Top quark production at CMS

Gabriele Benelli
University of Kansas
On behalf of the CMS Collaboration

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Top quark at the LHC

- Heaviest particle
  - Role in EWSB and BSM
- Decays before hadronizing:
  - Access bare quark from decay products (mostly b and W)
  - Measure mass, charge, spin and other properties
- The LHC is a top factory:
  - Precision results
  - Detailed differential measurements
  - Properties
- Top production benchmark for QCD theoretical predictions
- Instrumental for the commissioning of the experiments and for the rest of the LHC physics program
- Sensitive to new physics
Top Production at the LHC

- Top production mainly via strong interaction

- Electroweak interactions can produce single tops!

- CKM matrix element $V_{tb}$ is regulating also top decay:
Top quark production at CMS

- Covering a selection of recent top production results from CMS
  - Strong top pair production
  - Total and differential inclusive cross-section results
  - Electroweak single top production
  - Latest CMS results in all single top production channels
- Will not cover:
  - Associated production, mass, properties (see talks by Boris Mangano and Karl Ecklund)
- Summary of the current status
Top pair total x-sect @ 7TeV

Summary of all CMS 7TeV total pair production cross-section results

![Graph showing CMS Preliminary, $\sigma_{tt}$ summary, $\sqrt{s} = 7$ TeV results including CMS e/\mu+jets, CMS dilepton (ee,\mu,\mu), CMS dilepton ($e/\mu+\tau_{had}$), CMS $\tau_{had}$+jets, CMS all jets results with error bars and uncertainties.](graph.png)
Top pair total production $x$-sect

Dilepton channel ($ee, \mu\mu, e\mu$)

- Selection:
  - Two isolated oppositely charged leptons
  - At least two jets, at least one $b$-tagged

- Main backgrounds Drell-Yan (DY), single top, diboson events

- Single top and diboson from MC, Drell-Yan and fake leptons from data
Top pair total production x-sect

Cross-section measurement:

- Event counting
- Background subtraction

### Table

<table>
<thead>
<tr>
<th>System</th>
<th>e^+e^-</th>
<th>(\mu^+\mu^-)</th>
<th>e^\pm\mu^\mp</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\epsilon_{\text{total}}) (%)</td>
<td>0.203 ± 0.012</td>
<td>0.270 ± 0.017</td>
<td>0.717 ± 0.033</td>
</tr>
<tr>
<td>(\sigma_{t\bar{t}}) (pb)</td>
<td>244.3 ± 5.2 ± 18.6 ± 6.4</td>
<td>235.3 ± 4.5 ± 18.6 ± 6.1</td>
<td>239.0 ± 2.6 ± 11.4 ± 6.2</td>
</tr>
</tbody>
</table>

- Main systematics: signal modeling and Jet Energy Scale (JES)
- BLUE combination of three channels (for a 172.5 GeV top mass):

\[ \sigma_{t\bar{t}} = 239.0 \pm 2.1 \text{(stat.)} \pm 11.3 \text{(syst.)} \pm 6.2 \text{(lum.)} \text{ pb} \]

- Mass dependence quadratic in the range 160-185 GeV
- In agreement with NNLO perturbative QCD theoretical prediction:

\[ \sigma_{t\bar{t}} = 252.9^{+6.4}_{-8.6} \text{(scale)} \pm 11.7 \text{(PDF + } \alpha_s \text{)} \text{ pb} \]

JHEP 02 (2014) 024

Top pair differential cross-sections

- Differential cross-sections as a function of several top and top decay products kinematic variables probe perturbative QCD:
  - Different regions of phase space
  - Test and tune models with measurements
  - Increased sensitivity/window to new physics effects
  - Helpful to Higgs and Beyond the Standard Model (BSM) analyses
  - Full top reconstruction necessary
- Unfolding techniques used:
  - Account for acceptance and detector effects
  - Parton or particle level information to compare with generators
Top pair differential x-sect

- General strategy:

Dilepton

CMS PAS TOP-12-028

8 TeV 12.2 fb$^{-1}$

Selection

Bin by bin counting:
- Background subtraction
- Unfolding

CMS Preliminary, 12.2 fb$^{-1}$ at $\sqrt{s} = 8$ TeV

Kin. Reconstruction

Diff. x-section

CMS Preliminary, 12.2 fb$^{-1}$ at $\sqrt{s} = 8$ TeV

L+Jets

CMS PAS TOP-12-027
Top pair differential x-sect dilepton

- Normalized differential cross-sections measured as a function of:
  - \( p_{T,\text{Lead},t} \), \( y_{\text{Lead},t} \), \( p_{T,\text{NLead},t} \), \( y_{\text{NLead},t} \), \( p_{T,t} \), \( y_t \), \( p_{T,t^t} \), \( y_{t^t} \), \( m_{t^t} \)
  - \( p_{T,\text{Lead},l} \), \( \eta_{\text{Lead},l} \), \( p_{T,\text{NLead},l} \), \( \eta_{\text{NLead},l} \), \( p_{T,\text{Lead},b} \), \( p_{T,b} \), \( m_{b} \), \( \eta_{\text{Lead},b} \), \( p_{T,\text{NLead},b} \), \( \eta_{\text{NLead},b} \), \( m_{lb} \)

- Tension with theory predictions for top \( p_T \) softer in data than MC:

- Better agreement with approximate NNLO

- Effect present also in 7TeV data and in lepton+jets final state
Top pair differential cross-sections

- Event level variables in lepton+jets:
  - Template fit to determine background then unfolding
  - Key variables used in SM, rare processes and new physics searches
- $H_T = \sum_{all\text{jets}} p_T^{\text{jet}}$
- $S_T = H_T + E_{T\text{miss}} + p_T^{\text{lepton}}$
- $\sum_{W} p_T^{W} = \sqrt{(p_T^{lepton} + p_{T\text{miss}})^2 + (p_y^{lepton} + p_{T\text{miss}})^2}$
- $M_T^{W} = \sqrt{(E_T^{lepton} + E_{T\text{miss}})^2 - p_T^{W^2}}$

- Overall good agreement with theoretical predictions (similar to 7TeV)
- Main systematics: model uncertainties, JES and fit/unfolding
Single top at the LHC

- Three single top production modes:
  - **s-channel**
  - **t-channel**
  - **tW**

- Electroweak interaction production and decay
- Access to CKM element $V_{tb}$
- Sensitive to new physics, backgrounds to several analyses
- Top cross-sections at Tevatron and the LHC

### Cross sections (pb)

<table>
<thead>
<tr>
<th></th>
<th>s-channel</th>
<th>t-channel</th>
<th>tW channel</th>
<th>top pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tevatron: <a href="mailto:ppbar@1.96TeV">ppbar@1.96TeV</a></strong></td>
<td>1.05</td>
<td>2.08</td>
<td>0.22*</td>
<td>7.08</td>
</tr>
<tr>
<td>(arxiv.org/pdf/0909.0037)</td>
<td></td>
<td></td>
<td>*arxiv.org/pdf/0909.0037</td>
<td></td>
</tr>
<tr>
<td><strong>LHC: pp @ 7 TeV</strong></td>
<td>4.56</td>
<td>65.9</td>
<td>15.6</td>
<td>163</td>
</tr>
<tr>
<td><strong>LHC: pp @ 8 TeV</strong></td>
<td>5.55</td>
<td>87.2</td>
<td>22.2</td>
<td>234</td>
</tr>
</tbody>
</table>

*Top mass = 173 GeV*

tW not accessible at Tevatron
Single top $t$-channel

- Highest single top production cross-section
- Systematics dominated measurement
- Only leptonic $W$ decays considered ($e, \mu$ final states):
  - **Lepton + jets** topology:
    - Light quark jet (large $|\eta_{j'}|$)
    - Isolated lepton ($\mu$ or $e$)
    - Missing Transverse Energy ($\nu_e$ or $\nu_\mu$)
    - Central high $p_t$ b-jet
  - Potential extra b-jet, broad $|\eta|$ and low $p_t$
  - Main backgrounds $W$+jets, top pairs, QCD multi-jets
  - Strategy:
    - Fit pseudorapidity of light recoil jet $|\eta_{j'}|$
Single top t-channel

- Inclusive single top t-channel cross-section:
  $$\sigma_{t\text{-}ch.} = 83.6 \pm 2.3 \text{(stat.)} \pm 7.4 \text{(syst.) pb}$$

- Single t quark and antiquark t-channel cross-sections also obtained:
  $$\sigma_{t\text{-}ch.}(t) = 53.8 \pm 1.5 \text{(stat.)} \pm 4.4 \text{(syst.) pb}$$
  $$\sigma_{t\text{-}ch.}(\bar{t}) = 27.6 \pm 1.3 \text{(stat.)} \pm 3.7 \text{(syst.) pb}$$

- All three results in agreement with theoretical predictions

- Largest uncertainties: signal modeling and JES
Single top t-channel

- Cross-section ratios (top quark/antiquark, and 8/7 TeV)

\[ R_{8/7} = \frac{\sigma_{t\text{-ch.}}(8 \text{ TeV})}{\sigma_{t\text{-ch.}}(7 \text{ TeV})} = 1.24 \pm 0.08 \text{ (stat.)} \pm 0.12 \text{ (syst.)} \]

\[ R_{t\text{-ch.}} = \frac{\sigma_{t\text{-ch.}}(t)}{\sigma_{t\text{-ch.}}(t)} = 1.95 \pm 0.10 \text{ (stat.)} \pm 0.19 \text{ (syst.)} \]

- From the latter it is possible to compare the predictions of several PDF sets:

- High statistics of t-channel:
  - Differential cross-section studies (top/W polarization)
  - Gives best |V_{tb}| estimates:

\[
|f_{LV} V_{tb}| = 0.979 \pm 0.045 \text{ (exp.)} \pm 0.016 \text{ (theo.)}
\]

\[
|f_{LV} V_{tb}| = 0.998 \pm 0.038 \text{ (exp.)} \pm 0.016 \text{ (theo.)}
\]

\[ |V_{tb}| > 0.92 \text{ at 95\% C.L. (0} \leq |V_{tb}|^2 \leq 1) \]

See Karl Ecklund talk

Accepted by JHEP
arXiv:1403.7366

|V_{tb}| > 0.92 at 95\% C.L. (0 \leq |V_{tb}|^2 \leq 1)
Single top tW

- tW associated production observable at LHC for the first time!

- **Di-lepton** topology:

  - Two isolated leptons (ee, μμ, eμ)
  - $E_T^{miss}$ from the two neutrinos
  - One b-jet from top decay b quark

- Main backgrounds top pairs, Z+jets
- Signal and control regions to constrain top pair and b-tagging uncertainty:
  - 1 jet 1 b-tag ($1j1t$): signal region (15-20% tW, 75% top pairs, 5% Z+Jets)
  - 2 jets 1 b-tag ($2j1t$) and 2 jets 2 b-tags ($2j2t$) control regions
- Analysis strategy:
  - Data-driven normalization of Z+jets MC (reverse Z mass veto control region)
  - Kinematic variables used to disentangle tW from top pairs
  - Multivariate Boosted Decision Tree (BDT) analysis to extract signal
Single top $tW$

- Likelihood fit to BDT discriminant

- Expected significance from MC: $5.4 \pm 1.4\sigma$, observed: $6.1\sigma$

- Cross-section estimated using profile likelihood:
  - $\sigma_{tW} = 23.4 \pm 5.4\, \text{pb at 8TeV}$
  - Theoretical value ($m_{top}=173\, \text{GeV}$): $\sigma_{tW} = 22.2 \pm 0.6(\text{scale}) \pm 1.4(\text{PDF})\, \text{pb}$

- $V_{tb}$ matrix element estimate ($|V_{tb}| >> |V_{td}|, |V_{ts}|$ and $f_{LV}=1$):
  - $|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma_{th}}} = 1.03 \pm 0.12(\text{exp.}) \pm 0.04(\text{th.})$

- $|V_{tb}| > 0.78$ at 95% C.L. ($0 \leq |V_{tb}|^2 \leq 1$)

(Assume NNLQ) N. Kidonakis

Accepted by PRL
arXiv:1401.2942
Single top s-channel

- Very sensitive to new physics
- Lowest cross-section, irreducible large backgrounds (W+jets, top pairs, multijet QCD)

Analysis strategy:
- Multivariate analysis based on BDTs
- Data-driven QCD background estimate
- Top pair control region (3j2b-tags) used in the fit
- Binned maximum likelihood fit of BDT

Expected significance: 0.9σ, Observed 0.7σ

Cross-section measurement:
$$\sigma_{s\text{-ch.}} = 6.2 \pm 5.4(\text{exp.}) \pm 5.9(\text{th.}) \text{ pb} = 6.2 \pm 8.0 \text{ pb}$$

Theory prediction (NLO+NNLL order) at 8Tev:
$$\sigma_{s\text{-ch.}} = 5.55 \pm 0.08(\text{scale}) \pm 0.21(\text{PDF}) \text{ pb}$$

Assuming Standard Model signal FC 68%C.L.:
$$\sigma\text{-s-channel} = 6.2^{+8.0}_{-5.1} \text{ pb}$$

Upper limit on s-channel x-sect 11.5pb (95%C.L.)
Single top cross-sections

- Summary from CMS single top production analyses:

![Graph showing single top-quark production cross-sections](image)
Conclusions

• Top pair production cross-section measurements testing theoretical predictions
• Top pair differential cross-section challenging models
• Single top:
  • t-channel: precise new result, statistics allows for differential cross-section and properties studies
  • tW: first observation
  • s-channel: upper limit set
• No significant deviation from SM
• Analyses preparing for 13/14TeV LHC data
Thank you!
All results are public

- You can find all the CMS results with much more details at:

  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
Back-up
Top quark at the LHC

- While the LHC is preparing for Run II 13/14TeV pp collisions:
  - Final/ongoing Run I analysis completing:
    - 5 fb\(^{-1}\)@7TeV
    - 20fb\(^{-1}\)@8TeV
  - New analyses preparing for Run II
  - Detectors completing upgrades to cope with increased luminosity and pileup
The Compact Muon Solenoid

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm) ~16m² ~66M channels
- Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~6m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
Dataset(s)

- Excellent LHC performance
- Two large datasets exploited
- High recording efficiency
- Event pile-up challenge
Event pile-up

Peak: 37 pileup events
Design value
25 pileup events
(L=10^{34}, BX=25 ns)

Event from special high pu run:
78 reconstructed vertices and 2 muons...
Top Quark Signature

- Experimental challenges:
  - Detection in hadron collider environments:

- Top decays almost always into Wb:
  - Topology driven by W decay
  - Signatures are named after final states:
    - Di-lepton (both Ws leptonic decay)
    - Lepton+jets (1 leptonic, 1 hadronic)
    - Fully hadronic (both Ws hadronic decay)

- Whole detector capabilities are crucial:
  - Lepton Identification
  - Light and B jets reconstruction
  - B-tagging
  - Missing transverse energy
Top-ology

- Top decay signatures based on the fact top decay almost always into a W boson and a b quark:

<table>
<thead>
<tr>
<th>Top Pair Decay Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{t} \bar{s} )</td>
</tr>
<tr>
<td>( \bar{t} \bar{d} )</td>
</tr>
<tr>
<td>( e\bar{\tau} )</td>
</tr>
<tr>
<td>( e\bar{\mu} )</td>
</tr>
</tbody>
</table>

- Dilepton:
  - High S/B
  - Lower statistics
  - Two neutrinos
- Lepton plus jets:
  - Highest statistics
  - Good S/B
- All hadronic:
  - Full top reconstruction
  - Toughest background
- B-tagging efficiency typically 70%
Total production cross-section

- Event counts:

<table>
<thead>
<tr>
<th>Source</th>
<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
<th>$e^\pm\mu^\mp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drell-Yan</td>
<td>$386 \pm 116$</td>
<td>$492 \pm 148$</td>
<td>$194 \pm 58$</td>
</tr>
<tr>
<td>Non-W/Z leptons</td>
<td>$25 \pm 10$</td>
<td>$114 \pm 46$</td>
<td>$185 \pm 72$</td>
</tr>
<tr>
<td>Single top quark</td>
<td>$127 \pm 28$</td>
<td>$157 \pm 34$</td>
<td>$413 \pm 88$</td>
</tr>
<tr>
<td>VV</td>
<td>$30 \pm 8$</td>
<td>$39 \pm 10$</td>
<td>$94 \pm 21$</td>
</tr>
<tr>
<td>Total background</td>
<td>$569 \pm 120$</td>
<td>$802 \pm 159$</td>
<td>$886 \pm 130$</td>
</tr>
<tr>
<td>$t\bar{t}$ dilepton signal</td>
<td>$2728 \pm 182$</td>
<td>$3630 \pm 250$</td>
<td>$9624 \pm 504$</td>
</tr>
<tr>
<td>Data</td>
<td>$3204$</td>
<td>$4180$</td>
<td>$9982$</td>
</tr>
</tbody>
</table>

*JHEP 02 (2014) 024*
Total top pair x-sect 8TeV

- Data/MC agreement scaling top pair MC to measured x-sect:
### Top pair total x-section

- **Systematic uncertainties to top pair total cross-section (in pb)**

<table>
<thead>
<tr>
<th>Source</th>
<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
<th>$e^+\mu^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger efficiencies</td>
<td>4.1</td>
<td>3.0</td>
<td>3.6</td>
</tr>
<tr>
<td>Lepton efficiencies</td>
<td>5.8</td>
<td>5.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>0.6</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>10.3</td>
<td>10.8</td>
<td>5.2</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>3.2</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>b-jet tagging</td>
<td>1.9</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Pileup</td>
<td>1.7</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Scale ($\mu_F$ and $\mu_R$)</td>
<td>5.7</td>
<td>5.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Matching partons to showers</td>
<td>3.9</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>Single top quark</td>
<td>2.6</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>VV</td>
<td>0.7</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>10.8</td>
<td>10.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Non-W/Z leptons</td>
<td>0.9</td>
<td>3.2</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Total systematic</strong></td>
<td>18.6</td>
<td>18.6</td>
<td>11.4</td>
</tr>
<tr>
<td><strong>Integrated luminosity</strong></td>
<td>6.4</td>
<td>6.1</td>
<td>6.2</td>
</tr>
<tr>
<td><strong>Statistical</strong></td>
<td>5.2</td>
<td>4.5</td>
<td>2.6</td>
</tr>
</tbody>
</table>

8 TeV 5.3 fb$^{-1}$ Dilepton

JHEP 02 (2014) 024
Summary of all CMS 7TeV total pair production cross-section results

| CMS e/μ+jets | 158 ± 2 ± 10 ± 4 |
| PLB 720 (2013) 83 |
| L=2.2-2.3/fb |
| CMS dilepton (ee,μμ,μμ) | 162 ± 2 ± 5 ± 4 |
| JHEP 11 (2012) 067 (L=2.3/fb) |
| CMS dilepton (e/μ+τ_{had}) | 143 ± 14 ± 22 ± 3 |
| PRD 85 (2012) 112007 |
| L=2.2/fb |
| CMS τ_{had}+jets | 152 ± 12 ± 32 ± 3 |
| EPJC 73 (2013) 2386 (L=3.9/fb) |
| CMS all jets | 139 ± 10 ± 26 ± 3 |
| JHEP 05 (2013) 065 (L=3.5/fb) |

NNLO+NNLL (top=2.0), PDF4LHC, m_{τ_{had}} = 172.5 GeV

Scale uncertainty
scale PDF α_s uncertainty
Total pair total x-sect summary

**CMS Preliminary, $\sigma_{tt}$ summary, $\sqrt{s} = 7$ TeV**

- **CMS $e_1/\mu_1$+jets**
  PLB 720 (2013) 83
  (L=2.2-2.3/fb)
  $158 \pm 2 \pm 10 \pm 4$
  (val. ± stat. ± syst. ± lumi.)

- **CMS dilepton $(ee_1,\mu_1,\mu_1)$**
  JHEP 11 (2012) 067 (L=2.3/fb)
  $162 \pm 2 \pm 5 \pm 4$
  (val. ± stat. ± syst. ± lumi.)

- **CMS dilepton $(e_1/\mu_1+\tau_1)$**
  PRD 85 (2012) 112007
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- **CMS $\tau_1$+jets**
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  $139 \pm 10 \pm 26 \pm 3$
  (val. ± stat. ± syst. ± lumi.)

**CMS Preliminary, $\sigma_{tt}$ summary, $\sqrt{s} = 8$ TeV**

- **CMS dilepton $(ee_1,\mu_1,\mu_1)$**
  JHEP 02 (2014) 024 (L=5.3/fb)
  $239 \pm 2 \pm 11 \pm 6$ pb
  (val. ± stat. ± syst. ± lumi.)

- **CMS prel. $e_1/\mu_1$+jets**
  TOP-12-006 (L=2.8/fb)
  $228 \pm 9 \pm 29 \pm 26 \pm 10$ pb
  (val. ± stat. ± syst. ± lumi.)

---

**Note:**
- NNLO+NNLL (top++ 2.0), PDF4LHC, $m_{top} = 172.5$ GeV
- scale uncertainty
- scale @ PDF @ $\alpha_s$ uncertainty
Top pair production x-sect

- Mass dependence in the range 160-185GeV:

\[
\frac{\sigma_{tt}}{\sigma_{tt} (m_t = 172.5)} = 1.00 - 0.009 \times (m_t - 172.5) - 0.000168 \times (m_t - 172.5)^2
\]

- Using \( m_t = 173.2 \)GeV:

\[
\sigma_{tt} = 237.5 \pm 13.1 \text{ pb}
\]
Top pair total x-sect summary

- TOPLHCWG combination, individual measurement, NNLO prediction
Top pair differential x-sect dilepton

- Normalized differential cross-sections measured as a function of:
  - Lepton: $p_T$, pseudorapidity separately for leading and next to leading lepton
  - Lepton pair: $p_T$, mass
  - $b$-jet: $p_T$, pseudorapidity separately for leading and next to leading $b$-jet
  - Invariant Lepton+$b$-jet pair mass

- Good agreement with predictions within experimental uncertainties

[Graphs showing data and predictions for dilepton combined]
Top pair differential cross-sections

- Lepton+jets final state
  - Main backgrounds: W+jets, QCD multijet
  - Similar kinematic reconstruction and unfolding technique
  - Dominant systematics: JES and model uncertainties
  - “Same” differential cross-sections (one lepton only)
  - Similar top $p_T$ behavior observed

- Good agreement with predictions within experimental uncertainty
Single top t-channel

- Signal region:
  - Single isolated lepton (e/μ), MET
  - 2 jets, 1b-tag in top mass window (130<m_{lvb}<220GeV)
  - Fit pseudorapidity of light recoil jet |η_j'|
  - Shape of W+jets and top pairs from data control regions:
    - m_{lvb} sidebands, 3jets2b-tags

Accepted by JHEP
arXiv:1403.7366
tW channel Event Selection

Selection (3 final states ee, μμ, eμ):

- Exactly 2 isolated, oppositely charged leptons,
- Leptons invariant mass $m_{ll} > 20$ GeV
- All states

- $Z$ mass veto ($m_{ll} < 81$ GeV, $m_{ll} > 101$ GeV)
- $E_T^{\text{miss}} > 50$ GeV

- Signal and control regions defined by jet multiplicity and b-tagging:
  - 1 jet 1 b-tag ($1j1t$): signal region (15-20% tW, 75% top pairs, 5% Z+Jets)
  - 2 jets 1 b-tag ($2j1t$) and 2 jets 2 b-tags ($2j2t$) control regions to constrain top pair cross-section and b-tagging efficiency uncertainty

Analysis strategy:

- Data-driven normalization of Z+jets MC (reverse $Z$ mass veto control region)
- Kinematic variables used to disentangle tW from top pairs
- Multivariate Boosted Decision Tree (BDT) analysis to extract signal
tW channel Event Selection Objects

**Dileptonic Triggers:**
- Two leptons (e or $\mu$: ee, e$\mu$, $\mu\mu$)
- Leading lepton $p_t > 17$GeV, second lepton $p_t > 8$GeV

**Object selection:**

- **Electrons:**
  - $p_t > 20$GeV
  - $|\eta| < 2.5$
  - IP < 0.04cm from beamspot
  - RelIso < 0.15 in a cone of $\Delta R < 0.3$

- **Muons:**
  - $p_t > 20$GeV
  - $|\eta| < 2.4$
  - RelIso < 0.20 in a cone of $\Delta R < 0.4$

- **Dileptonic Triggers:**
  - Two leptons (e or $\mu$: ee, e$\mu$, $\mu\mu$)
  - Leading lepton $p_t > 17$GeV, second lepton $p_t > 8$GeV

- **Object selection:**
  - **Electrons:**
    - $p_t > 20$GeV
    - $|\eta| < 2.5$
    - IP < 0.04cm from beamspot
    - RelIso < 0.15 in a cone of $\Delta R < 0.3$
  - **Muons:**
    - $p_t > 20$GeV
    - $|\eta| < 2.4$
    - RelIso < 0.20 in a cone of $\Delta R < 0.4$
  - **Loose Electrons:**
    - $p_t > 10$GeV
    - $|\eta| < 2.5$GeV
  - **Loose Muons:**
    - $p_t > 10$GeV
    - $|\eta| < 2.5$GeV
  - **Jets:**
    - Anti-$k_t$
    - $p_t > 30$GeV
    - $|\eta| < 2.4$
    - Energy and $p_t$ corrected
  - **Loose Jets:**
    - Not “tight”
    - $p_t > 20$GeV
    - $|\eta| < 4.9$GeV
    - $|\eta| < 2.4$GeV (central)
  - **Loose Jets:**
    - Not “tight”
    - $p_t > 20$GeV
    - $|\eta| < 4.9$GeV
    - $|\eta| < 2.4$GeV (central)
- **Particle Flow corrected missing transverse energy ($E_T^{\text{miss}}$) used**
- **B tagging information:**
  - Tracking-based multivariate tagging algorithm
  - Data-driven pt dependent b-tagging scale factors applied
tW channel Event Selection

- Selection (3 final states ee, μμ, eμ):
  - Exactly 2 isolated, oppositely charged leptons,
  - Leptons invariant mass $m_{ll} > 20$ GeV

- Z mass veto ($m_{ll} < 81$ GeV, $m_{ll} > 101$ GeV)
- $E_T^{miss} > 50$ GeV

- Signal and control regions defined by jet multiplicity and b-tagging:
  - 1 jet 1 b-tag ($1j1t$): signal region (15-20% tW, 75% top pairs, 5% Z+Jets)
  - 2 jets 1 b-tag ($2j1t$) and 2 jets 2 b-tags ($2j2t$) control regions to constrain top pair cross-section

- Analysis strategy:
  - Data-driven normalization of Z+jets MC (reverse Z mass veto control region)
  - Kinematic variables used to disentangle tW from top pairs
  - Multivariate Boosted Decision Tree (BDT) analysis to extract signal
tW Boosted Decision Trees

- Training on 200k exclusive tW and top pair dilepton events (after selection and in the 1j1t region)
- 13 kinematic input variables chosen based on:
  - signal/background separation
  - data/MC agreement in several control regions (2j1t, 2j2t, 2j0t, 1j0t)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nloosejets</td>
<td>Number of loose jets, $p_T &gt; 20$ GeV, $</td>
</tr>
<tr>
<td>NloosejetsCentral</td>
<td>Number of loose jets, $p_T &gt; 20$ GeV, $</td>
</tr>
<tr>
<td>NbtaggedLoosejets</td>
<td>Number of loose jets, $p_T &gt; 20$ GeV, CSVM btagged</td>
</tr>
<tr>
<td>$p_{T,sys}$</td>
<td>Vector sum of $p_T$ of leptons, jet, and $E_T^{miss}$</td>
</tr>
<tr>
<td>$H_T$</td>
<td>Scalar sum of $p_T$ of leptons, jet, and $E_T^{miss}$</td>
</tr>
<tr>
<td>Jet $p_T$</td>
<td>$p_T$ of the leading, tight, b-tagged jet</td>
</tr>
<tr>
<td>Loose jet $p_T$</td>
<td>$p_T$ of leading loose jet, defined as 0 for events with no loose jet present</td>
</tr>
<tr>
<td>$p_{T,sys}/H_T$</td>
<td>Ratio of $p_{T,sys}$ to $H_T$ for the event</td>
</tr>
<tr>
<td>Msys</td>
<td>Invariant mass of the combination of the leptons, jet, and $E_T^{miss}$</td>
</tr>
<tr>
<td>centralityJLL</td>
<td>Centrality of jet and leptons</td>
</tr>
<tr>
<td>$H_T/leptons/H_T$</td>
<td>Ratio of scalar sum of $p_T$ of the leptons to the $H_T$ of full system</td>
</tr>
<tr>
<td>$p_{T,jll}$</td>
<td>Vector sum of $p_T$ of jet and leptons</td>
</tr>
<tr>
<td>$E_T^{miss}$</td>
<td>Missing transverse energy in the event</td>
</tr>
</tbody>
</table>
tW BDT Input Variables

- Sample input variable distributions in the control and signal regions:
  - **Number of loose jets** $p_T > 20\text{GeV}$
  - **$P_T$ of the system**

![Graphs showing distributions for different categories: 1j1t, 2j1t, 2j2t, 1j1t, 2j1t, 2j2t](image)

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Gabriele Benelli, Kansas University
tW Systematic Uncertainties

- Several sources of systematic uncertainties considered in both significance and cross-section estimate
- The 68% C.L. interval evaluated using profile likelihood
- **Theory shape uncertainties** estimated as the central value difference from value obtained setting nuisance parameters to +/- 1σ
- Externalized in the significance calculation
- For other sources nuisance parameters fixed to central value and confidence level interval change used as estimate
- “Statistical” uncertainty from fixing all other sources to central value

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>$\Delta\sigma$ (pb)</th>
<th>$\Delta\sigma/\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME/PS matching thresholds</td>
<td>3.25</td>
<td>14%</td>
</tr>
<tr>
<td>$Q^2$ scale</td>
<td>2.68</td>
<td>11%</td>
</tr>
<tr>
<td>Top quark mass</td>
<td>2.28</td>
<td>10%</td>
</tr>
<tr>
<td>Statistical</td>
<td>2.13</td>
<td>9%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.13</td>
<td>5%</td>
</tr>
<tr>
<td>JES</td>
<td>0.91</td>
<td>4%</td>
</tr>
<tr>
<td>$t\bar{t}$ cross section</td>
<td>0.87</td>
<td>4%</td>
</tr>
<tr>
<td>Z+jet data/MC scale factor</td>
<td>0.56</td>
<td>2%</td>
</tr>
<tr>
<td>tW DR/DS scheme</td>
<td>0.45</td>
<td>2%</td>
</tr>
<tr>
<td>PDF</td>
<td>0.33</td>
<td>1%</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>0.31</td>
<td>1%</td>
</tr>
<tr>
<td>JER</td>
<td>0.27</td>
<td>1%</td>
</tr>
<tr>
<td>B-tagging data/MC scale factor</td>
<td>0.20</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>$t\bar{t}$ Spin Correlations</td>
<td>0.12</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Top Pt Reweighting</td>
<td>0.12</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Event pile up</td>
<td>0.11</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>$E_T^{miss}$ modeling</td>
<td>0.07</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>0.02</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Total</td>
<td>5.58</td>
<td>24%</td>
</tr>
</tbody>
</table>

Accepted by PRL arXiv:1401.2942
tW Cross-check analyses

- Two cross-check analyses performed, using the same event selection and the same signal and control regions with the following exceptions:
  - $p_{T,\text{sys}}$ Fit:
    - Veto extra btagged loose jets events
    - Cut on $H_t$ in $\mu\nu$ channel ($H_t > 160\text{GeV}$)
    - Same fit as BDT but to the $p_{T,\text{sys}}$ distribution
  - Results:
    - Observed significance 4.0 sigma
    - Expected significance $3.2^{+0.4}_{-0.9}$ sigma
    - Cross section: $24.3 \pm 8.6$ pb

- Cut and Count:
  - Veto extra btagged loose jets events
  - Cut on $H_t$ in $\mu\nu$ channel ($H_t > 160\text{GeV}$)
  - Fit to the event counts only in each region
  - Results:
    - Observed significance 3.6 sigma
    - Expected significance $2.8 \pm 0.9$ sigma
    - Cross section: $33.9 \pm 8.6$ pb
Significance estimated using binned likelihood fit with pseudo-experiments (lots of them!):

- Excess of events with respect to the background-only hypothesis

- Observed significance in 12.2 fb$^{-1}$ of 8 TeV data: 6.1$\sigma$

- Expected significance from MC: 5.4 ± 1.4$\sigma$

Cross-section estimated using profile likelihood:

- $\sigma_{tW} = 23.4 \pm 5.4$ pb at 8 TeV

Theoretical value ($m_{top}=173$ GeV):

- $\sigma_{tW} = 22.2 \pm 0.6$(scale) ±1.4(PDF) pb

$V_{tb}$ matrix element estimate ($|V_{tb}| >> |V_{td}|, |V_{ts}|$ and $f_{Lv}=1$):

- $|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma_{th}}} = 1.03 \pm 0.12$ (exp.) ± 0.04 (th.)

- $|V_{tb}| > 0.78$ at 95% C.L. ($0 \leq |V_{tb}|^2 \leq 1$)
Single top s-channel

- BDT analysis still not very sensitive (main systematics model uncertainties):
  - Expected significance: 0.9 sigma
  - Observed significance: 0.7 sigma
- Cross-section measurement:
  \[ \sigma_{s\text{-ch.}} = 6.2 \pm 5.4(\text{exp.}) \pm 5.9(\text{th.}) \text{ pb} = 6.2 \pm 8.0 \text{ pb} \]
- Theory prediction (NLO+NNLL order) at 8 TeV:
  \[ \sigma_{s\text{-ch.}} = 5.55 \pm 0.08(\text{scale}) \pm 0.21(\text{PDF}) \text{ pb} \]
- Assuming Standard Model signal, Feldmann-Cousin confidence level interval is derived:
  \[ \sigma_{s\text{-ch.}} = 6.2^{+8.0}_{-5.1} \text{ pb} \]
- Upper limit on s-channel cross-section calculated with Bayesian approach 11.5 pb (95% C.L.)
Single top cross-sections

- Summary from CMS single top production analyses: