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Top mass measurements in ATLAS and CMS

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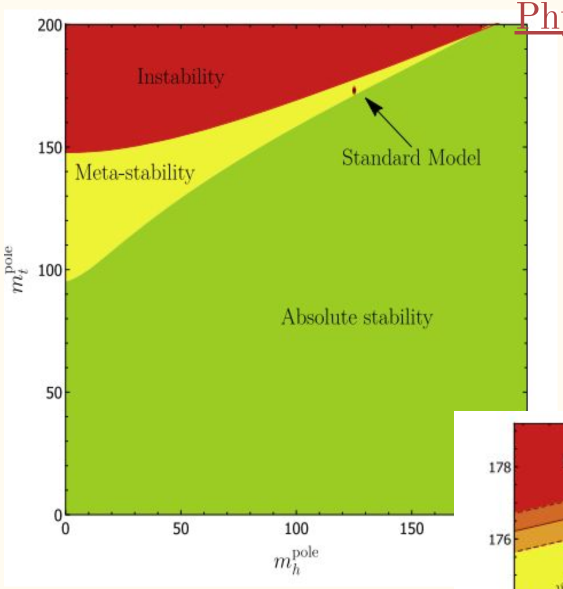
Blois

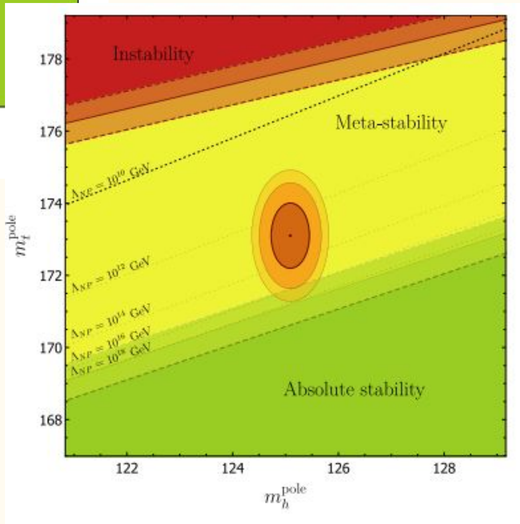
5/6/2019

Top mass: why we care

PhysRevD.97.056006

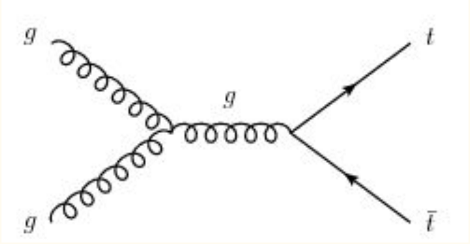


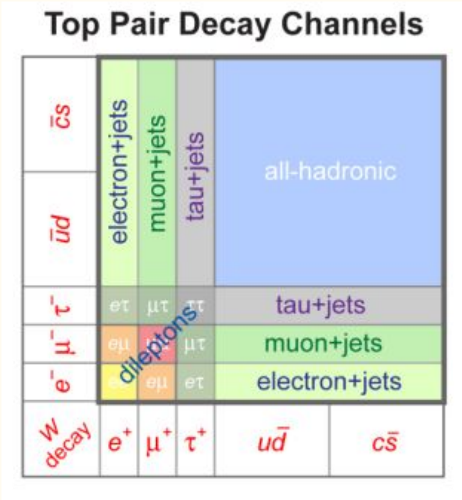
- m_t ~ 172.5 GeV
  - heaviest elementary particle
- critical input for EW precision tests
- crucial interplay with the Higgs
  - vacuum stability
  - quartic coupling
- cosmological consequences
  - e.g. Universe lifetime, see PhysRevD.97.056006
- challenging for experiments and theory
  - ambiguities on m_t interpretation at $O(\Lambda_{QCD})$ (see e.g. review arXiv:1903.0657)



Top mass measurement at the LHC

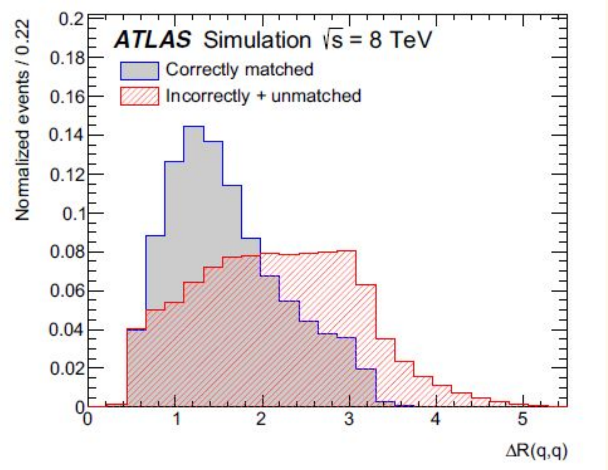
- Lots of data:
  - σ_{tt} ~ 830 pb @ 13 TeV (180 @ 7 TeV, 250 @ 8 TeV)
  - ~140/fb per experiment @ 13 TeV (4 @ 7 TeV, 20 @ 8 TeV)
- Direct measurements:
  - observable dependent on m_t
  - problem: measurement of "m_t^{MC}" due to color
- Indirect measurements:
  - property $f(m_t^{pole})$ (e.g. cross section) + theory → m_t(scheme)
  - problem: uncertainties in fixed-order calculations due to soft radiation, non-perturbative effects, ...
- Many decay channels, many experimental observables → sensitivity to different uncertainties → combination

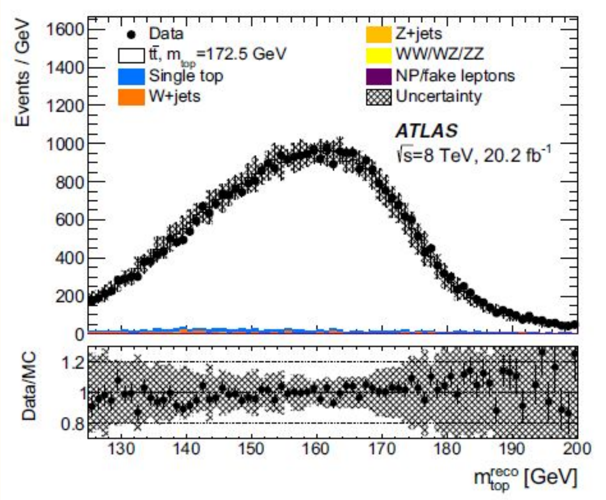




ℓ+jets channel: ATLAS 8 TeV

- 1 high-pt isolated e/mu, >=4 jets, =2 b-jets
- Topology reconstruction: KLFitter
  $L(m_t^{reco})$ maximised to assign jets to partons
- observables:
  - m_{top}^{reco}
  - m_W^{reco} → Jet Energy Scale
  - $R_{bq}^{reco}=(p_T^{b\text{-lep}}+p_T^{b\text{-had}})/(p_T^{q1}+p_T^{q2})$ → b-Jet Energy Scale
- selection on BDT score
  - kinematics used against wrong topological reconstruction





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ℓ+jets channel: ATLAS 8 TeV

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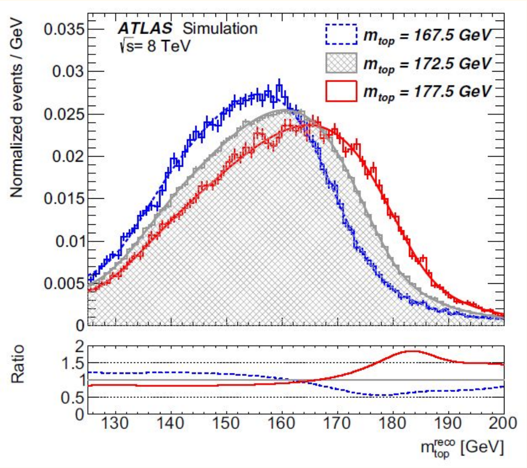
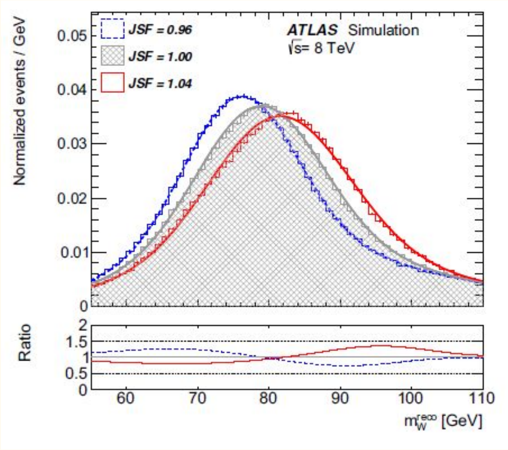
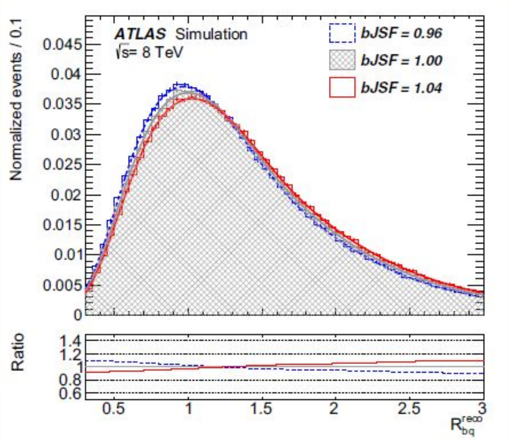
- 3-dimensional template fit to the 3 observables, templates as a function of m_t^{MC}







$$m_{\rm top} = 172.08 \pm 0.39\,({\rm stat})\,{\rm GeV},$$
$$\text{JSF} = 1.005 \quad \pm 0.001\,({\rm stat}), \quad \text{and}$$
$$\text{bJSF} = 1.008 \quad \pm 0.005\,({\rm stat}).$$

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

Dominant systematics:

- Jet Energy Scale: 0.58 GeV
- b-tagging: 0.38 GeV

ℓ+jets channel: ATLAS 8 TeV

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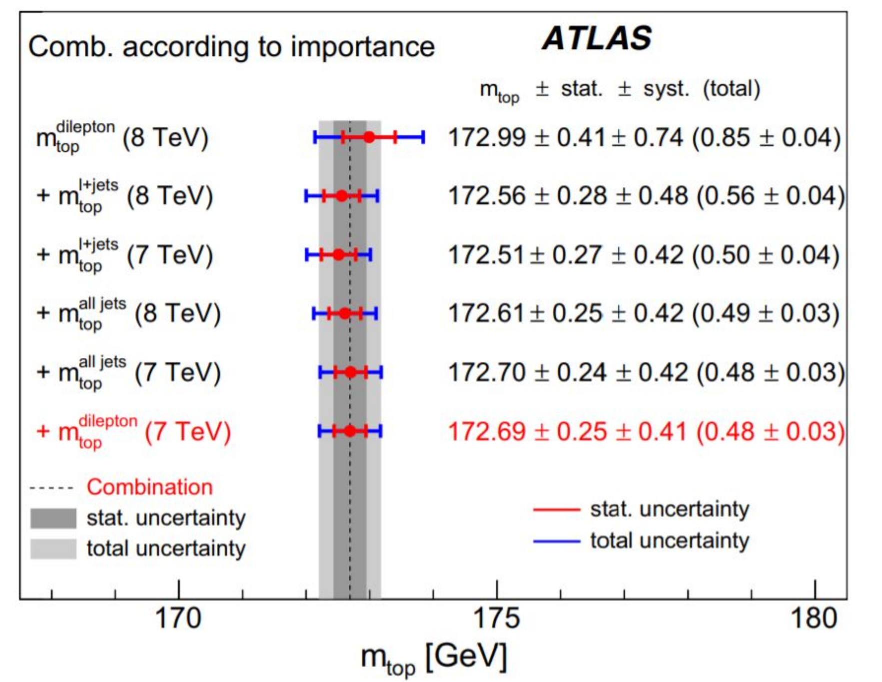
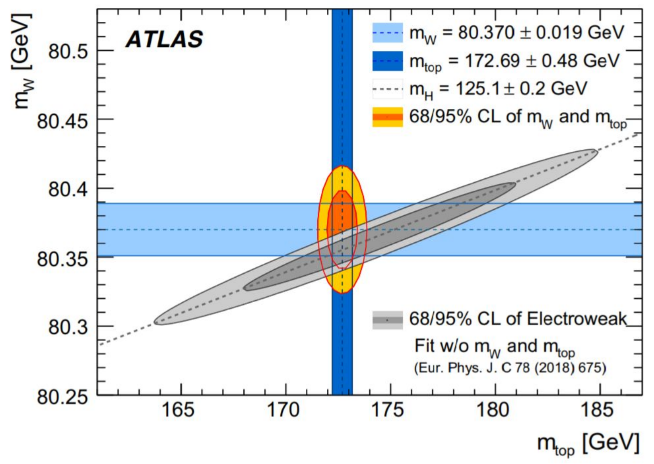
Anti-correlation of systematics in different analyses -> combination!

Dominant uncertainties after the combination:

- ME generator: 0.12 GeV
  - aMC@NLO vs Powheg
- Jet Energy Scale: 0.22 GeV
- b-Jet Energy Scale: 0.17 GeV
- b-tagging: 0.17 GeV





ℓ+jets channel: CMS 13 TeV

- 1 high-pt isolated e/mu, >=4 jets, exactly 2 b-jets
- kinematic fit: 2 combinations of b-jets with light-jets with 2 solutions for $p^{\nu}_{longitudinal}$ → 4 permutations
- permutations weighted by $P=e^{-\chi^2/2}$, P>0.2 applied
- background (~4%) from MC
- Ideogram method
  - m_t^{fit} and JSF PDFs from MC
    - W→qq' → JSF
  - likelihood fit in data
  - 1D fit (JSF=1), 2D fit (JSF free), hybrid (gaus. prior on JSF)

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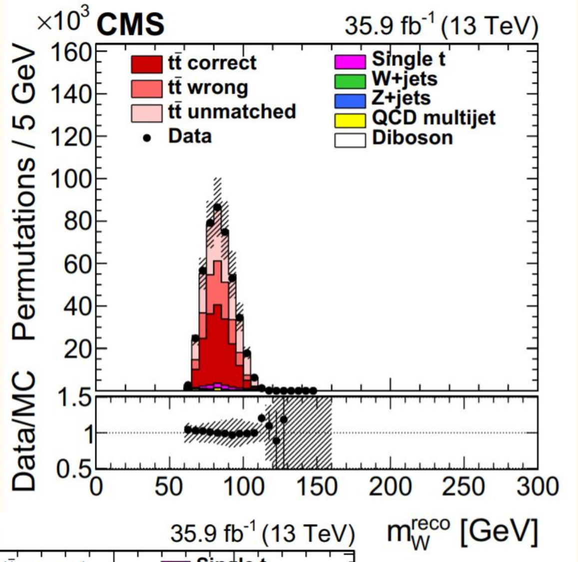

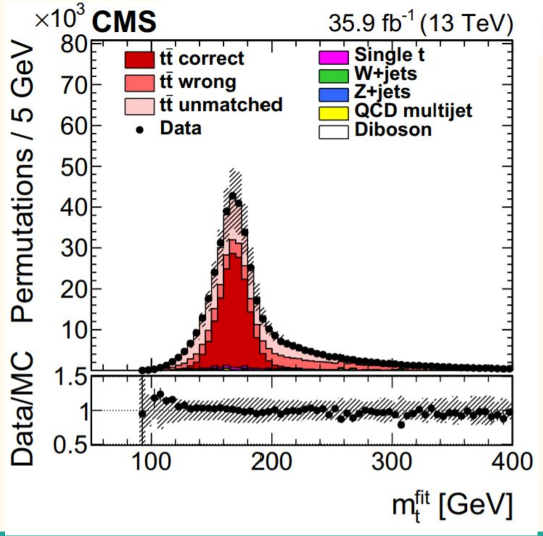

ℓ+jets channel: CMS 13 TeV

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- First top mass on Run-2 data
- First test of new generation of NLO generators

Results:

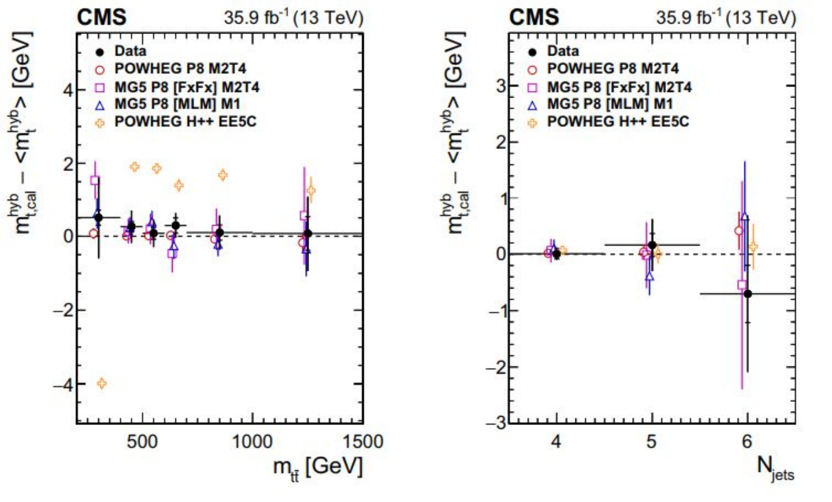
$$m_{t}^{hyb} = 172.25 \pm 0.08\,(\text{stat+JSF}) \pm 0.62\,(\text{syst})\,\text{GeV},$$
$$\text{JSF}^{hyb} = 0.996 \pm 0.001\,(\text{stat}) \pm 0.008\,(\text{syst}).$$

- Jet Energy Corrections → 0.18 GeV
- Jet Energy Resolution → 0.12 GeV
- JEC Flavor response → 0.39 GeV

- b-jet modelling → 0.12 GeV
- Generator →0.20 GeV
- FSR scale in parton shower → 0.13 GeV
- color reconnection → 0.31 GeV

Comparison of different MC models on differential m_t measurements as a function of several quantities

Model	χ^2 probability							
	$p_T^{t,had}$	$m_{t\bar{t}}$	$p_T^{t\bar{t}}$	N_{jets}	$p_T^{b,had}$	$\lvert\eta^{b,had}\rvert$	$\Delta R_{b\bar{b}}$	$\Delta R_{q\bar{q}'}$
POWHEG P8 M2T4	0.68	0.94	0.91	0.71	0.98	0.60	0.61	0.70
MG5 P8 [FxFx] M2T4	0.98	0.78	0.93	0.94	0.80	0.35	0.94	0.91
MG5 P8 [MLM] M1	0.48	0.84	0.99	0.41	0.98	0.17	0.71	0.61
POWHEG H++ EE5C	0.07	2×10^{-13}	0.52	0.72	2×10^{-4}	0.55	0.36	2×10^{-5}
POWHEG P8 ERD on	0.75	0.99	0.83	0.53	0.95	0.64	0.38	0.96
POWHEG P8 QCD inspired	0.80	0.94	0.94	0.66	0.99	0.71	0.49	0.90
POWHEG P8 gluon move	0.87	0.94	0.93	0.72	0.93	0.51	0.59	0.93



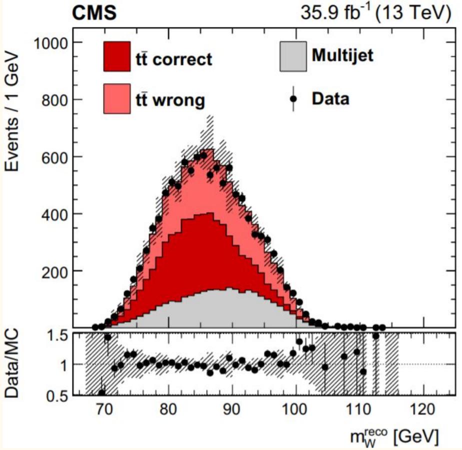
all-had channel: CMS 13 TeV

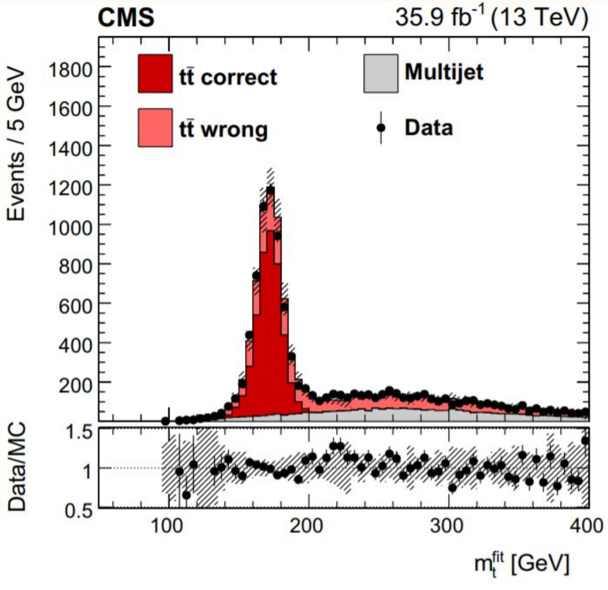
- >= 6 jets, >= 2 b-tagged jets, $\Delta R_{bb}>2$
- kinematic fit, analogous to l+jets
  - mulijet bkg (25%) from events with 0 b-jets
- ideogram method, analogous to l+jets
- best result from hybrid method

$$m_t^{hyb} = 172.34 \pm 0.20\,(\text{stat+JSF}) \pm 0.70\,(\text{syst})\,\text{GeV}$$

$$\text{JSF}^{hyb} = 0.997 \pm 0.002\,(\text{stat}) \pm 0.007\,(\text{syst}).$$

- dominant uncertainties:
  - Jet Energy Corrections → 0.15 GeV
  - JEC Flavor Response → 0.34 GeV
  - ME/PS matching → 0.24 GeV
  - ISR PS scale → 0.12 GeV
  - FSR PS scale → 0.18 GeV
  - Color reconnection → 0.36 GeV





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all-had+l-jets: CMS 13 TeV

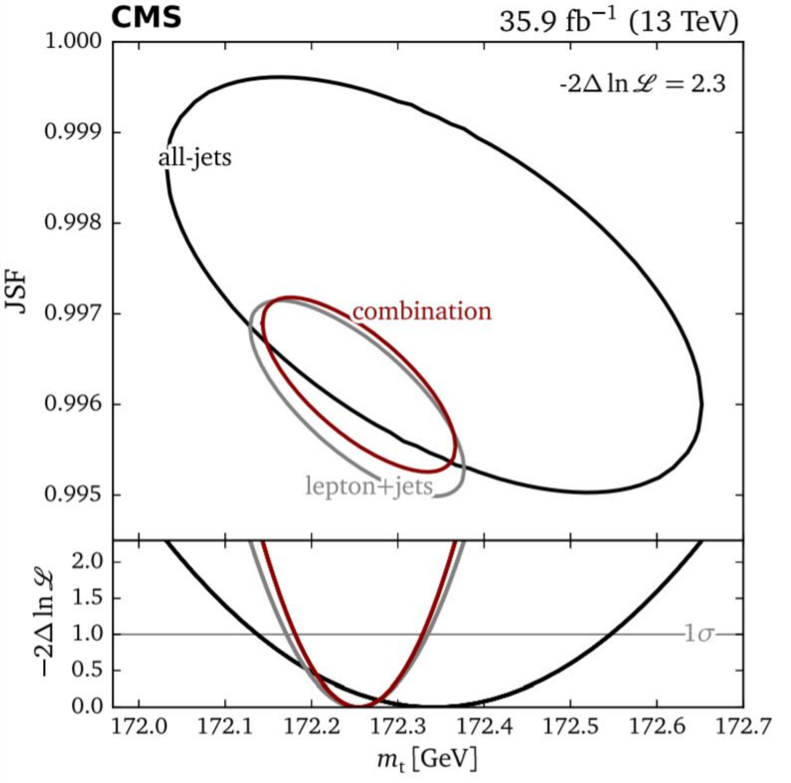
Same method for both channels → combined likelihood

$$\mathcal{L}(m_t, \mathrm{JSF}) = \mathcal{L}_A(m_t, \mathrm{JSF})\mathcal{L}_L(m_t, \mathrm{JSF}).$$

$$m_t^{hyb} = 172.26 \pm 0.07\,(\text{stat+JSF}) \pm 0.61\,(\text{syst})\,\text{GeV}$$
$$\mathrm{JSF}^{hyb} = 0.996 \pm 0.001\,(\text{stat}) \pm 0.007\,(\text{syst})$$

Dominant uncertainties:

- Jet Energy Corrections → 0.17 GeV
- JEC Flavor Response → 0.37 GeV
- Color reconnection modelling → 0.33 GeV
- ME generator → 0.21 GeV
- FSR PS scale → 0.12 GeV



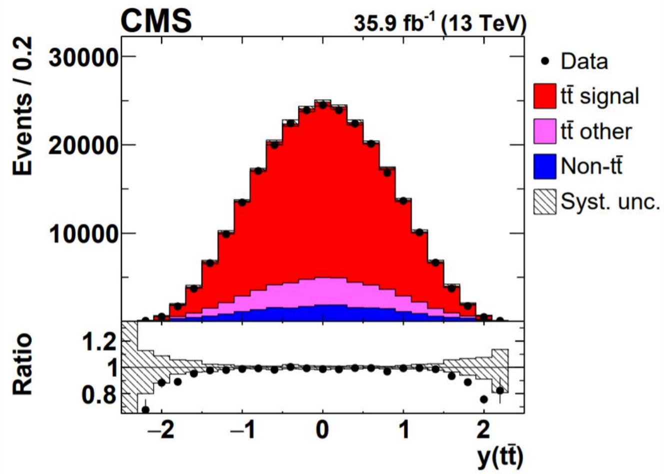
Dilepton channels: see BACKUP and Ref.:

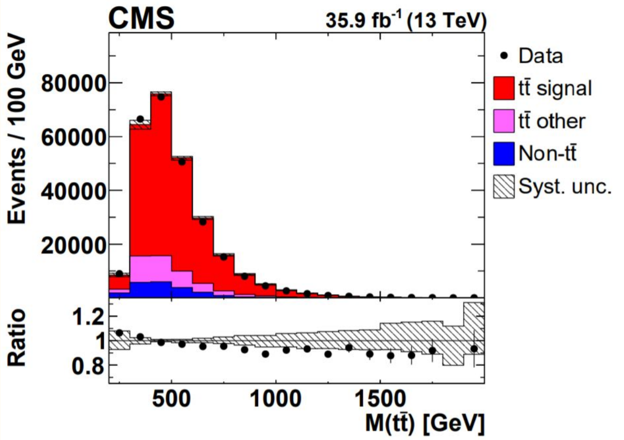
- PLB 761 (2016) 350
- Phys. Rev. D 96, 032002

Indirect: m_t^{pole} in dilepton events, CMS 13 TeV

measure σ_{tt} → sensitive to m_t^{pole}

- 2 isolated el/mu, opposite charge
- >=2 jets, >=1 b-tagged jet
- kinematic reconstruction:
  - invariant masses constraints imposed
  - toys with smeared momentum for each event to recover events with no solutions
  - toys weighted usign expected spectra
- modified algorithm for m_t^{pole} measurement
  - $\nu\nu$ reconstruction without imposing m_t as constraint



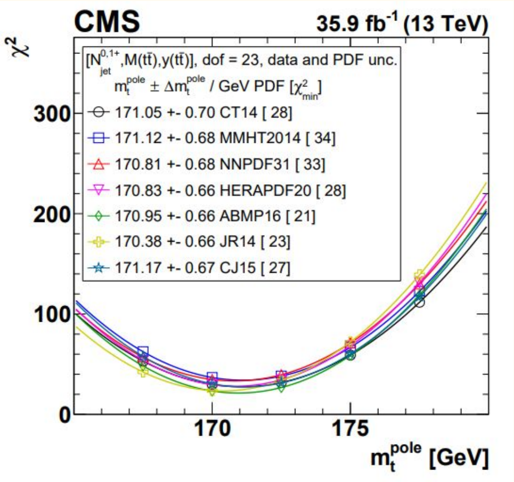


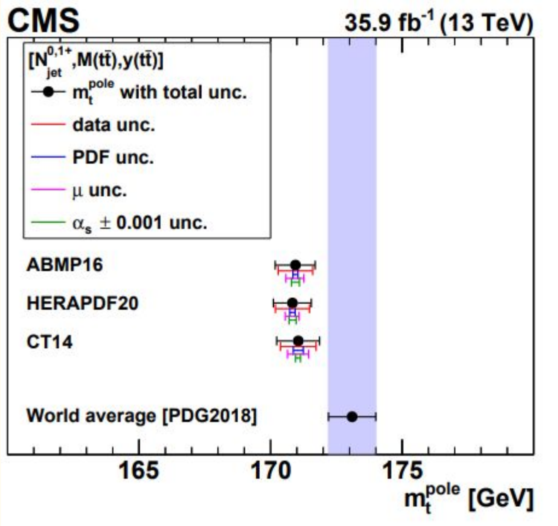
arXiv:1904.05237

<u>Indirect:</u> m_t^{pole} in dilepton events, CMS 13 TeV

arXiv:1904.05237

- measurement <u>unfolded</u> to parton-level <u>differential σ</u>
- α_s and m_t^{pole} from σ (N_{jets},M_{tt},y_{tt}) vs <u>fixed-order NLO calculations</u>
- m_t^{pole} measurement from χ^2 of pred. vs data for different hyp.
- JES is dominant exp. uncert.





Final measurement: simultaneous PDF, α_s, m_t^{pole} NLO fit including HERA DIS data

$$m_t^{pole} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3(\text{scale})\,\text{GeV} = 170.5 \pm 0.8(\text{total})\,\text{GeV}.$$

Indirect: m_t^{pole} in tt+1 jet, ATLAS 8 TeV

arXiv:1905.02302

- 1 isolated e/mu, >=5 jets, =2 b-tagged
- $p_T^{miss} \rightarrow p_T^{\nu}$, then m_W constraint imposed
- Ws and b-jets → top, $|m_t^{lep}-m_t^{had}|$ minimised
- leading jet not used for tops→ ISR candidate
- observable sensitive to m_t^{pole}:

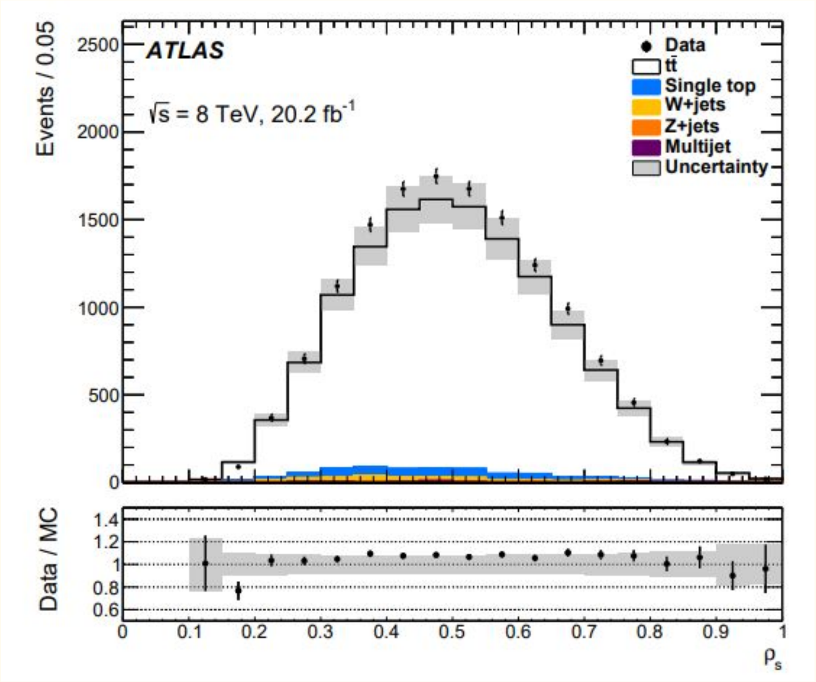
$$\mathcal{R}(m_t^{\rm pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}$$

with

$$\rho_s = 2m_0/m_{t\bar{t}+1\text{-jet}}$$

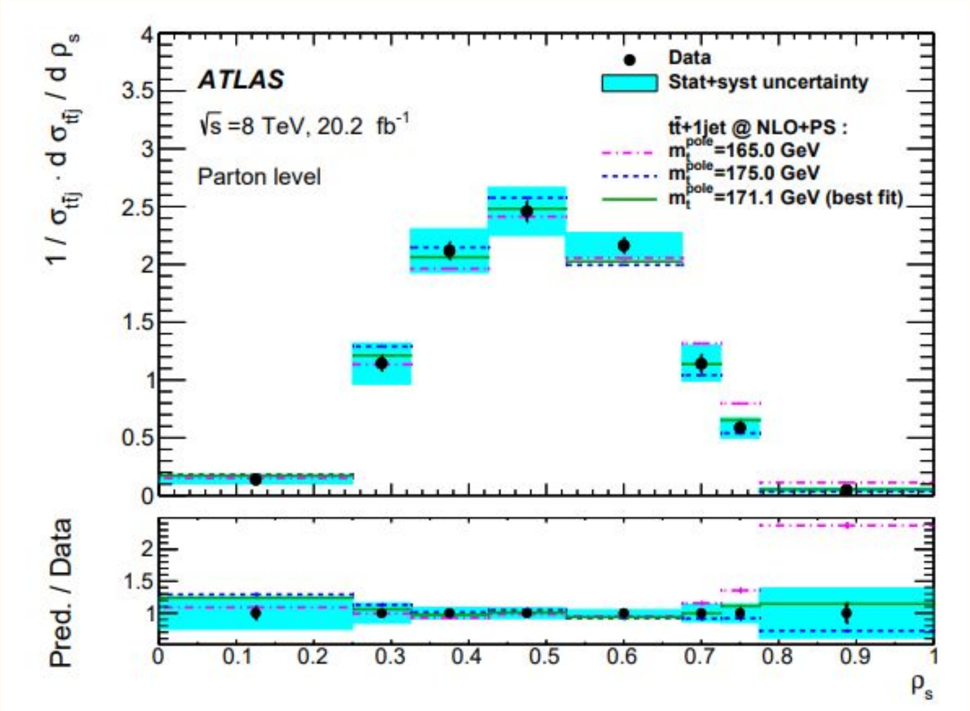
constant

invariant mass of tt+1 jet system



<u>Indirect:</u> m_t^{pole} in tt+1 jet, ATLAS 8 TeV

arXiv:1905.02302



- Data <u>unfolded</u> to parton level
- m_t^{pole} extracted with χ^2 minimization vs NLO+PS fixed order predictions
- Dominant <u>uncertainties</u>:
  - JES, JER
  - PS and hadronization
  - Color reconnection
  - Other modelling (e.g. UE)
  - Scale and PDF (theo)

$$m_t^{pole} = 171.1 \pm 0.4(\text{stat}) \pm 0.9(\text{syst}) \,^{+0.7}_{-0.3}(\text{theo})\ \text{GeV}$$

$\xrightarrow[\overline{\text{MS}}]{}$

$$m_t(m_t) = 162.9 \pm 0.5(\text{stat}) \pm 1.0(\text{syst}) \,^{+2.1}_{-1.2}(\text{theo})\ \text{GeV}$$

Direct/Indirect: CMS dilepton 13 Tev

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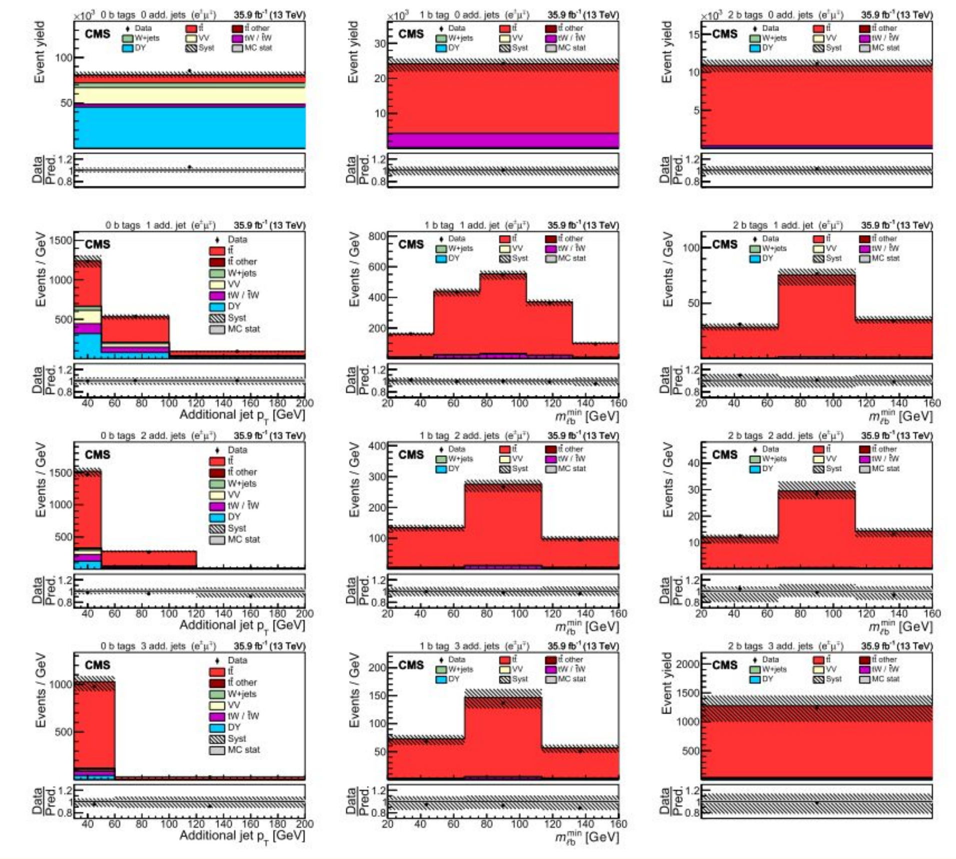
- eμ channel (opposite charge)
- 12 event categories in function of $N_{b\text{-jets}}$, $N_{nonb\text{-jets}}$
- $L(\sigma_{tt}, m_t^{MC})$ fit to observables (depending on region):
  - N_{events}
  - m_{lb}^{min} for >=1 b-jet
  - smallest non-bjet p_T
- results

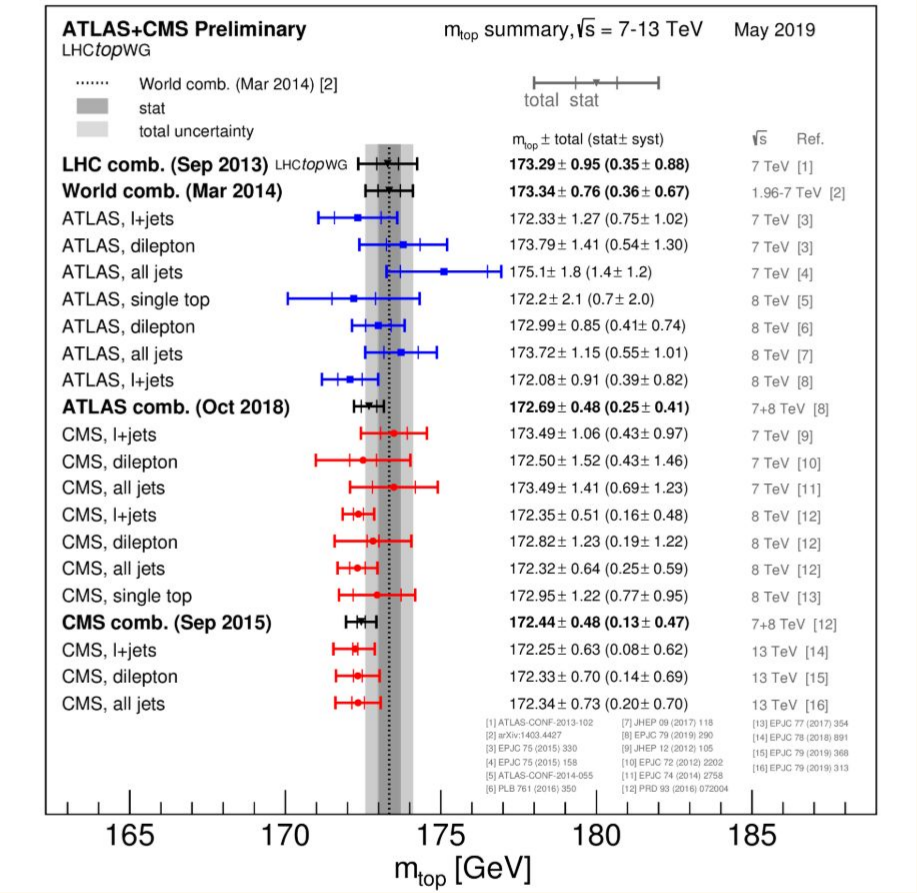
$$\sigma_{t\bar{t}} = 815 \pm 2\,(\text{stat}) \pm 29\,(\text{syst}) \pm 20\,(\text{lumi})\,\text{pb},$$
$$m_t^{MC} = 172.33 \pm 0.14\,(\text{stat})\,^{+0.66}_{-0.72}\,(\text{syst})\,\text{GeV}.$$

- dominant uncertainty: JES 0.57 GeV
- m_t^{pole} and m_t(MS-bar) are also measured



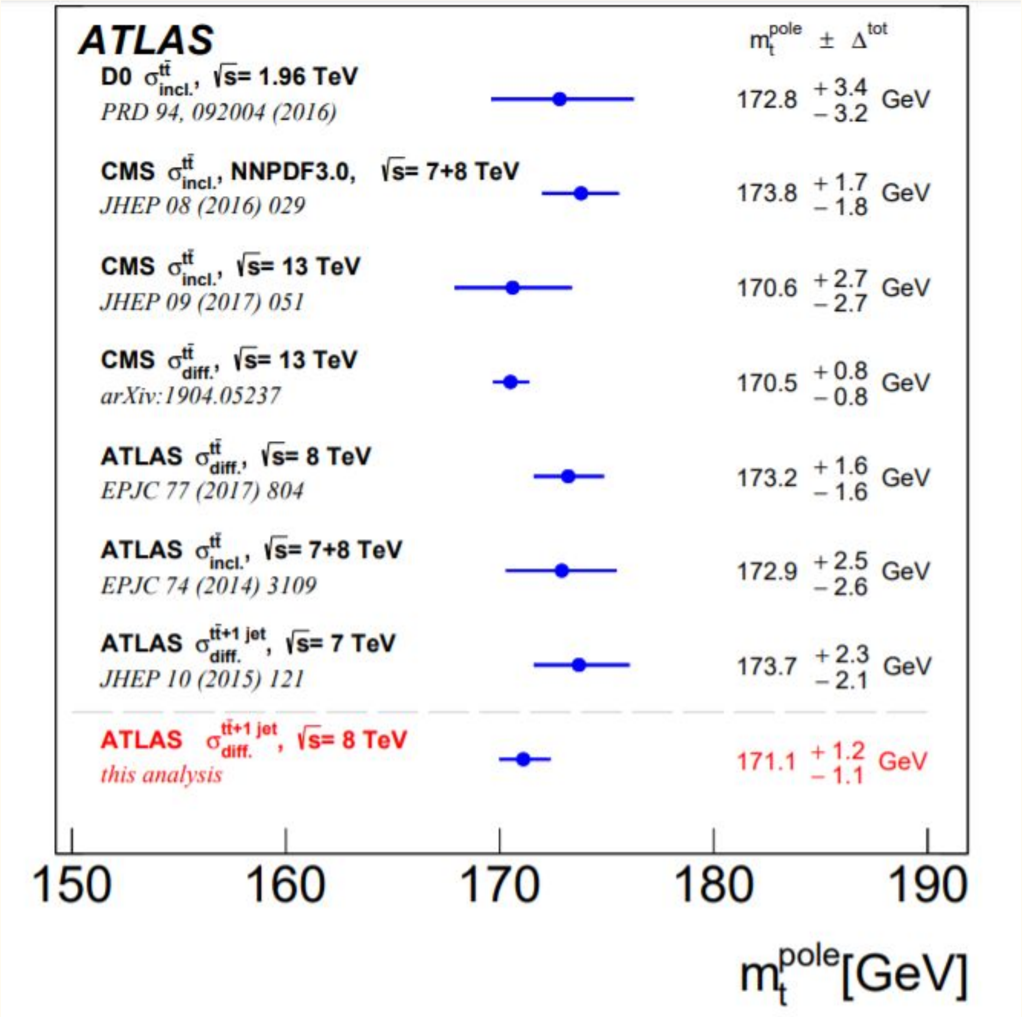
Conclusion

- Direct measurements <500 MeV uncertainty on m_t^{MC}
- Indirect measurements <1 GeV uncertainty on m_t^{pole}
- How to improve:
  - combining
  - jet uncertainties
  - tt MC modelling
- We need theory:
  - $m_t^{MC} \leftrightarrow m_t^{pole} \leftrightarrow m_t$(MS-bar)
    known up to 4-loops [1502.01030](1502.01030)
  - scale dependency of simulations/calculations
- Lots of data and new channels to explore
  - MC stat is also a challenge



summary of ATLAS and CMS direct measurements

BACKUP

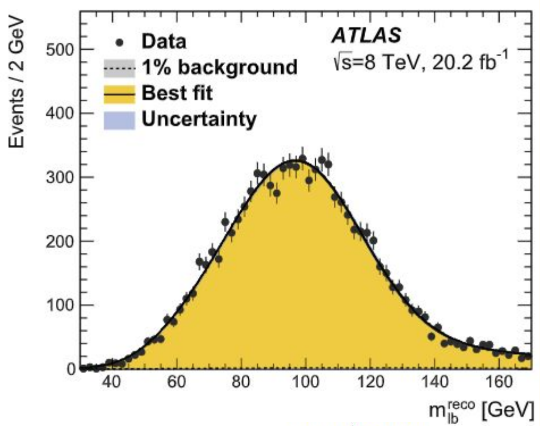


from
arXiv:1905.02302

Dilepton channel:

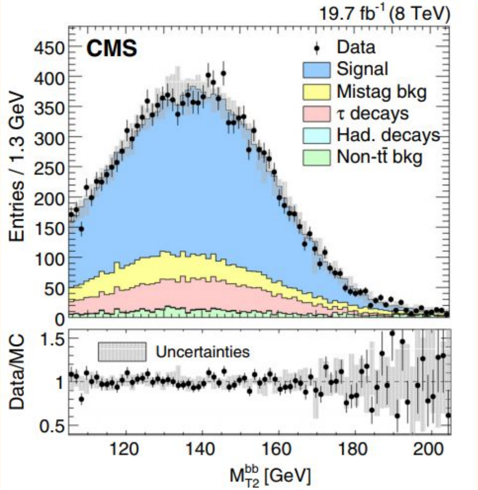
PLB 761 (2016) 350
Phys. Rev. D 96, 032002

- 8 TeV result from ATLAS $m_{top} = 172.99 \pm 0.41\,(\text{stat}) \pm 0.74\,(\text{syst})\,\text{GeV}$,
  - template fit to m_{lb}, dominant uncertainties:
    - hadronization modelling -> 0.22 GeV
    - ISR/FSR modelling -> 0.23 GeV
    - JES -> 0.54 GeV
    - b-JES -> 0.30 GeV



- 8 TeV result from CMS $172.22 \pm 0.18\,(\text{stat})\,^{+0.89}_{-0.93}\,(\text{syst})\,\text{GeV}$.
  - template fit to m_{lb} and M_{T2} (modified transverse mass)
  - 1D (JSF, correction to jet calibration, =1), 2D fit (m_t and JSF), hybrid (linear comibnation)
  - dominant uncertainties:
    - JES -> 0.46 GeV
    - b-fragmentation -> 0.40 GeV
    - top p_T -> 0.51 GeV
    - hard scattering scale -> 0.47 GeV
    - matching scale -> 0.31 GeV

some of these are very asymmetric up/down



ℓ+jets channel: ATLAS 8 TeV BDT

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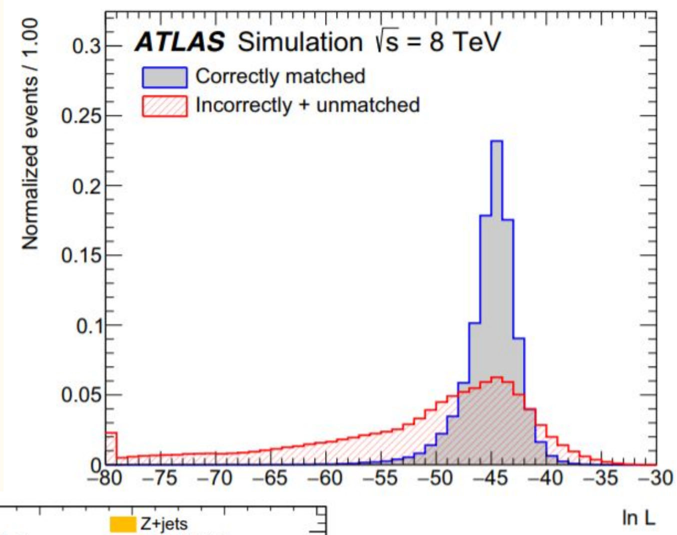
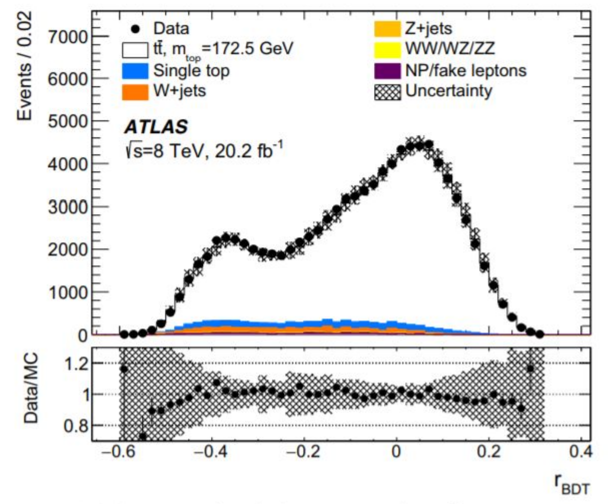
Table 2 The input variables to the BDT algorithm sorted by their separation

Separation (%)	Description
31	Logarithm of the event likelihood of the best permutation, ln L
13	ΔR of the two untagged jets q_1 and q_2 from the hadronically decaying W boson, $\Delta R(q, q)$
5.0	p_T of the hadronically decaying W boson
4.3	p_T of the hadronically decaying top quark
4.2	Relative event probability of the best permutation
2.0	p_T of the reconstructed $t\bar{t}$ system
1.7	p_T of the semi-leptonically decaying top quark
1.2	Transverse mass of the leptonically decaying W boson
0.3	p_T of the leptonically decaying W boson
0.3	Number of jets
0.2	ΔR of the reconstructed b-tagged jets
0.2	Missing transverse momentum
0.1	p_T of the lepton





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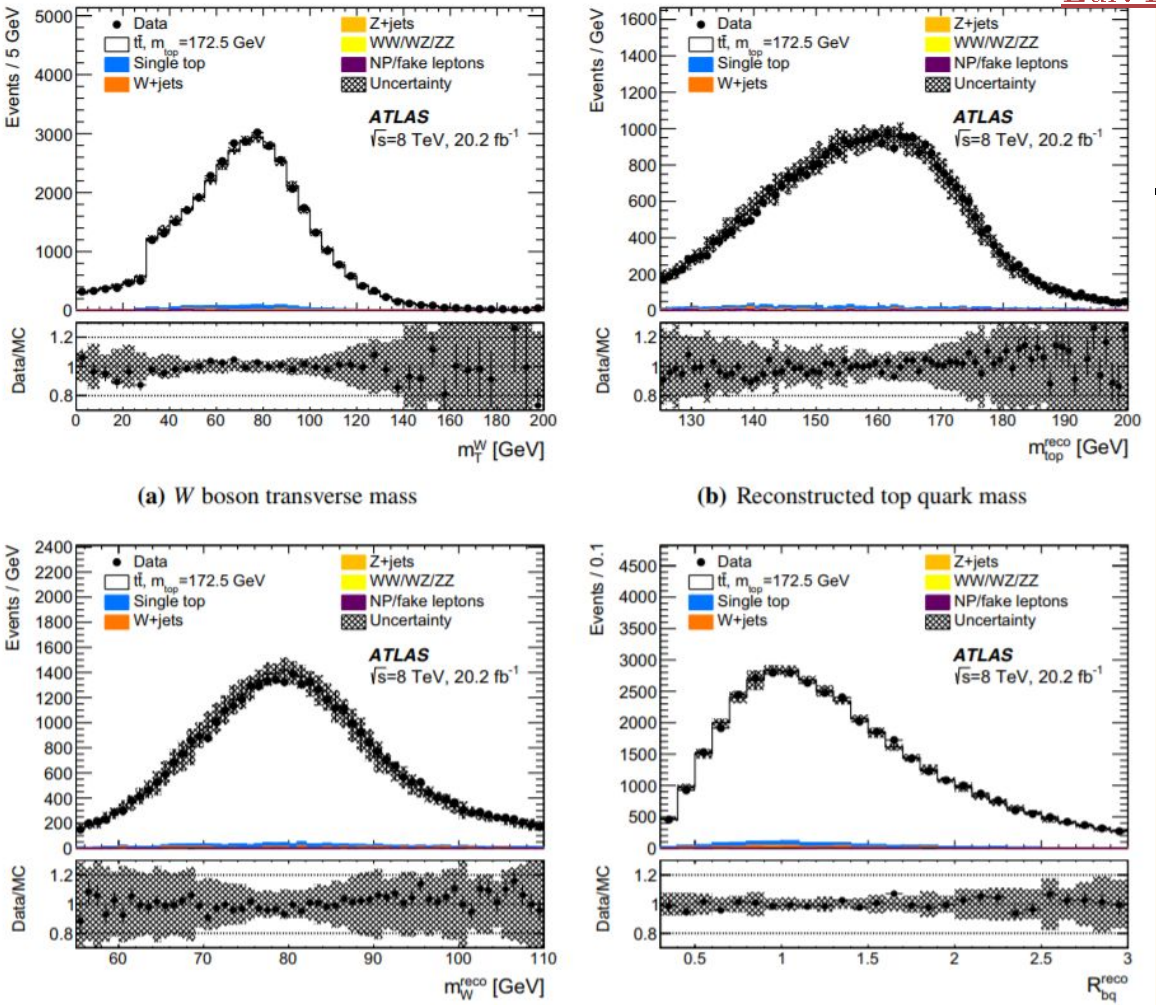
ℓ+jets channel: ATLAS 8 TeV



(a) W boson transverse mass

(b) Reconstructed top quark mass

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unbinned LH on i=1...N events

ℓ+jets channel: ATLAS 8 TeV fit

$$L^{\ell+\text{jets}}_{\text{shape}}(m_{\text{top}}, \text{JSF}, \text{bJSF}, f_{\text{bkg}}) = \prod_{i=1}^{N} P_{\text{top}}(m^{\text{reco},i}_{\text{top}} \mid m_{\text{top}}, \text{JSF}, \text{bJSF}, f_{\text{bkg}}) \times P_W(m^{\text{reco},i}_{W} \mid \text{JSF}, f_{\text{bkg}}) \times P_{R_{bq}}(R^{\text{reco},i}_{bq} \mid m_{\text{top}}, \text{JSF}, \text{bJSF}, f_{\text{bkg}}),$$

$$P_{\text{top}}(m^{\text{reco},i}_{\text{top}} \mid m_{\text{top}}, \text{JSF}, \text{bJSF}, f_{\text{bkg}}) = (1 - f_{\text{bkg}}) \cdot P^{\text{sig}}_{\text{top}}(m^{\text{reco},i}_{\text{top}} \mid m_{\text{top}}, \text{JSF}, \text{bJSF}) + f_{\text{bkg}} \cdot P^{\text{bkg}}_{\text{top}}(m^{\text{reco},i}_{\text{top}} \mid \text{JSF}, \text{bJSF}),$$

$$P_W(m^{\text{reco},i}_{W} \mid \text{JSF}, f_{\text{bkg}}) = (1 - f_{\text{bkg}}) \cdot P^{\text{sig}}_{W}(m^{\text{reco},i}_{W} \mid \text{JSF}) + f_{\text{bkg}} \cdot P^{\text{bkg}}_{W}(m^{\text{reco},i}_{W} \mid \text{JSF}), \quad \text{and}$$

$$P_{R_{bq}}(R^{\text{reco},i}_{bq} \mid m_{\text{top}}, \text{JSF}, \text{bJSF}, f_{\text{bkg}}) = (1 - f_{\text{bkg}}) \cdot P^{\text{sig}}_{R_{bq}}(R^{\text{reco},i}_{bq} \mid m_{\text{top}}, \text{JSF}, \text{bJSF}) + f_{\text{bkg}} \cdot P^{\text{bkg}}_{R_{bq}}(R^{\text{reco},i}_{bq} \mid \text{bJSF})$$

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ℓ+jets channel: ATLAS 8 TeV uncertainties

Event selection	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	
	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

ℓ+jets channel: CMS 13 TeV, ideogram method

$$\mathcal{L}(\text{sample}|m_t, \text{JSF}) = P(\text{JSF}) \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\text{gof}}(i) \times \left[\sum_j f_j \, P_j(m_{t,i}^{\text{fit}}|m_t, \text{JSF}) \, P_j(m_{W,i}^{\text{reco}}|m_t, \text{JSF}) \right] \right)^{w_{\text{evt}}}$$

i=i-th permutation in one event
j=correct permutation, uncorrect permutation, unmatched

- PDFs from samples with 7 different m_t and 5 different JSF values
- method bias estimated with pseudo-experiments and corrected

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	2D approach		1D approach	Hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
Experimental uncertainties					
Method calibration	0.05	< 0.1	0.05	0.05	< 0.1
JEC (quad. sum)	0.13	0.2	0.83	0.18	0.3
– InterCalibration	(− 0.02)	(< 0.1)	(+ 0.16)	(+ 0.04)	(< 0.1)
– MPFInSitu	(− 0.01)	(< 0.1)	(+ 0.23)	(+ 0.07)	(< 0.1)
– Uncorrelated	(− 0.13)	(+ 0.2)	(+ 0.78)	(+ 0.16)	(+ 0.3)
Jet energy resolution	− 0.20	+ 0.3	+ 0.09	− 0.12	+ 0.2
b tagging	+ 0.03	< 0.1	+ 0.01	+ 0.03	< 0.1
Pileup	− 0.08	+ 0.1	+ 0.02	− 0.05	+ 0.1
Non-$t\bar{t}$ background	+ 0.04	− 0.1	− 0.02	+ 0.02	− 0.1
Modeling uncertainties					
JEC Flavor (linear sum)	− 0.42	+ 0.1	− 0.31	− 0.39	< 0.1
– light quarks (uds)	(+ 0.10)	(− 0.1)	(− 0.01)	(+ 0.06)	(− 0.1)
– charm	(+ 0.02)	(< 0.1)	(− 0.01)	(+ 0.01)	(< 0.1)
– bottom	(− 0.32)	(< 0.1)	(− 0.31)	(− 0.32)	(< 0.1)
– gluon	(− 0.22)	(+ 0.3)	(+ 0.02)	(− 0.15)	(+ 0.2)
b jet modeling (quad. sum)	0.13	0.1	0.09	0.12	< 0.1
– b frag. Bowler–Lund	(− 0.07)	(+ 0.1)	(− 0.01)	(− 0.05)	(< 0.1)
– b frag. Peterson	(+ 0.04)	(< 0.1)	(+ 0.05)	(+ 0.04)	(< 0.1)
– semileptonic B decays	(+ 0.11)	(< 0.1)	(+ 0.08)	(+ 0.10)	(< 0.1)
PDF	0.02	< 0.1	0.02	0.02	< 0.1
Ren. and fact. scales	0.02	0.1	0.02	0.01	< 0.1
ME/PS matching	− 0.08 ± 0.09	+ 0.1	+ 0.03 ± 0.05	− 0.05 ± 0.07	+ 0.1
ME generator	+ 0.15 ± 0.23	+ 0.2	+ 0.32 ± 0.14	+ 0.20 ± 0.19	+ 0.1
ISR PS scale	+ 0.07 ± 0.09	+ 0.1	+ 0.10 ± 0.05	+ 0.06 ± 0.07	< 0.1
FSR PS scale	+ 0.24 ± 0.06	− 0.4	− 0.22 ± 0.04	+ 0.13 ± 0.05	− 0.3
Top quark p_T	+ 0.02	− 0.1	− 0.06	− 0.01	− 0.1
Underlying event	− 0.10 ± 0.08	+ 0.1	+ 0.01 ± 0.05	− 0.07 ± 0.07	+ 0.1
Early resonance decays	− 0.22 ± 0.09	+ 0.8	+ 0.42 ± 0.05	− 0.03 ± 0.07	+ 0.5
Color reconnection	+ 0.34 ± 0.09	− 0.1	+ 0.23 ± 0.06	+ 0.31 ± 0.08	− 0.1
Total systematic	**0.75**	**1.1**	**1.10**	**0.62**	**0.8**
Statistical (expected)	0.09	0.1	0.06	0.08	0.1
Total (expected)	**0.76**	**1.1**	**1.10**	**0.63**	**0.8**

ℓ+jets channel: CMS 13 TeV

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AllHad CMS 13 TeV: kinematic fit

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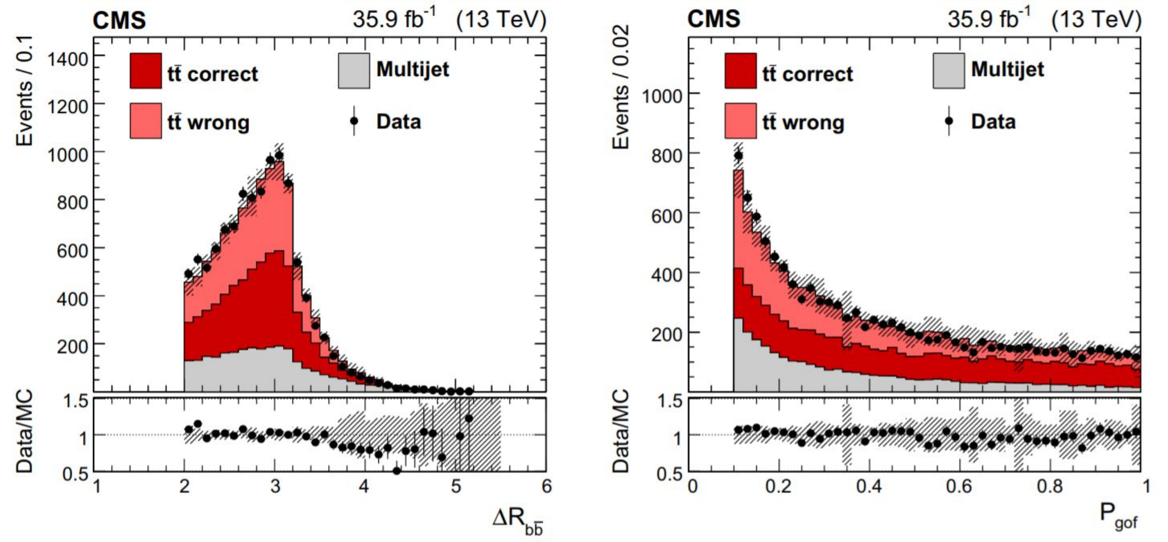
$$\chi^2 = \sum_{j \in \text{jets}} \left[\frac{\left(p_{\mathrm{T}}{}_j^{\text{reco}} - p_{\mathrm{T}}{}_j^{\text{fit}}\right)^2}{\sigma^2_{p_{\mathrm{T}\,j}}} + \frac{\left(\eta_j^{\text{reco}} - \eta_j^{\text{fit}}\right)^2}{\sigma^2_{\eta_j}} + \frac{\left(\phi_j^{\text{reco}} - \phi_j^{\text{fit}}\right)^2}{\sigma^2_{\phi_j}} \right]$$

$$P_{\text{gof}} \equiv 1 - \text{erf}\left(\sqrt{\frac{\chi^2}{2}}\right) + \sqrt{\frac{2\chi^2}{\pi}} e^{-\chi^2/2}$$

- all parton-jets assignments tested
- only b-jets used as candidate for b-quarks
- equivalent choices not considered separately
- only permutation with best □^{2} kept
- $P_{gof} > 0.1$ required



AllHad CMS 13 TeV: ideogram method

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$$\mathcal{L}(m_t, \mathrm{JSF}) = P(\mathrm{sample}|m_t, \mathrm{JSF}) = \prod_{\mathrm{events}} P(\mathrm{event}|m_t, \mathrm{JSF}) = \prod_{\mathrm{events}} P\left(m_t^{\mathrm{fit}}, m_W^{\mathrm{reco}}|m_t, \mathrm{JSF}\right)$$

multiplied by P(JSF) prior where appropriate

$$P\left(m_t^{\mathrm{fit}}, m_W^{\mathrm{reco}}|m_t, \mathrm{JSF}\right) = f_{\mathrm{sig}} P\left(m_t^{\mathrm{fit}}, m_W^{\mathrm{reco}}|m_t, \mathrm{JSF}\right) + (1 - f_{\mathrm{sig}}) P_{\mathrm{bkg}}\left(m_t^{\mathrm{fit}}, m_W^{\mathrm{reco}}\right) = f_{\mathrm{sig}} \sum_j f_j P_j\left(m_t^{\mathrm{fit}}|m_t, \mathrm{JSF}\right) P_j\left(m_W^{\mathrm{reco}}|m_t, \mathrm{JSF}\right) + (1 - f_{\mathrm{sig}}) P_{\mathrm{bkg}}\left(m_t^{\mathrm{fit}}\right) P_{\mathrm{bkg}}\left(m_W^{\mathrm{reco}}\right),$$

j=correct,wrong

- signal PDF from analytic functions, parameters from simultaneous fit to samples with 7 different m_t and 5 different input JSF
- bkg shape from spline interpolation as a function of m_t^{fit} and m_W^{reco}, but independent from m_t and JSF
- signal fraction and correct perm. fraction are free parameters
- for hybrid method, width of gaussian prior on JSF optimised to minimize uncertainty

AllHad CMS 13 TeV: ideogram method

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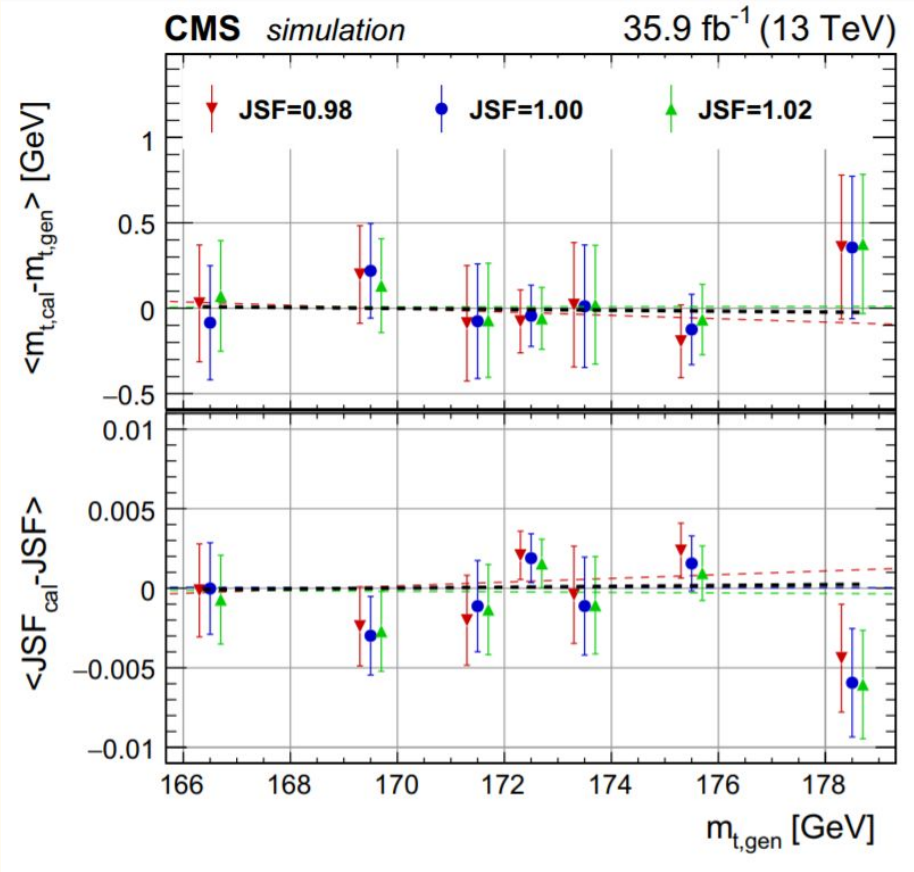

	2D		1D	Hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
Experimental uncertainties					
Method calibration	0.06	0.2	0.06	0.06	0.2
JEC (quad. sum)	0.18	0.3	0.73	0.15	0.2
Intercalibration	−0.04	−0.1	+0.12	−0.04	−0.1
MPFInSitu	−0.03	0.0	+0.22	+0.08	+0.1
Uncorrelated	−0.17	−0.3	+0.69	+0.12	+0.2
Jet energy resolution	−0.09	+0.2	+0.09	−0.04	+0.1
b tagging	0.02	0.0	0.01	0.02	0.0
Pileup	−0.06	+0.1	0.00	−0.04	+0.1
Background	0.10	0.1	0.03	0.07	0.1
Trigger	+0.04	−0.1	−0.04	+0.02	−0.1
Modeling uncertainties					
JEC flavor (linear sum)	−0.35	+0.1	−0.31	−0.34	0.0
Light quarks (uds)	+0.10	−0.1	−0.01	+0.07	−0.1
Charm	+0.03	0.0	−0.01	+0.02	0.0
Bottom	−0.29	0.0	−0.29	−0.29	0.0
Gluon	−0.19	+0.2	+0.03	−0.13	+0.2
b jet modeling (quad. sum)	0.09	0.0	0.09	0.09	0.0
b frag. Bowler–Lund	−0.07	0.0	−0.07	−0.07	0.0
b frag. Peterson	−0.05	0.0	−0.04	−0.05	0.0
Semileptonic b hadron decays	−0.03	0.0	−0.03	−0.03	0.0
PDF	0.01	0.0	0.01	0.01	0.0
Ren. and fact. scales	0.05	0.0	0.04	0.04	0.0
ME/PS matching	+0.32 ± 0.20	−0.3	−0.05 ± 0.14	+0.24 ± 0.18	−0.2
ISR PS scale	+0.17 ± 0.17	−0.2	+0.13 ± 0.12	+0.12 ± 0.14	−0.1
FSR PS scale	+0.22 ± 0.12	−0.2	+0.11 ± 0.08	+0.18 ± 0.11	−0.1
Top quark p_T	+0.03	0.0	+0.02	+0.03	0.0
Underlying event	+0.16 ± 0.19	−0.3	−0.07 ± 0.14	+0.10 ± 0.17	−0.2
Early resonance decays	+0.02 ± 0.28	+0.4	+0.38 ± 0.19	+0.13 ± 0.24	+0.3
CR modeling (max. shift)	+0.41 ± 0.29	−0.4	−0.43 ± 0.20	−0.36 ± 0.25	−0.3
"gluon move" (ERD on)	+0.41 ± 0.29	−0.4	+0.10 ± 0.20	+0.32 ± 0.25	−0.3
"QCD inspired" (ERD on)	−0.32 ± 0.29	−0.1	−0.43 ± 0.20	−0.36 ± 0.25	−0.1
Total systematic	0.81	0.9	1.03	0.70	0.7
Statistical (expected)	0.21	0.2	0.16	0.20	0.1
Total (expected)	0.83	0.9	1.04	0.72	0.7

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AllHad CMS 13 TeV

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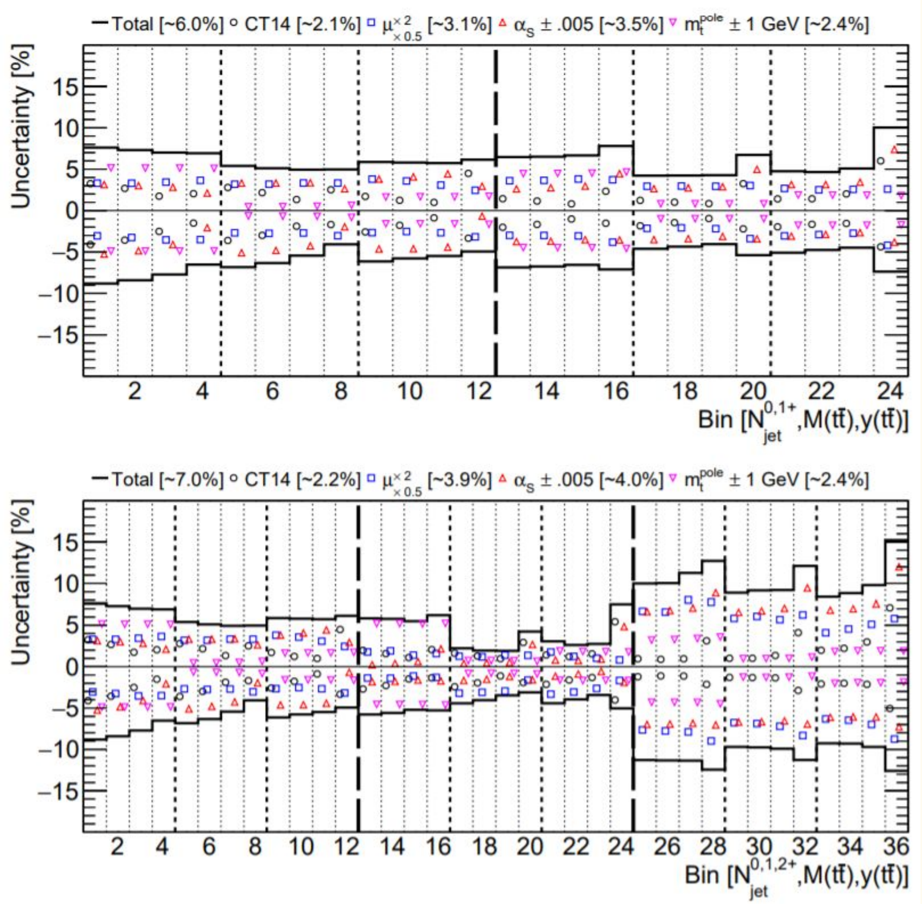
AllHad/l+jets CMS 13 TeV

	δm_t^{hyb} [GeV]		
	All-jets	ℓ+jets	Combination
Experimental uncertainties			
Method calibration	0.06	0.05	0.03
JEC (quad. sum)	0.15	0.18	0.17
Intercalibration	−0.04	+0.04	+0.04
MPFInSitu	+0.08	+0.07	+0.07
Uncorrelated	+0.12	+0.16	+0.15
Jet energy resolution	−0.04	−0.12	−0.10
b tagging	0.02	0.03	0.02
Pileup	−0.04	−0.05	−0.05
All-jets background	0.07	–	0.01
All-jets trigger	+0.02	–	+0.01
ℓ+jets background	–	+0.02	−0.01
Modeling uncertainties			
JEC flavor (linear sum)	−0.34	−0.39	−0.37
light quarks (uds)	+0.07	+0.06	+0.07
charm	+0.02	+0.01	+0.02
bottom	−0.29	−0.32	−0.31
gluon	−0.13	−0.15	−0.15
b jet modeling (quad. sum)	0.09	0.12	0.06
b frag. Bowler–Lund	−0.07	−0.05	−0.05
b frag. Peterson	−0.05	+0.04	−0.02
semileptonic b hadron decays	−0.03	+0.10	−0.04
PDF	0.01	0.02	0.01
Ren. and fact. scales	0.04	0.01	0.01
ME/PS matching	+0.24	−0.07	+0.07
ME generator	–	+0.20	+0.21
ISR PS scale	+0.14	+0.07	+0.07
FSR PS scale	+0.18	+0.13	+0.12
Top quark p_T	+0.03	−0.01	−0.01
Underlying event	+0.17	−0.07	−0.06
Early resonance decays	+0.24	−0.07	−0.07
CR modeling (max. shift)	−0.36	+0.31	+0.33
"gluon move" (ERD on)	+0.32	+0.31	+0.33
"QCD inspired" (ERD on)	−0.36	−0.13	−0.14
Total systematic	0.70	0.62	0.61
Statistical (expected)	0.20	0.08	0.07
Total (expected)	0.72	0.63	0.61

Indirect: m_t^{pole} in dilepton events, CMS 13 TeV



arXiv:1904.05237

Indirect: m_t^{pole} in dilepton events, CMS 13 TeV

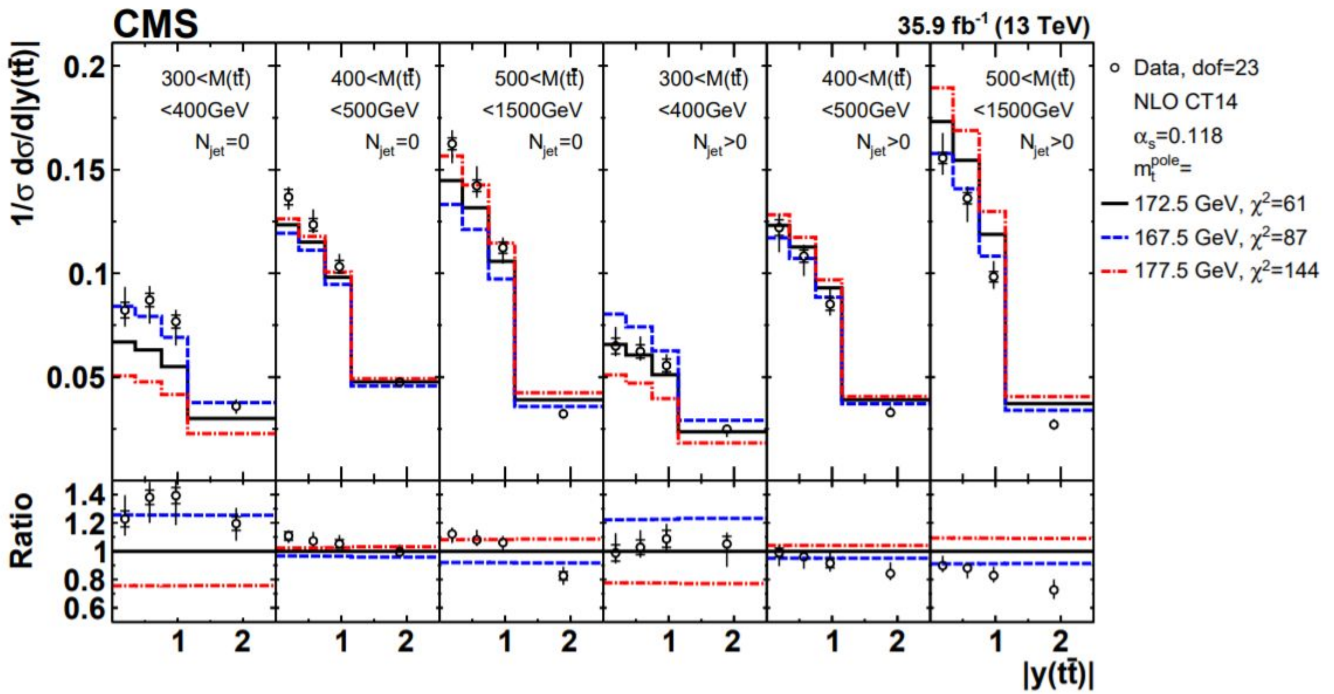


Figure 16: Comparison of the measured $[N_{jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$ cross sections to NLO predictions obtained using different m_t^{pole} values (further details can be found in Fig. 3). For each theoretical prediction, values of χ^2 and dof for the comparison to the data are reported.

arXiv:1904.05237

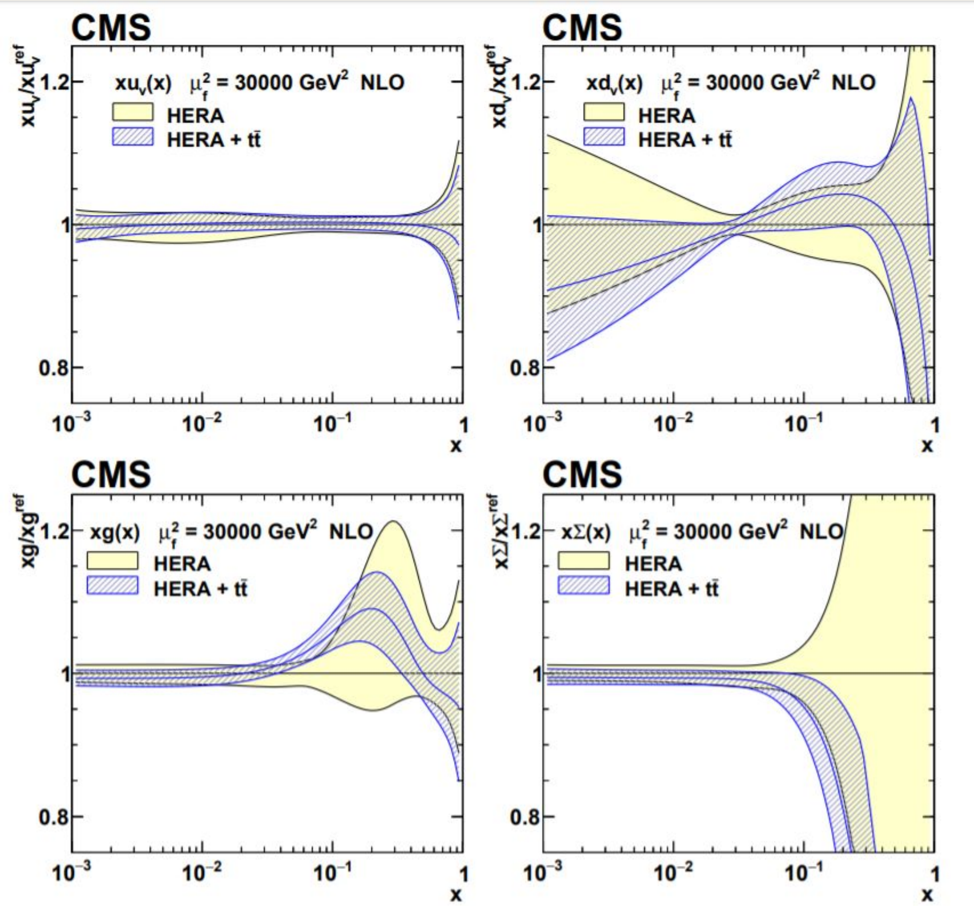
Indirect: m_t^{pole} in dilepton events, CMS 13 TeV

Table 2: The individual contributions to the uncertainties for the $\alpha_S(m_Z)$ and m_t^{pole} determination.

Parameter	Variation	$\alpha_S(m_Z)$	m_t^{pole} [GeV]
	Fit uncertainty		
Total	$\Delta\chi^2 = 1$	± 0.0016	± 0.7
	Model uncertainty		
f_s	$f_s = 0.5$	$+0.0001$	0.0
f_s	$f_s = 0.3$	0.0000	0.0
Q^2_{min}	$Q^2_{min} = 5.0\,GeV^2$	$+0.0002$	$+0.1$
Q^2_{min}	$Q^2_{min} = 2.5\,GeV^2$	-0.0004	-0.1
M_c	$M_c = 1.49\,GeV$	$+0.0001$	0.0
M_c	$M_c = 1.37\,GeV$	0.0000	0.0
Total		$^{+0.0002}_{-0.0004}$	$^{+0.1}_{-0.1}$
	PDF parametrisation uncertainty		
$\mu^2_{f,0}$	$\mu^2_{f,0} = 2.2\,GeV^2$	-0.0001	0.0
$\mu^2_{f,0}$	$\mu^2_{f,0} = 1.6\,GeV^2$	$+0.0002$	0.0
A'_g	set to 0	$+0.0002$	-0.1
E_g	set to 0	$+0.0008$	0.0
Total		$^{+0.0008}_{-0.0001}$	-0.1
	Scale uncertainty		
μ_r variation	$\mu_r = H$	$+0.0004$	-0.2
μ_r variation	$\mu_r = H/4$	$+0.0007$	$+0.1$
μ_f variation	$\mu_f = H$	-0.0002	$+0.3$
μ_f variation	$\mu_f = H/4$	$+0.0001$	-0.3
$\mu_{r,f}$ variation	$\mu_{r,f} = H$	$+0.0004$	$+0.1$
$\mu_{r,f}$ variation	$\mu_{r,f} = H/4$	$+0.0011$	-0.2
alternative $\mu_{r,f}$	$\mu_{r,f} = H/2$	-0.0005	$+0.1$
Total		$^{+0.0011}_{-0.0005}$	$^{+0.3}_{-0.3}$

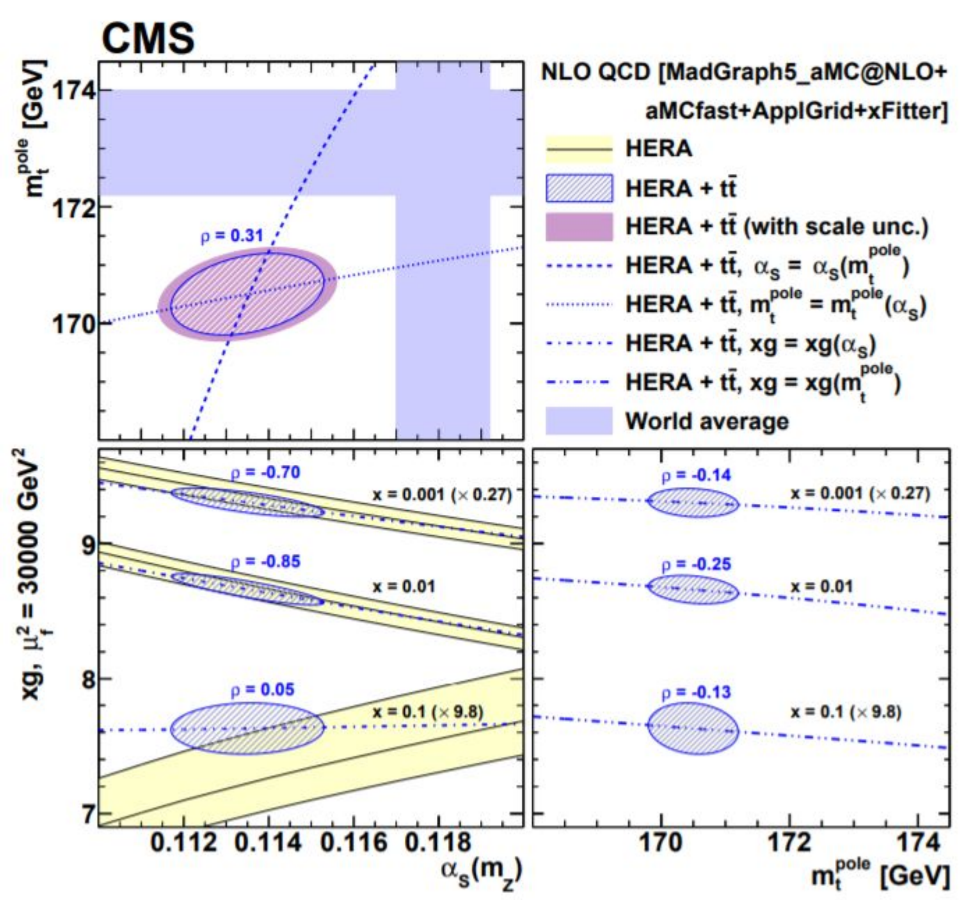
arXiv:1904.05237

Indirect: m_t^{pole} in dilepton events, CMS 13 TeV



[arXiv:1904.05237](https://arxiv.org/abs/1904.05237)

Indirect: m_t^{pole} in dilepton events, CMS 13 TeV



arXiv:1904.05237

Indirect: m_t^{pole} in tt+1 jet, ATLAS 8 TeV

arXiv:1905.02302

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)**

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

i,j=bins

Direct/Indirect: CMS dilepton 13 Tev

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Source	Uncertainty (%)
Trigger	0.4
Lepton ident./isolation	2.2
Muon momentum scale	0.2
Electron momentum scale	0.2
Jet energy scale	0.7
Jet energy resolution	0.5
b tagging	0.3
Pileup	0.3
$t\bar{t}$ ME scale	0.5
tW ME scale	0.7
DY ME scale	0.2
NLO generator	1.2
PDF	1.1
m_t^{MC}	0.4
Top quark p_T	0.5
ME/PS matching	0.2
UE tune	0.3
$t\bar{t}$ ISR scale	0.4
tW ISR scale	0.4
$t\bar{t}$ FSR scale	1.1
tW FSR scale	0.2
b quark fragmentation	1.0
b hadron BF	0.2
Colour reconnection	0.4
DY background	0.8
tW background	1.1
Diboson background	0.3
W+jets background	0.3
$t\bar{t}$ background	0.2
Statistical	0.2
Integrated luminosity	2.5
MC statistical	1.2
Total $\sigma_{t\bar{t}}^{vis}$ uncertainty	4.2
Extrapolation uncertainties	
$t\bar{t}$ ME scale	$\mp^{0.4}_{<0.1}$
PDF	$\pm^{0.8}_{0.6}$
Top quark p_T	$\pm^{0.2}_{0.3}$
$t\bar{t}$ ISR scale	$\mp^{0.2}_{<0.1}$
$t\bar{t}$ FSR scale	± 0.1
UE tune	<0.1
m_t^{MC}	$\mp^{0.2}_{0.3}$
Total $\sigma_{t\bar{t}}$ uncertainty	$^{+4.3}_{-4.2}$

Source	Uncertainty (GeV)
Trigger	0.02
Lepton ident./isolation	0.02
Muon momentum scale	0.03
Electron momentum scale	0.10
Jet energy scale	0.57
Jet energy resolution	0.09
b tagging	0.12
Pileup	0.09
$t\bar{t}$ ME scale	0.18
tW ME scale	0.02
DY ME scale	0.06
NLO generator	0.14
PDF	0.05
$\sigma_{t\bar{t}}$	0.09
Top quark p_T	0.04
ME/PS matching	0.16
UE tune	0.03
$t\bar{t}$ ISR scale	0.16
tW ISR scale	0.02
$t\bar{t}$ FSR scale	0.07
tW FSR scale	0.02
b quark fragmentation	0.11
b hadron BF	0.07
Colour reconnection	0.17
DY background	0.24
tW background	0.13
Diboson background	0.02
W+jets background	0.04
$t\bar{t}$ background	0.02
Statistical	0.14
MC statistical	0.36
Total m_t^{MC} uncertainty	$^{+0.68}_{-0.73}$

Direct/Indirect: CMS dilepton 13 Tev

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Table 6 Values of $m_t(m_t)$ obtained from the comparison of the $\sigma_{t\bar{t}}$ measurement with the NNLO predictions using different PDF sets. The first uncertainty shown comes from the experimental, PDF, and $\alpha_S(m_Z)$ uncertainties, and the second from the variation in the renormalization and factorization scales

PDF set	$m_t(m_t)$ (GeV)
ABMP16	161.6 ± 1.6 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
NNPDF3.1	164.5 ± 1.6 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
CT14	165.0 ± 1.8 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
MMHT14	164.9 ± 1.8 (fit + PDF + α_S) $^{+0.1}_{-1.1}$ (scale)

Table 7 Values of m_t^{pole} obtained by comparing the $\sigma_{t\bar{t}}$ measurement with predictions at NNLO+NNLL using different PDF sets

PDF set	m_t^{pole} (GeV)
ABMP16	169.9 ± 1.8 (fit + PDF + α_S) $^{+0.8}_{-1.2}$ (scale)
NNPDF3.1	173.2 ± 1.9 (fit + PDF + α_S) $^{+0.9}_{-1.3}$ (scale)
CT14	173.7 ± 2.0 (fit + PDF + α_S) $^{+0.9}_{-1.4}$ (scale)
MMHT14	173.6 ± 1.9 (fit + PDF + α_S) $^{+0.9}_{-1.4}$ (scale)