

Measurements of the top-quark mass using the ATLAS detector

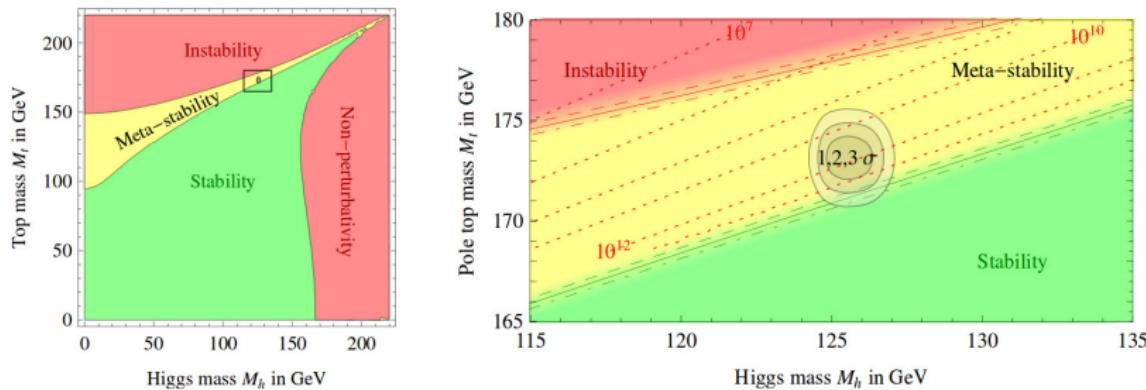
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On behalf of the ATLAS Collaboration

– EPS-HEP Conference Ghent, 11th July 2019 –



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 \approx few hundred MeV – 1 GeV of pole mass

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

- ➊ “direct” reconstruction methods at detector level
 - binned/unbinned template methods
 - matrix-element methods
 - ideogram method

↪ $t\bar{t}$ or single top topologies

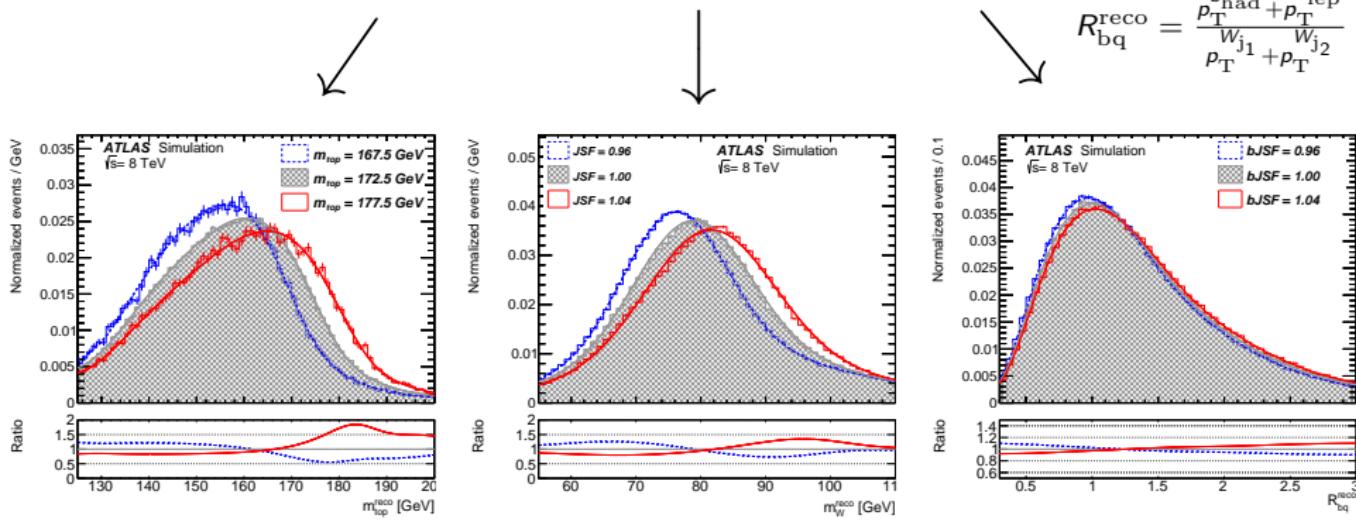
↪ very specific selections, such as J/Ψ
 - ➋ differential $\sigma(t\bar{t})$ cross-section: unfolded distributions
 - ➌ differential $\sigma(t\bar{t}+1\text{jet})$ cross-section: unfolded distributions
- ↪ will show today one example for each category

Lepton+jets analysis @ 8 TeV with a 3D template method

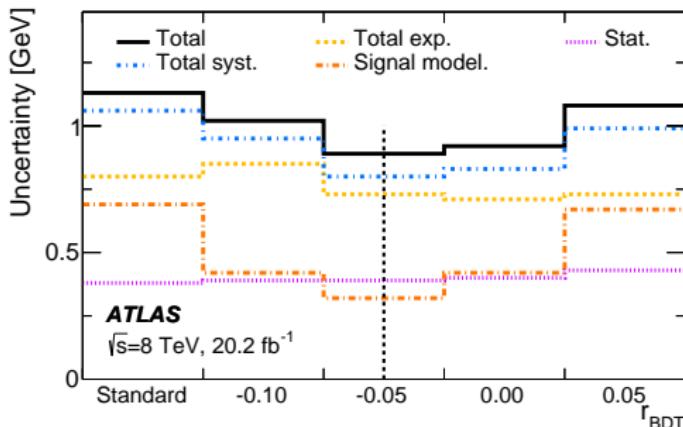
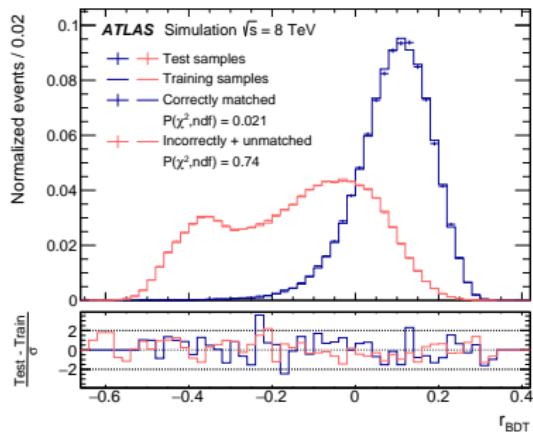
► EPJC 79 (2019) 290

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

- ↪ can be reduced by simultaneous measurement of m_{top} , jet energy scale factor (**JSF**) and relative b-to-light-jet energy scale factor (**bJSF**)
- ↪ done by performing a three dimensional template fit to data



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
 ↳ trade here statistical for reduced systematic uncertainties

What do we gain from the BDT optimisation?

	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$	
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

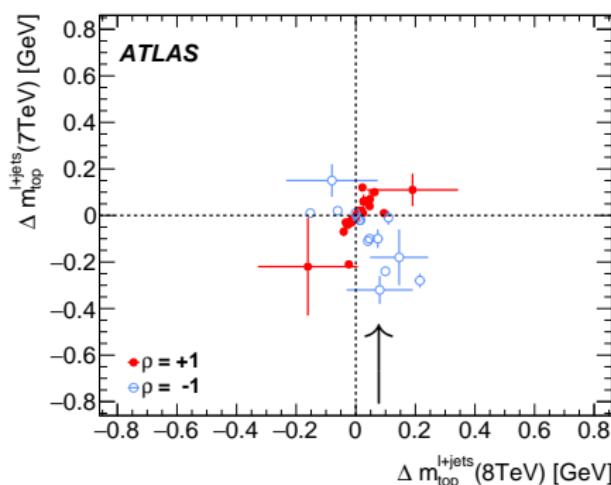
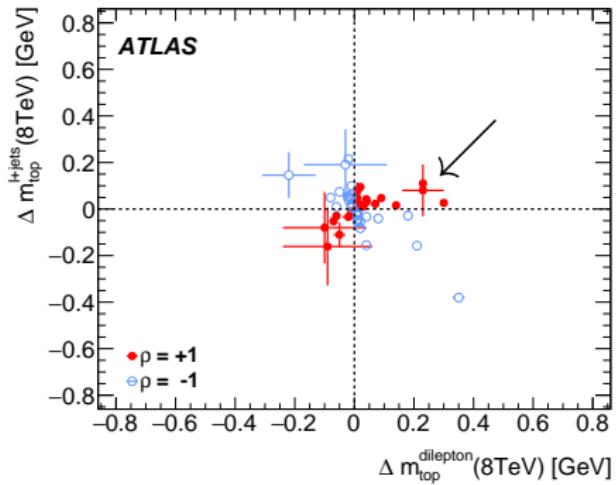
- total systematic uncertainties almost equal for standard selections at 7 and 8 TeV
- overall uncertainty is reduced by 19 % when using BDT optimisation

Precision of systematic uncertainty:

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

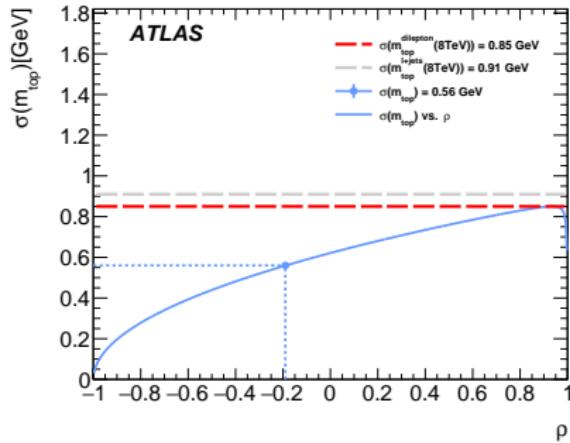
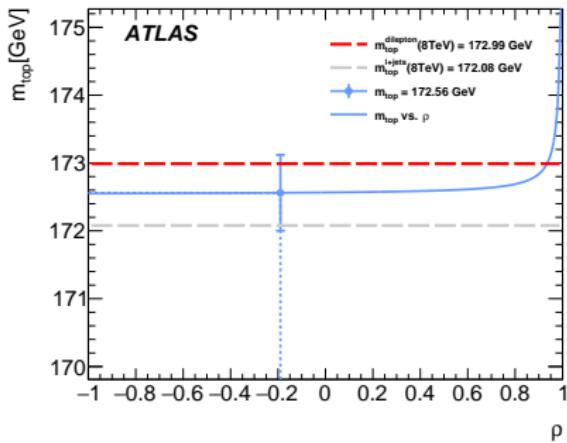
↪ used to test stability of combination

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 ± 0.07 , 1+jets (8 TeV): 0.08 ± 0.11 GeV
- ISR/FSR (right): 1+jets (7 TeV): -0.32 ± 0.06 , 1+jets (8 TeV): 0.08 ± 0.11 GeV

Systematic uncertainties: How low can we go?



Individual result and combination (BLUE software):

$$m_{\text{top}}^{\text{1+jets, 8 TeV}} = 172.08 \pm 0.39 \text{ (stat)} \pm 0.82 \text{ (syst)} \text{ GeV}$$

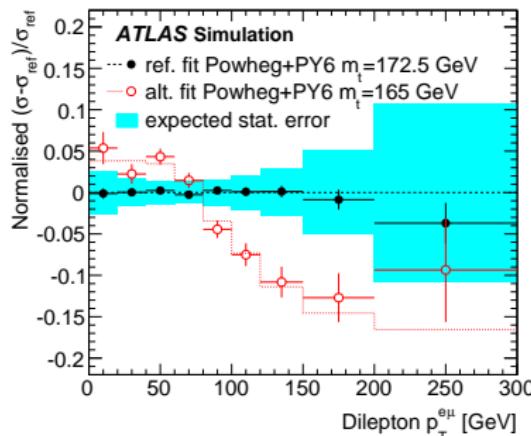
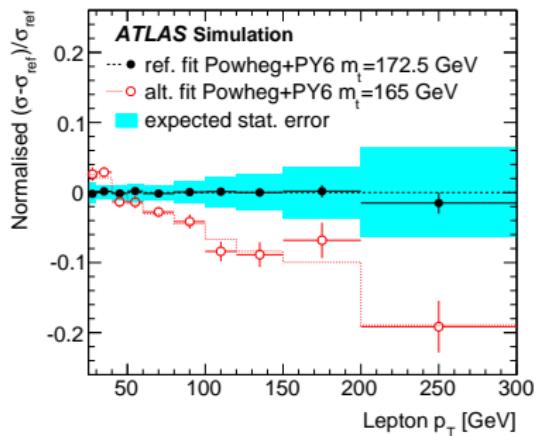
$$m_{\text{top}}^{\text{Combined}} = 172.68 \pm 0.26 \text{ (stat)} \pm 0.48 \text{ (syst)} \text{ GeV}$$

↪ reached a relative uncertainty of 0.29% !

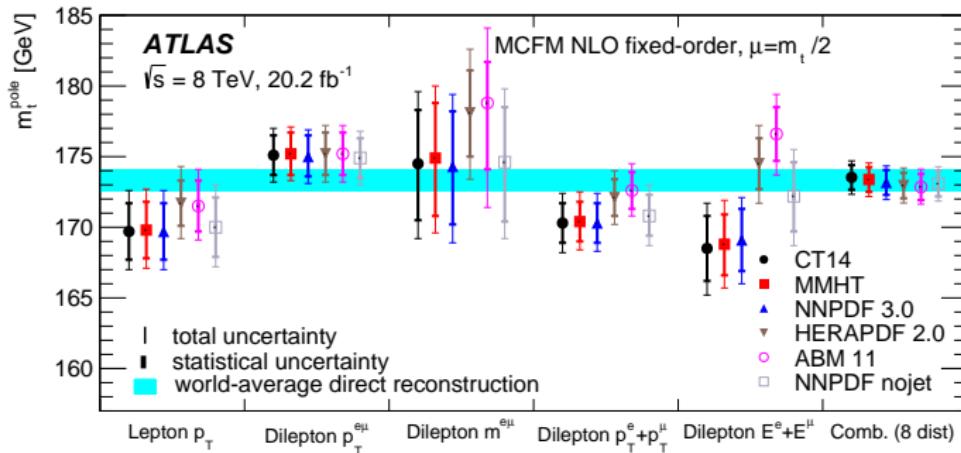
Dilepton differential cross-section at 8 TeV

► 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}
↪ unfold back to stable particle level
- obtain m_{top} and $m_{\text{top}}^{\text{pole}}$ using fits or from moments



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



- very good agreement with standard methods and other $m_{\text{top}}^{\text{pole}}$ measurements
- smallest uncertainty obtained from fit to $p_T^{e\mu}$ distribution
- largest uncertainty from choice of functional form for QCD scales
 ↪ benefit from NNLO predictions with QCD effects in top prod.+decay

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

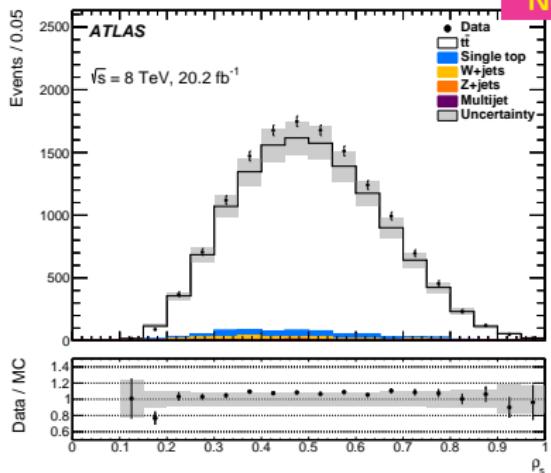
Differential cross-section for $t\bar{t} + 1 \text{ jet}$ production

arXiv:1905.02302

Sensitive variable ρ_s

$$\rho_s = \frac{2m_0}{m_{t\bar{t}+1j}} = \frac{2 \cdot 170 \text{ GeV}}{m_{t\bar{t}+1j}}$$

↪ measure $m_{\text{top}}^{\text{pole}}$ and \overline{MS} mass¹



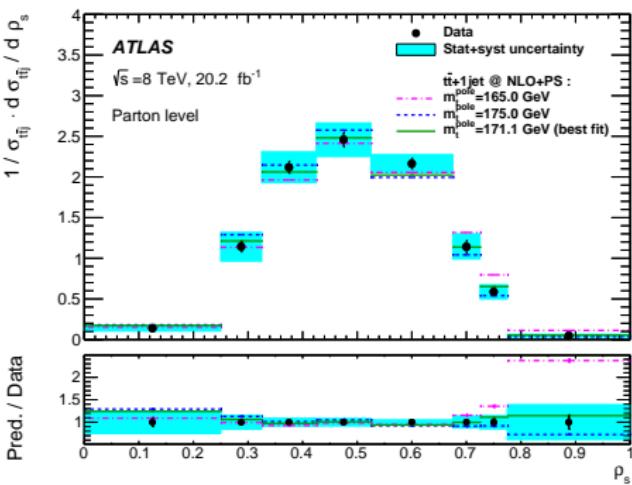
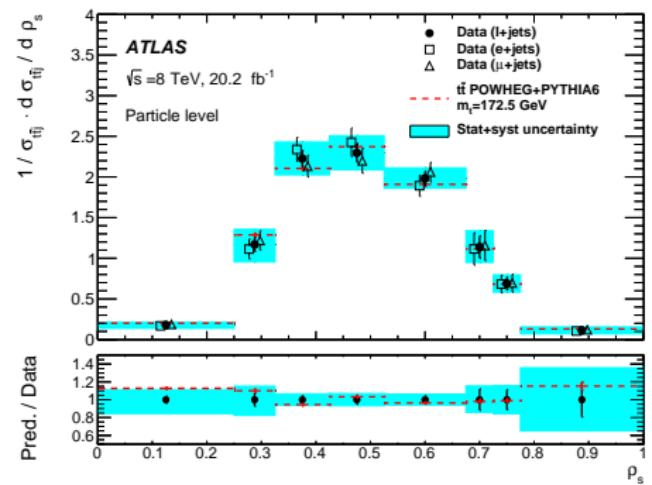
$\sigma_{t\bar{t}+1j}$ more sensitive than $\sigma_{t\bar{t}}$: gluon radiation depends on m_{top} (threshold/cone effects)

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

↪ 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 $t\bar{t} + 1 \text{ jet}$ production

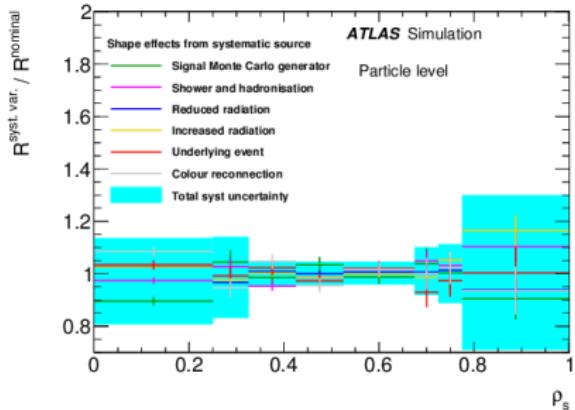


- unfold to stable particle level: remove detector effects
- unfold to parton level: compare to fixed-order calculations and extract mass via χ^2 :

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

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

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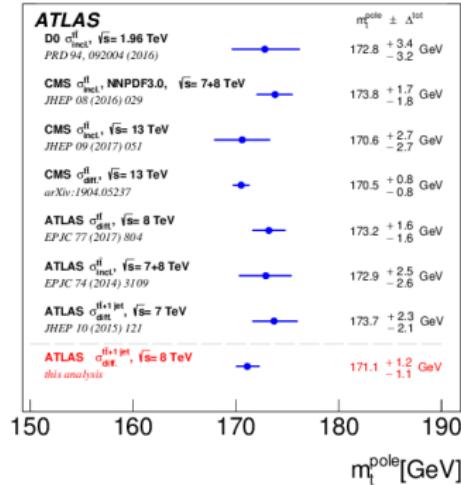
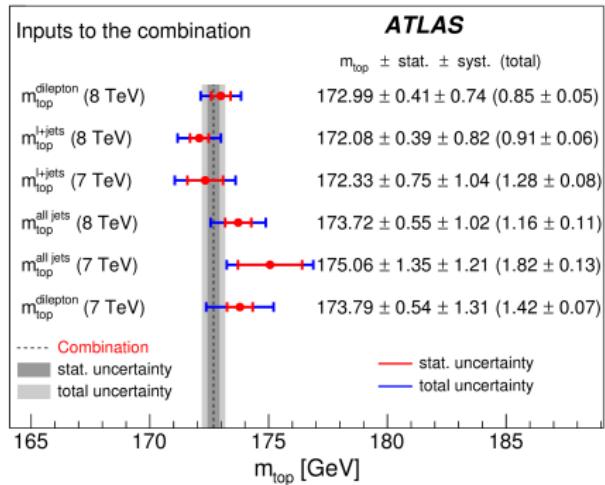


$$m_{\text{top}}^{\text{pole}} = 171.1 \pm 1.2 \text{ GeV } (0.7 \%)$$

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

Mass scheme	m_t^{pole} [GeV]	$m_t(m_t)$ [GeV]
Value	171.1	162.9
Statistical uncertainty	0.4	0.5
<i>Simulation uncertainties</i>		
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
<i>Detector response uncertainties</i>		
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
<i>Method uncertainties</i>		
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 $\oplus\alpha_s$	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)

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



Best individual measurements:

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

Summary

The top quark has come a long way since 1977:

Back then: missing quark, assumed to be similar to other quarks



Today: know that top quark is special

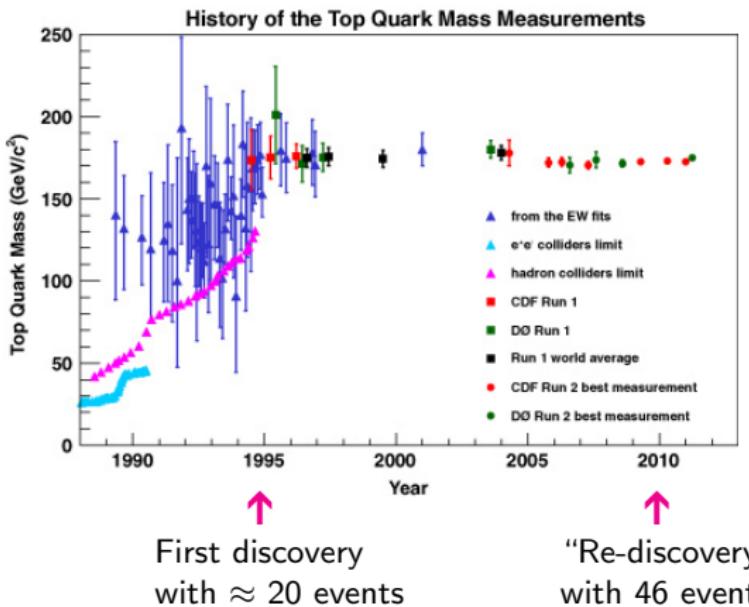
Live in precision era, top quark is key to an abundance of different research areas



Look to the future:

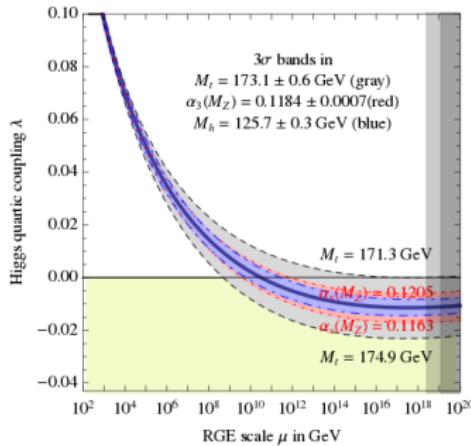
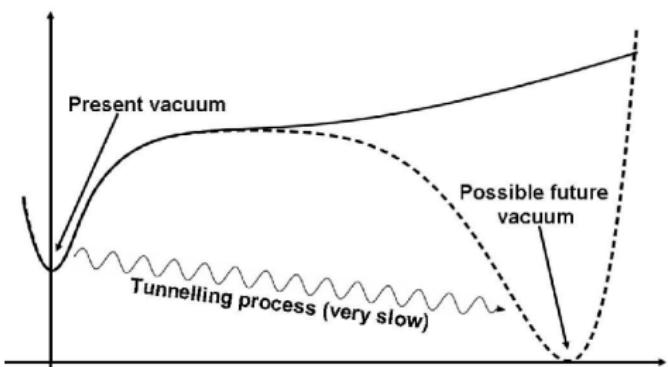
- ① Reduce systematic uncertainties: JES, signal modelling
- ② pole-mass analyses start to become competitive
- ③ theory community very active, important to state what mass we measure!

The top-quark mass over time



- today: 166 M $t\bar{t}$ events in Run II alone
- so: you don't need huge stats for a discovery, but it helps ;)

Stability of the Standard Model vacuum



Need precision measurement:

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

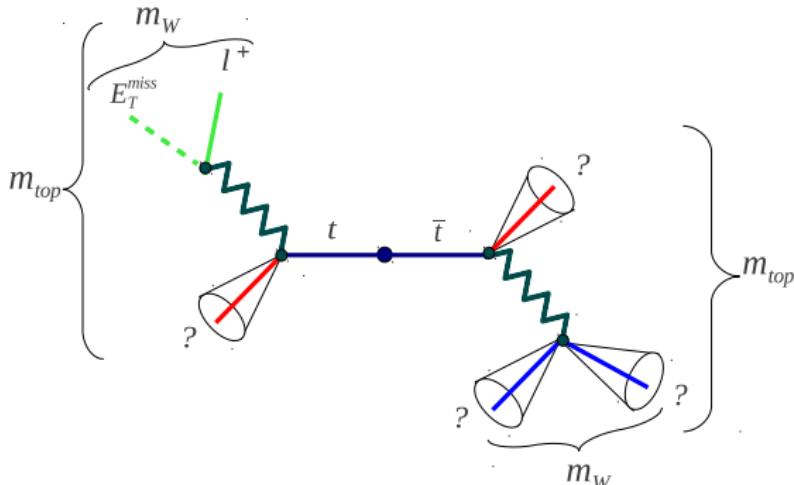
↪ need $\Delta m_t^{pole} < 250 \text{ MeV}$, $\alpha_S(m_Z) < 0.00025$

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

Event reconstruction

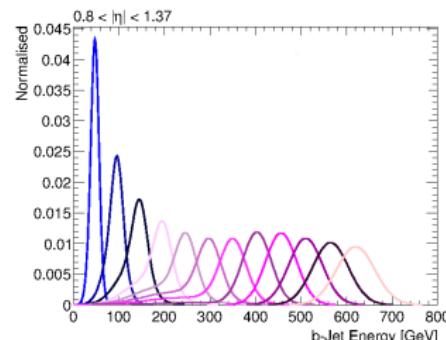
First approach:

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



Reconstruction with KLFitter

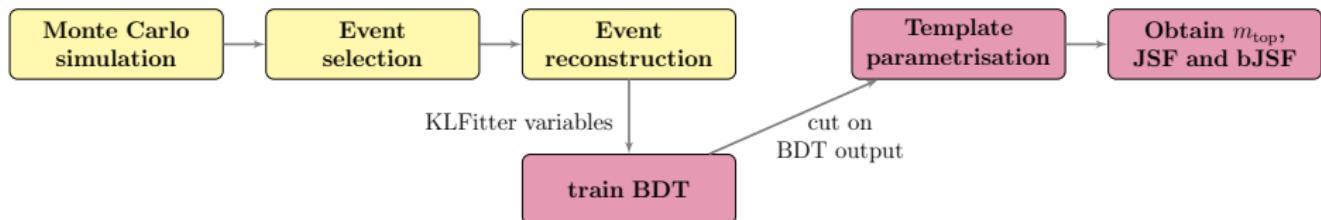
$$\begin{aligned}
 L &= BW(m_{q_1 q_2} | m_W, \Gamma_W) \cdot BW(m_{l\nu} | m_W, \Gamma_W) \\
 &\quad BW(m_{q_1 q_2 b_{had}} | m_{top}, \Gamma_{top}) \cdot BW(m_{l\nu b_{lep}} | m_{top}, \Gamma_{top}) \\
 W(\tilde{E}_{jet_1} | E_{b_{had}})W(\tilde{E}_{jet_2} | E_{b_{lep}})W(\tilde{E}_{jet_3} | q_1)W(\tilde{E}_{jet_4}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



- to increase reconstruction efficiency:
↪ 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

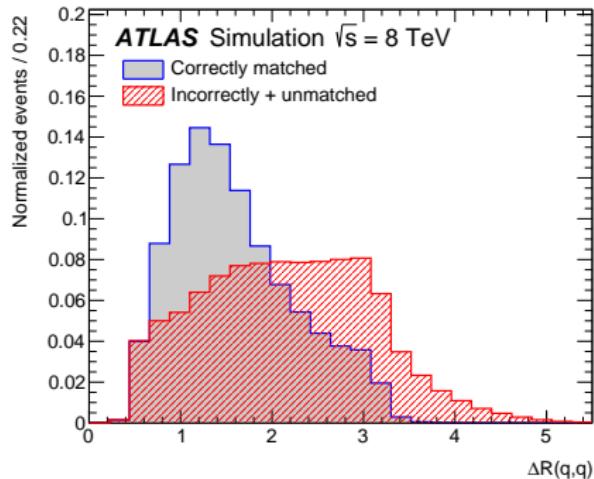
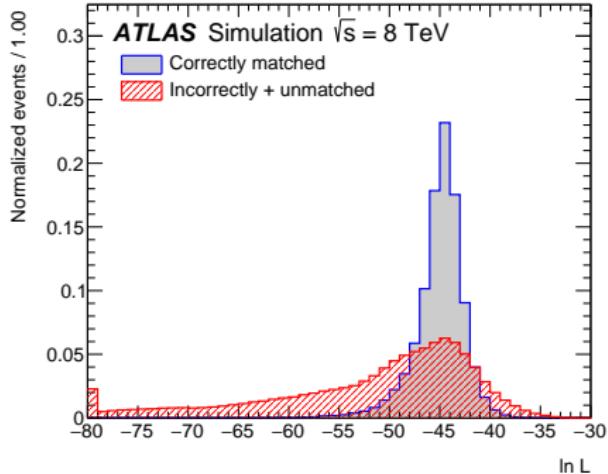
Refined analysis strategy



Two main changes:

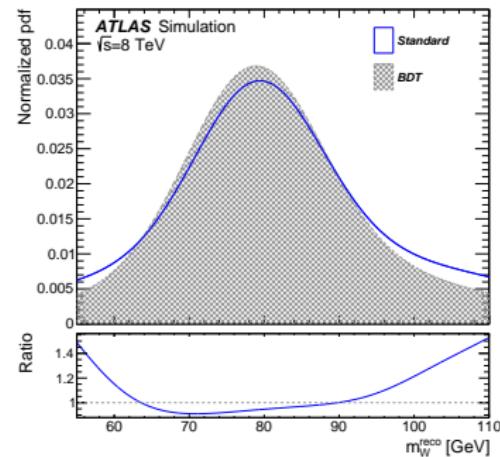
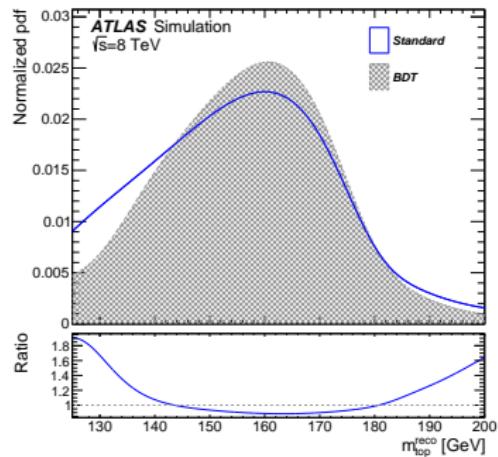
- ① cut on BDT output to reject badly reconstructed events: loose events
- ② extract also JSF and bJSF to reduce uncertainty on m_{top} :
 → larger statistical uncertainty, but reduces correlation with other channels

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
↪ 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:

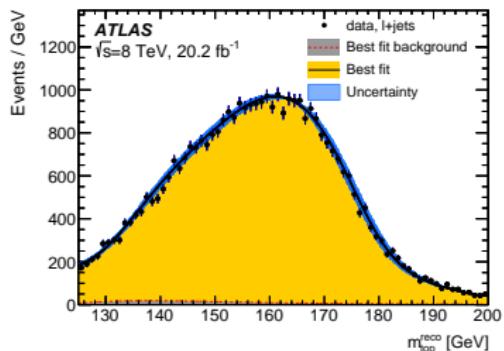
$$u \pm s = \sqrt{\sum_k u_k^2} \pm \frac{\sqrt{\sum_k (s_k^2 u_k^2)}}{u}$$

→ use to test stability of combination

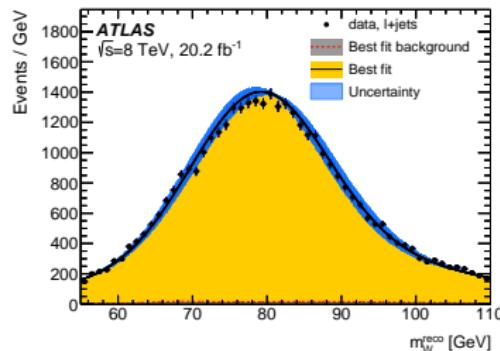
- total systematic uncertainties almost equal for standard selections at 7 and 8 TeV
- overall uncertainty is reduced by 19 % when using BDT optimisation

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

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



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

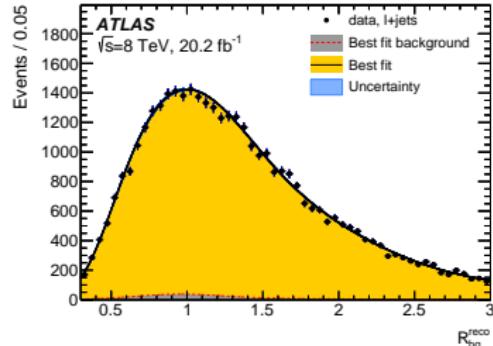


$$\text{bJSF} = 1.008 \pm 0.005 \text{ (stat)}$$

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

Final result lepton+jets channel:

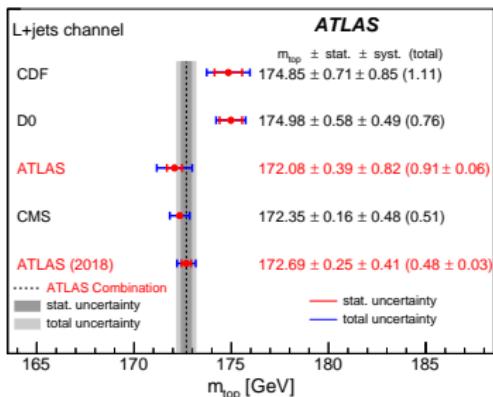
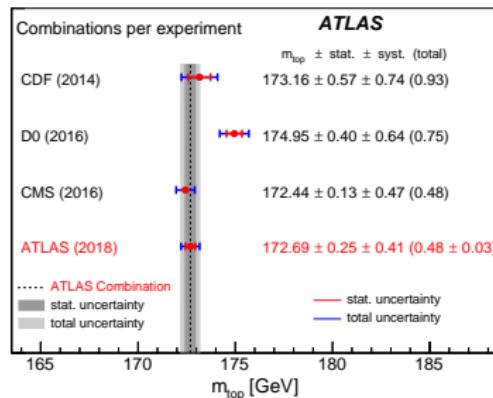
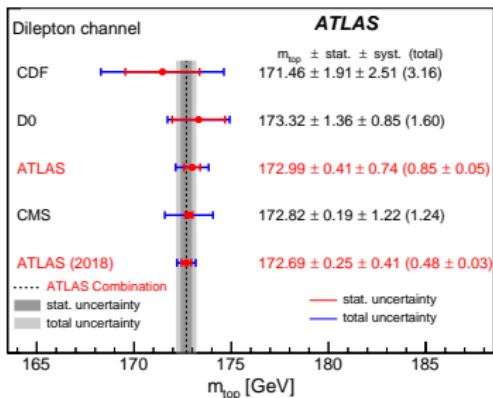
$$m_{\text{top}} = 172.08 \pm 0.39 \text{ (stat)} \pm 0.82 \text{ (syst)} \text{ GeV}$$



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 uncertainty has no equivalent at other centre-of-mass energy:
 - ↪ treat as independent

Comparison ATLAS and CMS



Dilepton differential cross-section at 8 TeV

► EPJC 77 (2017) 804

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

