Top quark: properties and beyond

Michele Gallinaro
LIP Lisbon

- Mass, Vtb, taus
- Spin correlation
- Charge asymmetry
- Boosted topology
- Searches for New Physics
Contents

- Introduction (discovery, object ID)
- Top pair production at the Tevatron
- Top pair production at LHC
- (differential) cross section
- Mass, heavy flavor content, taus
- Search for top partners and 4\textsuperscript{th} generation quarks
- Search for \(t\bar{t}\)bar resonances
- Spin correlation, charge asymmetry
- Single top production
- Flavor Changing Neutral Currents (FCNC)
Top quark mass and constraints

• Top quark mass is a fundamental parameter of the SM
  – Known with good accuracy from the Tevatron: 173.2±0.9 GeV (arXiv:1107.5255)
  – Indirect constraint on the Higgs boson mass via EW corrections
    $\Rightarrow m_H = 92^{+34}_{-26}$ GeV or <161 GeV

• Top is the only fermion with the mass of the order of EWSB scale
• Measuring precisely $m_W$ and $m_{\text{top}}$
  – Test consistency of SM
  – Search for new Physics

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\[ \delta m_W \propto m_t^2 \]
\[ \delta m_W \propto \log m_H \]
Jet reconstruction in Top events

- Top mass measurement needs parton information, but we measure jets
- Use calorimeter information to correct jets to particle level

- Contribution of uncertainty sources depend on $p_T$, $\eta$
- Jet energy correction uncertainty:
  - Look at quantities insensitive to JES (e.g. lepton $p_T$)
  - “b-jet” tag helps reducing number of permutations
- JES “in-situ” calibration in ttbar events
  - Use $W \rightarrow jj$ constraint to measured $W$ mass
Top as a calibration tool

- Top quarks can be used as calibration tool
  - Top mass, W mass, b/q jets
- can determine:
  - b-tagging efficiency
  - jet energy scale

...or alternatively...

- use b-tag as a probe
  - compare rates in different b-tag multiplicity bins
  - is the signal, ttbar or not?
- BSM may appear in the sample and “distort” the distribution
Jet energy correction from Top

- Use semi-leptonic events
  - 1 isolated $\mu$ ($p_T>$30 GeV)+≥4 jets (40 GeV)
- Estimate jet energy corrections by applying event-by-event kinematical fit to W and Top masses
- Likelihood is used to assign jets
- Kinematical fit returns $P(\chi^2)$
- Find best JES by minimizing $\chi^2$

![CMS simulation](chart)

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Measuring the top mass

Challenging:

- **Lepton+jets**
  - undetected neutrino
    - $P_x$ and $P_y$ from $E_T$ conservation
    - 2 solutions for $P_z$ from $M_W=M_{l\nu}$
  - leading 4-jet combinatorics
    - 12 possible jet-parton assignments
  - 6 with 1 b-tag
  - 2 with 2 b-tags
  - ISR + FSR

- **Dileptons**
  - (less statistics)
  - two undetected neutrinos
  - less combinatorics: 2 jets
Lepton+jet channel

• Best channel (for now) to measure top quark mass
• Compromise between large branching ratio (BR=30%) and a good background rejection
• Well defined final state (1 lepton, one neutrino, 2 b-jets, $W \rightarrow qq'$)
Lepton+jet channel

- in-situ calibration of the light quark JES from $W \rightarrow qq'$

**ATLAS**: template fit as function of JES and top quark mass

**CMS**: kinematic fit + “ideogram” method combine event-per-event likelihood

- $m_{top} = 174.4 \pm 0.6$ (stat) $\pm 2.3$ (syst) GeV
- $172.6 \pm 0.6$ (stat) $\pm 1.2$ (syst) GeV

ATLAS CONF-2011-120

CMS PAS-11-015

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Dilepton channel: challenges

• Combinatorics
  – Identify top quark decay products
  – Ambiguity
  – ISR/FSR introduces further complexity for selection
    (~70% of the events have both b-jets reconstructed and selected)

• Missing transverse energy
  – Constrains the contribution from undetected particles
  – In the dilepton channel: 2 neutrinos ⇒ \( E_T^{\text{miss}} = p_T^\nu + p_T^\bar{\nu} \)

• Jet energy scale
  – \( m_{\text{top}} \) reconstruction requires measuring the parton energy
  – Parton→jet affected by resolution and absolute energy scale

• Pile-up
  – Jet energy scale, MET measurement, extra jets/leptons
  – \( N_{\text{pileup}} \approx 6 \) (21) for most of data collected in 2011 (2012)
Reconstructed mass

- Select events
- Reconstruct mass

<table>
<thead>
<tr>
<th>Process</th>
<th>Pre-selection</th>
<th>KINb</th>
<th>=1 b-tag</th>
<th>≥ 2 b-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>Di-bosons</td>
<td>73 ± 14</td>
<td>55 ± 10</td>
<td>18 ± 4</td>
<td>4 ± 1</td>
</tr>
<tr>
<td>Single top</td>
<td>247 ± 92</td>
<td>182 ± 68</td>
<td>88 ± 33</td>
<td>76 ± 29</td>
</tr>
<tr>
<td>W+jets</td>
<td>22 ± 10</td>
<td>16 ± 8</td>
<td>8 ± 6</td>
<td>-</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \ell\ell$</td>
<td>1091 ± 97</td>
<td>756 ± 71</td>
<td>238 ± 29</td>
<td>47 ± 11</td>
</tr>
<tr>
<td>other $tt$</td>
<td>32 ± 4</td>
<td>28 ± 3</td>
<td>11 ± 2</td>
<td>14 ± 2</td>
</tr>
<tr>
<td>$tt$ dileptons</td>
<td>5057 ± 463</td>
<td>4209 ± 385</td>
<td>1379 ± 127</td>
<td>2623 ± 240</td>
</tr>
<tr>
<td>total expected</td>
<td>6522 ± 482</td>
<td>5246 ± 398</td>
<td>1742 ± 134</td>
<td>2765 ± 242</td>
</tr>
<tr>
<td>data</td>
<td>6358</td>
<td>5047</td>
<td>1692</td>
<td>2620</td>
</tr>
</tbody>
</table>

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Signal and background

- Signal component in the mass spectrum modelled: simulation
- Fit: Landau+Gaussian
- Categories: =1 and ≥2 b-tags

- Background component in the mass spectrum modelled with data +simulation
- Fit: Landau

\[ m_{\text{top}} = 172.5 \text{ GeV/c}^2 \]
Reconstructed mass

- Top quark mass is reconstructed in different categories
- Signal and background shapes
Correct for the bias

- Check and correct for the bias in the measurement
Jet energy scale (JES) is the largest unc.
- JES is varied up and down and difference in $m_{top}$ is accounted for as systematics
- Flavor (b) specific uncertainty added in quadrature

Other systematics:
- Difference with respect to reference sample used for signal
- MC: compare Alpgen and Powheg with Madgraph
- Vary factorization/matching scale, ISR/FSR

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta m_{top}$ (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>+1.90</td>
</tr>
<tr>
<td>flavor-JES</td>
<td>+1.08</td>
</tr>
<tr>
<td>JER</td>
<td>-1.13</td>
</tr>
<tr>
<td>LES</td>
<td>± 0.30</td>
</tr>
<tr>
<td>Unclustered $E_T^{miss}$</td>
<td>± 0.43</td>
</tr>
<tr>
<td>Fit calibration</td>
<td>± 0.40</td>
</tr>
<tr>
<td>DY normalization</td>
<td>± 0.40</td>
</tr>
<tr>
<td>Factorization scale</td>
<td>± 0.41</td>
</tr>
<tr>
<td>Jet parton matching scale</td>
<td>± 0.65</td>
</tr>
<tr>
<td>Pile-up</td>
<td>± 0.19</td>
</tr>
<tr>
<td>$b$-tagging uncertainty</td>
<td>± 0.30</td>
</tr>
<tr>
<td>mis-tagging uncertainty</td>
<td>± 0.43</td>
</tr>
<tr>
<td>MC generator</td>
<td>± 0.14</td>
</tr>
<tr>
<td>PDF uncertainty</td>
<td>± 0.39</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>+2.52</strong></td>
</tr>
<tr>
<td></td>
<td><strong>-2.63</strong></td>
</tr>
</tbody>
</table>
Final fit

CMS preliminary, $\sqrt{s}=7$ TeV, $\int L = 2.3$ fb$^{-1}$

$$m_{\text{top}} = 173.3 \pm 1.2\text{(stat.)}^{+2.5}_{-2.6}\text{(syst.)} \text{ GeV/c}^2$$

CMS TOP-11-016
Top quark mass

Results from LHC are rapidly improving (0.6%)

- dominated by $l^+\text{jet}$ channel
- Towards LHC and global combination

\[ m_t = 172.5 \pm 1.00 \, \text{GeV} \]
\[ m_t = 174.9 \pm 1.4 \, \text{GeV} \]
\[ m_t = 173.2 \pm 0.90 \, \text{GeV} \]

\[ \chi^2/\text{DoF} = 6.1/10 \]

arXiv:1107.5255 ±0.5%

Tevatron + LHC $m_{\text{top}}$ combination - Sep 2012

- CDF RunII, $l^+\text{jet}$: $172.9 \pm 0.5 \pm 1.0$
- CDF RunII, di-lepton: $170.3 \pm 2.0 \pm 3.1$
- CDF RunII, all jets: $172.5 \pm 1.4 \pm 1.4$
- CDF RunII, $L_{xy}$: $166.9 \pm 9.0 \pm 2.8$
- CDF RunII, MET+jet: $173.9 \pm 1.3 \pm 1.4$
- D0 RunII, $l^+\text{jets}$: $174.9 \pm 0.8 \pm 1.2$
- D0 RunII, di-lepton: $174.0 \pm 2.4 \pm 1.5$
- ATLAS 2011, $l^+\text{jets}$: $174.5 \pm 0.6 \pm 2.3$
- ATLAS 2011, di-lepton: $175.2 \pm 1.6 \pm 3.0$
- ATLAS 2011, all jets: $174.9 \pm 2.1 \pm 3.9$
- CMS 2011, $l^+\text{jets}$: $173.5 \pm 0.3 \pm 1.0$
- CMS 2011, di-lepton: $172.5 \pm 0.4 \pm 1.4$
- CMS 2011, all jets: $173.5 \pm 0.7 \pm 1.2$
- Tevatron July 2011: $173.2 \pm 0.6 \pm 0.8$
- World Comb. Sep 2012: $173.4 \pm 0.3 \pm 0.7$
Top-antiTop mass difference

- Test of CPT invariance: particle and anti-particle have same mass
  - If masses are different → CPT violation
  - Top quark is unique because it decays before hadronizing
- use $\mu$+jet ttbar events: positive/negative muons (L=1.1/fb)
  - Compare mass measured from $\mu^+/- +$jets
  - Use hadronic side

$\Delta m_t = m_t^{had} - m_{\bar{t}}^{had} = -272 \pm 196 \text{ (stat.)} \pm 121 \text{ (syst.) MeV}$

Dominant systematics:
- $b$ vs $b\bar{b}$ jet response
- signal fraction
- $b$ vs $b\bar{b}$ tagging

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Top mass from cross section

- Direct $m_{\text{top}}$ measurements rely on details of kinematics, reconstruction, calibration
- Experimental measurement has small uncertainty: $\sim 0.5$
- What mass is measured?
  - Could be interpreted as pole mass

- Compare theory prediction (measured) cross section vs pole mass ($=m_{\text{top}}$)
- Exploit relation of cross section and mass:
  - $\Delta \sigma/\sigma = -A \times \Delta m/m$ \hspace{1cm} (A=4-5)

S. Moch, P. Uwer, PRD 80 (2009) 054009
Top mass from cross section

- determine top quark pole mass using the experimental \( \text{ttbar} \) production cross section
  - from lepton+jets channel (ATLAS) with 35/pb
    \[
    m_{t_{\text{pole}}}^{\text{top}} = (166.4 \pm 7.8 \pm 7.3) \text{ GeV}
    \]
  - from dilepton cross section (CMS) with 1.1/fb
    \[
    m_{t_{\text{pole}}}^{\text{top}} = 170.3^{+7.3}_{-6.7} \text{ GeV}
    \]

Also determine \( m(M_{\text{MS}}) \):

<table>
<thead>
<tr>
<th>Approx. NNLO \times \text{HERAPDF15NNLO}</th>
<th>( m_{t_{\text{pole}}} ) / GeV</th>
<th>( m_{t_{\text{MS}}} ) / GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langenfeld et al. [7]</td>
<td>171.7^{+6.0}_{-5.9}</td>
<td>164.3^{+5.9}_{-5.7}</td>
</tr>
<tr>
<td>Ahrens et al. [9]</td>
<td>169.1^{+6.9}_{-6.6}</td>
<td>161.0^{+6.9}_{-6.1}</td>
</tr>
</tbody>
</table>

ATLAS Preliminary, \( \int L = 35 \text{ pb}^{-1} \)

CMS Preliminary, \( \sqrt{s} = 7 \text{ TeV}, \ L = 1.14 \text{ fb}^{-1} \)

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Not just cross sections

"core" $t\bar{t}$ region, e.g., $e\mu + \text{MET} + 2\ b$-tags

event selection region

BSM3

BSM2

BSM1

other SM

Drawing by C. Campagnari
Interesting physics with Top quark

PRODUCTION
Cross section
Resonances $X \rightarrow tt$
Fourth generation $t'$
Spin-correlations
New physics (SUSY)
Flavour physics (FCNC)
...

PROPERTIES
Mass
Kinematics
Charge
Lifetime and width
$W$ helicity
Spin
...

DECAY
Branching ratios
Charged Higgs (non-SM)
Anomalous couplings
Rare decays
CKM matrix elements
Calibration sample @LHC
...
Spin correlation

• Important tool for precise studies of top quark interactions
• Top quark produced are not polarized
  – …but spins between quark and anti-quark are correlated
• Top quark decays before spins decorrelate
  – Top quark decays before hadronization ($\tau \sim 10^{-25}$ sec) ⇒ spin information transmitted to the decay products (W boson, b quark)
• Spin correlation depends on the production mode

\[ \kappa = \frac{n_{\pm \pm} - n_{\pm \mp}}{n_{\pm \pm} + n_{\pm \mp}} \]

\[
\frac{1}{\sigma} \frac{d\sigma}{d\cos \theta_1 d\cos \theta_2} = \frac{1}{4} \left(1 + \kappa \cos \theta_1 \cos \theta_2 \right)
\]

• Analyze spin using angular distributions of decay products
  – $\theta_1$ and $\theta_2$ are the angles of decay products wrt a “quantization axis”
  – value of $\kappa$ depends on spin basis (for example, off-diagonal vs maximal)
Spin correlation

- Spin correlation may differ from that expected in the SM
  - top quark decays into a charged Higgs boson and a b quark (t→H⁺b)
  - Other BSM scenarios
Spin correlation: Tevatron vs LHC

\[ A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}} \]

- dominated by $q\bar{q}$ annihilation
- $t\bar{t}$ pairs close to the threshold
- beam axis as spin quantisation axis
  NLO QCD: $A = 0.78$
- optimised “off–diagonal” basis

- dominated by $gg$ fusion
- $t\bar{t}$ pairs far off the threshold
- helicity basis as spin quantisation axis
  NLO QCD: $A = 0.32$
- maximal basis

complementary between Tevatron and LHC
Spin correlation

- Access spin information via the angular distributions of its decay products
- Most sensitive probes are leptons and d-type quarks
- Strategy: fit $\Delta \phi$ dilepton distribution with binned SM distribution and in the case with uncorrelated spin distribution
- Translate result to maximal/helicity basis
- Main systematics: ISR/FSR and signal modelling
- Results in agreement with SM:

$$A_{\text{helicity}} = 0.34 \pm 0.07_{\text{stat}}^{+0.13}_{-0.09} \text{ syst} \quad A_{\text{helicity}}^{\text{SM}} = 0.32$$

$$A_{\text{maximal}} = 0.47 \pm 0.09_{\text{stat}}^{+0.18}_{-0.12} \text{ syst} \quad A_{\text{maximal}}^{\text{SM}} = 0.44$$
Charge asymmetry

- In $qq\bar{q}\rightarrow tt\bar{t}$ (Tevatron): top quarks are emitted in the direction of the incoming quark, anti-top quarks in the direction of the incoming anti-quark
- No FB asymmetry in $gg\rightarrow tt\bar{t}$ (LHC)

**SM:** Only small asymmetry due to ISR/FSR

**New physics:** production mechanisms with new exchange bosons could enhance the charge asymmetry

At LHC quarks have larger momentum than anti-quarks (larger average momentum fraction of quarks leads to an excess of top quarks produced in the forward directions)
Asymmetry $A_{FB}$ anomaly?

- Tevatron experiments observe a differential dependency on charge asymmetry
- Sign of new physics?

- At high mass, a $3\sigma$ discrepancy
- Study asymmetry vs mass of ttbar system

CDF: PRD 83(2011)112003
D0: PRL 100(2008)142002
CDF Note 10807
Charge asymmetry at LHC

\[ A_C = \frac{N^+ - N^-}{N^+ + N^-} \]

\( N^+(N^-) \): number of events with positive (negative) values in the sensitive variable

Anomalous axial-vector coupling of gluons to quarks could explain the Tevatron anomaly [PRD84:054017,2011]

⇒ Good agreement between data and SM expectations

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Constraints on New Physics

Inclusive

$\mu^+\mu^-$

$m_{\mu^+\mu^-} > 450$ GeV

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Heavy flavor content (i.e. $V_{tb}$)
Top quark decays

top decay $t \rightarrow Wb$, but really 100%?

Indirect measurement using the CKM matrix:
- Elements $|V_{ub}|$ and $|V_{cb}|$ measured to be very small from decay of B mesons
- Unitarity and only three generations implies $|V_{tb}|$ is 0.998 @ 90% CL

With top quark samples we can measure it directly as “R”:

$$ R \equiv \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} $$

where $q = \{d, s, b\}$

Use the ability to identify jets with a distinguished secondary vertex: b-tagging
- The number of b-tagged jets depends strongly on R and b-tagging efficiency $\varepsilon_b$

We classify the $t\bar{t}$ sample based on the number of b-tagged jets
- The relative rates of events with 0/1/2 b-tags is very sensitive to R

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Is $\text{BR}(t \rightarrow \text{Wb}) \sim 100\%$?

- In the SM, $R = \frac{\text{BR}(t \rightarrow \text{Wb})}{\text{BR}(t \rightarrow \text{Wq})} \sim |V_{tb}|^2$
- Measure $R$ by comparing the number of $t\bar{t}$ events with 0, 1 and 2 $b$-tags
- SM: $R=1$ constrained by CKM unitarity. $R<1$ could indicate new physics (e.g. 4th generation hep/ph-0607115)

\[ 0.9980 < R < 0.9984 \]

- Not yet sensitive to SM

Measure $R$ simultaneously with $t\bar{t}$ cross section:
Measure of $V_{tb}$

- Measurement with the single top production final state
- Direct measure of $|V_{tb}|$
- Sensitive to non-SM phenomena ($W'$, FCNC)
Measure R in dilepton channel

- Probe heavy flavor content of $t\bar{t}$ events
- Use $t\bar{t}$ dilepton final state

**Advantages:**
- Less background

**Disadvantages:**
- Lower statistics
- Jet assignment

$$R \equiv \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)}$$

- **Selection:**
  - 2 leptons + $\geq$2 jets + MET
  - No b-tagging in preselection

- **Clean signature**
- **Goals:**
  - Measure $\epsilon(b)$ and R

**Advantages:**
- Less background

**Disadvantages:**
- Lower statistics
- Jet assignment
How to model the background

Events are classified in 3 cases (weight $\alpha$):
1) 2 correctly assigned b-jet
2) 1 corr. ass. b-jet
3) 0 corr. ass. b-jet

$$M_{l,j} \approx \sqrt{m_t^2 - m_W^2} = 156 \text{ GeV/c}^2$$

Compute invariant mass of all lepton-jet pairs

Model background using:
- jets from different events
- rotate lepton direction

Background dominates at $M>M_{\text{cut}}$
Signal or background?

Data-driven determination of background

- Reconstruct lepton-jet invariant mass
  - Correct assignment
  - Wrong assignment

- Use tail to model background in signal region
Signal vs background

CMS simulation, $\sqrt{s}=8$ TeV

- misassignments
- correct

$\sqrt{m_t^2-m_W^2} \approx 153$ GeV

Invariant Mass [GeV]
Signal or background

Scale shape to match spectrum observed with $M_{lj} > 180$ GeV

after background subtraction

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Heavy flavor content

- Fully data-driven measurement
  - b-tagging multiplicity parametrized as function of $R \varepsilon_b, \varepsilon_q$, top contribution
  - Number of reconstructed $t \rightarrow Wq$ is estimated from lepton-jet invariant mass

- $R = 1.02 \pm 0.04$ (stat. $\oplus$ syst.)
  - Lower boundary with confidence interval @95%CL after requiring $R \leq 1 \Rightarrow R > 0.945$ @95%CL
Measure $R$

- Variation of the likelihood used to measure $R$ from data
- Fit different categories
Summary of R results

Most accurate measurement

\[ R = \frac{B(t \to Wb)}{B(t \to Wq)} \]

- CMS-PAS-TOP-12-035 (2013)
- CDF Note 10887 (2012)
- CMS-PAS-TOP-11-029 (2012)
- DØ PRL 107, 121802 (2011)
- DØ PRL 100, 192003 (2008)
- DØ PLB 639, 616 (2006)
- CDF PRL 95, 102002 (2005)
- CDF PRL 86, 3233 (2001)

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b-tagging efficiency

- Can determine b-tag efficiency and/or R
- b-tagging efficiency measured
  - (assume R=1)
- absolute *b-tagging* efficiency measured from data and predicted from simulation
- Ratio of data/simulation
- Total (stat.+syst.) uncertainties
Top quark decays and taus
Probing the Wtb vertex

• Measurement of ttbar cross section with tau leptons in final state is important:
  – channel not well explored
  – Cross-check to other channels
  – increase acceptance of ttbar events
  – involves only 3rd generation leptons/quarks
  – probe non-standard physics (t→H±b, …)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signature</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton(e/µ)</td>
<td>ee,µµ, eµ + 2b-jets</td>
<td>4/81</td>
</tr>
<tr>
<td>Single lepton</td>
<td>e,µ + jets + 2b-jets</td>
<td>24/81</td>
</tr>
<tr>
<td>All-hadronic</td>
<td>jets + 2b-jets</td>
<td>36/81</td>
</tr>
<tr>
<td>Tau dilepton</td>
<td>eτ, µτ +2 b-jets</td>
<td>4/81</td>
</tr>
<tr>
<td>Tau+jets</td>
<td>τ + jets + 2b-jets</td>
<td>12/81</td>
</tr>
</tbody>
</table>

• If top quark plays special role in EWK symmetry breaking, couplings to W may change
• Charged Higgs may alter coupling to W
• Search for final states with taus
Charged Higgs

- Tau dilepton channel is of particular interest as existence of charged Higgs can give rise to \textit{anomalous} tau lepton production

If top decays: $t \rightarrow H^+ b \ (m_H < m_t - m_b)$

$\Rightarrow$ directly observable in this channel
Charged Higgs

- BR(t→H⁺b) could be large
- H⁺→t⁺νₜ enhanced if tanβ large

⇒ observe more taus

(tanβ: ratio of vacuum expectation values)

⇒ number of tau dilepton events can be large
Taus in top quark decays

- **Selection:**
  - one isolated lepton (e/µ)
  - OS tau
  - at least two jets (one b-tagged)
  - MET>30 (45) GeV

- **Determine τ fakes from data**
  - Expected to be dominated by quark/gluon jets
  - Conservative approach: average W+jets and QCD
Tau fake rate

- Main background from “fake” tau jets
- Background estimated from data:
  - Select “W+≥3 jets (1 lepton+MET+≥3 jets)
  - Apply to every jet the “jet→tau probability”
  - tau fake probability evaluated from data
  - Function of $p_T$, $\eta$, jet width
- Good agreement with expectations

Quark vs gluon jets:
- Different coupling to strong field
- Gluon jets have higher multiplicities and softer constituents
Reconstruct mass in $t\bar{t}$ events with taus

Good agreement between measurements and predictions (for all decay modes)

$\sigma_{t\bar{t}} = 186 \pm 13 \text{ (stat.)} \pm 20 \text{ (syst.)} \pm 7 \text{ (lumi.) pb}$

$\sigma_{t\bar{t}} = 143 \pm 14 \text{ (stat.)} \pm 22 \text{ (syst.)} \pm 3 \text{ (lumi.) pb}$

$\pm 4\%$

CMS Preliminary, $\sqrt{s}=7\text{ TeV}$

TOP-11-024

CMS e/\mu+jets
TOP-11-003 (L=0.8-1.1/fb)

CMS $t\bar{t}$+jets
TOP-11-004 (L=3.9/fb)

CMS dilepton (ee,\mu\mu,\epsilon\mu) TOP-11-005 final (L=2.9/fb)

arXiv:1208.2671

CMS dilepton (et,\mu\tau) arXiv 1203.6810 (L=2.2/fb)

PRD 85,112007(2012)

CMS all-hadronic
TOP-11-007 (L=1.1/fb)

ATLAS $\pm 15\%$

CMS $\pm 16\%$

PLB 717(2012)89

PRD 85(2012)112007
Is there a charged Higgs?

- If anomalous tau production in $t\bar{t}$ decays there may be contribution from charged Higgs decays.

**Yields in agreement with expectations ⇒ set limits**

$80 < m_{H^+} < 160$ GeV

$BR(t \rightarrow H^+b) < 2 - 3\%$

Michele Gallinaro - "The top quark: a tool for discoveries" - April 22, 2013

CMS HIG-11-019
ttbar resonances
How else is top produced?

**Standard Model LHC Single Top Production**

1. $q \rightarrow W^* b \rightarrow t \bar{b} 
   \begin{align*}
   &64.57^{+2.09}_{-0.71}^{+1.51}_{-1.74} \text{ pb} \\
   \text{Kidonakis, N.} &\text{ PRD83:091503, 2011}
   \end{align*}$

2. $q \rightarrow W^* b \rightarrow t \bar{b} 
   \begin{align*}
   &4.63 \pm 0.07^{+0.19}_{-0.17} \text{ pb} \\
   \text{Kidonakis, N.} &\text{ PRD81:054028, 2010}
   \end{align*}$

3. $q \rightarrow W^* b \rightarrow t \bar{b} 
   \begin{align*}
   &15.74 \pm 0.40^{+1.10}_{-1.14} \text{ pb} \\
   \text{Kidonakis, N.} &\text{ PRD82:054018, 2010}
   \end{align*}$

**Resonance Production?**

**Top Color-Assisted Technicolor**

OR

??????

For single top: see A. Onofre, Lecture #7 May 8, 2013
Top quark pair resonance

- No resonance expected in SM
- Why is Top so heavy?
  - new physics?
  - is third generation ‘special’?
  - couples predominantly to third generation quarks
- Top is relatively unknown experimentally
- Experimental check
  - search for a bump in the invariant mass spectrum
Search for resonances

- Semi-leptonic (muon+jets) channel
- $Z' \rightarrow t\bar{t}$ cross section normalized to SM $t\bar{t}$
- Progressive loss in reconstruction ability due to jet merging
Search for heavy resonances

- search for massive neutral bosons decaying via a ttbar quark pair
- use dilepton/lepton+jet final states (electron and muon)
  - Reconstruct $M_{ttbar}$ in different categories (e/µ, n-jets, n b-tags)
  - l+jet events: full event reconstruction
  - Dileptons: use NN approach to improve S-B separation
- systematics include shape (JES, b-tag, theory model) and rates (eff. bkg yields)
Search for ttbar+jet resonance

- Search for a heavy new particle M produced in association with a top quark:
  \[ p\bar{p} \rightarrow M t \rightarrow t\bar{q}t \]
- Resonance in the system t+jets or ttbar+jets
- Select events in lepton+jets channel with at least 5 jets and 1 b-tag

CDF: 8.7 fb\(^{-1}\)

\[ \int L \, dt = 8.7 \, \text{fb}^{-1} \]
Boosted topology

Boosted Heavy Particle

QCD Jet
Jets and boosted topology

Jet

Jet

Hadrons are clustered together to make jets
Boosted topology

• In many models there is high potential to discover new physics in the top sector in search for heavy resonances
  \[ pp \rightarrow X \rightarrow t\bar{t} \]

• Simple approach to merge neighboring jets

• At LHC energy, EWK scale particles produced beyond threshold
• Jets are highly collimated
• Jet-parton matching breaks down
• Decay products and FSR collected in a fat jet
Boosted jet topology

- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Decay products and FSR collected in a fat jet

See also CDF note 10234
Jet/Event selection

• Locate hadronic energy deposit in detector by choosing initial jet finding algorithm

• Impose jet selection cuts on fat jet
  – Recombine jet constituents with new algorithm
  – Filtering: recombine n sub-jets min d(i,j)
  – Trimming: recombine sub-jets with min $p_T$

• Minimum distance between jets is $R$

UE, ISR, Pile-up, hard interaction
• **Highly boosted top**: three hadronic decays of the top are merged in one top jet.

• **Moderately boosted top**: three hadronic decays of the top are merged in one W jet plus and one b jet candidates.
Boosted top topology

Tested using hadronic top in semilep. tt events:
- One high-pT isolated muon from PV.
- At least two jets $p_T > 30$ GeV with a leading jet $p_T > 2$ GeV and at least one b-tagged jet.
- Events with W tagged jets used to reconstruct the W and the top mass of the hadronic side.
boosted semi-leptonic candidate event
Top quark and new physics

- Top quark production is main background in many searches for new physics
- Top quark sample may be contaminated by NP processes
- Is top quark sample compatible with top quark SM hypothesis?
- Need to compare distributions, gain good understanding of top sample
SUSY and 4th generation
Cross section measurements

One th. group predicts lower cross section values.
This study focuses on the mass range $100 \leq H^+ \leq 160 \text{ GeV/c}^2$, where we may observe an anomalous excess of events in the $\tau$ dilepton channel when compared to the SM decay of $t\bar{t} \rightarrow W^+ W^- b\bar{b} \rightarrow \tau \nu \tau l \nu_b b\bar{b}$, \( l = e, \mu \).

If top decays: $t \rightarrow H^+ b$ (\( m_H < m_t - m_b \))

\[ \Rightarrow \text{probe non-standard physics (} t \rightarrow H^\pm b, \ldots \) \]
Scalar top quark

- SUSY is one plausible extension of the SM
- due to the heavy top quark, mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ can be large, such that the lighter stop $\tilde{t}_1$ can be even lighter than the top quark
- Decays dictated by mass spectrum of other SUSY particles

- Light stop:
  \[ m_{\tilde{t}_1} \lesssim m_t, \quad \tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm \rightarrow b + \tilde{\chi}_1^0 + \nu + \ell \]

- Heavy stop:
  \[ \tilde{t} \rightarrow t \tilde{\chi}_0 \]

i.e. similar signature as in $t\bar{t}$
SUSY: direct stop production

- Due to the large top mass, the scalar top quark can be lighter than the top quark
- 1st and 2nd generation squarks can be very heavy
- Direct stop production:
SUSY: search for scalar top

• Status:
  – Final state: both dileptons and 1lepton+MET +2jets+2b jets
  – limitations due to small xsec, large ttbar background

Example signal: stop(250) → b χ^±
  m(χ^0) = 50 GeV
  x = 0.75

Hooberman et al.
Taus

• Assume each stop decays to tau and b (R-parity violation)

\[ \tilde{t}_1 \tilde{t}_1 \rightarrow \tau^+ \tau^- b \bar{b} \]

• Similar final state as in ttbar dilepton with taus

• Look for e/\mu + \geq 2 jets + MET

• Define 6 regions in: \( m_T(l, \text{MET}) \) vs \( N_{\text{jet}} \) plane

• Find 2 evts in signal region (2.2 expected)
Search for Dark Matter with taus

- search concentrates on heavy BSM particle production
  - astrophysical evidence for dark matter points to the existence of weakly-interacting massive particles (WIMPs) at EWSB scale
  - These particles escape detection ⇒ large MET

- Not constrained to a specific theory
  - general BSM search in events with jets, MET, and OS dileptons (at least one tau)
  - $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ final states
Multi-top production

- Production of 4 tops is an attractive scenario in a number of new physics models (SUSY, compositeness, resonances strongly coupled to top, etc.)
- The SM cross section is a few fb

Multi-top in SUSY?
\[ \tilde{g} \tilde{g} \rightarrow t\bar{t}t\bar{t}X_0X_0 \]

- Example: require one muon, at least 8 jets (one central)
- Yields in 30 fb\(^{-1}\) (gluino mass 450 GeV):
  - 330 signal events, 120 ttbar+jets, 30 W+jets
Multi-top production

- SUSY models with four top quarks
- Consider models of gluino pair production

Type A1: \( \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0 \)
Type A2: \( \tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \) (stop on-shell)

CMS Preliminary, \( \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 4.7 \text{ fb}^{-1} \)

Same Sign dileptons with btag selection

Exclusion \( \sigma^{\text{prod}} = \sigma^{\text{NLO+NLL}} \leq 1 \sigma \)

\( m(\tilde{\chi}_1^0) = 150 \text{ GeV} \)
\( m(\tilde{\chi}_1^0) = 50 \text{ GeV} \)
Multi-top production

- Study of SUSY signal with pairs of sbottom quarks

\[ \tilde{b}_1 \rightarrow t \chi^- \]

Type B1: \( pp \rightarrow \tilde{b}_1 \tilde{b}^*_1 \)
Type B2: \( pp \rightarrow \tilde{g} \tilde{b}_1, \quad \tilde{g} \rightarrow \tilde{b}_1 \tilde{b} \)

- Final states with up to 4 isolated leptons

\[ m(\tilde{b}_1) > 380 \text{ GeV} @95\% C.L. \]
• ttbar produced in association with H
  – ttbar is a “clean” tag
• direct measurement of H couplings
• Search for associated SM Higgs production: $ttH(\rightarrow b\bar{b})$
• Both “dilepton” and “l+jets” channels
  – ATLAS results only for l+jets ($\sim 11 \times$ SM)
• Simultaneous fit for S and B fractions
  – different categories: jet and b-jet multiplicity
• Use ANN to discriminate S and B
  – b-tagging information provides best discrimin.
• Main background: $tt\bar{t}(+b\bar{b}), Z+jets$
end