Top quark mass and cross-section with ATLAS and CMS

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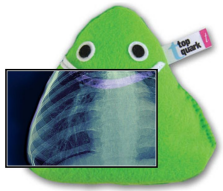
on behalf of the ATLAS and CMS Collaborations

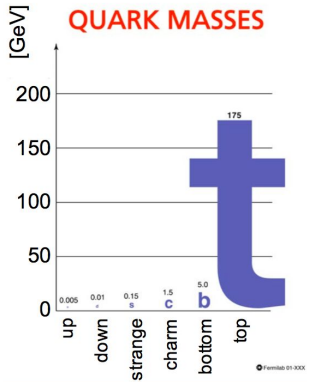


57th Rencontres de Moriond 2023

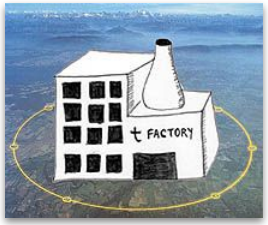
QCD & High Energy Interactions

La Thuile, 28th March 2023

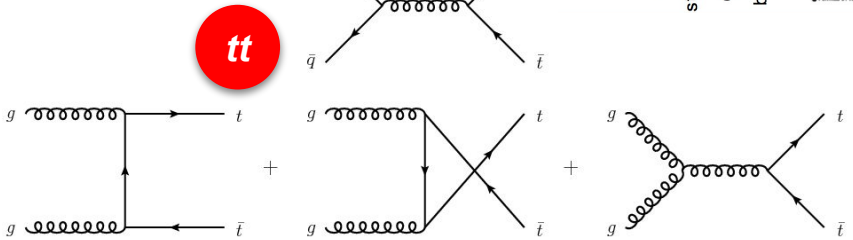
The top quark

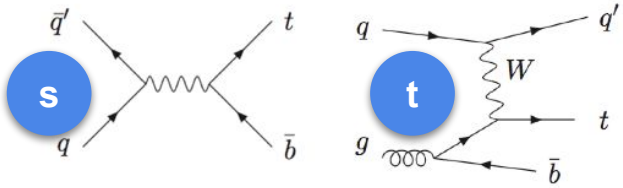


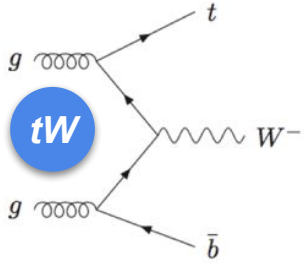
- **Heaviest** elementary particle:
  - same mass scale as *W*, *Z* and Higgs bosons
    - connection to **EW Symmetry Breaking** ?
  - Yukawa coupling $y_t \sim 1$

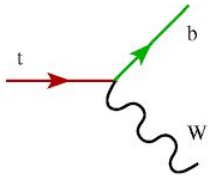


- **Copious production** at the LHC:
  - **strong** pair production: *tt*
  - EW **single production**:
    t-, s- and *Wt*-channels
  - **associated** production:
    tt+γ/W/Z/H, tt+bb, tt+tt...









- **Decays** (*before hadronising*):
  - almost exclusively to ***Wb***

Top precision physics

- Top (**strong**) production **cross-section** & **mass** measurements:
  - entering **high-precision regime** ⇒ **LHC** turning to **top precision factory**

- Essential to control better and better sources of **systematic uncertainties**:
  - **experimental effects**:
    - jet energy scale
    - b-tagging
    - lepton selection efficiencies
    - luminosity…
  - **theory modelling**:
    - $t\bar{t}$ production kinematics
    - top-quark decay
    - parton-shower evolution
    - (b-)quark fragmentation
    - colour reconnection…

▹ arXiv:2212.09379

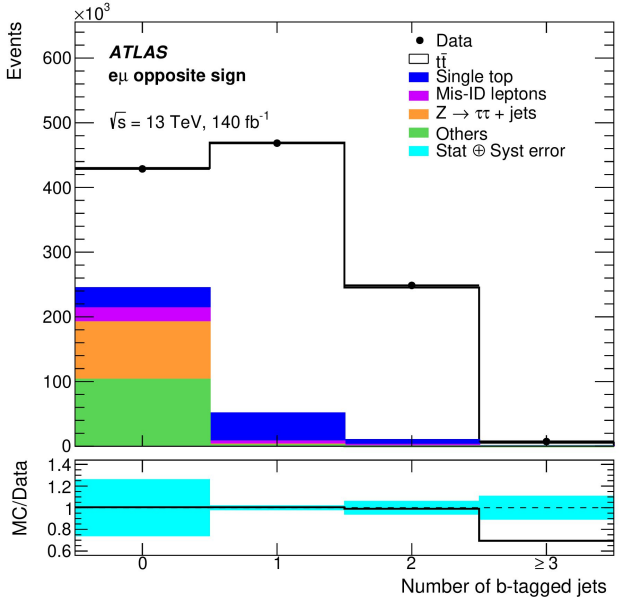
Improved luminosity determination at ATLAS:
Run 2, 13 TeV lumi error: 0.83% !

Disclaimer:
selection of ***some*** of the most recent results by **ATLAS** and **CMS**

tt̄ cross section in eμ events @13 TeV

▹ TOPQ-2018-26 New!

- Full Run 2 pp data, **eμ dilepton** channel
  - inclusive cross-section (total and fiducial)
    + differential vs. a number lepton kinematic variables

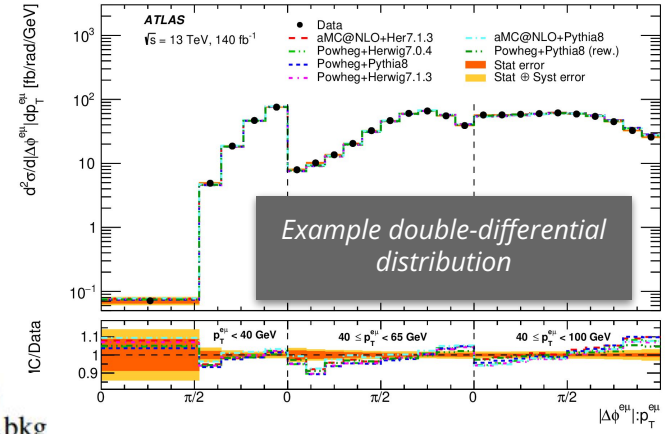


- **b-tag counting method**:
  - minimize **jet** & **b-tagging** syst.

$$N_1^i = \mathcal{L}\sigma_{t\bar{t}}^i G_{e\mu}^i 2\epsilon_b^i(1-\epsilon_b^i C_b^i) + N_{1,\mathrm{bkg}}^i$$

$$N_2^i = \mathcal{L}\sigma_{t\bar{t}}^i G_{e\mu}^i (\epsilon_b^i)^2 C_b^i + N_{2,\mathrm{bkg}}^i$$

effective b-jet selection efficiency



Dominant systematics:

- luminosity 0.9%
- Wt bkg. 0.6%
- top pT rew. 0.6%
- electron isolation 0.5%

σ(tt̄) = 829 ± 1 (stat) ± 13 (syst) ± 8 (lumi) ± 2 (beam) pb **[1.8%]**

theory (NNLO+NNLL): $832\ ^{+20}_{-29}$ (scale) $^{+23}_{-23}$ (mt) $^{+35}_{-35}$ (PDF+α_s) pb

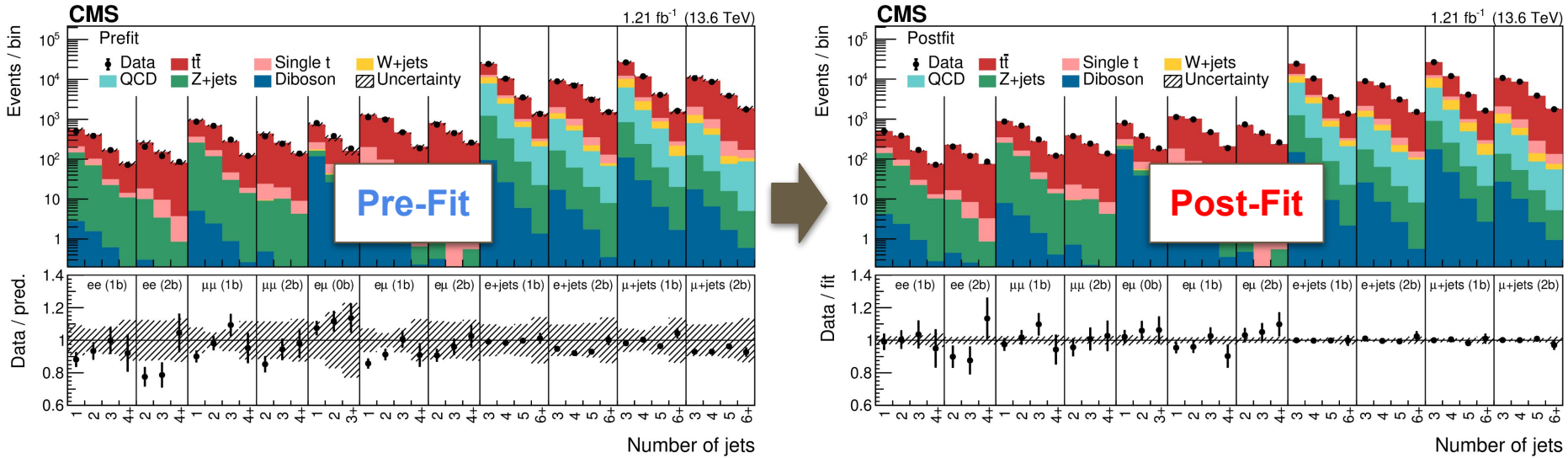
CMS: 791 ± 1 (stat) ± 21 (syst) ± 14 (lumi) pb **[3.1%]** (CMS-TOP-20-001)

Early tt̄ cross-section @13.6 TeV (Run 3)

UPDATED

▹ CMS-TOP-22-012

- Inputs = yields in 1ℓ and 2ℓ with different N^{jet} and $N^{b\text{-}tag}$
- **Profile likelihood fit** to **calibrate *in situ* b-tagging**, **jets** and **lepton SFs**
- Initial version (Sep '22 - CMS-PAS-TOP-22-012) → 7% precision already (6% **luminosity** uncertainty)
  - ***improved*** in publication version

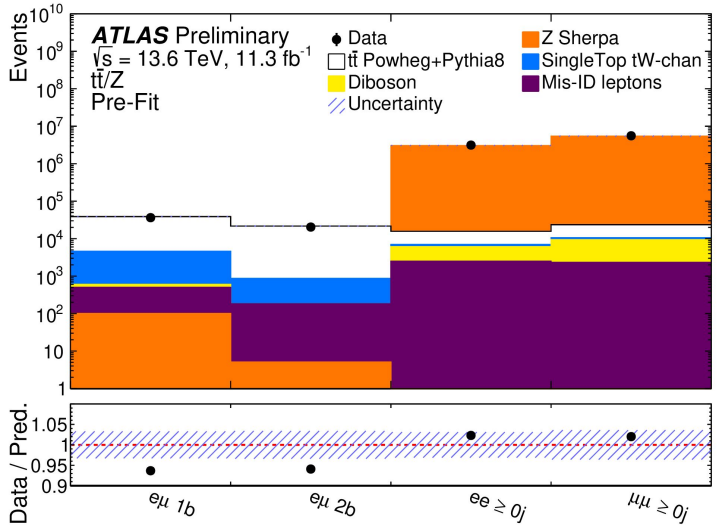


σ(tt̄) = 882 ± 23 (stat+syst) ± 20 (lumi) pb **[3.5%]**

theory: 921^{+29}_{-37} (scale+PDF) pb

Updated tt̄ cross section @13.6 TeV

- **b-tag counting** method, 11 fb^{-1} of Run 3 data:
  - superseding ATLAS-CONF-2022-070 (Nov '22):
    - 1.2 fb^{-1}, 10% **luminosity** uncertainty
- Simultaneous measurement of tt̄ from eμ and Z from ee & μμ:
  - in **ratio R = $\sigma_{t\bar{t}}$ / σ_Z** **luminosity** uncertainty cancelled (+ partially lepton-related systematics) + **PDF** sensitivity



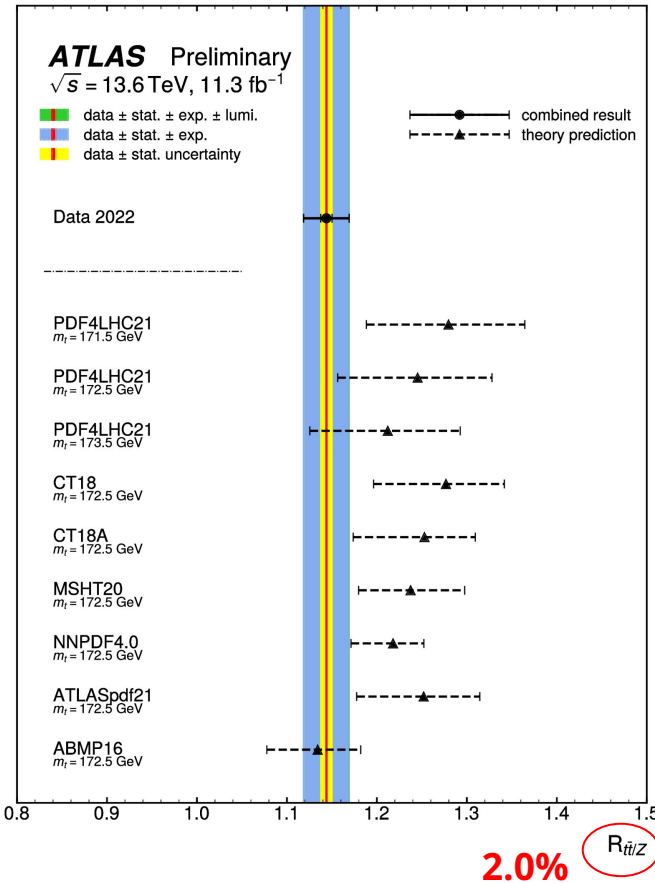
σ(tt̄) = 859 ± 4 (stat)
± 29 (syst+lumi) pb
[3.5%]

theory: 924^{+32}_{-40} (scale+PDF) pb

Main systematics on σ(tt̄):

- luminosity 2.3%
- lepton reco. 1.8%
- tt̄ PS & had. 1.1%
- pile-up 1.1%

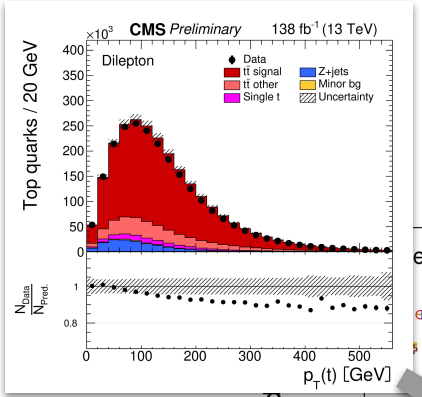
▹ ATLAS-CONF-2023-006 New!



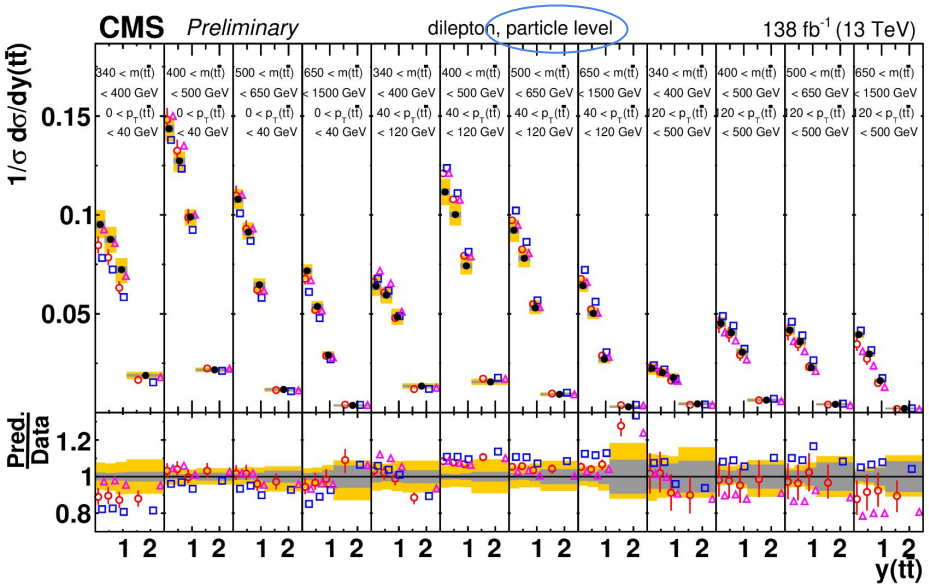
2.0%
precision

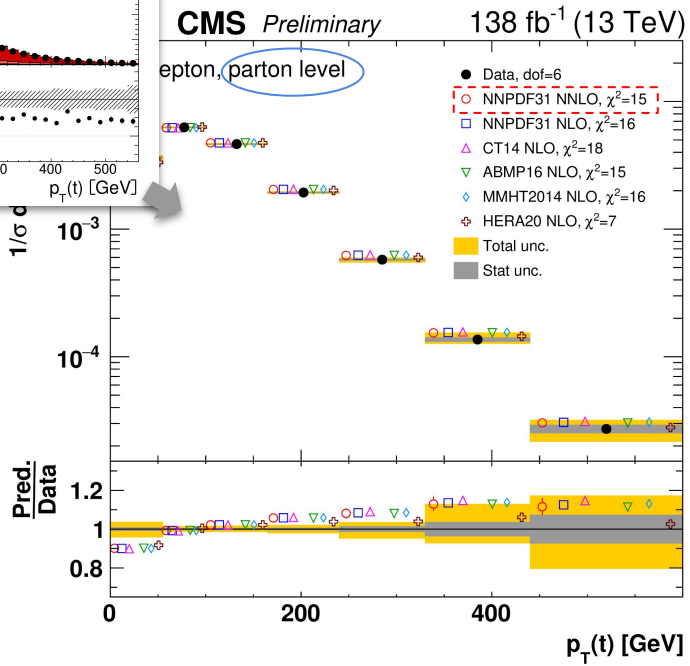
tt̄ and tt̄+jets fully differential cross-section @13 TeV

- Full Run 2 pp data, **dilepton** channel
  - **single**, **double** and **triple** differential σ
  - ***parton*** and ***particle*** level
  - as a function of number of additional jets and kinematics
- Comparison with **NLO** and **NNLO** predictions

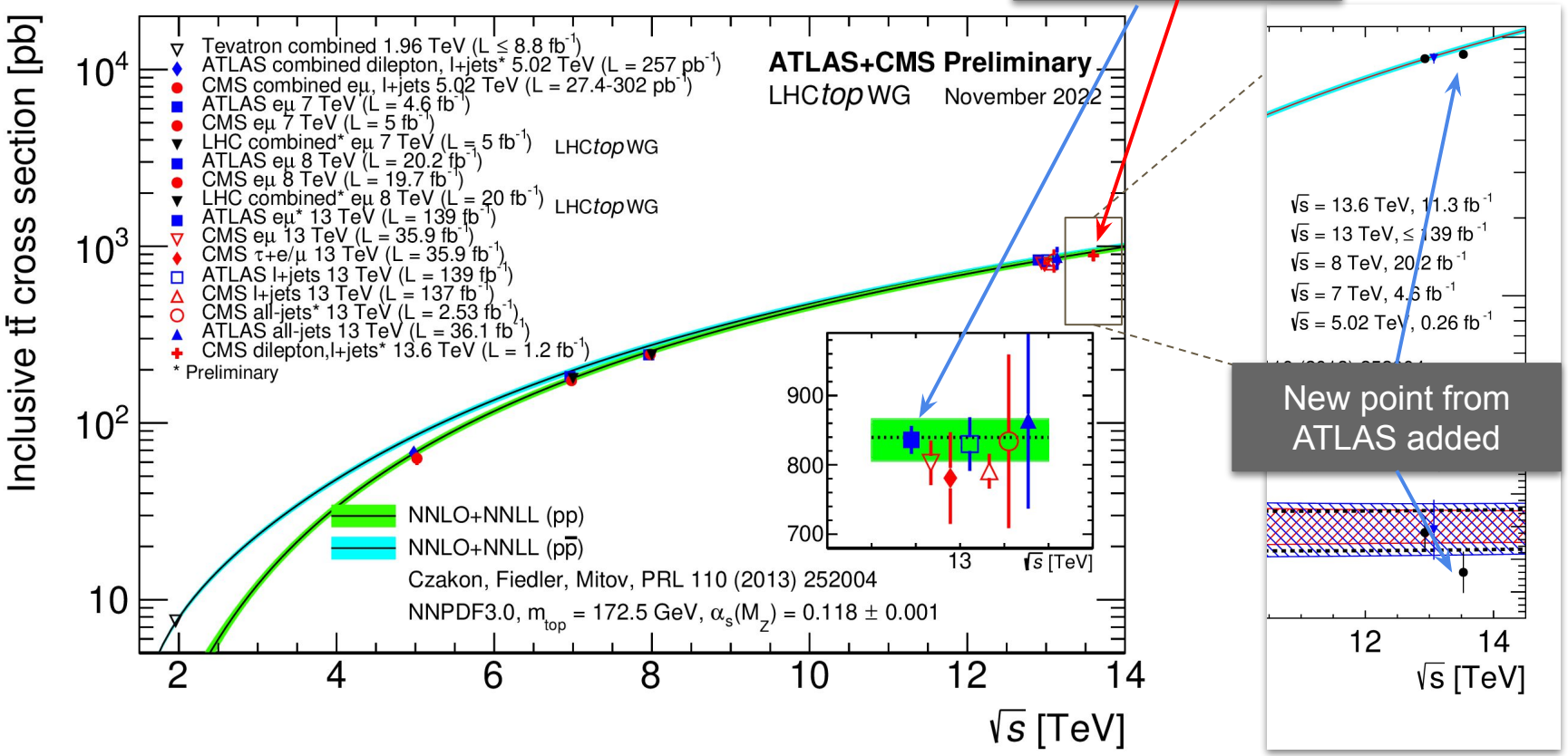


▹ CMS-PAS-TOP-20-006



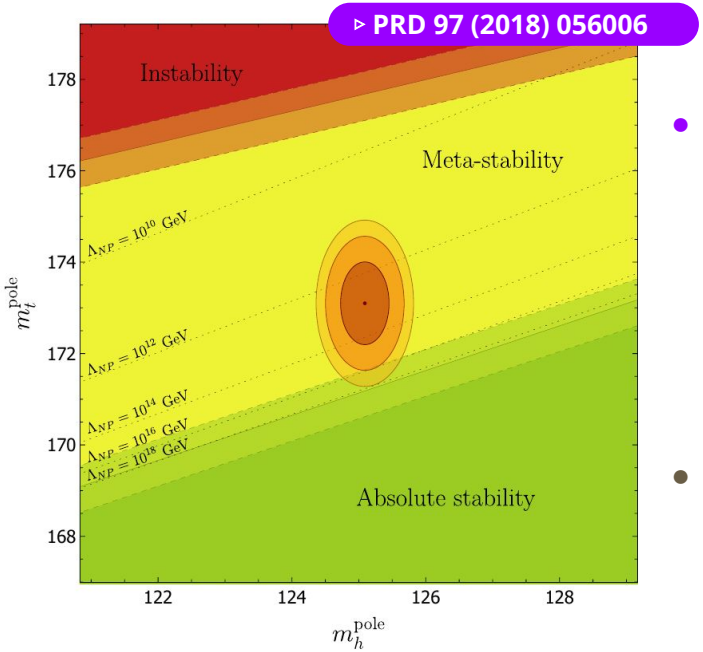


tt̄ cross-section summary

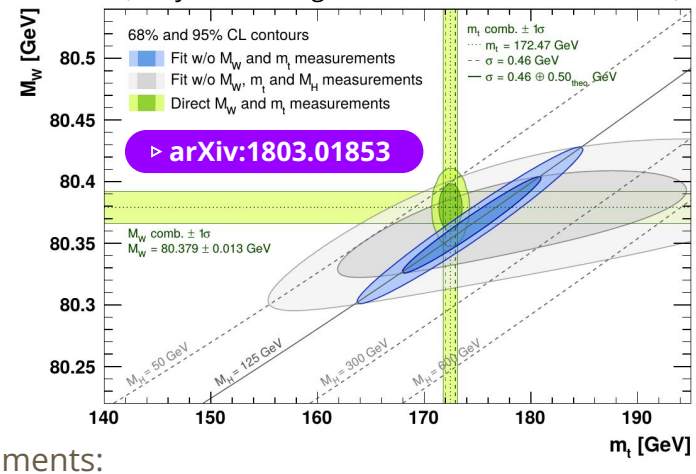


Top-quark mass

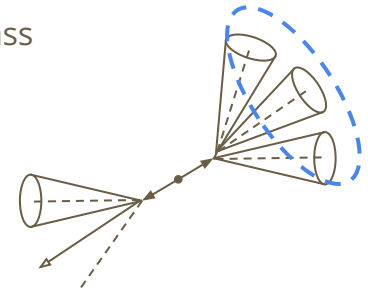
- $m_t + m_W + m_H$ measurements → over-constraints to SM fits
  - **measurements** can be compared to **EW fit predictions** to probe validity of SM
  - m_t important to determine SM **vacuum stability**



(not yet including latest W mass measurements)



- **Direct/standard** "m_t" measurements:
  - extraction from total or partial invariant mass of top decay products
  - relying on jets, parton showers (LO), non-perturbative effects
    ⇒ measuring "$m_t^{\rm MC}$"



- **Indirect** measurements from cross-sections (*inclusive or differential*)
  - in a well-defined renormalization scheme, e.g. $m_t^{\rm pole}$
    $\sigma^{\rm theor.}(\alpha_s, m_t, \text{PDF}, \mu_F, \mu_R, \ldots)$ vs. $\sigma^{\rm meas.}$

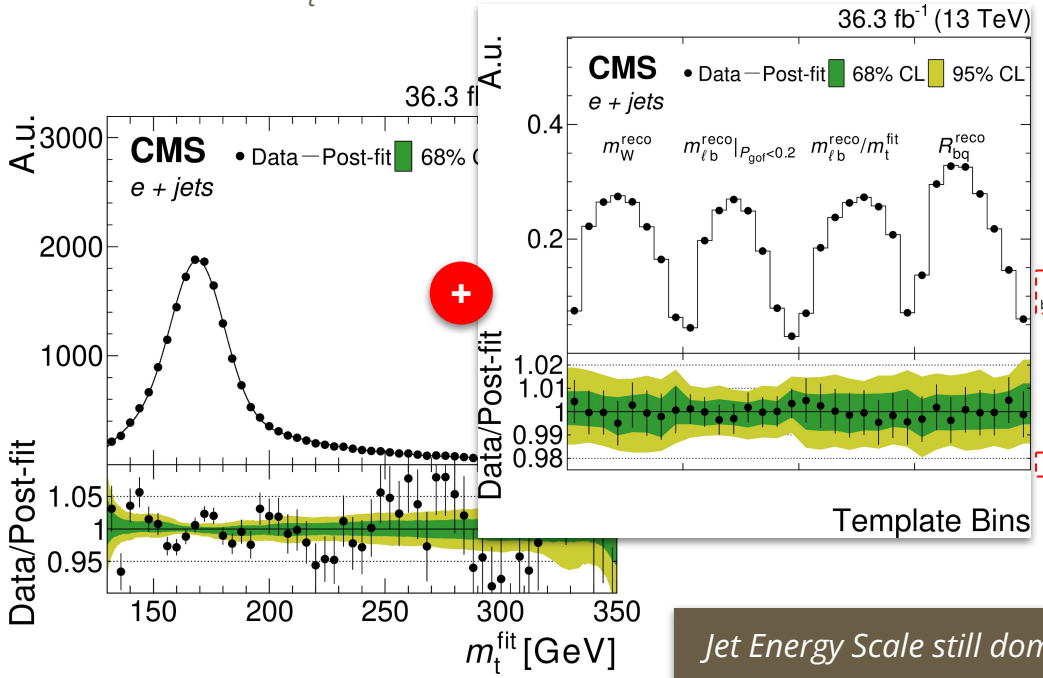
m(t) in ℓ+jets channel with profile likelihood

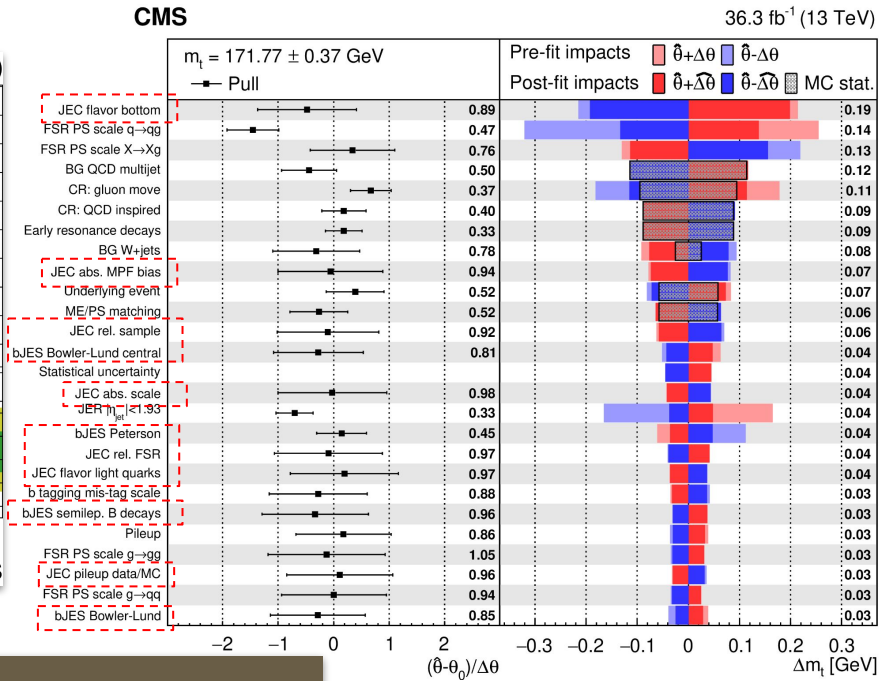
UPDATED

▹ CMS-TOP-20-008

- **Kinematic fit** in each event to extract m_t^{fit}
- Simultaneous fit of **5 observables** with **profile likelihood** → **in-situ constraint** of systematics
- Unpreceded precision result:

  m_t = 171.77 ± **0.37** GeV





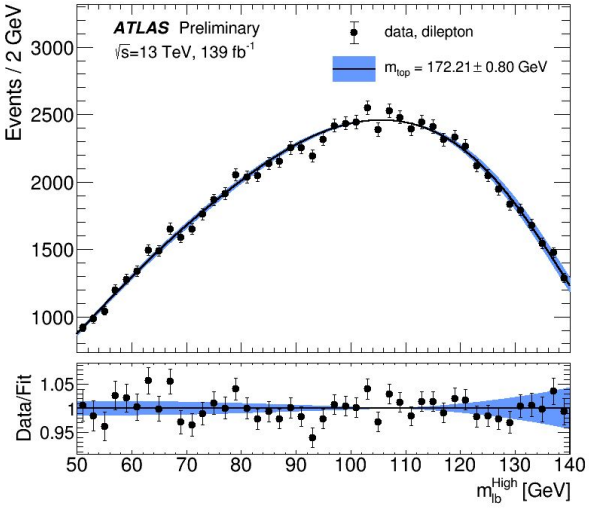
Jet Energy Scale still dominant uncertainties

m(t) in dilepton channel with template fit

UPDATED

▹ ATLAS-CONF-2022-058

- Partial m_t reconstruction:
  - $m(\ell b)$ with **DNN** for **ℓ-b pairing**
  - ℓ-b with highest $p_T^{\ell b}$ selected
- **Selection optimized** to minimize systematics:
  - $DNN^{High} > 0.65$
  - $p_T^{\ell b} > 160$ GeV
  - selected ℓ-b has max p_T^{b}



- **Unbinned likelihood fit**, calibrated with MC simulation
- Improving w.r.t. Run 1:
  $m_t = 172.21 \pm \underline{\mathbf{0.70}}$ GeV ± 0.39 GeV
  (recoil scheme in top decay)

	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single top modelling	0.01 ± 0.01
Background normalisation	0.03 ± 0.02
Jet energy scale	0.37 ± 0.02
b-jet energy scale	0.12 ± 0.02
Jet energy resolution	0.13 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.11 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.39 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.80 ± 0.06

m(t) from boosted tt̄

▹ CMS-TOP-21-012

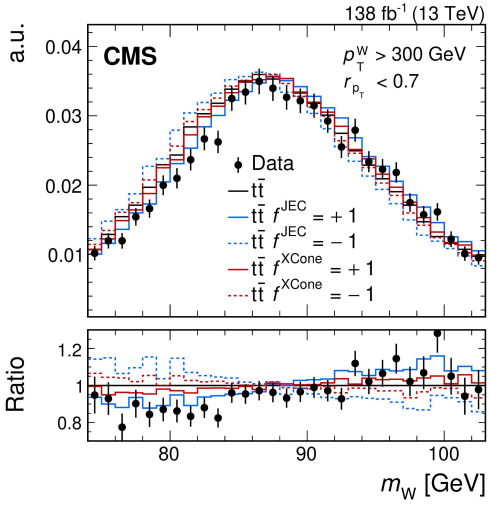
- Extracting top mass from mass of **large-*R* jet** with p_T > 400 GeV
  - **unfolding** to particle-level, then extract m_t
  - jet mass **calibrated using *W→jj***
  - **FSR reduced** by studying angular relations of the jet substructure

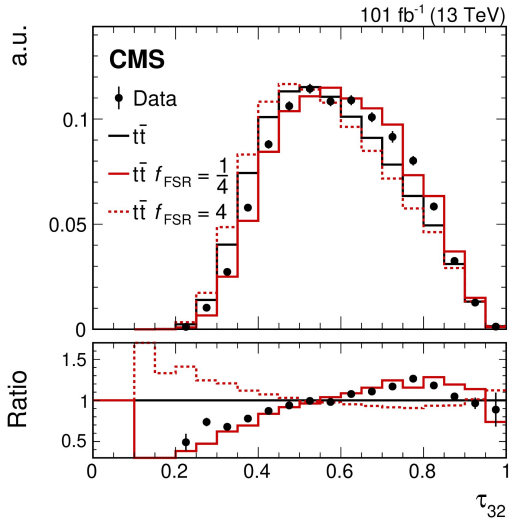
m_t = 172.76 ± **0.81** GeV

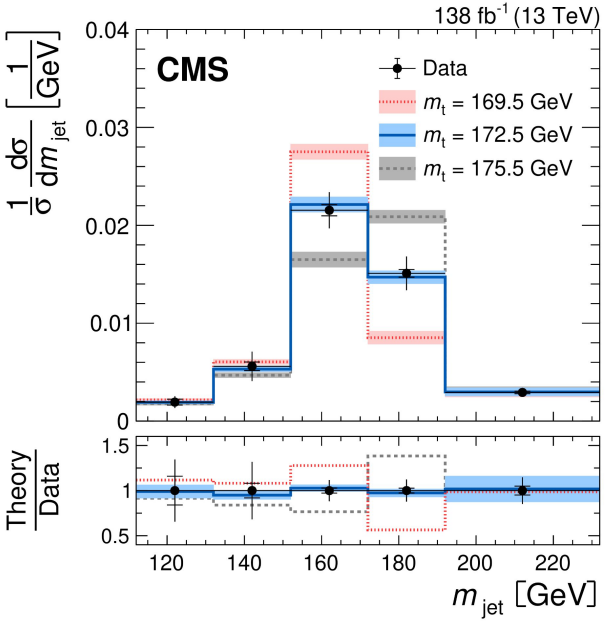
Potential to measure m_t^{pole}

using analytical predictions for m_{jet} e.g.:

▹ PRD 100, 074021 (2019)



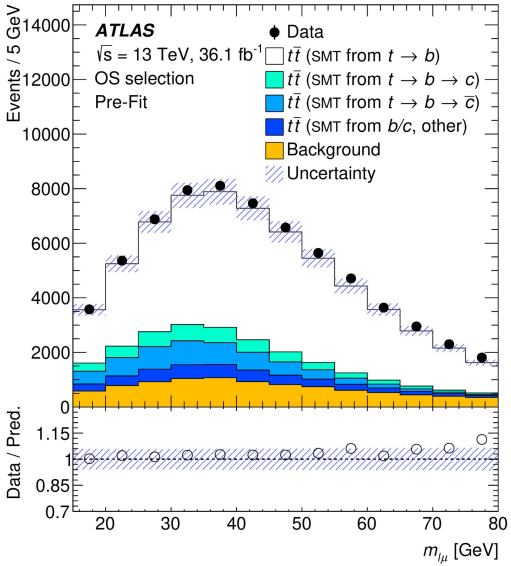


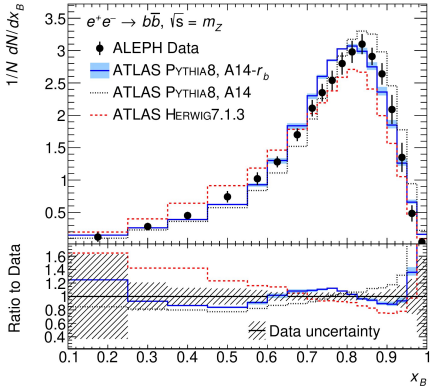


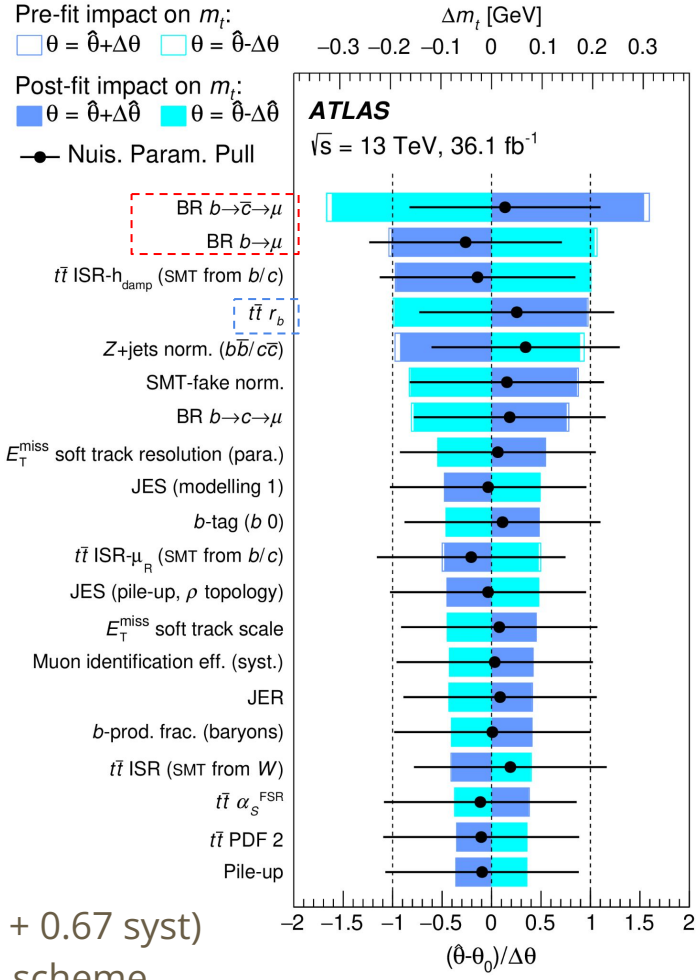
m(t) with soft muon tagging

▹ arXiv:2209.00583

- Non-standard technique, using **prompt-lepton – soft-muon invariant mass, $m_{\ell\mu}$**:
  - purely leptonic observable
    - **reduced systematics from jets**
  - modelling of ***b*-hadron production & decay** critical
    - b-frag. retuned to LEP data







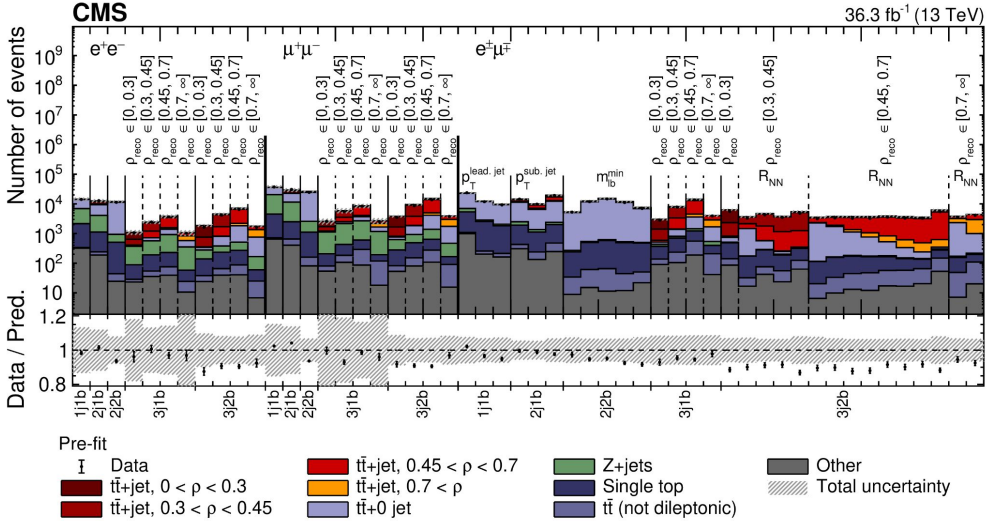
m_t = 174.41 ± **0.77** GeV (0.40 stat + 0.67 syst)
+ 0.25 GeV from recoil scheme

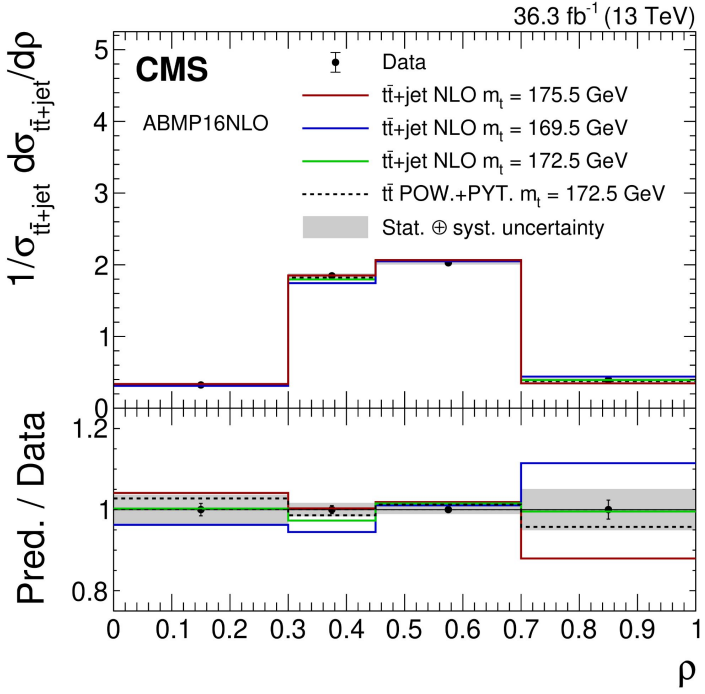
Indirect m(t) from tt̄+1j

▹ CMS-TOP-21-008

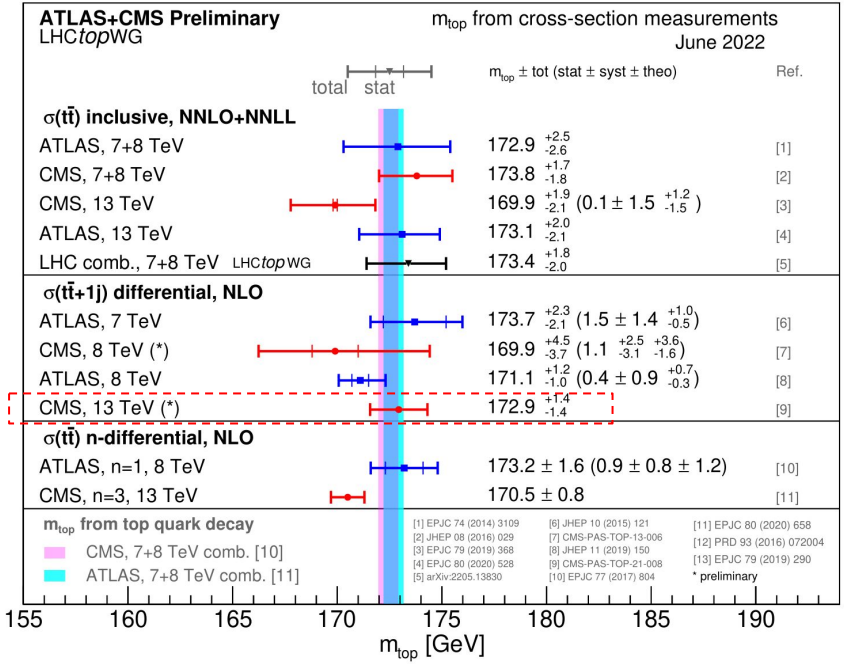
- **Jet emission** in $t\bar{t}$ sensitive to m_t
- Quantity $\rho \propto 1\backslash m(t\bar{t}+1\text{jet})$ used to extract top **pole mass**
- **Dilepton** $t\bar{t}$+1jet selection
- **Profile-likelihood unfolding**
  - allows ***combining*** several categories
- Comparison with **NLO predictions**:

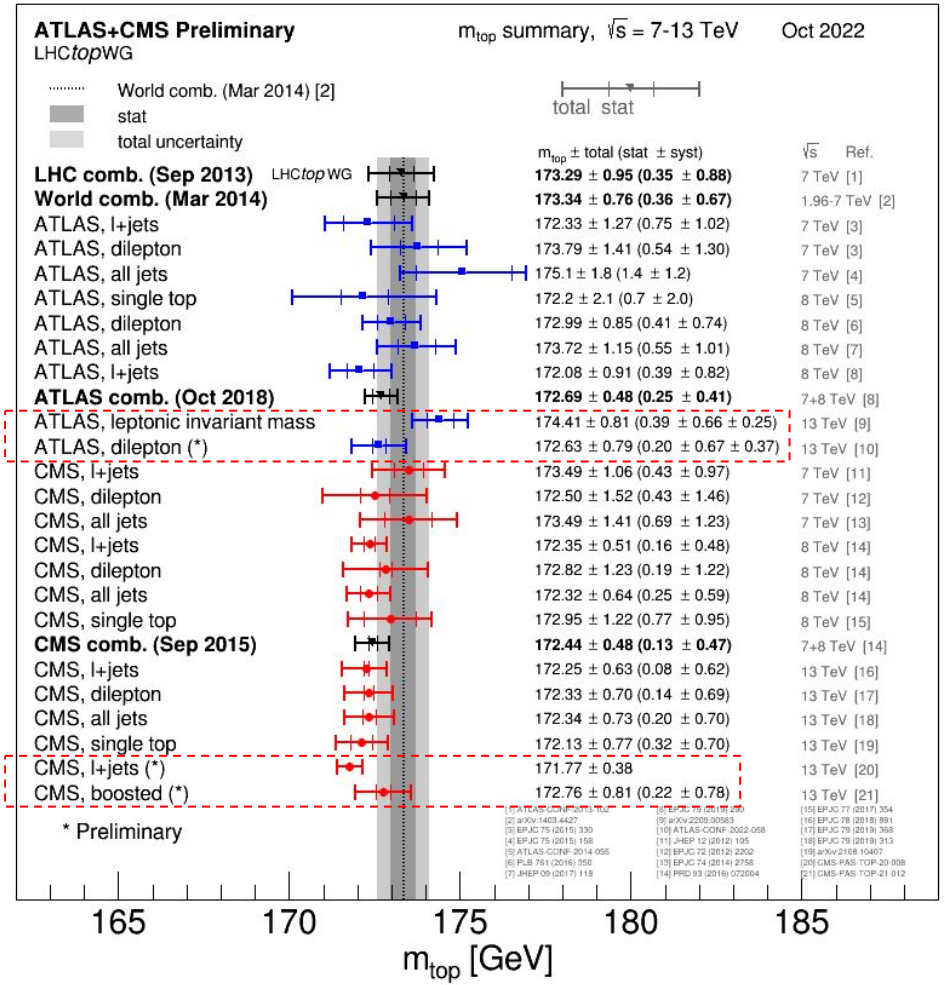
$$m_t^{pole} = 172.94 \pm \underline{\mathbf{1.37}}\ \text{GeV}$$





Top Mass Summary





Conclusions

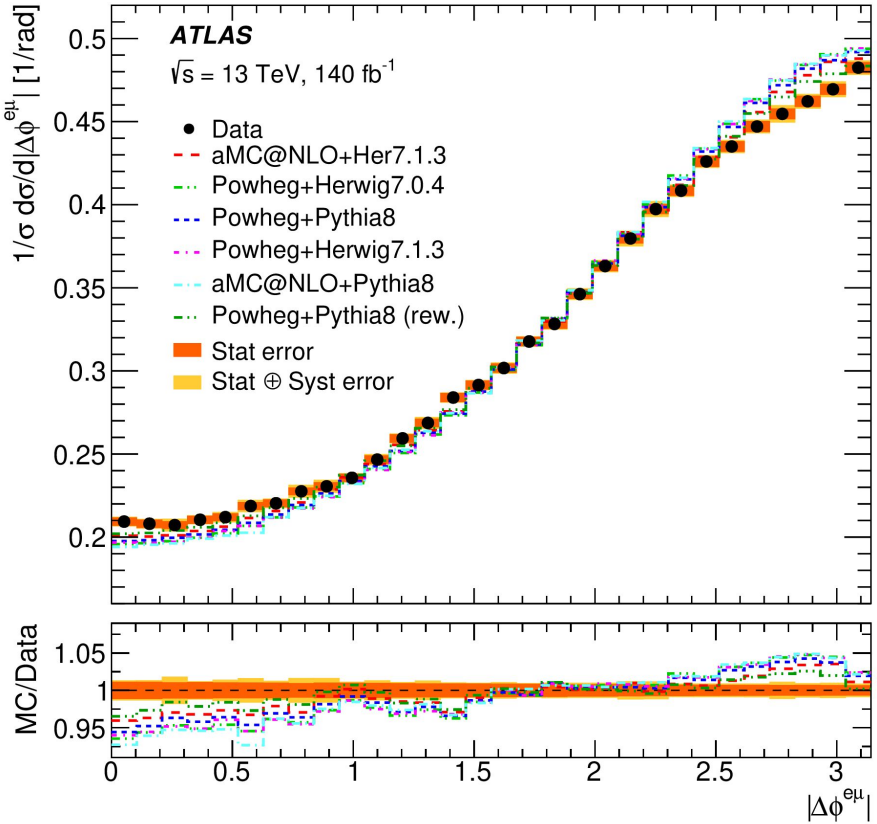
- **Top cross-section & mass measurements in CMS & ATLAS reaching unpreceded performance**:
  - more and more ***precise*** measurements using **advanced analysis and statistical methods**
  - overall ***good agreement*** with SM predictions… *until now*…
- **Analysis of Run 2 data not yet finished**:
  - full 13 TeV data potentials still to be fully exploited
- **First Run 3 measurements**:
  - $t\bar{t}$ one of the first processes rediscovered at the new centre-of-mass energy
  - early measurements ***essential*** to **test** full functionality of the **detectors** and **re-warming-up** the **collaborations**

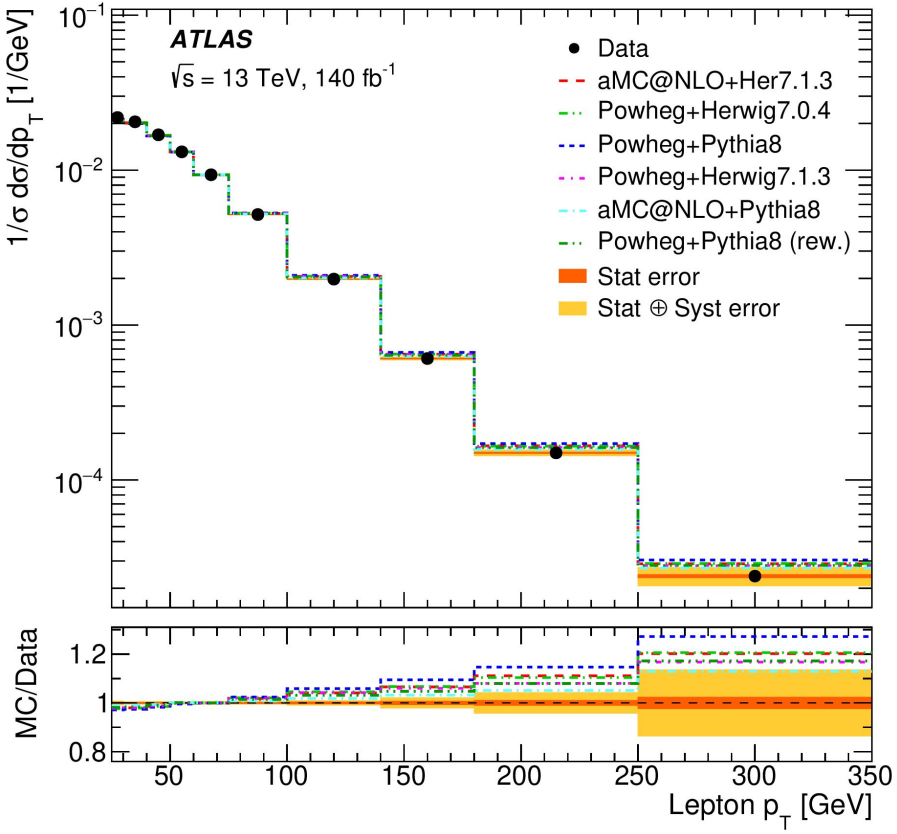
Backup

ATLAS tt̄ Run 2

Source of uncertainty	$\Delta\sigma_{t\bar{t}}^{\text{fid}}/\sigma_{t\bar{t}}^{\text{fid}}$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	0.15	0.15
MC statistics	0.04	0.04
Matrix element	0.12	0.16
h_{damp} variation	0.01	0.01
Parton shower	0.08	0.22
$t\bar{t}$ + heavy flavour	0.34	0.34
Top p_{T} reweighting	0.19	0.58
Parton distribution functions	0.04	0.43
Initial-state radiation	0.11	0.37
Final-state radiation	0.29	0.35
Electron energy scale	0.10	0.10
Electron efficiency	0.37	0.37
Electron isolation (in situ)	0.51	0.51
Muon momentum scale	0.13	0.13
Muon reconstruction efficiency	0.35	0.35
Muon isolation (in situ)	0.33	0.33
Lepton trigger efficiency	0.05	0.05
Vertex association efficiency	0.03	0.03
Jet energy scale & resolution	0.10	0.10
b-tagging efficiency	0.07	0.07
$t\bar{t}/Wt$ interference	0.37	0.37
Wt cross-section	0.52	0.52
Diboson background	0.34	0.34
$t\bar{t}V$ and $t\bar{t}H$	0.03	0.03
Z + jets background	0.05	0.05
Misidentified leptons	0.32	0.32
Beam energy	0.23	0.23
Luminosity	0.93	0.93
Total uncertainty	1.6	1.8

ATLAS tt̄ Run 2





CMS & ATLAS tt̄ Run 3

CMS

Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.7
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.6
ME scale, backgrounds	0.1
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Single t background	1.0
Z+jets background	0.3
W+jets background	0.0
Diboson background	0.5
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.6
Integrated luminosity	2.3

ATLAS

	Category	Uncert. [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{\text{fid.}}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	1.1	0.01	1.0
	$t\bar{t}$ scale variations	0.2	< 0.01	0.2
	Top quark p_{T} reweighting	0.6	0.02	0.5
Z	Z scale variations	0.2	0.5	0.3
Bkg.	Single top modelling	0.4	0.01	0.4
	Diboson modelling	0.1	0.06	< 0.01
	Mis-Id leptons	0.5	0.1	0.5
Lept.	Electron reconstruction	1.0	1.1	0.5
	Muon reconstruction	1.5	1.2	0.8
	Lepton trigger	0.4	0.7	0.8
Jets/tagging	Jet reconstruction	0.4	0.1	0.3
	Flavour tagging	0.2	0.01	0.2
	PDFs	0.4	0.2	0.4
	Pileup	1.1	1.1	< 0.01
	Luminosity	2.3	2.2	0.3
	Systematic Uncertainty	3.5	3.0	2.0
	Statistical Uncertainty	0.5	0.03	0.5
	Total Uncertainty	3.5	3.0	2.0

ATLAS tt̄ Run 3