Top physics and the top mass

Lecture 2/3

2013 CERN-Fermilab HCP Summer School

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Vrije Universiteit Brussel, Belgium
(and this year also: LHC Physics Centre, Fermilab)
Outline

• **Wednesday:**
  – Lecture 1: Intro to top physics and its jargon.

• **Thursday:**
  – Lecture 2: SM top physics and the top mass
    • Top mass physics motivation
    • Measuring top properties
    • QCD motivations for precision top physics

• **Friday:**
  – Lecture 3: SM and top physics, the portal to physics searches
The building blocks of matter

**Charge**

<table>
<thead>
<tr>
<th>Charge</th>
<th>Leptons</th>
<th>Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Electron neutrino (Mass: &gt;0)</td>
<td>Up (Mass: 5)</td>
</tr>
<tr>
<td>1</td>
<td>Electron (Mass: 0.511)</td>
<td>Charm (Mass: 1,500)</td>
</tr>
</tbody>
</table>

**Masses**

- Electron (Mass: 0.511 MeV/c²)
- Muon (Mass: 105.7 MeV/c²)
- Tau (Mass: 1,777 MeV/c²)
- Top (Mass: 175,000 MeV/c²)
- Bottom (Mass: 4,250 MeV/c²)
- Up (Mass: 5 MeV/c²)
- Charm (Mass: 1,500 MeV/c²)
- Down (Mass: 8 MeV/c²)
- Strange (Mass: 160 MeV/c²)

*Lepton and quark sizes represent proportional mass*

*Top quark is heavy!!!*

Masses are in millions of Electron Volts [MeV/c²]
History of the top quark

- 1989: Indirect constraints on top from precision measurements at LEP

\[ w^+ \bar{b} w^+ \]

- 1995: Observation of Top-quark at the TeVatron collider at Fermilab

- Historic perspective indirect -> **direct measurements** -> precision
Top quark mass in Standard Model

- 68% and 95% CL fit contours w/o $M_W$ and $m_t$ measurements
- $m_t^{\text{kin}}$ Tevatron average $\pm 1\sigma$
- $M_W$ world average $\pm 1\sigma$

$M_W$ [GeV] vs. $m_t$ [GeV]
Template method

- Isolate a sample rich in top events
  - Use some form of b-quark identification
- Select the most likely combination of jets, leptons and missing transverse energy
- Have templates of top signal at different masses and of background
- For each event, determine probability signal or background
  - Fit which mass is most probable
  - Modern analyses also use different templates for the di-jet W candidates

DISADVANTAGE:
Only use one possible permutation of jets, leptons, missing energy
Matrix element method

\[ P_{\tilde{t}\tilde{t}} = \frac{1}{12\sigma_{\tilde{t}\tilde{t}}} \int d\rho_1 dm_1^2 dM_1^2 dm_2^2 dM_2^2 \times \sum_{\text{perm. }\nu} |M_{\tilde{t}\tilde{t}}|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \Phi_6 W_{\text{jets}}(E_{\text{part}}, E_{\text{jet}}) \]

- Method first used for top physics by DØ in Tevatron Run 1
- Use LO matrix element
  ‘Standard’ integral (20D)
- put in all known information
  – Eight jet angles
  – Lepton 3-momentum
  – Conservation of energy and momentum (4x)

- Do Monte Carlo integration
  – |M(top)| for range of top masses
  – |M(BG)|^2 not dependent of top mass
- Get signal probability per event
  – used in likelihood fit

DISADVANTAGE:
Very computing intensive
Ideogram method

- Already used in LEP era
- Compromise:
  - Use all different permutations in weighted probability
  - Also makes use of topological information
- Takes into account resolutions as observed in simulation
- Include b quark identification
- Include mis-tags
“In situ” jet energy calibration

• Tevatron top mass measurements use *in situ* jet energy calibration
  – = Fit energy scale of jets to W mass simultaneously with top mass

• Impressive decrease uncertainties wrt expected!

• Not always necessary at LHC as leading systematic uncertainties can be different
JES no longer only leading syst. Uncertainty?

- But of course still crucial for accurate measurement

CMS preliminary, $L = 1.6 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$

<table>
<thead>
<tr>
<th>JEC uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total uncertainty</td>
</tr>
<tr>
<td>Absolute scale</td>
</tr>
<tr>
<td>Relative scale</td>
</tr>
<tr>
<td>Extrapolation</td>
</tr>
<tr>
<td>Pile-up, NPV=12</td>
</tr>
<tr>
<td>Jet flavor</td>
</tr>
<tr>
<td>Time stability</td>
</tr>
</tbody>
</table>

Anti-$k_T$, $R=0.5$ PF, $|\eta_{jet}|=0$

$\sqrt{s} = 8 \text{ TeV}$

$\mathbf{CMS}$ preliminary, $L = 1.6 \text{ fb}^{-1}$

$\mathbf{ATLAS}$ Preliminary

Data 2012, $\sqrt{s} = 8 \text{ TeV}$

$\eta = 0.0$

Freya Blekman (IIHE-VUB)
So let’s look at some measurements
State of the art measurements

Measurement of $m_{\text{top}}$ in the lepton+jets channel

CMS TOP2012

ATLAS paper

new ATLAS result (EPS)

ATLAS di-lepton

CMS di-lepton

ATLAS all-jets

CMS all-jets

LHC comb, June 2012

LHC comb. uncert. band

ISR/FSR:
- Reduced the parameter range used for estimating ISR/FSR systematics, improvement based on jet-veto analysis

JES:
- Improved baseline uncertainty

bJES:
- 40% reduction of the MC based bJES uncertainty

MC Generators:
- Moved to Powheg+Pythia P2011C for default top quark MC, extensive study of generators and their tunes for top quark physics

Freya Blekman (IIHE-VUB)
Good sensitivity to the underlying top quark mass.

Large dependence on the jet energy scale $\rightarrow$ large systematics!

Large dependence on the b-jet energy scale $\rightarrow$ large systematics!

- ATLAS CONF-2013-046
- Determine top mass while simultaneously constraining jet energy scale for light and b jets
ATLAS 3D mass

Good sensitivity to the underlying top quark mass.

• Constrain JES using W mass instead of top mass

Large dependence on the jet energy scale → large systematics!

Large dependence on the b-jet energy scale → large systematics!
Reconstructed top quark mass \( m_{\text{top}}^{\text{reco}} \) signal PDFs from top-antitop MC, as a function of:

- **input** \( m_{\text{top}} \)
- **JES**
- **bJES**

Good sensitivity to the underlying top quark mass.

Large dependence on the jet energy scale → large systematics!

Large dependence on the b-jet energy scale → large systematics!

- **Constrain JES for b jets using ration bJES/light JES**

**ATLAS 3D mass**

**F Freya Blekman (IIHE-VUB)**
With Data, before fit

- All this information combined in 3D template fit
Repeat in 1 b-tag/2 b-tag/combined

- Fits are consistent
- JES and bJES almost uncorrelated

- (stat uncertainties only)
After applying fit consistent picture in all three variables

And \( m_{\text{top}} = 172.31 \pm 0.75 \pm 1.35 \) GeV

\( JES, \text{stat} \) 

Other systematic uncertainties
Systematic uncertainties

<table>
<thead>
<tr>
<th></th>
<th>2d-analysis</th>
<th></th>
<th>3d-analysis</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$m_{\text{top}}$ [GeV]</td>
<td>JSF</td>
<td>$m_{\text{top}}$ [GeV]</td>
<td>JSF</td>
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<tr>
<td>Measured value</td>
<td>172.80</td>
<td>1.014</td>
<td>172.31</td>
<td>1.014</td>
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<td>Data statistics</td>
<td>0.23</td>
<td>0.003</td>
<td>0.23</td>
<td>0.003</td>
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<tr>
<td>Jet energy scale factor (stat. comp.)</td>
<td>0.27</td>
<td>n/a</td>
<td>0.27</td>
<td>n/a</td>
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<td>Jet energy scale factor (stat. comp.)</td>
<td>n/a</td>
<td>0.67</td>
<td>n/a</td>
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<tr>
<td>Method calibration</td>
<td>0.13</td>
<td>0.002</td>
<td>0.13</td>
<td>0.002</td>
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<tr>
<td>Signal MC generator</td>
<td>0.36</td>
<td>0.005</td>
<td>0.19</td>
<td>0.005</td>
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<tr>
<td>Hadronisation</td>
<td>1.30</td>
<td>0.008</td>
<td>0.27</td>
<td>0.008</td>
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<tr>
<td>Underlying event</td>
<td>0.02</td>
<td>0.001</td>
<td>0.12</td>
<td>0.001</td>
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<tr>
<td>Colour reconnection</td>
<td>0.03</td>
<td>0.001</td>
<td>0.32</td>
<td>0.001</td>
</tr>
<tr>
<td>ISR and FSR (signal only)</td>
<td>0.96</td>
<td>0.017</td>
<td>0.45</td>
<td>0.017</td>
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<tr>
<td>Proton PDF</td>
<td>0.09</td>
<td>0.000</td>
<td>0.17</td>
<td>0.000</td>
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<td>Single top normalisation</td>
<td>0.00</td>
<td>0.000</td>
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<tr>
<td>$W+$jets background</td>
<td>0.02</td>
<td>0.000</td>
<td>0.03</td>
<td>0.000</td>
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<tr>
<td>QCD multijet background</td>
<td>0.04</td>
<td>0.000</td>
<td>0.10</td>
<td>0.000</td>
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<tr>
<td>Jet energy scale</td>
<td>0.60</td>
<td>0.005</td>
<td>0.79</td>
<td>0.004</td>
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<td>$b$-jet energy scale</td>
<td>0.92</td>
<td>0.000</td>
<td>0.08</td>
<td>0.000</td>
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<td>Jet energy resolution</td>
<td>0.22</td>
<td>0.006</td>
<td>0.22</td>
<td>0.006</td>
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<tr>
<td>Jet reconstruction efficiency</td>
<td>0.03</td>
<td>0.000</td>
<td>0.05</td>
<td>0.000</td>
</tr>
<tr>
<td>$b$-tagging efficiency and mistag rate</td>
<td>0.17</td>
<td>0.001</td>
<td>0.81</td>
<td>0.001</td>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>0.03</td>
<td>0.000</td>
<td>0.04</td>
<td>0.000</td>
</tr>
<tr>
<td>Missing transverse momentum</td>
<td>0.01</td>
<td>0.000</td>
<td>0.03</td>
<td>0.000</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.03</td>
<td>0.000</td>
<td>0.03</td>
<td>0.000</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>2.02</td>
<td>0.021</td>
<td>1.35</td>
<td>0.021</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>2.05</td>
<td>0.021</td>
<td>1.55</td>
<td>0.021</td>
</tr>
</tbody>
</table>
Underlying event

Underlying event

Hard process

$x_1 \cdot p_1$

$x_2 \cdot p_2$

beam remnants

multiple interactions

$p_1$

$p_2$
Other generator uncertainties

- **From $t \bar{t}$ Pair To Observable Final State**
  - Hard process: evolution to lower scales in PDFs and hardonization.
  - Initial State Radiation (ISR) \([\text{adds jets to the event}]\)
  - Final State Radiation (FSR) \([\text{takes energy from the jet}]\)
  - ISR + FSR = Parton Shower
  - Underlying Event (UE) \([\text{adds soft particles to the final state}]\)
  - Colour Reconnection (CR): colour exchange between the decay products, e.g. $q \bar{q}$ from W hardonizes collectively with the rest of the event.
  - Colour Reconnection affects final state hadrons direction

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Freya Blekman (IIHE-VUB)
What top mass, really?

• When measurements are so accurate question is what one really measures
  – The top quark mass is a parameter of the SM
    • Mass is usually defined as a pole mass or $\overline{\text{MS}}$ mass
    • Definition is confusing, we typically use pole mass when dealing with mass/yukawa couplings, while $\overline{\text{MS}}$ is used for prediction cross sections.
    • There is a transformation from one scheme to the other, but this relies on order of calculation and strong coupling constant.

• The measured mass effectively is a number we use as input to a MC generator
Derive top mass from cross section

- Comparison of most accurate ttbar cross section measurement and do transformation mass
  - Measure xsec for different mTop
    - And $\alpha_s$, best NNLO calculation
    - $M_{t}^{\text{pole}} = 176.7^{+3.8}_{-3.4}$ GeV
Or use cross section to find $\alpha_S$

- Use precise pole mass measurement and compare to cross section

- Derive $\alpha_S$ using NNLO theoretical cross section predictions
  \[
  \alpha_S(m_Z) = 0.1151^{+0.0033}_{-0.0032}
  \]

- Strong pdf dependence!
Summary

Top quark mass

- On-shell scheme (pole mass) at NNLO in QCD

\[ m_t = 173.18 \pm 0.94 \pm \mathcal{O} \text{(few)} \text{ GeV} \]

- Running mass (\( \overline{\text{MS}} \) scheme) at NNLO in QCD

\[ m_t(m_t) = 163.3 \pm 2.7 \text{GeV} \]
• In di-lepton events the di-lepton mass has a direct kinematic correlation to the top mass
  – Or with possible new physics particles if applied to cascade decays
• Measuring ‘endpoint’ of m(ll) distribution accurately means measuring the top quark mass accurately
• Basis of CMS endpoint measurement (arXiv:1304.5783)
Detailed fit with backgrounds included

- Small **Background contribution** derived from data
Advantage: very different syst. uncertainties

- Jet energy scale still there, but few theory/modeling uncertainties

\[ M_t = 173.9 \pm 0.9 \text{ (stat.)}^{+1.7}_{-2.1} \text{ (syst.) GeV}. \]

- Not the best measurement in the world, but still competitive!

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta M_t ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>+1.3</td>
</tr>
<tr>
<td></td>
<td>-1.8</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>±0.5</td>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>+0.3</td>
</tr>
<tr>
<td></td>
<td>-0.4</td>
</tr>
<tr>
<td>Fit range</td>
<td>±0.6</td>
</tr>
<tr>
<td>Background shape</td>
<td>±0.5</td>
</tr>
<tr>
<td>Jet and lepton efficiencies</td>
<td>+0.1</td>
</tr>
<tr>
<td></td>
<td>-0.2</td>
</tr>
<tr>
<td>Pileup</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>QCD effects</td>
<td>±0.6</td>
</tr>
<tr>
<td>Total</td>
<td>+1.7</td>
</tr>
<tr>
<td></td>
<td>-2.1</td>
</tr>
</tbody>
</table>
Lifetime method

- Boost of b quark correlated with top mass

- Decay length of secondary vertex can be used to measure top mass
  - Also possible: momentum of soft leptons from b-quarks
  - Technique pioneered by CDF
      (CMS PAS TOP-12-030)
Examine decay length in dilepton and $l+jets$ channels.

**$e\mu$-channel**

- Data
- $\tau$ (172.5 GeV)
- other flavors
- single top
- $Z \to ll$
- WW

**$e+jets$ channel**

- Data
- $\tau$ (172.5 GeV)
- QCD
- single top
- $Z \to ll$
- $W \to lv$

**$\mu+jets$ channel**

- Data
- $\tau$ (172.5 GeV)
- QCD
- single top
- $Z \to ll$
- $W \to Iv$

- CMS preliminary, $\sqrt{s} = 8$ TeV, $L = 19.3 - 19.6$ fb$^{-1}$

\[ \hat{L}_{xy} = 0.682 \pm 0.004 \text{ cm} \]
\[ m_t^{MC} = 173.7 \pm 2.0 \text{ GeV} \]

\[ \hat{L}_{xy} = 0.6536 \pm 0.0013 \text{ cm} \]
\[ m_t^{MC} = 172.8 \pm 1.0 \text{ GeV} \]

\[ \hat{L}_{xy} = 0.6690 \pm 0.0013 \text{ cm} \]
\[ m_t^{MC} = 173.2 \pm 1.0 \text{ GeV} \]

Freya Blekman (IIHE-VUB)
Again – different systematic uncertainties

<table>
<thead>
<tr>
<th></th>
<th>( \mu+\text{jets} )</th>
<th>( e+\text{jets} )</th>
<th>( e\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jet energy scale</strong></td>
<td>0.30 ± 0.01</td>
<td>0.30 ± 0.01</td>
<td>0.30 ± 0.01</td>
</tr>
<tr>
<td><strong>Multijet normalization (( \ell)+jets))</strong></td>
<td>0.50 ± 0.01</td>
<td>0.67 ± 0.01</td>
<td>-</td>
</tr>
<tr>
<td><strong>W+jets normalization (( \ell)+jets))</strong></td>
<td>1.42 ± 0.01</td>
<td>1.33 ± 0.01</td>
<td>-</td>
</tr>
<tr>
<td><strong>DY normalization (( \ell)\ell))</strong></td>
<td>-</td>
<td>-</td>
<td>0.38 ± 0.06</td>
</tr>
<tr>
<td><strong>Other backgrounds normalization</strong></td>
<td>0.05 ± 0.01</td>
<td>0.05 ± 0.01</td>
<td>0.15 ± 0.07</td>
</tr>
<tr>
<td><strong>W+jets background shapes (( \ell)+jets))</strong></td>
<td>0.40 ± 0.01</td>
<td>0.20 ± 0.01</td>
<td>-</td>
</tr>
<tr>
<td><strong>Single top background shapes</strong></td>
<td>0.20 ± 0.01</td>
<td>0.20 ± 0.01</td>
<td>0.30 ± 0.06</td>
</tr>
<tr>
<td><strong>DY background shapes (( \ell)\ell))</strong></td>
<td>-</td>
<td>-</td>
<td>0.04 ± 0.06</td>
</tr>
<tr>
<td><strong>Calibration</strong></td>
<td>0.42 ± 0.01</td>
<td>0.50 ± 0.01</td>
<td>0.21 ± 0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>( \mu+\text{jets} )</th>
<th>( e+\text{jets} )</th>
<th>( e\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Theory</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Q^2)-scale)</td>
<td>0.47 ± 0.13</td>
<td>0.20 ± 0.03</td>
<td>0.11 ± 0.08</td>
</tr>
<tr>
<td>ME-PS matching scale</td>
<td>0.73 ± 0.01</td>
<td>0.87 ± 0.03</td>
<td>0.44 ± 0.08</td>
</tr>
<tr>
<td>PDF</td>
<td>0.26 ± 0.15</td>
<td>0.26 ± 0.15</td>
<td>0.26 ± 0.15</td>
</tr>
<tr>
<td>Hadronization model</td>
<td>0.95 ± 0.13</td>
<td>0.95 ± 0.13</td>
<td>0.67 ± 0.10</td>
</tr>
<tr>
<td>B-hadron composition</td>
<td>0.39 ± 0.01</td>
<td>0.39 ± 0.01</td>
<td>0.39 ± 0.01</td>
</tr>
<tr>
<td>B-hadron lifetime</td>
<td>0.29 ± 0.18</td>
<td>0.29 ± 0.18</td>
<td>0.29 ± 0.18</td>
</tr>
<tr>
<td>Top quark ( p_T ) modeling</td>
<td>3.27 ± 0.48</td>
<td>3.07 ± 0.45</td>
<td>2.36 ± 0.35</td>
</tr>
<tr>
<td>Underlying event</td>
<td>0.27 ± 0.51</td>
<td>0.25 ± 0.48</td>
<td>0.19 ± 0.37</td>
</tr>
<tr>
<td>Colour reconnection</td>
<td>0.36 ± 0.51</td>
<td>0.34 ± 0.48</td>
<td>0.26 ± 0.37</td>
</tr>
</tbody>
</table>

**Leading systematic:** \( p_T^{top} \) modeling

**Final results**

<table>
<thead>
<tr>
<th>Channel</th>
<th>( m_t ) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon+jets</td>
<td>173.2 ± 1.0_{stat} ± 1.6_{syst} ± 3.3_{pT(t)}</td>
</tr>
<tr>
<td>electron+jets</td>
<td>172.8 ± 1.0_{stat} ± 1.7_{syst} ± 3.1_{pT(t)}</td>
</tr>
<tr>
<td>electron-muon</td>
<td>173.7 ± 2.0_{stat} ± 1.4_{syst} ± 2.4_{pT(t)}</td>
</tr>
</tbody>
</table>

**Combination of all channels**

\[
m_t^{MC} = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{pT}^{top}
\]

src: Stijn Blyweert @EPS-HEP 2013

Freya Blekman (IIHE-VUB)
Top quark mass in Standard Model
The top mass vs stability of the universe

- Constraints from the SM can also be used to assess stability of physics laws
  - Example: arXiv:1205.6497
End of lecture two – questions?