Review of Top Quark Properties at LHC and Tevatron

J. Cuevas
U. Oviedo (Spain)
on behalf of the CMS, ATLAS, DZero and CDF collaborations

Heavy Quarks and Leptons,
22 – 27th may 2016, Blacksburg, Virginia
- Top quark properties
  - spin
  - Charge asymmetry
  - FCNC
  - Associated production
- Results on 7, 8 and 13 TeV data, and Tevatron
- Top mass
  - Direct and indirect measurements
A particle with unique characteristics

- Special because of its enormous mass: heaviest known particle
  - Still a point-like particle in our understanding
  - The top and the Higgs are “strongly” coupled \( y_t \approx 1 \quad m_t = y_t v / \sqrt{2} \)
  - The top mass dramatically affects the stability of the Higgs mass
    - If we consider the SM valid up to a certain scale \( \Lambda \)

\[
m_H^2 = m_{H0}^2 - \frac{3}{8\pi^2} y_t \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2
\]

\[
(125 \text{ GeV})^2 = m_{H0}^2 + \left[ -(2 \text{ TeV})^2 + (700 \text{ GeV})^2 + (500 \text{ GeV})^2 \right] \left( \frac{\Lambda}{10 \text{ TeV}} \right)^2
\]

- It is the only quark that does not hadronise
  - \( \tau(\text{had}) \sim h / \Lambda_{\text{QCD}} \sim 2 \times 10^{-24} \text{ s} \)
  - \( \tau(\text{top}) \sim h / \Gamma_{\text{top}} \sim 5 \times 10^{-25} \text{ s} \)
  - Compare with \( \tau(b) \sim 10^{-12} \text{ s} \)
    - Decays before forming a “dressed” top quarks
    - No bound tq states, its spin properties are directly passed to its decay products
    - QCD, Flavor and EWK physics at their best!
Top quark spin correlations

- Top quarks decay before spins de-correlate → measure
- Gluon helicities → top spin correlation → decay product. Max in low $M_{tt}$ regime
- Lepton final state → $\sim 100\%$ transmission (for quark, depends on flavor), 2l channel: access with azimuthal angle between leptons in lab frame or in top rest frame vs a direction basis (helicity,...) ...(direct).


$\mathbf{CMS}$, Phys. Rev. D 93, 052007 (2016)

$f_{SM} = 1.20 \pm 0.05^{(\text{Stat})} \pm 0.13^{(\text{Syst})}$

$19.5 \text{fb}^{-1}$ (8 TeV)
Spin Correlation: direct measurement

- 2 OS \( \ell, \geq 2 \) high \( p_T \) jet, \( \geq 1 \) b, large \( E_{\text{miss}} \)
- Inclusive distrib. unfolded (bayesian) at parton level
- Direct extraction of \( C = - A \alpha_1 \alpha_2 \)
- Dominated by: unfolding uncertainties, theoretical modeling and jet reconstruction

\[ \frac{1}{\sigma} \frac{d^2 N}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} \left( 1 + B_1 \cos \theta_1 + B_2 \cos \theta_2 - C_{\text{helicity}} \cos \theta_1 \cos \theta_2 \right) \]
Spin Correlation: direct measurement


- Dilepton channel, reconstruction of $tt$ final state.
- Unfolding all angular distributions, get asymmetries: $A_{\Delta\varphi}, A_h, A_{\cos\varphi}, A_P$, they provide direct measurement of spin correlation strength and polarization.

$A_h = -0.069 \pm 0.013\,\text{(Stat)} \pm 0.016\,\text{(Syst)}$

$\rightarrow f_{\text{SM}} = 0.87 \pm 0.17\,\text{(Stat)} \pm 0.21\,\text{(Syst)} \pm 0.04\,\text{(theo)}$

$A_P = -0.011 \pm 0.007\,\text{(Stat)} \pm 0.028\,\text{(Syst)}$

$P_{\text{CPC}} = (-2.2 \pm 5.8\,\%)$

$P_{\text{CPV}} = (-0.0 \pm 1.6\,\%)$

Search for top chromo-magnetic couplings

Uncertainties dominated by top $p_T$ modeling and JES
Spin correlation $1l+j$ 8TeV: ME method

arXiv 1511.06170, accepted PLB

- $\mu +$jets channel with 4,5 jets using kinematic fitter
- LO Matrix Element Method for event likelihoods (MadWeight) under SM or uncorrelated
  - Most precise in lepton+jets

$f_{SM} = 0.72 \pm 0.08 \text{(Stat.)} -0.13+0.15 \text{(Syst.)}$
Spin Correlations and polarization, Tevatron

Spin correlations are described by the correlation function:

\[ O_{ab} = \frac{4(S_t \cdot \hat{a})(S_t \cdot \hat{b})}{\sigma(\uparrow \uparrow) + \sigma(\downarrow \downarrow) - \sigma(\uparrow \downarrow) - \sigma(\downarrow \uparrow)} \]

where \( \sigma(\uparrow \uparrow) \), \( \sigma(\downarrow \downarrow) \), \( \sigma(\uparrow \downarrow) \), and \( \sigma(\downarrow \uparrow) \) are cross sections for different helicity states.

- Fit the data allowing the total cross section and the fraction of “With Spin Correlations” to Float, arXiv:1512.08818
- \( O_{\text{off}} = 0.89^{+0.16}_{-0.15} \) (stat)\( +0.15 \) (syst)
- Exclude the Uncorrelated scenario at 4.2\( \sigma \) level
- Assuming no BSM contributions, \( f_{gg} = 0.08^{+0.12}_{-0.11} \) (stat) \( +0.11 \) (sys) (NLO prediction 0.135)

Data are consistent with zero polarization, and with the predicted SM values.

First measurement of polarization along the transverse axis at a hadron collider.

Polarization: DZero 6471 (2015)

Tops are almost unpolarized at the Tevatron Transverse polarization allowed in strong interactions, and BSM can make them bigger.
Top quark spin correlations

\[ f_{SM} = \frac{N_{SM}}{N_{SM} + N_{Uncor}} \]

- **ATLAS**:
  - \( \Delta \phi 2 \ell \): 1.20 ± 0.14 (8 TeV)
  - \( 1.19 \pm 0.20 \) (7 TeV)
  - ME 2\( \ell \): 0.87 ± 0.18 (7 TeV)
  - \( \Delta \phi \ell + j \): 1.12 ± 0.25 (7 TeV)

- **CMS**
  - \( \Delta \phi 2 \ell \): 1.16 ± 0.15 (8 TeV)
  - D 2\( \ell \): 0.90 ± 0.16 (8 TeV)
  - ME \( \ell + j \): 0.72 −0.13+0.15 (8 TeV)

- **Consistent with SM**, already systematic limited for some of the measurements
Charge/FB asymmetry

- Top quarks pair production at NLO give non zero charge asymmetry from interferences between q-qbar initiated diagrams, gg interaction symmetric.

- Measurement of $A_{FB}$ at Tevatron and $A_{C}$ at LHC are complementary to evaluate new physics models:
  - Could be enhanced if new physics present like with $W'$, $G$, $\omega$, $\varphi$, $\Omega$.
- LHC has symmetric initial state (pp):
  - Quarks are mostly valence and anti--quarks are sea quarks
  - PDF’s are not symmetric, quarks carry more momentum than anti-quarks
  - Rapidity distribution of tops is broader
- Evaluate asymmetry based on fully reconstructed top quarks or leptons in dilepton channel
- Differential distributions ($m_{tt}$, $y_{tt}$, $p_{T_{tt}}$) sensitive to BSM physics

\[
A_{FB}^{ti} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}
\]

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

\[
\Delta y_{t\bar{t}} = y_{t} - y_{\bar{t}}
\]

\[
\Delta |y| = |y_{t}| - |y_{\bar{t}}|
\]
**A_{FB}** Measurements in $t\bar{t}$ at the Tevatron

Hot topic since the observation of a larger-than-expected asymmetry from CDF in Lep+Jets: $A_{FB} = 0.164 \pm 0.047$ and of the asymmetry as a function of $\Delta y$ and as a function of $M_{tt}$: $\text{Slope}_{\Delta y} = 0.253 \pm 0.062$ (PRD 87, 092002 (2012))

$A_{FB} \ (\text{NNLO SM}) = 0.095 \pm 0.007$ (Czakon, Fiedler & Mitov, PRL 115, 052001 (2015))

$\text{Slope}_{\Delta y} \ (\text{NNLO}) = 0.114^{+0.006}_{-0.012}$ (Czakon, Fiedler, Heimes & Mitov, arXiv:1601.05375)

**New $A_{FB}$ Results from CDF** arXiv: 1602.09015

Results with dilepton data:

$A_{FB} = 0.12 \pm 0.11 \text{(stat)} \pm 0.07 \text{(syst)} = 0.12 \pm 0.13$

Combined with CDF result in lepton+jets

$A_{FB} = 0.160 \pm 0.045$

Consistent with SM and DZero within 1.5σ

$- A_{FB} = 0.118 \pm 0.028$ DZero, PRD 92 052007 (2015)
Charge asymmetry: dilepton channel

- Asymmetry defined with decay leptons and reconstructed tops
- Kinematic reconstruction of the top anti-top quark four momenta.
  - Inclusive measurements corrected to parton level in the full phase space and fiducial regions.
  - Differential measurement in $m(tt)$, $|y(tt)|$, $p_T(tt)$

**ATLAS:**

- 7 TeV: JHEP05(2015)061
- 8 TeV [arXiv:1604.05538]

\[ A_C = [0.021 \pm 0.017 \text{ (stat+syst)}] \]
SM pred: (0.0123 ± 0.0005)

\[ A_{ll}^C = [0.024 \pm 0.03 \text{ (stat+syst)}] \]
SM pred: (0.0070 ± 0.0003)

\[ A_C = [0.021 \pm 0.016 \text{ (stat+syst)}] \]
SM pred: (0.0111 ± 0.0004)

\[ A_{ll}^C = [0.008 \pm 0.006 \text{ (stat+syst)}] \]
SM pred: (0.0064 ± 0.0003)

Comparison of the inclusive $A_C^{\ell \ell}$ and $A_{ll}^C$ measurement values in the full phase space to the SM NLO QCD+EW prediction and a benchmark BSM model with a heavy octet with mass with mass beyond the reach of the LHC.
Charge asymmetry: l+jets channel

- **Inclusive** and **differential** measurements unfolded at parton level, using a selection based on: 1 high $p_T$ tight $\ell$, large $E_t^{\text{miss}}$ and $m_T^W$. Full event reconstruction with kinematic fit.

  - 3 signal regions: 0, 1, 2 b-tag, Likelihood fit to reconstruct $tt$, Full Bayesian unfolding, Differential in $m(tt)$, $\beta_z(tt)$, $p_T(tt)$

- and Phys. Lett. B756 (2016) 52 in the boosted regime: $m(tt) > 0.75$ TeV
  - Leptonic decay resolved, Hadronic decay reconstructed as large R jet (R=1.0) with substructure, full Bayesian unfolding, differential in $m(tt)$

\[
A_C = [0.9 \pm 0.5 \text{ (stat+syst)}] \%
\]

SM pred: $(1.11 \pm 0.04)\%$

\[
A_C = [4.2 \pm 3.2 \text{ (stat+syst)}] \%
\]

SM pred: $(1.6 \pm 0.04)\%$, for $m(tt) > 0.75$ TeV
Charge asymmetry: $l+$jets channel

- **CMS 8 TeV: Inclusive and differential measurements unfolded at parton level.**

  - **Alternative template method using shape of $\Delta|\eta|$ distribution**

  \[
  \gamma_{tt} = \tanh(\Delta|\eta|)_{tt},
  \]

  Observable needs to be bounded.

  Use symmetric and asymmetric version of MC template to fit:

  \[
  \rho^\pm(X) = (\rho(X) \pm \rho(-X))/2
  \]

  which has a smaller statistical uncertainty than unfolding, larger model dependence.

**CMS**

\[
A_C = [0.33 \pm 0.26 \text{ (stat)} \pm 0.33 \text{ (syst)}] \%
\]
Charge asymmetry: LHC summary

**G_μ**: A new color-octet neutral vector boson exchanged in the s channel

**W**: A charged color-singlet vector boson Z exchanged in the t channel in $d\bar{d} \rightarrow t\bar{t}$

**φ**: A color-singlet scalar doublet with hypercharge $-1/2$ exchanged in the t channel

**Ω_4**: A charge 4/3 scalar color sextet exchanged in the u channel

**ω_4**: A charge 4/3 scalar color triplet exchanged in the u channel

Good agreement between theory and experiment

Statistical and systematic uncertainties are comparable in size

Several differential distributions available + results in high $m(\tau\tau)$ region where asymmetry is enhanced
Associated production of top and bosons at 8 TeV

- Measure couplings to bosons

- Important background for BSM searches

- Analyses are performed in bins of the number of selected leptons (2,3,4)
- Different number of leptons → different admixture of ttW and ttZ processes

- Four signal regions: opposite sign (OS) dilepton, same sign (SS) dilepton, 3 and 4 lepton.
- Further split into categories depending on jet multiplicity, number of b-tagged jets and $E_T^{miss}$, optimised individually to increase sensitivity.
- Fit for ttZ and ttW simultaneously in a binned likelihood fit

**CMS: tt+W/Z [JHEP 01 (2016) 096]**
- Also performed in many channels with different numbers of leptons, jets and b tags
- Additionally: perform event reconstruction by matching jets and leptons to W/Z bosons and top
  - Combine into linear discriminant
  - Choose best permutation
- Combine resulting match scores with kinematic quantities in BDTs
Associated tt+W/Z production at 8 TeV established

- $\sigma(ttW) = 369^{+100}_{-91} \text{ fb} - 5.0 \text{ obs. (3.2 exp)}$
- $\sigma(ttZ) = 176^{+58}_{-52} \text{ fb} - 4.2 \text{ obs. (4.5 exp)}$

- $\sigma(ttW) = 382^{+117}_{-102} \text{ fb} - 4.8 \text{ obs. (3.2 exp)}$
- $\sigma(ttZ) = 242^{+65}_{-55} \text{ fb} - 6.0 \text{ obs. (5.7 exp)}$
### Associated $tt+W/Z$ production at 13 TeV

**ATLAS-CONF-2016-003**

- **$ttW$:** select events with (b) jets and 2 or 3 leptons (one same-sign pair)
- **$ttZ$:** select events with (b) jets and 3 or 4 leptons (one Z -> ll candidate)
- **Diboson backgrounds from control regions:**
  - WZ: 3 leptons, 1 Z candidate, 3 untagged jets / ZZ: 4l, 2 Z candidates, low MET

<table>
<thead>
<tr>
<th>Process</th>
<th>$t\bar{t}$ decay</th>
<th>Boson decay</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}W^\pm$</td>
<td>$(\mu^\pm \nu_b)(q\bar{q}_b)$</td>
<td>$\mu^\pm \nu$</td>
<td>SS dimuon Trilepton</td>
</tr>
<tr>
<td>$t\bar{t}Z$</td>
<td>$(\ell^\pm \nu_b)(q\bar{q}_b)$</td>
<td>$\ell^\pm \ell$</td>
<td>Trilepton Tetralepton</td>
</tr>
</tbody>
</table>

**13 TeV**

**ATLAS**  

- $\sigma(ttW)$: $1.38 \pm 0.70$ (stat) $\pm 0.33$ (syst) pb  
- $\sigma(ttZ)$: $0.92 \pm 0.30$ (stat) $\pm 0.11$ (syst) pb  

**aMCatNLO**

- $0.57 \pm 0.06$ pb  
- $0.76 \pm 0.08$ pb
Asociated $tt+Z$ production at 13 TeV  

**CMS-TOP-PAS-16-009**

- Select events with 3 or 4 leptons and at least 2 jets from full 13 TeV dataset
- Data-driven estimates for non-prompt leptons, control regions for $WZ$ and $ZZ$
- Binned likelihood fit to all categories, including nuisance parameters

\[
\sigma(ttZ) = 1.065^{+0.352}_{-0.313} \text{(stat.)}^{+0.168}_{-0.142} \text{(syst.)} \text{ pb} / \text{aMCatNLO } 0.57 \pm 0.06 \text{ pb}
\]
\( \tt\gamma (l+jets, 7\text{TeV}) \) [ATLAS PRD 91 (2015) 072007]

- Sensitive to \( t\gamma \) coupling and models with composite top quarks and excited top quark production (\( t^* \rightarrow t\gamma \))
- Selection: l+jets + high \( E_T \) photon (\( E_T > 20 \text{ GeV} \))
  - Suppress misidentified \( \gamma : |m_{e\gamma} - m_Z| > 5 \text{ GeV} \)
- Prompt photons estimated from template fit to photon isolation variable
- Largest systematic uncertainties: jet energy scale.
- Fiducial cross section:
  \[ \sigma_{tt+\gamma} \times \text{BR} = 63 \pm 8(\text{stat})^{+17}_{-13}(\text{syst}) \pm 1(\text{lumi}) \text{ fb}\]
per lepton
- Consistent with SM expectation (\( \sigma_{tt+\gamma} = 48 \pm 10 \text{ fb} \)).
- First observation of the process \( \sigma=5.3 \text{ obs.} \).
Flavour-changing neutral current

- **SM**: no FCNC at tree level (GIM suppression), BR $\sim O(10^{-12} - 10^{-17})$

- $t \to u/c + X, X = g, \gamma, Z$ and $H$

- **BSM**: 2HDM, MSSM, and others, enhanced couplings, BR as high as $10^{-5}$

- FCNC: $t \to qg$ at 8TeV, Not possible in $tt$ because of multijet bck.

- t-channel single top selection:
  - 1 lepton, 1 b-tagged jet and missing ET
  - Neural network to separate signal from SM background

<table>
<thead>
<tr>
<th>Process</th>
<th>SM</th>
<th>2HDM(FV)</th>
<th>2HDM(FC)</th>
<th>MSSM</th>
<th>RPV</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \to Zu$</td>
<td>$7 \times 10^{-17}$</td>
<td>$\leq 10^{-6}$</td>
<td>$\leq 10^{-10}$</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-6}$</td>
<td>$-$</td>
</tr>
<tr>
<td>$t \to Zc$</td>
<td>$1 \times 10^{-14}$</td>
<td>$\leq 10^{-12}$</td>
<td>$\leq 10^{-8}$</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-6}$</td>
<td>$\leq 10^{-5}$</td>
</tr>
<tr>
<td>$t \to gu$</td>
<td>$4 \times 10^{-14}$</td>
<td>$\leq 10^{-6}$</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-6}$</td>
<td>$\leq 10^{-5}$</td>
<td>$\leq 10^{-6}$</td>
</tr>
<tr>
<td>$t \to gc$</td>
<td>$5 \times 10^{-14}$</td>
<td>$\leq 10^{-4}$</td>
<td>$\leq 10^{-8}$</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-6}$</td>
<td>$\leq 10^{-10}$</td>
</tr>
<tr>
<td>$t \to \gamma u$</td>
<td>$4 \times 10^{-16}$</td>
<td>$\leq 10^{-12}$</td>
<td>$\leq 10^{-8}$</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-6}$</td>
<td>$-$</td>
</tr>
<tr>
<td>$t \to \gamma c$</td>
<td>$5 \times 10^{-14}$</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-9}$</td>
<td>$\leq 10^{-8}$</td>
<td>$\leq 10^{-9}$</td>
<td>$\leq 10^{-9}$</td>
</tr>
<tr>
<td>$t \to hu$</td>
<td>$2 \times 10^{-17}$</td>
<td>$6 \times 10^{-6}$</td>
<td>$\leq 10^{-12}$</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-6}$</td>
<td>$\leq 10^{-9}$</td>
</tr>
<tr>
<td>$t \to hc$</td>
<td>$3 \times 10^{-15}$</td>
<td>$2 \times 10^{-3}$</td>
<td>$\leq 10^{-5}$</td>
<td>$\leq 10^{-5}$</td>
<td>$\leq 10^{-6}$</td>
<td>$\leq 10^{-4}$</td>
</tr>
</tbody>
</table>


$\sigma_{qg \to t} \times B(t \to Wb) < 3.4 \ (2.9 \ exp)$

$B(t \to ug) < 4 \times 10^{-5}$

$B(t \to cg) < 20 \times 10^{-5}$
Flavour-changing neutral current

- **CMS-PAS-TOP-14-020**
  - $t \to Hq \to bbq$ and $t \to Wb \to lvb$
  - $t \to Hq \to ZZq$ or $WWq$

- **CMS-PAS-TOP-14-019**
  - $t \to Hq \to \gamma\gamma q$ and
  - $t \to Wb \to lvb$ or $qqb$

- **CMS-PAS-TOP-13-017**
  - $t \to Hq \to ZZq$ or $WWq$ and $t \to Wb \to lvb$

- $B(t \to Hc) < 1.16\%$ (obs) at 95% CL
- $B(t \to Hu) < 1.92\%$ (obs) at 95% CL

Similar results from ATLAS (JHEP 12 (2015) 061)

- $B(t \to Hc) < 0.47\%$ (obs) at 95% CL
- $B(t \to Hu) < 0.42\%$ (obs) at 95% CL
Flavour-changing neutral current: Summary

Analyses assume all anomalous couplings are zero, but one.

Still above SM prediction, but sensitivity to certain BSM models getting closer or even already reached.

LEP, HERA, and Tevatron, give complementary results that start to be superseded by LHC.
Constraining the SM with the **top mass**

- The top mass, the W mass and the Higgs mass depend on each other
- **Direct mass measurement at Tevatron** $m(\text{top}) = 174.18 \pm 0.64$ GeV (July 2014)
- Not an observable, i.e. scheme-dependent
  - Pole-mass: viewing top quark as a free parton
    - inclusive cross section (NNLO) dependent on top-quark pole mass
  - MS scheme ("running mass"): 
    - "MC mass": (N)LO+PS yet different from pole or MS mass

**Direct reconstruction methods**
- Full reconstruction by resolving the pairing ambiguities (all channels studied)
- Use kinematic constrained fitting to improve the mass resolution
  - Constrain the light jet energy scale in situ by using the W mass constraint
- Fit the mass with MC template fits or event by event likelihood fits
  - Methods very sensitive to the description of radiation and JES uncertainties

**Indirect methods**
- Use the dependence on the top mass on other variables
  - Top pair cross section
  - Lepton $p_T$ and end-point methods
  - Invariant mass of the system $J/\Psi$+lepton from W
  - Decay length of the $b$ hadron
- Main issue: need of a lot of statistics
### CMS (MC) Top mass 8TeV


**Experimental uncertainty**

- **Method Calibration**
  - Jet-energy corrections
  - JEC: Inter-calibration
  - JEC: In situ calibration
  - JEC: Uncorrelated non-pileup
  - JEC: Uncorrelated pileup
  - Jet-energy resolution
  - b tagging
  - Pileup
  - Backgrounds
  - Trigger

**Modeling of hadronization**

- JQC: Flavor-dependent
  - light quarks (u d s)
  - charm
  - bottom
  - gluon
  - bjet modeling
  - b fragmentation
  - Semileptonic b hadron decays

**Modeling of perturbative QCD**

- PDF
  - Ren. and fact. scales
  - ME
  - Matching threshold
  - ME generator
  - Top quark
  - Top quark
  - Soft QCD

**Modeling of soft QCD**

- Underlying event
  - Color reconnection modeling
  - Total systematic

**Statistical uncertainty**

- Total

**Two-dimensional fit uncertainty comparable to world average**

\[
m_t^{2D} = 172.14 \pm 0.19 \text{ (stat+JSF)} \pm 0.59 \text{ (syst)} \text{GeV} \\
JSF = 1.005 \pm 0.002 \text{ (stat)} \pm 0.007 \text{ (syst)}
\]

**σ_{tot} = 0.62 \text{ GeV}**

**One-dimensional fit**

\[
m_t^{1D} = 172.56 \pm 0.12 \text{ (stat)} \pm 0.62 \text{ (syst)} \text{GeV} \\
m_t^{\text{hyb}} = 172.35 \pm 0.16 \text{ (stat+JSF)} \pm 0.48 \text{ (syst)}
\]
**ATLAS (MC) top mass**

- Event selection similar to CMS lepton+jets result.
  - Separate events into 1 b tag and ≥2 b tags.
- Reconstruct ttbar system with kinematic likelihood fit.
  - Improves purity and assignment of reconstructed jets to partons.
- **Template-based approach with observables:** \( m_{\text{top}}^{\text{reco}} \), \( m_W^{\text{reco}} \) and \( R_{bq} \) (ratio of \( p_T^{b\text{had}} \) and \( p_T^{b\text{lep}} \) over \( p_T^{W\text{jet1+2}} \)).
  - In-situ calibration of JES (\( m_W^{\text{reco}} \)) and bJES (\( R_{bq} \)), relative to udsg.

\[
\begin{align*}
  m_t &= 172.33 \pm 0.75 \text{ (stat+JSF+bJSF)} \\
       &\quad \pm 1.02 \text{ (syst)} \text{ GeV} \\
  \text{JSF} &= 1.019 \pm 0.003 \text{ (stat)} \pm 0.027 \text{ (syst)} \\
  \text{bJSF} &= 1.003 \pm 0.008 \text{ (stat)} \pm 0.023 \text{ (syst)}
\end{align*}
\]

**NEW ATLAS result on the dilepton channel at 8 GeV** (paper in preparation)

\( m_{\text{top}} = 172.99 \pm 0.41 \text{ (stat)} \pm 0.74 \text{ (syst)} \text{ GeV} \)

0.84 GeV in total
**CMS** + **ATLAS** $m_{\text{top}} (\text{MC})$

LHCTOPWG precision of 0.3%

---

**Analysis combined using BLUE, accounts for correlations between all uncertainties.**

**CMS combination**

$m_{\text{top}} = 172.44 \pm 0.48 \text{ GeV}$

**ATLAS combination**

(OLD) $m_{\text{top}} = 172.99 \pm 0.91 \text{ GeV}$

(NEW) $m_{\text{top}} = 172.84 \pm 0.70 \text{ GeV}$

(not in the combination plot)

**Tevatron combination**

$m_{\text{top}} = 174.34 \pm 0.64 \text{ GeV}$

---

**Total uncertainty is now well below 1 GeV**
top mass: Indirect Measurements

Access to top quark pole mass directly

• difference between MC & pole mass $O(1 \text{ GeV})$ (A. Hoang: arXiv:1412.3649v1)
  
• Pole Mass from $tt+1$-jet events @ 7 TeV (ATLAS) JHEP 10 (2015) 121

• $m_{\text{top}}$ from Production Cross-Section
  
  – Can take advantage of low backgrounds of $e\mu$ channel
  
  – Sensitivity not as strong as in direct measurements
  
  – Systematic uncertainties typically larger
    
  

• Measurement of $\sigma_{tt}$ together with NNLO theoretical prediction allows for extraction of the pole mass ($m_{\text{top}}$)

Extract top quark pole mass directly using differential $tt+1$-jet cross-section

\[
R(m_{\text{top}}^\text{pole}, \rho_s) = \frac{1}{\sigma_{tt+1}\text{-jet}} \cdot \frac{d\sigma_{tt+1}\text{-jet}}{d\rho_s}(m_{\text{top}}^\text{pole}, \rho_s)
\]

\[
\rho_s = \frac{2m_0}{\sqrt{s_{tt+1}\text{-jet}}}
\]

\[
m_{\text{top}}^\text{pole} = 173.7 \pm 1.5 \text{ (stat.)} \pm 1.4 \text{ (syst.)}^{+1.0}_{-0.5} \text{ (theory) GeV}
\]
Summary

- Top quark physics is a pillar of the current research program in HEP and provide stringent tests of pQCD. Both the CMS and ATLAS collaborations cover a wide range of top-related topics, as previously D0 and CDF did.

- Key to QCD, electro-weak and New Physics
  - Ideal probe for constraining (directly + indirectly) the symmetry breaking of the SM
    - The top is way heavy → the Higgs scalar mostly couples to tops
  - Ideal probe for looking for new physics beyond the model itself
    - Via precision measurements or direct searches for new signals

- Results in agreement with SM predictions
  - Spin correlations
  - Charge asymmetry
  - Associated production, observation of $tt+\gamma$, $tt+W/Z$, important to study top-Higgs couplings.
  - No signs of FCNC

- Top mass:
  - Direct measurement, giving excellent precision below 0.5 GeV
  - Indirect measurement (pole mass) precision below 2 GeV and compatible with direct measurement.
Backup
Charge asymmetry: dilepton channel

- Inclusive distribution unfolded @ parton level
- 2 OS $\ell$, $\geq$ 2 high $p_T$ jet, $\geq$ 1b, large $E_t^{\text{miss}}$
- Asymmetry defined with decay leptons and reconstructed tops
- Top reconstruction using matrix weighting technique
  - Regularised unfolding to parton level
  - Differential measurement in $m(t\bar{t})$, $|y(t\bar{t})|$, $p_T(t\bar{t})$
- CMS 8 TeV: arXiv:1603.06221, sub. to PLB

\[ A_C = [1.1 \pm 1.3 \text{ (stat+syst)}] \% \]
SM pred: $(1.11 \pm 0.04)\%$
\[ A_{\text{lep}}^C = [0.3 \pm 0.7 \text{ (stat+syst)}] \% \]
SM pred: $(0.64 \pm 0.03)\%$
CP asymmetry in ttbar events

- No observable CP violation in tt production in SM
- CP violation sign of new physics
- Probes of CP violation in tt production:
  - Four observables are chosen with asymmetry in presence of CP violation
  - Distributions are probed in 8 TeV data

\[ O_2 = \epsilon (P, p_b + p_b, p_\ell, p_j) \xrightarrow{\text{lab}} \alpha (\vec{p}_b + \vec{p}_b) \cdot (\vec{p}_\ell \times \vec{p}_j) \]
\[ O_3 = Q_\ell \epsilon (p_b, p_b, p_\ell, p_j) \xrightarrow{\text{CM}} \alpha Q_\ell \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_j) \]
\[ O_4 = Q_\ell \epsilon (P, p_b - p_b, p_\ell, p_j) \xrightarrow{\text{lab}} \alpha Q_\ell (\vec{p}_b - \vec{p}_b) \cdot (\vec{p}_\ell \times \vec{p}_j) \]
\[ O_7 = q \cdot (p_b - p_b) \epsilon (P, q, p_b, p_b) \xrightarrow{\text{lab}} \alpha (\vec{p}_b - \vec{p}_b)_z (\vec{p}_b \times \vec{p}_b)_z \]

\[ A_{CP} (O_i) = \frac{N_{\text{events}} (O_i > 0) - N_{\text{events}} (O_i < 0)}{N_{\text{events}} (O_i > 0) + N_{\text{events}} (O_i < 0)} \]
The distribution and orientation of energy inside jets is predicted to be an experimental handle on colour connections between the hard-scatter quarks and gluons initiating the jets.

The pull angle is measured for jets produced in $t\bar{t}$ events with one W boson decaying leptonically and the other decaying to jets.

Normalised fiducial $t\bar{t}$ differential cross-section is measured, and compared with SM and colour-octet W boson. It is found that the jet pull angle characterize the W boson as a colour singlet in agreement with the SM.
Flavour-changing neutral current

- **tt production with** $t \rightarrow Hq \rightarrow bbq$ and $t \rightarrow Wb \rightarrow l\nu b$
- **Categories based on jet, b-tag multiplicity,** $(4j, 3b)$ and $(4j, 4b)$ **most sensitive**
- **Signal/background discriminant:** with $P^{\text{sig}}, P^{\text{bkg}}$
  PDFs using the resonances and jet flavour content of final state

**ATLAS:** JHEP12 (2015) 061

- **Limit at 95% CL:** $B(t \rightarrow Hc) < 0.56\%$ (obs)
  $B(t \rightarrow Hu) < 0.61\%$ (obs)
Constraining the SM

• Can use the fact that $m_t$, $m_W$, $m_H$ are linked at loop level to constrain the SM
  
  ➢ The Higgs/symmetry breaking sector can be explored with more insights coming from top physics

\[ V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij}_v \psi^i_L \psi^j_R \phi \]

$\lambda$ now known at NNLO QCD. Vacuum meta-stability when the minimum of $V(\Phi)$ is just local

• The top quark also provide other direct constraints to the model
  
  ➢ Direct access to parameters of the SM ($m_t$, $V_{tb}$)
  ➢ Other stringent tests of SM (QCD in $d\sigma/dX$, couplings, CPT invariance,...)