Top Quark Pair Differential Cross-Sections with the ATLAS detector, eh?

Kyle Cormier, Riccardo Di Sipio, University of Toronto
## Differential xs analyses

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Energy ($\sqrt{s}$)</th>
<th>Luminosity (fb$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t} (l+jets/\ell\ell) + \gamma$</td>
<td>13 TeV</td>
<td>36</td>
<td>EPJC 79 (2019) 382</td>
</tr>
<tr>
<td>$t\bar{t} (l+jets/\ell\ell) + H.F.$</td>
<td>13 TeV</td>
<td>36</td>
<td>JHEP 04 (2019) 046</td>
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<tr>
<td>$t\bar{t}$ (all-jets) high-pT</td>
<td>13 TeV</td>
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<td>$t\bar{t}$ (l-jets) + jets</td>
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<td>JHEP 10 (2018) 159</td>
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<td>$t\bar{t}$ (l+jets) low-pT</td>
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<td>JHEP 11 (2017) 191</td>
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<td>$t\bar{t}$ (\ell\ell)</td>
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<td>$t\bar{t}$/tW (\ell\ell) interference</td>
<td>13 TeV</td>
<td>36</td>
<td>PRL 121 (2018) 152002</td>
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<td>PDF fits</td>
<td>8 TeV</td>
<td>20.2</td>
<td>ATL-PHYS-PUB-2018-017</td>
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<td>MC tuning Run2</td>
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<td>ATL-PHYS-PUB-2018-009</td>
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Also relevant, but not covered in this talk:

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<tbody>
<tr>
<td>$t\bar{t}$ spin correlations (\ell\ell)</td>
<td>13 TeV</td>
<td>36</td>
<td>arXiv:1903.07570</td>
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<td>Jet shapes (l+jets boosted)</td>
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<td>arxiv:1903.02942</td>
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<td>Color flow (l-jets)</td>
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<td>EPJC 78 (2018) 847</td>
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</table>
Comparison with theory

• **Fiducial phase-space**
  • Similar kinematic reconstruction at detector- and particle-level objects
  • Reduce extrapolation uncertainty
  • Valid for all Monte Carlo **event generators**
  • Endpoint of the theoretical prediction

• **Full phase-space**
  • **NNLO+NNLL** accuracy only available by asking to the theorists, slow turnaround
  • Larger **extrapolation** uncertainty to low-\(p_T\), high-\(\eta\).
  • Observables must be **infrared safe**
Kinematic reconstruction

**Single lepton resolved - PseudoTop**

Mass constrains ($m_W$, $m_t$) and b-tagging information to reconstruct decay chain

**Single lepton boosted**

- Kinematic constrains to reconstruct $t \rightarrow \ell \nu b$
- Hadronic top = large-$R$ trimmed jet

**Dilepton Neutrino weighting**

- Extra jet may also be photon, $b\bar{b}$ pair

**All-hadronic boosted “double double”**

Top quark candidates = 2 leading large-$R$ trimmed massive jets ($b$- and top-tagged)
Top Tagging in a Nutshell

Apply cut on substructure variable as a function of jet kinematic variables ($p_T, y, m$)
Top quark $p_T$

- Probably, the most important observable
- Sensitive to **final state radiation**
- Measurement up to ~1 TeV spans different kinematic regimes, requiring different reconstruction methods
- Many sources indicate data/theory **disagreement** with increasing $p_T$
Top quark $p_T$

― the devil is in the tails

Hadronic top
(single lepton channel)

Leptonic top
(dilepton channel)
Top quark $p_T$

Resolved and boosted channel “overlap” and reinforce the mismodelling

NNLO QCD + NLO EW corrections important
But do not fully explain discrepancy
$\bar{t}t$ ($\ell\nu 2j2b)$ + 0j

**ATLAS**

Fiducial phase-space

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

4-jet exclusive

![Graph showing the distribution of $d\sigma_{tt}/d\mathbb{P}_T$](image)

**ATLAS**

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

4-jet inclusive

![Graph showing jet multiplicity](image)
$\bar{t}t(\ell v2j2b) + 1j$

**ATLAS**

Fiducial phase-space

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

5-jet exclusive

- Data
- PWG+PY6 $h_{\text{damp}}=m_t$
- PWG+PY8 $h_{\text{damp}}=1.5$ $m_t$
- PWG+H7 $h_{\text{damp}}=1.5$ $m_t$
- aMC@NLO+PY8 ($\sqrt{m_t^2 + p_T^2}$)
- Sherpa 2.2.1

Stat. unc.
Stat.+Syst. unc.
$\bar{t}t$ ($\ell v2j2b$)+ ≥2j

**ATLAS**

Fiducial phase-space
$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
6-jet inclusive

$\frac{d\sigma_{\bar{t}t}}{dp_T^{\text{had}}}$ [pb · GeV$^{-1}$]

- **Data**
- PWG+PY6 $h_{\text{damp}}=m_t$
- PWG+PY8 $h_{\text{damp}}=1.5$ $m_t$
- PWG+H7 $h_{\text{damp}}=1.5$ $m_t$
- aMC@NLO+PY8 (√($m_t^2 + p_T^2$))
- Sherpa 2.2.1

**Prediction**
- Data
  - Single top
  - W+jets
  - Z+jets
  - Diboson
  - t+jets

**Events**

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
4-jet inclusive

**Data/Pred.**

Jet multiplicity
Poorest data/PP6 disagreement in $\tt (\ell v2j2b)+ 0j$

Improved agreement with more additional jets
Top quark $p_T$ (boosted)

Hadronic top (single lepton channel)

**JHEP 11 (2017) 191**

átlas

$\sqrt{s} = 13$ TeV, $3.2$ fb$^{-1}$

Boosted Fiducial phase-space

1/\sigma_{t\bar{t}} \cdot d\sigma_{t\bar{t}} / dp_T^{t,\text{had}} [1/\text{GeV}]

<table>
<thead>
<tr>
<th>Prediction</th>
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<tbody>
<tr>
<td>ATLAS PWG+PY8 $h_{\text{tamp}} = m_t$</td>
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<tr>
<td>ATLAS PWG+PY8 $h_{\text{tamp}} = 2m_t$, radHi</td>
<td>●</td>
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<tr>
<td>ATLAS PWG+PY8 $h_{\text{tamp}} = m_t$, radLo</td>
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<td>ATLAS PWG+PY8 $h_{\text{tamp}} = 1.5m_t$</td>
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<tr>
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Leading hadronic top (all-hadronic channel)


átlas

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

Fiducial phase space

1/\sigma_{t\bar{t}} \cdot d\sigma_{t\bar{t}} / dp_T^{t,\text{had}} [1/\text{GeV}]

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<tr>
<td>ATLAS MG5_aMC@NLO+Py8</td>
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<td>ATLAS Sherpa 2.2.1</td>
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$p_T^t > 500$ GeV
Top quark $y$ (low $p_T$)

Hadronic top (single lepton channel)

Leptonic top (dilepton channel)
Top quark $y$ (high $p_T$)

**Hadronic top**
(single lepton channel)

**Leading hadronic top**
(all-hadronic channel)
\( \bar{t}t \) system \( m, y, p_T \)

- Mass the most intriguing observable
- Appearance of bumps/deficits may indicate presence of BSM (resonances, interference)
- Rapidity sensitive to PDF
- \( p_T^{tt} \) sensitive to extra radiation
Generally well modelled, PWG+Herwig++ out-of-the-box disagrees with data

Low stats or low resolution at high-$m_{tt}$ limiting bump hunting

All-Hadronic boosted best resolution to this date at very high mass
• Good agreement with PWG+P8
• PWG+Herwig++ too hard/forward
Good agreement, but low stats and large uncertainties at high-\(p_T^{\tt}\)

aMC@NLO+P8 setup needs improvement
\( \bar{t}t \) transverse momentum

\( \bar{t}t (\ell v2j2b)+ 0j \)  
\( \bar{t}t (\ell v2j2b)+ 1j \)  
\( \bar{t}t (\ell v2j2b)+ \geq 2j \)

- NB: \( p_T(\bar{t}t) \) up to 300 GeV even in 4j excl bin
- Overall good agreement, ~20% uncertainties
Extra radiation

\( \bar{t}t (\ell \nu2j2b)+ 0j \)

- Additional radiation (esp ISR) test NLO, NNLO calculations
- Very useful for MC tuning
**Extra radiation**

$\bar{t}t (\ell\nu 2j2b) + 1j$

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Extra radiation

$\bar{t}t$ ($\ell v2j2b$)+ $\geq 2j$

- Additional radiation (esp ISR) test NLO, NNLO calculations
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• Additional radiation (esp ISR) test NLO, NNLO calculations
• Very useful for MC tuning
Extra radiation (HF)

- Associated emission of $t\bar{t}$ pair + heavy flavour complicated process!
- No decay chain reco in this measurement
- Smaller uncertainties for $e\mu + \geq 3b$ and $\ell + \text{jets}(\geq 6j, \geq 4b)$
- Total $\sigma$ higher than predicted after removing ttV and ttH
Extra radiation (HF)

- Associated emission of $t\bar{t}$ pair + heavy flavour complicated process!
- No decay chain reco in this measurement
- Smaller uncertainties for $e\mu+\geq 3b$ and $\ell+\text{jets}(\geq 6j, \geq 4b)$
- Total xs higher than predicted after removing $ttV$ and $ttH$
Extra radiation ($\gamma$)

- Top quarks have EM charge, emit light!
- But also quarks in the initial state...

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**ATLAS**

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

**Normalized cross-section**

Single lepton

**Dilepton**

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**ATLAS**

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

**Normalized cross-section**

Single lepton

**Dilepton**
PDF Fit

- **ATLASepWZtop18**: NNLO pQCD fit using ATLAS differential cross-sections at 7 TeV ($W, Z/\gamma^*$) and 8 TeV ($t\bar{t}$ $p_T$, $m_{tt}$ single lepton, $y_{tt}$ dilepton) + HERA $e^\pm p$ data

- Good fit to data when $p_T^t$ and $m_{tt}$ used separately, pull opposite ways >> decorrelation, effect due to IFSR modelling systematic. No significant impact on the shape of gluon PDF

- Impact of top diffxs: harder PDF, reduced high-x gluon uncertainty
MC Modeling

- **Early Run2 measurements:**
  Setup derived from extrapolation of 8 TeV diffxs. PWG+P6 workhorse, MC@NLO and H++ systematics, IFSR P2012

- **Baseline Run2 measurements:**
  Iterative process, make use of early Run2 results PWG+Pythia8 nominal, MG5_aMC@NLO and Herwig7 systematics, IFSR A14 tune

- Clear reduction of systematic uncertainties
tt/tW interference

- Double slit experiment with top quarks!
- Doubly ($t\bar{t}$) and singly ($tWb$) resonant productions have similar final states and thus interfere
- Interference “removed” with
  - “Traditional” methods (diagram removal, diagram subtraction)
  - Fully-consistent treatment (POWHEG bb4l)
**tt/tW interference**

- Double slit experiment with top quarks!
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  - Fully-consistent treatment (POWHEG bb4l)
tt/tW interference

- Invariant mass $(b, \ell)$ characteristic distribution in presence of resonance
- $m_{b\ell}^{\text{minimax}}$ sensitive to interference effects in the tail
- Uncertainty small enough to constrain different treatments
  - Resonance-aware treatment in better agreement with data

$$m_{b\ell}^{\text{minimax}} = \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

$$m_{b\ell}^{\text{minimax}} < \sqrt{m_t^2 - m_W^2}$$
Conclusions

• How well do we understand Standard Model interactions?

• High statistics allows both precision measurement and search for new physics.

• Most tt̅ measurements limited by systematics, affecting other measurements (e.g. ttH)
  • Hard-scattering and parton-shower modelling still a big source of systematic uncertainty
  • Run1 measurements used to improve PDFs
  • Tick-tock approach to reduce modelling systematics works!

• tt̅ complex final state, but not too complex, fostering:
  • Theoretical and experimental advancements
  • Fine details not yet completely understood: NNLO calculations still rather new / not matched to PS, tt/tW/WbWb interference effects, …
Backup
Inclusive cross-section in very good agreement with NNLO+NNLL calculations

\[ \Delta \sigma(\text{exp}) \approx \Delta \sigma(\text{th}) \]

Possible deviations still allowed:
- small corners of the phase-space
- differential cross-sections
- associate production
High-pT (Boosted) Tops

Top quark
Three-prong topology

$W$ boson
Two-prong topology

Quark/gluon
Axial topology

Trimming Thaler et al., JHEP 1002:084, 2010
Removes pileup by discarding $R=0.2$ subjets with $p_T < 5\% \ p_T(J)$

arXiv: 1903.02942
Detecting top quarks

Jet Mass
Expected to peak around resonance mass
\((t \sim 173 \text{ GeV}; W \sim 80.4 \text{ GeV})\)

Substructure
Distribution in \((\eta, \phi, E)\) of calo clusters reflects underlying top quark decay

- \(N\)-subjettiness ratio \(\tau_{32}\)
- Splitting scale \(\sqrt{d_{12}}\)
- Soft drop mass, multiplicity \(n_{SD}\)
- Les Houches Angularity (LHA)
- Energy correlation functions, \(C_{2}(\beta), D_{2}(\beta)\)

Typical simple tagger:
Apply \textbf{cut} on \textbf{substructure} variable as a function of jet \textbf{kinematic} variables \((p_T, y, m)\)
What you see is what you get

- Isolated $e/\mu$ lepton(s)
- Anti-$k_T$ R=0.4 ("narrow") jets
  - MVA b-tagging
- Objects-calibrated $E_T^{miss}$
  - Anti-$k_T$ R=1.0 ("large-R") jets
  - Trimmed R=0.2 $f=0.05$
  - Substructure information
What you see is what you get

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Single lepton resolved
What you see is what you get

- Isolated $e/\mu$ lepton(s)
- Anti-$k_T$ R=0.4 ("narrow") jets
  - MVA b-tagging
- Objects-calibrated $E_T^{\text{miss}}$
- Anti-$k_T$ R=1.0 ("large-R") jets
  - Trimmed R=0.2 f=0.05
- Substructure information

Single lepton boosted
What you see is what you get

- Isolated $e/\mu$ lepton(s) [veto]
- Anti-$k_T$ R=0.4 ("narrow") jets
- MVA b-tagging
- Objects-calibrated $E_T^{\text{miss}}$
- Anti-$k_T$ R=1.0 ("large-R") jets
- Trimmed R=0.2 $f=0.05$
- Substructure information
Top quark $p_T$

Hadronic top
(single lepton channel)

Resolved

Boosted
Uncertainties: Top quark $p_T$

**Single lepton**
- Jet energy scale 5%
- $b$-tagging < 5%
- Background modelling (low $p_T$) 2%
  - Signal modelling (high $p_T$) 5%

**Dilepton**
- Signal modelling >10%
- PDF 5%
- $b$-tagging < 5%

**All hadronic**
- Jet energy scale 5%
- Top-tagging 10%
- $b$-tagging < 10%
  - Signal modelling (ps/had) 15%
### Single lepton

<table>
<thead>
<tr>
<th>Scenario</th>
<th>( p_{T, \text{had}}^{l} )</th>
<th>( \chi^2/\text{NDF} )</th>
<th>( p )-val</th>
<th>( y_{T, \text{had}}^{l} )</th>
<th>( \chi^2/\text{NDF} )</th>
<th>( p )-val</th>
<th>( m_{tt} )</th>
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<td>7.8/18</td>
<td>9.8/11</td>
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### Dilepton

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<td>0.0/2</td>
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<td>1.3/3</td>
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<td>5.1/6</td>
<td>0.48</td>
<td>0.0/2</td>
<td>1.00</td>
<td>3.9/4</td>
<td>0.42</td>
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<td>SHERPA</td>
<td>3.8/4</td>
<td>0.43</td>
<td>1.3/3</td>
<td>0.73</td>
<td>5.1/6</td>
<td>0.48</td>
<td>0.0/2</td>
<td>1.00</td>
<td>3.9/4</td>
<td>0.42</td>
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<tr>
<td>PowHEG + PYTHIA 6 (radHi)</td>
<td>7.8/4</td>
<td>0.10</td>
<td>1.3/3</td>
<td>0.73</td>
<td>5.1/6</td>
<td>0.48</td>
<td>0.0/2</td>
<td>1.00</td>
<td>3.9/4</td>
<td>0.42</td>
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<tr>
<td>PowHEG + PYTHIA 6 (radLow)</td>
<td>5.5/4</td>
<td>0.24</td>
<td>1.3/3</td>
<td>0.73</td>
<td>5.1/6</td>
<td>0.48</td>
<td>0.0/2</td>
<td>1.00</td>
<td>3.9/4</td>
<td>0.42</td>
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</table>

### All-hadronic

<table>
<thead>
<tr>
<th>Observable</th>
<th>PWG+PY8</th>
<th>AMC@NLO +PY8</th>
<th>PWG+H7</th>
<th>PWG+PY8 (more IFSR)</th>
<th>PWG+PY8 (less IFSR)</th>
<th>SHERPA 2.2.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T^{l1} )</td>
<td>7.7/7</td>
<td>0.36</td>
<td>8.2/7</td>
<td>0.32</td>
<td>8.0/7</td>
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<tr>
<td>( y_T^{l1} )</td>
<td>7.5/5</td>
<td>0.18</td>
<td>12.2/5</td>
<td>0.03</td>
<td>6.8/5</td>
<td>0.24</td>
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<tr>
<td>( p_T^{l2} )</td>
<td>8.6/6</td>
<td>0.20</td>
<td>2.6/6</td>
<td>0.86</td>
<td>9.9/6</td>
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<td>( y_T^{l2} )</td>
<td>3.7/5</td>
<td>0.59</td>
<td>4.6/5</td>
<td>0.46</td>
<td>3.1/5</td>
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<tr>
<td>( m_t )</td>
<td>4.5/9</td>
<td>0.88</td>
<td>4.7/9</td>
<td>0.86</td>
<td>4.0/9</td>
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<td>( p_T^{ll} )</td>
<td>7.8/5</td>
<td>0.17</td>
<td>20.9/5</td>
<td>&lt;0.01</td>
<td>12.6/5</td>
<td>0.03</td>
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<tr>
<td>( y_T^{ll} )</td>
<td>1.1/5</td>
<td>0.95</td>
<td>2.2/5</td>
<td>0.83</td>
<td>0.9/5</td>
<td>0.97</td>
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<tr>
<td>( \chi_T^{ll} )</td>
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<td>12.7/6</td>
<td>0.05</td>
<td>13.6/6</td>
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<td>( y_T^{ll} )</td>
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<td>3.3/6</td>
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<tr>
<td>( \phi_T^{ll} )</td>
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<td>0.93</td>
<td>53.1/6</td>
<td>&lt;0.01</td>
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<tr>
<td>( \Delta \phi_T^{ll} )</td>
<td>0.9/3</td>
<td>0.84</td>
<td>16.3/3</td>
<td>&lt;0.01</td>
<td>2.0/3</td>
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<tr>
<td>( H_T^{ll} )</td>
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<tr>
<td>( \cos \theta^* )</td>
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<td>10.5/5</td>
<td>0.06</td>
<td>9.3/5</td>
<td>0.10</td>
</tr>
</tbody>
</table>
\( \bar{t}t \) rapidity

- Forward region sensitive to PDF
- 13 TeV data seems to prefer NNPDF 3.0
- 8 TeV Lepton differential
**tt̅ angle in Rest Frame**

All-hadronic

ATLAS

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

Fiducial phase space

- Data
- POWHEG+Py8
- POWHEG+H7
- MG5_aMC@NLO+Py8
- Sherpa 2.2.1
- Stat. Unc.

1/$\sigma_{tt} \cdot d\sigma_{tt}/d|\cos\theta^*|

- Fair agreement
- Something going on at low $\cos\theta^*$
Lepton differential and pole mass 8 TeV

**ATLAS**

\( \sqrt{s} = 8 \text{ TeV}, 20.2 \text{ fb}^{-1} \)

- data uncertainty

- MCFM+CT14
- MCFM+MMHT
- MCFM+NNPDF 3.0
- MCFM+HERAPDF 1.5
- MCFM+HERAPDF 2.0

Event display of a $\tilde{t}\tilde{t}$ candidate event in the 2015 data. The large-R anti-kt $R=1.0$ jets are shown in blue while the remaining jets are anti-kt $R=0.4$ jets. The jets identified as containing b-hadrons are shown in magenta. The centers of magenta ellipses in the top right pad correspond to secondary vertices. The transverse momenta of the leading and second-leading large-R jets are $961$ GeV and $824$ GeV, respectively. The dijet invariant mass of the two large-R jets is $3.33$ TeV while the $\tau_{32}$ values are 0.35 and 0.34 for the leading and second-leading large-R jets, respectively.