# Differentiating the top

## Experimental Top physics

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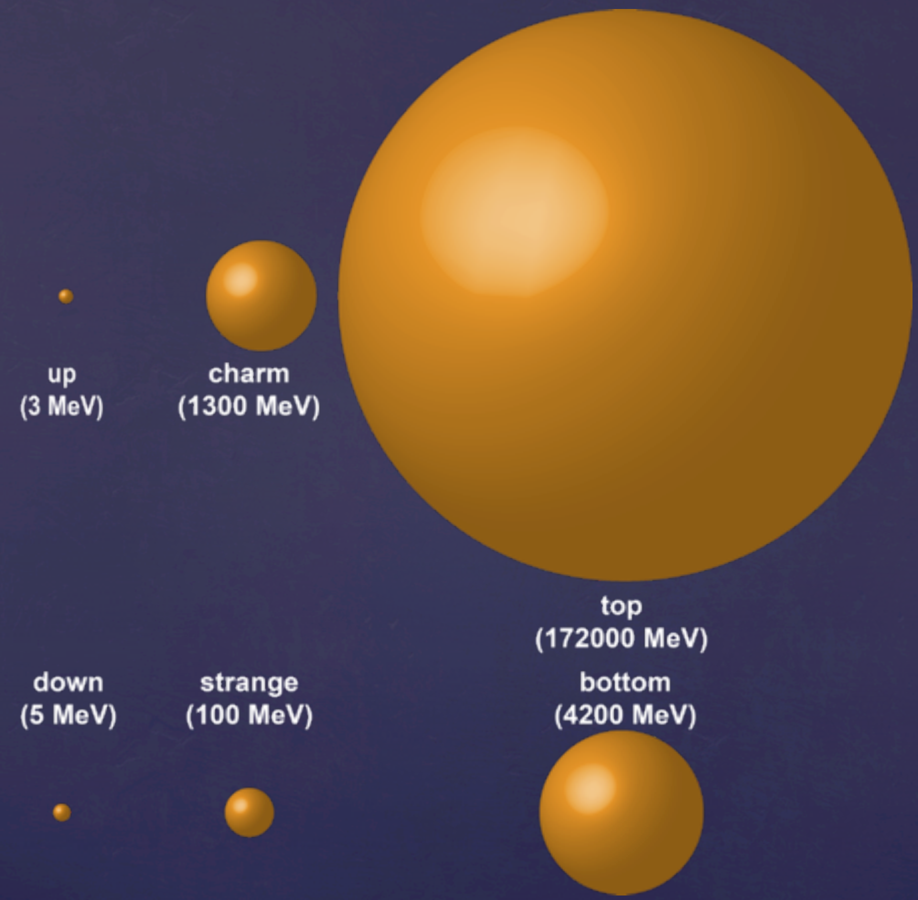
KITP workshop – Experimental challenges for the LHC Run II
29th March 2016

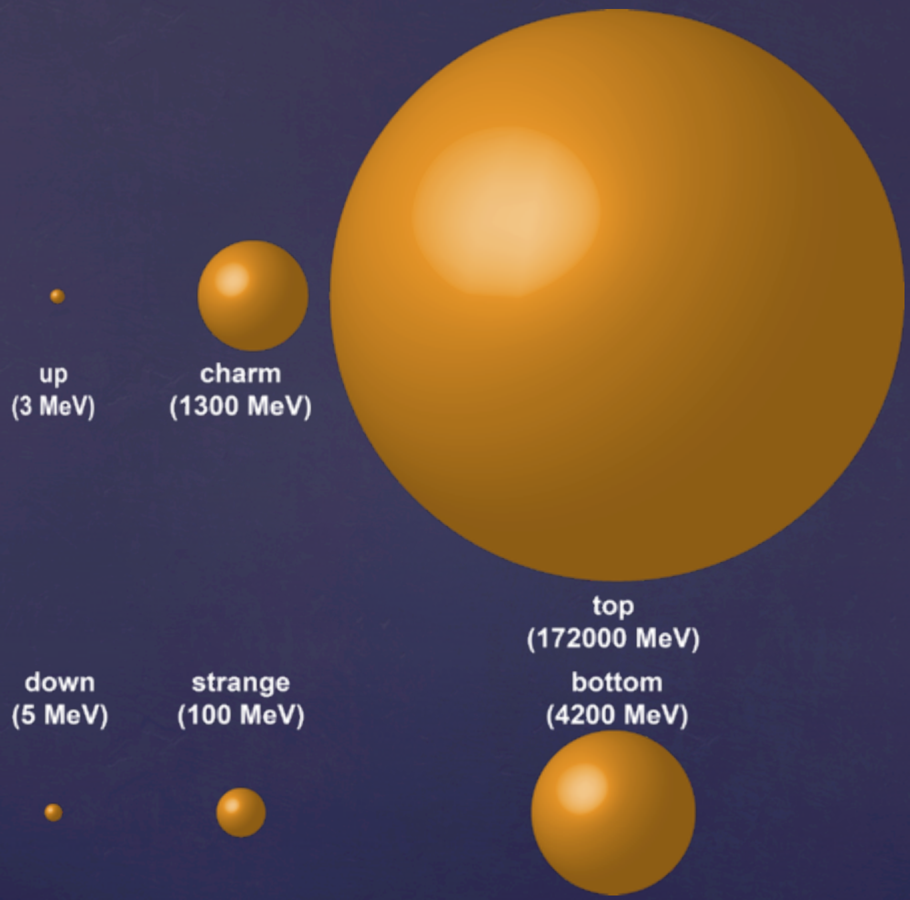
# What do we know about top




Experimentally confirmed facts:

- Top is the heaviest known fundamental particle
  - Mass ~ 173 GeV
- It is a quark (sees the strong force)
- Charge 2/3e
- Spin ½
- Decays almost exclusively to Wb
- Produced by strong and weak interactions

# Why we still care about top




- Only place to study the properties of a bare quark
  - Lifetime < hadronisation
- Self-consistency of the SM ($m_t$, stringent tests of QCD,...)
- Special role in EWSB?
  - Hierarchy problem
- First place a new particle could be observed
  - Particularly if new particle couples to mass
- Top is a background to many other searches

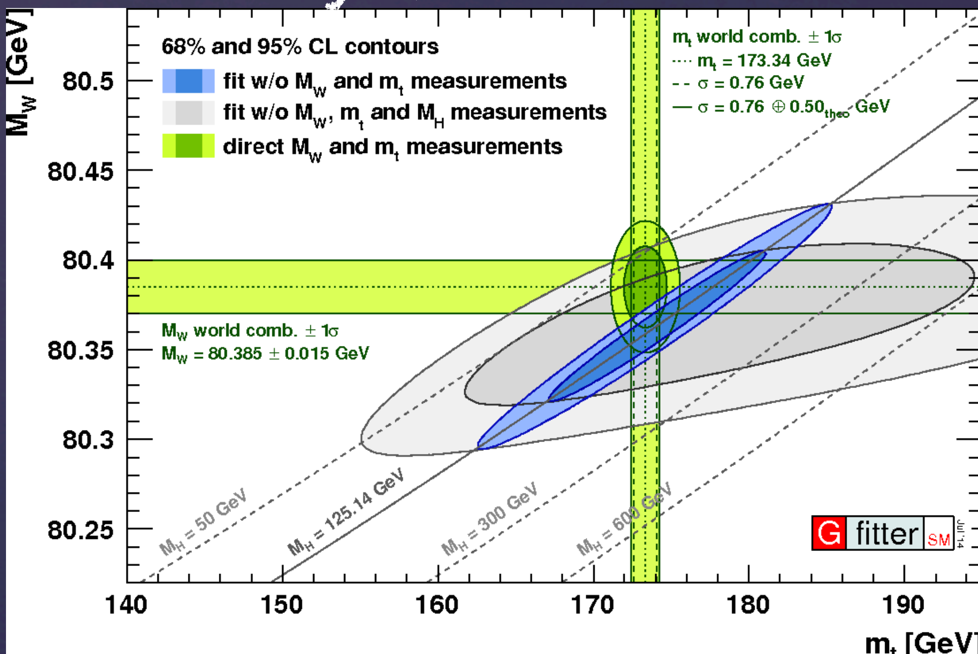
# Distractor

## Top Mass

(not a differential cross section… or is it?)

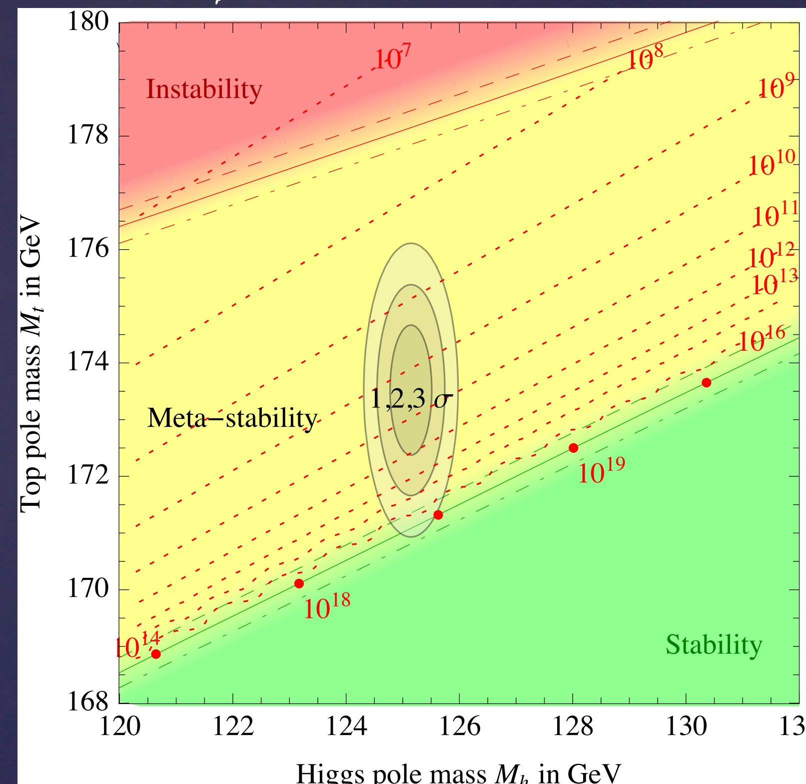
# Top Mass

## Consistency of SM



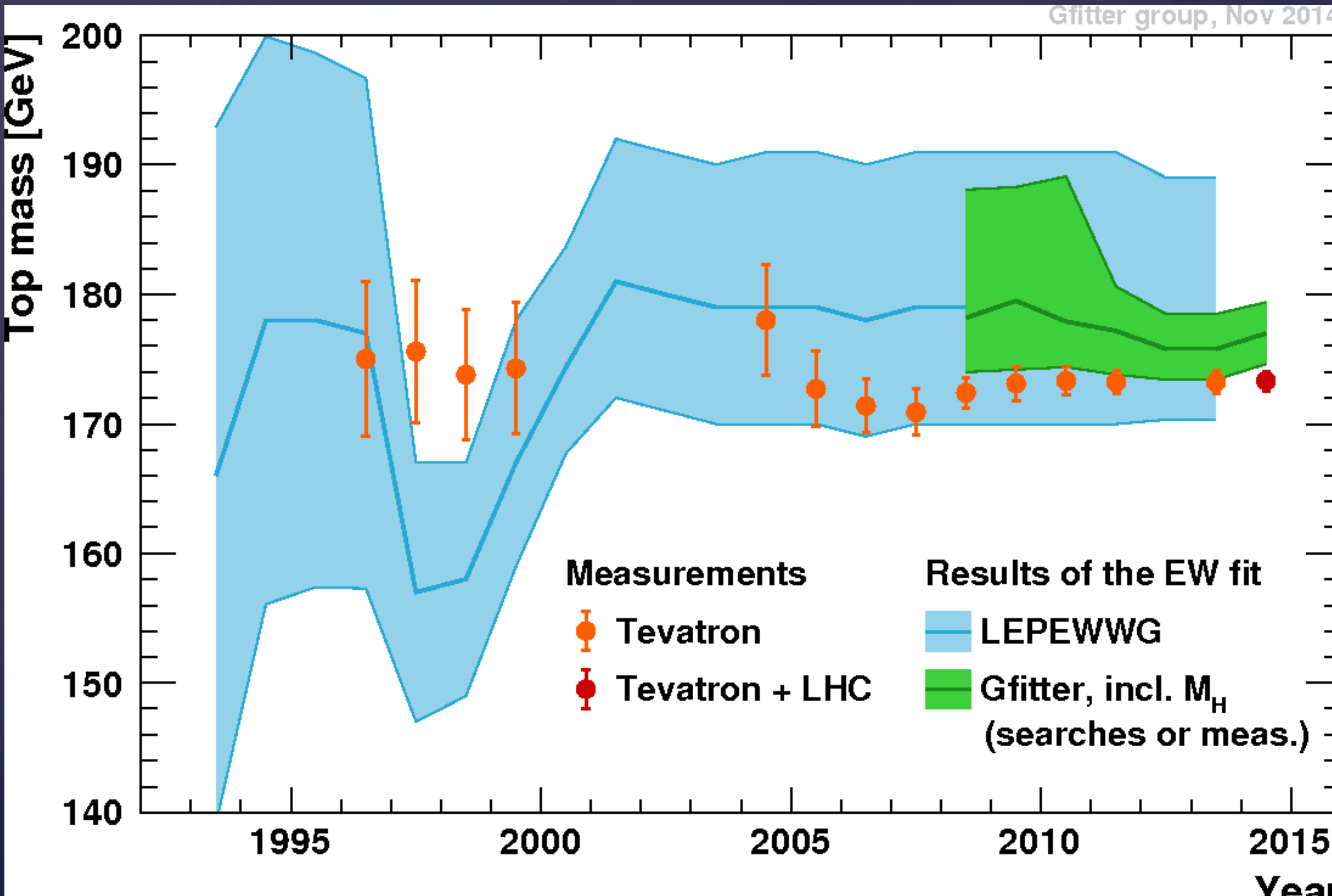

Gfitter, Nov 2014

## Fate of our universe




arXiv:1307.3536

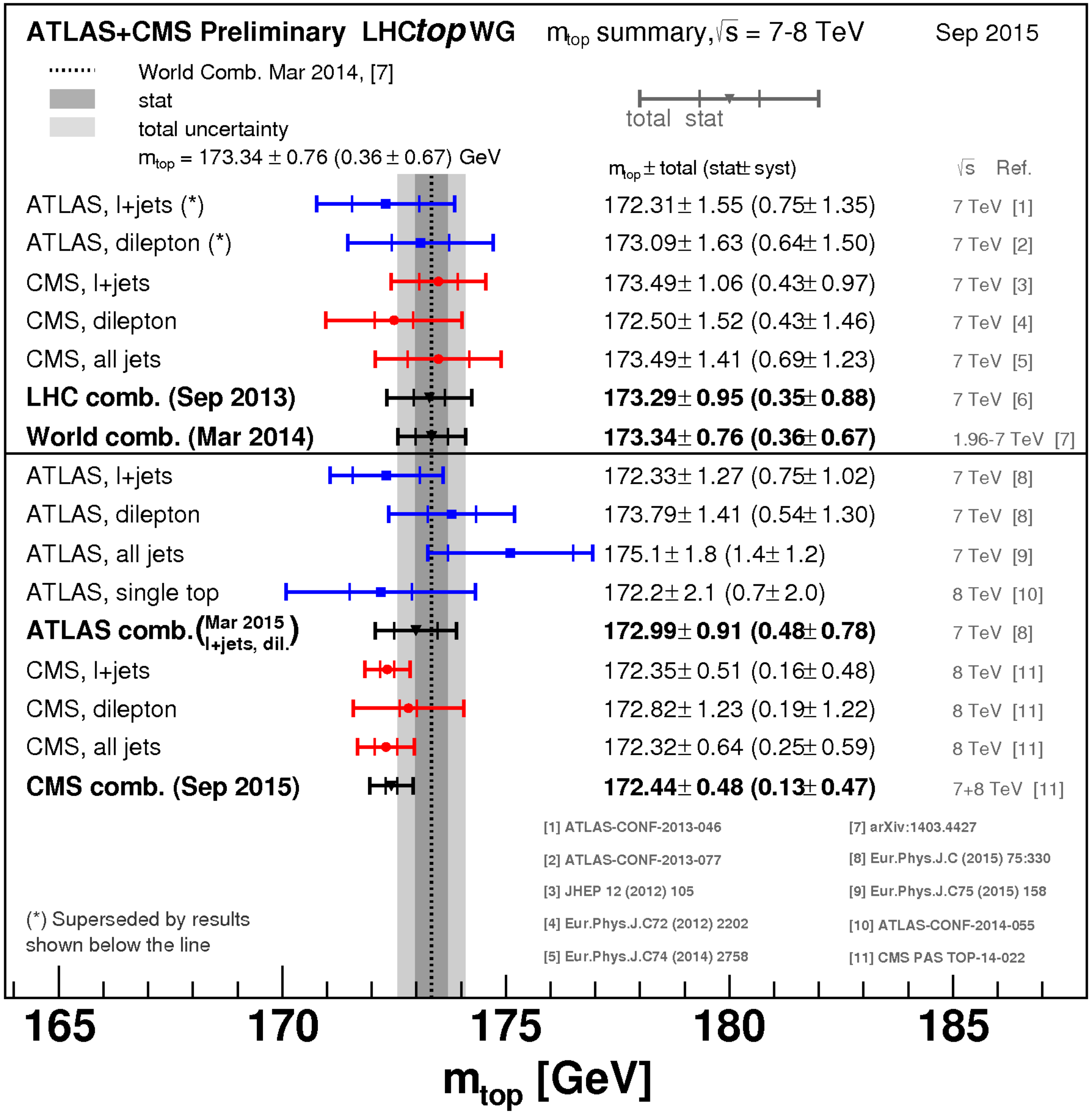
# Top Mass




Gfitter, Nov 2014

# Top Mass

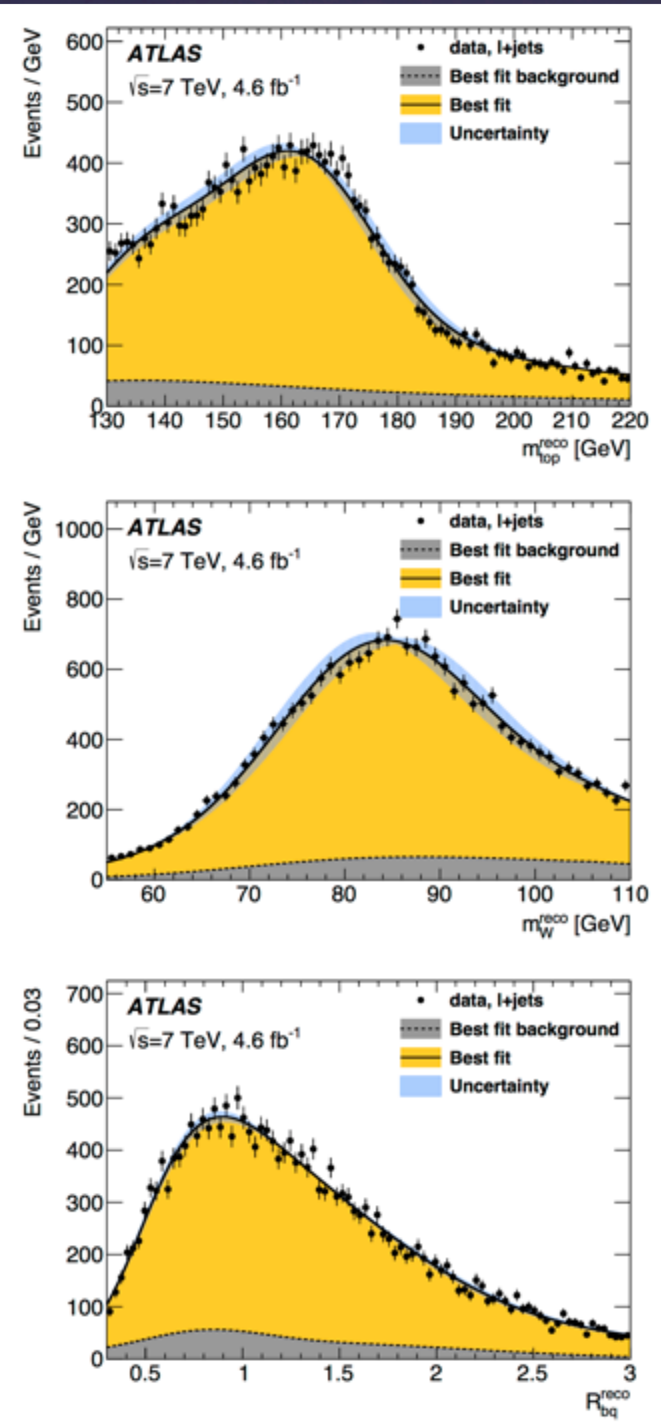
$m_{measured} = m_{MC}$

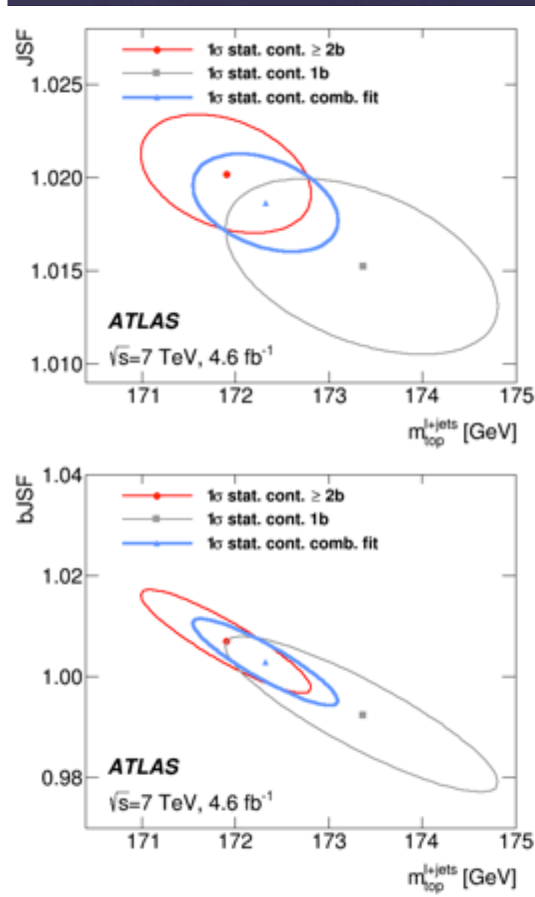


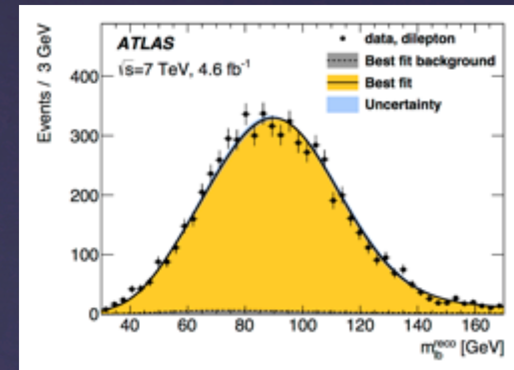

Measurement precision ~ 0.48 GeV (0.28%)

# Top Mass

arXiv:1503.05427




Innovations

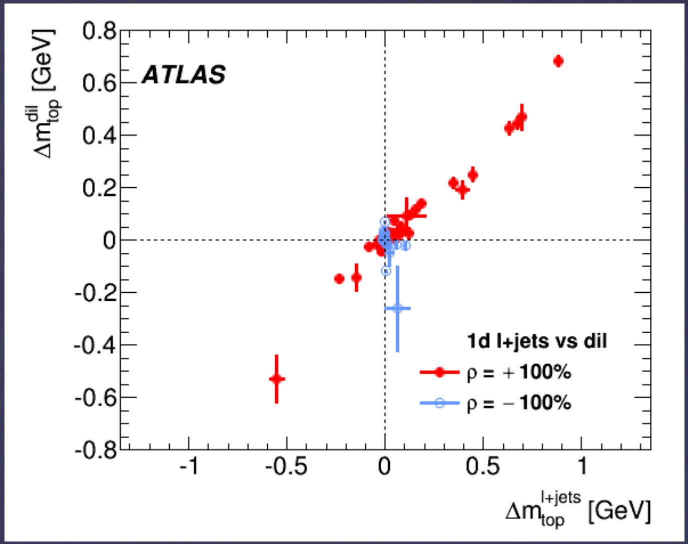
- 3D fit: top mass, W mass, Rbq
- Taking correlations between systematics into account

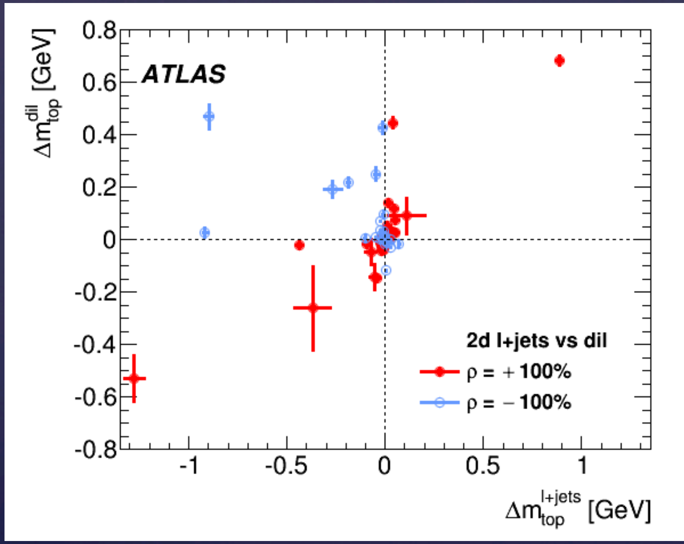
$m_{top}$ = 172.99±0.48(stat.)±0.78(syst.) GeV

$$\mathcal{R}_{bq} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{q_1} + p_T^{q_2}}.$$

# Top Mass

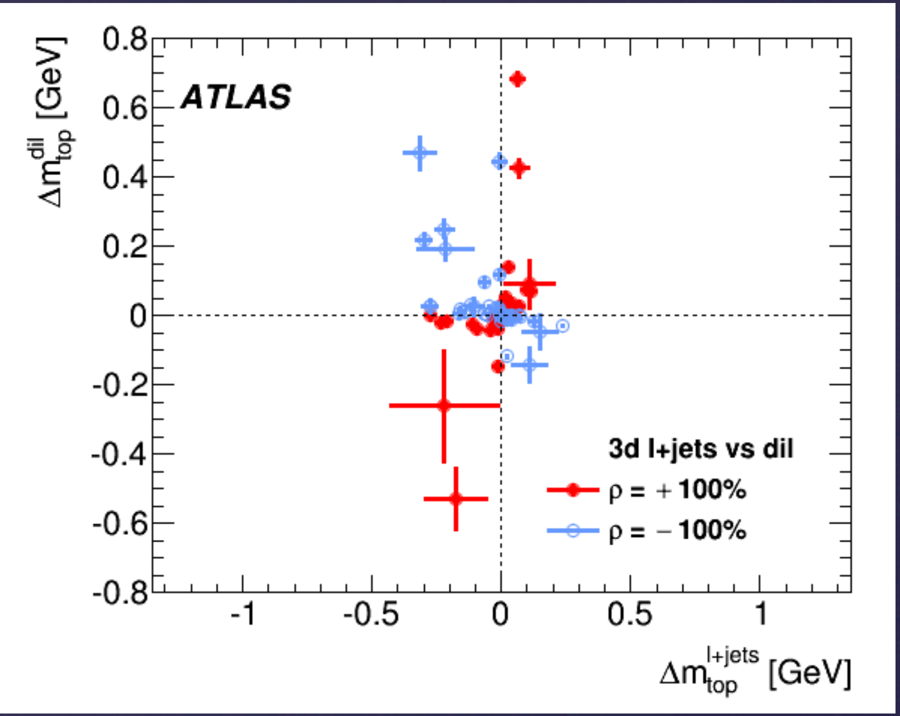
1D




2D

3D




Innovations

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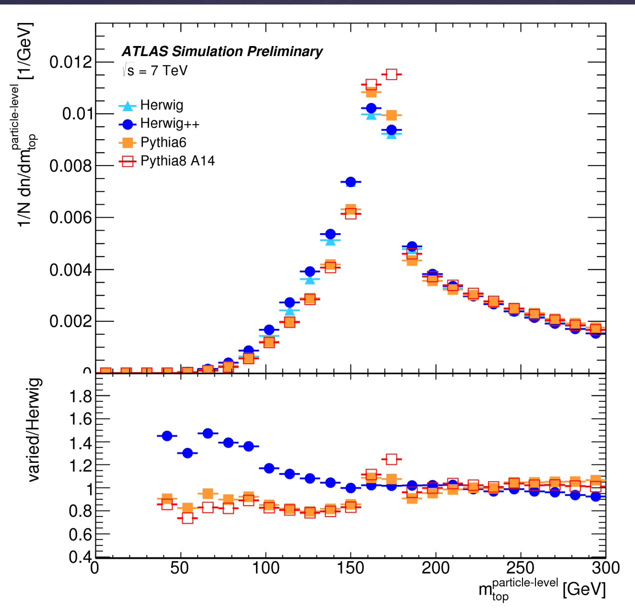
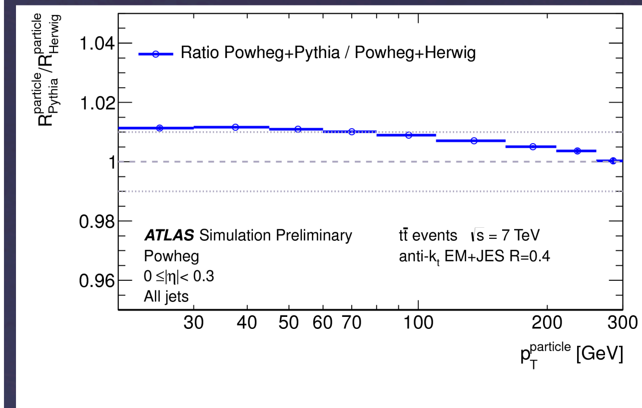
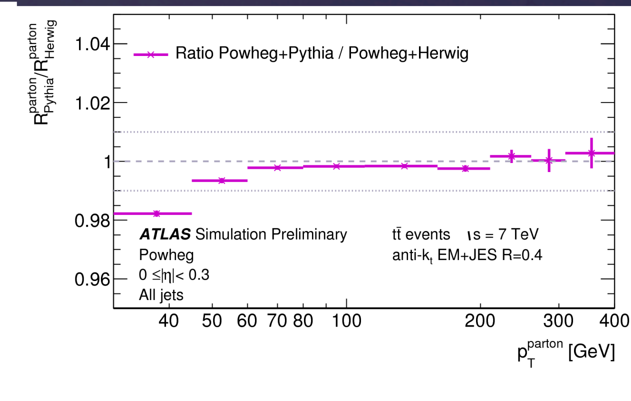
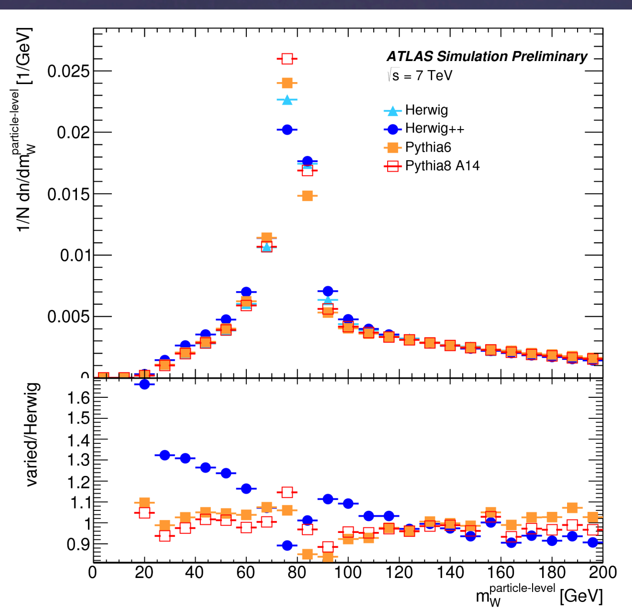
# Top Mass

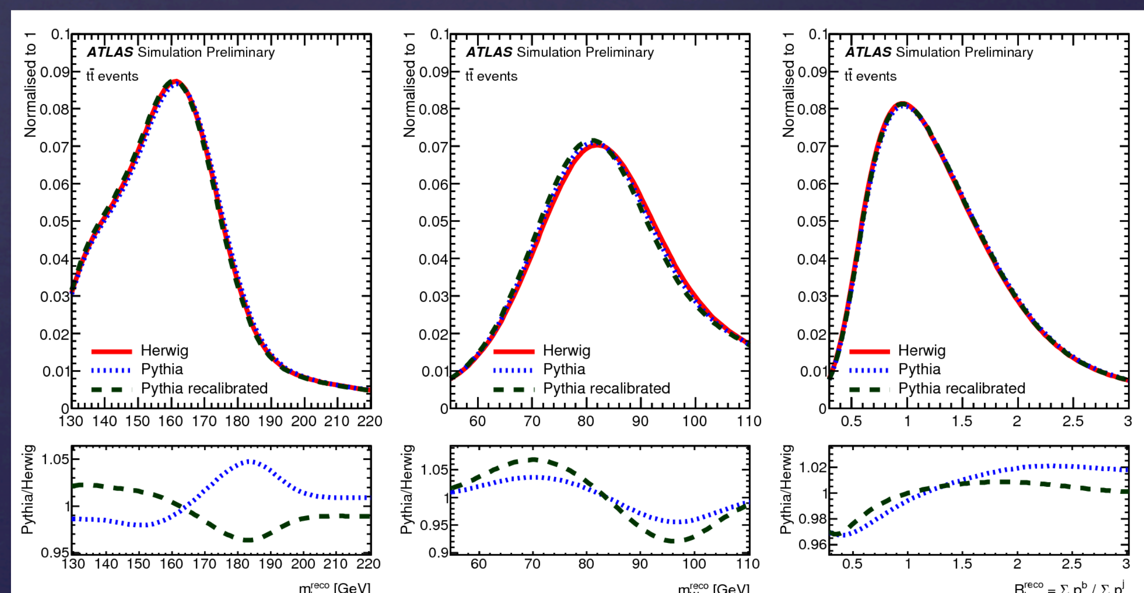
How much double-counting between JES and MC modelling? – *None on ATLAS*

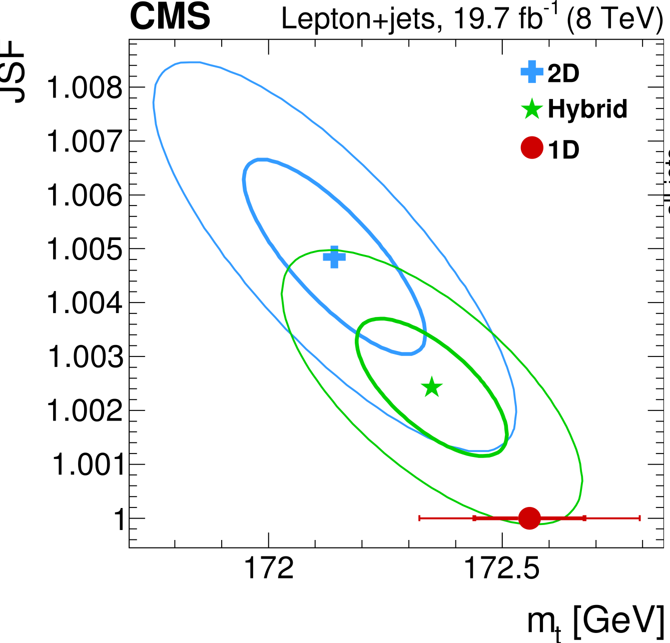


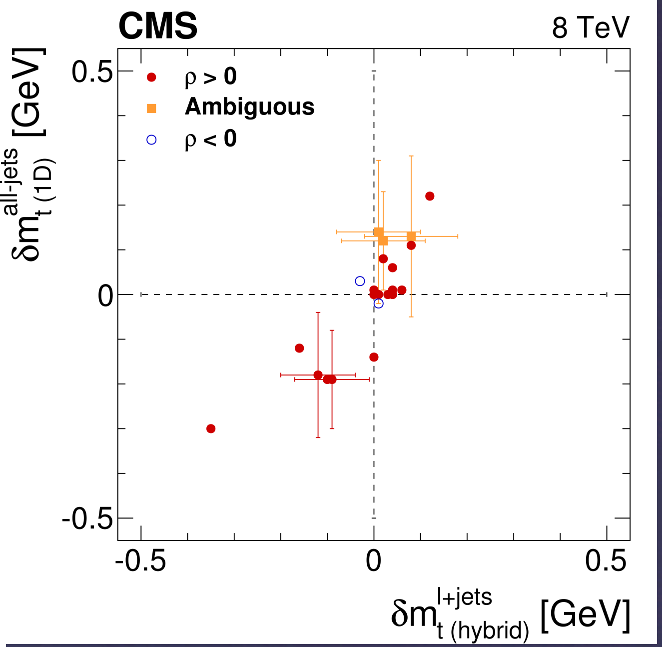



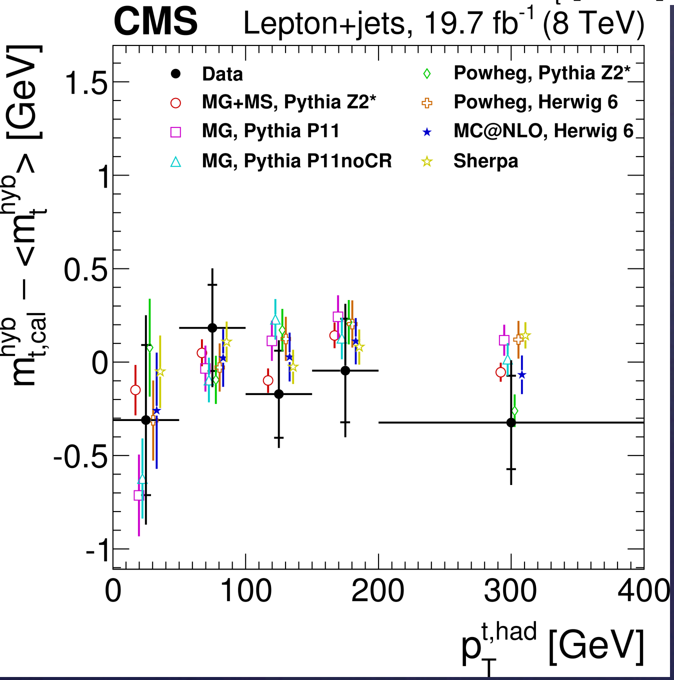






# Top Mass

Innovations

- Hybrid method
- Dependency of measurement on kinematic cuts (stability of measured mass)
- Also exploit correlations

| Combined $m_t$ result | $\delta m_t$(GeV) |
|---|---|
| Experimental uncertainties | |
| Method calibration | 0.03 |
| Jet energy corrections | |
| – JEC: Intercalibration | 0.01 |
| – JEC: In situ calibration | 0.12 |
| – JEC: Uncorrelated non-pileup | 0.10 |
| Lepton energy scale | 0.01 |
| $E_T^{miss}$ scale | 0.03 |
| Jet energy resolution | 0.03 |
| b tagging | 0.05 |
| Pileup | 0.06 |
| Backgrounds | 0.04 |
| Trigger | <0.01 |
| Modeling of hadronization | |
| JEC: Flavor | 0.33 |
| b jet modeling | 0.14 |
| Modeling of perturbative QCD | |
| PDF | 0.04 |
| Ren. and fact. scales | 0.10 |
| ME-PS matching threshold | 0.08 |
| ME generator | 0.11 |
| Top quark $p_T$ | 0.02 |
| Modeling of soft QCD | |
| Underlying event | 0.11 |
| Color reconnection modeling | 0.10 |
| Total systematic | 0.47 |
| Statistical | 0.13 |
| Total Uncertainty | 0.48 |

CMS 8 TeV

# Top Mass

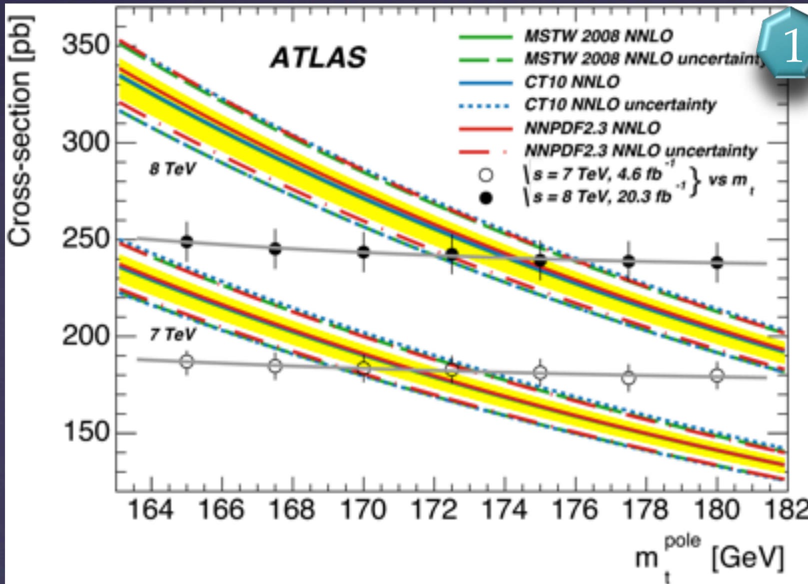
$m_{measured} = m_{MC}$

ATLAS 7 TeV

| | Combination | |
|---|---|---|
| | $m_{top}^{comb}$ [GeV] | $\rho$ |
| Results | 172.99 | |
| Statistics | 0.48 | 0 |
| – *Stat. comp.* ($m_{top}$) | | |
| – *Stat. comp. (JSF)* | | |
| – *Stat. comp. (bJSF)* | | |
| Method | 0.07 | 0 |
| Signal MC | 0.24 | +1.00 |
| Hadronisation | 0.34 | +1.00 |
| ISR/FSR | 0.04 | −1.00 |
| Underlying event | 0.06 | −1.00 |
| Colour reconnection | 0.01 | −1.00 |
| PDF | 0.17 | +0.57 |
| *W/Z*+jets norm | 0.02 | +1.00 |
| *W/Z*+jets shape | 0.16 | 0 |
| NP/fake-lepton norm. | 0.07 | +1.00 |
| NP/fake-lepton shape | 0.03 | +0.23 |
| Jet energy scale | 0.41 | −0.23 |
| *b*-Jet energy scale | 0.34 | +1.00 |
| Jet resolution | 0.03 | −1.00 |
| Jet efficiency | 0.10 | +1.00 |
| Jet vertex fraction | 0.00 | −1.00 |
| *b*-Tagging | 0.25 | −0.77 |
| $E_T^{miss}$ | 0.08 | −0.15 |
| Leptons | 0.05 | −0.34 |
| Pile-up | 0.01 | 0 |
| Total | 0.91 | −0.07 |

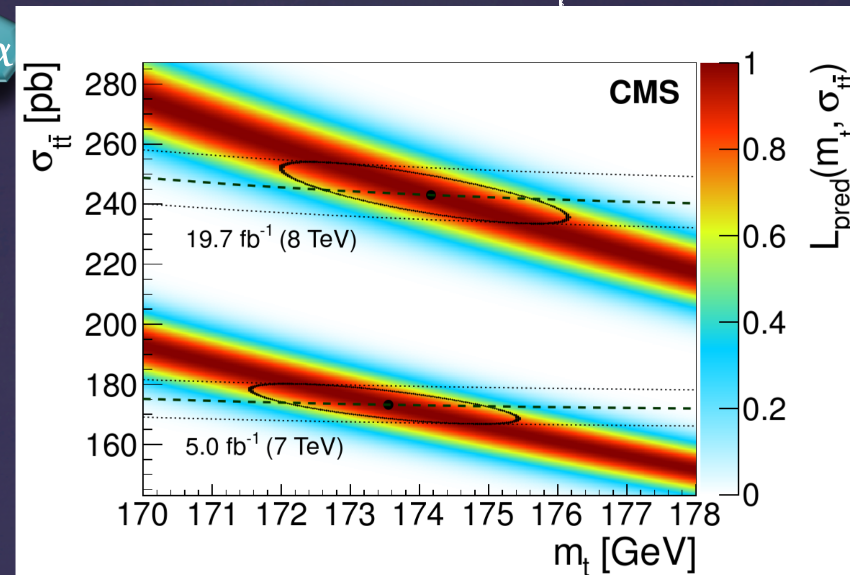
# Top Pole Mass

1

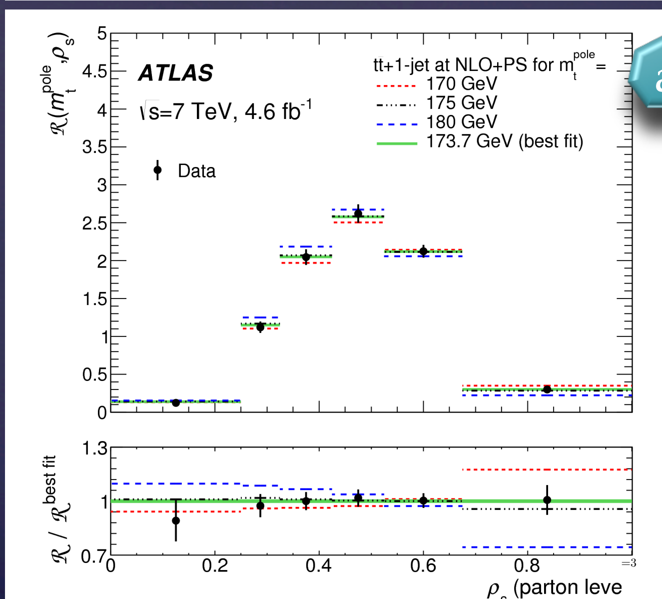



$|m_{MC} - m_{pole}| \sim$ GeV

α




a




$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$$

$\sqrt{s_{t\bar{t}j}}$ : invariant mass of ttj system

$m_0$ : arbitrary mass parameter, 170 GeV

1 $m_{top} = 172.9^{+2.5}_{-2.6}$ GeV

α $m_{top}$ $173.8^{+1.7}_{-1.8}$ GeV

a $m_{top} = 173.7 \pm 1.5(\text{stat.}) \pm 1.4(\text{syst.})^{+1.0}_{-0.5}(\text{theo.})$ GeV

$\Delta m_{top} \sim 2$ GeV

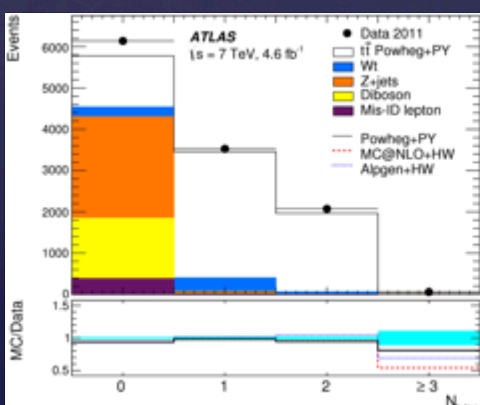
# Precision Cross sections

Inclusive and Differential

# Inclusive XS

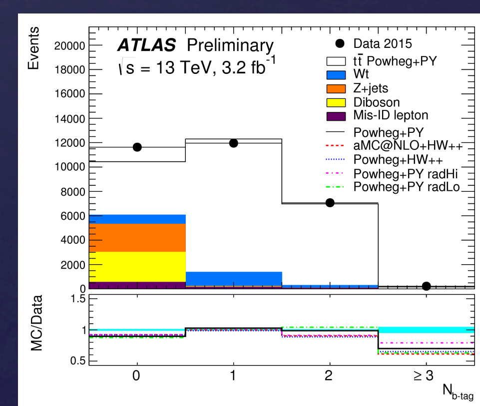
| Uncertainty (inclusive $\sigma_{t\bar{t}}$) | $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%) | $\Delta C_b/C_b$ (%) | $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%) |
|---|---|---|---|
| Data statistics | | | 1.69 |
| $t\bar{t}$ modelling | 0.71 | −0.72 | 1.43 |
| Parton distribution functions | 1.03 | - | 1.04 |
| QCD scale choice | 0.30 | - | 0.30 |
| Single-top modelling | - | - | 0.34 |
| Single-top/$t\bar{t}$ interference | - | - | 0.22 |
| Single-top $Wt$ cross-section | - | - | 0.72 |
| Diboson modelling | - | - | 0.12 |
| Diboson cross-sections | - | - | 0.03 |
| $Z$+jets extrapolation | - | - | 0.05 |
| Electron energy scale/resolution | 0.19 | −0.00 | 0.22 |
| Electron identification | 0.12 | 0.00 | 0.13 |
| Muon momentum scale/resolution | 0.12 | 0.00 | 0.14 |
| Muon identification | 0.27 | 0.00 | 0.30 |
| Lepton isolation | 0.74 | - | 0.74 |
| Lepton trigger | 0.15 | −0.02 | 0.19 |
| Jet energy scale | 0.22 | 0.06 | 0.27 |
| Jet energy resolution | −0.16 | 0.08 | 0.30 |
| Jet reconstruction/vertex fraction | 0.00 | 0.00 | 0.06 |
| $b$-tagging | - | 0.18 | 0.41 |
| Misidentified leptons | - | - | 0.41 |
| Analysis systematics ($\sigma_{t\bar{t}}$) | 1.56 | 0.75 | 2.27 |
| Integrated luminosity | - | - | 1.98 |
| LHC beam energy | - | - | 1.79 |
| Total uncertainty ($\sigma_{t\bar{t}}$) | 1.56 | 0.75 | 3.89 |

| Uncertainty (inclusive $\sigma_{t\bar{t}}$) | $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%) | $\Delta C_b/C_b$ (%) | $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$(%) |
|---|---|---|---|
| Data statistics | | | 0.9 |
| $t\bar{t}$ NLO modelling | 0.7 | -0.1 | 0.8 |
| $t\bar{t}$ hadronisation | -2.4 | 0.4 | 2.8 |
| Initial/final state radiation | -0.3 | 0.1 | 0.4 |
| Parton distribution functions | 0.5 | - | 0.5 |
| $t\bar{t}$ heavy-flavour production | - | 0.4 | 0.4 |
| 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 | 0.0 | 0.2 |
| Electron identification | 0.3 | 0.0 | 0.3 |
| Electron isolation | 0.4 | - | 0.4 |
| Muon momentum scale/resolution | -0.0 | 0.0 | 0.0 |
| Muon identification | 0.4 | 0.0 | 0.4 |
| Muon isolation | 0.2 | - | 0.3 |
| Lepton trigger | 0.1 | 0.0 | 0.2 |
| Jet energy scale | 0.3 | 0.1 | 0.3 |
| Jet energy resolution | -0.1 | 0.0 | 0.2 |
| $b$-tagging | - | 0.1 | 0.3 |
| Misidentified leptons | - | - | 0.6 |
| Analysis systematics | 2.7 | 0.6 | 3.3 |
| Integrated luminosity | - | - | 5.5 |
| LHC beam energy | - | - | 1.5 |
| Total uncertainty | 2.7 | 0.6 | 6.7 |

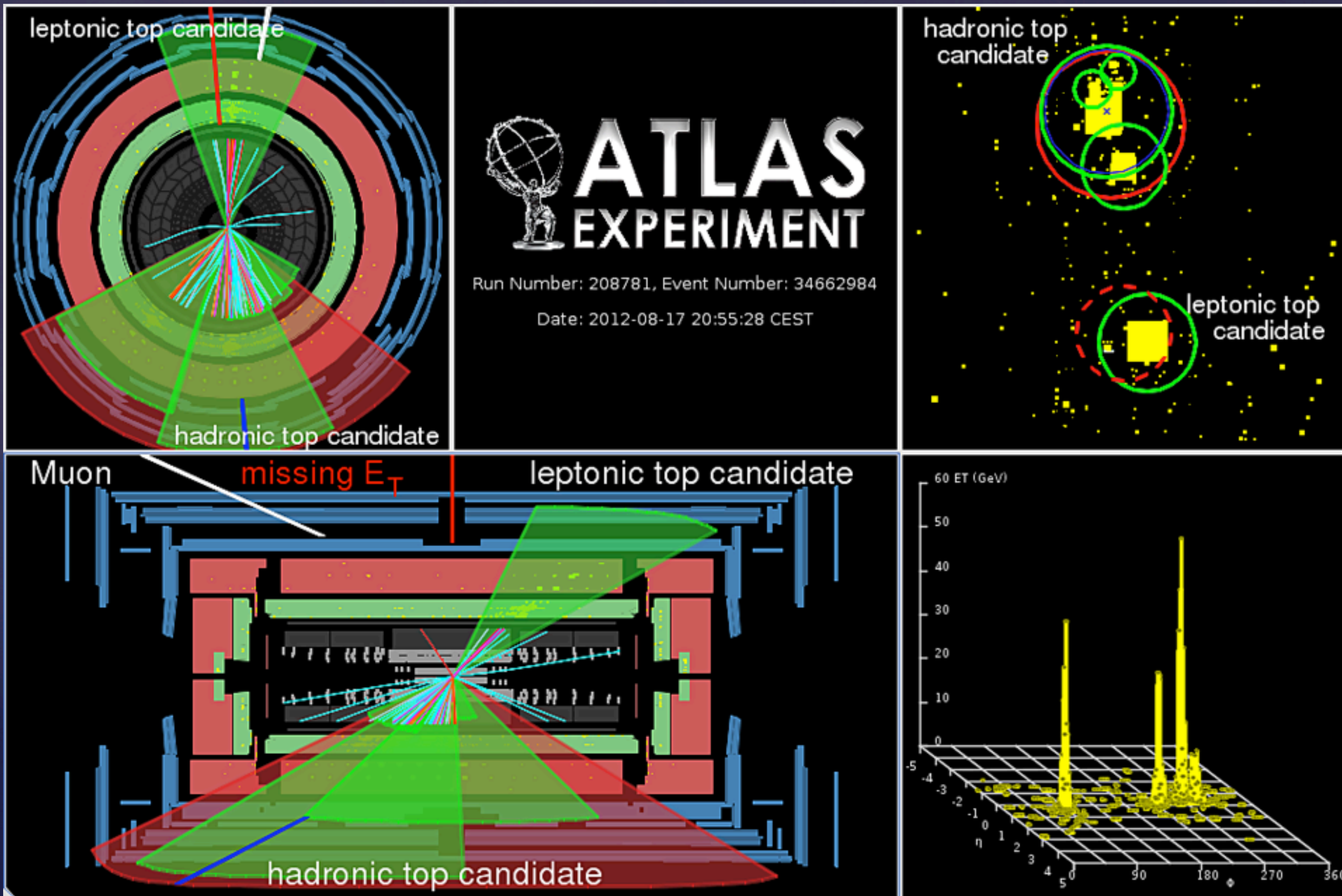



7&8 TeV

13 TeV



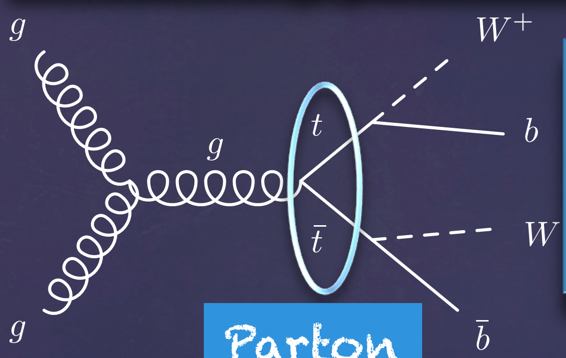
# Short break…



leptonic top candidate
hadronic top candidate
ATLAS EXPERIMENT
Run Number: 208781, Event Number: 34662984
Date: 2012-08-17 20:55:28 CEST
hadronic top candidate
leptonic top candidate
Muon
missing $E_T$
leptonic top candidate
hadronic top candidate
60 ET (GeV)
50
40
30
20
10
0
η
φ
0
90
180
270

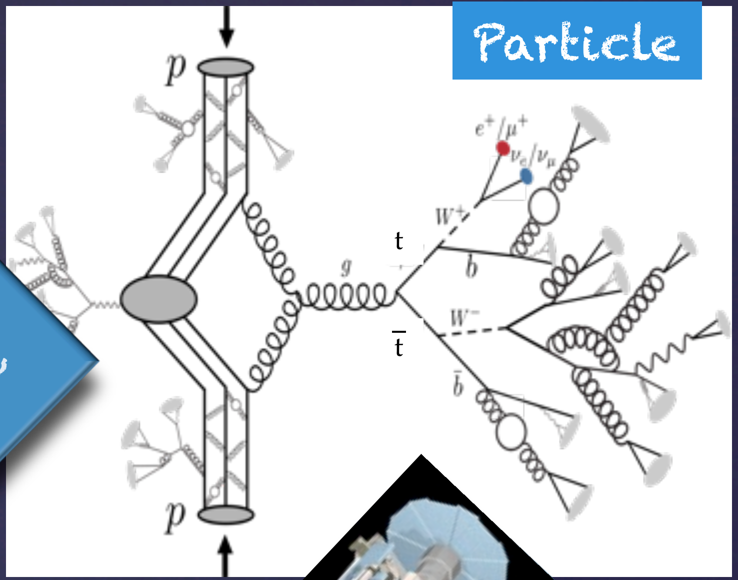
# Unfolding: Parton vs Particle

Matrix Element calculation (usually perturbative)

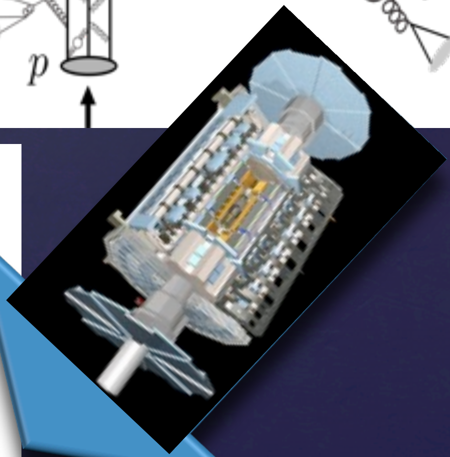



Parton

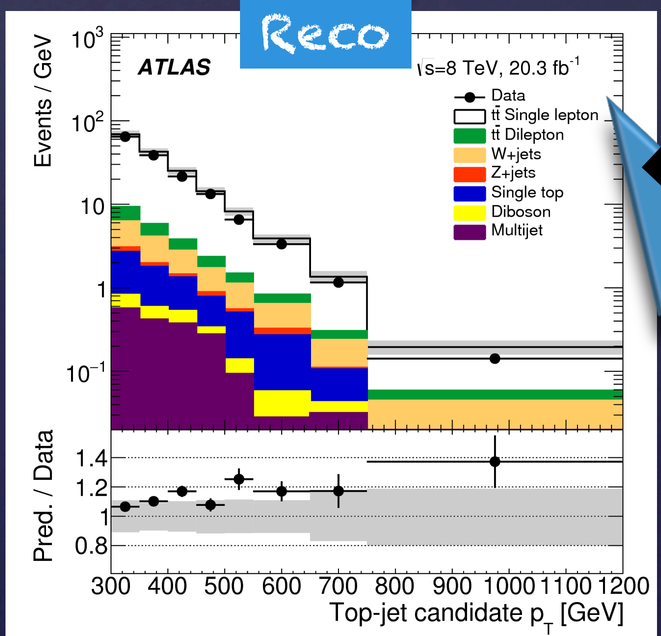
Fragmentation, parton shower, hadronisation, PDFs,... (often non-perturbative)



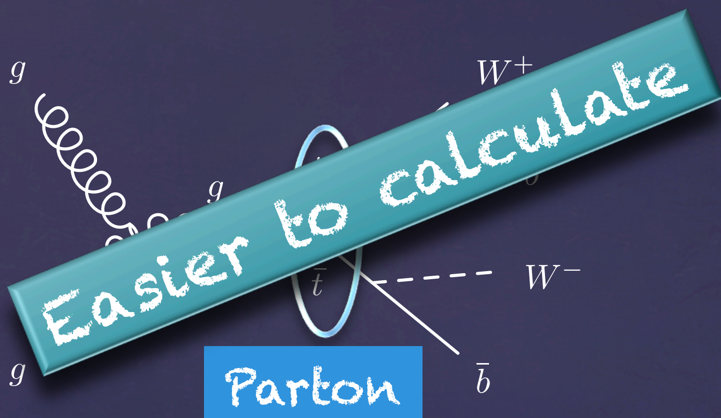

Particle

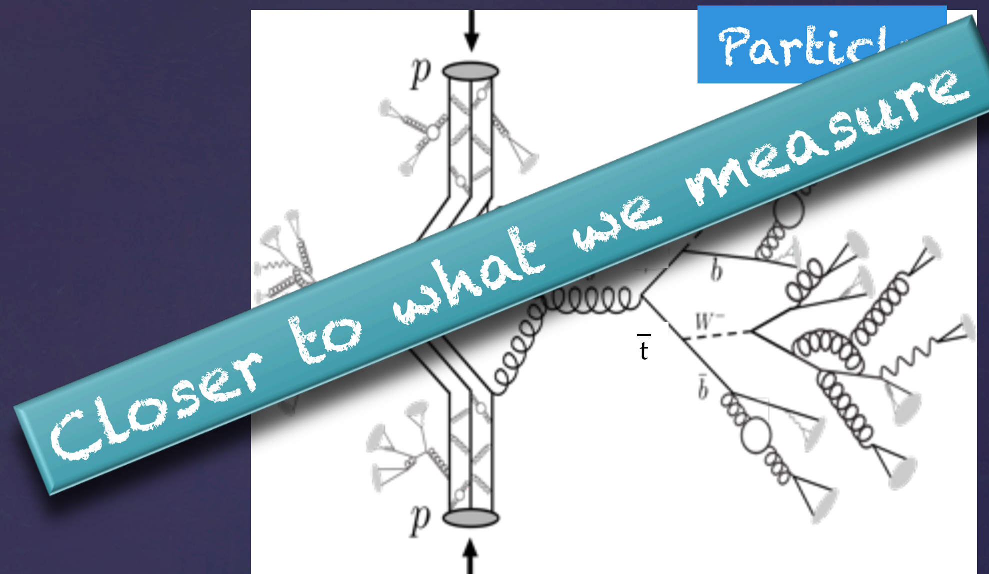


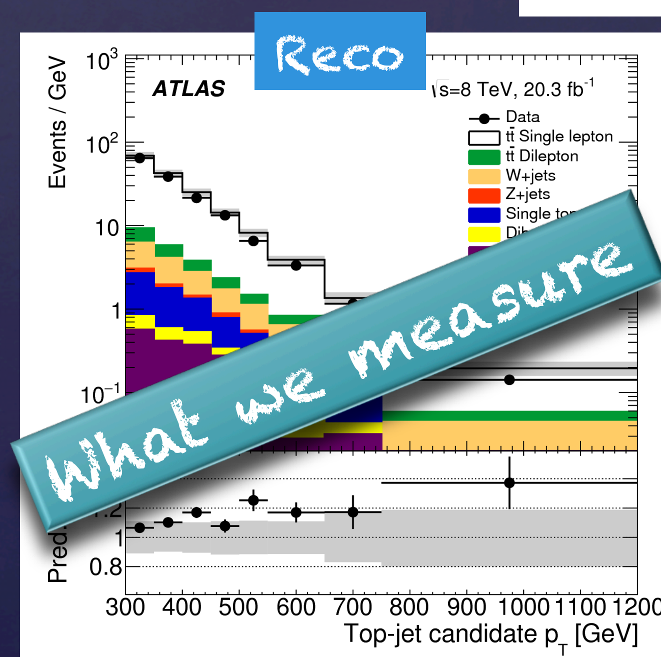
Reco



# Unfolding: Parton vs Particle



# Unfolding: Parton vs Particle

Reco | Particle | Parton

| Cut | Detector level | | Particle level |
|---|---|---|---|
| | $e$ + jets | $\mu$ + jets | |
| Leptons | $\lvert z_0\rvert < 2$ mm<br>$I_{\text{mini}} < 0.05$<br>$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$<br>$p_{\text{T}} > 25$ GeV | $\lvert z_0\rvert < 2$ mm and $\lvert d_0/\sigma(d_0)\rvert < 3$<br>$I_{\text{mini}} < 0.05$<br>$\lvert\eta\rvert < 2.5$<br>$p_{\text{T}} > 25$ GeV | $\lvert\eta\rvert < 2.5$<br>$p_{\text{T}} > 25$ GeV |
| Anti-$k_t$ $R = 0.4$ jets | $p_{\text{T}} > 25$ GeV<br>$\lvert\eta\rvert < 2.5$<br>JVF > 0.5 (if $p_{\text{T}} < 50$ GeV and $\lvert\eta\rvert < 2.4$) | | $\lvert\eta\rvert < 2.5$<br>$p_{\text{T}} > 25$ GeV |
| Overlap removal | if $\Delta R(e, \text{jet}_{R=0.4}) < 0.4$:<br>$\text{jet}'_{R=0.4} = \text{jet}_{R=0.4} - e$<br>if $\Delta R(e, \text{jet}'_{R=0.4}) < 0.2$:<br>$e$ removed and<br>$\text{jet}''_{R=0.4} = \text{jet}'_{R=0.4} + e$ | if $\Delta R(\mu, \text{jet}'_{R=0.4}) < 0.04 + 10\ \text{GeV}/p_{\text{T}}(\mu)$:<br>$\mu$ removed | None |
| $E_{\text{T}}^{\text{miss}}, m_{\text{T}}^{W}$ | $E_{\text{T}}^{\text{miss}} > 20$ GeV, $E_{\text{T}}^{\text{miss}} + m_{\text{T}}^{W} > 60$ GeV | | |
| Leptonic top | At least one anti-$k_t$ $R = 0.4$ jet with $\Delta R(\ell, \text{jet}_{R=0.4}) < 1.5$ | | |
| Hadronic top | The leading-$p_{\text{T}}$ trimmed anti-$k_t$ $R = 1.0$ jet has:<br>$p_{\text{T}} > 300$ GeV, $m > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV<br>$\Delta R(\text{jet}_{R=1.0}, \text{jet}_{R=0.4}) > 1.5$, $\Delta\phi(\ell, \text{jet}_{R=1.0}) > 2.3$ | | |
| $b$-tagging | At least one of:<br>1) the leading-$p_{\text{T}}$ anti-$k_t$ $R = 0.4$ jet with $\Delta R(\ell, \text{jet}_{R=0.4}) < 1.5$ is $b$-tagged<br>2) at least one anti-$k_t$ $R = 0.4$ jet with $\Delta R(\text{jet}_{R=1.0}, \text{jet}_{R=0.4}) < 1.0$ is $b$-tagged | | |

- Take top quark whose W decays hadronically
- Conisider top after QCD radiation (i.e. just before it decays)
- Correct back to all top decays (not just semi-leptonic)
- Require:
  - $p_T^{top} > 300$ GeV

# Unfolding: Parton vs Particle

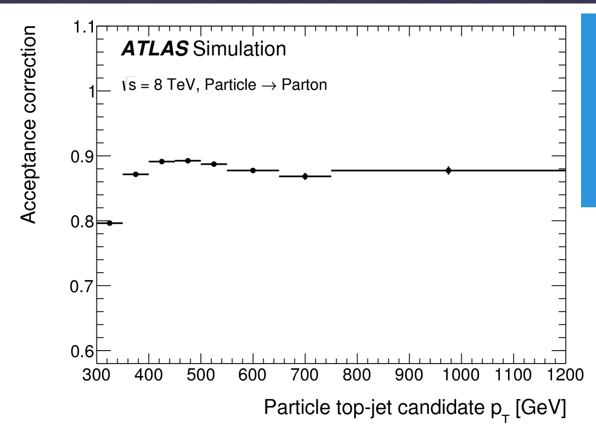
## Particle objects

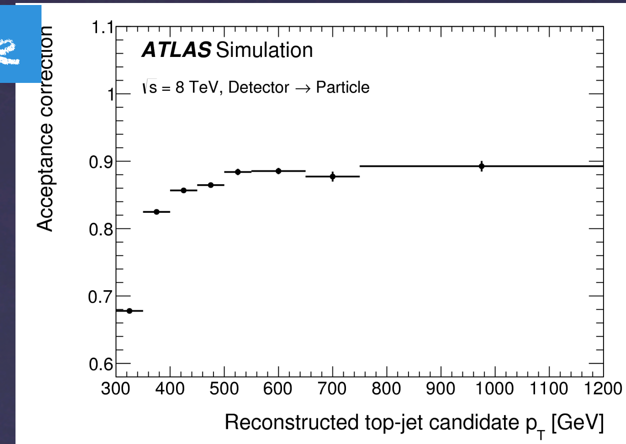
- Leptons:
  - Not from hadron (i.e. from W or from tau not from W)
  - Dressed with photons: dR<0.2 (maybe move to anti-kT in future)
- Jets: Same algorithm as used on detector objects but run over stable particles
  - Not including neutrinos (ATLAS) or including neutrinos (CMS)
- B-tagging: ghost association of b-hadron within jet
  - Set energy to tiny number, include in clustering
- MET: sum over all neutrinos not from hadrons
- Photons: photon not associated to a dressed lepton
- Reconstruct the ‘particle level top’ via algorithms as similar to those applied at detector level as possible. Compromise:
  - Don’t use the most complex detector level possible
  - Check the ‘diagonality’ of the matrix

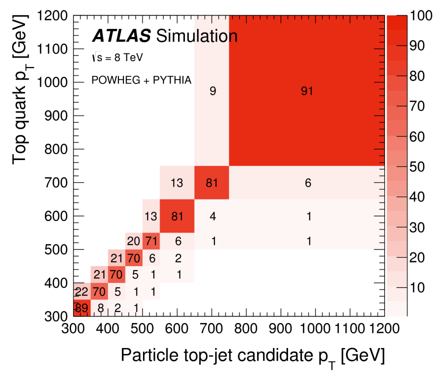
# Unfolding: Parton vs Particle

Parton (additional corrections)

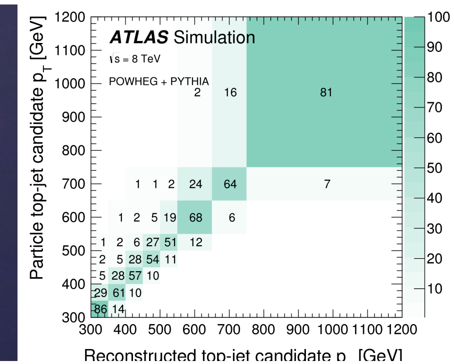
Particle

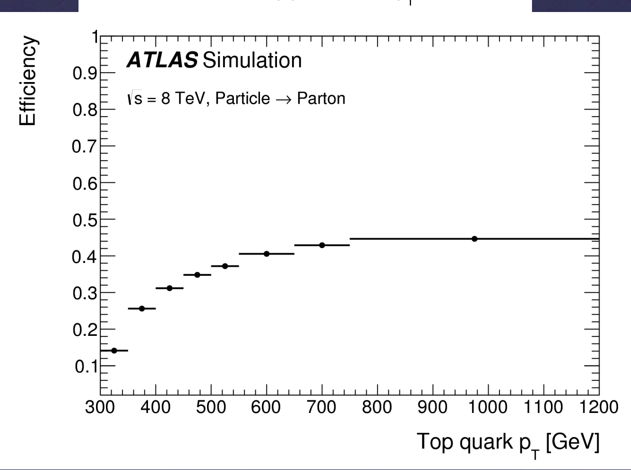


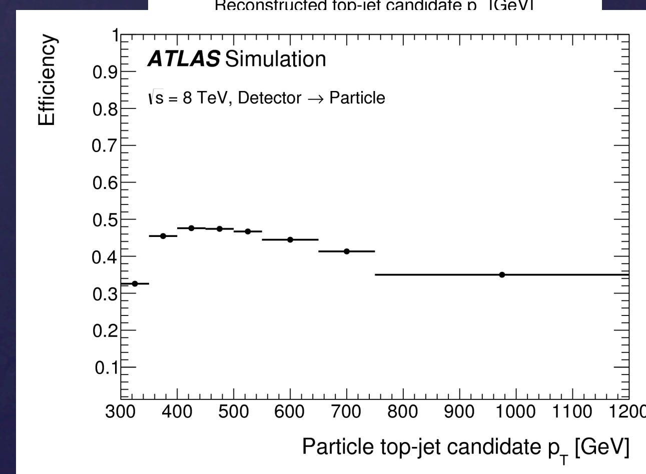



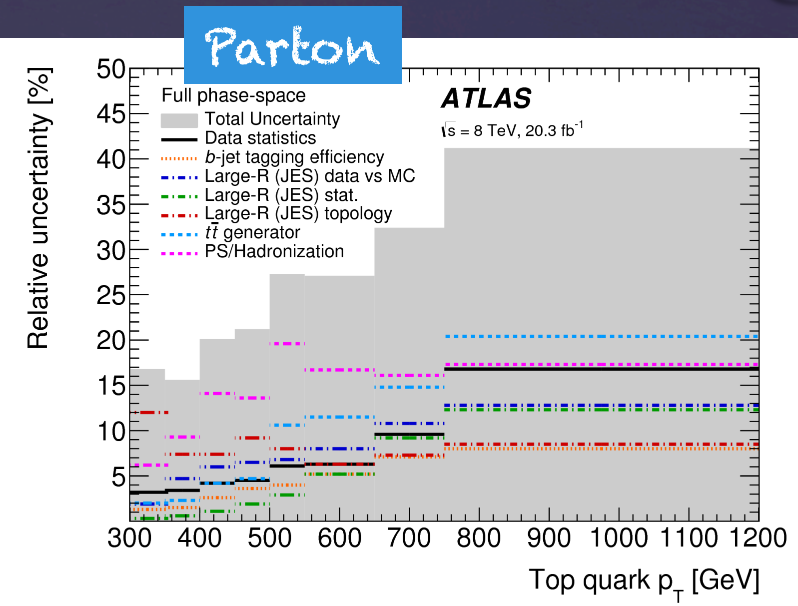

$$\frac{d\sigma_{t\bar{t}}}{dp_{\mathrm{T,ptcl}}}(p^i_{\mathrm{T,ptcl}}) = \frac{N^i_{\mathrm{ptcl}}}{\Delta p^i_{\mathrm{T,ptcl}}\mathcal{L}} = \frac{1}{\Delta p^i_{\mathrm{T,ptcl}}\mathcal{L} f^i_{\mathrm{ptcl!reco}}} \cdot \sum_j M^{-1}_{ij} f^j_{\mathrm{reco!ptcl}} f_{t\bar{t},\ell+\mathrm{jets}}(N^j_{\mathrm{reco}} - N^j_{\mathrm{reco,bgnd}}),$$

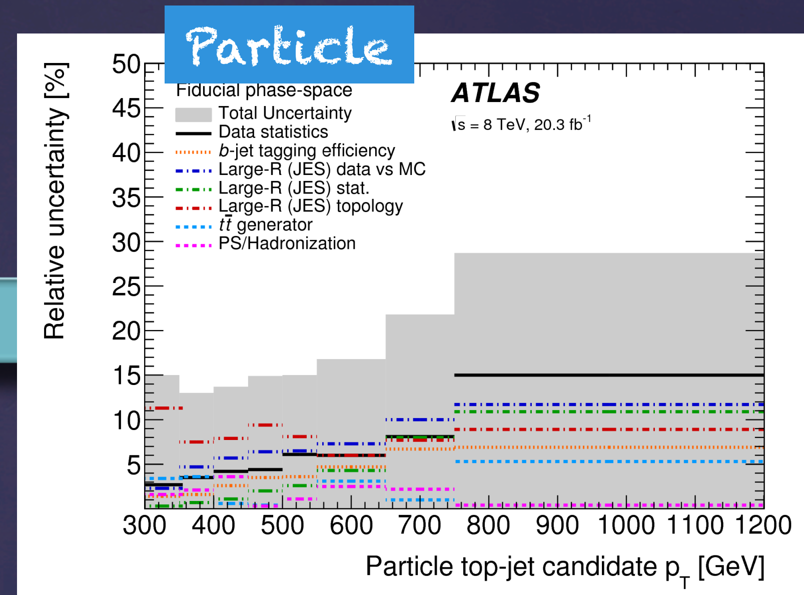


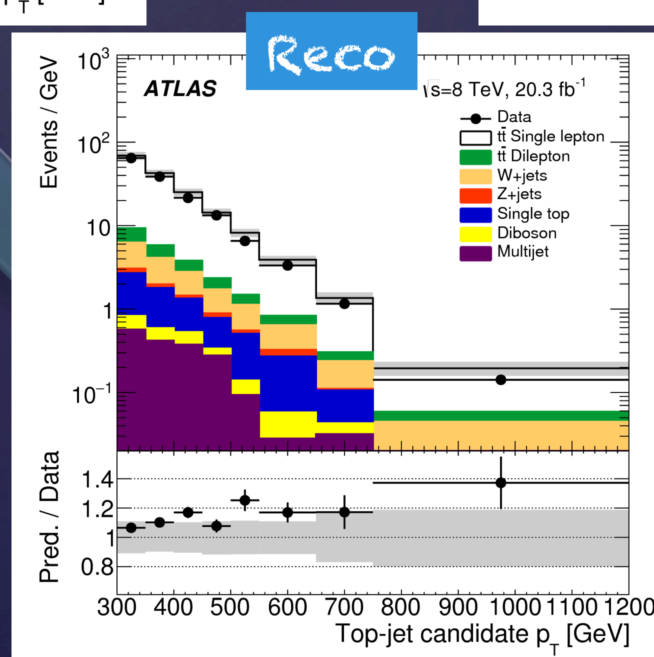



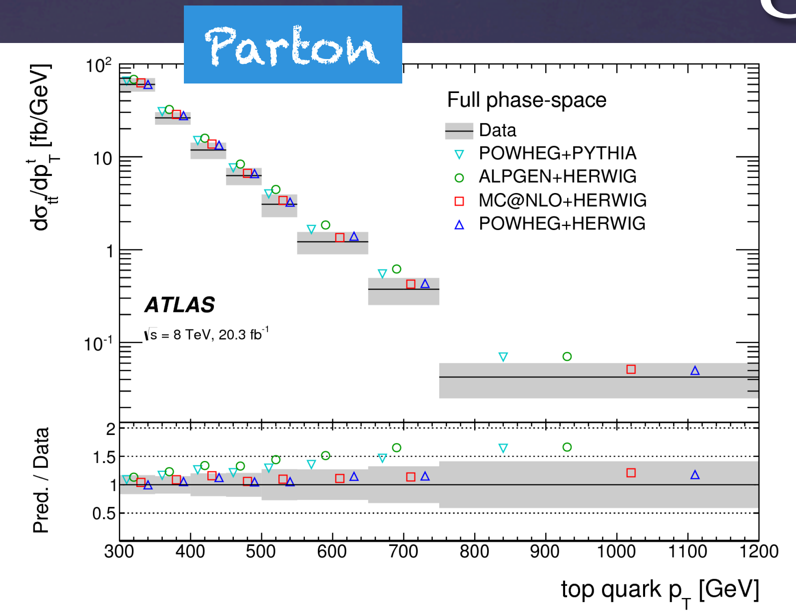
# Unfolding: Parton vs Particle

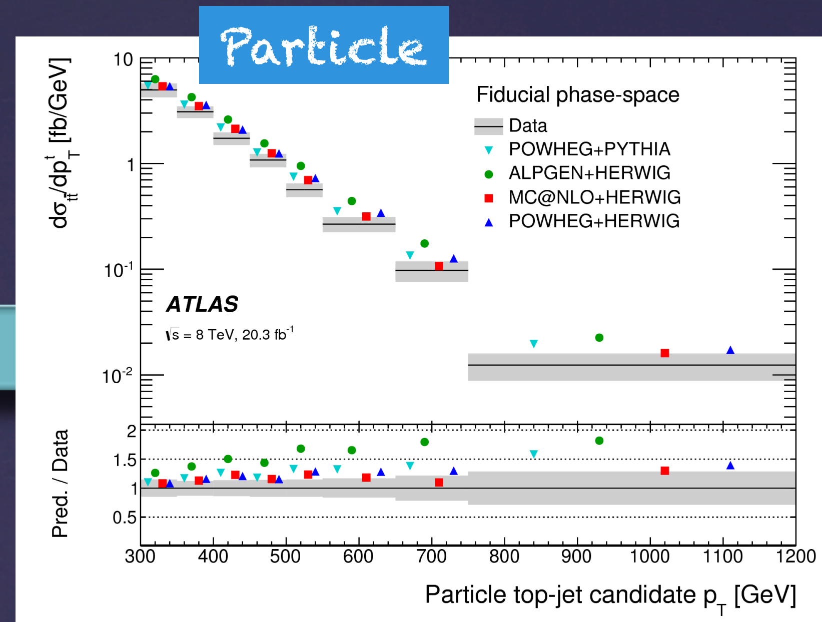


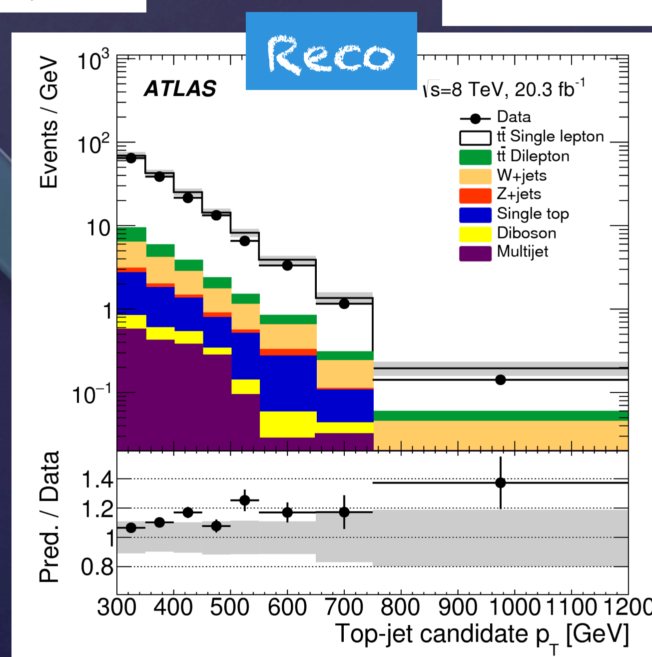



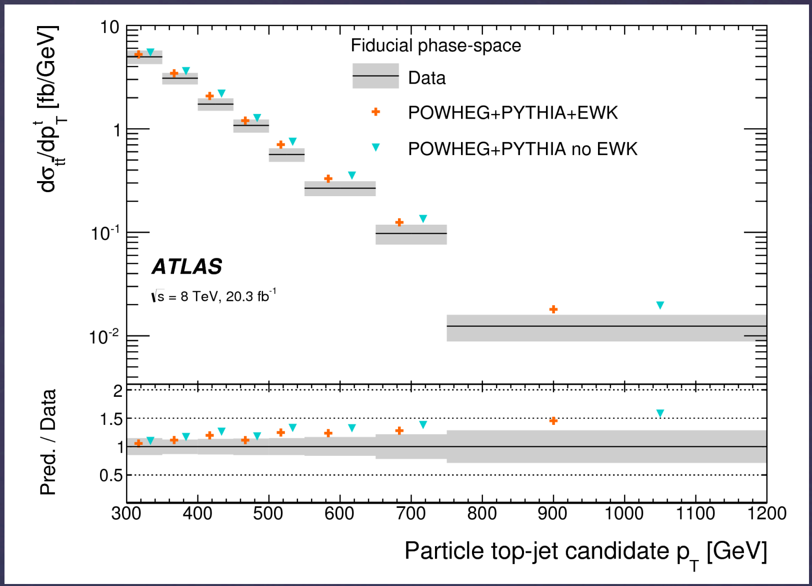
# Unfolding: Parton vs Particle

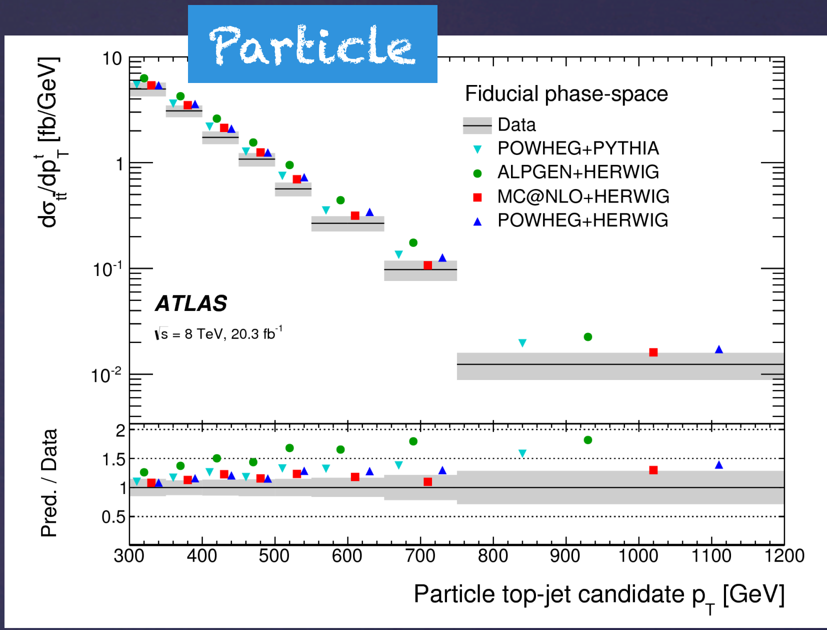


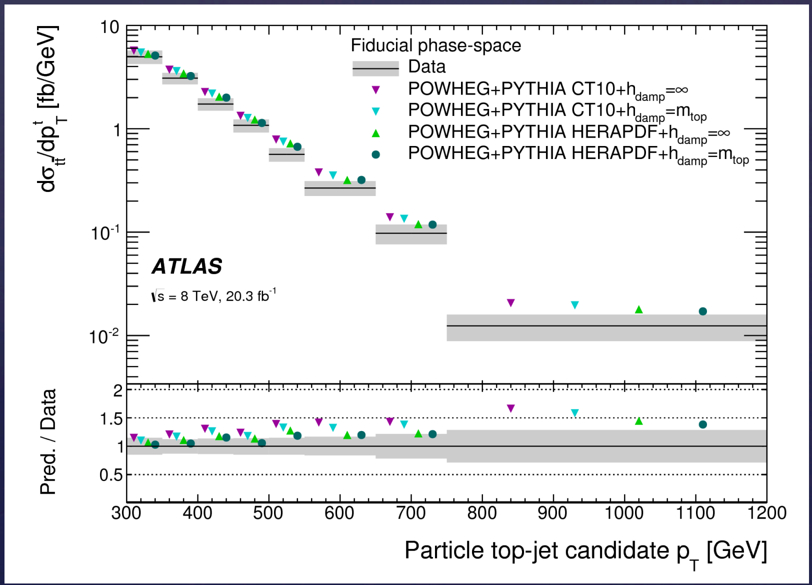



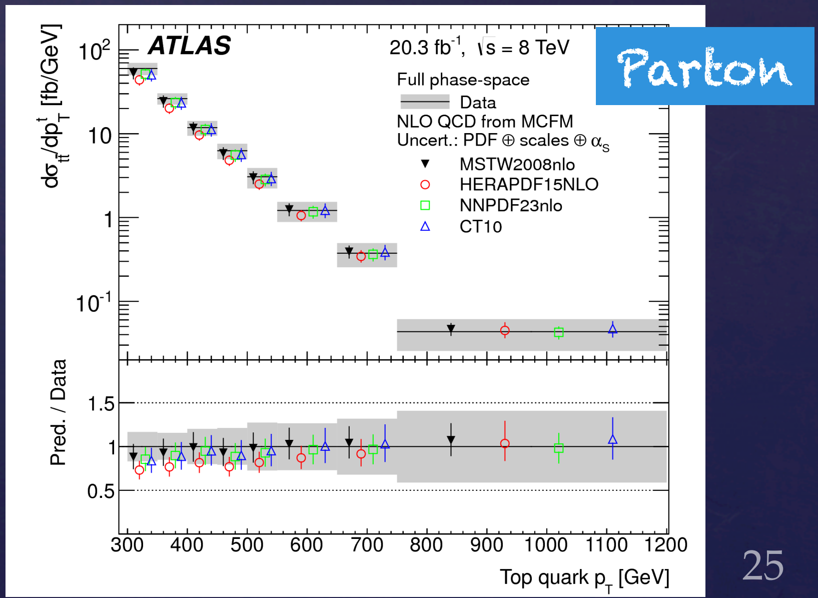



# Unfolding: Parton vs Particle

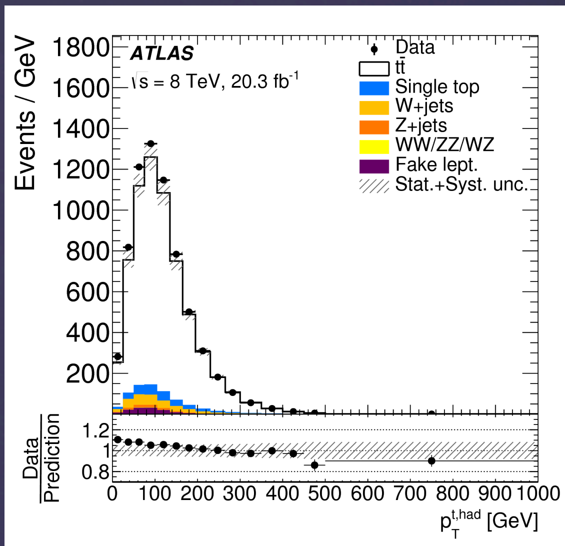


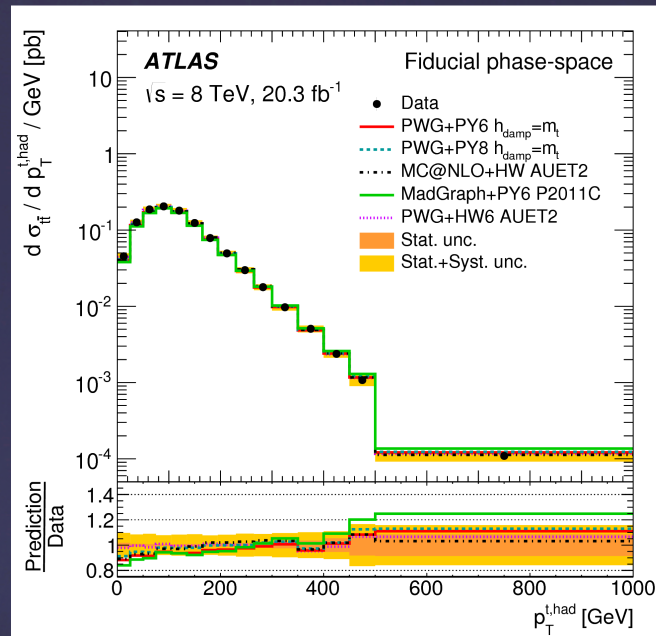



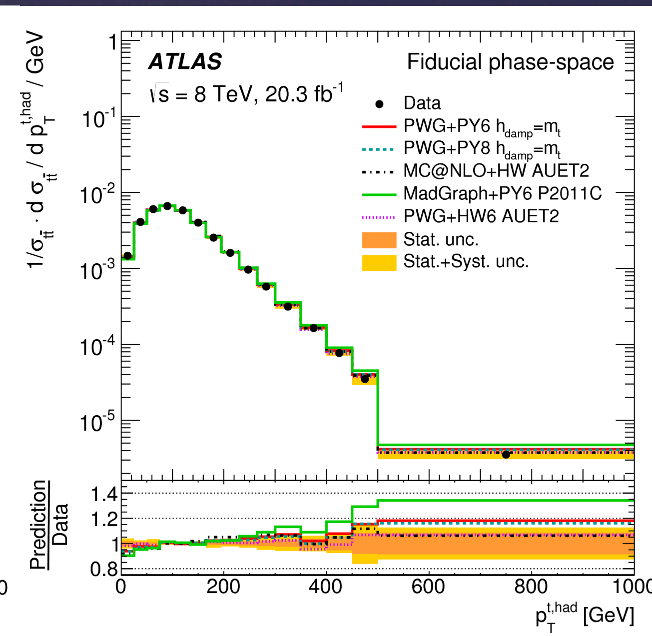



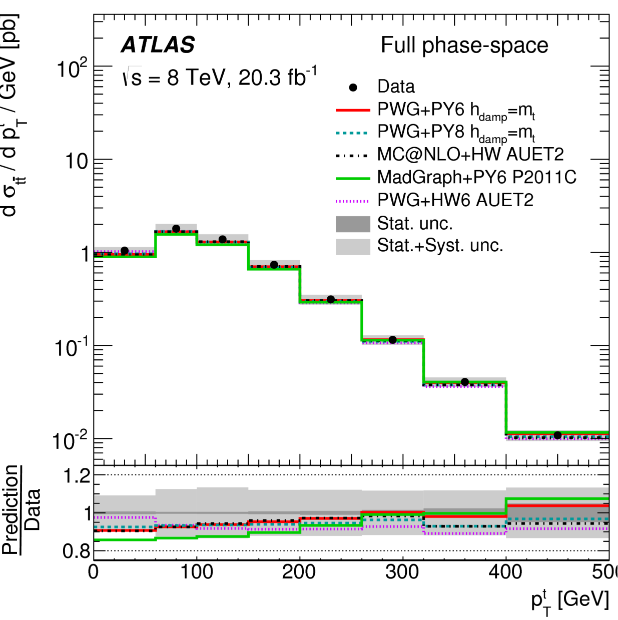



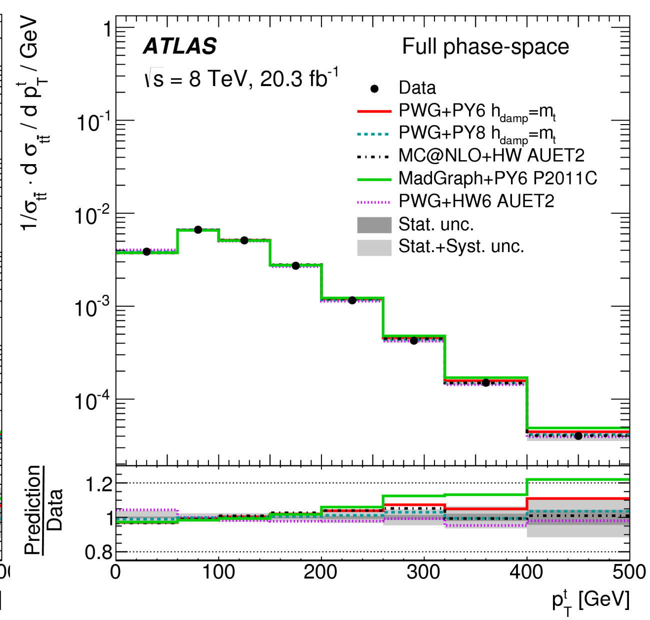
# Resolved l+jets: $p_T^t$

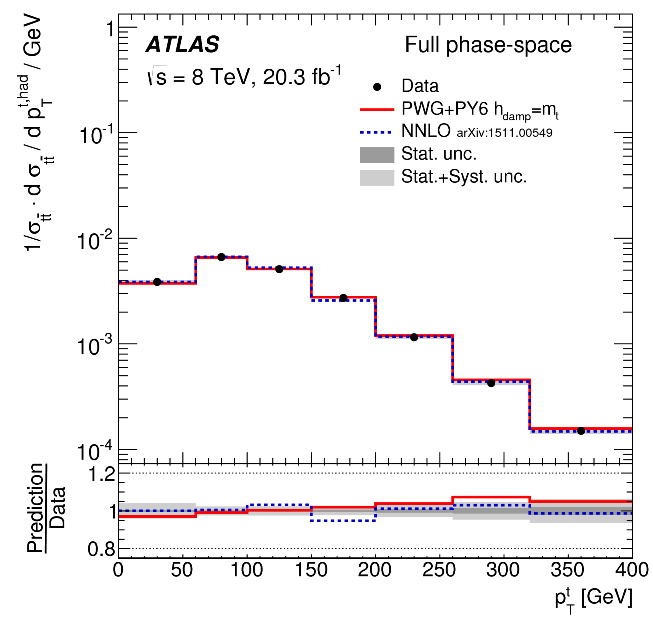


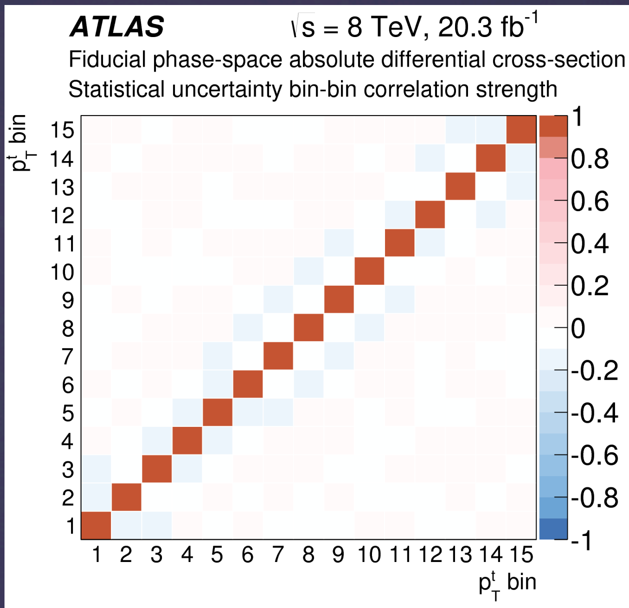



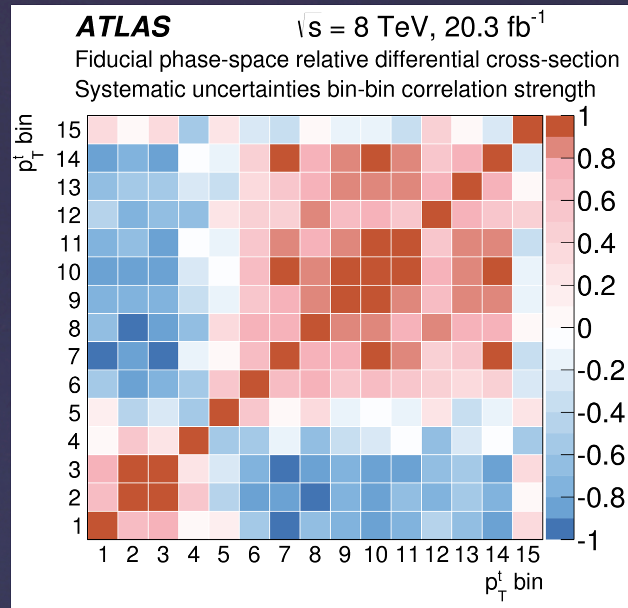



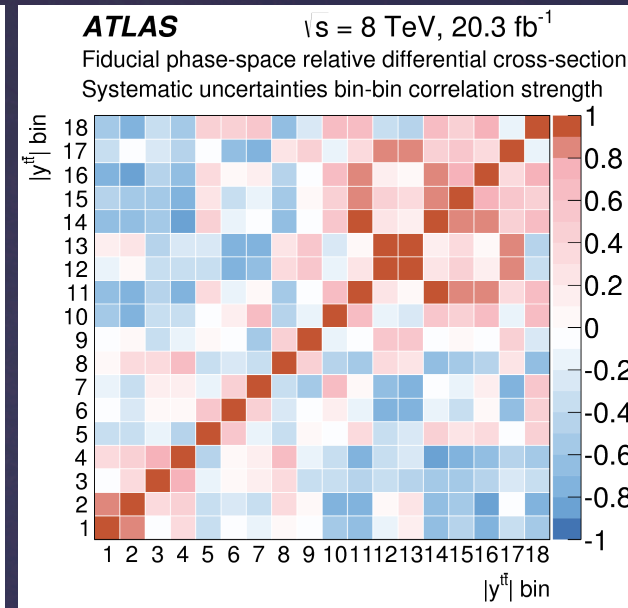
# Resolved l+jets

| Bins [GeV] | 350–400 | 400–450 | 450–500 |
|---|---|---|---|
| $1/\sigma \cdot d\sigma / d\, p_T^t$ | $1.64 \cdot 10^{-4}$ | $7.69 \cdot 10^{-5}$ | $3.49 \cdot 10^{-5}$ |
| Total Uncertainty [%] | $\pm5.78$ | $\pm7.73$ | $\pm16.0$ |
| Statistics [%] | $\pm3.55$ | $\pm5.39$ | $\pm8.19$ |
| Systematics [%] | $\pm4.46$ | $\pm5.40$ | $\pm13.7$ |
| $\eta$ intercalibration model (JES) [%] | $\pm0.21$ | - | $^{+0.36}_{-}$ |
| Single particle high-$p_T$ (JES) [%] | - | - | - |
| Effective stat. NP set 1 (JES) [%] | $\mp0.34$ | $\mp0.90$ | $\mp0.61$ |
| Effective stat. NP set 2 (JES) [%] | $\pm0.17$ | $^{+0.18}_{-0.12}$ | $^{+0.25}_{-}$ |
| Effective stat. NP set 3 (JES) [%] | $\mp0.33$ | $^{-0.24}_{+0.35}$ | $^{+0.37}_{-}$ |
| Effective detector NP set 1 (JES) [%] | $\pm1.71$ | $\pm2.46$ | $\pm2.56$ |
| Effective detector NP set 2 (JES) [%] | $\mp0.22$ | $\mp0.26$ | $^{-}_{+0.45}$ |
| Effective detector NP set 3 (JES) [%] | $^{+0.22}_{-0.30}$ | $^{+0.28}_{-0.14}$ | $^{+0.18}_{-}$ |
| Effective mixed NP set 1 (JES) [%] | $\pm1.18$ | $\pm1.45$ | $\pm1.52$ |
| Effective mixed NP set 2 (JES) [%] | $^{+0.15}_{-}$ | $\pm0.36$ | $^{+0.40}_{-}$ |
| Effective model NP set 1 (JES) [%] | - | $^{-0.76}_{+0.54}$ | $^{-}_{-0.33}$ |
| Effective model NP set 2 (JES) [%] | $^{+0.23}_{-0.34}$ | $\pm0.76$ | $\pm0.58$ |
| Effective model NP set 3 (JES) [%] | $\mp0.41$ | $^{-0.15}_{+0.26}$ | $^{-0.21}_{+0.33}$ |
| Effective model NP set 4 (JES) [%] | $^{+0.34}_{-0.48}$ | $^{+0.47}_{-0.26}$ | $\pm0.37$ |
| Pile-up offset $\mu$ (JES) [%] | - | $^{+0.24}_{-0.12}$ | $^{+0.24}_{-0.11}$ |
| Pile-up offset $N_{PV}$ (JES) [%] | - | $^{+0.13}_{-0.40}$ | $^{-0.19}_{+0.46}$ |
| Punch-through (JES) [%] | - | - | - |
| Pile-up offset $\rho$ topology (JES) [%] | - | $^{-1.01}_{+0.72}$ | $^{-0.14}_{+0.66}$ |
| Pile-up offset $p_T$ (JES) [%] | - | - | $^{-0.41}_{+0.71}$ |
| Flavour composition (JES) [%] | $^{-}_{+0.43}$ | $^{-1.54}_{+1.12}$ | $^{-0.44}_{+0.22}$ |
| Flavour response (JES) [%] | $\mp0.53$ | $^{-}_{-0.44}$ | $^{-0.16}_{+0.52}$ |
| $b$-Tagged jet energy scale (JES) [%] | $\pm0.53$ | $^{+0.34}_{-0.57}$ | $^{+0.38}_{-}$ |
| Jet reconstruction efficiency [%] | - | - | - |
| Jet energy resolution [%] | - | - | - |
| $b$-Quark tagging efficiency [%] | $\pm1.85$ | $\pm2.16$ | $\pm2.52$ |
| $c$-Quark tagging efficiency [%] | $\mp0.40$ | $\mp0.44$ | $\mp0.38$ |
| Light-jet tagging efficiency [%] | - | - | - |
| Electron energy scale [%] | - | - | - |
| Electron energy resolution [%] | - | - | - |
| Muon momentum scale [%] | - | - | - |
| Muon (ID) momentum resolution [%] | - | - | - |
| Muon (MS) momentum resolution [%] | - | - | - |
| Lepton trigger efficiency [%] | - | - | - |
| Lepton reconstruction efficiency [%] | - | - | - |
| Lepton identification efficiency [%] | - | - | - |
| $E_T^{miss}$ Soft jet scale [%] | - | - | - |
| $E_T^{miss}$ Soft jet resolution [%] | - | - | - |
| Jet vertex fraction [%] | $\pm0.54$ | $^{+0.75}_{-0.53}$ | $\pm0.79$ |
| Alternate hard-scattering model [%] | - | $\pm2.69$ | $\pm10.5$ |
| Alternate parton-shower model [%] | $\pm2.21$ | $\pm1.21$ | $\pm6.62$ |
| Monte Carlo sample statistics [%] | $\pm0.85$ | $\pm1.24$ | $\pm1.81$ |
| ISR/FSR + scale [%] | $^{+3.11}_{-0.10}$ | $^{+0.96}_{-}$ | $\pm3.38$ |
| Parton distribution functions [%] | $\mp0.57$ | $\mp0.74$ | $\mp0.88$ |
| Single top cross-section [%] | $\pm0.13$ | $\pm0.23$ | $\pm0.25$ |
| $W$+jets scale factors [%] | $\pm0.11$ | $\mp0.15$ | $\mp0.29$ |
| Fake lept. MC stat, $e$+jets ch. [%] | $^{-}_{-0.26}$ | $^{+0.47}_{-0.14}$ | $^{+1.08}_{-}$ |
| Fake lept. alternate fake CR, $e$+jets ch. [%] | $\mp0.25$ | $\mp0.24$ | $\pm0.16$ |
| Fake lept. alternate real CR, $e$+jets ch. [%] | - | - | - |
| Fake lept. alternate parametrization, $e$+jets ch. [%] | $\mp0.24$ | $\mp0.13$ | $\pm0.35$ |
| Fake lept. MC stat, $\mu$+jets ch. [%] | - | $^{+0.35}_{-}$ | - |
| Fake lept. alternate fake CR, $\mu$+jets ch. [%] | $\mp0.32$ | - | - |
| Fake lept. alternate real CR, $\mu$+jets ch. [%] | - | $\mp0.29$ | $\mp0.33$ |
| Fake lept. alternate parametrization, $\mu$+jets ch. [%] | - | - | $\mp0.25$ |
| $Z$+jets cross-section [%] | - | $\mp0.25$ | $\mp0.41$ |
| Diboson cross-section [%] | - | - | - |
| Luminosity [%] | - | - | - |

# Resolved l+jets

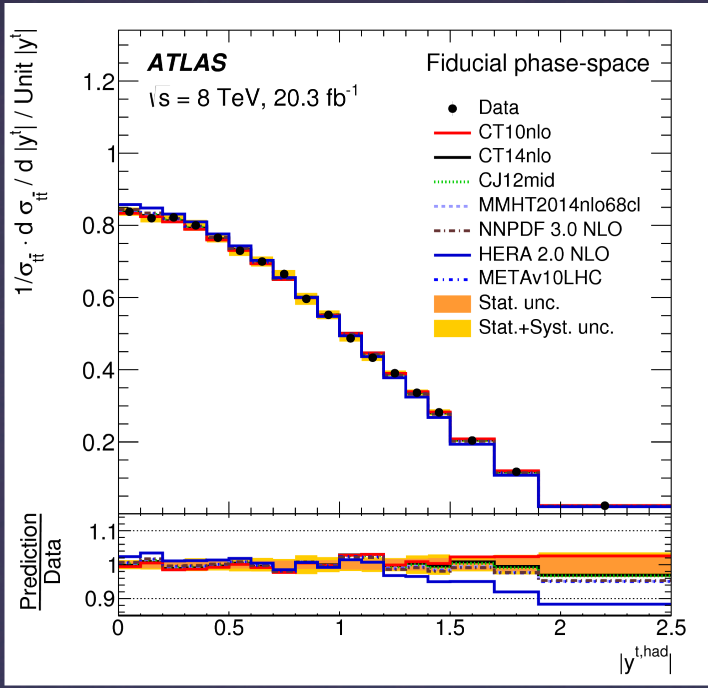


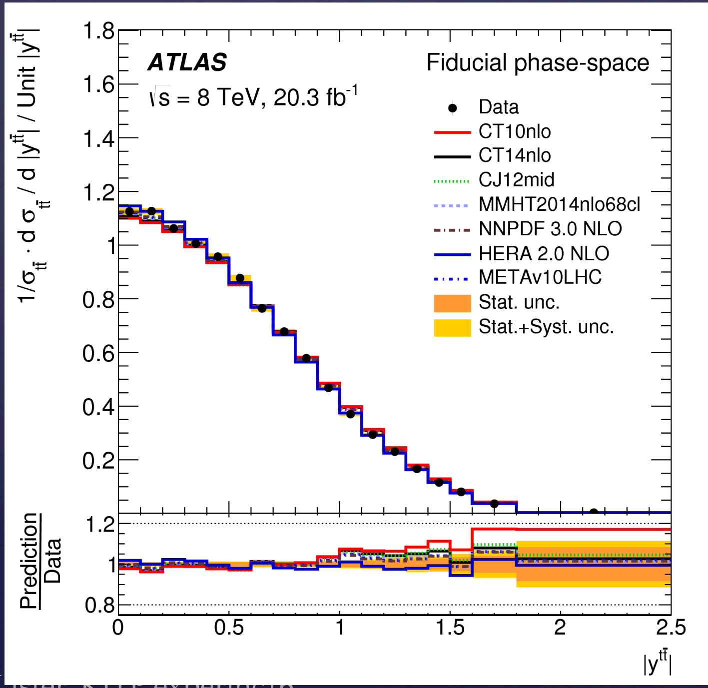



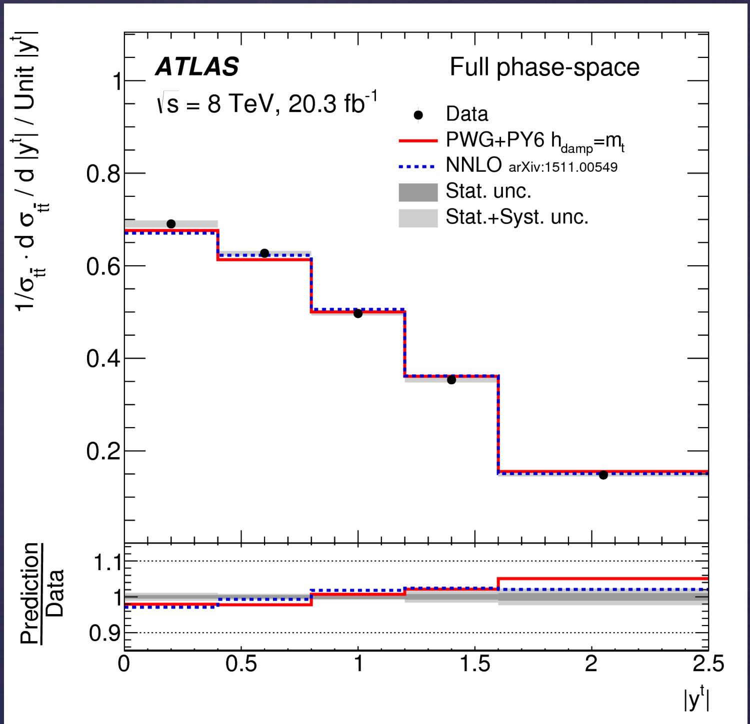




| Variable | PWG+PY8 CT10 $h_{\rm damp} = m_t$ | | MC@NLO+HW CT10 AUET2 | | PWG+PY6 CT10 $h_{\rm damp} = m_t$ | | PWG+HW6 CT10 $h_{\rm damp} = \infty$ | | MadGraph+PY6 MadGraph+PY6 P2011C | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\chi^2$/NDF | $p$-value | $\chi^2$/NDF | $p$-value | $\chi^2$/NDF | $p$-value | $\chi^2$/NDF | $p$-value | $\chi^2$/NDF | $p$-value |
| $p_{\rm T}^{t,\rm had}$ | 11/14 | 0.72 | 25/14 | 0.04 | 12/14 | 0.59 | 3.1/14 | 1.00 | 35/14 | <0.01 |
| $R_{Wt}$ | 20/11 | 0.05 | 24/11 | 0.01 | 25/11 | 0.01 | 4.2/11 | 0.96 | 60/11 | <0.01 |
| $\chi^{t\bar{t}}$ | 27/9 | <0.01 | 40/9 | <0.01 | 24/9 | <0.01 | 58/9 | <0.01 | 240/9 | <0.01 |
| $\lvert y^{t\bar{t}}\rvert$ | 110/17 | <0.01 | 77/17 | <0.01 | 100/17 | <0.01 | 110/17 | <0.01 | 210/17 | <0.01 |
| $m^{t\bar{t}}$ | 7.9/10 | 0.64 | 4.6/10 | 0.92 | 3.8/10 | 0.95 | 6.7/10 | 0.75 | 21/10 | 0.02 |
| $y_{\rm boost}^{t\bar{t}}$ | 83/15 | <0.01 | 56/15 | <0.01 | 76/15 | <0.01 | 80/15 | <0.01 | 160/15 | <0.01 |
| $\lvert p_{\rm out}^{t\bar{t}}\rvert$ | 2.4/5 | 0.79 | 9.0/5 | 0.11 | 8.8/5 | 0.12 | 11/5 | 0.05 | 3.3/5 | 0.66 |
| $\lvert y^{t,\rm had}\rvert$ | 22/17 | 0.18 | 11/17 | 0.88 | 20/17 | 0.27 | 15/17 | 0.60 | 13/17 | 0.72 |
| $p_{\rm T}^{t\bar{t}}$ | 1.3/5 | 0.93 | 2.6/5 | 0.75 | 3.1/5 | 0.68 | 4.2/5 | 0.52 | 2.9/5 | 0.71 |
| $H_{\rm T}^{t\bar{t}}$ | 8.2/14 | 0.88 | 12/14 | 0.59 | 13/14 | 0.52 | 2.3/14 | 1.00 | 38/14 | <0.01 |
| $\Delta\phi^{t\bar{t}}$ | 0.8/3 | 0.84 | 24/3 | <0.01 | 5.0/3 | 0.17 | 17/3 | <0.01 | 19/3 | <0.01 |

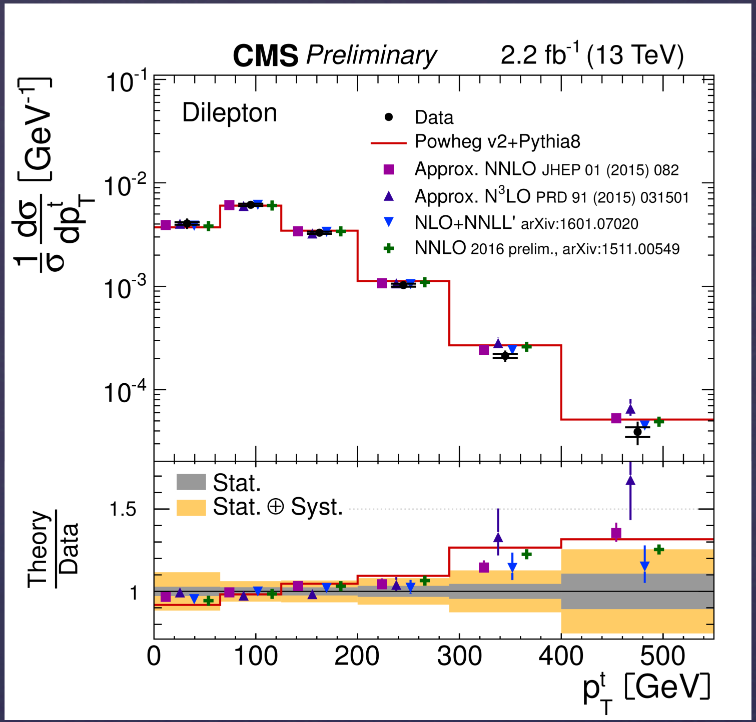
# Resolved l+jets PDF constraints



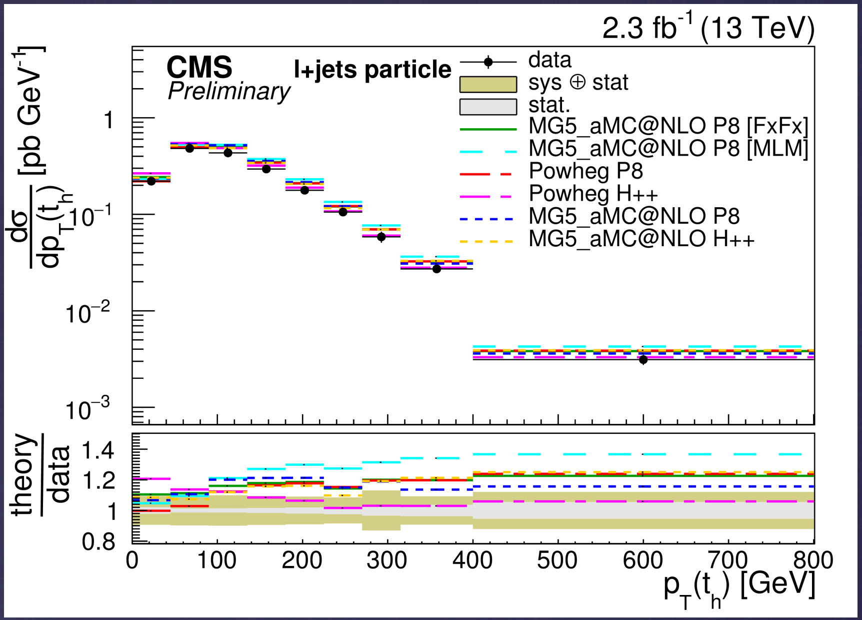



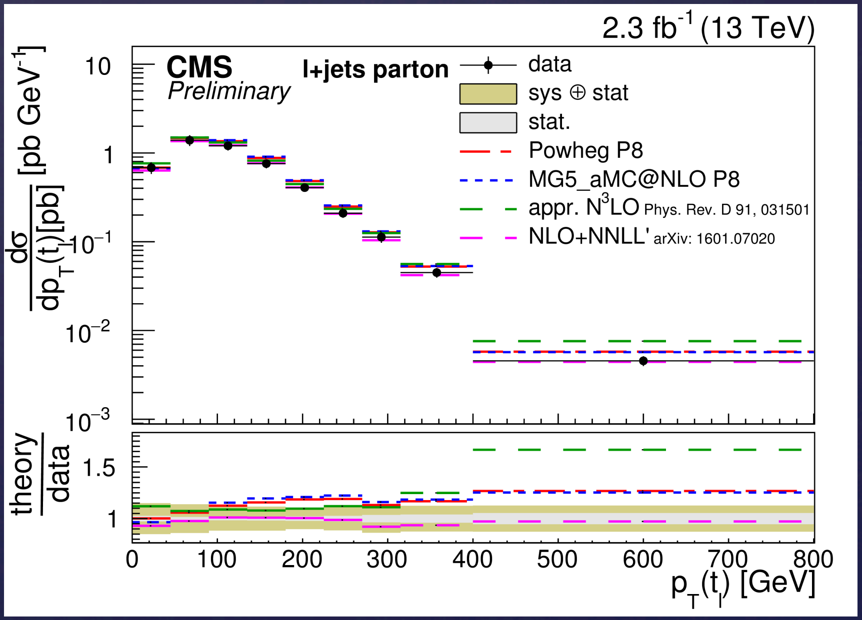
# More $p_T^t$



CMS Preliminary
2.2 fb-1 (13 TeV)
Dilepton
Data
Powheg v2+Pythia8
Approx. NNLO JHEP 01 (2015) 082
Approx. N3LO PRD 91 (2015) 031501
NLO+NNLL' arXiv:1601.07020
NNLO 2016 prelim., arXiv:1511.00549
Stat.
Stat. ⊕ Syst.
Theory / Data
pT t [GeV]

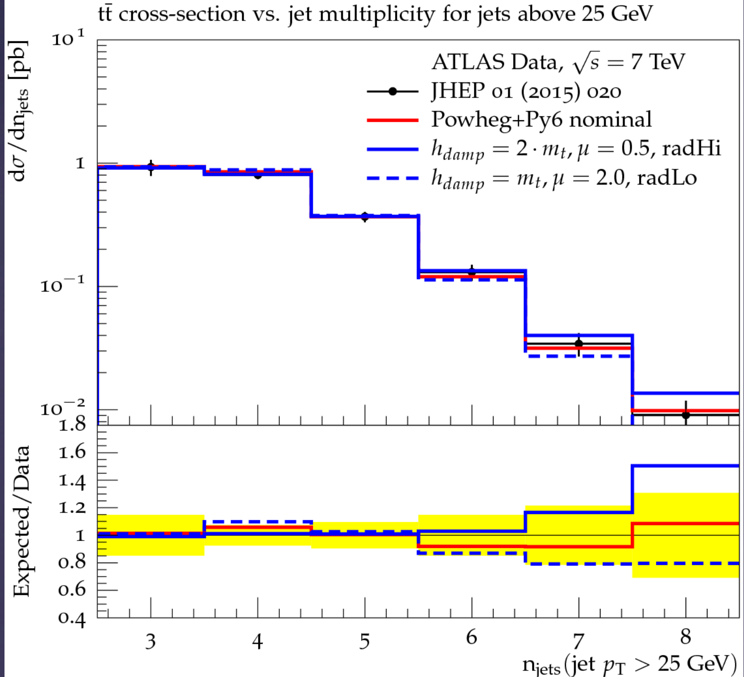



2.3 fb-1 (13 TeV)
CMS
Preliminary
l+jets particle
data
sys ⊕ stat
stat.
MG5_aMC@NLO P8 [FxFx]
MG5_aMC@NLO P8 [MLM]
Powheg P8
Powheg H++
MG5_aMC@NLO P8
MG5_aMC@NLO H++
theory / data
pT(th) [GeV]

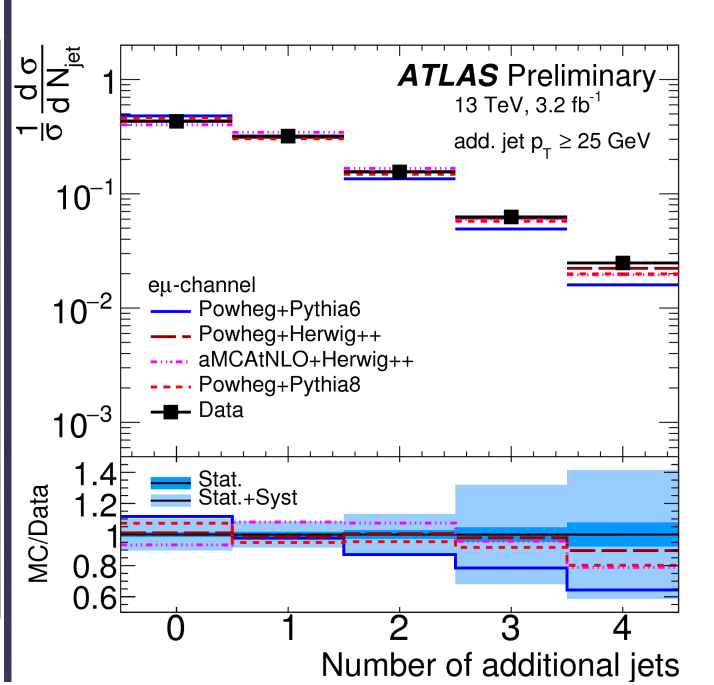



2.3 fb-1 (13 TeV)
CMS
Preliminary
l+jets parton
data
sys ⊕ stat
stat.
Powheg P8
MG5_aMC@NLO P8
appr. N3LO Phys. Rev. D 91, 031501
NLO+NNLL' arXiv: 1601.07020
theory / data
pT(tl) [GeV]

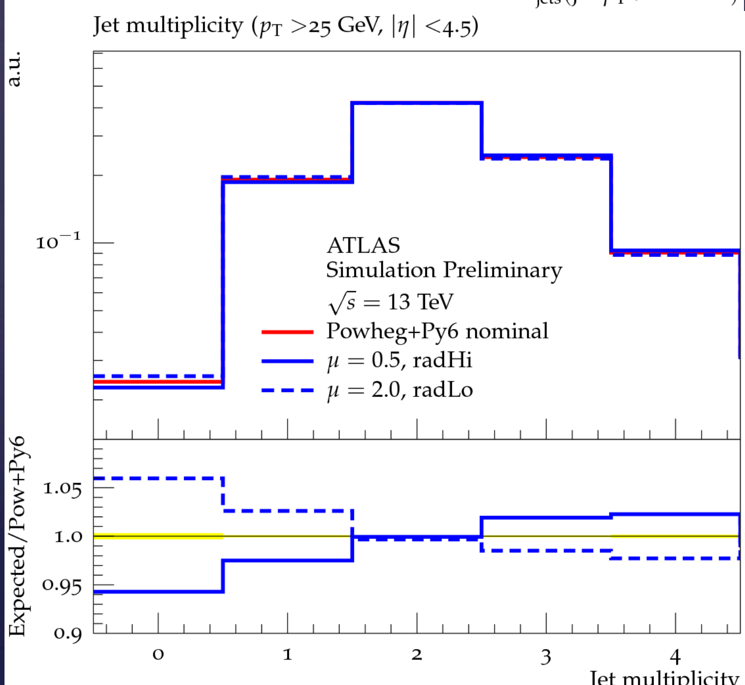
# tt+X



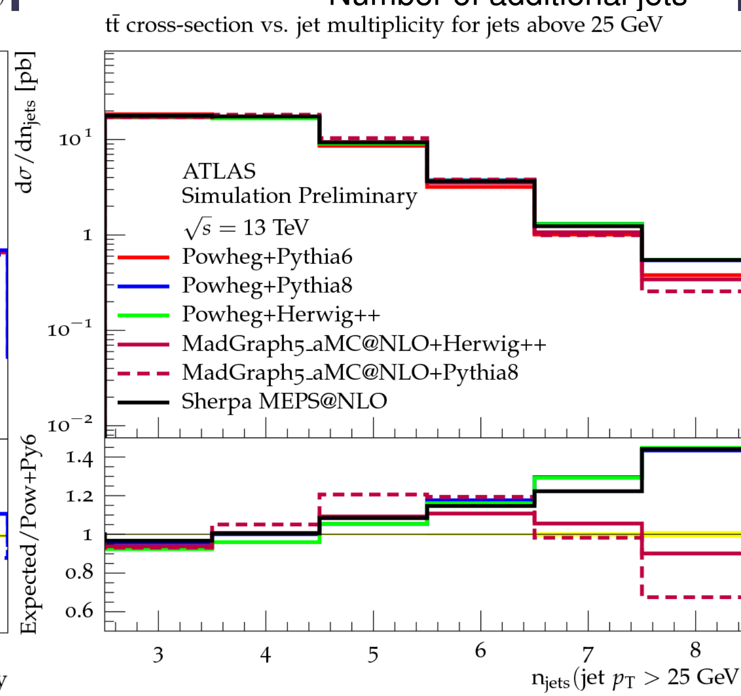
tt̄ cross-section vs. jet multiplicity for jets above 25 GeV
ATLAS Data, $\sqrt{s}$ = 7 TeV
JHEP 01 (2015) 020
Powheg+Py6 nominal
$h_{damp} = 2 \cdot m_t, \mu = 0.5$, radHi
$h_{damp} = m_t, \mu = 2.0$, radLo
$d\sigma / dn_{jets}$ [pb]
Expected/Data
$n_{jets}$(jet $p_T$ > 25 GeV)

$\frac{1}{\sigma}\frac{d\sigma}{dN_{jet}}$
ATLAS Preliminary
13 TeV, 3.2 fb$^{-1}$
add. jet $p_T \geq$ 25 GeV
eμ-channel
Powheg+Pythia6
Powheg+Herwig++
aMCAtNLO+Herwig++
Powheg+Pythia8
Data
Stat.
Stat.+Syst
MC/Data
Number of additional jets

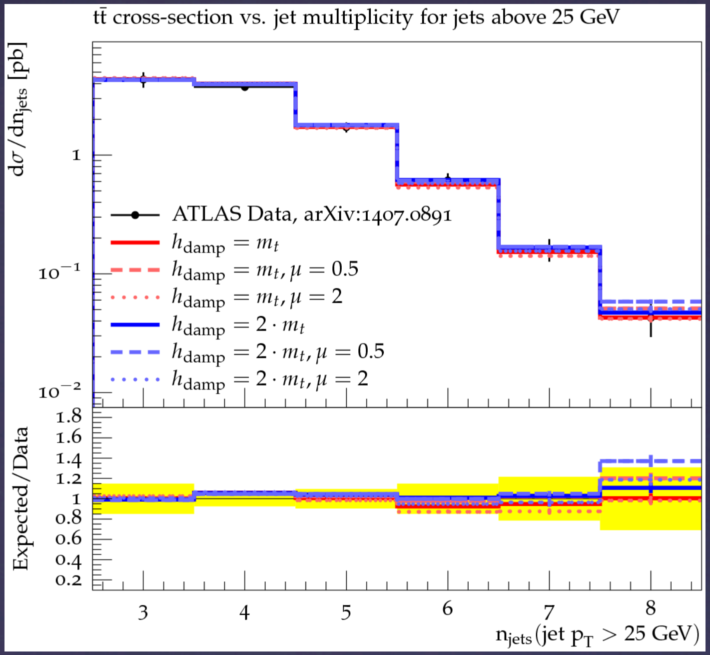
Jet multiplicity ($p_T$ >25 GeV, $|\eta|$ <4.5)
a.u.
ATLAS
Simulation Preliminary
$\sqrt{s}$ = 13 TeV
Powheg+Py6 nominal
$\mu = 0.5$, radHi
$\mu = 2.0$, radLo
Expected/Pow+Py6
Jet multiplicity

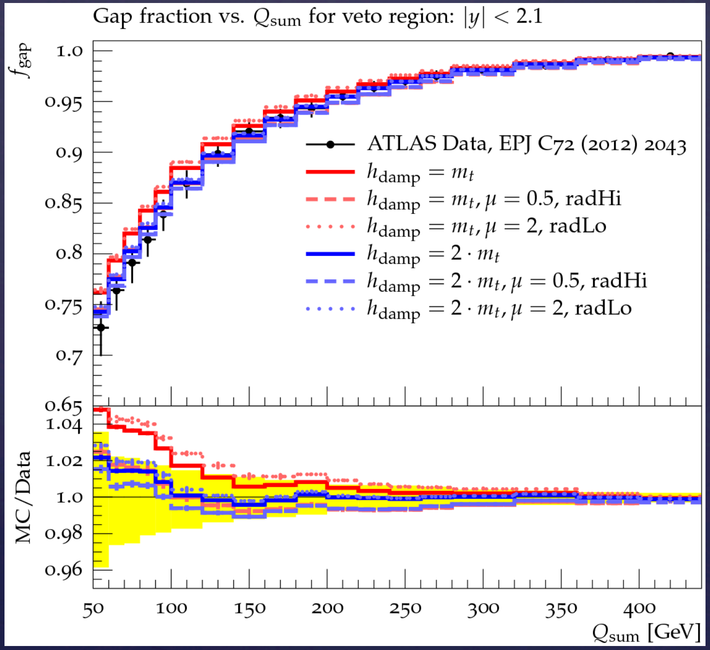



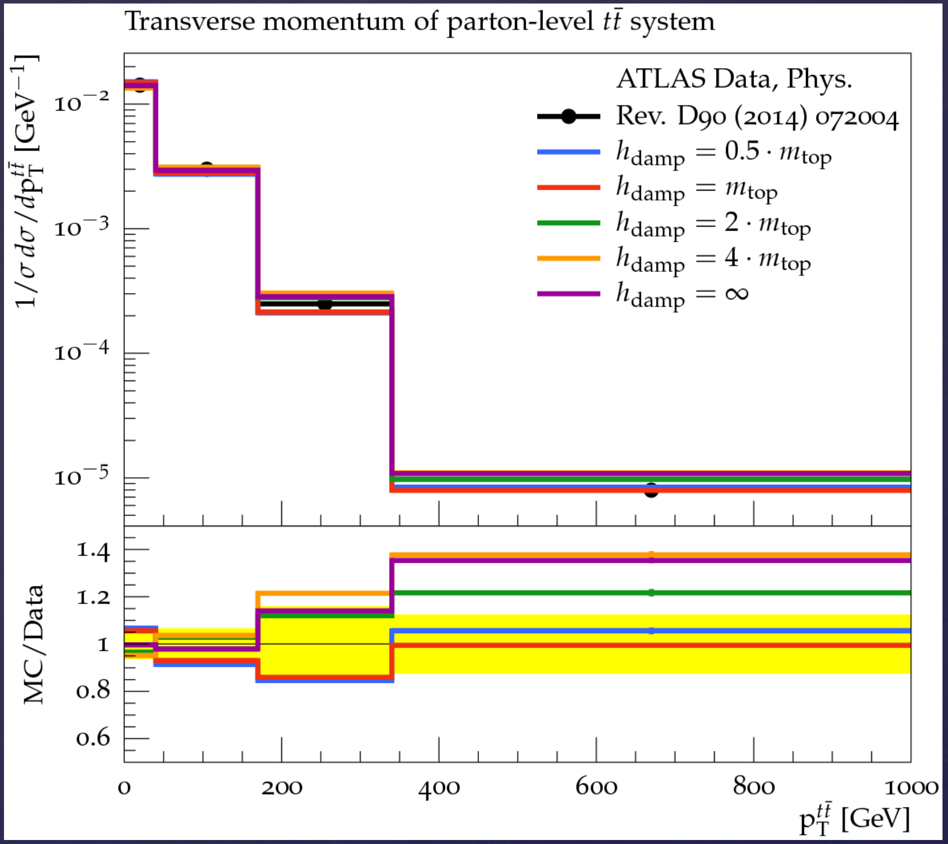
tt̄ cross-section vs. jet multiplicity for jets above 25 GeV
$d\sigma / dn_{jets}$ [pb]
ATLAS
Simulation Preliminary
$\sqrt{s}$ = 13 TeV
Powheg+Pythia6
Powheg+Pythia8
Powheg+Herwig++
MadGraph5_aMC@NLO+Herwig++
MadGraph5_aMC@NLO+Pythia8
Sherpa MEPS@NLO
Expected/Pow+Py6
$n_{jets}$(jet $p_T$ > 25 GeV)

# tt+X: QCD

## Scale choice



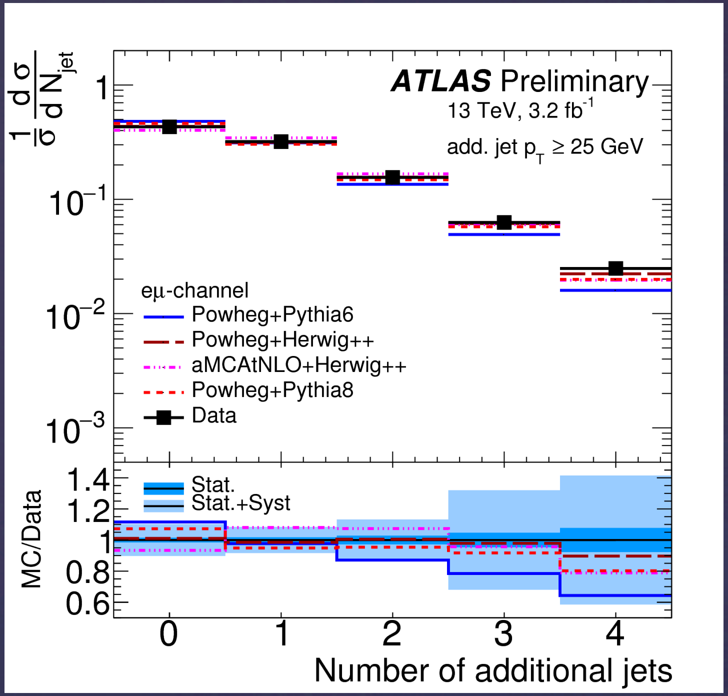



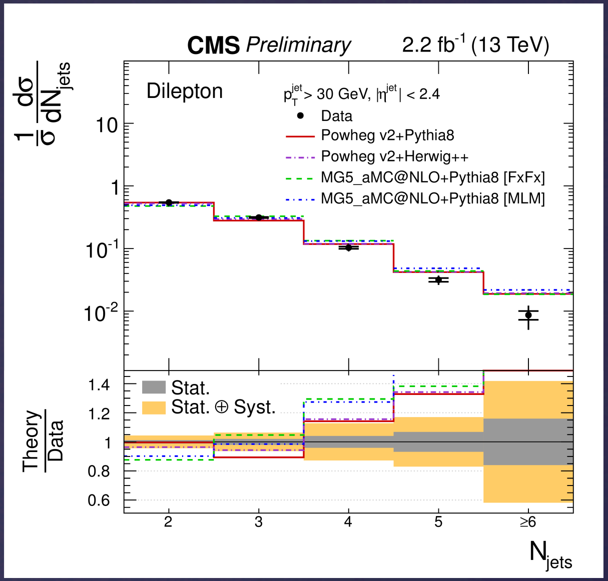



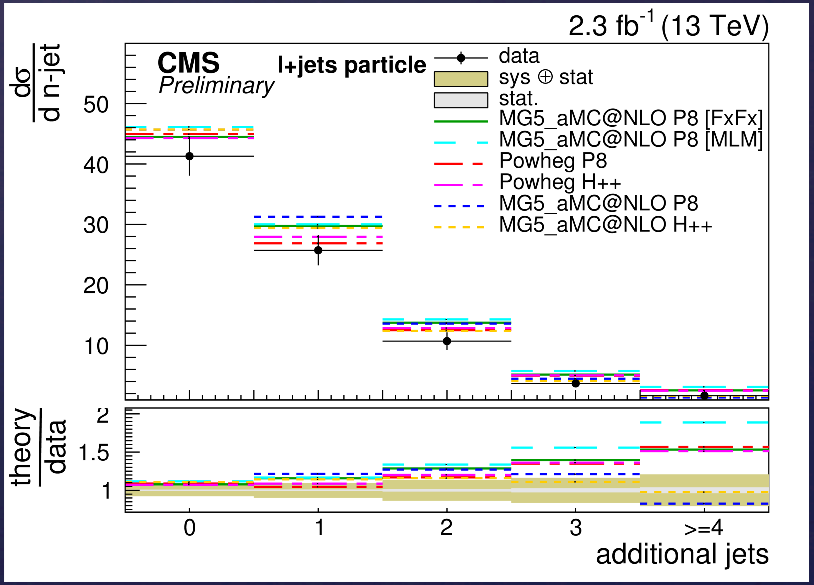

7 TeV

Preliminary 13 TeV

# tt+X: QCD



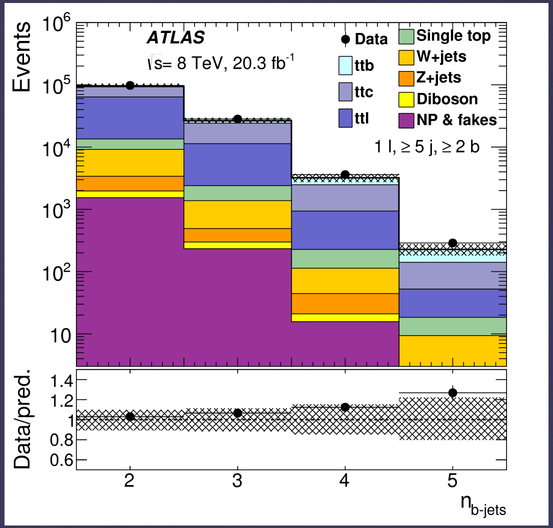



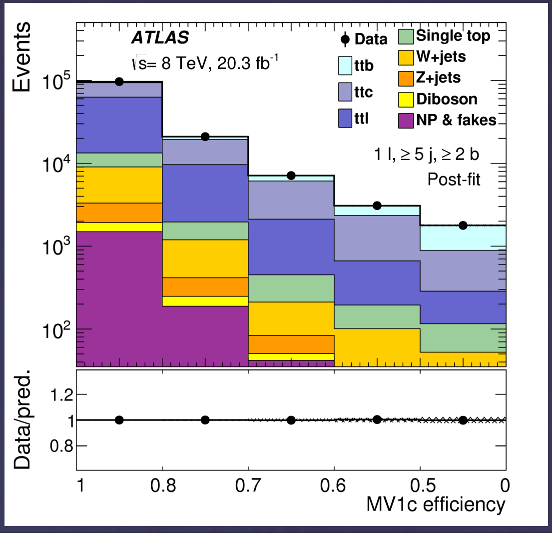



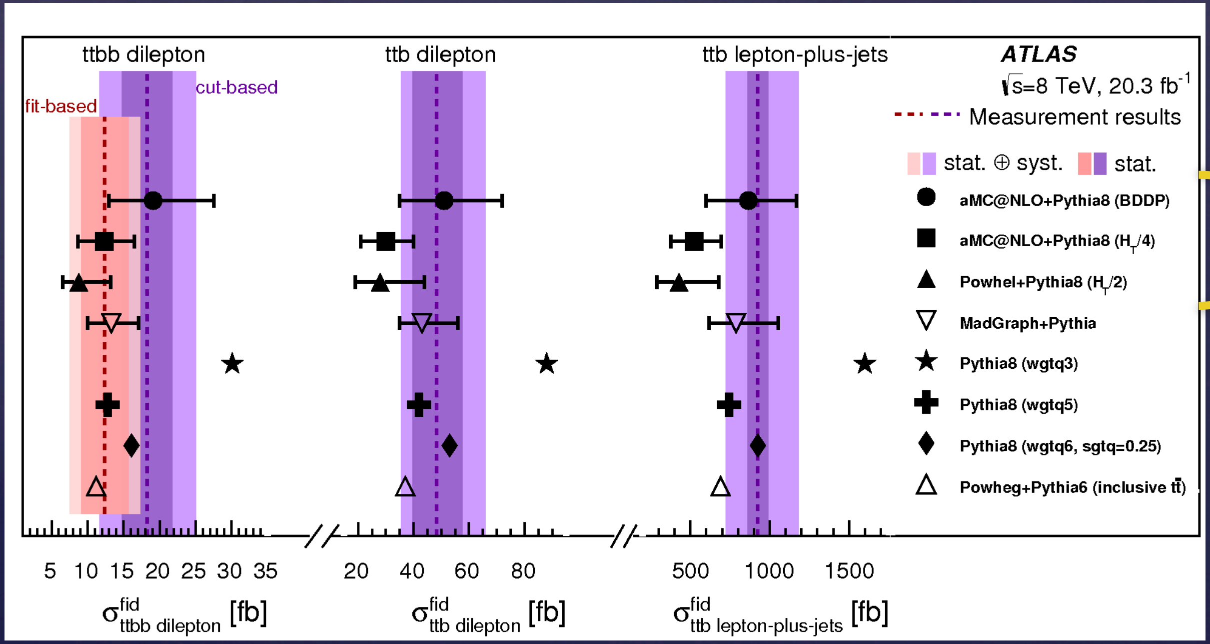

Not all pow+py8 are created equal?
Or data doesn't agree between experiments?

Fully fiducial definition

# tt+HF: QCD



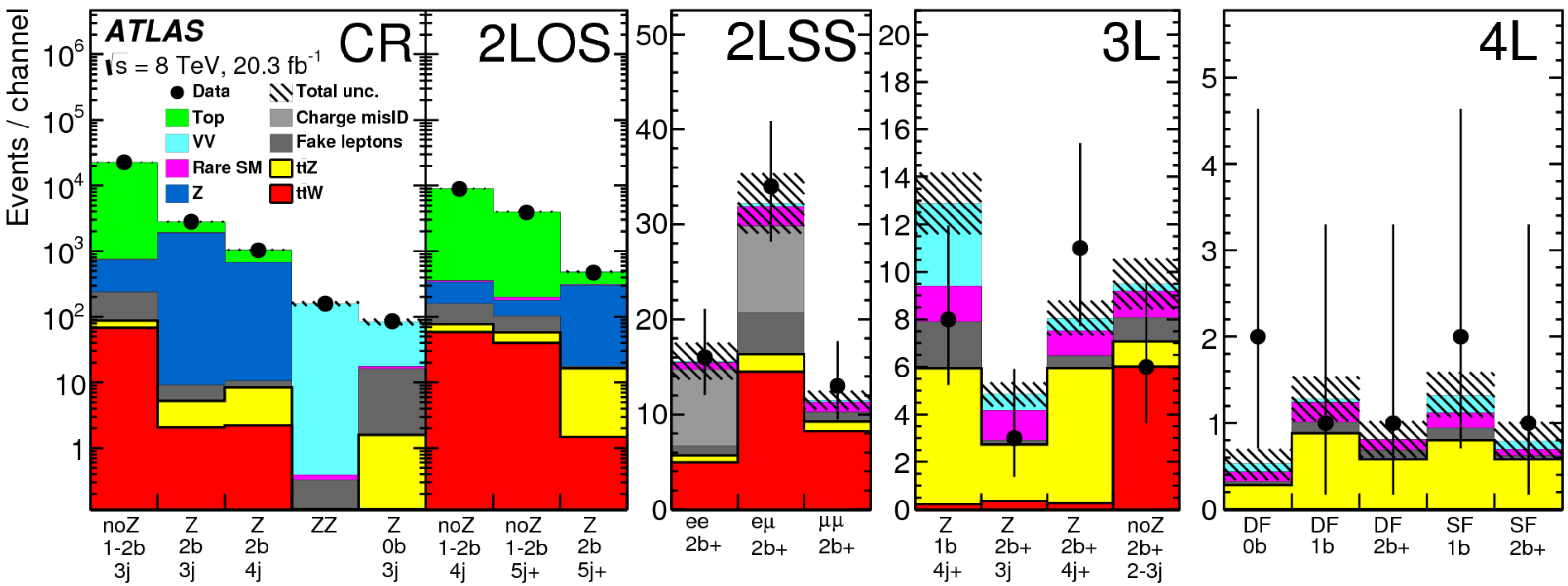



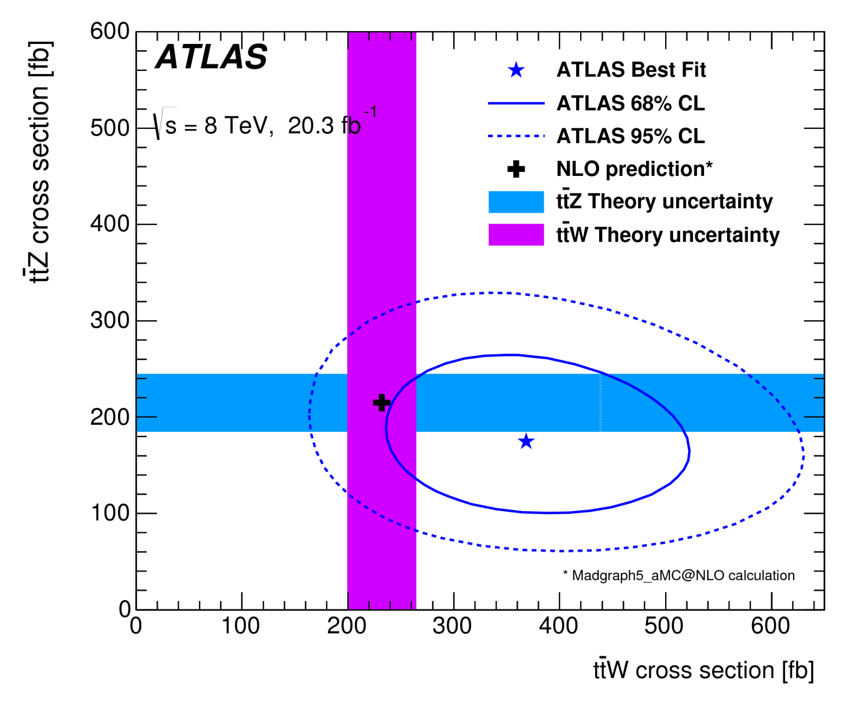

NLO ttbb

BDDP: $\mu = m_t^{1/2}(p_T^b p_T^{\bar{b}})^{1/4}$

$H_T/4$: $\quad \mu = \frac{1}{4}H_T = \frac{1}{4}\sum_i \sqrt{m_i^2 + p_{T,i}^2}$

# tt+V



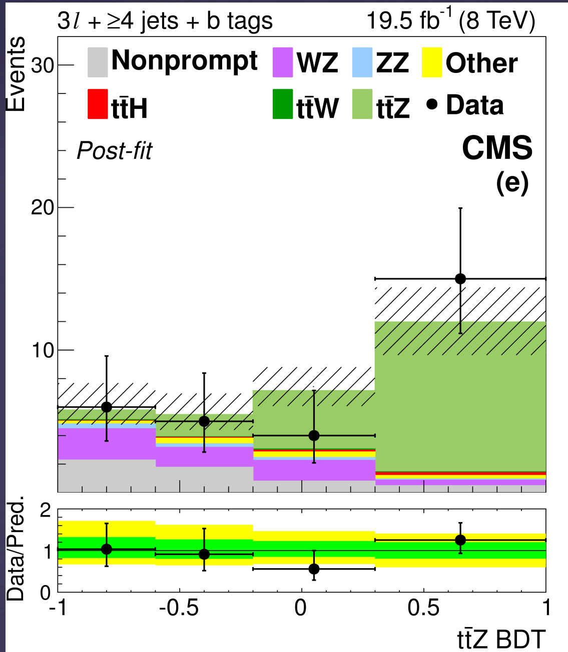

| Channel | $t\bar{t}W$ significance Expected | $t\bar{t}W$ significance Observed | $t\bar{t}Z$ significance Expected | $t\bar{t}Z$ significance Observed |
|---|---|---|---|---|
| $2\ell$OS | 0.4 | 0.1 | 1.4 | 1.1 |
| $2\ell$SS | 2.8 | 5.0 | - | - |
| $3\ell$ | 1.4 | 1.0 | 3.7 | 3.3 |
| $4\ell$ | - | - | 2.0 | 2.4 |
| Combined | 3.2 | 5.0 | 4.5 | 4.2 |

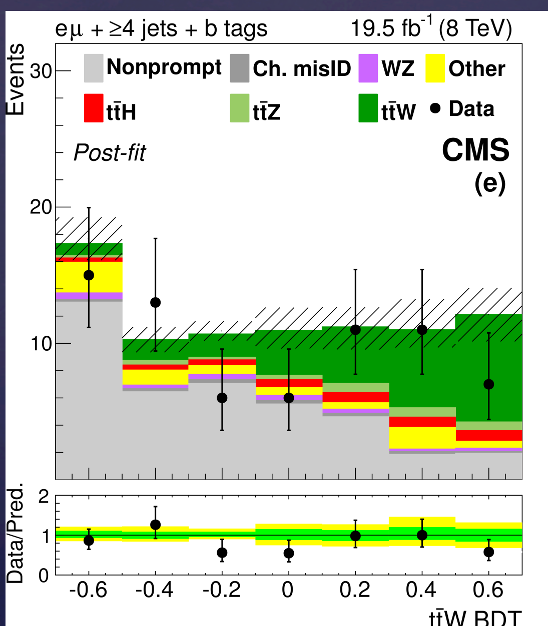
$$\sigma_{t\bar{t}W} = 369^{+86}_{-79}\,(\text{stat.}) \pm 44\,(\text{syst.})\,\text{fb} = 369^{+100}_{-91}\,\text{fb}$$

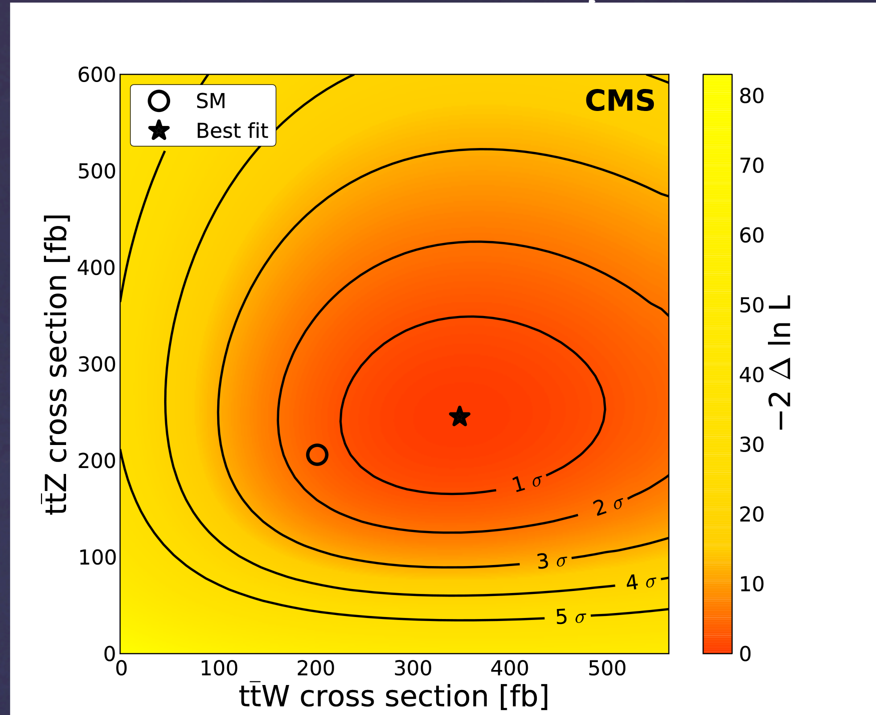
$$\sigma_{t\bar{t}Z} = 176^{+52}_{-48}\,(\text{stat.}) \pm 24\,(\text{syst.})\,\text{fb} = 176^{+58}_{-52}\,\text{fb}.$$

# Also used to place limits on anomalous couplings

# tt+V



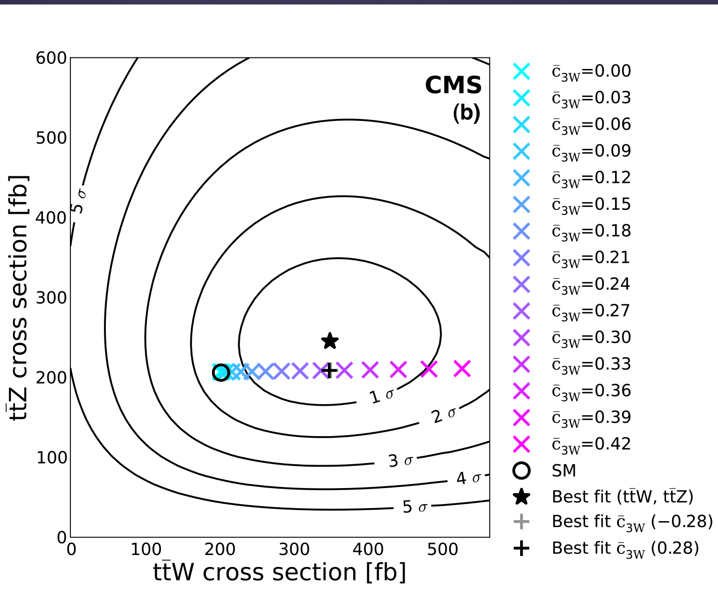



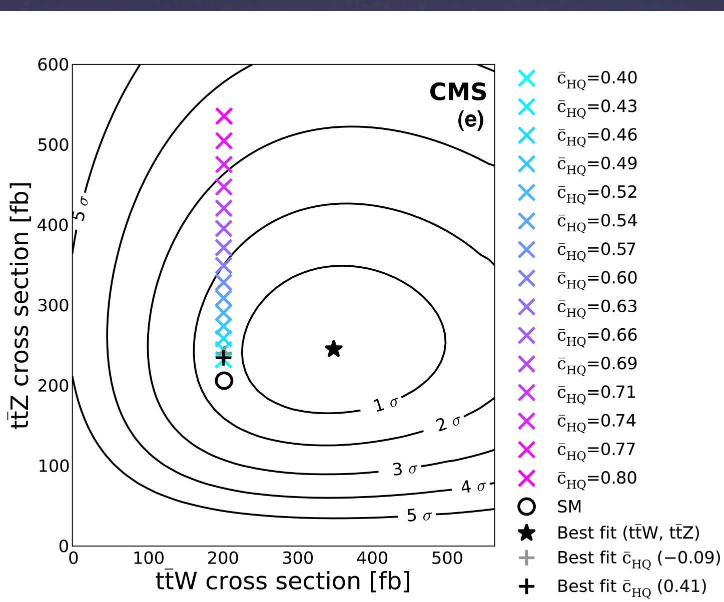




| $t\bar{t}W$ | Cross section (fb) | | Signal strength ($\mu$) | | Significance ($\sigma$) | |
|---|---|---|---|---|---|---|
| Channels | Expected | Observed | Expected | Observed | Expected | Observed |
| SS | $203^{+88}_{-73}$ | $414^{+135}_{-112}$ | $1.00^{+0.45}_{-0.36}$ | $2.04^{+0.74}_{-0.61}$ | 3.4 | 4.9 |
| $3\ell$ | $203^{+215}_{-194}$ | $210^{+225}_{-203}$ | $1.00^{+1.09}_{-0.96}$ | $1.03^{+1.07}_{-0.99}$ | 1.0 | 1.0 |
| SS + $3\ell$ | $203^{+84}_{-71}$ | $382^{+117}_{-102}$ | $1.00^{+0.43}_{-0.35}$ | $1.88^{+0.66}_{-0.56}$ | 3.5 | 4.8 |

| $t\bar{t}Z$ | Cross section (fb) | | Signal strength ($\mu$) | | Significance ($\sigma$) | |
|---|---|---|---|---|---|---|
| Channels | Expected | Observed | Expected | Observed | Expected | Observed |
| OS | $206^{+142}_{-118}$ | $257^{+158}_{-129}$ | $1.00^{+0.72}_{-0.57}$ | $1.25^{+0.76}_{-0.62}$ | 1.8 | 2.1 |
| $3\ell$ | $206^{+79}_{-63}$ | $257^{+85}_{-67}$ | $1.00^{+0.42}_{-0.32}$ | $1.25^{+0.45}_{-0.36}$ | 4.6 | 5.1 |
| $4\ell$ | $206^{+153}_{-109}$ | $228^{+150}_{-107}$ | $1.00^{+0.77}_{-0.53}$ | $1.11^{+0.76}_{-0.52}$ | 2.7 | 3.4 |
| OS + $3\ell$ + $4\ell$ | $206^{+62}_{-52}$ | $242^{+65}_{-55}$ | $1.00^{+0.34}_{-0.27}$ | $1.18^{+0.35}_{-0.29}$ | 5.7 | 6.4 |

# tt+V




Also used to place limits on anomalous couplings

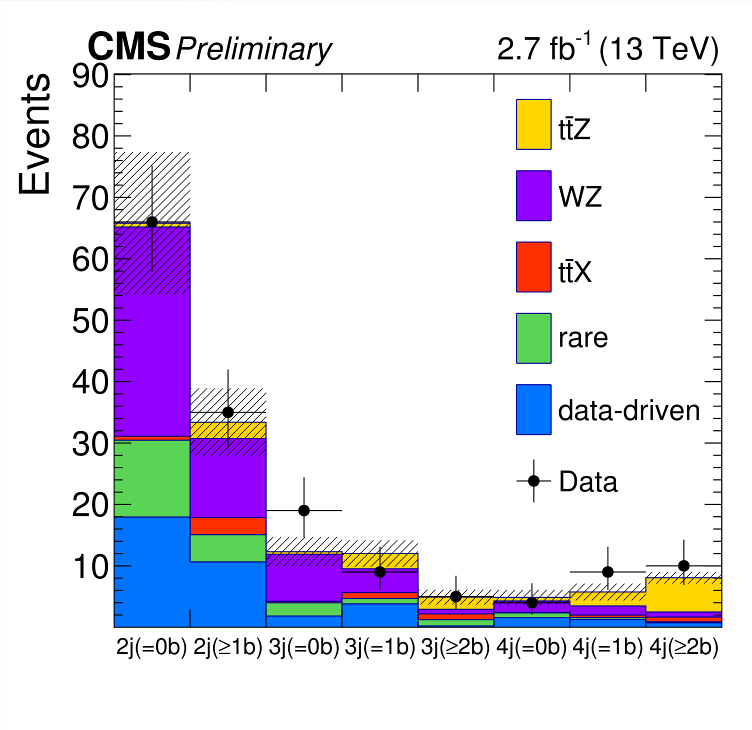
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_1 + \frac{1}{\Lambda^2}\mathcal{L}_2 + \cdots$$
$$= \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i (c_i\mathcal{O}_i + \text{h.c.}) + \frac{1}{\Lambda^2}\sum_j (c_j\mathcal{O}_j + \text{h.c.}) + \cdots,$$

$$C_{1,V} = C_V^{\text{SM}} + \frac{1}{4\sin\theta_w\cos\theta_w}\frac{v^2}{\Lambda^2}\text{Re}[\bar{c}'_{HQ} - \bar{c}_{HQ} - \bar{c}_{Hu}],$$
$$C_{1,A} = C_A^{\text{SM}} - \frac{1}{4\sin\theta_w\cos\theta_w}\frac{v^2}{\Lambda^2}\text{Re}[\bar{c}'_{HQ} - \bar{c}_{HQ} + \bar{c}_{Hu}].$$

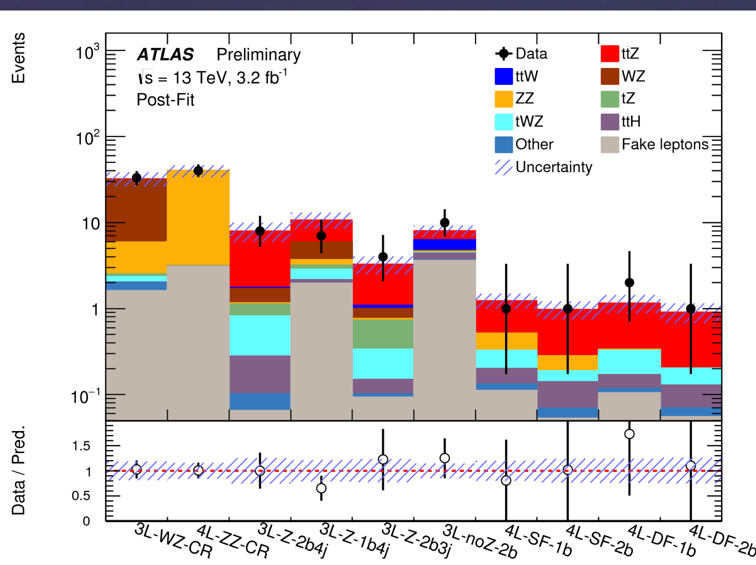
| Operator | Best fit point(s) | 1 standard deviation CL | 2 standard deviation CL |
|---|---|---|---|
| $\bar{c}_{uB}$ | −0.07 and 0.07 | [−0.11, 0.11] | [−0.14, 0.14] |
| $\bar{c}_{3W}$ | −0.28 and 0.28 | [−0.36, −0.18] and [0.18, 0.36] | [−0.43, 0.43] |
| $\bar{c}'_{HQ}$ | 0.12 | [−0.07, 0.18] | [−0.33, −0.24] and [−0.02, 0.23] |
| $\bar{c}_{Hu}$ | −0.47 and 0.13 | [−0.60, −0.23] and [−0.11, 0.26] | [−0.71, 0.37] |
| $\bar{c}_{HQ}$ | −0.09 and 0.41 | [−0.22, 0.08] and [0.24, 0.54] | [−0.31, 0.63] |

13 TeV

# tt+V




| Channel | Expected significance | Observed significance |
|---|---|---|
| $3\ell$ analysis | 2.9 | 3.5 |
| $4\ell$ analysis | 1.2 | 0.9 |
| $3\ell$ and $4\ell$ combined | 3.1 | 3.6 |




| Uncertainty | $\sigma_{t\bar{t}Z}$ | $\sigma_{t\bar{t}W}$ |
|---|---|---|
| Luminosity | 6.4% | 7.0% |
| Reconstructed objects | 7.0% | 7.3% |
| Backgrounds from simulation | 5.5% | 3.7% |
| Fake leptons and charge misID | 3.9% | 21% |
| Total systematic | 12% | 24% |
| Statistical | 32% | 51% |
| Total | 34% | 56% |

# Summary

- A lot of work still to be done in understanding generator and parton showering / hadronisation differences in the context of top quarks
  - Lots of parameters to 'tune'…
- Becoming a major limitation of many precision analyses: in top cross sections but also in top mass and other properties measurements