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 $M_{\text{top clus}}$
- Underlying Event (UE$_{\text{clus}}$) estimation and subtraction
- Systematics errors
- Summary
**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: $Pt > 200$ GeV.

**WHY --?**

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

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First NCP School on LHC Physics, 12-30 October 2009
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
  \[ \eta = -\ln \left( \tan \frac{\vartheta}{2} \right) \]

- 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
  \[ E_T^{\text{miss}} \]
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

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

- \( P^\text{top}_t > 200 \text{ GeV}, |\eta| < 3.0 \)
- \( P^\text{anti-top}_t > 200 \text{ GeV}, |\eta| < 3.0 \)
- \( P^\mu_t > 30 \text{ GeV}, |\eta| < 2.0 \)
- \( P^q_t > 20 \text{ GeV}, |\eta| < 2.5 \)

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</th>
<th>Int. luminosity fb(^{-1})</th>
<th>X-section pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>With pile-up</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \bar{t}t \rightarrow bW^+bW^- \rightarrow bbq\bar{q}l\nu(l = \mu) )</td>
<td>49535</td>
<td>7.23</td>
</tr>
</tbody>
</table>
Distributions at Decay Vertex (1)

**$P_t^{top}$**

![Graph of $P_t^{top}$]

- **Mean:** 285.3
- **RMS:** 80.27

**MC $\eta^{top}$**

![Graph of MC $\eta^{top}$]

- **Mean:** 0.9985
- **RMS:** 1.469

**$\Delta R(q,qbar)$**

![Graph of $\Delta R(q,qbar)$]

- **Mean:** 1.38
- **RMS:** 0.7437

**$P_t^W$**

![Graph of $P_t^W$]

- **Mean:** 169.6
- **RMS:** 80.12
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
Isolation Criteria

$$\sum \frac{P_{T,\text{tracks}}}{P_{T,\mu}} < 5\%$$  
$$\Delta R = 0.01-0.2$$  
Efficiency $> 92\%$

Most likely muon tracks
Jets Reconstruction and Identification

**combined b-tag discriminator**

\[ \text{combined b-tag disc.} > 0 \]

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

**Leading light jets**

\[ P_T^{\text{light jets}} > 20 \text{ GeV} \]

**Leading b-jets**

\[ P_T^{b\text{-jets}} > 20 \text{ GeV} \]

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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 $\Delta R < 0.4$

Four possible jet combinations:

- $(J_1,j_2), (q_1, q_2)$
- $(J_1,q_1), (j_1,q_2)$
- $(j_2, q_1), (j_2,q_2)$

$\Delta R(j_1,q_1)$
$\Delta R(j_1,q_2)$
$\Delta R(j_2,q_1)$
$\Delta R(j_2,q_2)$

$I_1 = \text{Max} (\Delta R(j_1,q_1), \Delta R(j_1,q_2))$
$I_2 = \text{Max} (\Delta R(j_2,q_1), \Delta R(j_2,q_2))$

Min($I_1, I_2$) < 0.4
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
### Kinematical cuts

<table>
<thead>
<tr>
<th>Kinematical cuts</th>
<th>Selection efficiency %</th>
<th>No. of events</th>
</tr>
</thead>
<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>$\geq 1$ iso muon $P_T &gt; 30$ GeV</td>
<td>92.7</td>
<td>45920</td>
</tr>
<tr>
<td>$\geq 1$ reco light jets $P_T &gt; 20$ GeV</td>
<td>91.1</td>
<td>45117</td>
</tr>
<tr>
<td>$\geq 2$ reco light jets $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$\geq 1$ b-jet $P_T &gt; 20$ GeV</td>
<td>55.6</td>
<td>27543</td>
</tr>
<tr>
<td>$\geq 2$ b-jets $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$</td>
<td>m_{jj} - m_{WW}^{nom}</td>
<td>&lt; 20$ GeV</td>
</tr>
</tbody>
</table>

$m_{WW}^{nom} = 65.24$ (gaussian fitted correctly jet-parton matching)

**b-jet with biggest angle wr.t muon called Hadronic b-jets**

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

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<td>92.7</td>
<td>45916</td>
</tr>
<tr>
<td>≥ 1 reco light jets $P_t &gt; 20$ GeV</td>
<td>92.7</td>
<td>45915</td>
</tr>
<tr>
<td>Exactlty 4 jets $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>Exactlty 2 light jets</td>
<td>8.0</td>
<td>3941</td>
</tr>
<tr>
<td>Exactlty 2 b-jets</td>
<td>8.0</td>
<td>3941</td>
</tr>
<tr>
<td>$</td>
<td>m_{jj} - m_W</td>
<td>&lt; 20$ GeV</td>
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</table>
Top Quark Selection: \( JJ \rightarrow W \)

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

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<tr>
<td>Before selection</td>
<td>100</td>
<td>49535</td>
</tr>
<tr>
<td>no of iso muons, ( P_t &gt; 30 \text{ GeV},</td>
<td>\eta</td>
<td>&lt; 2.0 )</td>
</tr>
<tr>
<td>2 ( jj \rightarrow W, P_t &gt; 20 \text{ GeV},</td>
<td>\eta</td>
<td>&lt; 2.5 )</td>
</tr>
<tr>
<td>( \geq 2 \text{ 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>
Nominal mass—fitted mass ~ 65 GeV

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

Comments on $M_{jjb}$
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

\[ \Delta R(jets-jets) \]

\[ 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 \]

\[ T \] \[ P_T \] (Top)

\[ 100 \ 150 \ 200 \ 250 \ 300 \ 350 \ 400 \ 450 \ 500 \]

\[ 0 \ 20 \ 40 \ 60 \ 80 \ 100 \]

\[ M_{jib}(P_{T_{top}}>200 \text{ GeV}) \]

Efficiency ~ 2%
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
- \( P_i \) is its 3-momenta vector
- Known: \( E, \eta, \phi \) about clusters
- Assumptions: considering particles to be mass-less

\[
m \approx 0 \Rightarrow E^2 \equiv P^2
\]
\[
P_x = E \sin \vartheta \cos \phi
\]
\[
P_y = E \sin \vartheta \sin \phi
\]
\[
P_z = E \cos \vartheta
\]
Reco clusters pseudo-rapidity

$E_{\text{clus}}^{\text{Th}} > 1\text{MeV}$

Calorimeters identifications

$$R = \sqrt{X^2 + Y^2}$$

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

![Graphs showing $E_T^{\text{clus}}$ distribution for different layers and eta regions.](image)
Reduce intrinsic complexities of effects due to energy leakage outside a narrow cone
Reduce system errors arising due to jet calibration
UE Estimation Method

- 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 variable

### Electromagnetic Calorimeter

<table>
<thead>
<tr>
<th>Jet Isolation</th>
<th>$&lt;E_t&gt;$ / cluster (MeV)</th>
<th>$&lt;E_t&gt;$ / high $P_t$ event</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 0.7$</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.4$</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.1$</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 3.0$</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&gt; 3.0$</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 5.0$</td>
</tr>
</tbody>
</table>

### Hadronic Calorimeter

<table>
<thead>
<tr>
<th>Jet Isolation</th>
<th>$&lt;E_t&gt;$ / no of clusters / high $P_t$ event</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
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<td>$</td>
<td>\eta</td>
</tr>
</tbody>
</table>

### Jet Isolation variable

- Hadronic Calorimeter
- Electromagnetic Calorimeter

- Min $\Delta R(jets,clus) > 0.7$
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 an 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.
### Systematic

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\Delta m_{\text{top}}$ (GeV/c²)</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.