65 GeV Top Quark
47th SLAC Summer Institute Project

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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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  Stability of the Electroweak vacuum
New top quark properties

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

\[ m_t = 173 \text{ GeV} \quad m_t = 65 \text{ GeV} \]
\[ m_b = 4.18 \text{ GeV} \quad m_b = 4.18 \text{ GeV} \]
\[ M_W = 80.4 \text{ GeV} \quad M_W = 80.4 \text{ GeV} \]
W boson and top quark

\[ \frac{-g}{\sqrt{2}} (\bar{u}_L, \bar{c}_L, \bar{t}_L) \gamma^\mu W^\mu_\mu V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.} \]

- \( W^+ \rightarrow t\bar{b} \) 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.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fraction ($\Gamma_i/\Gamma$)</th>
<th>Confidence level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_1$</td>
<td>$\ell^+ \nu$</td>
<td>[a] $(10.86 \pm 0.09)$ %</td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>$e^+ \nu$</td>
<td>$(10.71 \pm 0.16)$ %</td>
</tr>
<tr>
<td>$\Gamma_3$</td>
<td>$\mu^+ \nu$</td>
<td>$(10.63 \pm 0.15)$ %</td>
</tr>
<tr>
<td>$\Gamma_4$</td>
<td>$\tau^+ \nu$</td>
<td>$(11.38 \pm 0.21)$ %</td>
</tr>
<tr>
<td>$\Gamma_5$</td>
<td>hadrons</td>
<td>$(67.41 \pm 0.27)$ %</td>
</tr>
<tr>
<td>$\Gamma_6$</td>
<td>$\pi^+ \gamma$</td>
<td>$&lt; 7 \times 10^{-6}$ 95%</td>
</tr>
<tr>
<td>$\Gamma_7$</td>
<td>$D_s^+ \gamma$</td>
<td>$&lt; 1.3 \times 10^{-3}$ 95%</td>
</tr>
<tr>
<td>$\Gamma_8$</td>
<td>$cX$</td>
<td>$(33.3 \pm 2.6)$ %</td>
</tr>
<tr>
<td>$\Gamma_9$</td>
<td>$c\bar{s}$</td>
<td>$(31 \pm 13 \pm 11)$ %</td>
</tr>
<tr>
<td>$\Gamma_{10}$</td>
<td>invisible</td>
<td>[b] $(1.4 \pm 2.9)$ %</td>
</tr>
</tbody>
</table>

[a] $\ell$ indicates each type of lepton ($e$, $\mu$, and $\tau$), 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

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</tr>
<tr>
<td>$\Gamma_2$</td>
<td>$e^+ \nu$</td>
<td>10.71 ± 0.16 %</td>
</tr>
<tr>
<td>$\Gamma_3$</td>
<td>$\mu^+ \nu$</td>
<td>10.68 ± 0.13 %</td>
</tr>
<tr>
<td>$\Gamma_4$</td>
<td>$\tau^+ \nu$</td>
<td>11.30 ± 0.21 %</td>
</tr>
<tr>
<td>$\Gamma_5$</td>
<td>hadrons</td>
<td>(67.41 ± 0.27) %</td>
</tr>
<tr>
<td>$\Gamma_6$</td>
<td>$\pi^+ \gamma$</td>
<td>&lt; 7 × 10^-6</td>
</tr>
<tr>
<td>$\Gamma_7$</td>
<td>$D_s^+ \gamma$</td>
<td>&lt; 1.3 × 10^-3</td>
</tr>
<tr>
<td>$\Gamma_8$</td>
<td>$cX$</td>
<td>(33.3 ± 2.0) %</td>
</tr>
<tr>
<td>$\Gamma_9$</td>
<td>$c\bar{s}$</td>
<td>(31 ± 13 / -11) %</td>
</tr>
<tr>
<td>$\Gamma_{10}$</td>
<td>invisible</td>
<td>[b] (1.4 ± 2.9) %</td>
</tr>
</tbody>
</table>

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

[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**

<table>
<thead>
<tr>
<th>Mode</th>
<th>( t \rightarrow \text{Decay Mode} )</th>
<th>Fraction ((\Gamma_i/\Gamma))</th>
<th>Confidence level</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_1 )</td>
<td>( t \rightarrow W q (q = b, s, d) )</td>
<td>( (13.3 \pm 0.6) % )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_2 )</td>
<td>( t \rightarrow W b )</td>
<td>( (13.4 \pm 0.6) % )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_3 )</td>
<td>( t \rightarrow e \nu_e b )</td>
<td>( (7.1 \pm 0.6) % )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_4 )</td>
<td>( t \rightarrow \mu \nu_\mu b )</td>
<td>( (66.5 \pm 1.4) % )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_5 )</td>
<td>( t \rightarrow \tau \nu_\tau b )</td>
<td>[a] ( T1 ) ( [b] &lt; 5 \times 10^{-4} ) ( 95% )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_6 )</td>
<td>( t \rightarrow q \bar{q} b )</td>
<td>( 0 % )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_7 )</td>
<td>( t \rightarrow \gamma q (q=u,c) )</td>
<td>( \Delta T = 1 ) weak neutral current ((T1)) modes</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_8 )</td>
<td>( t \rightarrow H^+ b, \ H^+ \rightarrow \tau \nu_\tau )</td>
<td>[a] ( T1 ) ( [b] &lt; 1.9 \times 10^{-3} ) ( 95% )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_9 )</td>
<td>( t \rightarrow Z q (q=u,c) )</td>
<td>( T1 ) ( [b] &lt; 1.6 \times 10^{-3} ) ( 95% )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{10} )</td>
<td>( t \rightarrow H u )</td>
<td>( T1 ) ( &lt; 1.9 \times 10^{-3} ) ( 95% )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{11} )</td>
<td>( t \rightarrow H c )</td>
<td>( T1 ) ( &lt; 1.6 \times 10^{-3} ) ( 95% )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{12} )</td>
<td>( t \rightarrow \ell^+ \bar{q} q' (q=d,s,b; \ q'=u,c) )</td>
<td>( T1 ) ( &lt; 1.6 \times 10^{-3} ) ( 95% )</td>
<td></td>
</tr>
</tbody>
</table>

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

[b] This limit is for \( \Gamma(t \rightarrow Z q)/\Gamma(t \rightarrow W b) \).
New $t$ quark decay modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\frac{\Gamma_i}{\Gamma}$</th>
<th>Confidence Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_1$</td>
<td>$t \to W q (q = b, s, d)$</td>
<td>$13.3 \pm 0.6$ %</td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>$t \to W b$</td>
<td>$13.4 \pm 0.6$ %</td>
</tr>
<tr>
<td>$\Gamma_3$</td>
<td>$t \to e \nu_e b$</td>
<td>$7.1 \pm 0.6$ %</td>
</tr>
<tr>
<td>$\Gamma_4$</td>
<td>$t \to \mu \nu_\mu b$</td>
<td>$66.5 \pm 1.4$ %</td>
</tr>
<tr>
<td>$\Gamma_5$</td>
<td>$t \to \tau \nu_\tau b$</td>
<td>$[a]$</td>
</tr>
<tr>
<td>$\Gamma_6$</td>
<td>$t \to q \bar{q} b$</td>
<td>$[a]$</td>
</tr>
<tr>
<td>$\Gamma_7$</td>
<td>$t \to \gamma q (q = u, c)$</td>
<td>$T1$ $[b] &lt; 5 \times 10^{-4}$ 95%</td>
</tr>
<tr>
<td>$\Gamma_8$</td>
<td>$t \to H^+<em>b, H^+</em>\tau \to \tau \nu_\tau$</td>
<td>$T1$ $[b] &lt; 1.9 \times 10^{-3}$ 95%</td>
</tr>
</tbody>
</table>

$\Delta T = 1$ weak neutral current ($T1$) modes

| $\Gamma_9$ | $t \to Z q (q = u, c)$ | $T1$ $[b] < 5 \times 10^{-4}$ 95% |
| $\Gamma_{10}$ | $t \to H u$ | $T1$ $< 1.9 \times 10^{-3}$ 95% |
| $\Gamma_{11}$ | $t \to H c$ | $T1$ $< 1.6 \times 10^{-3}$ 95% |
| $\Gamma_{12}$ | $t \to \ell^+ \bar{q} \ell' (q = d, s, b; q' = u, c)$ | $T1$ $< 1.6 \times 10^{-3}$ 95% |

[a] This limit is for $\Gamma(t \to \gamma q)/\Gamma(t \to W b)$.
[b] This limit is for $\Gamma(t \to Z q)/\Gamma(t \to W b)$. 
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, \(\pi\))
  - leptons (\(\ell + \nu_\ell\))
  - \(\gamma\)
- top mesons might oscillate - \(c\) would no longer be the only up-type quark sector where CPV could be studied
## Table of $T$ mesons

<table>
<thead>
<tr>
<th>symbol</th>
<th>quark content</th>
<th>$I^G$</th>
<th>$J^{PC}$</th>
<th>S</th>
<th>C</th>
<th>B’</th>
<th>T</th>
<th>rest mass [GeV/$c^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T^+$</td>
<td>$\bar{t}d$</td>
<td>$\frac{1}{2}$</td>
<td>0$^-$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>$\sim 65$</td>
</tr>
<tr>
<td>$T^-$</td>
<td>$\bar{t}d$</td>
<td>$\frac{1}{2}$</td>
<td>0$^-$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>$\sim 65$</td>
</tr>
<tr>
<td>$\bar{T}^0$</td>
<td>$t\bar{u}$</td>
<td>$\frac{1}{2}$</td>
<td>0$^-$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>$\sim 65$</td>
</tr>
<tr>
<td>$\bar{T}^0$</td>
<td>$\bar{t}u$</td>
<td>$\frac{1}{2}$</td>
<td>0$^-$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>$\sim 65$</td>
</tr>
<tr>
<td>$T^+_s$</td>
<td>$t\bar{s}$</td>
<td>0</td>
<td>0$^-$</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>$\sim 65$</td>
</tr>
<tr>
<td>$T^-_s$</td>
<td>$\bar{t}s$</td>
<td>0</td>
<td>0$^-$</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>$\sim 65$</td>
</tr>
<tr>
<td>$\bar{T}^0_c$</td>
<td>$t\bar{c}$</td>
<td>0</td>
<td>0$^-$</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
<td>$\sim 66$</td>
</tr>
<tr>
<td>$\bar{T}^0_c$</td>
<td>$\bar{t}c$</td>
<td>0</td>
<td>0$^-$</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>-1</td>
<td>$\sim 66$</td>
</tr>
<tr>
<td>$T^+_b$</td>
<td>$t\bar{b}$</td>
<td>0</td>
<td>0$^-$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>$\sim 69$</td>
</tr>
<tr>
<td>$T^-_b$</td>
<td>$\bar{t}b$</td>
<td>0</td>
<td>0$^-$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>$\sim 69$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>$t\bar{t}$</td>
<td>$0^+$</td>
<td>0$^{--}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\sim 130$</td>
</tr>
</tbody>
</table>
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 $\bar{B}^0$:

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

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

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

New value: $\Delta m_B \approx 0.114 \text{ ps}^{-1}$

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:

![Diagram showing top quark production](image credit: CDF Collaboration (1991))

FIG. 1. Cross section for top-quark production in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. The solid curve is for $tt$ pair production and the dashed curve is for $W \rightarrow t\bar{b}$. The two curves for the $tt$ 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 pb$^{-1}$ of data at $\sqrt{s} = 1.8$ TeV. Using this data, top mass from 40 - 77 GeV was excluded.
- Estimated significance for 65 GeV top: 
  \[ \sigma = \frac{s}{\sqrt{s+b}} \sim \frac{55}{\sqrt{55+65}} \sim 5.02 \Rightarrow \text{DISCOVERY!} \]

Impact on Higgs physics

- Top Yukawa coupling:
  - $\lambda_t = \sqrt{2}m_t/v$
  - with $m_t = 173$ GeV,
    $\sigma_{ggH} = 48.6$ pb$^{-1}$
  - with $m_t = 65$ GeV,
    $\sigma_{ggH(65\text{GeV})} \approx 1.8\sigma_{ggH(173\text{GeV})} \approx 90$ 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

[diagram showing the stability and meta-stability regions in terms of Higgs mass $M_h$ in GeV and top mass $M_t$ in GeV]

[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

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

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

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

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

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