Measurement of top-quark properties with the ATLAS detector at the LHC

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Introduction

• The top quark is the **heaviest** known fundamental particle. Could it play a special role in electroweak symmetry breaking?

• The top quark has a **very short lifetime**, and is the only quark that decays before forming **hadronic bound states**

• This leads to many **measureable properties** that we can test from its decay products, probing the **predictions of QCD**

• **Understanding** \( t\bar{t} \) **production is crucial** for many searches for rare SM processes and **physics beyond the SM**

• **The LHC is a Top factory!**
Outline

• **Spin Correlation** [arXiv:1903.07570](http://arxiv.org/abs/1903.07570)
  • Review of, and updates to, ATLAS’ $36 \text{ fb}^{-1}$ 2019 $t\bar{t}$ Spin Correlation measurement and interpretations with respect to the Standard Model and Supersymmetry. Focussing on inclusive distributions today (differential by $m_{t\bar{t}}$ also available, see backup).

  • ATLAS’ $139 \text{ fb}^{-1}$ 2019 $t\bar{t}$ Charge Asymmetry measurement, which established evidence of a non-zero Charge Asymmetry to four standard deviations

  • ATLAS’ $139 \text{ fb}^{-1}$ 2019 $t\bar{t}$ Top Width measurement, the direct measurement may be used to probe a broad class of BSM physics
Spin Correlation

- Un-polarised top quark produced at LHC
- However spins are expected to be correlated
- Top quarks decay before hadronisation
  - Spin information is preserved in the angular distribution of the decay products!

- Measurements of spin correlation test the full chain from production to decay
- New Physics could show up through alternative top production mechanisms, or new intermediate particles
- Recent analyses have shown ‘steeper’ $\Delta\varphi$ in MC than data (backup)
Nominal $t\bar{t}$ MC:
- Powheg-Box NLO matrix element
- Pythia8 parton shower and fragmentation
- NNPDF3.0 NLO PDF

2015 + 2016 data (36 fb$^{-1}$) with a standard dilepton $e\mu$ selection:
- Exactly 2 opposite-sign leptons
- At least 2 jets
- At least one b-jet
- No cuts on $E_T^{\text{miss}}$ or $m_{\mu}$

Fiducial particle level:
- Stable particles in generator record
- Same kinematic cuts as above

Parton level, full phase space:
- $e\mu$ channel only (no $\tau$ decays)

Simultaneous profile-likelihood fit of SUSY+top prediction in two variables:
$\Delta \varphi$ – Uncorrelated tops from stops
$\Delta \eta$ – ME for production of tops and stops
All MC was found to deviate from the data in the inclusive measurement.

- Fraction of SM-like spin correlation $f_{SM}$ extracted using hypothesis templates fitted to parton-level, unfolded normalised cross-sections from data. The nominal templates consist of:
  - PP8 with spin correlations
  - PP8+Madspin with spin correlations “off”

**Powheg+Pythia8 [Nominal]**

- NLO in production
- Not full NLO in top quark decays
- Use NWA to factorisation production and decay (no interference between initial and final states)
Generator studies

- Full $t\bar{t} + tW$ processes without NWA (Powheg-Box-Res $bb4l$) compared to nominal $t\bar{t}$ and $tW$ MC – no significant differences

- NLO in decays of top quarks – MCFM generator – result is close to PP8

- Fixed order NNLO predictions became available, which are closer to the data but still deviate

- Powheg+Madspin+Pythia8 with spin correlations “on” differs slightly from nominal Powheg+Pythia8 An uncertainty was added to cover the difference ★
Generator studies

- A NLO QCD+Weak interaction corrections sample showed potential for good agreement but with very large scale uncertainties (see backup).

- NLO and NNLO samples expanding the normalised cross-section ratio in $\alpha_S$ (see here and here - A. Behring et al.).
  - ‘NLO expanded’ agrees well with ‘NLO QCD+Weak’
  - ‘NNLO expanded’ agrees well with previous NNLO, so expansion cannot solve this difference.

- $f_{SM}$: Re-evaluation of asymmetric scale uncertainties ★

SUSY
- Investigation of $m_t$ bias due to presence of top squarks
  - $\sigma_{t\bar{t}}$ overestimation $\rightarrow$ SUSY limits too stringent close to $m_t$
  - Tested bias corrections to $\sigma_{t\bar{t}}$ when setting SUSY cross-section limits for low $m_{\tilde{t}}$
  - No change to mass upper limits set by the paper.
None of the studied generators are able to reproduce the normalised $\Delta \phi$ distribution within the experimental errors.

Spin correlation found to be higher than that predicted by the SM as implemented in NLO MC generators with a significance of 2.2$\sigma$.

<table>
<thead>
<tr>
<th>Region</th>
<th>$f_{SM} \pm$ (stat.,syst.,theory)</th>
<th>Significance (excl. theory)</th>
</tr>
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<tbody>
<tr>
<td>Inclusive</td>
<td>$1.249 \pm 0.024 \pm 0.061$</td>
<td>$2.2 \pm 3.8$</td>
</tr>
<tr>
<td>$m_{t\bar{t}} &lt; 450$ GeV</td>
<td>$1.12 \pm 0.04 +0.12 -0.13$</td>
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<td>$450 \leq m_{t\bar{t}} &lt; 550$ GeV</td>
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<td>$m_{t\bar{t}} \geq 800$ GeV</td>
<td>$2.2 \pm 0.9 +2.5 -1.7$</td>
<td>$0.49 \pm 0.61$</td>
</tr>
</tbody>
</table>

SUSY limits unchanged (backup)
• LO $t\bar{t}$ production is symmetric
• Higher-order interferences between $q\bar{q}$ and $qg$ create an asymmetric production
  • $t$ is produced preferentially in the direction of the incoming $q$
• At the LHC, this produces a central-forward charge asymmetry:
  \[
  A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}
  \]
  \[
  \Delta|y| = |y_t| - |y_{\bar{t}}|
  \]
• Charge symmetric $gg$ production dilutes measurable asymmetry
• Several BSM models predict alterations to $A_C$ especially with variation as a function of $m_{t\bar{t}}$ and $\beta_{z,t\bar{t}}$
  • Anomalous vector/axial couplings (e.g. axigluons)
  • Heavy $Z'$ bosons

Possible to do an EFT interpretation to test many models!
- Full 140 fb$^{-1}$ dataset
- “Standard” + “Boosted” lepton+jets
- Measurement performed inclusively, and as a function of $m_{t\bar{t}}$, $\beta_{z,t\bar{t}}$
- BDT employed to further separate backgrounds

Fully Bayesian Unfolding to parton level - using nuisance parameter terms to marginalise systematics

$$P(T|D, M) \propto \mathcal{L}(D|T, M)\pi(T)$$
$A_C = 0.0060 \pm 0.0015$ (stat+syst.)

Both inclusive and differential measurements are found to be compatible with SM predictions, at NNLO in perturbation theory with NLO electroweak corrections.

EFT interpretation probes single important parameter in the Warsaw basis (see CONF note!): $C^-/\Lambda^2$

$C^-$ is linear combination of Wilson Coefficients

$\Lambda$ is scale of new physics

This is valid for many models (axigluons, kaluza-klein, randall-sundrum), for example:

$C^-/\Lambda^2 = -4g_s^2/m_A^2$

Tighter bounds achieved than for previous LHC 8 TeV combination!
One of the fundamental properties of the top quark is its decay width $\Gamma_t$

- Very high mass suggests very large decay width
- LO Perturbation theory in the SM leads to a prediction for $\Gamma_t$
  - Dependent on $m_t$, $G_F$, $|V_{tb}|$
- Most precise NNLO predictions give $\Gamma_t^{\text{NNLO}} = 1.322 \text{ GeV}$ for $m_t = 172.5 \text{ GeV}$
  - Corrections from $m_b$, $\Gamma_W$, NLO EW and NLO+NNLO QCD corrections
- Deviations from SM could provide hints of decays to charged Higgs, FCNC, modified CKM elements, non-SM radiative corrections to top-quark decays

- Direct measurements are less precise than indirect for $\Gamma_t$
  - Also less dependent on SM predictions (single-top cross-section, assumption of $|V_{tb}| = 1$…)
  - Less-model dependent – so could be used to probe broader classes of BSM physics
Measurement and Result

- Full 140 fb\(^{-1}\) dataset in dilepton channel using high-statistics \(e\mu\) events
- \(m_{lb}\) - Invariant mass of a charged lepton and b-tagged jet
- Profile-likelihood fit with simulated templates of top-quark decay widths to extract width from data – (for \(m_{lb} > 150\) GeV only)
  - Systematic uncertainties incorporated into the fit as NPs
  - Simultaneously fitting \(m_{b\bar{b}}\) to constrain systematics

\[\Gamma_t = 1.9 \pm 0.5\] GeV

<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>
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<tr>
<td>(E_T^{miss}) reconstruction</td>
<td>±0.09</td>
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<tr>
<td>Pile-up and luminosity</td>
<td>±0.09</td>
</tr>
<tr>
<td>Electron reconstruction</td>
<td>±0.07</td>
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<tr>
<td>PDF</td>
<td>±0.04</td>
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<tr>
<td>(t\bar{t}) normalisation</td>
<td>±0.03</td>
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<tr>
<td>Muon reconstruction</td>
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<td>Fake-lepton modelling</td>
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\(m_t = 172\) GeV

<table>
<thead>
<tr>
<th></th>
<th>Mean [GeV]</th>
<th>Unc. [GeV]</th>
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<tbody>
<tr>
<td>Measured</td>
<td>2.01</td>
<td>+0.53</td>
</tr>
<tr>
<td>Theory</td>
<td>1.306</td>
<td>&lt; 1%</td>
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</table>

\(m_t = 172.5\) GeV

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<tr>
<td>Measured</td>
<td>1.94</td>
<td>+0.52</td>
</tr>
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<td>1.322</td>
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\(m_t = 173\) GeV

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<tr>
<td>Measured</td>
<td>1.90</td>
<td>+0.52</td>
</tr>
<tr>
<td>Theory</td>
<td>1.333</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>
Summary

• The **LHC is a Top factory** (and a great place to study Top physics!). A breadth of studies are taking place with **increasingly high precision** and increasingly sophisticated interpretations.

• The **Spin Correlation** measurement has been updated, the deviation from the SM is in agreement with historical results but with **tighter uncertainties**. Many alternative **MC models** have been explored with no clear ‘good’ candidate.

• The **Charge Asymmetry** measurement establishes to 4σ a non-zero charge asymmetry, and sets **tighter limits on EFT coupling operators** than the LHC 8 TeV combination.

• The direct **Top Width** measurement finds **compatibility with the SM prediction** and may be used to probe BSM physics in the future.
BACKUP
“Direct” spin correlation measurements

• Extract parameters from the angular distribution of $t$ and $\bar{t}$ decay products in the parent top quark’s rest frame (various axes)

\[
\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_+^a d\cos\theta_-^b} = \frac{1}{4} \left(1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a, b) \cos\theta_+^a \cos\theta_-^b\right)
\]

• Requires full $t\bar{t}$ reconstruction in dilepton events $\rightarrow$ significant systematic uncertainties and resolution effects
13 TeV analysis summary

- 2015 + 2016 data (36 fb\(^{-1}\)) with a standard dilepton \(\text{e}\mu\) selection:
  - Exactly 2 opposite-sign leptons (27, 25 GeV)
  - At least one b-jet; \(\geq 2\) jets pT > 25 GeV
  - No cuts on \(E_{T}^{\text{miss}}\) or on \(m(\ell\ell)\)

- Fiducial particle level:
  - Stable particles in generator record
  - “Dressed” leptons with radiated photons
  - Anti-\(k_T\) R=0.4 jets with “ghost-matching” of intermediate B-hadrons for b-tagging
  - Same kinematic cuts as above

- Parton level, full phase space:
  - Tops defined after radiation but before decay
  - Leptons are taken before radiation (i.e. Born level)
  - \(\text{e}\mu\) channel only (no tau decays)
Spin Correlation

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

**Data**

- **ATLAS**
- NLO QCD+Weak (\( \mu_R/F = m_t \))
- MCFM
- NNLO
- Powheg+MadSpin
- Powheg+Pythia8

Parton level \( \Delta\phi(l^+, \bar{l})/\pi \) [rad/\pi]
Spin Correlation

- Top $p_T$ reweighting to NNLO fixed-order predictions was tested but showed similar difference to the nominal scale uncertainties.

- Full $t\bar{t} + tW$ processes without NWA (Powheg-Box-Res $bb4l$) compared to nominal $t\bar{t}$ and $tW$ MC – no significant differences.

- NLO in decays of top quarks – MCFM generator – result is close to PP8.

- Fixed order NNLO predictions became available, which are closer to the data but still deviate.

- A NLO QCD+Weak interaction corrections sample showed potential for good agreement but with very large scale uncertainties (see backup).

- NLO and NNLO samples with alternative definition of expanded normalised cross-section (see here and here - A. Behring et al.).
  - ‘NLO expanded’ agrees well with ‘NLO QCD+Weak’
  - ‘NNLO expanded’ agrees well with previous NNLO, so expansion cannot solve this difference.

- $f_{SM}$: Re-evaluation of asymmetric scale uncertainties.

- Powheg+Madspin+Pythia8 with spin correlations “on” differs slightly from nominal Powheg+Pythia8. An uncertainty was added to cover the difference.
Spin Correlation

- **NLO QCD+weak**: calculation
  - NLO QCD including weak interaction corrections
  - Expanded as a ratio to fixed order (c.f. computation of cross-section numerator/denominator)
  - **Fixed** scale choice: $\mu_{R/F} = m_{\text{top}}$

- Better agreement with data, but large scale uncertainties
- Gives

\[ f_{\text{SM}} = 1.03 \pm 0.07(\text{stat})^{+0.10}_{-0.14}(\text{scale}) \]
### Table 7: Summary of the extracted spin correlation values in the inclusive $\Delta\phi$ observable using different hypothesis templates.

<table>
<thead>
<tr>
<th>Generator</th>
<th>Inclusive</th>
<th>$m_{t\bar{t}} &lt; 450$ GeV</th>
<th>$450 \leq m_{t\bar{t}} &lt; 550$ GeV</th>
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<tbody>
<tr>
<td>$f_{SM}$ values</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>POWHEG + PYTHIA8</strong></td>
<td>1.25</td>
<td>1.12</td>
<td>1.18</td>
<td>1.65</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>POWHEG + PYTHIA8 (2.0 $\mu_F$, 2.0 $\mu_R$)</strong></td>
<td>1.29</td>
<td>1.14</td>
<td>1.23</td>
<td>1.79</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>POWHEG + PYTHIA8 (0.5 $\mu_F$, 0.5 $\mu_R$)</strong></td>
<td>1.18</td>
<td>1.09</td>
<td>1.11</td>
<td>1.40</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>POWHEG + PYTHIA8 (PDF variations)</strong></td>
<td>1.26</td>
<td>1.13</td>
<td>1.25</td>
<td>1.76</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>POWHEG + PYTHIA8 RadLo tune</strong></td>
<td>1.29</td>
<td>1.15</td>
<td>1.23</td>
<td>1.79</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>POWHEG + HERWIG7</strong></td>
<td>1.32</td>
<td>1.17</td>
<td>1.25</td>
<td>1.79</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>MadGraph5_aMC@NLO + PYTHIA8</strong></td>
<td>1.20</td>
<td>1.06</td>
<td>1.18</td>
<td>1.40</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>POWHEG + MadSpin + PYTHIA8</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NNLO QCD, $\mu_{R,F} = H_T/4$ [82]</td>
<td>1.16</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NLO (QCD + Weak expanded), $\mu_{R,F} = m_t$ [35, 83, 84]</td>
<td>1.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
</tbody>
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Spin Correlation

ATLAS

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

$m_{t\bar{t}} < 450$ GeV

$\langle s \rangle = 13$ TeV, 36.1 fb$^{-1}$

$f_{\text{SM}} = 1.12^{+0.14}_{-0.15}$

$450 < m_{t\bar{t}} < 550$ GeV

$f_{\text{SM}} = 1.18^{+0.20}_{-0.21}$

550 $< m_{t\bar{t}} < 800$ GeV

$f_{\text{SM}} = 1.6^{+0.4}_{-0.6}$

$m_{t\bar{t}} > 800$ GeV

$f_{\text{SM}} = 2.2^{+2.9}_{-2.5}$
## Spin Correlation

**arXiv:1903.07570**

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Inclusive</th>
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<tbody>
<tr>
<td>Matrix element</td>
<td>±0.006</td>
<td>±0.11</td>
<td>±0.064</td>
<td>±0.01</td>
<td>±0.3</td>
</tr>
<tr>
<td>Parton shower and hadronisation</td>
<td>±0.010</td>
<td>±0.02</td>
<td>±0.005</td>
<td>±0.01</td>
<td>±1.4</td>
</tr>
<tr>
<td>Radiation and scale settings</td>
<td>±0.055</td>
<td>±0.05</td>
<td>±0.061</td>
<td>±0.23</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>PDF</td>
<td>±0.002</td>
<td>&lt; 0.01</td>
<td>±0.003</td>
<td>±0.01</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Background modelling</td>
<td>±0.009</td>
<td>±0.01</td>
<td>+0.014</td>
<td>-0.015</td>
<td>±0.01</td>
</tr>
<tr>
<td>Lepton ID and reconstruction</td>
<td>±0.008</td>
<td>±0.01</td>
<td>+0.030</td>
<td>+0.03</td>
<td>+0.5</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>+0.004</td>
<td>-0.003</td>
<td>±0.025</td>
<td>+0.04</td>
<td>+0.1</td>
</tr>
<tr>
<td>Jet ID and reconstruction</td>
<td>+0.014</td>
<td>+0.02</td>
<td>+0.076</td>
<td>+0.17</td>
<td>+1.7</td>
</tr>
<tr>
<td>$E_T^{miss}$ reconstruction</td>
<td>&lt; 0.001</td>
<td>&lt; 0.02</td>
<td>+0.042</td>
<td>+0.12</td>
<td>+0.9</td>
</tr>
<tr>
<td>Pile-up effects</td>
<td>+0.013</td>
<td>&lt; 0.01</td>
<td>+0.015</td>
<td>+0.07</td>
<td>+0.2</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±0.001</td>
<td>&lt; 0.01</td>
<td>+0.002</td>
<td>&lt; 0.01</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>MC statistical uncertainty</td>
<td>±0.005</td>
<td>&lt; 0.01</td>
<td>±0.007</td>
<td>±0.03</td>
<td>±0.05</td>
</tr>
<tr>
<td>Total systematics</td>
<td>±0.061</td>
<td>+0.12</td>
<td>+0.13</td>
<td>+0.31</td>
<td>+2.5</td>
</tr>
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**Note:**
- $m_{t\bar{t}}$ regions require top reconstruction – via Neutrino Weighting, and also a requirement of 2 $b$-tagged jets
  - Only a subset of events ‘pass’ the reconstruction
- Dividing the data causes significant pain in statistical uncertainty
- The reconstruction also increases the contribution MET, $b$-tagging and leptonic systematic uncertainties
- Hence the differential results do not significantly deviate from the data
Some Historical Results

- Several measurements by ATLAS and CMS at various $\sqrt{s}$
- First exclusion of zero spin correlation at $>5\sigma$ by ATLAS at 7 TeV
- Observed $\Delta\phi$ to be “steeper” in predictions than the data
- Covered by systematic uncertainties at 7 and 8 TeV
• Investigation of $m_t$ bias due to presence of top squarks – leading to assumed $\sigma_{t\bar{t}}$ overestimation. SUSY Limits would be too stringent close to $m_t$

• Tested bias estimates from two papers – small shift in SUSY cross-section limits for low $m_{\tilde{t}}$ but no change to mass upper limits set by the paper.
Charge Asymmetry

\[ A_C \]

NNLO QCD + NLO EW

\[ \text{ATLAS Preliminary} \]

\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

Data (stat./total)

\( \beta_{z,\bar{t}t} \)
<table>
<thead>
<tr>
<th>$m_{t\bar{t}}$</th>
<th>$A_C$</th>
<th>Stat.</th>
<th>Syst.</th>
<th>MC stat.</th>
<th>Bias</th>
<th>Total unc.</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>0.0060</td>
<td>0.0011</td>
<td>0.0009</td>
<td>0.0005</td>
<td>0.001</td>
<td>0.0015</td>
<td>0.0064±0.0005</td>
</tr>
<tr>
<td>&lt; 500 GeV</td>
<td>0.0045</td>
<td>0.0028</td>
<td>0.0034</td>
<td>0.0013</td>
<td>0.001</td>
<td>0.0045</td>
<td>0.0055±0.0007</td>
</tr>
<tr>
<td>500-750 GeV</td>
<td>0.0051</td>
<td>0.0020</td>
<td>0.0021</td>
<td>0.0009</td>
<td>&lt;0.001</td>
<td>0.0031</td>
<td>0.0072±0.0006</td>
</tr>
<tr>
<td>750-1000 GeV</td>
<td>0.0100</td>
<td>0.0049</td>
<td>0.0046</td>
<td>0.0021</td>
<td>0.001</td>
<td>0.0070</td>
<td>0.0079±0.0005</td>
</tr>
<tr>
<td>1000-1500 GeV</td>
<td>0.0169</td>
<td>0.0072</td>
<td>0.0027</td>
<td>0.0029</td>
<td>0.0004</td>
<td>0.0083</td>
<td>0.0096±0.0009</td>
</tr>
<tr>
<td>&gt; 1500 GeV</td>
<td>0.0121</td>
<td>0.0277</td>
<td>0.0150</td>
<td>0.0092</td>
<td>0.0005</td>
<td>0.0329</td>
<td>0.0094±0.0015</td>
</tr>
<tr>
<td>$\beta_{z,t\bar{t}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3-0.6</td>
<td>0.0085</td>
<td>0.0031</td>
<td>0.0025</td>
<td>0.0013</td>
<td>0.0003</td>
<td>0.0042</td>
<td>0.0023±0.0006</td>
</tr>
<tr>
<td>0.6-0.8</td>
<td>0.0014</td>
<td>0.0029</td>
<td>0.0033</td>
<td>0.0015</td>
<td>0.0004</td>
<td>0.0047</td>
<td>0.0042±0.0003</td>
</tr>
<tr>
<td>0.8-1.0</td>
<td>0.0100</td>
<td>0.0026</td>
<td>0.0042</td>
<td>0.0013</td>
<td>0.0007</td>
<td>0.0051</td>
<td>0.0146±0.0012</td>
</tr>
</tbody>
</table>

Table 2: Results with statistical and systematic uncertainties, including the uncertainty due to limited number of MC events (MC stat. column), uncertainty due to the unfolding bias and the total uncertainty, for the inclusive and differential $A_C$ measurements. The total uncertainty is the sum-in-quadrature of the aforementioned uncertainties. The SM predictions are calculated at NNLO in QCD and NLO in electroweak theory [133].
Thanks for your attention

Jacob Kempster