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BSM physics at the LHC

Winter School on
Strings, Supergravity and Gauge Theories

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Plan of the lectures

1. A critical overview of the SM
2. Bottom-up approaches to BSM
3. SUSY: if so, which incarnation?
4. Other BSM ideas for the LHC

Where is the cutoff scale of the SM ?

SM = Effective Theory

Λ = effective UV cutoff (not necessarily universal)
= the scale of some (unspecified) new physics

$$L_{eff}^{SM} = \Lambda^4 + \Lambda^2 \Phi^2 \qquad (\Lambda^{n>0} \Rightarrow \textit{hierarchy problems!})$$

$$+ (D\Phi)^2 + \overline{\Psi} \not{D} \Psi + F \cdot F + F \cdot \widetilde{F} + \overline{\Psi}\Psi\Phi + \Phi^4$$

$$(\textit{controllable} \ \log\Lambda \ \textit{dependence via quantum corrections})$$

$$+ \frac{\overline{\Psi}\Psi\Phi^2}{\Lambda} + \frac{\overline{\Psi}\sigma^{\mu\nu}\Psi F_{\mu\nu}}{\Lambda} + \frac{\overline{\Psi}\Psi\overline{\Psi}\Psi}{\Lambda^2} + \frac{\Phi^2 F^{\mu\nu} F_{\mu\nu}}{\Lambda^2} + \ldots$$

$$(\Lambda^{n<0} \Rightarrow EW \ tests, \ \ flavour \ tests, \ \ \not{B}, \ \ \not{L}, \ \ \ldots)$$

Effective potential and running parameters

After including quantum corrections (in a suitable scheme)

$$V_{eff}(\phi) = \mu^2(Q^2)\ \phi^\dagger\phi + \lambda(Q^2)\ (\phi^\dagger\phi)^2 + \log - \mathrm{terms}$$

Leading effects absorbed into running parameters

$$\mu^2(Q^2) \quad \lambda(Q^2) \qquad Q = \mathrm{renormalization\ scale}$$

as long as the log-terms are small (Q of order v)

$$v^2 \simeq -\frac{\mu^2(v^2)}{\lambda(v^2)} \qquad m_h^2 \simeq 2\,\lambda(v^2)\,v^2 \qquad m_t^2 \simeq \frac{Y_t(v^2)\,v^2}{2}$$

Renormalization group equations:

$$\frac{d\lambda}{d\log Q^2} = \frac{3}{16\pi^2}[4\,\lambda^2 - Y_t^4 + 2\,\lambda\,Y_t^2 + \mathcal{O}(g^2)] \qquad \text{etc.}$$

Higgs mass vs. the scale of new physics

(Cabibbo, Maiani, Parisi, Petronzio 1979, …)

$$\frac{d\lambda}{d\log Q^2} = \frac{3}{16\pi^2}[4\,\lambda^2 - Y_t^4 + 2\,\lambda\, Y_t^2 + \mathcal{O}(g^2)]$$

The triviality bound (given m_t and Λ):

m_H too large $\Rightarrow$ $\lambda(Q)$ blows up (Landau pole) at $Q_0 < \Lambda$ $\Rightarrow$ upper bound on m_H for any given Λ. This leads to the well known constraints (supported by lattice calculations):

$m_H <$ 200 GeV if $\Lambda \sim M_P \longrightarrow m_H <$ 600 GeV if $\Lambda \sim$ 1 TeV

The stability bound (given m_t and Λ):

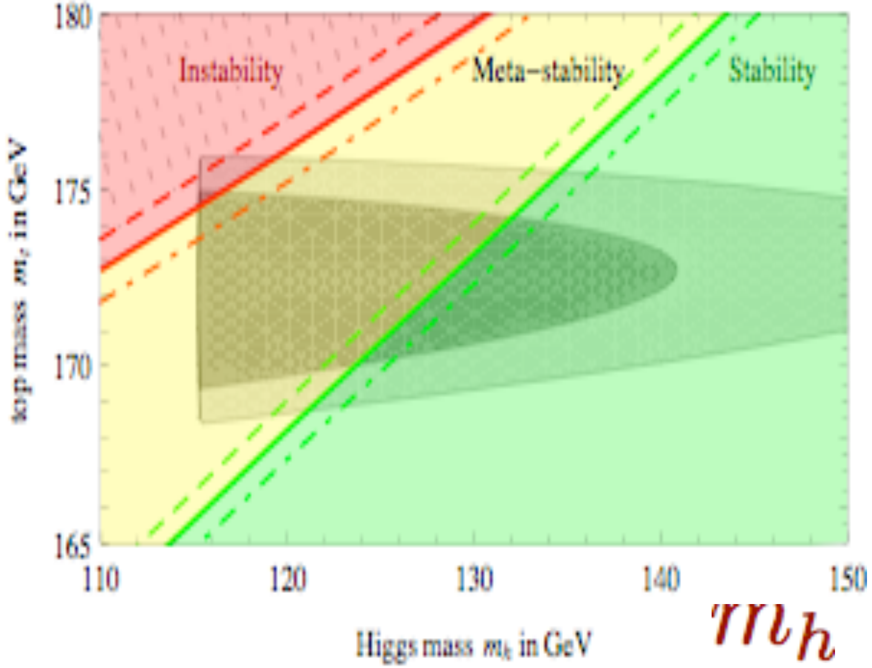
m_H too small $\Rightarrow$ $\lambda(Q)$ becomes negative at $Q_0 < \Lambda$

$\Rightarrow$ another minimum develops at $\langle\phi\rangle \sim Q_0$

$\Rightarrow$ lower bound on m_H for any given Λ.

Some illustrative pictures

m_t



m_h

$\Lambda = M_P$

$\alpha_s(m_Z) = 0.118 \pm 0.002$

(m_h, m_t) from (2007) EW fits

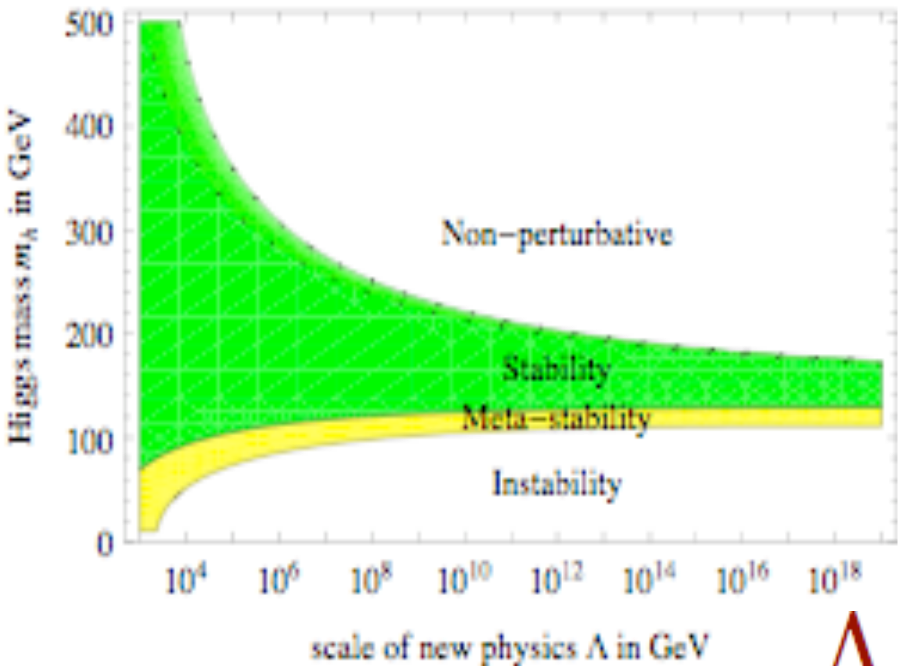
[Isidori-Rychkov-Strumia-Tetradis, 0712.0242 [hep-ph]]

$\lambda < 3\ (6)$

$m_t = 173\ GeV$

$\alpha_s(m_Z) = 0.118$

m_h



Λ

The SM as an effective theory, again

Λ = effective UV cutoff (not necessarily universal)
= the scale of some (unspecified) new physics

$$L_{eff}^{SM} = \Lambda^4 + \Lambda^2\Phi^2 \qquad (\Lambda^{n>0} \Rightarrow \textit{hierarchy problems!})$$

$$+ (D\Phi)^2 + \overline{\Psi}\,\not{D}\Psi + F\cdot F + F\cdot\widetilde{F} + \overline{\Psi}\Psi\Phi + \Phi^4$$

$$(\textit{controllable } \log\Lambda \textit{ dependence via quantum corrections})$$

$$+\frac{\overline{\Psi}\Psi\Phi^2}{\Lambda} + \frac{\overline{\Psi}\sigma^{\mu\nu}\Psi F_{\mu\nu}}{\Lambda} + \frac{\overline{\Psi}\Psi\overline{\Psi}\Psi}{\Lambda^2} + \frac{\Phi^2 F^{\mu\nu}F_{\mu\nu}}{\Lambda^2} + \ldots$$

$$(\Lambda^{n<0} \Rightarrow EW\ tests,\ \ flavour\ tests,\ \ \not{B},\ \ \not{L},\ \ \ldots)$$

Are there good reasons for/against $\Lambda \sim \text{TeV}$?

(the scale to be explored by the LHC experiments)

Lower bounds on the scale of new physics

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d \geq 5} \frac{c_n}{\Lambda^{d-4}} \, \mathcal{O}_n^{(d)}$$

The lower bounds on the NP scale depend on the dimensionless coefficients c_n and on the SM symmetries broken by the class of operators under consideration

SM gauge symmetry must always be respected (Higgsless effective theories in lecture 4)

Most conservative assumption: full SM flavour symmetry also respected by effective operators

$\Downarrow$

Lower bounds on NP scale from EW precision tests

Bounds vs. symmetries

- B number e.g. $\frac{c}{\Lambda^2} qqql$ (proton decay) $\Lambda > c^{1/2}\ 10^{15}$ GeV
- L number e.g. $\frac{c}{\Lambda} llhh$ (neutrino masses) $\Lambda \approx c\ 0.5\ 10^{15}$ GeV
- L_i numbers e.g. $\frac{c}{\Lambda^2} \mu^c \sigma^{\mu\nu} l_e F_{\mu\nu} h$ ($\mu \to e\gamma$) $\Lambda > c^{1/2}\ 10^{3}$ TeV

SM accidental symmetries

- Quark FCNC, CP e.g. $\frac{c}{\Lambda^2} \bar{s}\sigma^{\mu} d\, \bar{s}\sigma_{\mu} d$ (ε_K, Δm_K) $\Lambda > c^{1/2}$ 500 TeV SM: no tree level
- $\frac{c}{\Lambda^2} |h^{\dagger} D_{\mu} h|^2$, $\frac{c}{\Lambda^2} \bar{e}\sigma^{\mu} e\, \bar{e}_i \sigma_{\mu} e_i$ (EWPTs) $\Lambda > c^{1/2}$ 5 TeV

[transparency by Romanino]

EW precision tests vs. NP scale

SM with light Higgs in precise agreement with data

⬇

EW precision tests generically push for a high NP scale

$$\mathcal{L}_{eff}^{NP} = \frac{1}{\Lambda_{NP}^2}\left[c_1(\bar{e}\gamma^\mu e)^2 + c_2 W^I_{\mu\nu} B^{\mu\nu} H^\dagger \sigma^I H + \ldots\right]$$

Tree-level exchange of new particles with O(1) couplings

$$c_i = O(1) \quad \Rightarrow \quad \Lambda_{NP} > \text{several } TeV$$

Conflict avoided with weakly coupled NP
affecting low-energy observables only via loops
(and decoupled from flavour-violating operators)

$$c_i \sim \frac{\alpha}{2\pi} \quad and \quad \Lambda_{NP} \sim O(500)\ GeV$$

BSM parametrization of EW precision tests

If heavy new physics appears via vector-boson self-energies

$$\begin{aligned}\mathcal{L}_{NP} &= W_+^\mu \Pi_{+-}(q^2) W_{+\mu} + W_3^\mu \Pi_{33}(q^2) W_{3\mu} \\ &+ W_3^\mu \Pi_{3B}(q^2) B_\mu + B^\mu \Pi_{BB}(q^2) B_\mu\end{aligned}$$

(Zbb vertex separately)

Expanding in q^2, and absorbing trivial redefinitions of SM input parameters, there are 4 leading form factors:

Adimensional form factor	operator	effect
$(g'/g)\hat{S} = \Pi'_{W_3B}(0)$	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	correction to s_W
$M_W^2 \hat{T} = \Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)$	$\lvert H^\dagger D_\mu H\rvert^2$	correction to M_W/M_Z
$2M_W^{-2} Y = \Pi''_{BB}(0)$	$(\partial_\rho B_{\mu\nu})^2/2$	anomalous $g_1(E)$
$2M_W^{-2} W = \Pi''_{W_3W_3}(0)$	$(D_\rho W^a_{\mu\nu})^2/2$	anomalous $g_2(E)$

[Barbieri-Pomarol-Rattazzi-Strumia 04; table from Strumia]

Only S,T feel $SU(2)_L$ breaking, only T breaks custodial symmetry

Usefulness of general EW fits

Fit data once, can then compare quickly with models

Example: can we exclude a heavy SM-like Higgs?

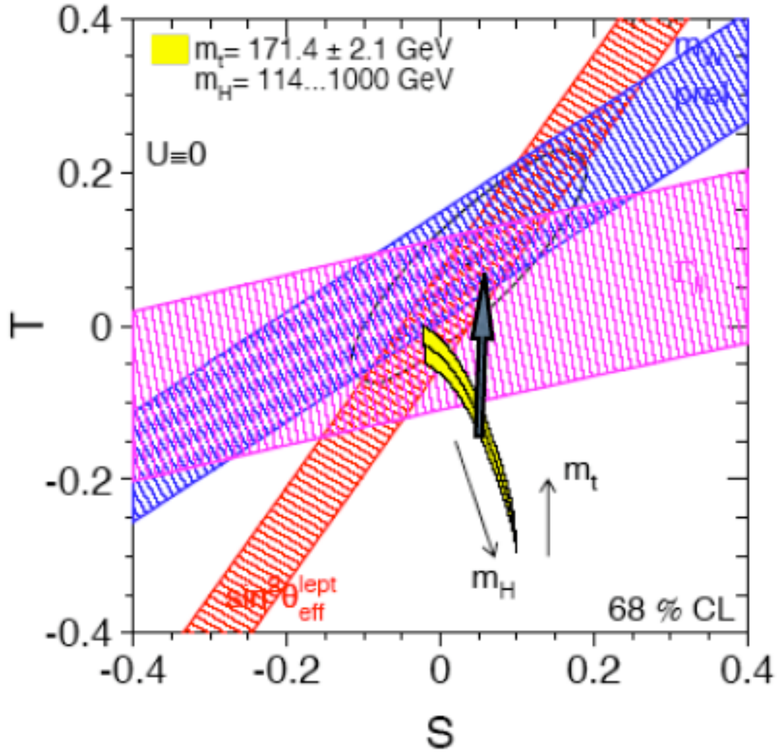
Beyond the SM, simple (but ad hoc) modifications
can reconcile precision tests with a heavier Higgs
(of course, effective SM cutoff must be low enough)

Pushing m_H up requires

$$\Delta T = 0.2 - 0.3 \quad \Delta S = small$$

Various possibilities explored:
[Peskin-Wells, Barbieri et al, …]

- A second "inert" doublet H_2
- SUSY with large NH_1H_2 coupling
- A (tuned) fourth generation
- New EW fermions



An example on the role of flavour [Isidori, LP07]

$$M(\mathrm{B_d}\text{-}\overline{\mathrm{B}}_\mathrm{d}) \sim \frac{(y_t V_{tb}^{*} V_{td})^2}{16\,\pi^2 M_W^{\,2}} + c_{NP}\,\frac{1}{\Lambda^2}$$

[similar structure in K-Kbar system]

c_{NP}:

$$\sim 1 \xrightarrow{\text{tree/strong + generic flavour}} \Lambda \gtrsim 2\times 10^4\ \text{TeV [K]}$$

$$\sim 1/(16\,\pi^2) \xrightarrow{\text{loop + generic flavour}} \Lambda \gtrsim 2\times 10^3\ \text{TeV [K]}$$

$$\sim (y_t V_{ti}^{*} V_{tj})^2 \xrightarrow{\text{tree/strong + MFV}} \Lambda \gtrsim 5\ \text{TeV [K \& B]}$$

$$\sim (y_t V_{ti}^{*} V_{tj})^2/(16\,\pi^2) \xrightarrow{\text{loop + MFV}} \Lambda \gtrsim 0.5\ \text{TeV [K \& B]}$$

MFV = flavour symmetry broken only by SM Yukawas

also BSM ➔ effective extension of GIM/CKM structure

The upper bound on the NP scale

comes by requiring naturalness [Wilson; ‘t Hooft; …]

coefficients small only because of symmetries

electron mass m_e in QED naturally small

chiral symmetry ➔ no linear dependence on cutoff

could have been used in NR theory to predict positron

$$\delta m_e \sim \alpha \Lambda \quad \rightarrow \quad \delta m_e \sim \alpha m_e \log \ldots$$

4-fermion FCNC “box diagram” with 3 light quarks

$$G_F^2 \Lambda^2 \sim G_F^2 m_W^2 \ \textit{too large!} \quad \rightarrow \quad G_F^2 m_c^2 \ \textit{OK}$$

Natural solution: GIM mechanism! New physics: charm!

Another example: charged/neutral pion mass difference

Naturalness works, we can take it seriously!

Naturalness problem of the SM

Higgs mass term (weak scale): gauge hierarchy problem

No quantum SM symmetry recovered for $m_H \rightarrow 0$

(scale invariance broken by quantum corrections and UV physics)

SM unnatural unless NP at the TeV scale

$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\,\pi^2}\Lambda^2 < O(m_H^2) \quad \rightarrow \quad \Lambda < O(600)\times\left(\frac{m_h}{200}\right)\ GeV$$

The lighter the Higgs, the lower the NP scale!

"Big" hierarchy problem for cutoff at M_P or M_{GUT}

Worse naturalness problem (when including gravity)

vacuum energy (10^{-3}eV scale): cosmological constant problem

No natural solution found so far, but not excluded either:

modifications of gravity at sub-mm scales still possible

even if bounds considerably improved in the last years

The "little" hierarchy problem

[as stressed, for example, by Barbieri-Strumia]

SM with light Higgs is in precise agreement with data

Naturalness pushes for a low NP scale

Precision tests (of both EW and flavour breaking) push for a high NP scale

The two requirements are difficult to reconcile: all simple models have some amount of fine-tuning, which can be tentatively quantified as follows:

$$\Lambda < 600\, GeV \times \left(\frac{m_h}{200\, GeV}\right) \times \frac{1}{\sqrt{\epsilon}}$$

where epsilon is the fine-tuning we allow between the top and other contributions to the Higgs squared mass

e.g.: NP at 6 TeV with m_h=200 GeV means a 1% fine-tuning

How to forbid a Higgs mass term $\mu^2|\varphi|^2$?

$\delta\varphi = \epsilon\,\varphi$

scale/conformal symmetry: SM-anomalous and likely not respected by UV physics

$\delta\varphi = \epsilon\, v$

shift symmetry

Higgs as (pseudo-)Goldstone boson: (forbids also Yukawa and quartic terms)

Higgs as a d>4 gauge field, with gauge symmetry protecting the vector mass

$\delta\varphi = \epsilon\cdot\psi$

Link to a fermionic field, with a chiral symmetry protecting the fermion mass

It is the case of SUPERSYMMETRY, discussed in lecture 3, while the alternative options will be discussed in lecture 4

BSM variations on SM Higgs searches

How could SM Higgs production/decay be altered?

Main mechanisms:

- New Higgs couplings to light enough exotic particles (if not excluded by direct searches or indirect constraints): not only new final states, also new virtual states in loops

- Modified tree-level couplings to SM particles, e.g. due to the mixing of the SM-like Higgs with other scalar states

Innumerable examples in extensions of the SM,
both supersymmetric and non-supersymmetric,
large number of possibilities to be kept in mind
detection can be easier or more difficult
Will see some cases in lectures 3 and 4

Hiding the Higgs at the LHC?

One can imagine "nasty" new physics, compatible with existing constraints even if not strongly motivated, that could make life much more difficult at the LHC

Simplest example:

[Wise et al, Wilczek et al, Grossman et al, …]

one real singlet scalar (or more) coupled to the SM only via a quartic mixing term in the Higgs potential

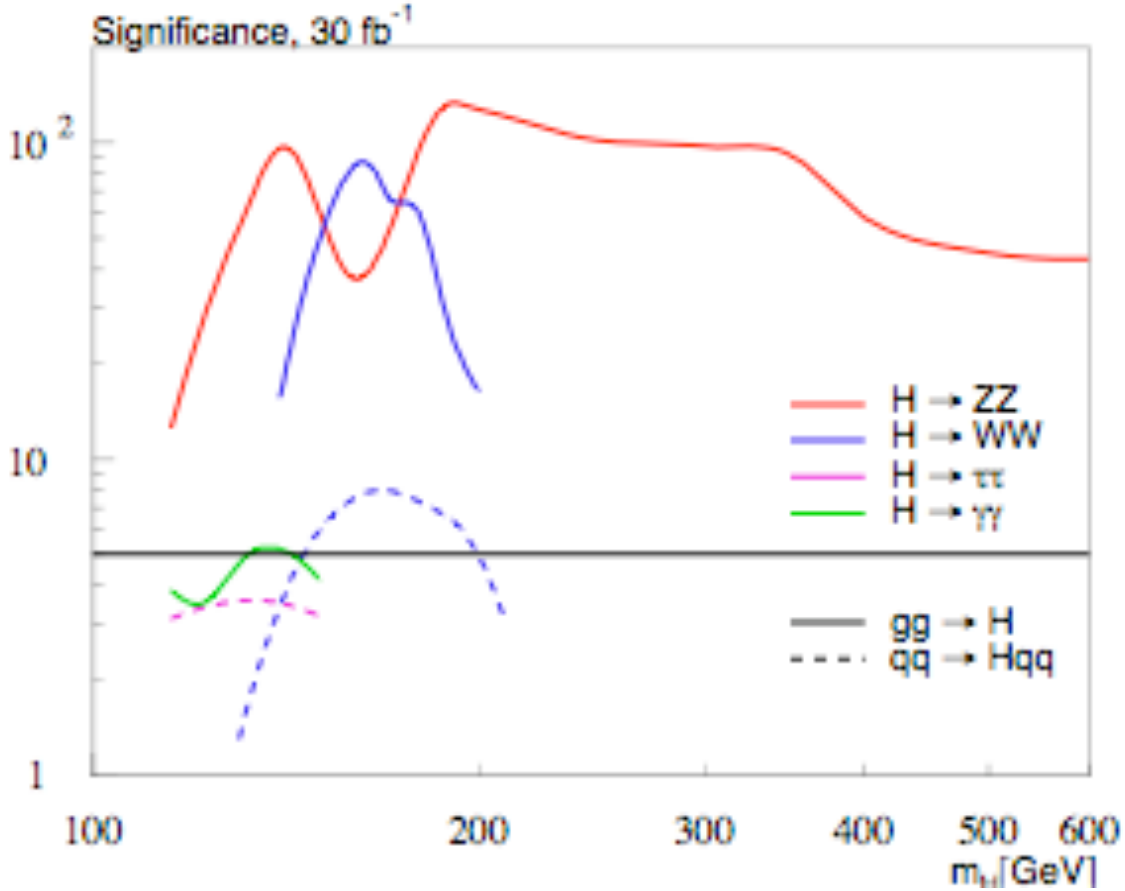
dilution of the SM Higgs signals via mixing and/or decays into invisible channels (a hidden sector)

"Subtle is the Lord, but not malicious…"

A stroke of luck at the LHC?

The counterpart of the previous examples of "nasty" new physics is some possible "lucky" new physics

e.g. a 4th generation increasing the Higgs signal
[Kribs-Plehn-Spannovsky-Tait 07]



Can be made compatible with EW precision tests (for a wider m_h range) by tuning the spectrum

Dramatic (loop) effects on Higgs physics: gold-plated signal 5-8 times the SM one (enhanced gg production)