Top physics in ATLAS and CMS

Jin Wang (IHEP, CAS)
On behalf of CMS and ATLAS Collaborations
Focus on new results published in 2018 and 2019

- Introduction

- Top quark production cross-section measurements
  - $t\bar{t}$ inclusive and differential cross sections
  - Single top quark production cross sections
  - Top+X production measurements

- Top quark properties measurements
  - Top quark mass measurements, top decay width
  - Top pair spin correlations, charge asymmetry

- New Physics searches
  - Flavour changing neutral currents from top-quark decays
  - Charged lepton-flavour violation in top-quark decays
The unique top quark

- Most massive of known fundamental particles ~ 173 GeV
- Mass is of order of the electroweak symmetry breaking scale
  - large couplings to new resonances predicted by New Physics models
  - large Yukawa coupling to Higgs boson
- The only quark that decays before it can hadronise
  - opportunity to study a bare quark
  - access to its spin and polarization
- Important backgrounds to many precision measurements and New Physics searches

Huge top quark production cross sections at the LHC

- >100 million top quarks produced in Run 2

Very interesting and important at the LHC
$t\bar{t}$ inclusive and differential cross sections
Core physics delivery of the LHC with statistics $O(1000)$ times Tevatron

- Unique test of QCD with massive partons and constraints on QCD soft scale modelling
- Constraints on SM parameters ($m_t, \alpha_S$) and PDFs
- Constraints on anomalous EFT terms
- Background for many BSM and Higgs signals

Good agreement between data and prediction
**Single measurement precision:** \( \sim 3.5\% \)

**Limited mainly by luminosity and signal model uncertainty.**
Latest $t\bar{t}$ inclusive cross sections

- **ATLAS, ATLAS-CONF-2019-041**
  - 13 TeV, 36.1 fb$^{-1}$ data
  - events with an opposite-charge $e\mu$ pair and one or two b-tagged jets
  - 2.4% precision

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

- **CMS, CMS-PAS-TOP-18-005**
  - 13 TeV, 35.9 fb$^{-1}$ data
  - events $t\bar{t} \rightarrow (l\nu_l)(\tau_\nu \tau_b)bb$
  - measured cross section

  \[ \sigma_{t\bar{t}} = 781 \pm 7 \text{ (stat)} \pm 62 \text{ (syst)} \pm 20 \text{ (lumi)} \text{ pb} \]

  - ratio of the partial width to the total width
  \[ \frac{\Gamma(t \rightarrow \tau_\nu b)}{\Gamma_{total}} = 0.1050 \pm 0.0009 \text{ (stat)} \pm 0.0071 \text{ (syst)} \]
Scrutinize tt production in many channels as a function of many observables

- precision tests of QCD in different regions of phase space
- sensitive to BSM physics

Kinematic variables consistent with NLO QCD in general
Data shows softer top $p_T$ than POWHEG+PYTHIA predicted in dilepton channel

- still see the trend with higher order QCD and EW corrections

- Other variables related to top $p_T$ are also in tension
$t\bar{t}$ differential cross sections - multidifferential

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

- **CMS**: 2D, 3D differential cross sections vs. top, $t\bar{t}$ kinematics and Njets, extracted $m_t^{pole}$, $\alpha_s$, PDF constraints.
Single top quark production cross sections
Single top quark production measurements

- Top quark electroweak production @ 13 TeV
  - t-channel: 216.99 pb, tW channel: 71.7 pb, s-channel: 10.32 pb, rare tZq production: ~ 1pb

2018 updates

ATLAS tW:

CMS tW:
JHEP 10 (2018) 117
Run1 ATLAS+CMS combinations on single-top-quark cross sections and $V_{tb}$

*JHEP 05 (2019) 088*
Top+X production measurements
Top+X production in a nutshell

Becoming accessible with Run2 data

**CMS:** most precise $\sigma(ttZ)$ to date, 1$^{\text{st}}$ differential cross sections, stringent limits on anomalous couplings

CMS, arXiv:1907.11270

**ATLAS:** 1$^{\text{st}}$ 13 TeV result, 1$^{\text{st}}$ differential cross sections

ATLAS, EPJC 79 (2019) 382

**CMS (77 fb$^{-1}$), observation > 5$\sigma$**

CMS, PRL 122 (2019) 132003

**ATLAS (36 fb$^{-1}$), 1$^{\text{st}}$ evidence: 4.2 (5.4) $\sigma$ obs (exp)**

ATLAS, PLB 780 (2018) 557

**CMS (36 fb$^{-1}$), evidence: 4.4 (3.0) $\sigma$ obs (exp)**

CMS, PRL 121 (2018) 221802

M. Aldaya
● Updates from CMS with 77.4 fb⁻¹ data from 2016 and 2017
● Binned maximum likelihood fit to BDTs of three signal regions and the WZ/ZZ control regions

![Graphs showing data and signal regions](image)

● Measured cross section with 15% precision:

\[ \sigma(tZq \rightarrow t\ell^+\ell^-q) = 111 \pm 13^{+11}_{-9} \text{(stat)} \pm 11 \text{(syst)} \text{ fb} \]

● First observation with observed (expected) significance 8.2 (7.7) \( \sigma \).

Corfu 2019  Tuesday, September 3, 2019
Tiny cross section in SM \( \sim 9 \text{fb} @13 \text{ TeV} \)

Many BSM models probes an increase

Searches performed in LHC with Run2 data

- ATLAS/CMS: single lepton and opposite-sign dilepton channels \( \text{arXiv:1811.02305} \), CMS-TOP-17-019
- CMS: same sign and multilepton final states CMS-TOP-18-003, using full Run2 data
- Important background to ttH(bb) production
- Different phase spaces compared to NLO MC simulations
- In general data exceeds the predictions

**Important background to ttH(bb) production**

**Different phase spaces compared to NLO MC simulations**

**In general data exceeds the predictions**
Top quark properties measurements
Top quark mass measurement

- Top quark mass is a key parameter of the Standard Model, important for electroweak vacuum stability
  - Need to measure the top mass in all possible ways with highest possible precision

- Direct measurement of “Monte Carlo mass” $m_t^{MC}$
  - Extracted from invariant mass of decay products

- Indirect measurement of the pole mass $m_t^{pole}$ from observables depending on $m_t$
  - E.g. inclusive or differential cross section $\sigma^{measure}$ compared to $\sigma^{theory}$
  - Measurement made in a given renormalization scheme

- Difference between $m_t^{MC}$ and $m_t^{pole}$ could be $\sim$ GeV
Direct top mass measurement

2018 updates

**ATLAS:** arxiv 1810.01772

Lepton+jets channel 8TeV 20.2 fb\(^{-1}\) data

172.08 ± 0.39(stat) ± 0.82(syst)

**CMS:** *Eur. Phys. J. C 78 (2018) 891*

Lepton+jets channel 2016 36 fb\(^{-1}\) data

172.25 ± 0.08 (stat+JSF) ± 0.62 (syst GeV)

reached ~0.5 GeV precision
Recent indirect measurement of the pole mass $m_t^{pole}$ extracted from differential measurement in ATLAS [arXiv:1905.02302] and CMS [arXiv:1904.05237]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Observation</th>
<th>$m_t^{pole}$ [GeV]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$c_{incl}^{diff}$, $\sqrt{s} = 1.96$ TeV</td>
<td>172.8 $\pm$ 3.4 $\pm$ 3.2</td>
<td>PRD 94, 092004 (2016)</td>
</tr>
<tr>
<td>CMS</td>
<td>$c_{incl}^{diff}$, NNPDF3.0, $\sqrt{s} = 7+8$ TeV</td>
<td>173.8 $\pm$ 1.7 $\pm$ 1.8</td>
<td>JHEP 08 (2016) 029</td>
</tr>
<tr>
<td>CMS</td>
<td>$c_{incl}^{diff}$, $\sqrt{s} = 13$ TeV</td>
<td>170.6 $\pm$ 2.7 $\pm$ 2.7</td>
<td>JHEP 09 (2017) 051</td>
</tr>
<tr>
<td>CMS</td>
<td>$c_{diff}^{incl}$, $\sqrt{s} = 13$ TeV</td>
<td>170.5 $\pm$ 0.8 $\pm$ 0.8</td>
<td>arXiv:1904.05237</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$c_{diff}^{incl}$, $\sqrt{s} = 8$ TeV</td>
<td>173.2 $\pm$ 1.6 $\pm$ 1.6</td>
<td>EPJC 77 (2017) 804</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$c_{incl}^{diff}$, $\sqrt{s} = 7+8$ TeV</td>
<td>172.9 $\pm$ 2.5 $\pm$ 2.6</td>
<td>EPJC 74 (2014) 3109</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$c_{diff}^{incl}$, $\sqrt{s} = 7$ TeV</td>
<td>173.7 $\pm$ 2.3 $\pm$ 2.1</td>
<td>JHEP 10 (2015) 121</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$c_{incl}^{1+jet}$, $\sqrt{s} = 8$ TeV</td>
<td>171.1 $\pm$ 1.2 $\pm$ 1.1</td>
<td>this analysis</td>
</tr>
</tbody>
</table>

CMS

$[N_{jet}^{0.1+}, M(tt), y(tt)]$

- $m_t^{pole}$ with total unc.
- data unc.
- PDF unc.
- $\mu$ unc.
- $\alpha_s \pm 0.001$ unc.

World average [PDG2018]

Most precise result so far
Latest top mass measurement in CMS

- Measure top mass $m_t$ from boosted jet mass ($m_{\text{jett}}$) observable
  - **CMS-PAS-TOP-19-005**
  - using highly boosted hadronic top quark decays produced in $t\bar{t}$ events
  - reconstruct highly-boosted top quark decays with a novel XCone jet algorithm [JHEP11(2015)072]

- the normalized differential cross section as a function of jet mass is compared to predictions from POWHEG with different values of $m_t$

- extract a value of the top quark mass of $172.56 \pm 2.47$ GeV
The running of top mass measurement in CMS

- First measurement of the running of the top quark mass from CMS
- CMS-PAS-TOP-19-007

- differential $t\bar{t}$ production cross section as a function of $m_{t\bar{t}}$ at the parton level, compared to NLO predictions in the $\overline{MS}$ scheme obtained with different values of $m_t$
- extract the running of the top quark mass (evolution of the top quark mass as a function of the scale), compared to the prediction from renormalization group equations (RGE) solved with one-loop precision assuming five active flavours.
Top quarks in $t\bar{t}$ production are mainly unpolarized, but the top pairs are strongly correlated.

Some BSM scenarios would lead to different top spin correlation.

Leptons from top decay carry the most spin information of the parent top.

The easiest observable is the azimuthal opening angle $\Delta\phi$ between $l^+l^-$.

In ATLAS and CMS, unfolded parton-level differential cross sections for $\Delta\phi(l^+l^-)$ are compared to different generator predictions.

Stronger spin correlation in data comparing to NLO prediction.

**arXiv:1903.07570** Parton level $\Delta\phi(l^+,l^-)/\pi$ [rad/$\pi$]

**arXiv:1907.03729**
Direct measurement of the top decay width $\Gamma_t$ in dilepton events in ATLAS with full Run2 data
- **ATLAS-CONF-2019-038**
- Compare data to MC templates with different $\Gamma_t$ assumptions
- The measured width is $\Gamma_t = 1.9 \pm 0.5$ GeV

Top pair charge asymmetry is measured in ATLAS using full Run2 data
- **ATLAS-CONF-2019-026**
- The inclusive $t\bar{t}$ charge asymmetry is measured as $A_C = 0.0060 \pm 0.0015$ (stat+syst.)
- 4 $\sigma$ deviation from zero
New Physics searches
Flavour changing neutral currents from top-quark decays

- In SM, quark flavours can only change at tree level via charged currents (W+/− bosons)
- FCNC processes occur via loops in the SM, highly suppressed by GIM mechanism
- An observation of FCNC would be unambiguous evidence of BSM.

Latest update from ATLAS gives improved limits
- Search for tqγ FCNC in single top + γ events using 81 fb⁻¹ 13TeV data
- arXiv:1908.08461
Test BSM models that allow the local non-conservation of charged lepton flavor

- E.g. minimal extension of the SM explaining neutrino mass

Latest results ATLAS-CONF-2018-044 from ATLAS use 79.8 fb\(^{-1}\) data collected from 2015 to 2017

- Search for \(t \rightarrow l^\pm l'^\mp q\) decay in \(t\bar{t}\) with the other top decays semileptonically

- Use binned maximum-likelihood fit on BDT discriminant to test for the presence of the signal events

The observed exclusion on cLFV decay branching ratio is

\[
\mathcal{B}(t \rightarrow l l' q) < 1.86 \times 10^{-5} \quad \text{(observed)}.
\]
Summary
LHC Run-2 data is taking a central stage in top physics studies, a broad range of new results were updated by ATLAS and CMS

- precision measurements of top production and decay, top quark properties
  - $t\bar{t}$, single top, top+$X$ cross sections
  - top quark mass, decay width, top pair spin correlations, charge asymmetries
- challenging and rare production/decay modes are exploited
  - four-top-quark production, $tZq$ observation
- improved limits on various new physic searches
  - FCNC, cLFV
- new studies on running of top mass, $tW$ and $t\bar{t}$ interference models, jet shapes etc.
- data results are generally consistent with theoretical predictions with a few exceptions that need further investigation
  - some differential distribution in $t\bar{t}$, $t\bar{t}+b\bar{b}$, top pair spin correlations

More potential and excitement for top quark physics with the upcoming results using full Run 2 data

- larger statistics $\sim 150$ fb$^{-1}$, improved MC models and theoretical calculations
- new BSM interpretations, access to rare processes, new physics searches etc.
Backup
Single measurement precision: ~3.5%

Limited mainly by luminosity and signal model uncertainty.
Probing interference between tW and $t\bar{t}$ production

- Treatments of the tW and $t\bar{t}$ NLO interference effects:
  - **Diagram removal (DR):** remove doubly resonant diagrams from Wtb matrix element
  - **Diagram subtraction (DS):** subtract gauge-invariant term from Wtb matrix element
  - arXiv:1607.05862 for details

- New study from ATLAS testing different models

- Use variable sensitive to interference effects
  \[ m_{bl}^{\text{minmax}} = \min \{ \max (m_{b_1\ell_1}, m_{b_2\ell_2}), \max (m_{b_1\ell_2}, m_{b_2\ell_1}) \} \]

- Results provide an important constraint on interference models and will guide future model development and tuning.
tZq measurements

- tZq rare production
  - unique sensitivity to some EFT operators due to $Wb \rightarrow tZ$ vertex
  - Challenging large SM backgrounds

Previous results

**CMS result with 2016 data**


- $\mu = 1.31^{+0.35}_{-0.33}(\text{stat})^{+0.31}_{-0.25}(\text{sys})$
- 3.7 (3.1) $\sigma$ Obs.(Exp.)

**ATLAS result with 2016 data**


- $\mu = 0.75 \pm 0.21(\text{stat}) \pm 0.17(\text{sys})$
- 4.2 (5.4)$\sigma$ Obs.(Exp.)

Both measurements with about 35% uncertainty
$t\bar{t} + \gamma$

**ATLAS**
\[\sqrt{s} = 8\,\text{TeV},\ 20.2\,\text{fb}^{-1}\]
Single lepton channel

- NLO Pred.
- Data (Stat.)
- Data (Stat.+Syst.)

**JHEP 11 (2017) 086**

$$\sigma_{t\bar{t}+\gamma} = 139 \pm 18\,\text{pb}$$

**JHEP 10 (2017) 006**

$$\sigma_{t\bar{t}+\gamma} = 127 \pm 27\,\text{pb}$$

**CMS**

- Data
- $t\bar{t}+\gamma$
- Single $t$
- $W/Z+\gamma$
- $W/Z+jets$
- Multijet
- Uncertainty

19.7 fb$^{-1}$ (8 TeV)

**Corfu 2019**

Tuesday, September 3, 2019
- Photon emitted by ISR, FSR from top quark
- Important background to $t\bar{t}H(\gamma\gamma)$ production or BSM processes
- Probe $t\gamma$ EW coupling

**ATLAS updated 13TeV results of inclusive and differential cross-sections for $t\bar{t} + \gamma$ with 2015+2016 data, recently submitted to EPJC**

**All measurements are in agreement with the theoretical predictions.**
Some tension found between data and prediction for reconstructed hadronical top $p_T$ in 4-jet exclusive configuration in both ATLAS and CMS.

POWHEG+PYTHIA also has difficulties simultaneously reproducing Njets and $p_T(t\bar{t})$. 

JHEP 10 (2018) 159

Results are in agreement with the standard model.
Constrained the anomalous EFT operators
Indirect top mass measurement

**CMS:** 13 TeV data, L = 2.2 fb⁻¹; lepton+jets final state
- Measure differential cross section wrt min(m_{lb}) in categories of N_{jet} and N_{b-jet}:
  \[ \sigma = 888 \pm 2 \text{ (stat)} \pm 27 \text{ (sys)} \pm 20 \text{ (lumi) pb} \]
- Extract pole mass from cross section:
  \[ m_{t}^{\text{pole}} = 170.6 \pm 2.7 \text{ (tot)} \pm 1.01 \text{ (syst.) GeV} \]

**ATLAS:** 8 TeV data, L = 20.2 fb⁻¹, dilepton with 1 or 2 b-jets
- 8 differential fiducial cross sections measured:
  \[ p_{T}, |\eta|, p_{T}^{e}, m_{\mu}, |y_{\mu}|, \Delta \phi_{e\mu}, p_{T}^{e}+p_{T}^{\mu}, E^{e}+E^{\mu} \]
- \[ m_{t}^{\text{pole}} \] extracted from combined fit to templates or distribution moments
  \[ m_{t}^{\text{pole}} = 173.2 \pm 0.9 \text{ (stat)} \pm 0.8 \text{ (syst)} \pm 1.2 \text{ (theo) GeV} \]

**EPJC 77 (2017) 804**

**JHEP 09 (2017) 051**
Top Width measurements

ATLAS: direct measurements from a partial kinematic reconstruction of the top decay

- Fit to $m(\ell b)$ and $\Delta R_{\text{min}}(j,b)$
- Width extracted assuming $m_{\text{top}} = 172.5$ GeV

CMS: direct measurement gives

$0.6 \text{ GeV} < \Gamma_t < 2.5 \text{ GeV}$ at 95% CL

[ TOP-PAS-16-019 ]

CMS also derived $\Gamma_t$ from t-channel single top production

\[
\Gamma_t = \frac{\sigma_{t\text{-ch.}}}{B(t \rightarrow Wb)} \cdot \frac{\Gamma(t \rightarrow Wb)}{\sigma_{t\text{-ch.}}} 
\]

$B(t \rightarrow Wb)$ is separately measured:

[ PLB 736 (2014) 33 ]

\[
\frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)} = 1.014 \pm 0.003(\text{stat}) \pm 0.032(\text{sys})
\]

Finally, combined with previous CMS t-channel single-top-quark cross section:

\[
\Gamma_t = 1.36 \pm 0.02(\text{stat})^{+0.14}_{-0.11}(\text{sys})
\]
Top charge asymmetry

At Tevatron, measure $A_{FB}$. At LHC, measure $A_{C}$:

$$A_{C} = \frac{N_{\Delta|y|>0} - N_{\Delta|y|<0}}{N_{\Delta|y|>0} + N_{\Delta|y|<0}}$$

Non-zero $A_{C}$ in SM due to higher order effects in $q \bar{q}$ annihilation

Use lep+jets events. Reconstruct $t \bar{t}$ events and unfold

LHC $A_{C}$ measurements ruled out a number of theories explaining the Tevatron $A_{FB}$ anomaly

High $t \bar{t}$ mass region has higher fraction of quark initiated production – $A_{C}$ is more sensitive to BSM
Flavour changing neutral currents from top-quark decays

- In SM, quark flavours can only change at tree level via charged currents (W+/− bosons)
- FCNC processes occur via loops in the SM, highly suppressed by GIM mechanism
- An observation of FCNC would be unambiguous evidence of BSM.

Current summary of 95% C.L. observed limits on the branching ratios of the top quark decays via FCNC in ATLAS and CMS.

Latest updates since Dec. 2017:

ATLAS with 2015+2016 36 fb−1 data

- JHEP 07 (2018) 176 $t \rightarrow qZ$ (q=u, c)
- Phys. Rev. D 98 (2018) 032002 $t \rightarrow Hq$ with $H \rightarrow$ multilepton
- ATLAS-CONF-2018-049 $t \rightarrow Hq$ with $H \rightarrow b\bar{b}, \tau\tau$

CMS with 35.9 fb−1 2016 data

- JHEP 06 (2018) 102 $t \rightarrow Hq$ with $H \rightarrow b\bar{b}$
Variables used in the multivariate analysis, sorted according to the method-specific ranking.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Separation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSSF lepton pair invariant mass</td>
<td>11</td>
</tr>
<tr>
<td>cLFV top mass</td>
<td>10</td>
</tr>
<tr>
<td>$p_T$ of the electron associated to the cLFV decay</td>
<td>9.1</td>
</tr>
<tr>
<td>$p_T$ of the muon associated to the cLFV decay</td>
<td>8.5</td>
</tr>
<tr>
<td>$p_T$ of the lepton associated to the SM decay</td>
<td>8.3</td>
</tr>
<tr>
<td>Scalar mass of all jets and leptons in the event</td>
<td>7.6</td>
</tr>
<tr>
<td>Same-sign electron pair invariant mass</td>
<td>6.9</td>
</tr>
<tr>
<td>Missing transverse momentum</td>
<td>6.8</td>
</tr>
<tr>
<td>Number of $b$-jets</td>
<td>6.7</td>
</tr>
<tr>
<td>$W$ transverse mass associated to the SM top lepton</td>
<td>6.6</td>
</tr>
<tr>
<td>$\Delta R$ between the cLFV electron and the cLFV light jet</td>
<td>6.5</td>
</tr>
<tr>
<td>SM top mass</td>
<td>6.4</td>
</tr>
<tr>
<td>$\Delta R$ between the cLFV muon and the cLFV light jet</td>
<td>6.3</td>
</tr>
<tr>
<td>BDT discriminant</td>
<td>44</td>
</tr>
</tbody>
</table>