Top quark physics at the LHC

María Aldaya (DESY)
for the ATLAS and CMS Collaborations

LP2019: 29th International Symposium on Lepton Photon Interactions at High Energies (U. Toronto, CA), 06.08.19
The top quark is special

- **Heaviest elementary particle known to date**
  - Decays before hadronizing: “bare” quark
    - No bound states, spin transferred to decay products
  
- **Couples strongly to Higgs**
  - $y_t \sim 1$ => special role in EWSB?

- **Precision measurements of SM parameters**
  - top mass, $\alpha_s$, couplings

- **Search for physics beyond SM**
  - Precision measurement of top quark properties
  
  Window to new physics that couples preferentially to tops
Top quark production and decay

- **Main: strong top pair (tt) production**
  - ~90% (13 TeV)

- **Electroweak single top production**
  - t-channel
  - tW-channel
  - s-channel

**Top decay:**
- In the SM:
  - ~100%
- (~13 TeV)

**Top Pair Branching Fractions**
- "alljets" 46%
- τ+jets 15%
- μ+jets 15%
- e+jets 15%

- BR(μ, e) ~ 6%
- Low bg: Z+jets
- BR(μ, e) ~ 34%
- Moderate bg: W+jets
- Huge bg: QCD

M. Aldaya

LP2019, 06.08.2019
Top quarks: rich experimental programme

- Cross sections
  - inclusive and (multi)differential
  - $t\bar{t}$, single top
  - boosted regime

- Rare production and decays
  - $t\bar{t}X$, $tX$, $ttt$tt
  - FCNC

- Mass and properties
  - mass, width, charge
  - spin correlations
  - asymmetries
  - couplings
  - branching fractions

- Interpretations
  - QCD parameters: $\alpha_s$, mass, PDFs
  - BSM constraints (e.g., EFT)

- Modelling
  - tuning of underlying event
  - colour reconnection
  - colour flow

Any significant deviation from the SM is a hint for new physics
Top quarks: rich experimental programme

Most top results so far use these data

Focus of Run2 top physics (and beyond):
- Ultimate precision measurements
- Properties and couplings (tt and single top)
- Low cross section frontier: tt+X, t+X, tt+tt

Today’s talk: Selection of most recent results from Run2 (13 TeV)

Results for Summer Conferences indicated by New
Rates and dynamics of $t\bar{t}$ production

• First step in understanding top physics
• Test of QCD calculations and search for new physics

→ More in parallel talk by A. Perrotta
Inclusive tt cross sections

Measured at all energies, dependence as a function of $\sqrt{s}$ well understood

- Measure all channels to look for the unexpected
- Good agreement with NNLO+NNLL calculations
- Highest precision: dilepton and $l+$jets channels $\sim4\%$, similar to theory prediction

LHCb catching up! $\rightarrow$ complementary measurements to ATLAS and CMS (see backup)

Top also observed in proton-nucleus (Pb) collisions! (CMS, PRL 119 (2017) 242001)
Latest inclusive \( \tt \) cross sections

- **ATLAS**: eroding the systematics wall using \( e\mu \) events
  - Simultaneous extraction of \( \sigma_{\tt} \) & efficiency to select, reconstruct and b-tag a jet in events with exactly 1 or 2 b-jets

\[
\sigma_{\tt} = 826.4 \pm 3.6 \text{ (stat)} \pm 11.5 \text{ (syst)} \pm 15.7 \text{ (lumi)} \pm 1.9 \text{ (beam)} \text{ pb}
\]

(2.4% !!)

- **CMS**: probing lepton universality in the top sector using \( l+\tau \) events
  - Fit to \( m_T(\text{lepton}, p_T^{\text{miss}}) \) in signal- and background-like regions

\[
\sigma_{\tt}(\ell\tau_h) = 781 \pm 7 \text{ (stat)} \pm 62 \text{ (syst)} \pm 20 \text{ (lumi)} \text{ pb}
\]

(8%)

- Ratios to \( \sigma(\tt) \) in dileptons (CMS, EPJC 79 (2019) 368):

\[
\frac{R_{\ell\tau_h/\ell\ell}}{} = 0.973 \pm 0.009 \text{ (stat)} \pm 0.066 \text{ (syst)}
\]

\[
\frac{\Gamma(t \rightarrow \tau\nu_tb)}{\Gamma_{\text{total}}} = 0.1050 \pm 0.0009 \text{ (stat)} \pm 0.0071 \text{ (syst)}
\]

(7%)
Differential tt cross sections

Scrutinize tt production in many channels as a function of many observables

→ Precision tests of pQCD in different regions of phase space, window to BSM physics

- Use final-state products to reconstruct top quark candidates
- Correct for detector effects & acceptance → unfolding

**Parton level**: compare to fixed-order calculations

**Particle level**: mimic detector-level selection & reconstruction (closer to what is measured); useful for MC tuning

- Dilepton, parton level
- Better described by NNLO calculations

\[
\frac{1}{\Delta p_T}(d\sigma/dp_T)[\text{GeV}]^{-1}
\]

\[
\begin{array}{c}
\text{CMS} \\
\text{Dilepton, parton level} \\
35.9 \text{ fb}^{-1} (13 \text{ TeV})
\end{array}
\]

\[
\begin{array}{c}
\text{Data} \\
\text{POWHEGv2 + PYTHIA} \\
\text{NNLO+}\alpha_S^2 (\text{LUXQED17}) m_t = 173.3 \text{ GeV} \\
\text{NNLO+}\alpha_S^2 (\text{LUXQED17}) m_t = 172.5 \text{ GeV} \\
\text{NNLO+}\alpha_S^2 (\text{NNPDF3.1}) m_t = 173.3 \text{ GeV} \\
\text{NNLO+}\alpha_S^2 (\text{NNPDF3.1}) m_t = 172.5 \text{ GeV} \\
\text{aNNLO} (\text{NNPDF3.0}) m_t = 172.5 \text{ GeV} \\
aNNLO (\text{CT14NNLO}) m_t = 172.5 \text{ GeV}
\end{array}
\]

\[
\begin{array}{c}
\text{MC / data} \\
\text{Theory} \\
\text{Data} \\
\text{Stat} \\
\text{Syst}
\end{array}
\]

\[
\frac{1}{\Delta p_T}(d\sigma/dp_T)[\text{GeV}]^{-1}
\]

\[
\begin{array}{c}
\text{ATLAS Preliminary} \\
\sqrt{s} = 13 \text{ TeV, 36.1 fb}^{-1} \\
\text{Data 2015-16} \\
\text{total uncertainty} \\
\text{Powheg+PY8} \\
\text{aMC@NLO+PY8}
\end{array}
\]

\[
\begin{array}{c}
\text{p_T(dilepton)} \\
\text{particle level}
\end{array}
\]

\[
\begin{array}{c}
\text{Dilepton p_T^\text{ch}} [\text{GeV}] \\
\text{MC / data}
\end{array}
\]

Good agreement with SM, but no single MC simulation describes well all measured distributions
Zooming in: going multidifferential!

Enhance further the sensitivity to QCD parameters, PDFs, and BSM effects

- **ATLAS**: 2D differential cross sections as a function of lepton and dilepton kinematics

- **General good agreement with different NLO simulations, except at low m(ll)**

- **CMS**: 2D, 3D diff. cross sections vs. top & tt kinematics and Njets, used to extract $m_t^{\text{pole}}$, $\alpha_s$, PDF

---

**PDF constraints**
High-p$_T$ tops: exploring the boosted regime

Measure tops at high p$_T$ using optimized event selection & reconstruction up to TeV range!

- Particularly sensitive to BSM: high-p$_T$ tops appear in many new physics scenarios

- New ATLAS, l+jets: 1D differential cross sections a function of top & tt-system kinematics (and more), and first 2D results!

New ATLAS, l+jets: 1D differential cross sections a function of top & tt-system kinematics (and more), and first 2D results!

Comparison to different MC models

- Larger data/MC discrepancy at high m(tt)
- Data starts to discriminate between models!
Single top

- Probe CKM matrix element $|V_{tb}|$, EWK coupling structure
- Probe alternative production mechanisms (e.g heavy bosons, FCNC)
- Sensitive to b-PDF and u/d-PDFs

→ More in parallel talk by A. Perrotta
Single top production: the big picture

- **Run1** legacy ATLAS+CMS cross sections and $V_{tb}$ combinations
  - JHEP 05 (2019) 088
  - Probing the Wtb vertex: best direct $V_{tb}$ determination to date!

  $|f_{LV} V_{tb}| = \frac{\sqrt{\sigma_{\text{meas.}}}}{\sigma_{\text{theo.}} (V_{tb} = 1)}$

  (assume $|V_{ts}|, |V_{td}| \ll |V_{tb}|$)

  $|f_{LV} V_{tb}| = 1.02 \pm 0.04 \text{ (meas.)} \pm 0.02 \text{ (theo.)}$ (3.7%)

- **Run2**: ramping up towards new era in precision
  - Differential cross sections
  - Properties
top production + “friends”

- Very low production cross sections O(fb)
- Need multivariate analysis techniques to maximize sensitivity

→ More in parallel talk by D. Dobur
Top+X production in a nutshell

Becoming accessible with Run2 data
Top+X production in a nutshell

Becoming accessible with Run2 data

CMS (77 fb⁻¹): most precise $\sigma$(ttZ) to date, first differential measurements

CMS, arXiv:1907.11270

ATLAS (36 fb⁻¹), evidence

ATLAS, PLB 780 (2018) 557

ATLAS (36 fb⁻¹): 1st 13 TeV result, including differential measurements

ATLAS, EPJC 79 (2019) 382
Top+X production in a nutshell

CMS (full Run2): same-sign dilepton & trilepton final states

**Significance:** 2.6 (2.7) $\sigma$ obs (exp)

ATLAS (36 fb$^{-1}$), leptonic channels: significance: 2.8 (1.0) $\sigma$ obs (exp)

Very rare, **not yet observed**:
\[ \sigma(tttt) \sim 12 \text{ fb}^{-1} \text{ (NLO+EW)} \]

Sensitive to BSM, direct access to top-Higgs Yukawa coupling

**top-Higgs Yukawa:** $|y_t/y_t^{SM}| < 1.7$ (95% CL)

**CMS Preliminary**

BDT (postfit) 137 fb$^{-1}$ (13 TeV)

- $\tttt$
- $\ttW$
- $\ttH$
- Nonprompt lep.
- $\ttW$
- $\ttH$
- Data

**ATLAS, PRD 99 (2019) 052009**
tt+bb production

Major background for tt+H(bb) (irreducible) and tttt

- Challenging to model: complex final state, very different scales (tt, bb)
- CMS: new dilepton & l+jets, all-jets
- Different phase spaces, comparison to NLO MC simulations
- in general, σ(ttbb) slightly higher in data, also for ATLAS (JHEP 04 (2019) 046)
- Improved precision will have an impact on upcoming ttH(bb) results
top properties
Top quark mass

Fundamental parameter in the SM, not an observable \( \rightarrow \) scheme-dependent

- **“Direct” measurements**: from reconstructed top decay products \( \rightarrow \) MC mass \( m_t^{\text{MC}} \) (mass as defined in the MC)
  - Highest sensitivity, reaching precision below 500 MeV (\(< 0.3\%\) )

- **“Indirect” measurements**: from fit to sensitive observable (e.g. \( t\bar{t} \) cross section) + theory
  \( \rightarrow \) top mass in a well-defined scheme (e.g. \( m_t^{\text{pole}}, m_t(m_t) \))

Difference between \( m_t^{\text{MC}} \) and \( m_t^{\text{pole}} \) estimated to be \( \sim \) few hundred MeV to 1 GeV

Need to measure the top mass in all possible ways with the highest possible precision

---

![Diagram](image.png)

**ATLAS+CMS Preliminary**

**m\(_{\text{top}}\) summary, \( \sqrt{s} = 7\text{–}13 \text{ TeV} \) May 2019

<table>
<thead>
<tr>
<th>LHC/topWG</th>
<th>LHC comb. (Sep 2013)</th>
<th>World comb. (Mar 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( m_t ) ± total (stat+syst)</td>
</tr>
<tr>
<td>ATLAS, J+ ( \ell )</td>
<td>172.49 ± 1.06 (0.43 ± 0.97)</td>
<td>7 TeV [9]</td>
</tr>
<tr>
<td>ATLAS, single top</td>
<td>174.95 ± 1.22 (0.77 ± 0.95)</td>
<td>8 TeV [13]</td>
</tr>
<tr>
<td>ATLAS, dijets</td>
<td>172.50 ± 1.52 (0.43 ± 1.46)</td>
<td>7 TeV [10]</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>172.33 ± 1.70 (0.75 ± 1.02)</td>
<td>7 TeV [3]</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>172.32 ± 1.15 (0.55 ± 1.01)</td>
<td>8 TeV [7]</td>
</tr>
<tr>
<td>ATLAS, single top</td>
<td>172.22 ± 2.1 (0.7 ± 2.0)</td>
<td>8 TeV [5]</td>
</tr>
<tr>
<td>ATLAS, dijets</td>
<td>174.91 ± 1.8 (1.4 ± 1.2)</td>
<td>7 TeV [4]</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>173.72 ± 1.15 (0.55 ± 1.01)</td>
<td>8 TeV [7]</td>
</tr>
</tbody>
</table>

**CMS comb. (Sep 2015)**

| CMS, J+ \( \ell \) | 172.44 ± 0.48 (0.13 ± 0.47) | 7 TeV [12] |
| CMS, single top | 172.55 ± 0.63 (0.08 ± 0.62) | 7 TeV [14] |
| CMS, dijets | 172.74 ± 1.30 (0.14 ± 0.59) | 13 TeV [15] |
| CMS, all jets | 172.34 ± 0.73 (0.20 ± 0.70) | 13 TeV [16] |

---

Top quark mass: “indirect” measurements

Mass dependence of predicted cross section allows determining $m_t$ from measured $\sigma(t\bar{t})$

- Inclusive cross sections:
  - **ATLAS**: latest $\sigma(t\bar{t})$ and NNLO+NNLL theory:
    - $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

ATLAS Preliminary

\begin{align*}
\text{\textbf{m}_t^{\text{pole}}: 173.1} & \pm 2.0 \pm 2.1 \text{ GeV} \\
\text{ATLAS, } & \text{arXiv:1905.02302}
\end{align*}
Top quark mass: “indirect” measurements

Mass dependence of predicted cross section allows determining $m_t$ from measured $\sigma(t\bar{t})$

- 1D differential cross sections:
  - ATLAS: Differential $\sigma(t\bar{t}+1\text{jet})$ and NLO+PS:
Top quark mass: “indirect” measurements

Mass dependence of predicted cross section allows determining $m_t$ from measured $\sigma(tt)$

- Multidifferential cross sections:
  - CMS: Simultaneous fit of $m_t^{\text{pole}}$, $\alpha_s$, PDF using 3D differential $\sigma(tt)$ and NLO theory:

  ![Graph showing $\sigma(tt)$ vs $m(tt)$, $|y(tt)|$, $N_{\text{jets}}$]  

  | $m(tt)$ (GeV) | $|y(tt)|$ range | $N_{\text{jets}}$ range | $\sigma_{\text{diff}}$ vs $m_{\text{HH}}$ |
  |----------------|----------------|--------------------------|----------------------------------|
  | $<400$         | $<0.6$        | $0$                      | NLO CT14, $\chi^2=61$            |
  | $400-500$      | $<0.8$        | $0$                      | NLO CT14, $\chi^2=87$            |
  | $<500$         | $<1$          | $0$                      | NLO CT14, $\chi^2=144$           |
  | $500-1500$     | $<1.2$        | $0$                      | NLO CT14, $\chi^2=172.5$ GeV        |
  | $<1500$        | $<1.4$        | $0$                      | NLO CT14, $\chi^2=167.5$ GeV        |
  | $1500-1800$    | $<1.6$        | $0$                      | NLO CT14, $\chi^2=177.5$ GeV        |

  **Data, $\text{dof}=23$**

  - CMS, $\sqrt{s}=7$ TeV
    - ATLAS, $\sqrt{s}=8$ TeV
      - Ratio $\sigma_{\text{diff}}$ vs $m_{\text{HH}}$

  **CMS, arXiv:1904.05237**

  Top pole mass measurements entering the sub-GeV precision!
Top mass from boosted jets

Towards understanding better the ambiguities between $m_t^{MC}$ and $m_t^{pole}$

- Highly boosted top quarks ($p_T > 400$ GeV) in $l+jets$ events: a single jet includes all top decay products: $t \rightarrow bW \rightarrow bq\bar{q}'$

- CMS: measure $m_{top}$ from boosted jet mass ($m_{jet}$) observable $\rightarrow$ can be calculated analytically
  - Use novel XConE jet algorithm (JHEP 11 (2015) 072): reconstruct large jets and 3 subjets per jet

- Top mass from $m_{jet}$ differential cross section: $m_t = 172.56 \pm 0.41$ (stat) $\pm 2.44$ (syst) GeV $(1.4\%)$
First measurement of the scale dependence ("running") of the top quark mass in the MSbar scheme

**CMS**: extract the running mass $m_t(\mu)$ at NLO from differential $\sigma(tt)$ as a function of $m(tt)$ using $e\mu$ events

- $d\sigma(tt)/dm(tt)$: measured at parton level via fit to multidifferential distributions
- Experimental dependence on $m_{tMC}$ taken into account in the fit

- To determine the running of $m_t(\mu)$, the top mass is extracted in bins of $m(tt)$ by comparing to NLO predictions
- Extracted running compatible with scale dependence predicted by RGE at 1-loop precision within 1.3 s.d.
Top decay width

Deviations from the expected top decay width can be a sign of non-SM top couplings

- **ATLAS (full Run2):** Direct measurement of the top decay width $\Gamma_t$ in dilepton events
- Compare data to MC templates with different $\Gamma_t$ assumptions
  - Use an observable in $\mu\mu$ events that partially reconstructs the top kinematics: $m_{lb}$
  - Constrain main systematics by fitting simultaneously to $m_{bb}$ in $ee$, $\mu\mu$ events

For $m_t = 172.5$ GeV: $\Gamma_t = 1.9 \pm 0.5$ GeV

NNLO $\Gamma_t = 1.322$ GeV, < 1% uncert

⇒ More in parallel talk by T. Dado
tt charge asymmetry

Top-pair angular asymmetries may indicate BSM top production interfering with SM

- NLO effect originating from interference of $qq\rightarrow tt$ diagrams, can be enhanced by BSM physics
- Several results in Run1, in agreement with SM but also compatible with zero
- **ATLAS (full Run2)** $l+jets$: inclusively and differentially in regions of phase space where $A_C$ can be enhanced, including the boosted regime

\[ A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)} \]

\( \Delta |y| = |y_{\text{top}}| - |y_{\text{antitop}}| \)

- Good agreement with NNLO (QCD) + NLO (EW) calculations

4\sigma from zero! ==> First evidence @ LHC!
**FCNC searches**

Flavour Changing Neutral Currents are highly suppressed in SM —> enhancement is clear sign of BSM physics

- **ATLAS (81 fb⁻¹):** Search for tqγ FCNC in single top + γ events

![Graph and diagram showing search results](image)

- $B(t \rightarrow γc) < 22 \times 10^{-5}$ obs
  - $27 \times 10^{-5}$ exp
- $B(t \rightarrow γu) < 2.8 \times 10^{-5}$ obs
  - $4.0 \times 10^{-5}$ exp

Most stringent limits so far
Summary & Outlook

- Top quark physics: key to QCD, electroweak, and BSM physics
- Very rich experimental programme at the LHC:
  - High precision top cross sections and properties
  - Rare processes becoming less rare — some even systematically limited!
  - A variety of BSM interpretations (e.g. Effective Field Theory) starts to appear (not covered today)
  - Started to challenge theory predictions in many respects

- Full Run2: ~150 fb$^{-1}$:
  - ~120M tt pairs, ~30M single top, ~120K ttZ, tZ events
  - Trade-off statistics for systematics
  - Access to new physics in the top environment
  - Improvements in MC models and theoretical calculations

The ultimate potential for top quark physics is ahead of us

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
Additional information
tt in proton-nucleus (Pb) collisions

First observation at $\sqrt{s}=8.16$ TeV (2016)

- Novel and theoretically precise probe of the nuclear gluon density at high virtualities
- Considering different event categories with 0, 1, $\geq 2$ b-tagged jets
- $t\bar{t}$ cross section extracted from comb. unbinned max. likelihood fit of $mjj'$ ($W\rightarrow jj'$)

\[ \sigma_{t\bar{t}} + \text{jets} = 44 \pm 3 \text{ (stat) } \pm 8 \text{ (syst) nb}, \]
\[ \sigma_{t\bar{t}} + \text{e+jets} = 56 \pm 4 \text{ (stat) } \pm 13 \text{ (syst) nb}, \]
\[ \sigma_{t\bar{t}} = 45 \pm 8 \text{ (total) nb} \]

J. Fernandez Menendez, LHCP2018
Latest top result from

- After a first observation of top quark production in the forward region in 2015
  - LHCb has started to **measure** top quark cross sections
  - Very valuable complementary measurements to ATLAS and CMS

**LHCb explores top quark production in the forward region of pp collisions**

- access larger values of Bjorken $x$
- increased contribution from quark-initiated production relative to central region
- test of perturbative QCD in unexplored region
- can provide unique constraints on gluon PDF at large-$x$

*ēūb final state, JHEP 08 (2018) 174*
ATLAS: $\sigma(\text{tt})$ in dileptons

### Uncerts. mtpole

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta m_t^{\text{pole}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>1.0</td>
</tr>
<tr>
<td>PDF+$\sigma_S$</td>
<td>+1.5, -1.4</td>
</tr>
<tr>
<td>QCD scales</td>
<td>+1.0, -1.5</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>+2.0, -2.1</td>
</tr>
</tbody>
</table>

### Uncerts. cross section

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta \epsilon_{em}/\epsilon_{em}$ (%)</th>
<th>$\Delta G_{em}/G_{em}$ (%)</th>
<th>$\Delta C_b/C_b$ (%)</th>
<th>$\Delta \sigma_{tt}/\sigma_{tt}$ (%)</th>
<th>$\Delta \sigma_{tt}^{\text{fid}}/\sigma_{tt}^{\text{fid}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data statistics</td>
<td>0.38</td>
<td>0.05</td>
<td>0.05</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td>$t\bar{t}$ mod.</td>
<td>0.24</td>
<td>0.42</td>
<td>0.25</td>
<td>0.43</td>
<td>0.10</td>
</tr>
<tr>
<td>$t\bar{t}$ hadronisation</td>
<td>0.30</td>
<td>0.26</td>
<td>0.16</td>
<td>0.45</td>
<td>0.67</td>
</tr>
<tr>
<td>Initial/final state radiation</td>
<td>0.01</td>
<td>0.01</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>$t\bar{t}$ heavy-flavour production</td>
<td>0.44</td>
<td>0.05</td>
<td>-</td>
<td>0.45</td>
<td>0.07</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>0.44</td>
<td>0.05</td>
<td>-</td>
<td>0.45</td>
<td>0.07</td>
</tr>
<tr>
<td>Simulation statistics</td>
<td>0.22</td>
<td>0.15</td>
<td>0.17</td>
<td>0.22</td>
<td>0.18</td>
</tr>
<tr>
<td>Lept.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>0.06</td>
<td>0.06</td>
<td>-</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Electron energy resolution</td>
<td>0.01</td>
<td>0.01</td>
<td>-</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Electron identification</td>
<td>0.34</td>
<td>0.34</td>
<td>-</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Electron charge mis-id</td>
<td>0.09</td>
<td>0.09</td>
<td>-</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Electron isolation</td>
<td>0.22</td>
<td>0.22</td>
<td>-</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>0.03</td>
<td>0.03</td>
<td>-</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Muon momentum resolution</td>
<td>0.01</td>
<td>0.01</td>
<td>-</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Muon identification</td>
<td>0.28</td>
<td>0.28</td>
<td>-</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Muon isolation</td>
<td>0.16</td>
<td>0.16</td>
<td>-</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Lepton trigger</td>
<td>0.13</td>
<td>0.13</td>
<td>-</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Jet/b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.02</td>
<td>0.02</td>
<td>0.06</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.01</td>
<td>0.01</td>
<td>0.04</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Pileup jet veto</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$b$-tagging efficiency</td>
<td>-</td>
<td>-</td>
<td>0.04</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>$b$-tag mis-tagging</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Single top cross-section</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td>Single-top/$t\bar{t}$ interference</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Single top modelling</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.34</td>
<td>0.34</td>
</tr>
<tr>
<td>$Z+\text{jets}$ extrapolation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Diboson cross-sections</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Diboson modelling</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Misidentified leptons</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>Analysis systematics</td>
<td>0.91</td>
<td>0.75</td>
<td>0.44</td>
<td>1.39</td>
<td>1.31</td>
</tr>
<tr>
<td>$L/E_b$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.90</td>
<td>1.90</td>
</tr>
<tr>
<td>Beam energy</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.91</td>
<td>0.75</td>
<td>0.44</td>
<td>2.40</td>
<td>2.36</td>
</tr>
</tbody>
</table>
• Boosted hadronic top is identified by re-clustering 0.4 jets with anti-$k_T$ R=1 algorithm.

• Re-clustering allows propagation of small-R JES and a mass cut is sufficient for background rejection.

$E_T^{\text{miss}} + m_T^W > 60$ GeV

$E_T^{\text{miss}} > 20$ GeV

Note: possible to have events where the leptonic top is at lower $p_T$. 
MC Setups

- PWG+PY8: Powheg + Pythia 8.210, NNPDF3.0, ttbar production at NLO, $h_{damp}=1.5m_t$ (tuned to previous ttbar data), A14 tune.
- PWG+PY8 Rad. Up: Powheg + Pythia8, ttbar production at NLO, $h_{damp}=3m_t$, factorisation & renormalisation scales 0.5*nominal, Var 3c up A14 eigentune.
- PWG+PY8 Rad. Down: Powheg + Pythia8, ttbar production at NLO, $h_{damp}=1.5m_t$, factorisation & renormalisation scales 2*nominal, Var 3c down A14 eigentune.
- PWG+H7: Powheg + Herwig 7.01, NNPDF3.0, ttbar production at NLO, H7-UE-MMHT tune.
- Sherpa: Sherpa 2.2.1, NNPDF3.0, ttbar production at NLO for 0 and 1 additional-jets, up-to 4 additional jets at LO, merged with MEPS@NLO, default Sherpa tune.
- aMC@NLO+PY8: MadGraph5_aMC@NLO 2.6.0 + Pythia 8.230, NNPDF3.0, shower starting scale set to HT/2 (tuned to previous ttbar data), A14 tune.
Single top Run1 combination

- Final word from Run1 ATLAS+CMS combinations on cross sections and $V_{tb}$

Cross sections

### 7 TeV combinations

- $\sigma_{t-ch} = 67.5 \pm 5.7$ pb (8.4%) NLO: 4.7%
- $\sigma_{tW} = 16.3 \pm 4.1$ pb (25%) NLO+NNLL: 7.9%

### 8 TeV combinations

- $\sigma_{t-ch} = 87.7 \pm 5.8$ pb (6.7%) NLO: 4.6%
- $\sigma_{tW} = 23.1 \pm 3.6$ pb (15.6%) NLO+NNLL: 7.0%
- $\sigma_{s-ch} = 4.9 \pm 1.4$ pb (30%) NLO: 4.8%

$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{meas.}}{\sigma_{theo.} (V_{tb} = 1)}}$

$f_{LV} = 1$ in SM

JHEP 05 (2019) 088
A well known running: \( \alpha_S \)

\[
\alpha_S(\mu) = \frac{\alpha_S(\mu_0)}{\alpha_S(\mu_0) \frac{11N_c - 2N_f}{12\pi} \ln \frac{\mu^2}{\mu_0^2}} \quad \text{(NLO)}
\]

**typical procedure** to measure \( \alpha_S \) running:

- extract \( \alpha_S(m_Z) \) from some final state observable in limited scale range (e.g. \( \mu = \text{jet } p_T \))
- convert \( \alpha_S(m_Z) \) to \( \alpha_S(\mu) \) using RGE, w. appropriate choice of \( \mu \) in each bin

**N.B.** this is equivalent to extracting \( \alpha_S(\mu) \) directly (RGE implicitly assumed)

- well-established procedure
- experimentally verified on a very wide range of scales, at different experiments
Running of quark masses

- similar procedure can be used to extract running of heavy quark masses

short distance $\overline{\text{MS}}$ mass can be expressed in terms of pole mass

$$m_q(m_q) = m_q^{\text{pole}} \left[ 1 - \frac{4}{3\pi} \alpha_S(m_q) + \mathcal{O}(\alpha_S^2) \right]$$

and evolved to an arbitrary scale $\mu$

$$m_q(\mu) = m_q(m_q) \left[ 1 - \frac{\alpha_S(\mu)}{\pi} \ln \frac{\mu^2}{m_q^2} + \mathcal{O}(\alpha_S^2) \right]$$

- running of $m_c$ has been experimentally determined at HERA experiments
- running of $m_b$ determined with data from different experiments

→ **goal:** determine running of $m_t$

using LHC data at 13 TeV
Analysis strategy

- Apply $t\bar{t}$ selection and kinematic reconstruction $\rightarrow m(t\bar{t})$

- Split the $t\bar{t}$ sample into 4 subsamples corresponding to bins of $m(t\bar{t})$ at parton level

- Each bin is treated as an independent signal and represents the $t\bar{t}$ production at the scale $\mu_k$, defined as the centre of gravity in bin $k$

- Measure $\sigma(t\bar{t})$ differentially as a function of $m(t\bar{t})$ via fit to multidifferential distributions
  - Experimental dependence on the $m_t^{MC}$ taken into account
  - Systematics constrained in the visible phase space
The measured $\sigma(tt)(\mu_k)$ are used to extract the running of the top MSbar mass at NLO as a function of the scale $\mu = m(tt)$

The top MSbar mass, $m_t(m_t)$, is determined independently in each bin of $m(tt)$ from a Chi2 fit to a fixed-order NLO calculation in MCFM (the top mass is treated in the MSbar scheme)

The measured $m_t(m_t)$ are converted to $m_t(\mu_k)$ using RunDec

- $\mu_k$ represents the scale of the process in a given bin of $m(tt)$
- Conversion performed with 1-loop precision assuming 5 active flavours
- This is equivalent to extracting directly $m_t(\mu_k)$ in each bin

Take ratios of $m_t(\mu_k)/m_t(\mu_{ref})$ to cancel correlated uncerts in the measured $\sigma(tt)(\mu_k)$
CMS: MSbar top mass in dileptons

Simultaneous extraction of $t\bar{t}$ cross section and $m_{t\text{MC}}$:

\[ \sigma_{t\bar{t}} = 815 \pm 2 \text{ (stat)} \pm 29 \text{ (syst)} \pm 20 \text{ (lumi)} \text{ pb} \]
\[ m_{t\text{MC}} = 172.33 \pm 0.14 \text{ (stat)} \pm 0.66 \text{ (syst)} \text{ GeV} \]

Residual dependence of the cross section on $m_{t\text{MC}}$

\[ \rightarrow \text{indirect } m_t(m_{t}) \text{ and } \alpha_s \text{ determination:} \]

alphaS summary plot

- ZEUS incl. jets in $\gamma^* p$ : NPB 864:1 (2012)
- H1 multijets at high $Q^2$ : arXiv 1406.4709 (2014)
- D0 incl. jets : PRD 80:111107 (2009)
- D0 ang. correl. : PLB 718:56 (2012)
- ATLAS TEEC 8TeV : EPJC 77:872 (2017)
- CMS $R_{32}$ 7TeV : EPJC 73:2604 (2013)
- CMS $t\bar{t}$ cross section 7TeV : PLB 728:496 (2014)
- CMS 3-Jet mass 7TeV : EPJC 75:186 (2015)
- CMS $R_{32}$ 8TeV : CMS-PAS-SMP-16-008 (2017)
- CMS $t\bar{t}$ cross section 13TeV : arXiv 1812.10505 (2018)
- CMS multi-diff $t\bar{t}$ 13TeV : CMS-PAS-TOP-18-004 (2018)
CMS: top mass from boosted jets (TOP-19-005) — 1


- exclusive jet algorithm → returns exactly $N$ jets
- jet axes found by minimizing $N$-jettiness
- cluster particles inside $R$ around axes

set-up for lepton+jets $t\bar{t}$ idea from: [J. Thaler and T. F. Wilkason, JHEP 1512 (2015) 051]

1. find 2 jets with large radius
2. calculate $\Delta R(\text{lep}, \text{jet})$ for both jets
3. lowest $\Delta R \rightarrow$ leptonic jet; other $\rightarrow$ hadronic jet
4. find subjets: 3 in hadronic jet, 2 in leptonic jet
5. combine subjets to final jet
CMS: top mass from boosted jets (TOP-19-005) — 2

- m_{jet} resolution comparable to AK8, stable against PU

- Large “merged” (i.e., decay products inside the jet) fraction

- no jet calibration for XConE so far
- idea: AK4 calibration + additional correction
- correction derived in all hadronic t\bar{t}
- correction applied dependent on p_T and \eta of subjets
CMS: top mass from boosted jets (TOP-19-005) — 3

Cross-check in W reco

closure in tW after correction

stable against PU
**tt+bb production**

Major background for tt+H(bb) (irreducible) and tttt

- Challenging to model: complex final state, very different scales (tt, bb)
- **ATLAS**: dilepton & l+jets
- **CMS**: new dilepton & l+jets, all-jets
- Different phase spaces, comparison to NLO MC simulations: in general, $\sigma$(ttbb) slightly higher in data
ATLAS: top width

<table>
<thead>
<tr>
<th>Source</th>
<th>Impact on $\Gamma_t$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet reconstruction</td>
<td>±0.24</td>
</tr>
<tr>
<td>Signal and bkg. modelling</td>
<td>±0.19</td>
</tr>
<tr>
<td>MC statistics</td>
<td>±0.14</td>
</tr>
<tr>
<td>Flavour tagging</td>
<td>±0.13</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ reconstruction</td>
<td>±0.09</td>
</tr>
<tr>
<td>Pile-up and luminosity</td>
<td>±0.09</td>
</tr>
<tr>
<td>Electron reconstruction</td>
<td>±0.07</td>
</tr>
<tr>
<td>PDF</td>
<td>±0.04</td>
</tr>
<tr>
<td>$t\bar{t}$ normalisation</td>
<td>±0.03</td>
</tr>
<tr>
<td>Muon reconstruction</td>
<td>±0.02</td>
</tr>
<tr>
<td>Fake-lepton modelling</td>
<td>±0.01</td>
</tr>
</tbody>
</table>

Table 3: Impact on the uncertainty of the $\Gamma_t$ measurement from different categories of systematic uncertainties. The categories with the highest impact are on the top of the table. The quoted values are obtained by repeating the fit while fixing a set of nuisance parameters from the corresponding category sources, and subtracting in quadrature the resulting total uncertainty of $\Gamma_t$ from the uncertainty from the full fit.

<table>
<thead>
<tr>
<th>$m_t$ = 172 GeV</th>
<th></th>
<th>$m_t$ = 172.5 GeV</th>
<th></th>
<th>$m_t$ = 173 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.01</td>
<td>±0.53</td>
<td>1.94</td>
<td>±0.52</td>
<td>1.90</td>
</tr>
<tr>
<td>1.306</td>
<td>&lt; 1%</td>
<td>1.322</td>
<td>&lt; 1%</td>
<td>1.333</td>
</tr>
</tbody>
</table>

Table 4: Fitted values and their uncertainties under different top-quark mass hypotheses. The theoretical values are extracted from the leading order values that are corrected following Ref. [6].
ATLAS: tqγ FCNC

- **ATLAS (81 fb⁻¹):** Search for tqγ FCNC in single top + γ events
  - Topology: 1 e/mu, 1 γ, 1 b-jet, MET

- NN to separate signal from background

- Fit to NN output in SR and CR dominated by main bgs from events with prompt γ
  - Contribution from events electrons/hadrons misID as γ estimated from data
**ATLAS: tqγ FCNC**

- **ATLAS** (81 fb\(^{-1}\)): Search for tqγ FCNC in single top + γ events

**Limits on:**
- strength of effective operators that introduce a left- or right-handed FC \( tqγ \) coupling with an up-type \( q \)
- cross sections for \( pp \rightarrow tqγ \)
- \( B(t \rightarrow qγ) \)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Vertex</th>
<th>Coupling</th>
<th>Obs.</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{uW}^{(13)<em>} + C_{uB}^{(13)</em>} )</td>
<td>( tuγ )</td>
<td>LH</td>
<td>0.19</td>
<td>0.22(^{+0.04}_{-0.03})</td>
</tr>
<tr>
<td>( C_{uW}^{(31)} + C_{uB}^{(31)} )</td>
<td>( tuγ )</td>
<td>RH</td>
<td>0.27</td>
<td>0.27(^{+0.05}_{-0.04})</td>
</tr>
<tr>
<td>( C_{uW}^{(23)<em>} + C_{uB}^{(23)</em>} )</td>
<td>( tcγ )</td>
<td>LH</td>
<td>0.52</td>
<td>0.57(^{+0.11}_{-0.09})</td>
</tr>
<tr>
<td>( C_{uW}^{(32)} + C_{uB}^{(32)} )</td>
<td>( tcγ )</td>
<td>RH</td>
<td>0.48</td>
<td>0.59(^{+0.12}_{-0.09})</td>
</tr>
<tr>
<td>( \sigma(pp \rightarrow tγ) ) [fb]</td>
<td>( tuγ )</td>
<td>LH</td>
<td>36</td>
<td>52(^{+21}_{-14})</td>
</tr>
<tr>
<td>( \sigma(pp \rightarrow tγ) ) [fb]</td>
<td>( tuγ )</td>
<td>RH</td>
<td>78</td>
<td>75(^{+31}_{-21})</td>
</tr>
<tr>
<td>( \sigma(pp \rightarrow tγ) ) [fb]</td>
<td>( tcγ )</td>
<td>LH</td>
<td>40</td>
<td>49(^{+20}_{-14})</td>
</tr>
<tr>
<td>( \sigma(pp \rightarrow tγ) ) [fb]</td>
<td>( tcγ )</td>
<td>RH</td>
<td>33</td>
<td>52(^{+22}_{-14})</td>
</tr>
<tr>
<td>( B(t \rightarrow qγ) ) [10(^{-5})]</td>
<td>( tuγ )</td>
<td>LH</td>
<td>2.8</td>
<td>4.0(^{+1.6}_{-1.1})</td>
</tr>
<tr>
<td>( B(t \rightarrow qγ) ) [10(^{-5})]</td>
<td>( tuγ )</td>
<td>RH</td>
<td>6.1</td>
<td>5.9(^{+2.4}_{-1.6})</td>
</tr>
<tr>
<td>( B(t \rightarrow qγ) ) [10(^{-5})]</td>
<td>( tcγ )</td>
<td>LH</td>
<td>22</td>
<td>27(^{+11}_{-7})</td>
</tr>
<tr>
<td>( B(t \rightarrow qγ) ) [10(^{-5})]</td>
<td>( tcγ )</td>
<td>RH</td>
<td>18</td>
<td>28(^{+12}_{-8})</td>
</tr>
</tbody>
</table>