ATLAS results on top-quark mass

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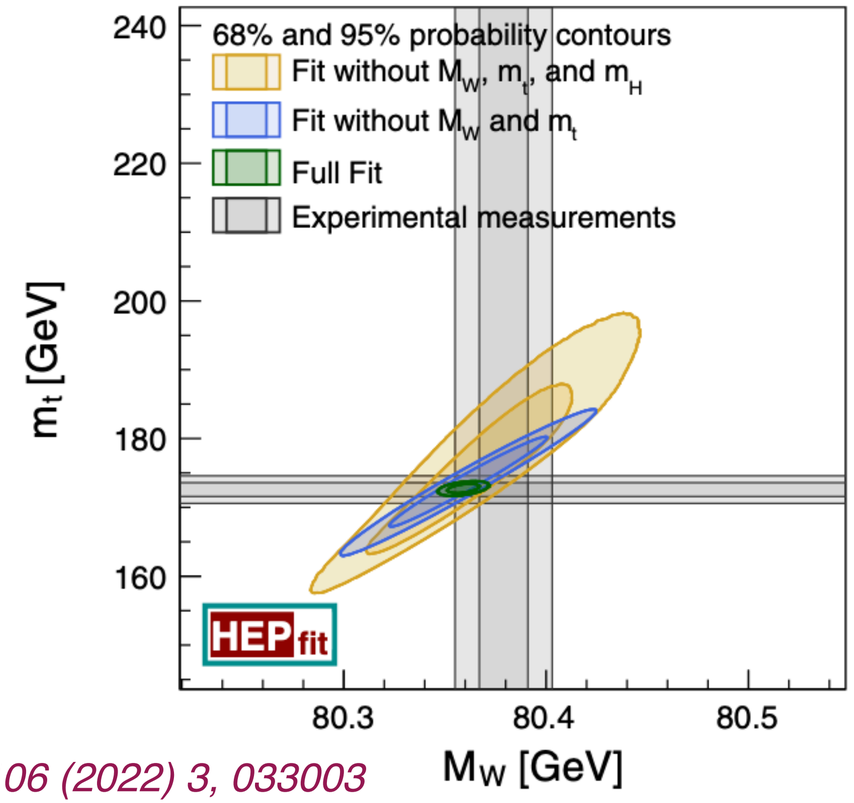
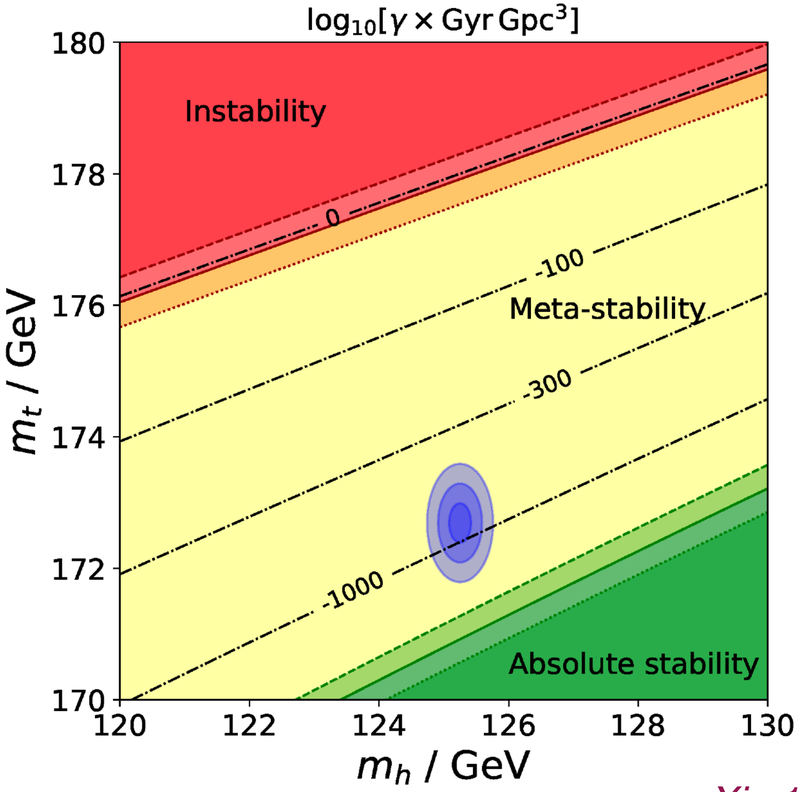
Motivation of the top quark mass measurement

The mass of the top quark (m_t) is one of the most distinctive properties of the Standard Model

- It is a fundamental parameters of the SM Lagrangian that must be determined experimentally
- The SM predicts a relation among masses of the Higgs boson, the W boson, and the top-quark.
- The mass close to electroweak scale affects the evolution of the Higgs quartic coupling to high scales
  - Determines the shape of the Higgs potential and the stability of the quantum vacuum
  - May provide hints of the energy scale beyond the SM



Phys.Rev.D 106 (2022) 3, 033003



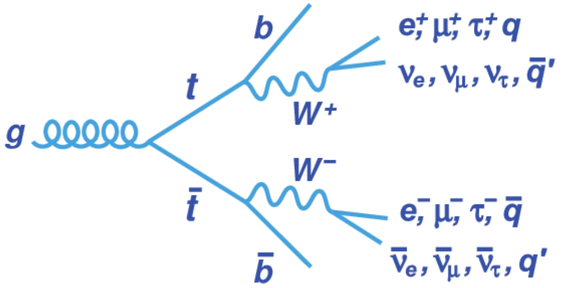
arXiv:1707.09301

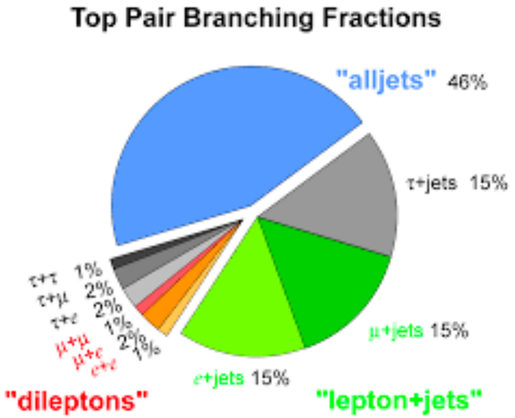
Top-quark mass measurements

Measurements of the top-quark mass can typically be classified into 2 categories:

Direct measurement

- The top-quark mass is reconstructed from the decay products of top-quarks
  - dilepton, lepton+jets, all jets from $t\bar{t}$ events
  - single top-quark events
  - novel approaches
    e.g.) partial reconstruction of top-quark mass
    using a soft muon or a $J/\psi \to \mu\,\mu$ from top-quark decay
- The top quark mass is derived by comparing the reconstructed mass distribution with its MC prediction
- Ambiguity exists in identifying the measured mass with the pole mass





Indirect mesurement

- Measured $t\bar{t}$ production observables (cross-section) are compared with its fixed-order calculation in a certain normalization scheme (e.g. pole mass, $\overline{\text{MS}}$ mass)

LHC top-quark mass combination with Run 1 data

Phys. Rev. Lett. 132 (2024) 261902

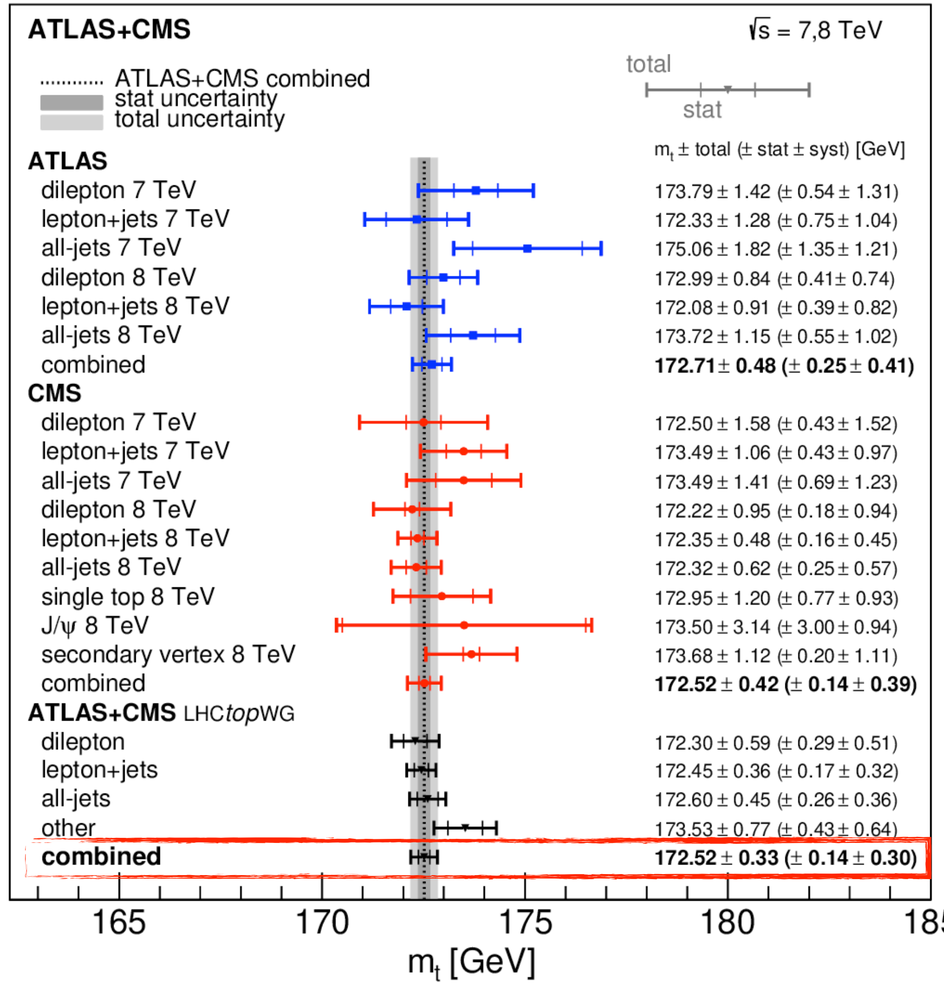
Multiple direct measurements of m_t have been performed using pp collision data collected by ATLAS and CMS at $\sqrt{s}$ = 7 and 8 TeV

15 ATLAS and CMS top-quark mass measurements are combined

- All correlations are considered in the combination
- Uncertainties are grouped into 25 categories
- Correlation between measurements in the same experiments are evaluated using covariance matrices
- Cross-experiment correlations are evaluated based on the similarities of approaches and input
- The combined result achieves a 31% improvement in precision compared to the single most precise input measurement

$$m_t = 172.52 \pm 0.33 \text{ GeV}$$

Currently the most precise top-quark mass measurement



Top-quark mass measurements with data at $\sqrt{s}$ = 13 TeV

ATLAS collected more data during Run 2, corresponding to an integrated luminosity of approximately 140 fb^{-1}

- The large Run 2 dataset enables top-quark mass measurement with the highest accuracy
- It opens the possibility of probing rare phase space region with the potential to reduce systematic uncertainties in the top-quark mass measurement

Three analysis are presented here:

(1) Direct mass measurement in dilepton events using the template method at $\sqrt{s}$ = 13 TeV
ATLAS-CONF-2022-058

(2) Top-quark pole mass in dileptonic $t\bar{t}$ + 1-jet events at $\sqrt{s}$ = 13 TeV → Recent result
arXiv:2507.02632

(3) Direct mass measurement using the boosted $t\bar{t}$ events at $\sqrt{s}$ = 13 TeV → Recent result
Phys. Lett. B 867 (2025) 139608

Direct mass measurement in dilepton events using template method

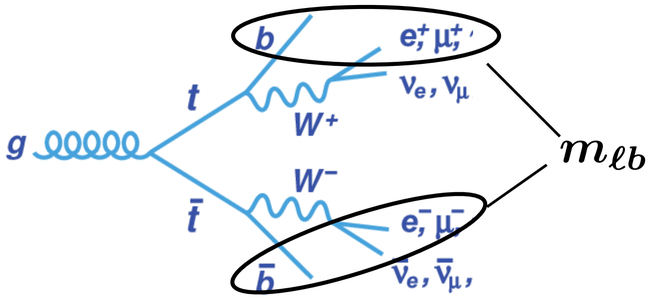
ATLAS-CONF-2022-058

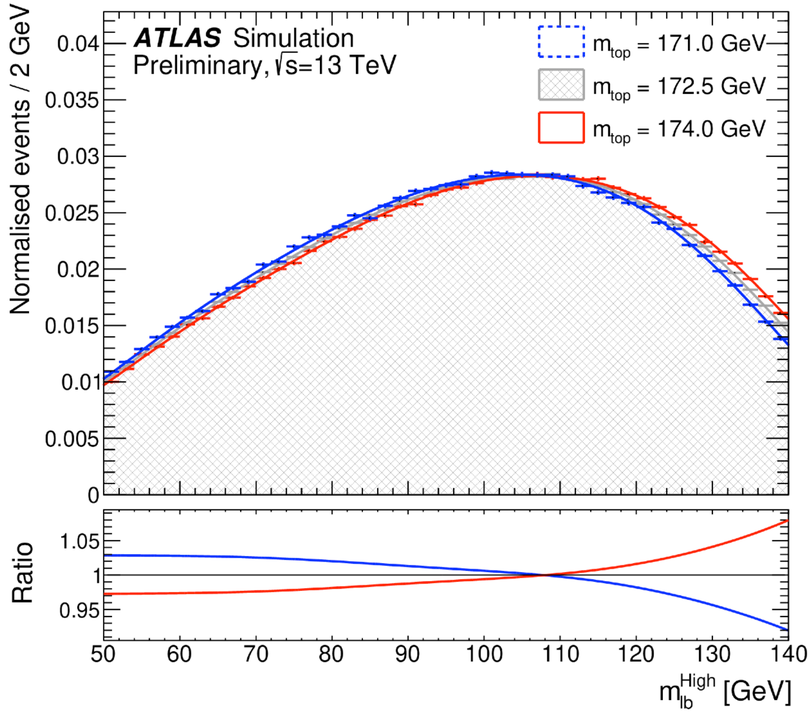
Compared to the 8 TeV measurement, the Run 2 analysis benefits from a larger dataset and improved analysis techniques

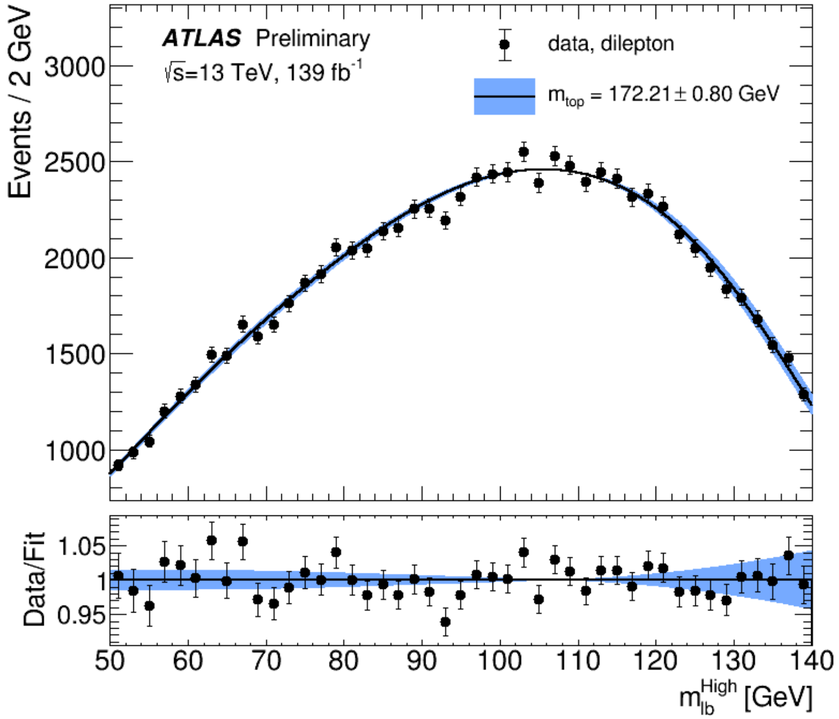
- Analysis targets the dilepton decay channel of top-quark pair production in Run 2
- Event reconstruction is improved by employing a machine-learning to select the best ℓ-b pairing
- The top-quark mass is extracted from an unbinned maximum-likelihood fit to $m_{\ell b}$ distribution
- Precision is limited by uncertainties in the jet energy scale and in the modeling of $t\bar{t}$ production

Event selection

- Exactly 2 oppositely charged leptons (events with low-mass resonance and Z events vetoed)
- At least two jets, with exactly two of them must be b-tagged







$$m_t = 172.21 \pm 0.20(\text{stat}) \pm 0.67(\text{syst}) \pm 0.39(\text{recoil})\ \text{GeV}$$

Pole mass measurement in dileptonic $t\bar{t}$+1-jet events

arXiv:2507.02632

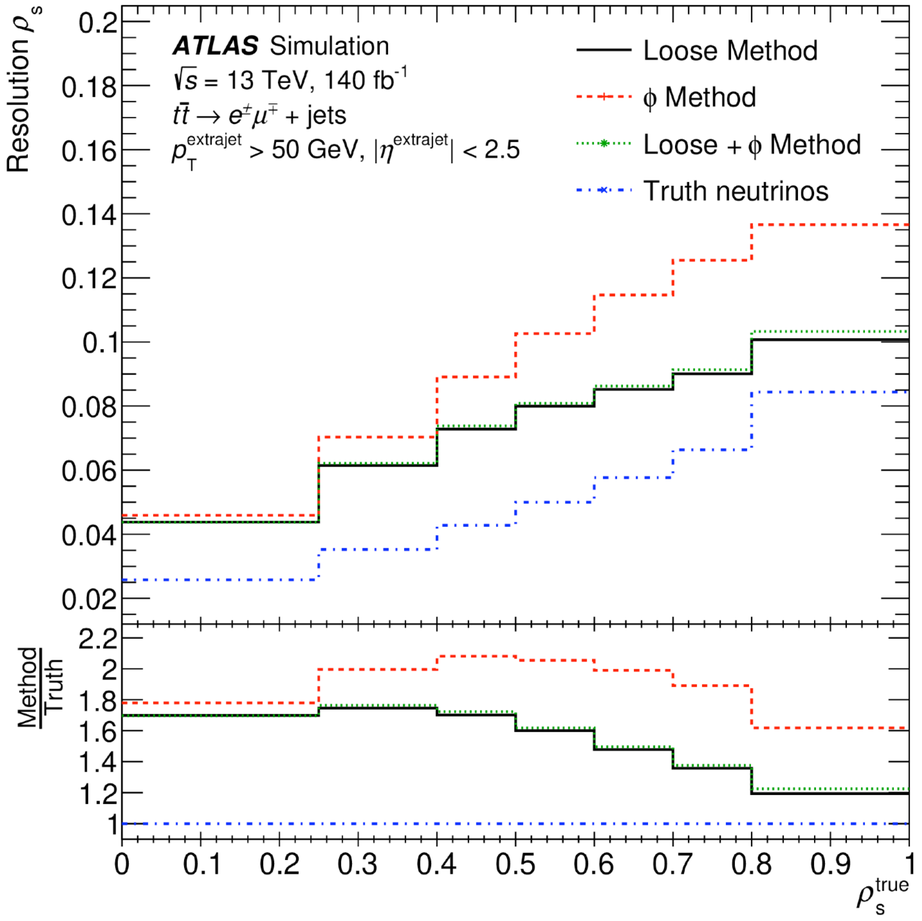
The pole mass(m_t^{pole}) is extracted from normalized cross-section as a function of ρ_s

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

$$m_0 = 170 \text{ GeV}$$

Event Selection :

- An oppositely charged e-μ pair
- Two b-tagged jets
- One additional jet with p_T > 50 (60) GeV
- $\boldsymbol{E_{\text{T}}^{\text{miss}}}$ > 30 GeV
- $\boldsymbol{m_{\ell b}}$ < 200 GeV



Reconstruction of the $t\bar{t}$ system

- The loose kinematic reconstruction *Eur. Phys. J. C 80 (2020) 658*
  - Determine kinematic properties of $\nu\bar{\nu}$ system
    - Transverse momentum : $\boldsymbol{E_{\text{T}}^{\text{miss}}}$
    - Longitudinal momentum : 4-momentum of e-μ pair
- The neutrino ϕ-weighting method *Phys. Rev. D 79 (2009) 072005*
  - Azimuthal angle of neutrinos is scanned with 100 random values from a uniform distribution
  - Minimize $\chi^2_\phi = (m_{\nu\bar{\ell}b} - m_{\bar{\nu}\ell\bar{b}})/(m_{\nu\bar{\ell}b} + m_{\bar{\nu}\ell\bar{b}})$

Pole mass measurement in dileptonic $t\bar{t}$+1-jet events

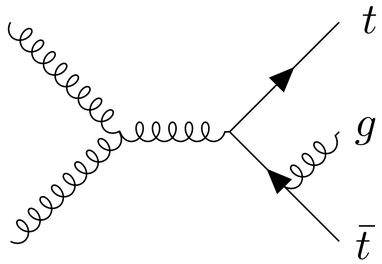
arXiv:2507.02632

To compare the measured observable with fixed-order calculations, the data are unfolded to the parton-level using Iterative Bayesian Unfolding

The measured results are compared separately to

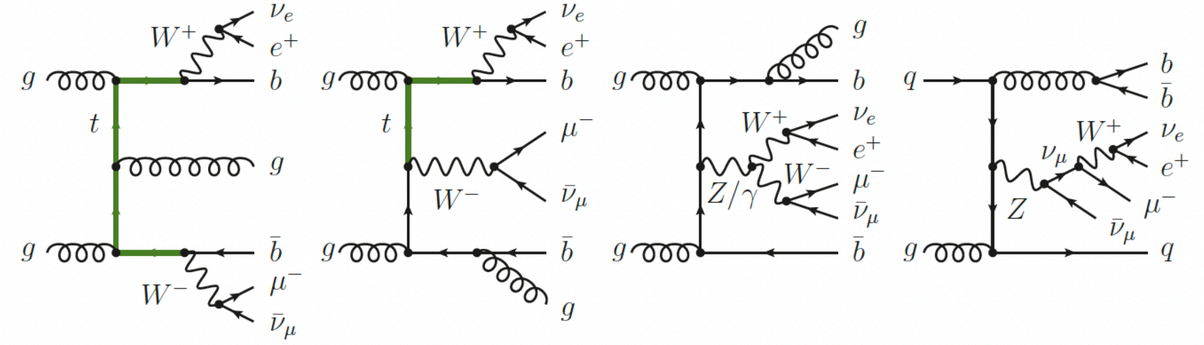
2→3 process *JHEP 05 (2022) 146*

→ describes $pp \to t\bar{t} + 1$ jet at parton level

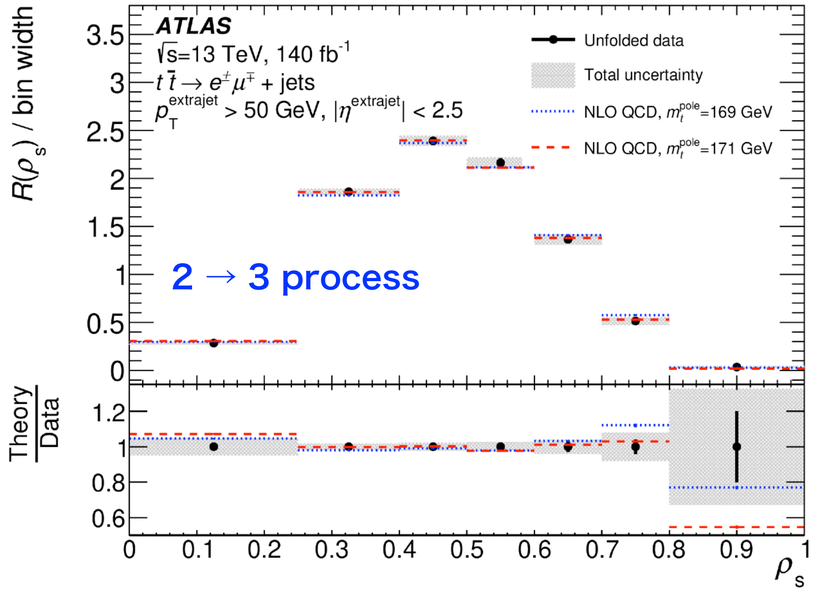


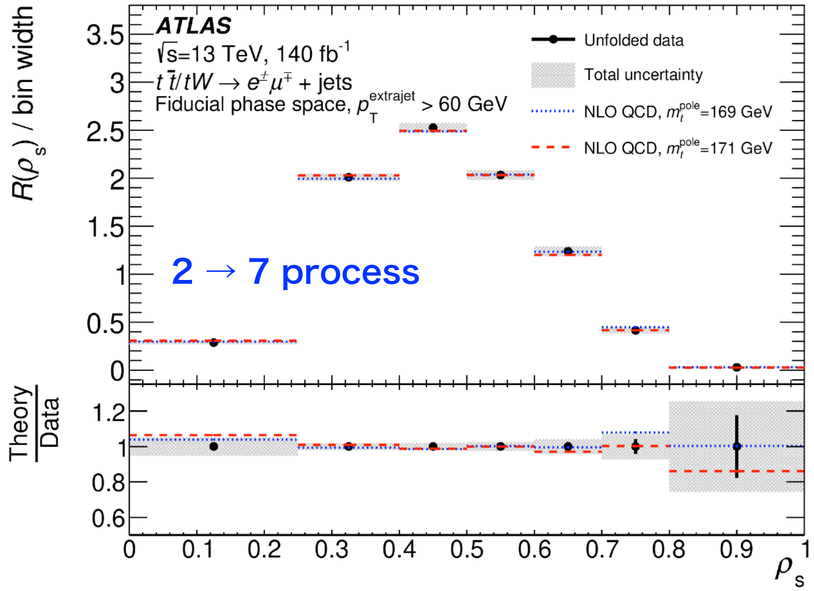
2→7 process *JHEP 11 (2016) 098*

→ describes $pp \to b\bar{b}\ell^+\nu\ell^-\bar{\nu}j$ including doubly-, single-, and non-resonant contributions



doubly-resonant single-resonant non-resonant





Pole mass measurement in dileptonic $t\bar{t}$+1-jet events

arXiv:2507.02632

The pole mass is extracted from the unfolded normalized differential cross-section $\mathcal{R}(\rho_s; m_t^{\text{pole}})$ with a least-square fit to fixed-order NLO QCD predictions

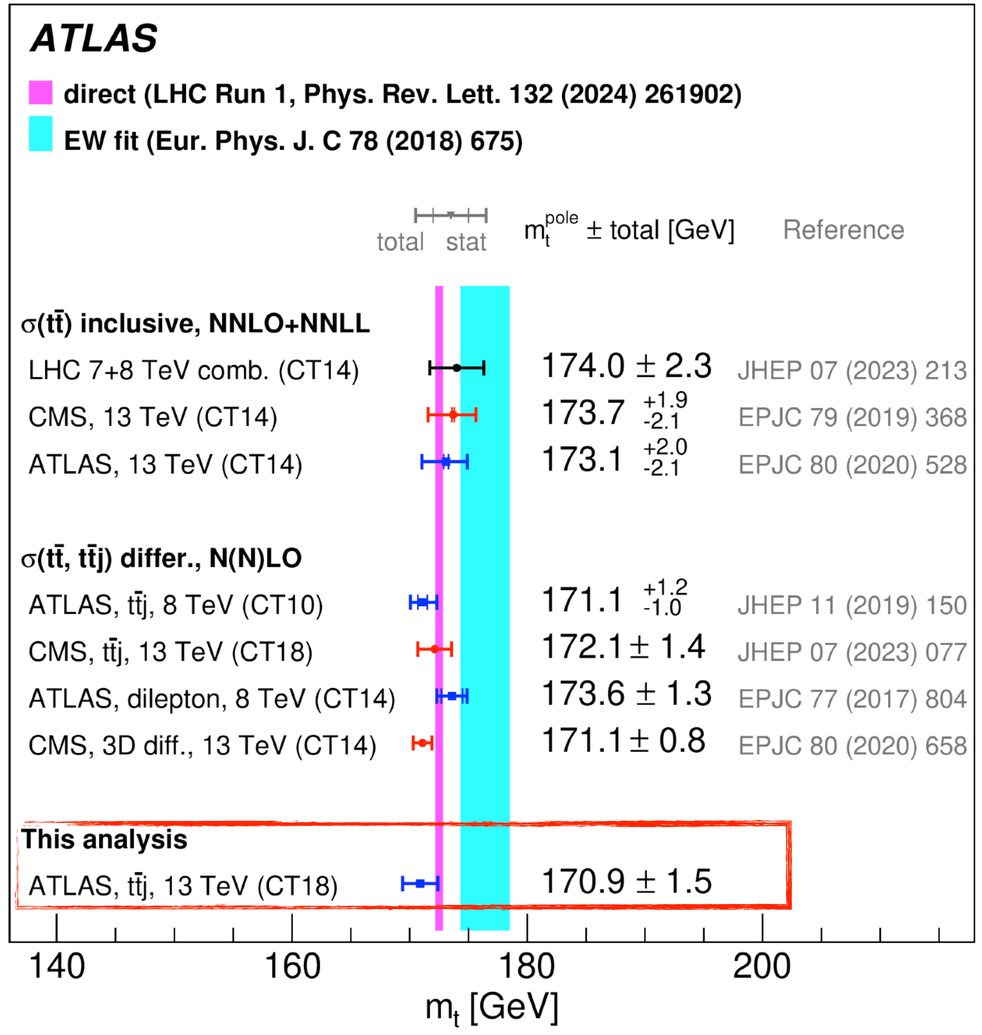
- Both statistical and systematic uncertainties are included in the covariance matrix
- Theory uncertainties are estimated from the variation of m_t^{pole} when changing theory inputs

The 2 → 3 approach is taken as the main result :

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

(PDF set : PDF4LHC21)

- The 2 → 7 result agrees within theoretical uncertainties
- Dominant systematic uncertainties arise from:
  - Detector : b-tagging and jet-response calibration
  - Modeling : choice of parton shower and recoil modeling
- The slightly larger uncertainty wrt CMS is due to the inclusion of a more extensive set of modeling uncertainties
- The results are consistent, within uncertainties, with other determinations of the top-quark mass



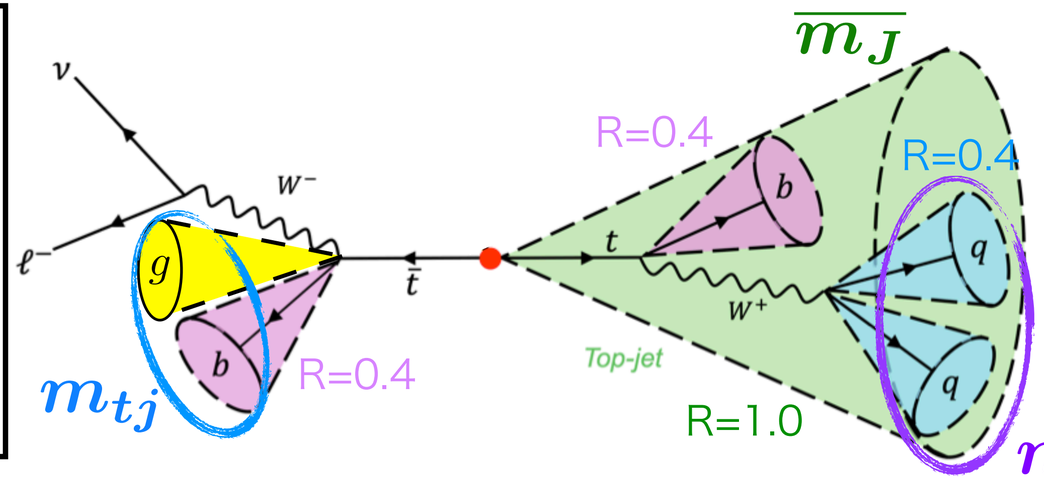
Direct mass measurement using boosted $t\bar{t}$ events

Phys. Lett. B 867 (2025) 139608

The first ATLAS measurement of the top-quark mass using boosted top-quark events

- Targets the lepton+jets decay channel in boosted top-quark pair production
- Simplifies the reconstruction of hadronically decaying top quarks

Leptonic top-quark decay
- Exactly one e or μ
- $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}} > 60$ GeV
- at least one b-tagged jet not associated with top-jet
- $\Delta R(\ell, b) < 2.0$
- $m_{\ell b} < 180$ GeV



Hadoronic top-quark decay
- at least 2 small-R(0.4) jets, where at least one is b-tagged
- A top-jet is formed by constituent jets.
- m_J is reconstructed by the sum of 4-momenta of constituent jets.
- $p_{\mathrm{T}} > 355$ GeV, $|\eta| < 2.0$
- 120 GeV $< m_{\mathrm{J}} < 220$ GeV

Top-quark mass is obtained from a profile-likelihood fit to three observables

1. Average top-jet mass : $\overline{m_J}$
   - Linearly dependent on the top-quark mass
2. Invariant mass of the 2 leading light jets inside the top-jet : m_{jj}
   - Sensitive to the jet energy scale
3. Invariant mass of the semi-leptonic top quark and closest jet : m_{tj}
   - Sensitive to the radiation from $t \to bW$

Direct mass measurement using boosted $t\bar{t}$ events

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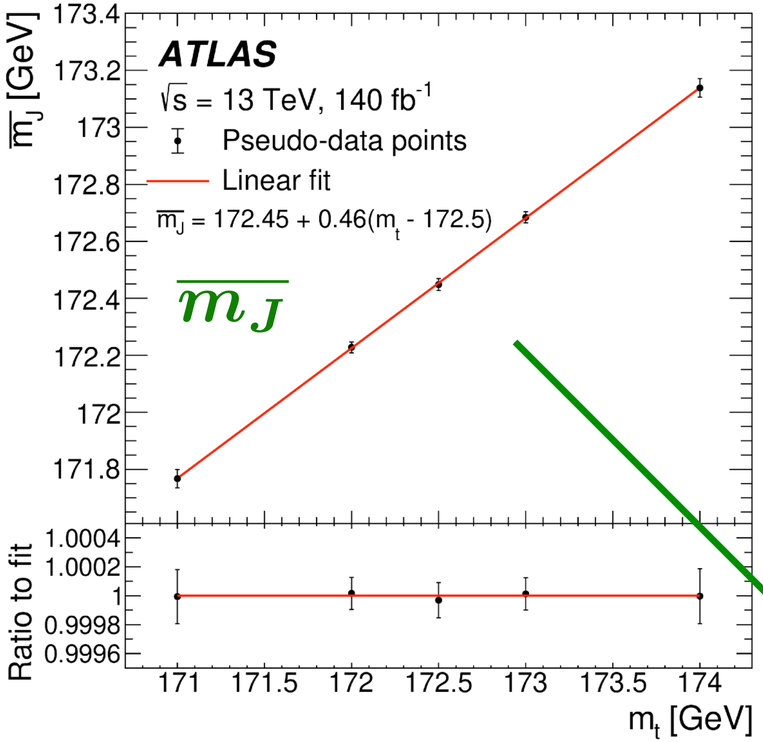

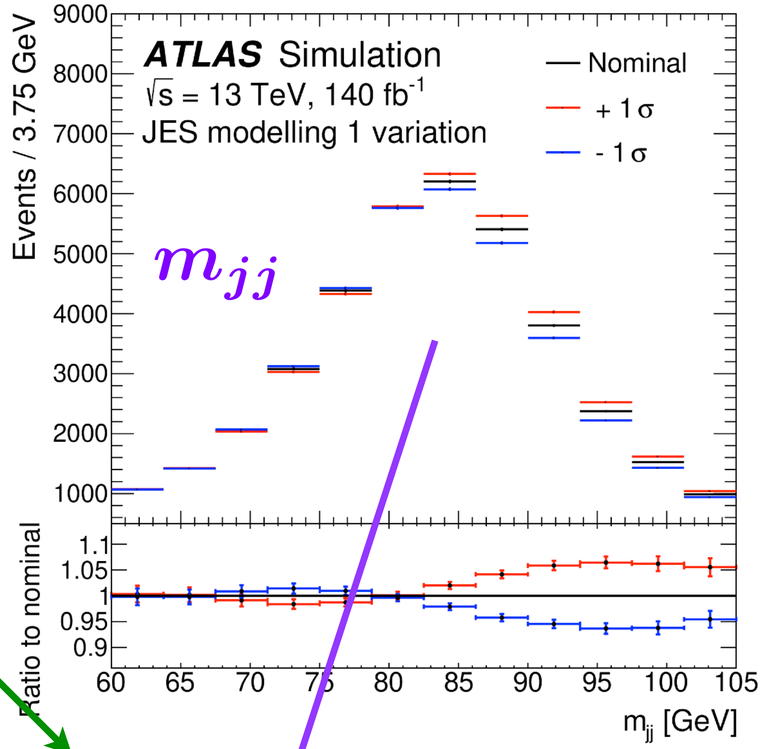

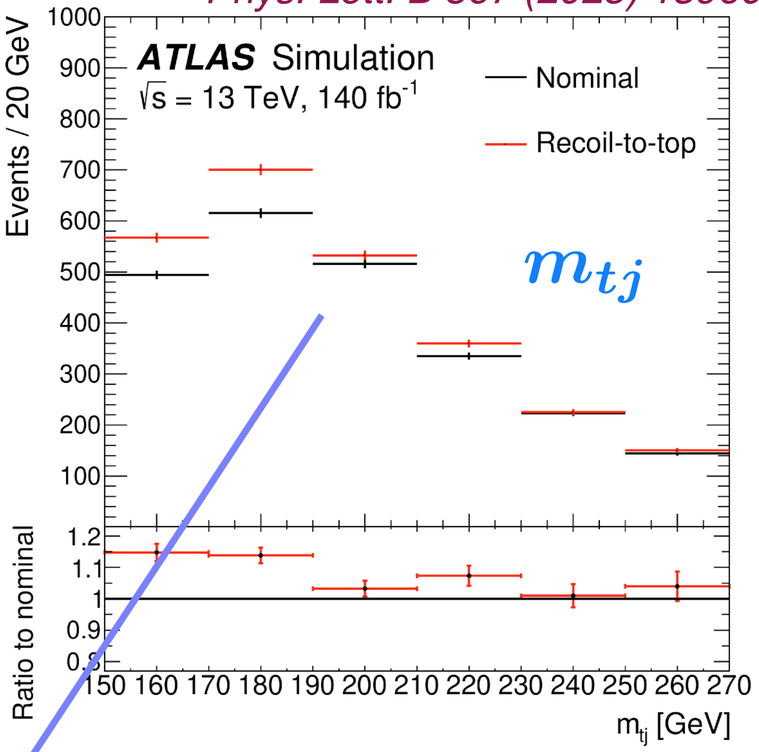

$$L\left(\overline{m_J}^d, \boldsymbol{n_{m_{jj}}}, \boldsymbol{n_{m_{tj}}} | m_t, \mu, \boldsymbol{\theta}\right) = G\left[\overline{m_J}^d | \overline{m_J}(m_t, \mu, \boldsymbol{\theta}), \sigma_{\overline{m_J}}\right]$$

$$\times \prod_i P\left[n_{m_{jj},i} | \nu_i(\mu, \boldsymbol{\theta})\right] \times \prod_k P\left[n_{m_{tj},k} | \rho_k(\mu, \boldsymbol{\theta})\right]$$

$$\times \prod_s G\left[\beta_s | \theta_s, 1\right],$$

G : Gaussian distribution
P : Poisson distribution
ν , ρ : expected number
θ : Nuisance parameters

··· Sensitive to m_t

··· Control and reduce systematics

··· Nuisance parameters constraints

A simultaneous profile-likelihood fit is performed to $\overline{m_J}$, m_{jj} , and m_{tj} with the m_t, signal strength(μ), and the nuisance parameters(θ) treated as free parameters

Direct mass measurement using boosted $t\bar{t}$ events

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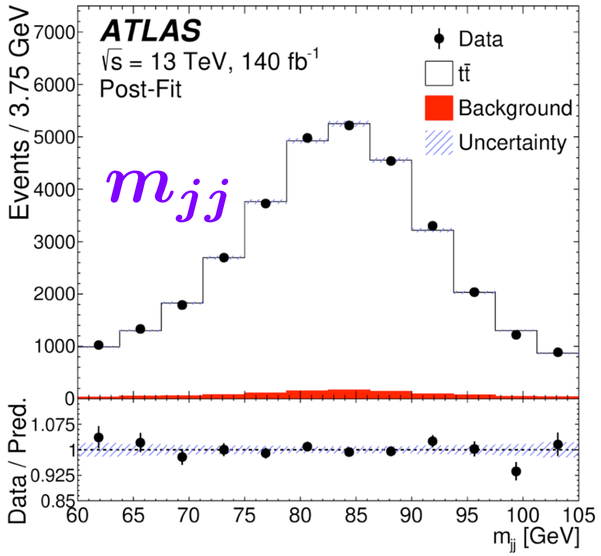
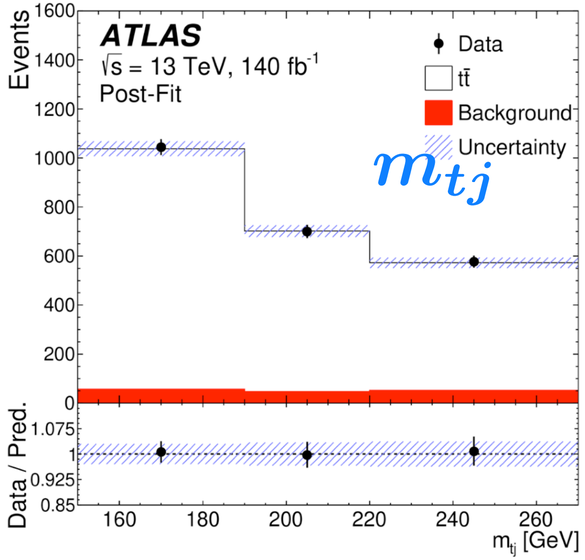
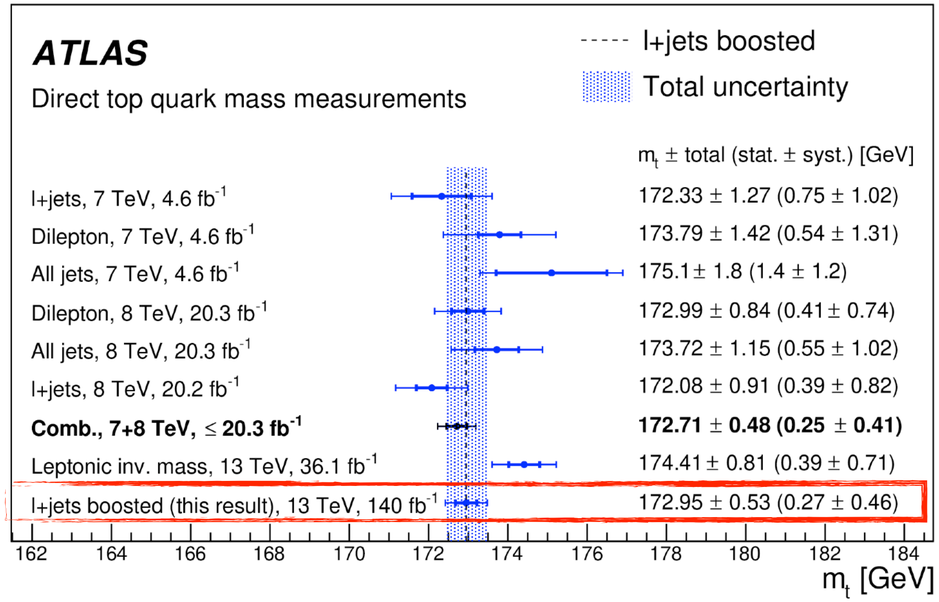
A simultaneous profile-likelihood fit is performed to $\overline{m_J}$, m_{jj} , and m_{tj} with the m_t, signal strength, and the nuisance parameters treated as free parameters







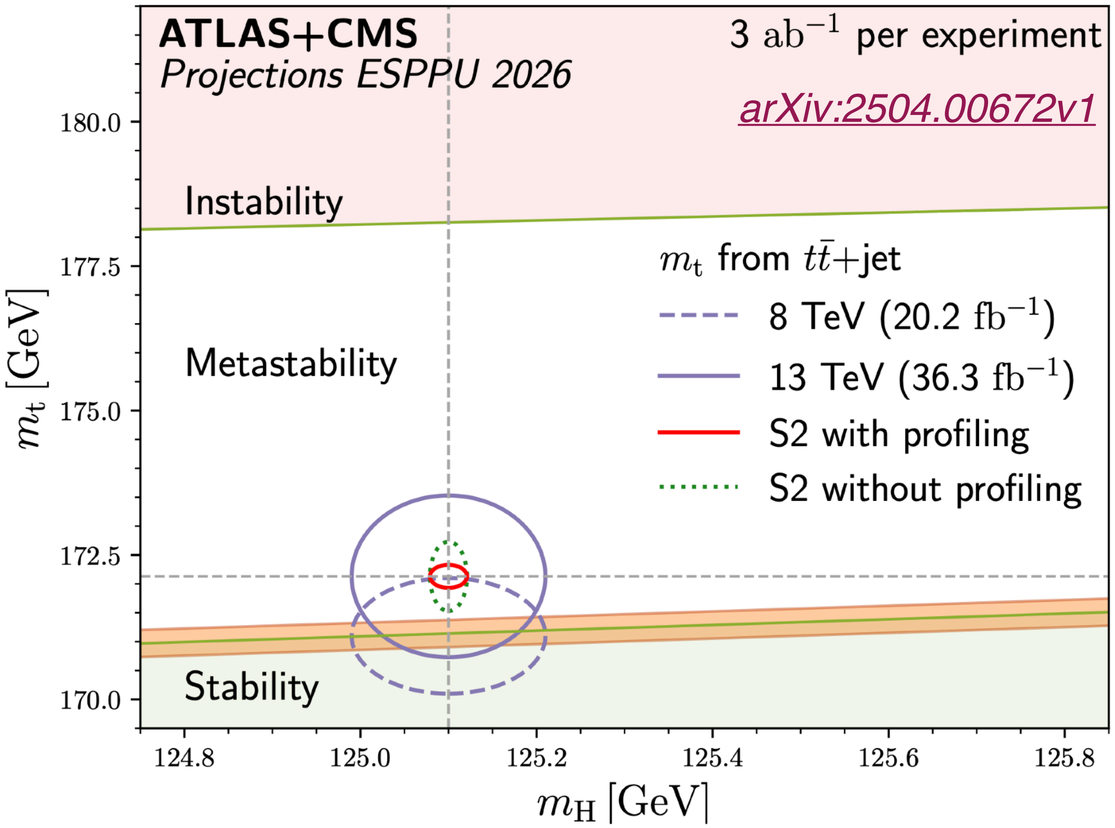
- The profile-likelihood fit using $\overline{m_J}$, rather than m_J full distribution, m_{jj} and m_{tj} constrains nuisance parameters and reduces the uncertainty while avoiding unnecessary shape dependencies.
- Signal Strength = 0.87 ± 0.09 in good agreement with cross-section measurement in *JHEP 06 (2022) 063*
- Including m_{jj} and m_{tj} improves the total uncertainties from 1.7 to 0.51 GeV
  (Jet energy scale : 1.4 GeV → 0.26 GeV, ISR/FSR : 0.82 GeV →0.14 GeV, Recoil : 0.36 GeV → 0.08 GeV)

$$m_t = 172.95 \pm 0.53 \text{ GeV}$$ → **The most precise ATLAS top-quark mass measurement in a single channel !**

Summary

- Recent ATLAS results on the top-quark mass measurements based on full Run 2 dataset have been presented
- The larger dataset allows us to measure the top-quark mass with improved precision.
- All measurements are consistent with the previous results
- With the data we already have and will take in the future, the precision of the top-quark mass measurements will continue to improve.
- Stay tuned for more measurements !!

- HL-LHC projections for m_H and m_t (For m_t, the projection is obtained from $t\bar{t}+\mathrm{jet}$ analysis)



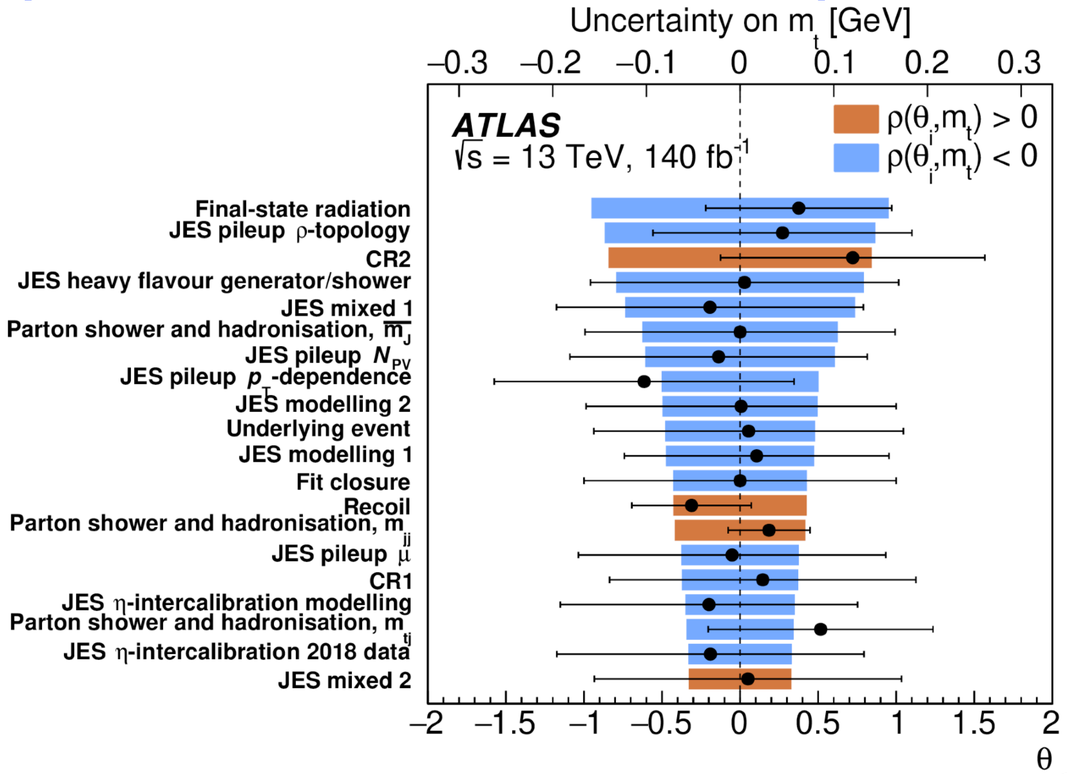
- The projection from boosted $t\bar{t}$ analysis indicates the potential to reach an uncertainty below 200-300 MeV.
  arXiv:2504.00672v1

Additional slides

Direct mass measurement using boosted $t\bar{t}$ events

Phys. Lett. B 867 (2025) 139608

Top-quark mass is obtained from a profile-likelihood fit to three observables



Colored bars (refer to upper x-axis):
The contribution of individual Nuisance parameters to the total uncertainty in m_t

Points (refer to lower x-axis):
The fitted values and post-ft uncertainties

$$\overline{m_J}(m_t, \mu, \boldsymbol{\theta}) = A + B \cdot (m_t - 172.5) + C \cdot (\mu - 1) + \sum_s \theta_s \Delta_s$$

$$L\left(\overline{m_J}^d, \boldsymbol{n_{m_{jj}}}, \boldsymbol{n_{m_{tj}}} | m_t, \mu, \boldsymbol{\theta}\right) = G\left[\overline{m_J}^d | \overline{m_J}(m_t, \mu, \boldsymbol{\theta}), \sigma_{\overline{m_J}}\right]$$

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