The top quark

Why top quarks?
- heaviest known particle, only “bare” quark
- high statistics allows precision measurements and search for new physics

Copious production at the LHC (top-factory):
- ~150 fb⁻¹ @13TeV collected in Run 2 by ATLAS…

\[
N = \mathcal{L} \cdot \sigma_{\bar{t}t},
\]
\[
\sigma_{\bar{t}t} \sim 830 \text{ pb}, \quad \Rightarrow \quad \mathcal{L} \sim 15 \cdot 10^{33} \text{ cm}^2 \text{ s}^{-1}
\]

~750 \( \bar{t}t \) pairs produced/minute
(125M @150fb⁻¹)
<table>
<thead>
<tr>
<th>Short Title</th>
<th>Journal Reference</th>
<th>Date</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search for FCNC t(\gamma) in single top</td>
<td>Submitted to Phys. Lett. B</td>
<td>22-AUG-19</td>
<td>13</td>
<td>80 fb(^{-1})</td>
</tr>
<tr>
<td>Differential t(\bar{t})bar-cross-sections in lepton+jets with 36 fb(^{-1})</td>
<td>Submitted to EPJC</td>
<td>20-AUG-19</td>
<td>13</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>K(<em>{S}^{*})0 and Lambda(</em>{0}) production in t(\bar{t})bar events at 7 TeV</td>
<td>Submitted to EPJC</td>
<td>25-JUL-19</td>
<td>7</td>
<td>5 fb(^{-1})</td>
</tr>
<tr>
<td>Measurement of the top-quark mass using t(\bar{t})+1 jet events at 8 TeV</td>
<td>Submitted to JHEP</td>
<td>06-MAY-19</td>
<td>8</td>
<td>20.3 fb(^{-1})</td>
</tr>
<tr>
<td>Spin correlation measurement at 13 TeV</td>
<td>Submitted to EPJC</td>
<td>18-MAR-19</td>
<td>13</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>Measurement of the jet shapes at 13 TeV</td>
<td>JHEP 08 (2019) 033</td>
<td>07-MAR-19</td>
<td>13</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>ATLAS+CMS combination of Run 1 single top measurements and extraction of V(\bar{t}b)</td>
<td>JHEP 05 (2019) 088</td>
<td>18-FEB-19</td>
<td>8</td>
<td>20 fb(^{-1})</td>
</tr>
<tr>
<td>Measurement of t(\bar{t})V in multilepton final states using 36.5 fb(^{-1}) at 13 TeV</td>
<td>Phys. Rev. D 99 (2019) 072009</td>
<td>11-JAN-19</td>
<td>13</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>Search for flavor-changing neutral current t to H(\bar{q}) with H-&gt;b(\bar{b})bar and taustau at 13 TeV</td>
<td>JHEP 05 (2019) 123</td>
<td>30-DEC-18</td>
<td>13</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>Measurement of the t(\bar{t})bb cross section at 13 TeV</td>
<td>JHEP 04 (2019) 046</td>
<td>29-NOV-18</td>
<td>13</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>4 top quark search with 1 or 2 leptons</td>
<td>Phys. Rev. D 99 (2019) 052009</td>
<td>06-NOV-18</td>
<td>13</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>Measurement of the top quark mass in the lepton+jets channel at 8 TeV</td>
<td>Eur. Phys. J. C 79 (2019) 290</td>
<td>03-OCT-18</td>
<td>8</td>
<td>20.2 fb(^{-1})</td>
</tr>
<tr>
<td>Same-sign dilepton plus b-jet search</td>
<td>JHEP 12 (2018) 039</td>
<td>31-JUL-18</td>
<td>13</td>
<td>36.1 fb(^{-1})</td>
</tr>
<tr>
<td>Quantum Interference Between Single and Doubly Resonant Top Quark Production</td>
<td>Phys. Rev. Lett. 121 (2018) 152002</td>
<td>12-JUN-18</td>
<td>13</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>Inclusive and lepton differential cross-sections in dilepton t(\bar{t})bar with 36 fb(^{-1})</td>
<td>ATLAS-CONF-2019-041</td>
<td>04-AUG-19</td>
<td>13</td>
<td>36 fb(^{-1})</td>
</tr>
<tr>
<td>Top width measurement in dilepton t(\bar{t})bar</td>
<td>ATLAS-CONF-2019-038</td>
<td>02-AUG-19</td>
<td>13</td>
<td>139 fb(^{-1})</td>
</tr>
<tr>
<td>Measurement of t(\bar{t})bar charge asymmetry at 13 TeV in H+jets</td>
<td>ATLAS-CONF-2019-026</td>
<td>09-JUL-19</td>
<td>13</td>
<td>139 fb(^{-1})</td>
</tr>
<tr>
<td>Search for charged lepton flavour violation in top quark decays</td>
<td>ATLAS-CONF-2018-044</td>
<td>13-SEP-18</td>
<td>13</td>
<td>80 fb(^{-1})</td>
</tr>
</tbody>
</table>
Outline

$t\bar{t}$ x-section
Talk: $t\bar{t}$ x-sec - Adam Bozson
29/08 h12:10
Outline

\textbf{tt \textit{x-section}}

Talk: tt x-section - Adam Bozson - 29/08 h12:10

\textit{Strange hadron production}
Outline

- **tt x-section**
  - Talk: tt x-section - Adam Bozson - 29/08 h12:10

- Strange hadron production

- Mass
  - Talk: top mass - Jiri Hejbal - 24/08 h11:50
Outline

Outline

\( \bar{t}t \) x-section
Talk: \( \bar{t}t \) x-sec - Adam Bozson - 29/08 h12:10

Strange hadron production

Mass

Talk: top mass - Jiri Hejbal - 24/08 h11:50

Properties
**Outline**

- **tt x-section**
  - Talk: tt x-section - Adam Bozson - 29/08 h12:10

- **Strange hadron production**

- **Mass**
  - Talk: top mass - Jiri Hejbal - 24/08 h11:50

- **top+W/Z/γ**
  - Talk: ttV - Paul Glaysher - 28/08 h16:50
  - Poster: 4 tops - Thibault Chevalieras - 26/08 h20:30
Outline

**tt x-section**
Talk: tt x-sec - Adam Bozson - 29/08 h12:10

**Strange hadron production**

**Searches**

**top+W/Z/γ**
Talk: ttV - Paul Glaysher - 28/08 h16:50
Poster: 4 tops - Thibault Chevalerias - 26/08 h20:30

**Mass**
Talk: top mass - Jiri Hejbal - 24/08 h11:50
Outline

**Properties**

- **tt x-section**
  
  Talk: tt x-section - Adam Bozson - 29/08 h12:10

- **Strange hadron production**

**Searches**

- **top+W/Z/γ**

  Talk: ttV - Paul Glaysher - 28/08 h16:50
  
  Poster: 4 tops - Thibault Chevalerias - 26/08 h20:30

**Conclusions**

Talk: top mass - Jiri Hejbal - 24/08 h11:50
Differential and 2-differential in the $\ell +\text{jets}$ channel, 36.1 fb$^{-1}$ @13 TeV

Resolved regime

- Single lepton with $p_T > 25$ GeV
- At least 4 jets with $p_T > 25$ GeV
- At least 2 bjet (if > 2 selected the highest $p_T$)

Leptonic top:
- Lepton
- $v$: $E_{T}^{\text{miss}}$ (use constraint on $W$ mass to find $p_T$ component)
- Closest b-jet to the lepton

Hadronic top:
- Use the two light jets (invariant mass near to $W$ mass)
- Other b-jet

Boosted regime

- $p_T > 300$ GeV
- $\Delta R > 1.5$

Unfolded to parton and particle level with Iterative D’Agostini method

Algorithms for event reconstruction employed (Pseudo-top and KLFitter)

Overlap with resolved events removed

Submitted to EPJC - NEW!
>60 spectra in total, compared with MC generators and NNLO predictions
Inclusive & (2D-)differential in eμ channel, 36.1 fb$^{-1}$ @13TeV

- $\sigma_{t\bar{t}} = 826.4\pm19.9$ pb
- highest precision, 2.4%
- CMS measurements
  - 4.0% in dilepton 2015+16,
  - 3.8% in l+jets 2015

**overestimate of $p_T$ spectra**

**sensitivity to PDF thanks to rapidity**

**extraction of $m_{\text{top}}^{\text{pole}}$ by unfolding**

<table>
<thead>
<tr>
<th>PDF set</th>
<th>$m_{\text{t}}^{\text{pole}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT14</td>
<td>173.1$^{+2.0}_{-2.1}$</td>
</tr>
<tr>
<td>CT10</td>
<td>172.1$^{+2.0}_{-2.0}$</td>
</tr>
<tr>
<td>MSTW</td>
<td>172.3$^{+2.0}_{-2.1}$</td>
</tr>
<tr>
<td>NNPDF2.3</td>
<td>173.4$^{+1.9}_{-1.9}$</td>
</tr>
<tr>
<td>PDF4LHC</td>
<td>172.1$^{+3.1}_{-2.0}$</td>
</tr>
</tbody>
</table>
Measurements of neutral strange particle production interesting

* to test theoretical jet fragmentation functions
* to constrain the underlying event (UE) effects
* → helpful to to tune strange particle content of MC models

Standard dilepton selection @7TeV data

* classification as inside bjet, inside non-b-jet and outside any jet
* unfolding to particle level

**some mismodelling for $K_s^0$ outside jets**

**$K_s^0$ and $\Lambda^0$ well described**
Top quark pole mass determinations compared to direct measurement

- **ATLAS Preliminary**
  - May 2019: NNLO+NNLL: t+jets inclusive PDF4LHC, 7 TeV 2014, 171.4 ± 2.6
  - NNLO+NNLL: t+jets inclusive PDF4LHC, 8 TeV 2014, 174.1 ± 2.7
  - NNLO+NNLL: t+jets inclusive PDF4LHC, 7-8 TeV 2014, 172.9 ± 2.6
  - NLO: t+jets, 7 TeV 2015, 173.7 ± 2.1
  - NLO: t+jets lepton differential, 8 TeV 2017, 173.2 ± 1.6
  - NLO: t+jets, 8 TeV 2019, 171.1 ± 1.2
  - Direct reconstruction 2018, 172.69 ± 0.48

- **Direct reconstruction 2018**
  - ATLAS, 7-13 TeV, 2018, 0.48 ± 0.51

<table>
<thead>
<tr>
<th>Source</th>
<th>Year</th>
<th>Mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS+CMS Preliminary</td>
<td>2019</td>
<td>m_{top} = 7-13 TeV</td>
</tr>
<tr>
<td>World comb. (Mar 2014)</td>
<td>2014</td>
<td>173.29 ± 0.95 (0.35 ± 0.88)</td>
</tr>
<tr>
<td>LHC comb. (Sep 2013)</td>
<td>2013</td>
<td>173.34 ± 0.76 (0.36 ± 0.67)</td>
</tr>
<tr>
<td>ATLAS, t+jets</td>
<td>2019</td>
<td>172.33 ± 1.27 (0.75 ± 1.02)</td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td>2019</td>
<td>173.79 ± 1.41 (0.54 ± 1.30)</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>2019</td>
<td>175 ± 1.1 (1.4 ± 1.2)</td>
</tr>
<tr>
<td>ATLAS, single top</td>
<td>2019</td>
<td>172.22 ± 2.1 (0.7 ± 2.0)</td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td>2019</td>
<td>172.99 ± 0.85 (0.41 ± 0.74)</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>2019</td>
<td>173.72 ± 1.15 (0.55 ± 1.01)</td>
</tr>
<tr>
<td>ATLAS, t+jets</td>
<td>2015</td>
<td>173.49 ± 1.05 (0.43 ± 0.97)</td>
</tr>
<tr>
<td>CMS, t+jets</td>
<td>2018</td>
<td>172.69 ± 0.48 (0.25 ± 0.41)</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>2018</td>
<td>173.49 ± 1.06 (0.43 ± 0.97)</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>2018</td>
<td>172.50 ± 1.52 (0.43 ± 1.46)</td>
</tr>
<tr>
<td>CMS, single top</td>
<td>2018</td>
<td>172.35 ± 1.41 (0.69 ± 1.23)</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>2018</td>
<td>172.82 ± 1.23 (0.19 ± 1.22)</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>2018</td>
<td>172.32 ± 0.64 (0.25 ± 0.59)</td>
</tr>
<tr>
<td>CMS, single top</td>
<td>2018</td>
<td>172.95 ± 1.22 (0.77 ± 0.95)</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>2018</td>
<td>172.44 ± 0.48 (0.13 ± 0.47)</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>2018</td>
<td>172.25 ± 0.63 (0.08 ± 0.62)</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>2018</td>
<td>172.33 ± 0.70 (0.14 ± 0.69)</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>2018</td>
<td>172.34 ± 0.73 (0.20 ± 0.70)</td>
</tr>
</tbody>
</table>

References:
- [12] PRD 93 (2016) 072004
- [16] EPJC 79 (2019) 313
In $\ell+$jets channel @8TeV

- $\sigma_{t\bar{t}+1}j$ more sensitive than $\sigma_{t\bar{t}}$
- unfold to parton and particle level

$\rho_S = \frac{2m_0}{m_{t\bar{t}+1}j} = \frac{2 \cdot 170 \text{ GeV}}{m_{t\bar{t}+1}j}$

sensitive to $m_{\text{top}}^{\text{pole}}$

$\rho_S$ = Parton level

$1/\sigma_{t\bar{t}} \cdot d\sigma/ d\rho_S$

ATLAS

$\sqrt{s}=8 \text{ TeV}, 20.2 \text{ fb}^{-1}$

\begin{align*}
\rho_S &= \frac{2m_0}{m_{t\bar{t}+1}j} = \frac{2 \cdot 170 \text{ GeV}}{m_{t\bar{t}+1}j} \\
\text{Data} \quad \text{Stat+syst uncertainty}
\end{align*}

\begin{align*}
\text{t}\bar{t}+1j @ \text{NLO+PS} : \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 165.0 \text{ GeV} \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 175.0 \text{ GeV} \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 171.1 \text{ GeV (best fit)}
\end{align*}

$\rho_S = \frac{2m_0}{m_{t\bar{t}+1}j}$

$\rho_S$ = Parton level

$1/\sigma_{t\bar{t}} \cdot d\sigma/ d\rho_S$

ATLAS

$\sqrt{s}=8 \text{ TeV}, 20.2 \text{ fb}^{-1}$

\begin{align*}
\rho_S &= \frac{2m_0}{m_{t\bar{t}+1}j} = \frac{2 \cdot 170 \text{ GeV}}{m_{t\bar{t}+1}j} \\
\text{Data} \quad \text{Stat+syst uncertainty}
\end{align*}

$\rho_S$ = Parton level

$1/\sigma_{t\bar{t}} \cdot d\sigma/ d\rho_S$

\begin{align*}
\text{t}\bar{t}+1j @ \text{NLO+PS} : \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 165.0 \text{ GeV} \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 175.0 \text{ GeV} \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 171.1 \text{ GeV (best fit)}
\end{align*}

Best individual differential measurement

$m_{\text{top}}^{\text{pole}} = 171.1 \pm 1.2 \text{ GeV (0.7 %)}$

dominated by JES and MC modelling uncertainties

$\rho_S = \frac{2m_0}{m_{t\bar{t}+1}j} = \frac{2 \cdot 170 \text{ GeV}}{m_{t\bar{t}+1}j}$

sensitive to $m_{\text{top}}^{\text{pole}}$

$\rho_S$ = Parton level

$1/\sigma_{t\bar{t}} \cdot d\sigma/ d\rho_S$

ATLAS

$\sqrt{s}=8 \text{ TeV}, 20.2 \text{ fb}^{-1}$

\begin{align*}
\rho_S &= \frac{2m_0}{m_{t\bar{t}+1}j} = \frac{2 \cdot 170 \text{ GeV}}{m_{t\bar{t}+1}j} \\
\text{Data} \quad \text{Stat+syst uncertainty}
\end{align*}

$\rho_S$ = Parton level

$1/\sigma_{t\bar{t}} \cdot d\sigma/ d\rho_S$

\begin{align*}
\text{t}\bar{t}+1j @ \text{NLO+PS} : \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 165.0 \text{ GeV} \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 175.0 \text{ GeV} \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 171.1 \text{ GeV (best fit)}
\end{align*}

$\rho_S = \frac{2m_0}{m_{t\bar{t}+1}j}$

$\rho_S$ = Parton level

$1/\sigma_{t\bar{t}} \cdot d\sigma/ d\rho_S$

ATLAS

$\sqrt{s}=8 \text{ TeV}, 20.2 \text{ fb}^{-1}$

\begin{align*}
\rho_S &= \frac{2m_0}{m_{t\bar{t}+1}j} = \frac{2 \cdot 170 \text{ GeV}}{m_{t\bar{t}+1}j} \\
\text{Data} \quad \text{Stat+syst uncertainty}
\end{align*}

$\rho_S$ = Parton level

$1/\sigma_{t\bar{t}} \cdot d\sigma/ d\rho_S$

\begin{align*}
\text{t}\bar{t}+1j @ \text{NLO+PS} : \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 165.0 \text{ GeV} \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 175.0 \text{ GeV} \\
&\text{m}_{t\bar{t}}^{\text{pole}} = 171.1 \text{ GeV (best fit)}
\end{align*}
In lepton+jets channel @8TeV

- sizeable uncertainties from JES and bJES
- ⇒ 3-D fit + BDT (19% improvement in Δm_{top})
- m_{top} = 172.08 ± 0.39 (stat) ± 0.82 (syst) GeV
- Combination of 6 measurements @7,8TeV
- → relative uncertainty 0.29%! 

<table>
<thead>
<tr>
<th>Experiment</th>
<th>m_{top}</th>
<th>stat. uncertainty</th>
<th>syst. (total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>171.46 ± 1.91 ± 2.51 (3.16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D0</td>
<td>173.32 ± 1.36 ± 0.85 (1.60)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>172.99 ± 0.41 ± 0.74 (0.85 ± 0.05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>172.82 ± 0.19 ± 1.22 (1.24)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ATLAS (2018) | 172.69 ± 0.25 ± 0.41 (0.48 ± 0.03) |
Charge asymmetry

Induced by Interference between Born and Box diagrams

- Analogue of Tevatron forward-backward asymmetry

“Charge asymmetry” only exists in higher-order $q\bar{q}$ production,

- $gg$-fusion is symmetric to all orders

- Challenging to measure at the LHC ($q\bar{q} \sim 10\%$ of production fraction at 13 TeV)

\[
A_C^{t\bar{t}} = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)} \quad \Delta |y| = |y(t)| - |y(\bar{t})|
\]
Charge asymmetry

Extracted from 139 fb$^{-1}$ @13 TeV data using single lepton (e/µ) selections

* resolved+boosted ($p_T(t) \gtrsim 400$ GeV)

* $|\Delta y|$ unfolded using a likelihood-based technique called “fully bayesian unfolding”

Charge asymmetry measured inclusively to be $A_C = 0.6\% \pm 0.15\%$

* in agreement with NNLO QCD + NLO EW predictions

* $4\sigma$ from 0-asymmetry hypothesis

* measurements reinterpreted in EFT

First evidence for charge asymmetry in pp collisions!
Decay width ($\Gamma$) is an important property of any particle

- BSM models predict different $\Gamma_t$ compared to SM
- prediction: $\Gamma_t^{\text{SM}} = 1.32 \text{ GeV}$ for $m_t = 172.5 \text{ GeV}$ (NNLO)
- precise 8 TeV measurement, still not enough to constrain BSM
  - $\Gamma_t = 1.76 \pm 0.33 \text{ (stat.)} + 0.79 - 0.68 \text{ (syst.) GeV}$ [Eur. Phys. J. C 78 (2018) 129]

Measurement performed with dilepton $t\bar{t}$ events, full Run II data (139 fb$^{-1}$)

- $m_{lb}$ very sensitive to $\Gamma_t$
  - templates created with different $\Gamma_t$
- profile likelihood with multiple templates
- control regions ($m_{bb}$ in $ee/\mu\mu$ channels)
**Top width**

<table>
<thead>
<tr>
<th>$m_t = 172$ GeV</th>
<th>$m_t = 172.5$ GeV</th>
<th>$m_t = 173$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean [GeV]</strong></td>
<td><strong>Unc. [GeV]</strong></td>
<td><strong>Mean [GeV]</strong></td>
</tr>
<tr>
<td>Measured</td>
<td>2.01</td>
<td>1.94</td>
</tr>
<tr>
<td></td>
<td>$+0.53$</td>
<td>$+0.52$</td>
</tr>
<tr>
<td></td>
<td>$-0.50$</td>
<td>$-0.49$</td>
</tr>
<tr>
<td>Theory</td>
<td>1.306</td>
<td>1.322</td>
</tr>
<tr>
<td></td>
<td>$&lt; 1%$</td>
<td>$&lt; 1%$</td>
</tr>
</tbody>
</table>

$\Gamma_t$ measured for different $m_{\text{top}}$

* good agreement with SM predictions

Significant improvement w.r.t. previous measurements

![](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>Impact on $\Gamma_t$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet reconstruction</td>
<td>$\pm 0.24$</td>
</tr>
<tr>
<td>Signal and bkg. modelling</td>
<td>$\pm 0.19$</td>
</tr>
<tr>
<td>MC statistics</td>
<td>$\pm 0.14$</td>
</tr>
<tr>
<td>Flavour tagging</td>
<td>$\pm 0.13$</td>
</tr>
<tr>
<td>$E_{\text{miss}}^T$ reconstruction</td>
<td>$\pm 0.09$</td>
</tr>
<tr>
<td>Pile-up and luminosity</td>
<td>$\pm 0.09$</td>
</tr>
<tr>
<td>Electron reconstruction</td>
<td>$\pm 0.07$</td>
</tr>
<tr>
<td>PDF</td>
<td>$\pm 0.04$</td>
</tr>
<tr>
<td>$t\bar{t}$ normalisation</td>
<td>$\pm 0.03$</td>
</tr>
<tr>
<td>Muon reconstruction</td>
<td>$\pm 0.02$</td>
</tr>
<tr>
<td>Fake-lepton modelling</td>
<td>$\pm 0.01$</td>
</tr>
</tbody>
</table>
\[ C = A\alpha_1\alpha_2 = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)} \]

Correlated spins between top pairs produced at LHC

* accessible via \(|\Delta \phi_{\ell\ell}|\), in dilepton \(t\bar{t}\) decays, no top reconstruction required

Measured @13 TeV (36 fb\(^{-1}\)) in e\(\mu\)+2b channel

* also differentially in \(m(t\bar{t})\)
* also measured the \(|\Delta \eta_{\ell\ell}|\) observable, sensitive to SUSY production
* unfolded to fiducial particle level and full phase-space parton level

![Graph showing ATLAS results for \(3\sigma\) from SM NLO.](image)
Lots of discussions in the theory community

- focus on the assumptions involved in the template hypotheses
- **NLO + Parton** shower MC consistent with fixed-order calculations from **MCFM**
- state-of the art **NNLO-QCD** predictions (Brun et. al.) closer to data (2.2σ)
- **NLO-QCD + EW** prediction agrees with data but with large scale uncertainties
  - ◊ agreement driven by ratio expansion method
- when ratio expanded at **NNLO**, the agreement disappears
**V_{tb}: ATLAS+CMS**

**JHEP 05 (2019) 088**

---

**t-channel**
Most abundant, Constrains PDF

**tW-channel**
Interference with $\bar{t}t$

**s-channel**
Small cross-section, BSM resonances?

---

**Combinations of single-top x-sections**

* data from pp collisions @7+8TeV
* all combined measurements consistent with corresponding SM predictions
Talk: “Measurements of $t\bar{t}$ pairs produced in association with electroweak gauge bosons using the ATLAS detector”
Paul Glaysher - 28/08 h16:50

Poster: “Searches for four top quarks production using the ATLAS detector”
Thibault Chevalerias - 26/08 h20:30

Associated production: $t(t) + W/Z/\gamma$
$\bar{t}t + b\bar{b}$

**JHEP 04 (2019) 046**

Important for new physics and rare searches
- state-of-the-art NLO predictions suffer from large uncertainty
- experimental input needed to test predictions

Fiducial and differential $\bar{t}t + b\bar{b}$ cross sections in $\ell+\text{jets}$ and dilepton channels using 36 fb$^{-1}$ (@13 TeV)
- unfolded to particle level
General excess w.r.t. various NLO predictions
- still compatible within total uncertainties
- **experimental uncertainty smaller than theory one**
**ttW/Z**

**Observed x-sections in agreement with SM**

Limits set to EFT $O_6$ Wilson coefficients

PRD 99 (2019) 072009

**ttγ**

Measurement in $\ell$+jets and dilepton $\gamma$ observables in agreement with SM


**4tops**

x-section enhanced in BSM models

Background to $\bar{t}t+H$

No significant excess observed


Further public results:
twiki.cern.ch/twiki/AtlasPublic/TopPublicResults
Searches

95%CL upper limits

Each limit assumes that all other processes are zero

Theory predictions from arXiv:1311.2028

ATLAS+CMS Preliminary
LHCTopWG
September 2018

ATLAS
CMS

Branching ratio

10^{-16} 10^{-13} 10^{-10} 10^{-7} 10^{-4} 10^{-1}
Flavour-changing neutral currents (FCNC)
- forbidden at tree level
- BSM can enhance FCNC production

\[ H \to b\bar{b}: \text{several regions (} N_{\text{jets}}, N_{\text{b-tags}} \text{)} \]
- likelihood discriminant employed

\[ H \to \tau_{\text{had}}\tau_{\text{had}}/\tau_{\text{lep}}\tau_{\text{had}}: 4 \text{ regions (based on } N_{\tau_{\text{had}}}) \]
- event reco. \((\chi^2)\) + MVA technique

Combination with \(\gamma\gamma\) and multilepton
- \(\text{BR}(t \to uH) < 12 \times 10^{-4} \) (8.3 \( \times 10^{-4} \))
- \(\text{BR}(t \to cH) < 11 \times 10^{-4} \) (8.3 \( \times 10^{-4} \))
- \(|\lambda_{tuH}| < 0.066\) (0.055)
- \(|\lambda_{tcH}| < 0.064\) (0.055)
Analysis performed @13TeV (81 fb⁻¹)

- lepton + 1 photon channel
- NN to discern tγu/tγc vs. background
Consistent with background-only hypothesis

<table>
<thead>
<tr>
<th>Observable</th>
<th>Vertex</th>
<th>Coupling</th>
<th>Obs.</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma(pp \rightarrow t\gamma) ) [fb]</td>
<td>tuy</td>
<td>LH</td>
<td>36</td>
<td>52^{+21}_{-14}</td>
</tr>
<tr>
<td>( \sigma(pp \rightarrow t\gamma) ) [fb]</td>
<td>tuc</td>
<td>LH</td>
<td>40</td>
<td>49^{+20}_{-14}</td>
</tr>
<tr>
<td>( \sigma(pp \rightarrow t\gamma) ) [fb]</td>
<td>tcy</td>
<td>RH</td>
<td>78</td>
<td>75^{+31}_{-21}</td>
</tr>
<tr>
<td>( \sigma(pp \rightarrow t\gamma) ) [fb]</td>
<td>tcy</td>
<td>RH</td>
<td>33</td>
<td>52^{+22}_{-14}</td>
</tr>
<tr>
<td>( B(t \rightarrow q\gamma) ) [10⁻⁵]</td>
<td>tuc</td>
<td>LH</td>
<td>2.8</td>
<td>4.0^{+1.0}_{-2.0}</td>
</tr>
<tr>
<td>( B(t \rightarrow q\gamma) ) [10⁻⁵]</td>
<td>tuc</td>
<td>RH</td>
<td>6.1</td>
<td>5.9^{+2.4}_{-1.6}</td>
</tr>
<tr>
<td>( B(t \rightarrow q\gamma) ) [10⁻⁵]</td>
<td>tuc</td>
<td>LH</td>
<td>22</td>
<td>27^{+11}_{-7}</td>
</tr>
<tr>
<td>( B(t \rightarrow q\gamma) ) [10⁻⁵]</td>
<td>tuc</td>
<td>RH</td>
<td>18</td>
<td>24^{+12}_{-8}</td>
</tr>
</tbody>
</table>
Conclusions

The top quark has come a long way since 1977

✴ back then: missing quark, assumed to be similar to other quarks
✴ today: know that top quark is special

In precision era, top quark is key to an abundance of different research areas

✴ production cross-section measurements of increasing precision…. 
  ◊ confirm Standard Model NLO predictions
✴ pole-mass analyses start to become competitive
  ◊ theory community very active, important to state what mass we measure!
✴ properties of top quark measured with ever-increasing precision
  ◊ first evidence of non-zero top charge asymmetry!
  ◊ first top width measurement @13TeV! Competitive with $\Delta m_{\text{top}}^{\text{pole}}$
  ◊ spin correlation: data/predictions tensions→ limitations in understanding of $\bar{t}t$
✴ $\bar{t}t$ associated production
  ◊ moving towards differential measurements for $\bar{t}t+W/Z/\gamma$
✴ top-related searches
  ◊ 1 order improvement on FCNC $tq\gamma$ limits

Thank you
Backup
Mass combination

EPJC 79 (2019) 290

![Graphs showing mass combination for different channels: dilepton, l+jets, and ATLAS.]

- ATLAS
- $\sigma(m_{\text{top}}(8\text{TeV})) = 0.85 \text{ GeV}$
- $\sigma(m_{\text{top}}) = 0.91 \text{ GeV}$
- $\sigma(m_{\text{top}}) = 0.56 \text{ GeV}$
- $\sigma(m_{\text{top}}) \text{ vs. } \rho$

- ATLAS
- $m_{\text{top}}(8\text{TeV}) = 172.99 \text{ GeV}$
- $m_{\text{top}}(8\text{TeV}) = 172.08 \text{ GeV}$
- $m_{\text{top}} = 172.56 \text{ GeV}$
- $m_{\text{top}} \text{ vs. } \rho$
Mass: comp. w/ EW fit

$\text{ATLAS}$

$\begin{array}{c}
m_W = 80.370 \pm 0.019 \text{ GeV} \\
m_{\text{top}} = 172.69 \pm 0.48 \text{ GeV} \\
m_H = 125.1 \pm 0.2 \text{ GeV} \\
68/95\% \text{ CL of } m_W \text{ and } m_{\text{top}}
\end{array}$

$68/95\% \text{ CL of Electroweak Fit w/o } m_W \text{ and } m_{\text{top}}$

Mass with $\bar{t}t + 1$ jet

Submitted to JHEP - NEW!

Differential $\bar{t}t + 1$ jet: dominated by JES and MC modelling unc. (0.7 %)
Measurements reinterpreted in EFT

- $C^- = 4$-fermion operator assuming flavour conservation and equal $u$-$d$ type couplings (simple axion model)

Inclusive and differential results surpass ATLAS+CMS Run I combination

- no large dependence on quadratic terms
- dimension 6 approach is stable and appropriate
Property measured many times by ATLAS and CMS, at each collision energy

\( f_{SM} = \) fraction of SM-like spin correlation

\( * f_{SM} = 1 \) is SM-like
\( * f_{SM} = 0 \) is uncorrelated

ATLAS and CMS consistently measure stronger than SM spin correlations using \( |\Delta \phi_{\ell\ell}| \)
Spin corr. (SUSY)

Use both the $|\Delta \varphi_{ll}|$ and $|\Delta \eta_{ll}|$ to set limits on SUSY stop production.

Exclude Stops with a mass below $\sim 220$ GeV for all kinematically-allowed neutralino masses.

* limit driven by $|\Delta \eta_{ll}|$ but additional modelling uncertainties included to account for the Data/Prediction disagreement in $|\Delta \varphi_{ll}|$
Spin corr. (SUSY)

Use both the $|\Delta \phi_{ll}|$ and $|\Delta \eta_{ll}|$ to set limits on SUSY stop production.

Exclude Stopped with a mass below ~ 220 GeV for all kinematically-allowed neutralino masses.

* limit driven by $|\Delta \eta_{ll}|$ but additional modelling uncertainties included to account for the Data/Prediction disagreement in $|\Delta \phi_{ll}|$.

$\chi \sim m(t) = (170, 0.5) \text{ GeV}$

$\chi \sim m(t) = (210, 0.5) \text{ GeV}$

$\chi \sim m(t) = (250, 0.5) \text{ GeV}$

$\chi \sim m(t) = (290, 0.5) \text{ GeV}$

$\chi \sim m(t) = (330, 0.5) \text{ GeV}$

$\chi \sim m(t) = (370, 0.5) \text{ GeV}$

$\chi \sim m(t) = (410, 0.5) \text{ GeV}$

$\chi \sim m(t) = (450, 0.5) \text{ GeV}$

$\chi \sim m(t) = (500, 0.5) \text{ GeV}$

$\chi \sim m(t) = (550, 0.5) \text{ GeV}$

$\chi \sim m(t) = (600, 0.5) \text{ GeV}$

$\chi \sim m(t) = (650, 0.5) \text{ GeV}$

$\chi \sim m(t) = (700, 0.5) \text{ GeV}$

$\chi \sim m(t) = (750, 0.5) \text{ GeV}$

$\chi \sim m(t) = (800, 0.5) \text{ GeV}$

$\chi \sim m(t) = (850, 0.5) \text{ GeV}$

$\chi \sim m(t) = (900, 0.5) \text{ GeV}$

$\chi \sim m(t) = (950, 0.5) \text{ GeV}$

$\chi \sim m(t) = (1000, 0.5) \text{ GeV}$
**Operator Expression**

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{Q}^{(3)}$</td>
<td>$(\phi^T i \overleftrightarrow{D} \phi)(Q \gamma^{\mu} \tau^I Q)$</td>
</tr>
<tr>
<td>$O_{Q}^{(1)}$</td>
<td>$(\phi^T i \overleftrightarrow{D} \phi)(\bar{Q} \gamma^{\mu} Q)$</td>
</tr>
<tr>
<td>$O_{tB}$</td>
<td>$(\phi^T i \overleftrightarrow{D} \phi)(\bar{t} \gamma^{\mu} t)$</td>
</tr>
<tr>
<td>$O_{tW}$</td>
<td>$(\bar{Q} \gamma^{\mu} \tau^I t)\tilde{W}_{\mu}$</td>
</tr>
<tr>
<td>$O_{tt}$</td>
<td>$(\bar{Q} \sigma^{\mu\nu} t)\tilde{B}_{\mu\nu}$</td>
</tr>
</tbody>
</table>

---

**Coefficients**

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>$C_{QQ}^{(3)}/\Lambda^2$</th>
<th>$C_{Qt}/\Lambda^2$</th>
<th>$C_{tB}/\Lambda^2$</th>
<th>$C_{tW}/\Lambda^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous indirect constraints at 68% CL</td>
<td>-4.7, 0.7</td>
<td>-0.1, 3.7</td>
<td>-0.5, 10</td>
<td>-1.6, 0.8</td>
</tr>
<tr>
<td>Previous direct constraints at 95% CL</td>
<td>-1.3, 1.3</td>
<td>-9.7, 8.3</td>
<td>-6.9, 4.6</td>
<td>-0.2, 0.7</td>
</tr>
<tr>
<td>Expected limit at 68% CL</td>
<td>-2.1, 1.9</td>
<td>-3.8, 2.7</td>
<td>-2.9, 3.0</td>
<td>-1.8, 1.9</td>
</tr>
<tr>
<td>Expected limit at 95% CL</td>
<td>-4.5, 3.6</td>
<td>-23, 4.9</td>
<td>-4.2, 4.3</td>
<td>-2.6, 2.6</td>
</tr>
<tr>
<td>Observed limit at 68% CL</td>
<td>-1.0, 2.7</td>
<td>-2.0, 3.5</td>
<td>-3.7, 3.5</td>
<td>-2.2, 2.1</td>
</tr>
<tr>
<td>Observed limit at 95% CL</td>
<td>-3.3, 4.2</td>
<td>-25, 5.5</td>
<td>-5.0, 5.0</td>
<td>-2.9, 2.9</td>
</tr>
<tr>
<td>Expected limit at 68% CL (linear)</td>
<td>-1.9, 2.0</td>
<td>-3.0, 3.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Expected limit at 95% CL (linear)</td>
<td>-3.7, 4.0</td>
<td>-5.8, 6.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Observed limit at 68% CL (linear)</td>
<td>-1.0, 2.9</td>
<td>-1.8, 4.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Observed limit at 95% CL (linear)</td>
<td>-2.9, 4.9</td>
<td>-4.8, 7.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Uncertainty**

<table>
<thead>
<tr>
<th>Source</th>
<th>Luminosity</th>
<th>Simulated sample statistics</th>
<th>Data-driven background statistics</th>
<th>JES/JER</th>
<th>Flavor tagging</th>
<th>Other object-related</th>
<th>Data-driven background normalization</th>
<th>Modeling of backgrounds from simulation</th>
<th>Background cross sections</th>
<th>Fake leptons and charge misID</th>
<th>Background cross sections</th>
<th>Fake leptons and charge misID</th>
<th>Total systematic</th>
<th>Statistical</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(%)</td>
<td>2.9%</td>
<td>2.0%</td>
<td>2.5%</td>
<td>1.9%</td>
<td>4.2%</td>
<td>3.7%</td>
<td>3.2%</td>
<td>5.3%</td>
<td>2.3%</td>
<td>1.8%</td>
<td>4.9%</td>
<td>10%</td>
<td>8.4%</td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td>(%)</td>
<td>4.5%</td>
<td>5.3%</td>
<td>6.3%</td>
<td>4.1%</td>
<td>3.7%</td>
<td>2.5%</td>
<td>3.9%</td>
<td>2.6%</td>
<td>4.9%</td>
<td>5.7%</td>
<td>0.7%</td>
<td>16%</td>
<td>15%</td>
<td>22%</td>
<td></td>
</tr>
</tbody>
</table>

---

**Data / Pred.**

<table>
<thead>
<tr>
<th>Data</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

**Events**

- ATLAS
- Data
- ttW
- tZ
- WZ
- Other
- Charge-flips
- Fake leptons
- Uncertainty

**Plot**

- Events vs Data / Pred.
- Luminosity 2.9% 4.5%
- Simulated sample statistics 2.0% 5.3%
- Data-driven background statistics 2.5% 6.3%
- JES/JER 1.9% 4.1%
- Flavor tagging 4.2% 3.7%
- Other object-related 3.7% 2.5%
- Data-driven background normalization 3.2% 3.9%
- Modeling of backgrounds from simulation 5.3% 2.6%
- Background cross sections 2.3% 4.9%
- Fake leptons and charge misID 1.8% 5.7%
- ttZ modeling 4.9% 0.7%
- ttW modeling 0.3% 8.5%

**Total systematic**

- 10% 16%

**Statistical**

- 8.4% 15%

**Total**

- 13% 22%
**Top quark physics with the ATLAS detector: recent highlights**

**PRD 99 (2019) 072009**

**ATLAS**

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Single lepton (%)</th>
<th>Dilepton (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal modelling</td>
<td>± 1.6</td>
<td>± 2.9</td>
</tr>
<tr>
<td>Background modelling</td>
<td>± 4.8</td>
<td>± 2.9</td>
</tr>
<tr>
<td>Photon</td>
<td>± 1.1</td>
<td>± 1.1</td>
</tr>
<tr>
<td>Prompt-photon tagger</td>
<td>± 4.0</td>
<td>-</td>
</tr>
<tr>
<td>Leptons</td>
<td>± 0.3</td>
<td>± 1.3</td>
</tr>
<tr>
<td>Jets</td>
<td>± 5.4</td>
<td>± 2.0</td>
</tr>
<tr>
<td>b-tagging</td>
<td>± 0.9</td>
<td>± 0.4</td>
</tr>
<tr>
<td>Pile-up</td>
<td>± 2.0</td>
<td>± 2.3</td>
</tr>
<tr>
<td>Luminosity</td>
<td>± 2.3</td>
<td>± 2.3</td>
</tr>
<tr>
<td>MC sample size</td>
<td>± 1.9</td>
<td>± 1.7</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>± 7.9</td>
<td>± 5.8</td>
</tr>
<tr>
<td>Data sample size</td>
<td>± 1.5</td>
<td>± 3.8</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>± 8.1</td>
<td>± 7.0</td>
</tr>
</tbody>
</table>
4 tops


ATLAS

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

\( t\bar{t}t\bar{t} \) (SM)

\( \text{tot (stat syst)} \)

- Single lep. / OS dilep.
  - SS dilep. / trilep.
  - Combined

\( \mu = \sigma_{\text{tot}} / \sigma_{\text{tot, SM}} \)

\( \text{Observed} \)

\( \text{Expected} \pm 1 \sigma \)

\( \text{Expected} \pm 2 \sigma \)

95\% CL limit on \( \mu = \sigma_{\text{tot}} / \sigma_{\text{tot, SM}} \)

Uncertainty source

\( \pm \Delta \mu \)

- \( t\bar{t}+\text{jets modeling} \)
- Background-model statistical uncertainty
- Jet energy scale and resolution, jet mass
- Other background modeling
- \( b \)-tagging efficiency and mis-tag rates
- JVT, pileup modeling
- \( t\bar{t} + H/V \) modeling
- Luminosity

Total systematic uncertainty

Total statistical uncertainty

Total uncertainty

[ N. Bruscino | Top quark physics with the ATLAS detector: recent highlights | ICNFP19 28-Aug-2019 ]