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Top mass combination: status and perspectives

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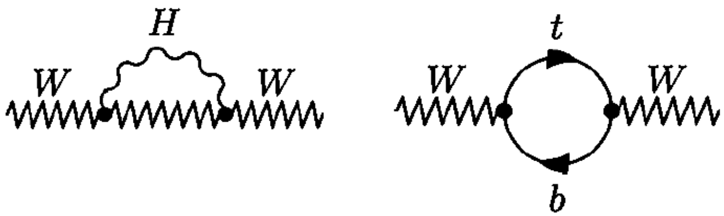
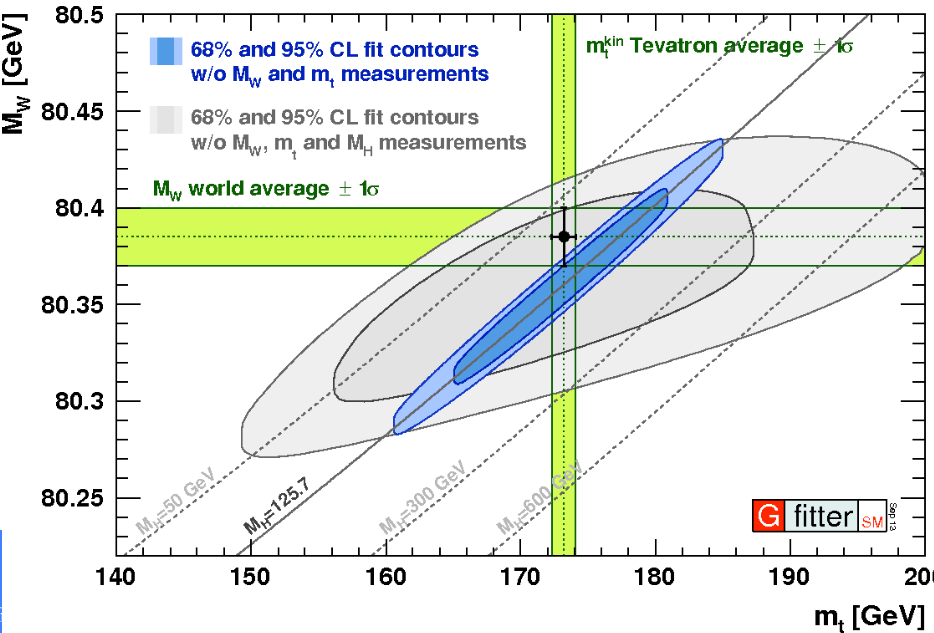
Top quark mass

Higgs, top quark, and W boson masses are related

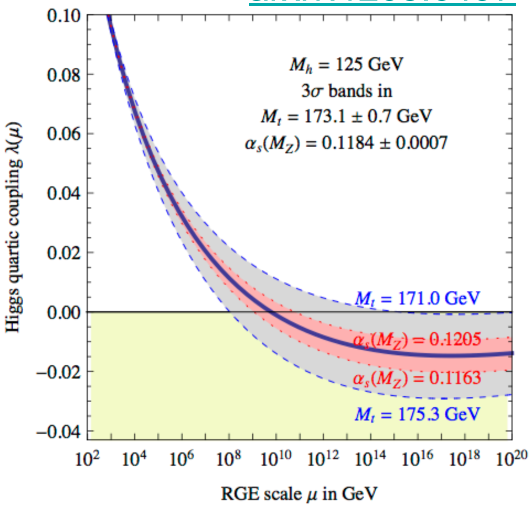


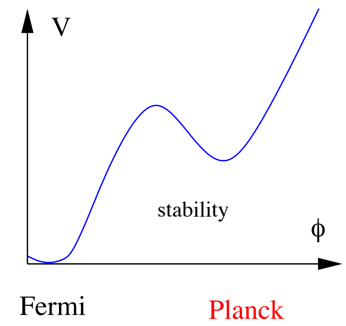
- A precise determination of m_{top} combined with EW precision measurements allows for stringent tests of the SM and its extensions

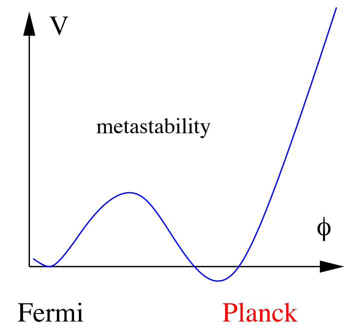


Eur. Phys. J. C 72, 2205 (2012)

arxiv:1205.6497



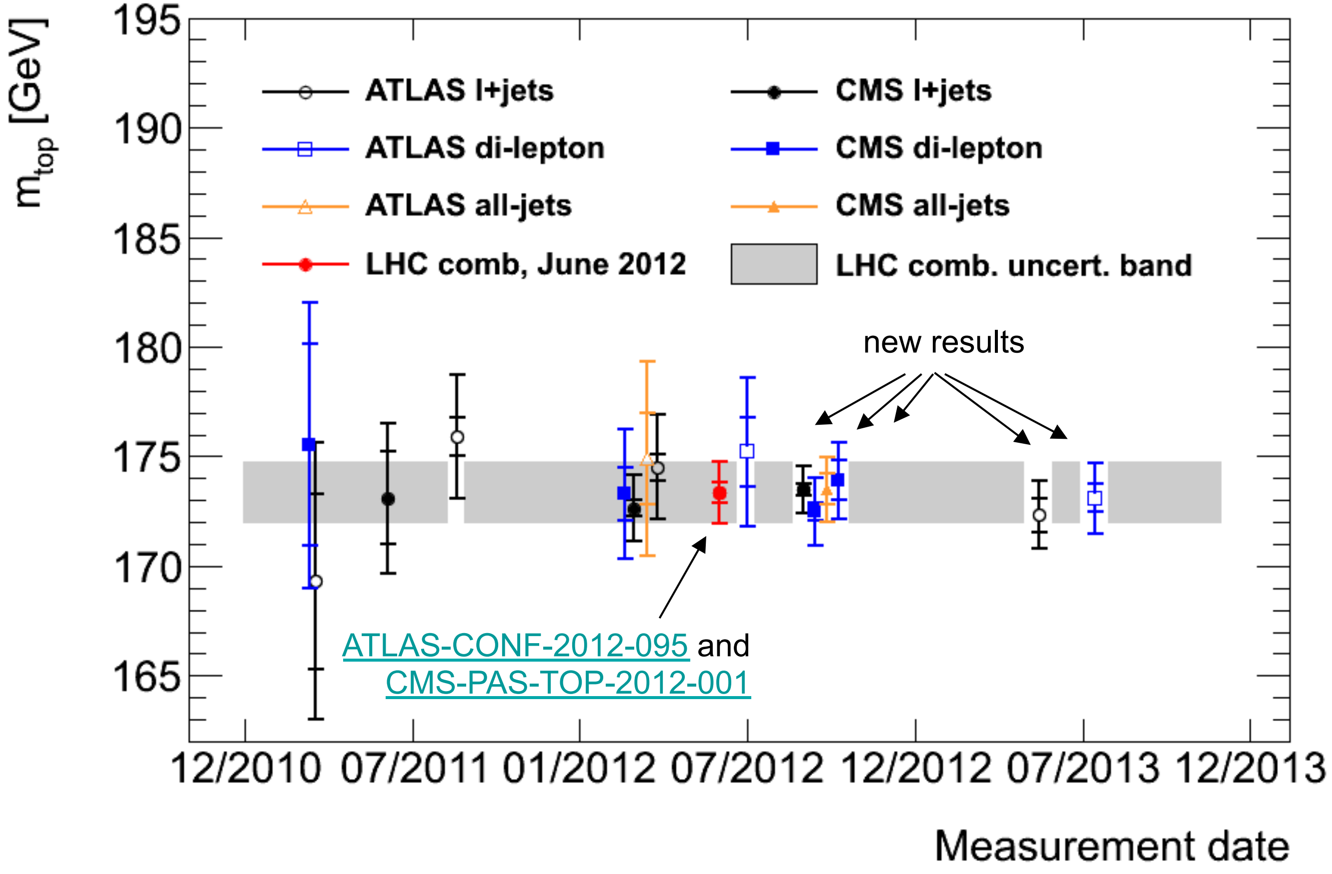




$$V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$$

- Interesting from the theoretical point of view:
  - Depending on the values of m_H and m_{top}, the Higgs quartic coupling could be rather small, vanish or even turn negative at a scale smaller than the Planck scale.
  - the experimental information on m_H and m_{top} gives us useful hints on the structure of the theory at very short distances

The LHC m_{top} measurements



- (approx) time evolution of the LHC m_{top} measurements with standard techniques (no m_{top} from x-sec, nor L_{xy} based)

- Since the first LHC m_{top} combination (June 2012):
  - new LHC measurements of increased precision are available
  - individual m_{top} measurements have reached a precision better than 1%.
- The time has come for updating the LHC combination…

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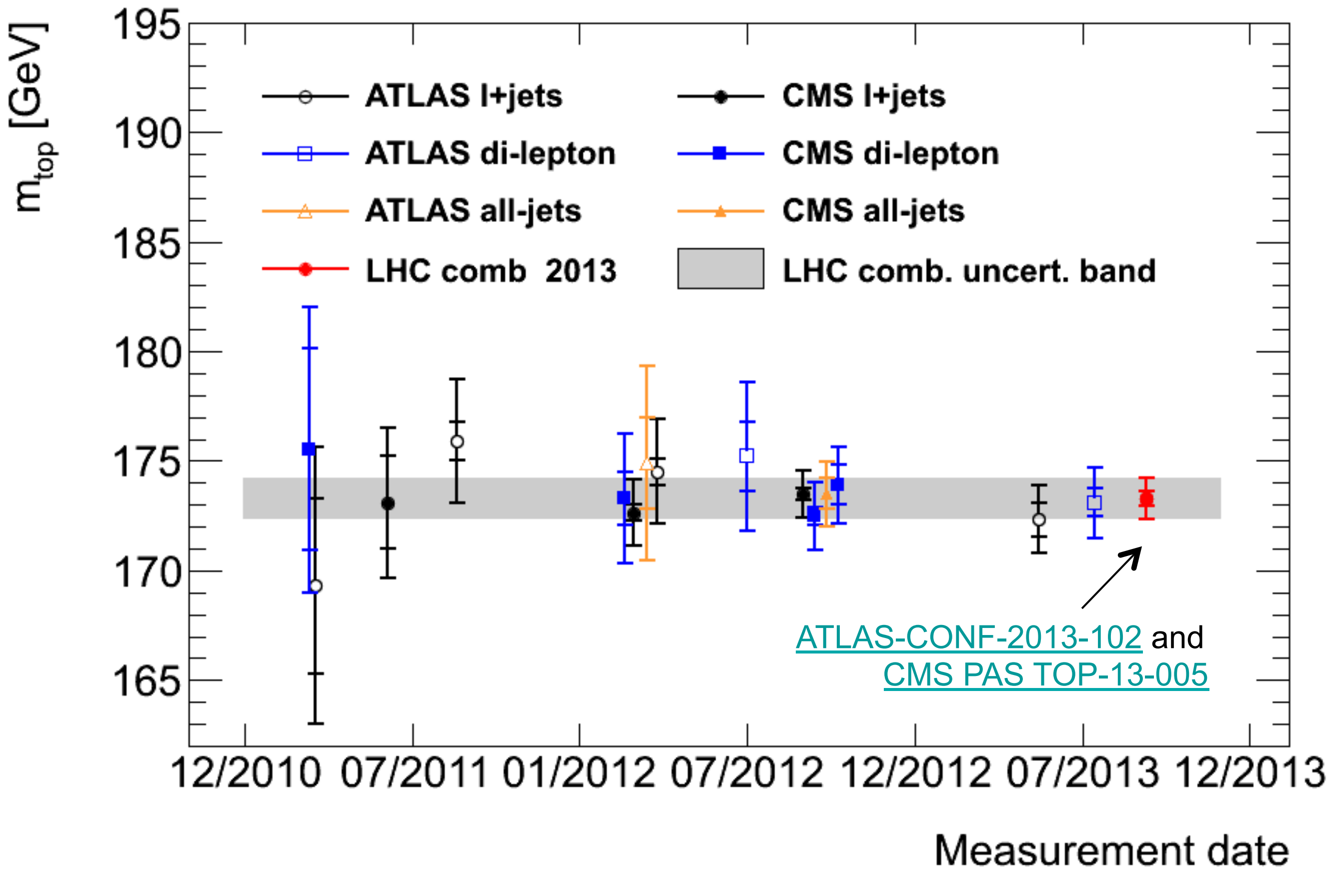
The LHC m_{top} measurements



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Comb. of ATLAS and CMS m_{top} results

Results based on the proton-proton LHC data collected in 2011 at $\sqrt{s}$ = 7 TeV.

- ***ATLAS:*** measurements in the lepton+jets and di-lepton channels
  - ATLAS-CONF-2013-046 (l+jets 4.7 fb^{-1})
    - 3dim template method: simultaneous determination of m_{top}, a global jet energy scale factor (JSF) from m_W, and a b-to-light quark jet energy scale factor (bJSF)
  - ATLAS-CONF-2013-077 (dilepton 4.7 fb^{-1})
    - 1-dim template method: m_{lb}

- ***CMS:*** measurements in the lepton+jets, di-lepton and all-jets channels:
  - JHEP 12 (2012) 105 (l+jets, 4.9 fb^{-1})
    - 2-dim ideogram method, for the simultaneous determination of m_{top} and JSF (from m_W).
  - Eur. Phys. J. C72 (2012) 2202 (dilepton, 4.9 fb^{-1})
    - the event reconstruction is performed using an analytical matrix weighting technique, where weights are assigned based on the PDF ($m_{top}|E_{lep}$)
  - arXiv:1307.4617 (all-jets, 3.5 fb^{-1})
    - 1-dim ideogram method

Note: older measurements based on 2010 data or partial 2011 data statistics were not included (the available information prevented the possibility to use the new / updated syst categorization in the combination)

Combination method: BLUE

- We use the BLUE method = *Best Linear Unbiased Estimator*
  - the same techniques employed for
  - the LEPEWWG fits
  - the Tevatron (arxiv:1305.3929), and LHC top mass combinations (ATLAS-CONF-2012-095 and CMS PAS TOP-12-001, ATLAS-CONF-2013-102 and CMS PAS TOP-13-005)
- Advantages of using BLUE for m_{top} combination
  - it allows a directly comparison of the LHC and Tevatron results
  - it will allow to perform readily a World combination (LHC+Tevatron)

BLUE determines the optimal set of coefficients (or weights) to be used in a linear combination of the input measurements, minimizing the total uncertainty on the combined result, taking into account statistical and systematic uncertainties and their correlations.

It is equivalent to a χ^2 minimization:

$$\chi^2 = [\, x\vec{e} - \vec{x}\,]^T \cdot V^{-1}(\,\vec{x}\,) \cdot [\, x\vec{e} - \vec{x}\,]$$

where, V = covariance matrix. For example for two measurements, and an uncertainty source S, it reads:

$$\boxed{V_S = \begin{pmatrix} \sigma^2_{1S} & \rho_{12S}\,\sigma_{1S}\,\sigma_{2S} \\ \rho_{12S}\,\sigma_{1S}\,\sigma_{2S} & \sigma^2_{2S} \end{pmatrix}}$$

Types of uncertainty sources

Beside statistics, the current input m_{top} are subject to the following uncertainties:

- Jet energy scale(s)
  - How well do we measure the response of the detector to various types of jets (b-, light- or gluon-originated jets).
- Theory/modelling
  - MC generator, hadronization models, initial and final state QCD radiation, choice of the factorization and of jet-to-parton matching scales (for multi leg generators), CR, UE and choice of the proton PDF
- Detector modelling
  - Resolution effects, reconstruction efficiencies, b-tagging modelling
- Background contamination
  - Impact of background on the measurements (shape and/or normalization variations)
- Environment
  - Modelling of the pileup conditions in the simulation with respect to data.

- A mapping of the uncertainty categories between ATLAS and CMS is performed (compatible with the categorization used for the Tevatron 2013 combination)

LHC combination

Uncertainty Categories			Size [GeV]					Correlation	
			ATLAS		CMS				
Tevatron	ATLAS	CMS	2011 l+jets	2011 di-l	2011 l+jets	2011 di-l	2011 all jets	ρ_{exp}	ρ_{LHC}
Measured m_{top}			172.31	173.09	173.49	172.50	173.49		
iJES	Jet Scale Factor		0.27		0.33				
iJES	bJet Scale Factor		0.67						
iJES	Sum (statistical comp.)		0.72		0.33			0	0
dJES	uncorrelated JES comp.		0.61	0.73	0.24	0.69	0.69	1	0
dJES	in-situ γ/Z JES comp.		0.29	0.31	0.02	0.35	0.35	1	0
dJES	intercalib. JES comp.		0.19	0.39	0.01	0.08	0.08	1	0.5
aJES	flavour JES comp.		0.36	0.02	0.11	0.58	0.58	1	0.0
bJES	b-jet energy scale		0.08	0.71	0.61	0.76	0.49	1	0.5
Signal: MC	MC Generator		0.19	0.20	0.02	0.04	0.19		
Signal: MC	Hadronisation		0.27	0.44					
Signal: MC	Sum		0.33	0.48	0.02	0.04	0.19	1	1
Signal: Rad	ISR/FSR		0.45	0.37					
Signal: Rad		Q^2-scale			0.24	0.55	0.22		
Signal: Rad		Jet-Parton scale			0.18	0.19	0.24		
Signal: Rad	Sum		0.45	0.37	0.30	0.58	0.33	1	1
Signal: CR	Colour reconnection		0.32	0.29	0.54	0.13	0.15	1	1
Signal: -	Underlying event		0.12	0.42	0.15	0.05	0.20	1	1
Signal: PDF	Proton PDF		0.17	0.12	0.07	0.09	0.06	1	1
DetMod	Jet Resolution		0.22	0.21	0.23	0.14	0.15		
DetMod	Jet Reco Efficiency		0.05						
DetMod	E_T^{miss}		0.03	0.05	0.06	0.12			
DetMod	Sum		0.23	0.22	0.24	0.18	0.28	1	0
DetMod	b-tagging		0.81	0.46	0.12	0.09	0.06	1	0.5
LepPt	Lepton reconstruction		0.04	0.12	0.02	0.14		1	0
Background from MC				0.14	0.13	0.05		1	1
Background from Data			0.10				0.13	0	0
Method			0.13	0.07	0.06	0.40	0.13	0	0
Multiple Hadronic Interactions			0.03	0.01	0.07	0.11	0.06	1	1
Statistics			0.23	0.64	0.27	0.43	0.69		
Systematics			1.53	1.50	1.03	1.46	1.23		
Total Uncertainty			1.55	1.63	1.06	1.52	1.41		

Correlation assumptions

Note:
differences between uncertainty size across analyses, can be caused by multiple concurring effects (event selection, kinematical reconstr., fitting procedures and detector performance)

Results

$$m_{\text{top}} = 173.29 \pm 0.23\ (\text{stat}) \pm 0.92\ (\text{syst})\ \ \text{GeV}.$$

or separating the iJES statistical contribution

$$m_{\text{top}} = 173.29 \pm 0.23\ (\text{stat}) \pm 0.26\ (\text{iJES}) \pm 0.88\ (\text{syst})\ \ \text{GeV}.$$

iJES: is the part of the JES uncertainty which originates from top quark based in situ calibration procedures

Correlation matrix for input measurements:

$$\mathcal{M}_\rho = \begin{array}{c} \begin{array}{ccccc} \text{ATL11 } l\text{+jets} & \text{ATL11 di-}l & \text{CMS11 } l\text{+jets} & \text{CMS11 di-}l & \text{CMS11 all jets} \end{array} \\ \left(\begin{array}{ccccc} 1.00 & & & & \\ 0.63 & 1.00 & & & \\ 0.26 & 0.35 & 1.00 & & \\ 0.18 & 0.25 & 0.64 & 1.00 & \\ 0.16 & 0.24 & 0.55 & 0.75 & 1.00 \end{array}\right) \end{array} \begin{array}{l} \\ \text{ATL11 } l\text{+jets} \\ \text{ATL11 di-}l \\ \text{CMS11 } l\text{+jets} \\ \text{CMS11 di-}l \\ \text{CMS11 all jets} \end{array}$$

Correl: [55%,75%] for measurements from the same exp.
[16%,35%] between ATLAS/CMS measurements

	LHC comb.
Measured m_{top}	173.29
iJES	0.26
uncorrelated JES comp.	0.29
in-situ JES comp.	0.10
intercalib. JES comp.	0.07
flavour JES comp.	0.16
b-jet energy scale	0.43
Monte Carlo simulation	0.14
Radiation modelling	0.32
Colour reconnection	0.43
Underlying event	0.17
Proton PDF	0.09
Detector modelling	0.20
b-tagging	0.25
Lepton reconstruction	0.01
Background from MC	0.08
Background from Data	0.04
Method	0.06
Multiple Hadronic Interactions	0.05
Statistics	0.23
Systematics	0.92
Total Uncertainty	0.95

~10% improvement with respect to the most precise single measurement

Compatibility between ATLAS and CMS results:

	Individual combinations	Parameter value	Correlations		χ^2/ndf (χ^2 probability)	
			m^{ATL}	m^{CMS}	m^{ATL}	m^{CMS}
m^{ATL}	172.65 ± 1.43	172.70 ± 1.43	1.00		–	
m^{CMS}	173.59 ± 1.03	173.50 ± 1.02	0.33	1.00	0.21/1 (0.65)	–

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\mathcal{M}_\rho = & \begin{pmatrix} 1.00 & & & & \\ \boxed{0.63} & 1.00 & & & \\ 0.26 & 0.35 & 1.00 & & \\ 0.18 & 0.25 & 0.64 & 1.00 & \\ 0.16 & 0.24 & 0.55 & 0.75 & 1.00 \end{pmatrix} \begin{array}{l} \text{ATL11 } l\text{+jets} \\ \text{ATL11 di-}l \\ \text{CMS11 } l\text{+jets} \\ \text{CMS11 di-}l \\ \text{CMS11 all jets} \end{array}
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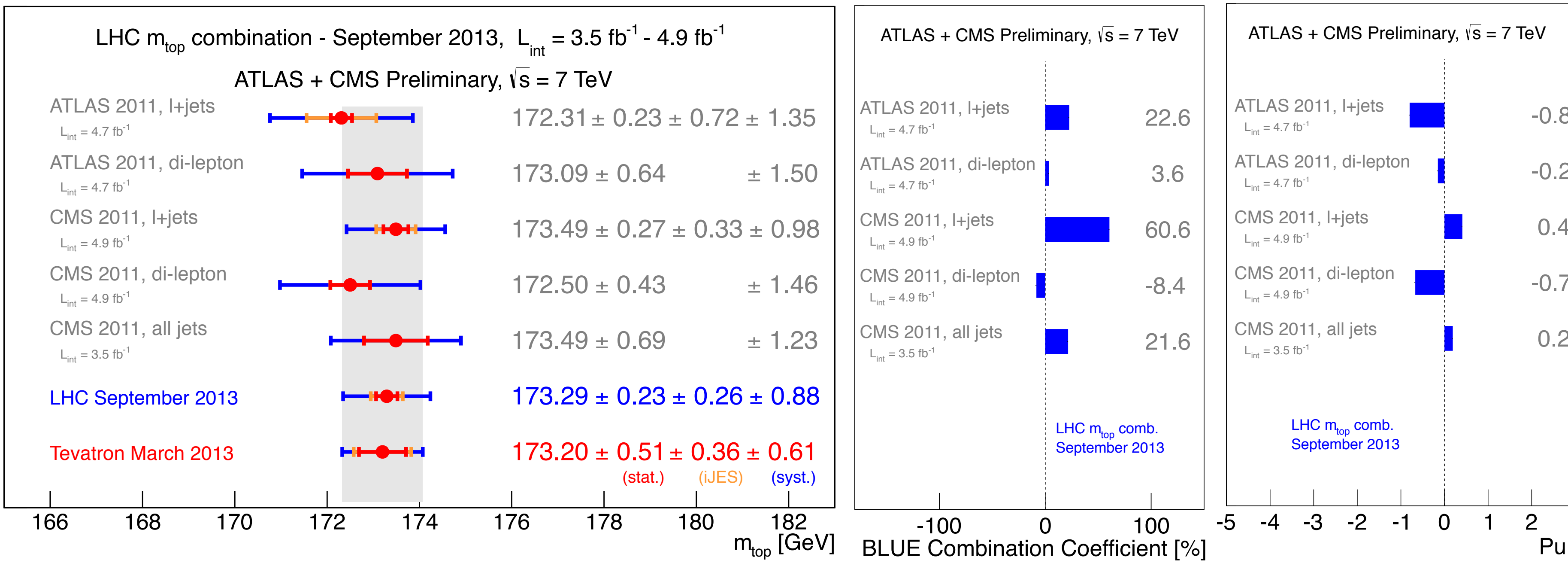
Compatibility between results by decay channel:

	Parameter value	Correlations			χ^2/ndf (χ^2 probability)		
		$m^{l\text{+jets}}$	$m^{\text{di-}l}$	$m^{\text{all jets}}$	$m^{l\text{+jets}}$	$m^{\text{di-}l}$	$m^{\text{all jets}}$
$m^{l\text{+jets}}$	173.18 ± 0.97	1.00			–		
$m^{\text{di-}l}$	172.85 ± 1.24	0.72	1.00		0.15/1 (0.70)	–	
$m^{\text{all jets}}$	173.64 ± 1.30	0.56	0.70	1.00	0.17/1 (0.68)	0.64/1 (0.42)	–

LHC combination



- The combined LHC results is ~10% more precise than the most precise single m_{top} determination from CMS.
- The total LHC m_{top} uncertainty is 0.95 GeV and is competitive with the latest Tevatron combination precision (0.87 GeV).
- The pull distribution indicates good consistency among all input measurements.

Measurements		BLUE comb. coeff. [%]	IIW [%]	MIW [%]
ATLAS *l*+jets	172.31 ± 1.55	22.6	37.3	8.2
ATLAS di-*l*	173.09 ± 1.63	3.6	33.8	0.2
CMS *l*+jets	173.49 ± 1.06	60.6	79.2	25.1
CMS di-*l*	172.50 ± 1.52	-8.4	38.8	0.7
CMS all jets	173.49 ± 1.41	21.6	45.0	4.4
Correlations	—	—	−134.1	—

- alternative figures of merit to quantify the impact of the inputs (and the correlation) [arXiv:1307.4003]:

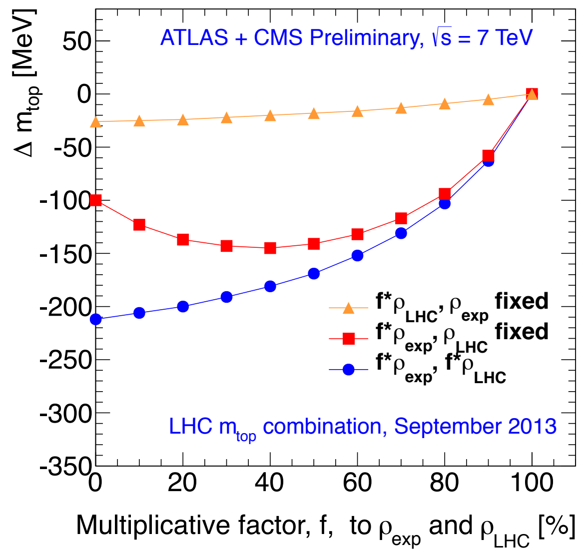
$$\mathrm{IIW}_i = \frac{1/\sigma_i^2}{1/\sigma_{m_{\mathrm{top}}}^2} = \frac{1/\sigma_i^2}{I}; \quad \mathrm{IIW}_{corr} = \frac{I - \sum_i 1/\sigma_i^2}{I}.$$

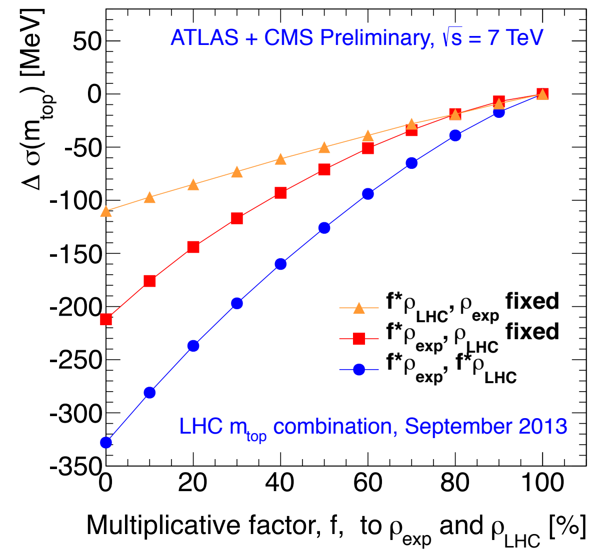
$$\mathrm{MIW}_i = \frac{I_{\text{n. meas}} - I_{\text{n}-1\text{ meas.: all but }i}}{I_{\text{n. meas}}}$$

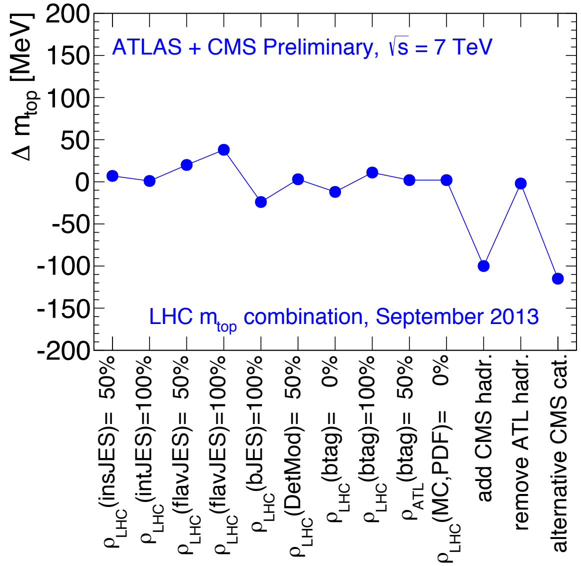
LHC combination stability checks

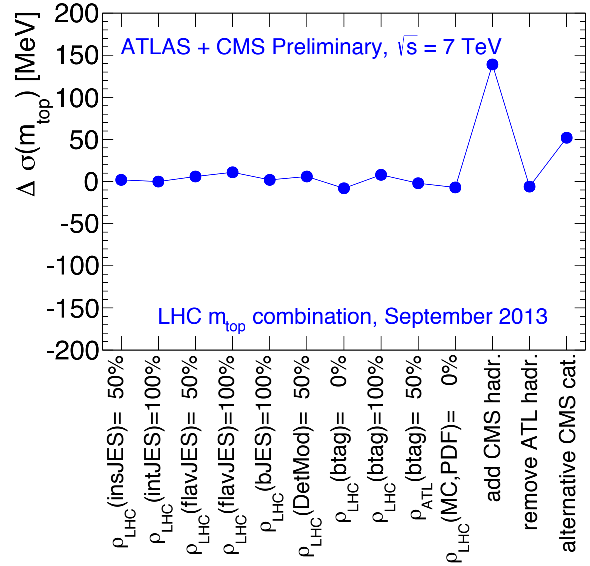
- The categorization and the correlation assumptions reflect the present understanding and the limitations due to the different choices made by the experiments when evaluating the individual uncertainty sources.

- Tests have been performed:
  - Varying ρ_{LHC} and ρ_{exp} coefficients via a multiplicative factor f in the range [0,1].
  - Changing specific correlation assumptions (JES in the components)
  - adding/removing/redefining the formulation of the systematic uncertainties (in particular the hadronization syst.)









ATLAS-CONF-2013-102 and CMS PAS TOP-13-005

Combination stability checks - 2

- Tests have been performed numerically (using the BlueFin software package [arXiv:1307.4003]) minimizing the information (I) by varying the correlation assumptions:

Combination	BLUE
Nominal correlations	173.29 ± 0.95
Minimize by global factor	173.29 ± 0.95
Minimize by error source	173.27 ± 0.95
Minimize by off-diagonal element	173.21 ± 0.95

- ByGlobFac", consists in rescaling all correlations by the same global rescaling factor
- ByErrSrc : rescaling all correlations within each error source by the same factor
- ByOffDiagElem", consists in rescaling in all error sources the correlation between measurements y_i and y_j by the same factor

LHC combination stability checks

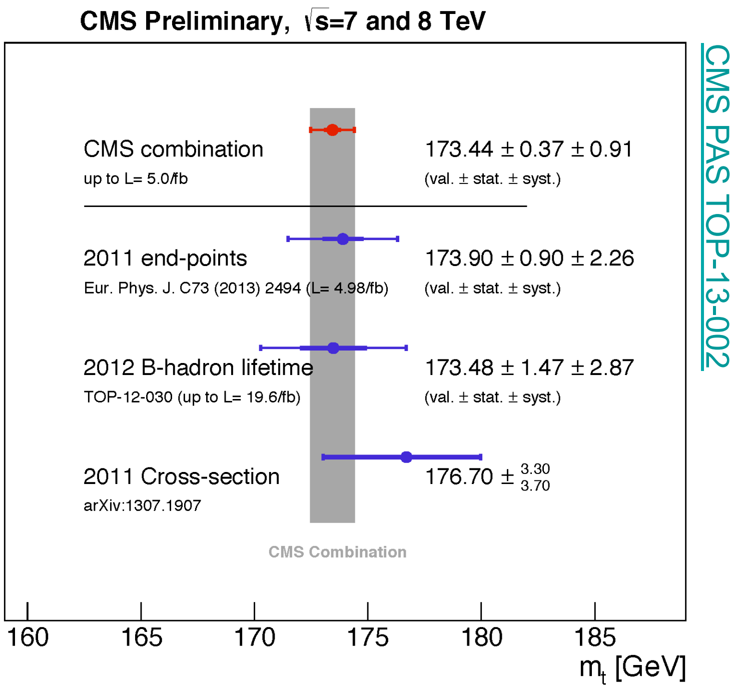
- The combination is relatively stable against variation of the correlation assumption between and across experiments.

- The largest effects are related to variations in the treatment of the hadronization (Pythia/Herwig) systematics at the analysis level (Δm_{top} ~ 100 MeV; $\Delta\sigma(m_{top})$ ~ 150 MeV).
  - On top of the Pythia/Herwig contributions to the JES uncertainty, ATLAS quote in addition an analysis specific hadronization uncertainty evaluated on top-quark pair MC (with the current inputs measurements removing it does not change significantly the combination result: the 3dTMT analysis greatly reduce this contribution).
  - CMS has also evaluated the full effect (Herwig/Pythia) in top quark pair events. These amounts to 0.58, 0.76, 0.93 GeV for the l+jets, di-lepton and all-jets analysis respectively (compared to 0.61, 0.75, 0.44 GeV quoted as “b-specific” part of JES).
  - Studies about the level of double counting between the analysis-specific and JES-specific hadronization uncertainty, and about possible alternative systematic categorizations to best account for the effects, are ongoing.
  - These are priority tasks in view of future combination updates.

Next steps

- Combine Tevatron + LHC measurements
  - Discussions started among experiment representatives:
    G.C. (ATLAS), F. Deliot (D0), G. Velev (CDF), S.W. (CMS)
  - Inputs measurements defined
  - Working on the finalization of the results and on the documentation
  - Aim at circulating a note draft to the experiments soon
  - Expect an improvement of the total uncertainty of the order of 100 MeV with respect to the Tevatron and LHC combinations

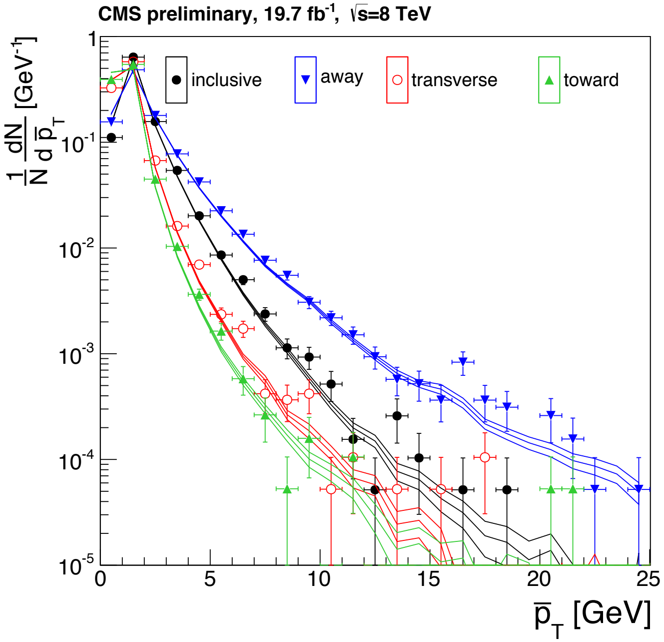
- Further exploit alternative experimental methods
  (important for example to get further in-sights on the relation between m_{top}^{MC} and m_{top}^{pole})
  - m_{top} from kinematical end-points
  - m_{top} from b-hadrons decay length
  - m_{top} from top-pair production x-sections
  - …



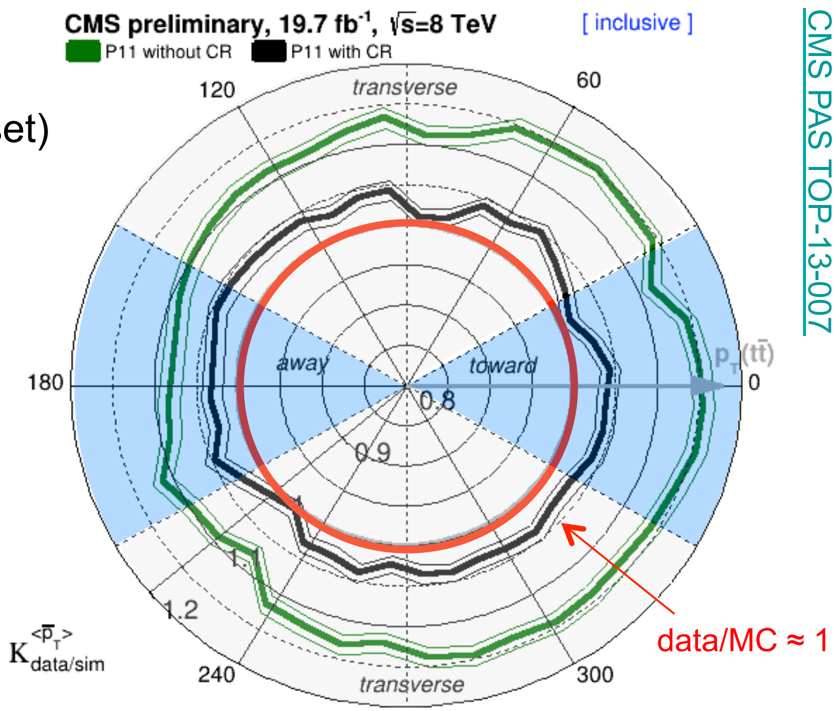
- Keep improving existing measurement techniques
  - Continue efforts on the harmonization of the systematics between experiments
  - Use the available LHC data to further constraint/refine modelling systematics

Possible modelling improvements

- Pilot study by CMS:
  - Using di-lepton top quark pair events (8 TeV dataset)
  - Check the data/MC prediction for various Underlying Event (UE) / and Colour Reconnection (CR) models



Tunes without CR effects are disfavoured by data. Derived constraints could be used to improve the signal modelling uncertainties



CMS PAS TOP-13-007

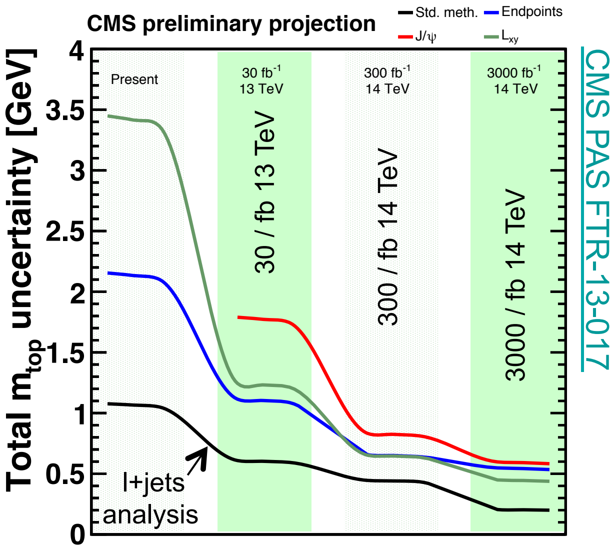
- Define away, toward and transverse regions wrt. the top quark pair transverse momentum

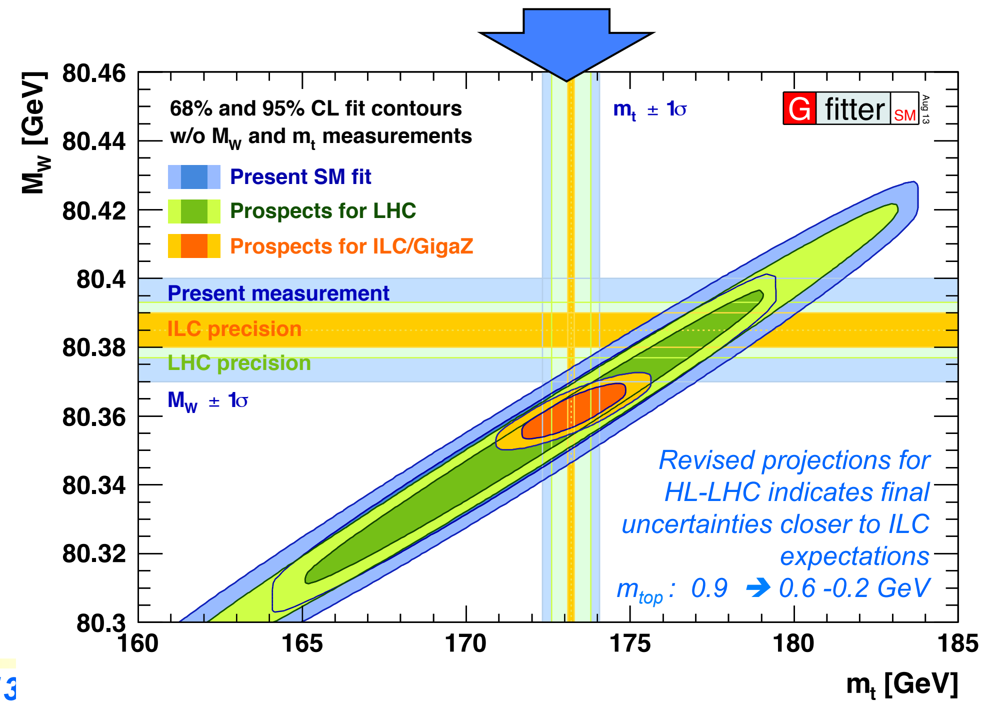
$$\vec{p}_T(t\bar{t}) = \vec{p}_T(b_1) + \vec{p}_T(b_2) + \vec{p}_T(\ell) + \vec{p}_T(\ell') + \vec{p}_T^{\,miss}$$

- Look at charged particles not associated to particle flow objects nor to pile-up
  - Multiplicity, Σ p_T, average p_T…

Perspectives and projections

- Current m_{top} measurements achieved precision better than 1%...
- What is to be expected by the LHC in the next years?
- m_{top} projection studies were performed by CMS assuming:
  - the use of 3D analysis techniques *ala* ATLAS
  - that the top quark pair cross section increase will compensate for inefficiencies due to higher pile-up conditions
  - that a x2 reduction of modelling systematics can be reached using particle level studies, and differential measurements





Conclusions

- A preliminary LHC combination has been performed using the BLUE technique, taking as input the public results from the ATLAS and CMS collaborations using 2011 LHC data.

- The current combination improves by 10% the uncertainty of the most precise single measurement, and has a total uncertainty of 0.95 GeV (compared to 1.4 GeV from the previous LHC combination).

  The results reads :

$$m_{top} = 173.29 \pm 0.23\,(\text{stat.}) \pm 0.92\,(\text{syst.})\ \text{GeV} = 173.29 \pm 0.95\ \text{GeV}$$

- With respect to its total uncertainty, the current result is stable against variation of the correlation assumptions.
- In view of future updates, the harmonization of the treatments of the hardonization systematics and the quantitative determination of the possible double counting with the JES specific uncertainties will constitute an high priority topic.

- Work is ongoing towards:
  - the first Tevatron+LHC combination
  - further improvements of the analyses techniques, and systematics harmonization between experiments

- Backup -

Key to systematic naming – 1

- **iJES:** this is the part of the JES uncertainty which originates from in situ calibration procedures (W→jj). This relates to analyses performing simultaneous m_{top} and JSF measurements (2dim analyses). For ATLAS l+jets this also includes the stat. contribution due to the simultaneous determination of the b-to-light jet energy scale factor (bJSF).
- **uncorr JES:** stat. components, detector effects, pileup subtraction, close-by jets, calorimeter stability
- **in-situ JES:** uncertainty related to the scale setting using γ/Z+jets events.
- **intercalib JES:** The part of the JES uncertainty originating from modeling of the radiation in the relative η inter-calibration procedures.
- **flavour JES:** The part of the JES uncertainty stemming from differences in the jet energy response for various jet flavors and the flavor mixture
- **bJES:** *b*-jets specific uncertainty: In ATLAS, this is evaluated by varying *b*-quark fragmentation, hadronization models and underlying event tunes using MC. In CMS, the Pythia and Herwig fragmentation models are used to evaluate the response variation for different jet flavor mixtures.

Key to systematic naming – 2

- **MC:** syst due to the choice of MC generator and the hadronization model.
  - PowHeg+Pythia is used in ATLAS and Madgraph+Pythia in CMS.
  - MC generator syst. is evaluated comparing MC@NLO/PowHeg within ATLAS, MadGraph/PowHeg within CMS (also accounts for possible width effects, not simulated in the MadGraph setup used).
  - The hadronization syst. for CMS is not included here but used in the combination stability checks.
- **Rad (radiation):** Initial and final state radiation, Q-scale/jet-to-parton matching (CMS only).
- **CR:** color reconnection: comparison of Pythia tunes Perugia2011 and Perugia2011noCR
- **Underlying event** : comparison of Pythia tunes Perugia2011 and Perugia2011 mpiHi.
- **PDF:** uncertainty due to the proton parton distribution function (PDF4LHC recommendations)
- **DTMO:** detector modelling systematics, b-tagging, lepton reconstruction
  - b-tagging: the full p_T/η dependence of the SF uncertainty is taken into account in ATLAS. Within CMS, the b-tagging selection cuts are varied to mimic the efficiency variations within uncertainty.
- **BGMC:** uncertainty on the modelling of the backgrounds stemming from MC (normalization/shape)
- **BGData:** uncertainty on the modelling of the data-driven backgrounds (normalization/shape)
- **Method calibration:** uncertainties related to the limited precision of the measurement calibrations
- **effects due to pileup**: modelling of the pileup conditions in the simulation with respect to data.

Combination method: BLUE

- Let us take as example the combination of two measurements, x_1 and x_2.
- Let us define $z = \sigma_2/\sigma_1$ and let it be $z>1$ (i.e.: let the second measurement be less precise than the first). The BLUE method will give:

Comb. Coeff. (or weights)

$$x = \alpha x_1 + \beta x_2 \qquad \text{with: } 1 = \alpha + \beta$$

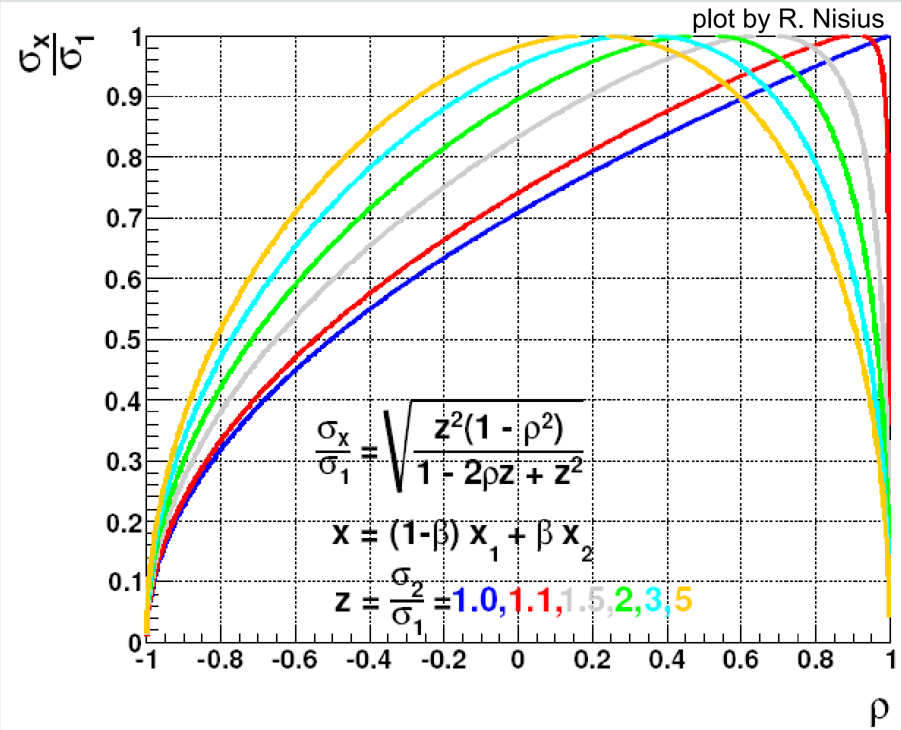
The relative improvement with respect to the most precise measurements, and the weight of the second measurement can be expressed as

$$\frac{\sigma_x}{\sigma_1} = \sqrt{\frac{z^2(1-\rho^2)}{1-2\rho z+z^2}},$$

$$\beta = \frac{1-\rho z}{1-2\rho z+z^2}.$$

ρ = correlation between measurements 1 and 2

Combination method: BLUE



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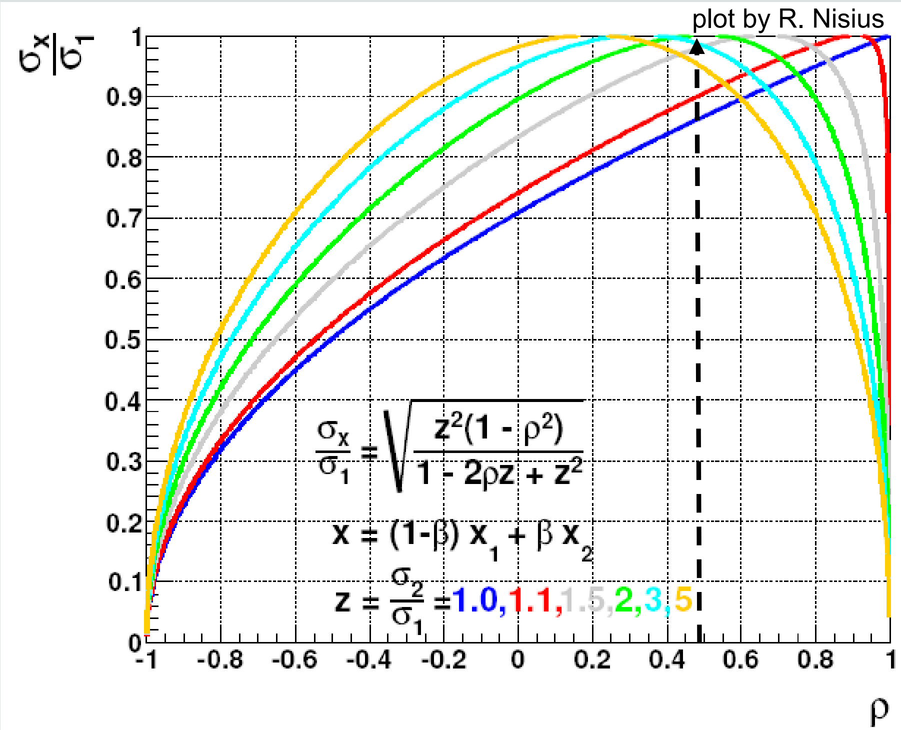
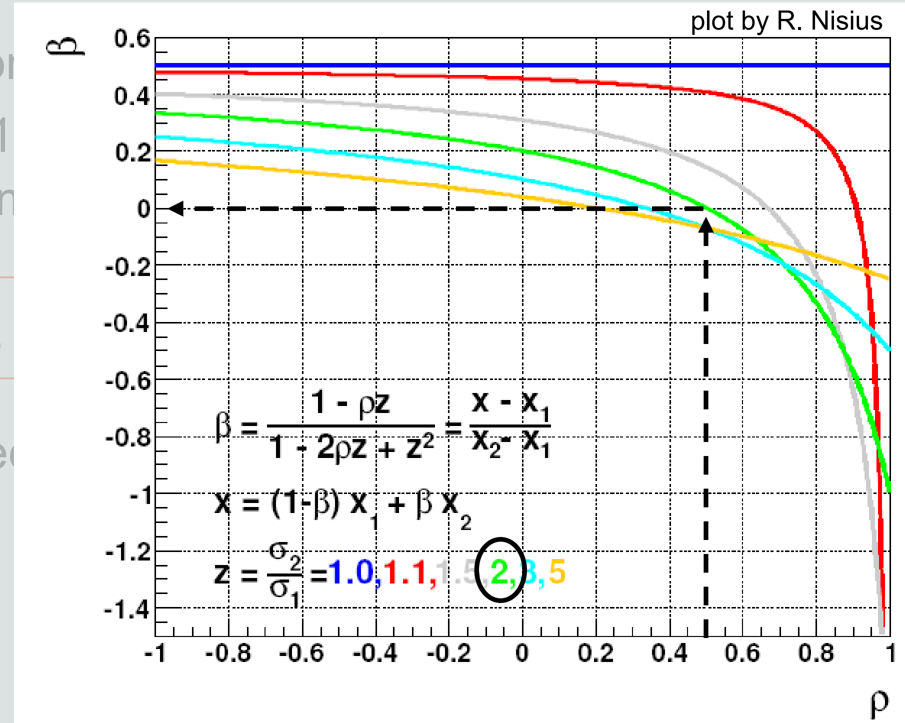
where: ρ = corr. between x_1 and x_2

Two important things to note:

1. The relative improvement of the combination and the weights of the input measurements depend only on their precisions and correlations: they are independent of the actual measured values, x_1 and x_2.

Combination method: BLUE





Two important things to note:

1. The relative improvement of the combination and the weights of the input measurements depend only on their precisions and correlations: they are independent of the actual measured values, x_1 and x_2.

2. Depending on the precision of the measurements and their correlation, negative weights can occur for the less precise measurement as soon as $\rho>1/z$

CMS m_{top} projections

- m_{top} projection studies by CMS assuming:
  - the use of 3D analysis techniques *ala* ATLAS
  - that the cross section increase will compensate for inefficiencies due to higher pile-up conditions.
  - that a x2 reduction of modelling systematics can be reached using particle level studies, and differential measurements

	Current	Future			Comment
Center-of-mass energy	7 TeV l+jets	13 TeV	14 TeV	14 TeV	
Integrated luminosity	5 fb^{-1}	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}	
Fit calibration	0.06	0.03	0.03	0.03	MC statistics
b-JES	0.61	0.27	0.09	0.03	3D fit
Residual JES	0.28	0.28	*0.2*	*0.06*	*differential*
Lepton energy scale	0.02	0.02	0.02	0.02	unchanged
Missing transverse momentum	0.06	0.06	0.06	0.06	unchanged
Jet energy resolution	0.23	0.23	*0.2*	*0.06*	*differential*
b tagging	0.12	0.06	0.06	0.06	factor 2 (data)
Pileup	0.07	0.07	0.07	0.07	unchanged
Non-$t\bar{t}$ background	0.13	0.06	0.06	0.06	factor 2 (S/B)
Parton distribution functions	0.07	0.04	0.04	0.04	factor 2 (PDF fits)
Renormalization and factorization scales	0.24	0.12	0.12	*0.06*	full NLO + *differential*
ME-PS matching threshold	0.18	0.09	0.09	*0.06*	full NLO + *differential*
Underlying event	0.15	0.15	0.15	*0.06*	*differential*
Color reconnection effects	0.54	0.27	*0.2*	*0.06*	factor 2 + *differential*
Systematic	0.98	0.60	0.44	0.20	
Statistical	0.43	0.15	0.05	0.01	
Total	1.07	0.62	0.44	0.20	

The top-pair cross-section increases by a factor 5.7 between 7 and 14 TeV. This allows for a loss of 30% in trigger efficiency and acceptance, combined with a deterioration of jet resolution by a factor two