Top Quark Production at the LHC

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U. Oviedo (Spain)
on behalf of the CMS and ATLAS collaborations

QCD@LHC 2015,
1st – 5th Sep 2015, London
• Top pair cross sections measurements
  • Inclusive
  • Differential
• Single top cross sections
• Associated production
• Results on 7, 8 and 13 TeV data

• A word on:
  • Top mass
  • Looking for new physics

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A particle with unique characteristics

• Special because of its enormous mass: heaviest known particle
  – Still a point-like particle in our understanding
  – The top and the Higgs are “strongly” coupled $y_t \approx 1$ $m_t = y_t v / \sqrt{2}$
  – The top mass dramatically affects the stability of the Higgs mass
    • If we consider the SM valid up to a certain scale $\Lambda$

\[
m^2_H = m^2_{H0} - \frac{3}{8\pi^2} y_t \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2
\]

\[(125 \text{ GeV})^2 = m^2_{H0} + [- (2 \text{ TeV})^2 + (700 \text{ GeV})^2 + (500 \text{ GeV})^2] \left( \frac{\Lambda}{10 \text{ TeV}} \right)^2
\]

• It is the only quark that does not hadronise
  o $\tau_{\text{had}} \sim h / \Lambda_{\text{QCD}} \sim 2 \times 10^{-24} \text{ s}$
  o $\tau_{\text{top}} \sim h / \Gamma_{\text{top}} \sim 5 \times 10^{-25} \text{ s}$
  o Compare with $\tau(b) \sim 10^{-12} \text{ s}$
  ➢ Decays before forming a “dressed” top quarks
  ➢ No bound tq states, its spin properties are directly passed to its decay products
  ➢ QCD, Flavor and EWK physics at their best!
Constraining the SM

- Can use the fact that $m_t$, $m_W$, $m_H$ are linked at loop level to constrain the SM
  
  - The Higgs/symmetry breaking sector can be explored with more insights coming from top physics

  \[ V(\phi) = -\mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2 + Y_{ij}^i \psi^*_L \psi^*_R \phi \]

  $\lambda$ now known at NNLO QCD. Vacuum meta-stability when the minimum of $V(\Phi)$ is just local

- The top quark also provide other direct constraints to the model
  
  - Direct access to parameters of the SM ($m_t$, $V_{tb}$)
  - Other stringent tests of SM (QCD in $d\sigma/dX$, couplings, CPT invariance, ...)

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Top quark production at LHC

<table>
<thead>
<tr>
<th>process</th>
<th>Events/s 8 TeV, peak lumi</th>
<th>Events/y 8 TeV, 25/fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>bb</td>
<td>$\sim 10^6$</td>
<td>$\sim 3 \times 10^{12}$</td>
</tr>
<tr>
<td>$W \rightarrow \ell \nu$</td>
<td>$\sim 70$</td>
<td>$\sim 2.5 \times 10^8$</td>
</tr>
<tr>
<td>$Z \rightarrow \ell \ell$</td>
<td>$\sim 6$</td>
<td>$\sim 25 \times 10^6$</td>
</tr>
<tr>
<td>tt</td>
<td>$\sim 1.5$</td>
<td>$\sim 6 \times 10^6$</td>
</tr>
</tbody>
</table>

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Top (pair) production at the LHC

- **Top pair** QCD production happens mainly via gluon fusion

- Final states depend on the decay of the W bosons

<table>
<thead>
<tr>
<th>( \sigma(\text{NNLO+NNLL}) \pm \text{scales} \pm \text{PDFs} \text{[pb]} )</th>
<th>7 TeV</th>
<th>8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Czakon, Fiedler, Mitov</td>
<td>172.0^{+4.4}<em>{-5.8}^{+4.7}</em>{-4.8}</td>
<td>245.8^{+6.2}<em>{-8.4}^{+6.2}</em>{-6.4}</td>
</tr>
</tbody>
</table>

- **dileptons**
  - BR~10%

- **lepton + jets**
  - BR~44%

- **all hadronic**
  - BR~46%

- Backgrounds coming from: W/Z+jets, single top (tW), QCD, di-boson

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Monitoring the total production cross section is the first fundamental step for understanding top physics at the LHC
- Test the presence of new production mechanisms
- In the frame of the SM, test QCD predictions and help constraining the PDFs (especially gluons)
  - Important for Higgs production

\[ \sigma_{t\bar{t}}(m_t) = \sum_{i,j} \int_0^1 dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}(m_t) \]
- Indirect determination of \( m_t \) or \( \alpha_s \).
- Constrain a very important background for many searches at the LHC

- Almost all decay modes are investigated at the LHC

- The measurements are performed at different level of complexity:
  - Counting experiment in acceptance
  - Fit to data in several portions of phase space with in situ constraining of various backgrounds
  - Multivariate analyses
  - Selections defined for inclusive cross sections are in general used for the rest of the measurements in that final state
ATLAS new results on $t\bar{t}$ production at 7 and 8 TeV

- New measurement at 7 TeV in $t\bar{t}\rightarrow l\tau_{\text{had}}$ (arXiv:1506.05074 sub. to PRD)
  - $\sigma_{t\bar{t}} = 183 \pm 9 \text{ stat} \pm 23 \text{ syst} \pm 3 \text{ lumi pb}$
  - also extract $\text{BF}(t\rightarrow l\nu b)$ and $\text{BF}(t\rightarrow q\bar{q}b)$
  - similar selection criteria for $l+$jets and dilepton

- Recent measurement in $t\bar{t}\rightarrow l+\text{jets}$ PRD 91 (2015) 112013
  - require $\geq 3$ jets, $\geq 1$ btag
  - extract $e+$jets and $\mu+$jets independently
  - template fit to likelihood discriminant with only two variables

\[ \text{Measured (top quark)} \]
\[ \begin{array}{c|c|c}
\sigma_{t\bar{t}} & 178 \pm 3 \text{ (stat.)} \pm 16 \text{ (syst.)} \pm 3 \text{ (lumi.) pb} \\
B_{t\bar{t}} & 66.5 \pm 0.4 \text{ (stat.)} \pm 1.3 \text{ (syst.)} \\
B_{t} & 13.3 \pm 0.4 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \\
B_{\bar{t}} & 13.4 \pm 0.3 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \\
B_{\tau} & 7.0 \pm 0.3 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \\
\end{array} \]
Inclusive $t\bar{t}$ cross section [pb]

- Tevatron combined* 1.96 TeV (L=8.8 fb$^{-1}$)
- ATLAS dilepton 7 TeV (L=4.6 fb$^{-1}$)
- CMS dilepton 7 TeV (L=2.3 fb$^{-1}$)
- ATLAS $l+j$ets* 7 TeV (L=0.7 fb$^{-1}$)
- CMS $l+j$ets 7 TeV (L=2.3 fb$^{-1}$)
- ATLAS dilepton 8 TeV (L=20.3 fb$^{-1}$)
- CMS dilepton 8 TeV (L=5.3 fb$^{-1}$)
- LHC combined $e\mu$* 8 TeV (L=5.3-20.3 fb$^{-1}$)
- ATLAS $l+j$ets 8 TeV (L=20.3 fb$^{-1}$)
- CMS $l+j$ets* 8 TeV (L=2.8 fb$^{-1}$)

* Preliminary

ATLAS+CMS Preliminary
TOPLHCWG

May 2015

NNLO+NNLL (pp)
NNLO+NNLL (p$\bar{p}$)

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
$m_{top} = 172.5$ GeV, PDF $\oplus \alpha_s$ uncertainties according to PDF4LHC

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tt cross section inclusive combination

TOPLHCWG combination of best $\sigma_{tt}$ measurements

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<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
<th>Correlation</th>
<th>LHC combination</th>
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<td>13.4</td>
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<tr>
<td>Total</td>
<td>9.4</td>
<td>13.6</td>
<td></td>
<td>8.5</td>
</tr>
</tbody>
</table>
• Measure the production cross sections at particle level in a fiducial range, defined within the kinematic acceptance of the ttbar decay particles that are directly visible in the detector.

• **Visible cross section** is defined for events at particle level containing a true opposite charge electron-muon pair from the decay chain $t \rightarrow W \rightarrow l$ (including $W \rightarrow \tau \rightarrow l$) and with both leptons with $p_T > 20$ GeV and $|\eta| < 2.4$

• Extrapolate visible cross section to obtain the cross section for ttbar production at parton level in the full phase space using $MC \ A_{e\mu}$ (Signal acceptance is taken from simulation assuming a top mass of 172.5 GeV.)
**CMS: Method:**

- **Jet variables used in order to constrain uncertainty from b-tagging, JES**
- **First divide events into three bins by number of b-jets:** $N_b = 1, 2$ and $0$ or $\geq 3$, then, each category is divided in 4 bins, as a function on the number of non b jets.
- **For each of these $N_{\text{events}}, p_T^{\text{lead}}, p_T^{\text{sublead}}$ and $p_T^{\text{lowest}}$ for events with 0, 1, 2 or 3 non b jets, respectively are taken (12 distributions in total)**

- **Template fit to lowest light jet $p_T$ for each category ($N_{\text{events}}$ if there are no light jets)**
  - **Allows the extraction of the b-tagging efficiency and constraining of syst. unc.**
  - **Signal and background templates taken from MC, fitted to data.**
  - **Templates normalized to luminosity (depending on the cross section)**
  - **Templates depend on systematic variations $\lambda_i$**
  - **Binned Poisson Likelihood used for fitting**

\[
s_1 = \mathcal{L} \cdot \epsilon_{\mu} \cdot \sigma_{tt}^{\text{vis}} \cdot 2\epsilon_{b} (1 - C_b \epsilon_{b})
\]
\[
s_2 = \mathcal{L} \cdot \epsilon_{\mu} \cdot \sigma_{tt}^{\text{vis}} \cdot 2\epsilon_{b}^2 C_b
\]
\[
s_0 = \mathcal{L} \cdot \epsilon_{\mu} \cdot \sigma_{tt}^{\text{vis}} \cdot (1 - 2\epsilon_{b}^2 C_b - 2\epsilon_{b} (1 - \epsilon_{b}) C_b)
\]

Allow to derive b-jet acceptance $\epsilon_{b}$ from data (Eur.Phys.J. C74 (2014) 3109)
CMS Results 7/8 TeV: cross section, pole mass, limit on stop production

\[ \sigma(7 \text{ TeV}) = 174.5 \pm 2.1(\text{stat})^{+4.5}_{-4.0}(\text{syst}) \pm 3.8(\text{lumi}) \text{ pb (}+3.6\% -3.4\%) \]

\[ \sigma(8 \text{ TeV}) = 245.6 \pm 1.3(\text{stat})^{+6.6}_{-5.5}(\text{syst}) \pm 6.5(\text{lumi}) \text{ pb (}+3.8\% -3.5\%) \]

\[ \sigma_{\text{vis}}(7 \text{ TeV}) = 3.05^{+0.11}_{-0.10} \text{ pb (}+3.5\% -3.4\%) \]

\[ \sigma_{\text{vis}}(8 \text{ TeV}) = 4.24^{+0.16}_{-0.14} \text{ pb (}+3.7\% -3.4\%) \]

\[ R(8/7 \text{ TeV}) = 1.41 \pm 0.06 \text{ (stat+syst)} \]

R(7/8 TeV, NNLO) = 1.430

Top pole mass \( m_t = 173.6^{+1.7}_{-1.8} \text{ GeV} \)

Susy Constraints from ttbar Cross Section: Stop quarks with masses below 189 GeV are excluded (for light neutralinos)

Similar level of exclusion by ATLAS

September 2015

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ATLAS Top pair cross section in the $\text{e}\mu$ channel at 13 TeV

• Analysis strategy follows Run1 best measurement
  – select OS $\text{e}\mu$, $p_T(\ell)>25$ GeV, jets (25 GeV), ≥1 btag, no MET required
• Count number of $\text{e}\mu$ events with
  – exactly one ($N_1$) and exactly two ($N_2$) b-tagged jets
  – extract $\sigma_{tt}$ and prob. to b-tag q from $t \rightarrow Wq(\epsilon_b)$

\[ N_1 = L\sigma_{t\bar{t}} \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_{bkg} \]
\[ N_2 = L\sigma_{t\bar{t}} \epsilon_{e\mu} C_b \epsilon_b^2 + N_{bkg} \]

bsample

sel. eff.+acc. incl. BR (0.9%)  
non-factorisation correction from MC $E_{bb}/E_b^2 = 1.005 \pm 0.006$
**ATLAS Top pair cross section in the $e\mu$ channel at 13 TeV**

<table>
<thead>
<tr>
<th>Event counts</th>
<th>$N_1$</th>
<th>$N_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>319</td>
<td>167</td>
</tr>
<tr>
<td>$Wt$ single top</td>
<td>29.0 ± 3.8</td>
<td>5.6 ± 2.0</td>
</tr>
<tr>
<td>Dibosons</td>
<td>1.1 ± 0.2</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>$Z(\rightarrow \tau\tau \rightarrow e\mu)$+jets</td>
<td>1.3 ± 0.7</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Misidentified leptons</td>
<td>6.0 ± 3.9</td>
<td>2.8 ± 2.9</td>
</tr>
<tr>
<td>Total background</td>
<td>37.3 ± 5.5</td>
<td>8.5 ± 3.5</td>
</tr>
</tbody>
</table>

\[
\varepsilon_b = 0.527 \pm 0.026_{\text{stat}} \pm 0.006_{\text{syst}}
\]

In good agreement with simulation (0.543), includes jet acceptance

\[
\sigma_{tt} (13 \text{ TeV}) = 825 \pm 49_{\text{stat}} \pm 60_{\text{syst}} \pm 83_{\text{lumi}} \text{ pb}
\]
CMS Top pair cross section in the $e\mu$ channel at 13 TeV

- **Same Cut and Count technique as in Run I** (TOP-11-005, TOP-12-007, TOP-13-004) is used for the measurement
- **Luminosity**: 42 pb$^{-1}$
- **Event selection**
  - $\geq 2$ (OS) leptons ($1\ e, 1\ \mu$), $p_T > 20$ GeV and $|\eta| < 2.4$, and invariant mass $> 20$ GeV
  - $\geq 2$ jets with $p_T > 30$ GeV and $|\eta| < 2.4$
- **Background estimation**
  - Drell Yan normalized to MC prediction by a data/MC SF (from Z peak in data)
  - Non W/Z: fully data driven technique
  - Single top ($tW$) and diboson are taken from MC

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events $e^{\pm}\mu^{\mp}$</th>
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<tbody>
<tr>
<td>Drell–Yan</td>
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<tr>
<td>Non-W/Z leptons</td>
<td>8.5 ± 4.3</td>
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<tr>
<td>Single top quark</td>
<td>10.6 ± 3.4</td>
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<tr>
<td>VV ($V = W$ or $Z$)</td>
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<td>Total background</td>
<td>28.1 ± 5.7</td>
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<tr>
<td>$tt$ dilepton signal</td>
<td>207 ± 16</td>
</tr>
</tbody>
</table>

Data 220
Comparison of ATLAS and CMS syst. uncertainties

- **luminosity uncertainty dominates (9%, 12%)**
  - will be reduced with dedicated VdM scans (performed weekend August 23th)

- **$t\bar{t}$ modeling**
  - $t\bar{t}$ hadronisation (4.5%, 1.8%)
  - $t\bar{t}$ NLO modeling, ISR/FSR radiation & PDF (2.9%, 2.4%)

- **detector-related**
  - lepton triggers (1.3%, 5.0%)
  - electron ID and isolation (4.2%), muon ID and isolation (1.6%); lepton efficiency (4.3%)
  - lepton mis-ID (1.3%, 1.0%)
  - jet energy scale (0.3%, 2.6%)

- **statistical uncertainty**
  - ATLAS analysed 78 pb$^{-1}$ (6.0%), CMS 42 pb$^{-1}$ (7.7%)

- **Cross section measurements (essentially same TOTAL systematic uncertainty)**
  \[
  \sigma_{t\bar{t}} = 825 \pm 49_{\text{stat}} \pm 60_{\text{syst}} \pm 83_{\text{lumi}} \text{ pb}, \quad \Delta \sigma_{t\bar{t}} / \sigma_{t\bar{t}} = 14\% \text{ (ATLAS)} \\
  \sigma_{t\bar{t}} = 772 \pm 60_{\text{stat}} \pm 62_{\text{syst}} \pm 93_{\text{lumi}} \text{ pb}, \quad \Delta \sigma_{t\bar{t}} / \sigma_{t\bar{t}} = 16\% \text{ (CMS)}
  \]
Comparison of **ATLAS** and **CMS** results at different CM energies

- Good agreement in central values, similar overall systematic uncertainty, but some differences in the central estimates

<table>
<thead>
<tr>
<th>Energy (TeV)</th>
<th>Experiment</th>
<th>$\sigma$(pb)</th>
<th>Stat (%)</th>
<th>Syst (%)</th>
<th>Lumi (%)</th>
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<tr>
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<td>5.9</td>
<td>7.2</td>
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</table>

ATLAS $t\bar{t}$ inclusive cross section summary

- ATLAS dilepton* $\sqrt{s} = 13$ TeV, $L = 78$ pb$^{-1}$
- ATLAS dilepton $\sqrt{s} = 8$ TeV, $L = 20.3$ fb$^{-1}$
- ATLAS dilepton $\sqrt{s} = 7$ TeV, $L = 4.6$ fb$^{-1}$
- Tevatron combined* $\sqrt{s} = 1.96$ TeV, $L = 8.8$ fb$^{-1}$

* Preliminary

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004

$m_{\text{top}} = 172.5$ GeV, PDF $\oplus \alpha_s$ uncertainties according to PDF4LHC

Inclusive $t\bar{t}$ cross section [pb]
CMS $t \bar{t}$ inclusive cross section summary

- Tevatron combined* $1.96$ TeV ($L=8.8$ fb$^{-1}$)
- CMS $e\mu$ $7$ TeV ($L=5$ fb$^{-1}$)
- CMS $t\bar{t}$+jets $7$ TeV ($L=2.3$ fb$^{-1}$)
- CMS $e\mu$ $8$ TeV ($L=19.7$ fb$^{-1}$)
- CMS $t\bar{t}$+jets $8$ TeV ($L=2.8$ fb$^{-1}$)
- LHC combined $e\mu$ $8$ TeV ($L=5.3-20.3$ fb$^{-1}$)
- CMS $e\mu$ $13$ TeV ($L=42$ pb$^{-1}$)

* Preliminary

Inclusive $t\bar{t}$ cross section [pb]

CMS Preliminary

$\sqrt{s}$ [TeV]

NNLO+NNLL (pp)

NNLO+NNLL (p$\bar{p}$)

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004

$m_{top} = 172.5$ GeV, PDF$\oplus \alpha_s$ uncertainties according to PDF4LHC
CMS Top pair differential cross sections

- Test top physics in different portions of the phase space
  - Test of perturbative QCD, constrain of different generators, theory uncertainties, systematic effects. Window to new physics
  - Use unfolding techniques on background-subtracted reconstructed distributions for a direct comparison to theory predictions
  - Propagation of the systematic errors (only shape errors important)
- Most relevant coming from background knowledge, radiation and hadronization
- Look at lepton, jets, and to more complex variables in top quark final states
  - Need a full reconstruction of top kinematics
  - Compare to reference generators and predictions on differential distribution from theory
  - No significant deviations from SM predictions.

\[ \frac{1}{\sigma} \frac{d\sigma^i}{dX} = \frac{1}{\sigma} \frac{N_{\text{Data}}^i - N_{\text{BG}}^i}{\Delta_X \epsilon^i L} \]

September 2015

Javier Cuevas, QCD@LHC 2015
**CMS Top pair differential in full phase space**

- Differential cross section measured as a function of the top quarks and the tt system at parton level in full phase space.
- Good agreement with SM predictions.
  - Observed top $p_T$ softer than most MC predictions.
  - $p_T(tt)$ in general well described.
  - $m(tt)$ has tail in data lower than prediction.

September 2015

Javier Cuevas, QCD@LHC 2015
**ATLAS tt differential: particle level top**

- Use well defined top definition at particle level
  - (LHCTOPWG recommendation)
  - fully fiducial, differential measurement
  - Top quark proxy constructed from stable particles/detector level observables

- Cut based analysis in $\ell+$jets channel
  - data well described by models
  - Discrepancy at low $m_{t\bar{t}}$
  - Main uncertainties: b-tagging, JES and JER

---

JHEP06 (2015) 100
CMS Preliminary 42 pb⁻¹ (13 TeV) 

Dilepton 

$\frac{1}{dN/dN_{jets}}$ 

$\frac{1}{d\sigma/dp_T}$ [GeV] 

$\frac{1}{d\sigma/dy_{ll}}$ [GeV] 

$\frac{1}{d\sigma/dm_{ll}}$ [GeV] 

$\frac{1}{d\sigma/dp_T}$ [GeV] 

$\frac{1}{d\sigma/dy_{ll}}$ [GeV] 

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$\frac{1}{d\sigma/dp_T}$ [GeV] 

$\frac{1}{d\sigma/dy_{ll}}$ [GeV] 

$\frac{1}{d\sigma/dm_{ll}}$ [GeV]
Single top quark production

- The production cross section gives direct access to the CKM matrix element $|V_{tb}|$
  - May also test the presence of a possible 4th generation quark
  - Check for presence of FCNC
  - Important background for Higgs searches in associated production $W/ZH \rightarrow qqbb$

- Investigate t-channel and tW production
  - s-channel still out of range for an observation
  - t-channel: 1 isolated e or $\mu$, one b-tagged jet, one forward jet, missing $E_T$
  - tW channel: 2 isolated charged leptons (e, $\mu$), one b-tagged jet, missing $E_T$

- Main backgrounds from top-pair production (both semileptonic and dileptonic topologies), $Z(l\bar{l})/W(l\nu)+$jets, Multijet QCD (reduced to extreme kinematic regions by selection cuts)
  - Use data whenever possible to constrain the backgrounds
CMS Single top t-channel

- Robust analysis based on data-driven methods
- Use of multivariate techniques (NN, BDT)
  - Optimize S/B separation using full event properties, constrain systematic effects by simultaneously analyzing signal and background dominated regions
- Cross sections in agreement with the SM expectations, $|V_{tb}|$ can be derived $|V_{td}|, |V_{ts}| << |V_{tb}|$

$$|V_{tb}| = \sqrt{\frac{\sigma_{t-ch.}}{\sigma_{t-ch.}^{th}}} = 1.020 \pm 0.046 \text{ (exp.)} \pm 0.017 \text{ (theor.)}$$

$$0.92 < |V_{tb}| \leq 1 \text{ @ 95\% C.L.}$$

- Analysis ported to 8 TeV (template fit to $|\eta_j|$)
  - Fit to the pseudorapidity of the recoil jet in the signal region $130 < m_{top} < 220$ GeV
  - $W/Z+jets$ and $tt$ background shapes are estimated from data (from top mass sidebands and 3 jets 2 b-tags event category, respectively)
  - QCD multijet background is fixed with a fit to the W transverse mass (muon channel)/ transverse missing energy (electron channel)

$$\sigma_{(t-ch., 8 \text{ TeV})} = 83.6 \pm 2.3 \text{ (stat)} \pm 7.4 \text{ (syst)} \text{ pb}$$

JHEP06(2014) 090

September 2015
Single top $tW$ channel

First evidence at 7 TeV, PRL 110, 022003 (2013)

$tW$ production observed at LHC

- Interesting topology (background to Higgs→WW searches), only leptonic (e, $\mu$) decays of W considered
- In the dilepton topology: two isolated leptons, MET and one b-jet, main backgrounds: Top pairs and Z+jets, all other processes easily reducible
- $tW$ mixing with top pair at NLO: Diagram Removal vs. Diagram Subtraction (DR/DS)

BDT based on 13 kinematic input variables chosen based on signal/background separation, data/MC in several control regions (2j1b, 2j2b, 2job,1job)

- Observed significance $6.1 \sigma$/Expected significance: $5.4 \pm 1.4 \sigma$.
- Cross-section estimated using profile likelihood: $\sigma_{tW} = 23.4 \pm 5.4$ pb at 8TeV, for ($m_{top}=173$GeV): $\sigma_{tW(th)} = 22.2 \pm 0.6$ (scale) $\pm 1.4$(PDF) pb

the choice of the control regions allows also to constrain b-tag efficiency in situ in the same likelihood fit, and reduce that systematic that would be overwhelming otherwise

September 2015  Javier Cuevas, QCD@LHC 2015
Single top s-channel searches

- **Smallest cross section at the LHC** among the single top processes
- **Observation at Tevatron** (March 2014, arXiv:1402.5126);
- **ATLAS**:
  - $|\Delta\varphi(t,b)|$ is the most discriminating variable
  - use BDT to increase sensitivity
  - ML fit to extract signal cross section
  - $\sigma(\text{s-channel}) = 5.0 \pm 4.3 \text{ pb}$, $<14.6 \text{ pb} @ 95\% \text{ C.L.}$
  - Significance $1.3 \sigma$ ($1.4 \sigma$ expect.)
- **CMS**:
  - **Upper limit**: $\sigma_{\text{s-chan}} < 11.5 (17.0, 9.0) \text{ pb} @ 95\% \text{ CL}$, $\sigma_{\text{s-channel}} = 5.55 \pm 0.08 \pm 0.21 \text{ pb}$, SM expectation

PLB 740 (2015) 118
Summary of the ATLAS and CMS Collaboration measurements of the single top production cross-sections in the t-channel at 8 TeV. The measurements are compared to a theoretical calculation based on NLO QCD complemented with NNLL resummation computed assuming a top mass of 172.5 GeV.

Cross-section measurements for the associated production of a top quark and a W boson performed by ATLAS and CMS, and combined result compared with the NLO+NNLL prediction. The uncertainties in the theoretical prediction are represented by dark and light gray bands for renormalisation/factorisation scale and PDF (evaluated using MSTW2008), respectively.
Summary of Single top at LHC

**Single top-quark production**

**Jan 2015**

<table>
<thead>
<tr>
<th>Total inclusive cross-section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS + CMS Preliminary TOPLHCWG</td>
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<tr>
<td>ATLAS t-channel PRD90(2014) 112006, ATLAS-CONF-2014-007</td>
</tr>
<tr>
<td>CMS t-channel JHEP12(2012) 035, JHEP06(2014) 090</td>
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<tr>
<td>CMS Wt production PRL110(2013) 022003, PRL112(2014) 231802</td>
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<td>LHC combination, Wt production ATLAS-CONF-2014-052, CMS-PAS-TOP-14-009</td>
</tr>
<tr>
<td>CMS s-channel, 95% C.L. CMS-PAS-TOP-13-009 arXiv:1404.7116</td>
</tr>
</tbody>
</table>

**t-channel**

| CMS 7+8 TeV t-channel = 1.00 ± 0.04 |
| Tevatron s+t-channel = 1.02 ± 0.06–0.05 |

**Wt-channel**

| LHC 8 TeV Wt-channel = 1.06 ± 0.11 in good agreement with |
| V_{tb} | global SM fit = 0.99914 ± 0.00005 |

September 2015

Javier Cuevas, QCD@LHC 2015
Differential measurement of the cross section of single top-quark production in the t-channel at 8 TeV

Unfolded $p_T$ and $\text{abs}(y)$ spectrum of the top quarks in the combined lepton+jets channel compared with the predictions from $\text{PowHeg}$+Pythia (solid), aMC@NLO+Pythia (dotted), and $\text{CompHEP}$ (dashed). The inner error bars indicate the statistical uncertainty while the outer error bars indicate the full (stat. + syst.) uncertainty.
Associated production of top and bosons at 8 TeV

- Measure couplings to bosons
- Important background for BSM searches
- Analyses are performed in bins of the number of selected leptons (2,3,4)
- Different number of leptons → different admixture of ttW and ttZ processes
  - Same-sign dilepton analysis: tt+W
  - Trilepton and Four-lepton analysis: tt+Z process

**tt+W/Z [ATLAS-CONF-2015-032 ]**
- Four signal regions: opposite sign (OS) dilepton, same sign (SS) dilepton, 3 and 4 lepton.
- Fit for ttZ and ttW simultaneously in a binned likelihood fit
- Further split into categories depending on jet multiplicity, number of b-tagged jets and $E_T^{\text{miss}}$, optimised individually to increase sensitivity.

**tt+W/Z [CMS PAS TOP-14-021 (2015) ]**
- Also performed in many channels with different numbers of leptons, jets and b tags
- Additionally: perform event reconstruction by matching jets and leptons to W/Z bosons and top
  - Combine into linear discriminant
  - Choose best permutation
- Combine resulting match scores with kinematic quantities in BDTs
As configured tt+W/Z production established

- $\sigma(ttW) = 369^{+100}_{-91} \text{ fb} - 5.0 \text{ obs. (3.2 exp)}$
- $\sigma(ttZ) = 176^{+58}_{-52} \text{ fb} - 4.2 \text{ obs. (4.5 exp)}$
- $\sigma(ttW) = 382^{+117}_{-102} \text{ fb} - 4.8 \text{ obs. (3.2 exp)}$
- $\sigma(ttZ) = 242^{+65}_{-55} \text{ fb} - 6.0 \text{ obs. (5.7 exp)}$
$tt+\gamma (l+jets, 7\text{TeV})$ \textbf{[ATLAS PRD 91 (2015) 072007]}

- Sensitive to $t\gamma$ coupling and models with composite top quarks and excited top quark production ($t^* \rightarrow t\gamma$)
- Selection: $l$+jets + high $E_T$ photon ($E_T > 20$ GeV)
  - Suppress misidentified $\gamma$: $|m_{e\gamma} - m_Z| > 5$ GeV
- Prompt photons estimated from template fit to photon isolation variable
- Largest systematic uncertainties: jet energy scale.
- Fiducial cross section:
  \[
  \sigma_{tt+\gamma} \times \text{BR} = 63 \pm 8(\text{stat})^{+17}_{-13} (\text{syst}) \pm 1(\text{lumi}) \text{ fb}
  \]
  per lepton
- Consistent with SM expectation
  \[
  (\sigma_{tt+\gamma} = 48 \pm 10 \text{ fb}).
  \]
- Null hypothesis excluded at $\sigma=5.3 \sigma_{\text{obs}}$. 

September 2015
Javier Cuevas, QCD@LHC 2015

![Diagram of t\gamma production and selection criteria]

![Graph showing cross section results]
CMS $\text{ttbb: } e/\mu^+ \text{ jets and dileptons}$

- Irreducible non resonant background in the search for $\text{ttH(bb)}$
- Test validity of NLO QCD calculations
- Measurement of ratio $\sigma(\text{ttbb})/\sigma(\text{ttjj})$
  - large uncertainties cancellation
  - $l^+\text{jets}$:
    - Selection: Jet $p_T > 40$ GeV
      - one isolated lepton, 4 jets, 2 b-tagged jets
    - Signal extraction by fit to the measured b-tagging discriminator
    - Jet flavour at gen level defined by leading quark flavour (parton) or presence of B hadron (particle)

\[
\frac{\sigma(\text{ttbb})}{\sigma(\text{ttjj})}^{\text{hadB}} = 0.0117 \pm 0.0040\text{(stat.)} \pm 0.0003\text{(syst.)}
\]

\[
\frac{\sigma(\text{ttbb})}{\sigma(\text{ttjj})}^{\text{hadronB}} = 0.0151 \pm 0.0049\text{(stat.)} \pm 0.0004\text{(syst.)}
\]

( $\frac{\sigma(\text{ttbb})}{\sigma(\text{ttjj})}^{\text{NLO}} = 0.0109^{+0.0043}_{-0.0026}$ [arXiv:1403.2046])

- dilepton:
  - Selection: events with 4 jets, 2 b-tagged jets
  - Signal extraction by fit to the measured b-tagging algorithm discriminators
  - Corrected to particle level

\[
\frac{\sigma(\text{ttbb})}{\sigma(\text{ttjj})} = 0.022 \pm 0.004\text{(stat.)} \pm 0.005\text{(syst.)}
\]
ATLAS $tt+bb$, $tt+b$

arXiv:1508.06868

- Cut-based and fit-based analyses for $tt+bb$ in dilepton channel
  - $\sigma(ttbb)/\sigma(ttjj) = 0.0130 \pm 0.0033\text{(stat.)} \pm 0.0028\text{(syst.)}$

- Fiducial measurements of $tt + b$ in $l+jets$ and $e\mu$ channels

- $ttV/H$ was subtracted to allow direct comparison to the predictions containing only the pure QCD matrix elements

- Comparison also with different $g \rightarrow bb$ splitting
The distribution and orientation of energy inside jets is predicted to be an experimental handle on colour connections between the hard-scatter quarks and gluons initiating the jets.

The pull angle is measured for jets produced in $t\bar{t}$ events with one W boson decaying leptonically and the other decaying to jets.

Normalised fiducial $t\bar{t}$ differential cross-section is measured, and compared with SM and colour-octet W boson. It is found that the jet pull angle characterize the W boson as a colour singlet in agreement with the SM.
Charge asymmetry

- NLO effect originating from the interference of $q$--$\bar{q}$bar diagrams producing top pairs. Could be enhanced if new physics present like with $W'$.
  - LHC has symmetric initial state (pp):
  - Quarks are mostly valence and anti--quarks are sea quarks
  - PDF's are not symmetric, quarks carry more momentum than anti-quarks
- Rapidity distribution of tops is broader
- $A_C$ studied e.g. in $l+\text{jets}$ using a template method
- Charge asymmetries in data are background subtracted and unfolded to parton level to allow comparison with theory
- Differential distributions ($m_{tt}$, $y_{tt}$, $p_T^{tt}$) sensitive to BSM physics
- New ATLAS measurement: ATLAS-TOP-2014-016 (to be submitted to EPJC)

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$
Constraining the SM with the top mass

- The top mass, the W mass and the Higgs mass depend on each other
- Direct mass measurement at Tevatron $m(\text{top}) = 173.18 \pm 0.94 \text{ GeV}$
- Not an observable, i.e. scheme-dependent
  - Pole-mass: viewing top quark as a free parton
    - inclusive cross section (NNLO) dependent on top-quark pole mass
- Direct reconstruction methods
  - Full reconstruction by resolving the pairing ambiguities (all channels studied)
  - Use kinematic constrained fitting to improve the mass resolution
    - Constrain the light jet energy scale in situ by using the W mass constraint
  - Fit the mass with MC template fits or event by event likelihood fits
    - Methods very sensitive to the description of radiation and JES uncertainties
- Indirect methods
  - Use the dependence on the top mass on other variables
    - Top pair cross section
    - Lepton $p_T$ and end-point methods
    - Invariant mass of the system $J/\Psi+\text{lepton}$ from $W$
    - Decay length of the $b$ hadron
  - Main issue: need of a lot of statistics

- MS scheme (“running mass”):
  - “MC mass”: (N)LO+PS yet different from pole or MS mass
- Colour Reconnection:
  - Soft interactions not calculable in pQCD
  - Present model uncertainties: 0.5 ... 1 GeV

Javier Cuevas, QCD@LHC 2015
CMS (MC) Top mass with lepton+jets events, 8TeV

$m_t = 172.04 \pm 0.19 \text{ (stat.+JSF)} \pm 0.75 \text{ (syst.) GeV}$

$\sigma_{\text{tot}} = 0.77 \text{ GeV}$

2D fit uncertainty comparable to world average

$m_t = 172.66 \pm 0.11 \text{ (stat)} \pm 1.29 \text{ (syst) GeV}$

September 2015

Javier Cuevas, QCD@LHC 2015
**ATLAS (MC)** top mass lepton+jets channel, 7 TeV

- Event selection similar to CMS lepton+jets result.
  - Separate events into 1 b tag and ≥2 b tags.
- Reconstruct ttbar system with kinematic likelihood fit.
  - Improves purity and assignment of reconstructed jets to partons.
- Template-based approach with observables: $m_{\text{top}}^{\text{reco}}$, $m_W^{\text{reco}}$ and $R_{bq}$ (ratio of $p_T^{b_{\text{had}}}$ and $p_T^{b_{\text{lep}}}$ over $p_T^{W_{\text{jet1+2}}}$)
  - In-situ calibration of JES ($m_W^{\text{reco}}$) and bJES ($R_{bq}$), relative to udsg.

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<table>
<thead>
<tr>
<th>Systematic uncertainties</th>
<th>$\Delta m_t$ (GeV)</th>
</tr>
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<tbody>
<tr>
<td>Jet energy scale</td>
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<tr>
<td>b jet energy scale</td>
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<td>Pile up</td>
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<td>Detector modeling</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>1.22</strong></td>
</tr>
</tbody>
</table>

---

**Signal + background fit to data**
Analysis combined using BLUE, accounts for correlations between all uncertainties.

**CMS combination**

\[ m_{\text{top}} = 172.38 \pm 0.65 \text{ (syst) GeV} \]

**ATLAS combination**

\[ m_{\text{top}} = 172.99 \pm 0.91 \text{ (syst) GeV} \]

**Tevatron combination**

\[ m_{\text{top}} = 174.38 \pm 0.64 \text{ syst GeV} \]

Total uncertainty is now below 1 GeV
Summary

• Top quark physics is a pillar of the current research program in HEP and provide stringent tests of pQCD. Both the CMS and ATLAS collaborations cover a wide range of top-related topics

• Key to QCD, electro-weak and New Physics
  ➢ Ideal probe for constraining (directly + indirectly) the symmetry breaking of the SM
    o The top is way heavy $\rightarrow$ the Higgs scalar mostly couples to tops
  ➢ Ideal probe for looking for new physics beyond the model itself
    o Via precision measurements
    o Via direct searches for new signals

• Results in agreement with SM predictions
  ➢ $t\bar{t}$ production
    ➢ Precision regime: $\sigma_{t\bar{t}} < 4\%$, $m(\text{top}) \lesssim 1 \text{ GeV}$. 
    ➢ First measurements at 13 TeV
  ➢ Single top production:
    ➢ $t$-channel large enough to investigate properties
    ➢ $tW$ channel observed at LHC. s-channel observed at Tevatron
  ➢ Associated production, observation of $t\bar{t}+\gamma$, $t\bar{t}+W/Z$, important to study top-Higgs couplings.