusion limit on $\sigma \times$BR for $\sqrt{s} = 7$ TeV by ATLAS is plotted. We assume 100% BR of $\langle S^\dagger S \rangle$ into two jets.

Summary

- **SM works perfectly – no signs of new physics**

- **The standard hierarchy problem suggests TeV scale physics … which did (so far…) not show up**

- **Revisit how the hierarchy problem may be solved**

• Embedding into new concepts beyond QFT at M_{planck}
  ←→ might be connected to $\lambda(M_{Planck}) = 0$?
  ➔ **precise value of top mass**

• Embeddings into QFTs with classical conformal symmetry
  → SM: Coleman Weinberg effective potential – excluded
  → extended versions: singlets, SM=subgroup, hidden sectors
  → implications for Higgs couplings, dark matter, neutrinos
    ➔ testable consequences @ LHC, DM search, neutrinos