Top Quark Properties

Efe Yazgan (National Taiwan University)
on behalf of ATLAS and CMS Collaborations
The Top Quark

• The most massive elementary particle known to date.

• Very short lifetime.

\[ \tau_t = \frac{1}{\Gamma_t} \sim 0.5 \times 10^{-24} \text{s} < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2} \sim 3 \times 10^{-21} \text{s} \ll \tau_b \sim 10^{-12} \text{s} \]

\[ \tau_t < \tau(\text{hadronization}) < \tau(\text{spin-decorrelation}) \ll \tau_b \]

No hadronic bound states \implies quark properties accessible

top quark spins

Recent measurements from ATLAS and CMS

Top quark mass and width - Yukawa coupling - CKM matrix elements - Asymmetries - Spin correlations - W boson polarization

All public results at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
Top Quark Mass Extraction from Decay (« Direct »)

<table>
<thead>
<tr>
<th>LHCbtopWG</th>
<th>m_{top} summary, \sqrt{s} = 7-13 TeV</th>
<th>May 2019</th>
</tr>
</thead>
</table>
| LHC btopWG | \begin{align*} m_{top} & = \text{total (stat + syst)} \pm \text{rel. unc.} \% \\
| World comb. (Mar 2014) | 172.79 \pm 1.41 \ (0.54 \pm 1.30) \ & \text{7 TeV} \ [2] \\
| ATLAS, l+jets | 172.33 \pm 1.27 \ (0.75 \pm 1.02) \ & \text{7 TeV} \ [3] \\
| ATLAS, dilepton | 173.79 \pm 1.41 \ (0.54 \pm 1.30) \ & \text{7 TeV} \ [3] \\
| ATLAS, single top | 175.1 \pm 1.8 \ (1.4 \pm 1.2) \ & \text{7 TeV} \ [4] \\
| ATLAS, all jets | 172.37 \pm 1.15 \ (0.55 \pm 1.01) \ & \text{7 TeV} \ [5] \\
| ATLAS, l+jets | 172.08 \pm 0.91 \ (0.39 \pm 0.82) \ & \text{7 TeV} \ [6] \\
| ATLAS comb. (Sep 2013) | 172.69 \pm 0.48 \ (0.25 \pm 0.41) \ & \text{7+8 TeV} \ [8] \\
| ATLAS comb. (Oct 2018) | 172.3 \pm 0.6 \ (0.3 \pm 0.97) \ & \text{7 TeV} \ [9] \\
| CMS, l+jets | 173.0 \pm 1.52 \ (0.43 \pm 1.46) \ & \text{7 TeV} \ [10] \\
| CMS, dilepton | 173.0 \pm 1.52 \ (0.43 \pm 1.46) \ & \text{7 TeV} \ [11] \\
| CMS, all jets | 173.49 \pm 1.41 \ (0.69 \pm 1.23) \ & \text{7 TeV} \ [12] \\
| CMS, single top | 172.5 \pm 1.23 \ (0.19 \pm 1.22) \ & \text{7 TeV} \ [13] \\
| CMS comb. (Oct 2018) | 172.4 \pm 0.48 \ (0.13 \pm 0.47) \ & \text{7+8 TeV} \ [14] \\
| CMS, l+jets | 172.25 \pm 0.63 \ (0.08 \pm 0.62) \ & \text{13 TeV} \ [15] \\
| CMS, dilepton | 172.33 \pm 0.70 \ (0.14 \pm 0.69) \ & \text{13 TeV} \ [16] \\
| CMS, all jets | 172.34 \pm 0.73 \ (0.20 \pm 0.70) \ & \text{13 TeV} \ [17] \\
| CMS comb. (Sep 2015) | 172.4 \pm 0.48 \ (0.13 \pm 0.47) \ & \text{7+8 TeV} \ [18] \\
| CMS, l+jets | 172.4 \pm 0.48 \ (0.13 \pm 0.47) \ & \text{7+8 TeV} \ [19] \\
| CMS, dilepton | 172.3 \pm 0.6 \ (0.3 \pm 0.97) \ & \text{7+8 TeV} \ [20] \\
| CMS, all jets | 172.3 \pm 0.6 \ (0.3 \pm 0.97) \ & \text{7+8 TeV} \ [21] \\
| CMS comb. (Sep 2015) | 172.4 \pm 0.48 \ (0.13 \pm 0.47) \ & \text{7+8 TeV} \ [22] \\
| CMS, l+jets | 172.4 \pm 0.48 \ (0.13 \pm 0.47) \ & \text{7+8 TeV} \ [23] \\
| CMS, dilepton | 172.3 \pm 0.6 \ (0.3 \pm 0.97) \ & \text{7+8 TeV} \ [24] \\
| CMS, all jets | 172.3 \pm 0.6 \ (0.3 \pm 0.97) \ & \text{7+8 TeV} \ [25] \\
| CMS comb. (Sep 2015) | 172.4 \pm 0.48 \ (0.13 \pm 0.47) \ & \text{7+8 TeV} \ [26] \\
| CMS, l+jets | 172.4 \pm 0.48 \ (0.13 \pm 0.47) \ & \text{7+8 TeV} \ [27] \\
| CMS, dilepton | 172.3 \pm 0.6 \ (0.3 \pm 0.97) \ & \text{7+8 TeV} \ [28] \\
| CMS, all jets | 172.3 \pm 0.6 \ (0.3 \pm 0.97) \ & \text{7+8 TeV} \ [29] \\
| CMS comb. (Sep 2015) | 172.4 \pm 0.48 \ (0.13 \pm 0.47) \ & \text{7+8 TeV} \ [30] \\
| CMS, l+jets | 172.4 \pm 0.48 \ (0.13 \pm 0.47) \ & \text{7+8 TeV} \ [31] \\
| CMS, dilepton | 172.3 \pm 0.6 \ (0.3 \pm 0.97) \ & \text{7+8 TeV} \ [32] \\
| CMS, all jets | 172.3 \pm 0.6 \ (0.3 \pm 0.97) \ & \text{7+8 TeV} \ [33] \\

- More recent measurements not included yet:
  - ATLAS: l+jets at 13 TeV
    - from soft muon tags
    \[ m_t = 174.48 \pm 0.78 \, GeV \] (rel. unc. = 0.45%)
  - CMS: all-jets + l+jets at 13 TeV
    - \( m_t \) determined simultaneously with JES (for both channels) in a joint likelihood fit
    \[ m_t = 172.26 \pm 0.61 \, GeV \] (rel. unc. = 0.36%)

- Combined measurements precision \( \sim 500 \, MeV \rightarrow 0.28\% \) (ATLAS & CMS)
  - Limited by jet energy scale calibration, b-tagging and modelling uncertainties.
  - Many individual measurements with < 1 GeV uncertainty at Run I and Run II.
  - Interpretation of top mass measurements is complicated by non-perturbative effects \( \sim 0.5-1 \, GeV \).
  - Important to measure top mass in well-defined mass schemes and with independent methods.
Top Mass Extraction from Production Observables

### Total and Differential ttbar Cross Sections

#### ATLAS+CMS Preliminary

<table>
<thead>
<tr>
<th>m_{top} from cross-section measurements</th>
<th>Sep 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_{top} ± tot (stat ± syst ± theo)</td>
<td>Ref.</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>(\sigma(t\bar{t})) inclusive, NNLO+NNLL</td>
<td></td>
</tr>
<tr>
<td>ATLAS, 7+8 TeV</td>
<td>172.9 ± 2.5 (\pm 2.6)</td>
</tr>
<tr>
<td>CMS, 7+8 TeV</td>
<td>173.8 ± 1.7 (\pm 1.8)</td>
</tr>
<tr>
<td>CMS, 13 TeV</td>
<td>169.9 ± 1.9 (\pm 2.1)</td>
</tr>
<tr>
<td>ATLAS, 13 TeV</td>
<td>173.1 ± 2.0 (\pm 2.1)</td>
</tr>
<tr>
<td>(\sigma(t\bar{t}+1j)) differential, NLO</td>
<td></td>
</tr>
<tr>
<td>ATLAS, 7 TeV</td>
<td>173.7 ± 2.3 (\pm 2.1) ((1.5 \pm 1.4 \pm 1.0))</td>
</tr>
<tr>
<td>CMS, 8 TeV</td>
<td>169.9 ± 3.7 (\pm 3.1) ((1.1 \pm 2.5 \pm 1.6))</td>
</tr>
<tr>
<td>ATLAS, 8 TeV</td>
<td>171.1 ± 1.2 (\pm 1.0) ((0.4 \pm 0.9 \pm 0.3))</td>
</tr>
<tr>
<td>(\sigma(t\bar{t})) n-differential, NLO</td>
<td></td>
</tr>
<tr>
<td>ATLAS, n=1, 8 TeV</td>
<td>173.2 ± 1.6 (\pm 0.9 \pm 0.8 \pm 1.2)</td>
</tr>
<tr>
<td>CMS, n=3, 13 TeV</td>
<td>170.9 ± 0.8 (\pm 0.9 \pm 1.0 \pm 0.3)</td>
</tr>
</tbody>
</table>

#### Note

- Measurements dominated by tt threshold production.
- Uncertainties due to PDFs and higher order corrections are important.

More details in next slides

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**ATLAS+CMS Preliminary**

LHC\(\text{top}\)WG

**m_{top}** from cross-section measurements

**m_{top} ± tot (stat ± syst ± theo)**

**Ref.**

- Measurements dominated by tt threshold production.
- Uncertainties due to PDFs and higher order corrections are important.

More details in next slides
Top Mass from Multi-Differential Cross Sections

Triple-differential normalised cross sections

\[ N_{jet}^{0,1+}, M(t\bar{t}), y(t\bar{t}) \]

Simultaneous fit of PDF, \( \alpha_s \) and \( m_t \) at NLO

\[ + \text{ HERA DIS data} \]

\[ \text{CMS} \]

Most (but not the only) sensitive region: \( M_{t\bar{t}} \sim 2m_t \)

\[ m_t^{\text{pole}} = 170.5 \pm 0.8 \text{ GeV} \]

\[ \alpha_s = 0.1135^{+0.0021}_{-0.0017} \]

\[ \text{Precision} = 0.5\% \]

Dominated by experimental and modelling uncertainties.

(possible effects from Coulomb and soft-gluon resummation near \( 2m_t \) are not studied in detail - effects known only with large uncertainty in cross section.)
Top Mass from differential distributions

• Extract top mass using $t\bar{t}+1$ jet events in lepton+jets channel.

• Parton level distribution is compared with QCD NLO+PS calculations to extract MSbar and pole mass.

$$R(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{jet}}} \frac{d\sigma_{t\bar{t}+1\text{jet}}}{d\rho_s}$$

$$\rho_s = \frac{2m_0}{m_{t\bar{t}+1\text{jet}}}, \ m_0 = 170 \ \text{GeV}$$

Reconstruction: b-jets + W boson candidates + the additional jet.

$m_t^p(m_t) = 162.9 \pm 0.5(stat) \pm 1.0(syst)^{+2.1}_{-1.2}(theo) \ \text{GeV}$

$m_t^{pole} = 171.1 \pm 0.4(stat) \pm 0.9(syst)^{+0.7}_{-0.3}(theo) \ \text{GeV}$

$m_t(m_t)$ translated to $m_t^{pole}$ is in good agreement w/ the extracted value.

$ightarrow m_t(m_t)$ has larger theory uncertainty due to the larger dependence on renorm. & fact. scales at $\sim 2m_t$. 

Scales, PDFs, parton shower, color reconnection, and jet energy scale are the dominant uncertainties.
The first experimental investigation of the running of the top mass

- Running mass $m_t(\mu)$ extracted at one-loop precision as a function of $m(tt)$ by comparing NLO calculations to the measurement corrected to the parton level in the $e\mu$-channel.
- The extracted running of $m_t$ up to $\sim 1$ TeV is in agreement with the scale dependence predicted by the renormalization group equation (RGE) within $1.1\sigma$.
- No-running scenario excluded at above 95% CL.

- Precision limited by integrated luminosity, lepton id, JES/JER and signal modelling.
- For improving the measurement, NNLO calculations in the MSbar scheme needed to allow extraction of the running at two-loop precision.
Top quark mass from boosted top-jet mass in lepton+jets channel

- XConé jet mass = invariant mass of all particle-flow candidates in the 3 XConé subjets.

- 2 large-radius XConé jets ($p_T > 400$ GeV)
- with 3 XConé subjets ($p_T > 30$ GeV)

- $m_t = 172.6 \pm 0.4\,(stat) \pm 1.6\,(exp) \pm 1.5\,(model) \pm 1.0\,(theo)$ GeV

- precision~1.4%

- Experimental: JES, JER, XConé jet energy correction, …
- Model: FSR, color reconnection, UE tune, top mass value, …

- $->$ Average energy scale ~$480$ GeV $>>$ the scale in other $m_t$ measurements.
Top Quark Mass using soft muon tags

- $e/\mu + \geq 4$ jets

- $\geq 2$ b-tagged jets: One with displaced vertex, One with soft muon tag

- Simultaneous template fit to $m_{\ell\mu}$ distributions from same-sign and opposite-sign samples

<table>
<thead>
<tr>
<th>Processes involving a $\mu$ from a $t$ or $\bar{t}$</th>
<th>OS [%]</th>
<th>SS [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \rightarrow B \rightarrow \mu$</td>
<td>73.6</td>
<td>51.2</td>
</tr>
<tr>
<td>$t \rightarrow B \rightarrow D \rightarrow \mu$</td>
<td>16.7</td>
<td>44.2</td>
</tr>
<tr>
<td>$t \rightarrow B \rightarrow \tau \rightarrow \mu$</td>
<td>2.0</td>
<td>1.3</td>
</tr>
<tr>
<td>$t \rightarrow B \rightarrow D \rightarrow \tau \rightarrow \mu$</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Processes involving a $\mu$ not from a $t$ or $\bar{t}$</th>
<th>OS [%]</th>
<th>SS [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow \mu$</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>$D \rightarrow \mu$</td>
<td>5.8</td>
<td>1.4</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>0.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Top Quark Mass using soft muon tags

- The fragmentation function in PYTHIA8 is improved by determining the $r_b$ parameter based in the b-quark fragmentation measured in e+e- data and extrapolated to pp collisions.
- $b$ and $c$ hadron decay branching ratios are adjusted to match those of the previous measurements (DELPHI, CLEO, ALEPH).

$$f(z) = \frac{1}{z^{1+r_b b m_q^2}}(1-z)^a exp\left(-\frac{b m_T^2}{z}\right)$$

fit to LEP and SLD data is performed using

$$x_B = 2p_B p_Z / m_Z^2$$

using $e^+ e^- \rightarrow Z \rightarrow b\bar{b}$ events.

$$\rightarrow r_b = 1.05 \pm 0.02$$

<table>
<thead>
<tr>
<th>Hadron</th>
<th>PDG</th>
<th>POWHEG+PYTHIA8</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \rightarrow \mu$</td>
<td>$0.1095^{+0.0029}_{-0.0025}$</td>
<td>0.106</td>
<td>1.032</td>
</tr>
<tr>
<td>$b \rightarrow \tau$</td>
<td>$0.0042 \pm 0.0004$</td>
<td>0.0064</td>
<td>0.661</td>
</tr>
<tr>
<td>$b \rightarrow c \rightarrow \mu$</td>
<td>$0.0802 \pm 0.0019$</td>
<td>0.085</td>
<td>0.946</td>
</tr>
<tr>
<td>$b \rightarrow \bar{c} \rightarrow \mu$</td>
<td>$0.016^{+0.003}_{-0.003}$</td>
<td>0.018</td>
<td>0.888</td>
</tr>
<tr>
<td>$c \rightarrow \mu$</td>
<td>$0.082 \pm 0.005$</td>
<td>0.084</td>
<td>0.976</td>
</tr>
</tbody>
</table>

$m_t = 174.48 \pm 0.40\,(stat) \pm 0.67\,(sys) \, GeV$

- precision~0.45%
- sensitive to different modelling effects which is also useful for combinations:
  - HF-hadron decay modeling: 0.39 GeV
  - Pile-up: 0.20 GeV
  - b-quark fragmentation: 0.19 GeV
Top Quark Width

- Direct measurement using a profile-likelihood template fit to m(l,b) distribution in the dilepton channel using full run2 data.

<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>Measured</td>
<td>Measured</td>
<td>Measured</td>
</tr>
<tr>
<td>2.01</td>
<td>1.94</td>
<td>1.90</td>
</tr>
<tr>
<td>0.53</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td>0.50</td>
<td>0.49</td>
<td>0.48</td>
</tr>
<tr>
<td>Theory</td>
<td>Theory</td>
<td>Theory</td>
</tr>
<tr>
<td>1.306</td>
<td>1.322</td>
<td>1.333</td>
</tr>
<tr>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

Dominant uncertainties: jet reconstruction, signal and bkg. modeling, MC stats., flavor tagging, ...

Agreement with NNLO predictions.

Gao et al. PRL 110 (2013) 042001
Yukawa Coupling

- Weak corrections ($\alpha_s^2 \alpha$) from vector or scalar bosons modify differential distributions at $\sim 2m_t$ if Yukawa coupling ($g_t$) is larger than 1.

\[ Y_t = \frac{g_t}{g_t^{SM}} \]

Yukawa coupling strength \[ g_f = \frac{\sqrt{2}m_f}{v} \]

Weak corrections as a function of $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ at various Yukawa parameter values

\[ Y_t = \frac{g_t(HATHOR)}{g_t(SM)} \]

to all ttbar samples so that their kinematics remain dependent on $Y_t$. 
Yukawa Coupling

Measurement in the dilepton channel: 2 opposite-sign leptons and 2 b-jets. Partial reconstruction results in a more sensitive measurement than using $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$.

\[
M_{b\ell} = M(b + \bar{b} + \ell + \bar{\ell})
\]

\[
|\Delta y|_{b\ell} = |y(b + \ell) - y(\bar{b} + \ell)|
\]

Requires each jet to be matched to the correct lepton through a kinematic fit.

CMS Higgs combination: $Y_t = 0.98 \pm 0.14$

but it is model dependent: assumes couplings of Higgs to particles other than top

A bit more sensitive than the only CMS result that exclusively depend on the top Yukawa coupling from 4top production cross section:

$Y_t < 1.7$ @95% CL

Dominant unc.: EW correction, PS, ME scales, JES flavor

full run2 data
CKM Matrix Elements from single top quark t-channel

• Processes directly sensitive to $V_{tb}$, $V_{td}$, and $V_{ts}$ matrix elements in production and decay.

• The yields of different signals extracted through a simultaneous fit to data in different event categories

• CKM matrix elements inferred from the signal strengths $\frac{\sigma_{t-chan} \times BR(meas)}{\sigma_{t-chan} \times BR(theo)}$

<table>
<thead>
<tr>
<th>Category</th>
<th>Enriched in</th>
<th>Cross section $\times$ branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2j1t</td>
<td>$ST_{b,b}$</td>
<td>$\sigma_{t-ch,b} B(t \rightarrow Wb)$</td>
</tr>
<tr>
<td>3j1t</td>
<td>$ST_{b,q}, ST_{q,b}$</td>
<td>$\sigma_{t-ch,b} B(t \rightarrow Wq), \sigma_{t-ch,q} B(t \rightarrow Wb)$</td>
</tr>
<tr>
<td>3j2t</td>
<td>$ST_{b,b}$</td>
<td>$\sigma_{t-ch,b} B(t \rightarrow Wb)$</td>
</tr>
</tbody>
</table>

Most discriminating vars.

- 2j1t: $|\eta'|$, $m(l,b)$
- 3j1t: MET, MVA b tagger
- 3j2t: $|\eta'|$, $m(l,j')$
CKM Matrix Elements from single top quark t-channel

• Signal strength from the fit \( \mu_b = 0.99 \pm 0.12 \)

• Assuming CKM unitarity of SM
  \[ |V_{tb}| > 0.970 \text{ @ 95\% C.L.} \]
  \[ |V_{td}|^2 + |V_{ts}|^2 < 0.057 \text{ @ 95\% C.L.} \]

• BSM1: Assuming additional quark families with \( m > m_t \)
  • No CKM unitarity but SM top quark decay channels.
  • Assume partial width of each top decay varies b/c of a modified CKM element.
    \[ |V_{tb}| = 0.988 \pm 0.051 \]
    \[ |V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06 \]

• BSM2: top quark width left unconstrained under the assumption that contributions to the total width from the mixing of the three families are negligible.
  \[ |V_{tb}| = 0.988 \pm 0.024 \]
  \[ |V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06 \]
  \[ \Gamma_t^{obs}/\Gamma_t = 0.99 \pm 0.42 \]

=> The first direct, model-independent measurements of the CKM matrix elements for the third-generation quarks, and provide the best determination of these fundamental SM parameters via single top quark measurements.
First Forward-Backward Asymmetry Measurement at the LHC

- Asymmetry due to NLO interference terms between qqbar diagrams $\rightarrow$ leads to a slightly positive asymmetry.

$$c^* = \cos \theta^*$$

$$A_{FB} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}$$

(analogous to Drell-Yan $A_{FB}$)

- Lepton+jets final states with « resolved » and « boosted » topologies selected and reconstructed through a kinematic fit.
- The parameters extracted from template-likelihood fits to the data based in differential models of extensions of LO tree-level cross sections for qqbar and gg initial states.

Multi-dimensional fit to $c^*$, $m_{t\bar{t}}$, $x_F = 2p_L/\sqrt{s}$

$$\hat{\mu}_t = -0.024^{+0.013}_{-0.009} (\text{stat}) + 0.016$$

$$|\hat{d}_t| < 0.03 \ @ 95\% \ C.L.$$
Evidence of Charge Asymmetry

- lepton+jets combining resolved and boosted topologies using full run II data.

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

\[ A_C = 0.0060 \pm 0.0015 \] differs 4σ from zero

\[ A_C^{N\text{NLO}} = 0.0064^{+0.0005}_{-0.0006} \]

PDF effect: On average, \( P(\text{valence quark}) > P(\text{sea anti-quark}) \)

\[ \rightarrow \] top quark rapidity broader than the anti-quark rapidity

Inclusive and differential measurements consistent with QCD NNLO + EWK NLO.

Limits on linear combination of Wilson coefficients of dim-6 EFT operators.
Spin Correlations

\begin{equation}
|M(q\bar{q}/gg \rightarrow t\bar{t} \rightarrow \ell^+\nu\ell^-\bar{\nu})|^2 \propto \rho \overline{R}\rho
\end{equation}

\[R \propto \tilde{A}1 \otimes 1 + \tilde{B}_i^+ \sigma^i \otimes 1 + \tilde{B}_i^- 1 \otimes \sigma^i + \tilde{C}_{ij} \sigma^i \otimes \sigma^j\]

- \(R = \) spin density matrix parametrized by 15 coefficients that fully characterise spin dependence of top quark pair production.
- Coefficients determined by 1D angular distributions unfolded to parton level in dilepton events.
- Lab frame asymmetries are also measured (not directly relate to the coefficients).

- All distributions and extracted parameters agree with the SM.
- No indication of new physics through anomalous couplings.
Spin Correlations

\texttt{arXiv:1903.07570}

- $\Delta \phi$, $\Delta \eta$, $\Delta \phi$ vs $m(tt)$ in the $e\mu$ channel.

- \textit{fraction of SM-like spin correlation} extracted using hypothesis templates that are fitted to the parton-level distributions using spin-correlated and -uncorrelated hypotheses

\[ f_{SM} = \frac{N_{\text{spin}}}{N_{\text{spin}} + N_{\text{nospin}}}, \quad f_{SM} = 1 \]

\[ f_{SM} = 1.249 \pm 0.024 \text{(stat)} \pm 0.061 \text{(sys)}^{+0.067}_{-0.090} \text{(theo)} \]

dom. uncertainties: ISR/FSR, scale settings

2.2$\sigma$ difference between POWHEG + PYTHIA8 prediction and data.

Alternative differential predictions with NLO QCD+Weak couplings / NNLO QCD using an expansion of the normalised diff. distribution in powers of the couplings.

\[ f_{SM} = 1.03 \pm 0.07 \text{(stat)}^{+0.10}_{-0.14} \text{(scale)} \]

(extracted using NLO (QCD + Weak expanded, $\mu=m_t$) template.

$\rightarrow$ consistent w/ Powheg+Pythia8, SM, CMS.

$\rightarrow$ NNLO expanded less consistent w/ data.

And no top squarks in $m=170$-230 GeV from $\tilde{t}_1\tilde{t}_1$ production using $\Delta \phi$ in bins of $\Delta \eta$. 
Spin Correlation

Very good agreement between ATLAS and CMS data and between ATLAS and CMS main MC predictions.

Good agreement of data with MG5_aMC@NLO with FXFX merging (2 additional jets from the matrix element).

Fair agreement with the NNLO calculation.

Paves the way for first 13 TeV ATLAS+CMS combination from TOPLHCWG.

W Boson Polarization

- W helicity fractions ($F_X$) sensitive to the Wtb (V-A) vertex structure.
- New ATLAS+CMS 8 TeV ttbar and single top combination with 20.2 and 19.7 fb$^{-1}$.
- BLUE (Best Linear Unbiased Estimate) method used for combination.
- Correlation assumptions studied in detail; drastic variation of correlation assumptions result in deviations covered by uncertainties of the combined measurement.
- Results dominated by statistical, background, radiation/scales, and MC statistics uncertainties.

\[
\frac{d\sigma}{d\cos\theta^*} \approx \frac{3}{8} (1 - \cos\theta^*)^2 F_L + \frac{3}{4} (\sin\theta^*)^2 F_0 + \frac{3}{8} (1 + \cos\theta^*)^2 F_R
\]

\( F_L \sim 0.3 \) (Left-handed (negative helicity))
\( F_0 \sim 0.7 \) (longitudinal (zero helicity))
\( F_R \sim 0 \) (Right-handed (positive helicity))

- Results in agreement with NNLO QCD.
- Precision \( \sim 2 \% \) in $F_0$ and $3.5\%$ for $F_L$.
- Improvement in precision of $25\%$ for $F_0$ and $29\%$ for $F_L$ wrt the most precise single measurement.
- Limits on anomalous couplings and Wilson coefficients.
Conclusions

- New Run II LHC top mass and properties results with increased precision (up to \textit{NNLO+NLO EWK level}), new methods, new observables.

  - Top quark mass
    - Combinations \textasciitilde 500 MeV uncertainty.
    - From (multi-) differential cross-section measurements.
    - With an average energy scale of \textasciitilde 480 GeV from boosted top-jet mass.
    - From soft-muon tags.
    - All the top mass definitions tested with the LHC data look consistent.
    - Running of the top quark mass tested up to 1 TeV.

  - Top quark width using full run II data.
  - Yukawa coupling with full run II data.
  - First \textit{ttbar} forward-backward asymmetry measurement at the LHC.
  - First evidence of \textit{ttbar} charge asymmetry with full run II data.
  - Precise spin correlation measurements and comparisons between ATLAS and CMS.
  - ATLAS+CMS \textit{W} boson polarisation combinations at 8 TeV.
  - Limits on new physics from many of the measurements.

More results to come w/ full Run 2 data Run 3 \textasciitilde 2x more \textit{ttbar} events HL-LHC \textasciitilde 20x more \textit{ttbar} events

More precise measurements \textasciitilde better understanding of some top properties and increased reach for new physics through direct searches and effective field theory.
Additional Slides
The first experimental investigation of the running of the top quark mass

Input distributions to the fit in the different event categories. The number of jets, the number of b-tagged jets, the number of events, and the \( p_T \) of the softest jet are denoted with \( N_{\text{jets}} \), \( N_b \), \( N_{\text{events}} \), and “jet \( p_T^{\min} \)”, respectively, while the category corresponding to the bin \( k \) in \( m_{tb}^{\text{reco}} \) is indicated with “\( m_{tb}^{\text{reco}} k \).”

<table>
<thead>
<tr>
<th>Bin</th>
<th>( m_{tb} ) [GeV]</th>
<th>Fraction [%]</th>
<th>( \mu_k ) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(&lt;420)</td>
<td>30</td>
<td>384</td>
</tr>
<tr>
<td>2</td>
<td>420–550</td>
<td>39</td>
<td>476</td>
</tr>
<tr>
<td>3</td>
<td>550–810</td>
<td>24</td>
<td>644</td>
</tr>
<tr>
<td>4</td>
<td>( &gt;810)</td>
<td>7</td>
<td>1024</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( N_{\text{jets}} &lt; 2 )</th>
<th>( N_{\text{events}} )</th>
<th>n.a.</th>
<th>( N_{\text{events}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{tb}^{\text{reco}} ) 1</td>
<td>( m_{tb}^{\min} )</td>
<td>jet ( p_T^{\min} )</td>
<td>( N_{\text{events}} )</td>
</tr>
<tr>
<td>( m_{tb}^{\text{reco}} ) 2</td>
<td>( m_{tb}^{\min} )</td>
<td>jet ( p_T^{\min} )</td>
<td>( N_{\text{events}} )</td>
</tr>
<tr>
<td>( m_{tb}^{\text{reco}} ) 3</td>
<td>( m_{tb}^{\min} )</td>
<td>jet ( p_T^{\min} )</td>
<td>( N_{\text{events}} )</td>
</tr>
<tr>
<td>( m_{tb}^{\text{reco}} ) 4</td>
<td>( N_{\text{events}} )</td>
<td>( N_{\text{events}} )</td>
<td>( N_{\text{events}} )</td>
</tr>
</tbody>
</table>
CKM Matrix Elements from single top quark t-channel

<table>
<thead>
<tr>
<th>Category</th>
<th>Enriched in</th>
<th>Cross section $\times$ branching fraction</th>
<th>Feynman diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>2j1t</td>
<td>$ST_{b,b}$</td>
<td>$\sigma_{t-ch,b}B(t \rightarrow Wb)$</td>
<td>$1a$</td>
</tr>
<tr>
<td>3j1t</td>
<td>$ST_{b,q}$, $ST_{q,b}$</td>
<td>$\sigma_{t-ch,b}B(t \rightarrow Wq)$, $\sigma_{t-ch,q}B(t \rightarrow Wb)$</td>
<td>$1b, 1c, 1d$</td>
</tr>
<tr>
<td>3j2t</td>
<td>$ST_{b,b}$</td>
<td>$\sigma_{t-ch,b}B(t \rightarrow Wb)$</td>
<td>$1a$</td>
</tr>
</tbody>
</table>
CMS Preliminary

**pp combination**

D0 (9.7 fb⁻¹)
PRD 92 (2015) 052007, $\sqrt{s}=1.96$ TeV

CDF (9.1 fb⁻¹)
PRD 93 (2016) 112005, $\sqrt{s}=1.96$ TeV

CDF+D0
PRL 120 (2018) 042001, $\sqrt{s}=1.96$ TeV

NNLO QCD (+ NLO EW)
Czakon et al. PRL 115 (2015) 052001, $\sqrt{s}=1.96$ TeV

**pp lepton+jets**

CMS (35.9 fb⁻¹)
TOP-15-018 (2019), $\sqrt{s}=13$ TeV

POWHEGv2 NLO
$q\bar{q}$, event counting, $\sqrt{s}=13$ TeV

**top quark forward-backward asymmetry (parton-level)**

$A_{FB}$ ± (stat.) ± (syst.)

D0 (9.7 fb⁻¹)
$0.118 \pm 0.025 \pm 0.013$

CDF (9.1 fb⁻¹)
$0.160 \pm 0.045$

CDF+D0
$0.128 \pm 0.021 \pm 0.014$

NNLO QCD (+ NLO EW)
$0.095 \pm 0.007$

CMS (35.9 fb⁻¹)
$0.048^{+0.088}_{-0.084} \pm 0.028$

POWHEGv2 NLO
$0.0512 \pm 0.0004$
W Boson Polarization

Limits on tWb anomalous couplings

<table>
<thead>
<tr>
<th>Coupling</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS+CMS combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re(V_R)</td>
<td>[-0.17, 0.25]</td>
<td>[-0.12, 0.16]</td>
<td>[-0.11, 0.16]</td>
</tr>
<tr>
<td>Re(g_L)</td>
<td>[-0.11, 0.08]</td>
<td>[-0.09, 0.06]</td>
<td>[-0.08, 0.05]</td>
</tr>
<tr>
<td>Re(g_R)</td>
<td>[-0.03, 0.06]</td>
<td>[-0.06, 0.01]</td>
<td>[-0.04, 0.02]</td>
</tr>
</tbody>
</table>

Limits on Wilson coefficients

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS+CMS combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_{phi}</td>
<td>[-5.64, 7.68]</td>
<td>[-3.84, 4.92]</td>
<td>[-3.48, 5.16]</td>
</tr>
<tr>
<td>C_{bW}</td>
<td>[-1.30, 0.96]</td>
<td>[-1.06, 0.72]</td>
<td>[-0.96, 0.67]</td>
</tr>
<tr>
<td>C_{tW}</td>
<td>[-0.34, 0.67]</td>
<td>[-0.62, 0.19]</td>
<td>[-0.48, 0.29]</td>
</tr>
</tbody>
</table>