Top quark mass measurements

An experimental review for the theory mini-workshop "top mass & vacuum stability"

Marcel Vos (IFIC, CSIC/UV, Valencia)

TOP24, St Malo, France, September 2024

Is our vacuum unstable?

Is our vacuum unstable?

Don't I have enough problems? Should I worry about this?

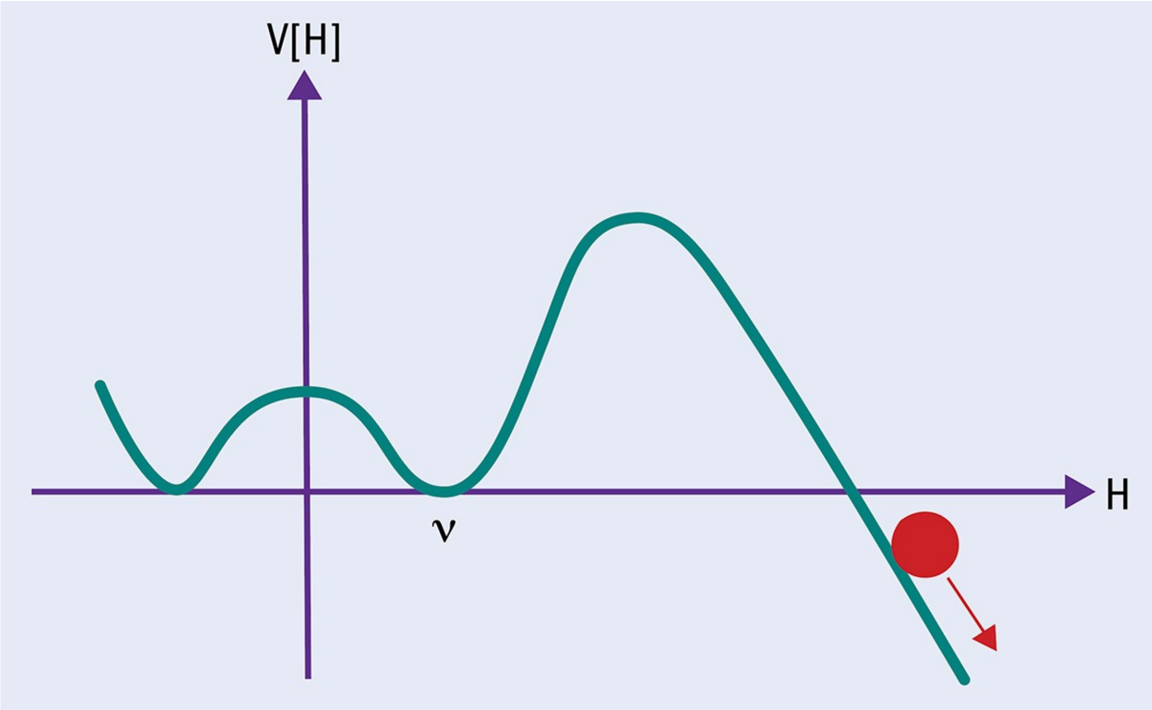
One key observation - we're here - indicates that our vacuum is at least meta-stable with a typical life time of the order of the age of the universe

That doesn't mean our vacuum cannot decay today, but I count on the sun coming up again tomorrow (whether we get to see it in St Malo or not)

marcel.vos@ific.uv.es

So what's this about?

In the SM the Higgs sector is connected to the top mass.



From John Ellis, https://cerncourier.com/a/the-higgs-and-the-fate-of-the-universe/

The shape of the Higgs potential depends on the Higgs self-coupling.
Our minimum is not necessarily the only one, or the deepest.

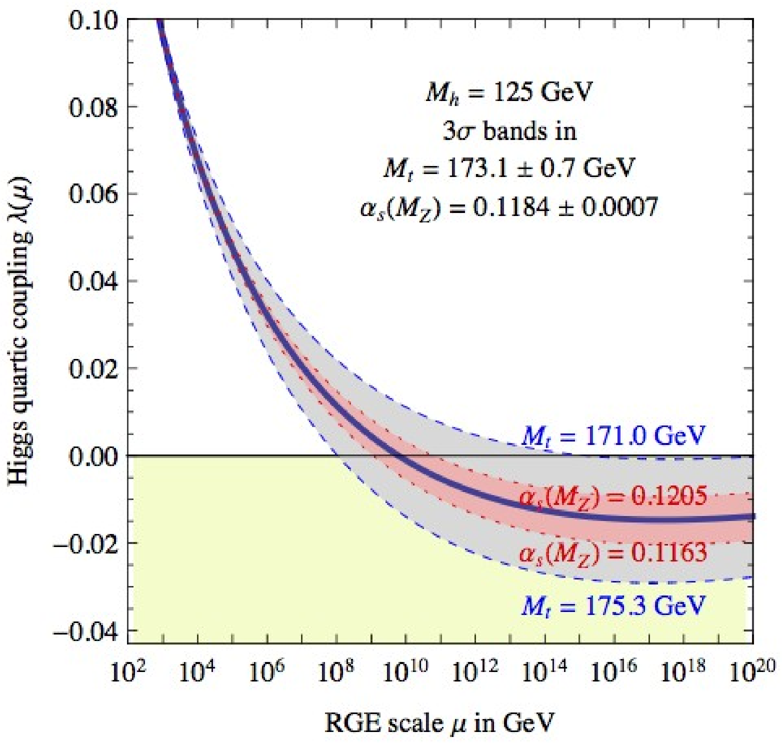
The Higgs quartic coupling

The Higgs quartic coupling:

At the EW scale λ is given by m_H and the VEV and is **positive**

Renormalization Group Equations predict λ at much higher scales.

Depending on m_t, λ can go **negative,** and leave the Higgs potential unbounded



Obviously, we're still here: if RGE predicts negative λ this is evidence that new physics must have come in, changed the evolution and saved our universe

Living on the edge

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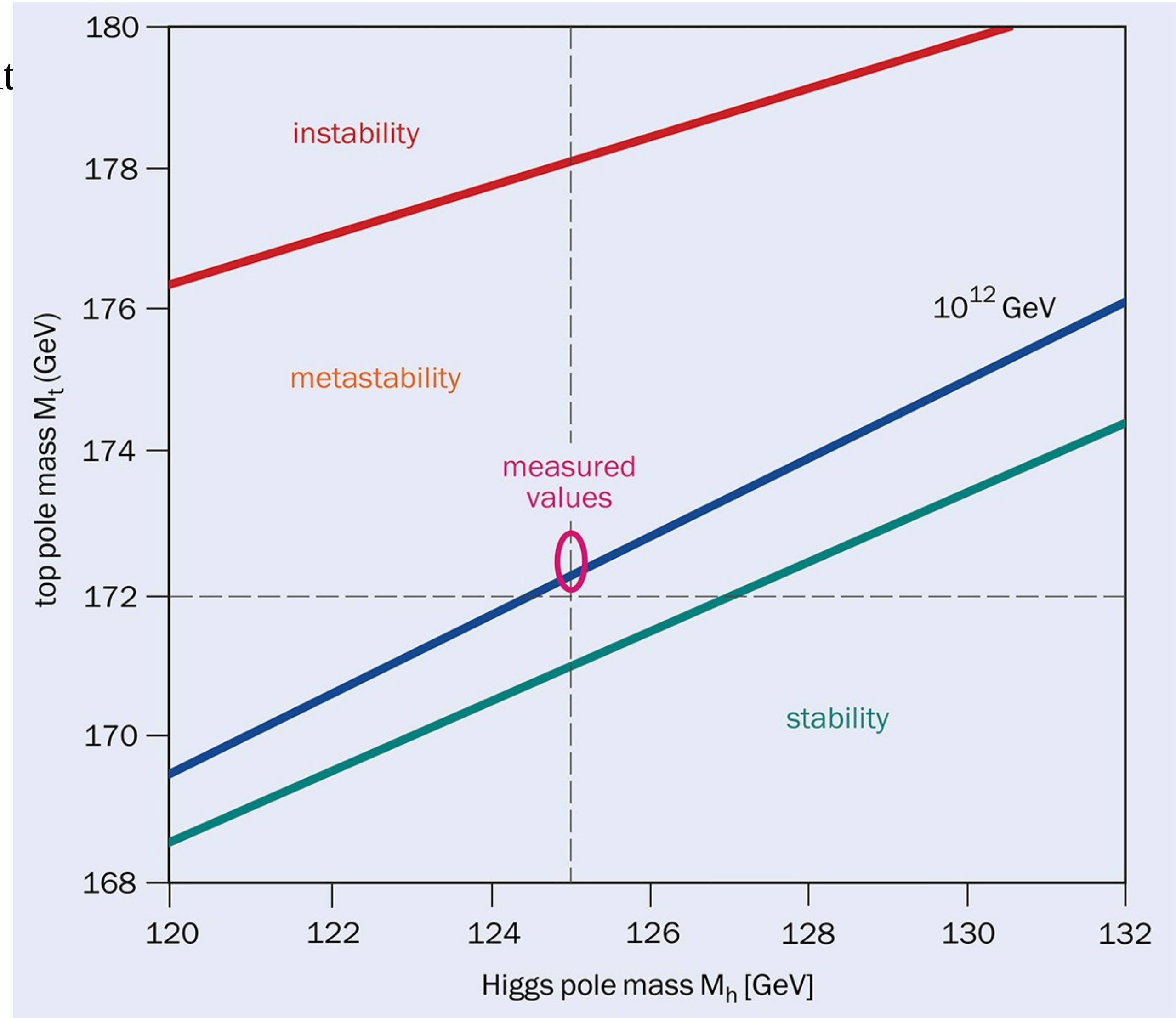


The world average values of the SM parameters leave us in the meta-stable region

I'll leave it to Isabella, Tom and Thomas to point out what that's telling us…

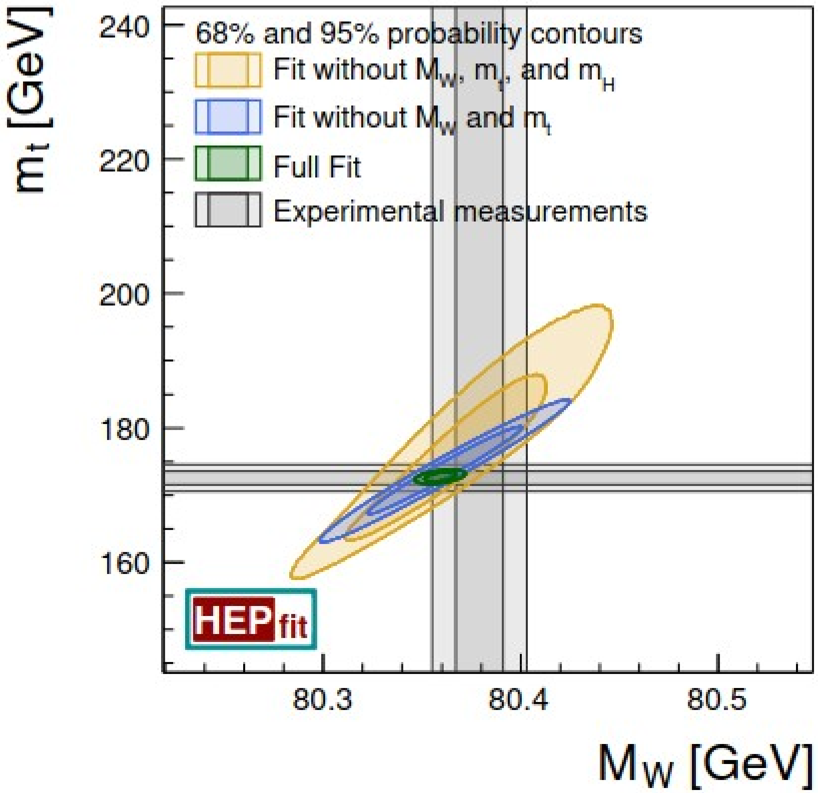
Similarly, EW precision fit

Same story, different parameters. The SM connects m_H, m_W and m_t

After LEP and SLD, but before top discovery at the Tevatron, one could infer the top quark mass from its effects on EW precision observables

If the SM is a good theory at the EW scale, the **blue ellipse** (all EW data without the m_W and m_t measurements) must agree with the **grey bands** (direct measurements)

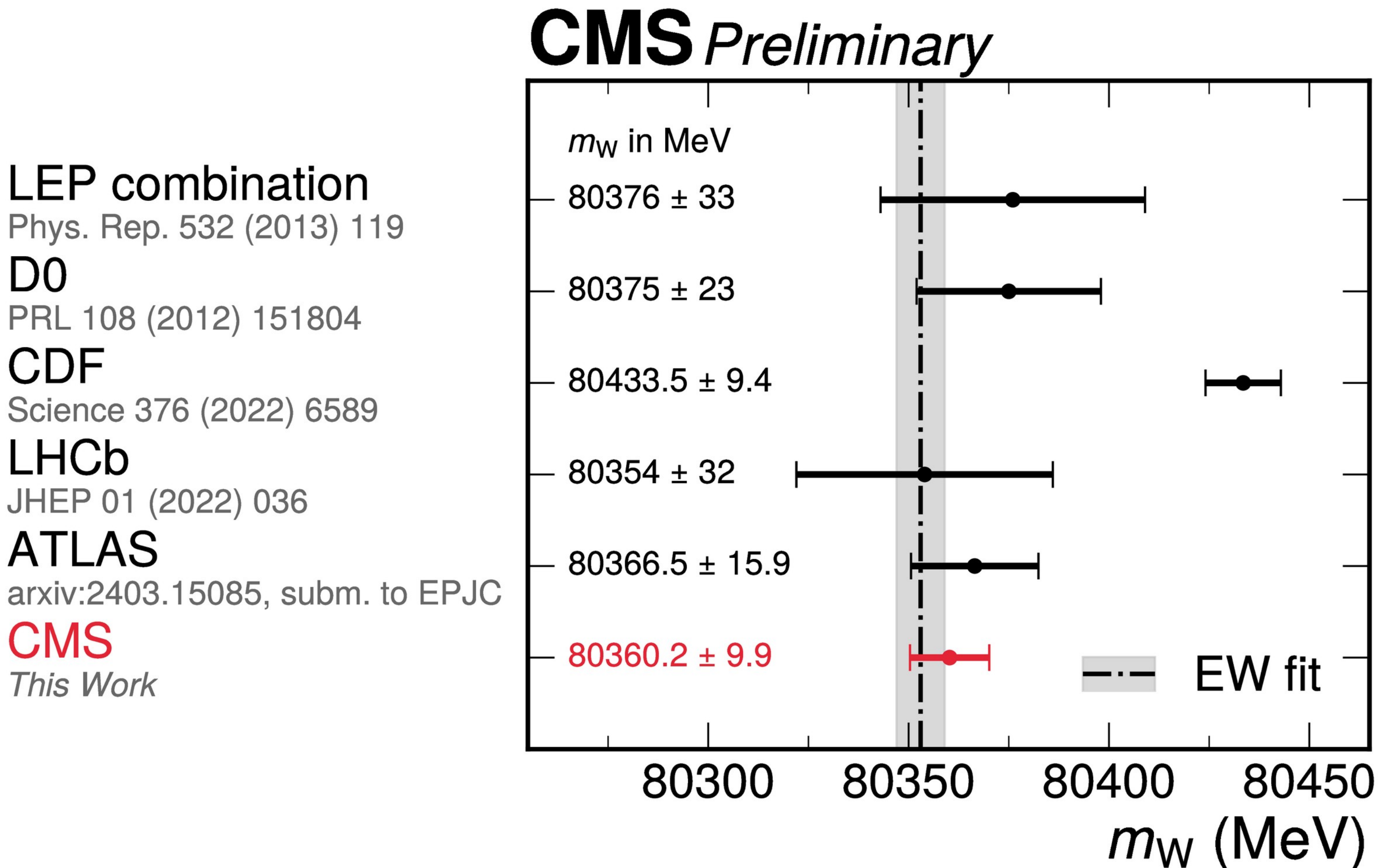
Tension in this plot implies new physics (or a problem with the measurements)



J. de Blas et al., arXiv:2112.07274

See 2204.04204 for impact of the CDF W-mass

W-mass (CMS-SMP-23-002)



- An important bottle neck in the EW fit is removed now
- A careful analysis can beat the theoretical limitations!

More motivation

The top quark mass is a fundamental parameter of the SM that is not predicted.

It can only be measured precisely at a collider that produces top quarks.

We happen to have access to the only machine that can do this.

Hence, it’s our job to provide the best possible measurement

Best = highest precision & credibility

So, how are we doing?

The bottom quark $\overline{\text{MS}}$ mass $m_b(m_b)$ is known to about 0.5 %

b	$I(J^P) = 0(\frac{1}{2}^+)$
	$m_b = 4.18^{+0.03}_{-0.02}$ GeV Charge $= -\frac{1}{3}\,e$ Bottom $= -1$
t	$I(J^P) = 0(\frac{1}{2}^+)$
	Charge $= \frac{2}{3}\,e$ Top $= +1$

Mass (direct measurements) $m = 172.69 \pm 0.30$ GeV [a,b] $(S = 1.3)$
Mass (from cross-section measurements) $m = 162.5^{+2.1}_{-1.5}$ GeV [a]
Mass (Pole from cross-section measurements) $m = 172.5 \pm 0.7$ GeV
$m_t - m_{\bar{t}} = -0.15 \pm 0.20$ GeV $(S = 1.1)$
Full width $\Gamma = 1.42^{+0.19}_{-0.15}$ GeV $(S = 1.4)$
$\Gamma(W\,b)/\Gamma(W\,q(q = b,\, s,\, d)) = 0.957 \pm 0.034$ $(S = 1.5)$

R.L. Workman et al. (Particle Data Group), Prog.Theor.Exp.Phys. 2022, 083C01 (2022)

So, how are we doing?

The top quark pole mass is known to 0.2 % (direct, with some CAVEATs)
The top quark pole mass is known to 0.4 % (from cross sections, other CAVEATs)
The top quark $\overline{\text{MS}}$ mass $m_t(m_t)$ is known to about 1 % (from cross sections)

b

$I(J^P) = 0(\frac{1}{2}^+)$

$m_b = 4.18^{+0.03}_{-0.02}$ GeV Charge $= -\frac{1}{3}\ e$ Bottom $= -1$

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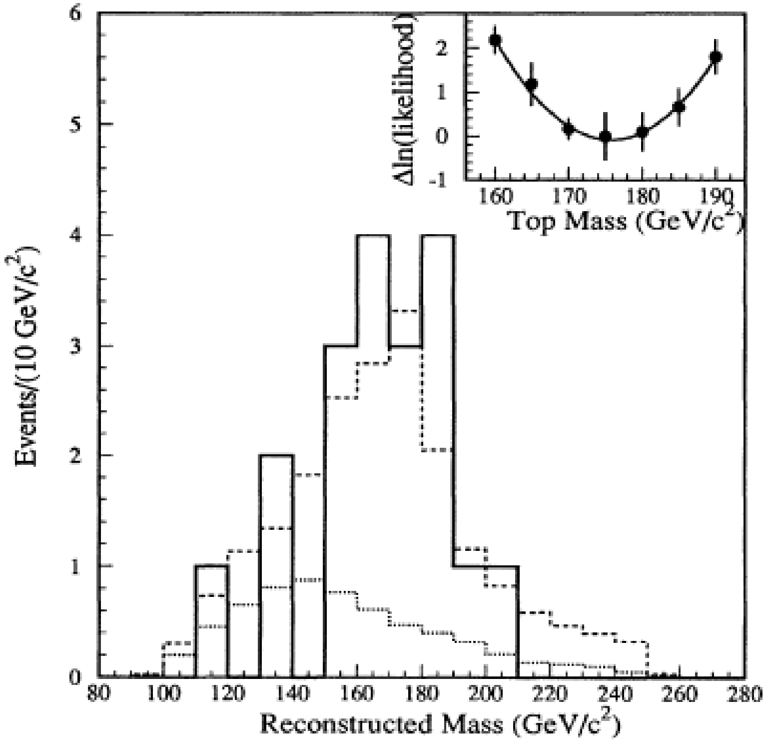
Warning: PDG selection of measurements and averaging procedure are debatable

Direct mass measurements



Top is a "naked" quark

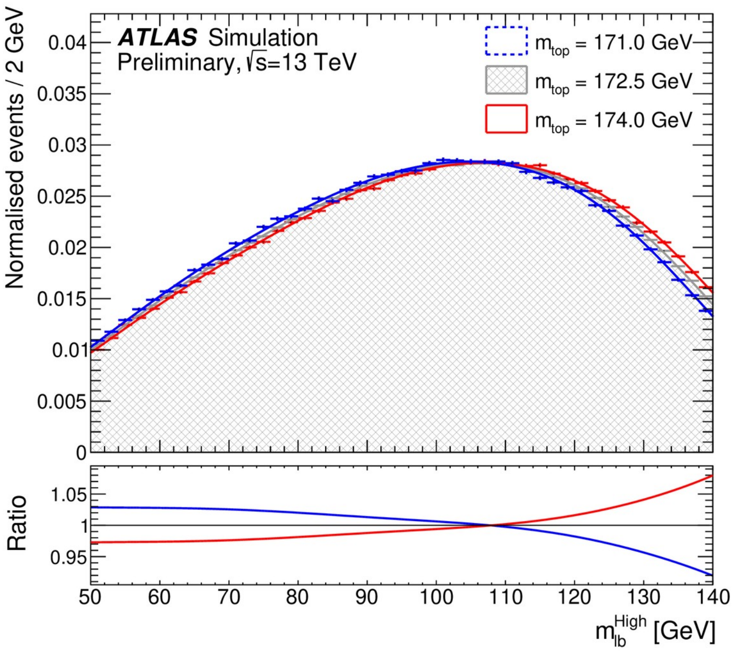
Top mass template fit

ATLAS-CONF-2022-058

1. Reconstruct top decay products

2. Generate Monte Carlo templates

3. Fit for the best value of the MC mass parameter



Experiment is extremely precise:
- 600 MeV for the most precise single measurements

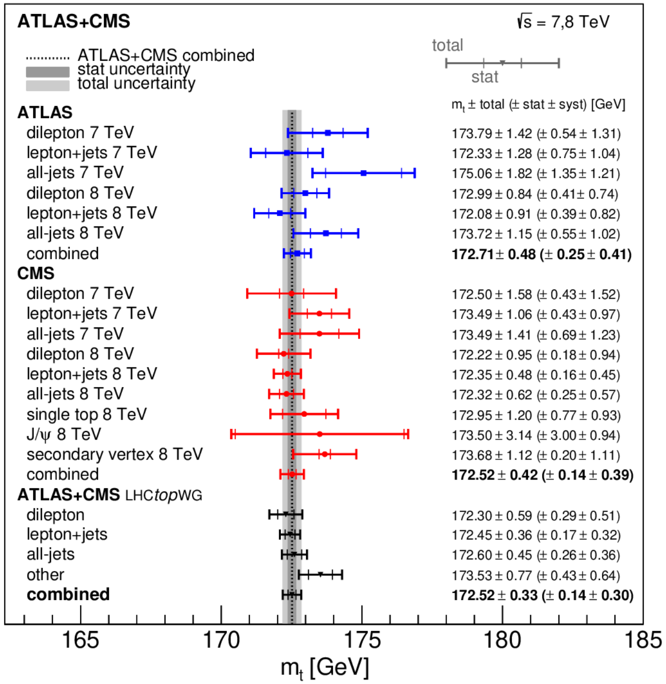
A large number and variety of such measurements exists
- different colliders: LHC and Tevatron experiments
- different final states: di-lepton, l+jets, fully hadronic
- different kinematic regimes: bulk vs. boosted
- alternative methods based on fully leptonic observables (J/psi, soft muon)

The power of combinations

ATLAS+CMS run 1 combination,
PRL 132 (2024)

Multiple (15!) direct measurements using different techniques

Combination yields 330 MeV uncertainty, with best measurement of ~600 MeV (link)



- average is dominated by "standard" template methods,
- alternative results provide "robustness" and reduce the total uncertainty

	ATLAS						CMS								
	2011 (7 TeV)			2012 (8 TeV)			2011 (7 TeV)			2012 (8 TeV)					
	dil	lj	aj	dil	lj	aj	dil	lj	aj	dil	lj	aj	t	J/ψ	vtx
Pull	+0.93	−0.15	+1.43	+0.61	−0.51	+1.09	−0.01	+0.96	+0.71	−0.33	−0.47	−0.37	+0.38	+0.31	+1.08
Weight	−0.02	+0.07	+0.00	+0.16	+0.17	+0.03	−0.08	−0.01	+0.03	+0.12	+0.34	+0.12	−0.03	+0.01	+0.08

Lessons: keep working on variety of methods, think about combinations during the design of the analysis, develop strategy to combine likelihood-based and classical template fits

IMHO, this should be your reference for direct top mass measurements (until run 2 analyses take over)

So, what could possibly go wrong?

Direct top quark mass measurements determine the best-fit value of the top quark mass parameter of today's Monte Carlo generator of choice (Powheg-hvq + Pythia8)

Modelling uncertainties "generalize" the result and make sure it's applicable to other setups available today (i.e. Powheg+Herwig in run 1)

We have evidence that what's missing in today's MC is not too important:

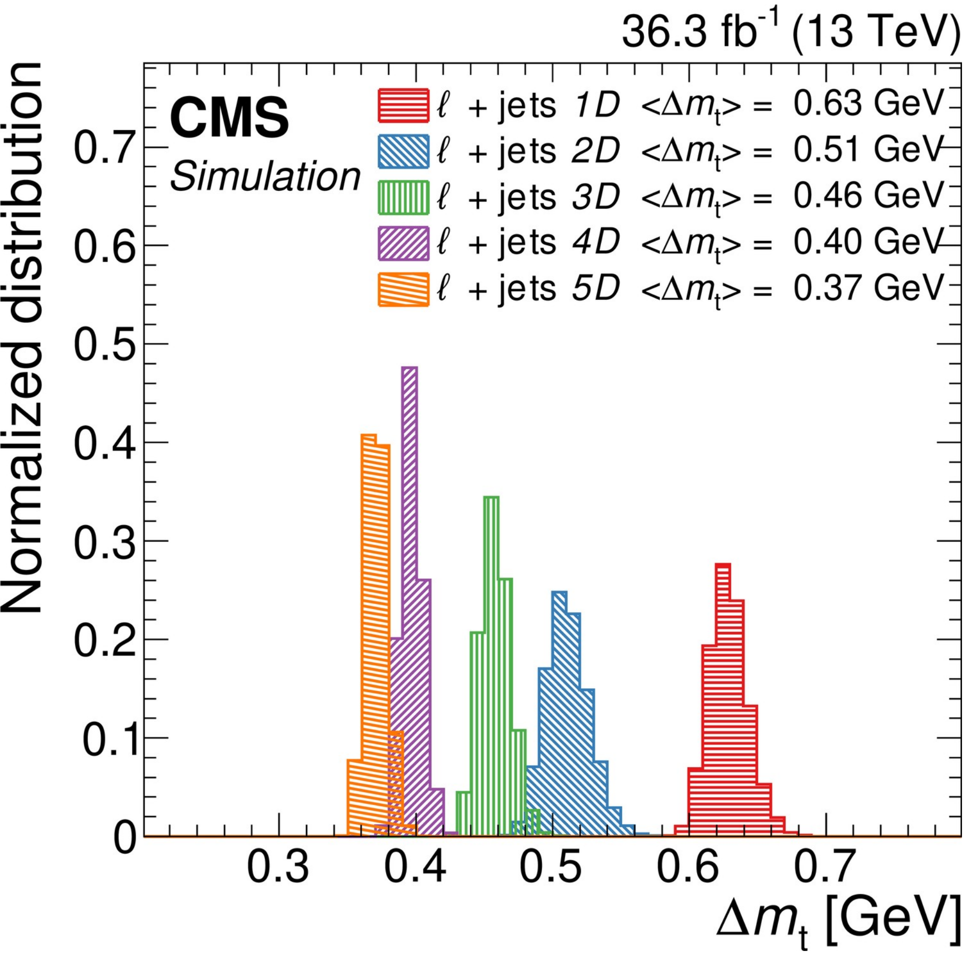
-- NNLO top quark production: estimated by reweighting, and found to be small
-- NLO + off-shell top decay: Powheg-bb4l checked in some analyses, but not systematically deployed in experiments yet
-- NLL parton shower: estimated with PS variations,
NLL PS in prepation, see references here
-- hadronization: estimated by comparing two old and ad-hoc models (if at all),
but... recent work by Hoang & Plaetzer

Glass-half-empty view: cannot avoid a sense of vertigo when thinking of a 1 per mille quark mass determination limited by ill-defined two-point comparisons

Glass-half-full view: variety of methods protects against missing an important effect (a tension would develop) and mitigates their impact (when agreement is good)

Run 2 developments: the power of PL fits

CMS top mass, l+jets, 36/fb: $m_t = 171.8 \pm 0.4$ (total), EPJC83 (2023), arXiv:2302.01967



CMS measurement demonstrates the power of profile-likelihood fits

- in-situ constraint of systematics (i.e. light-quark JES from W peak)
- uses data to refine the MC model (see also ATLAS+CMS W-mass)

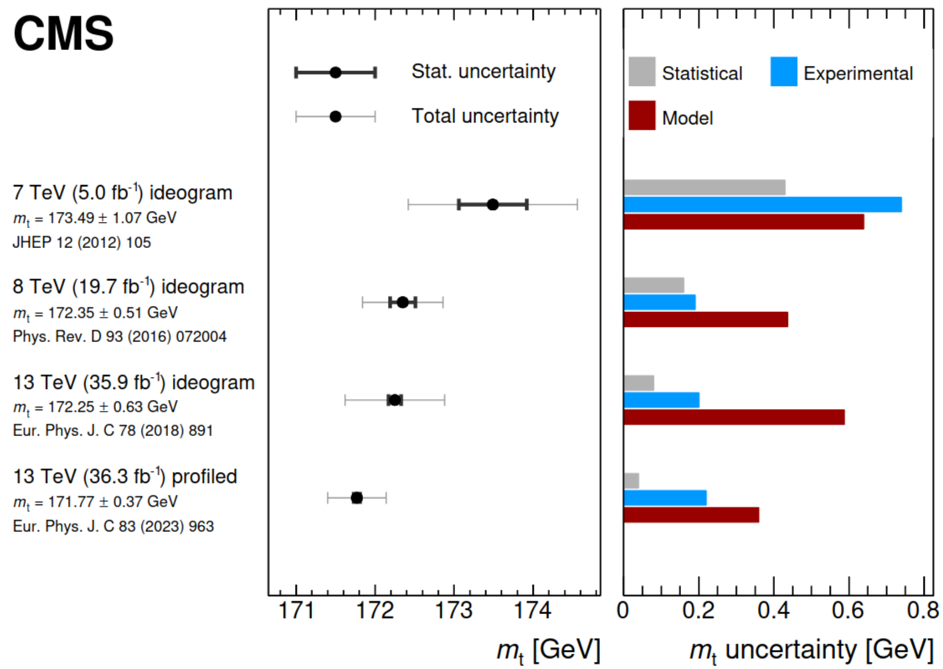
PL fits requires a more sophisticated uncertainty model and careful thought about correlations across regions

PS splitting kernel variations offer more physical set of NPs

CMS l+jets analyses - (r)evolution

Hybrid 2D fit

PL fit, 5 inputs



PL fit result shifted wrt to classical analysis of the same data
(0.5 GeV, 0.8σ wrt classical result, 1.3σ wrt itself)
PL / classical fits answer different questions: what's the best-fit top mass value given the fitted / nominal estimates of Nps?
Classical fits: templates are consistent if experiments adopt similar MC.
PL fits: constrained post-fit model can still be different.

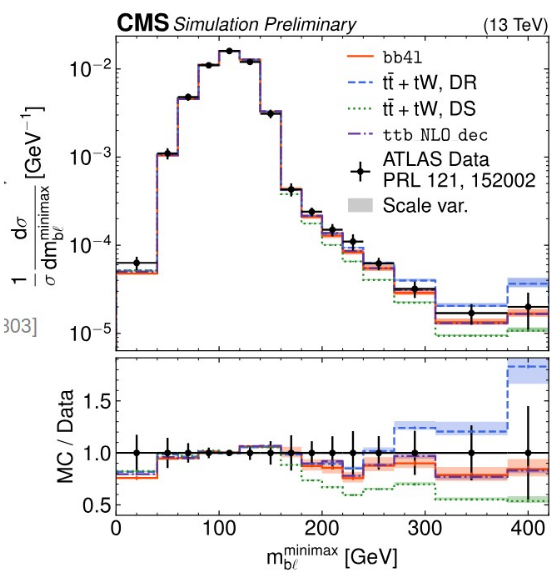
Run 2 developments - Powheg-bb4l (see Tomas Jezo's talk)

The Powheg-bb4l model includes a full 2 → 6 NLO calculation (tt+tW production, t→Wb)
Jezo & Nason '15, Jezo et al '16, Ferrario Ravasio et al. '18, Jezo et al. '23

Precision measurements in di-lepton and l+jets final states that require a precise model for top quark decay and off-shell effects should adopt this model

	bb4l-sl	hvq+ST$_{\mathtt{wtch}}$-DS	hvq+ST$_{\mathtt{wtch}}$-DR
$t \to Wb$ and $W \to q\bar{q}'$ decays	NLO+PS	LO+PS	LO+PS
tWb production	NLO+PS	LO+PS	LO+PS
$t\bar{t}$–tW interference	NLO+PS	-	LO+PS
off-shell effects	NLO+PS	approx.	approx.
non-resonant contributions	NLO+PS	-	-

Table: formal accuracy of bb4l and hvq



See also:
C. Herwig, T. Ježo, B. Nachmann, PRL 122 (2019), 2[illegible]
Laurids Jeppe, LHCtopWG meeting, November 2023
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2017-05/
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-042/

Run 2 developments: better control of jet response

The jet response is the limiting factor among experimental systematics

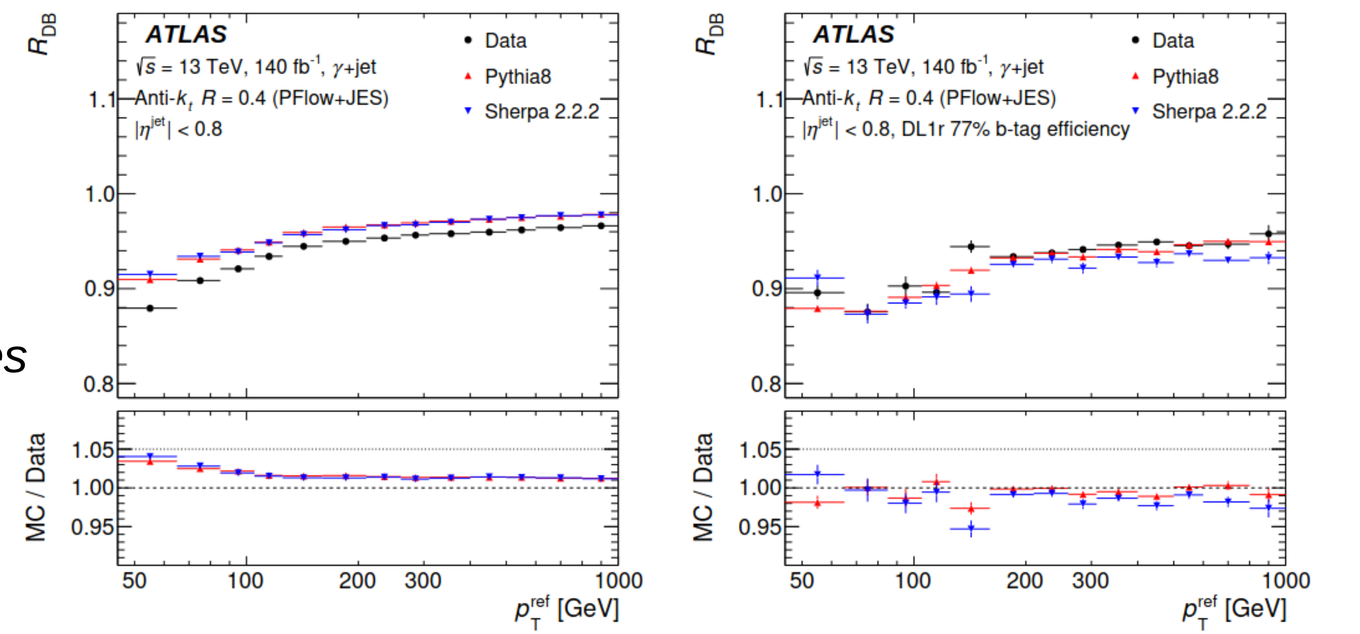
-- Light-quark jets have a natural solution, using the in-situ W-mass peak

-- Bottom quark jets are more difficult, but...

… statistics in Z+b-jet and γ+b-jet are sufficient to derive an in-situ bJES

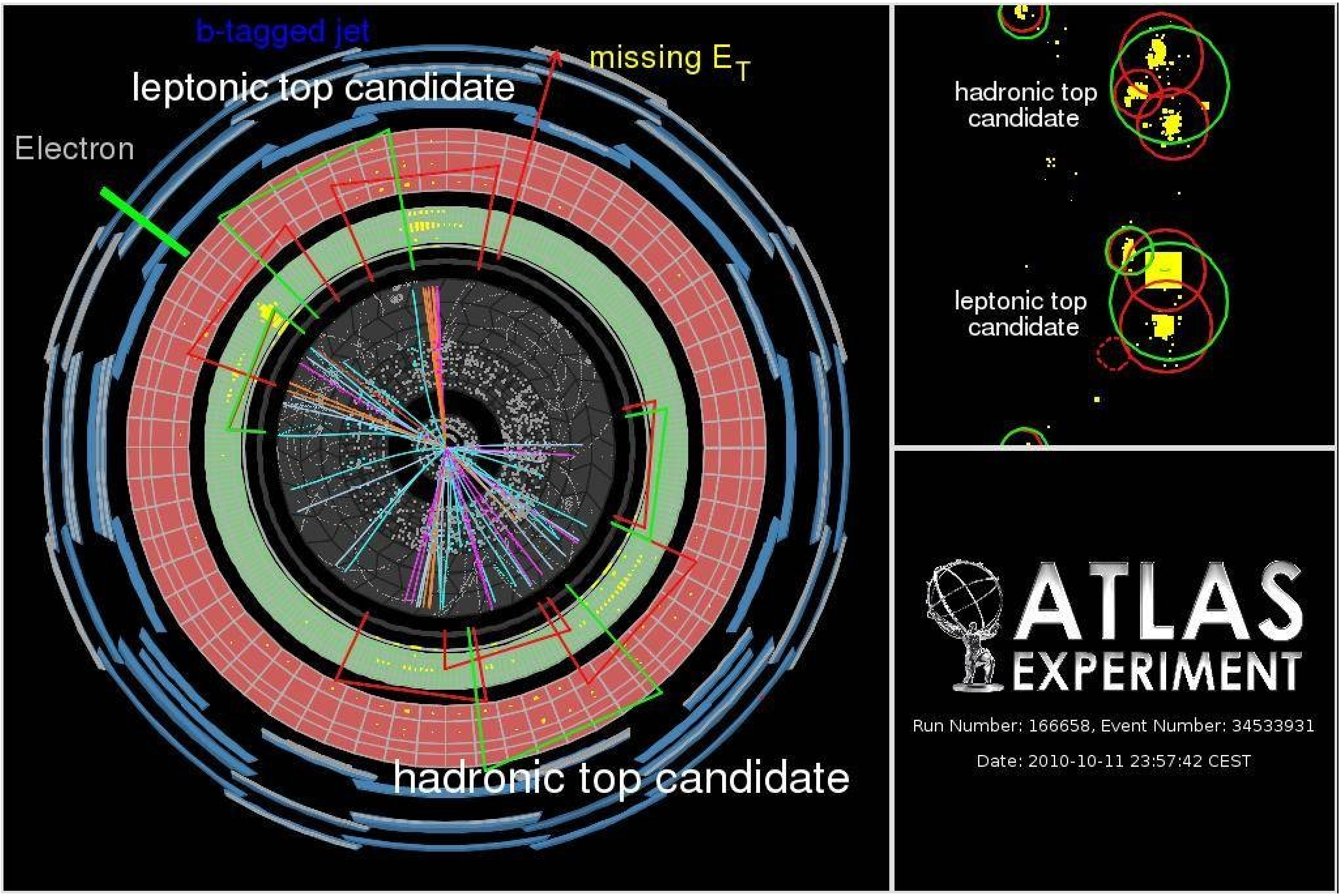
… important synergy with Higgs group to derive MC calibration for b-jets

ATLAS: new techniques for jet calibration, EPJC83 (2023)



Run 2 developments: boosted top quarks

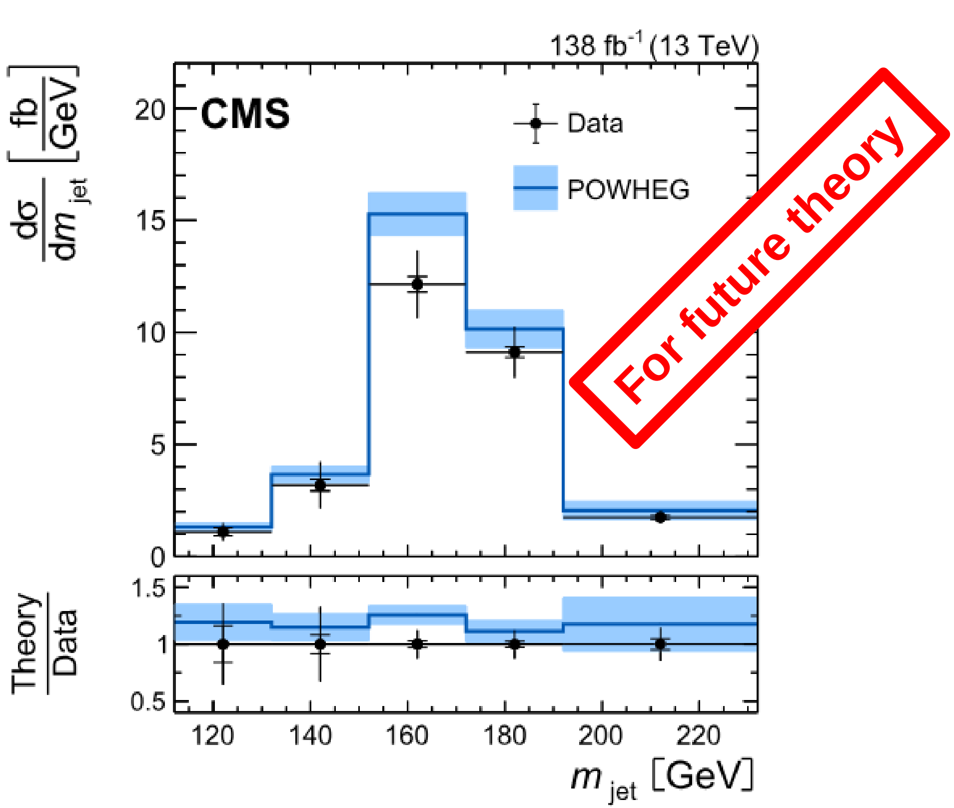
Boosted top quarks require special tools, developed since the 2010s.

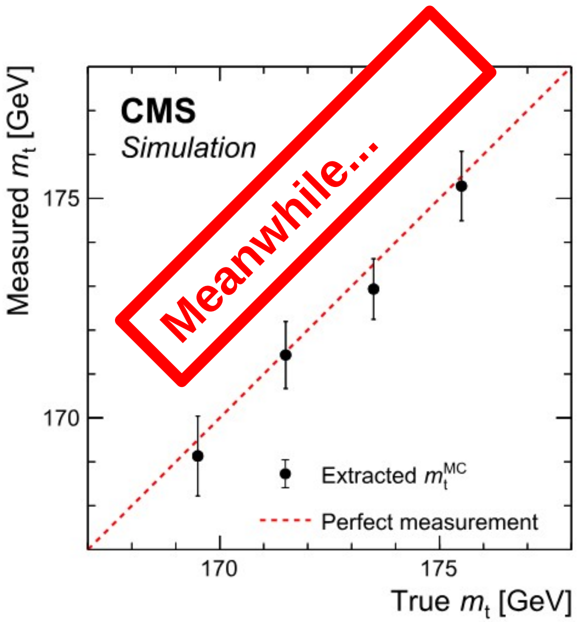


Boosted top quark mass measurements

Why? Because we can! A lot of work has gone into developing large-R jets, grooming, pile-up correction/mitigation and jet mass calibration

Because boosted is special! It is the one topology that is amenable to first-principle calculations at particle-level, that can be used to understand/calibrate MC





M_t^{MC} = 173.06 ± 0.84 GeV.

CMS, Measurement of the differential tt production cross section as a function of the jet mass and extraction of the top quark mass in hadronic decays of boosted top quarks, Eur. Phys. J. C (2023) 83:560

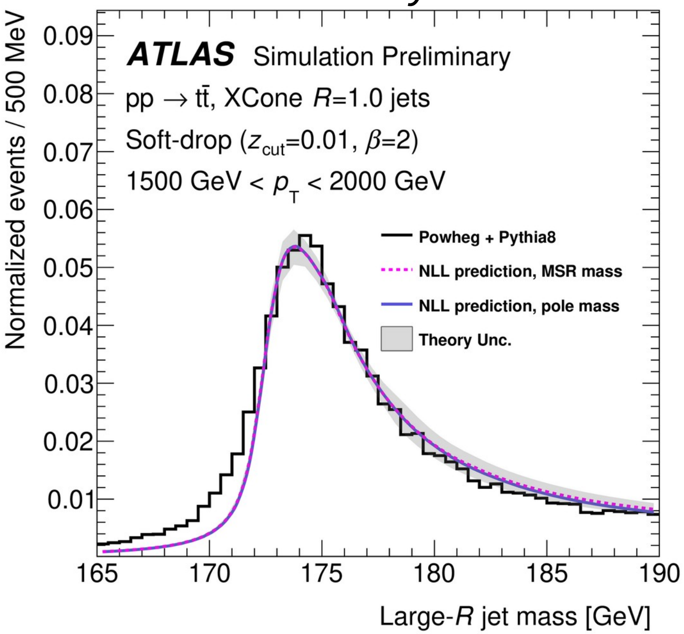
Interpretation of direct top mass measurements

The top mass parameter of Monte Carlo generators is "meant" to be the pole mass
-- the NLO Matrix Element and parton shower employ the pole scheme

However, the parton shower cut-off (typically 1-2 GeV) subtly alters the scheme
-- **analytic analysis** for Herwig shower in *Hoang,Plaetzer,Samitz, arXiv:1807.06617*

$$m_t^{\rm MC} - m_t^{\rm pole} = -(2/3) Q_0 \alpha_S(Q_0^2)$$

-- see also: A. Hoang, What is the top quark mass? Ann. Rev. Nucl. Part. Sci. 70 (2020)
-- executive summary in Section 3.3 of CMS' top quark review, arXiv:2403.01313

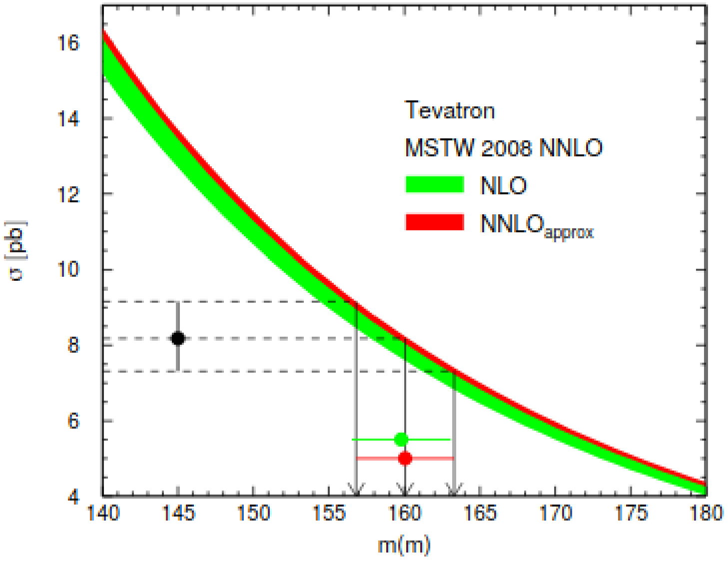


Calibration: fit first-principle calculations to Monte Carlo generator predictions

(Butenschoen et al., PRL 117 (2016), Hoang et al. PRD100 (2019), ATLAS, ATL-PHYS-PUB-2021-034, Dehnadi et al., JHEP 12 (2023), Bouchhar et al., work in progress)

Bottom line: **MC mass parameter is indeed within O(500 MeV) of the pole mass**; a more precise identification is possible

Mass measurements from the x-section



Inclusive cross section

The extraction of the top quark mass from the inclusive cross offers a robust interpretation and flexible mass scheme

--- fixed-order calculation of the inclusive cross section fixes the mass scheme (pole, $\overline{\text{MS}}$).

--- Monte Carlo is used to correct the data, but cross section is independent of MC mass

ATLAS+CMS cross section combination, JHEP07(2023)

$M_t^{pole} = 173.4\ ^{+1.8}_{-2.0}$ GeV, with NNPDF3.0

Important prize in precision for robust interpretation

Differential cross sections

Can we have both – mass sensitivity and a robust interpretation?

Differential cross section measurements!

This works: 2 GeV → 1 GeV. A combination can reach well below 1 GeV.

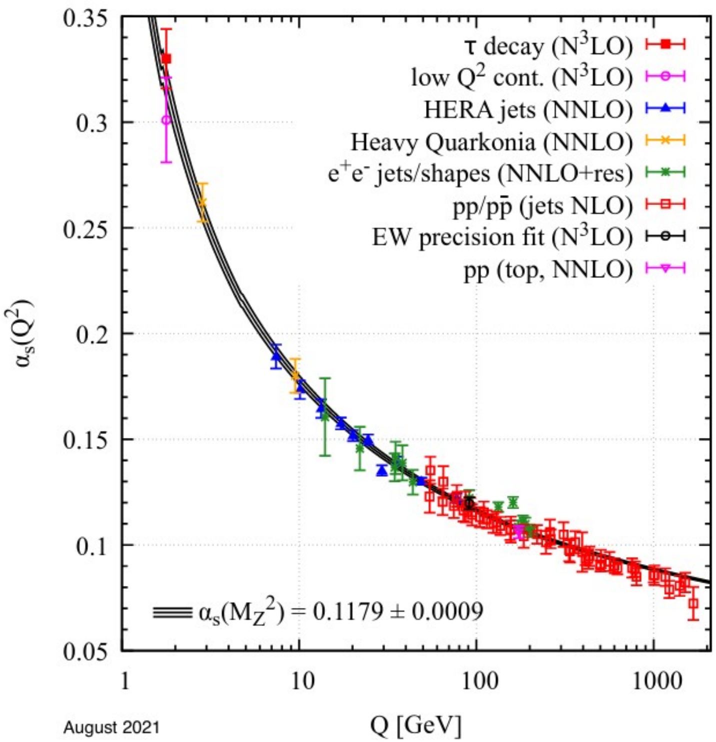
More is possible…, with better theory

- NNLO predictions for tt+jet, N3LO for tt
- Full calculations, including top decay 2→6 (+jet)
- "threshold" corrections due to Coulomb potential

Running couplings

Scale evolution of the strong coupling predicted by QCD:

$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$$



Precise determinations from 1 GeV to > 1 TeV!

Reference $\alpha_s(m_Z) = 0.118 \pm 0.001$ (PDG, <1%)

This plot collects α_s value extracted from measurements of many observables in several processes over a broad energy range

Running constants

Quark masses – parameters of the QCD Lagrangian – **must run too**

$$\frac{\partial m_q(\mu)}{\partial \log(\mu^2)} = \gamma_m[\alpha_s(\mu)]\, m_q(\mu)$$

Anomalous mass dimension

Experimental studies of “running” (some evidence that indeed it works):

- charm quark mass, HERA [Ghizko et al., PLB775 (2017)]

- bottom quark mass, DELPHI,SLD,ALEPH,OPAL, see cf. Kluth [hep-ex/0603011])

- top quark mass, CMS[PLB803 (2020)], Catani et al. [JHEP08 (2020)],

marcel.vos@ific.uv.es

Running of the bottom quark mass

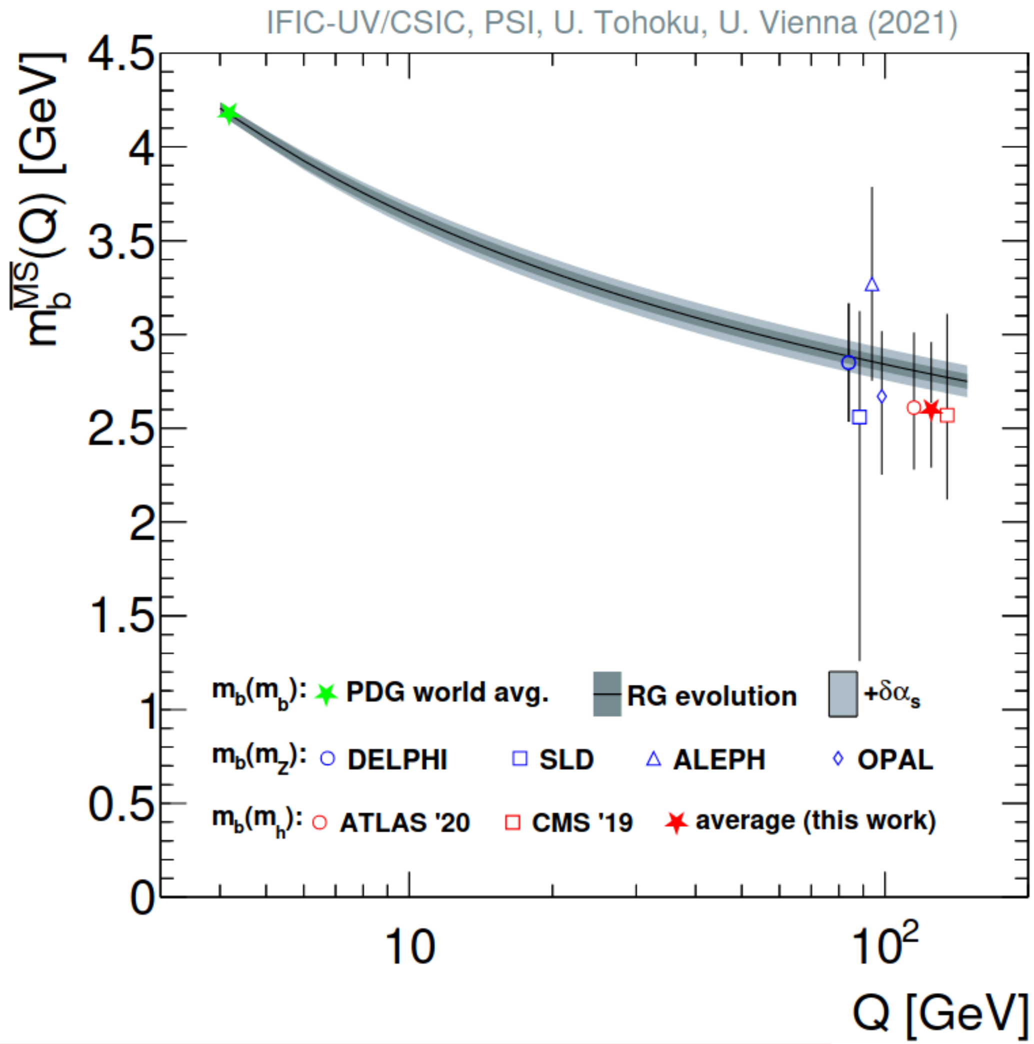
RG evolution from Revolver package, arXiv:2102.01085

Quark masses are not predicted by the SM, but QCD (RGE) does give a prescription for their scale evolution

Collecting measurements at different energies:

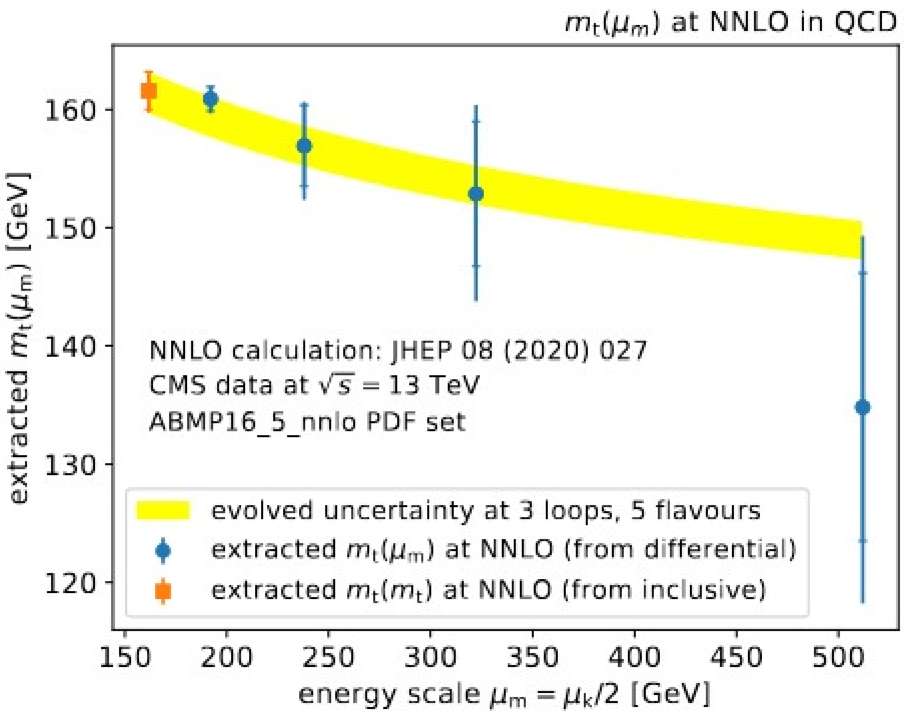
- $m_b(m_b)$ world average from low-energy expts
- $m_b(m_Z)$ from LEP experiments and SLD
- $m_b(m_H)$ from LHC Higgs Measurements!!

EW processes (no α_s at LO!) with clearly defined scale



The bottom quark mass runs!! *PRL128 (2022) 122001*

The running top quark mass



The top quark mass wants to run, too!!

"Although a hypothetical no-running scenario cannot be excluded, the result of this study indicates a clear preference for the RGE running hypothesis."
M. Defranchis et al., JHEP04 (2024)

Future prospects

HL-LHC prospects: we're already well beyond initial expectations

4.4 Top-quark physics

Given the large top quark cross-section, most of the top physics programme should be completed during the first few years of LHC operation [32]. In particular, the $t\bar{t}$ and the single-top production cross-sections should be measured more precisely than the expected theoretical uncertainties, and the determination of the top mass should reach an uncertainty (dominated by systematics) of ~ 1 GeV, beyond which more data offer no obvious improvement. *HL-LHC primer, hep-ph/0204087*

CMS study in 2019 yellow report promises direct mass measurement with 200 MeV (experimental) uncertainty, *arXiv:1902.04070*

 marcel.vos@ific.uv.es

The future

HL-LHC brings **MUCH more data**

→ J/psi method becomes competitive, trade statistics and systematics

Hard work from experimentalists

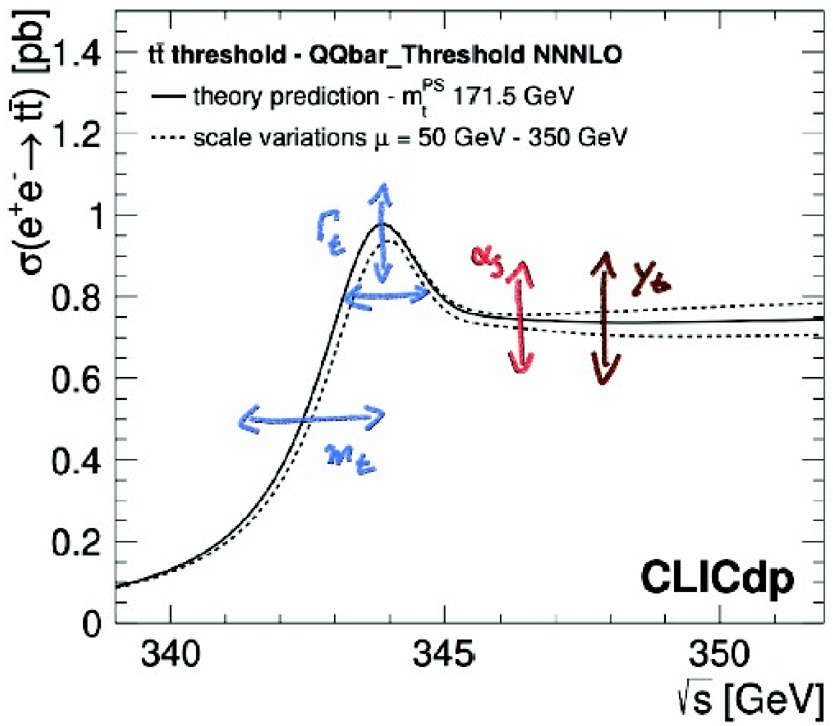
→ deploying MC generators, improving jet calibrations, developing better fits

Must be accompanied by **theory progress**

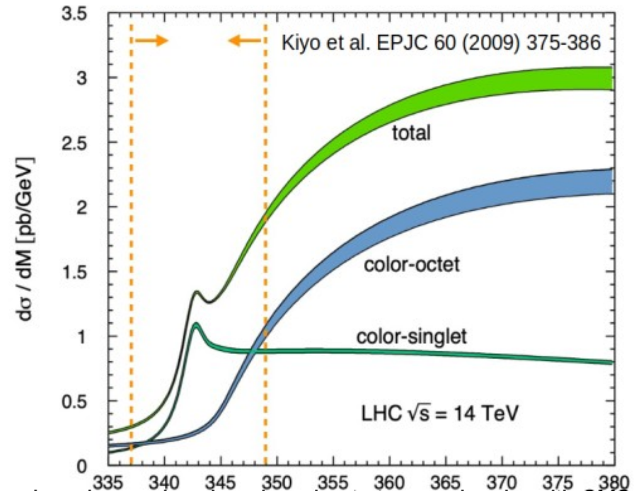
→ **better MC and fixed-order predictions, better uncertainty model**

Eventually, an e^+e^- Higgs/top factory can perform the ultimate top mass measurement if operated at sqrt(s) ~ 2 m_t

(→ Roberto's talk)



New possibilities?



Common lore: the "toponium" bound state is not accessible at the LHC

Some theorists do not agree...

IFT-UAM/CSIC-24-11
CERN-TH-2024-12

KEK-

Signatures of toponium formation in LHC run 2 data

Benjamin Fuks,[1,2,*] Kaoru Hagiwara,[3,†] Kai Ma,[4,5,6,‡] and Ya-Juan Zheng[7,§]

[1] *Sorbonne Université, CNRS, Laboratoire de Physique Théorique et Hautes Énergies, LPTHE, F-75005 Paris*
[2] *Institut Universitaire de France, 103 boulevard Saint-Michel, 75005 Paris, France*
[3] *KEK Theory Center, Tsukuba 305-0801, Japan*
[4] *School of Fundamental Physics and Mathematical Science, Hangzhou Institute for Advanced Study, UCAS, Hangzhou 310024, Zhejiang, China*
[5] *International Centre for Theoretical Physics Asia-Pacific, Beijing/Hangzhou, China*
[6] *Department of Physics, Shaanxi University of Technology, Hanzhong 723000, Shaanxi, China*
[7] *Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, U.S.A.*

Toponium Hunter's Guide

J. A. Aguilar-Saavedra[1]

[1] *Instituto de Física Teórica, IFT-UAM/CSIC, c/ Nicolás Cabrera 13-15, 28049 Madrid, Spain*

We address the discovery and characterisation of toponium production at the Large Hadron Collider. In the dilepton decay mode, multivariate analyses of spin and colour observables could provide evidence that an excess of events present near the $t\bar{t}$ threshold corresponds to a spin-zero colour singlet. The semileptonic decay mode may also exhibit an excess near threshold, but is not expected to play any role in the toponium characterisation.

… and, apparently, CMS has news for us!

(Samuel Baxter, Higgs Hunting, this week)

Combined Limit with η_t

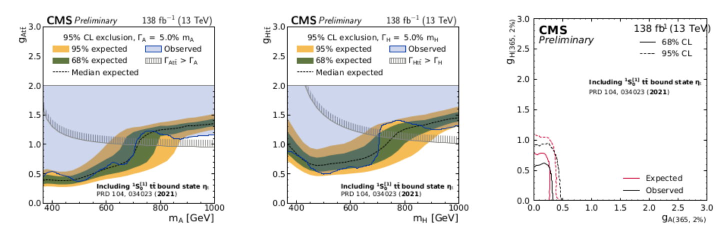


Figure: Limits for pseudoscalar(left), for scalar(centre) and 2-dimensional for both scalar and pseudoscalar (right), SM background with a model of the $t\bar{t}$ bound state

DESY. | Search for pseudoscalars and scalars decaying to top quark pairs with CMS Run 2 | Samuel Baxter | Higgs Hunting 2024, Paris, 24.09.2024 Page 15

Top becomes a "normal" quark

Summary

The LHC is delivering top mass measurements well beyond expectations

Ultra-precise single measurements based on profile-likelihood fits of run 2+3 data, with the best available MC + uncertainty model

A comprehensive experimental program with many checks of internal consistency (direct vs cross section, boosted vs bulk, nominal vs alternative)

Better theory required to make progress
Today: *Monte Carlo model including NLO top quark decays, PS with splitting kernel variations*
Longer-term: *first-principle predictions with "threshold" effects, next-generation PS models better understanding of hadronization*

marcel.vos@ific.uv.es