TOPLHCWG

Combination of top observables at the Large Hadron Collider

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und Forschung

What is the TOPLHCWG?

Top quark measurements at the LHC

- large top quark samples available at 7 and 8 TeV
- precise measurements at ATLAS and CMS (e.g. m_{top} , $\sigma(t\bar{t})$, ...)

TOPLHCWG

- forum for discussions (ATLAS+CMS+theory) on combinations and interpretation of top physics measurements at the LHC
- integrated into LPCC (LHC Physics Centre at CERN)
  - *20 closed and 3 open meetings*

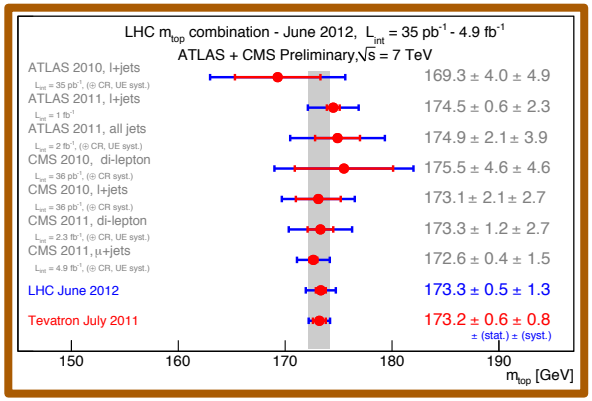
Results released so far

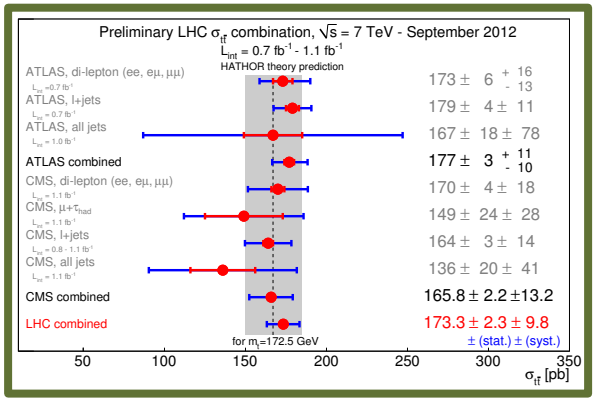
- top quark mass, July-12
- $t\bar{t}$ cross-section, September-12
- W polarisation in top decays, March-13

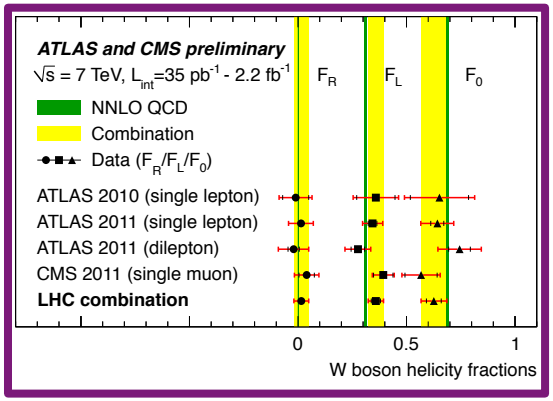
see http://lpcc.web.cern.ch/lpcc/index.php?page=top_wg_docs

First round of combinations

- allow to discuss/compare beyond the strict collaboration rules
- differences in systematics treatment identified
- recommendations for systematics of future measurements







Importance of combinations

- beware: results shown here are mostly outdated, since more precise measurements have been released by the collaborations
- but: procedures, categorisations, initial agreements reached; further improvements agreed upon/being discussed

Combination method: BLUE

BLUE method = *Best Linear Unbiased Estimator*

- optimal set of coefficients (weights) in a linear combination of input measurements
- minimising total uncertainty on the combined result
- takes uncertainties and correlations into account
  - *categorisation done based on physics origin and on correlation pattern*

Advantages

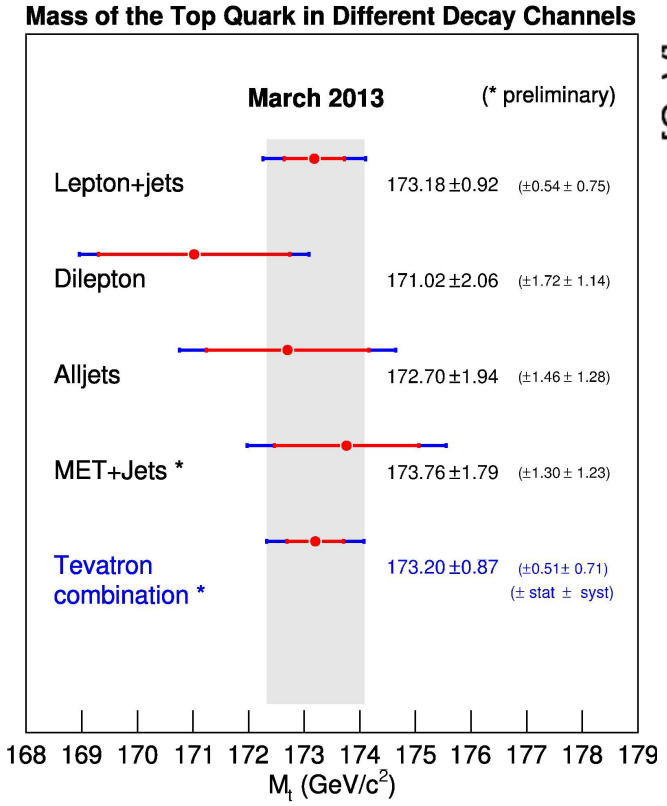
- well established, e.g. used for m_{top} at Tevatron
- makes future world averages technically easy

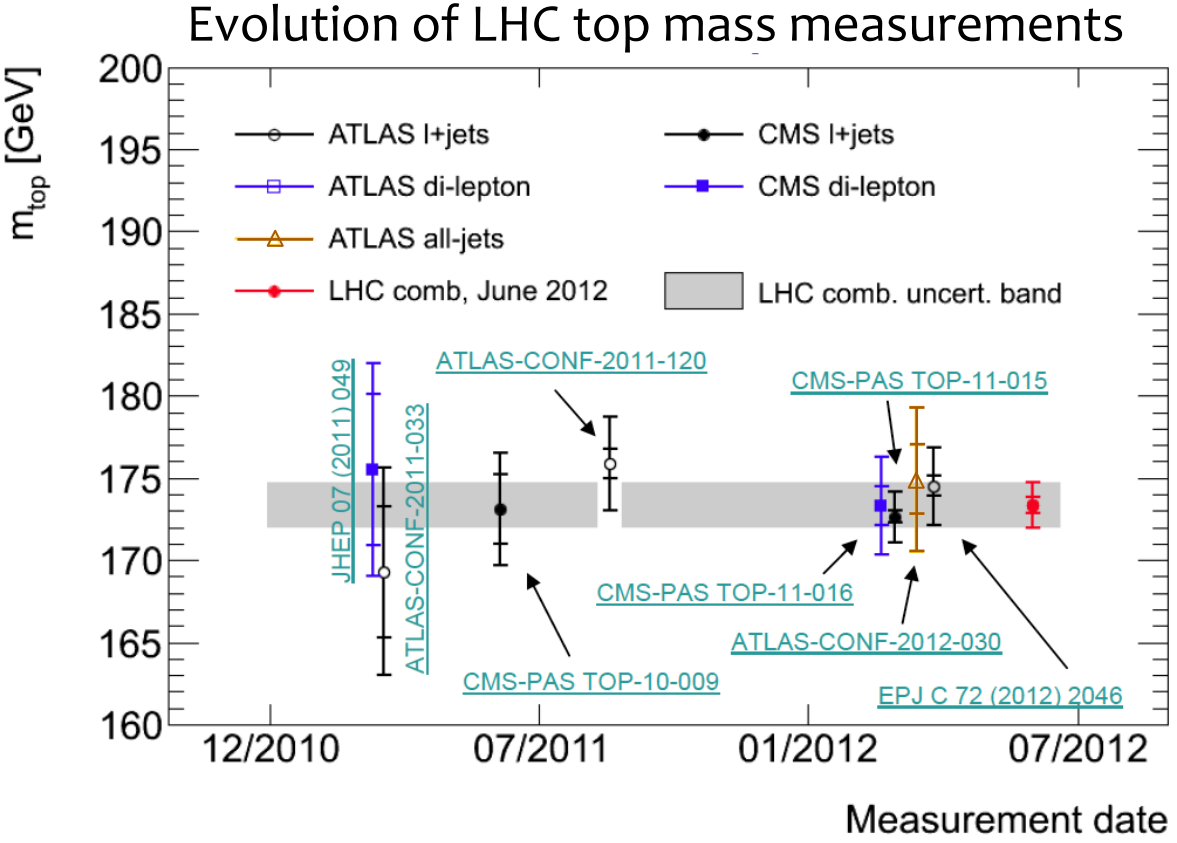
Experience/Features

- need to provide correlations (sometimes a good guess)
- typically requires symmetric uncertainties
- can yield neg. weights for correlated, less precise measurements
- cannot (trivially) enforce physical constraints

Top quark mass

TeVEWWG arXiv:1305.3929v1





- LHC and best Tevatron measurements are systematics limited
- combination at Tevatron improves on best measurement

  total uncert.: 1.11GeV (CDF ℓ+jets) → 0.87GeV (average) due to uncorrelated/ partially correlated systematics

Top mass combination

Careful categorisation of uncertainties

- following Tevatron convention for Jet Energy Scale (JES) categories
- not all systematics can be easily matched 1:1

Major numerical differences

- comparing best ℓ+jets 2011 measurements with similar 2D techiques

bJES
  - *ATLAS: large uncert. from dead material*

dJES
  - *CMS: performance of energy flow algorithm*

MC
  - *ATLAS: hadronisation uncertainty (Pythia vs Herwig) in $t\bar{t}$ events, in addition to hadronisation uncertainties included in JES*

	ATLAS	CMS
bJES	1.6GeV	0.7GeV
dJES	0.7GeV	0.2GeV
MC	0.4GeV	n/e

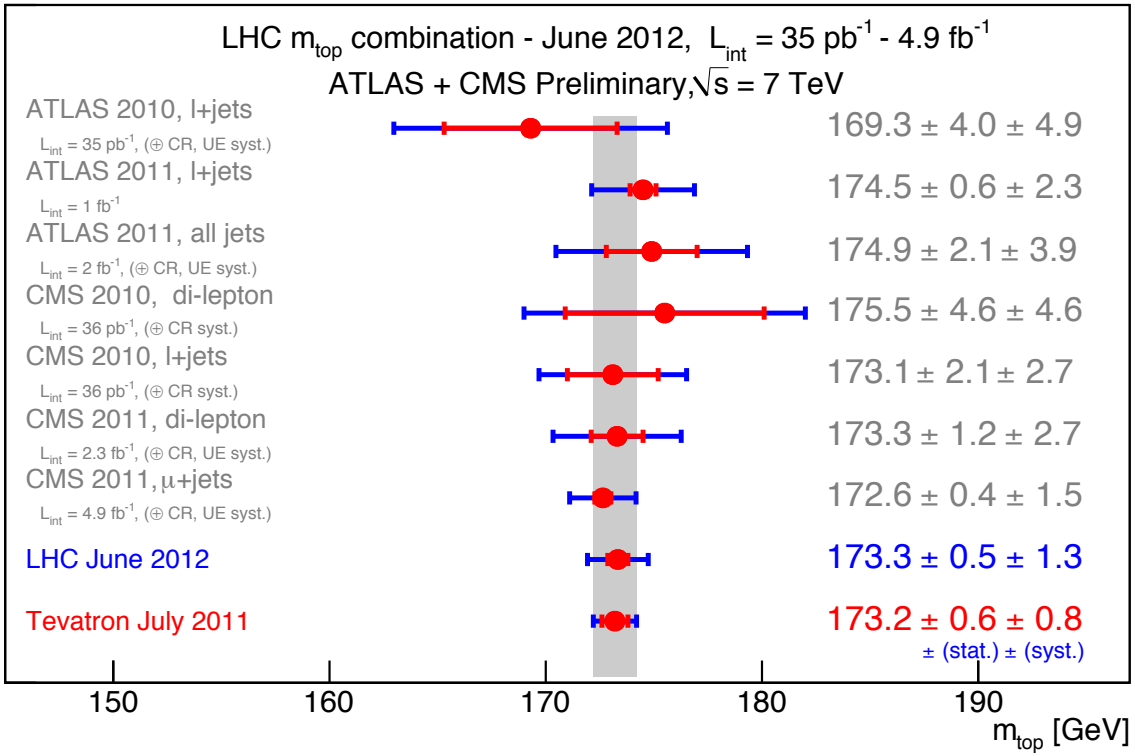
Top mass combination result

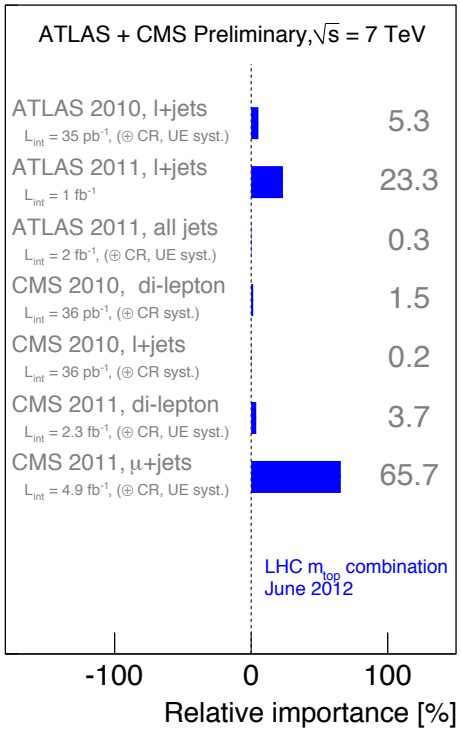
ATLAS-CONF-2012-095
CMS PAS TOP-12-001

	ATLAS			CMS				LHC
	2010	2011		2010		2011		
	l+jets	l+jets	all jets	di-l	l+jets	di-l	μ+jets	comb.
[GeV]								
Measured m_{top}	169.3	174.5	174.9	175.5	173.1	173.3	172.6	173.34
Stat	4.0	0.6	2.1	4.6	2.1	1.2	0.4	0.47
iJES	n/a	0.4	n/a	n/a	n/a	n/a	0.4	0.38
aJES	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
bJES	2.5	1.6	1.4	0.9	0.9	1.1	0.7	0.68
cJES	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
dJES	2.1	0.7	2.1	2.1	2.1	2.0	0.2	0.07
rJES	n/a	n/a	n/a	3.3	n/a	n/a	n/a	0.06
Lept	n/e	n/e	n/e	0.3	n/e	0.2	n/e	0.01
MC	1.0	0.4	0.5	0.4	n/e	0.1	n/e	0.04
Rad	2.5	1.0	1.7	0.9	1.2	0.8	0.8	0.69
CR	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.55
PDF	0.5	0.1	0.6	0.5	0.1	0.4	0.1	0.01
DTMO	1.2	0.3	0.5	0.6	0.4	0.7	0.3	0.19
UE	0.6	0.6	0.6	1.4	0.2	0.6	0.6	0.47
BGMC	1.8	0.1	n/a	0.1	0.2	n/a	0.1	0.01
BGDT	0.6	0.5	1.9	n/a	0.4	0.4	n/a	0.16
Meth	0.4	0.1	1.0	0.3	0.1	0.4	0.2	0.13
MHI	0.7	< 0.05	n/e	1.0	0.1	0.2	0.4	0.25
[GeV]								
Total Syst. Unc	4.9	2.3	3.9	4.6	2.7	2.7	1.5	1.33
Total Unc.	6.3	2.4	4.4	6.5	3.4	3.0	1.5	1.40
Comb. Coeff.[%]	-6.8	29.9	-0.4	-1.9	-0.2	-4.8	84.3	χ^2/ndf = 2.5/6
Relative importance[%]	5.3	23.3	0.3	1.5	0.2	3.7	65.7	χ^2 prob = 87%

Top mass summary

ATLAS-CONF-2012-095
CMS PAS TOP-12-001





- combined LHC result is 9% more precise than best input (CMS μ+jets)
- result is stable when varying the assumptions on correlations
- LHC m_{top} combination approaching Tevatron precision

Plans for future top mass combination

New results since first combination

- full 2011 dataset analysed by ATLAS and CMS
  - *CMS average: 173.54 ± 0.33 (stat.) ± 0.96 (syst.) GeV*
  - *ATLAS best ℓ+jets 172.31 ± 0.75 (stat.+JES+bJES) ± 1.35 (syst.) GeV*
  - *ATLAS dilepton 173.09± 0.64 (stat.) ± 1.50 (syst.) GeV*
- syst. uncert. cannot be directly compared due to different treatment
  - *for instance hadronisation*
- first 2012 analysis
  - *CMS B hadron decay length: 173.5 ± 1.5 (stat.) ± 1.3 (syst.) ± 2.6 ($p_{T(top)}$) GeV*

Next

- provide updated LHC combination
- combine with Tevatron → world average

Current work

Progress in categorisation of JES uncertainty

- methodologies and assumptions to derive corrections and uncertainties are not always directly comparable
- identified 5 categories according to physics and correlation

JES categories

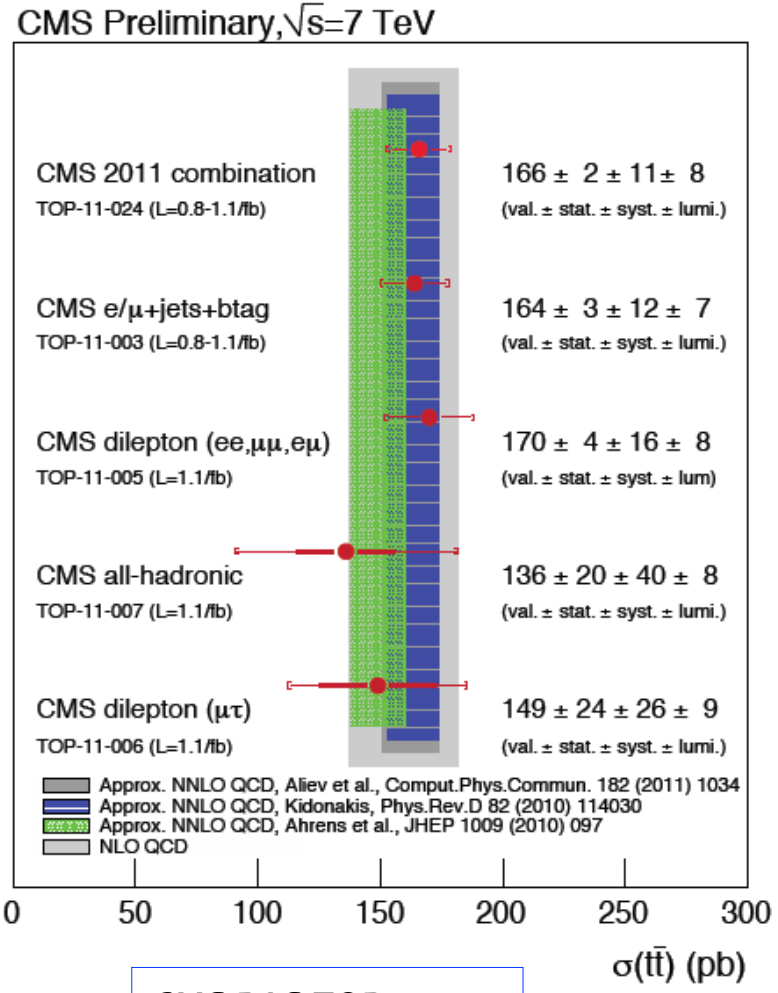
- uncorrelated
  - *e.g. statistical and detector-based components*
- common modeling in in-situ techniques (ρ= 0 – 0.5)
  - *γ-jet and Z-jet direct balance*
- model-dependence of relative calibration corrections (ρ= 0.5 – 1)
- jet response on partonic flavour (ρ= 0 – 1)
- b-jet energy scale (ρ= 0.5 – 1)

→ to be included in the next LHC top mass combination

similar work ongoing for b-tagging uncertainties

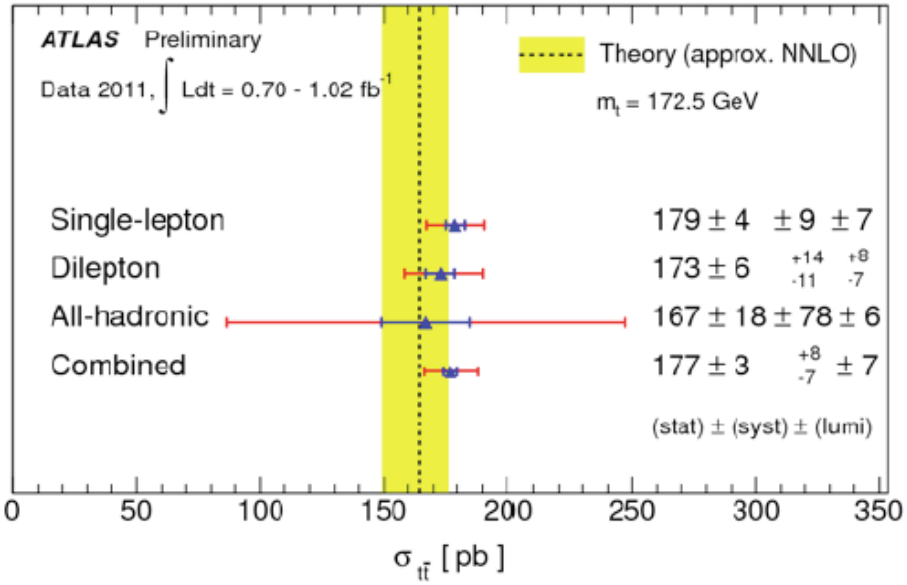
Combination of tt̄ production cross-section

Snapshot of 7 TeV results (Sept. 2012)



CMS PAS TOP-11-024

ATLAS-CONF-2012-024



Experiment combinations

ATLAS : 177 pb with 6.2% uncertainty

CMS: 166 pb with 8% uncertainty

Cross-section combination

ATLAS-CONF-2012-134
CMS PAS TOP-12-003

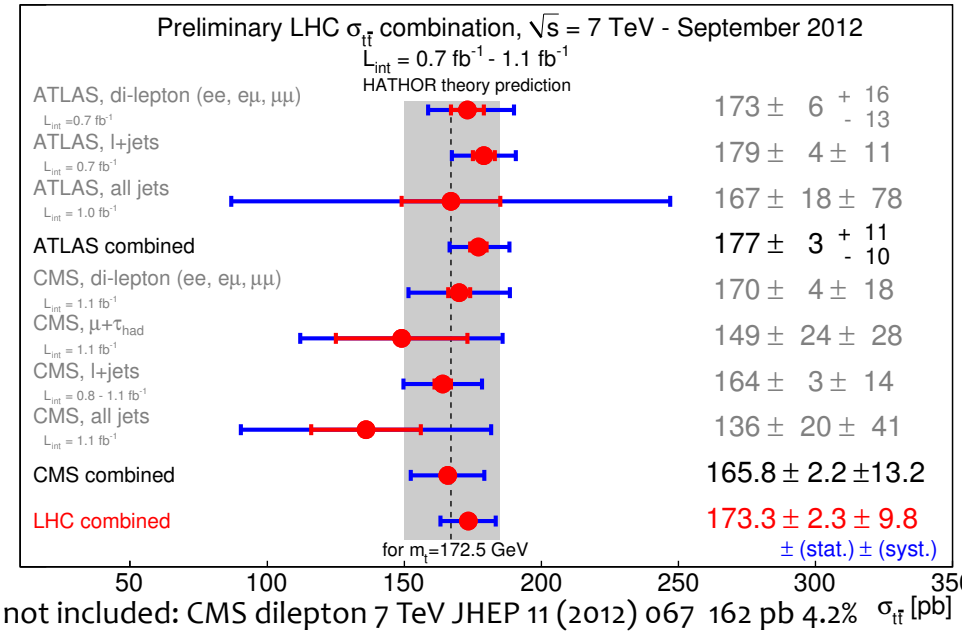
Combination

- Similar procedure and issues as for top quark mass combination

Luminosity uncertainty

- 53 (60)% of total uncertainty
- determined from van der Meer scans
  - *bunch currents: fully correlated*
  - *experiment specific: uncorrelated*

	ATLAS	CMS	Correlation	LHC combination
Cross-section	177.0	165.8		173.3
Uncertainty				
Statistical	3.2	2.2	0	2.3
Jet Enegy Scale	2.7	3.5	0	2.1
Detector model	5.3	8.8	0	4.6
•••				
Bunch current	5.3	5.1	1	5.3
Luminosity measurement	4.3	5.9	0	3.4
Total systematic	10.8	14.2		9.8
Total	11.3	14.4		10.1



Result

- total uncertainty reduced to 5.8%

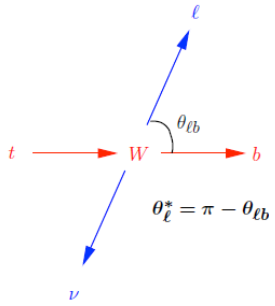
Next step

- combine 8 TeV measurements

W boson polarisation in top quark decays

Precisely predicted in SM

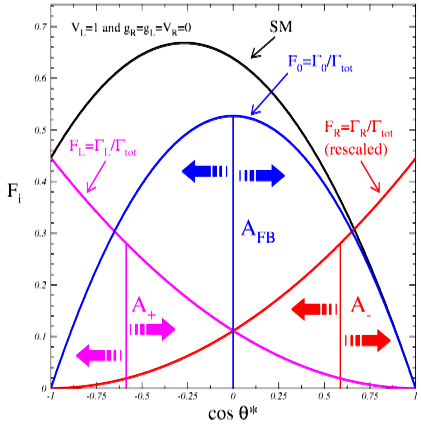
- right handed helicity F_R suppressed (V-A)
- measurements based on angle $\vartheta^*(l,-b)$ in W rest frame



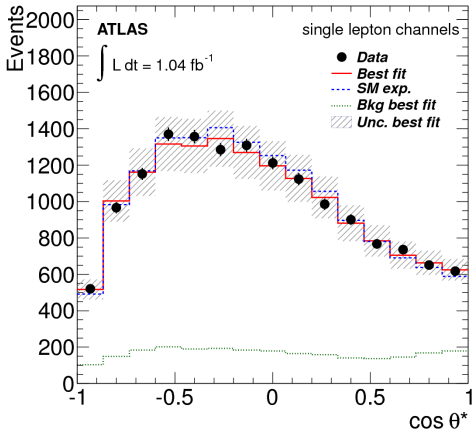
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_\mathrm{L} + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_\mathrm{R}$$

Use cosθ* distribution with different techniques

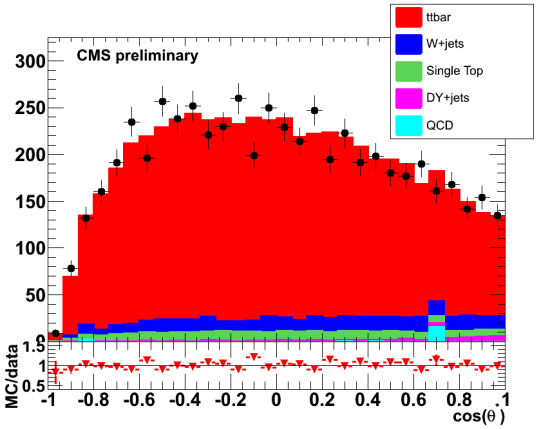
Angular asymmetries



Templates



Reweighting



- ATLAS 2010 ℓ+jets: templates
- ATLAS 2011 dilepton & ℓ+jets: templ./angular asymm.
- CMS 2011 μ+jets: reweighting

ATLAS-CONF-2011-037

JHEP 1206 (2012) 088

CMS PAS TOP-11-020

Inputs

ATLAS-CONF-2013-033
CMS PAS TOP-12-025

Modifications to the original measurements

- categories of systematic uncertainties
  - *merge several sources, like other combinations*
- new estimates of correlations (ATLAS)
  - *most important modification*
- uncertainty on top mass (ATLAS and CMS)
  - *changed to 1.4 GeV*
- pre-combination (ATLAS)
  - *according to channel not to method*

Detector modeling
Detector model
Jet energy scale
Luminosity and pile-up
Signal and background model
Monte Carlo
Radiation
Top-quark mass
PDF
Background (MC QCD)
Background (MC W + jets)
Background (MC other)
Background (data-driven)
Method-specific uncertainties
Method

Fit

- Simultaneous fit for F_0 and F_L
- Input to combination

More recent CMS dilepton result not included

Measurement	F_0	F_L	F_R
ATLAS 2010 (single lepton) [Alj2010]	$0.652 \pm 0.134 \pm 0.092$	$0.359 \pm 0.088 \pm 0.056$	$-0.011 \pm 0.060 \pm 0.046$
ATLAS 2011 (single lepton) [Alj2011]	$0.642 \pm 0.030 \pm 0.071$	$0.344 \pm 0.020 \pm 0.042$	$0.014 \pm 0.014 \pm 0.055$
ATLAS 2011 (dilepton) [Adil2011]	$0.744 \pm 0.050 \pm 0.087$	$0.276 \pm 0.031 \pm 0.051$	$-0.020 \pm 0.026 \pm 0.065$
CMS 2011 (single lepton) [Clj2011]	$0.567 \pm 0.074 \pm 0.048$	$0.393 \pm 0.045 \pm 0.024$	$0.040 \pm 0.035 \pm 0.043$

W polarisation result

ATLAS-CONF-2013-033
CMS PAS TOP-12-025

Correlations

- $\rho(F_i,F_j)$ from uncertainty propagation or averaged over measurements
- $\rho(F_0,F_0) = \rho(F_L,F_L) = -\rho(F_0,F_L)$

Main uncertainties

- statistical
- radiation and top quark mass
- detector model and JES

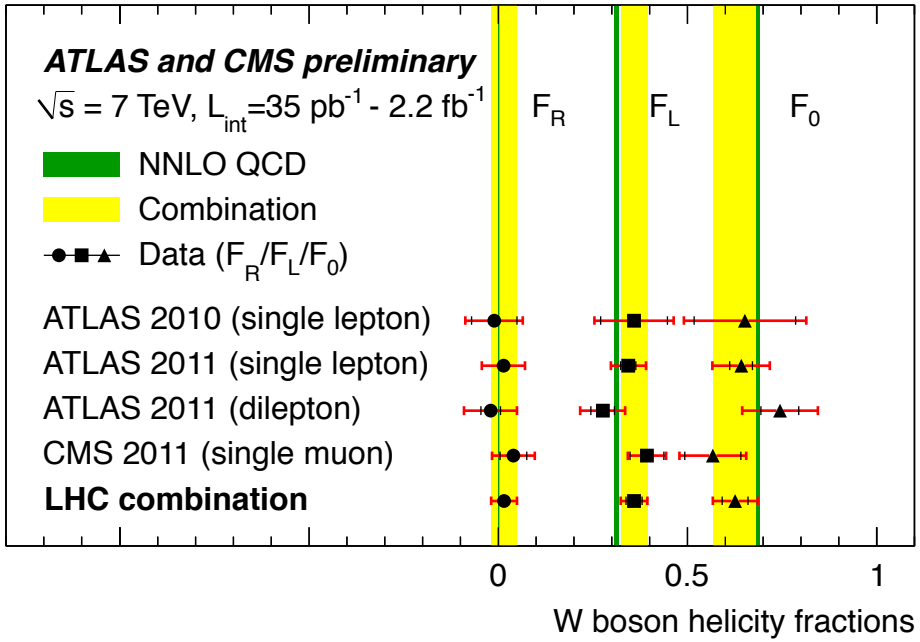
Result

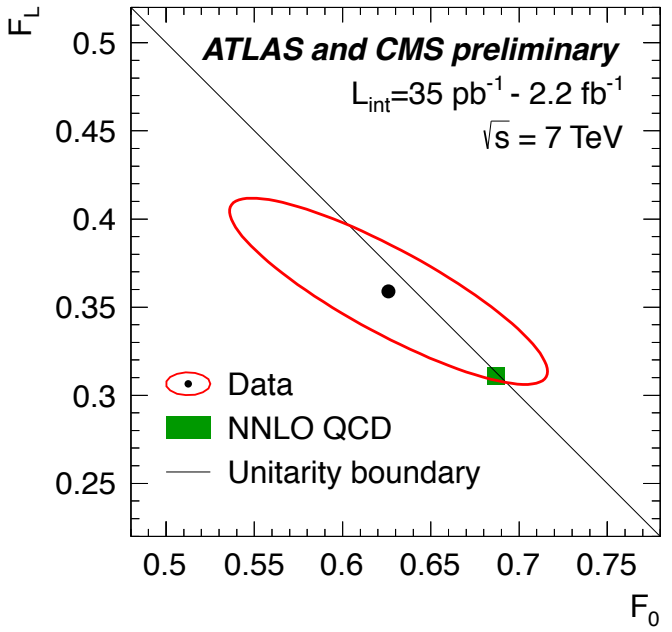
- $F_0 = 0.626 \pm 0.034_{stat} \pm 0.048_{syst}$
- $F_L = 0.359 \pm 0.021_{stat} \pm 0.028_{syst}$
- $F_R = 0.015 \pm 0.034$

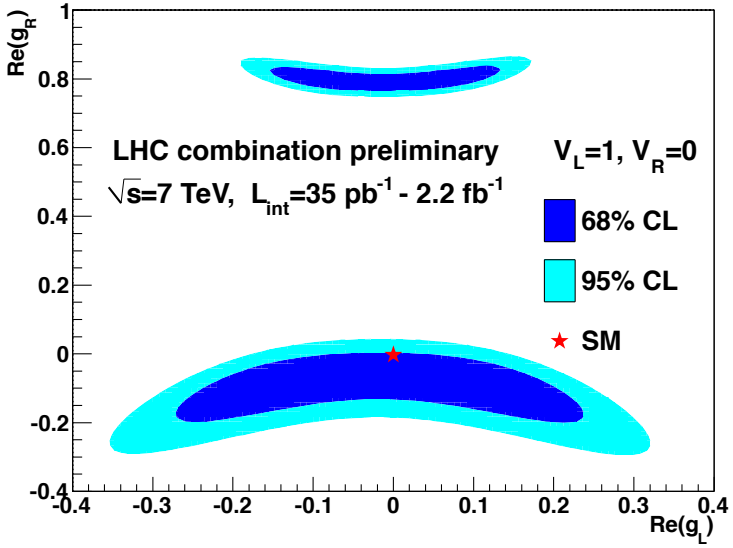
Category	LHC combination F_0	LHC combination F_L
Detector modeling		
Detector model	0.019	0.011
Jet energy scale	0.020	0.012
Luminosity and pile-up	0.006	0.003
Signal and background modeling		
Monte Carlo	0.012	0.008
Radiation	0.024	0.012
Top-quark mass	0.019	0.012
PDF	0.008	0.004
Background (MC QCD)	0.003	0.001
Background (MC W + jets)	0.007	0.002
Background (MC other)	0.011	0.006
Background (data-driven)	0.013	0.008
Method-specific uncertainties		
Method	0.008	0.005
Total uncertainties		
Total systematic uncertainty	0.048	0.028
Statistical uncertainty	0.034	0.021
Total uncertainty	0.059	0.035

Result and interpretation

ATLAS-CONF-2013-033
CMS PAS TOP-12-025







$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\,t\,W^-_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)\,t\,W^-_{\mu}$$

$SM: V_L = V_{tb} \approx 1$

$V_R = g_L = g_R = 0$

$$\mathrm{Re}(g_R) = -0.10 \pm 0.06\,(\mathrm{stat.})\,^{+0.07}_{-0.08}\,(\mathrm{syst.})$$

$$\frac{\mathrm{Re}(C^{33}_{uW})}{\Lambda^2} = -1.1 \pm 0.6\,(\mathrm{stat.})\,^{+0.9}_{-1.0}\,(\mathrm{syst.})\,\mathrm{TeV}^{-2}$$

Conclusion

First round of LHC top combinations

- m_{top}, $\sigma_{t\bar{t}}$ (7TeV), W polarisation and anom. couplings

Some lessons learnt

- very useful to compare and match systematics prescription
- results can be cross-checked and put on equal footing

Prepare for next round of combinations

- important to determine correlations between measurements
  - *progress in JES and b-tagging categorisation*
- new CMS and ATLAS mass measurements
- $t\bar{t}$ cross-section determined at 8 TeV
- started discussing further combinations

Links

- URL: http://lpcc.web.cern.ch/LPCC/index.php?page=top_wg
- Open e-mail list: lhc-toplhcwg@cern.ch

Credits

Contributions in TOPLHCWG meetings from

M.Aldaya, W.Bell, D.Bloch, T.Carli, R.Chierici, T.Chwalek, G.Cortiana, M.Costa, M.Cristinziani, F.Déliot, D.Del Re, C.Doglioni, J.Donini, T.Dorland, J.Ferrando, S.Frixione, D.Gillberg, M.Gosselink, K.Hatakeyama, D.Hirschbühl, J.Keaveney, H.Kirschenmann, K.Kröninger, P.Lenzi, L.Lista, B.Malaescu, M.Mangano, A.Meyer, L.Mijovic, A.Mitov, F.Moortgat, M.Mulders, P.Nason, J.Ott, M.Owen, F.Parodi, J.Rojo, F.P.Schilling, L.Scodellaro, M.Seidel, M.Senghi, E.Shabalina, P.Skands, F.Spanó, S.Strandberg, R.Tenchini, A.Valassi, W.Verkerke, M.Voutilainen, S.Wimpenny, J.C.Winter, M.zur Nedden

ATLAS CMS Theory

Backup

Combination stability checks

ATLAS-CONF-2012-095
CMS PAS TOP-12-001

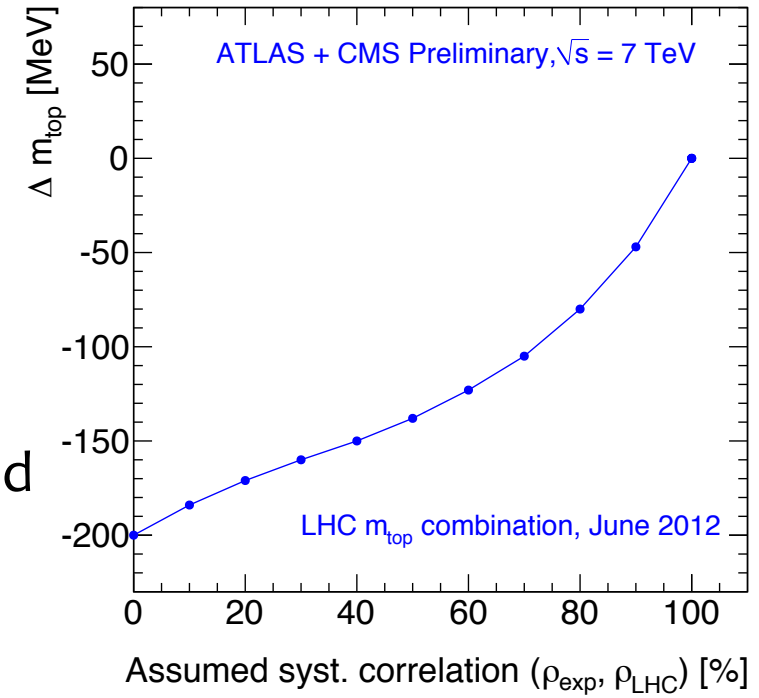
Assumptions on correlations

- reflect present knowledge and limitations
- impact of educated guess is evaluated by changing the assumed correlation across channels ρ_{exp} and experiments ρ_{LHC} in
  - *MC (ρ=50%) → 0% or 100%*
  - *Rad (ρ=50%) → 0% or 100%*
  - *bJES (ρ=50%) → 0% or 100%*
  - *dJES(ρ=100%) → 50%*
  - *DetMod (ρ=100%) → 50%*

Effect

- no change within the number of quoted significant digits for the final result

Varying simultaneously fully correlated sources from 100% to 0%



Mapping of uncertainty categories I

ATLAS-CONF-2012-095
CMS PAS TOP-12-001

Uncertainty Categories			Size [GeV]							Correlation	
			ATLAS			CMS				ρ_{exp}	ρ_{LHC}
Tevatron	ATLAS	CMS	2010 l+jets	2011 l+jets	2011 all jets	2010 di-l	2010 l+jets	2011 di-l	2011 μ+jets		
Statistics			4.0	0.6	2.1	4.6	2.1	1.2	0.4	0	0
iJES	Jet Scale Factor	Jet Scale Factor		0.4					0.4	0	0
aJES											
bJES	JES_{b-jet}	JES_{b-jet}	2.5	1.6	1.4	0.9	0.9	1.1	0.7	1	0.5 *
cJES											
dJES	$JES_{light-jet}$	$JES_{light-jet}$	2.1	0.7	2.1	2.1	2.1	2.0	0.2	1	0
rJES		residual-JES				3.3				0	0

* assumed partially correlated

- **iJES**: from in-situ calibration procedure; stat.uncert. of Jet Scale Factor when using W→jj invariant mass
- **bJES**: b-jet specific.
  - *ATLAS: sizeable contribution from dead material.*
  - *CMS: flavor dependence of the jet response for b/light/gluon jets.*
- **dJES**: p_T and η dependent calibration uncertainty
- **rJES**: fraction of JES not included above
  - *used for CMS 2010 measurements*
- other Tevatron categories (aJES, cJES) are not used

Mapping of uncertainty categories II

ATLAS-CONF-2012-095
CMS PAS TOP-12-001

Uncertainty Categories			Size [GeV]							Correlation	
			ATLAS			CMS					
Tevatron	ATLAS	CMS	2010 l+jets	2011 l+jets	2011 all jets	2010 di-l	2010 l+jets	2011 di-l	2011 μ+jets	ρ_{exp}	ρ_{LHC}
LepPt		Lepton p_T Scale				0.3		0.2		1	0
MC	MC Generator	MC Generator	0.7	0.3	0.5	0.4		0.1			
	Hadronisation		0.7	0.2	(*)						
	Sum	Sum	1.0	0.4	0.5	0.4		0.1		1	0.5*
Rad	ISR/FSR	ISR/FSR	2.5	1.0	1.7	0.2	0.2				
		Q-Scale				0.6	1.1	0.4	0.8		
		Jet-Parton Scale				0.7	0.4	0.7	0.3		
	Sum	Sum	2.5	1.0	1.7	0.9	1.2	0.8	0.8	1	0.5*
CR	Colour Recon.		*0.6*	0.6	*0.6*	*0.5*	*0.5*	0.5	0.5	1	1
PDF	Proton PDF	Proton PDF	0.5	0.1	0.6	0.5	0.1	0.4	0.1	1	1
DetMod	Jet Energy Res.	Jet Energy Res.	0.9	0.1	0.3	0.5	0.1	0.3	0.2		
	Jet Rec. Eff.		0.5	< 0.05	0.2						
	b-tagging	b-tagging	0.5	0.3	0.3	0.4	0.1	0.5	0.2		
	E_T^{miss}	E_T^{miss}		0.1		0.1	0.4	0.4	0.1		
	Sum	Sum	1.2	0.3	0.5	0.7	0.4	0.7	0.3	1	0

* assumed partially correlated

- **MC:** syst. uncert. due to the choice of generator/hadronization model
  - *ATLAS baseline MC@NLO+Herwig; CMS baseline Madgraph+ Pythia*
- **Rad:** Radiation
  - *ISR/FSR, (Q-scale, jet/parton matching). Measured from tt̄ dilepton gap fraction*
- **CR:** colour reconnection determined in 2011 and propagated to others
- **DetMod**: detector modeling systematics

Mapping of uncertainty categories III

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Uncertainty Categories			Size [GeV]							Correlation	
			ATLAS			CMS				ρ_{exp}	ρ_{LHC}
Tevatron	ATLAS	CMS	2010 l+jets	2011 l+jets	2011 all jets	2010 di-l	2010 l+jets	2011 di-l	2011 μ+jets		
UE	Underlying Event	Underlying Event	*0.6*	0.6	*0.6*	1.4	0.2	*0.6*	*0.6*	1	0
	W+jet Norm.		1.6								
	W+jet Shape		0.8	0.1							
		background				0.1	0.2		0.1		
BGMC	Sum	Sum	1.8	0.1		0.1	0.2		0.1	1	1
	W+jet Norm.			0.4							
	QCD Norm.	QCD Norm.	0.5	0.2			0.4	0.4			
	QCD Shape		0.4	0.3	1.9						
BGData	Sum	Sum	0.6	0.5	1.9		0.4	0.4		0	0
Method	Method Calib.	Method Calib.	0.4	0.1	1.0	0.3	0.1	0.4	0.2	0	0
MHI	Pile-up	Pile-up	0.7	< 0.05		1.0	0.1	0.2	0.4	1	1

- **UE:** underlying event, comparing different tunes
- **BGMC:** modeling of backgrounds from MC
  - *normalisation and shape*
- **BGData:** modeling of data-driven backgrounds
  - *normalisation and shape*
- **Method, MHI:** Method calibration and effects due to pile-up

Top mass combination result

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	ATLAS			CMS				LHC
	2010	2011		2010		2011		
	l+jets	l+jets	all jets	di-l	l+jets	di-l	μ+jets	comb.
[GeV]								
Measured m_{top}	169.3	174.5	174.9	175.5	173.1	173.3	172.6	173.34
Stat	4.0	0.6	2.1	4.6	2.1	1.2	0.4	0.47
iJES	n/a	0.4	n/a	n/a	n/a	n/a	0.4	0.38
aJES	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
bJES	2.5	1.6	1.4	0.9	0.9	1.1	0.7	0.68
cJES	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
dJES	2.1	0.7	2.1	2.1	2.1	2.0	0.2	0.07
rJES	n/a	n/a	n/a	3.3	n/a	n/a	n/a	0.06
Lept	n/e	n/e	n/e	0.3	n/e	0.2	n/e	0.01
MC	1.0	0.4	0.5	0.4	n/e	0.1	n/e	0.04
Rad	2.5	1.0	1.7	0.9	1.2	0.8	0.8	0.69
CR	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.55
PDF	0.5	0.1	0.6	0.5	0.1	0.4	0.1	0.01
DTMO	1.2	0.3	0.5	0.6	0.4	0.7	0.3	0.19
UE	0.6	0.6	0.6	1.4	0.2	0.6	0.6	0.47
BGMC	1.8	0.1	n/a	0.1	0.2	n/a	0.1	0.01
BGDT	0.6	0.5	1.9	n/a	0.4	0.4	n/a	0.16
Meth	0.4	0.1	1.0	0.3	0.1	0.4	0.2	0.13
MHI	0.7	< 0.05	n/e	1.0	0.1	0.2	0.4	0.25
[GeV]								
Total Syst. Unc	4.9	2.3	3.9	4.6	2.7	2.7	1.5	1.33
Total Unc.	6.3	2.4	4.4	6.5	3.4	3.0	1.5	1.40
Comb. Coeff.[%]	-6.8	29.9	-0.4	-1.9	-0.2	-4.8	84.3	χ^2/ndf = 2.5/6
Relative importance[%]	5.3	23.3	0.3	1.5	0.2	3.7	65.7	χ^2 prob = 87%