Measurements of the top-quark mass using the ATLAS detector

Andrea Knue

On behalf of the top mass analysis teams

– ATLAS Collaboration Week Berlin, 07th October 2019 –

What different ways are there to measure m_{top}?

1. "direct" reconstruction methods at detector level
   - binned/unbinned template methods

$\hookrightarrow$ $t\bar{t}$ or single top topologies

$\hookrightarrow$ very specific selections, such as J/Ψ, soft-muon tag

2. "indirect": inclusive and differential $\sigma(t\bar{t})$ and $\sigma(t\bar{t}$+1jet) cross-sections:

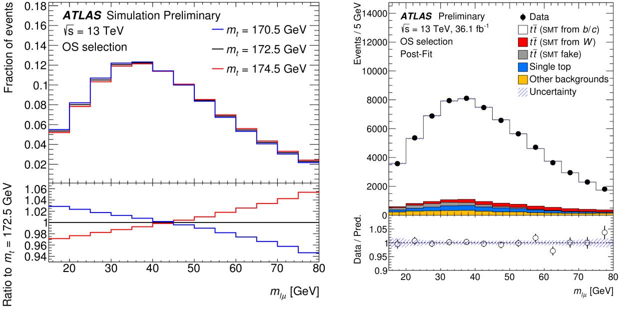
$\hookrightarrow$ unfolded distributions

$\hookrightarrow$ **will show today status updates for each category**

$\hookrightarrow$ list with person power for each analysis can be found in backup

Soft-muon-tag analysis, 36 fb-1 ▸ ATLAS-CONF-2019-046

- lepton+jets channel
- ≥ 1 b-tag, ≥ 1 SMT
- soft muon from B-hadron decay (BR $\approx 20\%$)
- less sensitive to JES, more sensitive to fragmentation



➔ binned profile-likelihood fit to $m_{\ell\mu}$ distr. (first time in $m_{\rm top}$ measurement in ATLAS)
➔ use both OS and SS events

$$m_{\rm top} = 174.48 \pm 0.40 \pm 0.67 \ \text{GeV} \qquad (0.45\ \%)$$

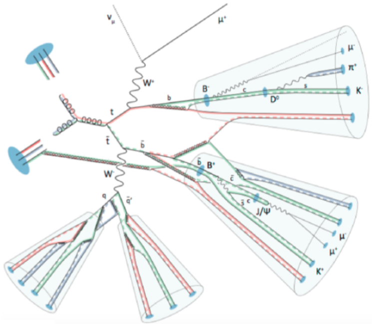
↪ dominated by hadron decay modelling (0.39 GeV) and pileup modelling (0.20 GeV)
↪ CONF note made public for TOP2019 conference, preparing paper

Mass measurement using different B-hadron decays

Motivation ‣ Old INT note Rel. 20.7

- using purely leptonic (or tracking) observables
  $\hookrightarrow$ less sensitive to JES than the ones from jet reconstruction
- partial reconstruction of decay
  $\hookrightarrow$ less sensitive to top p_T modelling than pure prompt lepton kinematics
- still sensitive to parton shower, hadronisation, b-fragmentation effects
- help to reduce the uncertainties in combination of all measurements

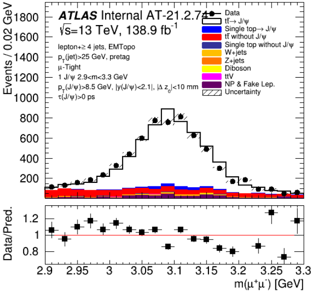
- $\mathrm{BR}(b \to \mu) \approx 0.2$
- $\mathrm{BR}(b \to J/\Psi \to \mu\mu) \approx 7 \cdot 10^{-4}$
- $\mathrm{BR}(b \to \mu D^0 \to \mu K\pi) \approx 5.9 \cdot 10^{-3}$
- $\mathrm{BR}(b \to D^*(2010) \to D^0\pi) \approx 2.2 \cdot 10^{-2}$



Template fit to $m_{\ell\mu\mu}$ or $m_{\ell\mu D}$ distributions

$\hookrightarrow$ public result for HL-LHC ‣ ATL-PHYS-PUB-2018-042

Mass measurement using different *B*-hadron decays

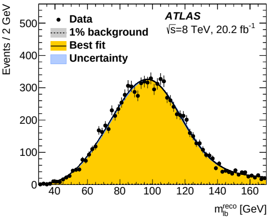


- statistical uncertainties in systematics:
  $\hookrightarrow$ cannot be evaluated in all cases
  (e.g. Powheg+H7 samples), broken truth info
- JES: can be reduced by cut on $p_T(b)$, analysis specific quark/gluon file
- first plots with PFlow done
- need more events for modelling samples!
- HL-LHC: expect $\sigma^{\text{total}}_{m_{\text{top}}} \approx$ 500 MeV

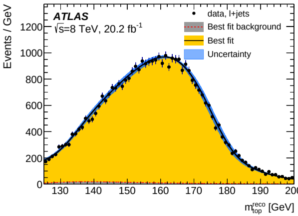
Source of uncertainty	$\sigma(m_{\text{top}})$ [GeV]	
Analysis	$J/\psi \to \mu^+\mu^-$	μD^0
Luminosity	139 fb^{-1}	36.1 fb^{-1}
Statistics	0.68	0.49
Method uncertainty	2.42 ± 0.24	
Modelling uncertainties	**4.50 ± 1.36**	**3.69 ± 0.20**
NLO modelling	2.40 ± 1.38	2.28 ± 0.47
PS and hadronisation	3.18 ± 1.03	2.87 ± 0.80
HF-hadron production fractions	0.06 ± 0.01	
HF-hadron decay modelling	0.01 ± 0.03	
Initial-state QCD radiation	0.24 ± 0.51	1.02 ± 0.52
Final-state QCD radiation	1.22 ± 0.41	1.58 ± 0.12
Underlying event(*)	0.01 ± 0.03	
PDF	0.41 ± 0.01	
Colour reconnection	1.63 ± 2.36	
Single top modelling	0.03 ± 0.00	
Background uncertainties	**0.55 ± 0.08**	
Diboson modelling	0.02 ± 0.00	
Z+jets modelling	0.09 ± 0.00	
W+jets modelling	0.13 ± 0.01	
Fake leptons modelling(*)	0.49 ± 0.09	
Soft muon fakes modelling(*)	0.19 ± 0.04	
Experimental uncertainties	**0.98 ± 0.18**	
Jet energy scale (JES)	0.45 ± 0.10	
b-jet energy scale	0.03 ± 0.06	
Jet energy resolution (JER)	0.74 ± 0.23	
Jet vertex fraction	0.00 ± 0.00	
b-tagging	0.00 ± 0.00	
c-tagging	0.00 ± 0.00	
mistagging	0.00 ± 0.00	
$E_{\text{T}}^{\text{miss}}$	0.08 ± 0.08	
Electrons	0.08 ± 0.02	
Muons	0.08 ± 0.04	
Pile-up	0.44 ± 0.00	
Total Systematics	5.24 ± 1.16	5.54
Total	5.28	5.56

Standard template method in $t\bar{t}$ events

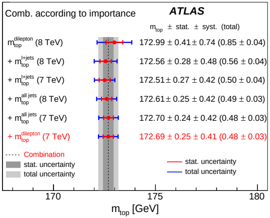
- Dilepton: 1D fit -



- Lepton + Jets: 3D fit -



– Combination –



Approach 1: start from 8 TeV strategy, optimise and develop further

Dilepton channel: $m_{\text{top}} = 172.99 \pm 0.41(\text{stat.}) \pm 0.74(\text{syst.})$ GeV ▸ PLB 761 (2016)

Lepton+jets channel: $m_{\text{top}} = 172.08 \pm 0.39(\text{stat.}) \pm 0.82(\text{syst.})$ GeV ▸ EPJC 79 (2019) 290

Cut on $p_{\text{T,lb}}$/BDT output: considerably reduced the sample size for achieving a **smaller total uncertainty** and a **better balance of statistical and systematic uncertainty** leading to reduced estimator correlations

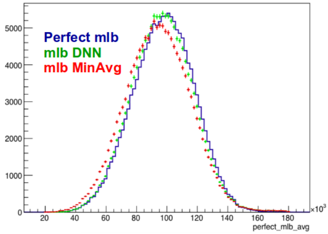
→ **significant gain in combination due to construction of estimators with low correlation!**

Approach 2

Considering in addition to investigate (binned) profile likelihood approach → nothing to show yet

Standard template method: event reconstruction

Dilepton channel:



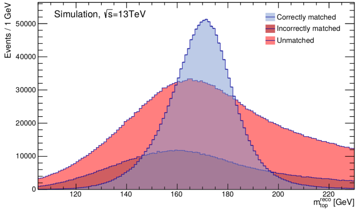
- at 8 TeV: use (ℓ,b)-permutation with minimum average $m_{\ell b}$
- now: use DNN to choose (ℓ,b)-permutation for analysis

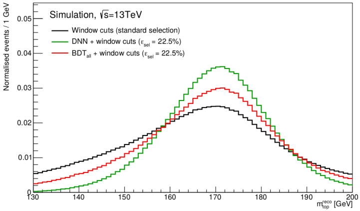
  ↪ matching efficiency increases from 82 to 88%

  ↪ resulting $m_{\ell b}$ distribution: closer to that of the correct permutation

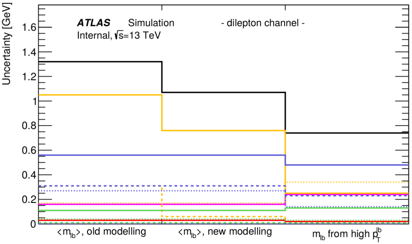
Lepton+jets channel (KLFitter):

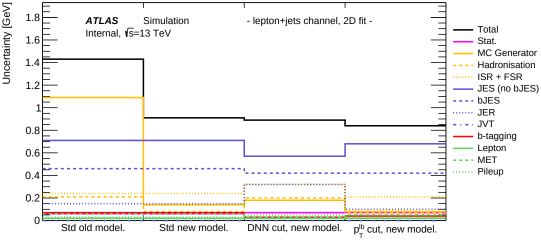
- train BDT and DNN: correctly matched vs. wrongly matched and unmatched events
- cut on BDT/DNN output reduces combinatorial background
- improved mass resolution when applying DNN cut



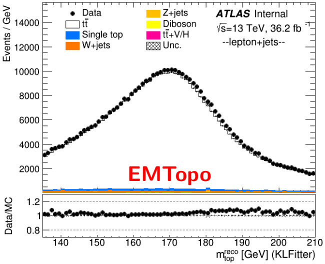


Standard template method: optimisation studies





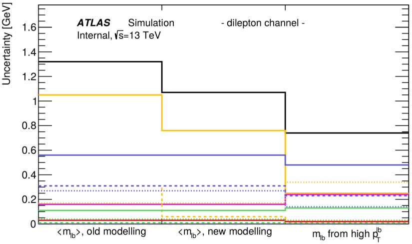
- both channels strongly benefit from new modelling samples
- $\sigma^{\rm dil}_{\rm total}$ significantly reduced when only using m_{lb} value with highest p_T^{lb}: lower than 8 TeV (few unc. missing)
- lepton+jets:
  ↪ 2D fit: already comparable uncertainties to 8 TeV result
  ↪ 3D fit: some systematic uncertainties are very large
- recipe for $\sigma_{\rm CR}$ not established yet (MC extension running)

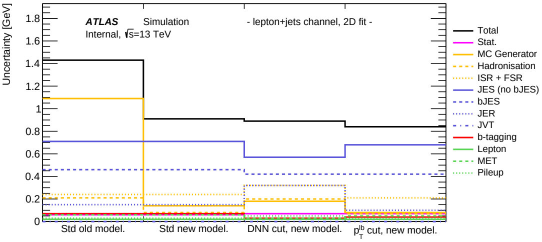


Dominating: JES Model1, jet flavour response, bJES, ISR/FSR

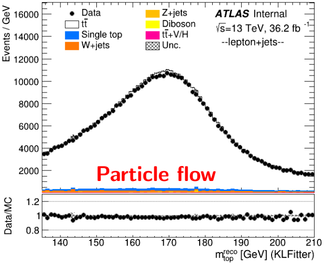
↪ Next steps: investigate 3D fit, uncertainties for PFlow jets

Standard template method: optimisation studies





- both channels strongly benefit from new modelling samples
- $\sigma^{\mathrm{dil}}_{\mathrm{total}}$ significantly reduced when only using m_{lb} value with highest p_T^{lb}: lower than 8 TeV (few unc. missing)
- lepton+jets:
  $\hookrightarrow$ 2D fit: already comparable uncertainties to 8 TeV result
  $\hookrightarrow$ 3D fit: some systematic uncertainties are very large
- recipe for σ_{CR} not established yet (MC extension running)



Dominating: JES Model1, jet flavour response, bJES, ISR/FSR

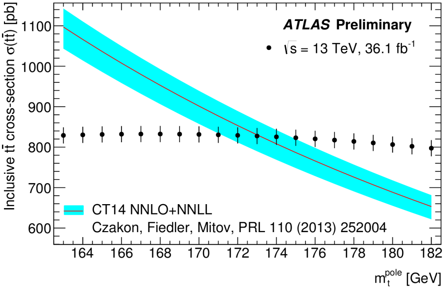
$\hookrightarrow$ Next steps: investigate 3D fit, uncertainties for PFlow jets

Dilepton cross-section at 13 TeV, 36 fb-1 ATLAS-CONF-2019-041

Measure inclusive $t\bar{t}$ cross-section in $e\mu$ events with 1 or 2 b-tagged jets:

Parametrisation used to extract $m_{\mathrm{top}}^{\mathrm{pole}}$ from $\sigma_{t\bar{t}}$:

$$\sigma_{t\bar{t}}^{\mathrm{theo}}(m_{\mathrm{top}}^{\mathrm{pole}}) = \sigma(m_{\mathrm{top}}^{\mathrm{ref}}) \left(\frac{m_{\mathrm{top}}^{\mathrm{ref}}}{m_{\mathrm{top}}^{\mathrm{pole}}}\right)^4 (1 + a_1 x + a_2 x^2) \qquad \text{with } x = \frac{m_{\mathrm{top}}^{\mathrm{pole}} - m_{\mathrm{top}}^{\mathrm{ref}}}{m_{\mathrm{top}}^{\mathrm{ref}}}$$



Uncertainty source	$\Delta m_t^{\mathrm{pole}}$ [GeV]
Experimental	1.0
PDF+α_S	$^{+1.5}_{-1.4}$
QCD scales	$^{+1.0}_{-1.5}$
Total uncertainty	$^{+2.0}_{-2.1}$

$$m_{\mathrm{top}} = 173.1 \pm 2.1 \;\; \mathrm{GeV} \qquad (1.2\ \%)$$

➔ measurement from differential distributions will be done as well

Pole mass measurement in the lepton+jets channel (1D+2D) ▸ INT note

1D distributions: $\frac{d\sigma}{dm_{t\bar{t}}}$ and $\frac{d\sigma}{dp_T^{\mathrm{t,had}}}$, 2D distribution: $\frac{d^2\sigma}{dm_{t\bar{t}}dp_T^{\mathrm{t,had}}}$

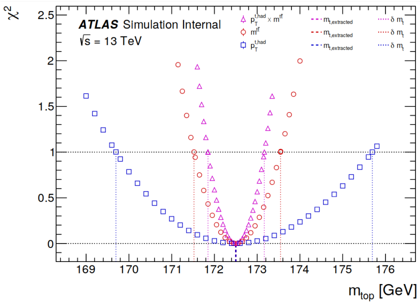
- unfolded to parton level, compare to NNLO calculation (incl. width correction)
- have three mass points @NNLO, use quadratic interpolation to get other masses
- obtain $m_{\mathrm{top}}^{\mathrm{pole}}$ from χ^2 minimisation, currently use only pseudo-data
- currently testing alternative calculation of covariance matrix
- in discussion with Paolo Nason about theory predictions and uncertainties
- full analysis machinery is in place!

First INT note available, aim for a result in winter 2020 with EMTopo jets

Pole mass measurement in the lepton+jets channel (1D+2D)

INT note

Source of uncertainty	$p_T^{t,had}$: $\Delta\, m_{top}$ (GeV)	$m_{t\bar{t}}$: $\Delta\, m_{top}$ (GeV)
Backgrounds	+0.51 – 1.03	+0.17 – 0.18
b-tagging	+0.28 – 0.28	+0.21 – 0.21
Jets	<0.01	+0.31 – 0.30
Leptons	+0.12 – 0.12	+0.03 – 0.03
Missing transverse momentum	+0.12 – 0.12	+0.04 – 0.04
PDF	+0.03 – 0.03	+0.10 – 0.10
Generator	+0.27 – 0.27	+0.20 – 0.20
ISR/FSR	+0.05 – 0.05	+0.35 – 0.19
Hadronisation	+0.32 – 0.32	+0.11 – 0.11
Total experimental systematic uncertainty	+0.80 – 1.16	+0.58 – 0.54
Total experimental statistical uncertainty	+0.05 – 0.05	+0.04 – 0.04
Theoretical (PDF+α_S)	+0.17 – 0.17	+0.67 – 0.39
Theoretical (Scale)	+0.79 – 0.55	+2.75 – 0.25
Total uncertainty	+1.15 – 1.31	+3.00 – 0.94



Dominating uncertainties: scale variations, ISR/FSR, PDF $+\alpha_S$

↪ large scale effect observed when width correction is applied: under investigation

↪ need to investigate parton shower effects (need truth-level samples)

Uncertainties from 2D approach: below 700 MeV (see figure)

↪ investigation of scale and higher-order uncertainties definition, fit procedure

↪ check of uncertainty propagation and stability of the uncertainty breakdown

All results: fit to pseudo-data, analysis still blind!

Differential cross-section for $t\bar{t}+1$ jet production

arXiv:1905.02302

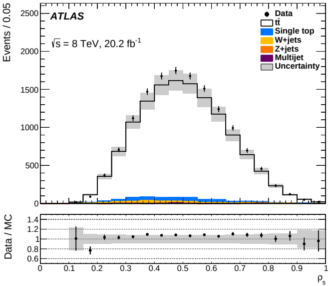
Sensitive variable ρ_S

$$\rho_S = \frac{2m_0}{m_{t\bar{t}+1j}} = \frac{2\cdot 170\,\mathrm{GeV}}{m_{t\bar{t}+1j}}$$

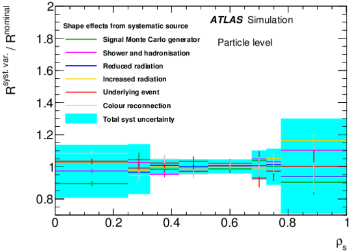
↪ measure $m_{\mathrm{top}}^{\mathrm{pole}}$ and $\overline{MS}$ mass[1]

↪ compare to fixed order (parton level)

↪ $\sigma_{t\bar{t}+1j}$ more sensitive: gluon radiation depends on m_{top} (threshold/cone eff.)



	$m_{\mathrm{top}}^{\mathrm{pole}}$	$m_{\mathrm{top}}(m_{\mathrm{top}})$
Total experimental systematic	**0.9**	**1.0**
Scale variations	(+0.6, −0.2)	(+2.1, −1.2)
Theory PDF⊕α_s	0.2	0.4
Total theory uncertainty	**(+0.7, −0.3)**	**(+2.1, −1.2)**
Total uncertainty	**(+1.2, −1.1)**	**(+2.3, −1.6)**



$$m_{\mathrm{top}}^{\mathrm{pole}} = 171.1 \pm 1.2\ \mathrm{GeV}\ \ (0.7\ \%)$$

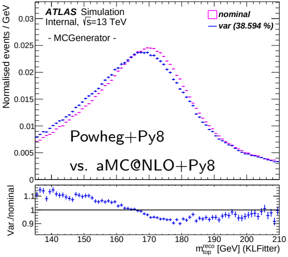
$$m_{\mathrm{top}}(m_{\mathrm{top}}) = 162.9 \pm 2.3\ \mathrm{GeV}\ \ (1.4\ \%)$$

↪ analysis team for 13 TeV in place

↪ currently migrating to Rel 21

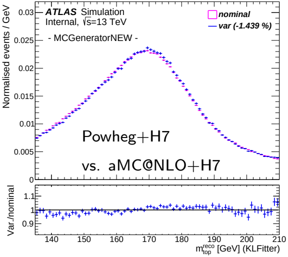
↪ lepton+jets and dilepton channel

CP and MC related studies

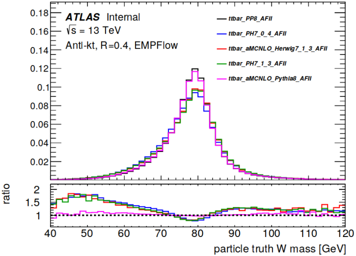


reduced ME

matching uncertainty



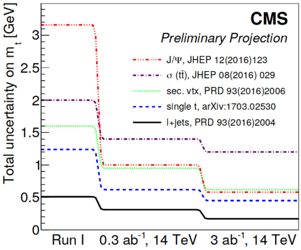
- some analyses strongly affected by jet unc.
- studies by T. Dado (see right plot) ▸ HCW:
  ↪ jet calibration using m_W from $t\bar{t}$ events
- studies (myself): effect of per-jet flavour uncertainties on m_{top}
  ↪ largest single unc. in 2D template fit (p 8)

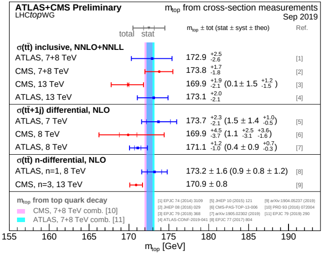


➔ larger differences between Pythia/Herwig on m_W, only small effects from ME matching

Summary

- top mass analyses: cornucopia of different approaches
- first 13 TeV measurements with partial dataset made public for TOP2019!
- direct reconstruction methods:
  - ↪ larger samples required for J/Ψ final state
  - ↪ need a recipe for CR: sample extensions are running
  - ↪ large JES/JER uncertainties: focus for standard template method
  - ↪ alternative approach: use profiling
- differential measurements:
  - ↪ limited by theoretical effects (mainly scale variation)
  - ↪ very promising precision, already better than projected in Yellow Report!





Analysis teams

Mass measurement using B-hadron decays

- F. Derue, J. Zahreddine, T. Andeen, C. Burton, P. Onyisi
- K. Barends, J. Keaveney, S. Yacoob

Soft muon tag analysis

- S. Amoroso, V. Boisvert, L. Cerrito, A. D'Onofrio
- U. DeSanctis, M. DeSantis, M. Pinamonti, M. Vanadia, L. Wilkins

Standard template method (lepton+jets and dilepton)

- Richard Nisius, Javier Jiminez Pena (+ one postdoc Job Advert)
- Andrea Knue, Joschka Birk, Steffen Ludwig (+ one PhD)

Analysis teams

1D and 2D differential (lepton+jets)

- L. Bellagamba, V. Boisvert, F. Deliot, F. Fabbri, F. LaRuffa, C. Ye
- T. Moskalets, M. Negrini, S. Palazzo, M. Romano, F. Spano, E. Tassi

1D differential (dilepton)

- R. Hawkings, S. Camarda

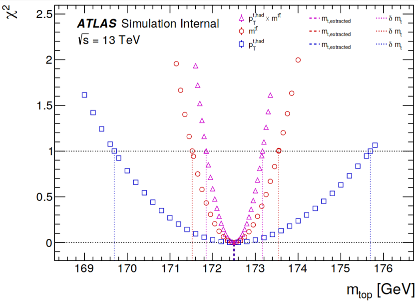
$t\bar{t}$+1 jet measurement

- J. Fuster, M. Vos, E. Fullana, D. Melini, (+ one postdoc)
- A. Prades, L. Monsonis

Pole mass measurement in the lepton+jets channel: 2D result

INT note

Source of uncertainty	$\Delta\, m_{top}$ (GeV)	$\Delta m_{top}/m_{top}$ (%)
Backgrounds	+0.03 – 0.01	+0.02 – 0.01
b-tagging	+0.02 – 0.02	+0.01 – 0.01
Jets	+0.06 – 0.06	+0.04 – 0.03
Leptons	+0.01 – 0.01	+0.01 – 0.01
Missing transverse momentum	+0.02 – 0.02	+0.01 – 0.01
PDF	+0.04 – 0.04	+0.03 – 0.02
Generator	+0.05 – 0.04	+0.03 – 0.03
ISR/FSR	+0.10 – 0.09	+0.06 – 0.05
Hadronisation	+0.05 – 0.03	+0.03 – 0.02
Total experimental systematic uncertainty	+0.15 – 0.14	+0.09 – 0.08
Total experimental statistical uncertainty	+0.04 – 0.04	+0.02 – 0.02
Theoretical (PDF+α_S)	+0.09 – 0.06	+0.05 – 0.03
Theoretical (Scale)	+0.04 – 0.44	+0.02 – 0.26
Total uncertainty	+0.20 – 0.50	+0.12 – 0.29



Dominating uncertainties: scale variations

↪ large scale effect observed when width correction is applied: under investigation

↪ need to investigate parton shower effects (need truth-level samples)

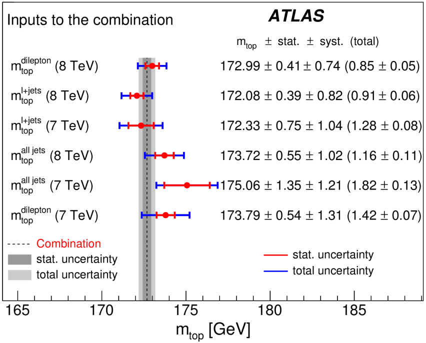
Numbers are being carefully scrutinised:

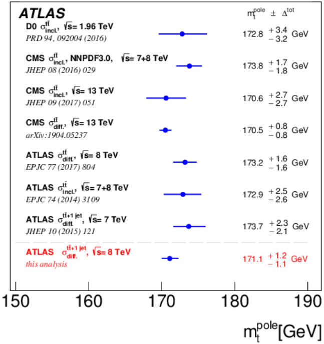
↪ investigation of scale and higher-order uncertainties definition, fit procedure

↪ check of uncertainty propagation and stability of the uncertainty breakdown

First INT note available, aim for a result this year with EMTopo jets

Comparison of different methods for $\sqrt{s} = 7\text{–}8$ TeV





Best individual measurements:

- differential $t\bar{t}$: dominated by functional form of scales (0.9 %)
- differential $t\bar{t} + 1$ jet: dominated by JES and MC modelling unc. (0.7 %)
- direct measurements (dil.): dominated by JES and MC modelling unc. (0.5 %)

Differential cross-section for $t\bar{t} + 1$ jet production

arXiv:1905.02302

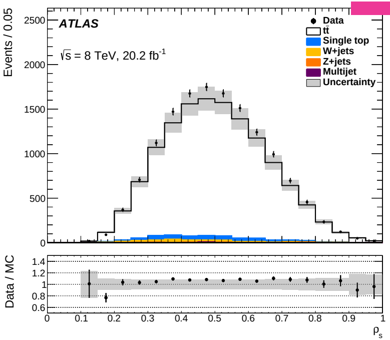
Sensitive variable ρ_S

$$\rho_S = \frac{2m_0}{m_{t\bar{t}+1j}} = \frac{2 \cdot 170\,\mathrm{GeV}}{m_{t\bar{t}+1j}}$$

↪ measure $m_{\mathrm{top}}^{\mathrm{pole}}$ and $\overline{MS}$ mass[1]

↪ unfold to parton level

↪ compare to fixed order calc.



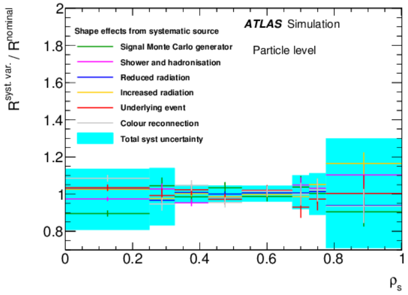
$\sigma_{t\bar{t}+1j}$ more sensitive than $\sigma_{t\bar{t}}$: gluon radiation depends on m_{top} (threshold/cone effects)

$$m_{\mathrm{top}}^{\mathrm{pole}} = \bar{m}_t(\bar{m}_t)\,[1 + 0.4244\alpha_S + 0.8345\alpha_S^2 + ... + \mathcal{O}(\alpha_S^5)]$$

↪ uncertainty of about 200 MeV for conversion, known up to four-loop accuracy

[1] $\overline{MS}$ scheme: modified minimal-subtraction scheme, μ_R dependent

Differential cross-section for $t\bar{t} + 1$ jet production ▸ arXiv:1905.02302



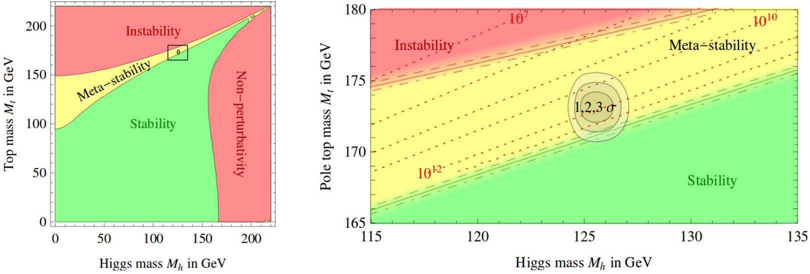
$$m_{\text{top}}^{\text{pole}} = 171.1 \pm 1.2 \text{ GeV} \quad (0.7\ \%)$$

$$m_{\text{top}}(m_{\text{top}}) = 162.9 \pm 2.3 \text{ GeV} \quad (1.4\ \%)$$

- ↪ analysis team for 13 TeV in place
- ↪ currently migrating to Rel 21
- ↪ lepton+jets and dilepton channel

Mass scheme	m_t^{pole} [GeV]	$m_t(m_t)$ [GeV]
Value	**171.1**	**162.9**
Statistical uncertainty	**0.4**	**0.5**
Simulation uncertainties		
Shower and hadronisation	0.4	0.3
Colour reconnection	0.4	0.4
Underlying event	0.3	0.2
Signal Monte Carlo generator	0.2	0.2
Proton PDF	0.2	0.2
Initial- and final-state radiation	0.2	0.2
Monte Carlo statistics	0.2	0.2
Background	<0.1	<0.1
Detector response uncertainties		
Jet energy scale (including b-jets)	0.4	0.4
Jet energy resolution	0.2	0.2
Missing transverse momentum	0.1	0.1
b-tagging efficiency and mistag	0.1	0.1
Jet reconstruction efficiency	<0.1	<0.1
Lepton	<0.1	<0.1
Method uncertainties		
Unfolding modelling	0.2	0.2
Fit parameterisation	0.2	0.2
Total experimental systematic	**0.9**	**1.0**
Scale variations	(+0.6, –0.2)	(+2.1, –1.2)
Theory PDF⊕α_s	0.2	0.4
Total theory uncertainty	**(+0.7, –0.3)**	**(+2.1, –1.2)**
Total uncertainty	**(+1.2, –1.1)**	**(+2.3, –1.6)**

Why measure the top-quark mass?



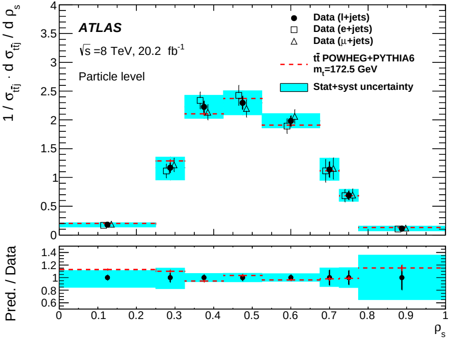
Need precision measurement:

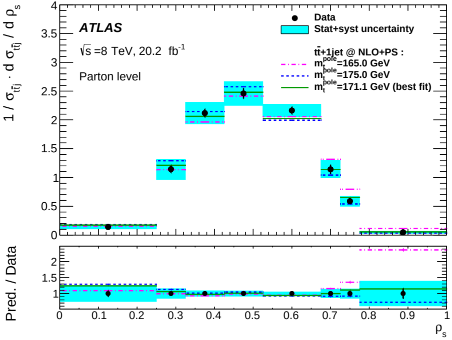
➔ fundamental parameter of the standard model

➔ test if the higgs potential is stable/meta-stable ▸ JHEP08 (2012) 098

➔ "MC mass" within ≈ few hundred MeV – 1 GeV of pole mass

Differential cross-section for $t\bar{t} + 1$ jet production





- unfold to stable particle level: remove detector effects
- unfold to parton level: compare to fixed-order calculations and extract mass via χ^2:

$$\chi^2 = \sum_{i,j} \left[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}} - \mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{NLO+PS}}(m_t^{\text{pole}})\right]_i \left[V^{-1}\right]_{ij} \left[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}} - \mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{NLO+PS}}(m_t^{\text{pole}})\right]_j$$

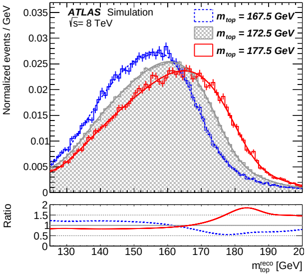
Lepton+jets analysis @ 8 TeV with a 3D template method ▸ EPJC 79 (2019) 290

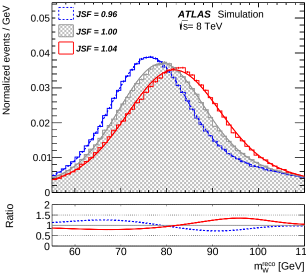
In lepton+jets channel: m_{top} has sizable uncertainties from JES and bJES

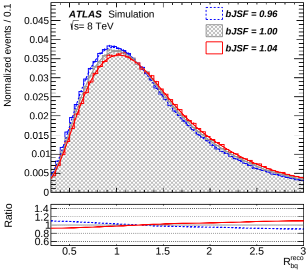
$\hookrightarrow$ can be reduced by simultaneous measurement of m_{top}, jet energy scale factor (JSF) and relative b-to-light-jet energy scale factor (bJSF)

$\hookrightarrow$ done by performing a three dimensional template fit to data

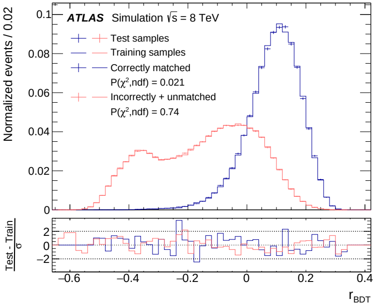
$$R_{\mathrm{bq}}^{\mathrm{reco}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{had}}} + p_{\mathrm{T}}^{b_{\mathrm{lep}}}}{p_{\mathrm{T}}^{W_{\mathrm{j}1}} + p_{\mathrm{T}}^{W_{\mathrm{j}2}}}$$

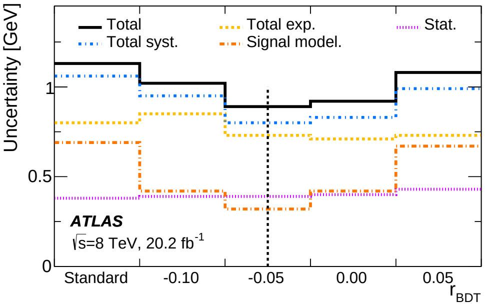






Optimisation of event selection: Utilise Boosted Decision Tree





- **assumption:** wrongly/unmatched events will have larger systematic uncertainties
- **idea:** need to distinguish correctly matched from wrongly/unmatched events
- **method:** train a BDT algorithm, cut on r_{BDT} and redo full analysis
- gain mostly caused by strongly reduced modelling uncertainties

  $\hookrightarrow$ trade here statistical for reduced systematic uncertainties

What do we gain from the BDT optimisation?

	$\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	
Event selection	Standard	Standard	BDT
m_{top} result [GeV]	172.33	171.90	172.08
Statistics	0.75	0.38	0.39
Signal Monte Carlo generator	0.22 ± 0.21	0.50 ± 0.17	0.16 ± 0.17
Initial- and final-state QCD radiation	0.32 ± 0.06	0.28 ± 0.11	0.08 ± 0.11
Colour reconnection	0.11 ± 0.07	0.37 ± 0.15	0.19 ± 0.15
Jet energy scale	0.58 ± 0.11	0.63 ± 0.02	0.54 ± 0.02
Total systematic uncertainty	1.04 ± 0.08	1.07 ± 0.10	0.82 ± 0.06
Total	1.28 ± 0.08	1.13 ± 0.10	0.91 ± 0.06

➔ total systematic uncertainties almost equal for standard selections at 7 and 8 TeV

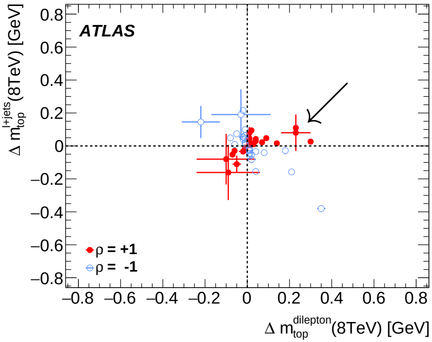
➔ **overall uncertainty is reduced by 19 %** when using BDT optimisation

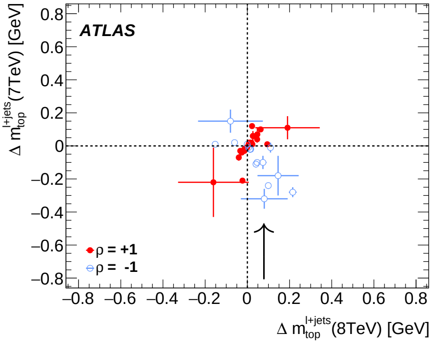
Precision of systematic uncertainty:

$$u \pm s = \sqrt{\Sigma_k u_k^2} \pm \frac{\sqrt{\Sigma_k (s_k^2 u_k^2)}}{u}$$

$\hookrightarrow$ used to test stability of combination

Pairwise estimator correlation for all systematic uncertainties



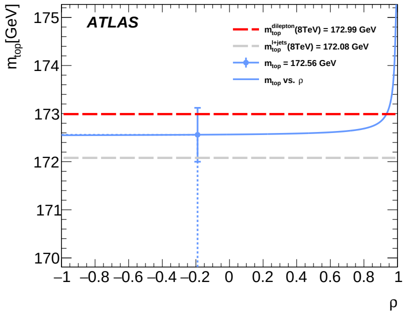


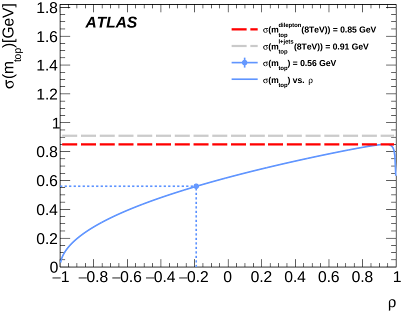
➔ red full points correspond to $\rho = +1$, blue open points to $\rho =$ -1

➔ ISR/FSR (left): dilepton (8 TeV): 0.23 $\pm$ 0.07, l+jets (8 TeV): 0.08 $\pm$ 0.11 GeV

➔ ISR/FSR (right): l+jets (7 TeV): -0.32 $\pm$ 0.06, l+jets (8 TeV): 0.08 $\pm$ 0.11 GeV

Systematic uncertainties: How low can we go?





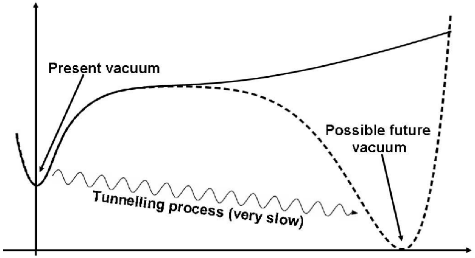
Individual result and combination (BLUE software):

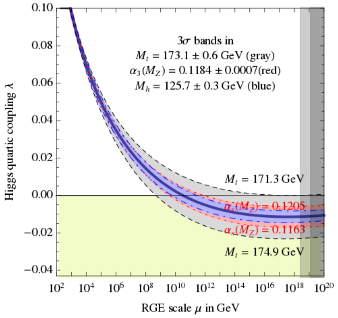
$$m_{\mathrm{top}}^{\mathrm{l+jets,8\ TeV}} = 172.08 \pm 0.39\,(\mathrm{stat}) \pm 0.82\,(\mathrm{syst})\ \mathrm{GeV}$$

$$m_{\mathrm{top}}^{Combined} = 172.68 \pm 0.26\,(\mathrm{stat}) \pm 0.48\,(\mathrm{syst})\ \mathrm{GeV}$$

$\hookrightarrow$ **reached a relative uncertainty of 0.29% !**

Stability of the Standard Model vacuum





Need precision measurement:

➔ rule out stability with $> 3\sigma$?

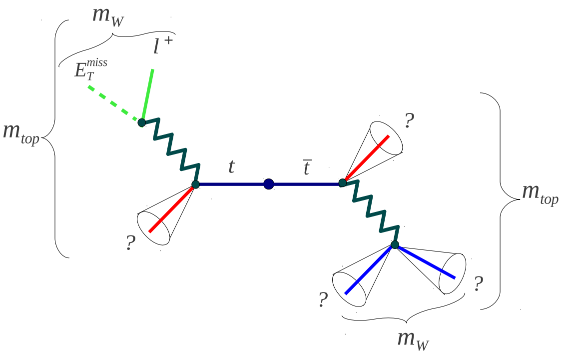
$\hookrightarrow$ need $\Delta m_t^{pole} < 250$ MeV, $\alpha_S(m_Z) < 0.00025$

➔ life-time of metastable vacuum $\tau_{SM} = 10^{139^{+102}_{-51}}$ years

Event reconstruction

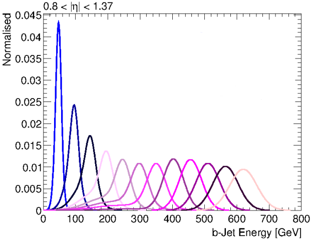
First approach:

- expect 4 jets
  $\Rightarrow$ 24 possible jet-parton assignments
- do not distinguish light jets within W
  $\Rightarrow$ 12 permutations left
- pick one for calculation of variables
  $\Rightarrow$ use kinematic fit to find best permutation



Reconstruction with KLFitter

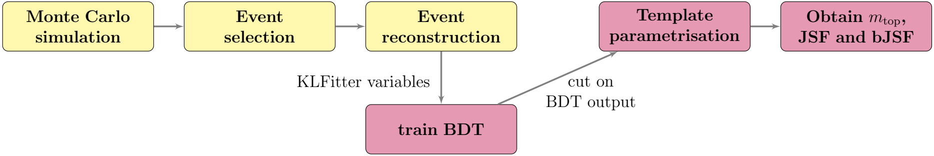
$$
\begin{aligned}
L = {} & BW(m_{q_1 q_2} | m_W, \Gamma_W) \cdot BW(m_{l\nu} | m_W, \Gamma_W) \\
& BW(m_{q_1 q_2 b_{had}} | m_{top}, \Gamma_{top}) \cdot BW(m_{l\nu b_{lep}} | m_{top}, \Gamma_{top}) \\
& W(\tilde{E}_{jet_1} | E_{b_{had}}) W(\tilde{E}_{jet_2} | E_{b_{lep}}) W(\tilde{E}_{jet_3} | q_1) W(\tilde{E}_{jet_4} | q_2) \\
& W(\tilde{E}_x^{miss} | p_{x,\nu}) W(\tilde{E}_y^{miss} | p_{y,\nu}) \left\{ \begin{array}{l} W(\tilde{E}_l | E_l) \\ W(\tilde{p}_{T,l} | p_{T,l}) \end{array} \right\}
\end{aligned}
$$



- to increase reconstruction efficiency:
  $\hookrightarrow$ use up to 6 jets with highest p_T as input
- detector resolution: encoded in transfer functions
- veto *b*-tagged jets in position of light jets and vice versa

➔ Choose jet-parton assignment with maximum Likelihood for analysis

Refined analysis strategy

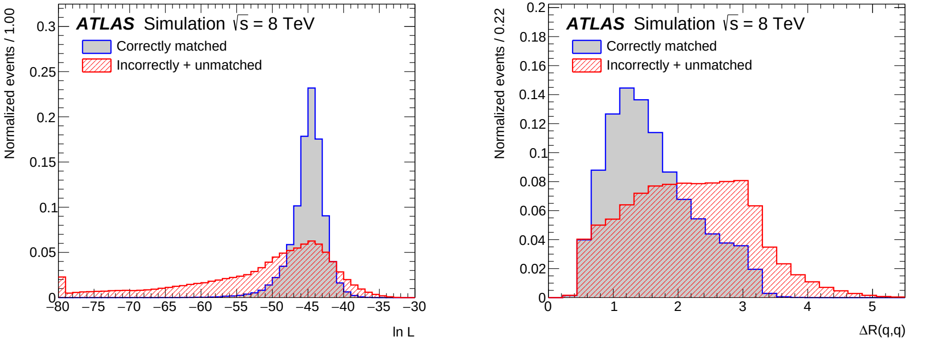


Two main changes:

1. cut on BDT output to reject badly reconstructed events: loose events
2. extract also JSF and bJSF to reduce uncertainty on m_{top}:

   $\hookrightarrow$ larger statistical uncertainty, but reduces correlation with other channels

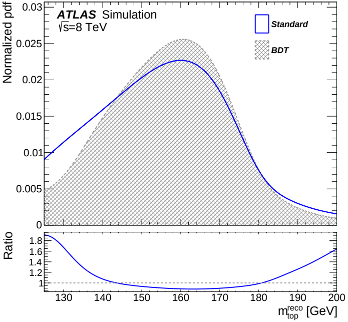
What input is used for the BDT?

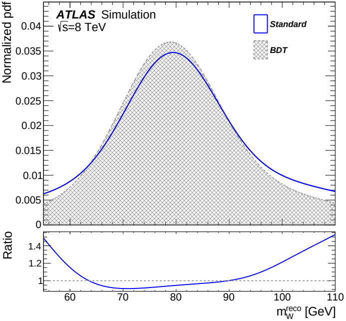


- in total 13 variables from KLFitter (transverse momenta of top, W, $t\bar{t}$, ...)
- best separation from log-likelihood and ΔR between W decay products

  $\hookrightarrow$ check now the performance of the training

Impact of the BDT selection on the observables





What do we gain from the BDT optimisation?

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	
Event selection	Standard	Standard	BDT
m_{top} result [GeV]	172.33	171.90	172.08
Statistics	0.75	0.38	0.39
– *Stat. comp.* (m_{top})	0.23	0.12	0.11
– *Stat. comp.* (JSF)	0.25	0.11	0.11
– *Stat. comp.* (bJSF)	0.67	0.34	0.35
Method	0.11 ± 0.10	0.04 ± 0.11	0.13 ± 0.11
Signal Monte Carlo generator	0.22 ± 0.21	0.50 ± 0.17	0.16 ± 0.17
Hadronization	0.18 ± 0.12	0.05 ± 0.10	0.15 ± 0.10
Initial- and final-state QCD radiation	0.32 ± 0.06	0.28 ± 0.11	0.08 ± 0.11
Underlying event	0.15 ± 0.07	0.08 ± 0.15	0.08 ± 0.15
Colour reconnection	0.11 ± 0.07	0.37 ± 0.15	0.19 ± 0.15
Parton distribution function	0.25 ± 0.00	0.08 ± 0.00	0.09 ± 0.00
Background normalization	0.10 ± 0.00	0.04 ± 0.00	0.08 ± 0.00
W+jets shape	0.29 ± 0.00	0.05 ± 0.00	0.11 ± 0.00
Fake leptons shape	0.05 ± 0.00	0	0
Jet energy scale	0.58 ± 0.11	0.63 ± 0.02	0.54 ± 0.02
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.05 ± 0.01	0.03 ± 0.01
Jet energy resolution	0.22 ± 0.11	0.23 ± 0.03	0.20 ± 0.04
Jet reconstruction efficiency	0.12 ± 0.00	0.04 ± 0.01	0.02 ± 0.01
Jet vertex fraction	0.01 ± 0.00	0.13 ± 0.01	0.09 ± 0.01
b-tagging	0.50 ± 0.00	0.37 ± 0.00	0.38 ± 0.00
Leptons	0.04 ± 0.00	0.16 ± 0.01	0.16 ± 0.01
Missing transverse momentum	0.15 ± 0.04	0.08 ± 0.01	0.05 ± 0.01
Pile-up	0.02 ± 0.01	0.14 ± 0.01	0.15 ± 0.01
Total systematic uncertainty	1.04 ± 0.08	1.07 ± 0.10	0.82 ± 0.06
Total	1.28 ± 0.08	1.13 ± 0.10	0.91 ± 0.06

Precision of systematic uncertainty:

$$u \pm s = \sqrt{\Sigma_k u_k^2} \pm \frac{\sqrt{\Sigma_k (s_k^2 u_k^2)}}{u}$$

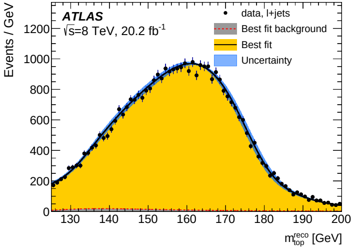
$\hookrightarrow$ use to test stability of combination

➔ total systematic uncertainties almost equal for standard selections at 7 and 8 TeV

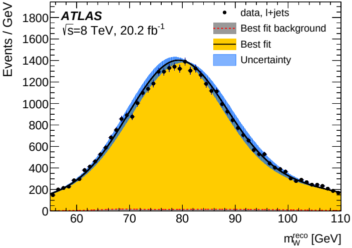
➔ overall uncertainty is reduced by 19 % when using BDT optimisation

Result in data for $r_{\mathrm{BDT}} >$ -0.05

$$m_{\mathrm{top}} = 172.08 \pm 0.39\,(\mathrm{stat})\,\mathrm{GeV}$$

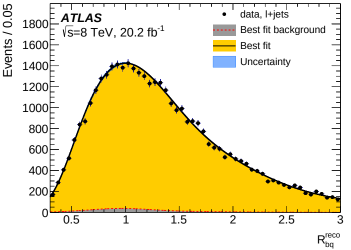


$$\mathrm{JSF} = 1.005 \pm 0.001\,(\mathrm{stat})$$



$$\rho_{\mathrm{stat}} = \begin{pmatrix} 1.0 & & \\ -0.27 & 1.0 & \\ -0.92 & -0.02 & 1.0 \end{pmatrix}$$

$$\mathrm{bJSF} = 1.008 \pm 0.005\,(\mathrm{stat})$$



Final result lepton+jets channel:

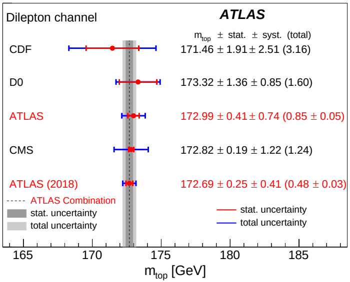
$$m_{\mathrm{top}} = 172.08 \pm 0.39\,(\mathrm{stat}) \pm 0.82\,(\mathrm{syst})\ \mathrm{GeV}$$

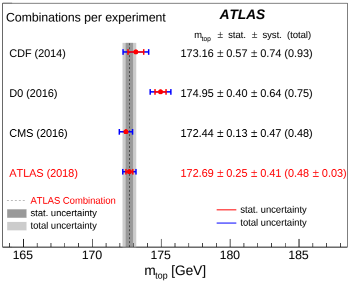
Combination procedure

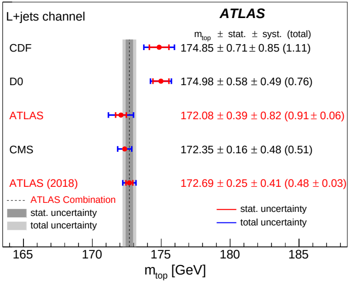
- use BLUE method (best linear unbiased estimator)
  Link hepforge | Eur. Phys. J. C (2014) 74
- for each source of uncertainty the correlation between any pair of analyses needs to be known
- need to properly map the uncertainty components between 7 and 8 TeV (JES, *b*-tagging)
- if uncertainy has no equivalent at other centre-of-mass energy:

  $\hookrightarrow$ treat as independent

Comparison ATLAS and CMS



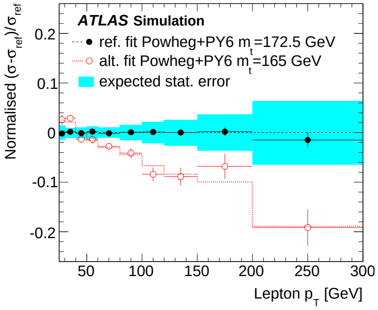


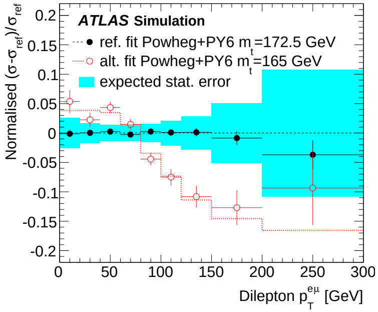


Dilepton differential cross-section at 8 TeV

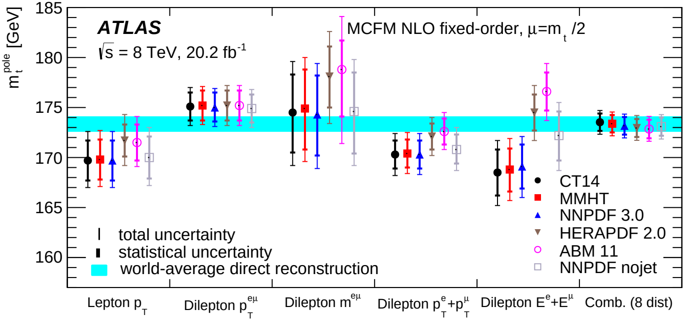
EPJC 77 (2017) 804

- take events with opposite sign leptons e/μ + 1 or 2 b-tagged jets
- take differential lepton distributions which are sensitive to m_{top}
  $\hookrightarrow$ unfold back to stable particle level
- obtain m_{top} and $m_{\text{top}}^{\text{pole}}$ using fits or from moments





$m_{\rm top}^{\rm pole}$ from fixed order predictions



- very good agreement with standard methods and other $m_{\rm top}^{\rm pole}$ measurements
- smallest uncertainty obtained from fit to $p_T^{e\mu}$ distribution
- largest uncertainty from choice of functional form for QCD scales

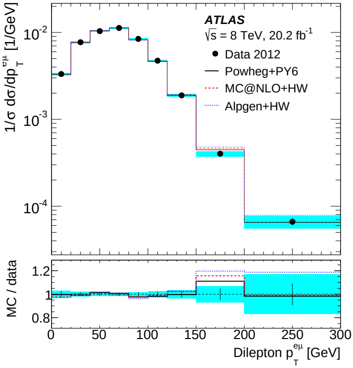
  $\hookrightarrow$ benefit from NNLO predictions with QCD effects in top prod.+decay

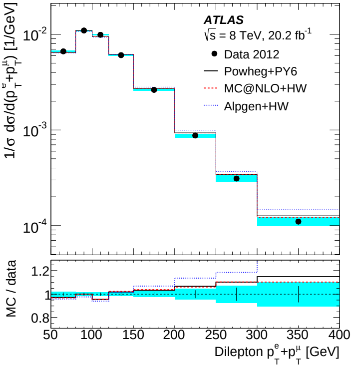
Combined fit: $m_{\rm top}^{\rm pole} = 173.2 \pm 0.9\ (\text{stat.}) \pm 0.8\ (\text{exp.}) \pm 1.2\ (\text{theor.})$ GeV (0.9%)

Dilepton differential cross-section at 8 TeV

EPJC 77 (2017) 804

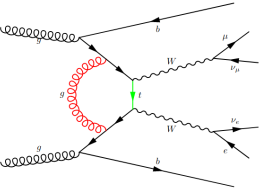
- take events with opposite sign leptons $e/\mu + 1$ or 2 b-tagged jets
- take differential lepton distributions which are sensitive to m_{top}
  $\hookrightarrow$ unfold back to stable particle level
- obtain m_{top} and $m_{\mathrm{top}}^{\mathrm{pole}}$ using fits or from moments

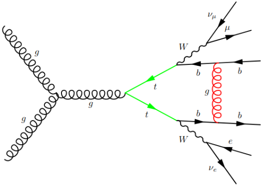


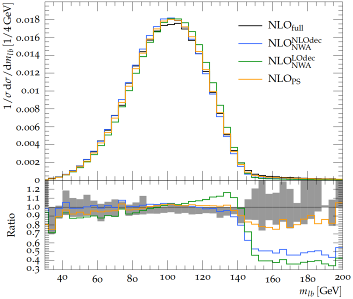


The impact of off-shell effects on m_{top}

JHEP (2018) 129

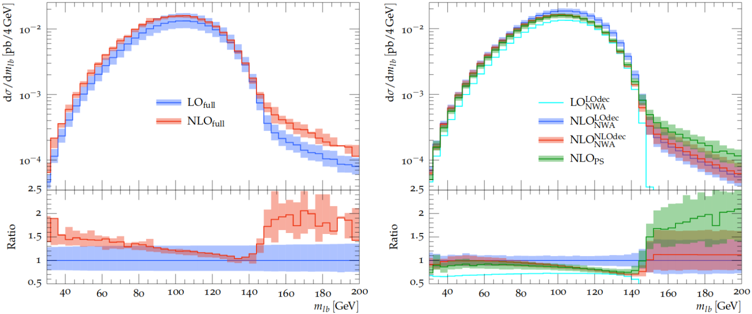






- full NLO $\rightarrow WWbb$: both singly resonant and non-resonant contributions
- 5FS, Sherpa, $\mu_R = \mu_F = m_t$
- narrow-width-approximation: factorisation of production and decay
- m_{lb} observable: better agreement between $\mathrm{NLO}_{\mathrm{full}}$ and $\mathrm{NLO}_{\mathrm{PS}}$

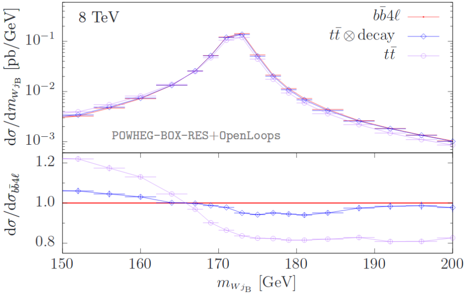
The impact of off-shell effects on m_{top} JHEP (2018) 129



- see smaller impact from non-resonant contributions than from NLO decay
- compare NLO$_{\text{full}}$ vs. NLO$_{\text{PS}}$: shift of 90 MeV
- compare NLO$_{\text{NWA}}^{\text{NLOdec}}$ vs. NLO$_{\text{PS}}$: shift of 960 MeV

  $\hookrightarrow$ mainly from $>$ 140 GeV $\rightarrow$ where resummation corrections come in

The impact of off-shell effects on m_{top} arXiv:1607.04538



- $b\bar{b}4l$: NLO in production and decay, finite width, interference of radiation in production and decay, spin correlation and off-shell effects, resonance-aware matching
- ttb_NLO_dec: NLO in production and decay, spin correlation, off-shell effects only at LO, Wt only at LO
- hvq: NLO in production, LO in decay

What mass do we measure?

Andre Hoang, TOP 2018

- direct reconstruction m_{top} measurements:
  $\hookrightarrow$ measured m_{top}^{MC} depends on renormalization scheme of MC generator
- m_{top} from cross-section measurements: closer to pole mass
- difference between m_{top}^{MC} and e.g. m_{top}^{pole} (and other mass schemes)
  $\hookrightarrow$ still subject of lively discussion

What mass do we measure?

Andre Hoang, TOP 2018

$$m_{\mathrm{top}}^{MC} = m_{\mathrm{top}}^{pole} + \Delta m^{pert.} + \Delta m^{non-pert.} + \Delta m^{MC}$$

- Andre Hoang et al:
  $\hookrightarrow \Delta m \approx 0.5$ GeV, $\Delta m^{pert.} \propto Q_0 \alpha_S(Q_0)$ with Q_0: shower cut
- Paolo Nason et al arXiv:1901.04737:
  $\hookrightarrow \Delta m^{non-pert.} \approx \Lambda_{\mathrm{QCD}}$, $\Delta m^{pert.}$ is negligible

Various definitions for the top-quark mass

Overview: G. Corcella, 1903.06574

- heavy quarks: need to subtract ultraviolet divergences in renormalized self energy $\Sigma^R(m_0, p, \mu_R)$
- renormalon: factorial growth of the coefficients in powers of the string coupling of the heavy quark self-energy

1) **pole mass:**
   renormalon ambiguity of about 250 GeV when translating into $\overline{MS}$ mass
2) $\overline{MS}$ **mass:** short-distance mass, depends on μ_R, no renormalon, only suitable far away from threshold
3) **MSR mass** $m_t^{MSR}(R, \mu_R)$:
   $\hookrightarrow$ interpolation between pole and $\bar{M}S$ mass, more stable:

$$m_t^{MSR}(R) \to m_{t,pole} \text{ for R} \to 0; \quad m_t^{MSR}(R) \to \bar{m}_t(\bar{m}_t) \text{ for R} \to \bar{m}_t(\bar{m}_t)$$

Can we translate the results into other mass schemes?

Andre Hoang, TOP 2018

$$m_{\text{top}}^{pole} - m_{\text{top}}^{MSR}(Q_0) = (0.35 \pm 0.25)\ GeV$$
$$m_{\text{top}}^{pole} - m_{\text{top}}^{CB}(Q_0) = (0.54 \pm 0.26)\ GeV$$

$$m_{\text{top}}^{MSR}(Q_0) - m_{\text{top}}^{CB}(Q_0) = (0.19 \pm 0.07)\ GeV$$

$\hookrightarrow$ no $O(\Lambda_{\text{QCD}})$ renormalon

$$m_{\text{top}}^{\text{pole}} = \bar{m}_t(\bar{m}_t)\ [1 + 0.4244\alpha_S + 0.8345\alpha_S^2 + ... + \mathcal{O}(\alpha_S^5)]$$

$\hookrightarrow$ uncertainty of about 200 MeV for conversion

$\hookrightarrow$ known up to four-loop accuracy!

Direct top-quark decay width measurement

Tomas Dado

September 2019

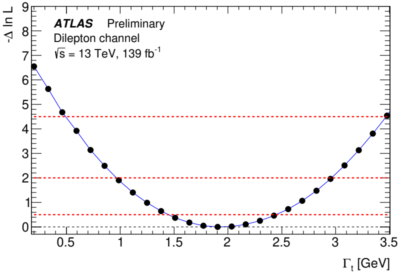
- Use lepton+jets and dilepton $t\bar{t}$ events
- Create templates by reweighting nominal samples
- Use observables sensitive to decay width and observables insensitive (control regions)
- Profile likelihood fit with multiple templates - a new technique
- Combine both $t\bar{t}$ channels

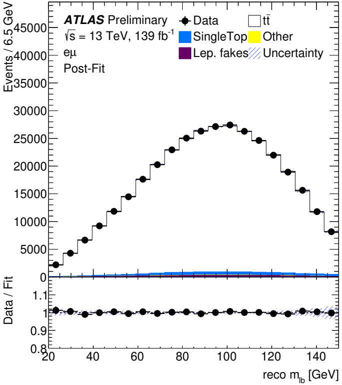
Status

- Dilepton result presented in LeptonPhoton - ATLAS-CONF-2019-038
- Lepton+jets result in progress
- Combination in progress
  - Aim: uncertainty on Γ_t below 0.5 GeV

Result - dilepton

- Simultaneous fit of both regions ($m_{\ell b}$ in $e\mu$ and $m_{b\bar{b}}$ in SF)
- Assuming $m_t = 172.5$ GeV
- Full syst. model: $\Gamma_t = 1.9 \pm 0.5$ GeV
- Stat-only fit: $\Gamma_t = 1.90 \pm 0.21$ GeV
- $t\bar{t}$ norm. consistent with prediction





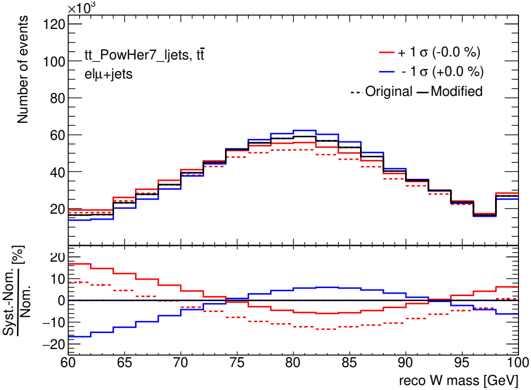
Dilepton result II

- Dominant systematic uncertainties:
  - Jet uncertainties
  - $t\bar{t}$ modelling
  - MC statistics
  - b-tagging
- Top mass not included as a systematic uncertainty
- Measuring width as a function of mass

Source	Impact on Γ_t [GeV]
Jet reconstruction	± 0.24
Signal and bkg. modelling	± 0.19
MC statistics	± 0.14
Flavour tagging	± 0.13
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	± 0.09
Pile-up and luminosity	± 0.09
Electron reconstruction	± 0.07
PDF	± 0.04
$t\bar{t}$ normalisation	± 0.03
Muon reconstruction	± 0.02
Fake-lepton modelling	± 0.01

	$m_t = 172$		$m_t = 172.5$ GeV		$m_t = 173$ GeV	
	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]
Measured	2.01	$^{+0.53}_{-0.50}$	1.94	$^{+0.52}_{-0.49}$	1.90	$^{+0.52}_{-0.48}$
Theory	1.306	$< 1\%$	1.322	$< 1\%$	1.333	$< 1\%$

- Sample machinery as for dilepton
- Selection optimised
- Ran many validation/stability tests
- Problem: $t\bar{t}$ modelling



Lepton+jets modelling

- Profiling the uncertainty - large constraints (0.2 σ)
- Studying the effects of modelling on W mass distribution
  - Almost exclusively caused by difference between Pythia and Herwig on truth level
  - Prepared slides for HCW with this issue: link
- Considering different observables as control regions in the lepton+jets channel

Backup