ATLAS results on top quark mass and properties

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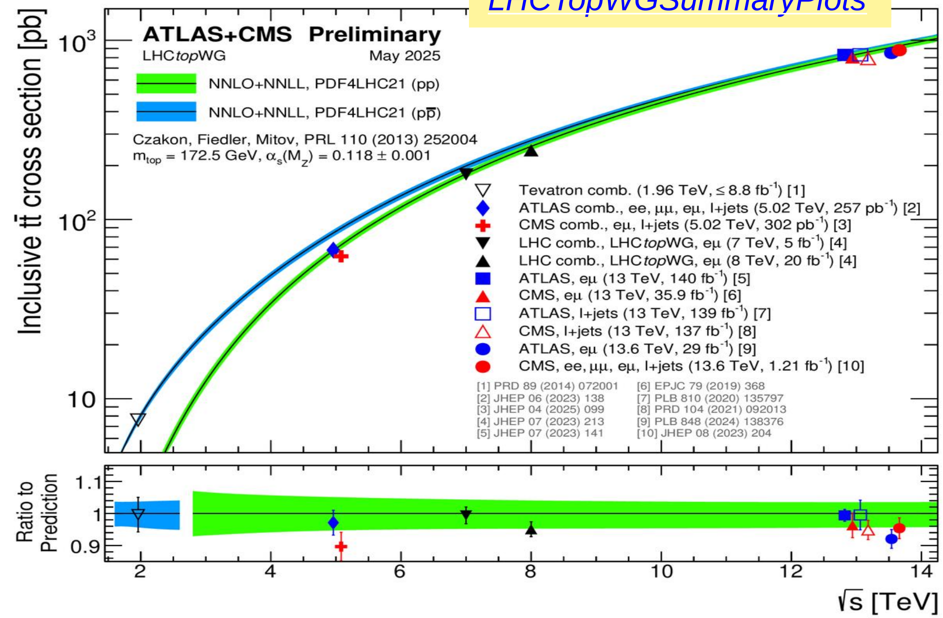
on behalf of the ATLAS Collaboration

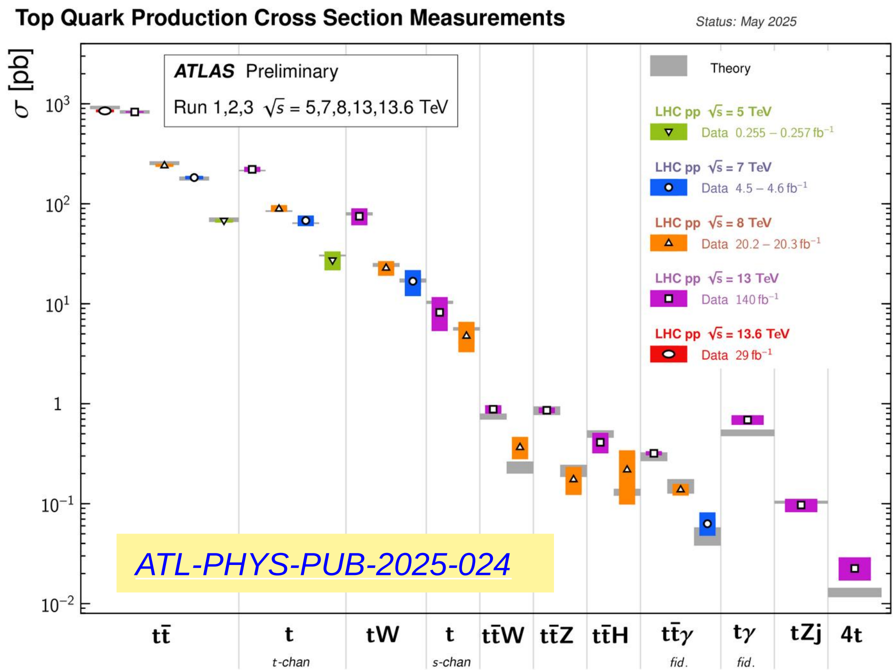
- introduction
- top-quark properties
- mass measurements
- conclusion

Top quark as a probe for the SM

- **Most striking properties**
  - heaviest fundamental particle known
    - Yukawa coupling to Higgs boson ~1
    - high relevance to EWK Symmetry Breaking mechanism
  - very short lifetime $\tau \sim 5\times10^{-25}$ ps
    - inhibits to form bound states
    - unique way to study quasi free quark
- **High production rate at LHC**
  - probed cross sections from ~800 pb to ~20 fb
    - O(100) millions $t\bar{t}$ produced in Run 2 and Run 3
  - allowing for deep understanding of the production mechanisms
  - increasing number of differential measurements with high precision, exploiting new datasets, high-p_T regime
- **Multiple of interesting SM/top properties measurements**

LHCTopWGSummaryPlots

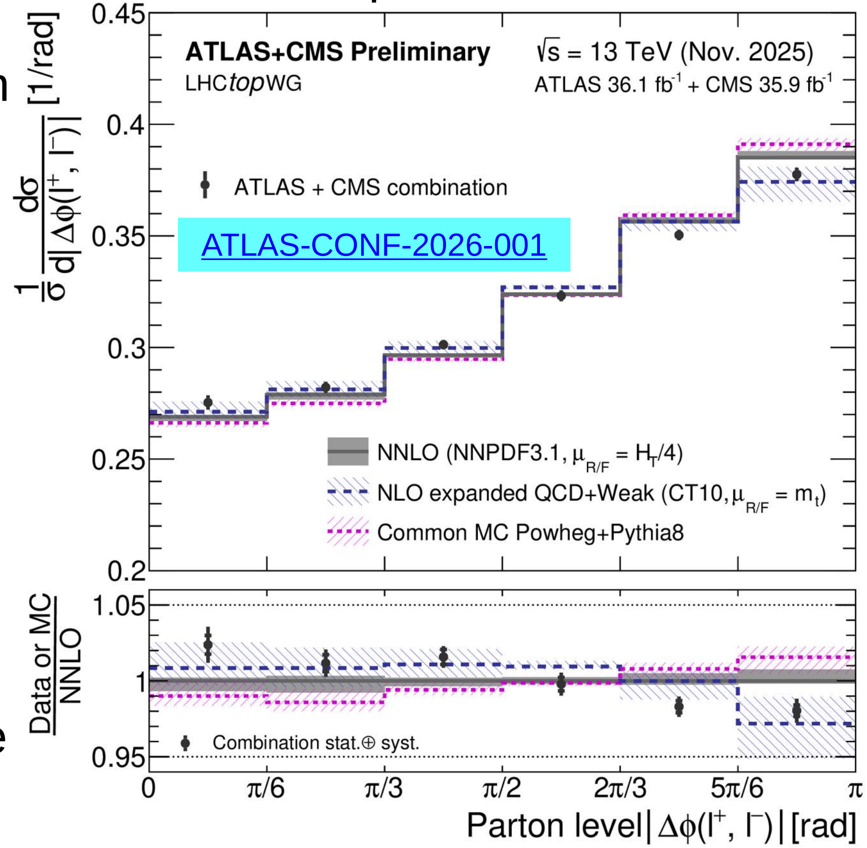




ATL-PHYS-PUB-2025-024

Spin correlation, ATLAS+CMS combination

- **Motivation**
  - top quarks produced in pairs are almost unpolarized in the SM, but the spins of the top and antitop are correlated
    - information of the top quark's spin is preserved in its decay products
  - spin correlation measurements are all consistent with SM expectations, but there are some tensions in a narrow interval in the $t\bar{t}$ production threshold region
  - study the angles of the top decay products
    - $\Delta\phi$ difference in azimuth of charged leptons in their parent top- and antitop-quark rest frames



- **Selection/Analysis**
  - ATLAS: 2015+2016, 36 fb^{-1}, $e\mu$ channel, no $t\bar{t}$ reconstruction
  - CMS: 2016, 36 fb^{-1}, $ee/e\mu/\mu\mu$ channels, includes $t\bar{t}$ reconstruction
  - unfolding to parton level
  - combination done with the Convino package ([*Eur. Phys. J. C 77 (2017) 792*])

Tension between data and common MC Powheg+Pythia8 prediction
Better agreement with fixed-order theoretical predictions
with higher-order corrections (*Phys. Rev. Lett. 123 (2019) 082001*)

$|V_{cb}|$ CKM matrix element in $t\bar{t}$ decays

- **Motivation**
  - first measurement of $|V_{cb}|$ using on-shell W-boson decays to b and c
    - previous measurements used B-hadron decays, i.e. probed bound states
  - Current world average (PDG 2024) : $|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$
    - 3σ tension between inclusive and exclusive B-hadron decay measurements (PRD 113 (2026) 012008)

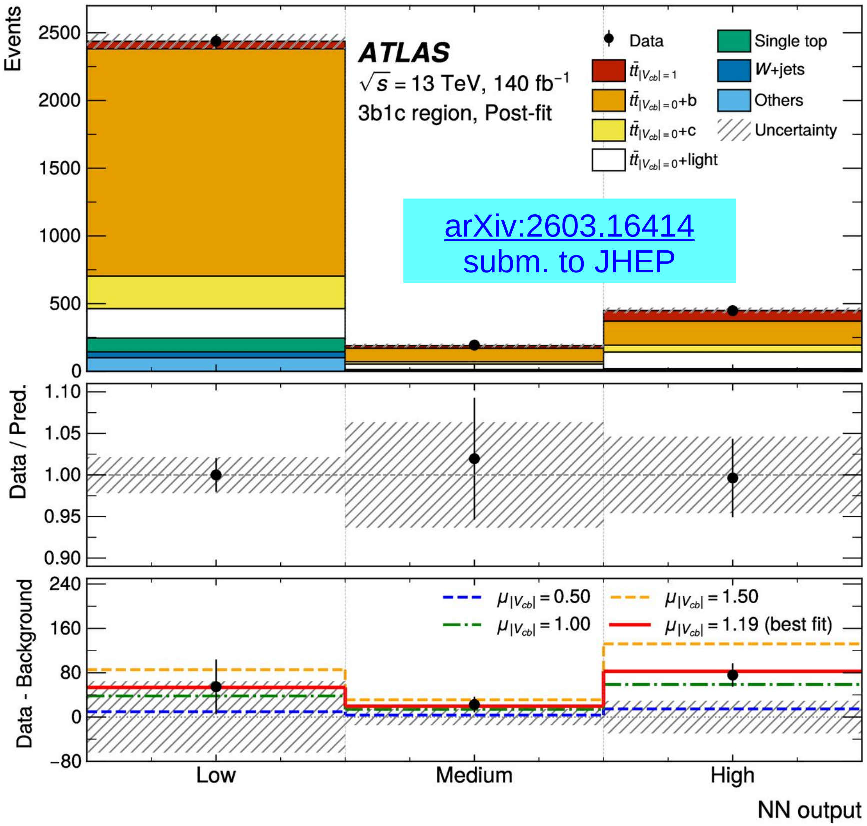
- **Selection/Analysis**
  - $t\bar{t}$ events with 1 lepton (e or μ) and 4 jets

$$|V_{cb}|^2 = \frac{|V_{cb}|^2}{\sum_q |V_{cq}|^2} = \frac{\mathcal{B}(W^+ \to c\bar{b})}{\mathcal{B}(W^+ \to c\bar{q})} = \frac{\mathcal{B}(t \to b\bar{b}c)}{\mathcal{B}(t \to b\bar{q}c)} = \frac{\mathcal{N}(t\bar{t} \to b\bar{b}c\ \bar{b}\ell^-\bar{\nu})}{\mathcal{N}(t\bar{t} \to b\bar{q}c\ \bar{b}\ell^-\bar{\nu})},$$

  - categorisation: # of b- and c- jets (3b1c most signal like)
  - neural net for signal-background discrimination (jet-parton matching)
  - $t\bar{t}$-MC sample split into $|V_{cb}|$ on/off
  - $|V_{cb}|$ obtained from normalisation of $t\bar{t}(|V_{cb}|=\text{on})$

$|V_{cb}| = ((50^{+7}_{-9}\ (\text{stat})\ ^{+9}_{-10}(\text{syst})) \times 10^{-3}$

Systematic uncertainties dominated by $t\bar{t}$+b/c/light calibration, modelling of $|V_{cb}|$=on, statistics (3b1c, high region)



arXiv:2603.16414
subm. to JHEP

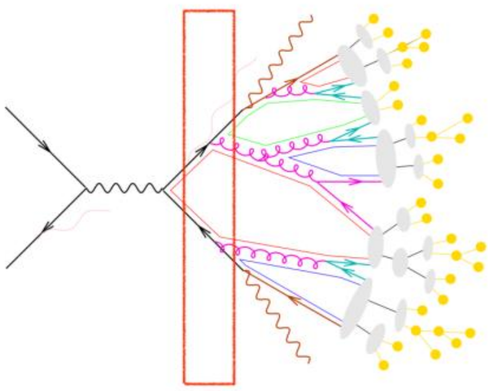
Result in agreement but not (yet) competitive with B-hadron measurements
Novel approach and first measurement of $|V_{cb}|$ at the weak scale
using the rare hadronic t→bbc decay at high momentum-transfer

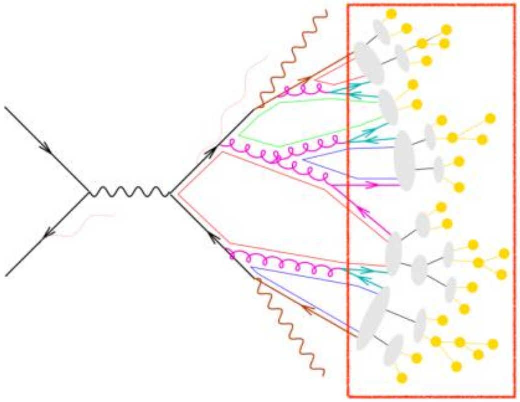
m_t measurements : indirect vs direct methods

The top quark mass m_t, since it is a free parameter of the SM, has to be determined experimentally

- **Indirect measurements (m_t^{pole})**
  - based on cross-section measurements and perturbative QCD predictions
  - performed in a well-defined renormalization scheme (e.g., pole, MS)
    - reduced MC modeling dependence (unfolding)
  - precision:
    - *O*(2 GeV) (inclusive measurements)
    - *O*(1 GeV) (differential measurements)

- **Direct measurements (m_t^{MC})**
  - extracted from kinematic reconstruction of top-quark decay products
  - data compared to MC templates with varying values of m_t^{MC}
    - inherently depends on MC modeling of non-perturbative effects
  - precision:
    - *O*(500 MeV)





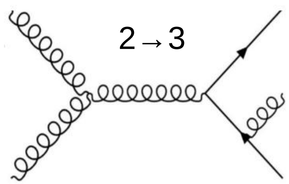
Measure top-quark mass m_t in different channels, kinematic regimes and using different experimental techniques

m_t from $t\bar{t}$+1-jet cross-section

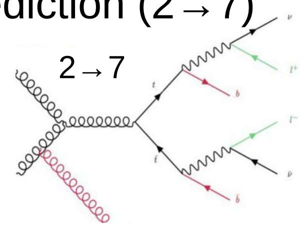
- **Indirect measurement of m_t**
  - ○ dependence of differential cross-section on invariant mass of $t\bar{t}$+1-jet system
- **Selection/Analysis**
  - ○ $t\bar{t}$ events with exactly 2 leptons (eμ), 2 b-jets and 1 additional jet with p_T>50 (60) GeV
- **Observable**

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+\text{jet}}} \frac{d\sigma_{t\bar{t}+\text{jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s)\ , \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+\text{jet}}}}$$

  - ○ unfolded at parton-level and compared to
    - stable top-quarks prediction (2→3)
    - off-shell top-quarks prediction (2→7)

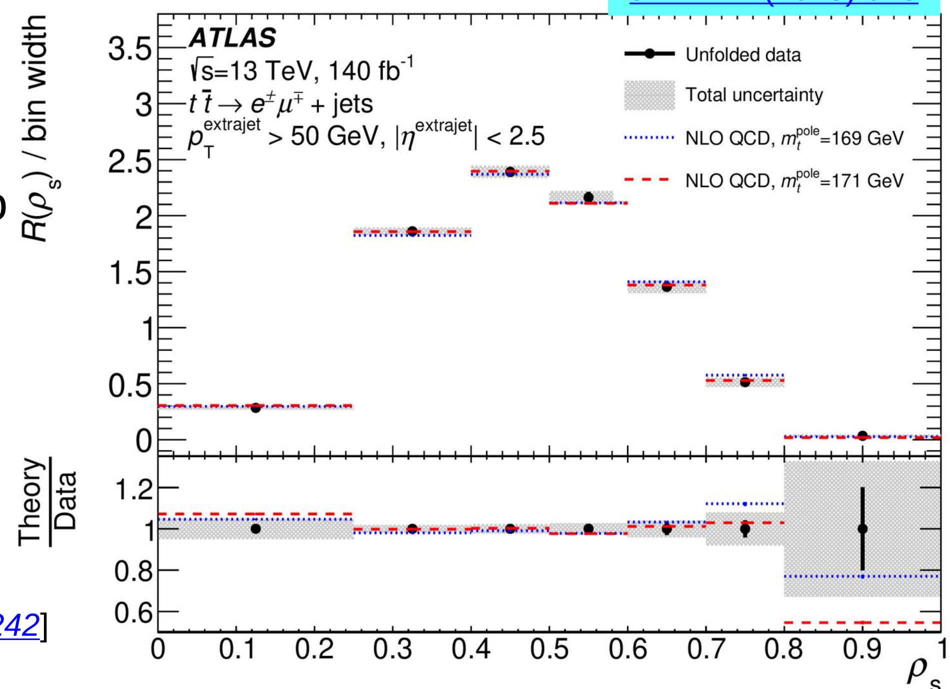


Fixed order NLO QCD
$t\bar{t}$+1-jet



Fixed order NLO QCD
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j+X$
prov. By M. Worek [arXiv 1509.09242]

JHEP 12 (2025) 023



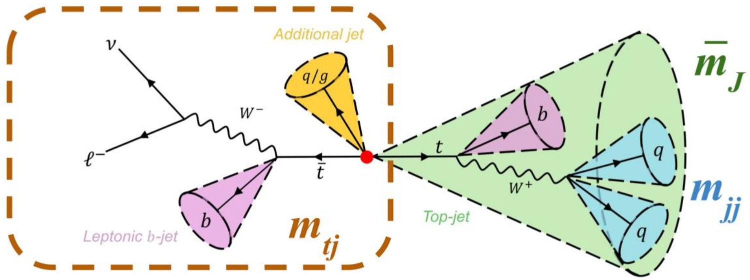
2→3 prediction : m_t^{pole} = 170.73 ± 0.33 (stat) ± 1.36 (syst) $^{+0.34}_{-0.28}$ (scale) ± 0.24 (PDF⊕α_S) GeV

2→7 prediction : m_t^{pole} = 171.69 ± 0.41 (stat) ± 1.68 (syst) $^{+0.66}_{-1.34}$ (scale) $^{+0.49}_{-0.46}$ (PDF⊕α_S) GeV

Systematic uncertainties dominated by σ(JES, Jet Energy Scale)=0.65 GeV
and σ(b-tag)= 0.44 GeV, σ(PS-recoil)=0.68 GeV, σ(PS-had)=0.43 GeV (here for 2→3)

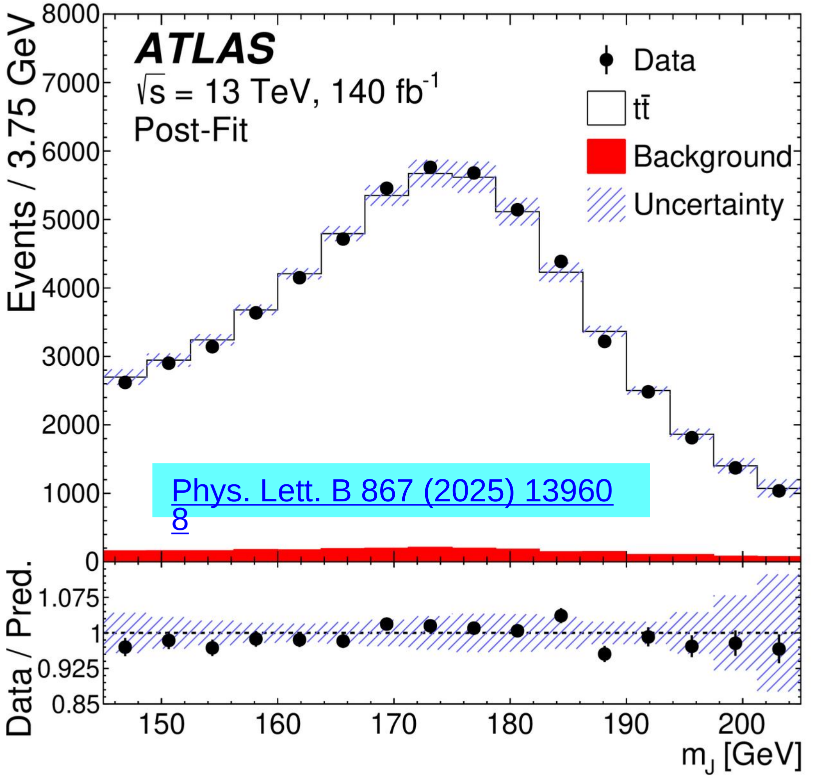
m_t at high p_T

- **Direct measurements from top-quark decays**
  - extract m_t from events with sufficiently energetic hadronically-decaying top



- **Selection/Analysis**
  - $t\bar{t}$ events where one top quark decays leptonically (e or μ) in the final state and the other decays hadronically
  - hadronically decaying top reconstructed as a large-radius (R=1.0) jet with p_T>355 GeV

- **Observables**
  - mean of top-jet mass $\overline{m}_J$
    - reduced sensitivity on m_J shape
  - reduction of JES and recoil syst. uncertainty:
    - inv. mass of jets from W decay m_{jj}
    - inv. mass of semileptonically decaying top and closest jet (if exits) m_{tj}
  - to extract m_t, a simultaneous profile likelihood fit is performed to $\overline{m}_J$, m_{jj} and m_{tj}



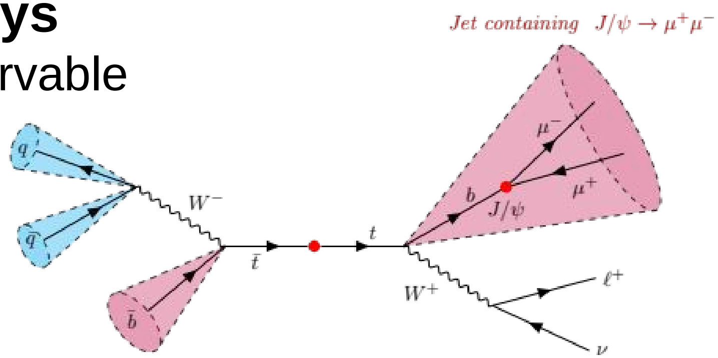
[Phys. Lett. B 867 (2025) 139608]

m_t = 172.95 ± 0.27 (stat) ± 0.46 (syst) GeV

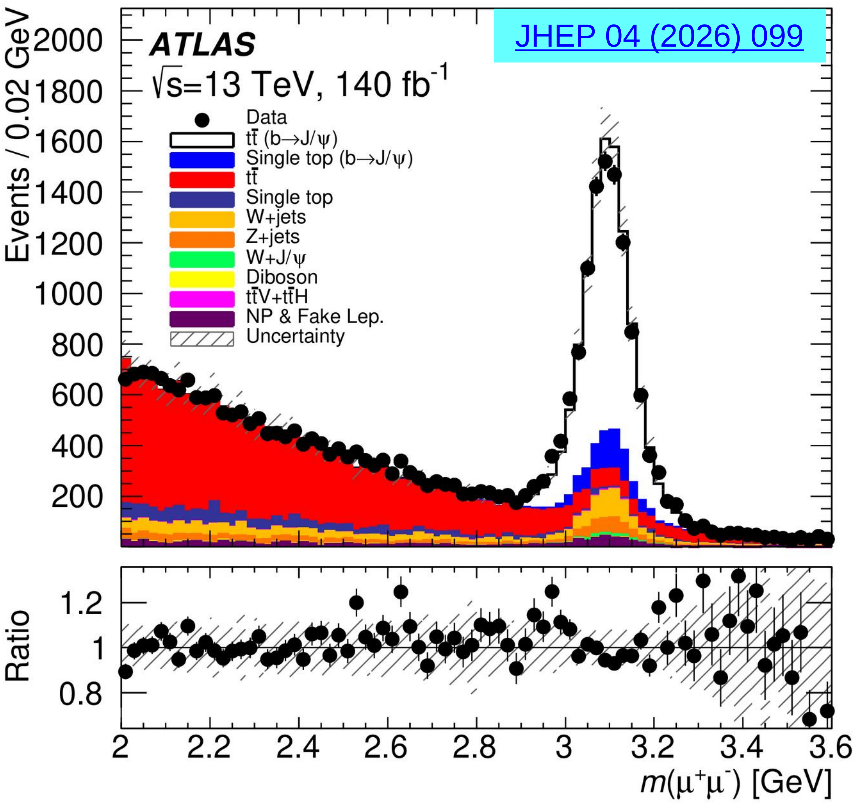
Leading uncertainties : σ(JES)=0.26 GeV, σ(ISR/FSR)=0.14 GeV - σ(recoil) reduced to 0.08 GeV

m_t using top quark decays with a $J/\psi \rightarrow \mu^+\mu^-$

- **Direct measurements from top-quark decays**
  - extract m_t from events using purely leptonic observable
    - reduced sensitivity to Jet Energy Scale



- **Selection/Analysis**
  - events where one top quark decays leptonically (e or μ) in the final state and the b-quark decays into $J/\psi \rightarrow \mu^+\mu^-$



- **Several challenges**
  - small branching fraction of the signal process

$$\mathcal{B}(t\bar{t} \rightarrow (W^+b)(W^-b) \rightarrow (l\nu_l J/\psi(\rightarrow \mu^+\mu^-)X)(qq'b)) \sim 3.8 \times 10^{-4}$$

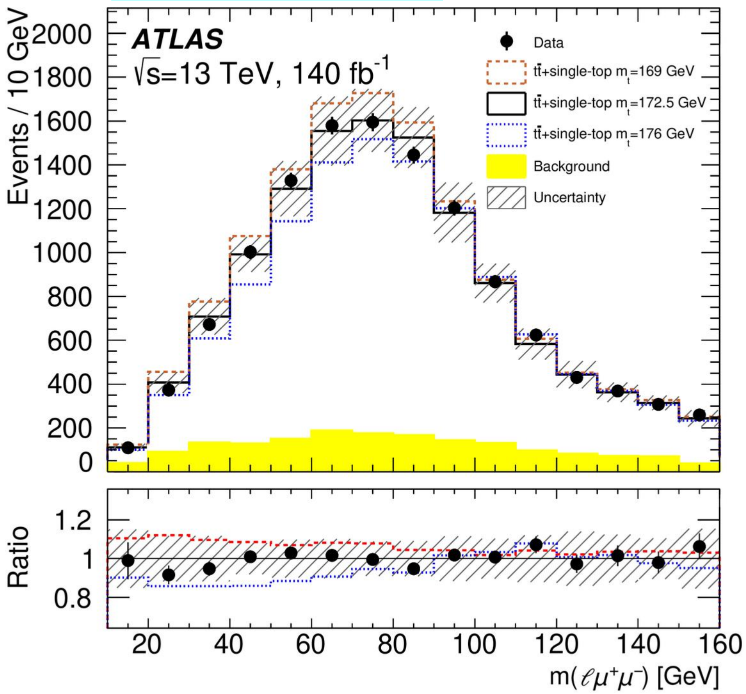
Data	12 165
$t\bar{t}$ ($b \rightarrow J/\psi \rightarrow \mu^+\mu^-$)	7941 ± 737
Single-top-quark ($b \rightarrow J/\psi \rightarrow \mu^+\mu^-$)	964 ± 109
$t\bar{t}$	1411 ± 145
Single-top-quark	164 ± 43
$t\bar{t}V + t\bar{t}H$	38 ± 8
W+jets	777 ± 258
Z+jets	468 ± 138
$W + J/\psi$	78 ± 41
diboson	16 ± 9
Non-prompt and fake lepton	322 ± 99
Signal+background	12 180 ± 821
Expected background fraction	0.27 ± 0.01
Data/(Signal+background)	1.00 ± 0.07

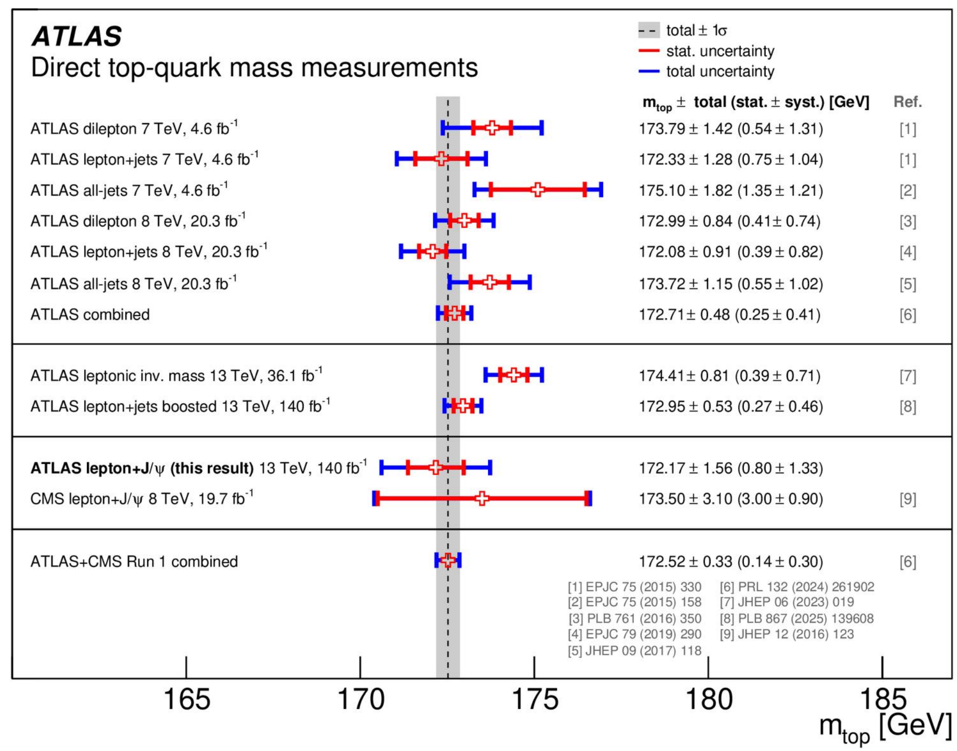
  - sensitivity to some signal-process modelings

m_t using top quark decays with a $J/\psi \to \mu^+\mu^-$

- **Observables**
  - invariant mass of isolated lepton and J/ψ system $m(\ell\mu^+\mu^-)$
  - unbinned maximum-likelihood fit performed to extract m_t

JHEP 04 (2026) 099





$m_t = 172.17 \pm 0.80\ (\text{stat}) \pm 0.81\ (\text{syst}) \pm 1.07\ (\text{recoil})$ GeV

Leading systematic uncertainties : σ(PS-had)=0.40 GeV, σ(b-frag)=0.15 GeV, σ(W/Z+j)=0.40 GeV and σ(recoil)=1.07 GeV but reduced σ(JES)=0.07 GeV and σ(b-JES)=0.04 GeV !

Conclusion

Presented a selection of recent results in top-quark property measurements using the ATLAS Run 2 datasets

- **Top-quark propeties**
  - ATLAS+CMS combination on spin correlation (*ATLAS-CONF-2026-001*)
  - First measurement of |Vcb| at the weak scale

    $|V_{cb}| = (50^{+11}_{-14})\times 10^{-3}$ (*arXiv:2603.16414*)

- **Top-quark mass measurement**
  - $t\bar{t}$+jet in dileptonic decays: pole mass extracted in a well-defined scheme

    $m_t^{pole} = 170.73 \pm 1.45$ GeV (*JHEP 12 (2025) 023*)
  - $t\bar{t}$ events with sufficiently energetic hadronically-decaying top

    $m_t = 172.95 \pm 0.53$ GeV (*Phys. Lett. B 867 (2025) 139608*)
  - $t\bar{t}$ events with $J/\psi \rightarrow \mu^+\mu^-$: leptonic method with reduced jet systematics

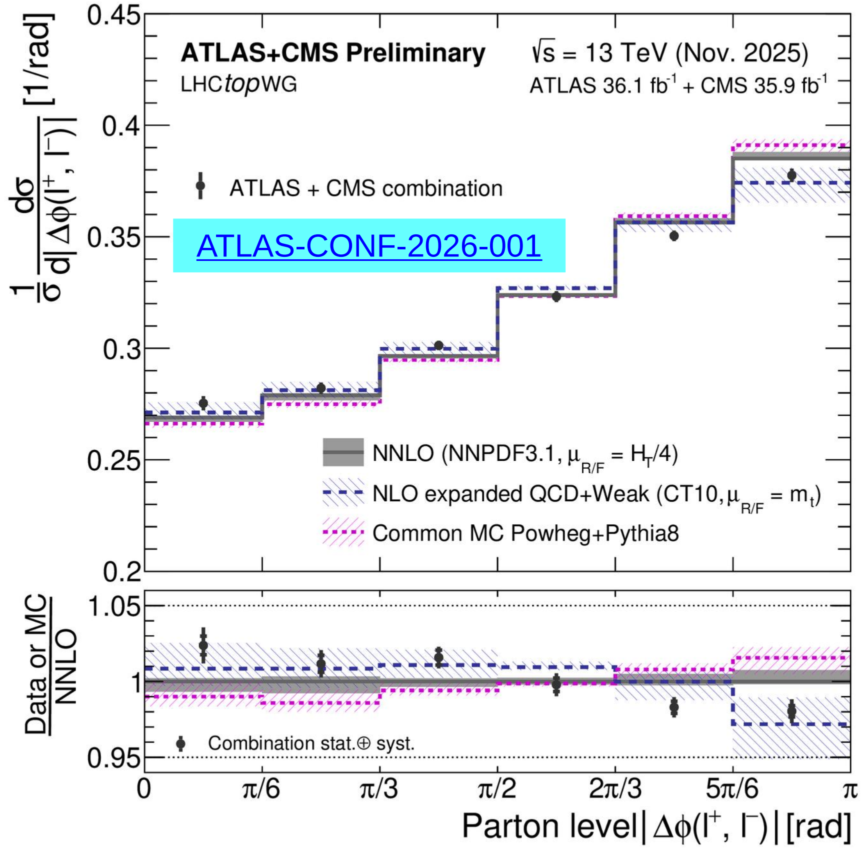
    $m_t = 172.17 \pm 1.56$ GeV (*JHEP 04 (2026) 099*)

All ATLAS results on top quark physics can be found in:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

Backup slides

Spin correlation, ATLAS+CMS combination

- **Selection/Analysis**
  - ATLAS: 2015+2016, 36 fb^{-1}, eμ channel, no $t\bar{t}$ reconstruction
    - repeated to match CMS binning
  - CMS: 2016, 36 fb^{-1}, ee/eμ/$\mu\mu$ channels, includes $t\bar{t}$ reconstruction
  - unfolding to parton level
  - combination done with the Convino package
    - χ^2 minimization,
    - takes systematic uncertainties and correlations within each experiment into account
    - combination of two normalised differential cross-sections => N-1 degrees of freedom



Tension between data and common MC Powheg+Pythia8 prediction
Better agreement with fixed-order theoretical predictions with higher-order corrections

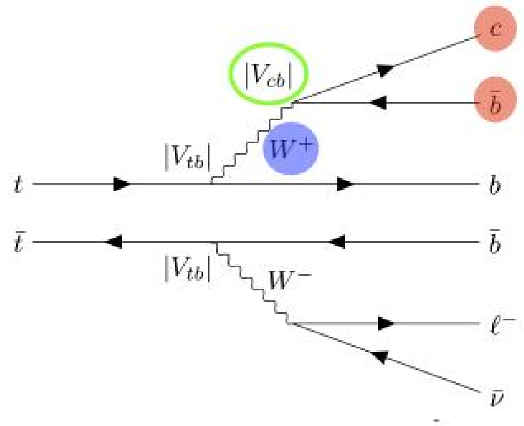
$|V_{cb}|$ CKM matrix element in $t\bar{t}$ decays

arXiv:2603.16414
subm. to JHEP

- **Selection/Analysis**
  - $t\bar{t}$ events with 1 lepton (e or μ) and 4 jets

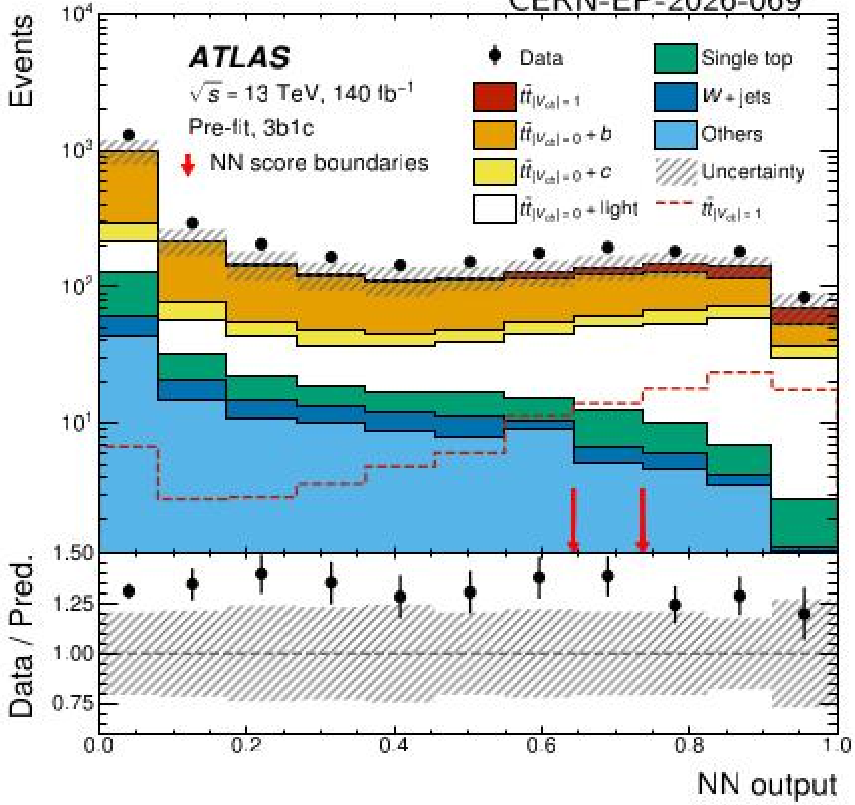
$$|V_{cb}|^2 = \frac{\mathcal{B}(W^+ \to c\bar{b})}{\mathcal{B}(W^+ \to c\bar{q})} = \frac{\mathcal{N}(t\bar{t} \to b\bar{b}c\ \bar{b}\ell^-\bar{\nu})}{\mathcal{N}(t\bar{t} \to b\bar{q}c\ \bar{b}\ell^-\bar{\nu})}$$

  - categorisation: # of b- and c- jets (3b1c most signal like)



- **Jet-assignment Neural Network for jet–parton matching**
  - signal: $t\bar{t}$ events with correctly assigned jets
  - background: wrong jet assignments and $t\bar{t}$+heavy-flavour

CERN-EP-2026-069



$|V_{cb}|$ CKM matrix element in $t\bar{t}$ decays

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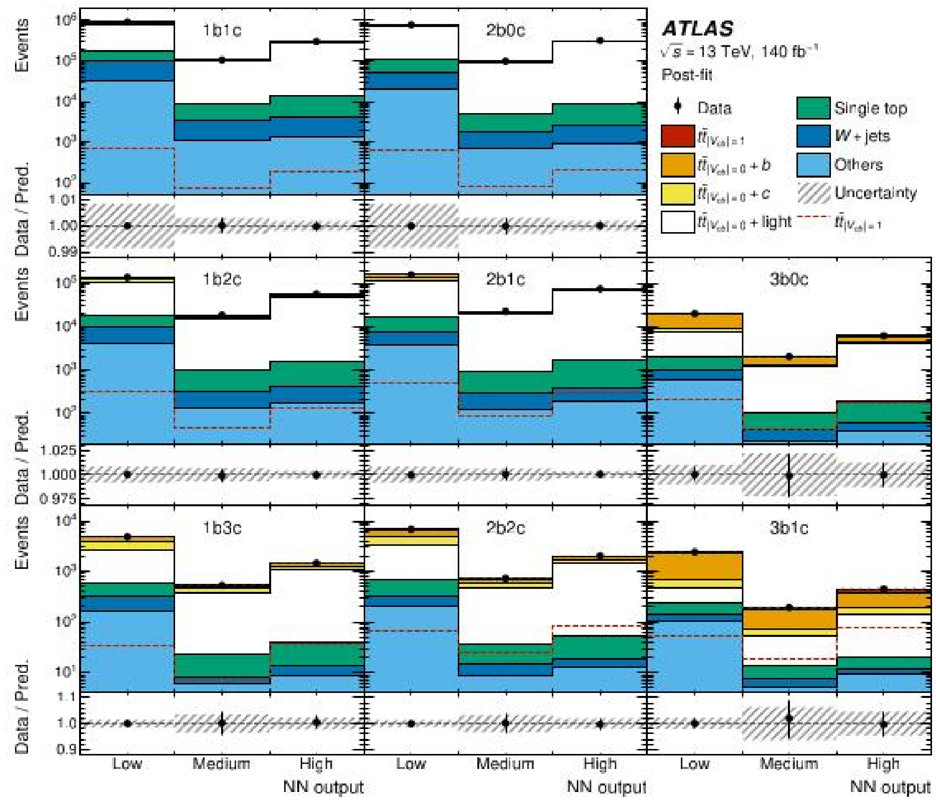
subm. to JHEP

- **Profile likelihood fit**
  - $t\bar{t}$ MC split into $|V_{cb}|$ on/off samples
    - $|V_{cb}|$ extracted from normalization of $t\bar{t}(|V_{cb}|\text{=on})$
  - fit parameters
    - scale factor for $t\bar{t}(|V_{cb}|\text{=on})$
    - inclusive $t\bar{t}$ normalizations
    - background normalizations ($t\bar{t}$+b/c)
    - c-jet (c-to-b) tagging (mistagging) efficiencies
  - dominant uncertainties
    - $t\bar{t}$+b/c/light calibration, modelling of $|V_{cb}|$=on, statistics (3b1c, high region)

CERN-EP-2026-069



$$|V_{cb}| = ((50^{+7}_{-9}\,(\text{stat})\,^{+9}_{-10}(\text{syst})) \times 10^{-3}$$

Systematic uncertainties dominated by $t\bar{t}$+b/c/light calibration, modelling of $|V_{cb}|$=on, statistics (3b1c, high region)

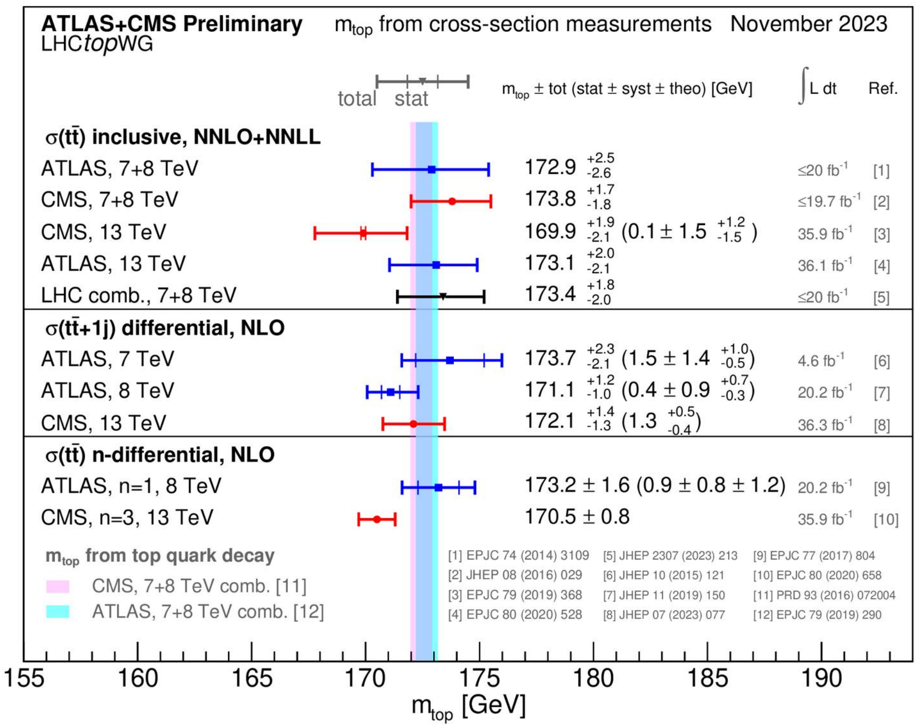
Result in agreement but not (yet) competitive with B-hadron measurements
Novel approach and first measurement of $|V_{cb}|$ at the weak scale using the rare hadronic $t \rightarrow bbc$ decay at high momentum-transfer

Measuring the Top Quark Mass: Direct vs. Indirect

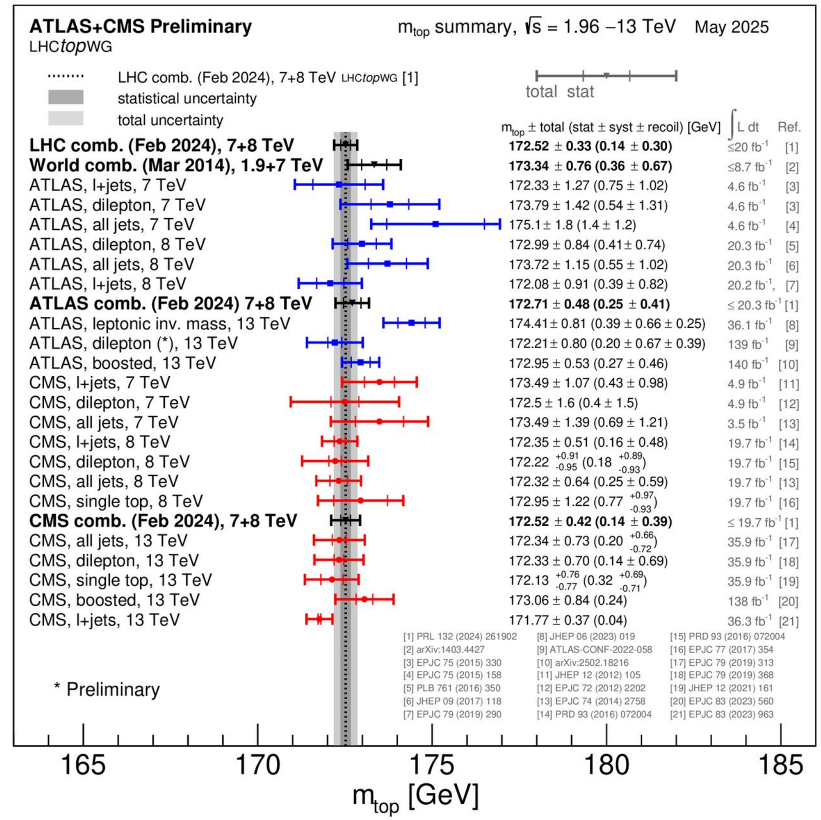
The top quark mass m_t, since it is a free parameter of the SM,
has to be determined experimentally

ATL-PHYS-PUB-2025-025

- **Indirect measurements (m_t^{pole})**



- **Direct measurements (m_t^{MC})**

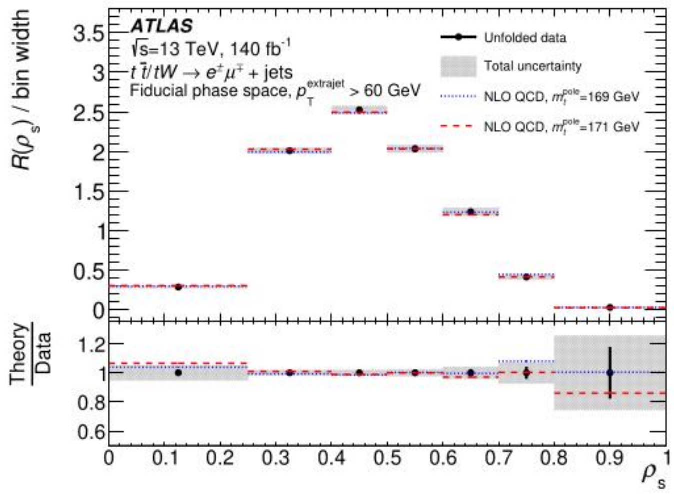


m_t from $t\bar{t}$+1-jet cross-section

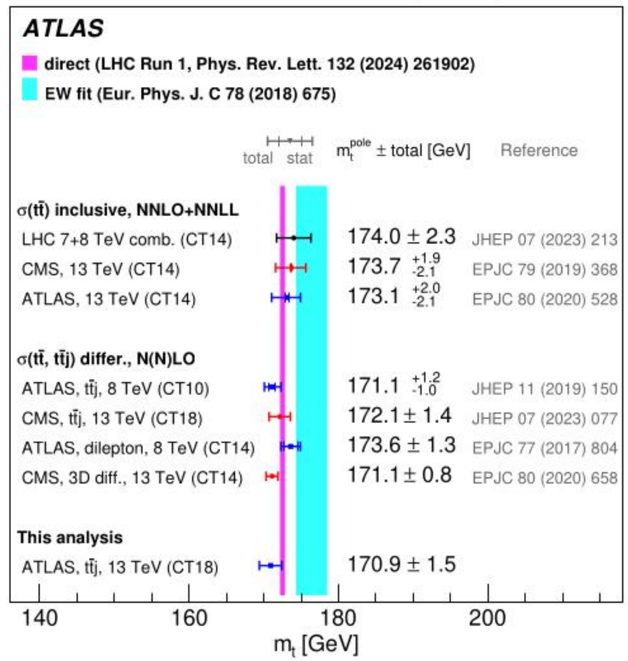
Uncertainty table (2 → 3

Uncertainty source	Δm_t^{pole} [GeV]	MC stat. unc. [GeV]
Data statistics	0.33	-
Detector unc.		
b-tagging and mistag	0.44	0.06
Jets	0.65	0.06
Leptons	0.25	0.06
Others	0.18	0.06
Modeling unc.		
MC statistical uncertainty	0.08	-
Backgrounds normalization	0.02	-
Single-top modeling	0.03	0.06
m_t^{MC} dependence	0.10	0.09
PS Recoil model	0.68	0.06
Parton shower	0.43	0.14
Underlying event	0.39	0.12
Color reconnection	0.13	0.08
ME+PS matching: p_T^{hard}	0.09	0.06
ME+PS matching: h_{damp}	0.26	0.06
ME+PS matching: line shape	0.38	0.12
3D NNLO reweight	0.21	0.06
PDF	0.26	0.06
Initial-state radiation	0.24	0.06
Final-state radiation	0.04	0.16
Factorization scales	0.09	0.06
Renormalization scales	0.03	0.06
Theory unc.		
Scale variations	+0.34 -0.28	+0.05 -0.06
PDF ⊕ α_S	0.24	+0.06 -0.06
Total	+1.47 -1.44	-

Unfolded distribution (2 → 7



Previous measurements (2 → 3 process)



m_t using top quark decays with a $J/\psi \to \mu^+\mu^-$

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Source of uncertainty	Unc. in m_{top} [GeV]	Stat. precision [GeV]
Data and Monte Carlo samples		
Statistical error in data	0.80	
Statistical error in signal and background model	0.27	±0.06
Method	0.06	±0.10
Luminosity	0.01	< ±0.005
Pile-up	0.11	±0.02
Modelling of $t\bar{t}$ process		
Matrix element matching	0.14	±0.20
NNLO reweighting	0.01	±0.02
Top-quark decay lineshape	0.07	±0.02
Parton shower and hadronisation	0.40	±0.19
b-hadron production fractions	0.04	±0.02
b-hadron decay BR	0.08	±0.02
Initial-state QCD radiation	0.10	±0.07
Final-state QCD radiation	0.21	±0.05
Underlying event	0.20	±0.12
Colour reconnection	0.04	±0.28
Parton distribution function	0.03	< ±0.005
b-quark fragmentation r_b	0.15	±0.04
Modelling of single-top-quark process		
Matrix element matching	0.02	±0.11
$t\bar{t}$–tW interference	0.15	±0.07
Parton shower and hadronisation	0.09	±0.11
b-hadron production fractions	0.09	±0.07
b-hadron decay BR	0.02	< ±0.005
Initial-state QCD radiation	0.05	±0.04
Final-state QCD radiation	0.06	±0.04
Parton distribution function	0.01	< ±0.005
b-quark fragmentation r_b	0.05	±0.07
Modelling of background processes		
$t\bar{t}V + t\bar{t}H$, diboson	0.02	±0.01
W/Z+jets	0.40	±0.12
$W + J/\psi$	0.04	< ±0.005
Non-prompt and fake lepton	0.15	±0.01
Fake soft-μ	0.01	< ±0.005
Detector response		
Isolated leptons	0.08	±0.01
Soft-μ	0.12	±0.01
Light jet energy scale	0.07	±0.01
b-jet energy scale	0.04	±0.01
Jet energy resolution	0.02	±0.01
Flavour tagging	0.02	< ±0.005
Total systematic uncertainty (excluding recoil)	0.81	±0.15
Total stat. and syst. uncertainty (excluding recoil)	1.14	±0.15
Recoil uncertainty	1.07	±0.22
Total uncertainty	1.56	±0.18

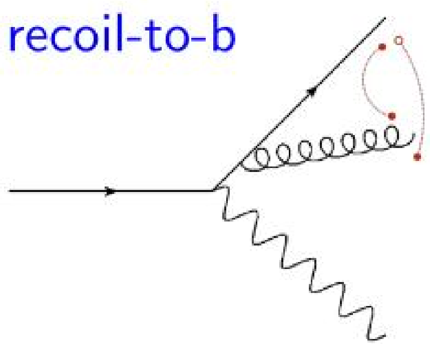
Leading systematic uncertainties : σ(PS-had)=0.40 GeV, σ(b-frag)=0.15 GeV, σ(W/Z+j)=0.40 GeV and σ(recoil)=1.07 GeV but reduced σ(JES)=0.07 GeV and σ(b-JES)=0.04 GeV !

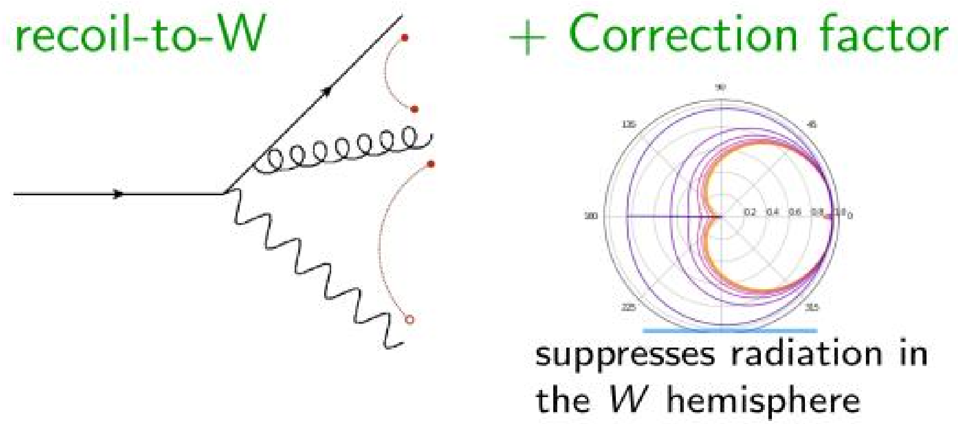
Recoil modelling in t → Wb decay

Treatment of recoil in second gluon emission (dipole showers):

- ○ Recoil-to-b (default)
- ○ Recoil-to-W + correction ⇒ recoil-to-top

Talk by P. Skands





- ○ First emission: controlled by Matrix Element Calculation
- ○ Second emission: in dipole showers different possible strategies for the recoil result in different momentum reassignment between t, W, b and different coverage of the phase space