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Top-quark mass measurement results and prospects

26/12/25 (Fri.)

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From Nagoya University

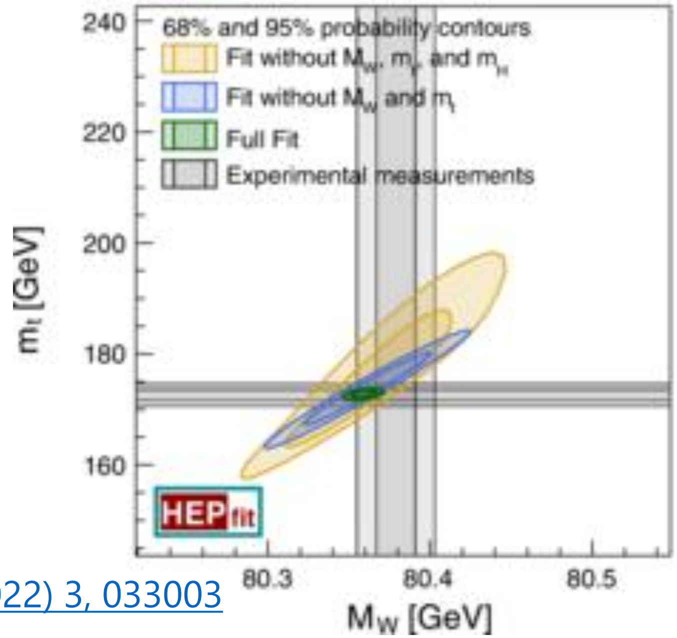
Tera-Scale workshop 2025 @University of Osaka

Motivation of top-quark mass measurement

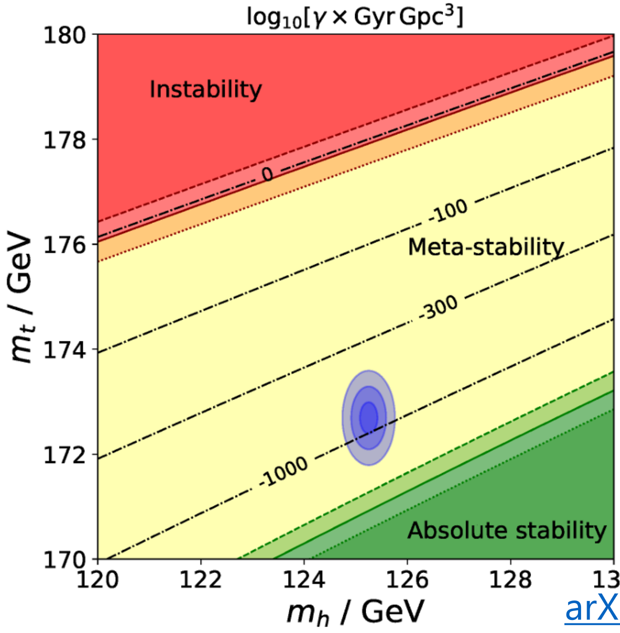
Top quark is the heaviest elementary particle among the observed ones.

- Top-quark mass (m_{top}) is a fundamental parameter of the SM.
  - Relationship among the Higgs-boson mass, W-boson mass, and m_{top} helps to test the SM by comparing to the EW fit predictions.
  - The Higgs quartic coupling λ at high scales depends on the m_{top} and determine the EW vacuum stability.

→ Precise m_{top} measurements are crucial for the validation of the SM.



PRD 106 (2022) 3, 033003



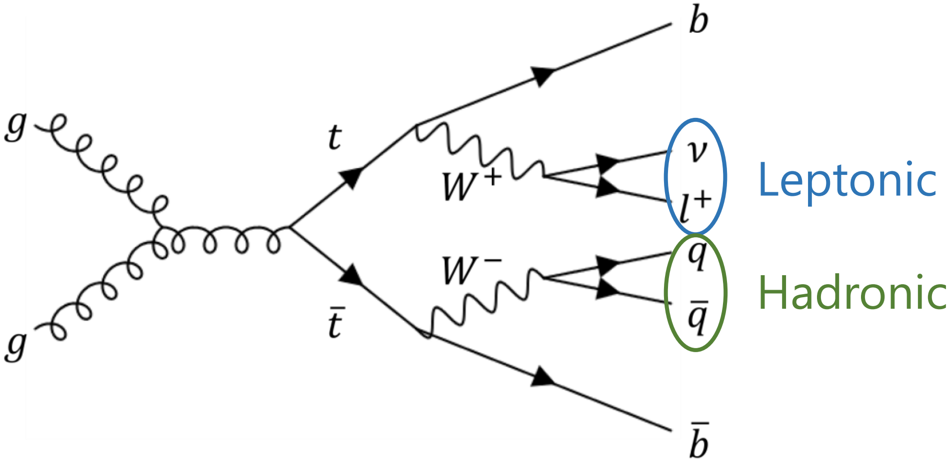
arXiv:1707.09301

Top-quark mass measurements

- Direct measurements
  - Reconstruct the top quark from final-state kinematics and extract the mass by comparing distributions with MC predictions.
  - Measure the MC mass: input to MC simulations, including non-perturbative QCD effects modeled by the MC framework.
- Indirect measurements
  - Derived from measurements of the $t\bar{t}$ production cross section.
  - Measure the pole mass (or similar): parameter in quantum field theory and more straightforward to interpret theoretically.

$t\bar{t}$ events are classified into three decay channels based on the W-boson decay modes:

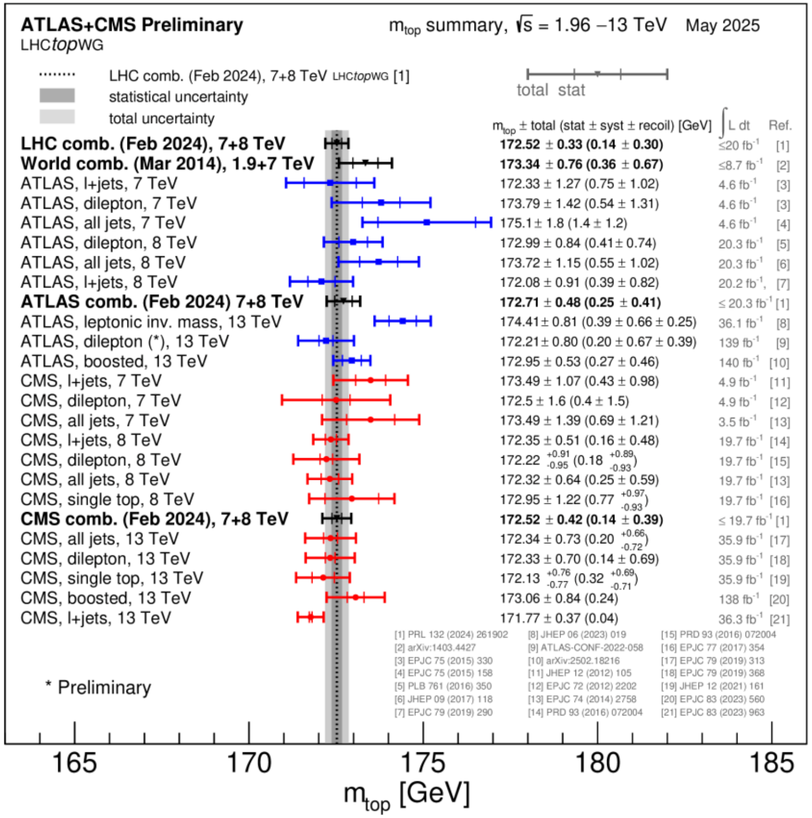
- Dilepton (~7%)
- All hadronic (~55%)
- ℓ+jets (~38%)



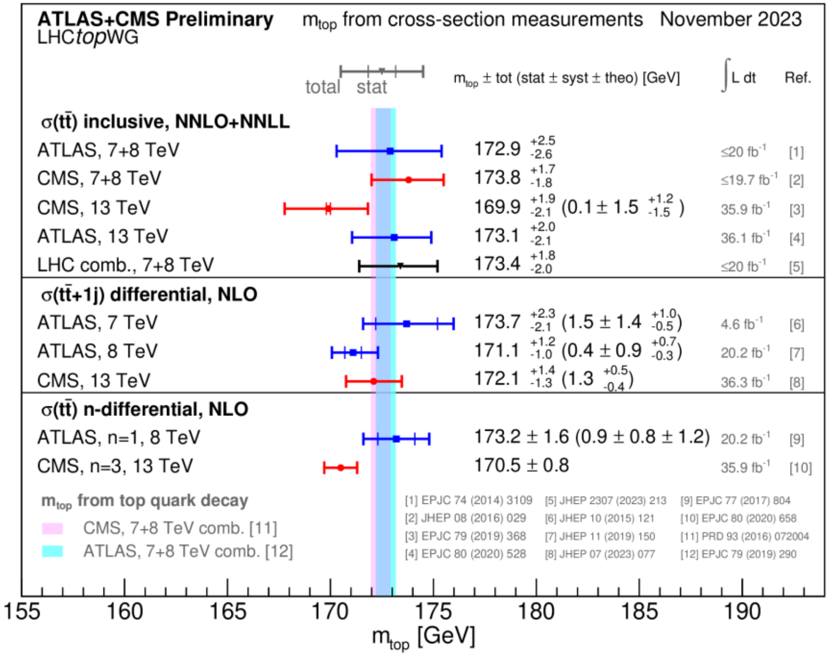
LHC results

ATL-PHYS-PUB-2025-025

Direct measurements



Indirect measurements



LHC Run 1 combined results:

$\mathbf{172.52 \pm 0.33}$ **GeV**

$\mathbf{173.4^{+1.8}_{-2.0}}$ **GeV** ($\sigma(t\bar{t})$ inclusive)

The relation between MC mass and the pole mass remains an open question.

- The conversion is estimated to have an ambiguity (0.5—1 GeV).

Ann. Rev. Nucl. Part. Sci.70, 225 (2020)

Top mass measurement in 2025

Using Run 1 dataset, m_{top} has been already measured with high precision.

→ Further improvements require reducing systematic uncertainties, e.g. by exploiting rare phase space regions.

This year, LHC reported three m_{top} measurements.

- Full Run 2 dataset ($\sqrt{s}$=13 TeV, 140 fb^{-1}) is used.

- **Measurement of the top quark mass with the ATLAS detector using $t\bar{t}$ events with a high transverse momentum top quark**
  - Physics Letters B 867 (2025) 139608
- **Measurement of the top-quark mass using decays with a J/ψ meson at $\sqrt{s}$=13 TeV with the ATLAS detector**
  - arXiv:2511.23091 (Submitted to JHEP)

Direct measurements

- **Measurement of the top-quark pole mass in dileptonic $t\bar{t}$ + 1-jet events at $\sqrt{s}$=13 TeV with the ATLAS experiment**
  - JHEP 12 (2025) 023

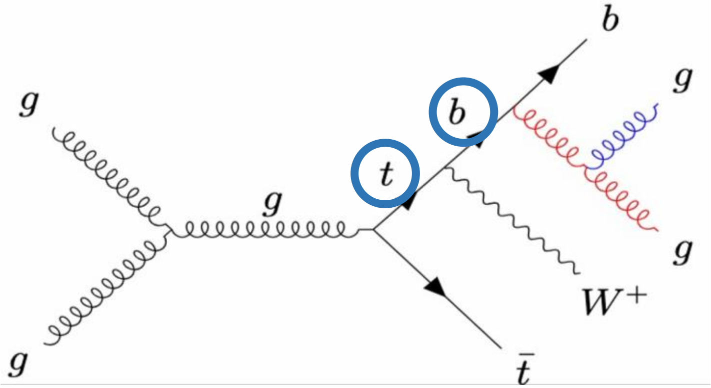
Indirect measurements

Significant uncertainties in MC mass

Uncertainties in the Jet Energy Scale (JES)

- JES calibration restores the jet energy to that of jets reconstructed at the particle level.
- One of the dominant uncertainties in Run 1 measurements.

Uncertainty from the choice of secondary gluon radiation models.



Model in Pythia8	Recoiler
Recoil-To-Colour=ON	b
Recoil-To-Top (new)	t

- Difference between the two models taken as uncertainty.

  - A new model was proposed by the Pythia8 authors a few years ago.
- Affects $p_\mathrm{T}(b\text{ jet})$, $p_\mathrm{T}(\ell)$, $\Delta R(\ell,\text{jet})$, and b-quark fragmentation modelling.
- Currently, only ATLAS accounts for this uncertainty.

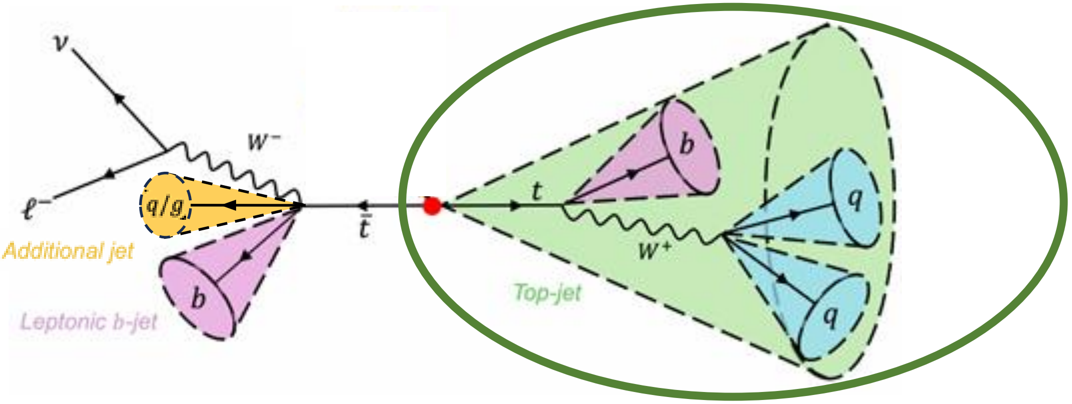
MC mass using high p_{T} top quark

PLB 867 (2025) 139608

Using a rare phase space:
events where the top quarks have high transverse momenta (p_{T}).

- **The first measurement using boosted topology in ATLAS.**

In the boosted regime, top decay products are collimated into a single large-*R* jet (**top-jet**).



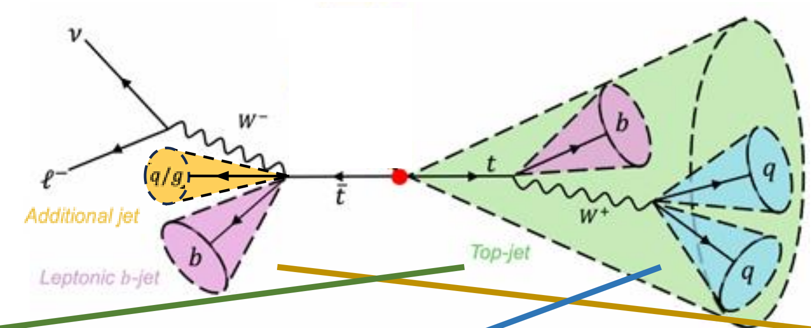
Clear identification of jets from a single top quark,
reducing systematics from jet combinations.

Performing **a simultaneous profile likelihood fit to three observables.**

- One is the invariant mass of top-jet (m_J), sensitive to m_{top}.
- **The additional ones are to control and reduce syst uncertainties.**

Observables

Tuned to be mutually uncorrelated.



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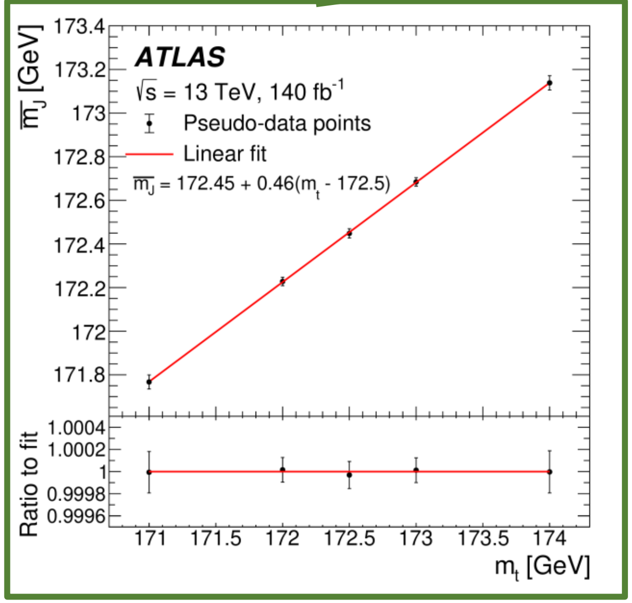

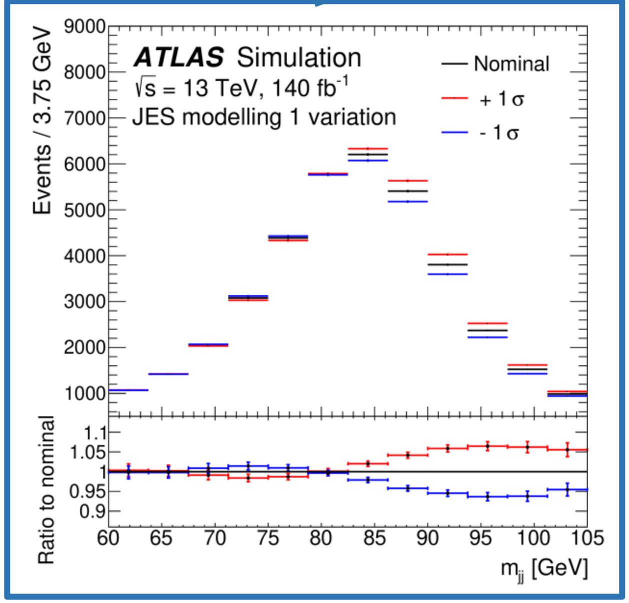

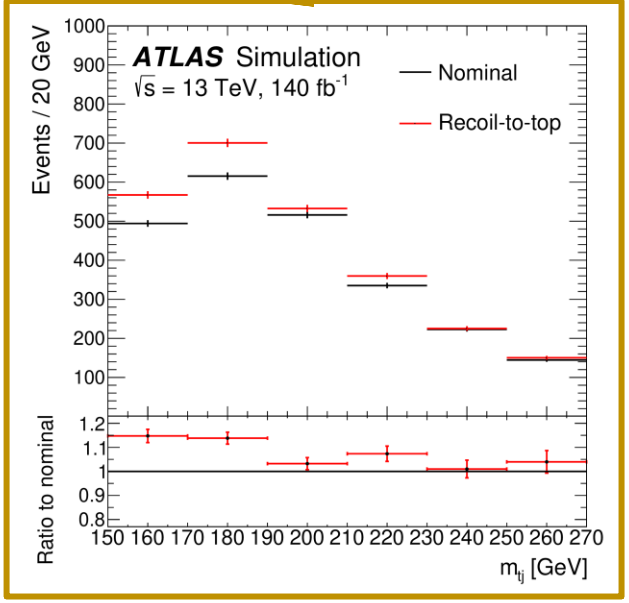

Mean value of m_J ($\overline{m_J}$)

- Calculated with $145<m_J<205$ GeV events.
- Sensitive to m_{top}.

Inv. mass of the two non b-tagged constituent jets (m_{jj})

- Sensitive to JES.

Inv. mass of the semi-leptonically decaying top quark and the closest additional jet (m_{tj})

- Sensitive to QCD radiation.

Impact on the uncertainty estimation

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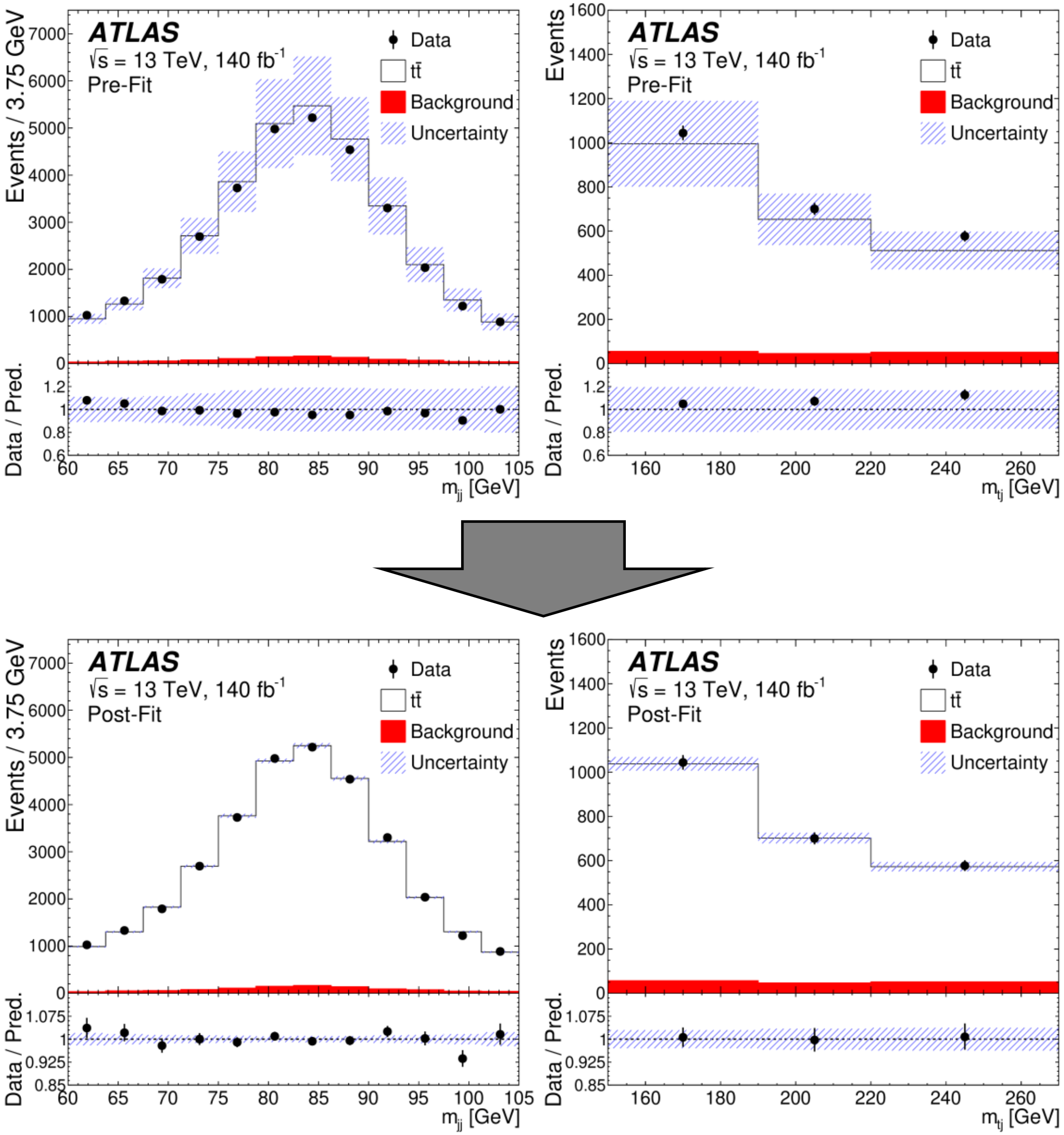


m_{top}=172.5 GeV:

Source	Uncertainty [GeV]	
	Pre fit	Post fit
JES	1.4	0.26
ISR & FSR	0.82	0.14
Recoil	0.36	0.08
Total	1.7	0.51

Significant improvement on the precision by adding m_{jj} and m_{tj} to the fit.

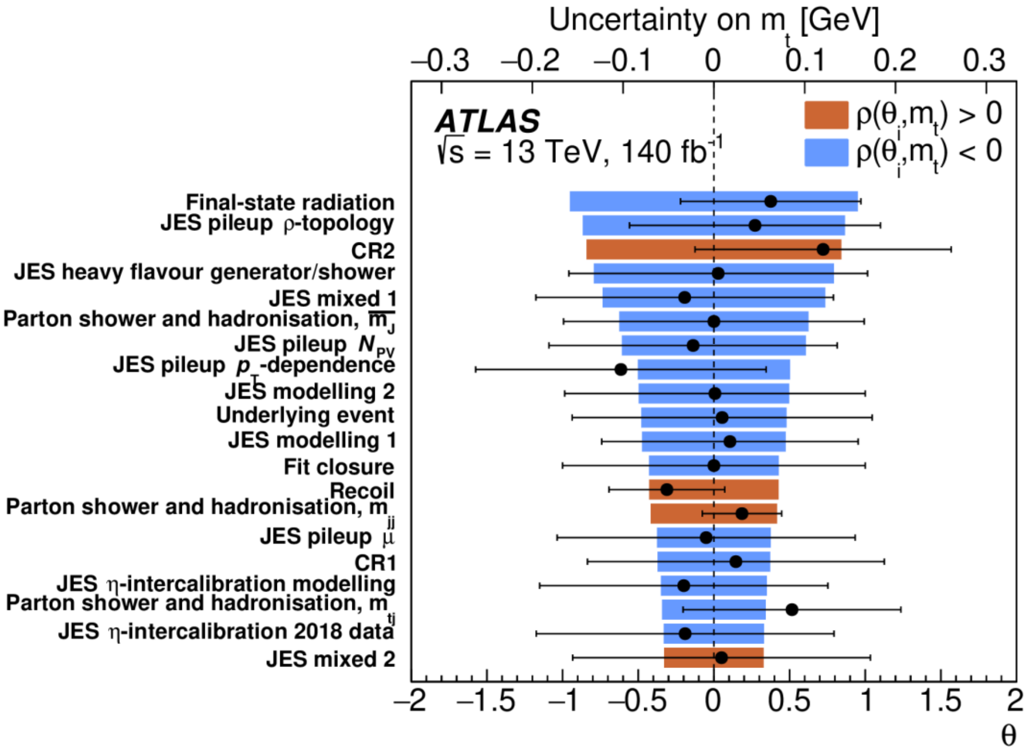
Result

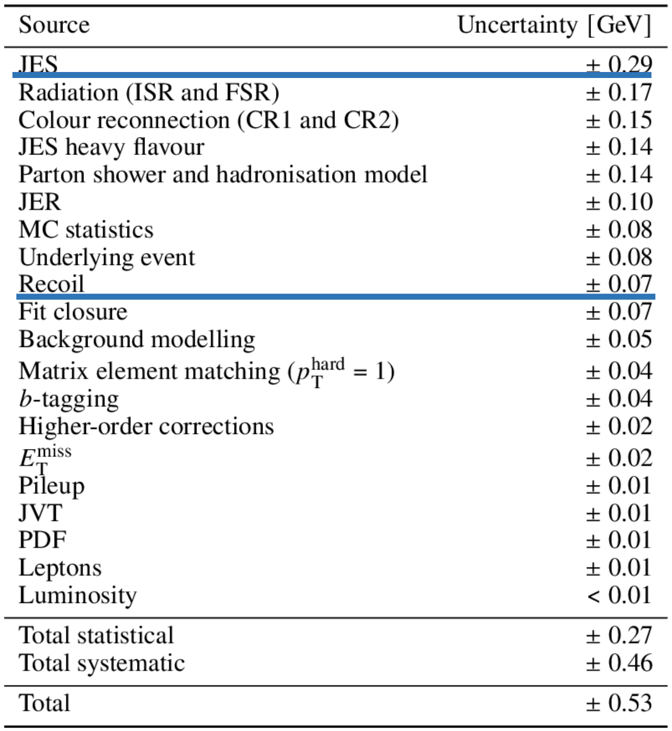
[PLB 867 (2025) 139608](PLB 867 (2025) 139608)

$$\boxed{m_{\mathrm{top}} = 172.95 \pm 0.53\ \mathrm{GeV}}$$

The most precise ATLAS m_{top} measurement in a single channel.

The profile likelihood fit with three observables successfully reduced the uncertainties due to JES and recoil effect by ~80%.





Source	Uncertainty [GeV]
JES	± 0.29
Radiation (ISR and FSR)	± 0.17
Colour reconnection (CR1 and CR2)	± 0.15
JES heavy flavour	± 0.14
Parton shower and hadronisation model	± 0.14
JER	± 0.10
MC statistics	± 0.08
Underlying event	± 0.08
Recoil	± 0.07
Fit closure	± 0.07
Background modelling	± 0.05
Matrix element matching ($p_T^{\mathrm{hard}} = 1$)	± 0.04
b-tagging	± 0.04
Higher-order corrections	± 0.02
E_T^{miss}	± 0.02
Pileup	± 0.01
JVT	± 0.01
PDF	± 0.01
Leptons	± 0.01
Luminosity	< 0.01
Total statistical	± 0.27
Total systematic	± 0.46
Total	± 0.53

MC mass using J/ψ meson

arXiv:2511.23091

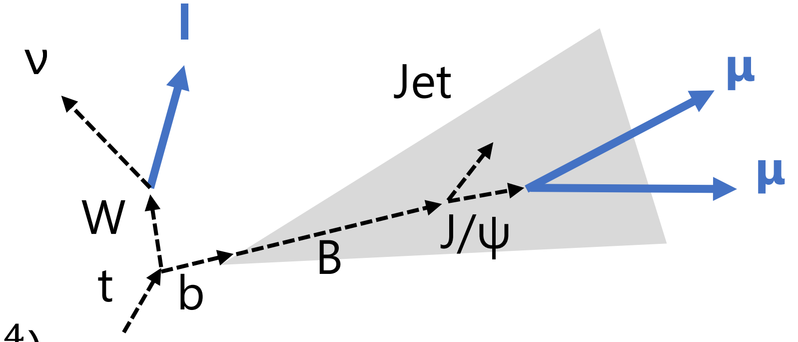
Motivations:

- Purely leptonic observables.
  → Less sensitive to JES than the ones from jet reconstruction.
- Partial reconstruction of decay.
  → Less sensitive to top p_T modelling than pure prompt lepton kinematics.

Complementary measurement with different syst. uncertainty sources.
→ Help to reduce the uncertainties in combination.

$\boldsymbol{t \rightarrow (W \rightarrow l\nu)(b \rightarrow J/\psi + X \rightarrow \mu^{+}\mu^{-} + X)}$ **process ($\boldsymbol{l = e, \mu}$) is used.**

- The first measurement using this phase space in ATLAS.



Challenges:

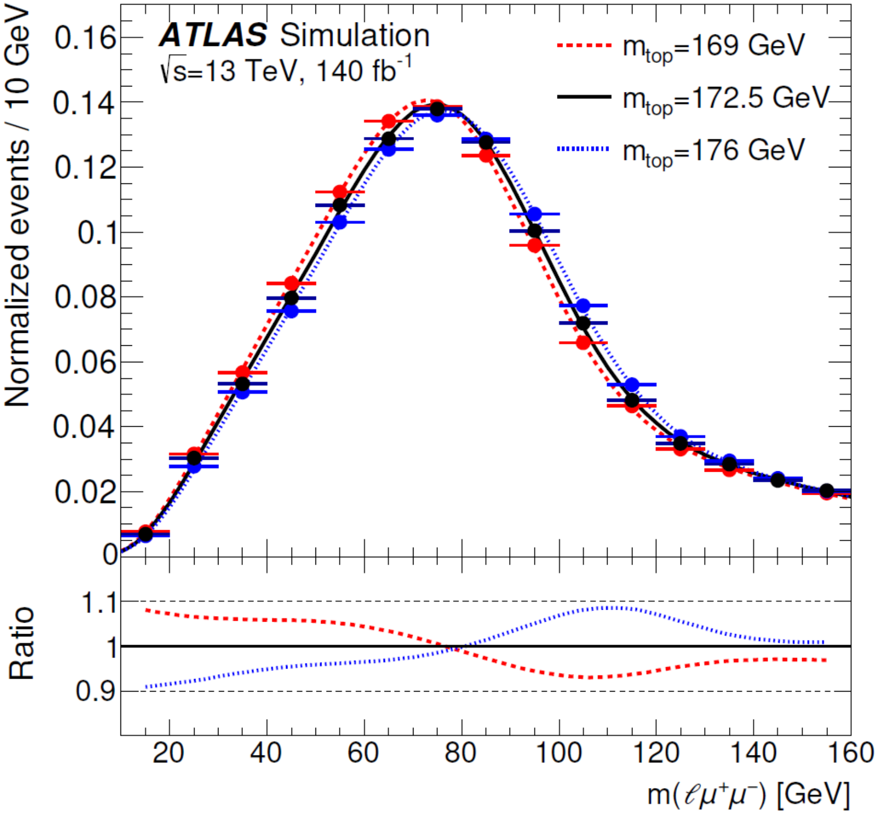
- Small BR of the signal process ($\sim 2.7 \times 10^{-4}$)
  → Expected large stat. uncertainty.
- Still sensitive to parton shower, hadronization, and b-fragmentation effects.
  → Must be controlled well.

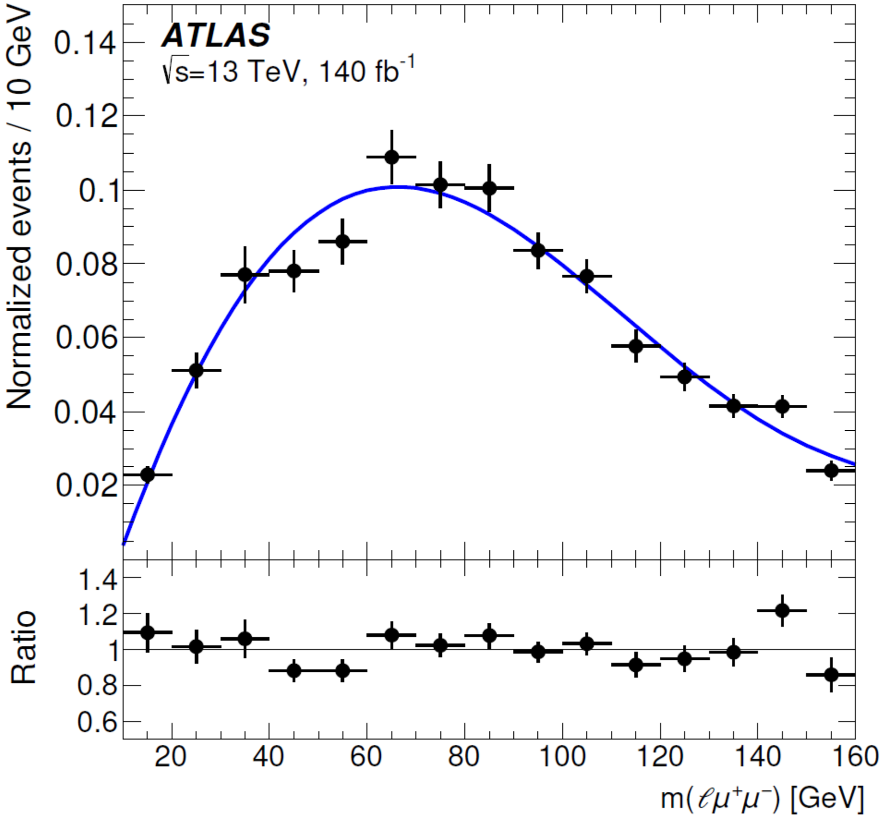
PDF for likelihood fit

arXiv:2511.23091

m_{top} is obtained by the unbinned likelihood fit to **the $\boldsymbol{m(\ell\mu^+\mu^-)}$ distribution.**
The distribution shape is parametrized by the following functions:

- $t\bar{t}$ and single-top events: m_{top}-dependent component.
  - PDF=Gaussian + Lognormal
- V+jets, fake lepton events, etc: m_{top}-independent component.
  - PDF=Chebyshev polynomial

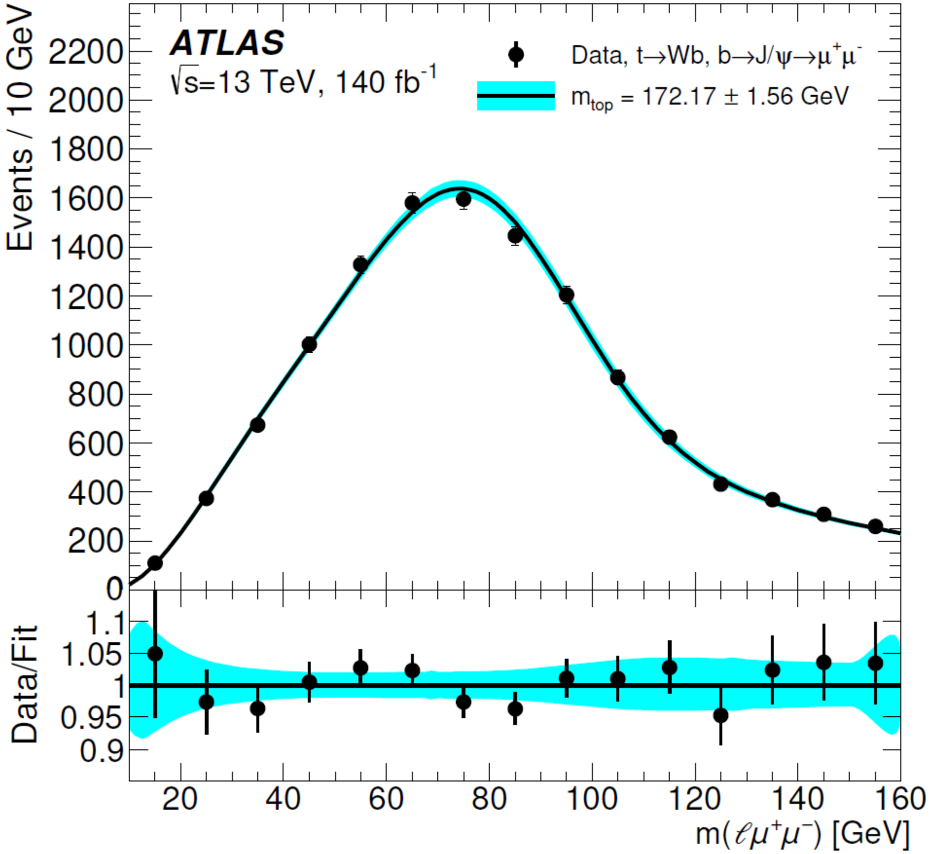




Result

arXiv:2511.23091

$$m_{\mathrm{top}} = 172.17 \pm 0.80\,(\mathrm{stat}) \pm 0.81\,(\mathrm{syst}) \pm 1.07\,(\mathrm{recoil})\ \mathrm{GeV}$$
$$= 172.17 \pm 1.56\ \mathrm{GeV}$$



Stat. uncertainty is of the same order as in other measurements.

Jet-related uncertainties are smaller than in any measurements using other channels (<100 MeV).

The recoil modeling uncertainty is dominant:1.07±0.22 GeV.

Impact on b-fragmentation modelling is significant.

- b-frag. model in new recoil scheme has not been tuned yet.

→The uncertainty is conservatively included, separately from other systematic modelling uncertainties.

Other syst. uncertainties are well controlled and reduced to a level comparable to the stat uncertainty.

Pole mass using dileptonic $t\bar{t}$+1 jet

JHEP 12 (2025) 023

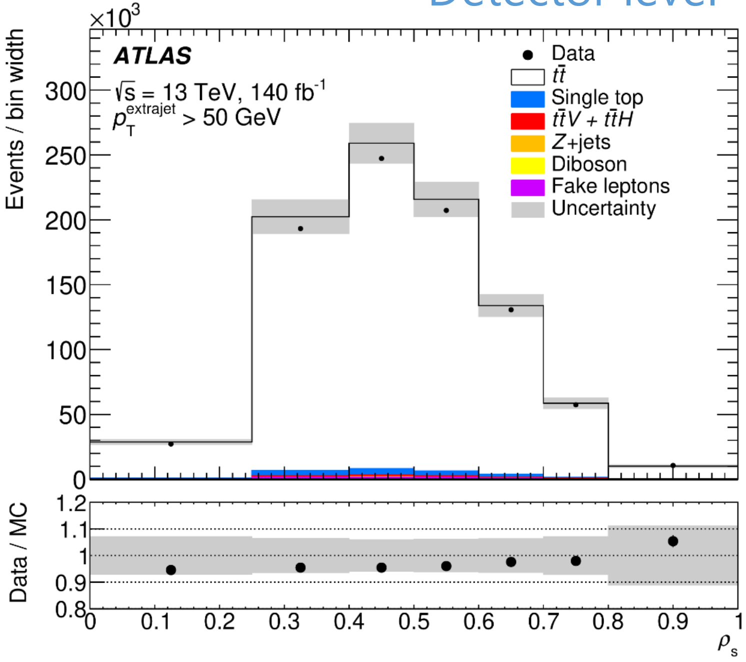
The normalized differential cross-section defined as

$$\mathcal{R}\left(\rho_s; m_t^{pole}\right) = \frac{1}{\sigma_{t\bar{t}+1-\mathrm{jet}}} \cdot \frac{d\sigma_{t\bar{t}+1-\mathrm{jet}}}{d\rho_s}, \text{ with } \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1-\mathrm{jets}}}} \quad (m_0 = 170\text{ GeV})$$

- $\sqrt{s_{t\bar{t}+1-\mathrm{jets}}}$ is the invariant mass of the reconstructed $t\bar{t}$+1-jet system.

- Existence of an extra 1 jet enhances sensitivity of cross-section to the pole mass.
- Dilepton channel, especially required $e^{\pm}\mu^{\mp}$.
- 98% efficiency in $t\bar{t}$ reconstruction by combined two dedicated methods to estimate the kinematics of neutrinos.
- 95% purity of final selection with extra jet of p_{T}>50 GeV, $|\eta|$<2.5.

Detector level



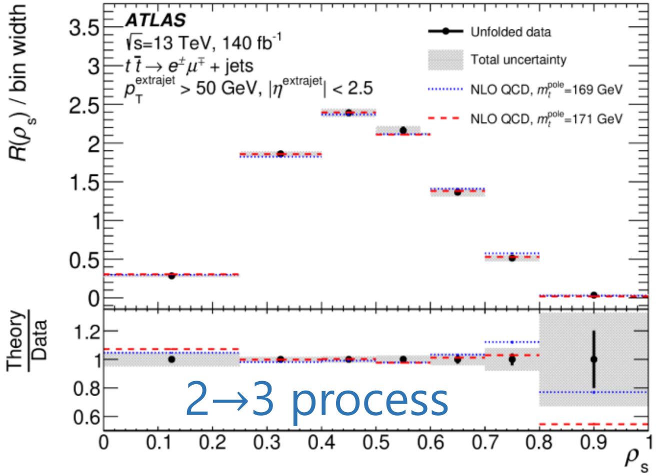
Unfolding and χ^2 fit

[JHEP 12 (2025) 023](https://doi.org/)

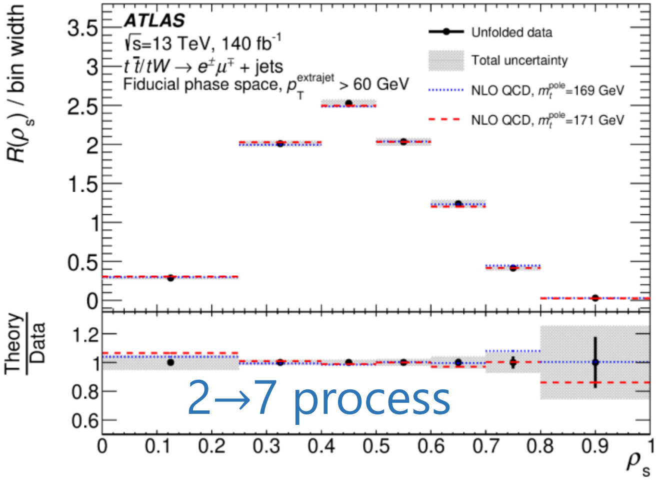
The ρ_s distribution is unfolded to the parton level by using Iterative Bayesian Unfolding.

Measurement is performed
for the two theoretical predictions separately:

- $\boldsymbol{pp \to t\bar{t}j}$ **(2→3) process**
  - JHEP 05 (2022) 146
  - Top quarks are taken as stable particles.
- $\boldsymbol{pp \to b\bar{b}\ell^{+}\nu\ell^{-}\bar{\nu}j}$ **(2→7) process**
  - JHEP 11 (2016) 098
  - Includes top-quark decays to the dilepton final state and off-shell effects.



2→3 process



2→7 process

χ^2 fit of the unfolded normalized differential cross-section distribution.

Result

JHEP 12 (2025) 023

Measurement using 2→3 process shows the best precision:

$$m_t^{\mathrm{pole}} = 170.73 \pm 0.33\ (\mathrm{stat.}) \pm 1.36\ (\mathrm{syst.})\ ^{+0.34}_{-0.28}\ (\mathrm{scale})\ \pm 0.24\ (\mathrm{PDF} \oplus \alpha_s)\ \mathrm{GeV}$$

(PDF set : PDF4LHC21)

→Main result of this analysis.

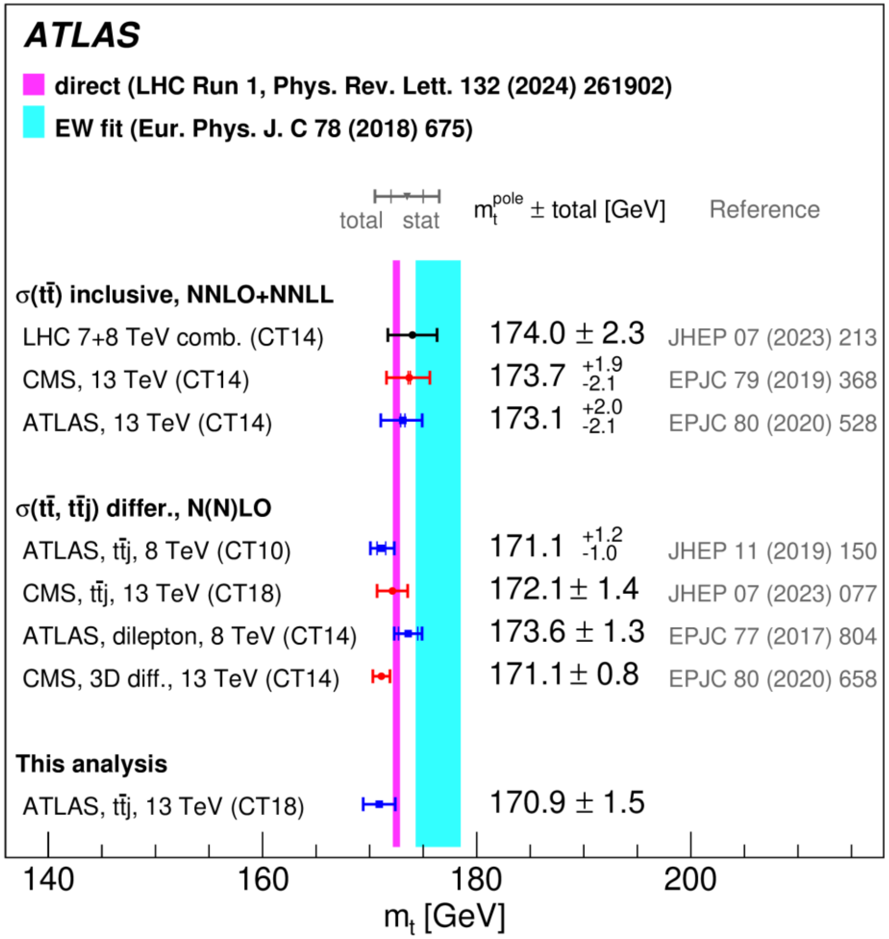
- $t\bar{t}$ modelling, JES and b-tagging are dominant source of uncertainties.

Compatible with 2 → 7 one.

- 2 → 7 has reduced sensitivity to m_t^{pole} and suffers from larger theoretical scale uncertainties (expected).

Overall good compatibility with other determinations.

- A difference of ~5 GeV from EW precision observables.



	m_t^{pole} ± total [GeV]	Reference
σ($t\bar{t}$) inclusive, NNLO+NNLL		
LHC 7+8 TeV comb. (CT14)	174.0 ± 2.3	JHEP 07 (2023) 213
CMS, 13 TeV (CT14)	$173.7^{+1.9}_{-2.1}$	EPJC 79 (2019) 368
ATLAS, 13 TeV (CT14)	$173.1^{+2.0}_{-2.1}$	EPJC 80 (2020) 528
σ($t\bar{t}$, $t\bar{t}j$) differ., N(N)LO		
ATLAS, $t\bar{t}j$, 8 TeV (CT10)	$171.1^{+1.2}_{-1.0}$	JHEP 11 (2019) 150
CMS, $t\bar{t}j$, 13 TeV (CT18)	172.1 ± 1.4	JHEP 07 (2023) 077
ATLAS, dilepton, 8 TeV (CT14)	173.6 ± 1.3	EPJC 77 (2017) 804
CMS, 3D diff., 13 TeV (CT14)	171.1 ± 0.8	EPJC 80 (2020) 658
This analysis		
ATLAS, $t\bar{t}j$, 13 TeV (CT18)	170.9 ± 1.5	

Summary

The LHC has pursued top-quark mass measurements intensively.

- Run 1: combined results already achieved high precision.
- **Run 2: further reduction of systematic uncertainties using advanced analysis**, e.g. simultaneous fits, rare phase space.
  - Central values are broadly consistent across analyses.

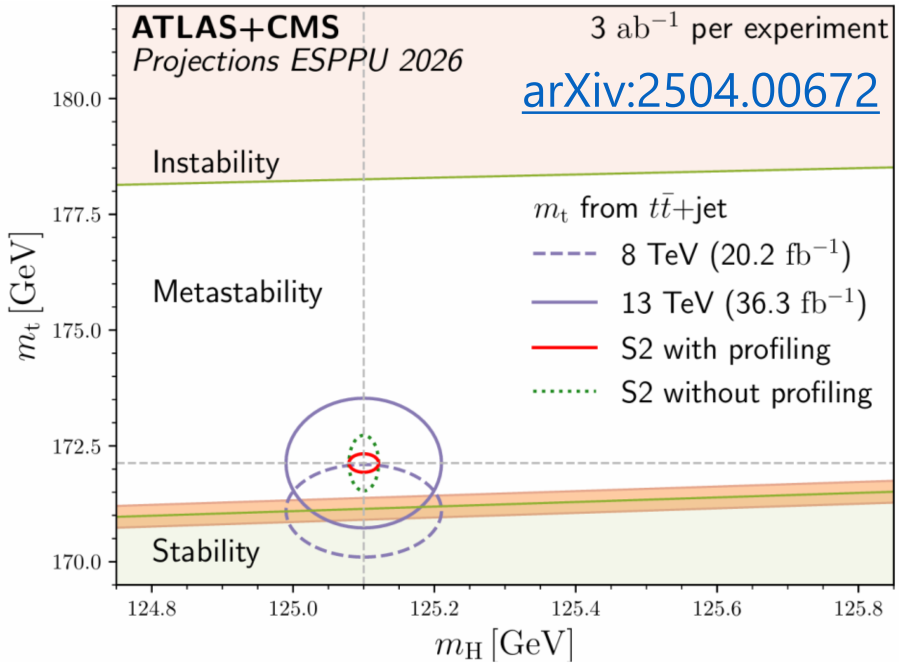
Projection of the m_{top} measurements for **HL-LHC** has been performed.

- **Profile likelihood fits** with large datasets are expected to significantly reduce measurement uncertainties

m_{top} measurements using LHC and HL-LHC dataset will show further improvements and help advance validation of the SM.

- E.g. EW fit, vacuum stability.

Stay tuned for future results!



With profiling, precision will be ~200 MeV.

Backup