Higgs Physics in the Standard Model with Four Chiral Generations

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Based on arXiv:1109.5140

The Standard Model

Gauge group:

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

Particle content:

QUARKS		LEPTONS		HIGGS	
Q	$(\mathbf{3},\mathbf{2})_{1/3}$	L	$(\mathbf{1},\mathbf{2})_{-1}$	H	$(\mathbf{1},\mathbf{2})_{-1}$
$\bar{u}$	$(\bar{\mathbf{3}},\mathbf{1})_{-4/3}$	$\bar{e}$	$(\mathbf{1},\mathbf{1})_{2}$		
$\bar{d}$	$(\bar{\mathbf{3}},\mathbf{1})_{2/3}$	$\bar{\nu}$	$(\mathbf{1},\mathbf{1})_{0}$		

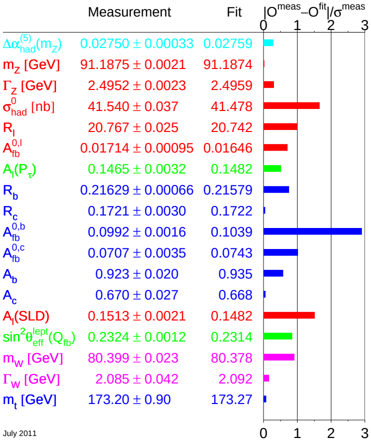
Parameters:

~~19 (massless neutrinos)~~, 26 (Dirac neutrinos), 28 (Majorana)

The Standard Model

Excellent agreement between theory and data

The LEP Electroweak Working Group, Plots for Summer 2011



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1039
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27

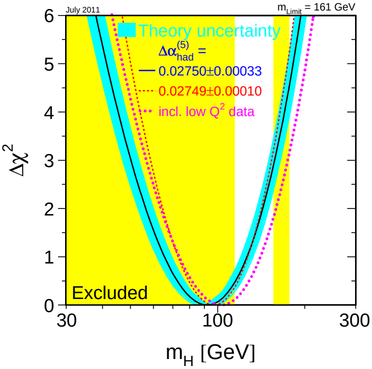
The Standard Model

But the Higgs makes people nervous . . .

Preferred $m_H = 92$ GeV, upper limit $m_H < 185$ GeV (95% C.L.)

LEP: $m_H > 114.4$ GeV (and recently LHC: $m_H < 145$ GeV)

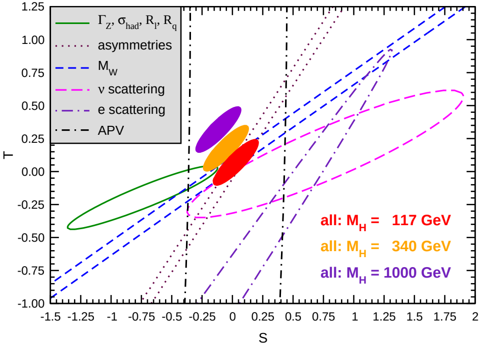
The LEP Electroweak Working Group, Plots for Summer 2011



Why a Fourth Generation?

Fourth generation masses can be chosen in such a way that S, T parameters are consistent with heavier Higgs, see e.g. Kribs et al. arXiv:0706.3718

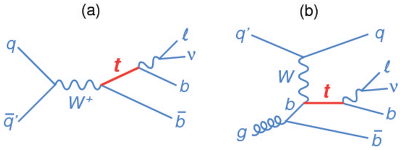
PDG Review Article by J. Erler and P. Langacker, "Electroweak model and constraints on new physics"



Why a Fourth Generation?

- Single top production
  DØ Collaboration, V. M. Abazov *et al.*, arXiv:0903.0850

$$\begin{aligned} |V_{tb}\, f_1^L| &= 1.07 \pm 0.12\,(\text{stat+syst}) \text{ assuming upper bound of } 1 \\ |V_{tb}| &> 0.78 \quad \text{@95\% C.L. with no assumptions} \end{aligned}$$



- $t\bar{t}$ production
  DØ Collaboration, V. M. Abazov *et al.*, hep-ex/0603002.

$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 1.03^{+0.19}_{-0.17}$$

Why a Fourth Generation?

- J. Alwall *et al.*, "Is V(tb) = 1?," *Eur. Phys. J.* **C49** (2007) 791–801, hep-ph/0607115.

  $|V_{tb}| = 1$ need not necessarily hold; $|V_{tb}| > 0.9$; constraints from R_b, $b \to s\gamma$, S, T

- M. Bobrowski, A. Lenz, J. Riedl, and J. Rohrwild, arXiv:0902.4883.

  Constraints from FCNCs and $b \to s\gamma$; small mixing of 3rd and 4th family favored, but sizable mixing $\theta_{34} \sim 42^\circ$ possible

- M. S. Chanowitz, arXiv:0904.3570.

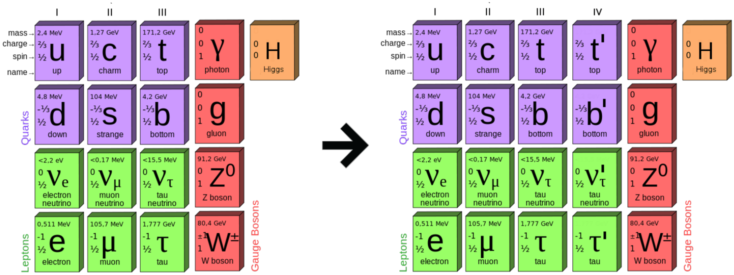
  Mixing can be as large as $\theta_{34} \sim 13^\circ$; main constraints come from S, T; large(r) mixing as suggested by Bobrowski et al. excluded

- Only sizable coupling of 4th generation is to 3rd generation:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad \begin{array}{ll} \leftarrow & \sum V_{uq}^2 \simeq 1 \\ \leftarrow & \sum V_{cq}^2 \simeq 1 \\ \leftarrow & \sum V_{tq}^2 \gtrsim 0.78 \end{array}$$

Why a Fourth Generation?

- Why not?
- $|V_{tb}| \neq 1$ is still a possibility
- Allows for heavier Higgs
- No explanation for number of generations in SM

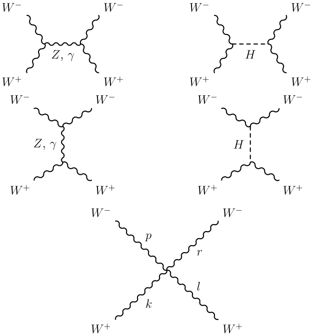


The Higgs Boson in the SM4

So how heavy can the Higgs boson be?

➢ Unitarity bound: $m_H \lesssim 1000$ GeV ?

B. W. Lee, C. Quigg, and H. Thacker, "The Strength of Weak Interactions at Very High-Energies and the Higgs Boson Mass," *Phys.Rev.Lett.* **38** (1977) 883–885.

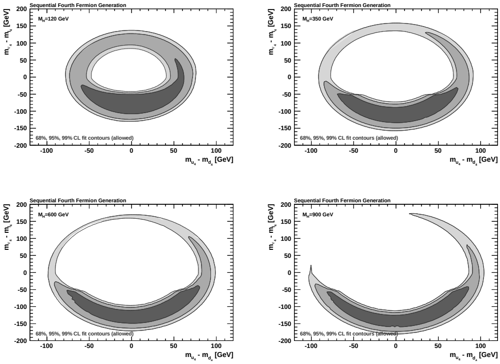


The Higgs Boson in the SM4

So how heavy can the Higgs boson be?

➢ Electroweak precision measurements: $m_H \lesssim 900$ GeV ?

`GFITTER Collaboration`, arXiv:1107.0975.

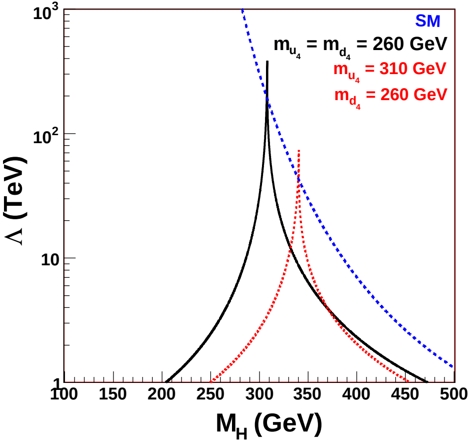


The Higgs Boson in the SM4

So how heavy can the Higgs boson be?

➢ Stability and triviality bounds: $m_H \lesssim 470$ GeV ?

Kribs et al. arXiv:0706.3718



Stability & Triviality Bound in the SM4

Stability

& Triviality

Stability & Triviality Bound in the SM4

We extend the stability & triviality analysis:

- Full 2-loop RGEs to run all SM parameters
- Include massive fourth generation neutrino
- 1-loop matching corrections for Higgs and top
- Non-zero mixing between the third and the fourth generation
- Constraints from the perturbativity of the Yukawa couplings

2-loop renormalization group equations

- Main reference for the RGEs

M. E. Machacek and M. T. Vaughn, “Two Loop Renormalization Group Equations in a General Quantum Field Theory. 1. Wave Function Renormalization,” *Nucl. Phys.* **B222** (1983) 83.

M. E. Machacek and M. T. Vaughn, “Two Loop Renormalization Group Equations in a General Quantum Field Theory. 2. Yukawa Couplings,” *Nucl. Phys.* **B236** (1984) 221.

M. E. Machacek and M. T. Vaughn, “Two Loop Renormalization Group Equations in a General Quantum Field Theory. 3. Scalar Quartic Couplings,” *Nucl. Phys.* **B249** (1985) 70.

- Some typos corrected

H. Arason, D. Castano, B. Keszthelyi, S. Mikaelian, E. Piard, *et al.*, “Renormalization group study of the standard model and its extensions. 1. The Standard model,” *Phys.Rev.* **D46** (1992) 3945–3965.

C. Ford, D. Jones, P. Stephenson, and M. Einhorn, “The Effective potential and the renormalization group,” *Nucl.Phys.* **B395** (1993) 17–34, `hep-lat/9210033`.

M.-x. Luo and Y. Xiao, “Two-loop renormalization group equations in the standard model,” *Phys. Rev. Lett.* **90** (2003) 011601, `hep-ph/0207271`.

- Neutrino masses included

Y. F. Pirogov and O. V. Zenin, “Two-loop renormalization group restrictions on the standard model and the fourth chiral family,” *Eur. Phys. J.* **C10** (1999) 629–638, `hep-ph/9808396`.

1-loop matching corrections for Higgs and top

$$\lambda(\mu) = \frac{m_H^2}{v^2}\left(1+\delta_H(\mu)\right)\Big|_{\mu=m_H}, \quad y_t(\mu) = \frac{\sqrt{2}m_t}{v}\left(1+\delta_t(\mu)\right)\Big|_{\mu=m_t}$$

- At tree-level: Relation between $\lambda \leftrightarrow m_H$ and $y_t \leftrightarrow m_t$
- At one-loop: Correction between $\overline{\mathrm{MS}}$ couplings and physical masses
- Input: $\lambda(M_Z)$, m_t $\quad\rightsquigarrow\quad$ Solve for: m_H, $y_t(M_Z)$
- Use $\lambda(M_Z)$, $y_t(M_Z)$ as boundary conditions for RGE
- We know physical Higgs mass from solution of equations
  Pole mass of top was already known from the start

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$$-\frac{12\log\left(c^2\right)c^4}{\xi}+\frac{12\log\left(\frac{\mu^2}{m_Z^2}\right)c^4}{\xi}+\frac{3\log\left(\frac{c^2m_Z^2}{\mu^2}\right)c^4}{c^2-\xi}-\frac{12Z\left(\frac{c^2}{\xi}\right)c^4}{\xi}+\frac{16c^4}{\xi}-\frac{14\log\left(c^2\right)c^2}{s^2}+28\log\left(c^2\right)c^2-\frac{3\xi\log\left(\frac{m_H^2}{\mu^2}\right)c^2}{c^2-\xi}-20\log\left(\frac{\mu^2}{m_Z^2}\right)c^2+4Z\left(\frac{c^2}{\xi}\right)c^2$$

$$-32c^2-17s^2-\frac{3m_{b'}^4V_{tb'}^2}{\left(m_t^2-m_{b'}^2\right)m_Z^2}+\frac{3m_t^4V_{tb'}^2}{\left(m_t^2-m_{b'}^2\right)m_Z^2}-\frac{3m_{b'}^4V_{t'b'}^2}{\left(m_{t'}^2-m_{b'}^2\right)m_Z^2}+\frac{3m_{t'}^4V_{t'b'}^2}{\left(m_{t'}^2-m_{b'}^2\right)m_Z^2}-\frac{3m_b^4V_{tb}^2}{\left(m_t^2-m_b^2\right)m_Z^2}+\frac{3m_t^4V_{tb}^2}{\left(m_t^2-m_b^2\right)m_Z^2}-\frac{3m_b^4V_{t'b}^2}{\left(m_{t'}^2-m_b^2\right)m_Z^2}+\frac{3m_{t'}^4V_{t'b}^2}{\left(m_{t'}^2-m_b^2\right)m_Z^2}$$

$$-\frac{m_{\tau'}^4U_{\tau'\nu'}^2}{\left(m_{\nu'}^2-m_{\tau'}^2\right)m_Z^2}+\frac{m_{\nu'}^4U_{\tau'\nu'}^2}{\left(m_{\nu'}^2-m_{\tau'}^2\right)m_Z^2}-\frac{3}{2}\sqrt{3}\pi\xi+\frac{25\xi}{2}+8s^2\log\left(c^2\right)-\xi\log\left(c^2\right)+\frac{17\log\left(c^2\right)}{s^2}-29\log\left(c^2\right)+\frac{6m_b^4V_{tb}^2\log\left(\frac{m_b^2}{\mu^2}\right)}{\left(m_t^2-m_b^2\right)m_Z^2}+\frac{6m_b^4V_{t'b}^2\log\left(\frac{m_b^2}{\mu^2}\right)}{\left(m_{t'}^2-m_b^2\right)m_Z^2}+\frac{6m_{b'}^4V_{tb'}^2\log\left(\frac{m_{b'}^2}{\mu^2}\right)}{\left(m_t^2-m_{b'}^2\right)m_Z^2}$$

$$+\frac{6m_{b'}^4V_{t'b'}^2\log\left(\frac{m_{b'}^2}{\mu^2}\right)}{\left(m_{t'}^2-m_{b'}^2\right)m_Z^2}+\frac{2m_{\tau'}^4U_{\tau'\nu'}^2\log\left(\frac{m_{\tau'}^2}{\mu^2}\right)}{\left(m_{\nu'}^2-m_{\tau'}^2\right)m_Z^2}+6\xi\log\left(\frac{\mu^2}{m_H^2}\right)-\frac{6m_t^4V_{tb'}^2\log\left(\frac{m_t^2}{\mu^2}\right)}{\left(m_t^2-m_{b'}^2\right)m_Z^2}-\frac{6m_t^4V_{tb}^2\log\left(\frac{m_t^2}{\mu^2}\right)}{\left(m_t^2-m_b^2\right)m_Z^2}-\frac{6m_{t'}^4V_{t'b'}^2\log\left(\frac{m_{t'}^2}{\mu^2}\right)}{\left(m_{t'}^2-m_{b'}^2\right)m_Z^2}-\frac{6m_{t'}^4V_{t'b}^2\log\left(\frac{m_{t'}^2}{\mu^2}\right)}{\left(m_{t'}^2-m_b^2\right)m_Z^2}$$

$$-\frac{2m_{\nu'}^4U_{\tau'\nu'}^2\log\left(\frac{m_{\nu'}^2}{\mu^2}\right)}{\left(m_{\nu'}^2-m_{\tau'}^2\right)m_Z^2}-\frac{24m_{b'}^4\log\left(\frac{\mu^2}{m_Z^2}\right)}{m_Z^4\xi}-\frac{8m_{\tau'}^4\log\left(\frac{\mu^2}{m_Z^2}\right)}{m_Z^4\xi}-\frac{24m_t^4\log\left(\frac{\mu^2}{m_Z^2}\right)}{m_Z^4\xi}-\frac{24m_{t'}^4\log\left(\frac{\mu^2}{m_Z^2}\right)}{m_Z^4\xi}-\frac{8m_{\nu'}^4\log\left(\frac{\mu^2}{m_Z^2}\right)}{m_Z^4\xi}+\frac{6\log\left(\frac{\mu^2}{m_Z^2}\right)}{\xi}+\frac{6m_{b'}^2\log\left(\frac{\mu^2}{m_Z^2}\right)}{m_Z^2}$$

$$+\frac{2m_{\tau'}^2\log\left(\frac{\mu^2}{m_Z^2}\right)}{m_Z^2}+\frac{6m_t^2\log\left(\frac{\mu^2}{m_Z^2}\right)}{m_Z^2}+\frac{6m_{t'}^2\log\left(\frac{\mu^2}{m_Z^2}\right)}{m_Z^2}+\frac{2m_{\nu'}^2\log\left(\frac{\mu^2}{m_Z^2}\right)}{m_Z^2}-2\log\left(\frac{\mu^2}{m_Z^2}\right)+\frac{24m_{b'}^4\log\left(\frac{m_{b'}^2}{m_Z^2}\right)}{m_Z^4\xi}-\frac{6m_{b'}^2\log\left(\frac{m_{b'}^2}{m_Z^2}\right)}{m_Z^2}+\frac{8m_{\tau'}^4\log\left(\frac{m_{\tau'}^2}{m_Z^2}\right)}{m_Z^4\xi}-\frac{2m_{\tau'}^2\log\left(\frac{m_{\tau'}^2}{m_Z^2}\right)}{m_Z^2}$$

$$+\frac{24m_t^4\log\left(\frac{m_t^2}{m_Z^2}\right)}{m_Z^4\xi}-\frac{6m_t^2\log\left(\frac{m_t^2}{m_Z^2}\right)}{m_Z^2}+\frac{24m_{t'}^4\log\left(\frac{m_{t'}^2}{m_Z^2}\right)}{m_Z^4\xi}-\frac{6m_{t'}^2\log\left(\frac{m_{t'}^2}{m_Z^2}\right)}{m_Z^2}+\frac{8m_{\nu'}^4\log\left(\frac{m_{\nu'}^2}{m_Z^2}\right)}{m_Z^4\xi}-\frac{2m_{\nu'}^2\log\left(\frac{m_{\nu'}^2}{m_Z^2}\right)}{m_Z^2}+11s^2\log\left(\frac{c^2m_Z^2}{\mu^2}\right)-7\log\left(\frac{c^2m_Z^2}{\mu^2}\right)+\frac{3}{2}\xi\log(\xi)$$

$$-\frac{1}{2}\xi Z\left(\frac{1}{\xi}\right)-\frac{6Z\left(\frac{1}{\xi}\right)}{\xi}+2Z\left(\frac{1}{\xi}\right)-\xi Z\left(\frac{c^2}{\xi}\right)+\frac{24m_{b'}^4Z\left(\frac{m_{b'}^2}{m_Z^2\xi}\right)}{m_Z^4\xi}-\frac{6m_{b'}^2Z\left(\frac{m_{b'}^2}{m_Z^2\xi}\right)}{m_Z^2}+\frac{8m_{\tau'}^4Z\left(\frac{m_{\tau'}^2}{m_Z^2\xi}\right)}{m_Z^4\xi}-\frac{2m_{\tau'}^2Z\left(\frac{m_{\tau'}^2}{m_Z^2\xi}\right)}{m_Z^2}+\frac{24m_t^4Z\left(\frac{m_t^2}{m_Z^2\xi}\right)}{m_Z^4\xi}-\frac{6m_t^2Z\left(\frac{m_t^2}{m_Z^2\xi}\right)}{m_Z^2}$$

$$+\frac{24m_{t'}^4Z\left(\frac{m_{t'}^2}{m_Z^2\xi}\right)}{m_Z^4\xi}-\frac{6m_{t'}^2Z\left(\frac{m_{t'}^2}{m_Z^2\xi}\right)}{m_Z^2}+\frac{8m_{\nu'}^4Z\left(\frac{m_{\nu'}^2}{m_Z^2\xi}\right)}{m_Z^4\xi}-\frac{2m_{\nu'}^2Z\left(\frac{m_{\nu'}^2}{m_Z^2\xi}\right)}{m_Z^2}-\frac{48m_{b'}^4}{m_Z^4\xi}-\frac{16m_{\tau'}^4}{m_Z^4\xi}-\frac{48m_t^4}{m_Z^4\xi}-\frac{48m_{t'}^4}{m_Z^4\xi}-\frac{16m_{\nu'}^4}{m_Z^4\xi}+\frac{8}{\xi}+\frac{12m_{b'}^2}{m_Z^2}+\frac{4m_{\tau'}^2}{m_Z^2}+\frac{12m_t^2}{m_Z^2}+\frac{12m_{t'}^2}{m_Z^2}+\frac{4m_{\nu'}^2}{m_Z^2}+\frac{19}{2}$$

Stability

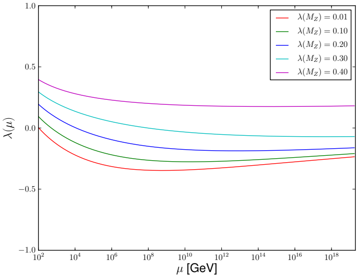
- Require that effective potential not become unbounded from below

  N. Cabibbo, L. Maiani, G. Parisi, and R. Petronzio, "Bounds on the Fermions and Higgs Boson Masses in Grand Unified Theories," *Nucl.Phys.* **B158** (1979) 295–305

- Well-approximated by criterion that quartic Higgs coupling λ not become negative anywhere

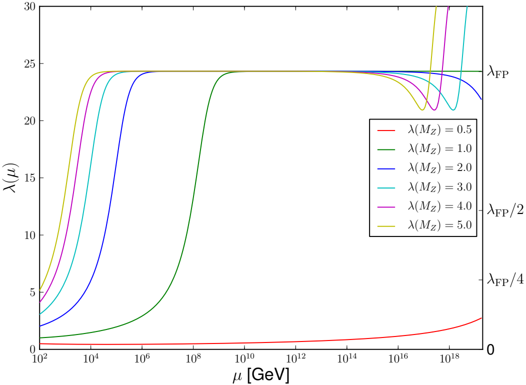
  G. Altarelli and G. Isidori, "Lower limit on the Higgs mass in the standard model: An Update," *Phys.Lett.* **B337** (1994) 141–144

  J. A. Casas, J. R. Espinosa, and M. Quiros, "Standard Model stability bounds for new physics within LHC reach," *Phys. Lett.* **B382** (1996) 374–382



Triviality

- At 1-loop: Higgs coupling $\lambda \to \infty$ for renormalization scale $\mu \to \infty$
- At 2-loop: Higgs coupling $\lambda \to \lambda_{\mathrm{FP}}$ (fixed point)
- Criterion for perturbativity: $\lambda < \lambda_{\mathrm{FP}}/4$ (tight) or $\lambda < \lambda_{\mathrm{FP}}/2$ (loose)



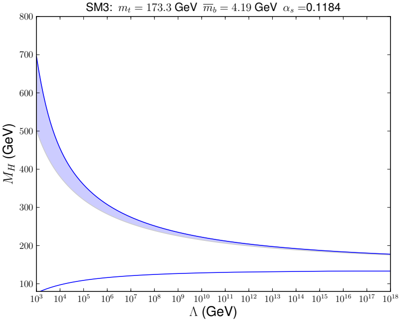
Higgs Mass Bounds in the Standard Model

- Stability & triviality curves for the Standard Model
- Higgs exclusion from LHC and electroweak precision measurements
- Onset of new physics

$m_H > 133$ GeV ↔ $\Lambda = \infty$,

$m_H = 130$ GeV ↔ $\Lambda = 1.2 \times 10^{11}$ GeV, $m_H = 125$ GeV ↔ $\Lambda = 1.7 \times 10^{8}$ GeV

$m_H = 120$ GeV ↔ $\Lambda = 5.9 \times 10^{6}$ GeV, $m_H = 115$ GeV ↔ $\Lambda = 650$ TeV



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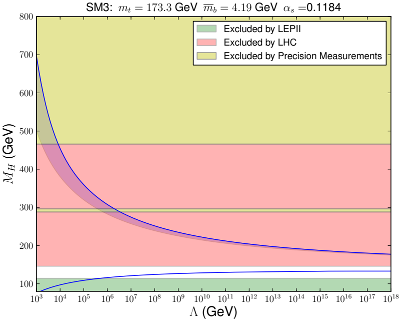
$m_H = 120$ GeV $\leftrightarrow \Lambda = 5.9 \times 10^{6}$ GeV, $m_H = 115$ GeV $\leftrightarrow \Lambda = 650$ TeV



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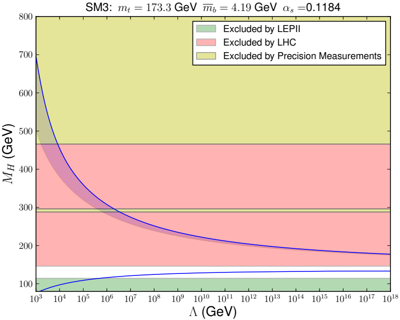
$m_H > 133 \text{ GeV} \leftrightarrow \Lambda = \infty,$

$m_H = 130 \text{ GeV} \leftrightarrow \Lambda = 1.2 \times 10^{11} \text{ GeV},$ $m_H = 125 \text{ GeV} \leftrightarrow \Lambda = 1.7 \times 10^{8} \text{ GeV}$

$m_H = 120 \text{ GeV} \leftrightarrow \Lambda = 5.9 \times 10^{6} \text{ GeV},$ $m_H = 115 \text{ GeV} \leftrightarrow \Lambda = 650 \text{ TeV}$



Higgs Mass Bounds in the Standard Model

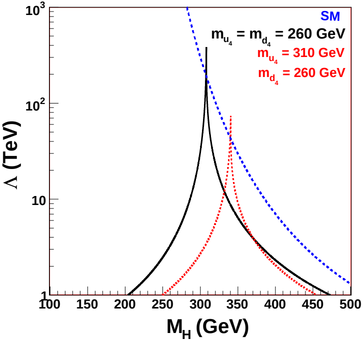
Nota bene:

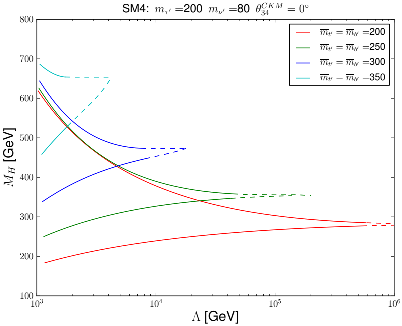
- Conclusions only valid in framework of SM
- New particles at low scale?
- More than one Higgs doublet?
- Vacuum metastable?
- Perturbativity lost, so what! Condensates?
- Non-exhaustive list . . .

Comparison with 1-loop Case

- ➢ $m_{t'} = m_{b'} \simeq 250$ GeV: $\Lambda \simeq 300$ TeV ↔ $\Lambda \simeq 200$ or $\Lambda \simeq 40$ TeV

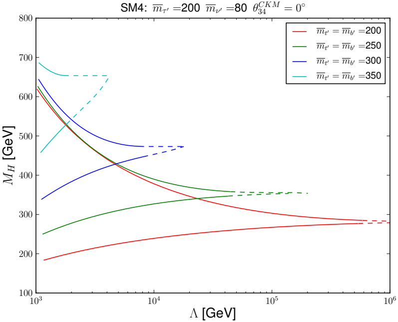
Kribs et al. arXiv:0706.3718





Higgs Bounds in the SM4

- Dependence on quark mass scale, $m_{b'}$, $m_{\tau'}$, $m_{\nu'}$, quark mixing
- Conclusion 1: Strong dependence on quarks, weak dependence on leptons, mixing negligible for angles allowed by EWP data
- Conclusion 2: Yukawas become non-perturbative $m_{q,\ell} \sim 400$ GeV
- Conclusion 3: $200 < m_H < 700$ GeV for all quark and lepton masses



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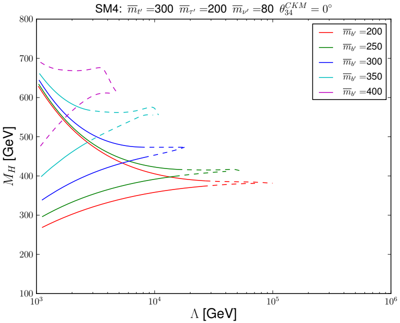

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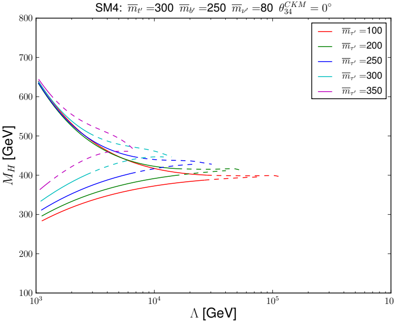

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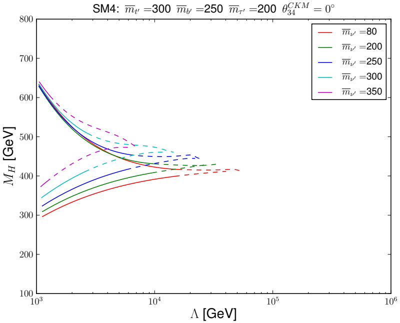

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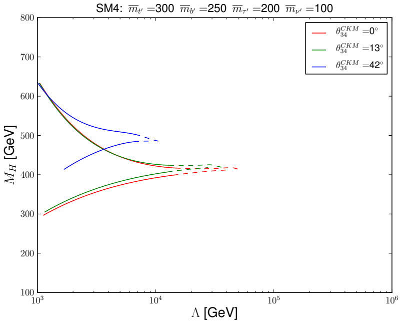

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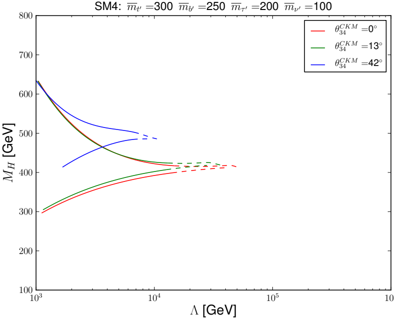

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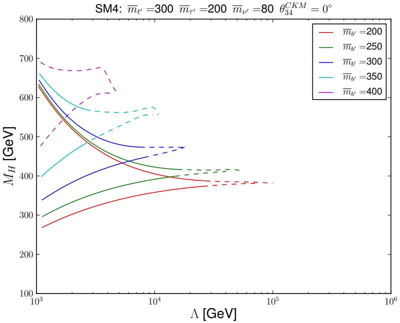

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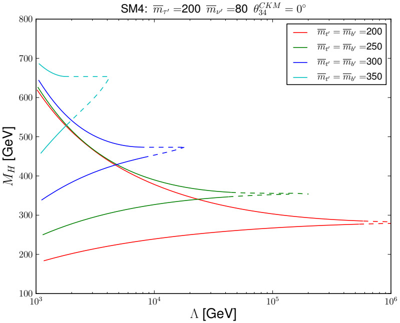
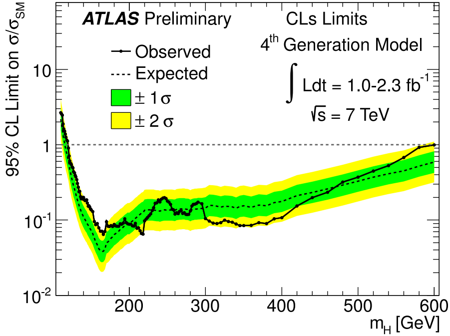


Fermion Mass Limits From Theory

- Higgs in SM4 excluded for $120 < m_H < 600$ GeV
- Turn argument around:
  $m_H > 600$ GeV $\rightsquigarrow$ $m_{t'}, m_{b'} > 300$ GeV and $m_{\tau'}, m_{\nu'} > 350$ GeV
- Excluding $m_H < 700$ GeV kills fourth generation w/perturbative couplings

ATLAS Collaboration, CONF-2011-135, 2011.



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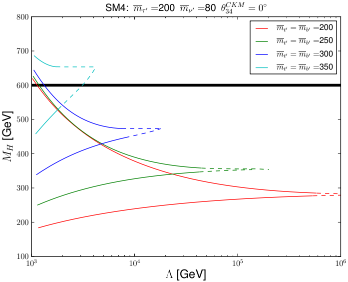

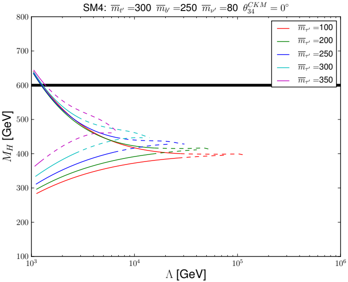

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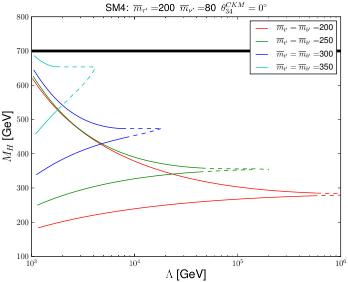

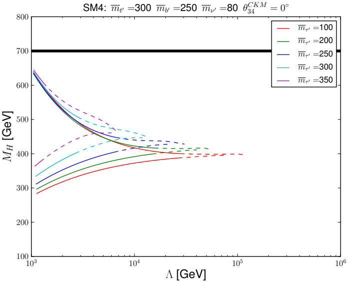

Collider Limits on Fourth Generation Masses

- Limits from theory & experiment

$\overline{m}_{t'} > 300$,	$\overline{m}_{b'} > 300$,	$\overline{m}_{\tau'} > 350$,	$\overline{m}_{\nu'} > 350$	Theory
$m_{t'} > 358$,	$m_{b'} > 372$,	$m_{\tau'} > 100.8$,	$m_{\nu'} > 80.5$	Tevatron, LEP
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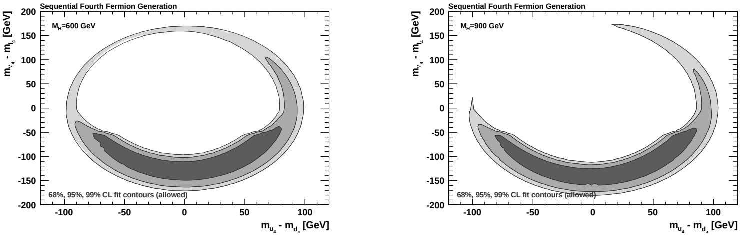
CDF Collaboration, T. Aaltonen *et al.*, (2011) 1107.3875.

Assumes $t' \longrightarrow Wb$, Ws, Wd, **but does not consider** $t' \longrightarrow Wb'$

"…small mass splitting preferred …such that $m_{b'} + M_W > m_{t'}$"

`GFITTER Collaboration`, arXiv:1107.0975.



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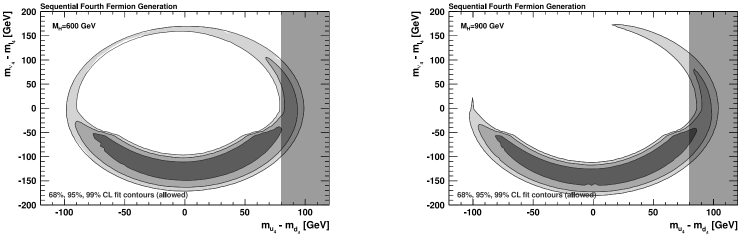

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- Limit on b' mass

CDF Collaboration, T. Aaltonen *et al.*, *Phys. Rev. Lett.* **106** (2011) 141803, `1101.5728`.

Assumes branching ratio for $b' \longrightarrow Wt$ to be 100%

C. J. Flacco, D. Whiteson, T. M. Tait, and S. Bar-Shalom, "Direct Mass Limits for Chiral Fourth-Generation Quarks in All Mixing Scenarios," *Phys.Rev.Lett.* **105** (2010) 111801, `1005.1077`.

Bounds on $m_{b'}$ can be weakened by 10-20%

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- Most recent limits on t' and b' masses from CMS

CMS Collaboration, `CMS-PAS-EXO-11-054`.

Assumes that t' and b' are degenerate in mass

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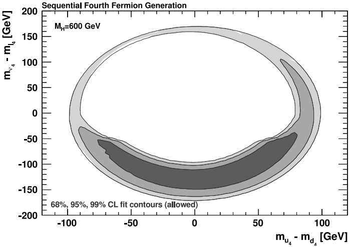

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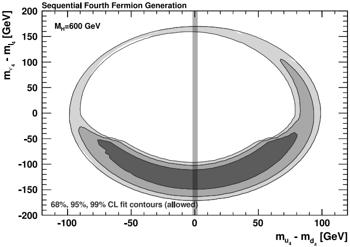

Conclusions

- Derived Higgs mass bounds from stability & triviality
    - Higgs is between 200 and 700 GeV
    - Large difference between 1-loop and 2-loop analyses
    - Stronger bounds than from unitarity, EWP measurements
- Bounds on Higgs imply bounds on fourth generation fermions
    - Quark bounds are competitive with Tevatron limits
    - Lepton bounds are stronger than collider limits
    - Excluding Higgs lighter than 700 GeV kills fourth generation
- Assumptions in fourth generation quark searches need to be critically reviewed