TOP QUARK PHYSICS AT THE LHC:
TOP QUARK MASS

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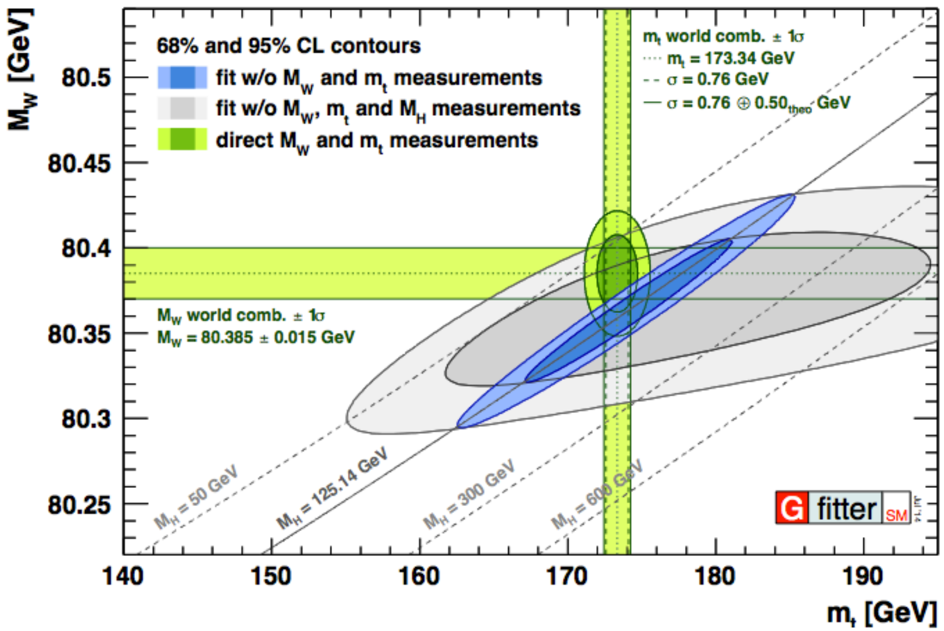
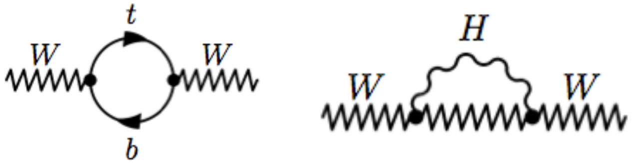
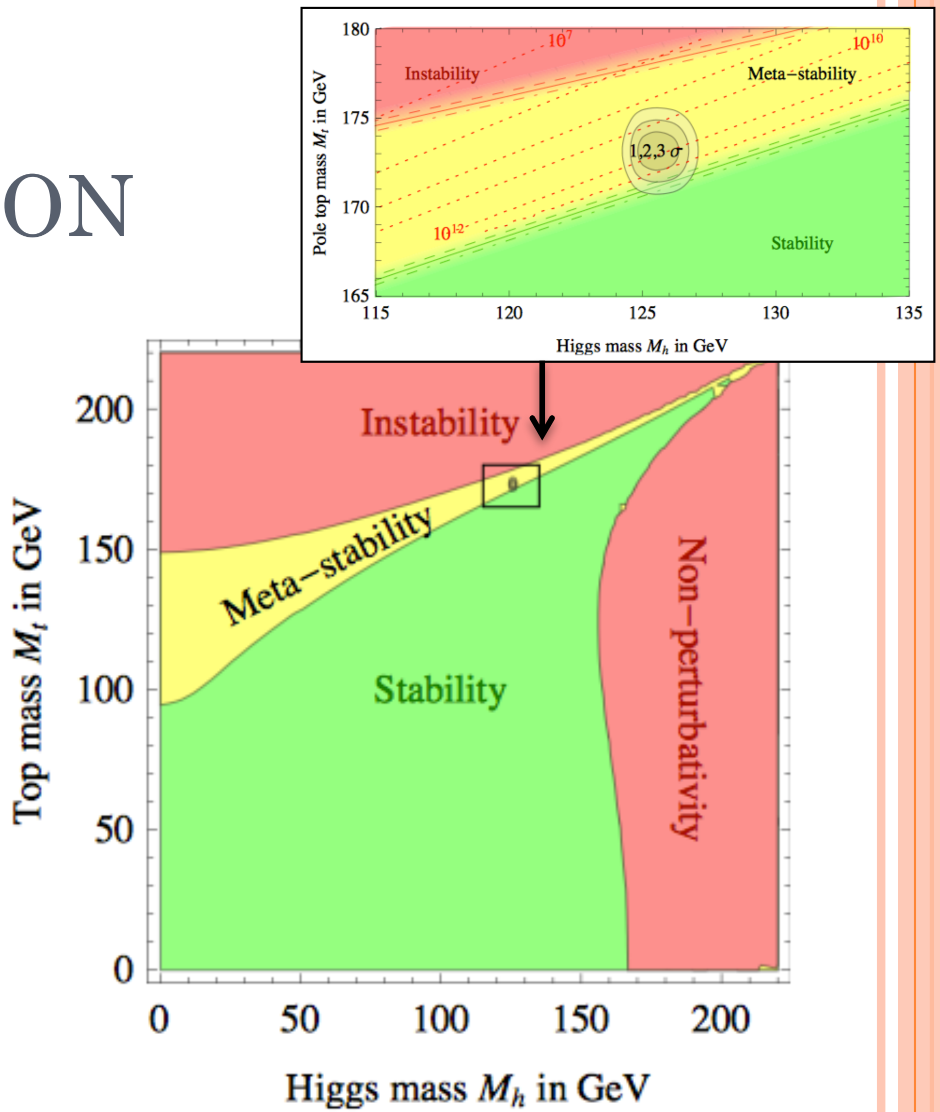
TOP MASS - MOTIVATION





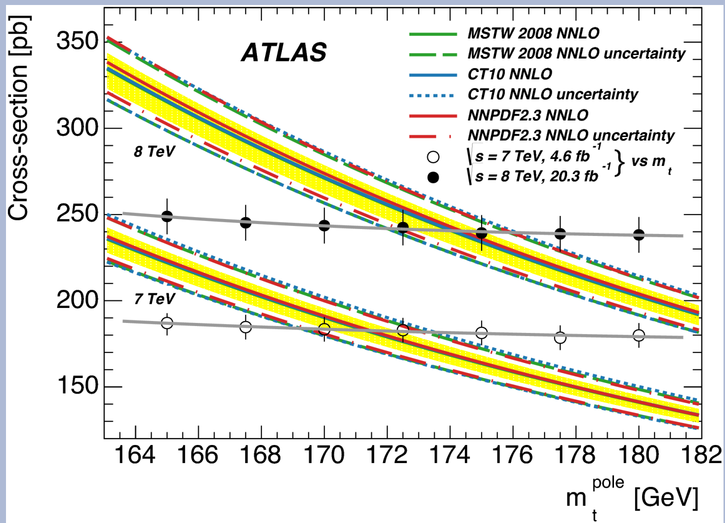


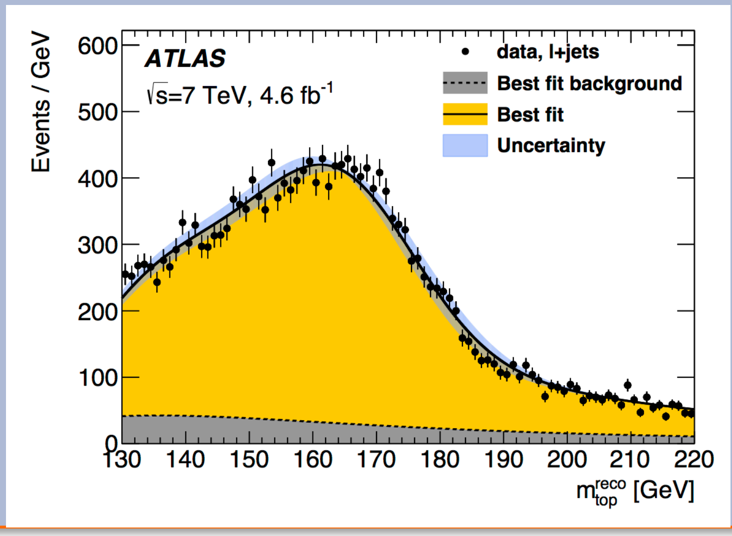
We can test the self consistency of the SM using the top mass and other inputs.

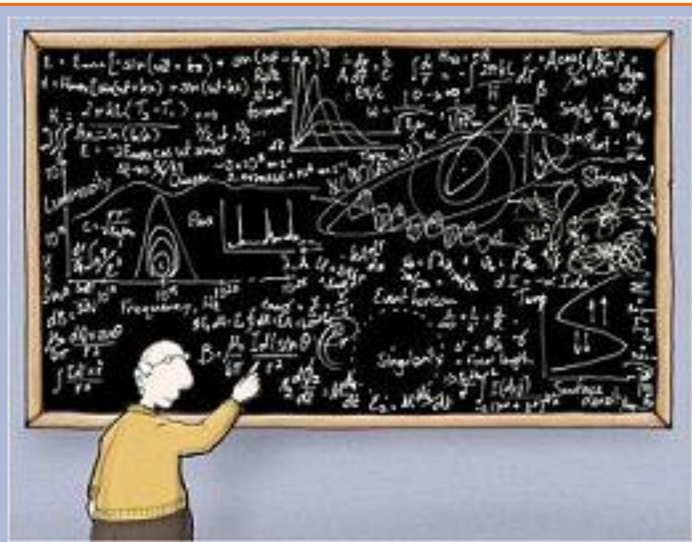
Knowing the top mass might just reveal the fate of our universe.

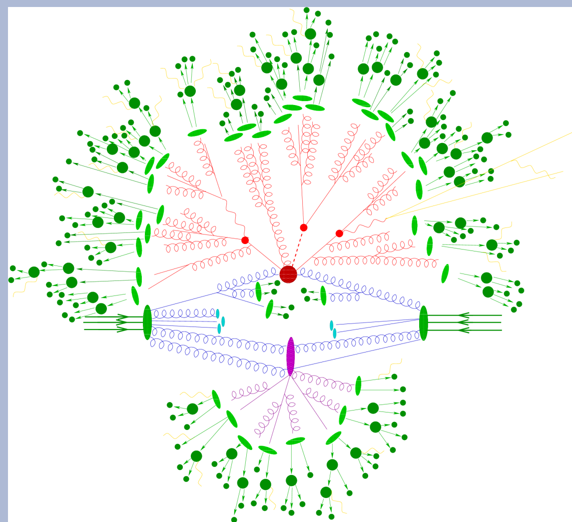
HOW CAN WE MEASURE IT?

- Comparing an experimental result with a theory prediction





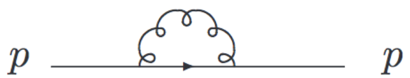




The extracted mass in the one used in the theory prediction.

TOP MASS IN QCD PERTURBATIVE PREDICTIONS

Top-quark mass definitions - Subtraction of the UV divergences in the self energy $\Sigma(p)$



Renormalized propagator: $d = 4 - 2\epsilon$

$$S(p) = -\frac{i}{\not{p} - m_t^0 + \Sigma^R(p, m_t^0, \mu)}$$

$$\Sigma^R \sim \left[\frac{1}{\epsilon} - \gamma + \ln 4\pi + A(m_t^0, p, \mu)\right] \not{p} - \left[4\left(\frac{1}{\epsilon} - \gamma + \ln 4\pi\right) + B(m_t^0, p, \mu)\right] m_t^0 + (Z_2 - 1)\not{p} - (Z_2 Z_m - 1) m$$

On-shell renormalization (pole mass): $\Sigma^R(p) = 0$, $(\partial \Sigma^R / \partial \not{p}) = 0$ for $\not{p} = m$

$\overline{\mathrm{MS}}$ renormalization: counterterm to subtract $(1/\epsilon + \gamma_E - \ln 4\pi)$

$$S^R_{o.s.}(p) \sim \frac{i}{\not{p} - m_{\mathrm{pole}}} \quad ; \quad S^R_{\overline{\mathrm{MS}}} \sim \frac{i}{\not{p} - m_{\overline{\mathrm{MS}}} - (A - B) m_{\overline{\mathrm{MS}}}}$$

MSR masses in terms of an infrared scale R, e.g. μ_F, $\bar{m}(\mu)$, etc., in SCET (A.Hoang et al)

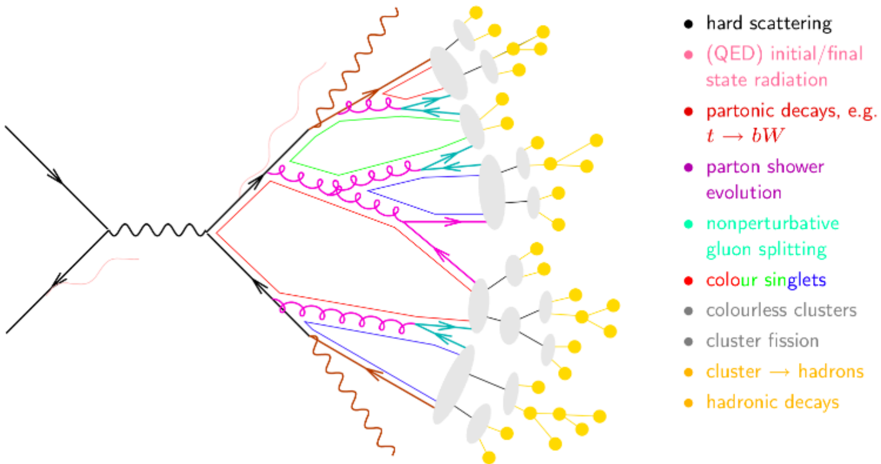
$$m^{\mathrm{MSR}}(R) = m^{\mathrm{pole}} - \Sigma^{\mathrm{fin}}(R, \mu) \quad \text{for} \quad R < m$$

$m_t^{\mathrm{MSR}}(R) \to m_{\mathrm{pole}}$ for $R \to 0$; $m^{\mathrm{MSR}}(R) \to \bar{m}_t(\bar{m}_t)$ for $R \to \bar{m}_t(\bar{m}_t)$

$$\frac{dm_{\mathrm{pole}}}{d\ln \mu} = 0 \Rightarrow \frac{dm^{\mathrm{MSR}}(R, \mu)}{d\ln \mu} = -R\gamma[\alpha_S(\mu)]$$

Slide from G. Corcella

MONTE CARLO TOP QUARK MASS



Slide from A. Hoang

1) Matrix elements (LO/NLO)
2) Parton shower (LL)
3) Hadronization model

- Full simulation of all processes (all experimental aspects accessible)
- QCD-inspired: partly first principles QCD ⇔ partly model
- Description power of data better than intrinsic theory accuracy.
- Top quark in parton shower: treated like a real particle ($m_t^{MC} \approx m_t^{pole}$ +?).
- Top quark in matrix elements: $m_t^{MC} = m_t^{pole}$

But pole mass ambiguous by $O(\Lambda_{QCD})$ due to confinement.
Short mass definition more suitable.

What is the meaning of the MC QCD parameters? → Need calibration.

MONTE CARLO TOP QUARK MASS

- Different approaches are being followed by theorists to calibrate de Monte Carlo top quark mass of a given generator (i.e. to relate it precisely with a theoretically well defined mass).
- The relation may also depend on the MC tuning and the set of observables used in the analysis.

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{MSR}}(R = 1\ \mathrm{GeV}) + \Delta_{t,\mathrm{MC}}(R = 1\ \mathrm{GeV})$$

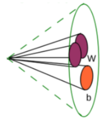
$$\Delta_{t,\mathrm{MC}}(1\ \mathrm{GeV}) = \bar{\Delta} + \boxed{\delta\Delta_{\mathrm{MC}} + \delta\Delta_{\mathrm{pQCD}} + \delta\Delta_{\mathrm{param}}}$$

- This is a challenging and active topic within theory community. See EPS 2017 talk from G.Corcella: https://indico.cern.ch/event/466934/contributions/2575362/attachments/1489674/2315013/corcella_eps_top.pdf
- Will show as an example the method of M.Butenshoen et al., Phys.Rev.Lett. 117 (2016) no.23, 232001.

MC TOP MASS CALIBRATION

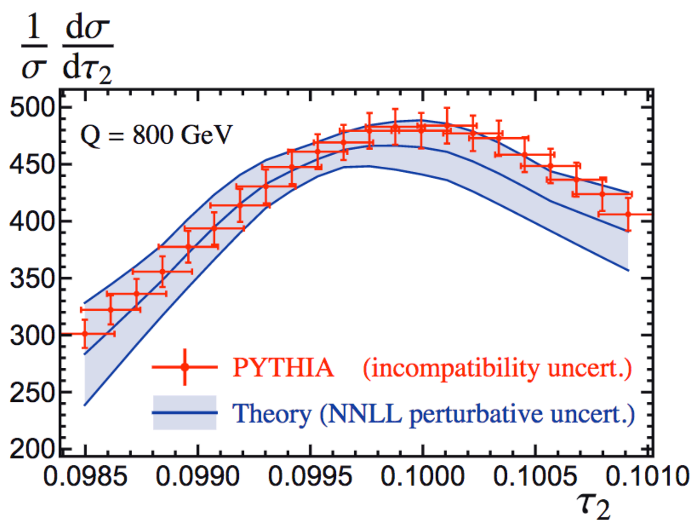
1 Observable studied: 2-jetiness in $e^+e^- \rightarrow$ ttbarX for $Q=2p_T >> m_t$ (boosted tops)

$$\tau_2 = 1 - \max_{\vec{n}_t} \frac{\sum_i |\vec{n}_t \cdot \vec{p}_i|}{Q}$$



$$\tau_2^{peak} = 1 - \sqrt{1 - \frac{4m_t^2}{Q^2}}$$ (at tree level)

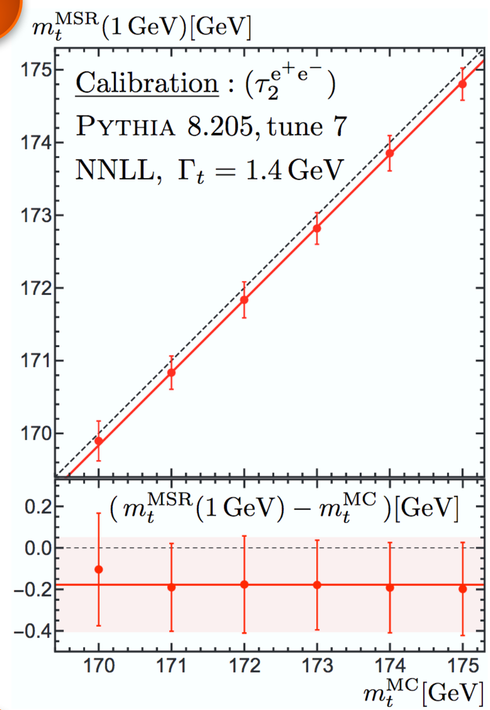
2



M.Butenshoen et al., Phys.Rev.Lett. 117 (2016) no.23, 232001.

- Strategy:
  1. Find strongly mass-sensitive hadron level observable.
  2. Compute accurate hadron level QCD prediction at ≥NLL/NLO with full control over the quark mass scheme dependence.
  3. Fit to observable to find the relation between QCD masses and m_t^{MC}.
  4. Cross check observable independence/universality.

3



within uncertainties: $m_t^{MC} \simeq m_t^{MSR}(1\mathrm{GeV})$

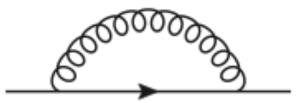
But m_t^{MC} differs from m_t^{pole} by 900/600 MeV!

TOP QUARK MASS MEASUREMENTS

- It has been measured using different techniques, at 7 and 8 CM E, and in various channels: ttbar (lepton+jets, dilepton, all hadronic), single top t-channel.
- CMS also released a first measurement at 13 TeV (not as precise yet as the Run-I measurements).
- We can distinguish 2 type of measurements:

(1) Determinations of m_t^{MC} ("Standard Methods but also some alternative techniques")

(2) Determinations of m_t^{pole}.



$m_t^{MC} = m_t^{pole} + \Delta_t^{MC}$

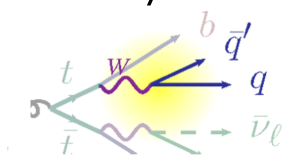
$\Delta_t^{MC} \simeq O(1\ \text{GeV})$

The most precise results are obtained with the Standard Methods but the parameter which is extracted is the Monte Carlo top quark mass.

The direct pole mass determinations are currently dominated by theoretical uncertainties.

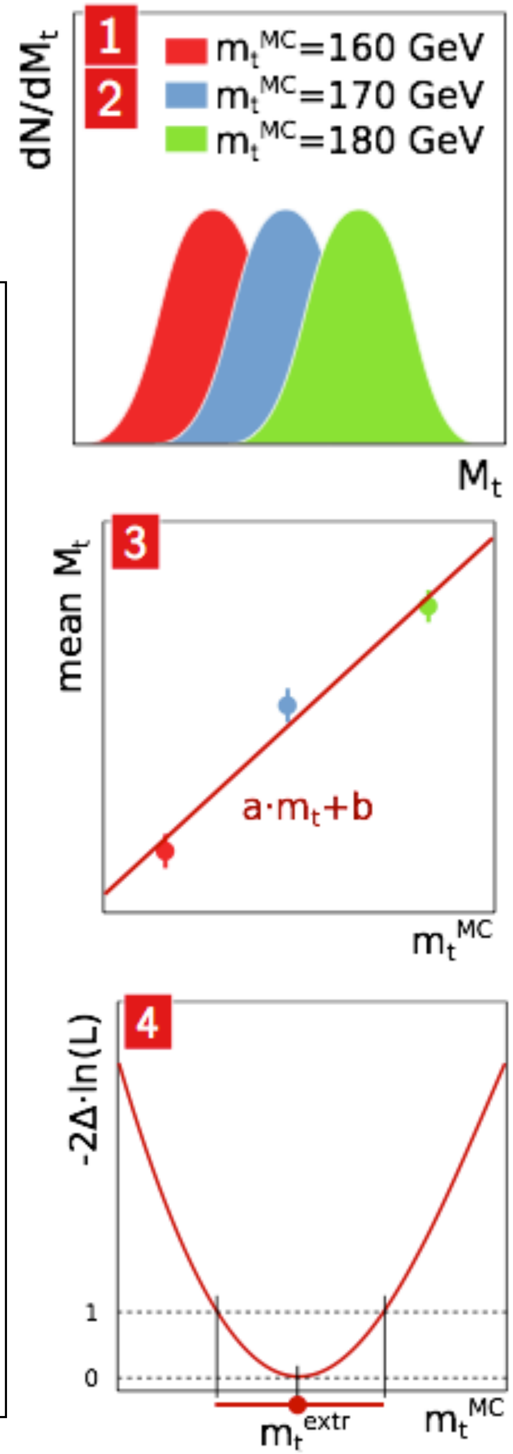
MC TOP MASS DETERMINATIONS

1. Select top events
2. Construct observable (other observables can be used to constrain main systematics JES, bJES)



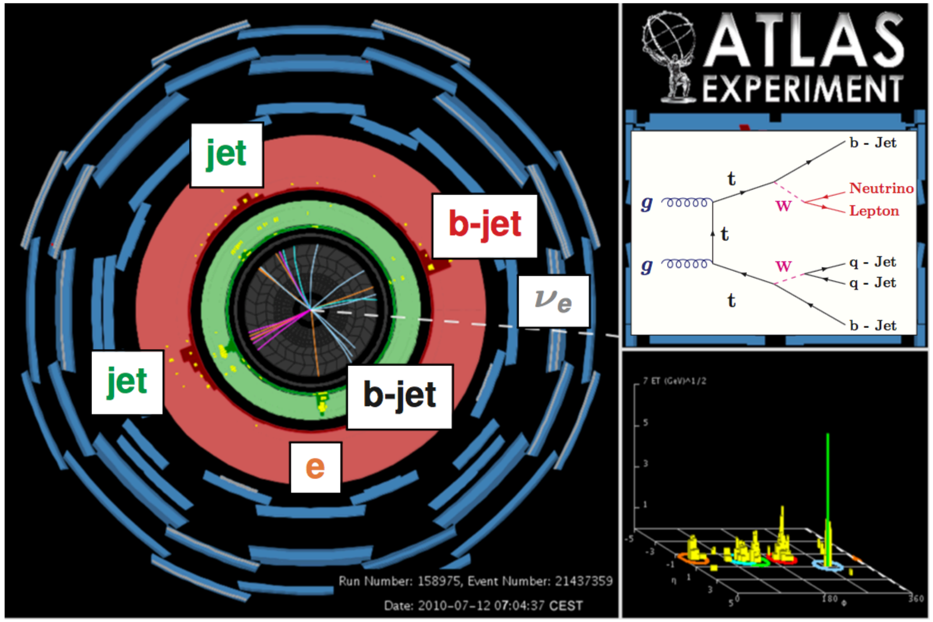
3. Parametrise observable in m_{top} using MC simulation
4. Fit to data, extract m_{top}.

- Lead to most precise results but the parameter which is extracted is the MC top mass.
- Most precise measurements in lepton+jets (CMS) and dilepton (ATLAS) ttbar channels with Run-I data.
- A first preliminary measurement at 13 TeV recently provided by CMS.

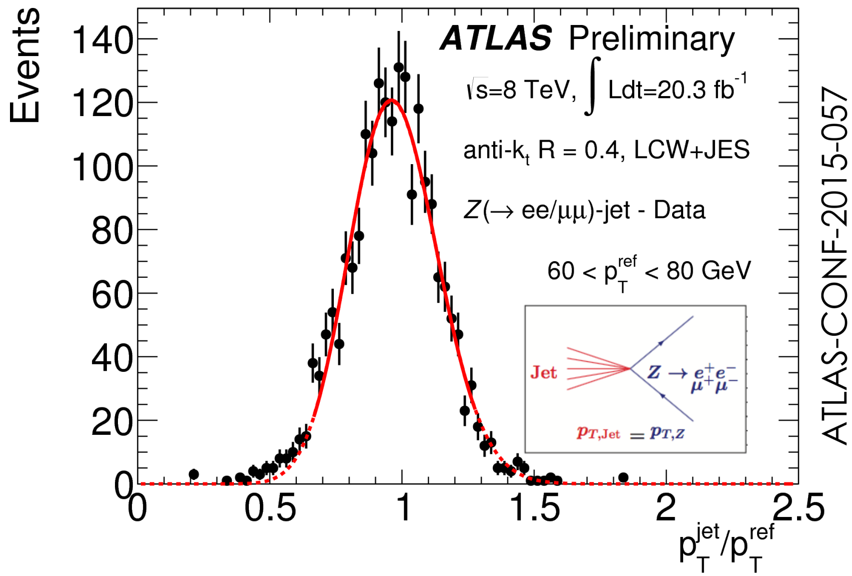


JET ENERGY SCALE UNCERTAINTIES

$t\bar{t} \rightarrow (b\, e\, \nu)\,(b\, q\, q),\quad M(qq) = m_W,\quad M(bqq) = m_{top}$

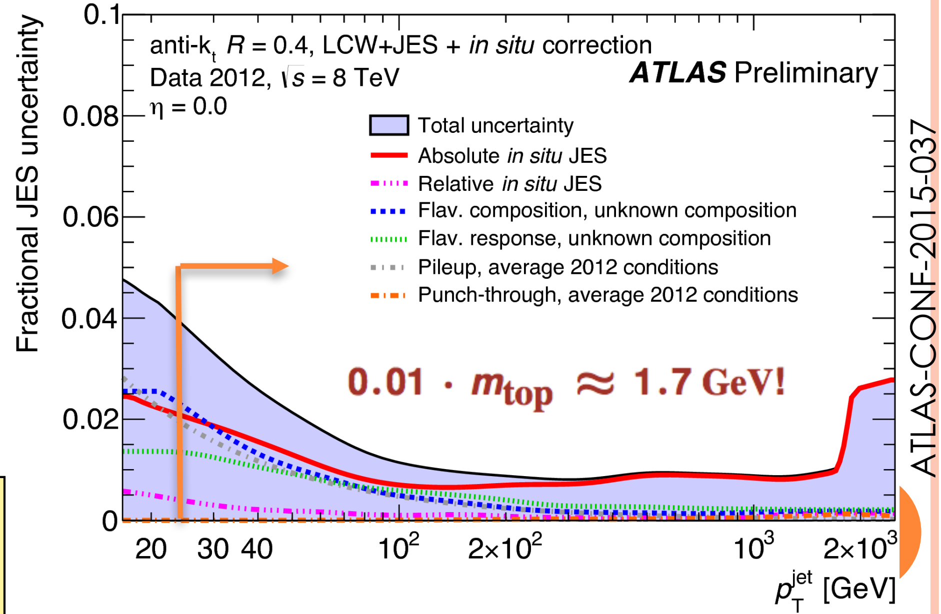


Calibration via p_T balance



- Precise determinations of energy scale of inclusive jets (JES) and the relative b-to-light jet energy scale are vital for precise measurements of m_{top}.
- The possibility of in-situ calibrations of the mean JES and bJES are extremely helpful.

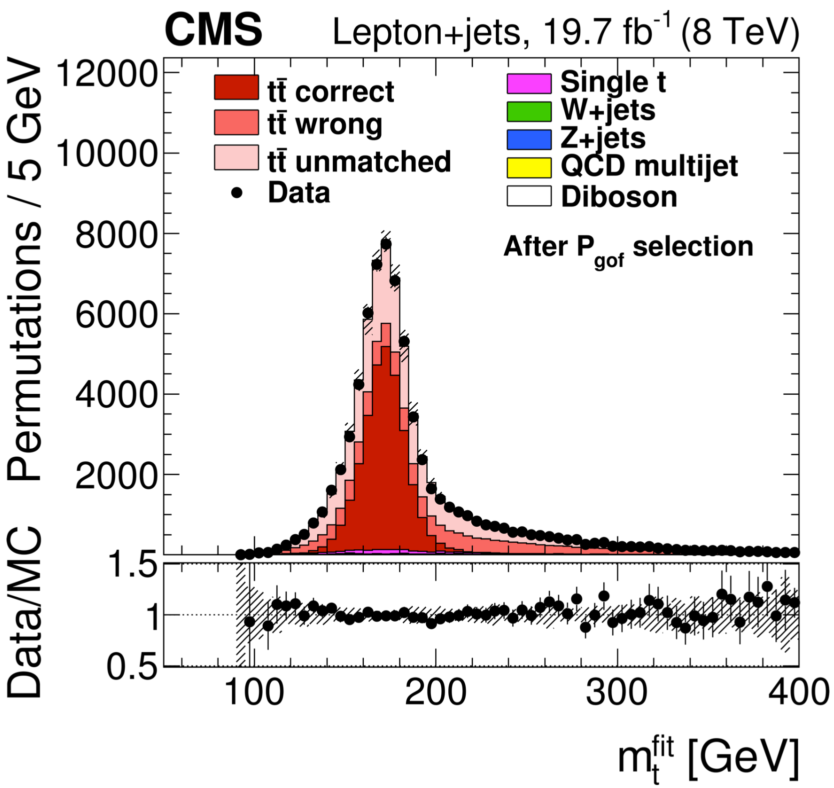
Essential to control the jet energy scale induced uncertainties!

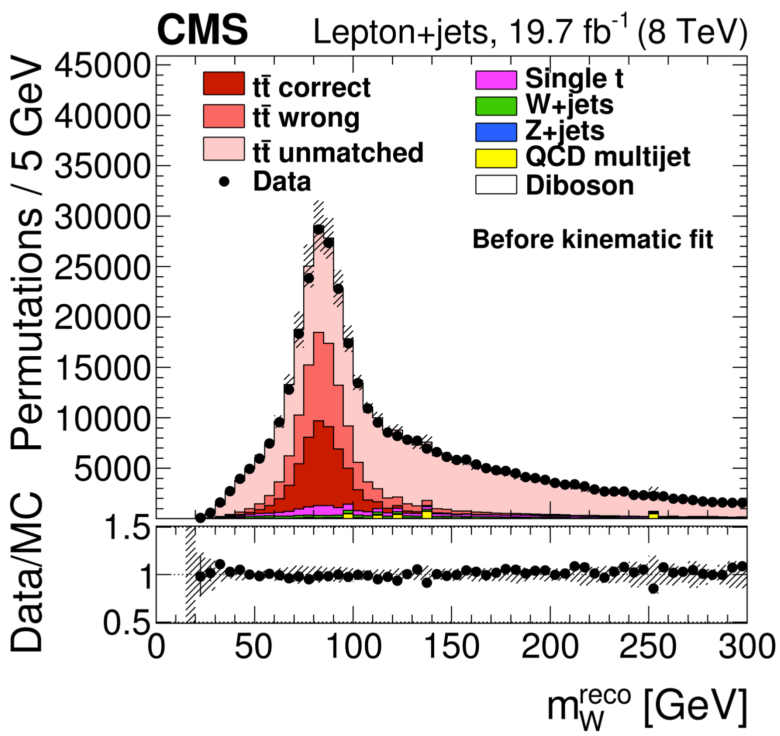


CMS BEST RESULT - CMS l+jets @ 8 TeV

- Method: 2D fit to m_{top}^{reco}, m_W^{reco} using W-mass constraint → extract m_{top} and Jet Scale Factor (JSF)

PRD 93 (2016) 072004





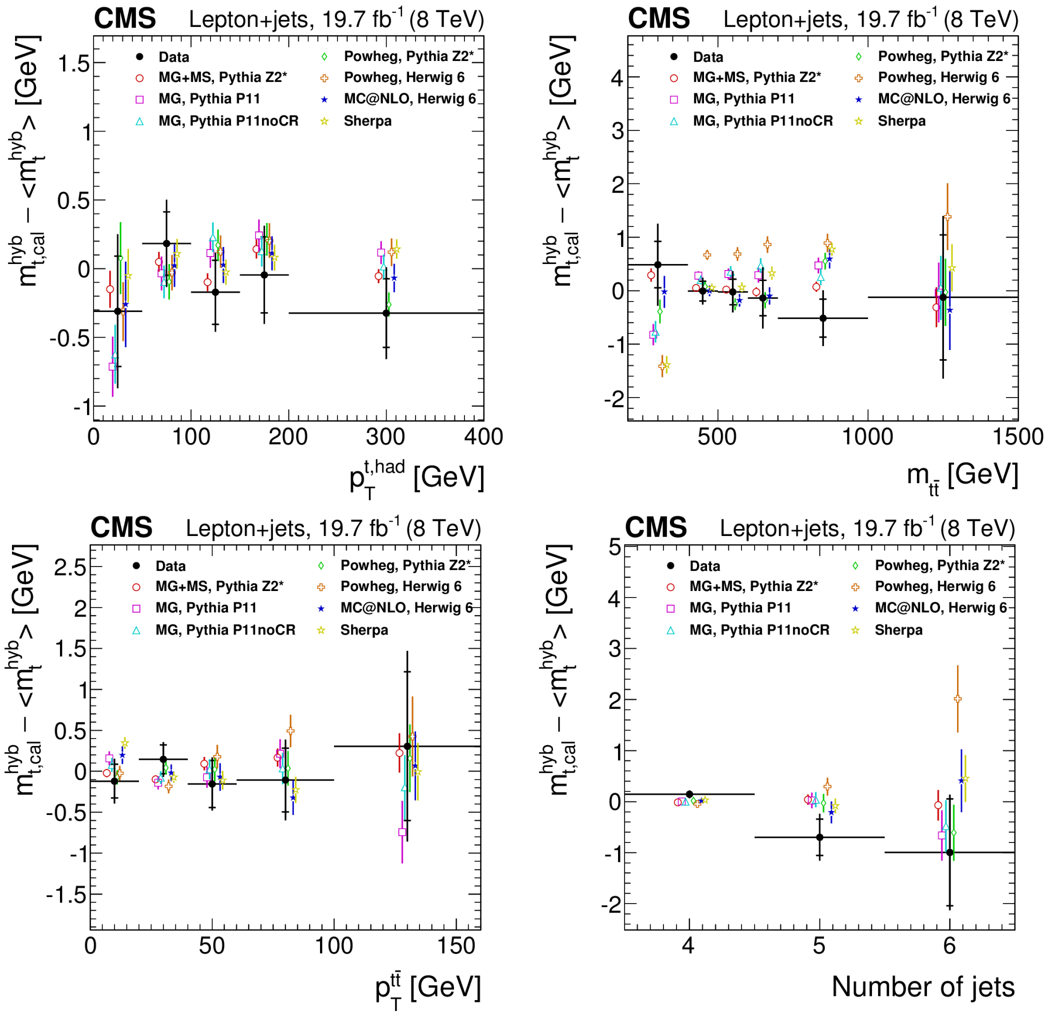
$$m_t^{hyb} = 172.35 \pm 0.16\,(\text{stat+JSF}) \pm 0.48\,(\text{syst})\ \text{GeV}$$

(0.29%)
(dominant uncertainties: flavour dependent JEC)

Most precise single measurement!

CMS BEST RESULT - CMS l+jets @ 8 TeV

- To search for biases in the measurement and potential limitations in the event generators, differential measurements of m_{top} are provided as a function of kinematical properties.



Eur. Phys. J. C (2015) 75:330

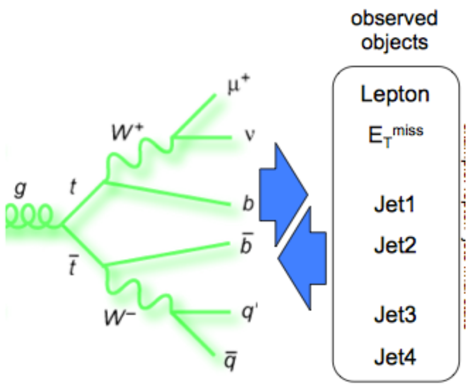
ATLAS MEASUREMENT: l+jets @ 7 TeV

- Method: 3D template fit to m_{top}^{reco}, m_W^{reco} and R_{lb}^{reco} → m_{top}, JSF, bJSF.

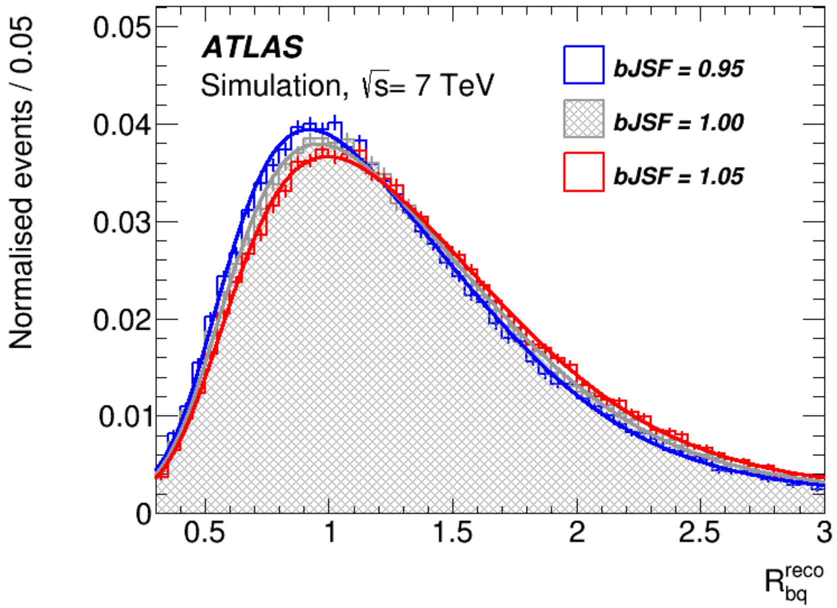
$$m_W^{reco} = 2E_1E_2(1 - \cos\theta_{12}) \propto \mathrm{JSF}^2$$

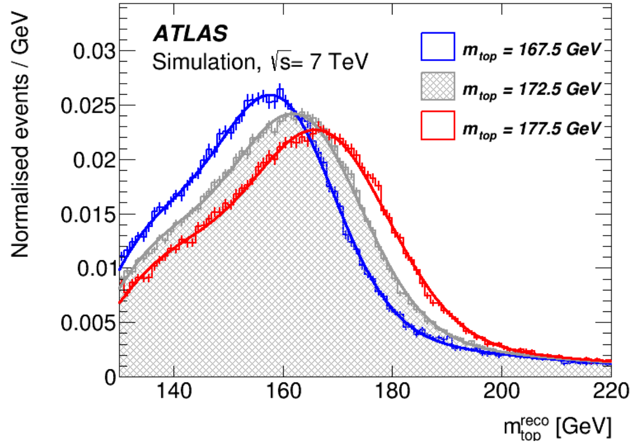
$$R_{bq}^{reco} = \frac{\sum p_t(b)}{\sum p_t(q)} \propto \frac{\mathrm{bJSF}\cdot\mathrm{JSF}}{\mathrm{JSF}} = \mathrm{bJSF}$$

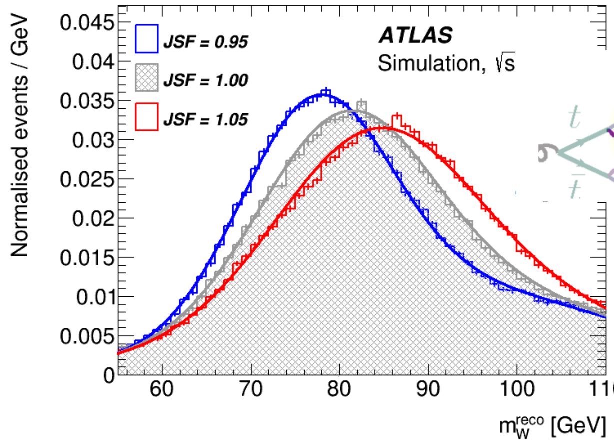
R_{lb}^{reco} sensitive to bJES → constrain bJES from data

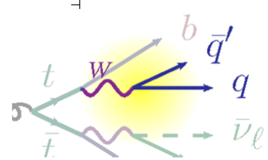


Use a kinematic fit to the decay hypothesis → m_{top}^{reco}





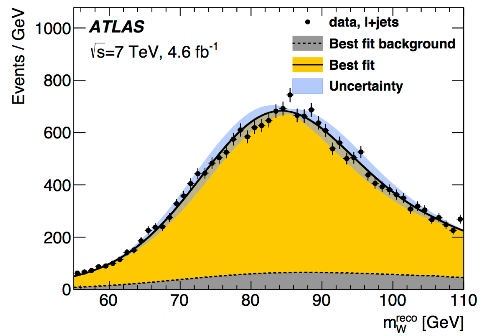


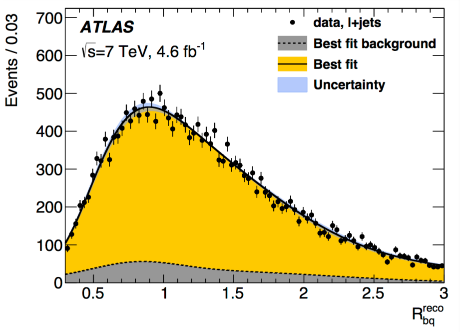


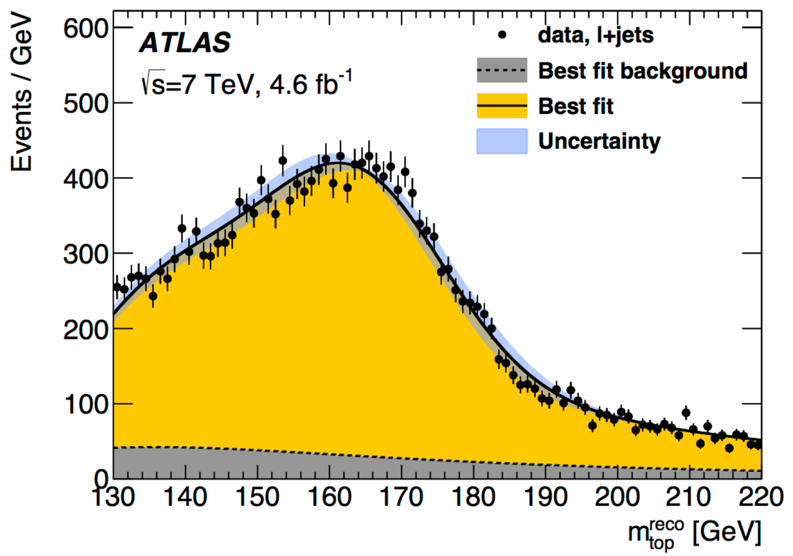
$$R_{lb}^{reco} = \frac{p_T^{blep} + p_T^{bhad}}{p_T^{l1} + p_T^{l2}} \quad \text{(2b-tagged jet events)}$$

$$R_{lb}^{reco} = \frac{p_T^{btagged}}{p_T^{average,l1,l2}} \quad \text{(1b-tagged jet events)}$$

ATLAS MEASUREMENT - l+jets @ 7 TeV







$$m_{\text{top}}^{\ell+\text{jets}} = 172.33 \pm 0.75\ (\text{stat} + \text{JSF} + \text{bJSF})\ \text{GeV},$$
$$\text{JSF} = 1.019 \pm 0.003\ (\text{stat}),$$
$$\text{bJSF} = 1.003 \pm 0.008\ (\text{stat}),$$

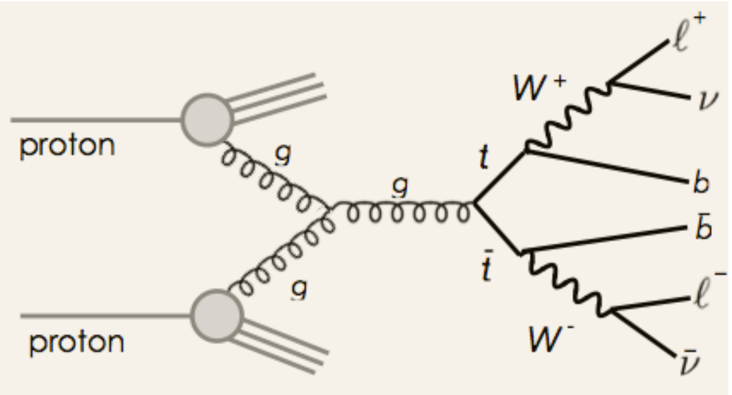
	$m_{\text{top}}^{\ell+\text{jets}}$ [GeV]
Results	172.33
Statistics	0.75
Method	0.11 ± 0.10
Signal Monte Carlo generator	0.22 ± 0.21
Hadronisation	0.18 ± 0.12
Initial- and final-state QCD radiation	0.32 ± 0.06
Underlying event	0.15 ± 0.07
Colour reconnection	0.11 ± 0.07
Parton distribution function	0.25 ± 0.00
Background normalisation	0.10 ± 0.00
W/Z+jets shape	0.29 ± 0.00
Fake leptons shape	0.05 ± 0.00
Jet energy scale	0.58 ± 0.11
Relative *b*-to-light-jet energy scale	0.06 ± 0.03
Jet energy resolution	0.22 ± 0.11
Jet reconstruction efficiency	0.12 ± 0.00
Jet vertex fraction	0.01 ± 0.00
b-tagging	0.50 ± 0.00
Leptons	0.04 ± 0.00
$E_{\text{T}}^{\text{miss}}$	0.15 ± 0.04
Pile-up	0.02 ± 0.01
Total systematic uncertainty	1.03 ± 0.31
Total	1.27 ± 0.33

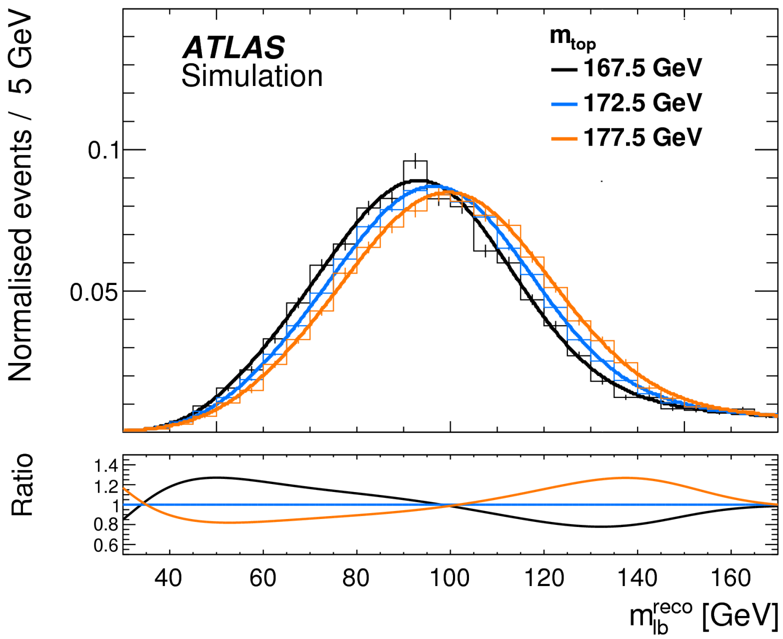
(Rel. total uncertainty: 0.74%)

Dominant uncertainties: b-tagging, JES, stat)

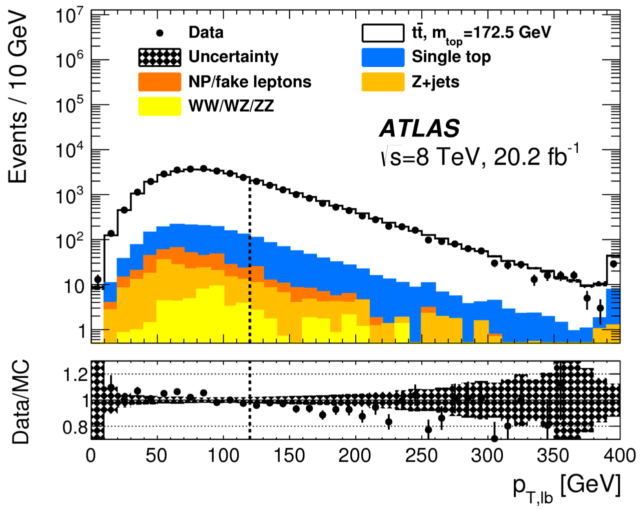
ATLAS MEASUREMENT dilepton @ 7 TeV and 8 TeV

7 TeV: Eur. Phys. J. C (2015) 75:330
8 TeV: Phys. Lett. B 761 (2016) 350





- Background fraction ≤ 2%.
- Under-constrained event kinematics.
- Use 1D template method with m_{lb} observable as estimator (exploiting a partial reconstruction).
- 8 TeV analysis: Additional cut on $p_{T,lb}$ > 120 GeV → significant reduction of JES and modelling. uncertainties



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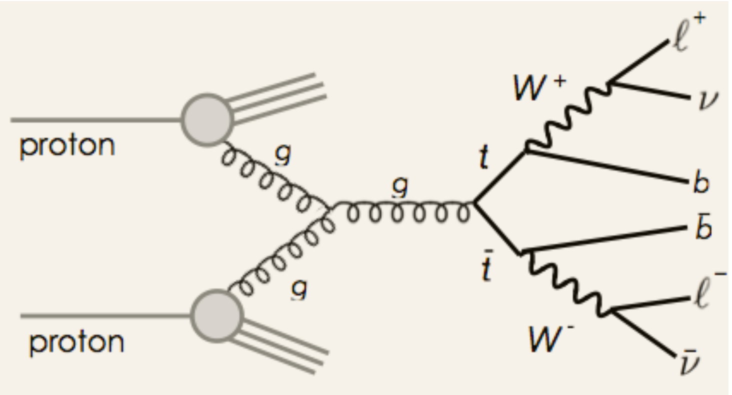
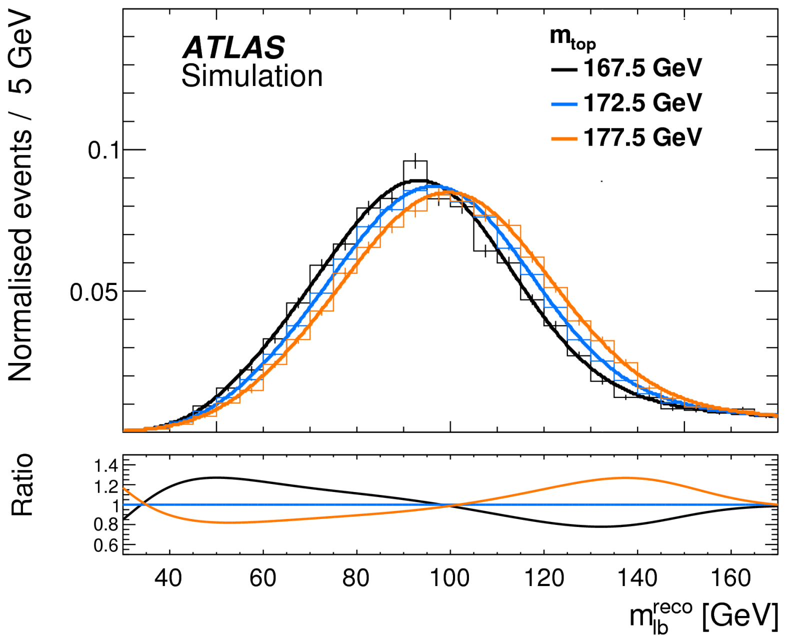
dilepton @ 7 TeV and 8 TeV

7 TeV: Eur. Phys. J. C (2015) 75:330
8 TeV: Phys. Lett. B 761 (2016) 350





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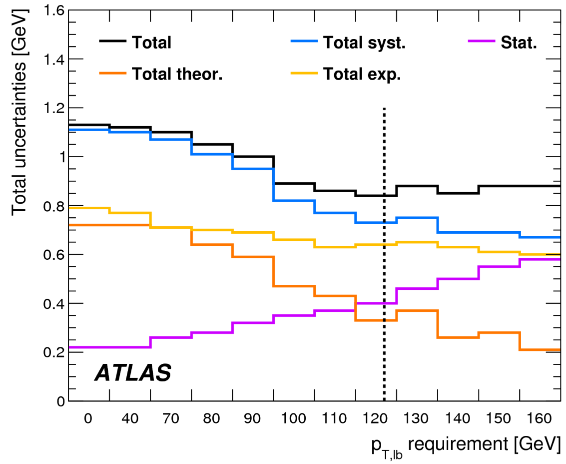
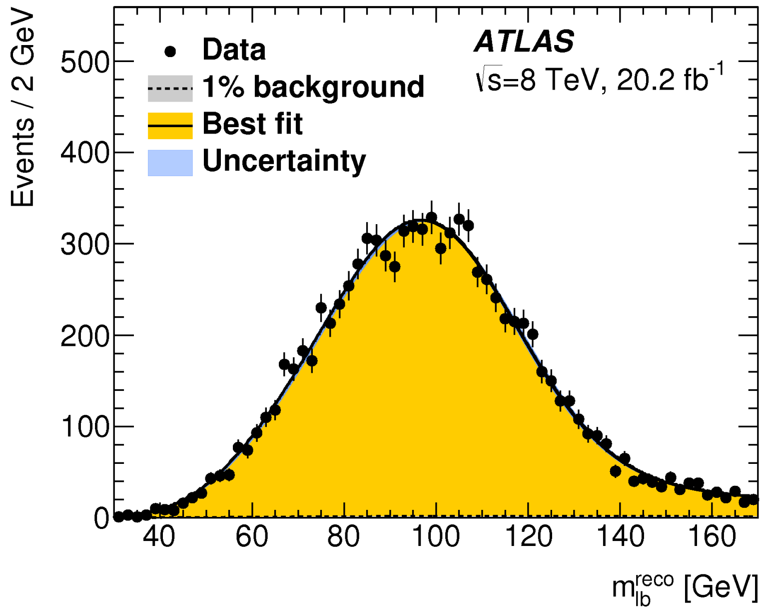


ATLAS MEASUREMENT dilepton @ 7 TeV and 8 TeV

7 TeV: Eur. Phys. J. C (2015) 75:330
8 TeV: Phys. Lett. B 761 (2016) 350



- Best precision achieved in ATLAS: dilepton channel @ 8 TeV; Rel. total uncertainty 0.49% (dominant uncertainties: JES, bJES, stat, signal modelling).

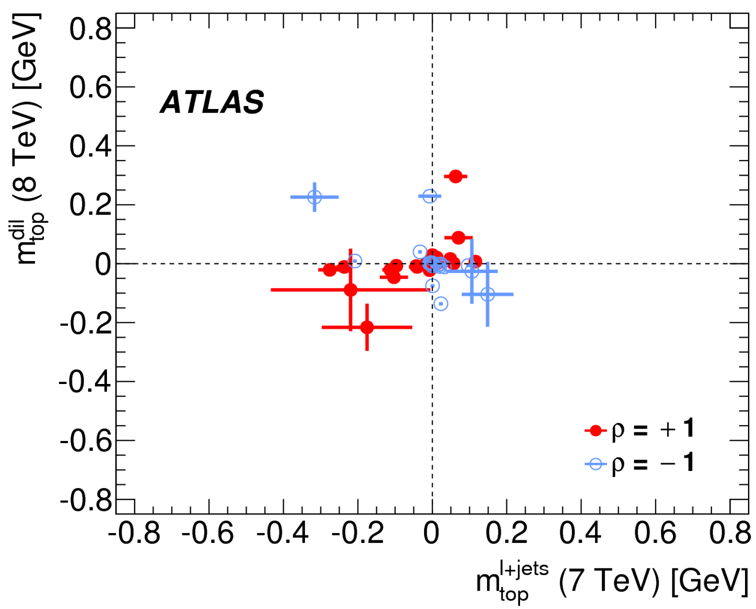
	7 TeV m_{top}^{dil} [GeV]	8 TeV m_{top}^{dil} [GeV]
Results	173.79	172.99
Statistics	0.54	0.41
Method	0.09 ± 0.07	0.05 ± 0.07
Signal Monte Carlo generator	0.26 ± 0.16	0.09 ± 0.15
Hadronisation	0.53 ± 0.09	0.22 ± 0.09
Initial- and final-state QCD radiation	0.47 ± 0.05	0.23 ± 0.07
Underlying event	0.05 ± 0.05	0.10 ± 0.14
Colour reconnection	0.14 ± 0.05	0.03 ± 0.14
Parton distribution function	0.11 ± 0.00	0.05 ± 0.00
Background normalisation	0.04 ± 0.00	0.03 ± 0.00
W/Z+jets shape	0.00 ± 0.00	0
Fake leptons shape	0.01 ± 0.00	0.08 ± 0.00
Jet energy scale	0.75 ± 0.08	0.54 ± 0.04
Relative b-to-light-jet energy scale	0.68 ± 0.02	0.30 ± 0.01
Jet energy resolution	0.19 ± 0.04	0.09 ± 0.05
Jet reconstruction efficiency	0.07 ± 0.00	0.01 ± 0.00
Jet vertex fraction	0.00 ± 0.00	0.02 ± 0.00
b-tagging	0.07 ± 0.00	0.03 ± 0.02
Leptons	0.13 ± 0.00	0.14 ± 0.01
E_T^{miss}	0.04 ± 0.03	0.01 ± 0.01
Pile-up	0.01 ± 0.00	0.05 ± 0.01
Total systematic uncertainty	1.31 ± 0.23	0.74 ± 0.29
Total	1.41 ± 0.24	0.84 ± 0.29

8 TeV $m_{top} = 172.99 \pm 0.41\ (\mathrm{stat}) \pm 0.74\ (\mathrm{syst})\ \mathrm{GeV}$

7 TeV $m_{top}^{dil} = 173.79 \pm 0.54\ (\mathrm{stat}) \pm 1.30\ (\mathrm{syst})\ \mathrm{GeV}.$

ATLAS TOP QUARK MASS COMBINATION

- The 3 measurements combined using the BLUE method taking correlations into account.



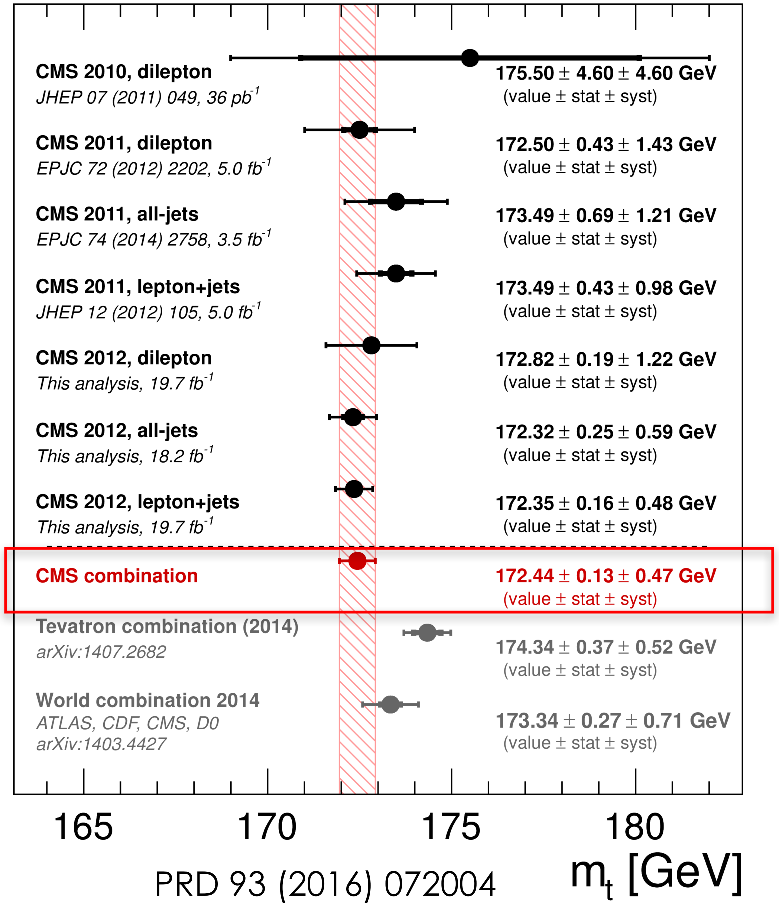
Phys. Lett. B 761 (2016) 350

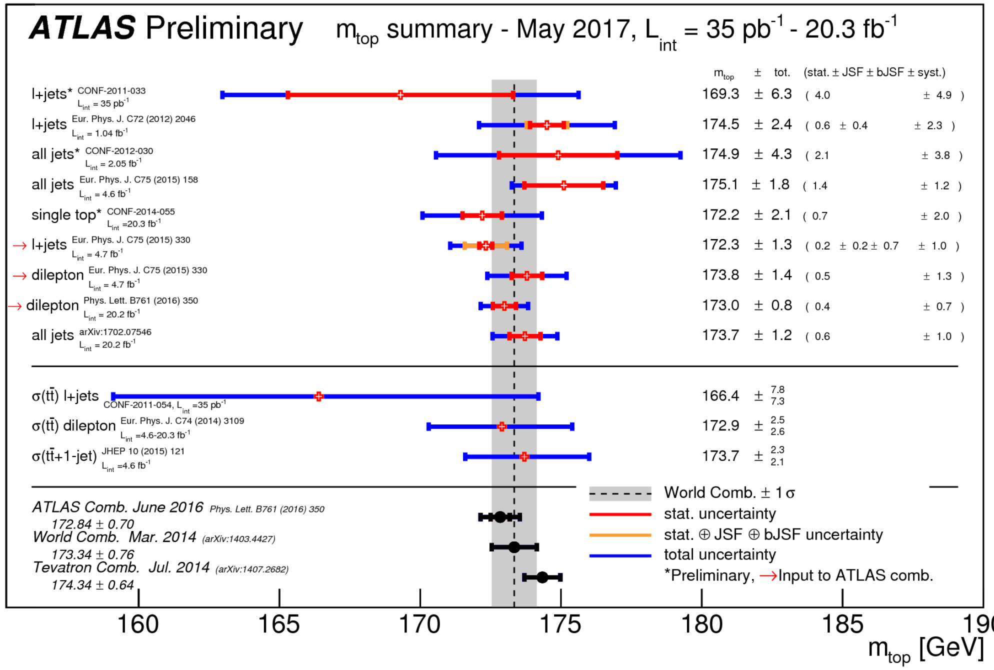
$$m_{top} = 172.84 \pm 0.34\,(\text{stat}) \pm 0.61\,(\text{syst})\ \text{GeV},$$

	m_{top}^{all} [GeV]
Results	172.84
Statistics	0.34
Method	0.05
Signal Monte Carlo generator	0.14
Hadronisation	0.23
Initial- and final-state QCD radiation	0.08
Underlying event	0.02
Colour reconnection	0.01
Parton distribution function	0.08
Background normalisation	0.04
W/Z+jets shape	0.09
Fake leptons shape	0.05
Jet energy scale	0.41
Relative b-to-light-jet energy scale	0.25
Jet energy resolution	0.08
Jet reconstruction efficiency	0.04
Jet vertex fraction	0.02
b-tagging	0.15
Leptons	0.09
E_T^{miss}	0.05
Pile-up	0.03
Total systematic uncertainty	0.61
Total	0.70

(Rel. total uncertainty: 0.40%)
Dominant uncertainties: JES, stat, bJES, Hadronisation)

MC TOP QUARK MASS - SUMMARY





- Most precise value of MC top mass from CMS combination (0.28%!)
- A different treatment of uncertainties in ATLAS and CMS under discussion: how to deal with the double counting between JES/Hadronisation uncertainties.

TOP QUARK POLE MASS STRATEGY

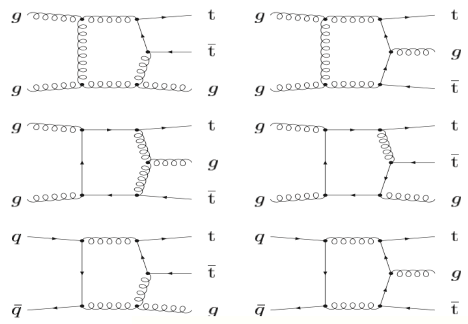
- Measure an observable that can be calculated in QCD perturbation theory using a well defined top mass scheme (e.g. pole mass).
- Some of these observables are:
  - Top quark pair cross section (predictions at NNLO+NNLL, Czakon, Fielder and Mitov, '13)

$$\sigma_{\rm tot} = \sum_{i,j} \int d\beta \; \Phi_{ij}(\beta, \mu_F^2) \; \hat{\sigma}_{ij} \quad , \quad \beta = \sqrt{1 - 4m^2/\hat{s}} \quad , \quad \Phi_{ij} = \frac{2\beta}{1-\beta^2} \, x \, (f_i \otimes f_j)$$

  - Normalised ttbar+1-jet differential cross section as a function of the inverse of the invariant mass of the ttbar+1-jet system (predictions at NLO+PS, S.Alioli et al., '13, J.Fuster et al., '17) (better sensitivity!)

$$\mathcal{R} = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}(m_t^{\rm pole})}{d\rho_S}$$

$$\rho_S = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}} \quad , \quad m_0 = 170 \text{ GeV}$$



  - Lepton differential normalised cross sections in ttbar dilepton (predictions at NLO, MCFM)

Frixioni & Mitov '14.

$$p_T(\ell^+)$$
$$p_T(\ell^+\ell^-)$$
$$M(\ell^+\ell^-)$$
$$E(\ell^+) + E(\ell^-)$$
$$p_T(\ell^+) + p_T(\ell^-)$$

m_t^{pole} FROM ttbar CROSS SECTION

- Taking as input the ttbar cross section measured in the emu channel.

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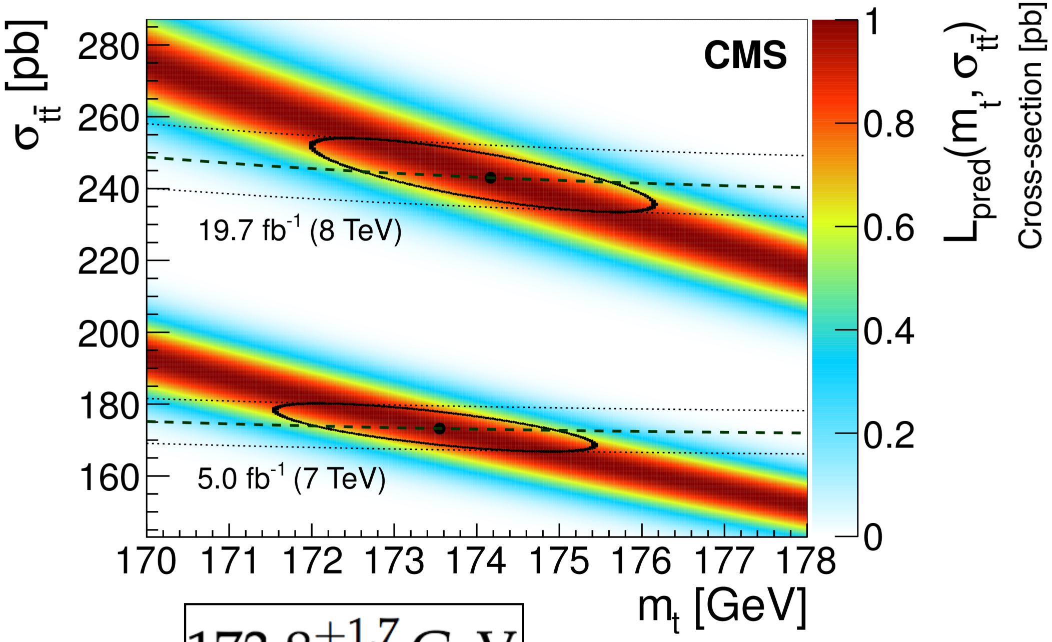

$173.8^{+1.7}_{-1.8}$ GeV

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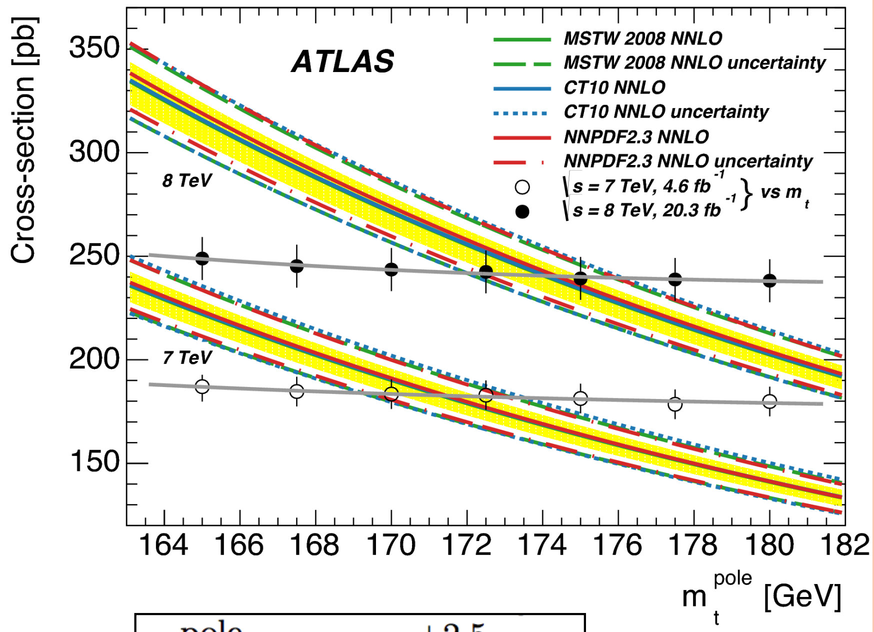
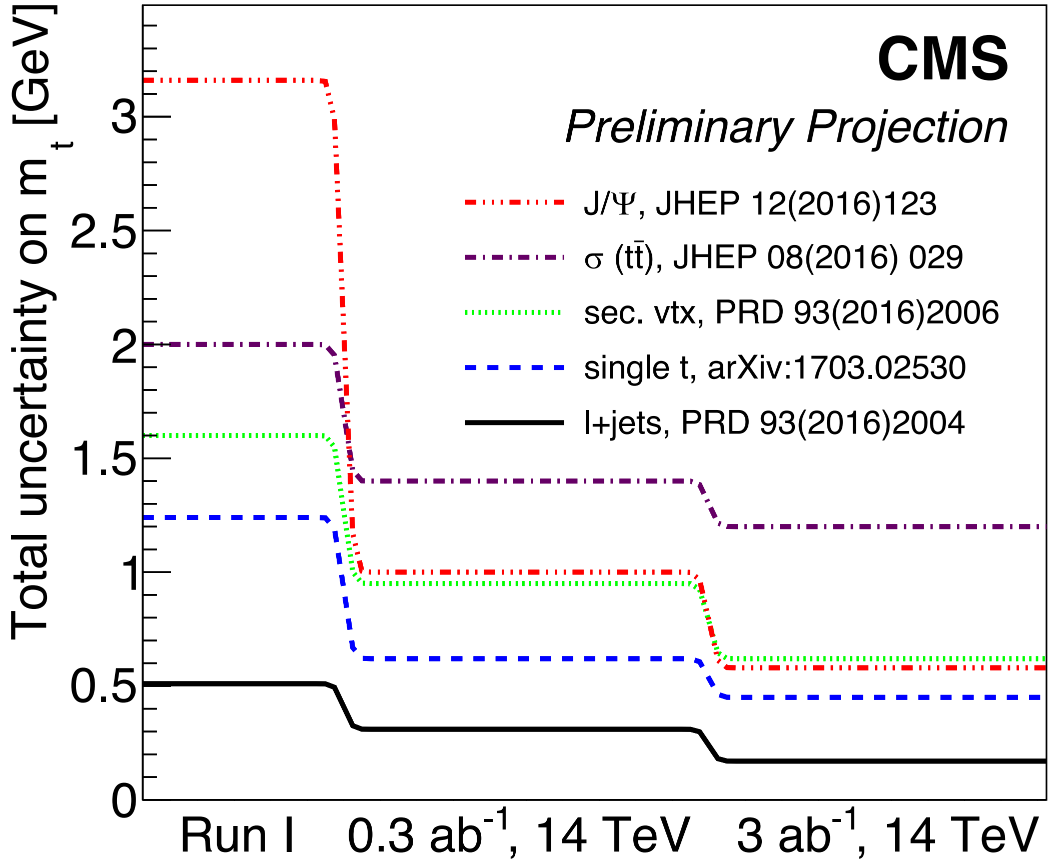


$m_t^{pole} = 172.9^{+2.5}_{-2.6}$ GeV

- Important to obtain measurements as independent as possible on the assumed top quark mass.
- Uncertainty reached at the level of 1%.
- Measurements dominated by theory uncertainties as PDF.

m_t^{pole} FROM ttbar CROSS SECTION



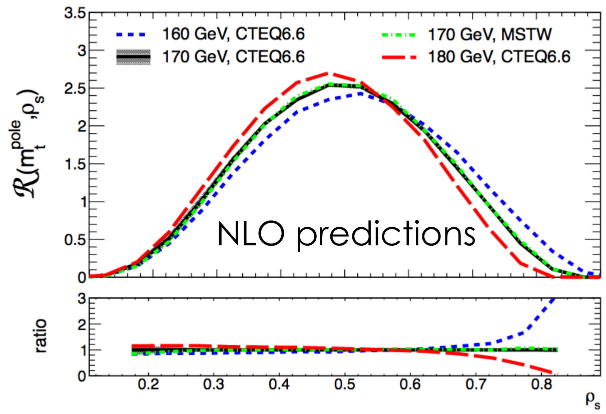
- CMS extrapolation from inclusive XS measurements: Could reach 0.5% with a reduction to 5% theory and 2% experimental uncertainties (CMS-PAS-FTR-16-006).

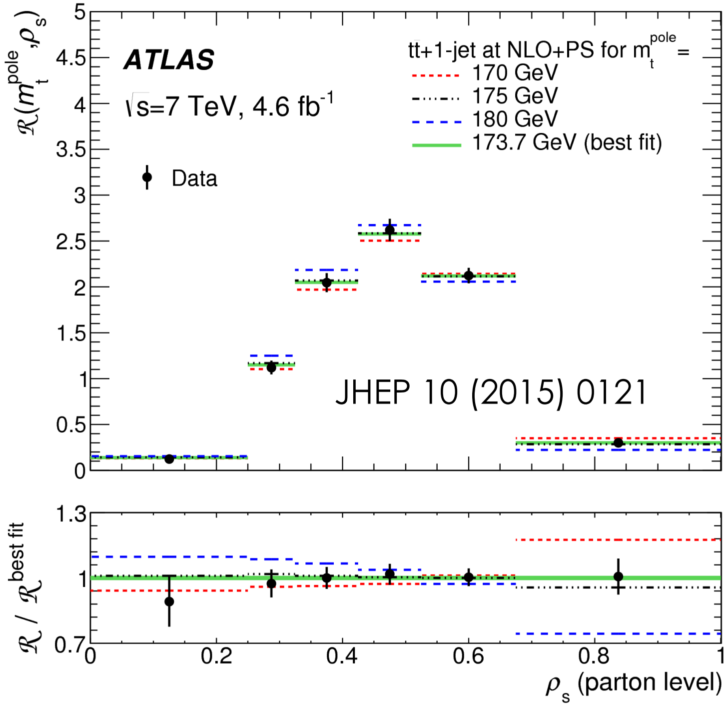
m_t^{pole} FROM ttbar+1jet XS

- Sensitivity enhanced by mass dependent radiation.
- The observable is 5 times more sensitive than the inclusive cross section.
- Large sensitivity for $\rho_s \geq 0.7$.
  - $\rho_s \to 1$ at threshold.
  - $\rho_s \to 0$ for boosted production.
- Requiring one additional jet to the standard ttbar lepton+jets selection.
- Data is unfolded to parton level and compared to ttbar+1jet NLO+PS (difference NLO vs NLO+PS ~300 MeV)

$$\mathcal{R} = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}(m_t^{\text{pole}})}{d\rho_S}$$

$$\rho_S = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}} \quad , \quad m_0 = 170 \text{ GeV}$$



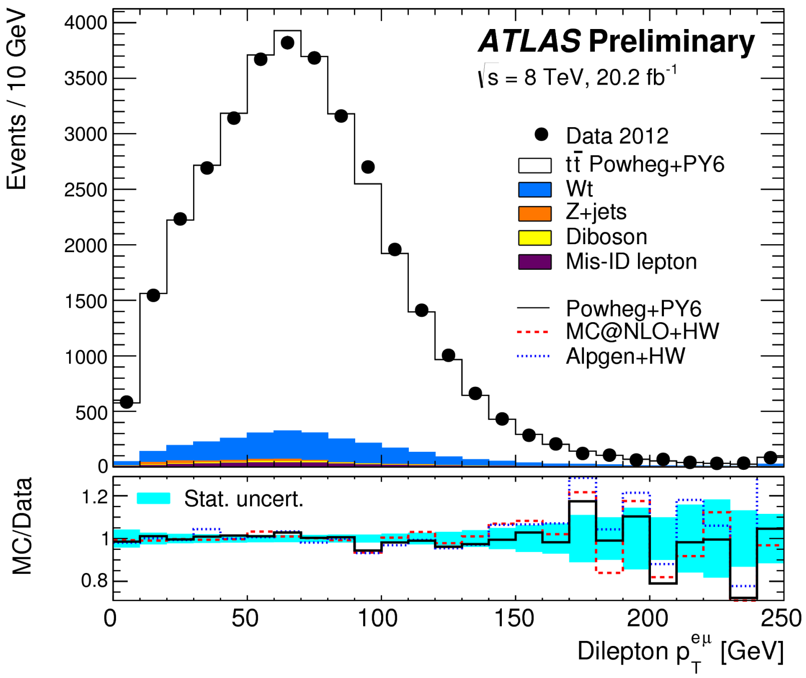


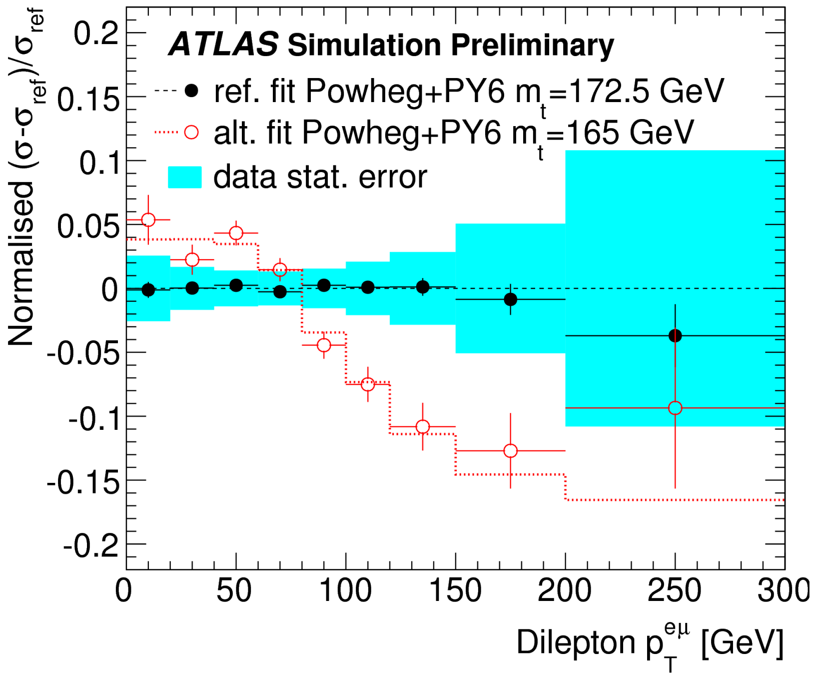
$$m_t^{\text{pole}} = 173.7 \pm 1.5 \text{ (stat.)} \pm 1.4 \text{ (syst.)} \,^{+1.0}_{-0.5} \text{ (theory) GeV}$$

- Uncertainty reached at the level of 1.3%.
- Main uncertainties: statistics, signal QCD radiation modelling and JES uncertainties → can be reduced with more data.

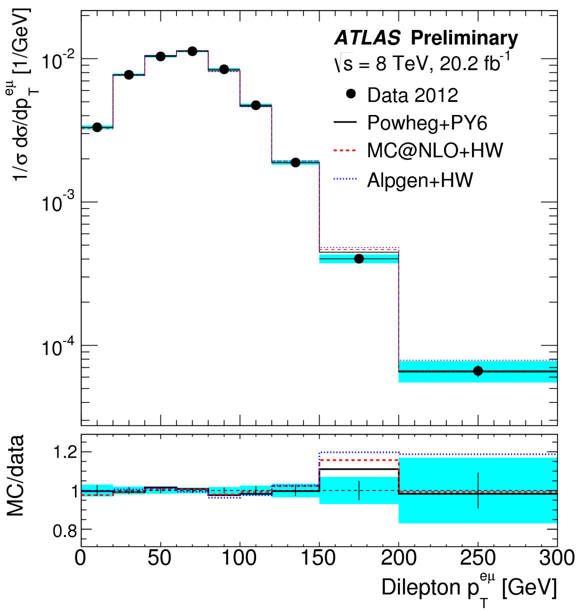
m_t^{pole} FROM LEPTON DIFFERENTIAL

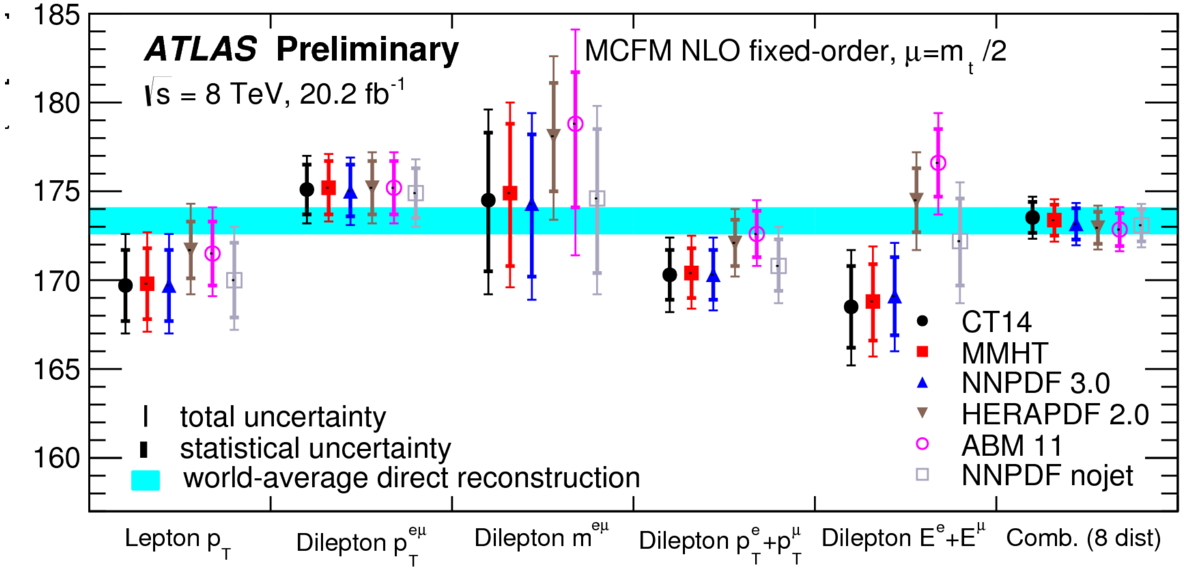
- Measure a number of lepton differential distributions in ttbar → eμ+X events.
- Subtract background, correct to stable particles and convert them into normalised differential distributions.
- Clear sensitivity for x= p_T^l, $p_T^{e\mu}$, $m^{e+\mu}$, $p_T^e+p_T^\mu$, E^e+E^μ but not for $|\eta^l|$, $|y^{e\mu}|$, $\Delta\varphi^{e\mu}$





m_t^{pole} FROM LEPTON DIFFERENTIAL



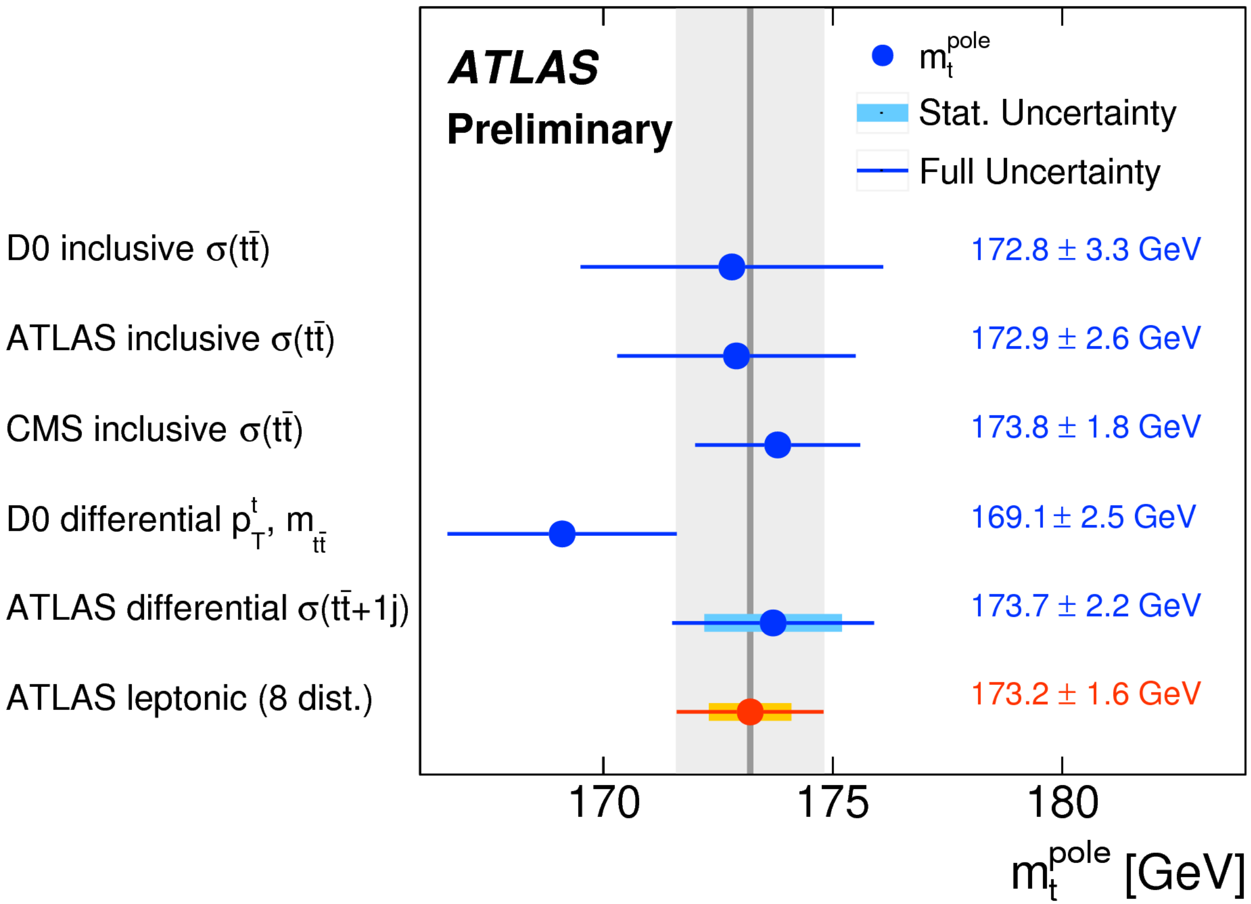


- Simultaneous fit of the theory predictions to 8 measured distributions (including also $|\eta^l|$, $|y^{e\mu}|$, $\Delta\phi^{e\mu}$ to constrain systematic uncertainties):

$$m_{top}^{pole} = 173.2 \pm 0.9\ (\text{stat.}) \pm 0.8\ (\text{syst.}) \pm 1.2\ (\text{theo.})\ \text{GeV} = 173.2 \pm 1.6\ \text{GeV}$$

- Most precise direct measurement of the top quark pole mass.
- Uncertainty reached 0.9% is dominated by theory uncertainties of MCFM predictions (mainly from scale variations).
- Could benefit from calculations including NNLO effects in both production and decay.

TOP QUARK POLE MASS - SUMMARY



- Most precise value of top pole mass from ATLAS (0.9%)
- Theoretical progress is the key to improve the precision and be competitive with the MC top pole mass determinations (0.28% precision from CMS combination).

CONCLUSIONS

- Top quark mass is a fundamental parameter of the SM that needs to be measured as precise as possible.
- Since the top quark is not a free particle the mass definition is not unique.
  - Mass definitions used in QCD perturbartive calculations (e.g. pole top mass) (used in EW fits, or EW vacuum stability studies).
    - The relations among these mass definitions is well known.
  - Mass as implemented in the Monte Carlo generators: m_{top}^{MC}.
    - To find out precisely the relation between the MC mass and the masses defined in perturbation theory is a big theoretical challenge!

$$\boxed{m_t^{MC} = m_t^{pole} + \Delta_t^{MC}}$$

- Experiments have performed a wide range of top quark mass measurements using different techniques and datasets.
  - Very precise measurements of m_{top}^{MC} (0.28%!).
  - Direct measurements of m_{top}^{pole} also available (0.9%) where theoretical progress is key to improve the precision.

BACKUP

ATLAS (7 TeV, lepton+jets)

	$m_{top}^{\ell+jets}$ [GeV]
Results	172.33
Statistics	0.75
Method	0.11 ± 0.10
Signal Monte Carlo generator	0.22 ± 0.21
Hadronisation	0.18 ± 0.12
Initial- and final-state QCD radiation	0.32 ± 0.06
Underlying event	0.15 ± 0.07
Colour reconnection	0.11 ± 0.07
Parton distribution function	0.25 ± 0.00
Background normalisation	0.10 ± 0.00
W/Z+jets shape	0.29 ± 0.00
Fake leptons shape	0.05 ± 0.00
Jet energy scale	0.58 ± 0.11
Relative *b*-to-light-jet energy scale	0.06 ± 0.03
Jet energy resolution	0.22 ± 0.11
Jet reconstruction efficiency	0.12 ± 0.00
Jet vertex fraction	0.01 ± 0.00
b-tagging	0.50 ± 0.00
Leptons	0.04 ± 0.00
E_T^{miss}	0.15 ± 0.04
Pile-up	0.02 ± 0.01
Total systematic uncertainty	1.03 ± 0.31
Total	1.27 ± 0.33

CMS (lepton+jets)

	hybrid δm_t^{hyb} (GeV)
Experimental uncertainties	
Method calibration	0.04
Jet energy corrections	
– JEC: Intercalibration	+0.01
– JEC: In situ calibration	+0.12
– JEC: Uncorrelated non-pileup	−0.10
– JEC: Uncorrelated pileup	−0.04
Lepton energy scale	+0.01
E_T^{miss} scale	+0.04
Jet energy resolution	−0.03
b tagging	+0.06
Pileup	−0.04
Backgrounds	+0.03
Modeling of hadronization	
JEC: Flavor-dependent	
– light quarks (u d s)	+0.05
– charm	+0.01
– bottom	−0.32
– gluon	−0.08
b jet modeling	
– b fragmentation	<0.01
– Semileptonic b hadron decays	−0.16
Modeling of perturbative QCD	
PDF	0.04
Ren. and fact. scales	−0.09 ± 0.07
ME-PS matching threshold	+0.03 ± 0.07
ME generator	−0.12 ± 0.08
Top quark p_T	+0.02
Modeling of soft QCD	
Underlying event	+0.08 ± 0.11
Color reconnection modeling	+0.01 ± 0.09
Total systematic	0.48
Statistical	0.16
Total	0.51

m_t^{pole} FROM TOP PAIR CROSS SECTION

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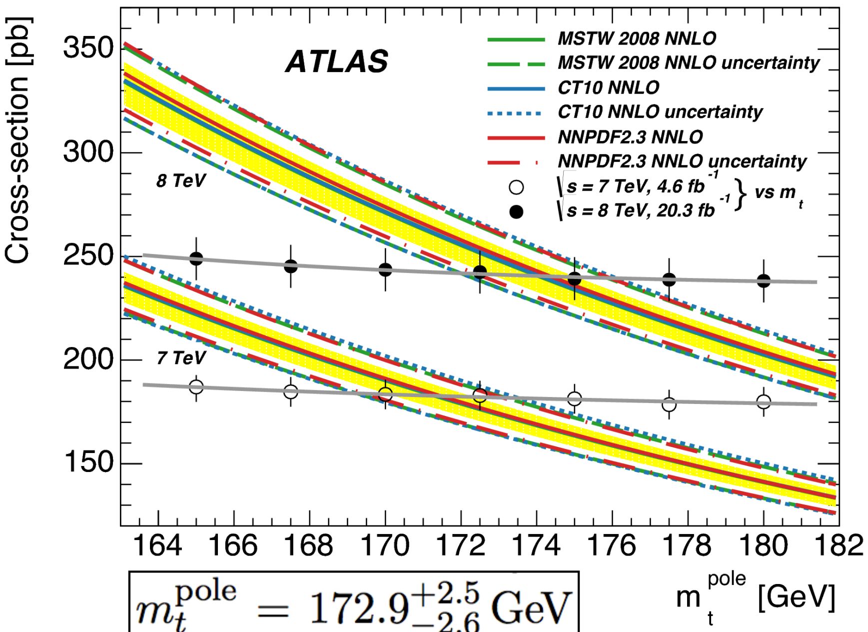

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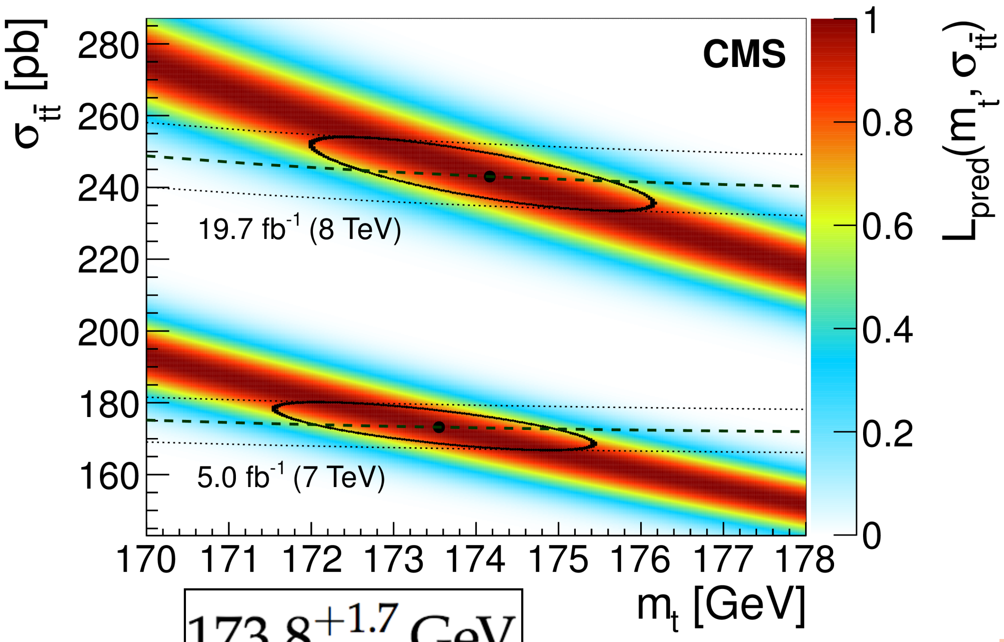

$$173.8^{+1.7}_{-1.8}\ \text{GeV}$$

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- Measurements dominated by theory uncertainties (in particular PDF).
- CMS extrapolation: Could reach 0.5% with a reduction to 5% theory and 2% experimental uncertainties (CMS-PAS-FTR-16-006).