How to Measure Top Quark Mass with CMS Detector

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Outlines

- High Pt top basic idea
- Methods for jets selection
- Top quark mass reconstruction from jets
- Jets clustering and clusters method for $M_{\text{top}}^{\text{clus}}$
- Underlying Event (UE$_{\text{clus}}$) estimation and subtraction
- Systematics errors
- Summary
Large Hadron Collider (LHC) Experiment

Event Rate

\[ R = \sigma \times L = 80 \text{mb} \times 10^{34} \text{cm}^{-2} \text{s}^{-1} \approx 10^9 / \text{s} \]

\[ L = \frac{\gamma f k_b N_p}{4 \pi \varepsilon_n \beta} F = 10^{34} \text{cm}^{-2} \text{s}^{-1} \]

- Large distance collisions
  - Soft scattering
- Short distance collisions
  - Hard scattering (rare events)

Integrated luminosity = 10fb\(^{-1}\) = 10\(^{33}\) s\(^{-1}\) cm\(^{-2}\)
The CMS Detector

22 m long & 15 m in diameter

More than 1 Million Geometrical volumes

International Scientific Spring NCP, 01-06 March 2010
Top quark properties and Decays

- Heaviest particle (spin \(\frac{1}{2}\), charge 2/3)
- Origin of mass, EWSB
- Short life time
- No bound state

\[ \sigma(t\bar{t}) \approx 830 \pm 100 \text{ pb}^{-1} \]

- 90% lepton + jets
- 10% muons, b-jets, light jets (u,d,c,s), missing E_T(neutrinos)

\[ ~44\% \]

\[ ~29\% \]

\[ ~4.9\% \]
Boosted Top Quark Analysis

- Highly boosted top quarks: Decay back-to-back
- Higher top boost: Small opening angle of W-boson and b-quark
- High Pt top quarks: Large probability of jets overlapping in space.
- Invariant mass of the objects (jets/clusters) in larger cone around the top quark flight direction: Correlation with the real top quark mass.
- Top quark needs to have a larger boost: \( Pt > 200 \text{ GeV} \).

- Reduces the combinatorial background.
- The systematic effects due to jet energy calibration and gluon effects
- Potential to reduce the systematic errors
Kinematical variables

- Invariant mass
  \[ m^2 = p^\mu p_\mu = E^2 - p^2 \]
- Transverse momentum
  \[ p_T^2 = p_x^2 + p_y^2 \]
- Transverse mass
  \[ m_T^2 = m^2 + p_T^2 = E^2 - p_z^2 \]
- Transverse energy
  \[ E_T = E \sin \vartheta \]
- Pseudo-rapidity
  \[ \eta = - \ln \left( \frac{\tan \vartheta}{2} \right) \]
- Rapidity
  \[ y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) = \ln \left( \frac{E + p_z}{m_T} \right) \]
- Jet cone radius
  \[ \Delta R = \sqrt{\Delta \eta^2 + \Delta \varphi^2} \]
- Missing Transverse Energy
  \[ E_T^{\text{miss}} \]
Event Simulation: Tools and Methods

1. Event generation (PYTHIA, TOPREX, CMKIN)
2. Simulation of the interaction of the generated particles with the detector (OSCAR, FAMOS, CMSSW : GEANT4)
3. Simulation of digitized phase (FAMOS, CMSSW, ORCA)
   - Level-1 trigger (100 KHz)
   - High Level Trigger (100 Hz)
4. Local and global event reconstruction (FAMOS, CMSSW, ORCA)
5. Physics Analysis tools (PAW, ROOT)
Even Selection at Partonic Level

\[
t \bar{t} \rightarrow bW^+bW^- \rightarrow b\bar{q}q\mu\nu
\]

- \( P_t^{\text{top}} > 200 \text{ GeV}, |\eta| < 3.0 \)
- \( P_t^{\text{anti-top}} > 200 \text{ GeV}, |\eta| < 3.0 \)
- \( P_t^\mu > 30 \text{ GeV}, |\eta| < 2.0 \)
- \( P_t^q > 20 \text{ GeV}, |\eta| < 2.5 \)

Fast simulation based samples
- 165 Top mass point = 20K events
- 175 Top mass point = 50K events
- 185 Top mass point = 20K events

Pile-up events are included

Cross-section approximately 1% of the total tT cross-section

<table>
<thead>
<tr>
<th>No. of events With pile-up</th>
<th>Int. luminosity fb(^{-1})</th>
<th>X-section pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{t}t \rightarrow bW^+bW^- \rightarrow b\bar{q}qbl\nu )</td>
<td>49535</td>
<td>7.23</td>
</tr>
</tbody>
</table>
Distributions at Decay Vertex (1)

- $P_t^{\text{top}}$
  - Mean: 285.3 GeV
  - RMS: 80.27 GeV

- MC $\eta^{\text{top}}$
  - Mean: -0.039557
  - RMS: 1.469

- $\Delta R(q,q\bar{q})$
  - Mean: 1.38
  - RMS: 0.7437

- $P_t^W$
  - Mean: 169.6 GeV
  - RMS: 80.12 GeV

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Distributions at Decay Vertex (2)

\( \Delta R(\text{top,b-par}) \)

\( \Delta R(\text{top,W}) \)

\( \Delta R(\text{top, min W-quarks}) \)

\( \Delta R(\text{top, max W-quarks}) \)
Reconstruction

- MET -> Missing Transverse Energy
- MET > 30 GeV
- At least 1 iso. muon, $P_T > 20$ GeV, $|\eta| < 2.0$

leptonic W reco mass

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Muon reconstruction and isolation

Isolation Criteria

\[ \sum \frac{P_{T_{\text{trks}}}}{P_{T_{\mu}}} < 5\% \]
\[ (\Delta R = 0.01 - 0.2) \]
Efficiency > 92%

Most likely muon tracks
Leading light jets $P_t^{\text{jets}} > 20$ GeV

Leading b-jets $P_t^{b\text{-jets}} > 20$ GeV

combined b-tag discriminator

combined b-tag disc. > 0

(60% b-tag efficiency based on the secondary vertex, a vertex which is displaced from the primary vertex.)
Jet-Parton Matching

- 2 light jets corresponds to 2 quarks from W boson
- Four possible jet combinations
- Take best combination which gives correctly matching

Correctly matched if $\Delta R < 0.4$

$\Delta R(j_1,q_1)$
$\Delta R(j_1,q_2)$
$\Delta R(j_2,q_1)$
$\Delta R(j_2,q_2)$
$I_1 = \text{Max (}\Delta R(j_1,q_1), \Delta R(j_1,q_2))$
$I_2 = \text{Max (}\Delta R(j_2,q_1), \Delta R(j_2,q_2))$
$\text{Min}(I_1, I_2) < 0.4$
Various Approaches for Jets Selection

Steps to measure top quark direction

- Leading jets $\geq 2$ b-tagged jets, $\geq 2$ non b-tagged jets
- Exactly 4 jets, =2 b-tagged jets, = 2 non b-tagged jets
- $> 2$ leading b-jets, 2 light jets with $m_{jj}$ closest to W mass
Top Quark Selection: Leading Jets Topology

1 quark matched = 42.7%
2 quarks matched = 18.17%

<table>
<thead>
<tr>
<th>Kinematical cuts</th>
<th>Selection efficiency %</th>
<th>No. of events</th>
</tr>
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<tbody>
<tr>
<td>Before selection</td>
<td>100</td>
<td>49535</td>
</tr>
<tr>
<td>no of iso. muons</td>
<td>93.6</td>
<td>46370</td>
</tr>
<tr>
<td>≥ 1 iso muon $P_T &gt; 30$ GeV</td>
<td>92.7</td>
<td>45920</td>
</tr>
<tr>
<td>≥ 1 reco light jets $P_T &gt; 20$ GeV</td>
<td>91.1</td>
<td>45117</td>
</tr>
<tr>
<td>≥ 2 reco light jets $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>≥ 1 b-jet $P_T &gt; 20$ GeV</td>
<td>55.6</td>
<td>27543</td>
</tr>
<tr>
<td>≥ 2 b-jets $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$</td>
<td>m_{jj} - m_W^{nom}</td>
<td>&lt; 20$ GeV</td>
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$m_W^{nom} = 65.24$ (gaussian fitted correctly jet-parton matching)

b-jet with biggest angle wr.t muon called Hadronic b-jets
**Top Quark Selection: Four Jets Topology**

**Hadronic top selection**
- Four highest Pt jets selection
- b-jets identification with b-tagging
- Two light jets invariant mass reconstruction
- Hadronic b-jet requires
  - for away from isolated muon with maximum distance 0.4
  - or closests to light jets

1 quark matched = 20.98%
2 quarks matched = 43.26%

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<tr>
<td>≥ 1 reco light jets P_t &gt; 20 GeV</td>
<td>92.7</td>
<td>45915</td>
</tr>
<tr>
<td>Exectly 4 jets</td>
<td>η</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>Exectly 2 light jets</td>
<td>8.0</td>
<td>3941</td>
</tr>
<tr>
<td>Exectly 2 b-jets</td>
<td>8.0</td>
<td>3941</td>
</tr>
<tr>
<td></td>
<td>mjj − m_W</td>
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- Four highest Pt jets selection
- b-jets identification with b-tagging
- Two light jets invariant mass reconstruction
- Hadronic b-jet requires
  - for away from isolated muon with maximum distance 0.4
  - or closests to light jets
**Top Quark Selection: J\(\rightarrow\)W**

1 quark matched = 20.76%
2 quarks matched = 40.6%

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<th>No. of events</th>
</tr>
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<tbody>
<tr>
<td>Before selection</td>
<td>100</td>
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</tr>
<tr>
<td>no of iso muons, (P_t &gt; 30 \text{ GeV},</td>
<td>\eta</td>
<td>&lt; 2.0)</td>
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<tr>
<td>2 jj (\rightarrow)W, (P_t &gt; 20 \text{ GeV},</td>
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<td>&lt; 2.5)</td>
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<tr>
<td>(\geq 2) b-jets (P_t &gt; 20 \text{ GeV},</td>
<td>\eta</td>
<td>&lt; 2.5)</td>
</tr>
<tr>
<td>(</td>
<td>m_{jj} - m_W</td>
<td>&lt; 20 \text{ GeV} )</td>
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</table>

**Histograms:**
- Number of events vs recoil top mass (true) and wrong.
- Distributions of \(W_i\) and \(W_j\) with and without event selection.
W Mass from Three Approaches

Nominal mass—fitted mass ~ 65 GeV

Same $m_W^{\text{nominal}}$ used in all selections (JPM)
Comments on $M_{jjb}$

- Study based on shape of distributions for top direction determination.
- Explored three types of selection criteria for hadronic top mass reconstruction
  - Four jets selection results low efficiency with higher W purity
  - Jets with invariant mass close to W have higher efficiency with intermediate purity of W
  - Leading jets selection gives sharp and narrow dist. shape with less long tail behaviour and reasonable selection efficiency
Top Quark Selection: Leading Jets Topology

- First peak from the wrong jet combination
  - Exchanging the leptonic b-jet into hadronic b-jet
  - One of the 4 leading jets could be coming from the gluon radiation
  - Soft QCD events

- Second peak corresponds to the correct combinations
  - At preselection level we demand high Pt jets

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**Mean** 0.9274  
**Meany** 146.8  
**RMS** 0.224  
**RMSy** 77.97

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**Top P_T (GeV/c)**

- Right
- Wrong

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**Efficiency ~ 2%**

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**Entries** 4306  
**Mean** 144  
**RMS** 78.17

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**Entries** 945  
**Mean** 157  
**RMS** 51.66
Calibrated Top Quark Mass

Peaks are shifted towards the nominal Top mass
Invariant mass of all calorimeters clusters in $\Delta \eta \times \Delta \phi$ around top direction

Calorimetric Clusters Reconstruction Method

$$m_{\text{clusters}}(\Delta R) = (E^2 - P^2) = \left( \sum_{i=0.7} E_i \right)^2 - \left( \sum_{i=0.7} P_i \right)^2$$

- $E_i$ represents total energy of the $i$th cluster
- $nDR$ runs over all clusters within selected cone size
- $P_i$ its 3-momenta vector
- Known: $E, \eta, \varphi$ about clusters
- Assumptions: considering particles to be mass-less

$m \approx 0 \Rightarrow E^2 \equiv P^2$

$$Px = E \sin \vartheta \cos \phi$$

$$Py = E \sin \vartheta \sin \phi$$

$$Pz = E \cos \vartheta$$
Reco clusters pseudo-rapidity

$E^{Th}_{\text{clus}} > 1 \text{ MeV}$

Calorimeters identifications

\[ R = \sqrt{X^2 + Y^2} \]

- ECAL ($|Z|<350 \text{ cm, } R < 170 \text{ cm}$)
- HCAL ($|Z|<350 \text{ cm, } R < 300 \text{ cm}$)

\[ E_{\text{clus}}^L = 2 \text{ GeV} \]
$E_T^{\text{clus}}$ Deposition

![Histograms showing $E_T^{\text{clus}}$ deposition for different layers and pseudorapidity regions.](image-url)
**M_{top}^clus** Determination

Clusters lie close to the top quark flight direction

Reduce intrinsic complexities of effects due to energy leakage outside a narrow cone

Reduce system errors arising due to jet calibration

Jets decay back-back
It is not only minimum bias event. The underlying event is everything except the two outgoing hard scattered jets. In a hard scattering process, the underlying event has a hard component (initial+final state radiation and particles from the outgoing hard scattered partons) and a soft component (beam-beam remnants).

### Jet Isolation

| $|\eta| <$ 0.7 | $|\eta| <$ 1.4 | $|\eta| <$ 2.1 | $|\eta| <$ 3.0 | $|\eta| >$ 3.0 | $|\eta| >$ 5.0 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **$\Delta R = 0.7$** | 626.89          | 509.19          | 445.77          | 363.00          | 236.77          | 326.78          |
|                 | 38              | 88              | 134             | 229             | 182             | 352             |
| **$\Delta R = 0.8$** | 623.07          | 503.17          | 439.69          | 356.43          | 236.76          | 321.39          |
|                 | 33              | 80              | 125             | 218             | 181             | 33              |
| **$\Delta R = 0.9$** | 618.47          | 496.66          | 433.11          | 349.36          | 236.69          | 315.67          |
|                 | 29              | 73              | 116             | 180             | 330             | 208             |
| **$\Delta R = 1.1$** | 614.85          | 485.24          | 420.82          | 335.58          | 236.35          | 304.62          |
|                 | 22              | 22              | 22              | 22              | 22              | 22              |
| **$\Delta R = 1.5$** | 599.83          | 459.49          | 394.11          | 306.64          | 237.03          | 283.05          |
|                 | 8               | 28              | 66              | 136             | 169             | 53              |

### Electromagnetic Calorimeter

| $|\eta| <$ 0.7 | $|\eta| <$ 1.4 | $|\eta| <$ 2.1 | $|\eta| <$ 3.0 | $|\eta| >$ 3.0 | $|\eta| >$ 5.0 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **$\Delta R = 0.7$** | 201.24          | 173.59          | 102.26          | 708             | 102.26          | 708             |
|                 | 76              | 81              | 708             | 708             | 309             | 1383            |
| **$\Delta R = 0.8$** | 199.50          | 172.54          | 100.71          | 100.71          | 53.99           | 78.73           |
|                 | 66              | 66              | 66              | 66              | 66              | 66              |
| **$\Delta R = 0.9$** | 198.50          | 171.20          | 99.28           | 99.28           | 54.01           | 76.23           |
|                 | 57              | 146             | 630             | 630             | 303             | 1285            |
| **$\Delta R = 1.1$** | 197.46          | 168.08          | 96.26           | 96.26           | 54.17           | 73.79           |
|                 | 41              | 112             | 546             | 546             | 283             | 1175            |
| **$\Delta R = 1.5$** | 182.09          | 164.27          | 91.25           | 90.88           | 54.77           | 86.68           |
|                 | 16              | 55              | 372             | 922             | 266             | 922             |

### Hadronic Calorimeter

It is not only minimum bias event. The underlying event is everything except the two outgoing hard scattered jets. In a hard scattering process, the underlying event has a hard component (initial+final state radiation and particles from the outgoing hard scattered partons) and a soft component (beam-beam remnants).
A correlation with a slope about 0.7866 is observed, which implies that error of 0.9 GeV in the mean of peak translates to statistical uncertainty of $0.9/0.786 = 1.1456$ GeV/c in $M_{jjb}$ and $1.1 - 1.6$ GeV/c in $M_{clus}^{top}$.  

50K events corresponds to 7.2 fb$^{-1}$, statistical uncertainty about $\delta m = 1 - 1.5$ GeV on top mass.
<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\Delta m_{\text{top}}$(GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re-calibration</td>
<td>0.9</td>
</tr>
<tr>
<td>Electronic noise</td>
<td>1.2</td>
</tr>
<tr>
<td>ISR on/off</td>
<td>0.14</td>
</tr>
<tr>
<td>FSR on/off</td>
<td>0.07</td>
</tr>
<tr>
<td>B-quark fragmentation</td>
<td>0.3</td>
</tr>
<tr>
<td>UE estimate (+-10%)</td>
<td>1.34</td>
</tr>
<tr>
<td>Cluster mis calibration: +/-1(5) %</td>
<td>0.7(1.3)</td>
</tr>
<tr>
<td>Calorimeter: e/h=1.25 (1.63)</td>
<td>0.8(0.3)</td>
</tr>
</tbody>
</table>
An alternate method for top mass reconstruction in CMS is presented, which strongly depends on CMS Calorimeters.

A new method for Underlying Event (UE) estimation, subtraction and calibration is developed.

This analysis is performed with both Full and Fast Simulations techniques.

Statistical error on top mass $M_{jjb}(1-1.5 \text{ GeV})$ and $1.1 -- 1.6 \text{ GeV/c}$ in $M_{clus}^{\text{top}}$ is estimated.