Overview on inclusive and differential single top-quark cross-sections and results on $|V_{tb}|$

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Single top-quark production

- Production via the weak interaction

  \[ \sigma_{7\text{TeV}} = 64 \text{ pb (4.6\% unc.)} \]
  \[ \sigma_{8\text{TeV}} = 85 \text{ pb (4.4\% unc.)} \]

  PRD 86 (2012) 010001

  \[ \sigma_{7\text{TeV}} = 4.6 \text{ pb (4.3\% unc.)} \]
  \[ \sigma_{8\text{TeV}} = 5.6 \text{ pb (3.6\% unc.)} \]

  PRD 82 (2010) 054018

  \[ \sigma_{7\text{TeV}} = 16 \text{ pb (7.0\% unc.)} \]
  \[ \sigma_{8\text{TeV}} = 22 \text{ pb (6.7\% unc.)} \]

  PRD 81 (2010) 054028

- Final state: Lepton + \( E_{T,\text{miss}} \) + two to three jets (one or two b-tagged)
- In case of Wt production: Dilepton + \( E_{T,\text{miss}} \) + one b-tagged jet
- Main backgrounds are W+jets production and top-quark pair production
t-channel single top-quark production

- Single top quark production via t-channel: largest cross section @LHC
- Checks of the Standard Model:
  
  **Golden Ticket**

  **Ratio of u- and d-quark PDF**
  
  Measure \( R_t = \sigma_t(t)/\sigma_t(\bar{t}) \)

  **Direct measurement of** \( |V_{tb}|^2 \) (\( \alpha \) cross section)
  
  **Unitarity test of CKM matrix**

  **Measurement of** \( \sigma_t(t+\bar{t}) \), extract \( |V_{tb}| \)

  **Test of the b-quark PDF**

  **Top quark properties:** Polarization, \( p_T \), rapidity

  **Measure differential distributions**
Cross-section measurements

ATLAS and CMS worked consistently in Run 1 on the t-channel single top-quark cross sections.

Latest results:

- CMS, 8 TeV, 19.7 fb\(^{-1}\): JHEP 06 (2014) 090
  - \(\sigma(tq) = 53.8 \pm 1.5 \text{ (stat.)} \pm 4.4 \text{ (syst.)} \text{ pb} \rightarrow 9\%
  - \(\sigma(\bar{t}q) = 27.6 \pm 1.3 \text{ (stat.)} \pm 3.7 \text{ (syst.)} \text{ pb} \rightarrow 14\%
  - \(\sigma(tq + \bar{t}q) = 83.6 \pm 2.2 \text{ (stat.)} \pm 7.4 \text{ (syst.)} \text{ pb} \rightarrow 9\%
- ATLAS, 7 TeV, 4.59 fb\(^{-1}\): PRD 90, 112006 (2014)
  - \(\sigma(tq) = 46 \pm 1 \text{ (stat.)} \pm 6 \text{ (syst.)} \text{ pb} \rightarrow 12\%
  - \(\sigma(\bar{t}q) = 23 \pm 1 \text{ (stat.)} \pm 3 \text{ (syst.)} \text{ pb} \rightarrow 16\%
  - \(\sigma(tq + \bar{t}q) = 68 \pm 2 \text{ (stat.)} \pm 8 \text{ (syst.)} \text{ pb} \rightarrow 12\%
- All results agree well with the SM prediction within the total uncertainty.

Dominant uncertainties:
- Jet energy scale (forward jets)
- Signal modeling
Fiducial cross section

- Fiducial cross section reduces the extrapolation uncertainties from the measured region to the inclusive region, which are determined from Monte Carlo
- Cross section measured within the detector acceptance
- Fiducial region defined as signal region, but using particle-level objects
- $\sigma_{\text{fid}}(tq+\bar{t}q) = 3.37 \pm 0.05 \text{ (stat.)} \pm 0.48 \text{ (syst.) pb} \rightarrow 14\%$ uncertainty

- Reduction on signal modeling uncertainty of about 3%
- Provides feedback to the generator community
- Fiducial cross section can be extrapolated to the inclusive cross section using the acceptance of the different generators and the BR(t→Wb)
Top-quark to top-antiquark production

- Charge of the top quark corresponds to type of initial light quark

\[
\begin{align*}
\text{q} & \rightarrow \text{q'} \\
\text{w} & \rightarrow \text{t} \\
\text{b} & \rightarrow \bar{b}
\end{align*}
\]

- \( R_t = \sigma_t(t)/\sigma_t(\bar{t}) \) sensitive to ratio of u- and d-quark PDFs

- Momentum fraction of light quarks in single top-quark events: \( 0.02 < x < 0.5 \)

Results on ratio \( R_t \):

- \( R_t = 2.04 \pm 0.13 \) (stat.) \( \pm 0.12 \) (syst.), 8.7%, ATLAS, 7 TeV, 4.59 fb\(^{-1}\) \( \text{PRD 90, 112006 (2014)} \)

- \( R_t = 1.95 \pm 0.10 \) (stat.) \( \pm 0.19 \) (syst.), 10.9%, CMS, 8 TeV, 19.7 fb\(^{-1}\) \( \text{JHEP 06 (2014) 090} \)

- Both results are comparable even though done at different energies

- Measurements can profit from more data
t-channel single top-quark production

- Single top quark production via t-channel: largest cross section @LHC
- Checks of the Standard Model:

  - Ratio of u- and d-quark PDF
  - Test of the b-quark PDF
  - Direct measurement of $|V_{tb}|^2$ (α cross section)
  - Unitarity test of CKM matrix
  - Measurement of $\sigma_t(t+\bar{t})$, extract $|V_{tb}|$
  - Top quark properties: Polarization, $p_T$, rapidity
  - Measure differential distributions

- Measurement of $\sigma_t(t+t)$, extract $|V_{tb}|$
- t-channel events in LHC Run 1:
  - 7 TeV: ~5500 events (ATLAS, 4.6 fb⁻¹)
  - 8 TeV: ~10000 events (CMS, 19.7 fb⁻¹)
Differential cross section

- Use a multivariate discriminant to define a high purity region
- Measure differential cross section as function of $p_T(t)$, $p_T(\bar{t})$, $|y(t)|$, and $|y(\bar{t})|$ (ATLAS) or $p_T(t+t)$ and $|y(t+t)|$ (CMS)
- So far, unfolded to parton-level top quark

Reconstructed distributions

ATLAS, 7 TeV, 4.59 fb$^{-1}$
PRD 90, 112006 (2014)
CMS, 8 TeV, 19.7 fb$^{-1}$
CMS PAS TOP-14-004
Results on differential cross sections

Top Quark

\[ \frac{1}{\sigma} \frac{d\sigma}{dp_T(t)} \]

\[ p_T(t) \] [GeV]

Data / NLO

\[ |y| \]

\[ \frac{1}{\sigma} \frac{d\sigma}{dy(|t|)} \]

\[ |y(t)| \]

\[ \text{ATLAS, 7 TeV, 4.59 fb}^{-1} \]

\[ \text{PRD 90, 112006 (2014)} \]

9-22%

8.5-15%

Top Antiquark

\[ \frac{1}{\sigma} \frac{d\sigma}{dp_T(\bar{t})} \]

\[ p_T(\bar{t}) \] [GeV]

Data / NLO

\[ |y| \]

\[ \frac{1}{\sigma} \frac{d\sigma}{dy(|\bar{t}|)} \]

\[ |y(\bar{t})| \]

\[ \text{ATLAS, 7 TeV, 4.59 fb}^{-1} \]

\[ \text{PRD 90, 112006 (2014)} \]

15-67%

17-19%
Results on differential cross sections

- All distributions from ATLAS and CMS agree well with SM predictions
- Measurements still limited by data statistics and background modelling -> precision at best around 10%

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Polarization of the top quark

- CMS measured also the top quark polarization in single top-quark events -> 100% polarized, V-A coupling structure
- \( \cos \theta^* \text{(lepton, untagged jet)} \) is unfolded to access the top quark spin asymmetry. \( e^+\mu \) combined result: \( A_l = 0.41 \pm 0.06 \text{ (stat.)} \pm 0.16 \text{ (syst.)} \) -> 41%
- Polarization: \( P_t = 2 A_l / \alpha_l = 0.82 \pm 0.12 \text{ (stat.)} \pm 0.32 \text{ (syst.)} \) assuming that the spin analyzing power of the lepton \( \alpha_l \) is 100%.
- Uncertainty is dominated by systematic uncertainties
Cross-section of W-associated single top-quark production

- Both, ATLAS and CMS measure $Wt$ production in the dilepton final state with one additional b-tagged jet and in case of ATLAS a significant amount of $E_{T,\text{miss}}$
- Boosted Decision Trees are trained to separate the signal from the dominant $t\bar{t}$ background
- Important variables:
  - number of loose jets ($p_T(j) > 20$ GeV, $|\eta| < 4.9$)
  - vector sum of all transverse momenta in event $p_T^{\text{sys}}$
Cross-section of W-associated single top-quark production

- Uncertainty on inclusive cross section of 23% (21%) for CMS (ATLAS), dominated by systematic uncertainties -> $t\bar{t}$ and signal modeling
Extraction of $|V_{tb}|$

**Assumptions** for $|V_{tb}|$ extraction from the $t$-channel and $Wt$-channel cross sections:

- $|V_{tb}| \gg |V_{td}|, |V_{ts}|$
- $\text{BR}(t\rightarrow Wb) = 1$
- $Wtb$ interaction is a SM-like left-handed weak coupling

**Determination** of $|V_{tb}|$:

- $|V_{tb}|^2 = \sigma(tq+\bar{t}q)/\sigma_{\text{theo}}(tq+\bar{t}q)$
- CMS, 7 and 8 TeV combined, $t$-channel:
  $|V_{tb}| = 0.998 \pm 0.038$ (exp) $\pm 0.016$ (theo) $\rightarrow$ 4.1%
- ATLAS, 7 TeV, $t$-channel:
  $|V_{tb}| = 1.02 \pm 0.06$ (exp) $\pm 0.02$ (theo) $\rightarrow$ 6.2%

**Limit:**

- Flat prior between 0 and 1
- Assumption, that $|V_{tb}| \leq 1$
- CMS: $|V_{tb}| > 0.92$ at 95% C.L.
- ATLAS: $|V_{tb}| > 0.88$ at 95% C.L.

- Additional measurement of $|V_{tb}|$ in $\bar{t}\bar{t}$ events via: $\mathcal{R}_b = \frac{\mathcal{B}(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wq)}$
- Most precise value, **BUT** assumption of unitarity of the CKM matrix
s-channel single top-quark production

- Due to the small cross section of s-channel single top-quark production, there has been no evidence of the production in LHC Run 1 for the time being
- Both ATLAS and CMS have performed a search with the full dataset at 8 TeV
- BDTs are trained to separate signal from background
- The observed (expected) significances are 0.7 (0.9) for CMS and 1.3 (1.4) for ATLAS
- Upper limits are set on the cross section of 11.5 pb (CMS) or 14.6 pb (ATLAS) at 95% C.L.

ATLAS, 8 TeV, 20.3 fb$^{-1}$ PLB 740 (2015) 118
CMS, 8 TeV, 19.3 fb$^{-1}$ CMS PAS TOP-13-009
Prospects for LHC Run 2

Cross section ratios of 13 TeV to 8 TeV:

<table>
<thead>
<tr>
<th></th>
<th>13/8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>t-channel</td>
<td>2.6</td>
</tr>
<tr>
<td>Wt-channel</td>
<td>3.2</td>
</tr>
<tr>
<td>s-channel</td>
<td>2.0</td>
</tr>
<tr>
<td>tt̅</td>
<td>3.3</td>
</tr>
</tbody>
</table>

- **t-channel:**
  - Measurements of top-quark properties will gain from improved statistics
  - -> more bins
  - -> smaller statistical uncertainty
  - Maybe possible to look at the spectator b-quark

- **Wt-channel**
  - Will still be challenging as tt̅ background increases with the same fraction
  - BUT will profit from more statistics

- **s-channel:**
  - Evidence or observation with more luminosity?
  - -> will remain tough
Conclusion

• Both ATLAS and CMS have performed extensive measurements of single top-quark production in Run 1
• In t-channel single top-quark production an uncertainty ~10% has been achieved for the inclusive cross section
• High statistics allow separate measurements of top-quark and top-antiquark production as well as differential measurements of top-quark properties
• First fiducial measurements have been performed
• Wt-channel single top-quark production has been observed for the first time
• Run 2 will see improvements of current as well as new exciting measurements
BACK - UP
Details on the fiducial region used in ATLAS-CONF-2014-007

• Stable particles = particles with a lifetime > 30 ps
• Particle-level leptons (e, μ and neutrinos):
  – reject leptons from hadronic decays
  – request a W boson decay
  – accept leptons from τ decays in W boson decay
  – e, μ are dressed with photons within a cone of ΔR < 0.1
• $E_{T}^{\text{miss}}$ is the vectorial of the selected neutrinos
• Particle-level jets:
  – reconstructed using Anti-$k_t$ algorithm with the FASTJET package with a width of R=0.4
  – all stable particles are used for clustering except for the selected leptons
  – b-tagging is done by B-Hadron matching within a jet
• A lepton overlap removal is applied if ΔR(jet,lepton)<0.4 (as for reconstructed selection)
• All cuts on the reconstructed phase space are also applied to the fiducial phase space
Both, ATLAS and CMS, show measurements unfolded to a parton-level top quark for measurements of the top-quark properties.

- 7 TeV ATLAS measurement uses Powheg+Pythia6 as generator, top quark is taken from the pythia particle record as the particle with abs(pdg_id)=6.
- CMS does the same for their 8 TeV measurements.
The future: pseudo-tops

• Both ATLAS and CMS plan to unfold to particle-level “pseudo-tops” in their future differential cross section measurements.
• Here, the decay products at particle-level are used to reconstruct the “pseudo-top”
• Both experiments have presented results for differential measurements of $t\bar{t}$ production unfolding to the “pseudo-top” -> see previous talk