Top Quark Physics

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Outline

• Introduction. Discovery and Puzzles
• Basic production processes at colliders
• Decays and spin correlations
• Top mass, $V_{tb}$, Top Yuakawa coupling
• ”New Physics” via top quark
• Conclusions

Top quark

- $Q_{em}^t = \frac{2}{3} \ | e |$
- Weak isospin partner of $b$ quark: $T^t_3 = \frac{1}{2}$
- Color triplet
- Spin-$\frac{1}{2}$

\[
Q^i_L = \begin{pmatrix}
  u_L \\
  d_L \\
  s_L \\
\end{pmatrix}
\begin{pmatrix}
  c_L \\
  t_L \\
  b_L \\
\end{pmatrix}, \quad \begin{array}{c}
  SU(3) \\
  SU(2) \\
  U(1)_Y \\
\end{array}
\begin{pmatrix}
  3 \\
  2 \\
  \frac{1}{6} \\
\end{pmatrix}
\]

\[
u^i_R =
\begin{pmatrix}
  u_R \\
  c_R \\
  t_R \\
\end{pmatrix}, \quad \begin{array}{c}
  SU(3) \\
  SU(2) \\
  U(1)_Y \\
\end{array}
\begin{pmatrix}
  3 \\
  1 \\
  \frac{2}{3} \\
\end{pmatrix}
\]

\[
d^i_R =
\begin{pmatrix}
  d_R \\
  s_R \\
  b_R \\
\end{pmatrix}, \quad \begin{array}{c}
  SU(3) \\
  SU(2) \\
  U(1)_Y \\
\end{array}
\begin{pmatrix}
  3 \\
  1 \\
  -\frac{1}{3} \\
\end{pmatrix}
\]

In the Standard Model top quark couplings are uniquely fixed by the principle of gauge invariance, the structure of the quark generations, and a requirement of including the lowest dimension interaction Lagrangian.
Top quark has been found by the Fermilab CDF and D0 collaborations. RUN1 results:

- $M_t = 174.3 \pm 3.2 (\text{stat}) \pm 4.0 (\text{syst})$
- $\sigma_{tt}(CDF, M_t = 175 \text{GeV}) = 6.5^{+1.7}_{-1.4} \text{pb}$
- $\sigma_{tt}(D0, M_t = 172 \text{GeV}) = 5.9 \pm 1.7 \text{pb}$
- $\lambda_t(M_t) = 1.00 \pm 0.03$
- $|V_{tb}| > 0.78$ (90% CL)
- The 95% Confidence Level Limit on single top production cross section:
  - 13.5 pb by CDF
  - 39 pb (17 pb Neural Network) (s-channel) and
  - 58 pb (22pb Neural Network) (W-gluon fusion) by D0
- SM prediction: $\sigma_{SM} = 2.43 \pm 0.32 \text{ pb}$
Top quark is the heaviest elementary particle found so far with a mass slightly less than the mass of the gold nucleus.

- Top decays ($\tau_t \sim 5 \times 10^{-25} \text{ sec}$) much faster than a typical time-scale for a formation of the strong bound states ($\tau_{QCD} \sim 3 \times 10^{-24} \text{ sec}$). So, top provides, in principle, a very clean source for a fundamental information.
- Top is so heavy and point like at the same time. So, one might expect a possible deviations from the SM predictions more likely in the top sector.
- Top Yukawa coupling $\lambda_t = 2^{3/4}G_F^{1/2}m_t$ is very close to unit. Studies of top may shed a light on an origin of the mechanism of the EW symmetry breaking.

Top quark physics will be a very important part of research programs for all future hadron and lepton colliders.
At hadron and lepton colliders, top quarks may be produced either in pairs or singly. At the Tevatron and LHC: Top pair (left), Single top (right)

Three mechanisms of the single top production:
t-channel \( (Q_W^2 < 0) \)
s-channel \( (Q_W^2 > 0) \)
associated tW \( (Q_W^2 = M_W^2) \)

\( Q_W^2 \) - W-boson virtuality
Basic production processes cross sections

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{\text{NLO}}$ (pb)</th>
<th>$q\bar{q} \rightarrow t\bar{t}$</th>
<th>$gg \rightarrow t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron ($\sqrt{s} = 1.8$ TeV $p\bar{p}$)</td>
<td>$4.87 \pm 10%$</td>
<td>$90%$</td>
<td>$10%$</td>
</tr>
<tr>
<td>Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)</td>
<td>$6.70 \pm 10%$</td>
<td>$85%$</td>
<td>$15%$</td>
</tr>
<tr>
<td>LHC ($\sqrt{s} = 14$ TeV $pp$)</td>
<td>$833 \pm 15%$</td>
<td>$10%$</td>
<td>$90%$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>$s$ channel</th>
<th>$t$ channel</th>
<th>$Wt$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)</td>
<td>$0.90 \pm 5%$</td>
<td>$2.1 \pm 5%$</td>
<td>$0.1 \pm 10%$</td>
</tr>
<tr>
<td>LHC ($\sqrt{s} = 14$ TeV $pp$)</td>
<td>$10.6 \pm 5%$</td>
<td>$250 \pm 5%$</td>
<td>$75 \pm 10%$</td>
</tr>
</tbody>
</table>

LHC will the Top factory: about 10 mln top quarks per year (or 1 top per second) with 10 $fb^{-1}$ luminosity
DØ Run II Preliminary

**dilepton**
$L=146 \text{ pb}^{-1}$

**l+jets (topological)**
$L=143 \text{ pb}^{-1}$

**l+jets (soft $\mu$ tag)**
$L=93 \text{ pb}^{-1}$

**$e\mu$ (Vertex tag)**
$L=158 \text{ pb}^{-1}$

**l+jets (Impact parameter)**
$L=164 \text{ pb}^{-1}$

**l+jets (Vertex tag)**
$L=164 \text{ pb}^{-1}$

**all hadronic**
$L=162 \text{ pb}^{-1}$

---

Cacciari et al. JHEP 0404:068(2004), $m_t = 175 \text{ GeV/c}^2$
The best 95% confidence level upper limits on single top production cross sections in RUN2 by D0 collaboration are

hep-ex/0505063

6.4 pb in the s-channel and
5.0 pb in the t-channel

The first Single Top observation is expected at the Tevatron RUN2 rather soon when accumulated integrated luminosity will be about 1-1.5 $fb^{-1}$

Main problem is large backgrounds ($W + jets, Wb\bar{b}, tt$ etc.) and complicated analysis to extract the signal
Top pair and single top in $e^+e^-$ collisions (ILC)

$$e^+e^- \rightarrow t\bar{t} \rightarrow WWb\bar{b}, \quad W \rightarrow ff',$$

where e.g. for $W^+$

$$f = u, c, \nu_e, \nu_\mu, \nu_\tau, \nu_\mu; \quad f' = d, s, e, \mu, \tau$$

Gauge invariant s-channel subset of 10 diagrams

One should split top pair and single top contributions in the s-channel subset
Gauge invariant t-channel subset of 10 diagrams

All the diagrams contribute to Single Top
(at LEP2 the rate is too small, about $10^{-5}$ pb)
In case of $\gamma \gamma$ collisions there are no nontrivial gauge invariant subsets. A situation is similar to single top at the LHC in $Wt$ mode.

The top pair rate has to be removed in order to get the correct single top rate.
Single Top Diagrams in $\gamma e$ Collisions

This is one of so called "gold plated" processes in $\gamma e$ collision mode of ILC
Cross sections of Top production processes at LC

\[ \sigma \ (fb) \]

- \( e^+e^- \rightarrow t\bar{t} \)
- \( \gamma\gamma \rightarrow t\bar{t} \)
- \( \gamma e^- \rightarrow \nu_b \bar{t} \)
- \( e^+e^- \rightarrow e^+\nu_b b\bar{t} + \text{h.c.} \) (t-channel)

\[ \sqrt{s} \ (\text{TeV}) \]
In SM top decays to W-boson and b-quark practically with 100% probability

$$d\Gamma \sim |\mathcal{M}|^2 \sim (t + ms) \cdot \ell b \cdot \nu,$$
where in the top-quark rest frame, the spin four-vector is $s = (0, \hat{s})$, and $\hat{s}$ is a unit vector that defines the spin quantization axis of the top quark.

In the top quark rest frame:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_\ell} = \frac{1}{2} (1 + \cos \theta_\ell)$$

Hence the charged lepton tends to point along the direction of top spin.
Spin_correlations: theoretical_view

Single top quark is produced highly polarized via the Wtb vertex. Since top quarks do not have a time to form strong bound state, we can investigate a top polarization. There is a unique top spin decomposition axis in the top rest frame: momentum of lepton in top the rest frame from top decay: \( t \rightarrow b \ l \ \nu_l \)

For t-channel the best variable \( \theta_{ql}^* \) - angle between lepton and quark momenta in the top rest frame

The top polarization can be defined as parameter \( P \) in a distribution

\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_{ql}^*} = \frac{1 + P \cos \theta_{ql}^*}{2}
\]

In ideal theoretical situation we have for t-channel:

\( P_{top} \approx 90\% \)
Top quark mass.

In SM W-boson, Top quark and H boson masses are connected to each other via loop contributions to W and Z propagators

\[ M_W^2 = \frac{\pi \alpha}{\sqrt{2} G_F} \frac{s_W}{M_Z^2} \] where \( \Delta r \) contains the one-loop corrections.

\[(\Delta r)_{\text{top}} \approx -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2 t_W^2} \frac{1}{t_W^2} \] where \( t_W^2 \equiv \tan^2 \theta_W \).

This one-loop correction depends quadratically on the top-quark mass.

\[(\Delta r)_{\text{Higgs}} \approx \frac{\frac{11G_F M_Z^2 c_W^2}{24\sqrt{2}\pi^2}}{\ln \frac{m_h^2}{M_Z^2}} \]

This one-loop correction depends only logarithmically on the Higgs-boson mass, so \( \Delta r \) is not as sensitive to \( m_h \) as it is to \( m_t \).
Mass of the Top Quark (*Preliminary)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$M_{\text{top}}$ [GeV/c$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I</td>
<td>$167.4 \pm 11.4$</td>
</tr>
<tr>
<td>DØ-I</td>
<td>$168.4 \pm 12.8$</td>
</tr>
<tr>
<td>CDF-II</td>
<td>$165.3 \pm 7.3$</td>
</tr>
<tr>
<td>CDF-I l+j</td>
<td>$176.1 \pm 7.3$</td>
</tr>
<tr>
<td>DØ-I l+j</td>
<td>$180.1 \pm 5.3$</td>
</tr>
<tr>
<td>CDF-II l+j*</td>
<td>$173.5 \pm 4.1$</td>
</tr>
<tr>
<td>DØ-II l+j*</td>
<td>$169.5 \pm 4.7$</td>
</tr>
<tr>
<td>CDF-I all-j</td>
<td>$186.0 \pm 11.5$</td>
</tr>
</tbody>
</table>

$\chi^2 / \text{dof} = 6.5 / 7$

Tevatron Run-I/I* $172.7 \pm 2.9$

hep-ex/0507091  CDF and D0 combined
At the Tevatron Run II with $2 \text{fb}^{-1}$ one expects:

\[ \delta M_W \sim 27 \text{ MeV} \]
\[ \delta M_t \sim 3 \text{ GeV} \]

yielding a prediction for the Higgs mass with an uncertainty of

\[ \frac{\delta M_h}{M_h} \sim 40\% \]

At the LHC with $10 \text{ fb}^{-1}$

\[ \delta M_t \sim 0.7 \text{ GeV} \]

At ILC with $500 \text{ fb}^{-1}$ from the top pair threshold scan one can get

\[ \delta M_t \sim 0.1 \text{ GeV} \]
$|V_{tb}|$ measurements

At LHC and Tevatron Run2 via single top

$V_{tb}^2$ could be measured with an accuracy of 10% dominated by systematics

At ILC (1 TeV, 500 $fb^{-1}$) in $e\gamma$ collisions -
2-3 % accuracy dominated by statistics
Top Yukawa coupling $ttH$ measurements

For the LHC complete NLO computations have been performed
(LO diagrams are shown)

Top Yukawa could be measured with an accuracy from 16% at low Lumi to 11% at high Lumi regime
New Physics via Top (examples):

- $W_{tb}$ anomalous couplings
- FCNC
- Various SUSY effects without and with R-parity violation
- Charged Higgs in top decays
- New strong dynamics ($W'$, $Z'$, $\pi_T$, $\rho_T$, topgluon, $W_L W_L \rightarrow t \bar{t}$ ...)
- Kaluza-Klein graviton excitations and radion in ADD and RS scenarious
- ...

Maximal value of the CP even light Higgs in MSSM is about 135-140 GeV (not $M_Z$) due to large top quark mass

\[ M_h^{max} = \sqrt{M_Z^2 + \epsilon} \]

\[ \epsilon = \frac{3G_F m_t^4}{\sqrt{2}\pi^2 \sin^2 \beta} \left[ f(t) \right], \quad \text{where} \quad t = \log \left( \frac{M_S^2}{m_t^2} \right) \]
Anomalous Top Couplings

The top quark interactions of dimension 4:

$$\mathcal{L}_4 = -g_s \bar{t} \gamma^\mu T^a t G^a_\mu - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \bar{t} \gamma^\mu (v_{tq}^W - a_{tq}^W \gamma_5) q W^+_{\mu}$$

$$- \frac{2}{3} e \bar{t} \gamma^\mu t A_\mu - \frac{g}{2 \cos \theta_W} \sum_{q=u,c,t} \bar{t} \gamma^\mu (v_{tq}^Z - a_{tq}^Z \gamma_5) q Z_\mu$$

The dimension 5 couplings have the generic form:

$$\mathcal{L}_5 = -g_s \sum_{q=u,c,t} \frac{\kappa^g_{tq} \Lambda}{\Lambda} \bar{t} \sigma^{\mu\nu} T^a (f_{tq}^g + i h_{tq}^g \gamma_5) q G^a_{\mu\nu} - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \frac{\kappa^W_{tq} \Lambda}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_{tq}^W + i h_{tq}^W \gamma_5) q W^{\mu\nu}_{+}$$

$$- e \sum_{q=u,c,t} \frac{\kappa^\gamma_{tq} \Lambda}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_{tq}^\gamma + i h_{tq}^\gamma \gamma_5) q A_{\mu\nu} - \frac{g}{2 \cos \theta_W} \sum_{q=u,c,t} \frac{\kappa^Z_{tq} \Lambda}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_{tq}^Z + i h_{tq}^Z \gamma_5) q Z_{\mu\nu}$$

where $|f|^2 + |h|^2 = 1$. 
Present constrains come from

- Low energy data via loop contributions
  \[ K_L \rightarrow \mu^+\mu^-, K_L - K_S \text{ mass difference}, b \rightarrow l^+l^-X, b \rightarrow s\gamma \]

- LEP2

- Tevatron Run1

- HERA

- Unitarity violation bounds
Anomalous Wtb Couplings

- Lagrangian

\[ \mathcal{L} = \frac{g}{\sqrt{2}} V_{tb} \left[ W_\nu^{-} \bar{b} \gamma_\mu P_\tau t - \frac{1}{2M_W} W_{\mu \nu}^{-} \bar{b} \sigma^{\mu \nu} (F^L_2 P_\tau + F^R_2 P_\tau) \right] + \text{h. c.} \]

with \( W_{\mu \nu}^{\pm} = D_\mu W_\nu^{\pm} - D_\nu W_\mu^{\pm} \), \( D_\mu = \partial_\mu - ieA_\mu \), \( \sigma^{\mu \nu} = i/2[\gamma_\mu, \gamma_\nu] \) and \( P_\pm = (1 \pm \gamma_5)/2 \). The couplings \( F^L_2 \) and \( F^R_2 \) are proportional to the coefficients of the effective Lagrangian

\[ F_{L2} = \frac{2M_W}{\Lambda} \kappa_{tb}^W (-f_{tb}^W - i h_{tb}^W), \]
\[ F_{R2} = \frac{2M_W}{\Lambda} \kappa_{tb}^W (-f_{tb}^W + i h_{tb}^W), \quad |F_{L2,R2}| < 0.6 \text{ from unitary bounds} \]

- \( |V_{tb}| \) is very close to 1 in SM with 3 generations. \( (|V_{tb}| \) is very weakly constrained in case of 4 generations, e.g.)

- A possible \( V + A \) form factor is severely constrained by the CLEO \( b \to s \gamma \) data to \( 3 \times 10^{-3} \) level
$Wtb$ anomalous couplings limit on TEVATRON and LHC:

(E. Boos, L. Dudko, T. Ohl, EPJ99)
Uncorrelated limits on anomalous couplings from measurements at different machines.

<table>
<thead>
<tr>
<th></th>
<th>$F_2^L$</th>
<th>$F_2^R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron ($\Delta_{sys.} \approx 10%$)</td>
<td>$-0.18 \div +0.55$</td>
<td>$-0.24 \div +0.25$</td>
</tr>
<tr>
<td>LHC ($\Delta_{sys.} \approx 5%$)</td>
<td>$-0.052 \div +0.097$</td>
<td>$-0.12 \div +0.13$</td>
</tr>
<tr>
<td>$\gamma e (\sqrt{s_{e^+e^-}} = 0.5$ TeV)</td>
<td>$-0.1 \div +0.1$</td>
<td>$-0.1 \div +0.1$</td>
</tr>
<tr>
<td>$\gamma e (\sqrt{s_{e^+e^-}} = 2.0$ TeV)</td>
<td>$-0.008 \div +0.035$</td>
<td>$-0.016 \div +0.016$</td>
</tr>
</tbody>
</table>
**FCNC couplings**

- Couplings: $tqg$, $tq\gamma$, $tqZ$, where $q = u, c$

\[
\Delta L_{\text{eff}} = \frac{1}{\Lambda} \left[ \kappa_{tq}^{\gamma, Z} e \bar{t} \sigma_{\mu \nu} q F_{\gamma, Z}^{\mu \nu} + \kappa_{tq}^{g} g_s \bar{t} \sigma_{\mu \nu} \frac{\lambda^i}{2} q G^{i \mu \nu} \right] + \text{h.c.}
\]

Information on FCNC couplings come from either top pair production with subsequent decays to rear modes $t \rightarrow qV$, where $V = \gamma, Z, g$
or from additional contributions to the single top production
All present and expected limits are presented in terms of Br fractions:

\[
\begin{align*}
\Gamma(t \to qg) &= \left(\frac{\kappa_{tg}}{\Lambda}\right)^2 \frac{8}{3} \alpha_s m_t^3, \\
\Gamma(t \to q\gamma) &= \left(\frac{\kappa_{tg}}{\Lambda}\right)^2 2\alpha m_t^3, \\
\Gamma(t \to qZ)_\gamma &= \left(\frac{|v_{tg}|^2 + |a_{tg}|^2}{4M_Z^2 \sin^2 2\theta_W}\right) \alpha m_t^3 \frac{1}{4M_Z^2 \sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_Z^2}{m_t^2}\right), \\
\Gamma(t \to qZ)_\sigma &= \left(\frac{\kappa_{tg}}{\Lambda}\right)^2 \alpha m_t^3 \frac{1}{\sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(2 + \frac{M_Z^2}{m_t^2}\right).
\end{align*}
\]

Current constraints

<table>
<thead>
<tr>
<th></th>
<th>CDF</th>
<th>LEP-2</th>
<th>HERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR(t \to gg)</td>
<td>≤ 29%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR(t \to γq)</td>
<td>≤ 3.2%</td>
<td></td>
<td>≤ 0.7%</td>
</tr>
<tr>
<td>BR(t \to Zq)</td>
<td>≤ 32%</td>
<td>≤ 7.0%</td>
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</tr>
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## Future expectations

<table>
<thead>
<tr>
<th>$t \to$</th>
<th>Tevatron Run II</th>
<th>LHC</th>
<th>$e^+e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g q$</td>
<td>0.06%</td>
<td>$1.6 \times 10^{-3}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\gamma q$</td>
<td>0.28%</td>
<td>$2.5 \times 10^{-5}$</td>
<td>$3 \times 10^{-6}$</td>
</tr>
<tr>
<td>$Z q$</td>
<td>1.3%</td>
<td>$1.6 \times 10^{-4}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Charged Higgs in Top Decay (impact of tau polarization)

In the rest frame of top $t \rightarrow bR \rightarrow b\tau \nu_\tau \rightarrow b\nu_\tau \bar{\nu}_\tau \pi$
where a resonance $R$ is W boson or charged H

$$\frac{1}{\Gamma} \frac{d\Gamma}{dy_\pi} = \frac{1}{x_{\max} - x_{\min}}$$

$$\begin{cases} (1 - P_\tau) \log \frac{x_{\max}}{x_{\min}} + 2P_\tau y_\pi \left( \frac{1}{x_{\min}} - \frac{1}{x_{\max}} \right), & 0 < y_\pi < x_{\min} \\ (1 - P_\tau) \log \frac{x_{\max}}{y_\pi} + 2P_\tau (1 - \frac{y_\pi}{x_{\max}}), & x_{\min} < y_\pi \end{cases}$$

where $y_\pi = \frac{E_{\pi}^{top}}{M_{top}}$, $x_{\min} = \frac{E_{\min}}{M_{top}}$, $x_{\max} = \frac{E_{\max}}{M_{top}}$, $E_\tau^{min} = \frac{M_R^2}{2M_{top}}$, $E_\tau^{max} = \frac{M_{top}}{2}$

$P_\tau = -1$ for W boson and $P_\tau = 1$ for charged Higgs
\( e^+e^- \rightarrow t\bar{t} \rightarrow \tau\nu_\tau b\bar{b} + 2\text{jets} \)

Simulations are performed for \( e^+e^- \) collisions at 500 GeV cms and for 500 \( fb^{-1} \) integrated luminosity.

\( \pi^- \)-meson energy spectrum for the MSSM point
\( \tan\beta = 50, \mu = 500, M_{H^\pm} = 130 \text{ GeV with } Br(t \rightarrow H^+b) = 9.1\% \)

E.B., S.Bunichev, M.Carena, C.Wagner

From the signal+backgr fit \( M_{H^\pm} = 129.4 +/-.9 \) GeV
The NLO rate of $q \bar{q}' \rightarrow W, W' \rightarrow t \bar{b}$ ($\sigma_S$) in pb at the Tevatron (lower curves) and LHC (upper curves) for various coupling parameters.
The LO rate of single top production through the reaction $c \bar{b} \rightarrow \pi^+ \rightarrow t \bar{b}$ as a function of $M_{\pi^\pm}$ in the top-color model.
Generic search for a resonance in top pair production at the LHC (MSSM Higgses H/A, $Z'$, topgluon, RS-graviton, KK excitations in UED etc.)

Measured $t\bar{t}$ invariant mass distribution for reconstruction of a narrow resonance of mass 1600 GeV decaying to $t\bar{t}$ and value of $\sigma \times \text{BR}$ required for a 5$\sigma$ discovery potential.
**Conclusions**

Discovery of the top quark has opened up many new avenues to interesting physics

- Precision measurements of top quark characteristics such as mass, production cross sections, decay width and branching fractions, spin correlations are needed to test the SM
- Tests and understanding all possible deviations from the SM expectations to check if top is exotic in some way
- Precise calculations and simulations, and measurements of the top event kinematical characteristics to understand backgrounds to many other possible New physics processes
- Possible discovery and study of various New physics effects via top production and/or decay
New physics for sale