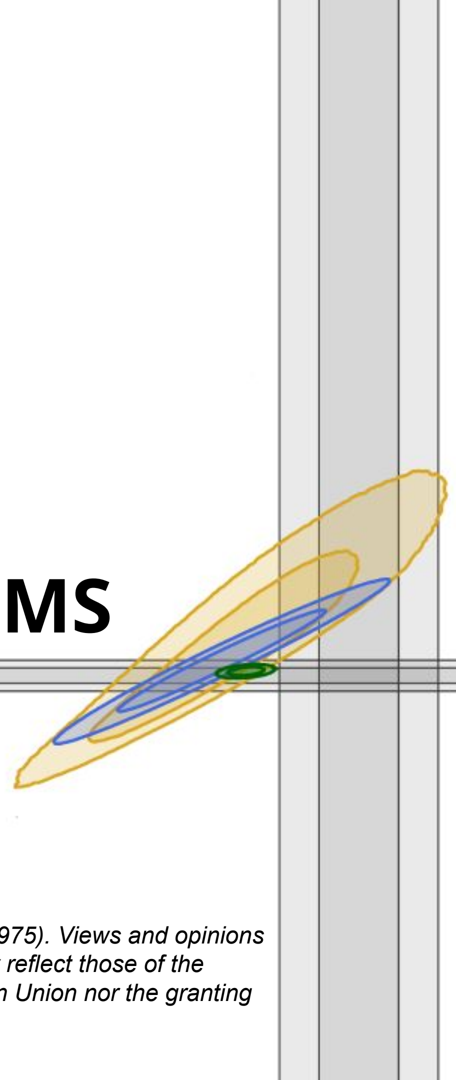
Top mass measurements at CMS



Mikael Myllymäki, Helsinki Institute of Physics

Particle Physics Day 12.10.2023 Jyväskylä

Funded by the European Union

European Research Council
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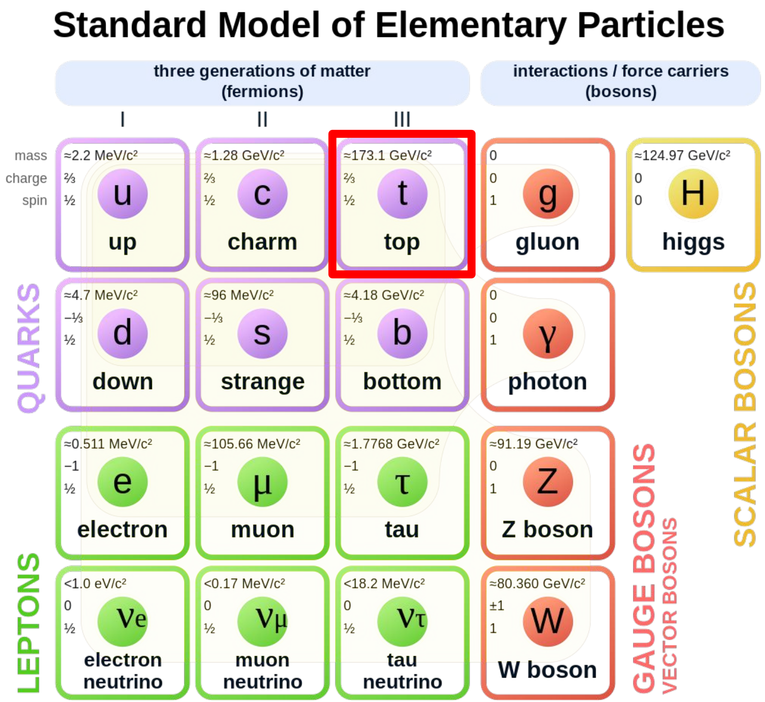
"Funded/Co-funded by the European Union (ERC, JEC4HL-LHC, 101043975). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them."

Motivation

- Top quark is the heaviest elementary particle
  - top mass is a significant parameter in the SM
  - connection to Higgs physics and BSM physics



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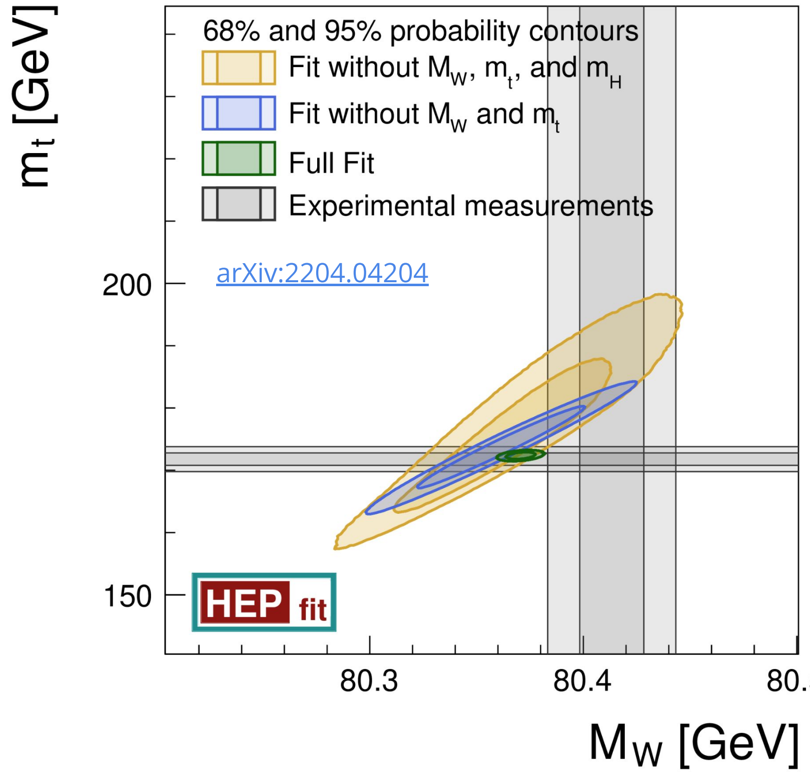

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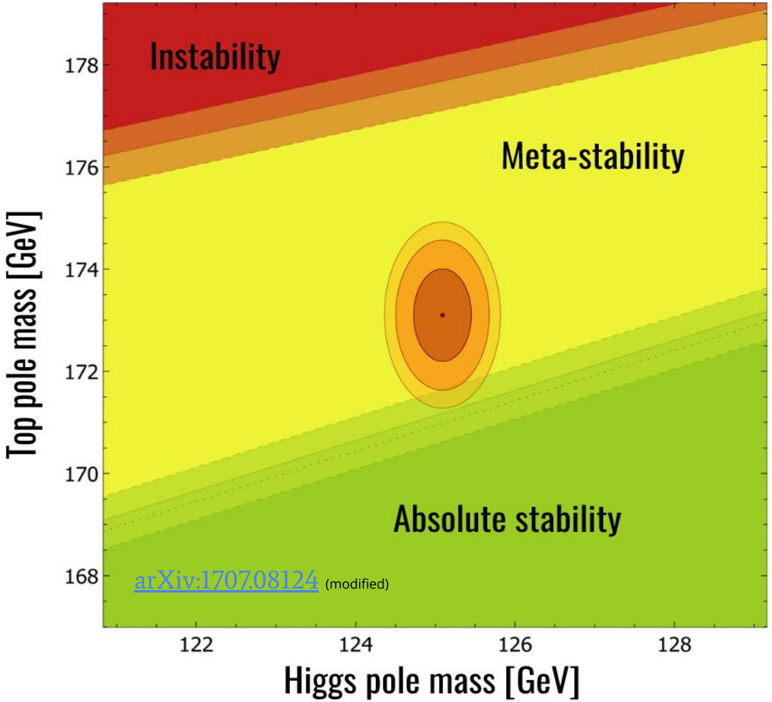
- Stability of the EW vacuum
  - “To rule out absolute stability to 3σ confidence, the uncertainty on the top quark pole mass would have to be pushed below 250 MeV” arxiv:1707.08124



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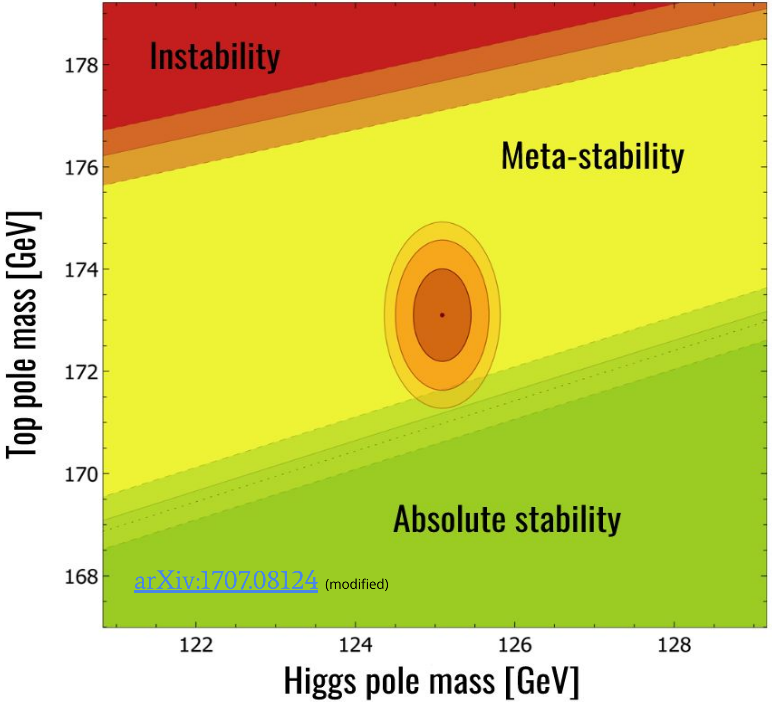
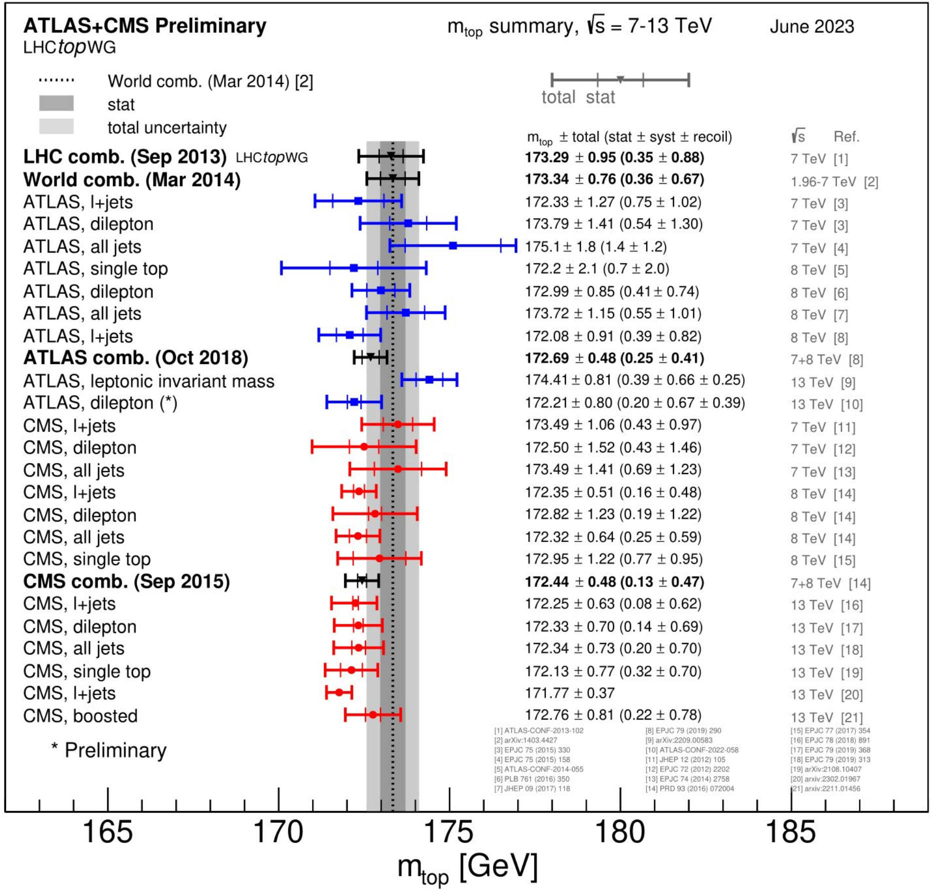
- Challenges
  - $t\bar{t}$ modelling
  - jet energy scale
  - b-quark fragmentation
  - final state radiation



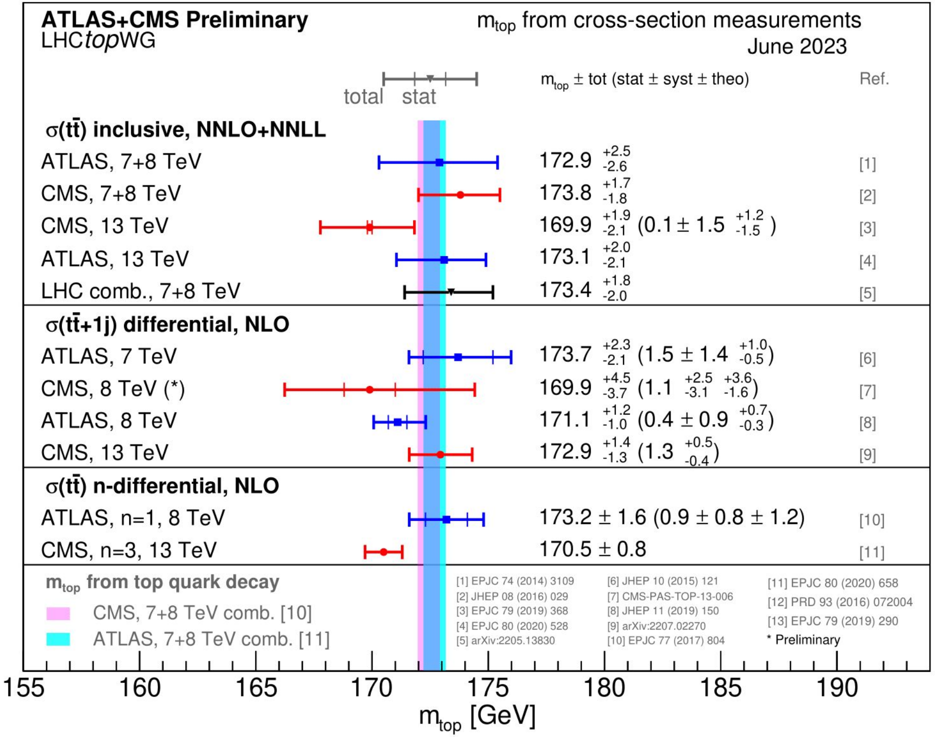
Direct measurements m_t^{MC}

→ reconstruct invariant mass from decay products



Indirect measurements m_t^{pole}

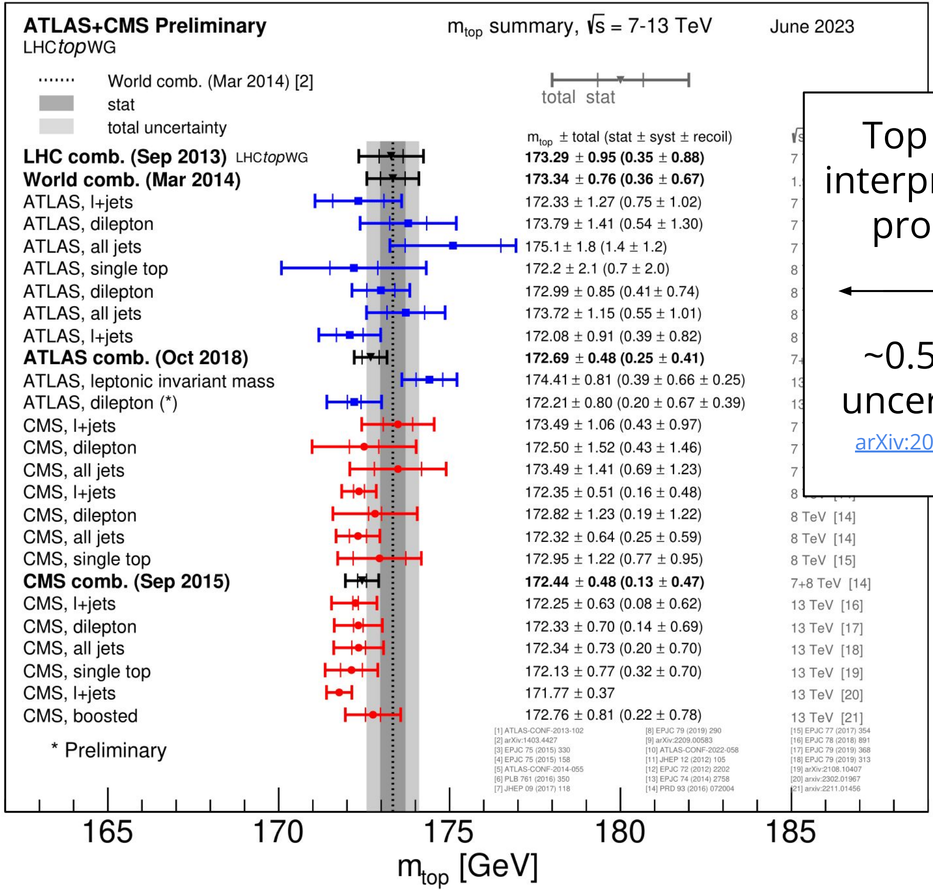
→ measure observable sensitive to mass e.g. cross-section



LHCWG summary plots

Direct measurements m_t^{MC}

→ reconstruct invariant mass from decay products



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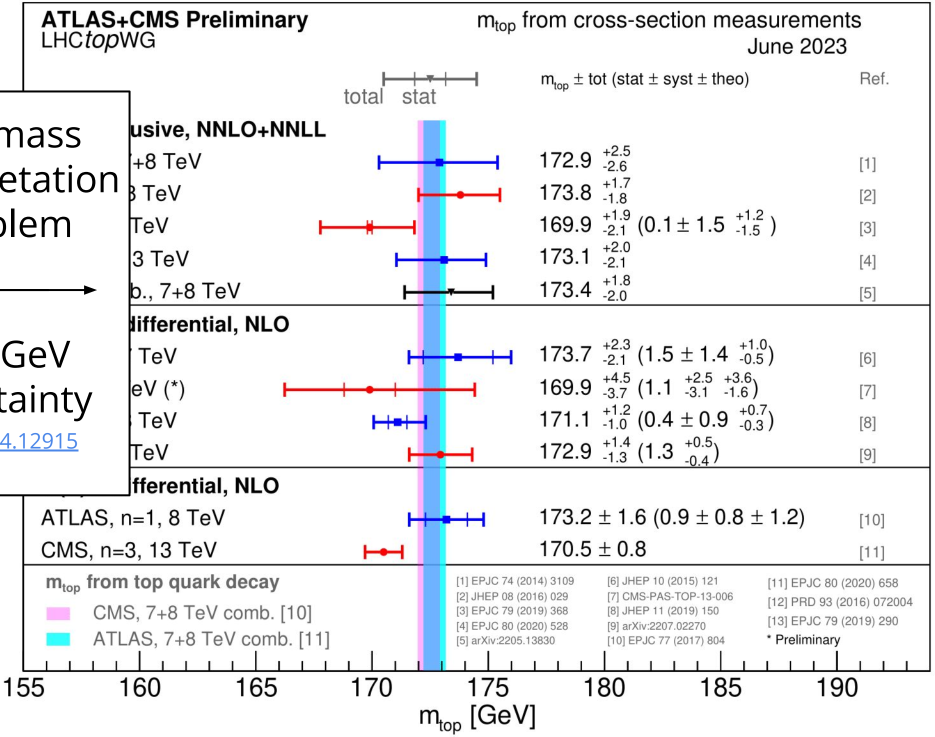


Top mass interpretation problem

←→

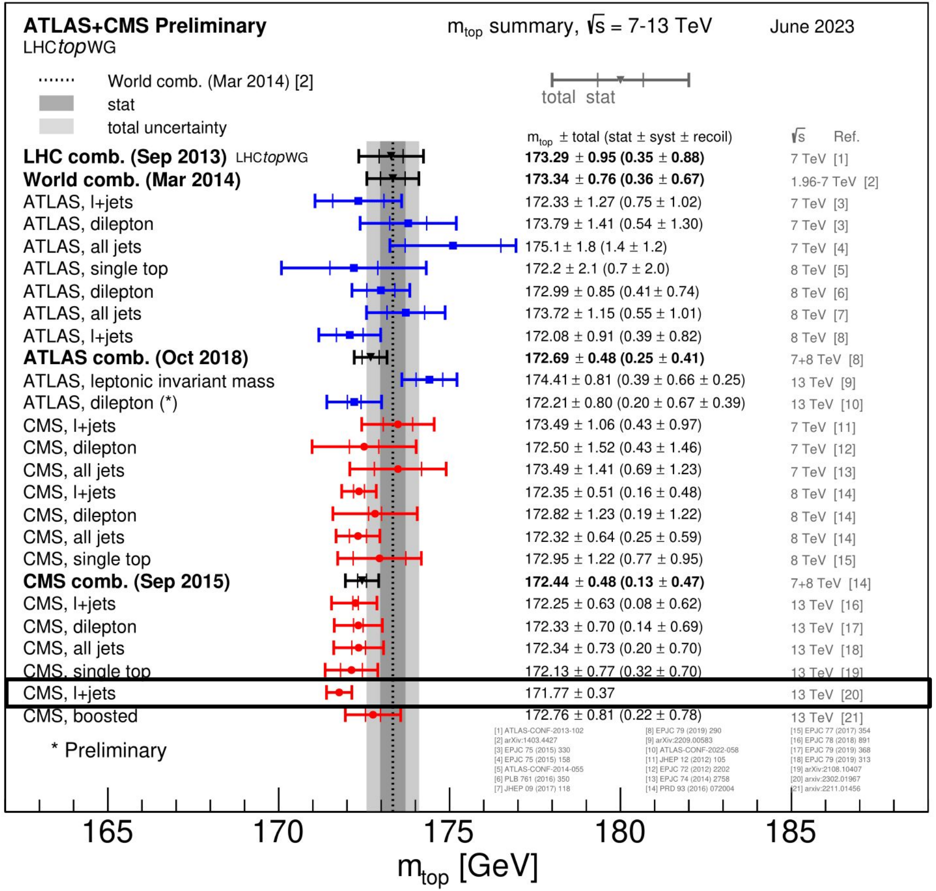
~0.5 GeV uncertainty

arXiv:2004.12915

LHCWG summary plots

Direct measurements $\mathbf{m_t^{MC}}$

→ reconstruct invariant mass from decay products



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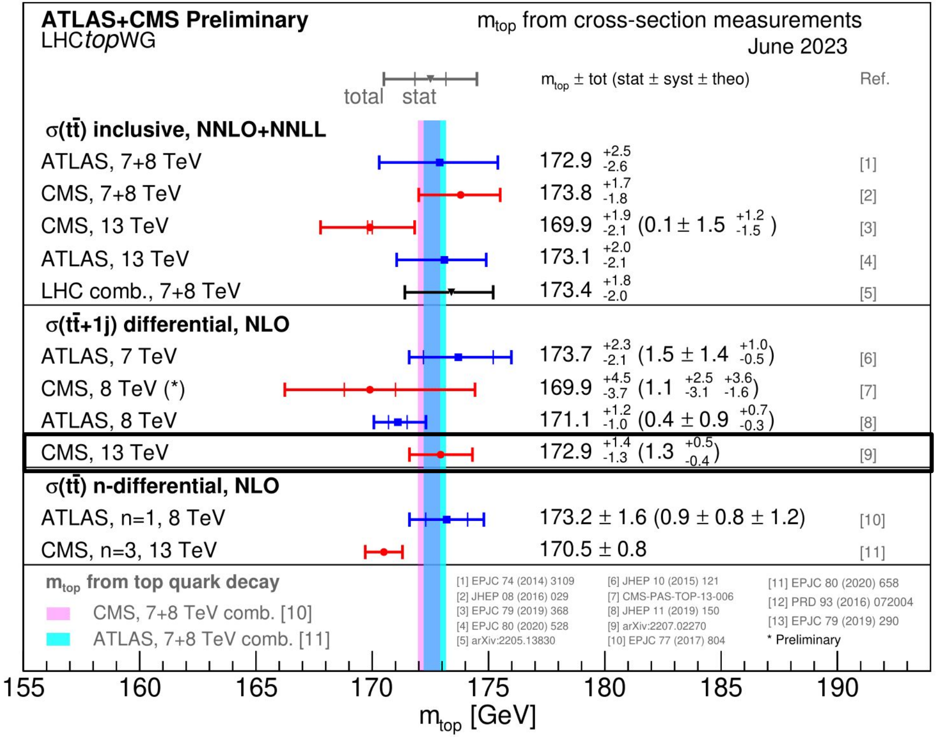


covered in this talk

LHCWG summary plots

Direct measurements $\mathbf{m_t^{MC}}$

→ reconstruct invariant mass from decay products

"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"

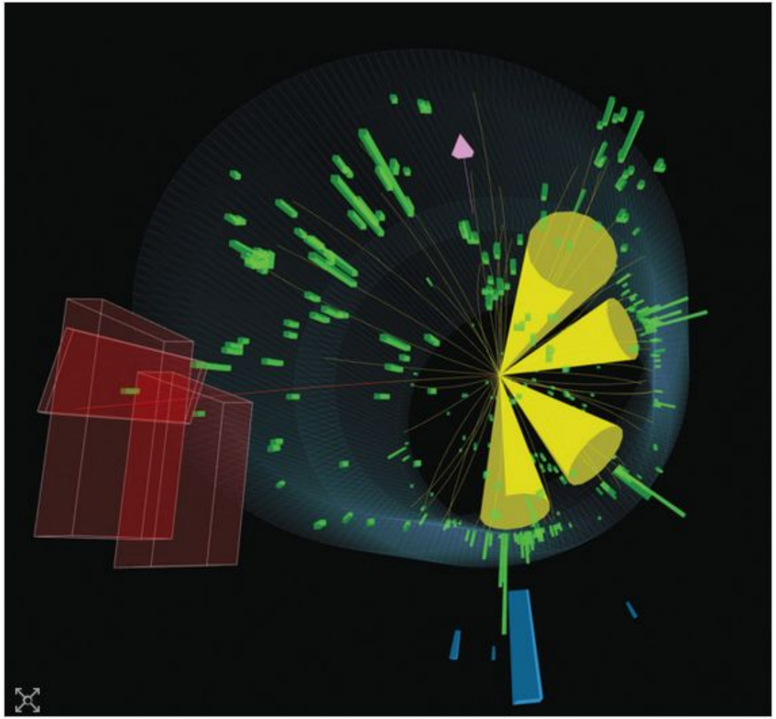
$t\bar{t}$ lepton+jets

arXiv:2302.01967 (submitted to EPJC)

HIGGS AND ELECTROWEAK | NEWS

Top quark weighs in with unparalleled precision

1 July 2022

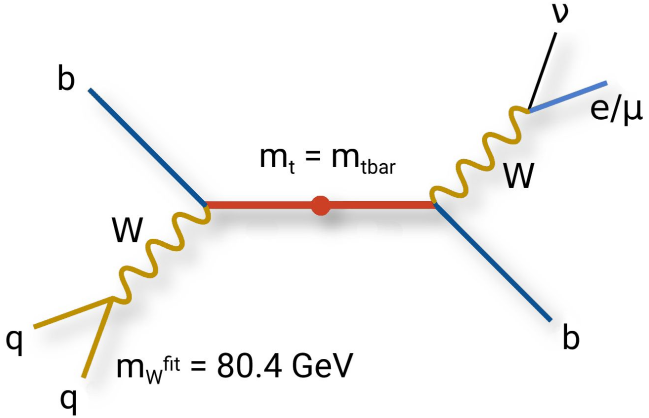


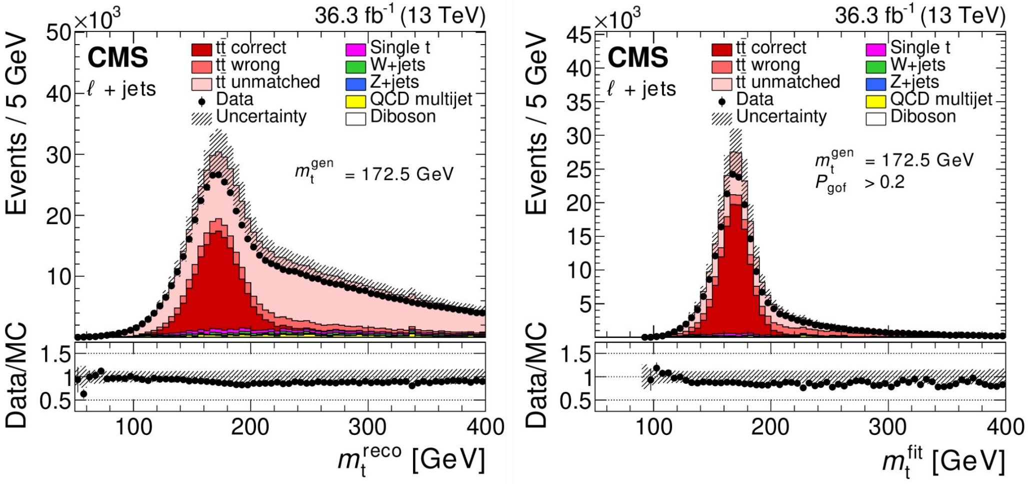
Top marks The classic signature of a top-quark pair at the LHC is four jets (yellow cones), one muon (red line and boxes) and missing energy from a neutrino (pink arrow). Credit: CMS

https://cerncourier.com/a/top-quark-weighs-in-with-unparalleled-precision/

Event selection

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



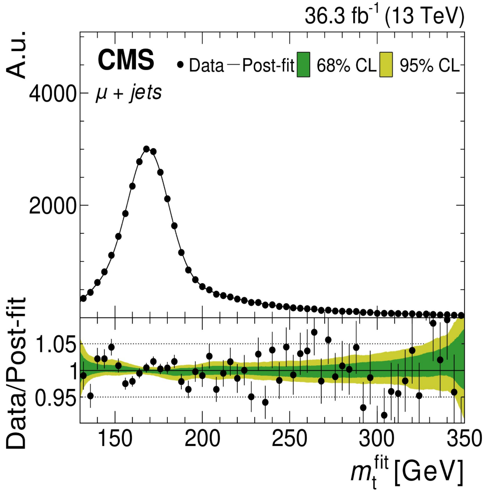


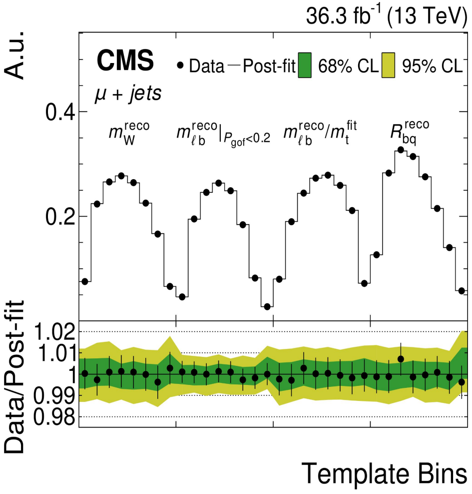
- **Kinematic fit**
  - best event hypothesis chosen from χ^2 minimization
  - based on parton-object resolution functions
  - constraints
    - m_W^{fit} = 80.4 GeV
    - $m_t^{hadr} = m_t^{lept}$
  - $P_{gof} = \exp(-\chi^2/2) > 0.2$ used as a default cut

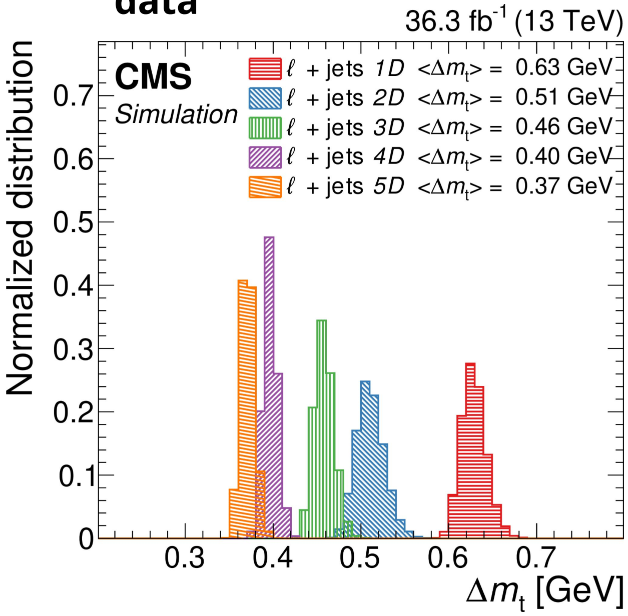
Profiled maximum-likelihood fit

arXiv:2302.01967 (submitted to EPJC)
$t\bar{t}$ lepton+jets
Run2 2016 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**



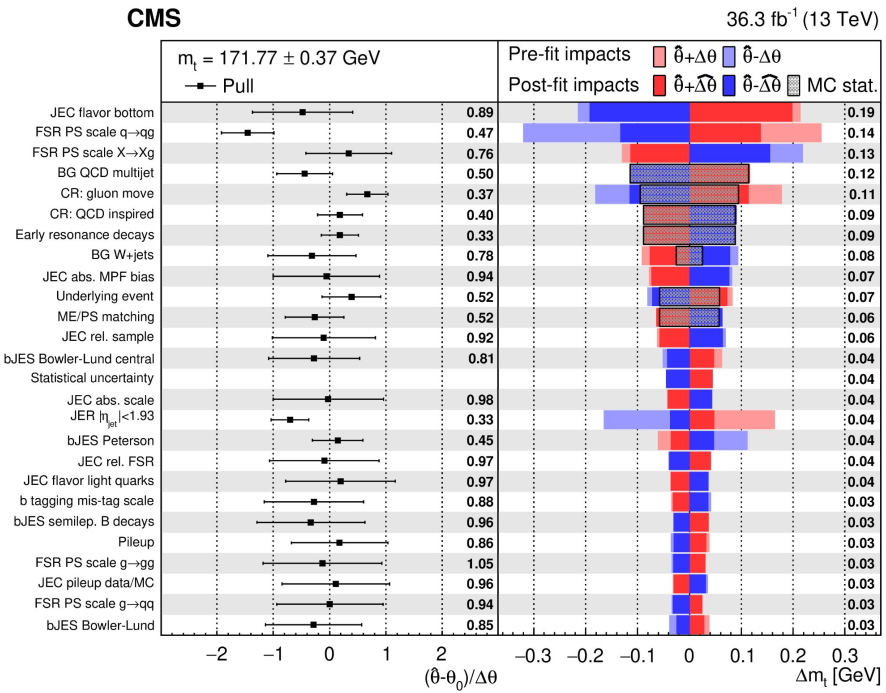




m_t^{fit}	→	for m_t	} parametrized
m_W^{reco}	→	light quark JES	binned
$R_{bq}^{reco} = (p_T^{b1} + p_T^{b2})/(p_T^{q1} + p_T^{q2})$	→	b-JES	binned
$m_{lb}^{red} = m_{lb}^{reco} / m_t^{fit}$	→	for lep syst.	binned
m_{lb}^{reco} ($P_{gof} < 0.2$)	→	for full statistics	binned

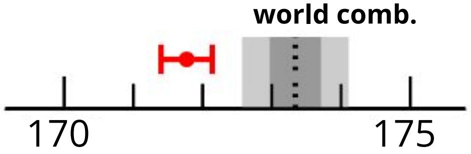
Results

arXiv:2302.01967 (submitted to EPJC)
$t\bar{t}$ lepton+jets
Run2 2016 36.3fb^{-1} 13 TeV



- Most precise individual result to date **171.77 ± 0.37 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

Results

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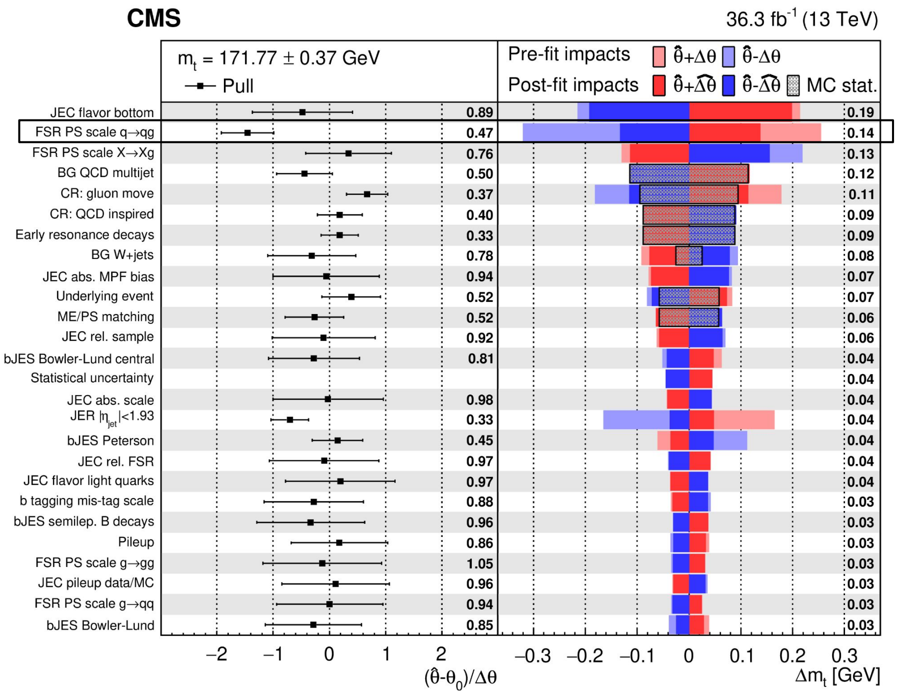
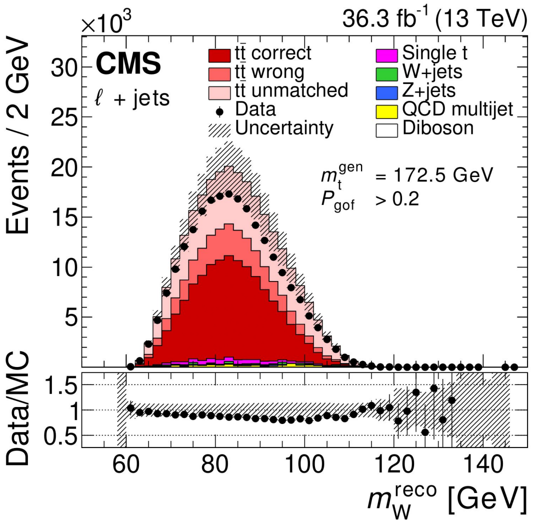


- Most precise individual result to date **171.77 ± 0.37 GeV**
  - statistical uncertainty in data: 0.04 GeV
- qFSR ~ -1.5 σ

→ **related to m_W^{reco} peak**



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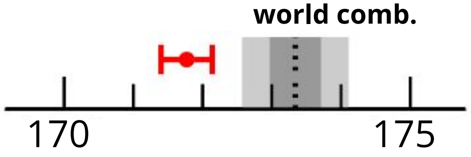

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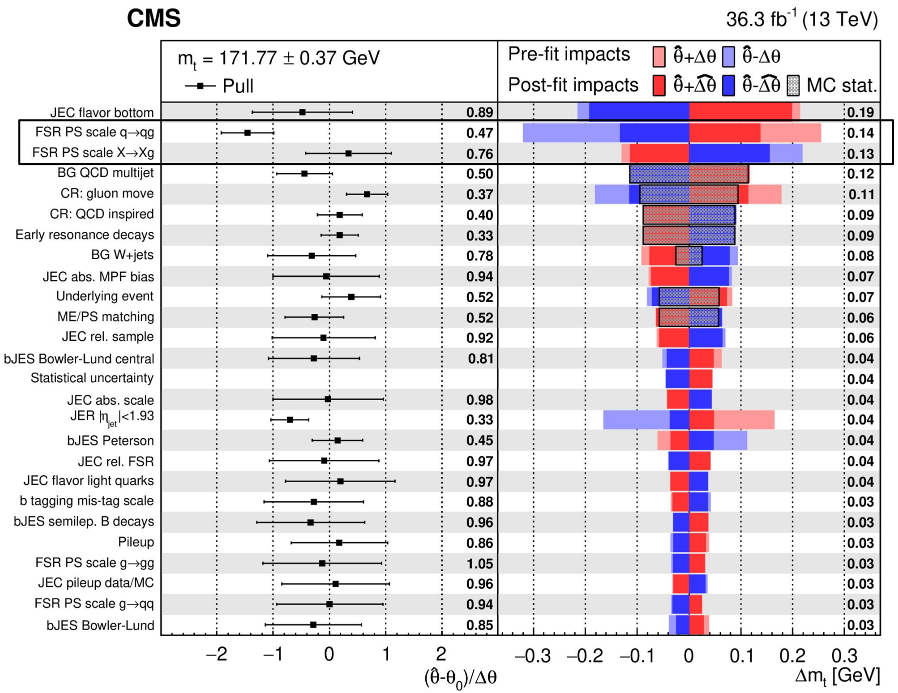

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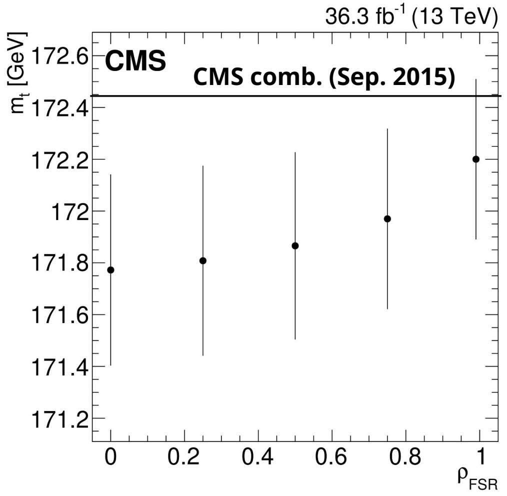
  → **treated fully decorrelated ρ=0**



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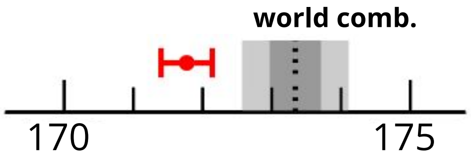

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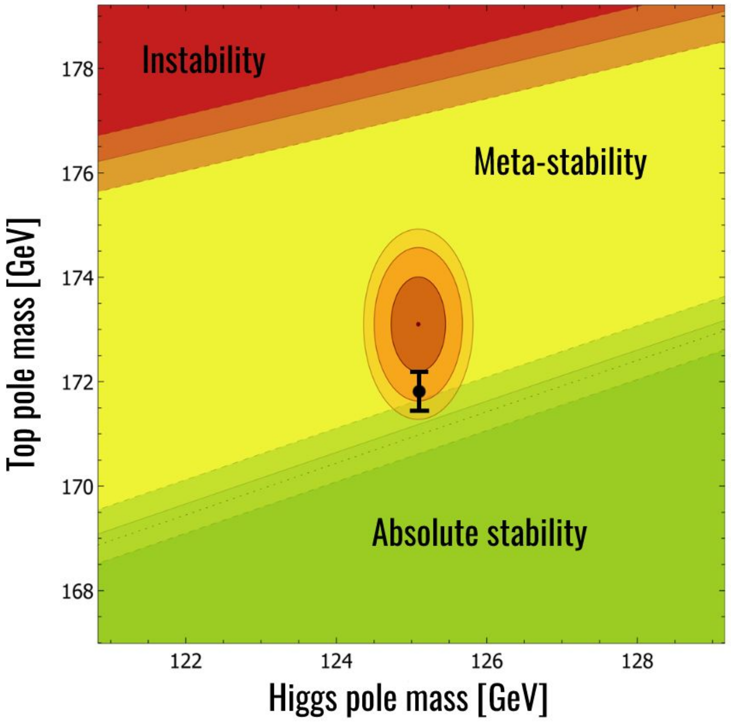

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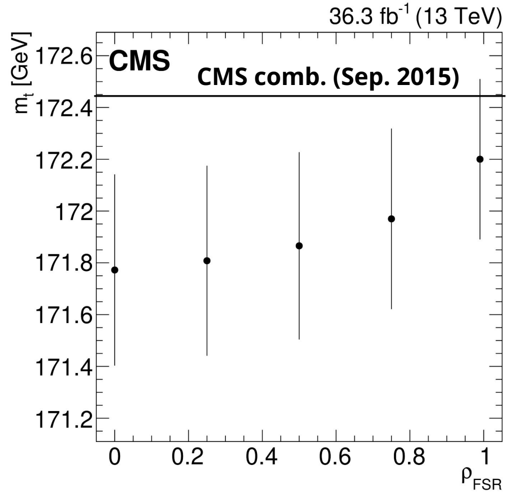

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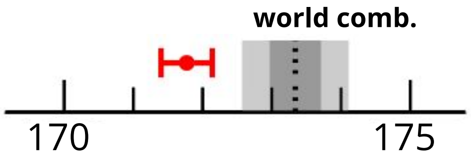

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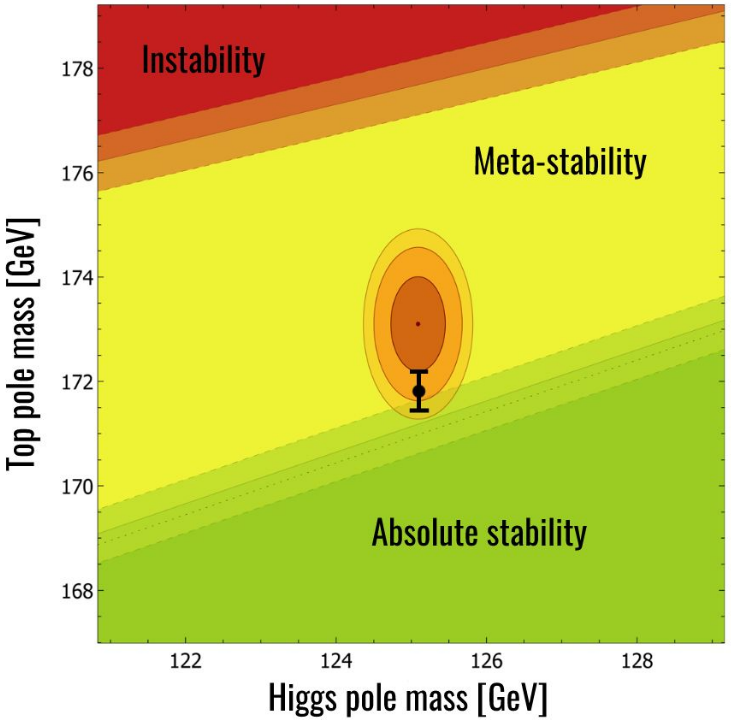
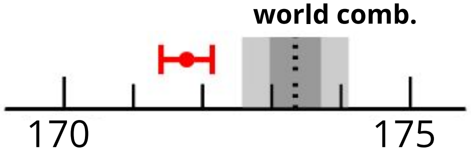


Our analysis in Helsinki extends this by including data from 2017-2018

~100 fb^{-1} → around 3 times more than 2016

m_t=171.77 ± 0.37 GeV



Dominant uncertainties

- b JEC
- q FSR scale
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Indirect measurements $\mathbf{m_t^{pole}}$

→ measure observable sensitive to mass e.g. cross-section

"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

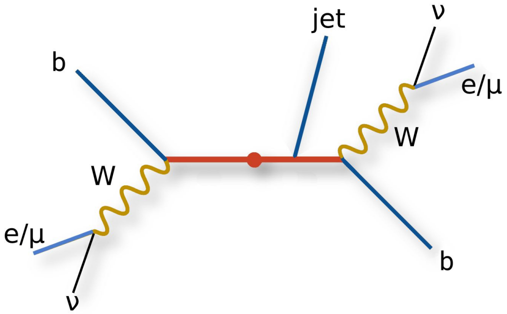
$t\bar{t}$+1jet in dilepton channel

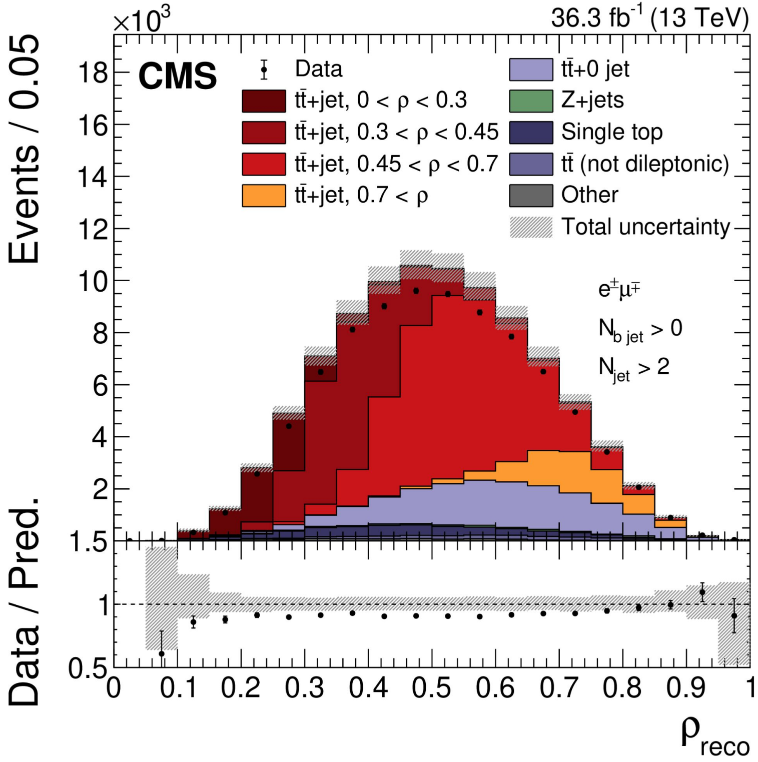
JHEP 07 (2023) 077
$t\bar{t}$+1j pole mass
Run2 2016 36.3 fb^{-1} 13 TeV

- **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

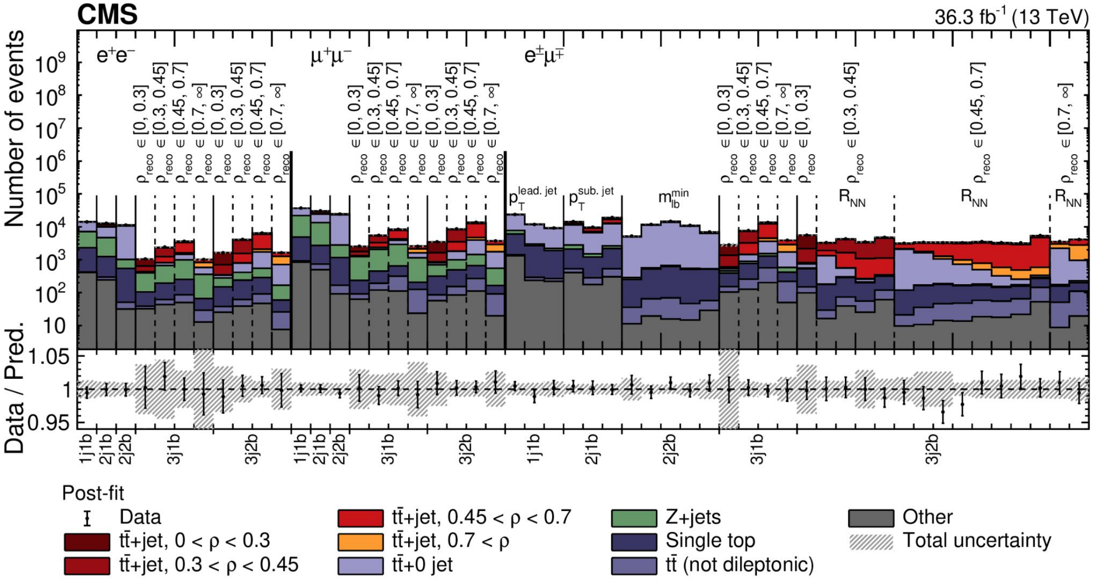


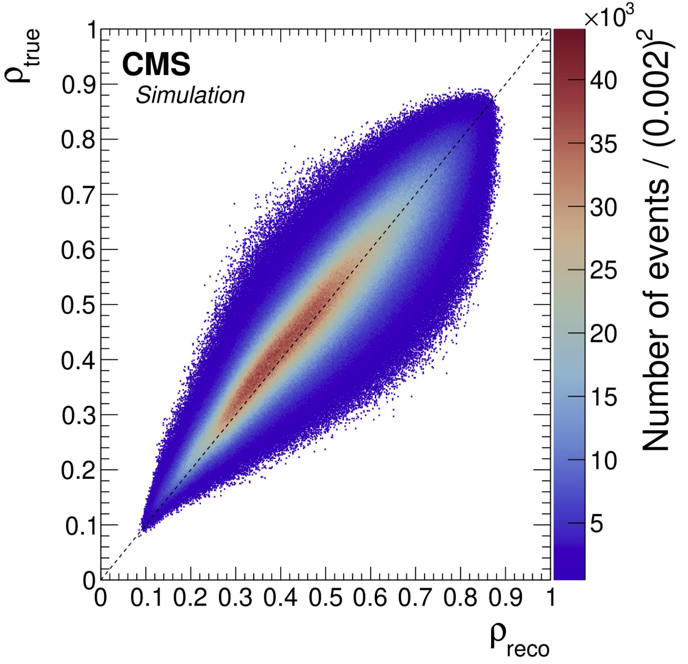


ρ reconstruction

JHEP 07 (2023) 077
$t\bar{t}$+1j pole mass
Run2 2016 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

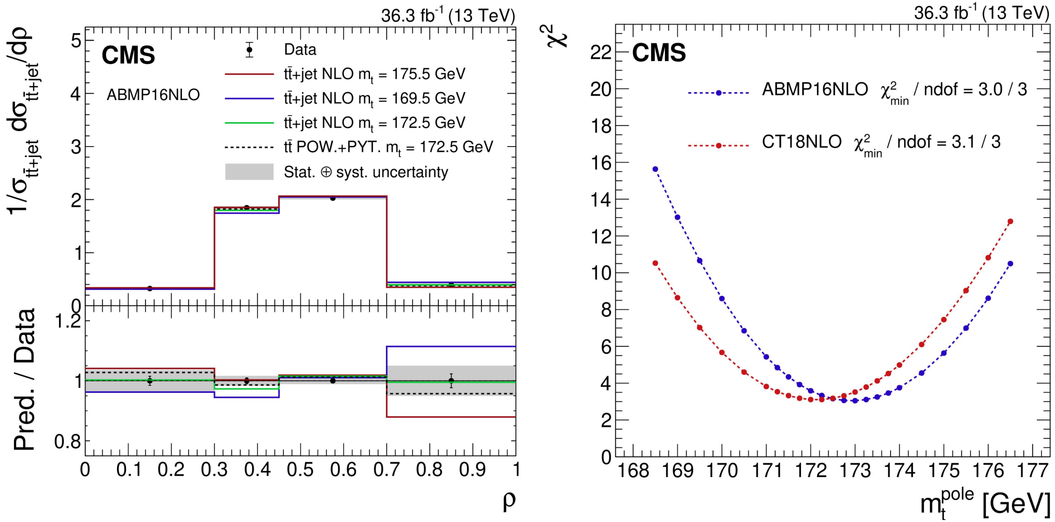




- Event categories based on jet and b-jet multiplicities

Results

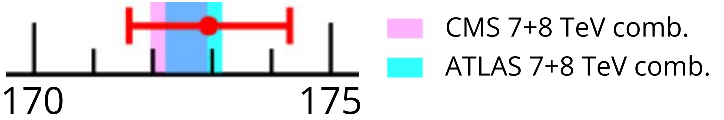
- m_t^{pole} from χ^2 fit of the normalized differential cross section at NLO, where m_t^{MC} as a free parameter
- No assumptions on the relationship between $m_t^{MC} \leftrightarrow m_t^{pole}$
- In good agreement with m_t^{pole} tt̄+jet measurement by ATLAS at 8 TeV arXiv:1905.02302



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

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

m_t^{pole}=172.93 ± 1.36 GeV



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

"Combination of measurements of the top quark mass from data collected by the ATLAS and CMS experiments at √s = 7 and 8 TeV"

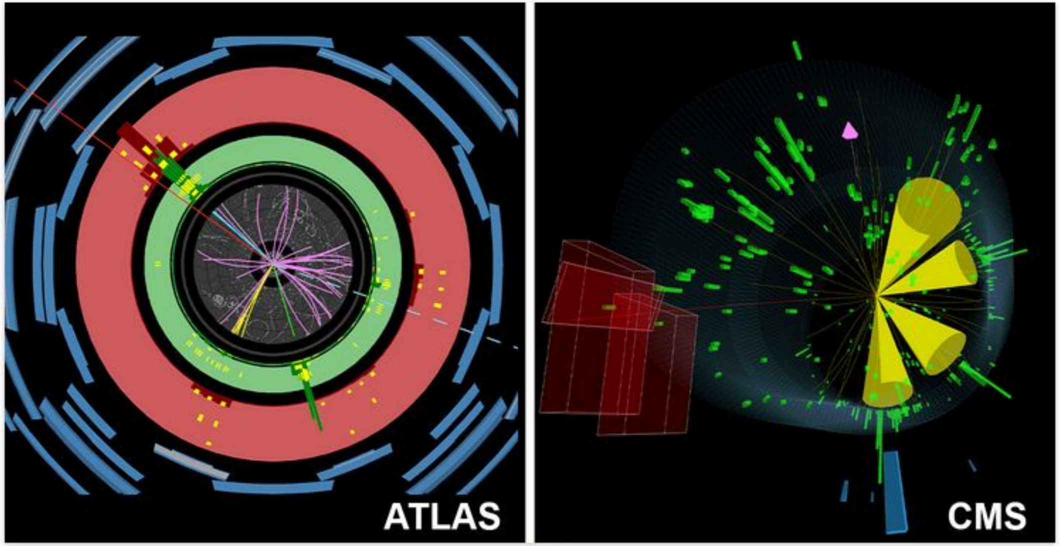
ATLAS + CMS Run1 combination

ATLAS-CONF-2023-066

ATLAS and CMS unite to weigh in on the top quark

The new result combines 15 previous measurements to give the most precise determination of the top-quark mass to date

11 OCTOBRE, 2023 https://home.cern/fr/node/188765



Collision event displays of top-quark production from ATLAS (left) and CMS (right). (Image: ATLAS/CMS/CERN)

Run1 combination

ATLAS-CONF-2023-066
ATLAS + CMS Run1 combination
Run1 7,8 TeV

- 15 input measurements by ATLAS and CMS
  - direct measurements → $\mathbf{m_t^{MC}}$
- **BLUE** = **B**est **L**inear **U**nbiased **E**stimator
  - to properly handle correlations in systematics
  - 25 categories - correlations between pairs of measurements evaluated within experiment
  - then correlation ρ between ATLAS and CMS
    - Uncorrelated: ρ = 0
    - Partially correlated: ρ = 0.5
    - Strongly correlated: ρ = 0.85

	dilepton	lepton +jets	all -jets	Other final states and topologies
7 TeV	*Eur. Phys. J. C* **72** (2012) 2202 *Eur. Phys. J. C* **75** (2015) 330	*JHEP* **12** (2012) 105 (*Eur. Phys. J. C* **75** (2015) 330)	*Eur. Phys. J. C* **74** (2014) 2758 *Eur. Phys. J. C* **75** (2015) 158	
8 TeV	*Phys. Rev. D* **96** (2017) 032002 *Phys. Lett. B* **761** (2016) 350	*Phys. Rev. D* **93** (2016) 092006 *Eur. Phys. J. C* **79** (2019) 290	*JHEP* **09** (2017)118	**Single top:** *Eur. Phys. J. C* **77** (2017) 354 **Secondary vertex:** *Phys. Rev. D* **93** (2016) 092006 **J/psi:** *JHEP* **12** (2016) 123

Uncertainty category	ρ	Scan range	$\Delta m_t/2$ [MeV]	$\Delta\sigma_{m_t}/2$ [MeV]
LHC JES 1	0	—	—	—
LHC JES 2	0	[−0.25, +0.25]	8	7
LHC JES 3	0.5	[+0.25, +0.75]	1	<1
LHC b-JES	0.85	[+0.5, +1]	26	5
LHC g-JES	0.85	[+0.5, +1]	2	<1
LHC l-JES	0	[−0.25, +0.25]	1	<1
CMS JES 1	—	—	—	—
JER	0	[−0.25, +0.25]	5	1
Leptons	0	[−0.25, +0.25]	2	2
b tagging	0.5	[+0.25, +0.75]	1	1
p_T^{miss}	0	[−0.25, +0.25]	<1	<1
Pileup	0.85	[+0.5, +1]	2	<1
Trigger	0	[−0.25, +0.25]	<1	<1
ME generator	0.5	[+0.25, +0.75]	<1	4
LHC radiation	0.5	[+0.25, +0.75]	7	1
LHC hadronization	0.5	[+0.25, +0.75]	1	<1
CMS B hadron BR	—	—	—	—
Color reconnection	0.5	[+0.25, +0.75]	3	1
Underlying event	0.5	[+0.25, +0.75]	1	<1
PDF	0.85	[+0.5, +1]	1	<1
Top quark p_T	—	—	—	—
Background (data)	0	[−0.25, +0.25]	8	2
Background (MC)	0.85	[+0.5, +1]	2	<1
Method	0	—	—	—
Other	0	—	—	—

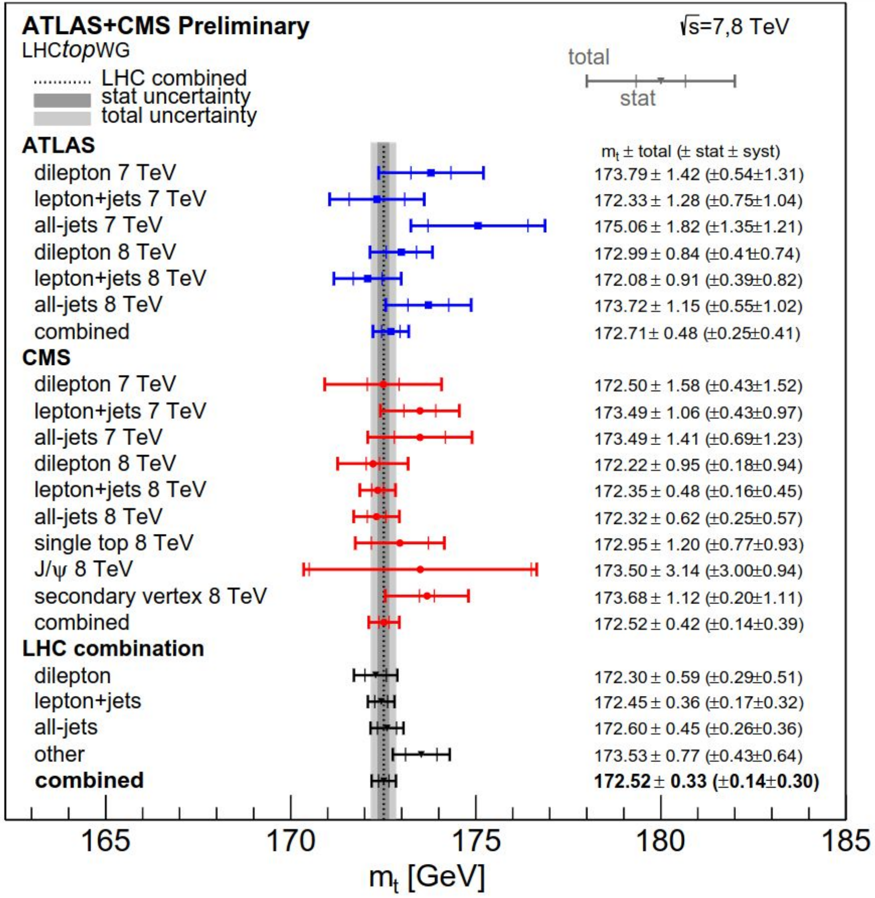
Most precise m_t measurement to date

ATLAS-CONF-2023-066
ATLAS + CMS Run1 combination
Run1 7,8 TeV

ATLAS
172.71 ± 0.25 (stat) ± 0.41 (syst)

CMS
172.52 ± 0.14 (stat) ± 0.39 (syst)

172.52 ± 0.33 GeV



Dominant uncertainties
- b-JES
- b-tagging
- ME generator
- JES

Summary

- m_t measurements by CMS with increasing **precision** and **understanding** of systematics
- Three measurements introduced
  - m_t^{MC} tt̄ lepton+jets **171.77 ± 0.37 GeV**
  - m_t^{pole} tt̄+1j pole mass **172.93 ± 1.36 GeV**
  - Run1 combination **172.52 ± 0.33 GeV**
- Stability of the EW vacuum
  - “To rule out absolute stability to 3σ confidence, the uncertainty on the top quark pole mass would have to be pushed below 250 MeV” arxiv:1707.08124
- Top mass interpretation problem
  - $m_t^{MC} \rightarrow m_t^{pole}$