Top2015 conference on Ischia
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Statistical and systematic treatment issues in top mass combinations

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on behalf of the ATLAS and CMS collaborations

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Why combinations?

- The top quark mass has been measured with ever increasing precision using

	Combined?
direct measurements	yes
pole mass measurements	no
alternative measurements	no

- Further precision gain by
  - careful optimisation of several medium-sized uncertainties
  - combination of sufficiently uncorrelated measurements

How m_{top} is combined

- Best Linear Unbiased Estimate[1] (BLUE)
  - combined result is a linear weighted sum of input measurements
  - coefficients are chosen to minimize variance, taking into account all uncertainty components and the corresponding estimator correlations
  - normalisation condition ($\sum w_i = 1$) preserves unbiased estimate

Focus on combination and uncertainties of direct ATLAS and CMS measurements

[1] NIM A270 (1988) 110

Uncertainties and correlations

- For a reliable combination it is mandatory to
  - first **find a mapping** between e.g. ATLAS and CMS uncertainty categories and unify the approaches if necessary

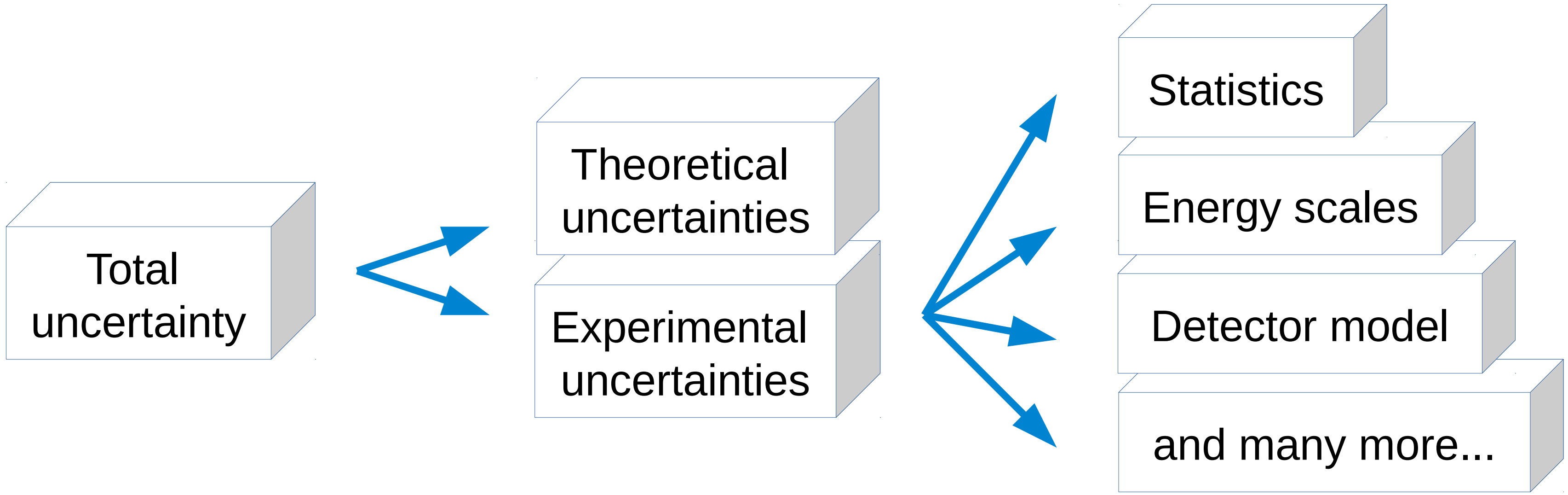
Worked out within the LHCtopWG

Description	Component names, CMS	Component name, ATLAS	Correlation range
1a. Statistical	RelativeStatEC2; RelativeStatHF; AbsoluteStat	Statistical components for *in situ* calibration, **Z**-jet width	Uncorrelated
1b. Detector	AbsoluteScale; RelativeJEREC1; RelativeJEREC2; RelativeJERHF	Electron/photon energy scale, γ-jet jet energy resolution	Uncorrelated
2. Modeling uncertainties for γ-jet **and Z**-jet	AbsoluteMPFBias	γ-jet and **Z**-jet: radiation suppression, out-of-cone and MC generator difference; γ-jet photon purity; **Z**-jet extrapolation;	0-50%
3. Modeling uncertainties for relative correction	RelativeFSR	$\eta-$intercalibration modeling	50-100%
4. Uncertainties related to jet partonic flavor	Flavor; AbsoluteFlavorMapping	Flavor composition and response	0-100%
5. $b-$**jet uncertainties**	Flavor	$b-$jet response	50-100%
6. Pileup correction	PileUpDataMC; PileUpPtBB; PileUpBias; PileUpOOT; PileUpJetRate; PileUpPtEC; PileUpPtHF	Pileup calibration; effects of pileup on *in situ* methods	Uncorrelated
7. High-p_T **uncertainties**	HighPtExtra; SinglePion	High-p_T	Uncorrelated
8. Close-by jet uncertainties		Close-by	Uncorrelated
9. Other uncertainties not matching between the two experiments	Time	Multijet balance components, Closure of the calibration	Uncorrelated

ATL-PHYS-PUB-2014-020 / CMS PAS JME-14-003

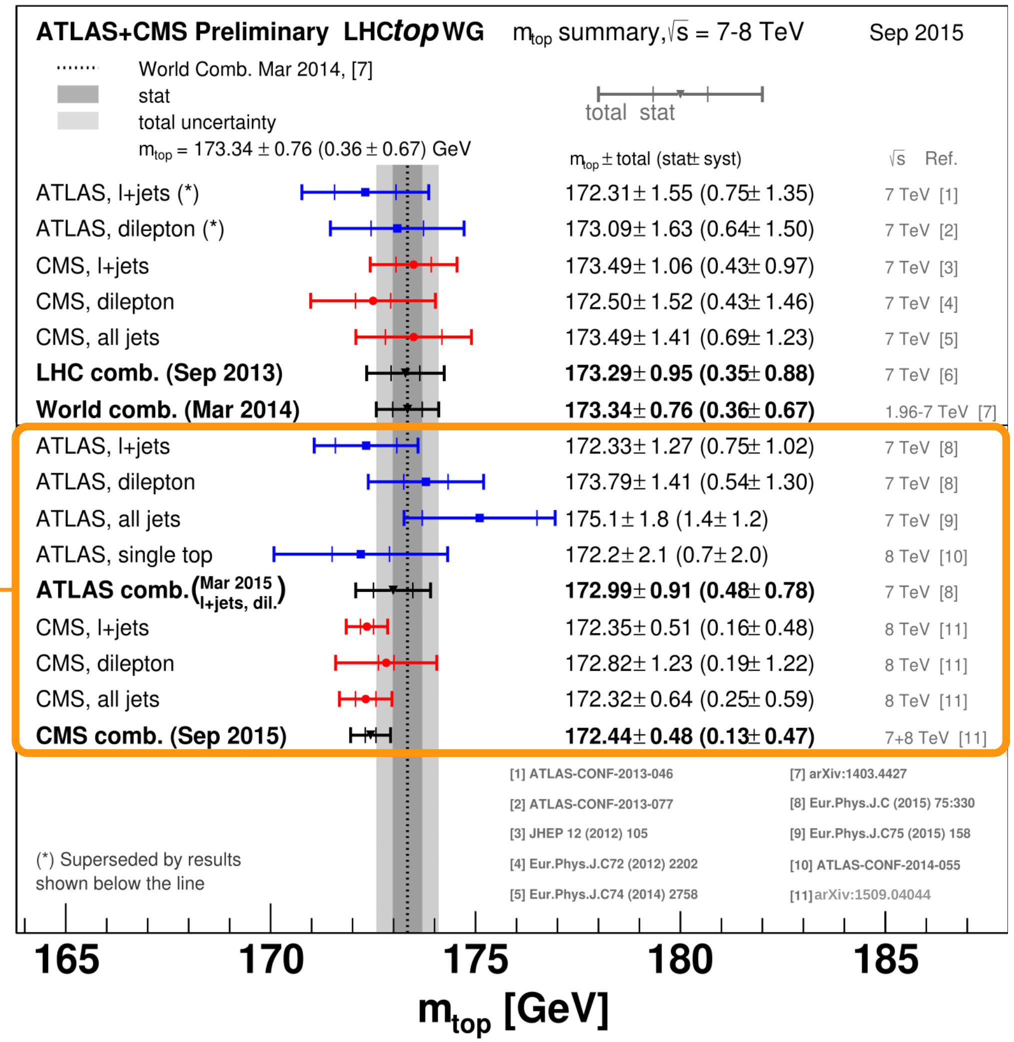
Uncertainties and correlations

- For a reliable combination it is mandatory to
  - first **find a mapping** between e.g. ATLAS and CMS uncertainty categories and unify the approaches if necessary
  - then **understand and test the correlations** for each uncertainty category



Top mass combinations

- The most precise measurements per channel have been combined for
  - Tevatron and LHC[1] (2014)
  - LHC[2] (2013)
  - Tevatron[3] (2014)
  - CMS only[4] (2015)
  - ATLAS only[5] (2015)
- The relevant correlations have carefully been estimated and stability tests have been performed
- The progress on the most important issues regarding the combination of measurements will be shown in the following



New results waiting for combination!
(in addition to latest results from Tevatron)

[1]arXiv:1403.4427 [hep-ex] [2]ATLAS-CONF-2013-102 / CMS PAS TOP-13-005 [3]arXiv:1407.2682 [hep-ex] [4]arXiv:1509.04044 **NEW** [5]Eur. Phys. J. C (2015) 75:330

Radiation uncertainties

Pythia / Herwig comparison and hadronisation

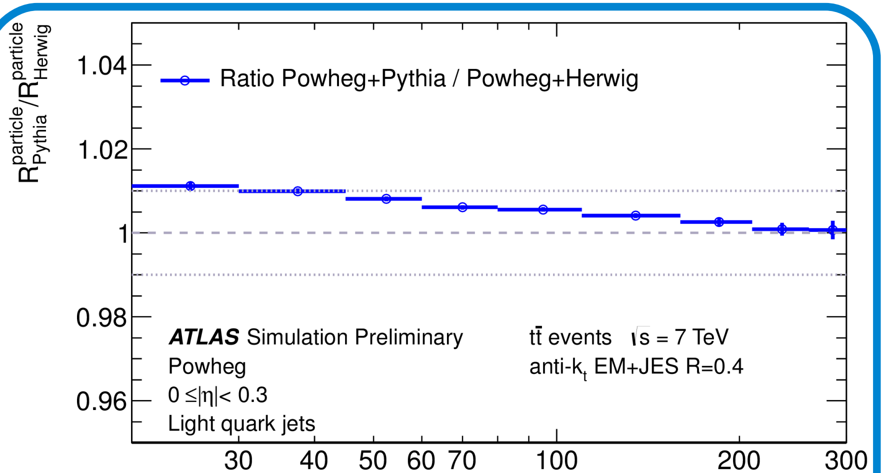
- Uncertainty related to parton shower / hadronisation models
  - at ATLAS, it is evaluated by a direct comparison of Pythia and Herwig samples, thus covering e.g. different parton showers (p_T vs. angular ordered), parton shower matching, fragmentation functions, tunes, hadronisation model (cluster vs. string) etc.
  - at CMS, Pythia / Herwig comparison in is performed as a cross-check, alternative uncertainties are quoted
- JES evaluation is also partially based on Pythia / Herwig particle level jet response comparison
  - → Possible double-counting for ATLAS!
- Needs to be clarified, since impact on analysis can be large, up to O(500 MeV)!

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

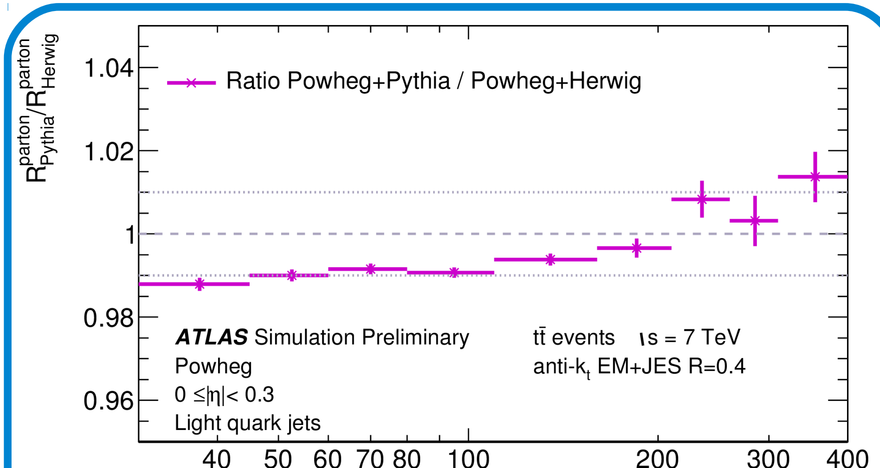
JES double-counting at ATLAS

... in Pythia / Herwig comparison

- ATLAS assumes effects are beyond those included in the JES, quotes full Pythia / Herwig difference
- Recalibrate Pythia sample to match jet response in Herwig → removes response differences
  - flavour inclusively (removes JES double-counting)
  - flavour-by-flavour, using parton matching (removes JES and bJES double-counting)



Particle level response



Parton level response

ATL-PHS-PUB-2015-042 **NEW**

JES double-counting at ATLAS

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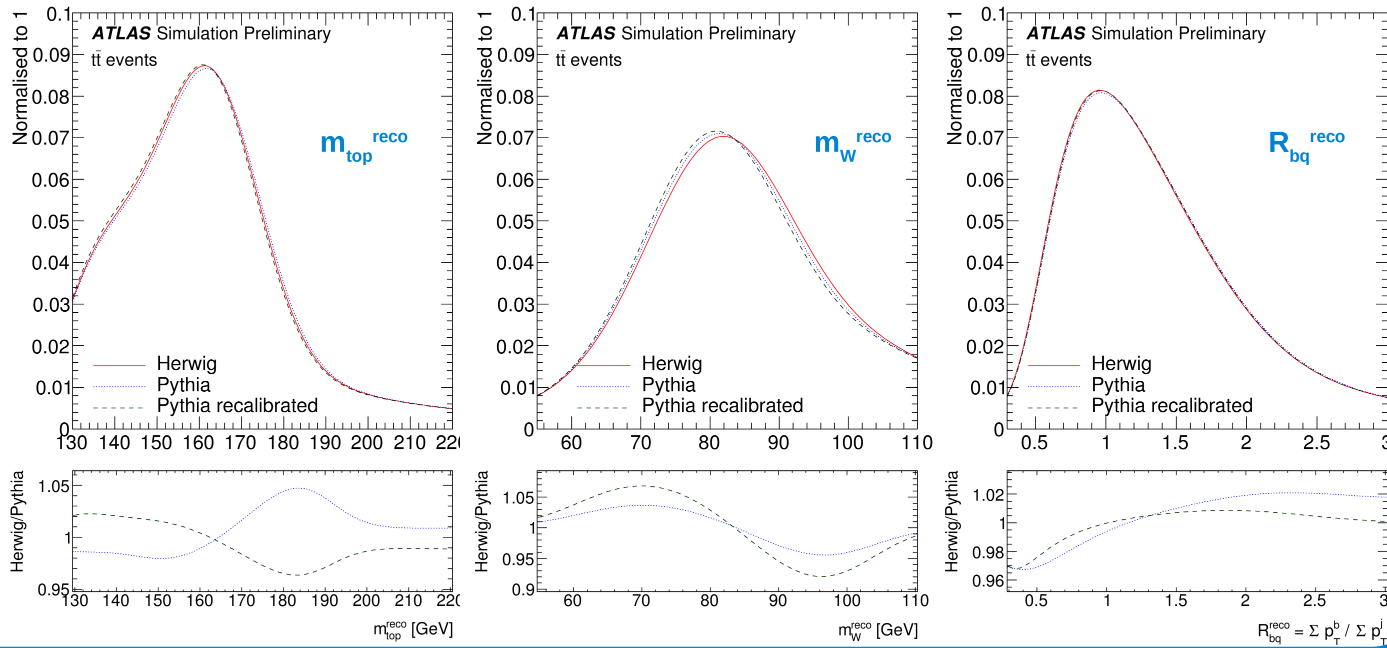
  - flavour-by-flavour, using parton matching (removes JES and bJES double-counting)

Recalibration effect on sample fits



ATL-PHS-PUB-2015-042 **NEW**

JES double-counting at ATLAS

… in Pythia / Herwig comparison

- ATLAS assumes effects are beyond those included in the JES, quotes full Pythia / Herwig difference
- Recalibrate Pythia sample to match jet response in Herwig → removes response differences
  - flavour inclusively (removes JES double-counting)
  - flavour-by-flavour, using parton matching (removes JES and bJES double-counting)
- Particle and parton level Pythia / Herwig jet response differences are partly responsible for the observed mass shifts*
- Observation:
  - a fit within the framework of the l+jets analysis shows no significant change in hadronisation uncertainty

➡ Double-counting between Pythia / Herwig comparison and JES for the 3d l+jets analysis is small

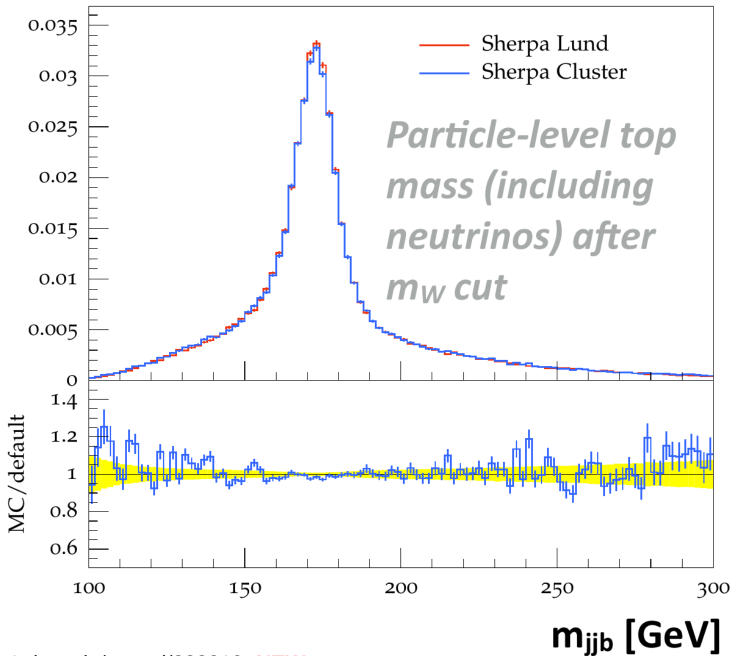
ATL-PHS-PUB-2015-042 **NEW**

*more information in the backup

Hadronisation uncertainty at CMS

Details and studies

- CMS quotes alternative uncertainties:
  - **flavour dependent hadronisation uncertainty:** flavour-dependent difference (gluon, light, *b*) with respect to nominal response is evaluated from Pythia and Herwig according to expected flavour composition of the sample
  - ***b*-fragmentation and *B*-branching fraction:** variation of tunes and branching ratio
  - no extra ttbar (event topology) specific hadronisation considered
- Studies:
  - particle level study with Sherpa using same parton shower but different hadronisation models. Minor effect on particle jet response and observable distributions[1].
  - no evidence for topology dependence seen in bJES from Z+*b* events[1]
  - Pythia / Herwig difference appears to be mainly due to parton shower and tuning differences[2]



[1]May 21st 2015 LHCtopWG talk: https://indico.cern.ch/event/375429

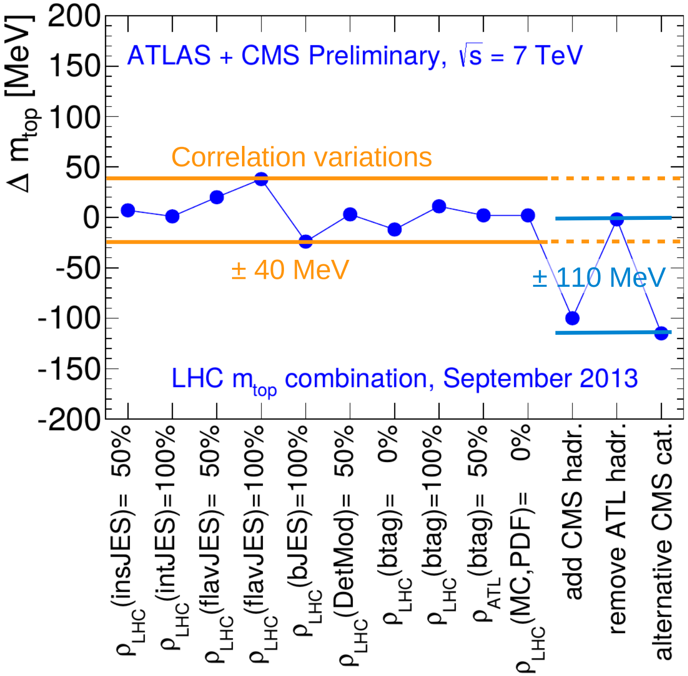
[2]https://bib-pubdb1.desy.de/record/222219 NEW

How to assign the correlations

Assignment and variation

- Assign correlation ρ_{exp}, ρ_{LHC} and ρ_{year} depending on case by case arguments and verify the stability of the choice.

ρ_{exp}	→	within experiments	→	eg. dil⊕l+jets
ρ_{LHC}	→	across experiments	→	ATLAS⊕CMS
ρ_{year}	→	across datasets	→	eg. 7⊕8 TeV

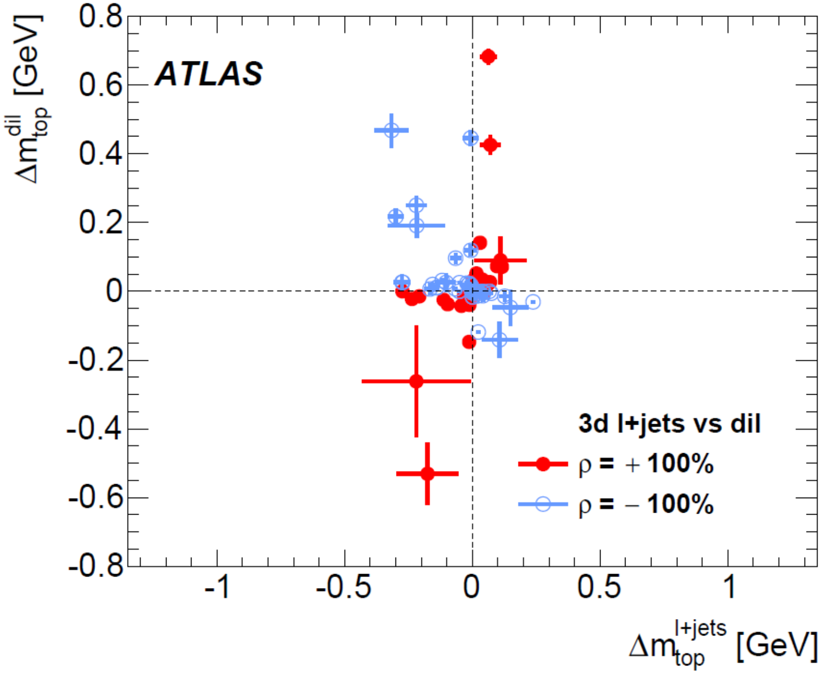


Uncertainty categories			Chosen central values for correlations		
General	ATLAS	CMS	$\rho_{exp}^{[1]}$	$\rho_{LHC}^{[1]}$	$\rho_{year}^{[2]}$
Statistical			0	0	0
Method			0	0	0
Background from data			0	0	0
MC modelling	Background from MC		1	1	1
	MC generator		1	1	1
	Hadronisation		1		1
	Radiation		1	1	1
	Colour reconnection		1	1	1
	Underlying event		1	1	1
Proton PDF			1	1	1
Reco.	Jet reconstruction		1	0	1
	Lepton reconstruction		1	0	1
	E_T^{miss}		1	0	1
b-tagging			1	0.5	1
JES	uncorrelated JES comp.		1	0	0
	in-situ γ/Z JES comp.		1	0	1
	intercalib. JES comp.		1	0.5	1
	flavour JES comp.		1	0	1
	b-jet energy scale		1	0.5	1

[1]ATLAS-CONF-2013-102 / CMS PAS TOP-13-005 [2]CMS-PAS-TOP-14-015 JES uncertainty correlations discussed in ATL-PHYS-PUB-2014-020 / CMS PAS JME-14-003

Direct evaluation of correlations

ATLAS combination in the dilepton and l+jets channel



- Analyses use same setup and uncertainty definitions
  - systematic sources are assumed to be 100% correlated
- Determination of the correlation of effect on estimators for every source of systematic uncertainty
  - vary systematic effect simultaneously and investigate m_{top} changes
  - estimates are either fully correlated (both up or down) or anti-correlated (one up, one down), distinction is unambiguous in this case
- Total correlation of the channels: $\rho_{tot} = -7\,\%$

- Combination of the channels using the BLUE technique[1] yields a **28% precision gain** with respect to the most precise input measurement!

$$m_{top}^{l+jets} = \ 172.33 \pm 1.27 \ \ \mathrm{GeV}$$

-28% uncertainty

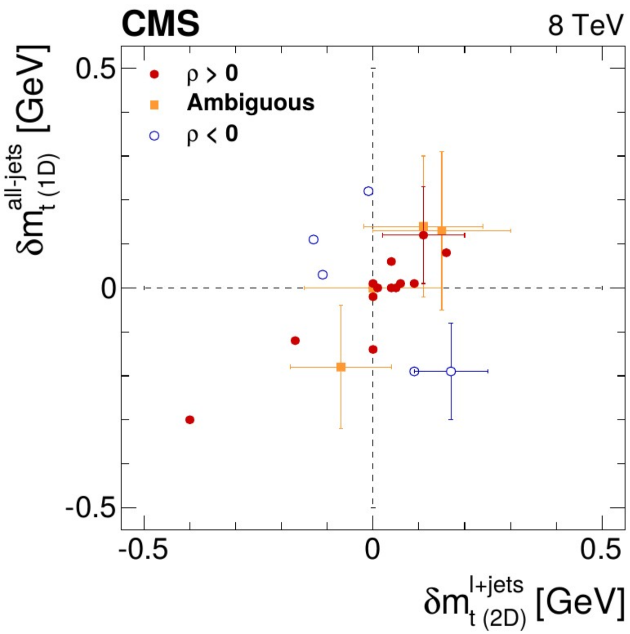
$$m_{top}^{comb} = \ 172.99 \pm 0.91 \ \ \mathrm{GeV}$$

Eur. Phys. J. C (2015) 75:330

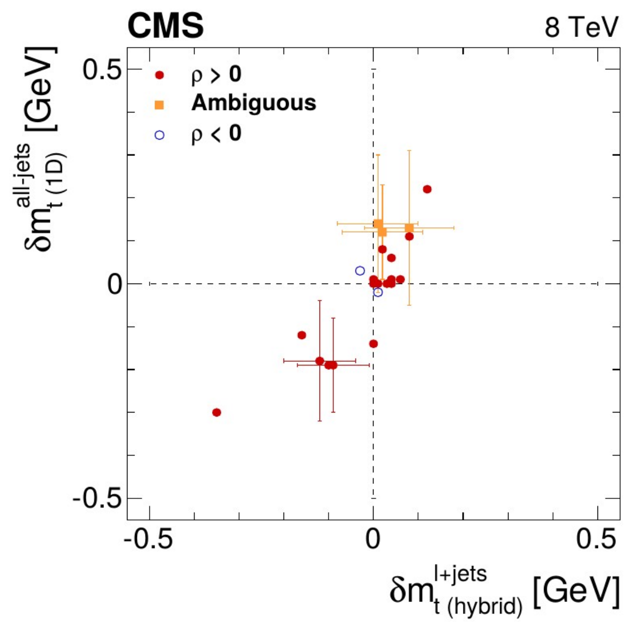
[1]http://blue.hepfoge.org

Direct evaluation of correlations

CMS combination between all three channels



- Analyses use same setup and uncertainty definitions
- Same as for ATLAS, but uncertainties cannot be unambiguously matched to a quadrant
- Hybrid fit, employing a soft constraint on the jet energy calibration in addition to its fit, removes anti-correlations



- CMS defines correlations as $\rho = \frac{\sigma_i}{\sigma_j}$, with $\sigma_i < \sigma_j$ being the two uncertainty components under study
- This ensures $\rho < 1$ and results in a combined value of

$$m_{\text{top}}^{\text{l+jets}} = 172.35 \pm 0.51 \text{ GeV} \qquad m_{\text{top}}^{\text{l+jets}} = 172.14 \pm 0.62 \text{ GeV}$$

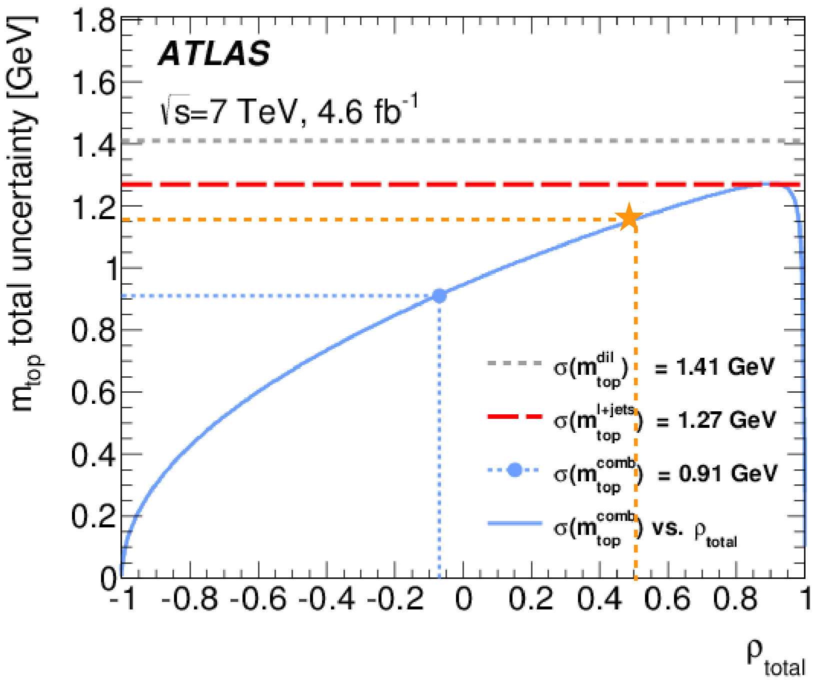
-4% (hybrid) **-21% (2D)**

$$m_{\text{top}}^{\text{comb}} = 172.44 \pm 0.49 \text{ GeV}$$

arXiv:1509.04044 **NEW**

Comparison to standard scenario

Gain by proper correlation estimation



Most precise input measurement (l+jets)
-0%

Standard correlations à la LHC comb.
-9%

Evaluated correlations from ATLAS comb.
-28%

- Assigned correlations often turn out to be too large
- Different estimators may even have negative correlations!
- The table shows the effect for the leading systematic uncertainties for the ATLAS combination

	Assigned		Evaluated	
Uncertainty categories	$\rho_{\rm exp}^{[2]}$	$m_{\rm top}^{[3]}$	$\rho_{\rm exp}^{[1]}$	$m_{\rm top}^{[1]}$
Central calues		172.91		172.99
Hadronisation	1.00	0.32	1.00	0.34
ISR/FSR	1.00	0.38	-1.00	0.04
Colour reconnection	1.00	0.12	-1.00	0.00
JER	1.00	0.21	-1.00	0.03
b-tagging	1.00	0.33	-0.77	0.25
JES	1.00	0.65	-0.23	0.41
bJES	1.00	0.31	1.00	0.34
Total Syst		1.05		0.78
Full	0.51[3]	1.16	-0.07	0.91

- Improvement with respect to most precise input and number of combined measurements in the
  - LHC combination: -10% 8 meas.
  - world combination: -28% 11 meas.
- A lot to be gained! What do we need for that?

Values taken from: [1]ATLAS comb.: Eur. Phys. J. C (2015) 75:330 [2]LHC comb.: ATLAS-CONF-2013-102 / CMS PAS TOP-13-005 [3]BLUE combination using unc. from [1] and corr. from [2]

Thoughts on future combinations

… across experiments

Unification

MC modelling

- Have one identical MC setup across experiments - studies already ongoing[1]
- Decide for a standard and use the others as systematic variation
- Improve understanding of residual Pythia / Herwig differences

Detector modelling

- Improve the matching of uncertainty components. JES is already well advanced[2].

Optimisation

Analysis design

- Find estimators with different sensitivity to the main uncertainties
- Use different techniques (1D, 2D, 3D, templates, matrix, endpoint...)

Measurement selection

- Non-unified or non-unifiable measurements yield little improvement and may even dilute the picture

⇨ Less independence and more discussion, but gain for physics!

[1]May 21st 2015 LHCtopWG talk: https://indico.cern.ch/event/375429

[2]ATL-PHYS-PUB-2014-020 / CMS PAS JME-14-003

Conclusions

Summary

- Unification of uncertainty categories is progressing, intense discussions within the LHCtopWG and other forums
- Plenty of new and precise measurements are waiting to be combined!

Outlook

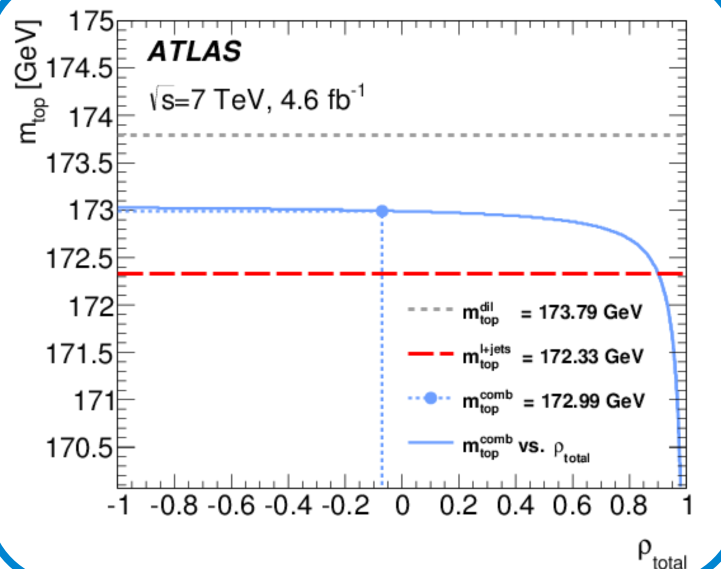
- The potential gain of combinations is large
- A detailed understanding of correlations is the key to successful combinations
- This is only possible with a well motivated uncertainty mapping across experiments

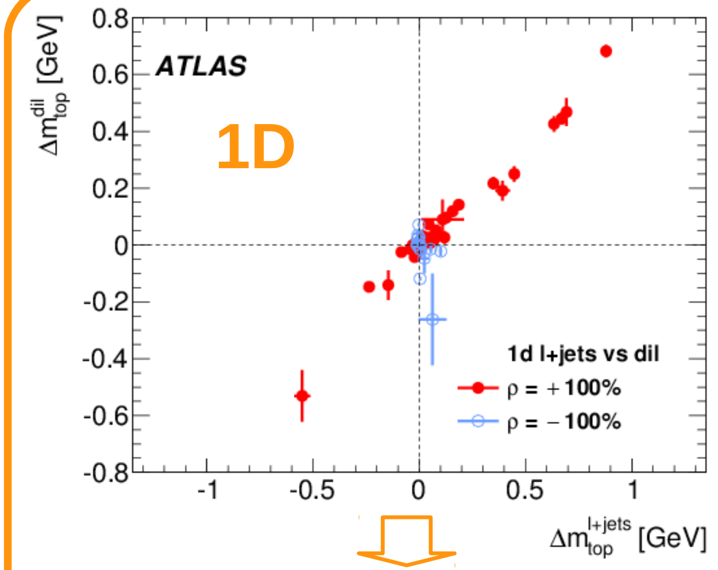
Move from combining published measurements to publishing combined measurements?

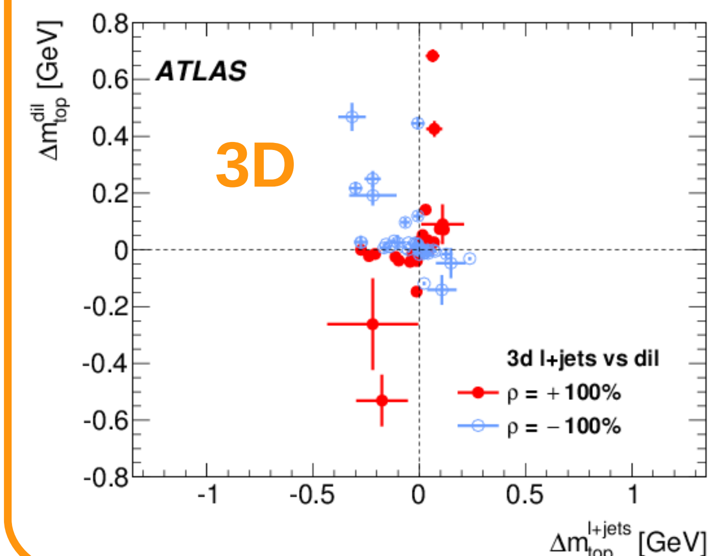
Thank you for your attention!

Supporting figures: decorrelation

- Dependence of the combined central value for the ATLAS combination on the total correlation ρ
- Reduction of the uncertainties and estimator correlations caused by additional dimensions







How to assign the correlations

Statistical and modelling uncertainties

- Assign correlation ρ_{exp}, ρ_{LHC} and ρ_{year} depending on case by case arguments and verify the stability of the choice.

ρ_{exp}	→	within experiments	→	eg. dil⊕l+jets
ρ_{LHC}	→	across experiments	→	ATLAS⊕CMS
ρ_{year}	→	across datasets	→	eg. 7⊕8 TeV

Statistical, fit method related and data based uncertainties are uncorrelated

Full correlation for modelling uncertainties is assumed, because they describe mostly the same physics effects in both experiments

Modelling of detector specific effects regarding jet, lepton and E_T^{miss} reconstruction (other than JES and *b*-tagging)

Modelling of b-tagging efficiency and light jet rejection factors. For the LHC combination, ρ_{LHC} has been assigned a value with conservative effect on the total uncertainty.

Variation: ρ_{LHC} = 0 – 1

Uncertainty categories			Chosen central values for correlations		
General	ATLAS	CMS	ρ_{exp} [1]	ρ_{LHC} [1]	ρ_{year} [2]
Statistical			0	0	0
Method			0	0	0
Background from data			0	0	0
MC modelling	Background from MC		1	1	1
	MC generator		1	1	1
	Hadronisation		1		1
	Radiation		1	1	1
	Colour reconnection		1	1	1
	Underlying event		1	1	1
Proton PDF			1	1	1
Reco.	Jet reconstruction		1	0	1
	Lepton reconstruction		1	0	1
	E_T^{miss}		1	0	1
b-tagging			1	0.5	1
JES	uncorrelated JES comp.		1	0	0
	in-situ γ/Z JES comp.		1	0	1
	intercalib. JES comp.		1	0.5	1
	flavour JES comp.		1	0	1
	b-jet energy scale		1	0.5	1

[1]ATLAS-CONF-2013-102 / CMS PAS TOP-13-005 [2]CMS-PAS-TOP-14-015

How to assign the correlations

Jet energy scale uncertainty components

- Assign correlation ρ_{exp}, ρ_{LHC} and ρ_{year} depending on case by case arguments and verify the stability of the choice.

ρ_{exp}	→	within experiments	→	eg. dil ⊕ l+jets
ρ_{LHC}	→	across experiments	→	ATLAS ⊕ CMS
ρ_{year}	→	across datasets	→	eg. 7 ⊕ 8 TeV

Effects from limited data statistics in the JES calibration, pile-up suppression techniques, detector specifics and single high p_T particles

Relative balance modeling, η and p_T intercalibration uncertainty. Same generators are used for modelling at ATLAS and CMS, but different analysis procedures have decorrelating effects.

Variation: ρ_{LHC} = 0 – 0.5

Uncertainty categories			Chosen central values for correlations		
General	ATLAS	CMS	$\rho_{exp}^{[1]}$	$\rho_{LHC}^{[1]}$	$\rho_{year}^{[2]}$
Statistical			0	0	0
Method			0	0	0
Background from data			0	0	0
MC modelling	Background from MC		1	1	1
	MC generator		1	1	1
	Hadronisation		1		1
	Radiation		1	1	1
	Colour reconnection		1	1	1
	Underlying event		1	1	1
Proton PDF			1	1	1
Reco.	Jet reconstruction		1	0	1
	Lepton reconstruction		1	0	1
	E_T^{miss}		1	0	1
b-tagging			1	0.5	1
JES	uncorrelated JES comp.		1	0	0
	in-situ γ/Z JES comp.		1	0	1
	intercalib. JES comp.		1	0.5	1
	flavour JES comp.		1	0	1
	b-jet energy scale		1	0.5	1

[1]ATLAS-CONF-2013-102 / CMS PAS TOP-13-005 [2]CMS-PAS-TOP-14-015 JES uncertainty correlations discussed in ATL-PHYS-PUB-2014-020 / CMS PAS JME-14-003

How to assign the correlations

Jet energy scale uncertainty components

- Assign correlation ρ_{exp}, ρ_{LHC} and ρ_{year} depending on case by case arguments and verify the stability of the choice.

ρ_{exp}	→	within experiments	→	eg. dil ⊕ l+jets
ρ_{LHC}	→	across experiments	→	ATLAS⊕CMS
ρ_{year}	→	across datasets	→	eg. 7⊕8 TeV

Inter-experiment correlation due to similar techniques (Z-jet ballance, MPF[1]), and shared components. Other components and uncertainty evaluation are not shared.

[1]E_T^{Miss} Projection Fraction

Variation: ρ_{LHC} = 0 – 0.5

For the flavour response (no *b*-flavour) uncertainty, the same generators are used in both experiments

Variation: ρ_{LHC} = 0 – 1

Uncertainty categories			Chosen central values for correlations		
General	ATLAS	CMS	$\rho_{exp}^{[1]}$	$\rho_{LHC}^{[1]}$	$\rho_{year}^{[2]}$
Statistical			0	0	0
Method			0	0	0
Background from data			0	0	0
MC modelling	Background from MC		1	1	1
MC modelling	MC generator		1	1	1
MC modelling	Hadronisation		1		1
MC modelling	Radiation		1	1	1
MC modelling	Colour reconnection		1	1	1
MC modelling	Underlying event		1	1	1
Proton PDF			1	1	1
Reco.	Jet reconstruction		1	0	1
Reco.	Lepton reconstruction		1	0	1
Reco.	E_T^{miss}		1	0	1
b-tagging			1	0.5	1
JES	uncorrelated JES comp.		1	0	0
JES	in-situ γ/Z JES comp.		1	0	1
JES	intercalib. JES comp.		1	0.5	1
JES	flavour JES comp.		1	0	1
JES	*b*-jet energy scale		1	0.5	1

[1]ATLAS-CONF-2013-102 / CMS PAS TOP-13-005 [2]CMS-PAS-TOP-14-015 JES uncertainty correlations discussed in ATL-PHYS-PUB-2014-020 / CMS PAS JME-14-003

How to assign the correlations

Jet energy scale uncertainty components

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ρ_{LHC} → across experiments → ATLAS⊕CMS
ρ_{year} → across datasets → eg. 7⊕8 TeV

Uncertainty categories			Chosen central values for correlations		
General	ATLAS	CMS	$\rho_{\rm exp}^{[1]}$	$\rho_{\rm LHC}^{[1]}$	$\rho_{\rm year}^{[2]}$
Statistical			0	0	0
Method			0	0	0
Background from data			0	0	0
MC modelling	Background from MC		1	1	1
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	Radiation		1	1	1
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Proton PDF			1	1	1
Reco.	Jet reconstruction		1	0	1
	Lepton reconstruction		1	0	1
	$E_{\rm T}^{\rm miss}$		1	0	1
b-tagging			1	0.5	1
JES	uncorrelated JES comp.		1	0	0
	in-situ γ/Z JES comp.		1	0	1
	intercalib. JES comp.		1	0.5	1
	flavour JES comp.		1	0	1
	b-jet energy scale		1	0.5	1

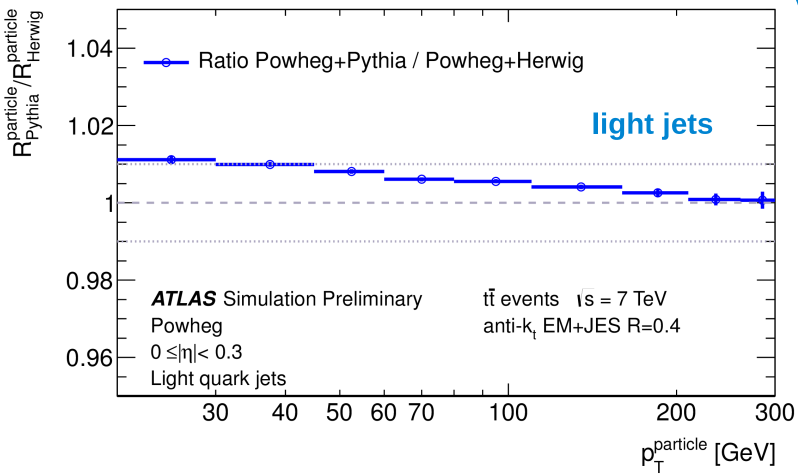
Covers b-fragmentation, hadronisation and soft radiation modelling for ATLAS and the full "flavour-dependent" response difference between light and *b*-jets for CMS

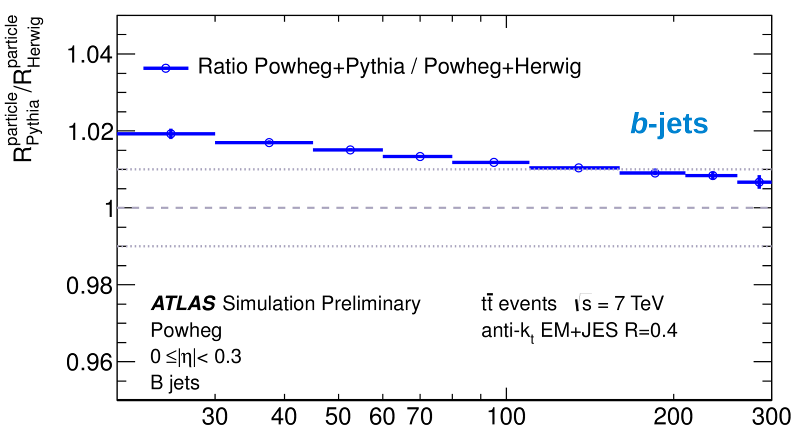
Variation: ρ_{LHC} = 0.5 - 1

[1]ATLAS-CONF-2013-102 / CMS PAS TOP-13-005   [2]CMS-PAS-TOP-14-015   JES uncertainty correlations discussed in ATL-PHYS-PUB-2014-020 / CMS PAS JME-14-003

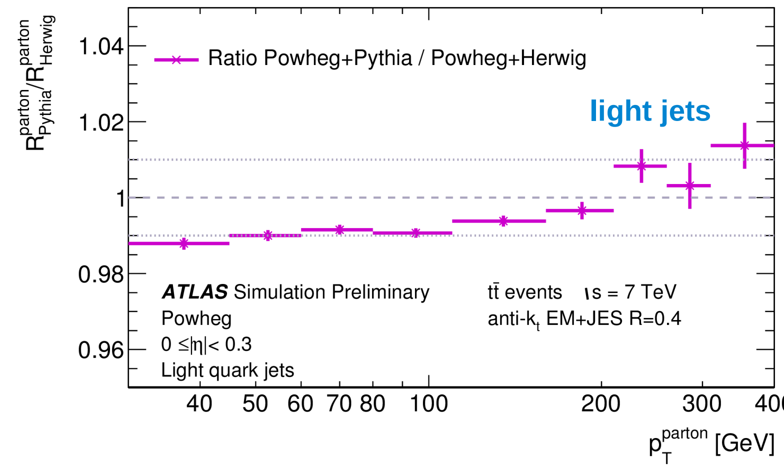
JES double-counting at ATLAS

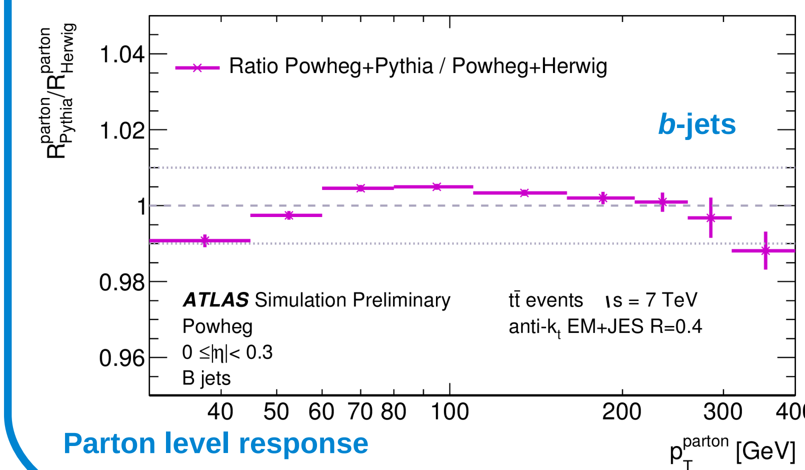
... in Pythia / Herwig comparison





Particle level response





Parton level response

- Different effects on p_T between particle and parton level with respect to detector level

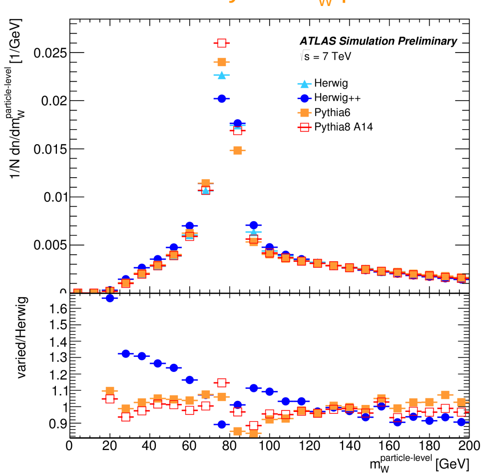
ATL-PHS-PUB-2015-042 **NEW**

JES double-counting at ATLAS

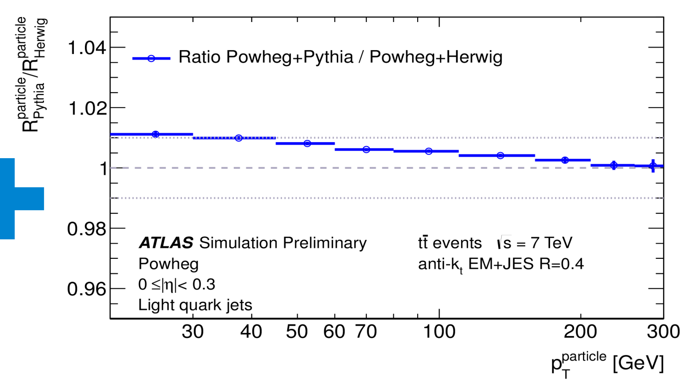
… in Pythia / Herwig comparison

- ATLAS assumes effects are beyond those included in the JES, quotes full Pythia / Herwig difference
- Recalibrate Pythia sample to match jet response in Herwig → removes response differences
  - flavour inclusively (removes JES double-counting)
  - flavour-by-flavour, using parton matching (removes JES and bJES double-counting)
- Particle and parton level Pythia / Herwig jet response differences are partly responsible for the observed mass shifts

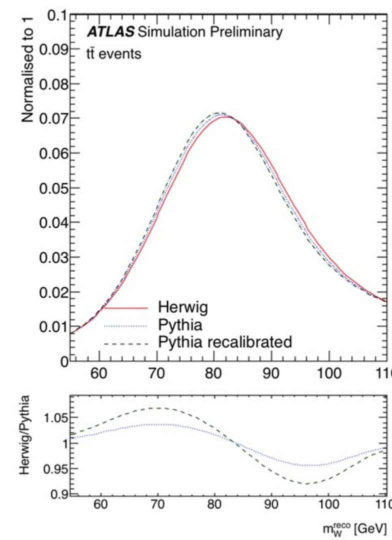
Particle level: Pythia m_W peak is low



Pythia is scaled down to match Herwig



m_W agreement becomes worse



ATL-PHS-PUB-2015-042 **NEW**

JES double-counting at ATLAS

… in Pythia / Herwig comparison

- Relative size of the hadronisation uncertainty for the different analyses

fit type	Channel	$\Delta m_{\text{top}}^{\text{tot}}$	$\Delta m_{\text{top}}^{\text{stat}}$	$\Delta m_{\text{top}}^{\text{had}}$
one-dimensional analysis:				
	fully hadronic [9]	1.0%	0.79%	0.29%
	di-lepton [2]	0.81%	0.31%	0.30%
	single top [10]	1.2%	0.40%	0.40%
two-dimensional analysis:				
	l+jets [11]	0.89%	0.20%	0.75%
three-dimensional analysis:				
	l+jets [11]	0.89%	0.43%	0.15%
	l+jets [2]	0.79%	0.43%	0.10%

- Relative effect of the recalibration procedure for the l+jets analysis

dim	jet calibration type	$\frac{\Delta m_{\text{top}}^{\text{had}\,\text{new}}}{\Delta m_{\text{top}}^{\text{had}\,\text{standard}}}$	$\frac{\Delta \text{JSF}^{\text{new}}}{\Delta \text{JSF}^{\text{standard}}}$	$\frac{\Delta \text{bJSF}^{\text{new}}}{\Delta \text{bJSF}^{\text{standard}}}$
1	inclusive re-calibration	-0.55	-	-
	flavour re-calibration	-1.00	-	-
2	inclusive re-calibration	1.01	2.01	-
	flavour re-calibration	0.70	1.80	-
3	inclusive re-calibration	1.21	2.03	0.95
	flavour re-calibration	1.29	1.81	0.54

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