65 GeV Top Quark

47th SLAC Summer Institute Project

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August 22, 2019

Prompt

Imagine a hypothetical scenario where the top quark mass was 65 GeV while all other SM parameters are the same as they actually are.

- What observations would be affected directly or indirectly and to what extent they would differ?
- How the affected experimental programs would have adjusted their approaches?

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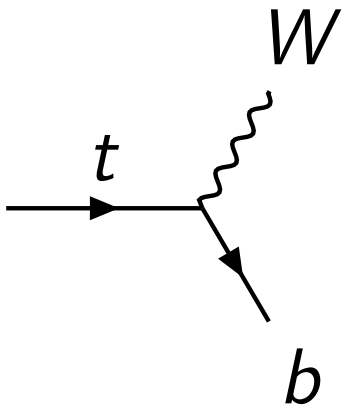
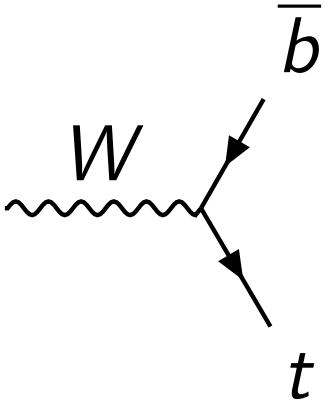
New top quark properties

- decay channel $t \to W^+ b$ no longer available
- t decay width decreases, lifetime *increases* - no longer decays before hadronization can occur
- top hadrons!

W boson and top quark





$$m_t = 173\,\text{GeV}$$
$$m_b = 4.18\,\text{GeV}$$
$$M_W = 80.4\,\text{GeV}$$

$$m_t = 65\,\text{GeV}$$
$$m_b = 4.18\,\text{GeV}$$
$$M_W = 80.4\,\text{GeV}$$

W boson and top quark

- $\frac{-g}{\sqrt{2}} \left(\overline{u_L}, \overline{c_L}, \overline{t_L}\right) \gamma^\mu W_\mu^+ V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$
- $W^+ \to t\bar{b}$ would likely be the dominant decay ($V_{tb} > V_{cs}$)
- W decay width increases, lifetime *decreases*
  - Using $V_{tb} \approx 0.99$ and $V_{cs} \approx 0.97$, can calculate roughly how branching ratios would change

W boson decay modes

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	(10.86 ± 0.09) %	
Γ_2	$e^+\nu$		(10.71 ± 0.16) %	
Γ_3	$\mu^+\nu$		(10.63 ± 0.15) %	
Γ_4	$\tau^+\nu$		(11.38 ± 0.21) %	
Γ_5	hadrons		(67.41 ± 0.27) %	
Γ_6	$\pi^+\gamma$		$< 7 \times 10^{-6}$	95%
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	95%
Γ_8	cX		(33.3 ± 2.6) %	
Γ_9	$c\overline{s}$		$(31 \; {}^{+13}_{-11})$ %	
Γ_{10}	invisible	[b]	(1.4 ± 2.9) %	

[a] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[b] This represents the width for the decay of the W boson into a charged particle with momentum below detectability, p$<$ 200 MeV.

New W boson decay modes

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	~~(10.86 ± 0.09) %~~	8%
Γ_2	$e^+\nu$		~~(10.71 ± 0.16) %~~	8%
Γ_3	$\mu^+\nu$		~~(10.63 ± 0.15) %~~	8%
Γ_4	$\tau^+\nu$		~~(11.38 ± 0.21) %~~	9%
Γ_5	hadrons		~~(67.41 ± 0.27) %~~	
Γ_6	$\pi^+\gamma$		~~$< 7 \times 10^{-6}$~~	95%
Γ_7	$D_s^+\gamma$		~~$< 1.3 \times 10^{-3}$~~	95%
Γ_8	cX		~~(33.3 ± 2.6) %~~	
Γ_9	$c\bar{s}$		~~(31^{+13}_{-11}) %~~	23%
Γ_{10}	invisible	[b]	~~(1.4 ± 2.9) %~~	
	$t\,\bar{b}$		24%	

[a] ... er them.

[b] This represents the width for the decay of the W boson into a charged particle with momentum below detectability, p< 200 MeV.

t quark decay modes

t DECAY MODES

	Mode		Fraction (Γ_i/Γ)		Confidence level
Γ_1	$t \to W q (q = b, s, d)$				
Γ_2	$t \to W b$				
Γ_3	$t \to e \nu_e b$		(13.3 ± 0.6) %		
Γ_4	$t \to \mu \nu_\mu b$		(13.4 ± 0.6) %		
Γ_5	$t \to \tau \nu_\tau b$		(7.1 ± 0.6) %		
Γ_6	$t \to q \overline{q} b$		(66.5 ± 1.4) %		
Γ_7	$t \to \gamma q (q=u,c)$		[a]		
Γ_8	$t \to H^+ b,\ H^+ \to \tau \nu_\tau$				
	$\Delta T = 1$ weak neutral current ($T1$) modes				
Γ_9	$t \to Z q (q=u,c)$	$T1$	[b] < 5	$\times 10^{-4}$	95%
Γ_{10}	$t \to H u$	$T1$	< 1.9	$\times 10^{-3}$	95%
Γ_{11}	$t \to H c$	$T1$	< 1.6	$\times 10^{-3}$	95%
Γ_{12}	$t \to \ell^+ \overline{q} \overline{q}' (q=d,s,b;\ q'=u,c)$	$T1$	< 1.6	$\times 10^{-3}$	95%

[a] This limit is for $\Gamma(t \to \gamma q)/\Gamma(t \to W b)$.

[b] This limit is for $\Gamma(t \to Z q)/\Gamma(t \to W b)$.

New t quark decay modes

t DECAY MODES

	Mode		Fraction (Γ_i/Γ)		Confidence level
Γ_1	$t \to W q (q = b, s, d)$				
Γ_2	$t \to W b$				
Γ_3	$t \to e \nu_e b$		(13.3 ± 0.6) %		
Γ_4	$t \to \mu \nu_\mu b$		(13.4 ± 0.6) %		
Γ_5	$t \to \tau \nu_\tau b$		(7.1 ± 0.6) %		
Γ_6	$t \to q \overline{q} b$		(66.5 ± 1.4) %		
Γ_7	$t \to \gamma q (q{=}u,c)$		[a]		
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[a] This limit is for $\Gamma(t \to \gamma q)/\Gamma(t \to W b)$.

[b] This limit is for $\Gamma(t \to Z q)/\Gamma(t \to W b)$.

Top hadrons

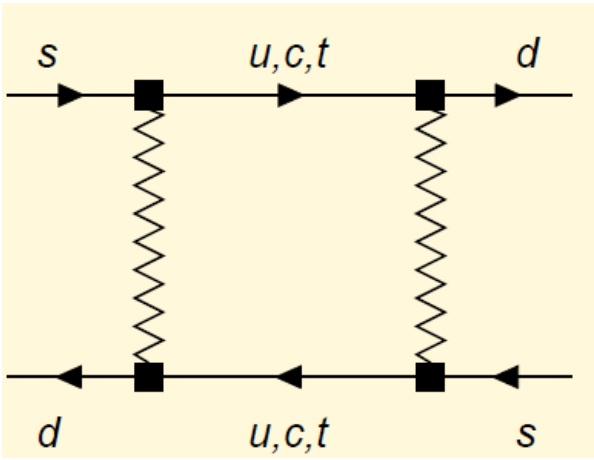
- top quark would form baryons and mesons like other quarks
- we are not going to discuss about the numerous top baryons and their properties
- the top mesons would decay like other mesons:
  - lighter mesons (B, D, K, π)
  - leptons ($\ell + \nu_\ell$)
  - γ
- top mesons might oscillate - c would no longer be the only up-type quark sector where CPV could be studied

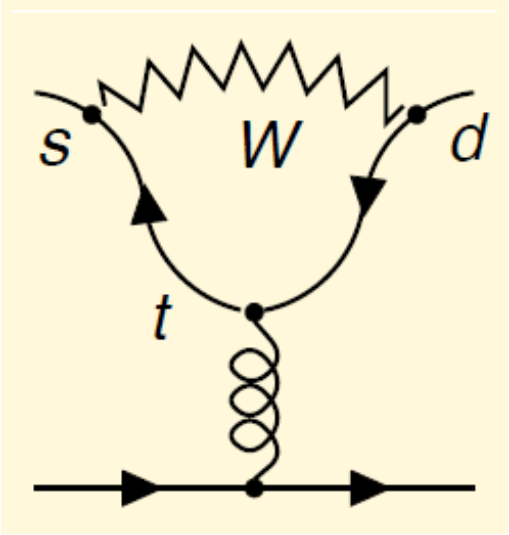
Table of T mesons

symbol	quark content	I^G	J^{PC}	S	C	B'	T	rest mass $[GeV/c^2]$
T^+	$t\bar{d}$	½	0^-	0	0	0	+1	~65
T^-	$\bar{t}d$	½	0^-	0	0	0	-1	~65
T^0	$t\bar{u}$	½	0^-	0	0	0	+1	~65
$\overline{T}^0$	$\bar{t}u$	½	0^-	0	0	0	-1	~65
T_s^+	$t\bar{s}$	0	0^-	+1	0	0	+1	~65
T_s^-	$\bar{t}s$	0	0^-	-1	0	0	-1	~65
T_c^0	$t\bar{c}$	0	0^-	0	-1	0	+1	~66
$\overline{T}_c^0$	$\bar{t}c$	0	0^-	0	+1	0	-1	~66
T_b^+	$t\bar{b}$	0	0^-	0	0	+1	+1	~69
T_b^-	$\bar{t}b$	0	0^-	0	0	-1	-1	~69
θ	$t\bar{t}$	0^+	0^{-+}	0	0	0	0	~130

Flavor Changing Neutral Current (FCNC)

- Flavor Changing Neutral Current (FCNC) are sensitive to top quark
- both box diagram (mixing) and penguin diagram (decay) are affected
- GIM suppression amplified because top quark mass closer to other quarks masses





[image credit: Ulrich Nierste, SSI 2019 lecture]

B meson mixing

Example: Mass difference between B^0 and $\overline{B}^0$:

$$\Delta m_B = 2\frac{G_F^2 m_W^2 \eta_B m_B B_B f_B^2}{12\pi^2} S_0\left(m_t^2/m_W^2\right)\left(V_{td}^* V_{tb}\right)$$

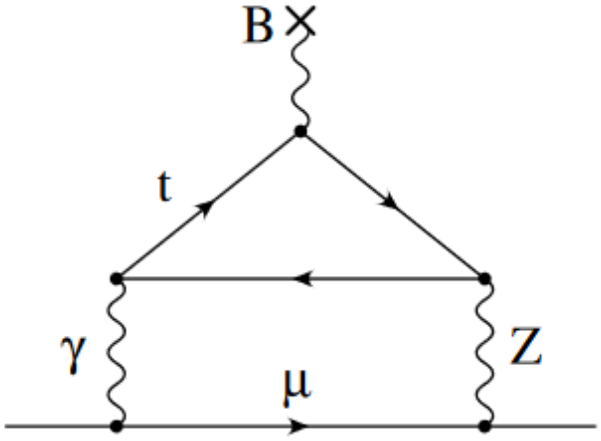
where $S_0(x_t) \approx 0.784 x_t^{0.76}$

Current value: $\Delta m_B = 0.5064 \pm 0.0019\ ps^{-1}$
New value: $\Delta m_B \approx 0.114\ ps^{-1}$

[reference: M. Tanabashi et al. (Particle Data Group), *Phys. Rev. D* **98**, 030001 (2018).]

Impact on other processes

- top loop contribution to muon g-2
- Mixing and decay of Kaons, similar to B mesons
- multiple other processes involving top quark loops (usually neglected)



Discovery of the top quark

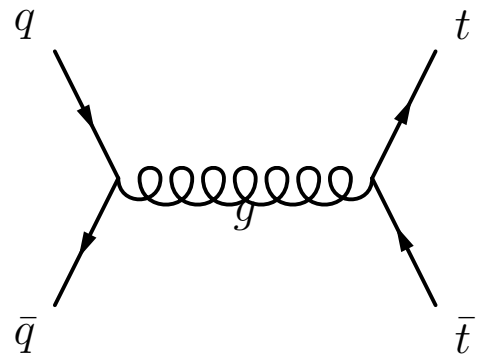
- 1973: t quark first postulated in famous Kobayashi and Maskawa paper
- 1977: b quark discovered
- 1983: W and Z bosons discovered

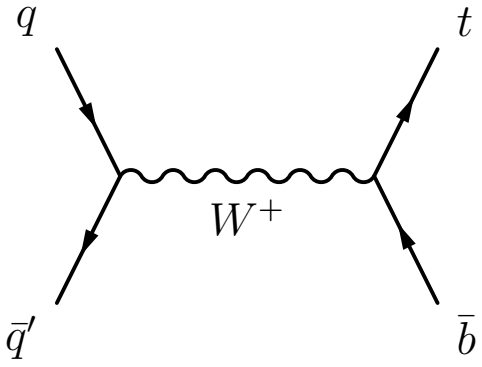
- 1991: Discovery of 65 GeV t quark at CDF
- 2012: Higgs boson discovered

- 1995: t quark discovered at 173 GeV
- ?: Higgs boson discovered

top production at the Tevatron

- Two production mode of the top at the Tevatron:





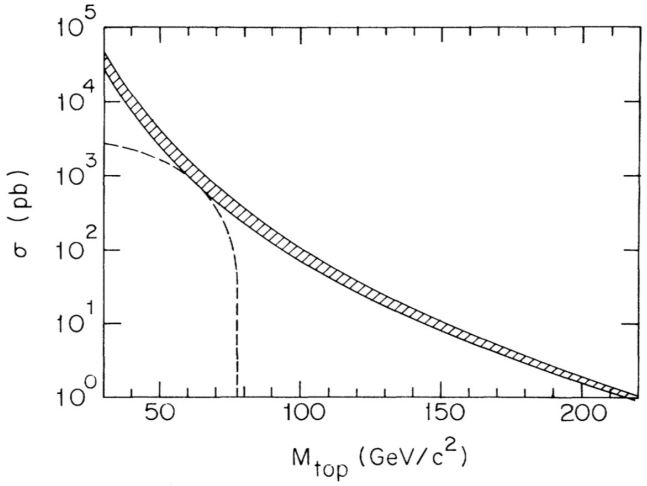


FIG. 1. Cross section for top-quark production in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. The solid curve is for $t\bar{t}$ pair production and the dashed curve is for $W \to t\bar{b}$. The two curves for the $t\bar{t}$ pair-production cross section represent the upper and lower bounds on the theoretical calculation as estimated in Ref. 7.

[image credit: CDF Collaboration (1991)]

Discovery of the top at CDF

- By 1991, CDF took $4.4\,\mathrm{pb}^{-1}$ of data at $\sqrt{s} = 1.8\,\mathrm{TeV}$. Using this data, top mass from 40 - 77 GeV was excluded.
- Estimated significance for 65 GeV top:
  $\sigma = \frac{s}{\sqrt{s+b}} \sim \frac{55}{\sqrt{55+65}} \sim 5.02 \Rightarrow$ DISCOVERY!

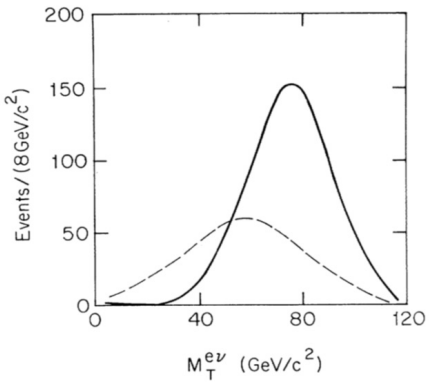
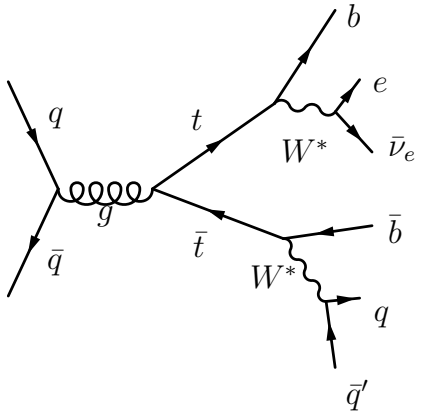


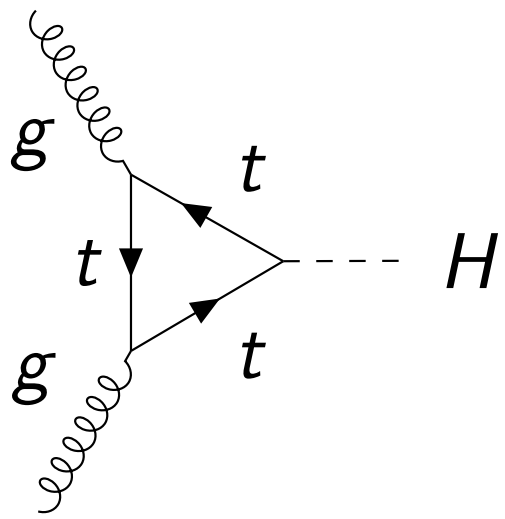
FIG. 17. Monte Carlo distributions of $M_T^{e\nu}$ for top quarks with $M_{\mathrm{top}} = 75\ \mathrm{GeV}/c^2$ (dashed curve) and $W+2$ jet events (solid curve).

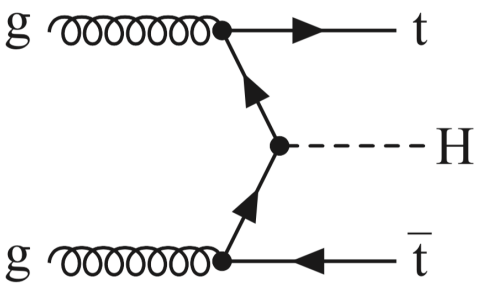


[reference: CDF Collaboration. Top-quark search in the electron + jets channel in proton-antiproton collisions at $\sqrt{s} = 1.8\,\mathrm{TeV}$ *Phys. Rev. D* **43**, 664 (1991).]

Impact on Higgs physics

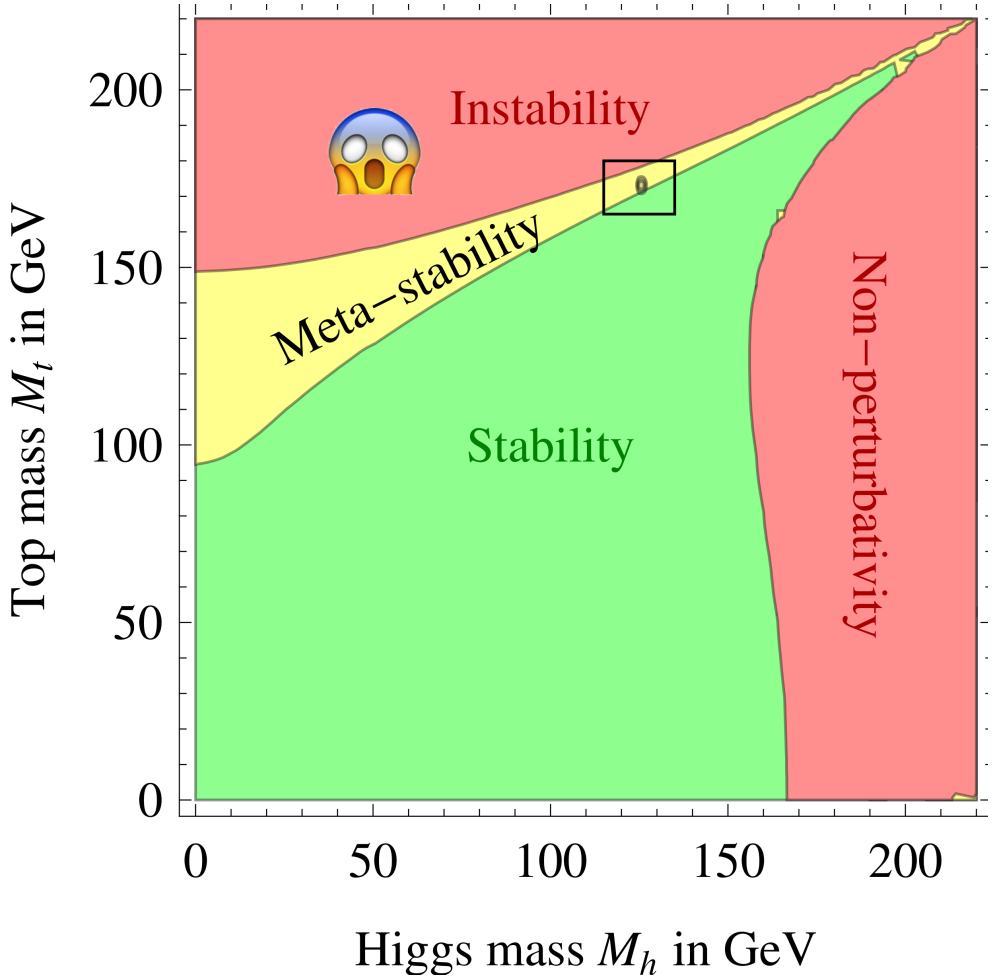
- Top Yukawa coupling:
  - $\lambda_t = \sqrt{2} m_t / v$
  - with $m_t = 173\,\text{GeV}$, $\sigma_{ggH} = 48.6\,\text{pb}^{-1}$
  - with $m_t = 65\,\text{GeV}$, $\sigma_{ggH(65\,GeV)} \approx 1.8 \sigma_{ggH(173\,GeV)} \approx 90\ \text{pb}^{-1}$
- With smaller m_t, Higgs would likely be discovered slightly earlier than 2012
- $\sigma(ttH)_{65} \approx 1.4 \sigma(ttH)_{173}$, but now t decays differently, so probably this observation would be delayed





Last but not least...

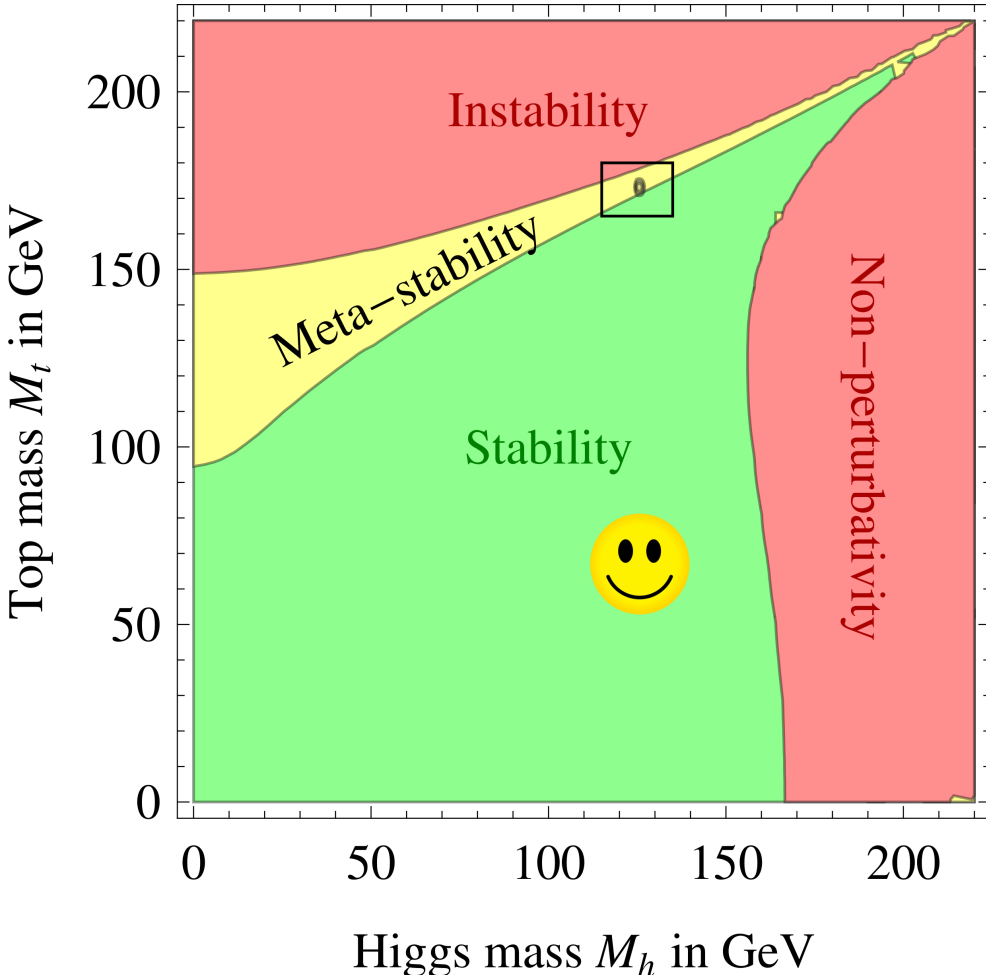
Meta-stability of the EW vacuum



[image credit: 1512.01222]

Last but not least...

A 65 GeV top would make the universe a safer place!



[image credit: 1512.01222]

Thank you!

W boson and t quark

$$\frac{\Gamma_{cs}}{\Gamma_{old}} = 0.31$$

$$\Gamma_{new} = \Gamma_{old} + \Gamma_{tb}$$

$$\frac{\Gamma_{new}}{\Gamma_{old}} = 1 + \frac{\Gamma_{tb}}{\Gamma_{old}}$$

$$\frac{\Gamma_{tb}}{\Gamma_{old}} = \frac{\Gamma_{cs}}{\Gamma_{old}} \frac{|V_{tb}|^2}{|V_{cs}|^2}$$

$$\Rightarrow \frac{\Gamma_{new}}{\Gamma_{old}} = 1.32$$