Andrea Castro
- University of Bologna and INFN -

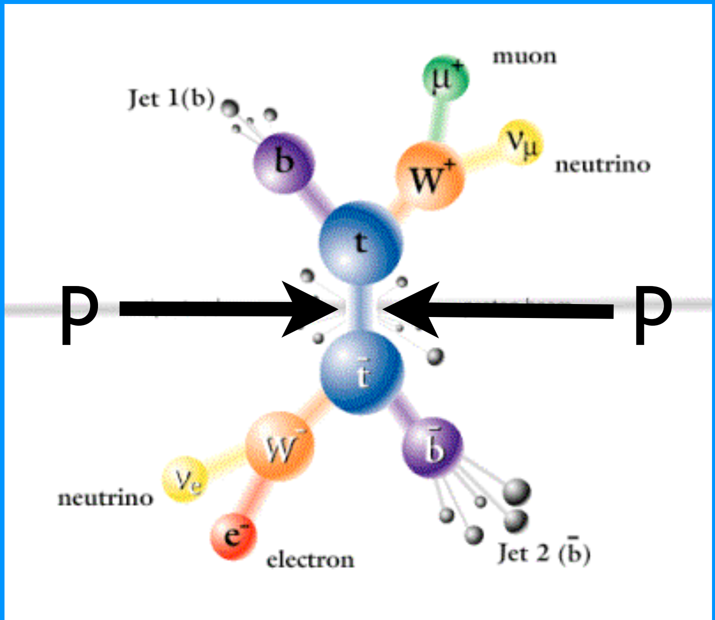
Top Quark Mass measurements at the LHC - standard methods -

***On behalf of ATLAS and CMS** collaborations*

TOP2015 - Ischia

The top quark at LHC

$pp \rightarrow t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$



Physics objects:

- isolated energetic e or μ
- energetic jets
- b-tagged jets
- momentum imbalance (MET)

- LHC is a top factory (≈5 million pairs per experiment in 2012), each **t** decays ≈100% to W+b
- Characterized by leptons from W decays:

  2 ⇒ dilepton: DIL, BR(DIL)≈5%, low yield, high purity

  1 ⇒ lepton + jets: LJ, BR(LJ)≈30%, golden channel, good yield and good S/B

  0 ⇒ all-jets: AJ, BR(AJ)≈45%, max yield, large bkgd

- + single top EWK production

All of them useful for completeness and with (some) uncorrelated systematics

Why measure M_t ?

1) M_t free parameter of SM

- measurement strongly pursued in past 20 years

*Indeed **t** is the most accurately measured quark (better than 0.5% - 2014 world average)*

- **t** decays well before hadronizing ⇒ measure M_t directly from decay products

We compare to Monte Carlo expectations, so what we really measure is M_t^{MC} parameter.

For theoretical interpretations see G. Corcella's talk

Why measure M_t ?

2) Participates in quantum loop radiative corrections to M_W together with M_H

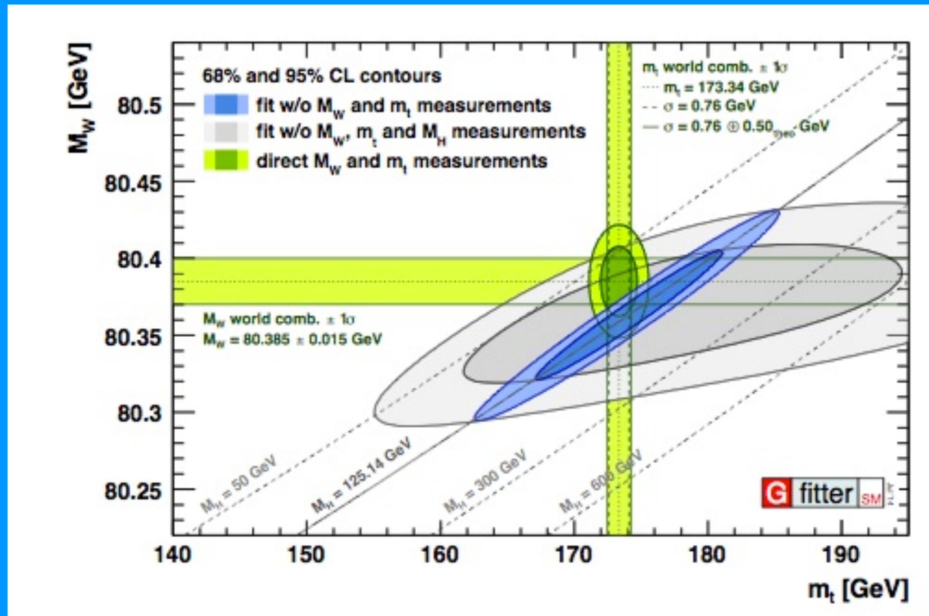
⇒ assessment of self-consistency within SM

EPJC 74 (2014) 3046, arXiv:1407.3792

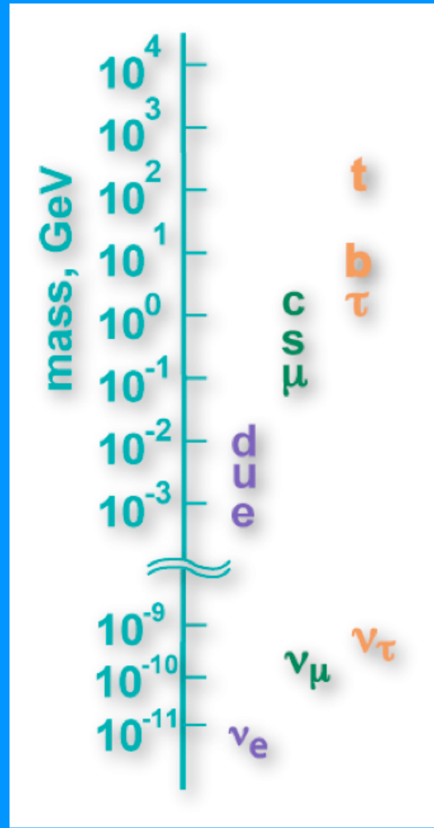
$$\Delta M_W \propto M_t^2$$

$$\Delta M_W \propto \ln M_H$$

M_W vs M_t correlations not shown

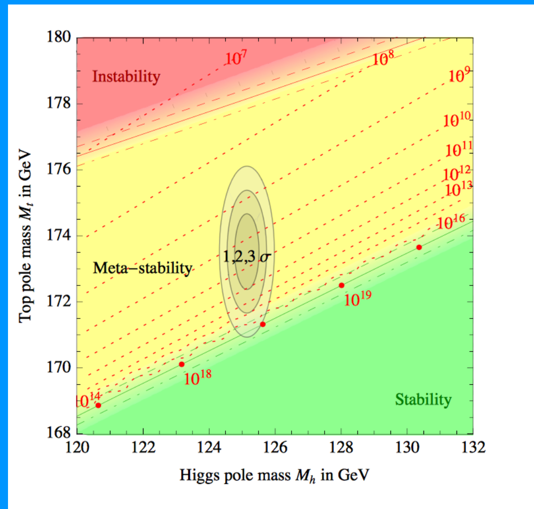


Why measure M_t ?



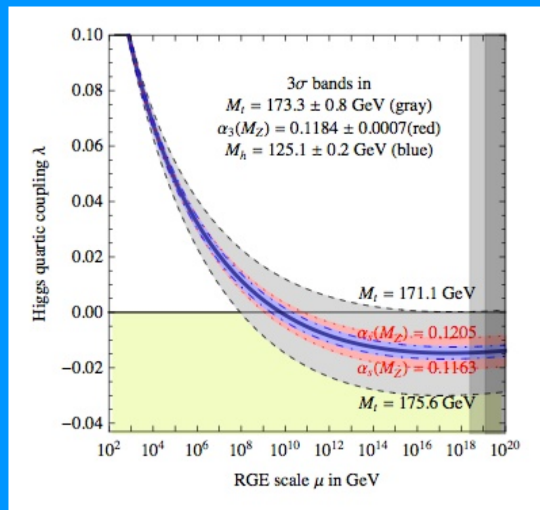
3) M_t is close to scale of EWSB, so **t** might play a special role, or in new physics like topcolor models for EW dynamical breaking

4) M_t related with M_H and vacuum stability of SM (and of Universe): near criticality of M_H



[arXiv:1307.3536]

When λ becomes negative, Higgs potential becomes unbounded from below



See J. Espinosa's talk

[arXiv:1307.3536]

Measuring M_t

M_t measurement:

- different techniques with complementary features
- starting point: reconstruction of

$$pp \rightarrow t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$$

Important issues:

– choice of final state topology

– event selection

– mapping of physics objects to leptons/quarks in LO final state (combinatorial ambiguities)

– dependence on detector modeling (e.g. energy calibration)

– unknown quantities (neutrino p_z or the sharing of MET between multiple ν's) → underconstrained kinematics for DIL channel

Methods for measuring M_t

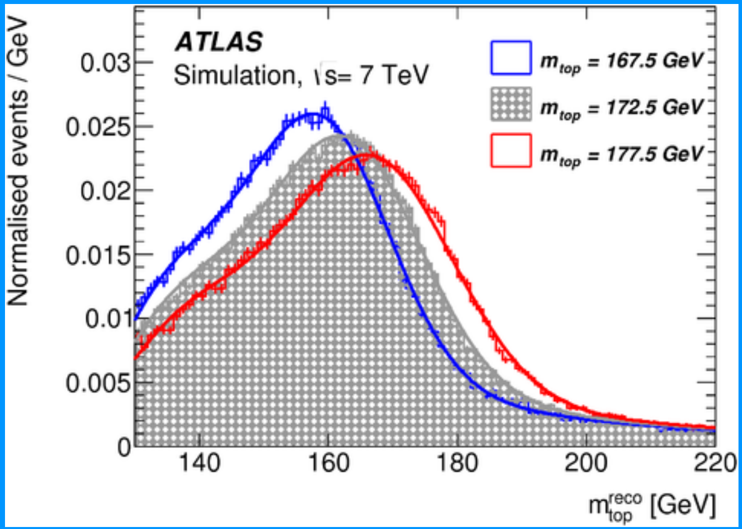
1) *Template method:* distributions of variables sensitive to M_t, e.g., reconstructed M_t^{reco} from χ^2 fit to WbWb

Pdf's derived for MC events assuming different M_t^{MC}; parametrized vs M_t

Likelihood from pdf's; outcome calibrated for biases (pull-mean and pull-width of pseudo-experiments)

M_W templates for in-situ calibration of JES

Possible to add constraints on b-jet JES



Relatively simple, fast, but non optimal statistical uncertainty

Methods for measuring M_t

2) *Ideogram method:* modification of template method using multiple permutations with different weights

Starts from kinematical reconstruction, then computes event likelihood as a function of M_t

Different pdf's used for different jet-quark assignments

Event likelihoods (ideograms) are given by

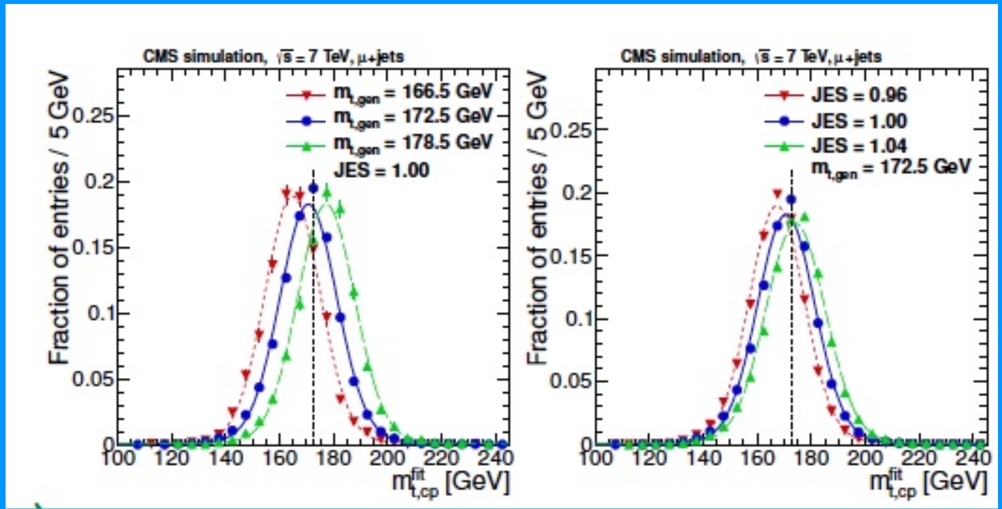
$$\mathcal{L}\left(\text{event}|m_t,\text{JSF}\right) = \sum_{i=1}^{n} P_{\text{gof}}\left(i\right)\left\{f_{\text{sig}}P_{\text{sig}}\left(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}}|m_t,\text{JSF}\right) + \left(1-f_{\text{sig}}\right)P_{\text{bkg}}\left(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}}\right)\right\}$$

$P_{gof}=\exp(-\chi^2/2)$

$$\mathcal{L}\left(\text{sample}|m_t,\text{JSF}\right) = \prod_{\text{events}} \mathcal{L}\left(\text{event}|m_t,\text{JSF}\right)^{w_{\text{event}}}$$

$w_{event}=\sum P_{gof}(i)$

$P_{sig}^{cp}(m_t^{fit}|M_t,JSF)$



Methods for measuring M_t

3) *Analytical Matrix Weighting technique:* (used for DIL)
- a given M_t used to constrain the $t\bar{t}$ system (1 GeV increments in range 100-600 GeV)
- inferring p^{ν} from MET and assuming values for unobserved quantities
- multiple solutions for each assignment, and weights assigned to solutions

The mass with highest sum weight becomes the mass estimator (AMWT mass)

Templates are built from the AMWT mass

... and then there are alternative methods, see talk by M. Vos

Systematic uncertainties

Statistical uncertainties becoming smaller and smaller
⇒ systematic uncertainties become dominant

Different sources of systematics, related to:
- Experimental effects
- Signal modeling
- Background modeling
- Features of the method

For every source, measurements performed (usually with pseudo-experiments) with modified parameters; change of M_t ⇒ syst. uncertainty

Systematic uncertainties

Experimental *(i.e. imperfect knowledge of)*:
- Jet Energy Scale (JES)
- b-Jet Energy Scale (bJES)
- jet energy resolution and reconstruction
- MET scale
- b-tagging scale factor
- lepton energy scale and reconstruction
- pileup
- trigger

Signal modeling *(i.e. imperfect knowledge of theory regarding)*:
- MC generator
- hadronization
- amount of ISR/FSR
- flavor-dependent hadronization
- b-quark fragmentation and BRs
- renormaliz./factoriz. scales
- PDF's
- Color reconnection
- Underlying event

Background modeling *(i.e. uncertainty on)*:
- MC normalization and shape
- normalization and shapes of data-driven backgrounds

Features of the method *(i.e. dependence on)*:
- parametrization of pdf's
- calibration
- MC statistics

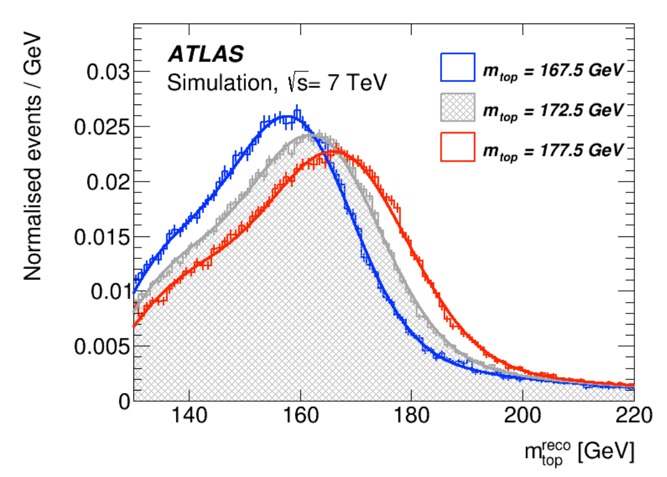
Agreement between ATLAS and CMS is essential

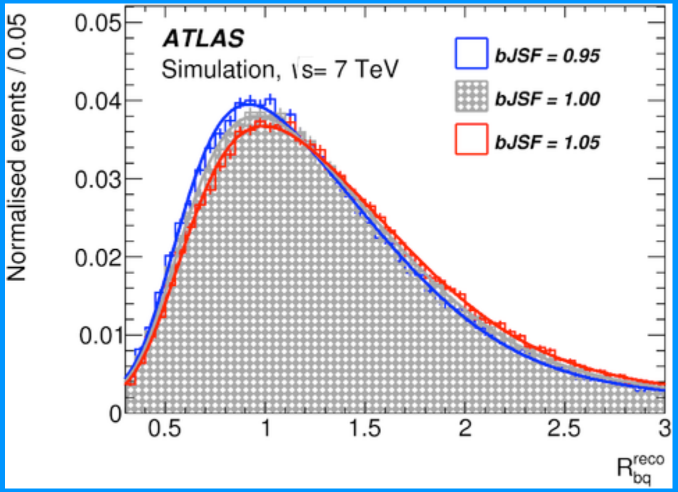
See A. Maier's talk

M_t with ATLAS: lepton + jets

3D *Template* (m_t^{reco}, m_W^{reco}, R_{bq})
also *in situ bJSF* ! (7 TeV, 4.6 fb^{-1})

EPJC 75 (2015) 330,
arXiv:1503.05427





$$R_{bq}^{reco,1b} = \frac{p_T^{b_{tag}}}{(p_T^{W_{jet_1}} + p_T^{W_{jet_2}})/2}$$

$$R_{bq}^{reco,2b} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{W_{jet_1}} + p_T^{W_{jet_2}}}$$

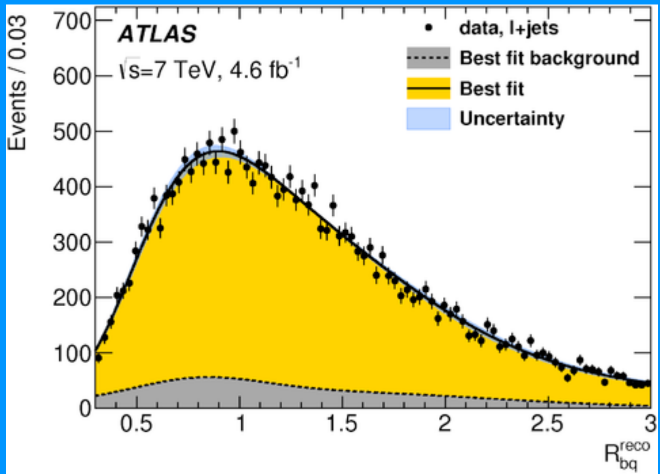
m_t^{reco} strongly depends on bJSF (i.e. residual difference between light-jets and b-jets, after JES corrections)

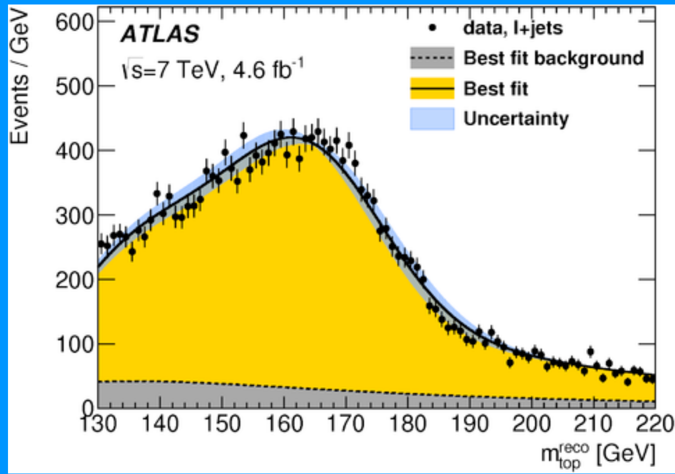
Large systematic uncertainty unless bJSF calibrated in-situ
Calibration based on R_{bq} i.e. b/W p_T balance

M_t with ATLAS: lepton + jets

3D *Template* (m_t^{reco}, m_W^{reco}, R_{bq})
w. in situ JSF and bJSF (7 TeV, 4.6 fb^{-1})

EPJC 75 (2015) 330,
arXiv:1503.05427





syst	GeV
JES	0.58
b-tagging	0.50
ISR/FSR	0.32

M_t=172.33±0.75(stat)±1.02(syst) GeV

M_t=172.33±1.27 GeV (±0.73%)

ATLAS single best measurement!

JSF=1.019±0.003(stat)

bJSF=1.003±0.008(stat)

M_t with CMS: lepton + jets

Ideogram method (m_t^{reco}, m_W^{reco})
w. in situ JSF (8 TeV, 19.7 fb^{-1})

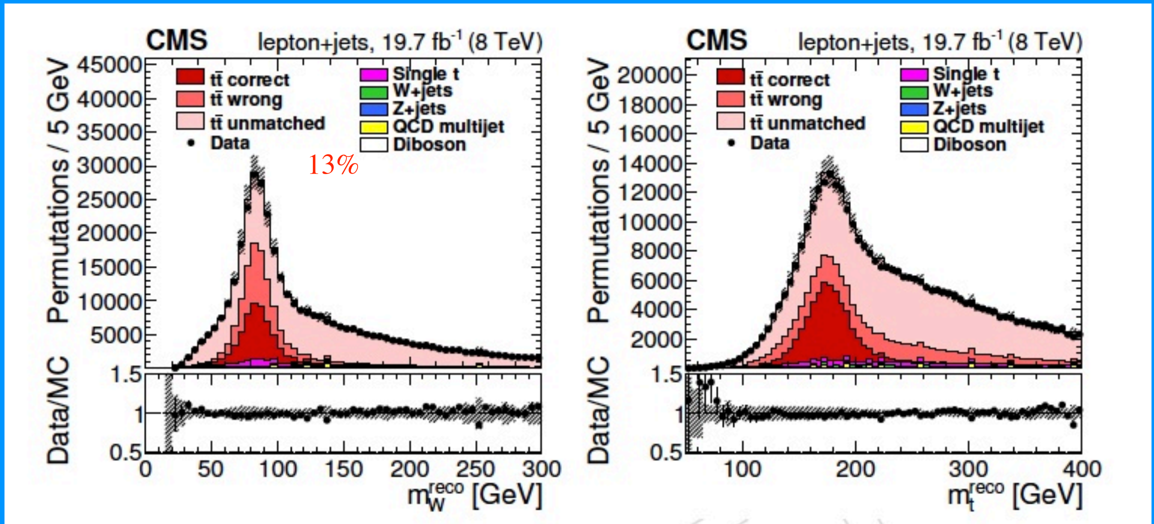
Submitted to PRD

arXiv:1509.04044

NEW

Possible combinations treated separately:

- correct: 4 jets match the 4 quarks correctly
- wrong: wrong permutation
- unmatched: at least one quark does not match any jet



- 2D or 1D fit: w. or w/o JSF calibration

- Hybrid fit: JSF with Gaussian constraint incorporating JES prior knowledge

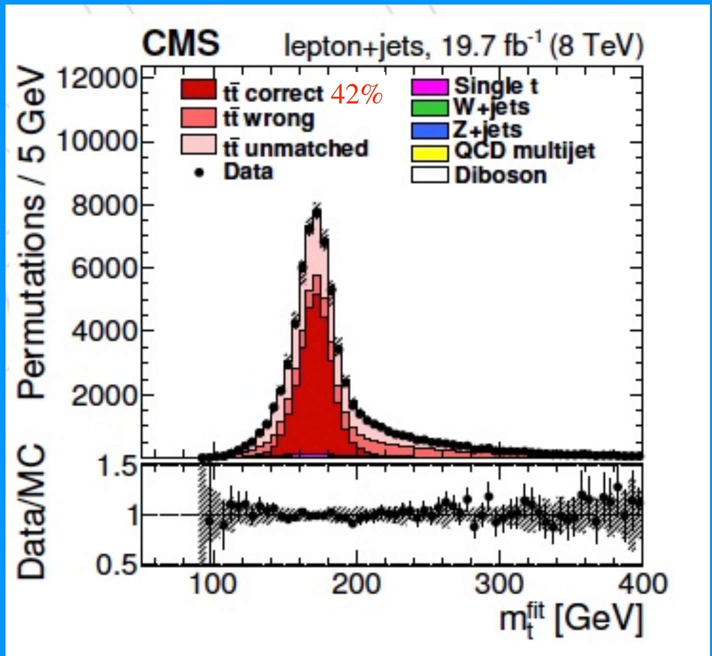
M_t with CMS: lepton + jets

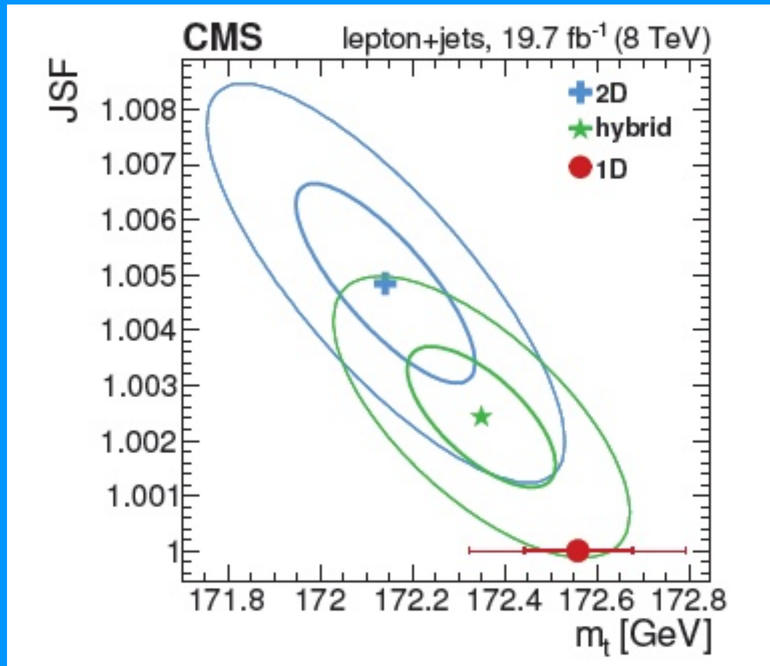
Ideogram method (m_t^{reco}, m_W^{reco})
w. in situ JSF (8 TeV, 19.7 fb^{-1})

Submitted to PRD

arXiv:1509.04044

NEW





syst	GeV
bJES	0.32
ME generator	0.12
underlying evt	0.11

Hybrid fit

M_t=172.35±0.16(stat+JSF)±0.48(syst) GeV

M_t=172.35±0.51 GeV (±0.29%)

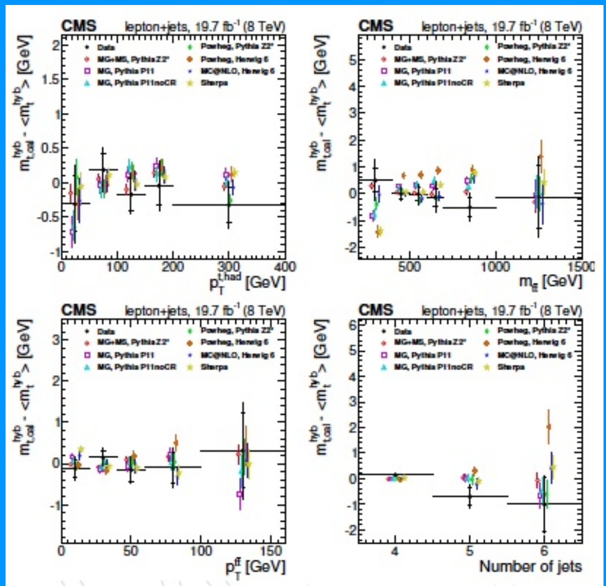
CMS single best measurement!

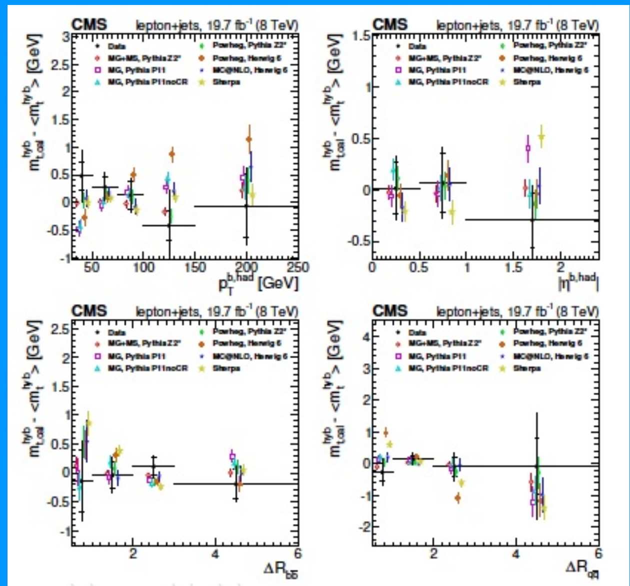
weighting by $P_{gof}=\exp(-\chi^2/2)$

$P_{gof}=\exp(-\chi^2/2)>0.2$

M_t with CMS: lepton + jets

Ideogram method (m_t^{reco}, m_W^{reco})
w. in situ JSF (8 TeV, 19.7 fb^{-1})





Submitted to PRD

arXiv:1509.04044

NEW

Simulation	χ^2	Standard deviations
MG + PYTHIA 6 Z2*	17.55	0.10
MG + PYTHIA 6 P11	37.68	1.73
MG + PYTHIA 6 P11noCR	31.57	1.15
POWHEG + PYTHIA 6 Z2*	19.70	0.20
POWHEG + HERWIG 6	76.48	4.84
MC@NLO + HERWIG 6	20.47	0.24
SHERPA	46.79	2.56

ndof=27

Kinematic quantities sensitive to modeling
comparison of differential measurements
with simulations, looking for biases

data well described by models
possible exception
POWHEG+HERWIG

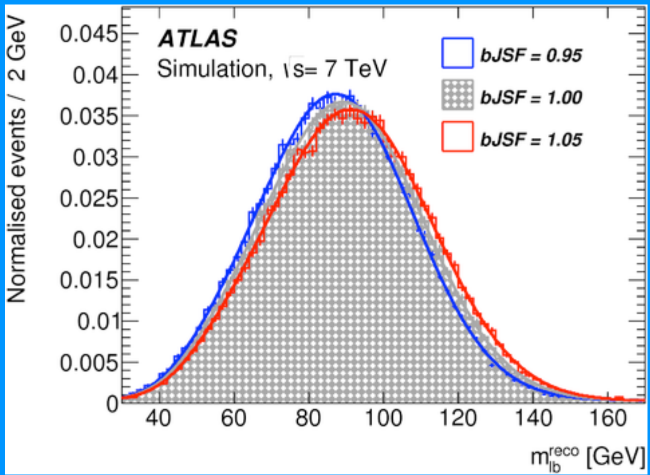
M_t with ATLAS: dilepton

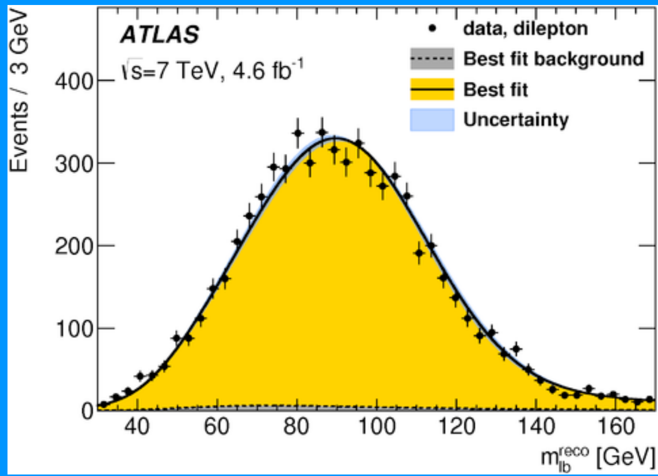
Template ($m_{\ell b}$)

(7 TeV, 4.6 fb^{-1})

EPJC 75 (2015) 330,

arXiv:1503.05427





syst	GeV
JES	0.75
bJES	0.68
hadronization	0.53

Underconstrained so the M_t-sensitive quantity is the ℓ-b invariant mass

M_t=173.79±0.54(stat)±1.30(syst) GeV

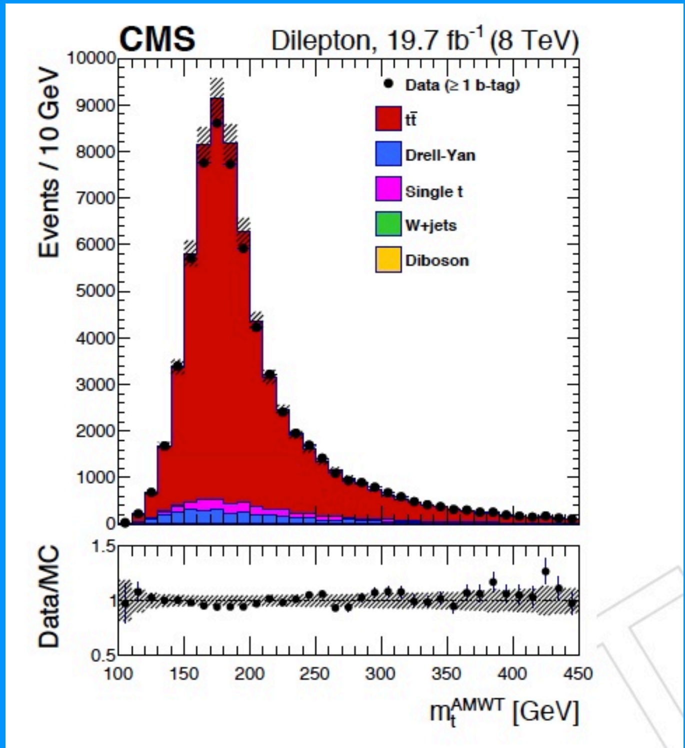
M_t=173.79±1.41 GeV (±0.81%)

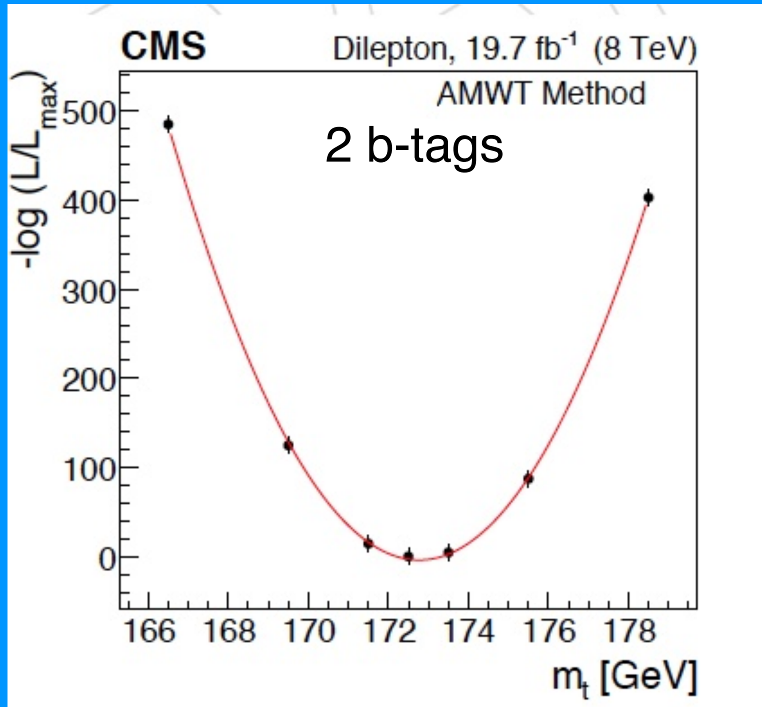
M_t with CMS: dilepton

AMWT method
(8 TeV, 19.7 fb^{-1})

Submitted to PRD
arXiv:1509.04044

NEW





syst	GeV
scales	0.75
b-frag	0.69
bJES	0.34

data (≥1 b-tag) well described by simulations

M_t=172.82±0.19(stat)±1.22(syst) GeV

M_t=172.82±1.23 GeV (±0.71%)

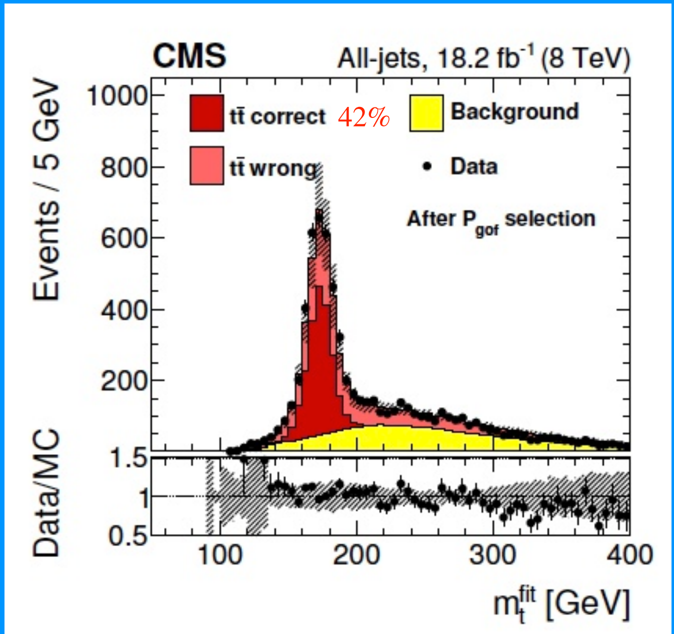
M_t with CMS: all-jets

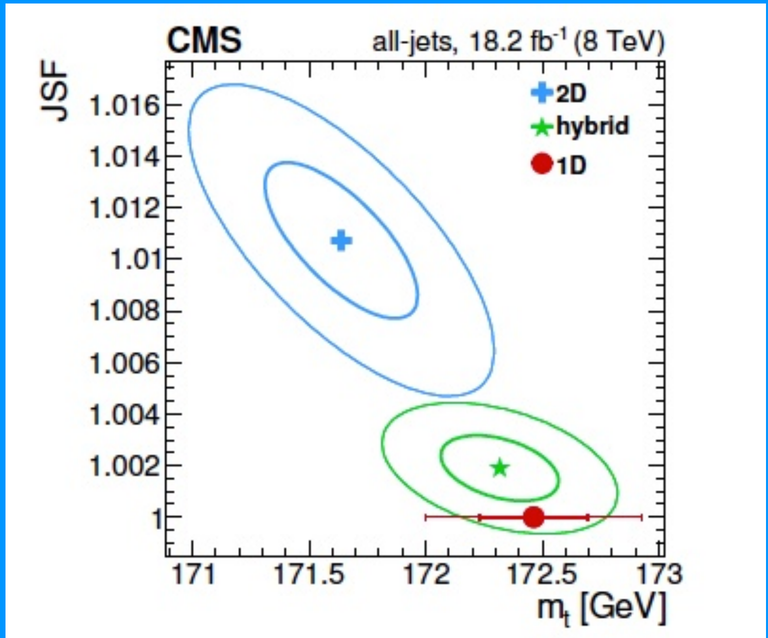
Ideogram method (m_t^{reco}, m_W^{reco})
w. in situ JSF (8 TeV, 18.2 fb^{-1})

Submitted to PRD

arXiv:1509.04044

NEW





syst	GeV
bJES	0.29
JES	0.26
bckgd	0.20

- $P_{gof}=\exp(-\chi^2/2)>0.1$
- $\Delta R(bb)>2.0$

Hybrid fit

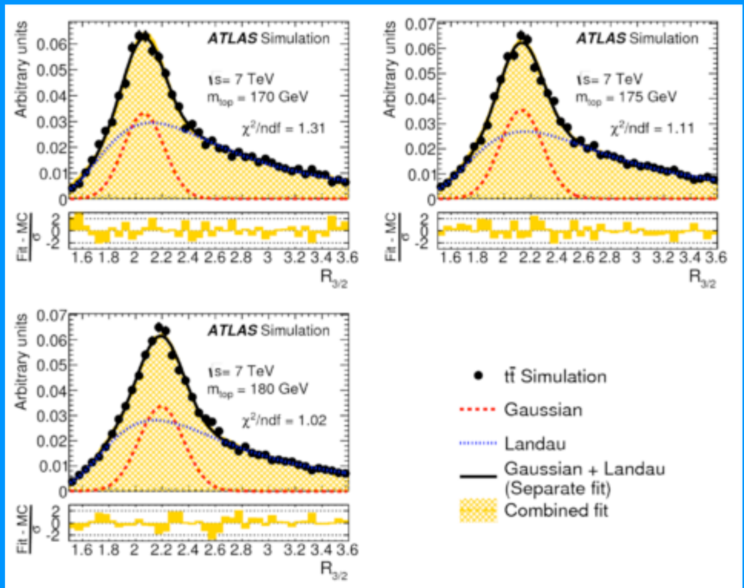
M_t=172.32±0.25(stat+JSF)±0.59(syst) GeV

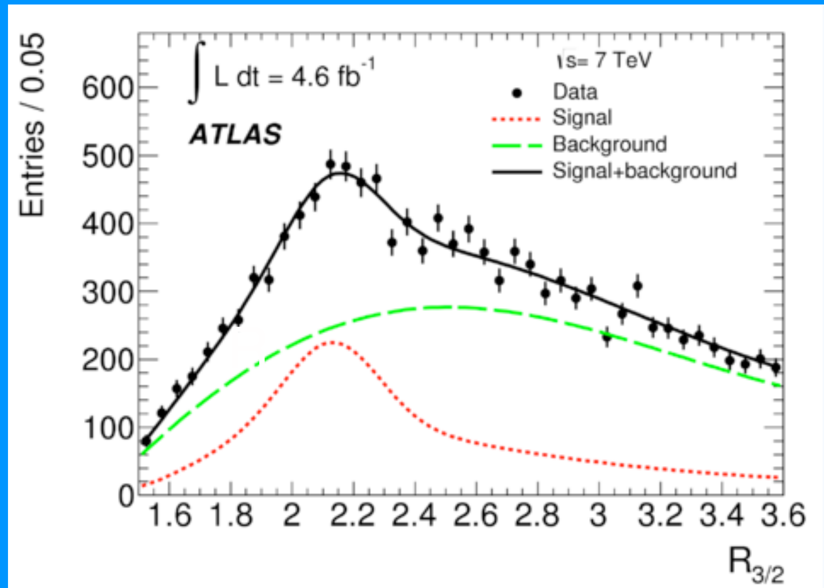
M_t=172.32±0.64 GeV (±0.37%)

M_t with ATLAS: all-jets

Template ($R_{3/2}$)
(7 TeV, 4.6 fb^{-1})

EPJC 75 (2015) 158,
arXiv:1409.0832





syst	GeV
bJES	0.62
JES	0.51
hadronization	0.50

$R_{3/2}=m_t^{reco}/m_W^{reco}$ templates:
- Gaussian for correct combinations
- Landau for combinatorial bckgd

$M_t=175.1\pm1.4(stat)\pm1.2(syst)$ GeV

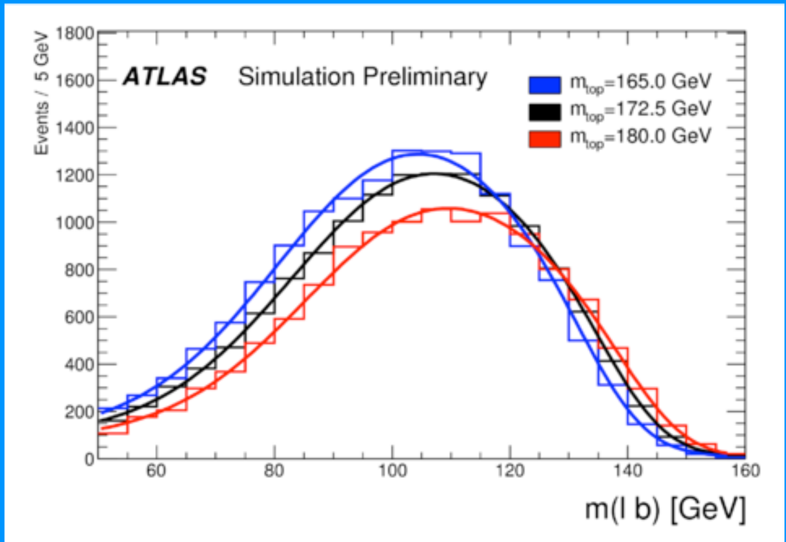
$M_t=175.1\pm1.8$ GeV (±1.05%)

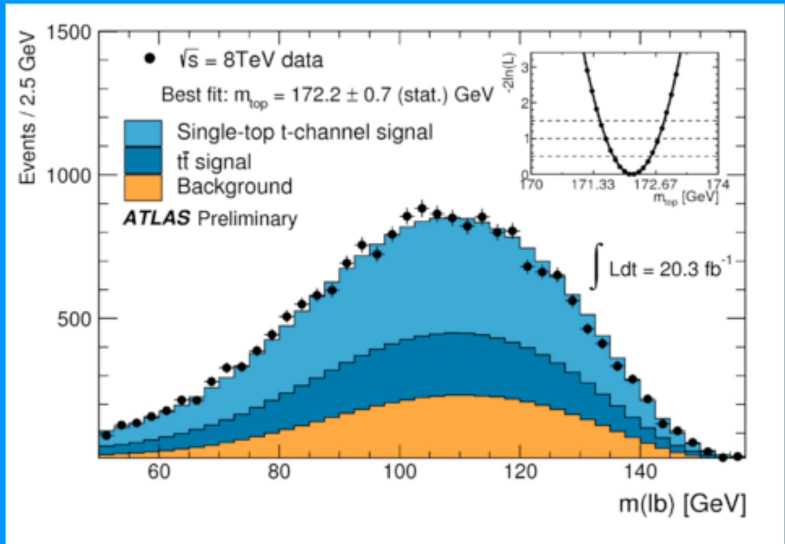
Data-driven bckgd using control regions in $P_T^{6th\text{-}jet}$ and N_{btag}

M_t with ATLAS: single top

Template (m_{lb})
(8 TeV, 20.3 fb^{-1})

ATLAS-CONF-2014-055





syst	GeV
JES	1.5
hadronization	0.7
W+jets bckgd	0.4

Use t-channel (σ=84 pb)
- 1 high-p_T lepton, large MET
- >=2 high-p_T jets, 1 btag

Neural Network selection

M_t=172.2±0.7(stat)±2.0(syst) GeV

M_t=172.2±2.1 GeV (±1.24%)

ATLAS 7 TeV combination

Combination of LJ+DIL (7 TeV) results computed with the Best Linear Unbiased Estimator, accounting for correlations ρ in the systematics
(ρ signs are relevant for large systematics)

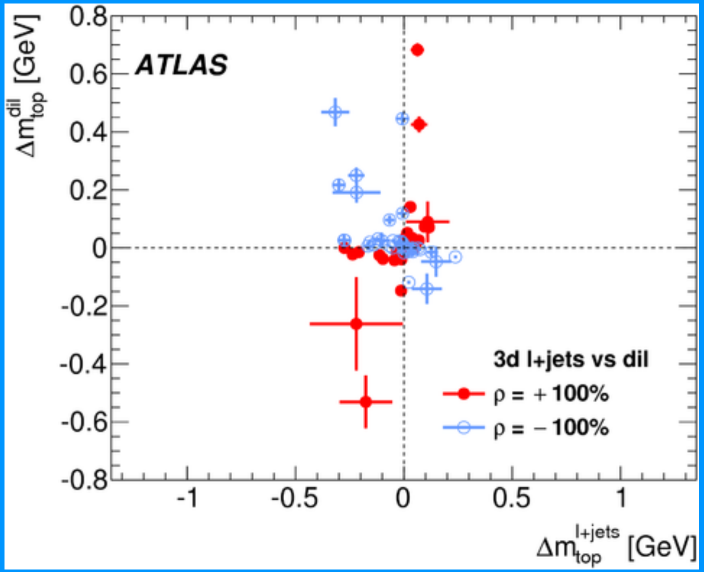
March 2015 value:

M_t=172.99±0.48(stat)±0.78(syst) GeV

M_t=172.99±0.91 GeV (±0.52%)

EPJC 75 (2015) 330,

arXiv:1503.05427



Allowing for anti-correlations reduces effect of systematics

CMS Run1 combination

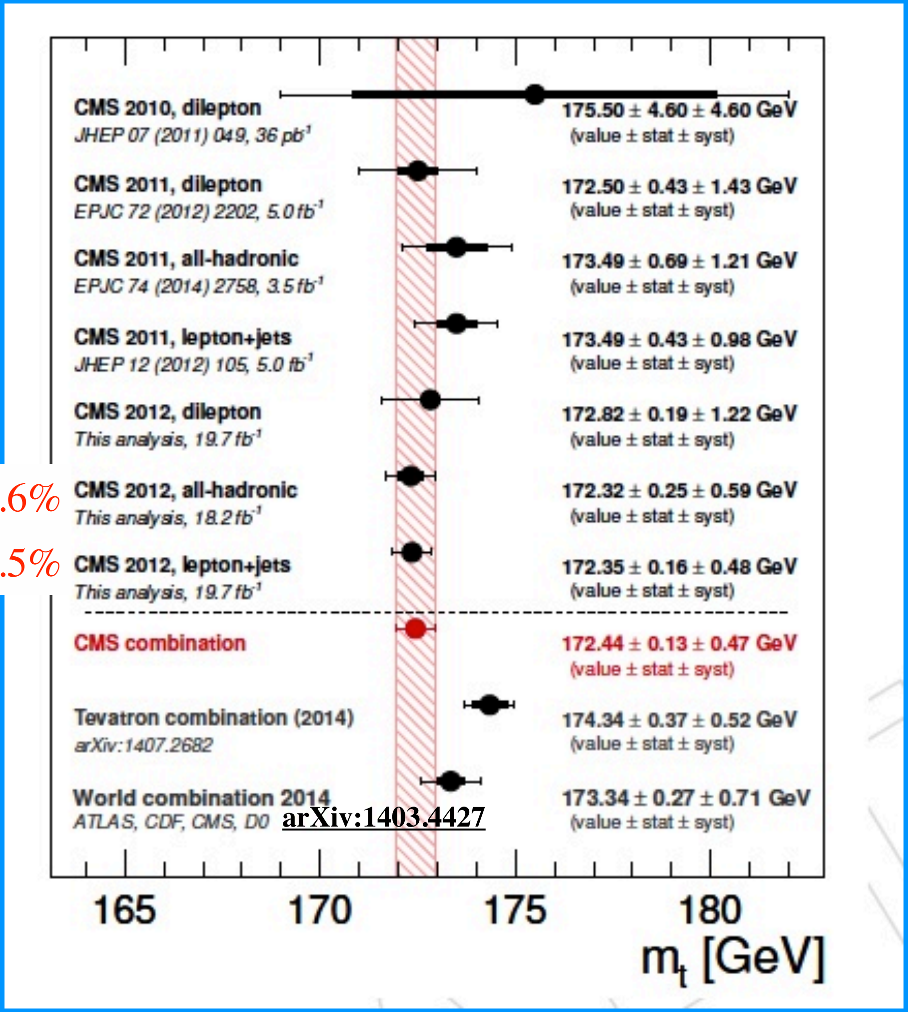
Submitted to PRD

arXiv:1509.04044

NEW

Fine break-down of systematics and study of correlations ρ

Combination computed with BLUE, accounting for correlations and possible anti-correlations



September 2015 value:

M_t=172.44±0.13(stat)±0.47(syst) GeV

M_t=172.44±0.49 GeV (±0.28%)

Conclusions

Level of precision reached (<0.3%) in measuring M_t impressive but comes from 20 years of continuous improvements

Even better precision expected from Run2

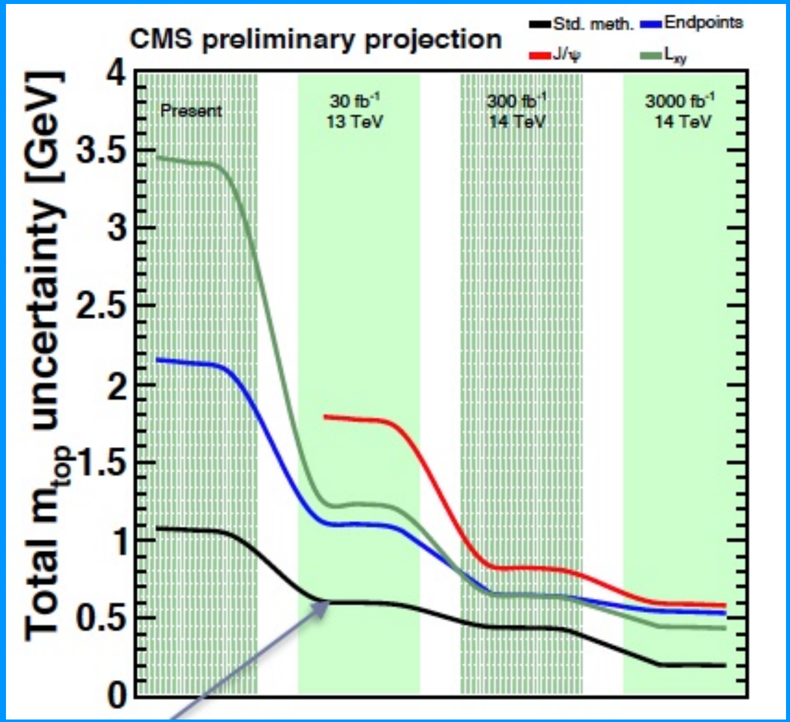
Help to explore fundamental issues like:
– cosmological models for inflation
– vacuum stability of SM
– physics beyond SM

Important to work on reducing systematics
e.g. those related to theory and signal modeling

Outlook

Run1 legacy measurements of M_t being completed
⇒ published soon

Ultimate precision of few hundreds MeV expected merging measurements/experiments, accounting for correlations and taking advantage of improvements in MC modelling



Differences between M_t^{MC} and theoretical definitions (pole mass, lagrangian mass): important issue to deal with

Backup

ATLAS event selection

Lepton+jets:

- one isolated e (μ) with $E_T>25$ ($p_T>20$) GeV, $|\eta|<2.1$
- >= 4 jets with $p_T>25$ GeV, $|\eta|<2.5$
- at least 1 b-tagged jet
- MET>30 (20) GeV for e (μ) + M_t^W

Dilepton:

- two oppositely-charged isolated e (μ) with $E_T>25$ ($p_T>20$) GeV, $|\eta|<2.1$
- $M_{ll}>15$ GeV and $|M_{ll}-MZ|>10$
- >= 2 jets with $p_T>25$ GeV, $|\eta|<2.5$
- 1 b-tagged jet
- MET>60 GeV for ee/μμ
- HT>130 GeV for eμ

All-jets:

- no high-P_T lepton, no MET
- >=5 jets with $p_T>55$ GeV, $|\eta|<2.5$; >=6 with $p_T>30$ GeV
- $C=\sum p_T/M_{all\text{-}jets}>0.6$
- 2 b-tagged jets among the 4 leading jets

Single top:

- one isolated e (μ) with $p_T>25$ GeV, $|\eta|<2.5$
- 2 jets with $p_T>30$ GeV, $|\eta|<4.5$
- 1 b-tagged jet
- MET>30 GeV
- Neural Network discriminant

CMS event selection

Lepton+jets:

- one isolated e (μ) with p_T>33 GeV, $|\eta|$<2.1
- >= 4 jets with p_T>30 GeV, $|\eta|$<2.4
- 2 b-tagged jets (medium)

All-jets:

- no high-P_T lepton
- 4 jets with p_T>60 GeV, $|\eta|$<2.4
- 2 more jets with p_T>30 GeV, $|\eta|$<2.4
- 2 b-tagged jets (tight)

Dilepton:

- two oppositely-charged isolated e or μ with p_T>20 GeV, $|\eta|$<2.5 (2.4) for e (μ)
- >= 2 jets with p_T>30 GeV, $|\eta|$<2.4
- at least one1 b-tagged jets (loose)
- MET>40 GeV for ee and μμ

Methods for measuring M_t

4) The *Matrix Element* method computes the probability to obtain the observed set **x** of variables given an assumed top quark mass and a generated set **y** of variables
The full event information is used and compared to what derived from the matrix elements, the PDF's and the transfer functions *W(x,y)*

$$P(t\bar{t}; M_t) \propto \int \sum_{flavors} dq_1 dq_2 \frac{d\sigma(p\bar{p} \to t\bar{t} \to y; M_t)}{dy} f(q_1) f(q_2) W(x,y) dy$$

An event probability is defined in terms of $P(t\bar{t})$ and P(bkg), then a total likelihood is computed and maximized

What mass are we measuring ?

The mass measured so far is the mass used as input in the MC generation (typically LO or NLO) and is affected by several perturbative/non-perturbative sub-1% uncertainties

The increasing level of accuracy requires to relate this to theory-based quantities like:

– the *pole mass*, universal but theoretically ambiguous by amounts $\mathbf{O}(\Lambda_{QCD})$ due to soft gluon radiation (*infrared renormalon problem*)

– lagrangian masses, theoretically unambiguos but not universal, like the $\overline{MS}$ *mass* which is defined only in perturbation theory

These masses can be derived from a comparison of the measured cross section to theoretical predictions of σ_{tt} on M_t

Of course one has to make assumptions on what Mt^{MC} is equal to