Top quark results using CMS data at 7 TeV

Karl M. Ecklund
Rice University
on behalf of the
CMS Collaboration
Compact Muon Solenoid

General Purpose Detector
- Precision Silicon Tracking
- EM Calorimeter
- Hadron Calorimeter
- 3.8 T Magnetic Field
- Muon Detectors

For Top:
- b-tag 2nd vertex
- Electrons
- Missing Energy
- Muons

Integrated Particle Flow Reconstruction

Transverse Slice

15 m

Longitudinal Slice

21 m

JINST 3 08004 (2008)
Transverse slice through CMS
CMS Data Samples

2010 Dataset
36 $\text{pb}^{-1}$ for Top Analysis
(good: calorimeters, muon, tracking)

2011 Dataset
$\sim 1.0 \text{ fb}^{-1}$ for Top Analysis available for EPS/DPF
Doubled again since restart of LHC Physics
Today Peak luminosity $> 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
Challenges for triggering on top samples
Motivation for Top Physics @ LHC

• Top is heavy
  ◦ large Yukawa - perhaps a role in EWSB
  ◦ loop corrections to Higgs mass ($m_t^2$)

• Precision measurements using top quarks
  ◦ top production and decay
  ◦ top properties can be probed for BSM physics
    • even if indirect, may be important confirmation of other discoveries!
  ◦ LHC is a top factory - large samples available
    • $160 \text{ pb} \times 1000 \text{ pb}^{-1} = 160 \text{ k t tbar pairs produced}$
    • kinematic reach beyond the Tevatron

• New Physics
  ◦ preferential coupling to top?
  ◦ new particles decaying to top ($Z'$, 4th generation, ...)
  ◦ new physics can modify top couplings
Top Pair Cross Section Measurements

- SM Production
  - gluon fusion \(\sim 85\% \text{ LHC}\)
  - \(qq\) annihilation \(\sim 15\% \text{ LHC}\)

- SM cross sections
  - \(\sigma_{\text{NNLO}} = 163^{+11}_{-10}\) pb \(\text{Kidonakis PRD 82 114030 (2010)}\)
  - \(\sigma_{\text{NNLO}} = 164^{+10}_{-13}\) pb \(\text{Langenfeld et al. PRD 80 054009 (2009)}\)

- SM Decay
  - Expect \(\sim 100\% \ t\rightarrow Wb \ (|V_{tb}|\sim 1)\)
  - \(tt\) channels characterized by \(W\) decays
    - dilepton: \(tt\rightarrow W^+bW^-b\rightarrow \ell^+\nu\ell^-\nu b\)
    - lepton+jets: \(tt\rightarrow \ell\nu bqqb\)
    - fully hadronic: \(tt\rightarrow qqqbqqb\)

2010 Results (36/pb): dilepton, lepton+jets
New Results (1.09/fb): Fully hadronic, \(\mu\tau\)

See S. Khalil talk for details (5pm)
Cross Section Summary

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

- **CMS hadronic**
  - TOP-11-007 (L=1.09/fb)
  - $136 \pm 20^{+40}_{-40} \pm 8$
    
  (val ± stat. ± syst. ± lumi)

- **CMS tau dilepton**
  - TOP-11-006 (L=1.09/fb)
  - $149 \pm 24^{+26}_{-26} \pm 9$
    
  (val ± stat. ± syst. ± lumi)

- **CMS combined**
  - TOP-11-001 (L=36/pb)
  - $158 \pm 18^{+6}_{-18}$
    
  (val ± tot. ± lumi)

- **CMS $t\bar{t}$+jets+btag**
  - TOP-10-003 (L=36/pb)
  - $150 \pm 9^{+17}_{-17} \pm 6$
    
  (val ± stat. ± syst. ± lumi)

- **CMS dilepton**
  - arXiv:1105.5661 (L=36/pb)
  - $168 \pm 18^{+14}_{-14} \pm 7$
    
  (val ± stat. ± syst. ± lumi)

- **CMS $t\bar{t}$+jets**
  - arXiv:1106.0902 (L=36/pb)
  - $173 \pm 14^{+36}_{-29} \pm 7$
    
  (val ± stat. ± syst. ± lumi)

- **NLO QCD**
  - MSTW2008(N)NLO PDF, scale @ PDF(90% C.L.) uncertainty

- **Approx. NNLO QCD**
  - (pp)

- **CMS combined (L=36 pb⁻¹)**
  - CDF
  - D0

- **Top Pair Production Cross Section [pb]**

- **$\sqrt{s}$ [TeV]**

- **NLO QCD (pp)**
  - Approx. NNLO QCD (pp)
  - Scale uncertainty
  - Scale @ PDF uncertainty
  - Approx. NNLO QCD (pT)
  - Scale uncertainty
  - Scale @ PDF uncertainty

- **See S. Khalil talk for details (5pm)**
Single Top Production

• Standard Model Production
  - $t$ channel
  - $tW$ channel
  - $s$ channel

• Probes New Physics through top couplings
  - non-SM production or decay
• Single top discovered at the Tevatron
• CMS Search for $t$-channel at 7 TeV
  - large cross section with distinctive signature
  - two searches with 2010 data (36/pb)

arXiv 1106.3052 CMS-PAS-TOP-10-008
See T. Speer talk for details 10 Aug
CMS Single Top t-channel

- Event Selection
  - $t \to W b$ with leptonic $W \to \ell \nu$ (e or $\mu$)
    - lepton: $p_T > 20$ GeV muons and $p_T > 30$ GeV electrons
    - Neutrino from Missing ET: require $M_T > 40$ (50) GeV $\mu$ (e)
  - Exactly two anti-$k_T$ jets ($R=0.5$) with $p_T > 30$ GeV $|\eta| < 5$
    - one jet $b$ tagged with high purity tagger

- Two analysis methods:
  - 2D template fit in $\eta_j$ and $\cos \theta^*_{\ell_j}$
    - t-channel signal has a non-central light jet & V-A predicts: $\frac{d\Gamma}{d \cos \theta^*} \propto 1 + A \cos \theta^*$
  - Multi-variate analysis using a boosted decision tree
    - 37 observables exploiting expected kinematics ($W$, top, $b$-jet, …)
    - higher sensitivity

- Backgrounds
  - QCD - modeled from data in control region using $M_T$
  - W+light jets - fit simultaneously or data-driven estimate
  - VQQ - MC normalized from top pair cross section analysis
Single Top Fits

Projections of 2D Fit

Binned bdt discriminant

Good Agreement in Control Region (no b-tag)

Both analyses find evidence for single top t-channel

arXiv 1106.3052 CMS-PAS-TOP-10-008

9 Aug 11

CMS Top Results - Karl.Ecklund@rice.edu
Single Top Measurement (t-channel)

- Combination of two analyses by BLUE (51% corr.)
  - $\sigma=83.6 \pm 30_{\text{stat+syst}} \pm 3_{\text{lumi}}$ pb
- Combined significance 3.5$\sigma$
- In agreement with SM
- 95% CL Limit on $|V_{tb}|$
  - $|V_{tb}|>0.62$ (0.68)
- Results accepted by PRL
  - arXiv 1106.3052 CMS-PAS-TOP-10-008
- Work in progress with >1/fb of 2011 data, including s,tW channels

See T. Speer talk for details 10 Aug
Top Mass in Dilepton Channel

Dilepton Channel 36 pb$^{-1}$

- Mass via two known techniques (Tevatron) with improvements
  - KINb
  - AMWT
- Careful systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>KINb</th>
<th>AMWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall jet energy scale</td>
<td>$+3.1/−3.7$</td>
<td>$3.0$</td>
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<tr>
<td>b-jet energy scale</td>
<td>$+2.2/−2.5$</td>
<td>$2.5$</td>
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<tr>
<td>Lepton energy scale</td>
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<tr>
<td>Underlying event</td>
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<tr>
<td>Pileup</td>
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<td>Jet-parton matching</td>
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<td>Factorisation scale</td>
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<td>Fit calibration</td>
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<td>MC generator</td>
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<td>Parton density functions</td>
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<tr>
<td>b-tagging</td>
<td>$0.3$</td>
<td>$0.5$</td>
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</tbody>
</table>

First top mass measurement from LHC

<table>
<thead>
<tr>
<th>Method</th>
<th>Measured $m_{\text{top}}$ (in GeV/c$^2$)</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMWT</td>
<td>$175.8 ± 4.9$ (stat.) $± 4.5$ (syst.)</td>
<td>0.65</td>
</tr>
<tr>
<td>KINb</td>
<td>$174.8 ± 5.5$ (stat.) $± 4.5$ (syst.)</td>
<td>0.35</td>
</tr>
<tr>
<td>Combined</td>
<td>$175.5 ± 4.6$ (stat.) $± 4.6$ (syst.) $\chi^2$/dof = 0.040 (p-value = 0.84)</td>
<td></td>
</tr>
</tbody>
</table>

See A. Avetisyan talk for details 12 Aug

9 Aug 11

CMS Top Results - Karl.Ecklund@rice.edu
Top Mass in Lepton + Jets

**Lepton+Jets Channel (36 pb⁻¹)**

- Again two methods
  - **Template Method**
    - jointly with jet energy scale
    - 2 btags required; µ+jets
  - **Ideogram Method**
    - event-by-event likelihoods
    - best precision from kinematic fit taking all event information

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<table>
<thead>
<tr>
<th>Source</th>
<th>Ideogram analysis δmₜ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES (overall data/MC)</td>
<td>+2.4-2.1</td>
</tr>
<tr>
<td>JES p_T and η dependence</td>
<td>-</td>
</tr>
<tr>
<td>light vs b-jet scale</td>
<td>-</td>
</tr>
<tr>
<td>JER (10% effect)</td>
<td>0.07</td>
</tr>
<tr>
<td>MET (10% effect)</td>
<td>0.4</td>
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<tr>
<td>Factorization scale</td>
<td>1.1</td>
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<td>ME-PS matching threshold</td>
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<td>ISR/FSR</td>
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<td>Underlying event</td>
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<tr>
<td>Pile-up effect</td>
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<tr>
<td>PDF</td>
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<td>Background</td>
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<td>B-tagging</td>
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<td>Fit calibration statistics</td>
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<tr>
<td>Total systematic uncertainty</td>
<td>+2.8-2.5</td>
</tr>
</tbody>
</table>

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**Ideogram Result: e/µ+jets**

**Preliminary**

\[ m_t = 173.1 \pm 2.1 \text{(stat)}^{+2.8}_{-2.5} \text{(syst)} \text{ GeV.} \]

**Combination with dilepton channel**

\[ m_t = 173.4 \pm 1.9 \text{(stat)} \pm 2.7 \text{(syst)} \text{ GeV.} \]
Top Pair Invariant Mass

CMS-PAS-TOP-10-007

- Resonance search in $t\bar{t}$
  - $Z'$, Kaluza-Klein gluons, ...
- “Low mass” analysis
  - following $(e/\mu)+$jet reconstruction
  - 8 channels
    - 3 jets w/ b-tag
    - 4 jets w/ 0,1,2 tags
  - kinematic fit
  - simultaneous template fits
- No deviation from SM
  - limits on narrow $Z'$

See S. Rappoccio talk for details 11 Aug
Top Pair Invariant Mass

See S. Rappoccio talk for details 11 Aug

- High mass/boosted tops
  - fully hadronic channel
  - using jet substructure or top/W tagging
    - validated with boosted μ+jet sample
- Data driven QCD bkgd

Limit on KK Gluons $M > 1.5$ TeV
Top Charge Asymmetry

Top - Anti Top asymmetries from interference of LO, box, radiative diagrams

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

Look at pseudorapidity or rapidity difference

Forward-backward
Observed by D0 & CDF
D0 PRL 100 142002 (2008)
CDF PRL 101, 202001 (2008)
arXiv 1101.0034

\~2\sigma Larger than SM; Esp. \( M_{tt} > 450 \) GeV
Perhaps new physics? Axigluons?

“Width” difference
CMS 36/pb
CMS-PAS-TOP-10-010

Now updated to 1.09/fb
CMS-PAS-TOP-11-014

SM Prediction
Tevatron \~5%
LHC \~1% (dilution from gg production)

Kuhn & Rodrigo PRL 81, 49 (1998)
(updated for pdfs, \( m_{\text{top}} \))

See M. Segala talk for details 12 Aug
Lepton + Jets
Discrimination from
• ≥1 b-tagged jet (new)
  & Template fits to
  • Missing ET
  • M3 as \( M_{\text{top}} \) estimator

Clean top sample

Best jet combination from
Likelihood using
• kinematics
• btagging
• \( m_t \), \( m_W \)

\[ M_3 = \text{invariant mass of 3 jets with max vector sum of } p_T \]
Raw and Unfolded Asymmetry

Raw asymmetry is background-subtracted
Then unfolded for acceptance & resolution effects

<table>
<thead>
<tr>
<th>Observable</th>
<th>Raw $A_C$</th>
<th>BG-subtracted $A_C$</th>
<th>Unfolded (and corrected) $A_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta</td>
<td>\eta</td>
<td>$</td>
<td>$-0.004 \pm 0.009$</td>
</tr>
<tr>
<td>$\Delta(y^2)$</td>
<td>$-0.004 \pm 0.009$</td>
<td>$-0.007 \pm 0.010$</td>
<td>$-0.013 \pm 0.026^{+0.026}_{-0.021}$</td>
</tr>
</tbody>
</table>
Top Charge Asymmetry Results

CMS Measurement 1.09/fb

\[ A_\eta^V = -0.016 \pm 0.030 \text{ (stat.)}^{+0.010}_{-0.019} \text{ (syst.)} \]

\[ A_\eta^V = -0.013 \pm 0.026 \text{ (stat.)}^{+0.026}_{-0.021} \text{ (syst.)} \]

SM Expectation

\[ A_\eta^V = 0.013 \pm 0.001 \]

\[ A_\eta^V = 0.011 \pm 0.001 \]

• No significant difference from SM
  ◦ No trends versus tt invariant mass (not yet unfolded in \( M_{tt} \))

See M. Segala talk for details 12 Aug
Summary & Conclusion

• Large samples of top quarks produced and analyzed
  ◦ Cross sections in agreement with (N)NLO SM predictions
    • Channels: dilepton (including \(\tau\)), lepton+jets, fully hadronic
  ◦ Single top: evidence seen at SM level for t-channel EWK production
  ◦ Future: differential cross sections

• Top mass measurement
  ◦ dilepton and lepton + jet channels at ~2% level

• Top samples used to probe for BSM physics
  ◦ Search for peaks in M(t t\(\bar{t}\)) - high M sensitivity beyond Tevatron
    • new jet substructure analysis in fully hadronic channel
  ◦ Charge asymmetry consistent with SM (needs statistics)
  ◦ And more properties to come: Wtb couplings, charge, ...

• Analysis of > 1 fb\(^{-1}\) in progress (updates coming soon)
CMS Top Presentations at DPF

- See dedicated CMS talks for additional analysis details
  - Top pair cross section - S. Khalil 9 Aug @ 5 pm
  - Single Top measurement - T. Speer 10 Aug @ 2 pm
  - New physics $M(t\bar{t})$ - S. Rappoccio 10 Aug @ 5:30 pm
  - $M_{top}$ - A. Avetisyan 12 Aug @ 8:40 am
  - $t\bar{t}$ charge asymmetry - M. Segala 12 Aug @ 9:40 am