

# TOP QUARK PAIR PRODUCTION AND PROPERTIES WITH ATLAS

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QCD@LHC 2016

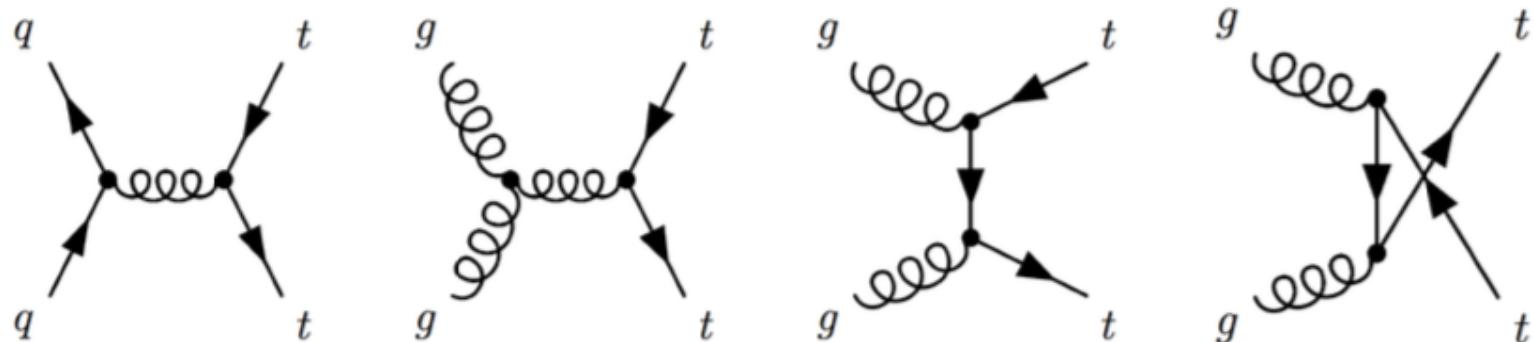
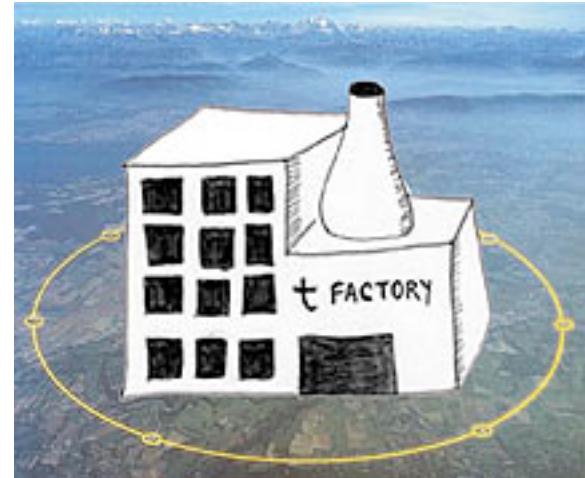
Ki Lie (University of Illinois at Urbana-Champaign)

On behalf of ATLAS Collaboration



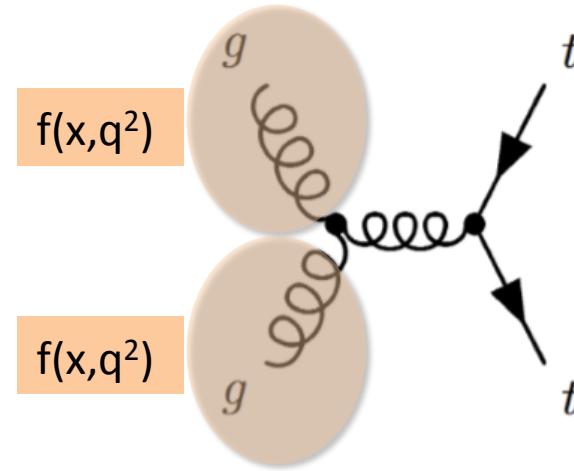
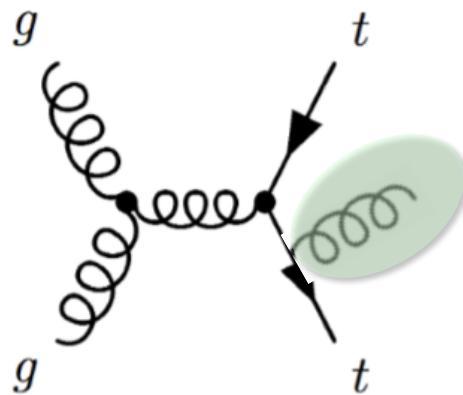
# Top pair production at the LHC

- Top quark pairs ( $t\bar{t}$ ) are predominantly produced via **strong interaction** at the LHC
- Precision tests of **QCD**
  - In a wide range of different scales
  - Tuning of modeling parameters
- Sensitive to **new physics**
  - particularly if they couple to mass
- Background to **many searches**



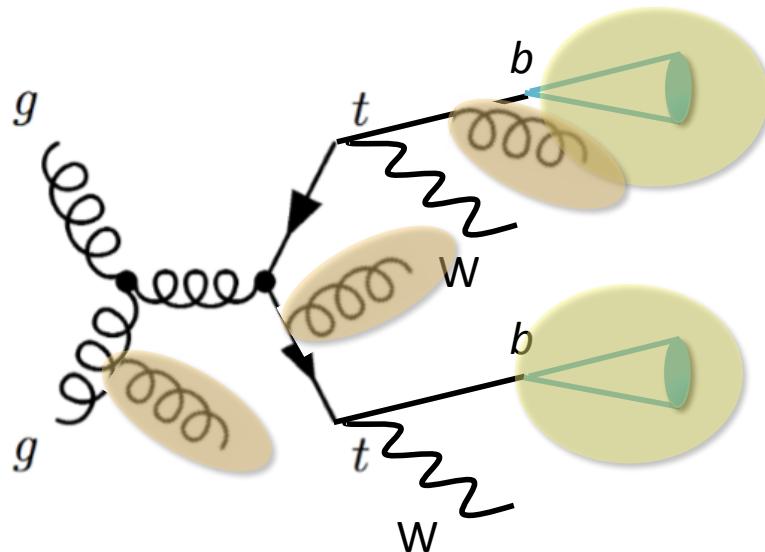
Leading order contributions at the LHC:  $gg \sim O(90\%)$ ,  $qq \sim O(10\%)$  at 13-14 TeV

# Precision tests of QCD



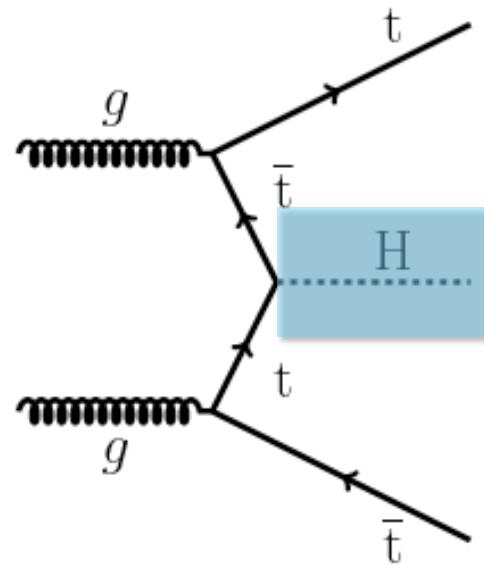
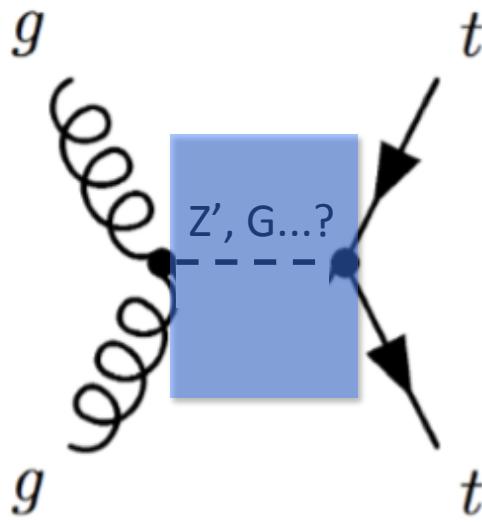
Significant higher-order corrections  
➤ probe pQCD

Gluon fusion as production mode  
➤ constrain gluon PDF



Soft radiation in production and decay  
➤ constrain modeling of parton shower  
and hadronisation

# New physics and searches



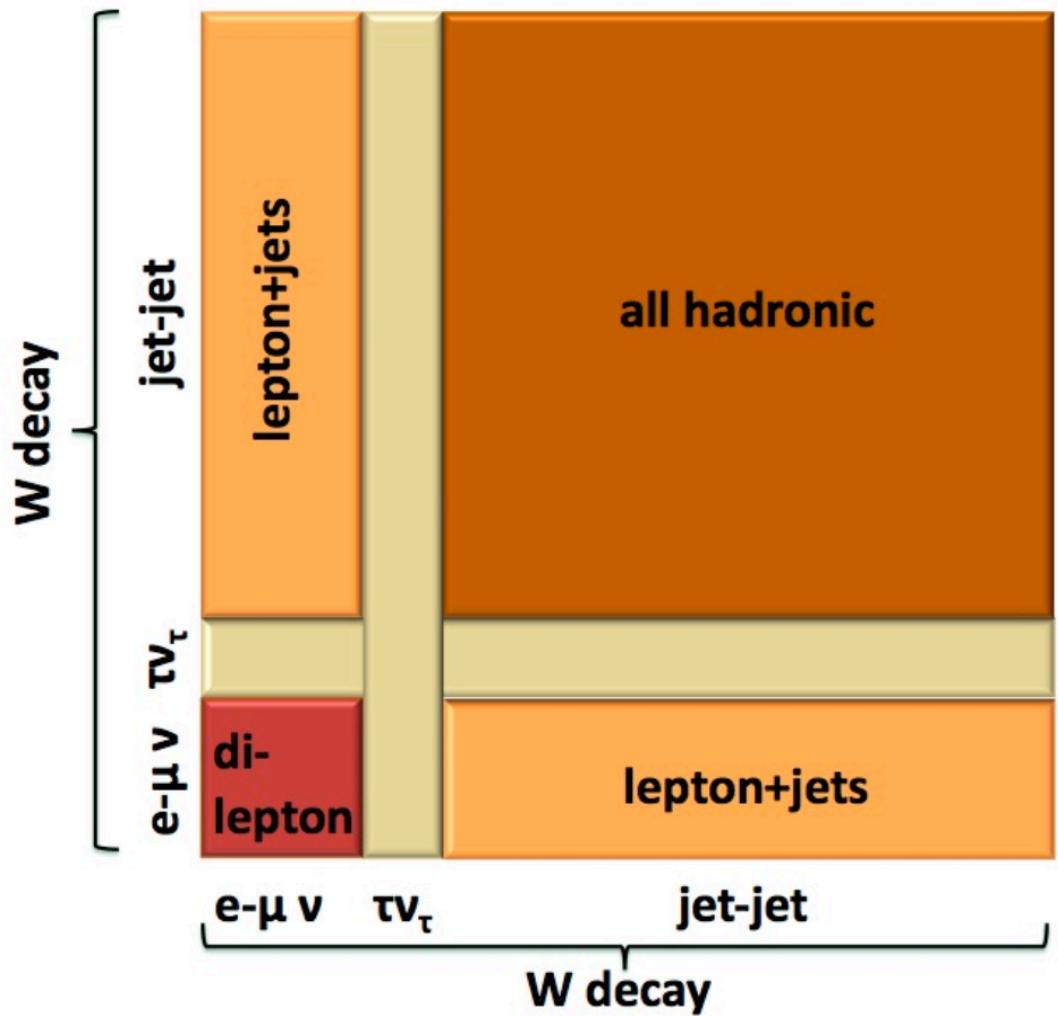
Many new physics involve  $t\bar{t}$  signature

- $t\bar{t}$  measurements constrain **new physics** and backgrounds for **searches**

# Signatures of $t\bar{t}$

Decay modes and BR:

- ~46% all hadronic
- ~30% lepton+jets
- ~4% dilepton\*



\* ~6% if including  $\tau \rightarrow e/\mu$

# Outline

## Top quark pair production

- Inclusive and differential cross-sections

## Top quark pair production with X

- X = additional jets
- X = weak (W/Z) bosons

## Top properties

- Charge asymmetry
- Top mass

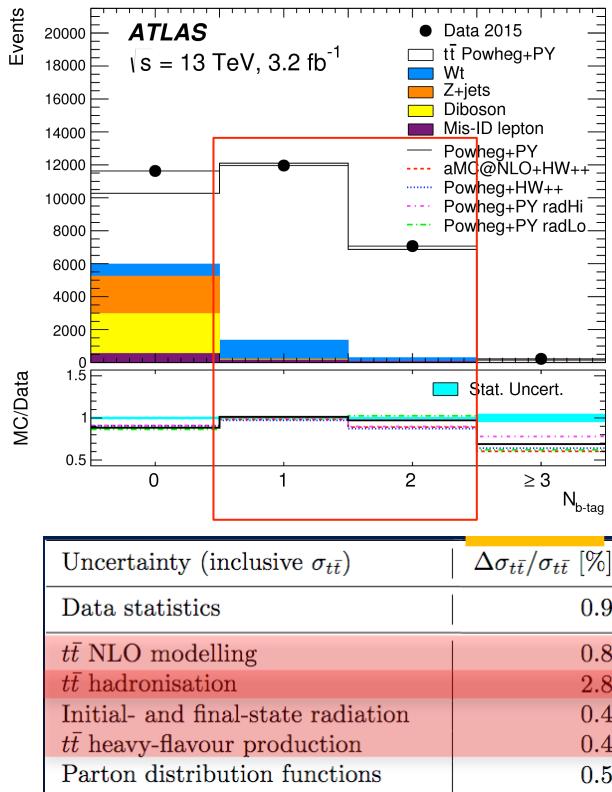
Note: Recent results for t $\bar{t}$ +b $\bar{b}$  (8TeV) are not covered here due to time concern

# TOP QUARK PAIR PRODUCTION

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Inclusive and differential cross-sections

# $t\bar{t}$ inclusive: $e\mu$ 13 TeV



## Main features

- High-purity  $e\mu$  events with 1 and 2 b-tags
- Carefully designed to:
  - Minimize systematic uncertainties
  - Measure as much as possible in-situ
- Similar strategy as in Run 1

$$N_1 = \mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_1^{bkg}$$

$$N_2 = \mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu} C_b \epsilon_b^2 + N_2^{bkg}$$

- Dominant uncertainties from hadronisation

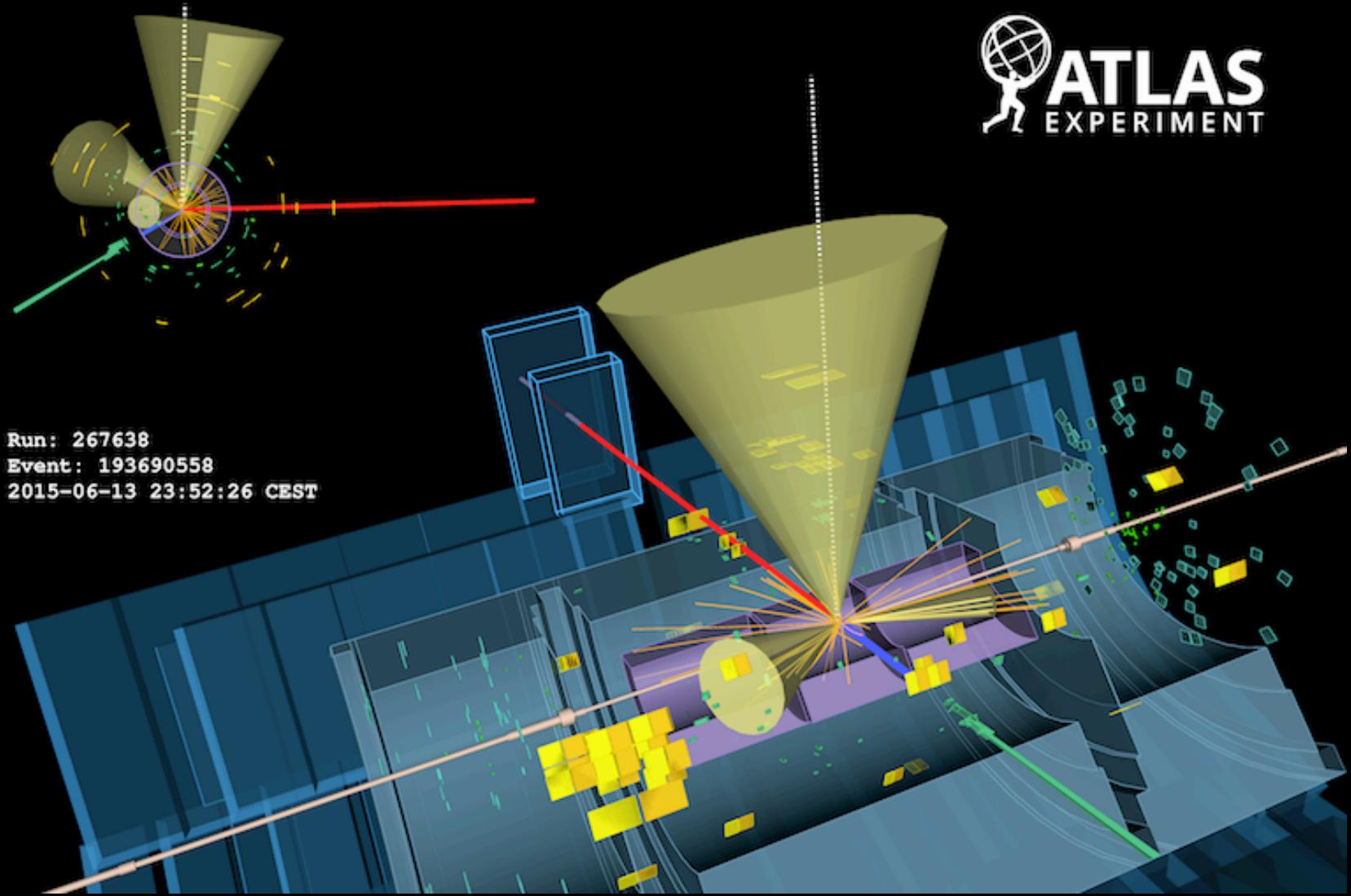
$$\sigma_{t\bar{t}}^{\text{meas.}} = 818 \pm 8 \text{ (stat)} \pm 27 \text{ (syst)} \pm 19 \text{ (lumi)} \pm 12 \text{ (beam)} \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{NNLO}} = 832^{+40}_{-46} \text{ pb}$$

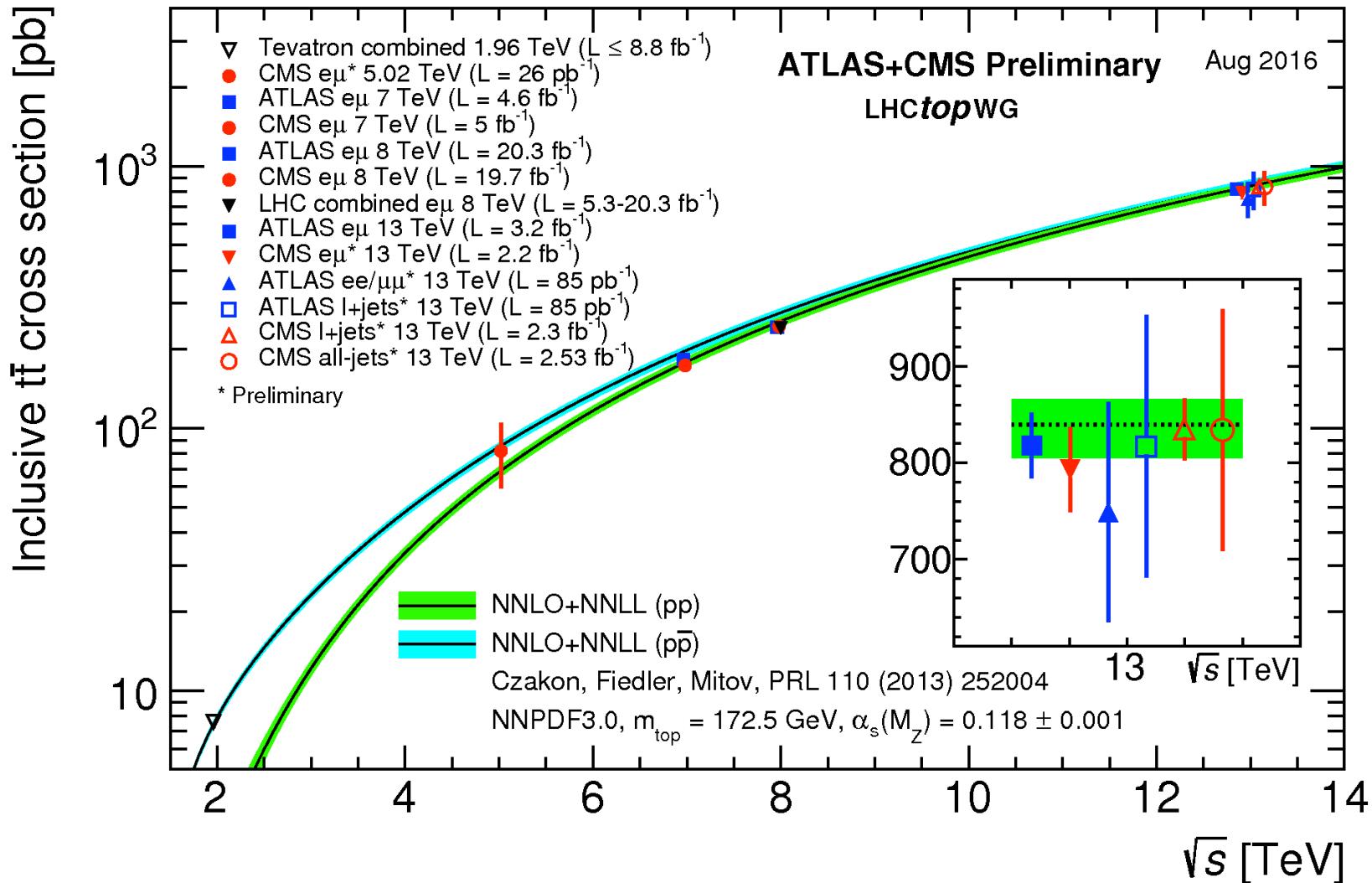
4.4%

+4.8%  
-5.5%

# $t\bar{t}$ event in ATLAS @ 13 TeV



# Summary of $t\bar{t}$ cross-sections



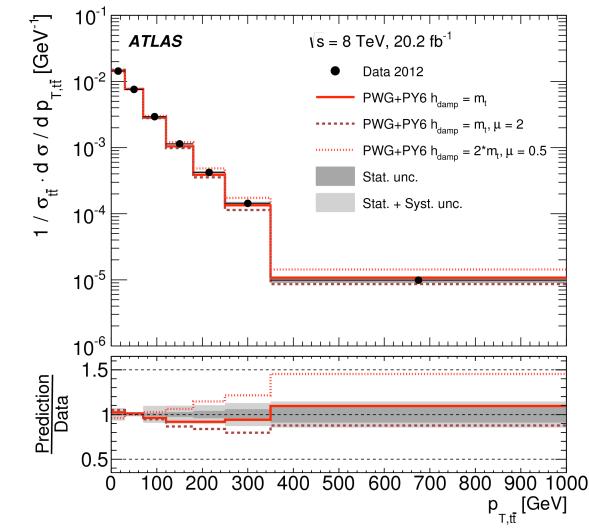
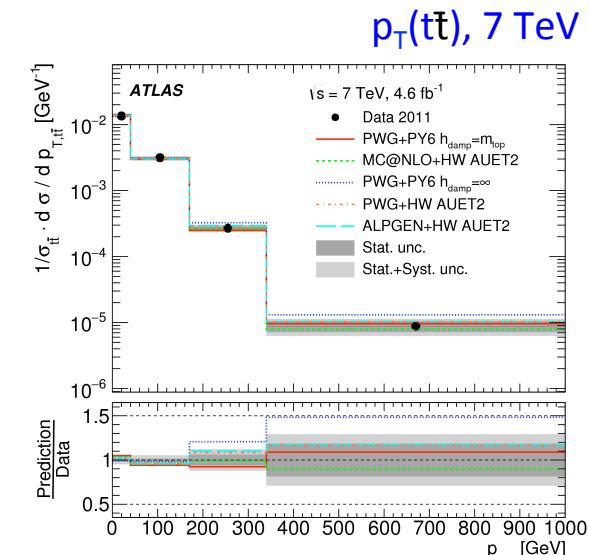
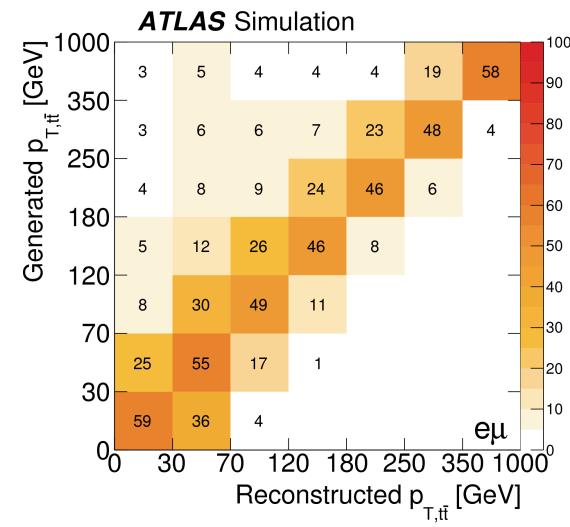
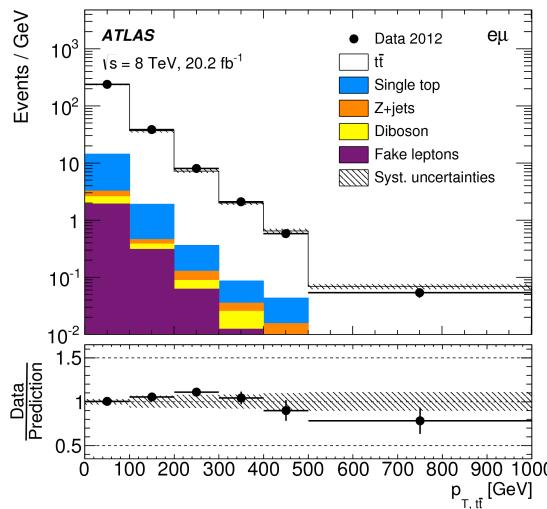
# $t\bar{t}$ differential: dilepton 7 and 8 TeV

## Main features

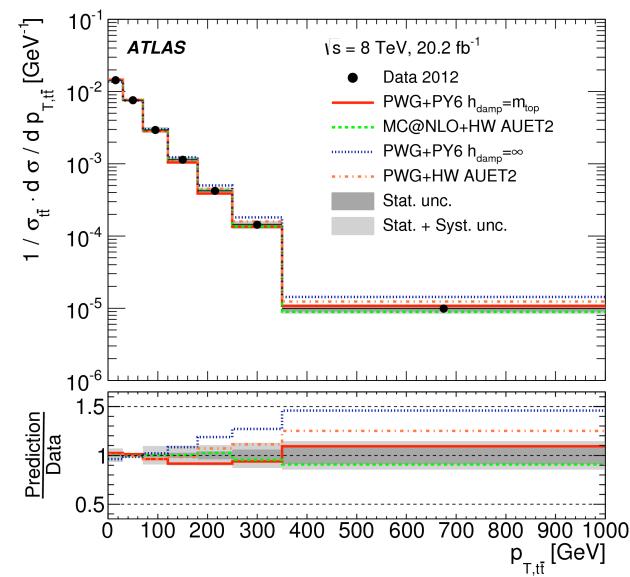
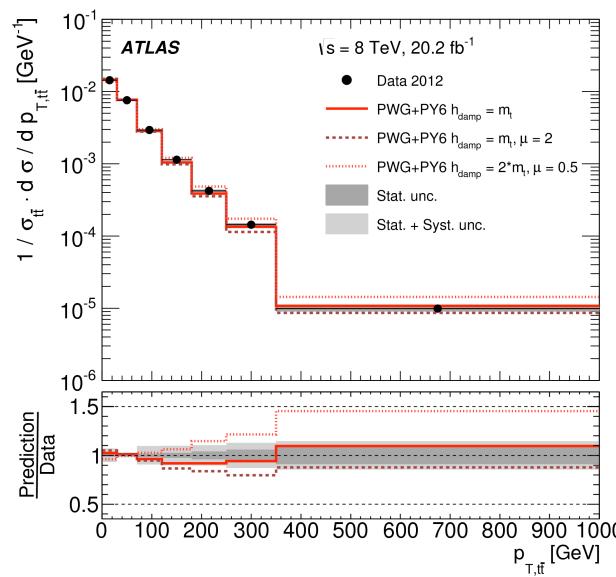
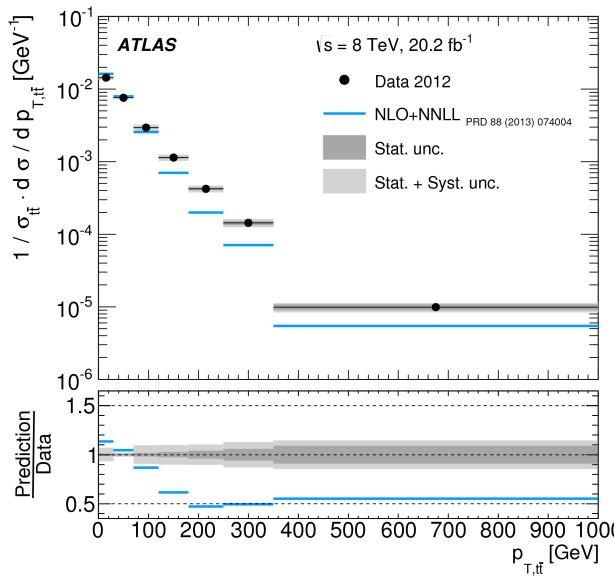
- Measure  $t\bar{t}$  observables in dilepton channel
- No top reconstruction needed (only  $t\bar{t}$ -system considered)
- Unfolded to parton-level; useful for tests of pQCD, MC generators and PDFs
- Dominant uncertainties from top modeling

$p_T(t\bar{t})$ ,  $m(t\bar{t})$ ,  $|y(t\bar{t})|$

$p_T(t\bar{t})$ , 8 TeV

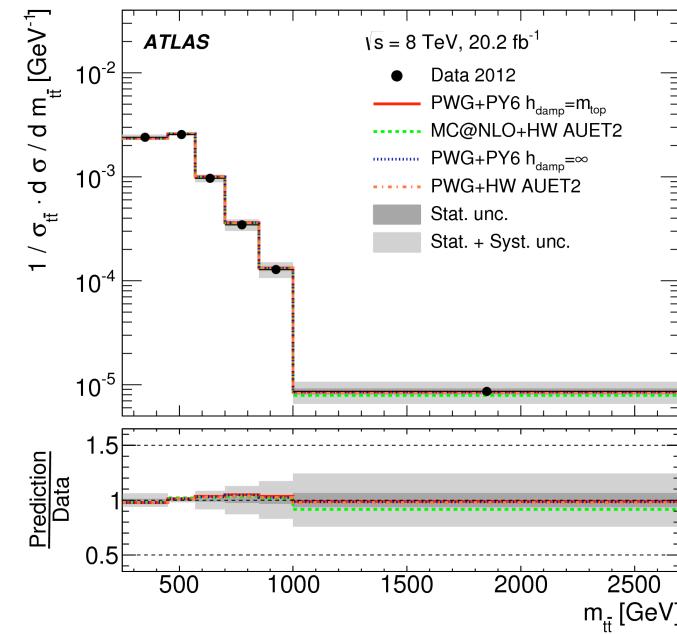
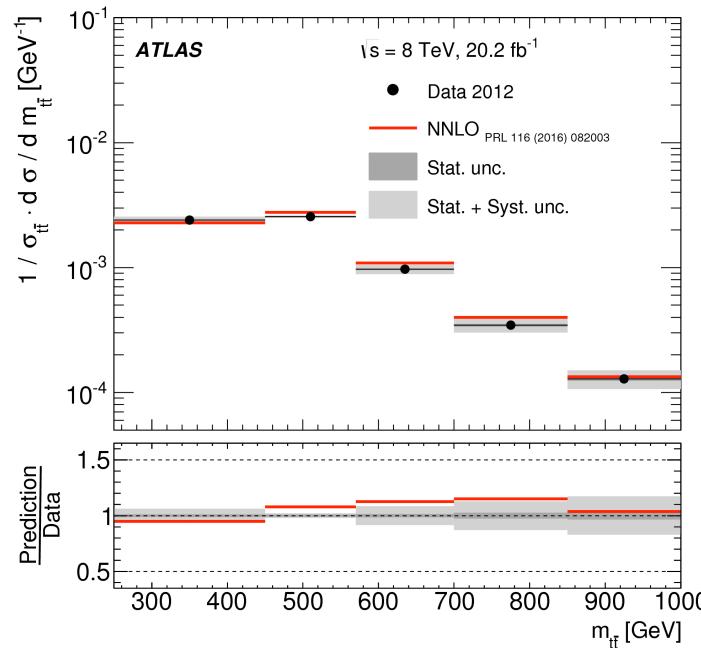


# $t\bar{t}$ differential: dilepton 7 and 8 TeV



- $pT(t\bar{t})$  not well-described by NLO+NNLL at 7 and 8 TeV
- Sensitive to radiation scale and MC tuning parameters
- Sensitive to MC generators and parton shower models

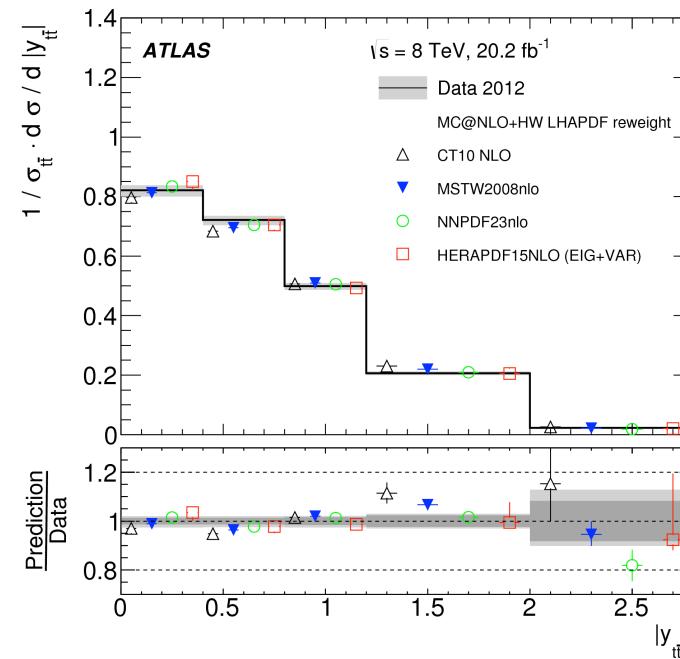
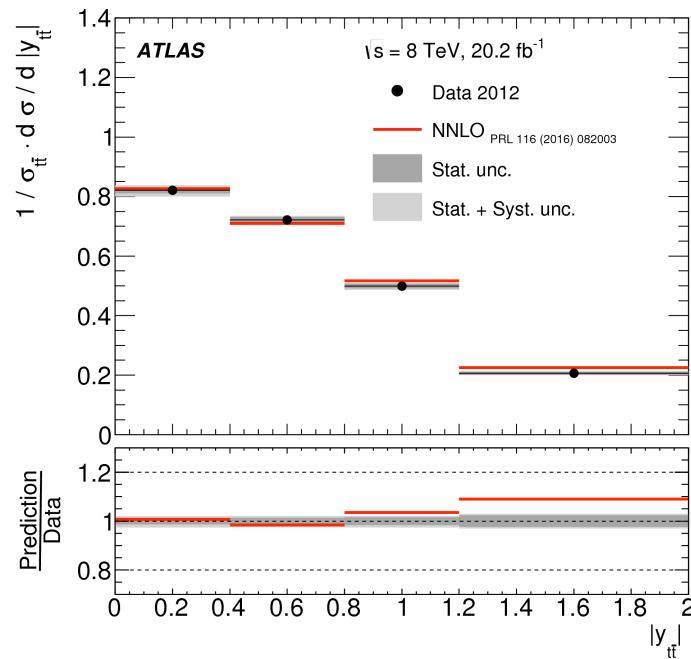
# $t\bar{t}$ differential: dilepton 7 and 8 TeV



| $m_{t\bar{t}}$                 |                     |                  |
|--------------------------------|---------------------|------------------|
| QCD calculation                | $\chi^2/\text{NDF}$ | $p\text{-value}$ |
| NLO+NNLL ( $\sqrt{s} = 7$ TeV) | 5.0/4               | 0.29             |
| NLO+NNLL ( $\sqrt{s} = 8$ TeV) | 5.9/5               | 0.32             |

- $m(t\bar{t})$  is well-described at 7 and 8 TeV

# $t\bar{t}$ differential: dilepton 7 and 8 TeV



- Absolute rapidity shows interesting trends, some tension between data and NNLO calculation at high rapidity
- Sensitive to different PDF sets (CT10 p-value <0.01)

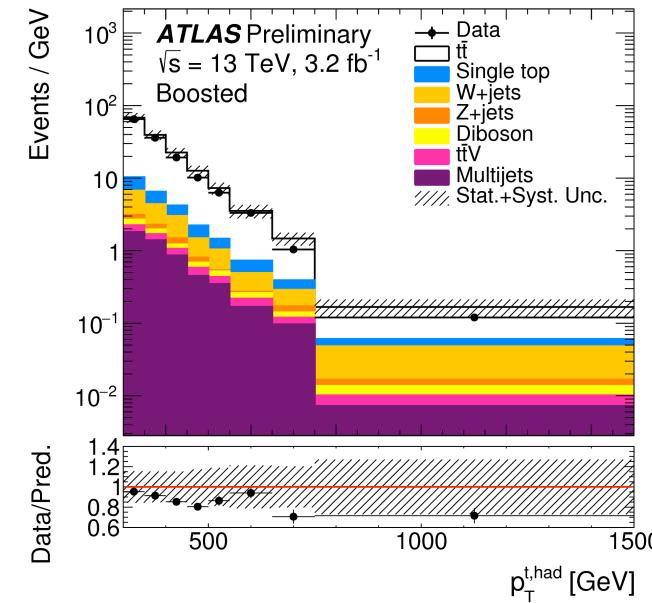
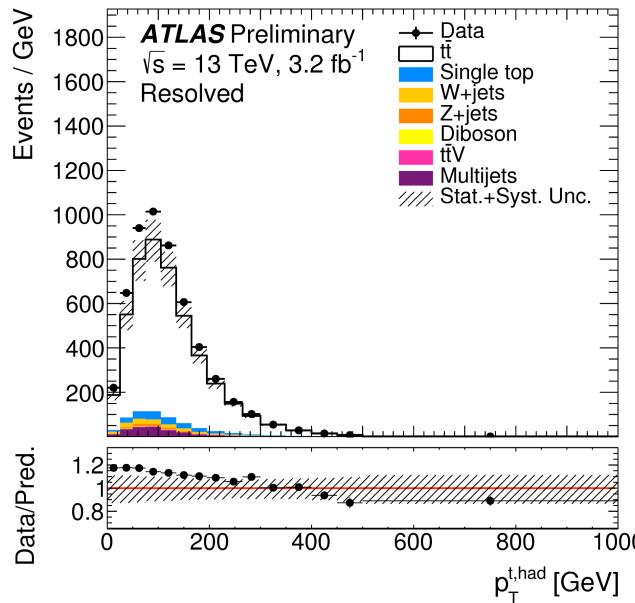
# $t\bar{t}$ differential: l+jets 13 TeV

## Main features

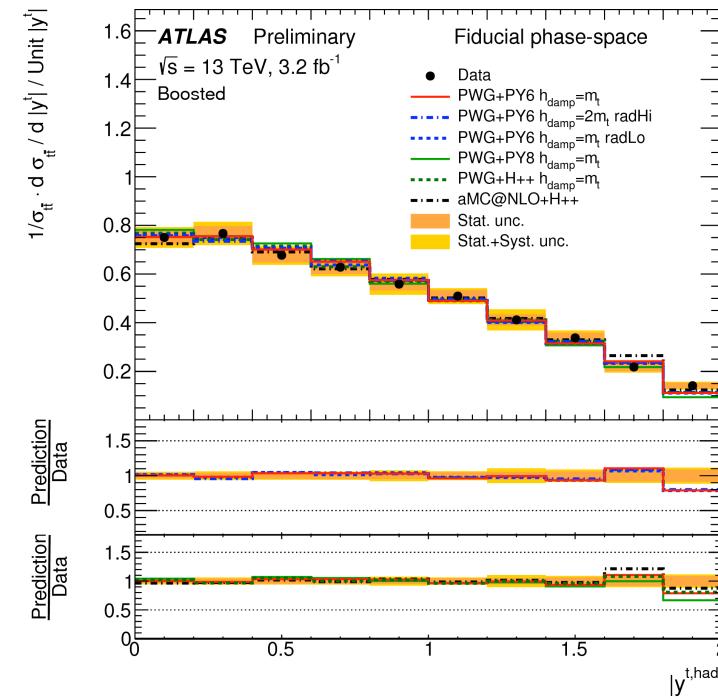
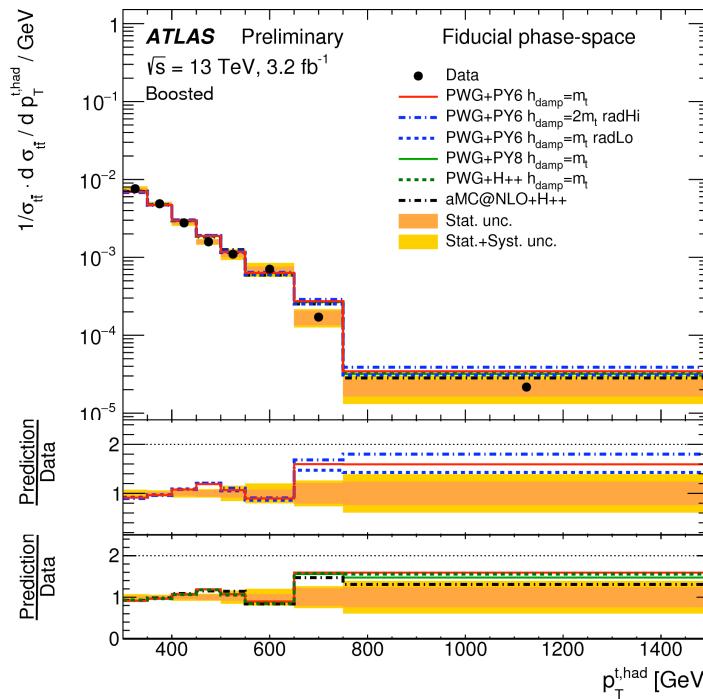
$p_T(t)$ ,  $|y(t)|$

$p_T(t\bar{t})$ ,  $m(t\bar{t})$ ,  $|y(t\bar{t})|$

- Differential cross-sections in resolved and boosted events using lepton+jets channel
- Unfolded to stable particle level, in fiducial phase-space
- Similar measurements and strategy also done at 8 TeV

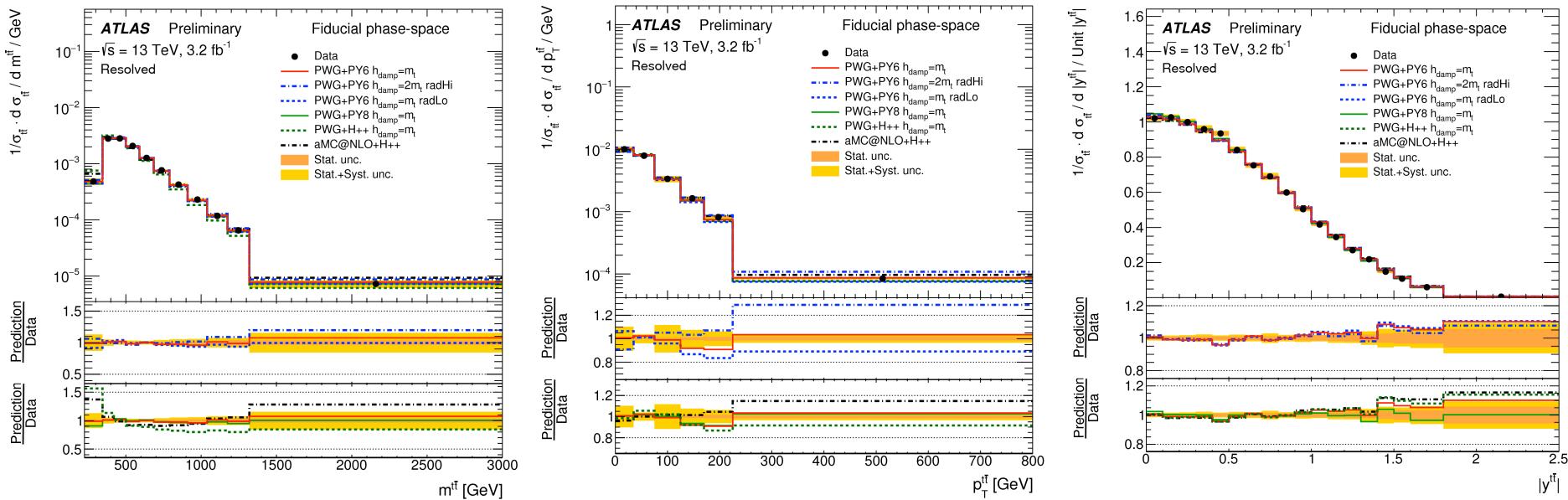


# $t\bar{t}$ differential: l+jets 13 TeV



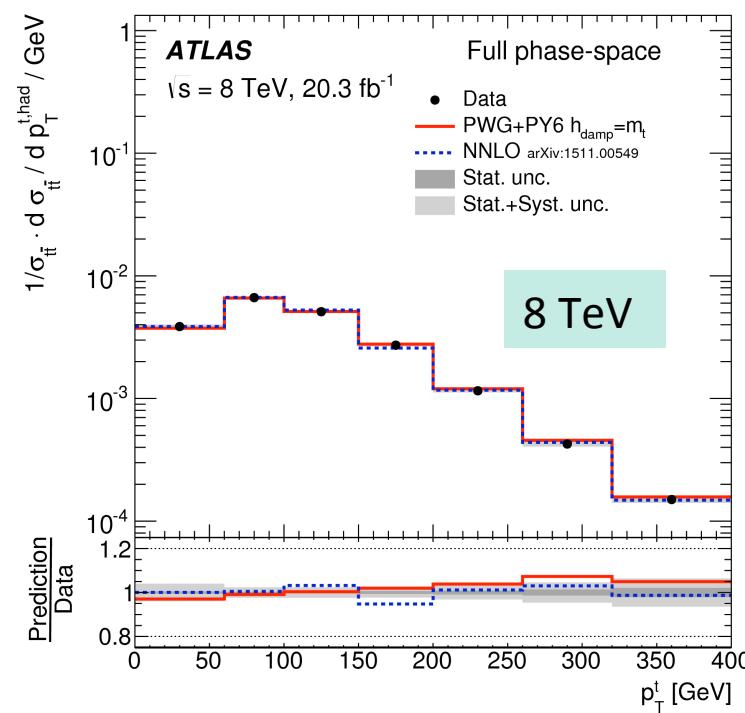
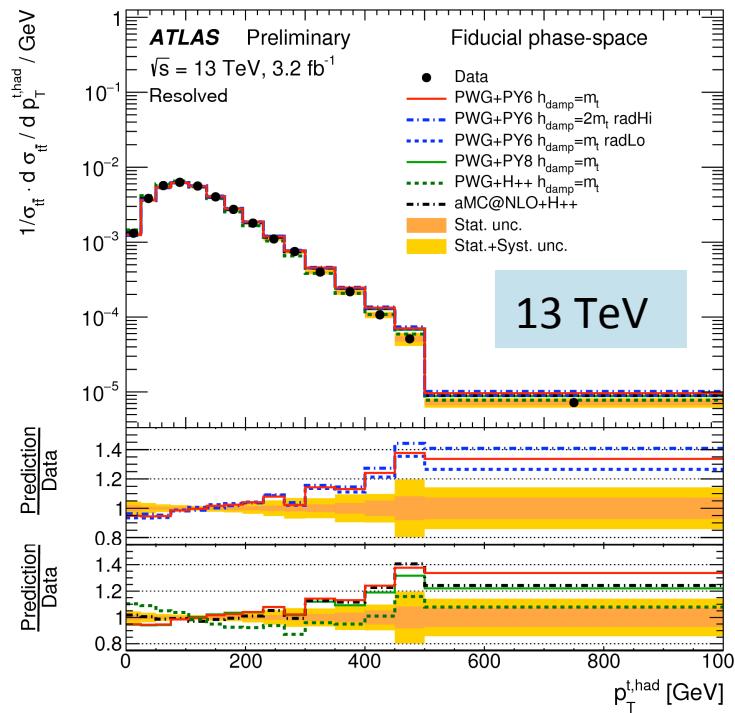
- Good agreement between data and predictions in a wide kinematic region

# $t\bar{t}$ differential: l+jets 13 TeV



- Dominant uncertainties: JES and flavor tagging
- Good agreement between data and predictions in general
- Results also available in absolute cross-sections

# $t\bar{t}$ differential: top $p_T$



- Data tends to be softer than NLO predictions at high  $p_T(t)$ ; similar trends observed in both resolved and boosted cases
- Similar trends also observed in previous results
  - NNLO calculation seems to bring back agreement to data (8 TeV)

# TOP QUARK PAIR PRODUCTION WITH X

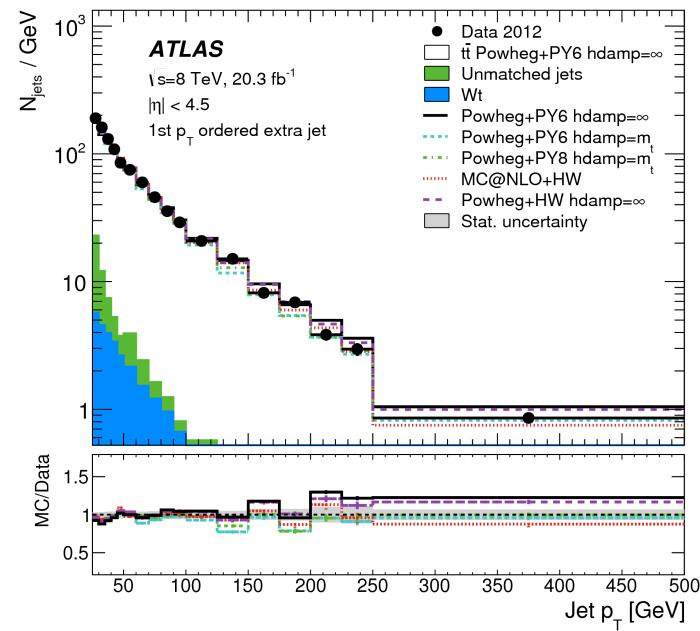
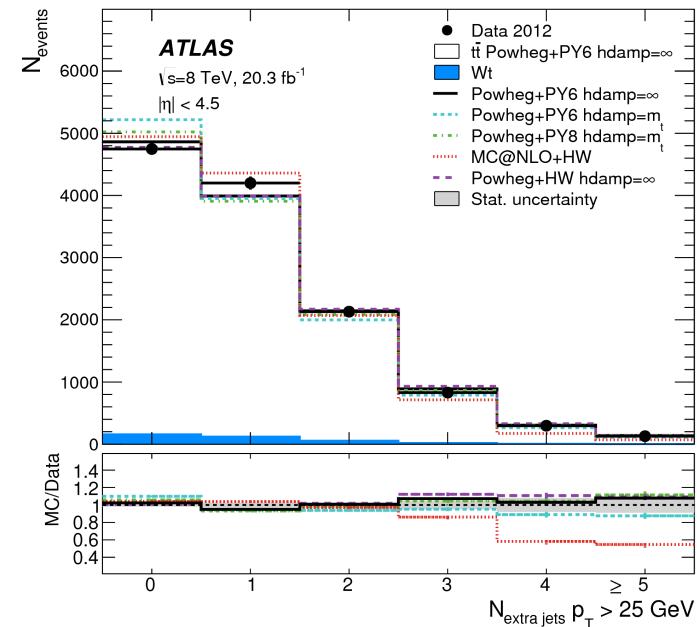
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X = additional jets, W/Z bosons

# tt+jets: e $\mu$ 8 TeV

## Main features

- Measure additional jets in  $t\bar{t}$  events
  - Additional jets = all jets excl. 2 leading b-tagged jets
- Unfolded to particle level
- Measured observables:
  - **Jet multiplicity and jet  $p_T$** 
    - Unfolded simultaneously
  - **Gap fraction**
    - Fraction of events without additional jets above  $p_T$  threshold within a rapidity region



# tt+jets: e $\mu$ 8 TeV

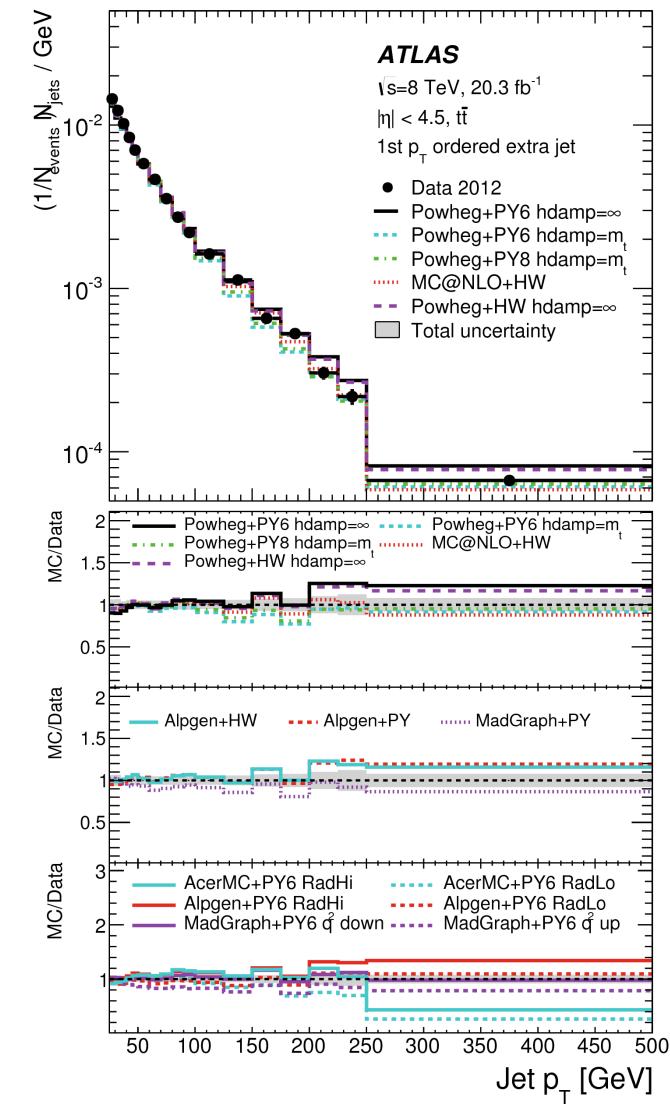
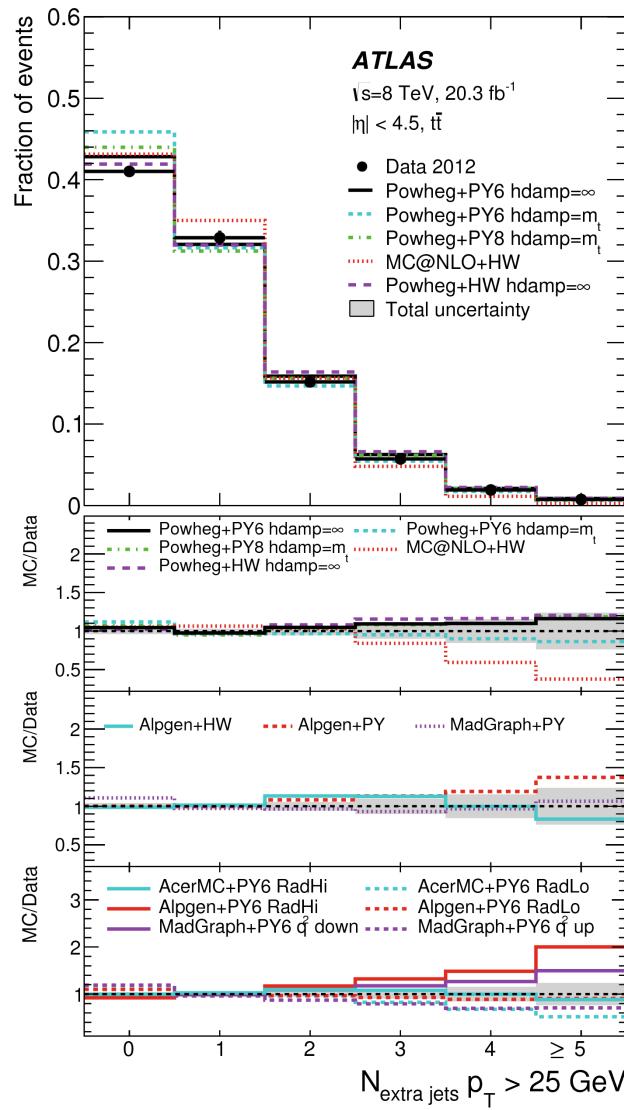
Dominant uncertainties:

- Data statistics (high pT)
- JES, tt modeling (low pT)

NLO MC

LO MC

Radiation setting



# tt+jets: e $\mu$ 8 TeV

## Gap fraction:

- Fraction of events without additional jets above  $p_T$  threshold within a rapidity region
- Sensitive to non-tt hard emission; useful observable for constraining radiation systematics

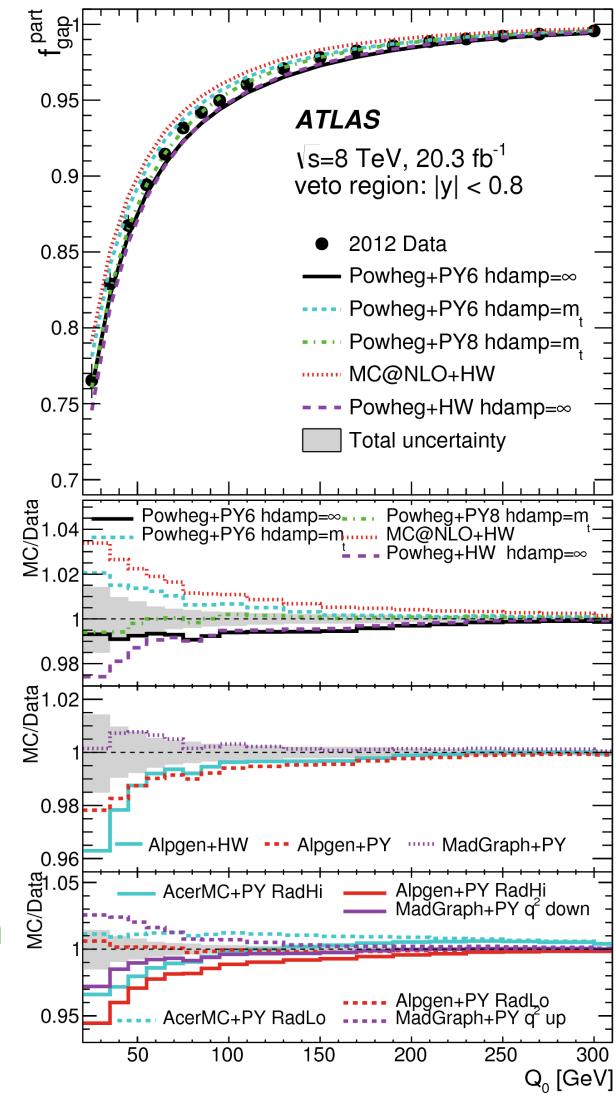
## Dominant uncertainties:

- JES (low  $p_T$ )
- tt modeling and statistics (high  $p_T$ )

NLO MC

LO MC

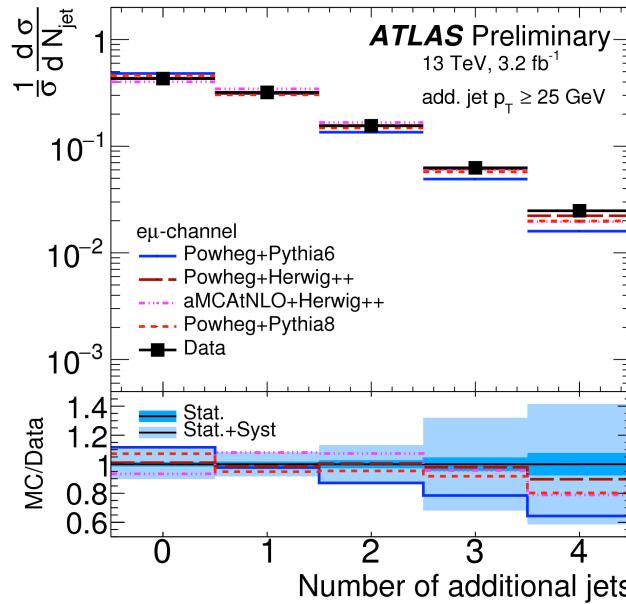
Radiation setting



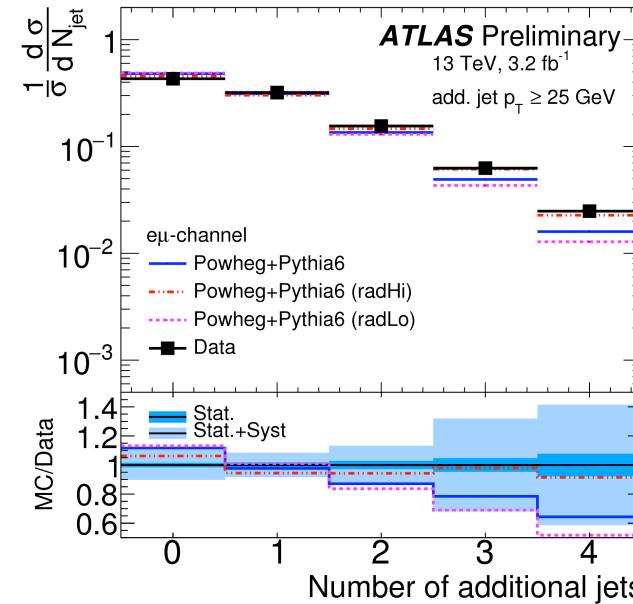
# tt+jets: dilepton 13 TeV

## Main features

- Measure additional jet multiplicities with dilepton channel
- Dominant uncertainties from JES and  $t\bar{t}$  modeling
- Results: Powheg+Pythia6 (ATLAS nominal) may have too little extra radiation?



## Additional jet multiplicities



# $t\bar{t}+W/Z$ : 13 TeV

## Motivation

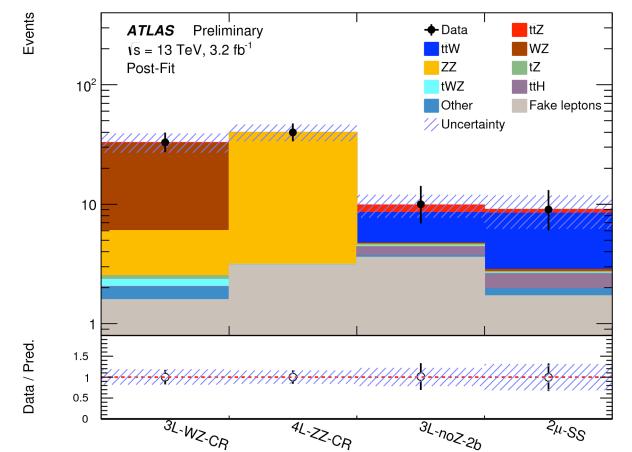
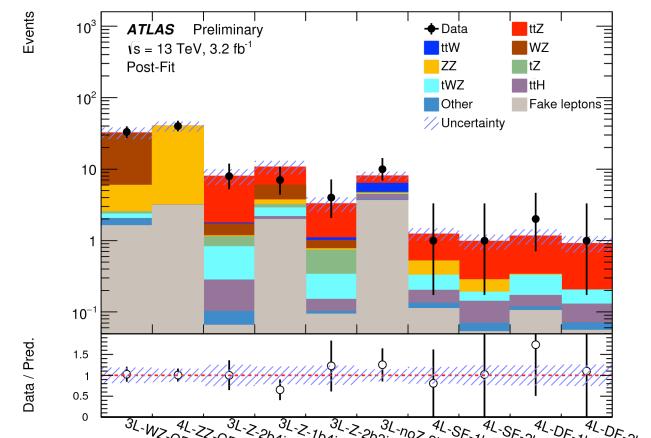
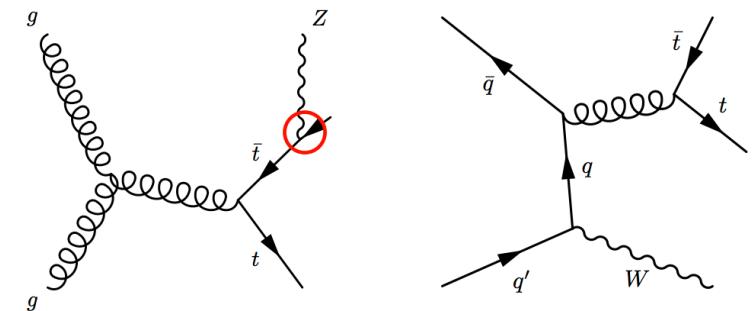
- $t\bar{t}Z$ : probe  $tZ$  coupling
- $t\bar{t}W$ : background to many searches

## Main features

- Use 2(SS), 3 or 4 leptons
- Separate fit for  $t\bar{t}Z$  and  $t\bar{t}W$

## Results

- $\sigma_{t\bar{t}Z} = 0.9 \pm 0.3 \text{ pb}$
- $\Sigma_{t\bar{t}W} = 1.4 \pm 0.8 \text{ pb}$ 
  - Still statistically limited
- NLO prediction (JHEP 07 (2014) 079)
  - $\sigma_{t\bar{t}Z} = 0.76 \text{ pb} \pm 11\% \text{ pb}$
  - $\sigma_{t\bar{t}W} = 0.57 \text{ pb} \pm 11\% \text{ pb}$



# TOP PROPERTIES

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Charge asymmetry, top mass

# Charge asymmetry

- SM QCD high-order processes introduce charge asymmetry
  - Only from quark-induced top production
- Observables at the LHC
  - $t\bar{t}$  charge asymmetry

$$\Delta|y| = |y_t| - |\bar{y}_t|,$$

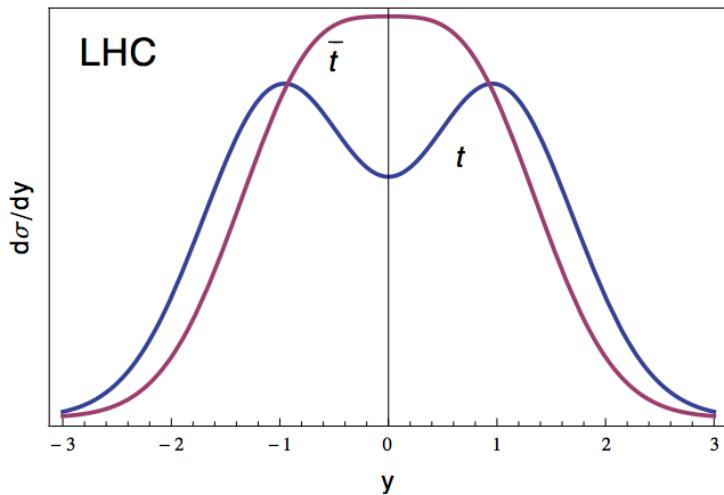
$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)},$$

- Leptonic charge asymmetry (dilepton)

$$\Delta|\eta| = |\eta_{\ell^+}| - |\eta_{\ell^-}|.$$

$$A_C^{\ell\ell} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)},$$

Kühn, Rodrigo, JHEP 1201 (2012) 063  
Bernreuther, Si, Phys. Rev. Lett. D 86 (2012) 034026



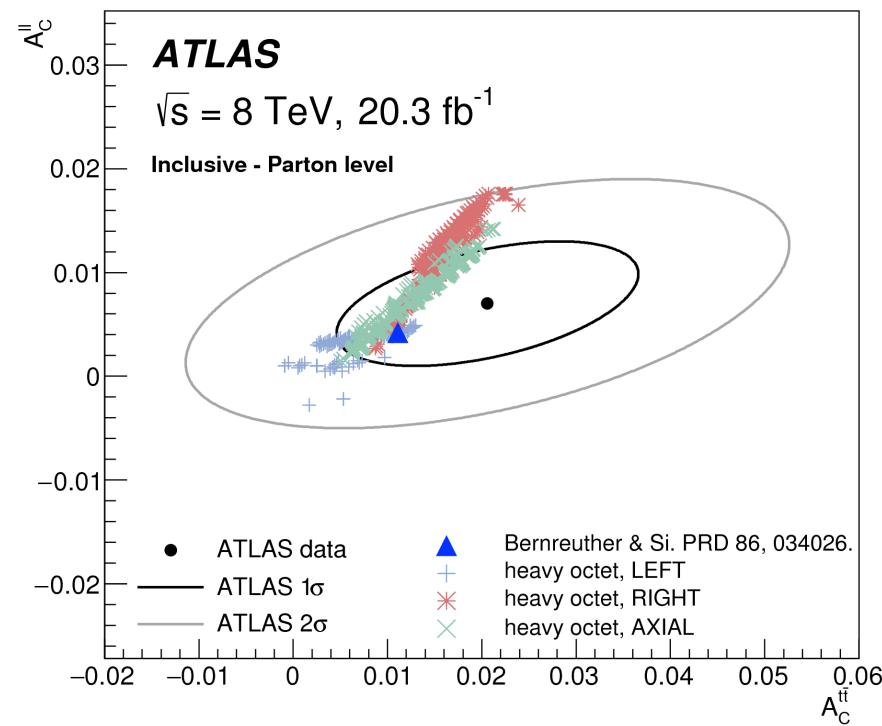
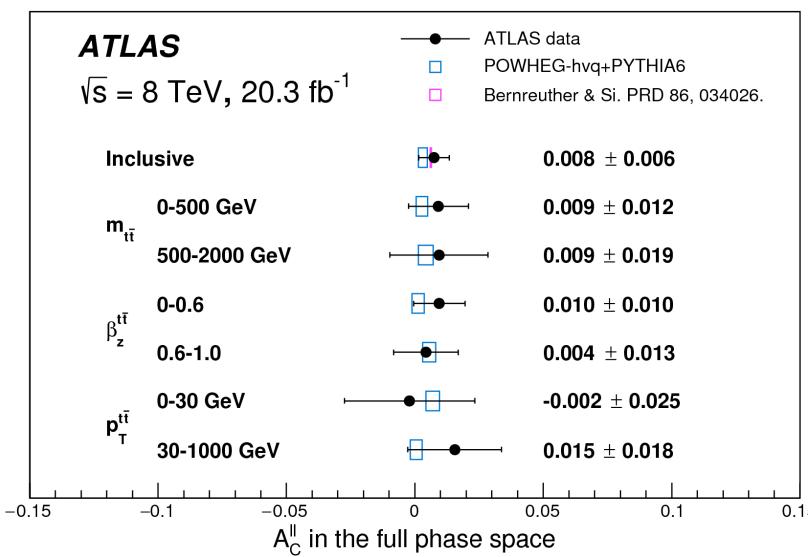
NLO QCD prediction:  
 $A_C^{t\bar{t}} = 0.0111 \pm 0.0004$   
 $A_C^{\ell\ell} = 0.0064 \pm 0.0003$

# Charge asymmetry: dilepton 8 TeV

- Use dilepton  $t\bar{t}$  events ( $l=e, \mu$ )
- Unfolded to full phase-space parton level and fiducial-region particle level
- Inclusive and differential measurements in  $m(t\bar{t})$ ,  $p_T(t\bar{t})$  and  $\beta_z(t\bar{t})$

## Results

- Statistically limited;  
consistent with QCD NLO predictions

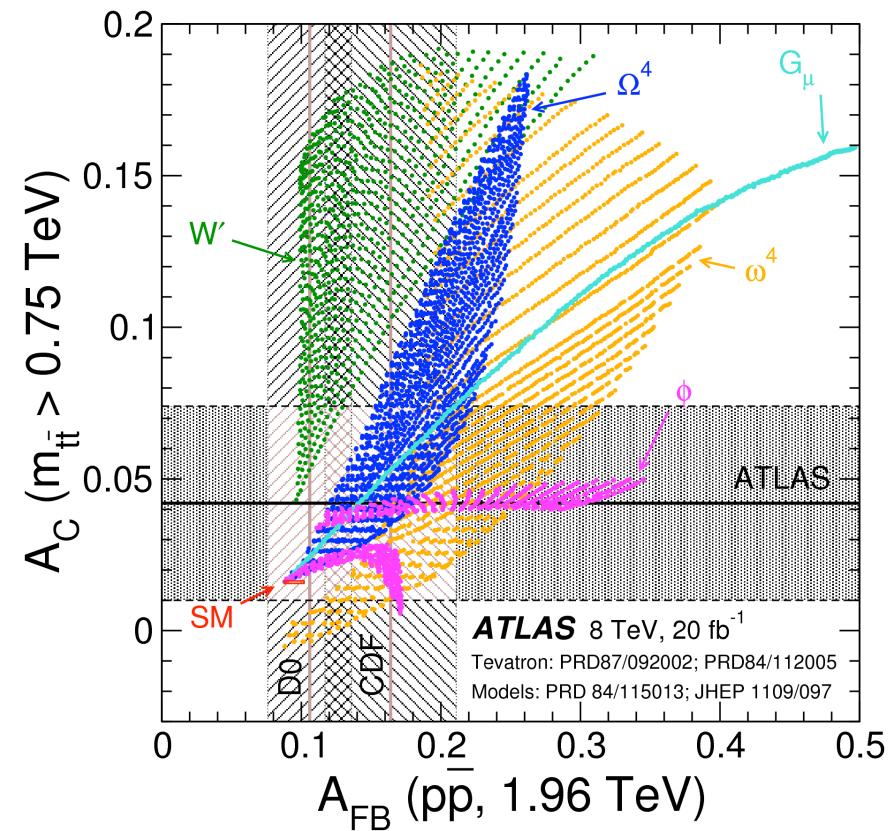
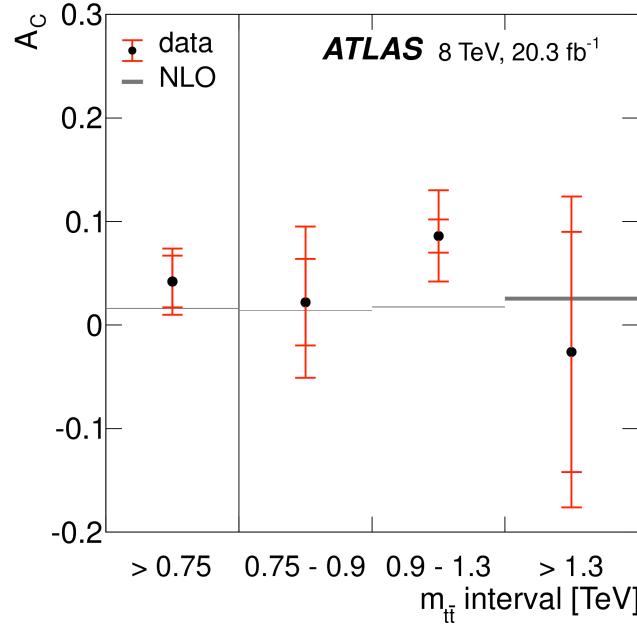


# Charge asymmetry: boosted 8 TeV

- Boosted  $t\bar{t}$  + jets events with  $m(t\bar{t}) > 750$  GeV and  $-2 < |\Delta y| < 2$
  - Unfolded to parton level
  - Inclusive and differential measurements in high  $m(t\bar{t})$

## Results

- Inclusive:  $A_C = (4.2 \pm 3.2)\%$   
consistent with SM:  $A_C = (1.60 \pm 0.04)\%$

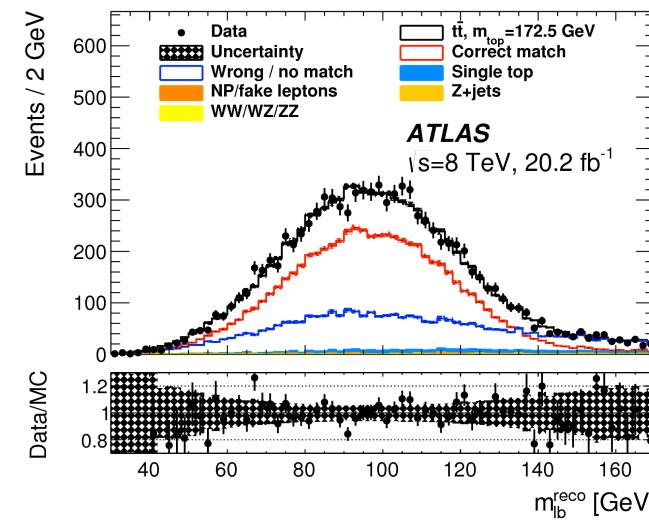
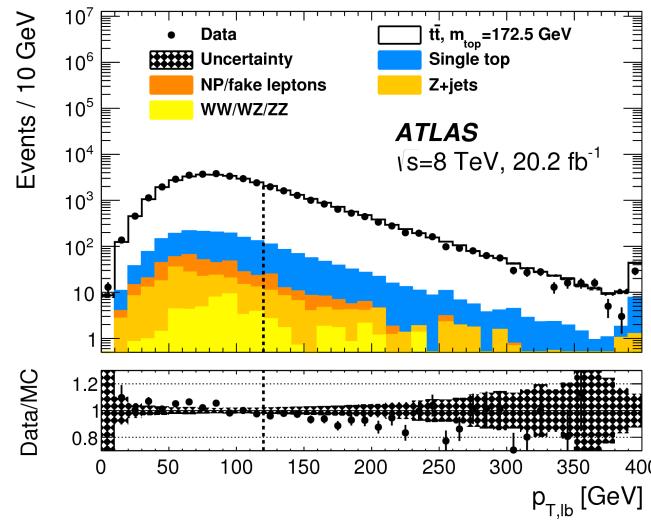


# Top mass: dilepton 8 TeV

- Use dilepton  $t\bar{t}$  events ( $l=e, \mu$ )
- Template method with lepton-b-jet pair mass ( $m_{lb}$ )
- Dominant uncertainties: JES, hadronisation, I/FSR

## Results

- $m_{top} = 172.99 \pm 0.84 \text{ GeV}$
- Combination with previous ATLAS measurements:
  - $m_{top} = 172.84 \pm 0.70 \text{ GeV}$

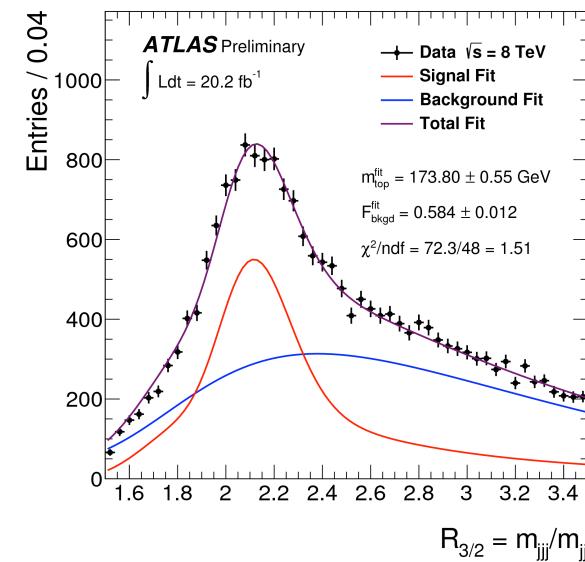
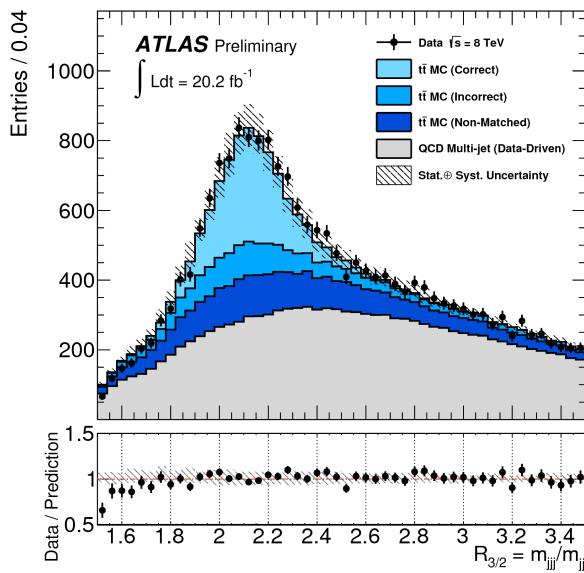


# Top mass: all-hadronic 8 TeV

- Use  $\geq 6$  jets with  $\geq 2$  b-jets  $t\bar{t}$  events
- Templates fit to ratio of 3-jet and di-jet mass ( $R_{3/2}$ )
- QCD multi-jet background modeled with data
- Dominant uncertainties from hadronisation and JES

## Results

$m_{top} = 173.80 \pm 1.15 \text{ GeV}$



# Top mass summary

**ATLAS Preliminary**

$m_{\text{top}}$  summary - Aug. 2016,  $L_{\text{int}} = 4.6 \text{ fb}^{-1} - 20.3 \text{ fb}^{-1}$

all jets Eur. Phys. J. C75 (2015) 158  
 $L_{\text{int}} = 4.6 \text{ fb}^{-1}$

single top\* CONF-2014-055  
 $L_{\text{int}} = 20.3 \text{ fb}^{-1}$

→ l+jets Eur. Phys. J. C75 (2015) 330  
 $L_{\text{int}} = 4.7 \text{ fb}^{-1}$

→ dilepton Eur. Phys. J. C75 (2015) 330  
 $L_{\text{int}} = 4.7 \text{ fb}^{-1}$

→ dilepton arXiv:1606.02179  
 $L_{\text{int}} = 20.2 \text{ fb}^{-1}$

all jets\* CONF-2016-064  
 $L_{\text{int}} = 20.2 \text{ fb}^{-1}$

$\sigma(t\bar{t})$  dilepton Eur. Phys. J. C74 (2014) 3109  
 $L_{\text{int}} = 4.6-20.3 \text{ fb}^{-1}$

$\sigma(t\bar{t}+1\text{-jet})$  JHEP 10 (2015) 121  
 $L_{\text{int}} = 4.6 \text{ fb}^{-1}$

**ATLAS Comb. June 2016** (arXiv:1606.02179)  
 $172.84 \pm 0.70$

$m_{\text{top}}$  ± tot. (stat. ± JSF ± bJSF ± syst.)  
 $175.1 \pm 1.8 \quad (1.4 \pm 1.2)$

$172.2 \pm 2.1 \quad (0.7 \pm 2.0)$

$172.3 \pm 1.3 \quad (0.2 \pm 0.2 \pm 0.7 \pm 1.0)$

$173.8 \pm 1.4 \quad (0.5 \pm 1.3)$

$173.0 \pm 0.8 \quad (0.4 \pm 0.7)$

$173.8 \pm 1.2 \quad (0.6 \pm 1.0)$

**NEW**

$172.9 \pm 2.5$

$173.7 \pm 2.3$

--- ATLAS Comb. ± 1 $\sigma$

— stat. uncertainty

— stat. ⊕ JSF ⊕ bJSF uncertainty

— total uncertainty

\*Preliminary, → Input to comb.

**NEW**

165

170

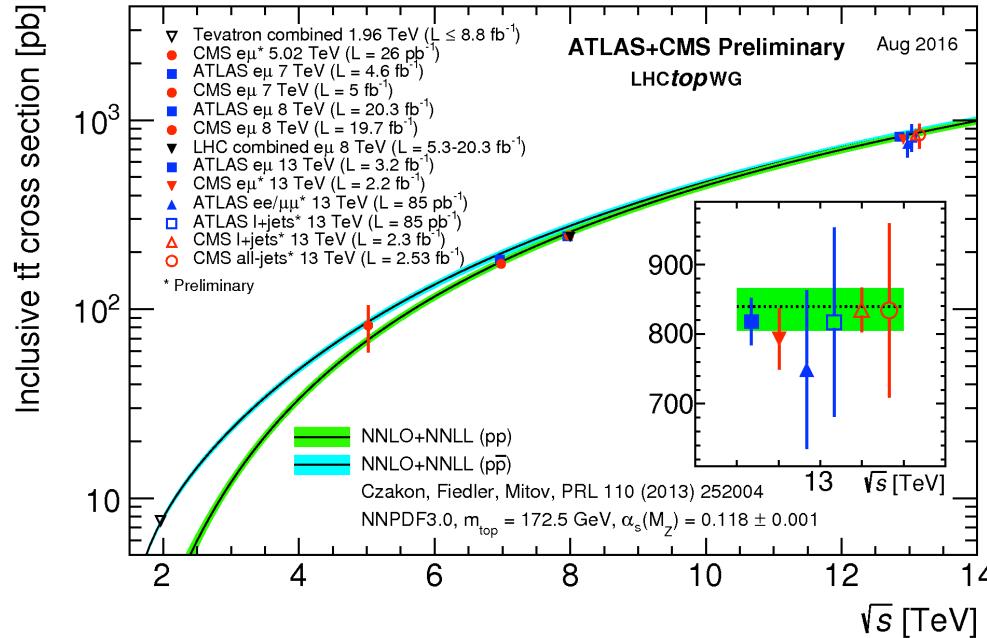
175

180

185

$m_{\text{top}}$  [GeV]

# Summary



- ATLAS has a rich and robust program of measurements in top quark pair production and properties at 7, 8 and 13 TeV
- These results are probing a wide range of phase-spaces in top quark pair production and test QCD at higher-order levels
- New ATLAS data will continue to refine our understanding of the SM and beyond.

# References

## New results:

### **t̄t production:**

- Inclusive cross-section: eμ 13 TeV ([arXiv:1606.02699](#))
- Differential cross-sections: dilepton 7+8 TeV ([arXiv:1607.07281](#))
- Differential cross-sections: l+jets 13 TeV ([ATLAS-CONF-2016-040](#))
- Top pair production with jets: emu 8 TeV ([arXiv:1606.09490](#))
- Top pair production with jets: dilepton 13 TeV ([ATLAS-CONF-2015-065](#))
- Top pair production with vector boson: 13 TeV ([ATLAS-CONF-2016-003](#))

### **Top properties:**

- Charge asymmetry: l+jets 8 TeV ([Eur. Phys. J. C76 \(2016\) 87](#))
- Charge asymmetry: boosted 8 TeV ([Phys. Lett. B \(2016\) 756](#))
- Charge asymmetry: dilepton 8 TeV ([arXiv:1604.05538](#))
- Top mass: dilepton 8 TeV ([arXiv:1606.02179](#))
- Top mass: all-hadronic 8 TeV ([ATLAS-CONF-2016-064](#))

All ATLAS Top results: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults>

# EXTRA SLIDES

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# Full references

New results:

- Inclusive cross-section: dilepton 13 TeV ([arXiv:1606.02699](https://arxiv.org/abs/1606.02699))
- Differential cross-sections: dilepton 7+8 TeV ([arXiv:1607.07281](https://arxiv.org/abs/1607.07281))
- Differential cross-sections: l+jets 8 TeV ([arXiv:1511.04716](https://arxiv.org/abs/1511.04716))
- Differential cross-sections: boosted 8 TeV ([Phys. Rev. D93 \(2016\) 032009](https://doi.org/10.1103/PhysRevD.93.032009))
- Differential cross-sections: l+jets 13 TeV ([ATLAS-CONF-2016-040](#))
- Top pair production with jets 13 TeV ([ATLAS-CONF-2015-065](#))
- Top pair production with jets 8 TeV ([arXiv:1606.09490](https://arxiv.org/abs/1606.09490))
- Top pair production with heavy flavor 8 TeV ([Eur. Phys. J. C76 \(2016\) 11](https://doi.org/10.1140/epjc/v76n11-16067-1))
- Top pair production with vector boson: 13 TeV ([ATLAS-CONF-2016-003](#))
- Four top production: 13 TeV ([ATLAS-CONF-2016-020](#))
- Top mass: dilepton 8 TeV ([arXiv:1606.02179](https://arxiv.org/abs/1606.02179))
- Top mass: all-hadronic 8 TeV ([ATLAS-CONF-2016-064](#))
- Charge asymmetry: l+jets 8 TeV ([Eur. Phys. J. C76 \(2016\) 87](https://doi.org/10.1140/epjc/v76n11-16067-1))
- Charge asymmetry: boosted 8 TeV ([Phys. Lett. B \(2016\) 756](https://doi.org/10.1016/j.physlettb.2016.07.056))
- Charge asymmetry: dilepton 8 TeV ([arXiv:1604.05538](https://arxiv.org/abs/1604.05538))
- FCNC t->Hq: 8 TeV ([JHEP 12 \(2015\) 061](https://doi.org/10.1007/JHEP12(2015)061))
- FCNC t->Zq: 8 TeV ([Eur. Phys. J. C76 \(2016\) 12](https://doi.org/10.1140/epjc/v76n12-16067-1))

All ATLAS Top results: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults>

# RUN 2 VS RUN 1

Courtesy by A. Lister

\* Will be updated with final Run1 lumi

13 TeV

| Uncertainty (inclusive $\sigma_{t\bar{t}}$ ) | $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%] |
|--|---|
| Data statistics                              | 0.9   |
| $t\bar{t}$ NLO modelling                     | 0.8   |
| $t\bar{t}$ hadronisation                     | 2.8   |
| Initial- and final-state radiation           | 0.4   |
| $t\bar{t}$ heavy-flavour production          | 0.4   |
| Parton distribution functions                | 0.5   |
| Single-top modelling                         | 0.3   |
| Single-top/ $t\bar{t}$ interference          | 0.6   |
| Single-top $Wt$ cross-section                | 0.5   |
| Diboson modelling                            | 0.1   |
| Diboson cross-sections                       | 0.0   |
| $Z+jets$ extrapolation                       | 0.2   |
| Electron energy scale/resolution             | 0.2   |
| Electron identification                      | 0.3   |
| Electron isolation                           | 0.4   |
| Muon momentum scale/resolution               | 0.0   |
| Muon identification                          | 0.4   |
| Muon isolation                               | 0.3   |
| Lepton trigger                               | 0.2   |
| Jet energy scale                             | 0.3   |
| Jet energy resolution                        | 0.2   |
| $b$ -tagging                                 | 0.3   |
| Misidentified leptons                        | 0.6   |
| Analysis systematics                         | 3.3   |
| Integrated luminosity                        | 2.3   |
| LHC beam energy                              | 1.5   |
| Total uncertainty                            | 4.4   |

7 TeV 8 TeV

| $\sqrt{s}$                                   | $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%) | $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%) |
|--|---|---|
| Data statistics                              | 1.69  | 0.71  |
| $t\bar{t}$ modelling                         | 1.43  | 1.22  |
| Parton distribution functions                | 1.04  | 1.13  |
| QCD scale choice                             | 0.30  | 0.30  |
| Single-top modelling                         | 0.34  | 0.42  |
| Single-top/ $t\bar{t}$ interference          | 0.22  | 0.15  |
| Single-top $Wt$ cross-section                | 0.72  | 0.69  |
| Diboson modelling                            | 0.12  | 0.13  |
| Diboson cross-sections                       | 0.03  | 0.03  |
| $Z+jets$ extrapolation                       | 0.05  | 0.02  |
| Electron energy scale/resolution             | 0.22  | 0.51  |
| Electron identification                      | 0.13  | 0.41  |
| Muon momentum scale/resolution               | 0.14  | 0.02  |
| Muon identification                          | 0.30  | 0.42  |
| Lepton isolation                             | 0.74  | 0.37  |
| Lepton trigger                               | 0.19  | 0.16  |
| Jet energy scale                             | 0.27  | 0.52  |
| Jet energy resolution                        | 0.30  | 0.51  |
| Jet reconstruction/vertex fraction           | 0.06  | 0.03  |
| $b$ -tagging                                 | 0.41  | 0.40  |
| Misidentified leptons                        | 0.41  | 0.34  |
| Analysis systematics ( $\sigma_{t\bar{t}}$ ) | 2.27  | 2.26  |
| Integrated luminosity                        | 1.98  | 3.10 *  |
| LHC beam energy                              | 1.79  | 1.72  |
| Total uncertainty ( $\sigma_{t\bar{t}}$ )    | 3.89  | 4.27  |

# t̄t differential cross-sections: dilepton 7+8 TeV

“t̄t” reconstruction:

$$\begin{aligned} E_{\text{total}} &= E(\ell_1) + E(\ell_2) + E(j_1) + E(j_2) + E_T^{\text{miss}} \\ p_x &= p_x(\ell_1) + p_x(\ell_2) + p_x(j_1) + p_x(j_2) + E_x^{\text{miss}} \\ p_y &= p_y(\ell_1) + p_y(\ell_2) + p_y(j_1) + p_y(j_2) + E_y^{\text{miss}} \\ p_z &= p_z(\ell_1) + p_z(\ell_2) + p_z(j_1) + p_z(j_2) \end{aligned}$$

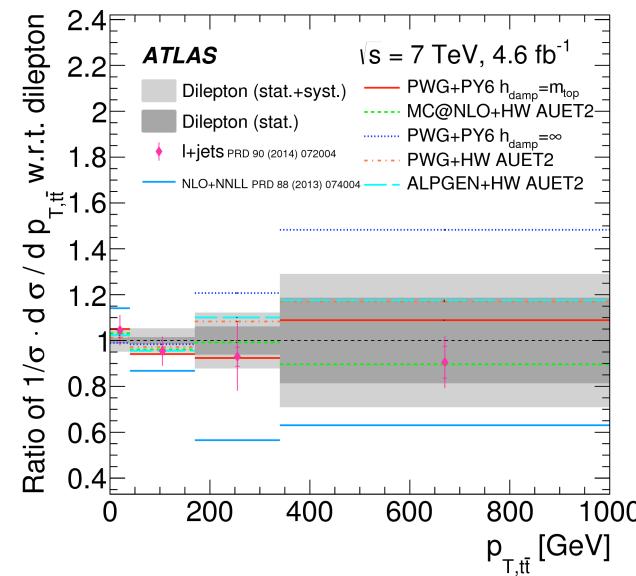
# t̄t differential cross-sections: dilepton 7+8 TeV

Sensitivity to different PDF sets:

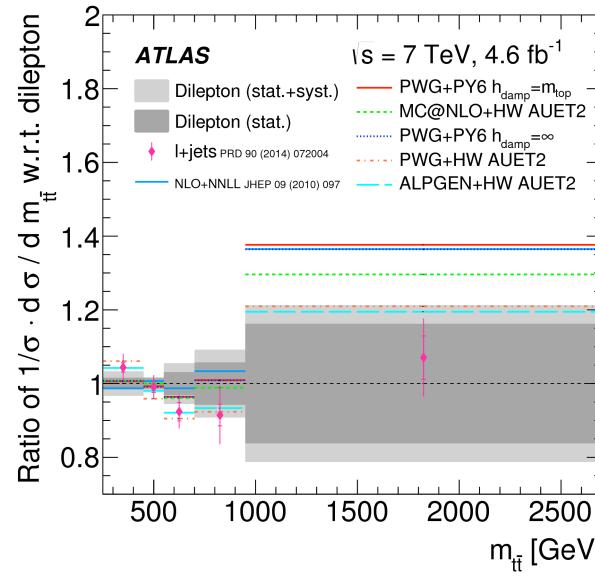
| PDF          | $m_{t\bar{t}}$      |                  | $p_{T,t\bar{t}}$    |                  | $ y_{t\bar{t}} $    |                  |
|--------------|---------------------|------------------|---------------------|------------------|---------------------|------------------|
|              | $\chi^2/\text{NDF}$ | $p\text{-value}$ | $\chi^2/\text{NDF}$ | $p\text{-value}$ | $\chi^2/\text{NDF}$ | $p\text{-value}$ |
| CT10 NLO     | 2.0/5               | 0.85             | 0.4/6               | 1.00             | 29.8/4              | <0.01            |
| MSTW2008nlo  | 2.1/5               | 0.83             | 0.6/6               | 1.00             | 11.6/4              | 0.02             |
| NNPDF23nlo   | 2.3/5               | 0.81             | 0.4/6               | 1.00             | 3.2/4               | 0.53             |
| HERAPDF15NLO | 2.4/5               | 0.79             | 2.3/6               | 0.89             | 5.6/4               | 0.23             |

# $t\bar{t}$ differential: dilepton vs l+jets 7 TeV

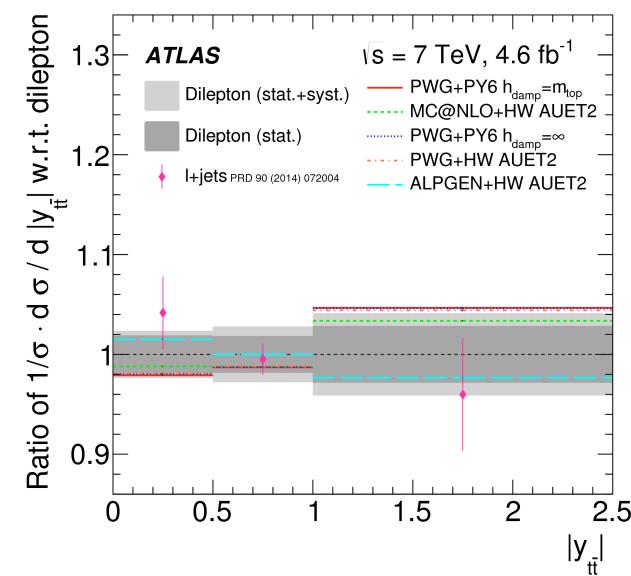
$p_T(t\bar{t})$



$m(t\bar{t})$



$|y(t\bar{t})|$

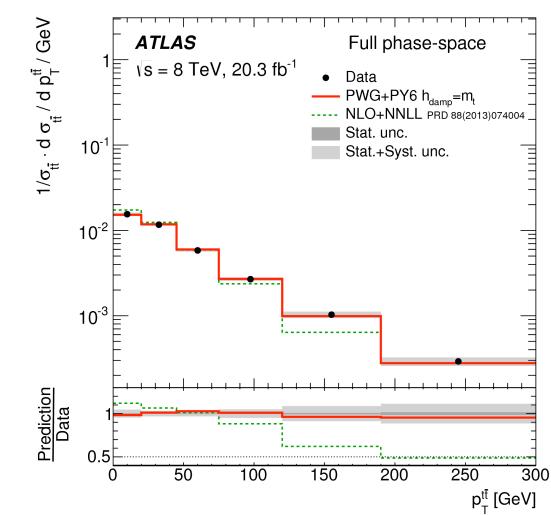
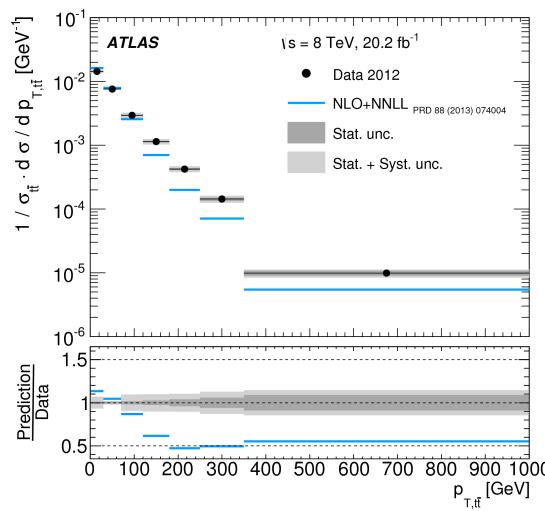


- Run 1 dilepton and l+jets results show similar behaviors
- Dilepton still statistical limited at 7 TeV; improved at 8 TeV

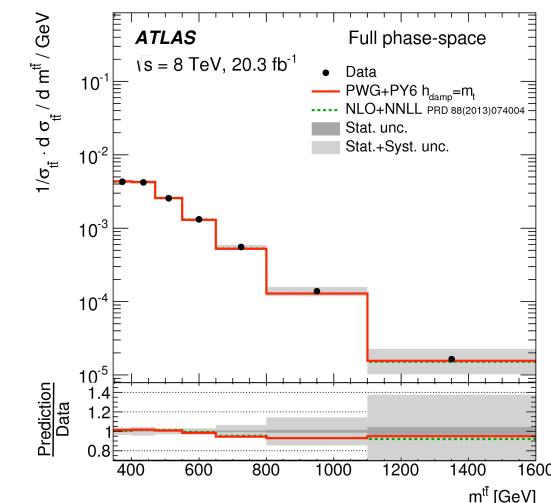
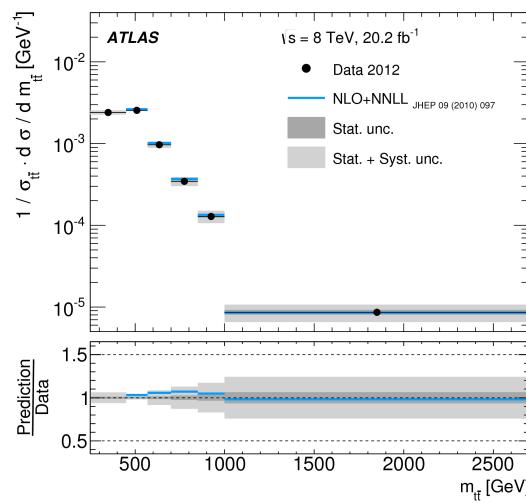
# $t\bar{t}$ differential: dilepton vs l+jets 8 TeV

- Data vs NLO+NNLL

$p_T(t\bar{t})$



$m(t\bar{t})$



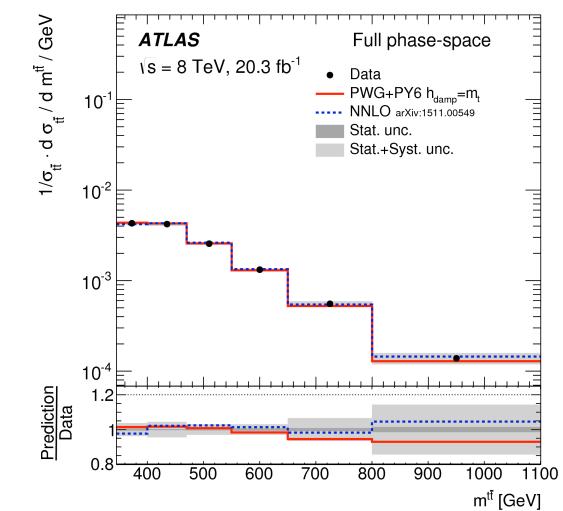
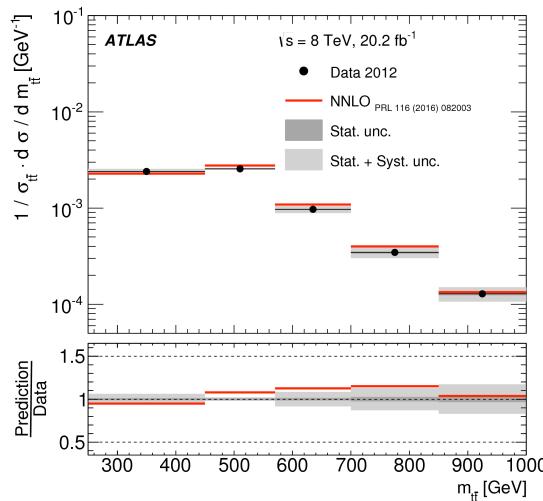
dilepton

l+jets

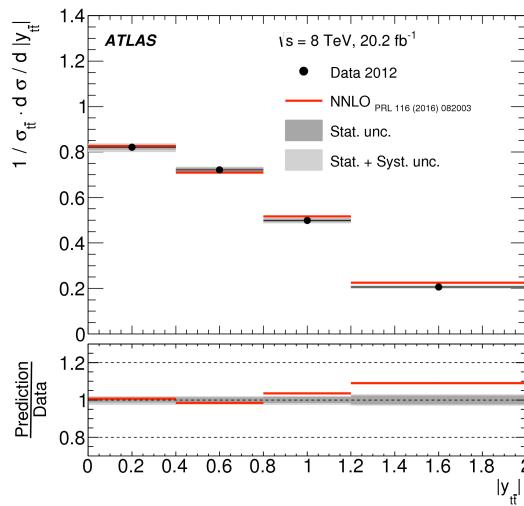
# $t\bar{t}$ differential: dilepton vs l+jets 8 TeV

- Data vs NNLO

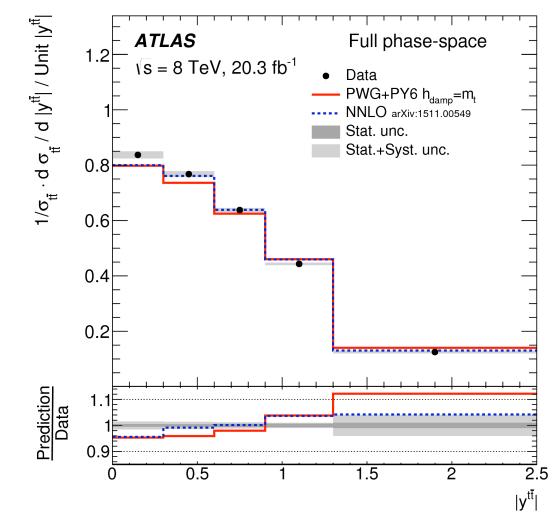
$m(t\bar{t})$



$|y(t\bar{t})|$

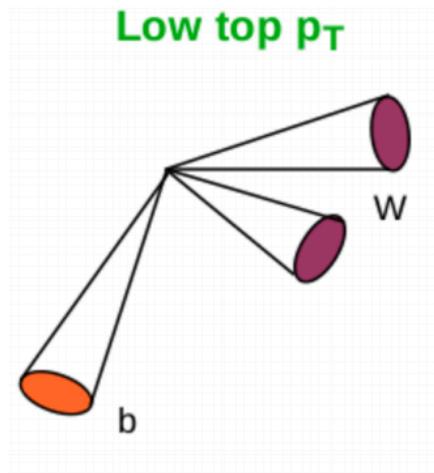


dilepton



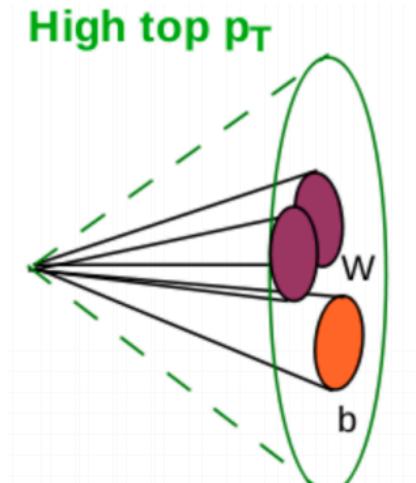
l+jets

# $t\bar{t}$ differential: l+jets 13 TeV



## Resolved Top

- Leptonic Top: Imposes  $W$ -mass constraint to solve for neutrino  $p_z$ . Pairs  $b$ -jet closest in  $\Delta R$  to lepton.
- Hadronic Top: Pair non-tagged jets closest to  $W$  mass + remaining highest  $pT$   $b$ -jet.



## Boosted Top

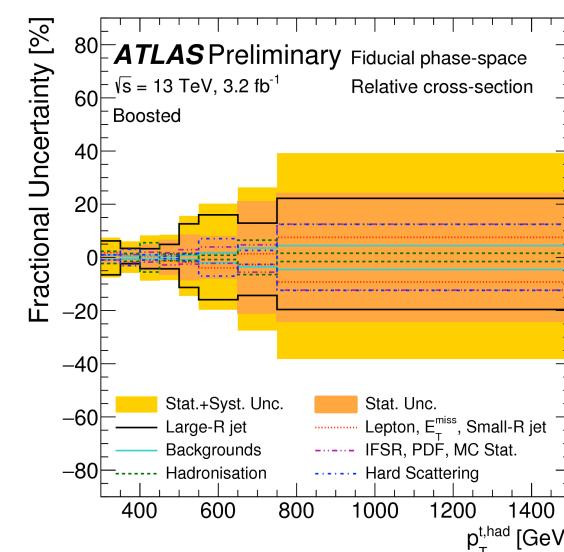
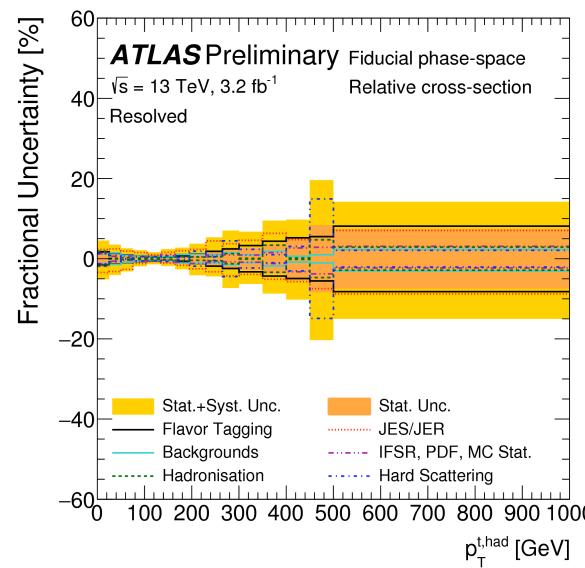
- Hadronic Top: Large- $R$  jet with mass close to  $m(t)$ , trimmed, and top-tagged using calib. jet mass and N-sub-jettiness ratio " $\tau_{32}$ ".

Courtesy by J. Howarth

# $t\bar{t}$ differential: l+jets 13 TeV

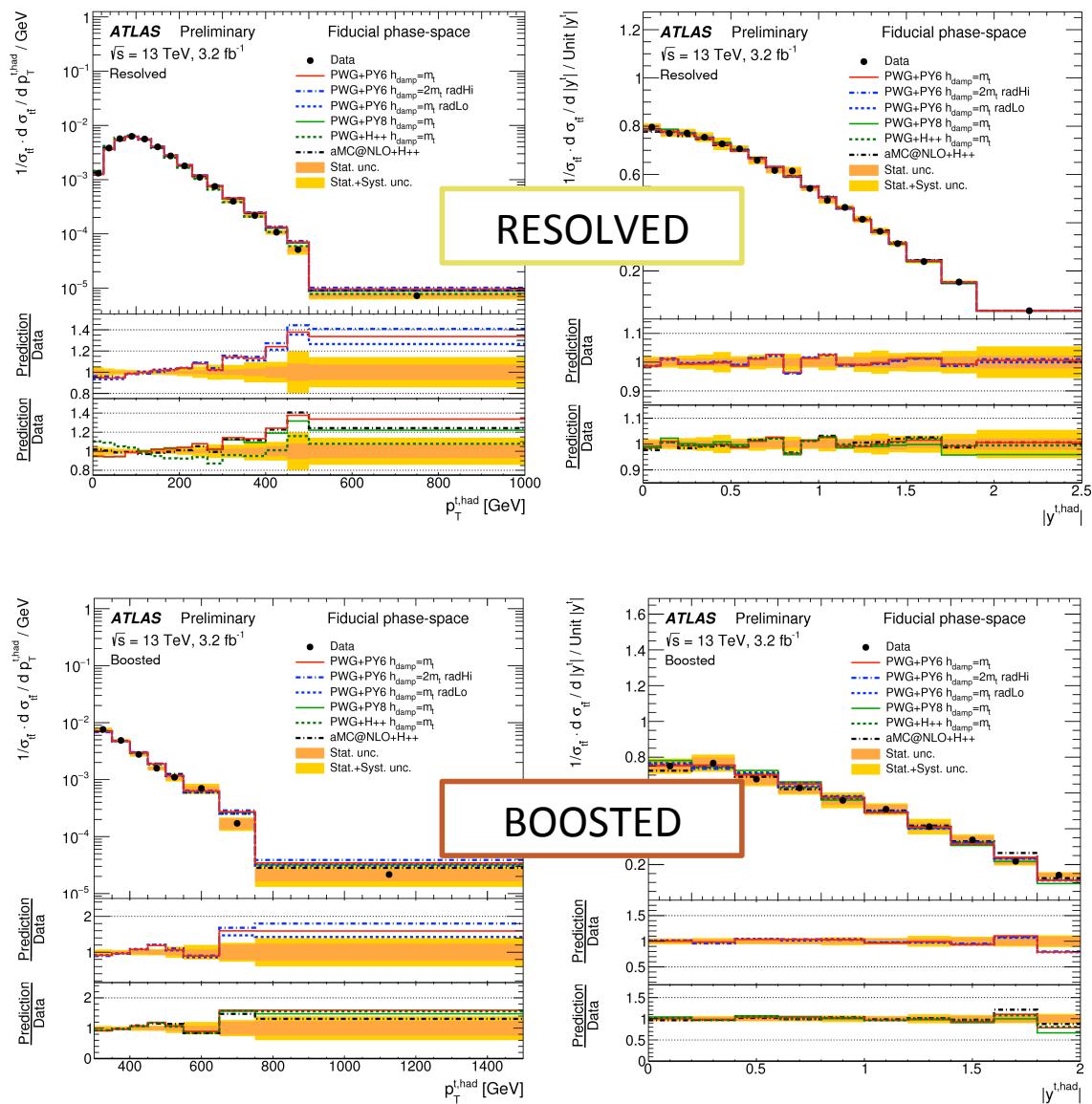
$p_T(t)$

## Uncertainties



# $t\bar{t}$ differential: l+jets 13 TeV

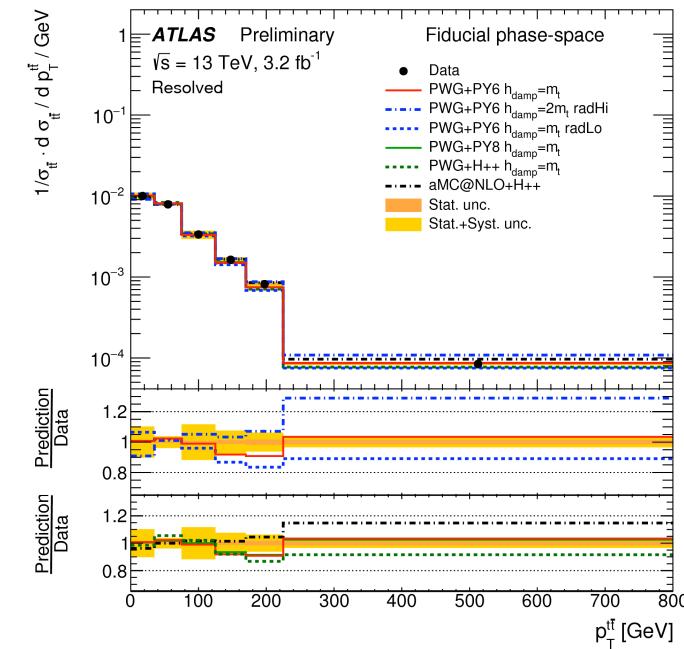
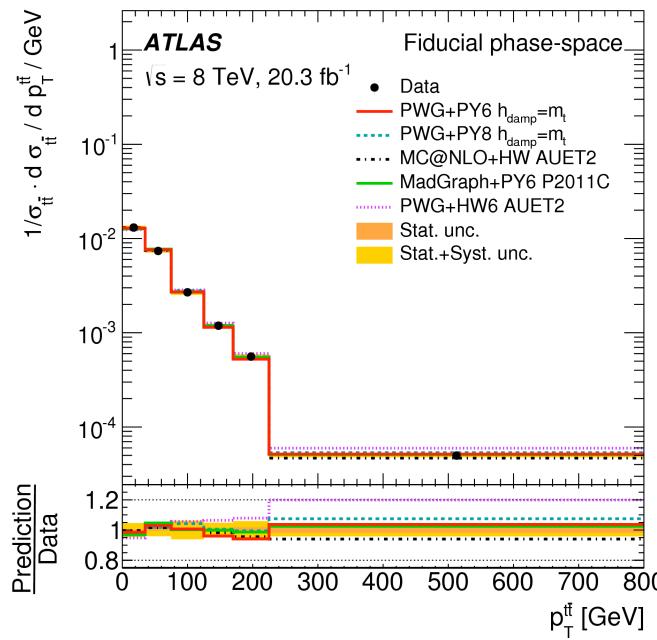
- Good agreement between data and predictions in a wide kinematic region



# $t\bar{t}$ differential: l+jets 8 TeV vs 13 TeV

$p_T(t\bar{t})$

- Fiducial phase-space

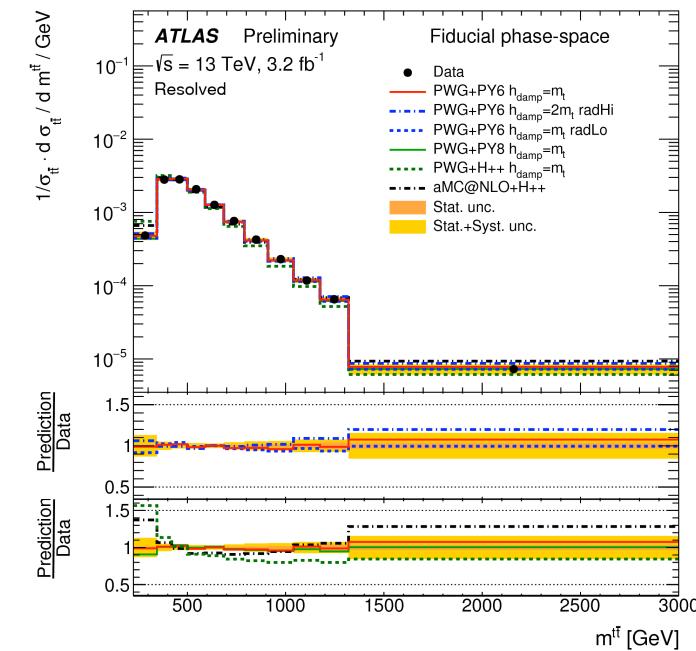
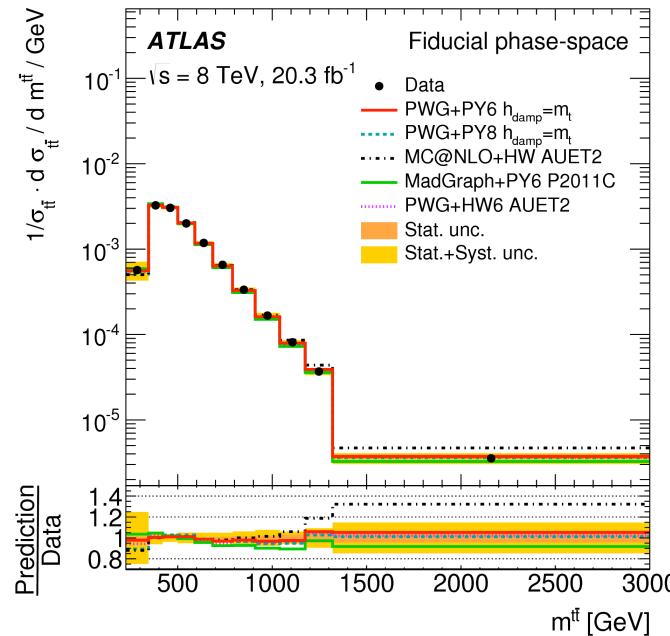


- Nominal Powheg+Pythia6  $h_{\text{damp}}=m_t$  describes data well in  $pT(t\bar{t})$  at both 8 and 13 TeV
- Similar behavior seen in dilepton parton-level results at 7 and 8 TeV

# $t\bar{t}$ differential: l+jets 8 TeV vs 13 TeV

$m(t\bar{t})$

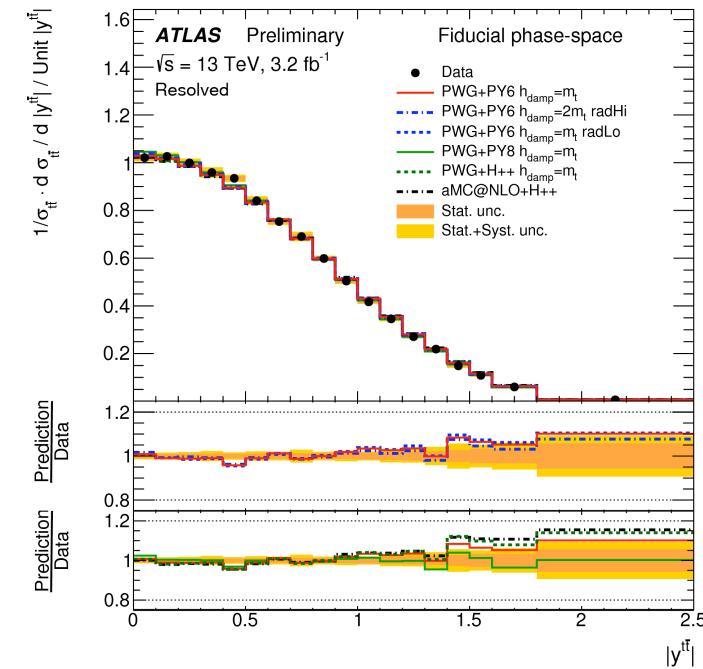
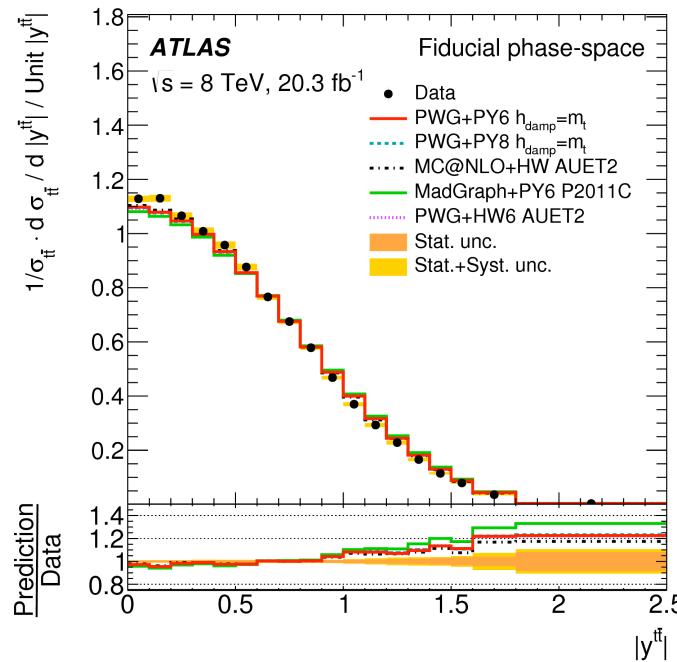
- Fiducial phase-space



# $t\bar{t}$ differential: l+jets 8 TeV vs 13 TeV

$|y(t\bar{t})|$

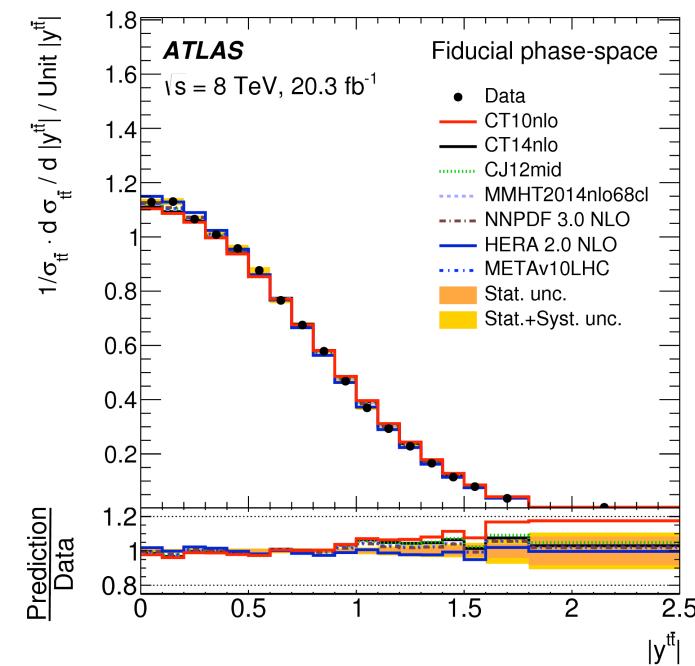
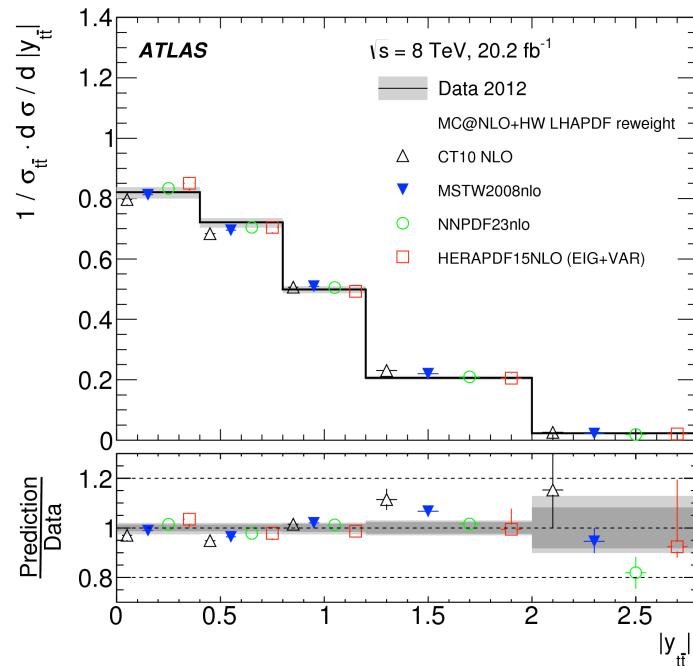
- Fiducial phase-space



# $t\bar{t}$ differential: dilepton 7 TeV vs l+jets 8 TeV

$|y(t\bar{t})|$

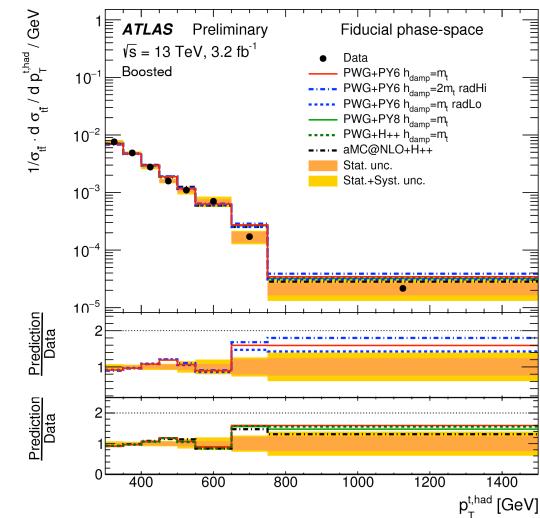
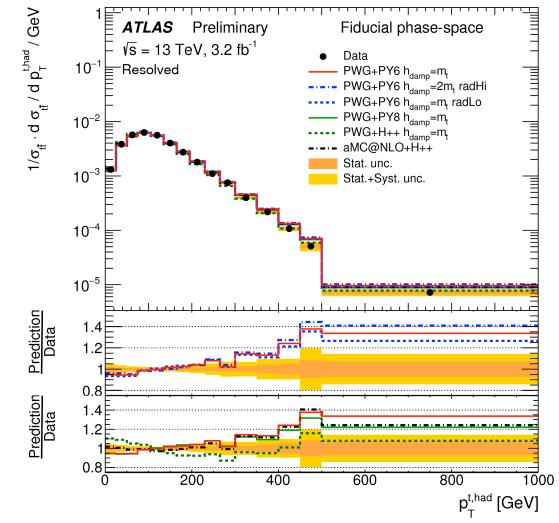
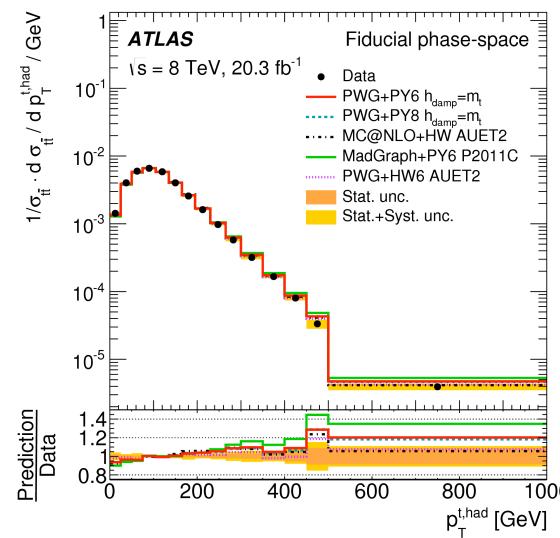
- PDF



# $t\bar{t}$ differential: top $p_T$ 8 TeV vs 13 TeV

$p_T(t\bar{t})$

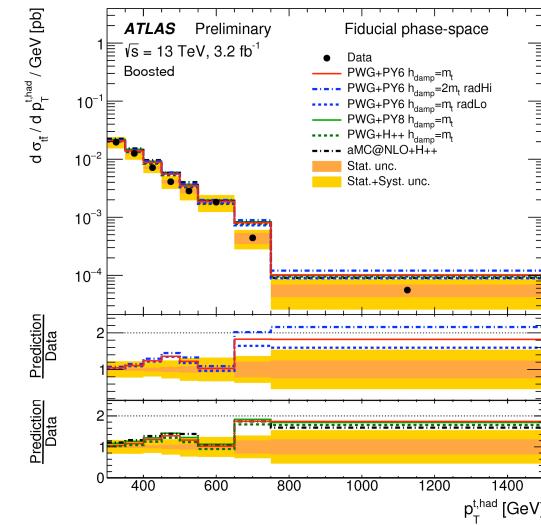
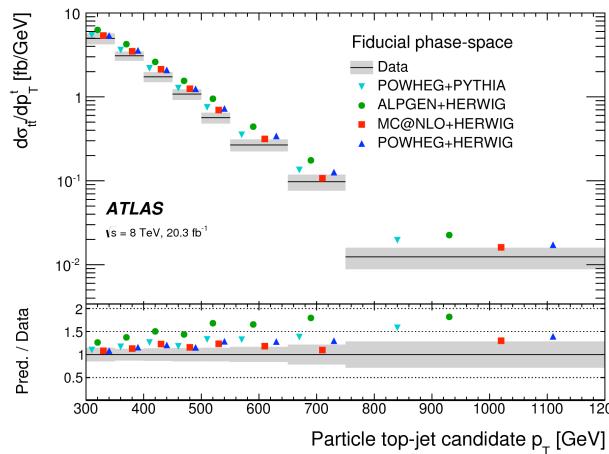
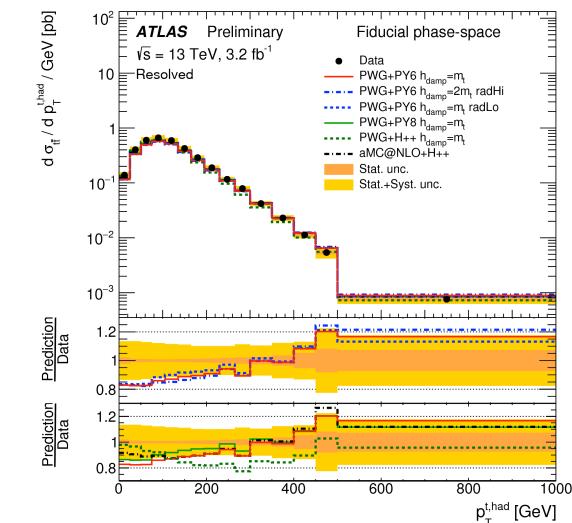
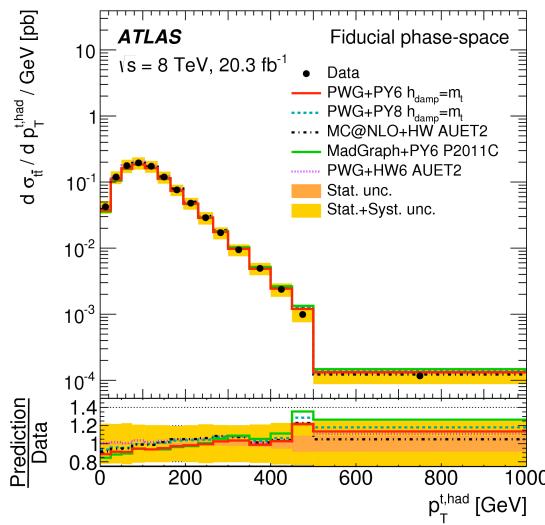
- Normalised cross-sections



# $t\bar{t}$ differential: top $p_T$ 8 TeV vs 13 TeV

$p_T(t\bar{t})$

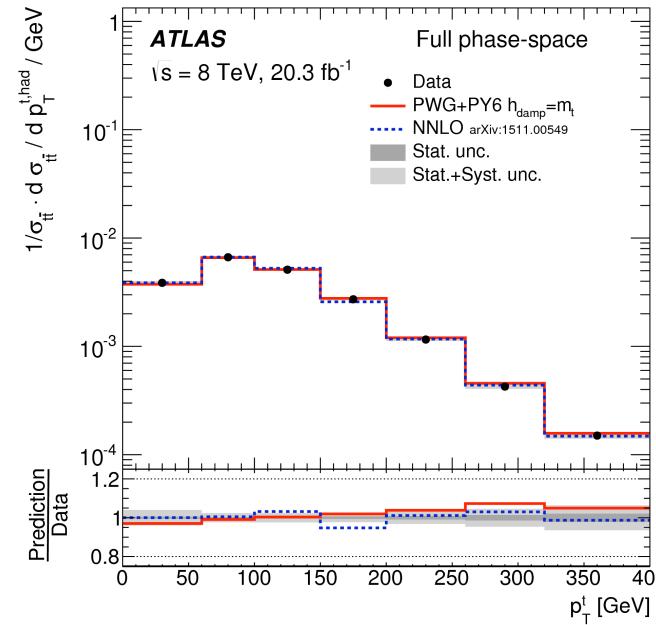
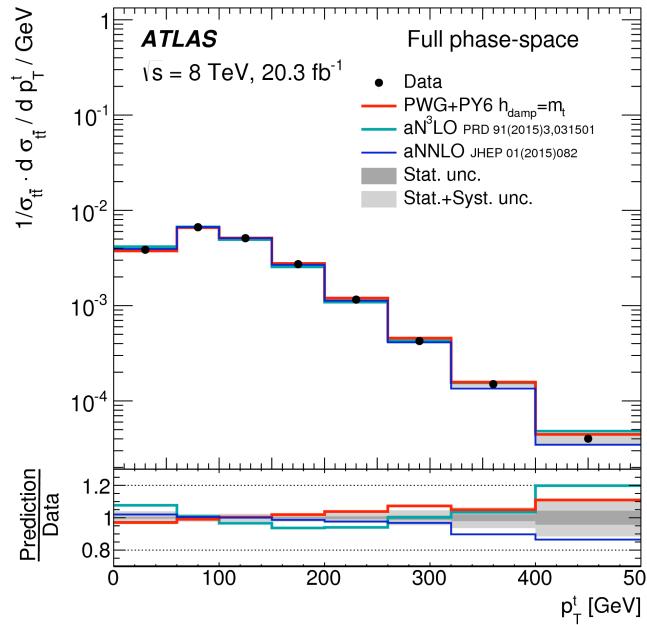
- Absolute cross-sections



# $t\bar{t}$ differential: top $p_T$ I+jets 8 TeV

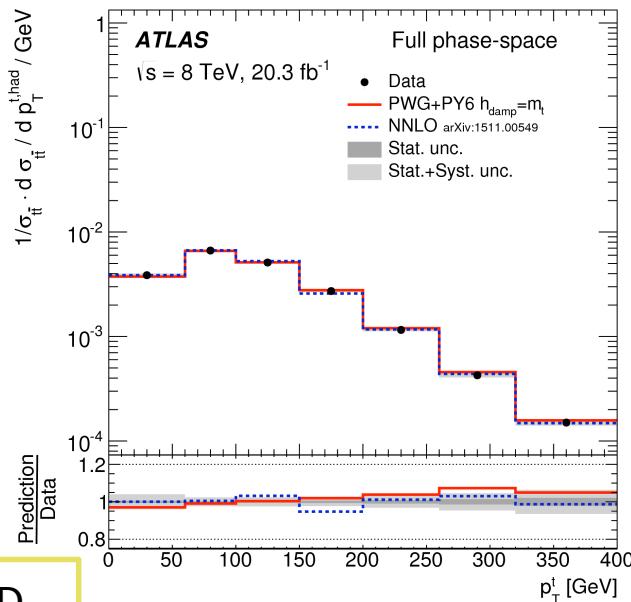
$p_T(t)$

- Data (I+jets) vs QCD calculations
  - aN<sup>3</sup>LO, aNNLO
  - NNLO



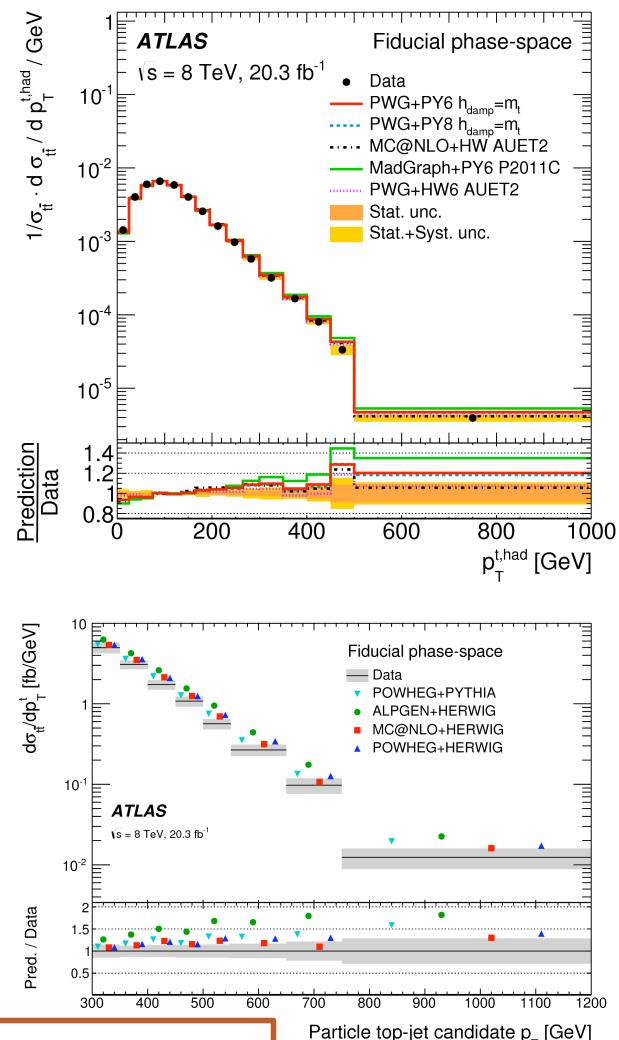
# $t\bar{t}$ differential: top $p_T$ l+jets 8 TeV

- Data tends to be softer than NLO predictions at high  $pT(t)$
- Similar trends observed in both resolved and boosted cases
- NNLO calculation seems to bring back agreement to data



RESOLVED

RESOLVED

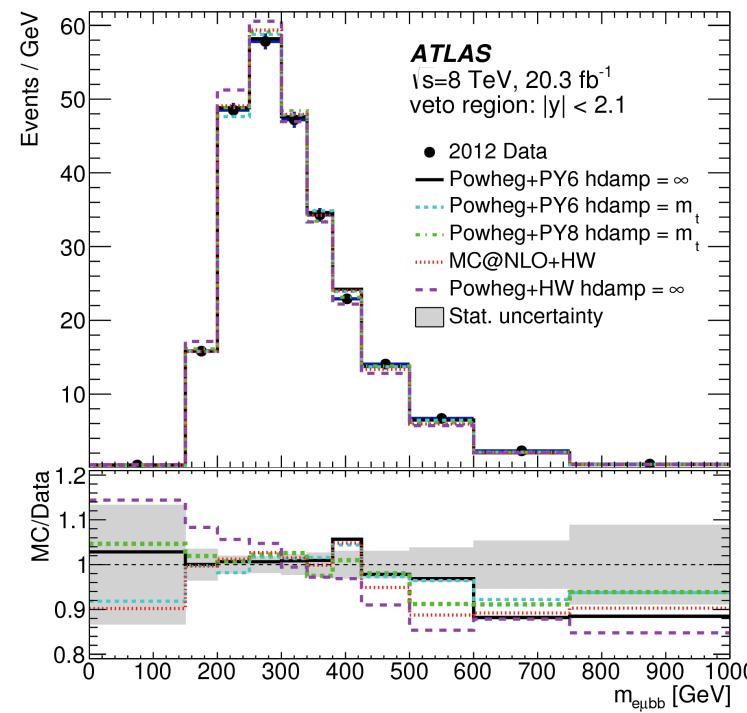
 $p_T(t)$ 

BOOSTED

# $t\bar{t}$ +jets: $e\mu$ 8 TeV

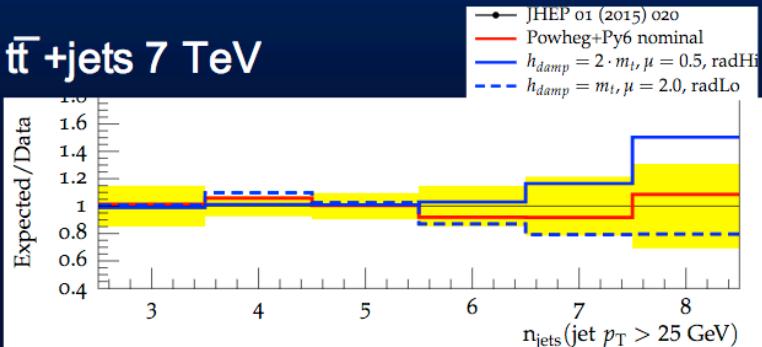
$m(e\mu bb)$

- Data has higher radiation in high mass region

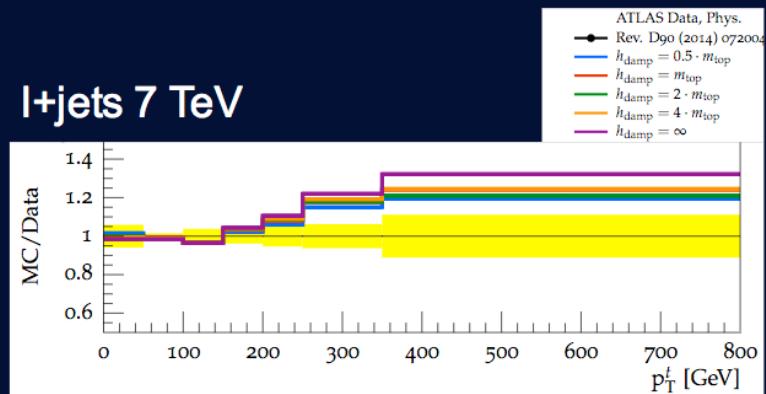


# ADDITIONAL RADIATION

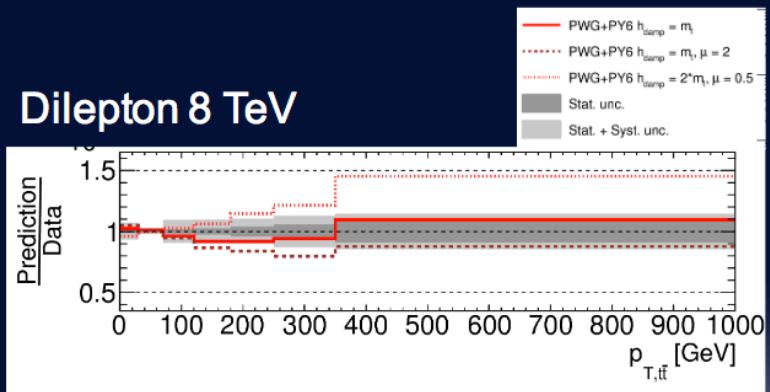
$t\bar{t}$  + jets 7 TeV



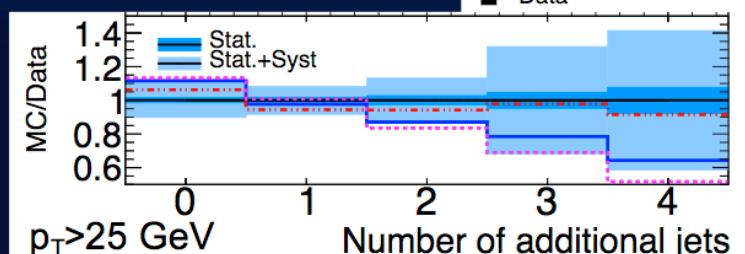
I+jets 7 TeV



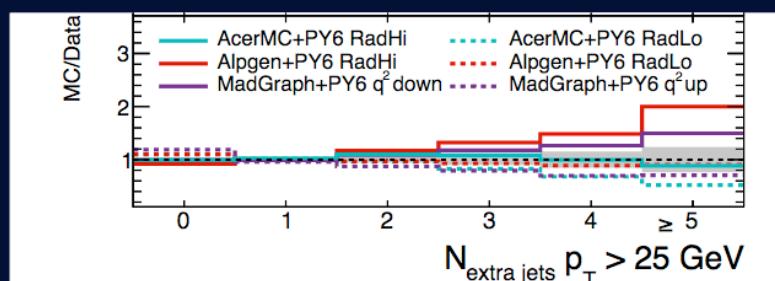
Dilepton 8 TeV



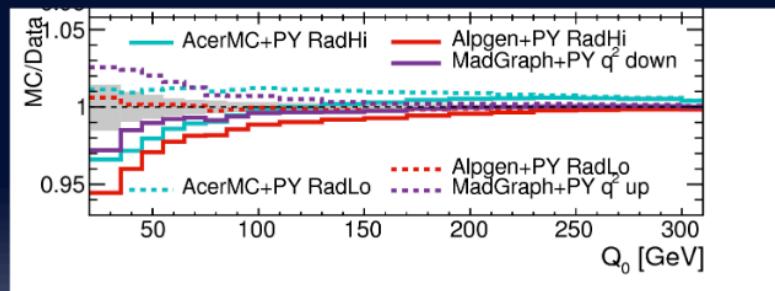
$t\bar{t}$  + jets 13 TeV



$t\bar{t}$  + jets 8 TeV



Gap fraction 8 TeV  $|\eta| < 0.8$

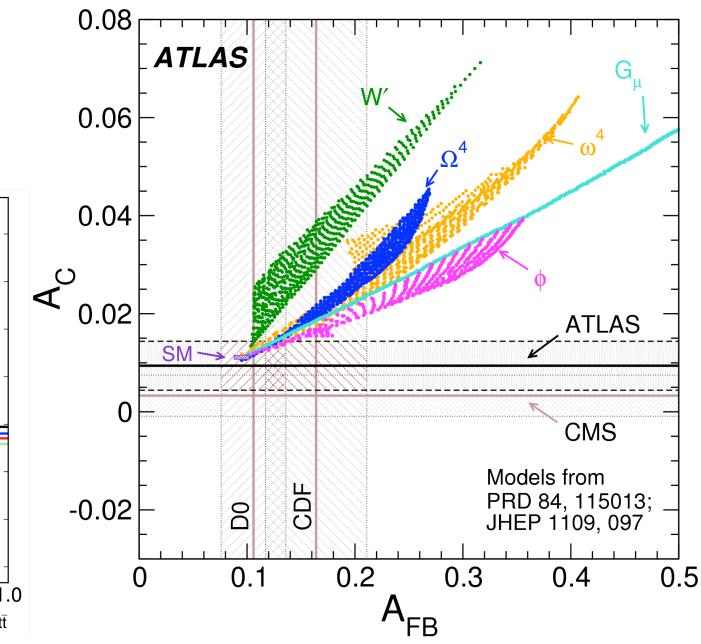
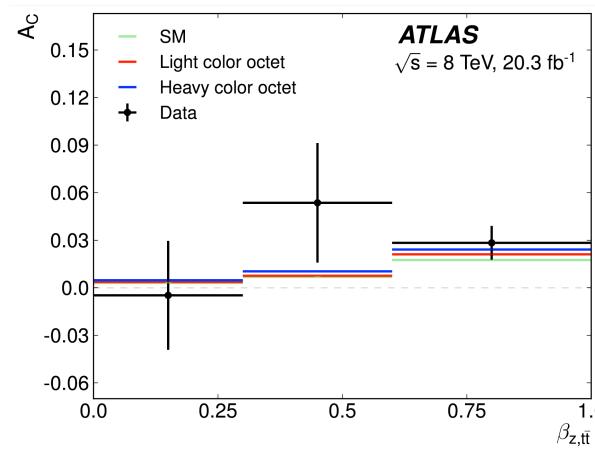
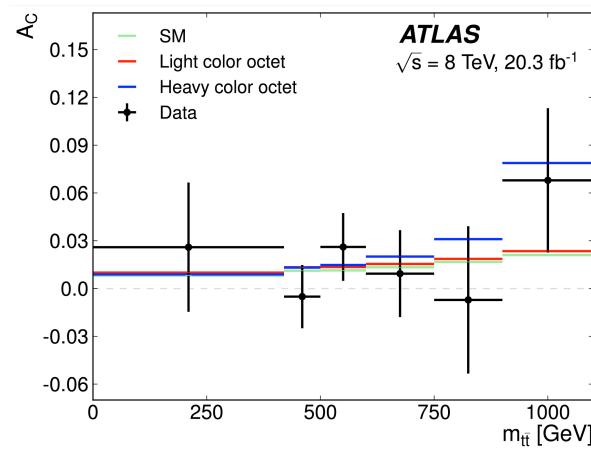


# Charge asymmetry: l+jets 8 TeV

- Single-lepton ( $e/\mu$ ) events used
- Unfolded to parton level
- Inclusive and differential measurements as a function of:  
Invariant mass  $m(t\bar{t})$ , transverse momentum  $p_T(t\bar{t})$ , longitudinal boost  $\beta_z(t\bar{t})$

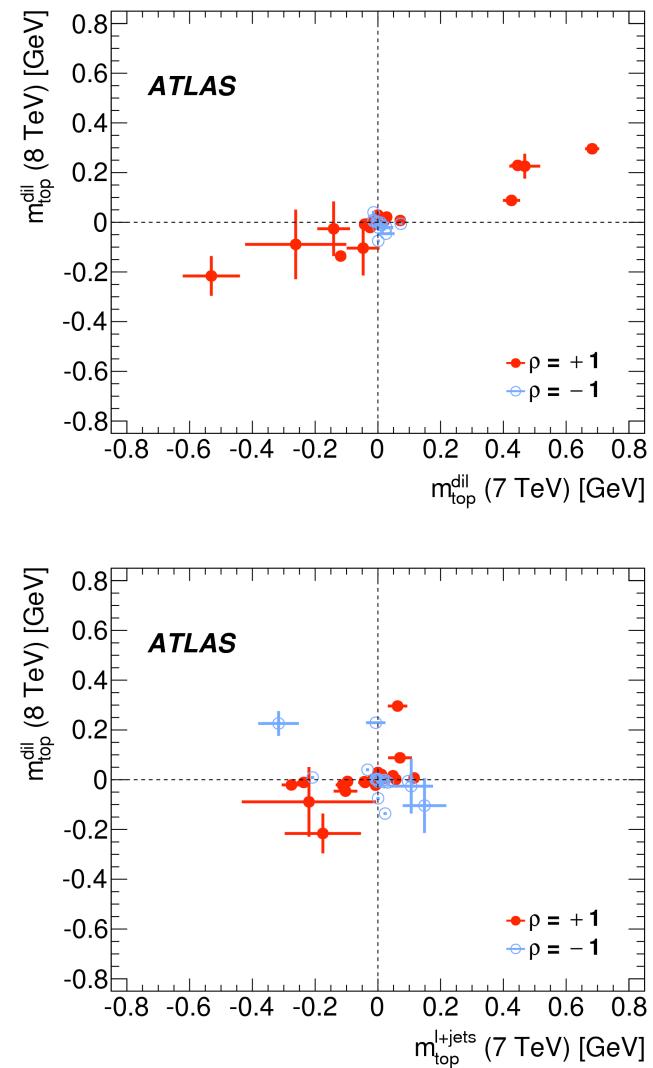
## Results

- All results statistically limited
- Inclusive ( $A_C = 0.009 \pm 0.005$ ) and differential consistent with SM QCD NLO predictions



# Top mass: dilepton 8 TeV

| Selection                    | Pre-selection    |  | Final selection |  |
|------------------------------|------------------|--|-----------------|--|
| $t\bar{t}$ signal            | $34300 \pm 2700$ |  | $9670 \pm 770$  |  |
| Single-top-quark signal      | $1690 \pm 110$   |  | $363 \pm 23$    |  |
| Fake leptons                 | $240 \pm 240$    |  | $31 \pm 31$     |  |
| $Z + \text{jets}$            | $212 \pm 83$     |  | $20.6 \pm 8.5$  |  |
| $WW/WZ/ZZ$                   | $57 \pm 21$      |  | $10.2 \pm 3.8$  |  |
| Signal+background            | $36600 \pm 2800$ |  | $10100 \pm 770$ |  |
| Data                         | $36359$          |  | $9426$          |  |
| Expected background fraction | $0.01 \pm 0.01$  |  | $0.01 \pm 0.00$ |  |
| Data / (Signal+background)   | $0.99 \pm 0.07$  |  | $0.93 \pm 0.07$ |  |
| Matching efficiency [%]      | $78.4 \pm 0.2$   |  | $95.3 \pm 0.4$  |  |
| Selection purity [%]         | $51.6 \pm 0.1$   |  | $69.8 \pm 0.3$  |  |
| Unmatched events [%]         | $34.2 \pm 0.1$   |  | $26.7 \pm 0.1$  |  |
| Wrongly matched events [%]   | $14.2 \pm 0.1$   |  | $3.4 \pm 0.0$   |  |



# Top mass: dilepton 8 TeV

|   | $\sqrt{s} = 7 \text{ TeV}$                |                                     | $\sqrt{s} = 8 \text{ TeV}$          | Correlations |             |             | Combinations                           |                                     |                                     |
|---|---|-------------------------------------|-------------------------------------|--------------|-------------|-------------|--|-------------------------------------|-------------------------------------|
|   | $m_{\text{top}}^{\ell+\text{jets}}$ [GeV] | $m_{\text{top}}^{\text{dil}}$ [GeV] | $m_{\text{top}}^{\text{dil}}$ [GeV] | $\rho_{01}$  | $\rho_{02}$ | $\rho_{12}$ | $m_{\text{top}}^{7 \text{ TeV}}$ [GeV] | $m_{\text{top}}^{\text{dil}}$ [GeV] | $m_{\text{top}}^{\text{all}}$ [GeV] |
| Results                                 | 172.33                                    | 173.79                              | 172.99                              |              |             |             | 172.99                                 | 173.04                              | 172.84                              |
| Statistics                              | 0.75                                      | 0.54                                | 0.41                                | 0            | 0           | 0           | 0.48                                   | 0.38                                | 0.34                                |
| Method                                  | $0.11 \pm 0.10$                           | $0.09 \pm 0.07$                     | $0.05 \pm 0.07$                     | 0            | 0           | 0           | 0.07                                   | 0.05                                | 0.05                                |
| Signal Monte Carlo generator            | $0.22 \pm 0.21$                           | $0.26 \pm 0.16$                     | $0.09 \pm 0.14$                     | +1.00        | +1.00       | +1.00       | 0.24                                   | 0.10                                | 0.14                                |
| Hadronisation                           | $0.18 \pm 0.12$                           | $0.53 \pm 0.09$                     | $0.22 \pm 0.08$                     | +1.00        | +1.00       | +1.00       | 0.34                                   | 0.24                                | 0.23                                |
| Initial- and final-state QCD radiation  | $0.32 \pm 0.06$                           | $0.47 \pm 0.05$                     | $0.23 \pm 0.05$                     | -1.00        | -1.00       | +1.00       | 0.04                                   | 0.24                                | 0.08                                |
| Underlying event                        | $0.15 \pm 0.07$                           | $0.05 \pm 0.05$                     | $0.10 \pm 0.11$                     | -1.00        | -1.00       | +1.00       | 0.06                                   | 0.10                                | 0.02                                |
| Colour reconnection                     | $0.11 \pm 0.07$                           | $0.14 \pm 0.05$                     | $0.03 \pm 0.11$                     | -1.00        | -1.00       | +1.00       | 0.01                                   | 0.03                                | 0.01                                |
| Parton distribution function            | $0.25 \pm 0.00$                           | $0.11 \pm 0.00$                     | $0.05 \pm 0.00$                     | +0.57        | -0.29       | +0.03       | 0.17                                   | 0.04                                | 0.08                                |
| Background normalisation                | $0.10 \pm 0.00$                           | $0.04 \pm 0.00$                     | $0.03 \pm 0.00$                     | +1.00        | +0.23       | +0.23       | 0.07                                   | 0.03                                | 0.04                                |
| $W/Z+\text{jets}$ shape                 | $0.29 \pm 0.00$                           | $0.00 \pm 0.00$                     | 0                                   | 0            |             |             | 0.16                                   | 0.00                                | 0.09                                |
| Fake leptons shape                      | $0.05 \pm 0.00$                           | $0.01 \pm 0.00$                     | $0.08 \pm 0.00$                     | +0.23        | +0.20       | -0.08       | 0.03                                   | 0.07                                | 0.05                                |
| Jet energy scale                        | $0.58 \pm 0.11$                           | $0.75 \pm 0.08$                     | $0.54 \pm 0.04$                     | -0.23        | +0.06       | +0.35       | 0.41                                   | 0.52                                | 0.41                                |
| Relative $b$ -to-light-jet energy scale | $0.06 \pm 0.03$                           | $0.68 \pm 0.02$                     | $0.30 \pm 0.01$                     | +1.00        | +1.00       | +1.00       | 0.34                                   | 0.32                                | 0.25                                |
| Jet energy resolution                   | $0.22 \pm 0.11$                           | $0.19 \pm 0.04$                     | $0.09 \pm 0.03$                     | -1.00        | 0           | 0           | 0.03                                   | 0.08                                | 0.08                                |
| Jet reconstruction efficiency           | $0.12 \pm 0.00$                           | $0.07 \pm 0.00$                     | $0.01 \pm 0.00$                     | +1.00        | +1.00       | +1.00       | 0.10                                   | 0.01                                | 0.04                                |
| Jet vertex fraction                     | $0.01 \pm 0.00$                           | $0.00 \pm 0.00$                     | $0.02 \pm 0.00$                     | -1.00        | +1.00       | -1.00       | 0.00                                   | 0.02                                | 0.02                                |
| $b$ -tagging                            | $0.50 \pm 0.00$                           | $0.07 \pm 0.00$                     | $0.03 \pm 0.02$                     | -0.77        | 0           | 0           | 0.25                                   | 0.03                                | 0.15                                |
| Leptons                                 | $0.04 \pm 0.00$                           | $0.13 \pm 0.00$                     | $0.14 \pm 0.00$                     | -0.34        | -0.52       | +0.96       | 0.05                                   | 0.14                                | 0.09                                |
| $E_T^{\text{miss}}$                     | $0.15 \pm 0.04$                           | $0.04 \pm 0.03$                     | $0.01 \pm 0.01$                     | -0.15        | +0.25       | -0.24       | 0.08                                   | 0.01                                | 0.05                                |
| Pile-up                                 | $0.02 \pm 0.01$                           | $0.01 \pm 0.00$                     | $0.05 \pm 0.01$                     | 0            | 0           | 0           | 0.01                                   | 0.05                                | 0.03                                |
| Total systematic uncertainty            | $1.03 \pm 0.31$                           | $1.31 \pm 0.23$                     | $0.74 \pm 0.25$                     |              |             |             | 0.77                                   | 0.74                                | 0.61                                |
| Total                                   | $1.27 \pm 0.33$                           | $1.41 \pm 0.24$                     | $0.84 \pm 0.25$                     | -0.07        | 0.00        | 0.51        | 0.91                                   | 0.84                                | 0.70                                |

# Top mass: all-hadronic 8 TeV

| Cut   | Data   | Event yields (thousands) |              |      |
|---|--------|--------------------------|--------------|------|
|   |        | $t\bar{t}$               | all-hadronic | (MC) |
| Initial   | 850450 | 2338                     | $\pm$        | 1    |
| Primary vertex with $> 4$ tracks                            | -      | -                        | -            | -    |
| No high- $p_T$ isolated $e/\mu$                             | -      | -                        | -            | -    |
| Jets $ \eta  < 2.5$   | 33476  | 308.7                    | $\pm$        | 0.6  |
| Trigger: 5 jets with $p_T > 55 \text{ GeV}$                 | 16110  | 241.4                    | $\pm$        | 0.5  |
| No 2 good jets ( $j_i, j_k$ ) in $\Delta R(j_i, j_k) < 0.6$ | 7646   | 142.9                    | $\pm$        | 0.4  |
| $\geq 6$ jets with $p_T > 25 \text{ GeV}$                   | 7646   | 142.9                    | $\pm$        | 0.4  |
| $\geq 5$ jets with $p_T > 60 \text{ GeV}$                   | 3303   | 51.4                     | $\pm$        | 0.2  |
| $E_T^{\text{miss}} < 60 \text{ GeV}$                        | 3021   | 46.3                     | $\pm$        | 0.2  |
| $\Delta\phi(b_i, b_j) > 1.5$                                | 1737   | 30.9                     | $\pm$        | 0.2  |
| $\chi^2 < 11$   | 645.8  | 22.3                     | $\pm$        | 0.1  |
| $N_{b_{\text{tag}}} \geq 2$                                 | 21.9   | 6.61                     | $\pm$        | 0.08 |
| $\langle \Delta\phi(b, W) \rangle < 2$                      | 12.9   | 4.40                     | $\pm$        | 0.07 |

# Top mass: all-hadronic 8 TeV

| <i>Uncertainty</i>                       | $\Delta m_{\text{top}} [\text{GeV}]$ |
|--|--------------------------------------|
| Monte Carlo generator                    | $0.18 \pm 0.21$                      |
| Hadronisation modelling                  | $0.64 \pm 0.15$                      |
| Parton distribution functions            | $0.04 \pm 0.00$                      |
| Initial/final-state radiation            | $0.10 \pm 0.28$                      |
| Underlying event                         | $0.13 \pm 0.16$                      |
| Colour reconnection                      | $0.12 \pm 0.16$                      |
| Bias in template method                  | 0.06                                 |
| Signal and bkgd parameterisation         | 0.09                                 |
| Non all-hadronic $t\bar{t}$ contribution | 0.06                                 |
| ABCD method <i>vs.</i> ABCDEF method     | 0.16                                 |
| Trigger efficiency                       | $0.08 \pm 0.01$                      |
| Lepton/ $E_T^{\text{miss}}$ calibration  | $0.02 \pm 0.01$                      |
| Overall flavour tagging                  | $0.10 \pm 0.00$                      |
| Jet energy scale (JES)                   | $0.60 \pm 0.05$                      |
| b-Jet energy scale (bJES)                | $0.34 \pm 0.02$                      |
| Jet energy resolution                    | $0.10 \pm 0.04$                      |
| Jet vertex fraction                      | $0.03 \pm 0.01$                      |
| <b>Total Systematic</b>                  | 1.01                                 |
| <b>Total Statistical</b>                 | 0.55                                 |
| <b>Total</b>                             | 1.15                                 |

# Top mass summary

**ATLAS Preliminary**  $m_{\text{top}}$  summary - Aug. 2016,  $L_{\text{int}} = 35 \text{ pb}^{-1} - 20.3 \text{ fb}^{-1}$

