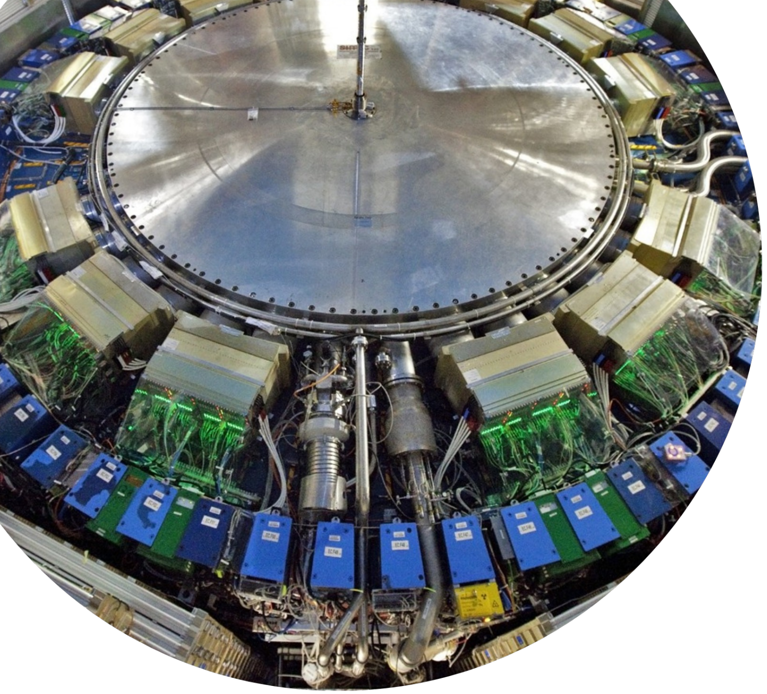


LHC combination of the top-quark mass measurements in Run I

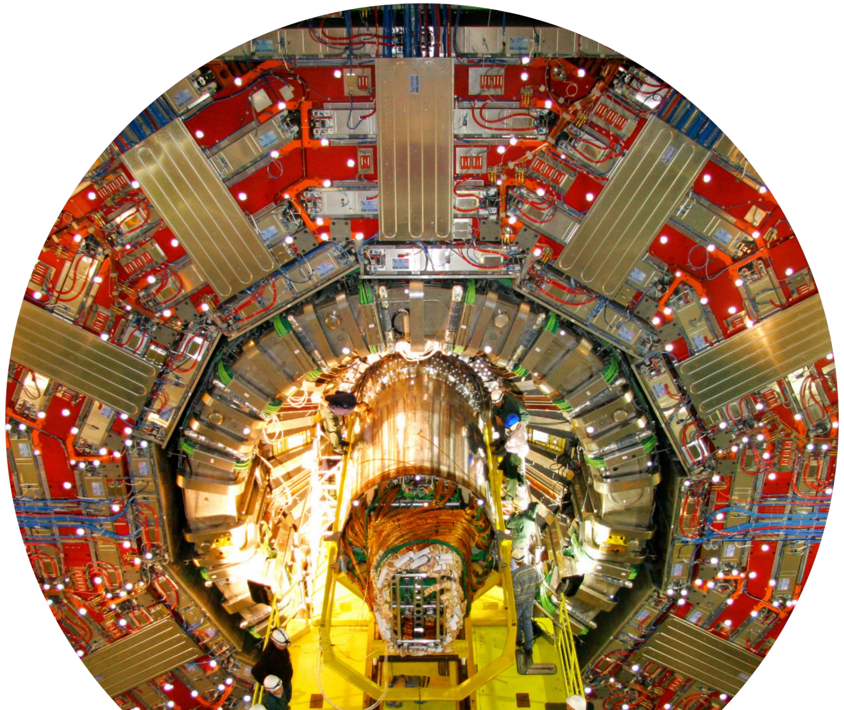
Clara Nellist (ATLAS)

University of Amsterdam and NIKHEF

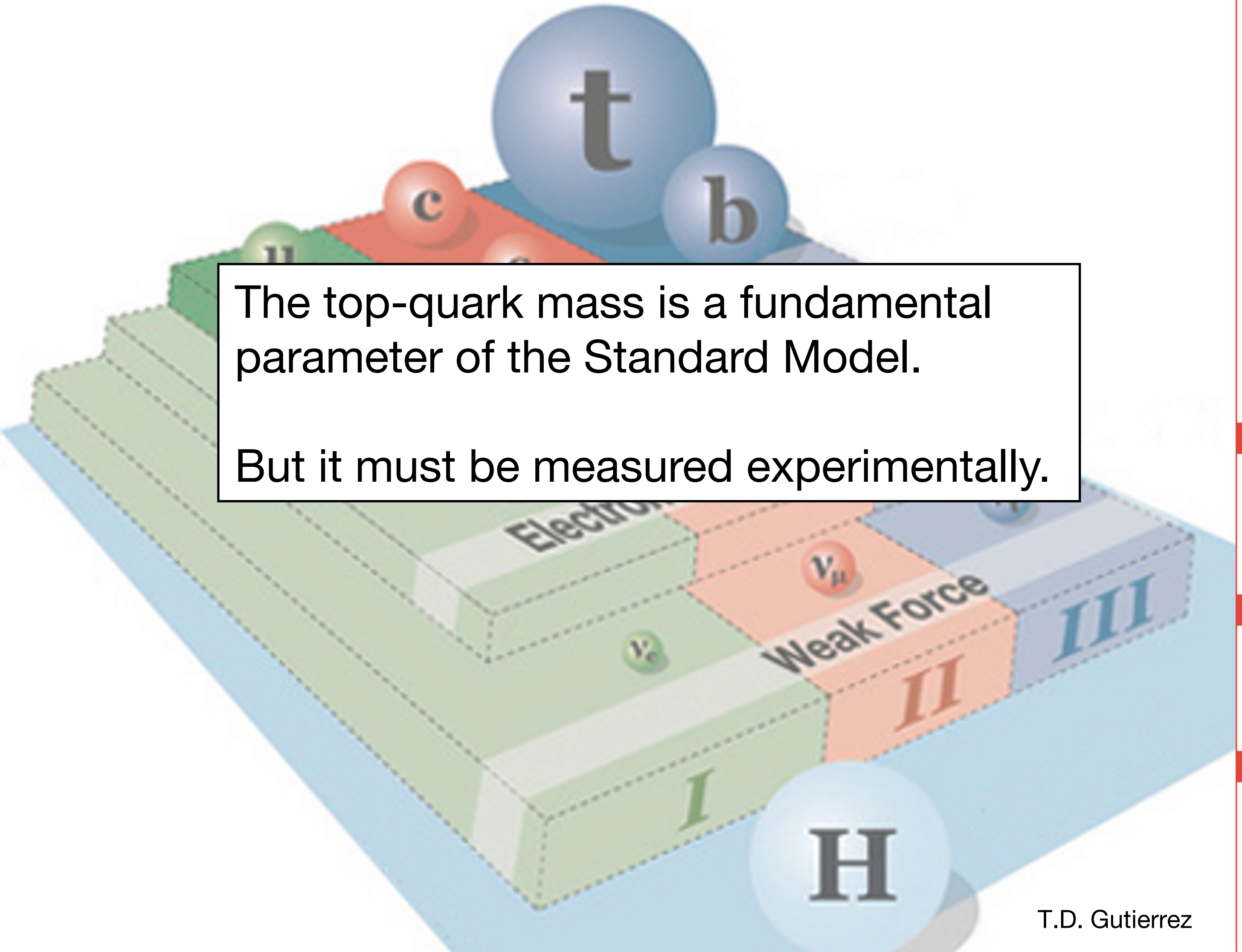
On behalf of ATLAS and CMS

TOP2023, Traverse City, USA

26th September 2023



Motivation



The top-quark mass is a fundamental parameter of the Standard Model.

But it must be measured experimentally.

T.D. Gutierrez

1

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H\partial_\mu H -$$
$$\tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} +$$
$$\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$
$$gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$

3

$$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

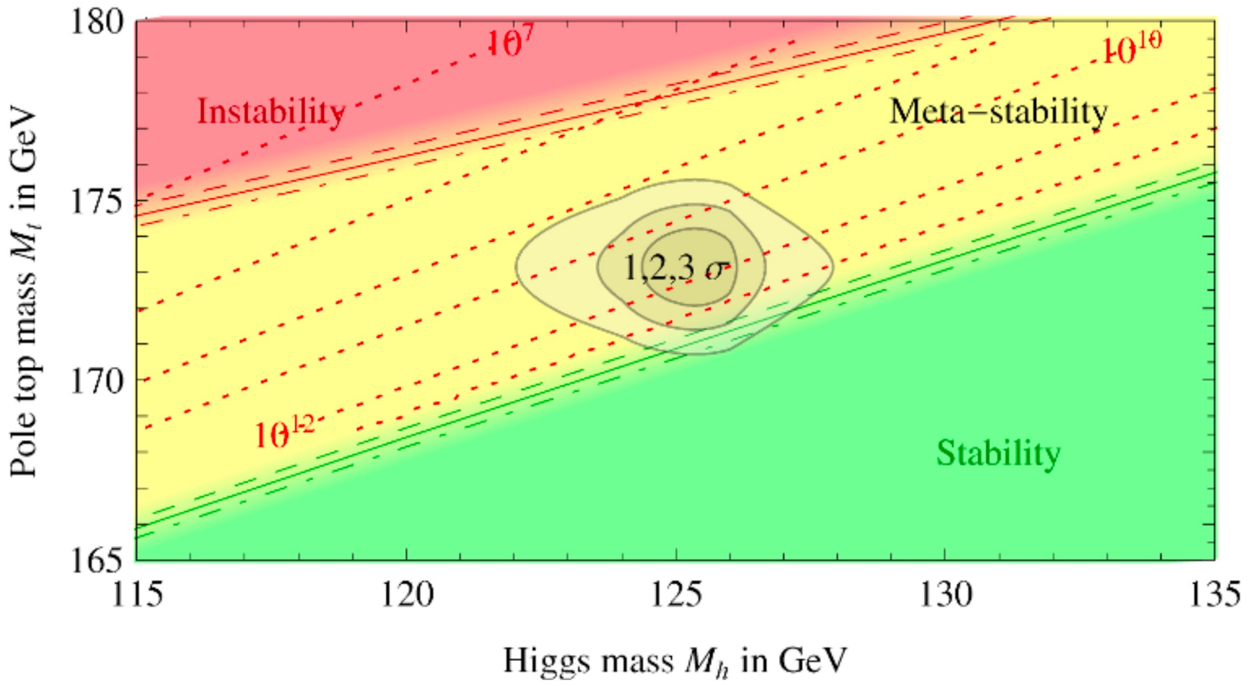
$$\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5

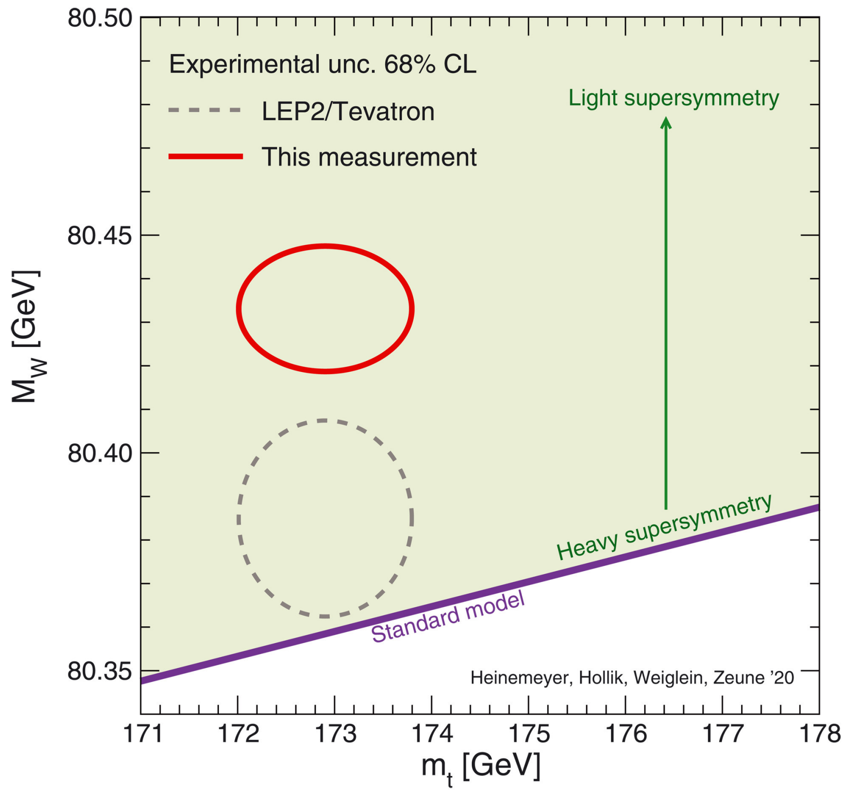
$$\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Motivation

It is key to our understanding of the SM at high energies and determining the stability of the EW vacuum at the Plank scale.



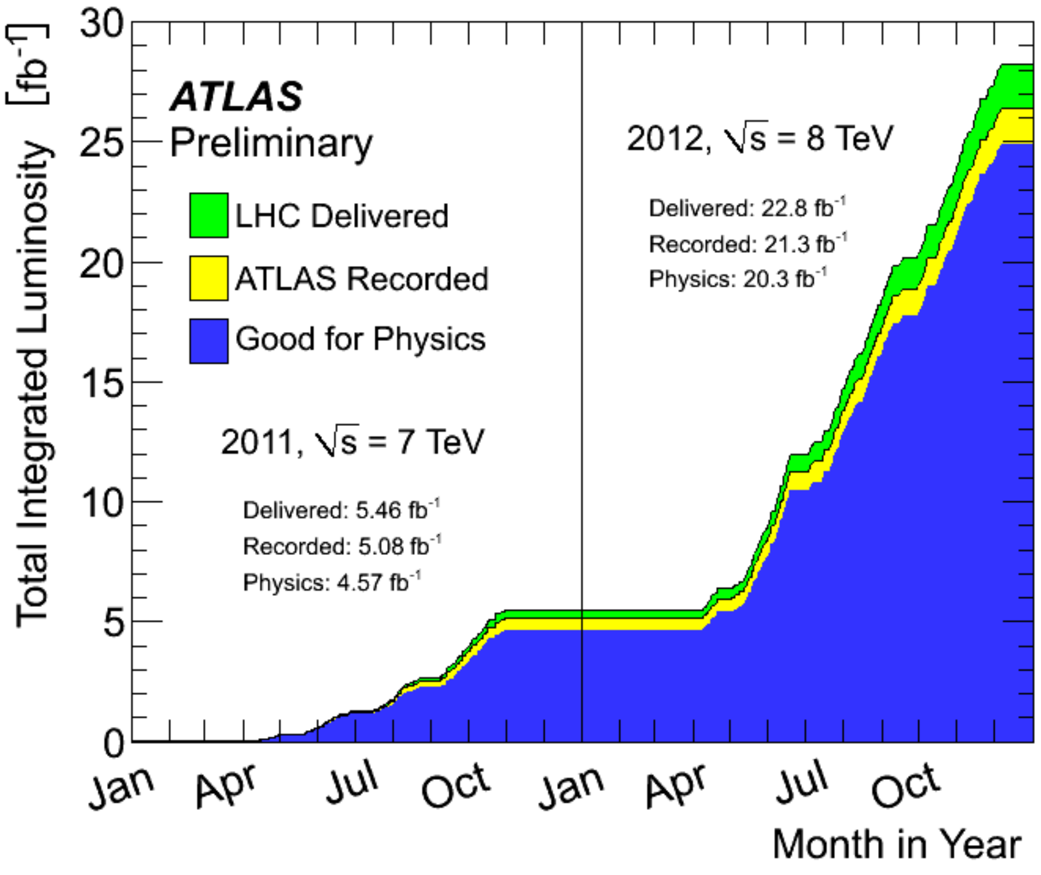
https://link.springer.com/article/10.1007/JHEP08(2012)098

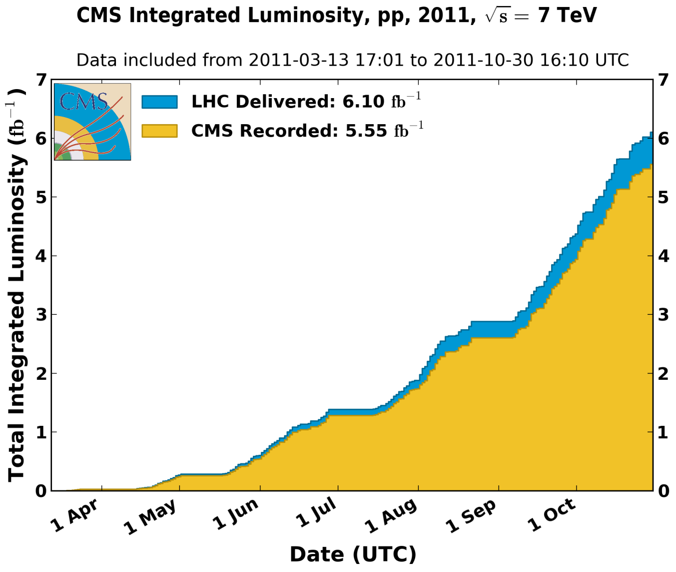


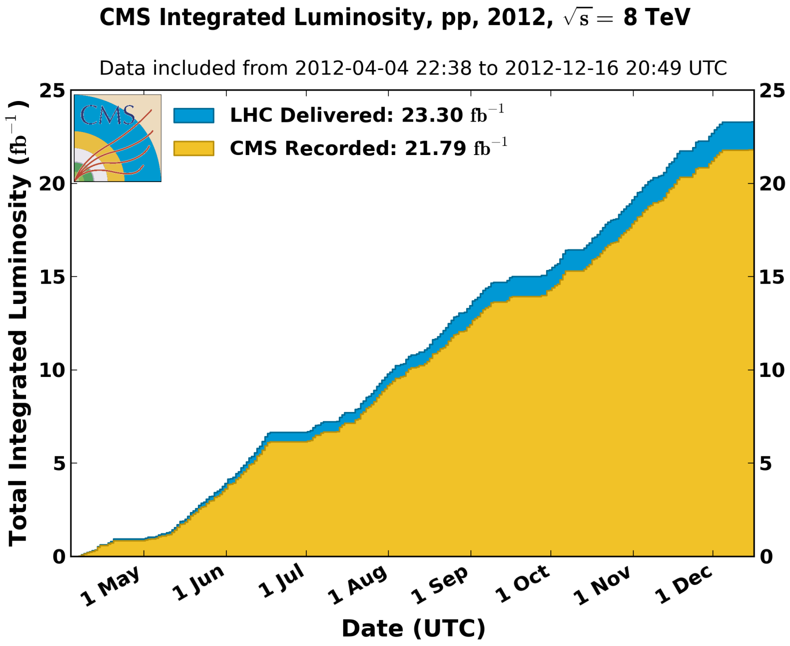
https://www.science.org/doi/10.1126/science.abk1781

Run 1

Cast your mind back to 2011-2012…







Measurement

Colour scheme:
ATLAS
CMS

Combination of "direct" measurements from Run-1 results from ATLAS and CMS.

Using **15** input measurements:

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

Measurement

This is the **first time** that a **full combination of top-quark mass** measurements from the **ATLAS and CMS** experiments has been performed.

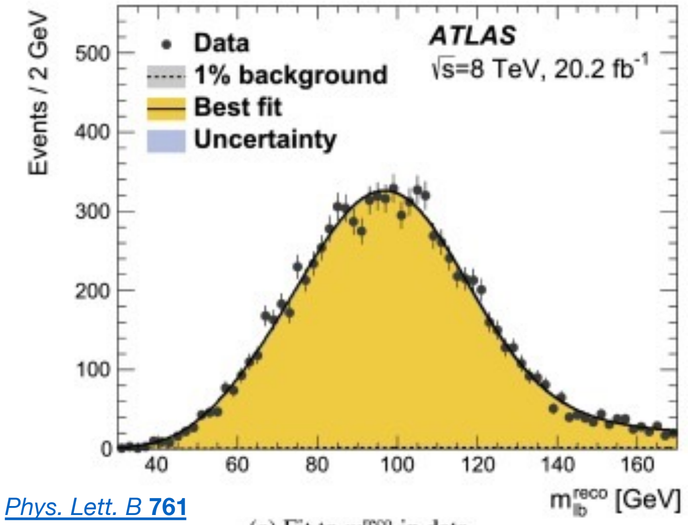
dilepton

Eur. Phys. J. C **72** (2012) 2202 *Phys. Lett. B* **761** (2016) 350 *Phys. Rev. D* **96** (2017) 032002 *Eur. Phys. J. C* **75** (2015) 330

ATLAS: minimised average m_{lb} for the observable sensitive to m_t.

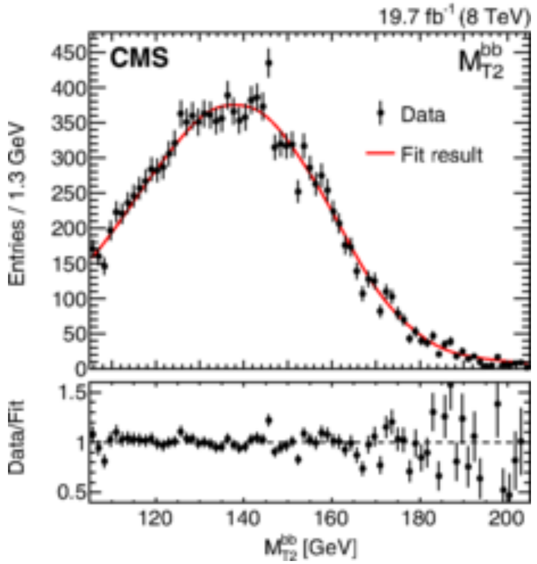
CMS: simultaneously extracted m_t and the global JES.

- Kinematic reconstruction with analytical matrix weighting technique
- A fit to the M_{bl} and M^{bb}_{T2} distributions

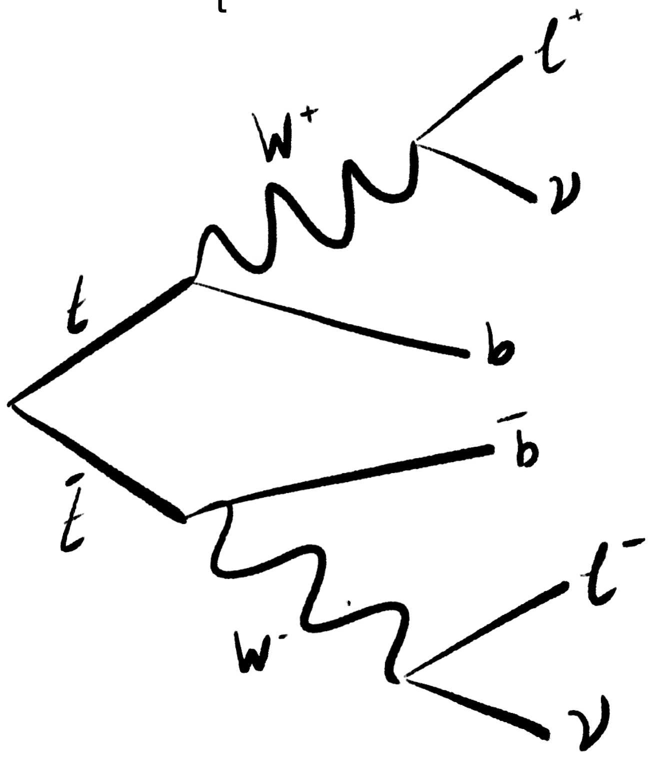


(c) Fit to $m_{\ell b}^{reco}$ in data

Phys. Lett. B **761** (2016) 350



Phys. Rev. D **96** (2017) 032002

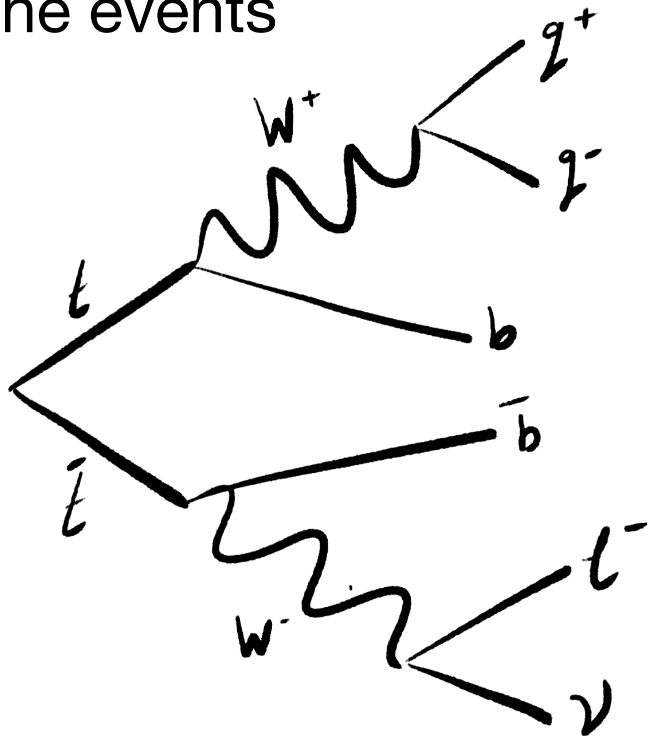


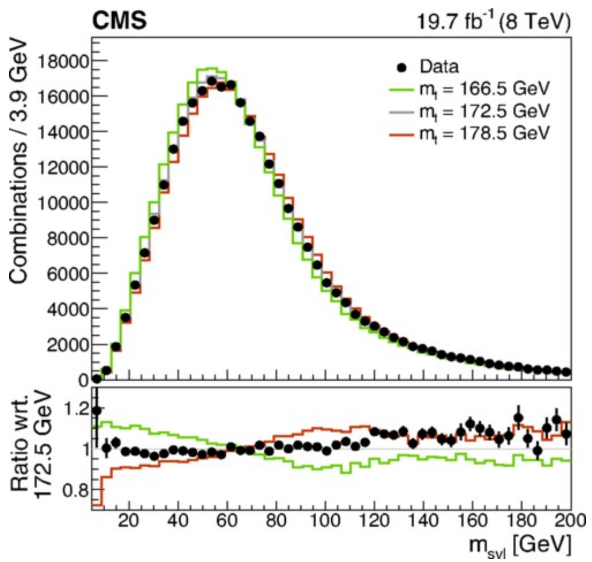
lepton +jets

[Eur. Phys. J. C **75** (2015) 330] [JHEP **12** (2012) 105] [Eur. Phys. J. C **79** (2019) 290] [Phys. Rev. D **93** (2016) 092006]

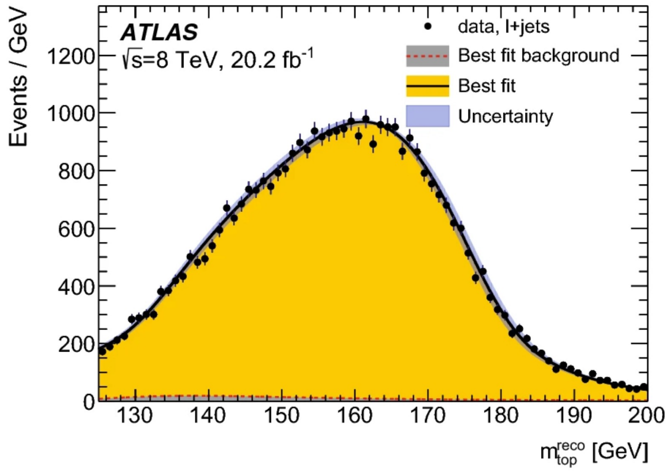
CMS and ATLAS: reconstruct m_t using a kinematic fit to the events and an additional observable measuring global JES.

ATLAS: fits a scale factor for relative JES between b and light q jets / gluons jets.





Phys. Rev. D **93** (2016) 092006



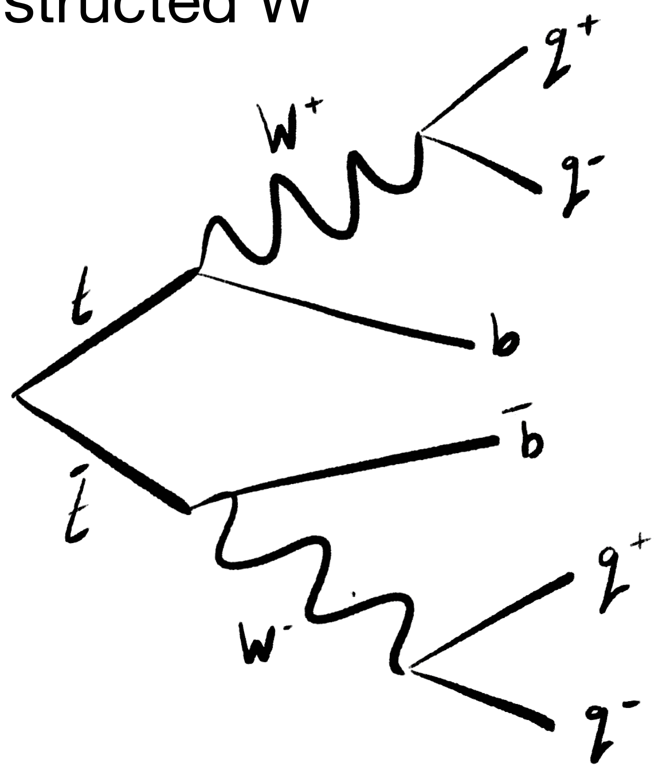
Eur. Phys. J. C **79** (2019) 290

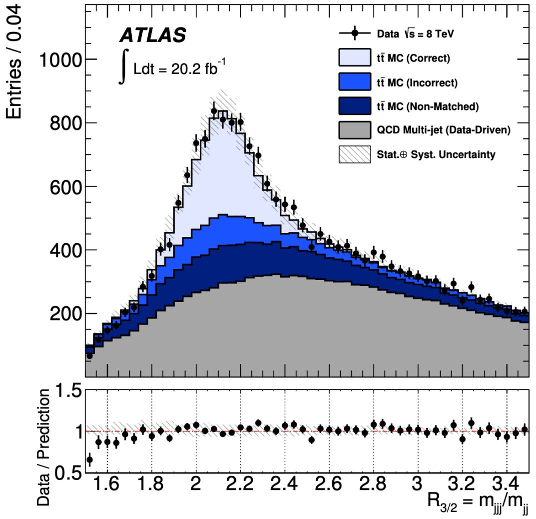
all -jets

[*Eur. Phys. J. C* **74** (2014) 2758](#) [*Eur. Phys. J. C* **75** (2015) 158](#) [*Phys. Rev. D* **93** (2016) 092006](#) [*JHEP* **09** (2017)118](#)

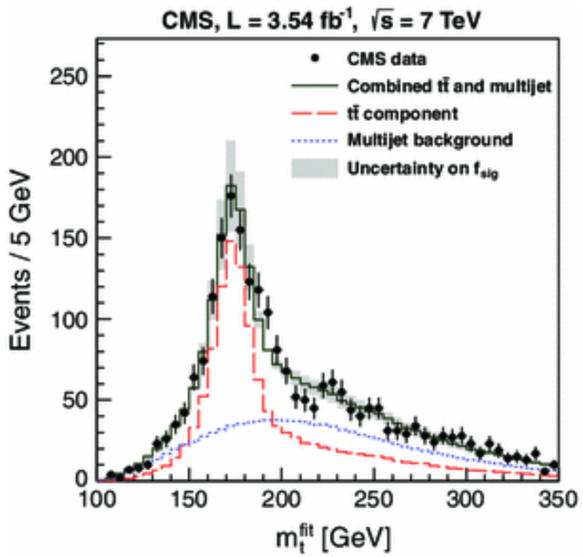
ATLAS: uses the ratio of the reconstructed m_t to the reconstructed W mass.

CMS: fits the reconstructed top mass to extract mt. The larger stats at 8 TeV allows the use of the W mass to constrain global JES.





JHEP **09** (2017)118



Eur. Phys. J. C **74** (2014) 2758

[**Single top:** *Eur. Phys. J. C* **77** (2017) 354]

[**Secondary vertex:** *Phys. Rev. D* **93** (2016) 092006]

[**J/psi:** *JHEP* **12** (2016) 123]

CMS: employs fits to invariant masses that are sensitive to m_t.

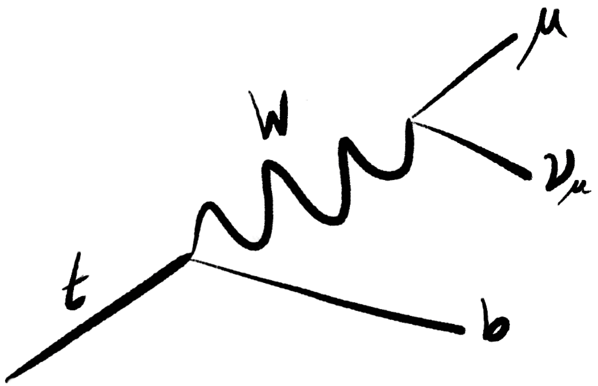
Single top (t-channel): uses invariant mass of l, ν and b-jet.

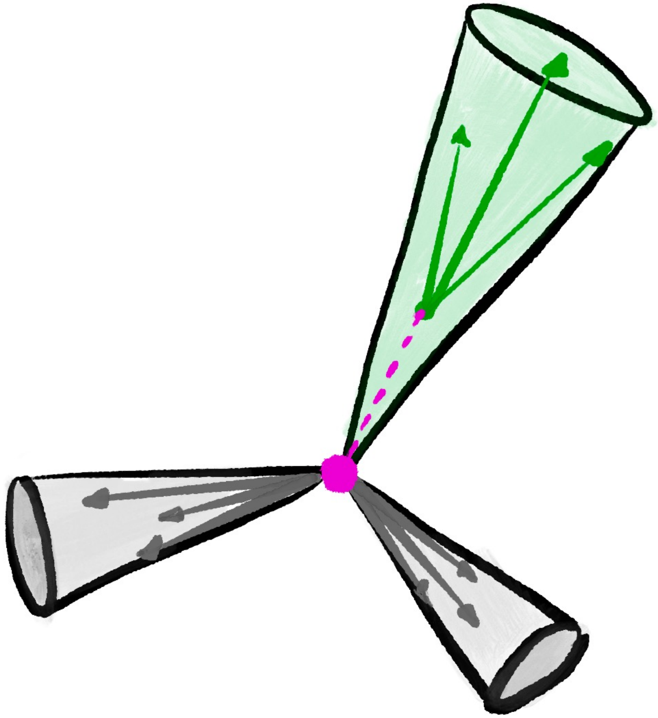
Secondary vertex: uses invariant mass of l and charged particles from a displaced secondary vertex.

- Uses all tt final states.

J/psi: uses invariant mass of the l and two μ from J/psi decay.

- Uses all tt final states and single top.





Monte Carlo

Mass measurements are done by matching to MC simulation.

- Matrix element calculations are performed at fixed order in QCD
  - interfaced to parton shower algorithm that provides resummation of soft and colinear QCD radiation
  - hadronization model that simulates non-perturbative formation of hadrons.

- Simulate tt:
  - **ATLAS**: *POWHEG* generator at NLO in the strong coupling constant is interfaced to *PYTHIA6*.
  - **CMS**: *MADGRAPH5*, which includes LO terms for tt production with up to 3 additional partons, also interfaced to *PYTHIA6*.

- Beyond LO in QCD: value of m_t depends on renormalisation scheme.

- Note: precise identification of top-quark mass parameter in MC with a field-theoretic mass scheme is the subject of theoretical studies. [*Ann. Rev. Nucl. Part. Sci* **70** (2020) 225]

SoftwareX **11** (2020) 100468

Combination

Previous combination was preliminary for world average (2013) [https://pdglive.lbl.gov/DataBlock.action?node=Q007TP]

- Didn't include most precise 8 TeV measurements.

PDG combination: cannot precisely assess the ATLAS/CMS correlations.

Best Linear Unbiased Estimator = BLUE

$$m_t = \sum w_i m^i_t, \text{ where } \sum w_i = 1$$

How to estimate correlations:

- Split systematics into sources
- Assign / assess correlations
- Sum covariance matrices

- Statistically: each measurement is orthogonal
  - Except CMS secondary vertex analysis (overlaps with dilepton & l+jets).
    - Due to diff. observables, assumed uncorrelated.
      - Tested by increasing stat. correlation to stat. overlap - no significant impact on combination.

Systematic correlations

Two types of correlations: inter- and intra-experimental.

Each measurement is mapped onto 25 categories.

- Correlations between pairs of measurements from a single experiment are determined

ATLAS: small changes made to b-tagging and pile-up corrections.

CMS: jet flavour uncertainties are correlated between flavours, but here are assumed uncorrelated to match ATLAS.

Then, the correlation strength, ρ, between ATLAS and CMS is assessed:

- **Uncorrelated: ρ = 0**
- **Partially correlated: ρ= 0.5**
- **Strongly correlated: ρ= 0.85**

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	—	—	—

Systematic correlations

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	—	—	—

Uncertainty categories can influence m_t in opposite directions.

- This effect is included via negative correlation coefficients.

For uncertainty categories composed of multiple categories (e.g. b tagging), absolute sign between ATLAS and CMS is assumed to be +ve.

- Alternative assumption (-ve) was checked and does not significantly effect the result.

Other:

- Single top quark modelling uncert. (CMS).
- Modelling of J/psi mass distribution (CMS).
- b hadron composition (CMS secondary vertex).
- Lepton reconstruction & identification (CMS 8 TeV dilepton).
- Eff. of jet reconstruction & selections used to reject jets from pile-up (ATLAS).
- Using fast simulation in ATLAS 7 TeV all-jets.

Systematic correlations

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	—	—	—

Statistical and other uncorrelated components of JES

Light flavour uncertainties approach different for ATLAS and CMS

Correlation from reliance on MC for flavour composition in the tt calibration samples

Different JES calibrations, but sensitive to same MC modelling of radiation

similar MC comparisons (Pythia v Herwig)

No large changes in central value.

ATLAS+CMS Preliminary

$\sqrt{s}$=7,8 TeV

	ATLAS dil 7 TeV	ATLAS lj 7 TeV	ATLAS aj 7 TeV	ATLAS dil 8 TeV	ATLAS lj 8 TeV	ATLAS aj 8 TeV	CMS dil 7 TeV	CMS lj 7 TeV	CMS aj 7 TeV	CMS dil 8 TeV	CMS lj 8 TeV	CMS aj 8 TeV	CMS t 8 TeV	CMS J/Ψ 8 TeV	CMS vtx 8 TeV
ATLAS dil 7 TeV	1.00	-0.07	0.42	0.51	0.06	0.07	0.13	0.22	0.11	0.18	0.23	0.13	0.10	-0.06	-0.15
ATLAS lj 7 TeV	-0.07	1.00	-0.01	0.00	-0.07	-0.02	0.09	0.08	0.03	0.08	0.04	0.01	0.10	0.02	-0.04
ATLAS aj 7 TeV	0.42	-0.01	1.00	0.29	-0.06	0.00	0.11	0.19	0.11	0.13	0.21	0.16	0.09	-0.01	-0.04
ATLAS dil 8 TeV	0.51	0.00	0.29	1.00	-0.18	0.31	0.09	0.16	0.08	0.12	0.16	0.10	0.07	-0.04	-0.10
ATLAS lj 8 TeV	0.06	-0.07	-0.06	-0.18	1.00	-0.03	0.02	-0.00	-0.00	-0.04	0.05	-0.03	0.03	-0.01	0.00
ATLAS aj 8 TeV	0.07	-0.02	0.00	0.31	-0.03	1.00	0.10	0.11	0.06	-0.01	0.14	0.08	0.07	0.01	0.10
CMS dil 7 TeV	0.13	0.09	0.11	0.09	0.02	0.10	1.00	0.31	0.57	0.31	0.46	0.36	0.26	0.08	0.13
CMS lj 7 TeV	0.22	0.08	0.19	0.16	-0.00	0.11	0.31	1.00	0.53	0.10	0.41	0.45	0.29	-0.03	0.03
CMS aj 7 TeV	0.11	0.03	0.11	0.08	-0.00	0.06	0.57	0.53	1.00	0.12	0.34	0.35	0.21	-0.03	0.07
CMS dil 8 TeV	0.18	0.08	0.13	0.12	-0.04	-0.01	0.31	0.10	0.12	1.00	0.23	0.07	0.09	-0.04	-0.16
CMS lj 8 TeV	0.23	0.04	0.21	0.16	0.05	0.14	0.46	0.41	0.34	0.23	1.00	0.70	0.48	0.06	0.15
CMS aj 8 TeV	0.13	0.01	0.16	0.10	-0.03	0.08	0.36	0.45	0.35	0.07	0.70	1.00	0.47	0.05	0.22
CMS t 8 TeV	0.10	0.10	0.09	0.07	0.03	0.07	0.26	0.29	0.21	0.09	0.48	0.47	1.00	-0.01	0.08
CMS J/Ψ 8 TeV	-0.06	0.02	-0.01	-0.04	-0.01	0.01	0.08	-0.03	-0.03	-0.04	0.06	0.05	-0.01	1.00	0.12
CMS vtx 8 TeV	-0.15	-0.04	-0.04	-0.10	0.00	0.10	0.13	0.03	0.07	-0.16	0.15	0.22	0.08	0.12	1.00

Results

per experiment

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

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

Result similar to *Eur. Phys. J. C* **79** (2019) 290, with slight difference from change in correlation assumption for b-tagging and pile-up uncertainties.

- Correlation assumption for b-tagging algorithm between all-jets and l+jets/dilepton changed from +1 to 0
  - Due to different algorithm & calibration method used.
- Correlation assumption for pile-up between all channels at same E changed from 0 to +1.
  - Due to common modelling of the pile-up.
- Correlation for pile-up for different E is 0.

Result is improved compared to previous combination.

Improvements come from including:

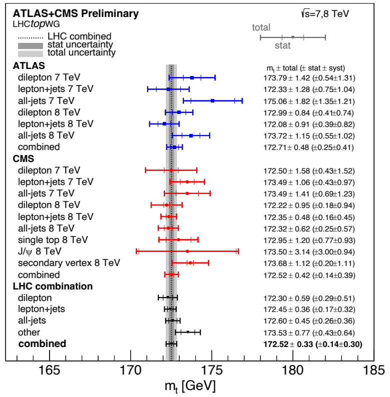
- a more precise 8 TeV dilepton measurement,
- the single top, secondary vertex and J/psi measurements,
- the effect of anticorrelations in systematic uncertainties between input measurements.

Results

Combination of all ATLAS and CMS measurements

m_t = 172.52 ± 0.14 (stat) ± 0.30 (syst) GeV

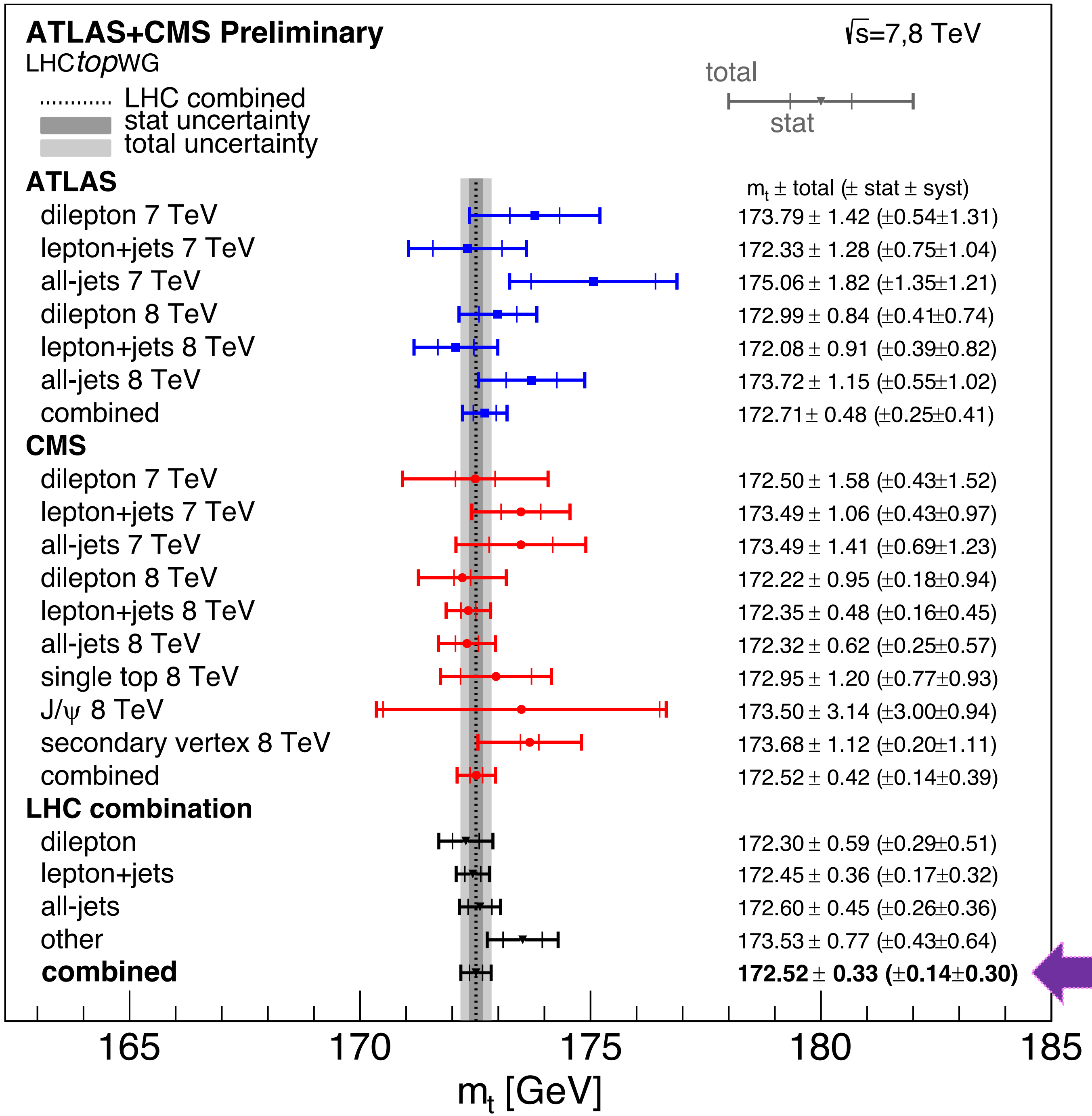
m_t = 172.52 ± 0.33 GeV

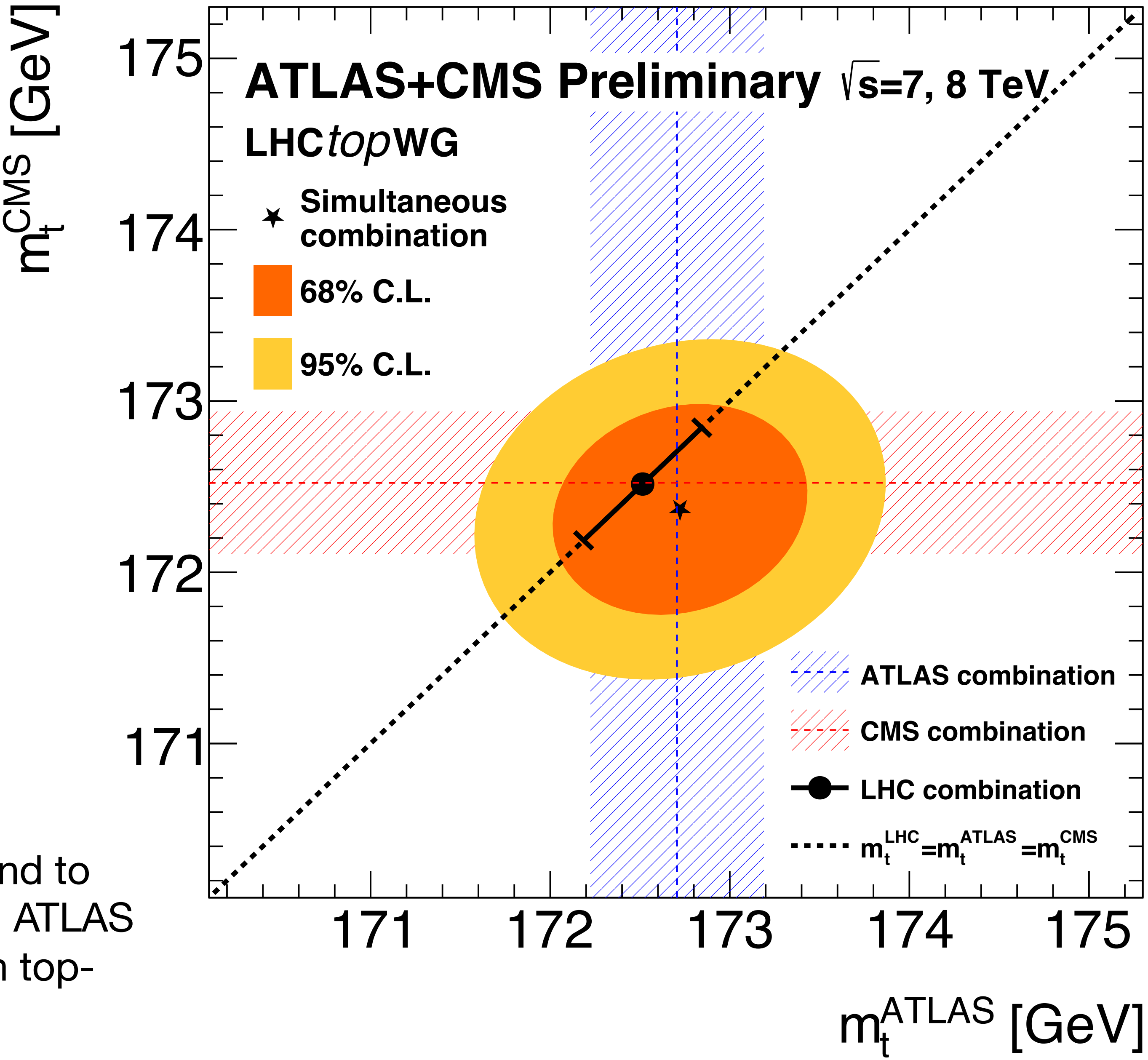


The most precise m_t result to date

- **Consistency checks** were performed using different top mass per decay channel
- **Impact of the stat. precision of the estimates of the syst. uncert.** evaluated using pseudo-experiments varying systs by uncertainties and combining.
    - RMS of m_t (σ_{mt}) is found to be 63 (19) MeV -> **stability of the combination.**

Uncertainty category	Uncertainty impact [GeV] LHC	ATLAS	CMS
LHC b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
LHC JES 1	0.08	0.18	0.06
LHC JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS B hadron BR	0.07	—	0.12
LHC radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
Top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
LHC g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
LHC l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
LHC JES 3	0.02	0.07	0.01
LHC hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematics	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42



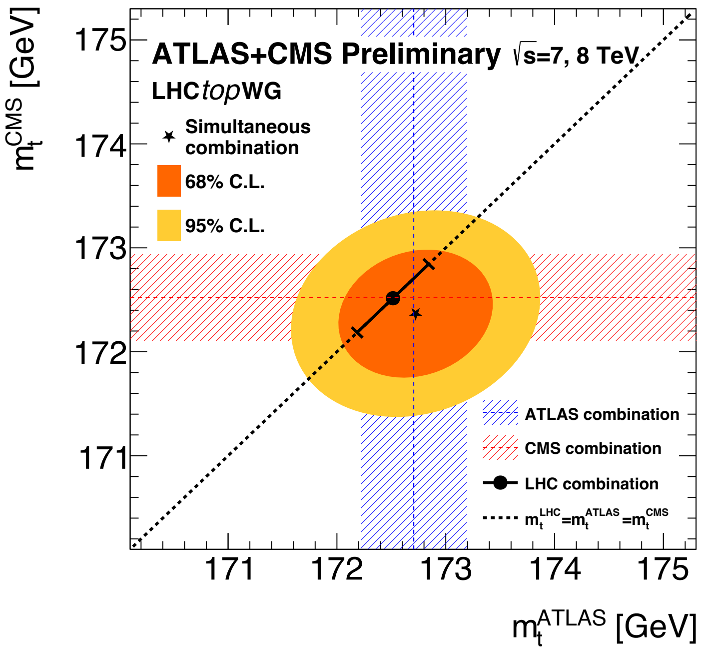


Measurements are found to be consistent between ATLAS and CMS and between top-pair decay channels.

The present

m_t = 172.52 ± 0.14 (stat) ± 0.30 (syst) GeV

Systematically limited with main uncertainties seen to be coming from JES, b-tagging, and $t\bar{t}$ modelling.



The future

The understanding of top quark production has continued to evolve.

Additional data has been collected at 13 and 13.6 TeV, and developments in simulations and in analysis techniques continue.

Larger datasets allow us to use this to further improve the experimental uncertainties.

Note: Advancements may either increase or decrease the mass uncertainty.

thank you!

Backup

Here's one I prepared earlier

Cross-check: modelling recoil to top

The understanding of top quark production has continued to evolve.

- Developments in simulations:
  - Improved modelling of off-shell effects.
  - Reduced uncertainties in additional QCD radiation.
  - New models of colour reconnection.
  - MC simulations at NNLO precision in QCD.
  - Investigations into the radiation patterns in the top-quark decay.

- **Note:** Advancements may either increase or decrease the mass uncertainty.

- Improvements in analysis techniques for Run 2+.

Weights

Table A.4: Pulls and weights of each input measurement in the LHC combination.

	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

Table A.5: Weights for each input measurement for the simultaneous combination of the four different channels. The CMS alternative measurements are assigned to the "other" channel.

	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
ll	+0.02	+0.03	−0.07	+0.55	+0.18	−0.08	+0.10	−0.02	−0.07	+0.33	−0.19	+0.22	−0.08	<0.01	+0.08
lj	−0.04	+0.09	+0.01	+0.09	+0.18	+0.03	−0.10	+0.03	+0.03	+0.05	+0.71	−0.06	−0.06	+0.01	+0.06
aj	−0.03	+0.08	+0.05	+0.04	+0.17	+0.15	−0.13	−0.13	+0.13	+0.12	−0.12	+0.67	−0.05	+0.01	+0.04
other	+0.02	+0.05	+0.03	+0.02	+0.12	+0.04	−0.18	−0.04	+0.10	+0.14	−0.12	−0.18	+0.46	+0.05	+0.49

The future

The understanding of top quark production has continued to evolve.

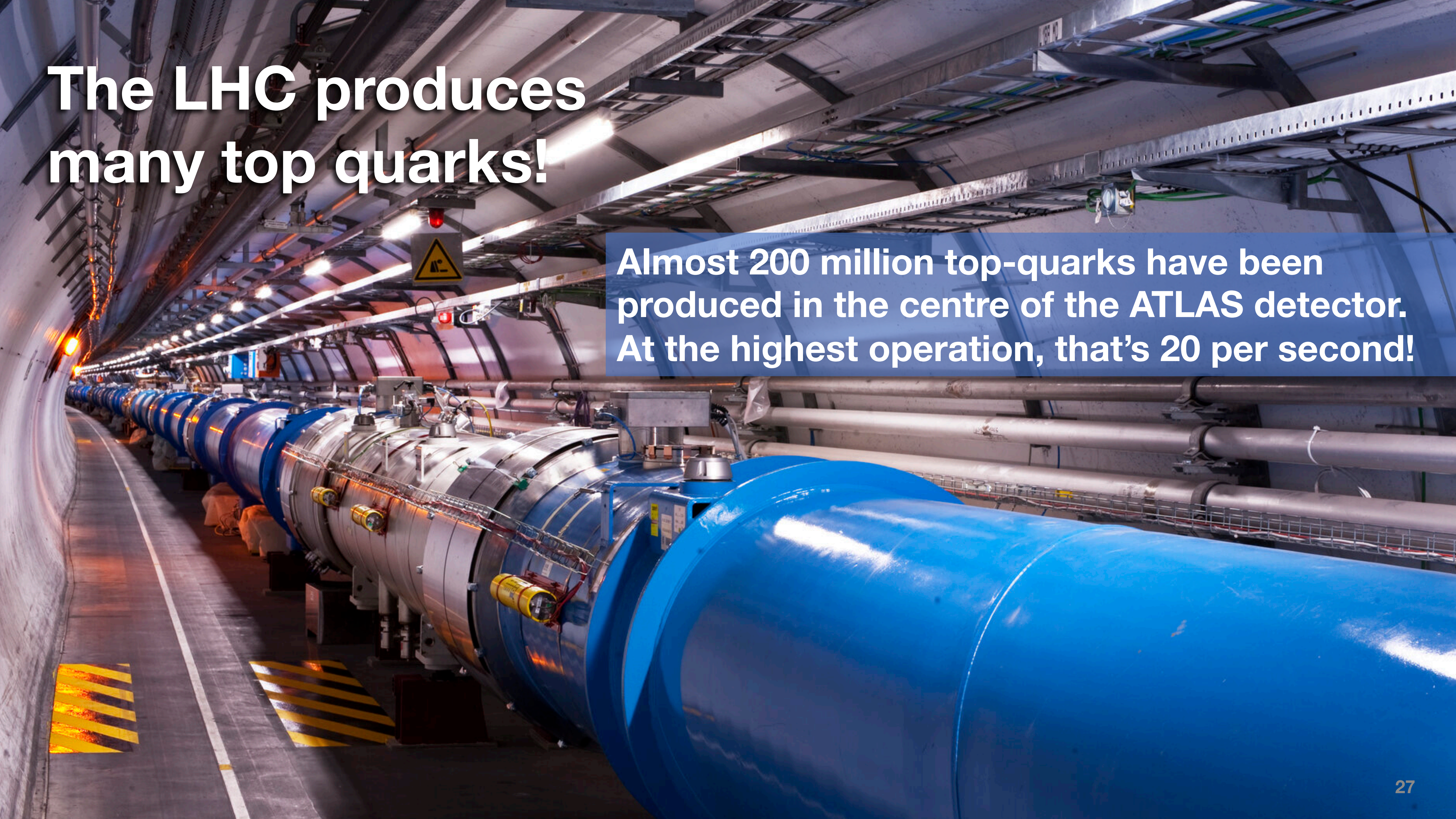
- Developments in simulations:
  - Improved modelling of off-shell effects.
  - Reduced uncertainties in additional QCD radiation.
  - New models of colour reconnection.
  - MC simulations at NNLO precision in QCD.
  - Investigations into the radiation patterns in the top-quark decay.

- **Note:** Advancements may either increase or decrease the mass uncertainty.

- Improvements in analysis techniques for Run 2+.

* Cross-check was performed to verify that potential modelling uncertainties in recoil to the top-quark decay do not significantly affect the combination.

The LHC produces many top quarks!



Almost 200 million top-quarks have been produced in the centre of the ATLAS detector. At the highest operation, that’s 20 per second!