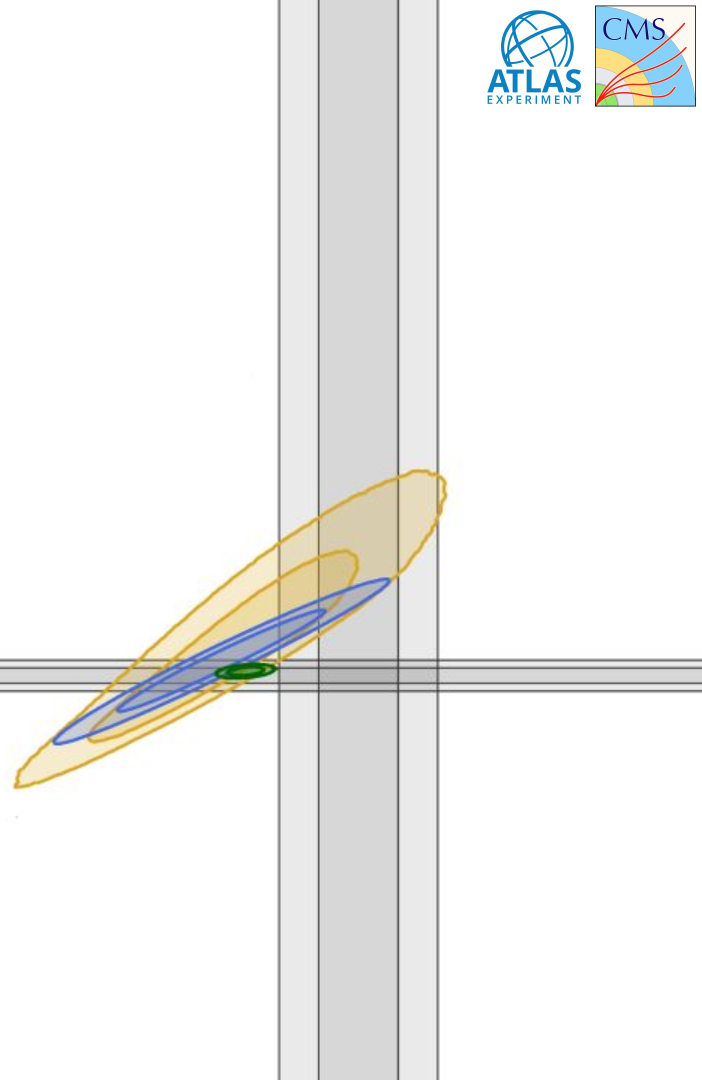
Top mass measurements

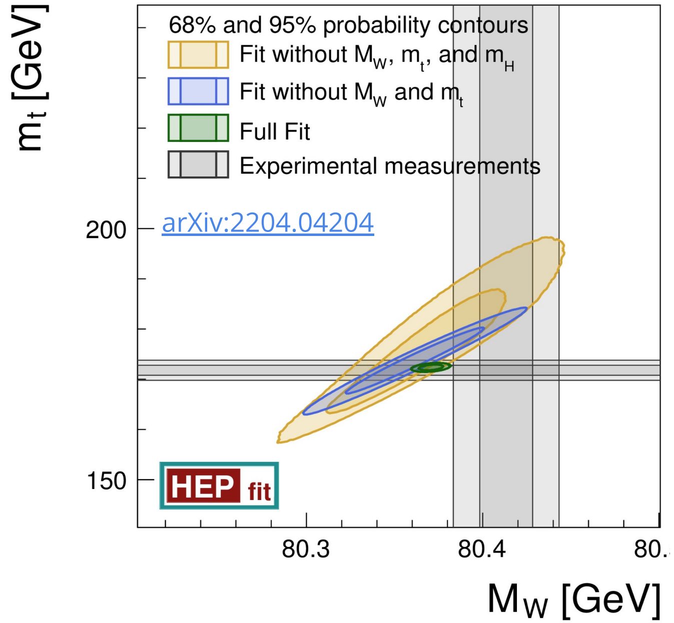


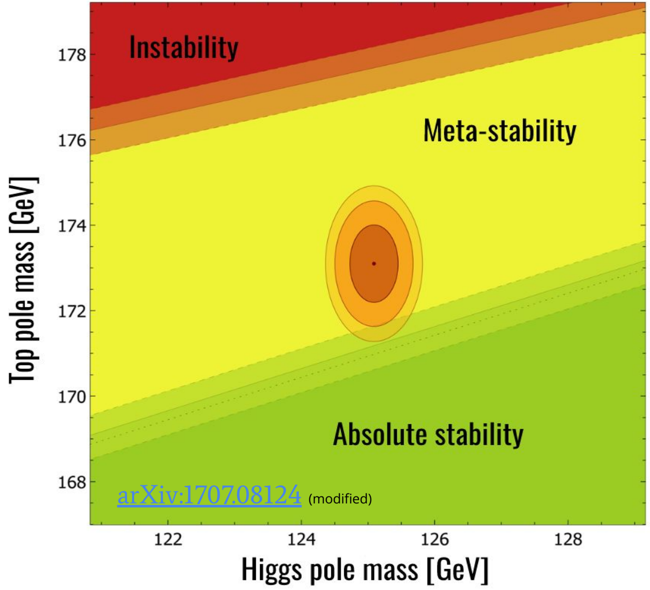
Mikael Myllymäki, Helsinki Institute of Physics
on behalf of the **ATLAS** and **CMS** collaborations

TOP2023 September 26th Traverse City, MI

Motivation

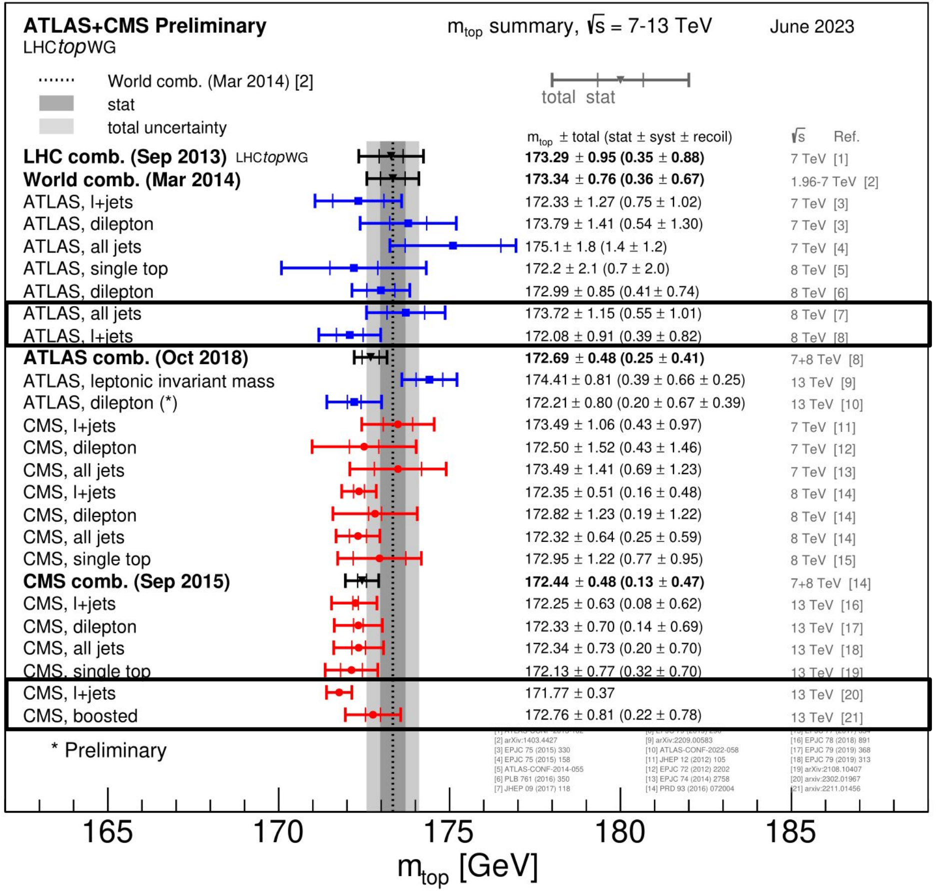
- Stability of the EW vacuum
- Global EW fits → SM consistency
- Connection to Higgs physics
- BSM physics



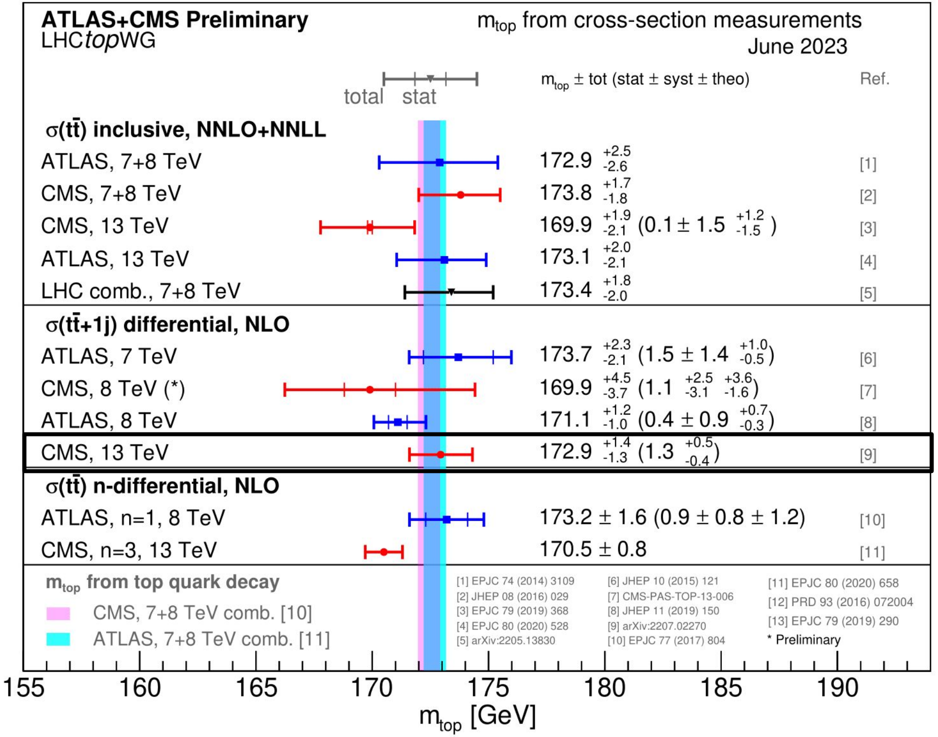


- Challenges
  - tt̄ modelling
  - jet energy scale
  - b-quark fragmentation
  - final state radiation
  - top mass interpretation

Direct measurements m_t^{MC}



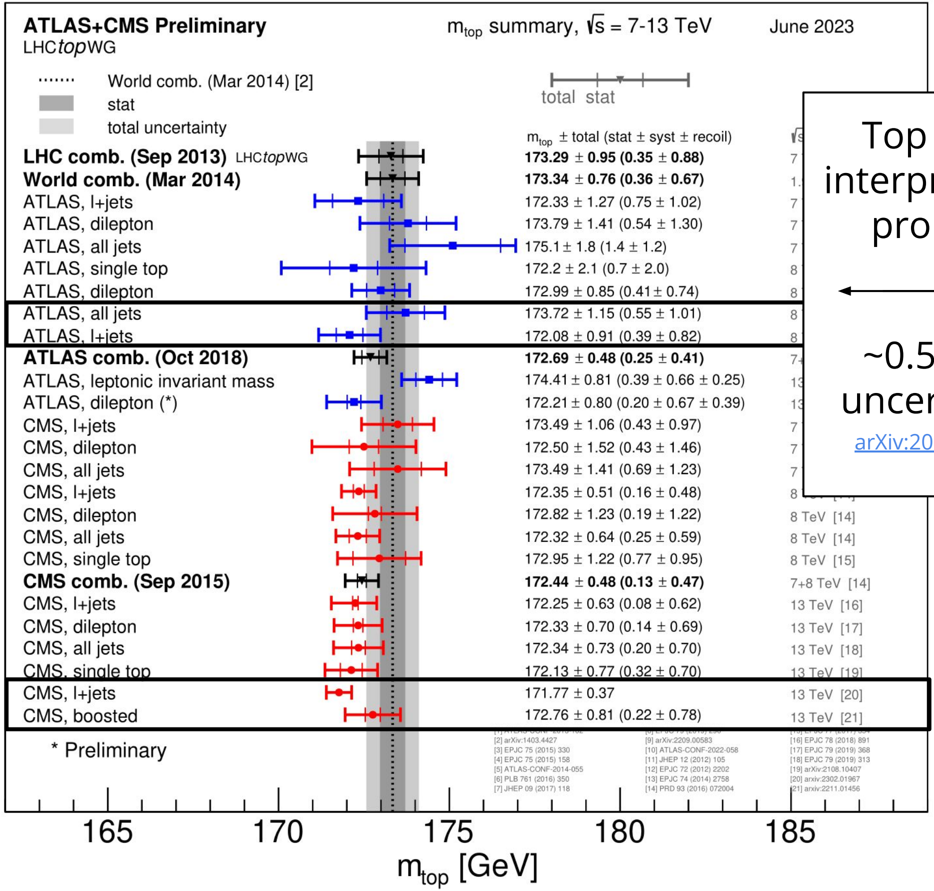
Indirect measurements m_t^{pole}



covered in this talk

LHCWG summary plots

Direct measurements m_t^{MC}



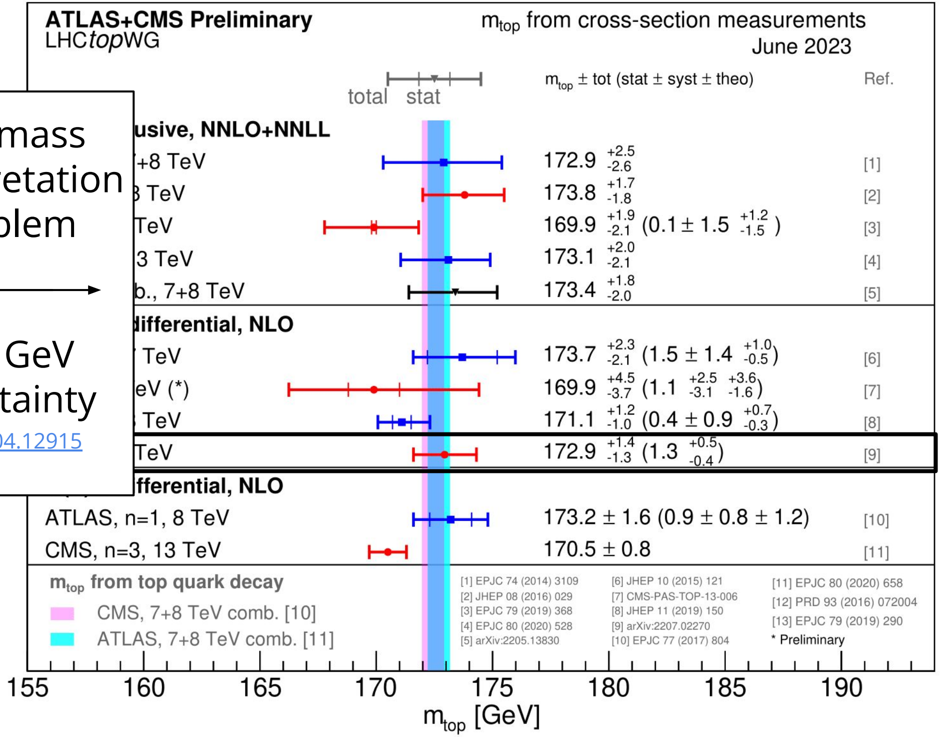
Top mass interpretation problem

↔

~0.5 GeV uncertainty

arXiv:2004.12915

Indirect measurements m_t^{pole}



covered in this talk

LHCWG summary plots

“Measurement of the top quark mass using a profile likelihood approach with the lepton+jets final states in proton-proton collisions at $\sqrt{s}$=13 TeV”

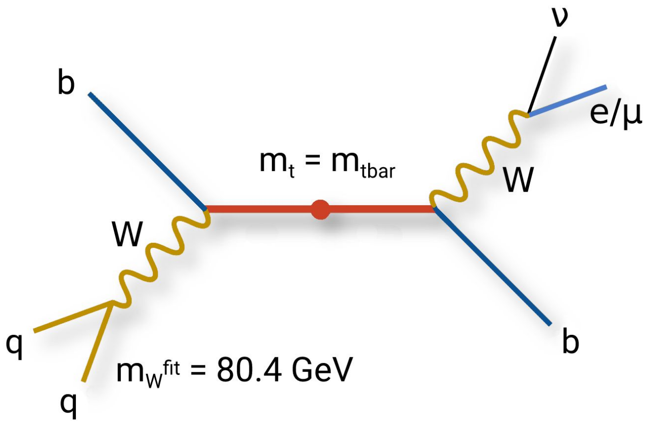
$t\bar{t}$ lepton+jets

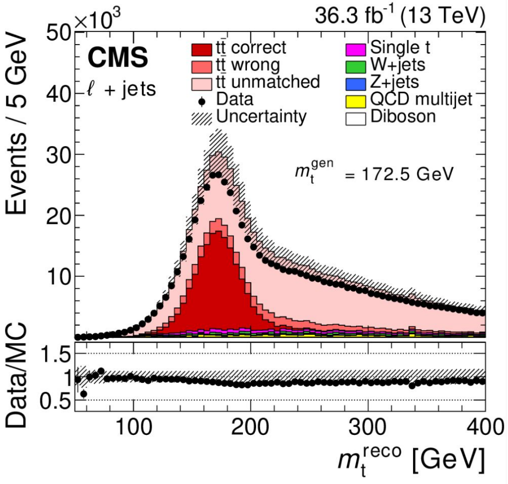
arXiv:2302.01967 (submitted to EPJC)

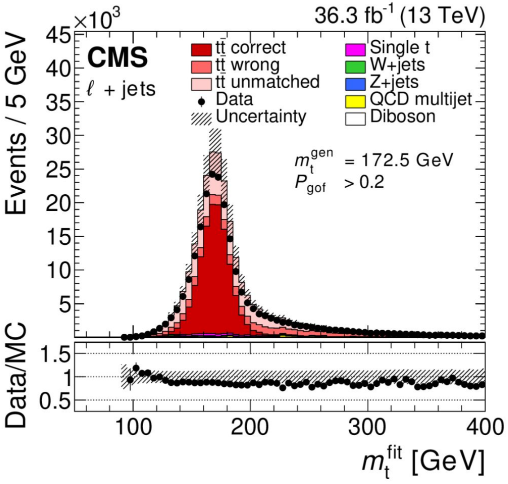
Event selection

arXiv:2302.01967 (submitted to EPJC)
tt̄ lepton+jets
36.3fb^{-1} 13 TeV

- Exactly one muon/electron
- 2 b-jets
  → correct assignment challenging
- 2 light quark jets from W
  → boosted W's introduce complications





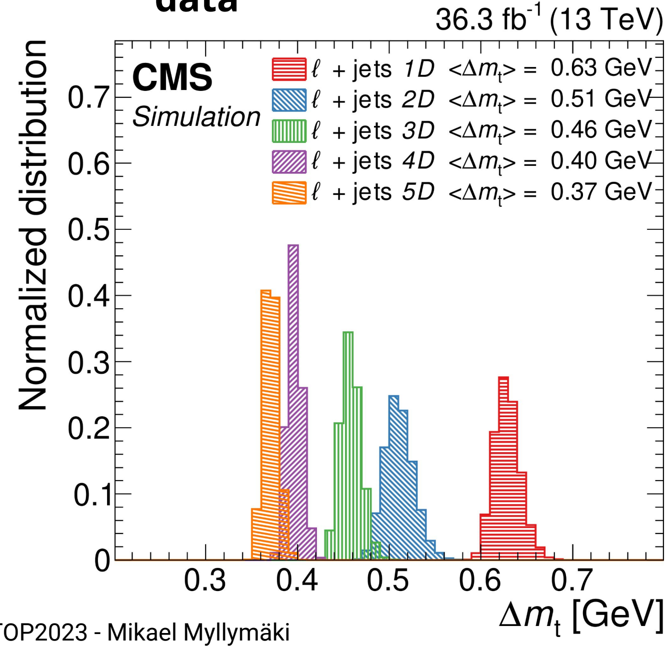


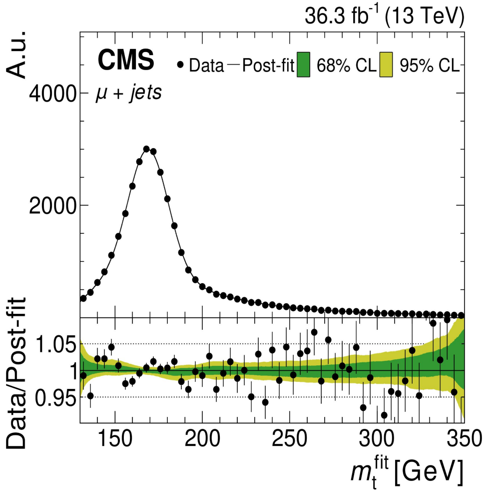
- **Kinematic fit**
  - best event hypothesis chosen from χ^2 minimization
  - based on parton-object resolution functions
  - constraints
    - m_W^{fit} = 80.4 GeV
    - $m_t^{hadr} = m_t^{lept}$
  - $P_{gof} = \exp(-\chi^2/2) > 0.2$ used as a default cut

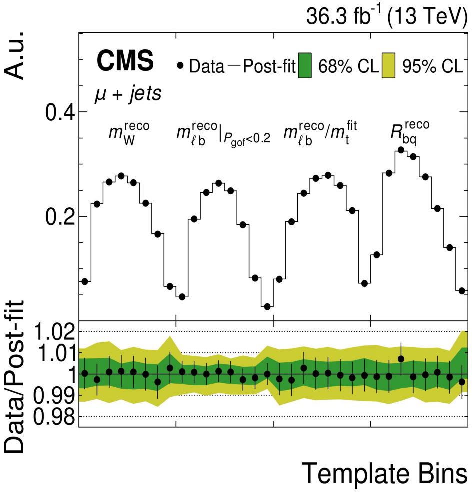
Profiled maximum-likelihood fit

arXiv:2302.01967 (submitted to EPJC)
$t\bar{t}$ lepton+jets
36.3fb^{-1} 13 TeV

- **m_t^{MC}** from profiled maximum-likelihood fit using 5 observables
- Nuisance parameters for syst. uncertainties
- **Possible to constrain systematics with data**



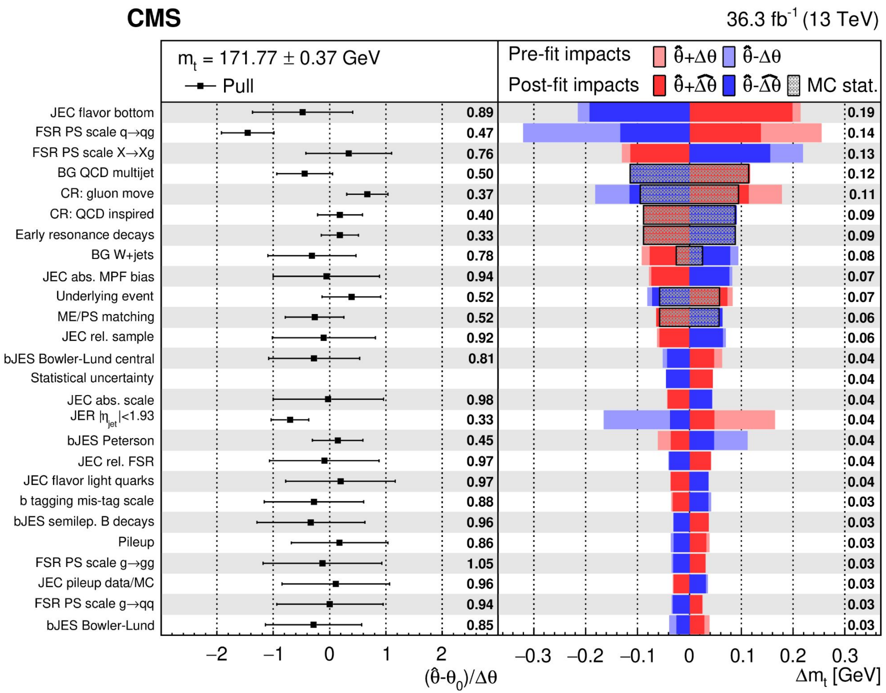




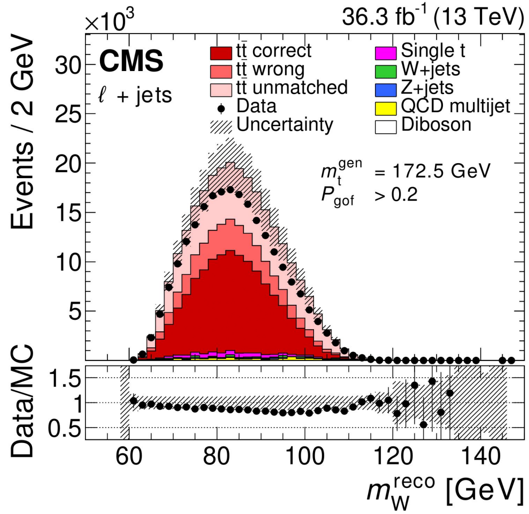
m_t^{fit}	→	for m_t	} parametrized
m_W^{reco}	→	light quark JES	binned
$R_{bq}^{reco} = (p_T^{b1} + p_T^{b2})/(p_T^{q1} + p_T^{q2})$	→	b-JES	binned
$m_{lb}^{red} = m_{lb}^{reco} / m_t^{fit}$	→	for lep syst.	binned
m_{lb}^{reco} ($P_{gof} < 0.2$)	→	for full statistics	binned

Impacts

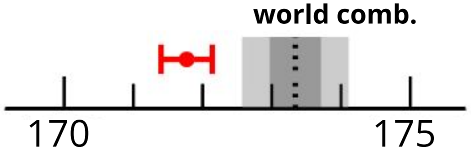
arXiv:2302.01967 (submitted to EPJC)
$t\bar{t}$ lepton+jets
36.3fb^{-1} 13 TeV



- **Most precise result to date**
- qFSR and bFSR pulls in opposite direction
  → **treated fully decorrelated**
- qFSR ~ -1.5 σ
  → **related to m_W^{reco} peak**
- Previous result
  arXiv:1805.01428
  → m_t=172.25±0.63 GeV
- Statistical uncertainty in data: 0.04 GeV



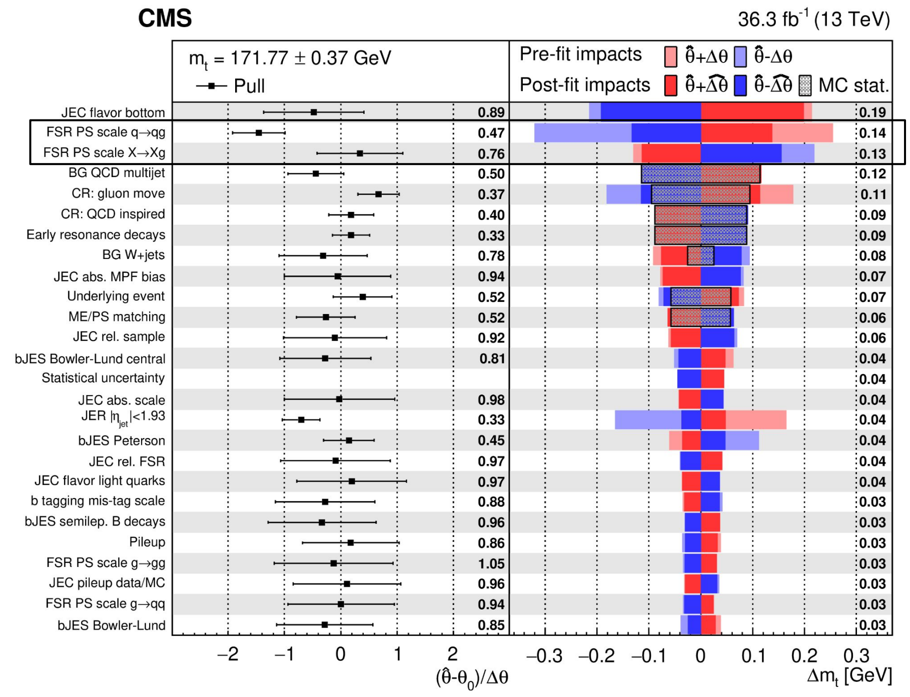
m_t=171.77 ± 0.37 GeV



Dominant uncertainties
- b JEC
- q FSR scale
- b FSR scale

Impacts

[arXiv:2302.01967](https://arxiv.org/abs/2302.01967) (submitted to EPJC)
$t\bar{t}$ lepton+jets
36.3fb^{-1} 13 TeV



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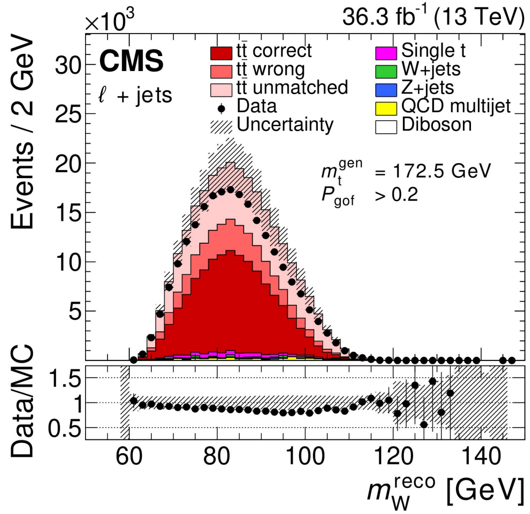

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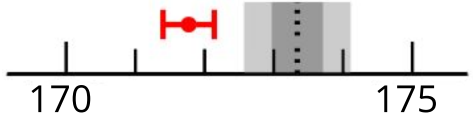


Dominant uncertainties
- b JEC
- q FSR scale
- b FSR scale

“Measurement of the differential $t\bar{t}$ production cross section as a function of the jet mass and extraction of the top quark mass in hadronic decays of boosted top quarks”

boosted top

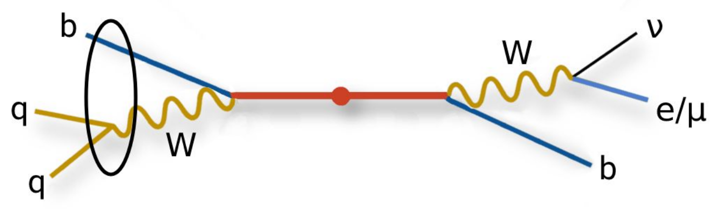
Eur. Phys. J. C 83 (2023) 560

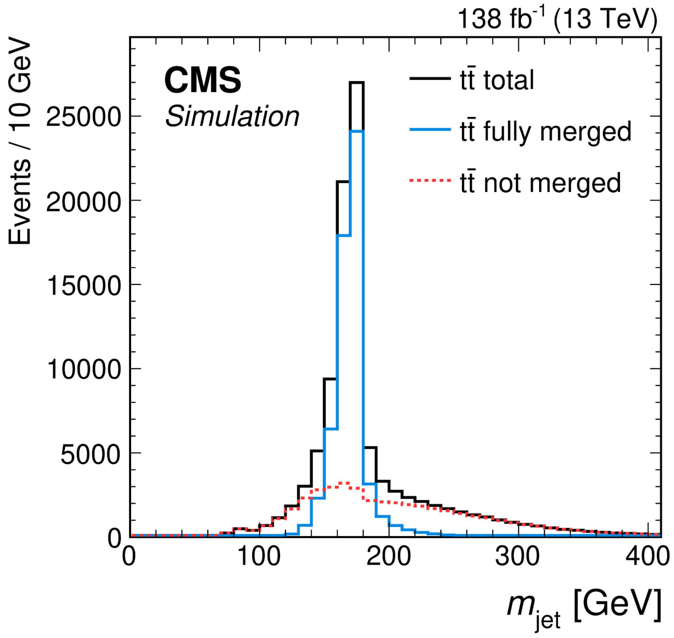
CMS

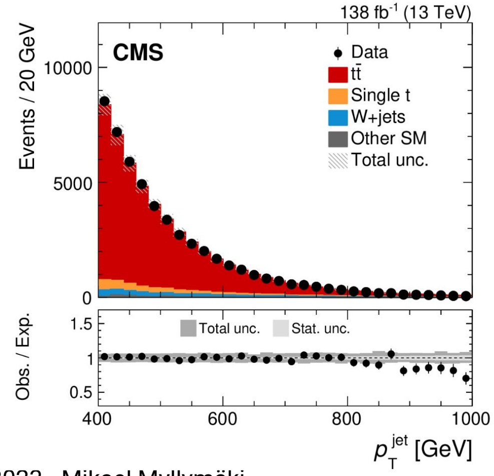
$t\bar{t}$ lepton+jets channel

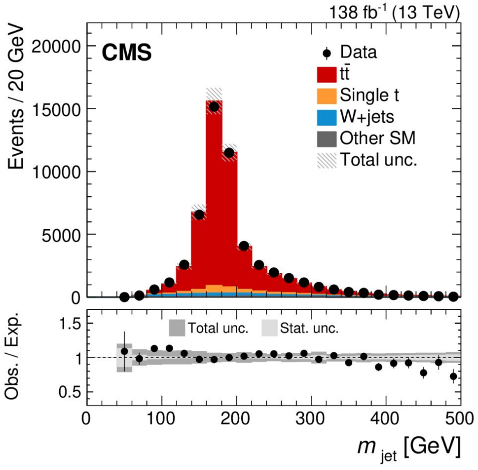
Eur. Phys. J. C 83 (2023) 560
boosted top
138 fb^{-1} 13 TeV

- **XCone** jet reconstruction arXiv:1508.01516
  - R = 1.2, p_T > 400 GeV, N_{sub} = 3
- Differential cross section as a function of jet mass $\mathbf{m_{jet}}$
- No analytical calculations in perturbative QCD yet
  - here used to determine m_t^{MC} with Powheg
  - offers sensitivity to different systematic uncertainties
  - **possible for the m_t^{pole} in future**





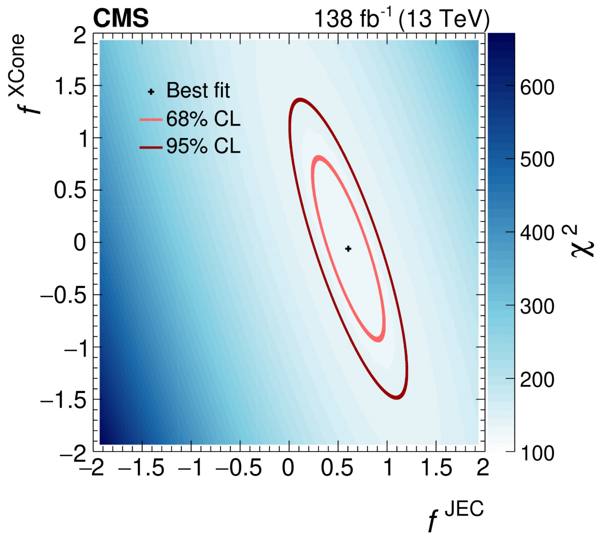


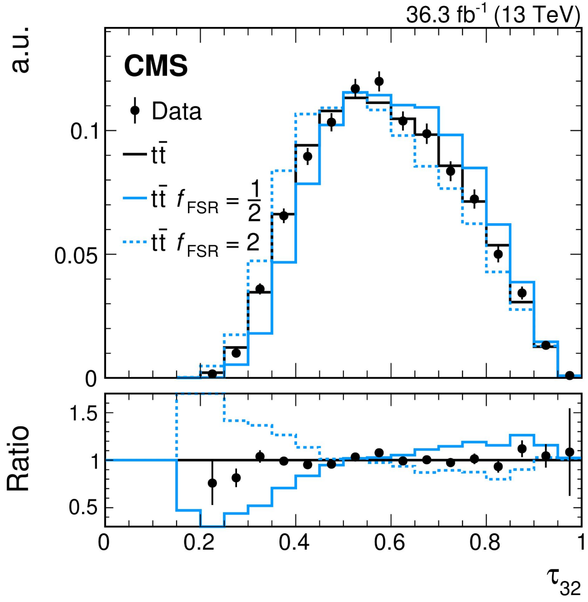


Calibrations

[Eur. Phys. J. C 83 (2023) 560]
boosted top
138 fb^{-1} 13 TeV

- **Jet mass calibration**
  - invariant mass of two **XCone** subjets → hadronic W decay
  - JMS in simulation calibrated using m_W peak
    - $\mathbf{f^{JEC}}$ → jet energy scale
    - $\mathbf{f^{XCone}}$ → XCone jet correction





- **FSR calibration**
  - $\alpha_s^{FSR}(m_Z^2)$ in CP5 tune not optimal for the modelling of jet substructure observables in $t\bar{t}$ production
  - energy scale μ in FSR simulation multiplied by a factor f_{FSR}
  - f_{FSR} fitted to data using the N-subjettiness ratio $\tau_{32} = \tau_3/\tau_2$
    - sensitive to angular distribution of the energy density inside jets

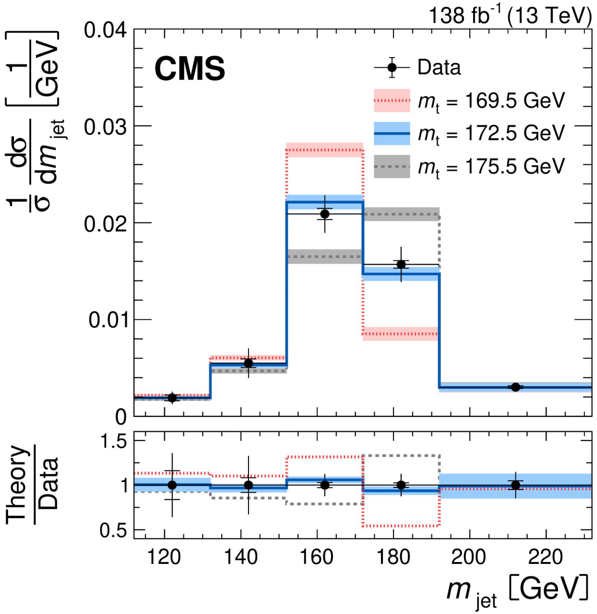
$$f_{\mathrm{FSR}} = 0.97 \pm 0.07\ (0.33 \pm 0.02)\ \text{for 2016 (2017+2018)}$$
$$\alpha_S^{\mathrm{FSR}}(m_Z^2) = 0.1373^{+0.0017}_{-0.0018}\ \text{for 2016}$$
$$\alpha_S^{\mathrm{FSR}}(m_Z^2) = 0.1416^{+0.0019}_{-0.0018}\ \text{for 2017+2018}$$

Results

Eur. Phys. J. C 83 (2023) 560
boosted top
138 fb^{-1} 13 TeV

- χ^2 fit for normalised differential cross section to extract $\mathbf{m_t}$
  - not sensitive to uncertainties in the normalisation
- Validated using simulations with different m_t
- **> x3 improvement in precision compared to previous result** arXiv:1911.03800
  - uncertainty comparable to direct measurements
- Different leading uncertainties
- $m_t = 173.06 \pm 0.24\,(\text{stat}) \pm 0.61\,(\text{exp}) \pm 0.47\,(\text{model}) \pm 0.23\,(\text{theo})\,\text{GeV}$

Source	Uncertainty [GeV]
Jet energy resolution	0.38
Jet mass scale	0.37
Jet mass scale b flavour	0.26
...	
Choice of m_t	0.41
Colour reconnection	0.17
...	
Underlying event tune	0.13
FSR	0.11
μ_F, μ_R scales	0.10
...	



$\mathbf{m_t}$=173.06 ± 0.84 GeV

Dominant uncertainties
- Choice of m_t
- Jet energy resolution
- Jet mass scale

“Measurement of the top-quark mass using a leptonic invariant mass in pp collisions at √s=13 TeV with the ATLAS detector”

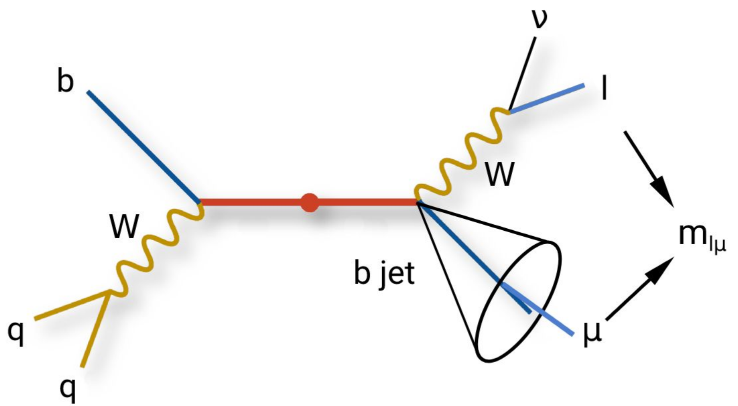
soft muon tagging

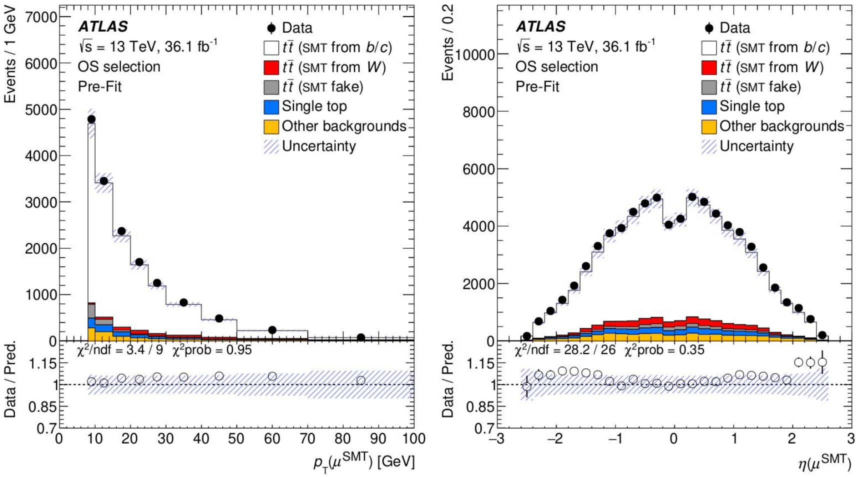
JHEP 06 (2023) 019

Soft muon tagging

JHEP 06 (2023) 019
soft muon tagging
36.1 fb^{-1} 13 TeV

- **$m_{l\mu}$** at $t\bar{t}$ lepton+jets channel
  - μ from the semileptonic decay of b-hadron
- Offers measurement with different systematics
  - less sensitive to:
    - jet energy calibration and resolution
    - top-quark production modelling
  - sensitive to b-fragmentation modelling





- b-jets identified using the **displaced jet tagging** and the **soft muon tagging**
  - SMT tight muon dR < 0.4 of selected jet candidate
  - SMT muon and primary lepton dR < 2
    → both from the same top-decay
- Similar method previously
  - CDF measurement arXiv:0906.5371
  - J/Ψ by CMS: arXiv:1608.03560

b-quark modelling

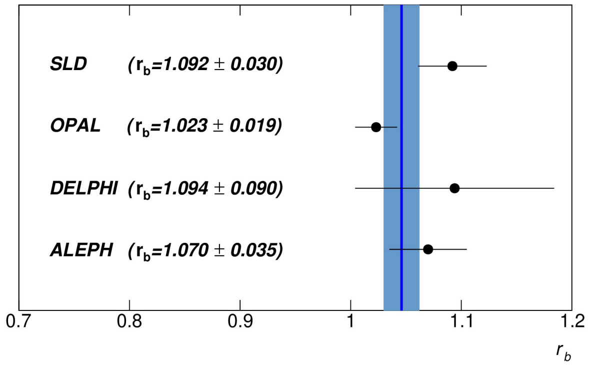
JHEP 06 (2023) 019
soft muon tagging
36.1 fb^{-1} 13 TeV

- Lund-Bowler parameterisation in Pythia8 used
- b-quark fragmentation in the ATLAS A14 tune improved by fitting $\mathbf{r_b}$
- Data from **ALEPH**, **DELPHI** and **OPAL** at LEP and **SLD** at SLC
- $\mathbf{r_b}$ from binned χ^2 test on the experimental $\mathbf{x_B}$ distribution
  - using stat. and syst. uncertainties of each experiment

$$f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp(-bm_T^2/z)$$

$$x_B = 2p_B \cdot p_Z/m_Z^2$$

$$\boxed{r_b = 1.05 \pm 0.02}$$



- Production fractions and branching ratios for b/c hadrons **rescaled to world averages**

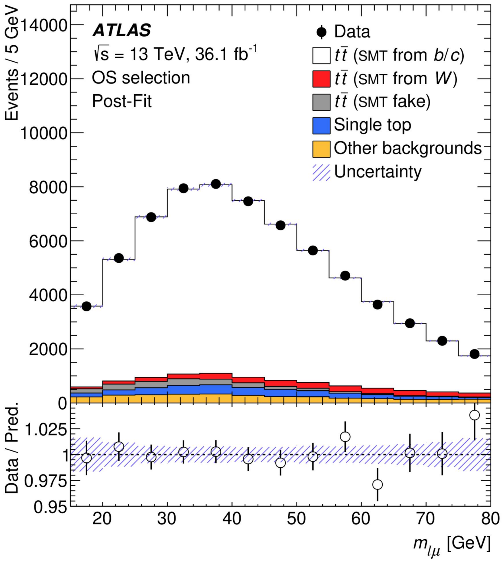
Hadron	PDG	Powheg+Pythia8	Scale Factor
B^0	0.404 ± 0.006	0.429	0.941 ± 0.014
B^+	0.404 ± 0.006	0.429	0.942 ± 0.014
B_s^0	0.103 ± 0.005	0.095	1.088 ± 0.052
b-baryon	0.088 ± 0.012	0.047	1.87 ± 0.26
D^+	0.226 ± 0.008	0.290	0.780 ± 0.027
D^0	0.564 ± 0.015	0.553	1.020 ± 0.027
D_s^0	0.080 ± 0.005	0.093	0.857 ± 0.054
c-baryon	0.109 ± 0.009	0.038	2.90 ± 0.24

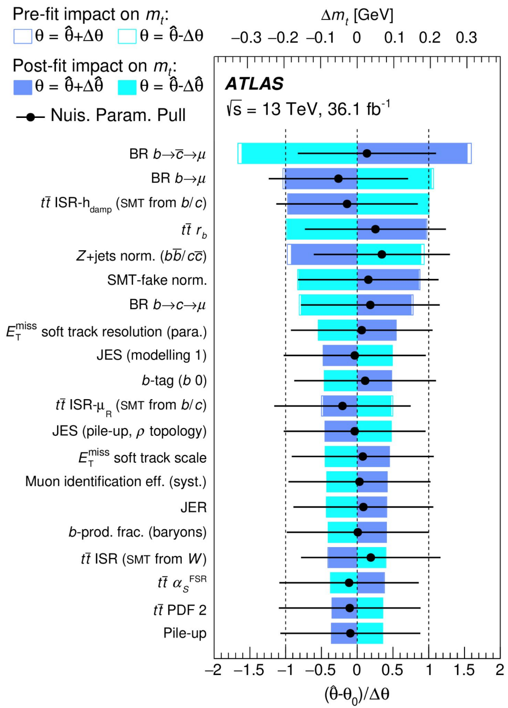
Hadronic Decay Mode	PDG	Powheg Pythia8+EvtGen	Scale Factor
$b \to \mu$	$0.1095\ ^{+0.0029}_{-0.0025}$	0.106	$1.032\ ^{+0.0027}_{-0.0023}$
$b \to \tau$	0.0042 ±0.0004	0.0064	0.661 ±0.062
$b \to c \to \mu$	0.0802 ±0.0019	0.085	0.946 ±0.022
$b \to \bar{c} \to \mu$	0.016 ±0.003	0.018	0.89 ±0.17
$c \to \mu$	0.082 ±0.005	0.084	0.976 ±0.059

Results

JHEP 06 (2023) 019
soft muon tagging
36.1 fb^{-1} 13 TeV

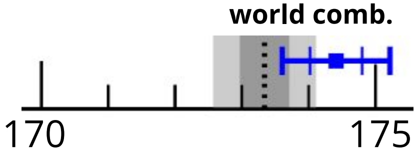
- m_t extracted from $m_{l\mu}$ in [15, 80] GeV
- **Binned-template profile likelihood fit with syst. uncertainties as nuisance parameters**
- Gluon recoil-to-top added as an uncertainty
  - based on particle level simulation
  - no dedicated tune yet
    → possible over-estimation
  - ±0.25 GeV additional uncertainty outside of the profile likelihood fit





$$m_t = 174.41 \pm 0.39\ (\text{stat.}) \pm 0.66\ (\text{syst.}) \pm 0.25\ (\text{recoil})\ \text{GeV}$$

m_t=174.41 ± 0.81 GeV



Dominant uncertainties
- BR b→c→μ
- BR b→μ
- Recoil effect

Results

JHEP 06 (2023) 019
soft muon tagging
36.1 fb^{-1} 13 TeV

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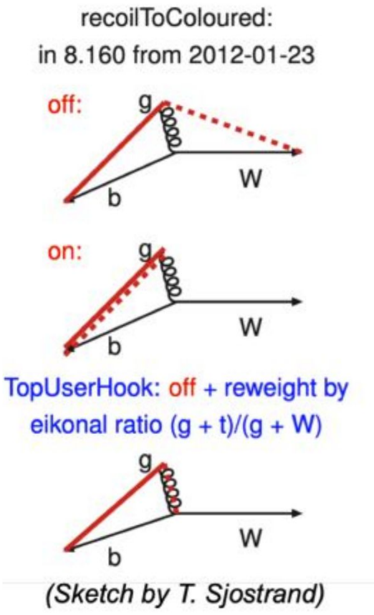
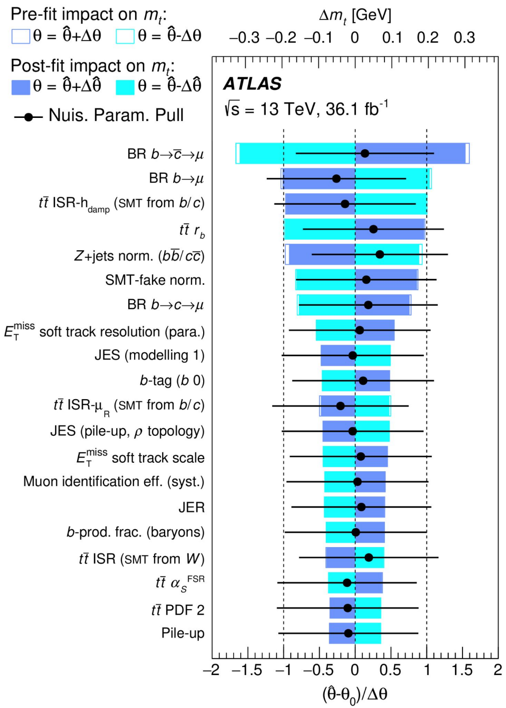
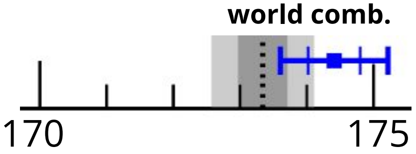




$$m_t = 174.41 \pm 0.39\,(\text{stat.}) \pm 0.66\,(\text{syst.}) \pm 0.25\,(\text{recoil})\ \text{GeV}$$

m_t=174.41 ± 0.81 GeV



Dominant uncertainties
- BR b→c→μ
- BR b→μ
- Recoil effect

“Measurement of the top-quark mass in $t\bar{t} \rightarrow$ dilepton events with the ATLAS experiment using the template method in 13 TeV pp collision data”

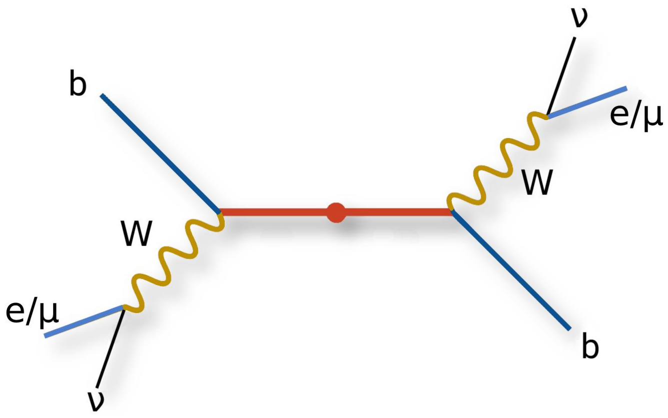
$t\bar{t}$ dilepton

ATLAS-CONF-2022-058

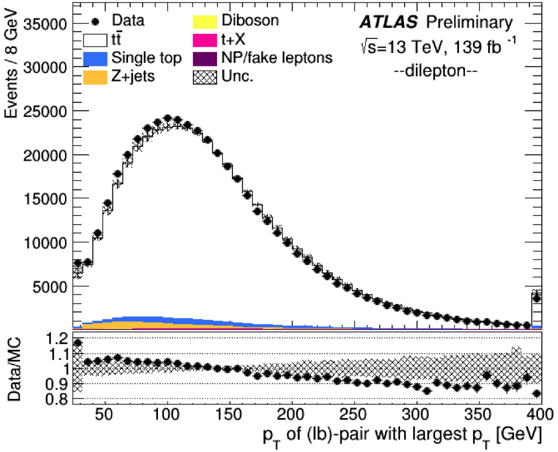
Event selection

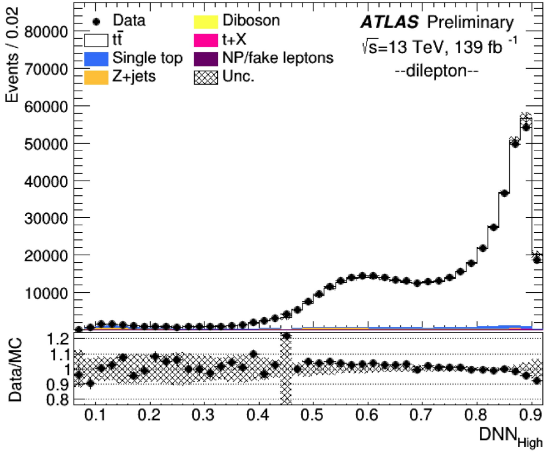
ATLAS-CONF-2022-058
$t\bar{t}$ dilepton
139 fb^{-1} 13 TeV

- Pair of opposite sign charged leptons + two b-jets
- DNN to identify the best **lb-pairing**
  - input variables:
    - invariant mass, p_T, η of each lb-pair
    - ΔR between lepton and b-tagged jet of each pair
    - individual p_T and η for leptons and b-jets and the invariant mass of the pair of b-jets
  - purity further increased using DNN_{High} cut



events passing preselection:



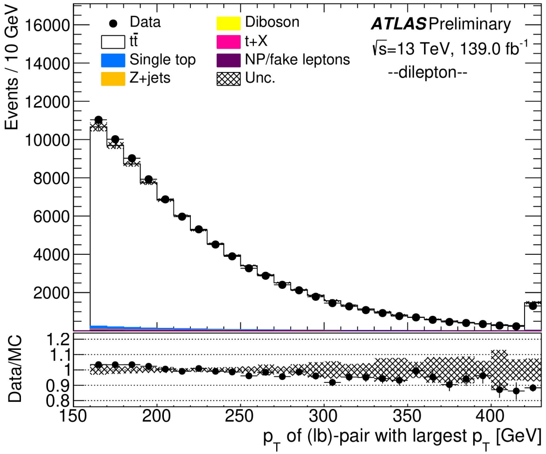


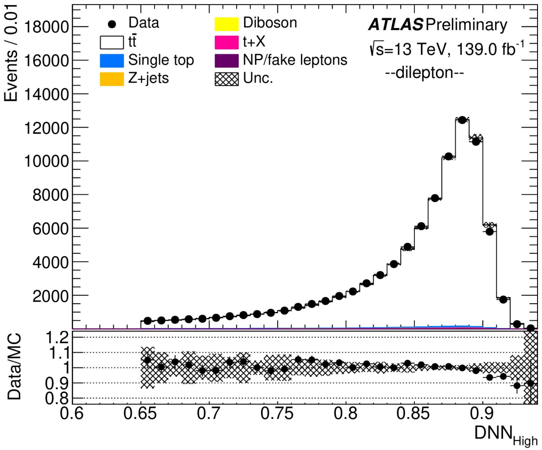
Optimised selection

- lb-pair with largest p_T for measurement
  - must be the leading b-jet
- Reduces signal modelling and jet systematics
- $DNN_{High} > 0.65$
- $p_{T,lb} > 160$ GeV

- ~10% more events in simulation
  - p_{Tlb} >160 GeV selection
    → p_T spectrum softer for data than for MC
  - missing NNLO top p_T corrections
- Signal reweighting based on NNLO calculation as a function of $p_{T,top}$, $p_{T,t\bar{t}}$ and $m_{t\bar{t}}$ at parton level
  - Δm_t = +0.10 ± 0.01 GeV observed
  - covered by scale-variation uncertainties

events passing optimised selection:

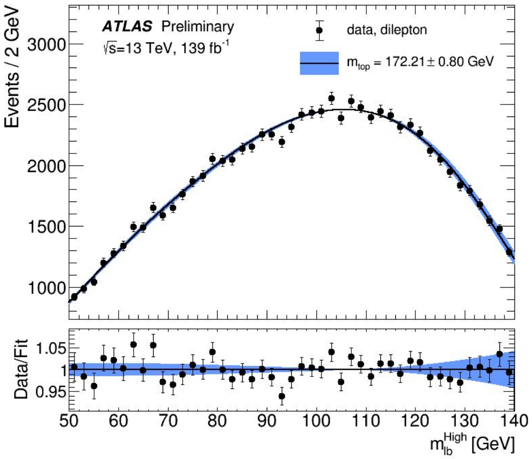




Results

ATLAS-CONF-2022-058
$t\bar{t}$ dilepton
139 fb^{-1} 13 TeV

- Unbinned ML fit to data
  - 50 GeV < m_{lb}^{High} < 140 GeV
- Samples of $t\bar{t}$ and single-top with different m_t generated → no background template
- Recoil-to-top slightly larger than for SMT analysis
- Off-shell and non-resonant effects studied
  - bb4l generator in Powheg
  - Δm_T= -0.28 ± 0.13 GeV observed
  - smaller than modelling unc → not considered



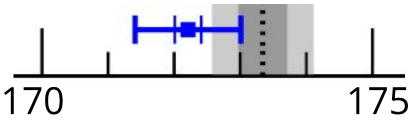
	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single 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

- Without recoil effect **17% improvement** compared to 8 TeV result

$$m_{top}^{dilepton} = 172.21 \pm 0.20\,(\text{stat}) \pm 0.67\,(\text{syst}) \pm 0.39\,(\text{recoil})\ \text{GeV}$$

m_t=172.21 ± 0.80 GeV

world comb.



Dominant uncertainties
- Matrix-element matching
- Recoil effect
- Jet energy scale

“Measurement of the top quark pole mass using $t\bar{t}$+jet events in the dilepton final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV”

$t\bar{t}$+1j pole mass

[JHEP 07 (2023) 077]

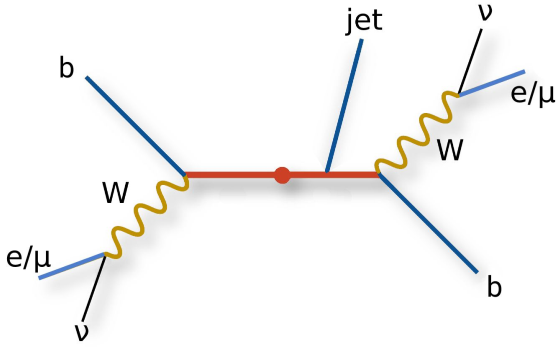
$t\bar{t}$+1jet in dilepton channel

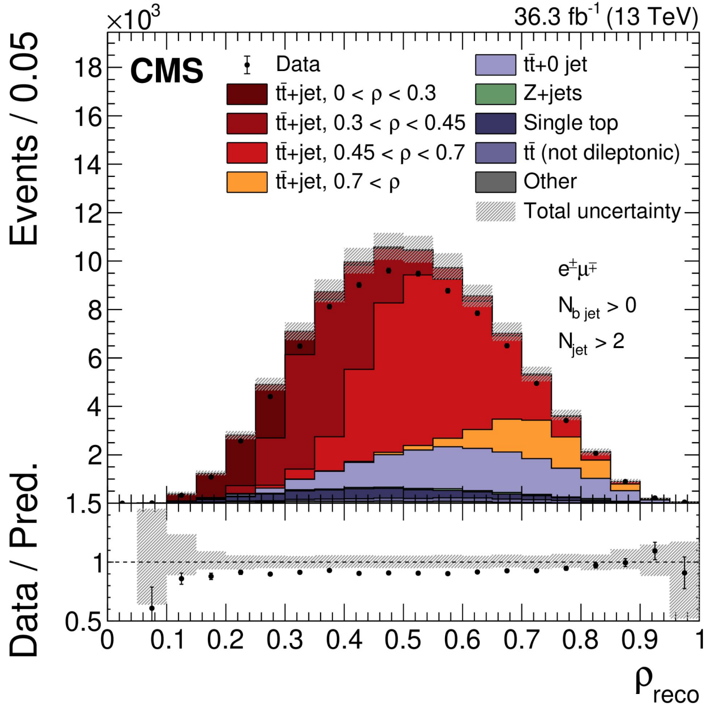
JHEP 07 (2023) 077
$t\bar{t}$+1j pole mass
36.3 fb^{-1} 13 TeV

- **Normalised differential cross section measured at detector level and unfolded using maximum likelihood method with profiled nuisance parameters**
- As a function of ρ

$$\rho = \frac{2m_0}{m_{t\bar{t}+\mathrm{jet}}}$$

- m_0 scaling constant = 170 GeV
- high sensitivity expected close to the production threshold ρ>0.65

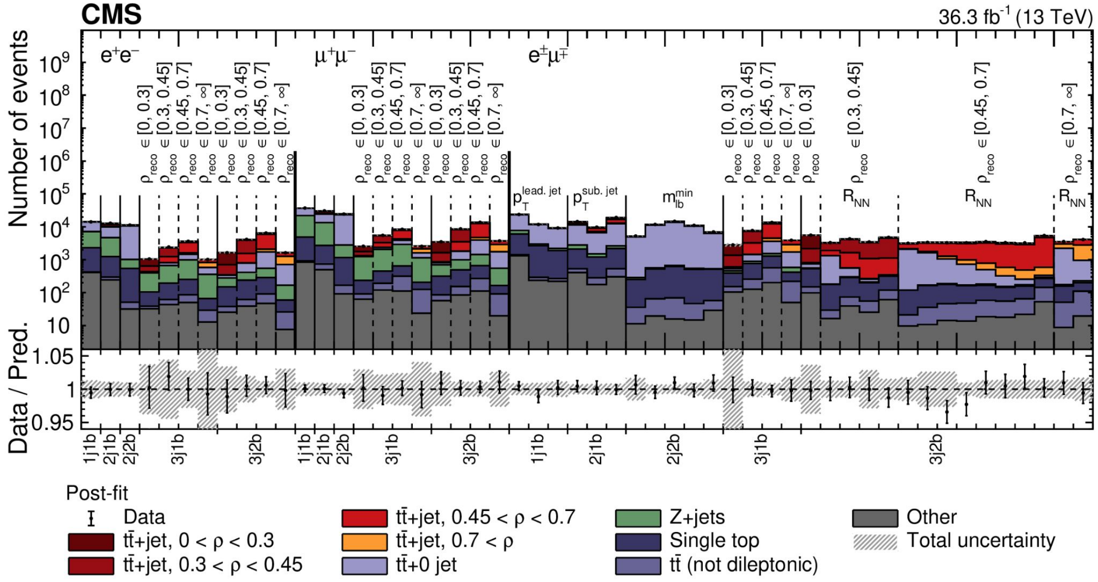


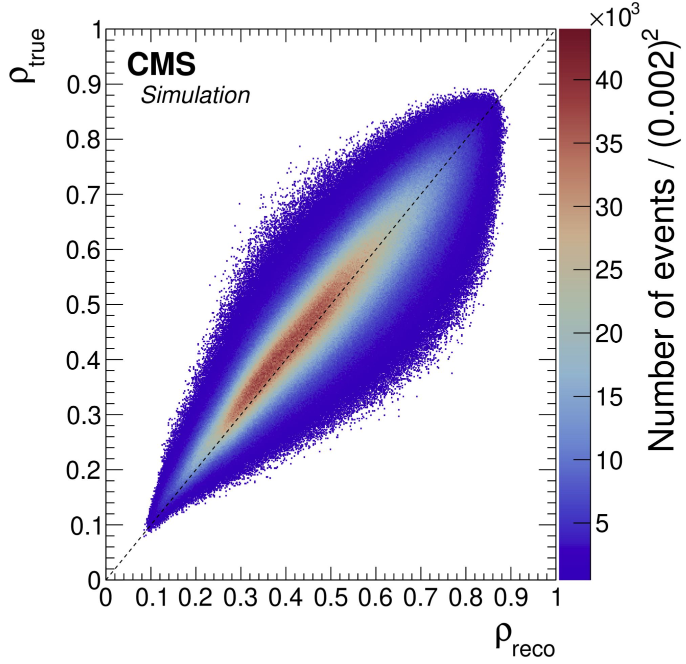


ρ reconstruction

JHEP 07 (2023) 077
$t\bar{t}$+1j pole mass
36.3 fb^{-1} 13 TeV

- Regression NN
  - target variable is parton-level ρ
  - ~100 variables from which **10 most relevant selected**
- Event classifier developed using the same interface as for regression NN with three output classes $t\bar{t}$+jet, Z+jets, $t\bar{t}$+0jets





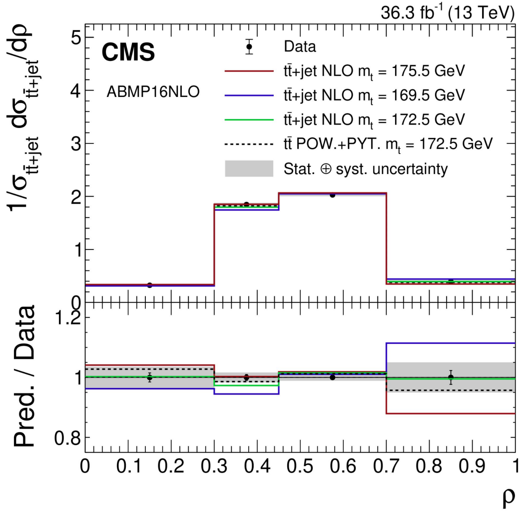
- Event categories based on jet and b-jet multiplicities
- RNN = relative signal response of the NN classifier

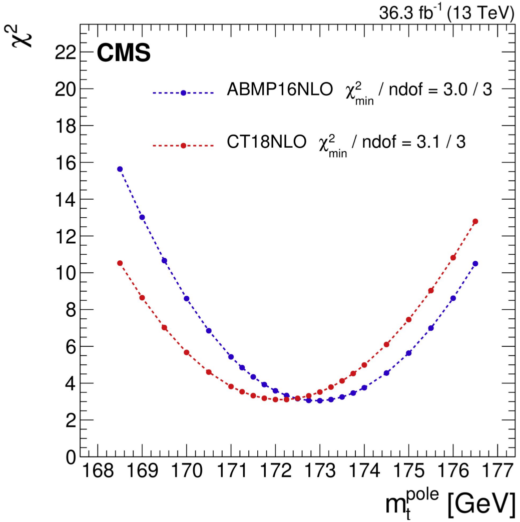
Results

JHEP 07 (2023) 077
$t\bar{t}$+1j pole mass
36.3 fb^{-1} 13 TeV

- m_t^{pole} from χ^2 fit of the normalized differential cross section at NLO, where m_t^{MC} as a free parameter
- No assumptions on the relationship between $m_t^{MC} \leftrightarrow m_t^{pole}$

- In good agreement with m_t^{pole} $t\bar{t}$+jet measurement by ATLAS at 8 TeV
  arXiv:1905.02302
  - Here PDF uncertainties by comparing fits with full covariance matrix with/without PDF uncertainties → increase in total uncertainty

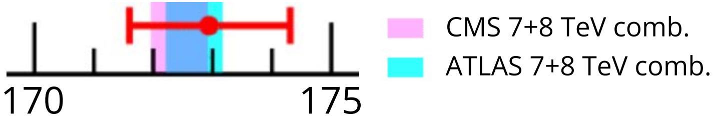




ABMP16NLO: $m_t^{\text{pole}} = 172.93 \pm 1.26\,(\text{fit})\,^{+0.51}_{-0.43}\,(\text{scale})\,\text{GeV}$

CT18NLO: $m_t^{\text{pole}} = 172.13 \pm 1.34\,(\text{fit})\,^{+0.50}_{-0.40}\,(\text{scale})\,\text{GeV}$

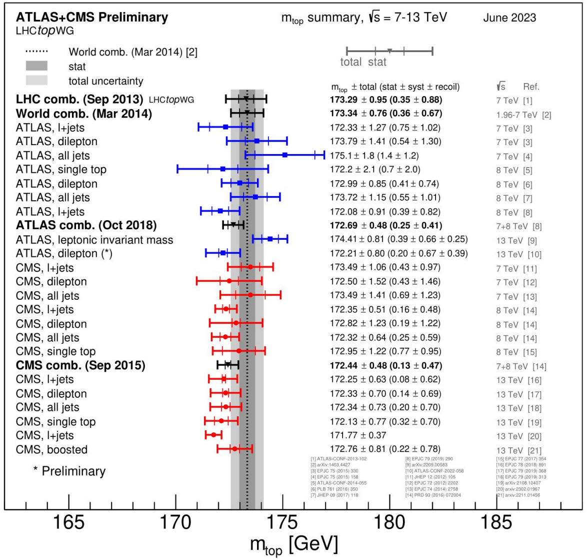
m_t^{pole}=172.93 ± 1.36 GeV



Dominant uncertainties
- Jet energy scale
- Background normalisation
- Electron identification

Summary

- Measurements by CMS and ATLAS with increasing **precision** and **understanding** of systematics
- Measurements with different strategies and systematics essential for cross-checking
- Modelling and uncertainties:
  - recoil effect
  - final state radiation → udsc-FSR / b-FSR correlation
  - b-quark fragmentation
  - top-quark modelling
- Top mass interpretation problem



arXiv:2302.01967	**tt̄ lepton+jets**	**m_t=171.77 ± 0.37 GeV**	**bJEC, qFSR, bFSR**
Eur. Phys. J. C 83 (2023) 560	**boosted top**	**m_t=173.06 ± 0.84 GeV**	**Choice of mt, JER, JMS**
JHEP 06 (2023) 019	**soft muon tagging**	**m_t=174.41 ± 0.81 GeV**	**BR b→c→μ, BR b→μ, Recoil effect**
ATLAS-CONF-2022-058	**tt̄ dilepton**	**m_t=172.21 ± 0.80 GeV**	**ME matching, Recoil effect, Jet energy scale**
JHEP 07 (2023) 077	**tt̄+1j pole mass**	**m_t=172.93 ± 1.36 GeV**	**Jet energy scale, BKG normalisation, Electron ID**