ATLAS EXPERIMENT

CMS

7th International Workshop on Top Quark Physics

top 2014

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Cannes, France

Review of recent top-quark LHC combinations

on behalf of the ATLAS and CMS Collaborations within the TOPLHCWG

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The TOPLHCWG

- Formed in 2011, the TOPLHCWG constitutes a forum for:
  - the study of the experimental and theoretical systematics in the measurements of top quark properties
  - the definition of measurements and tools (MC generators, theory calculations…)
  - the combination of the results of the experiments and their presentation for a proper theoretical interpretation

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  - the definition of measurements and tools (MC generators, theory calculations…)
  - the combination of the results of the experiments and their presentation for a proper theoretical interpretation
- It is structured
  - in several working-groups: cross section (single / pair top quark prod.), mass, W polarization, charge asymmetry, differential distributions
  - and task forces for dedicated discussions (Jet/MET, *b*-tagging, common acceptance/pseudo-top definition, QCD radiation and MC generators, common theoretical x-sec references…)

Combination assumptions/tools/inputs

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  - Uncertainties are Gaussian distributed
  - All sources of uncertainty are independent

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- Tools:
  - *B*est *L*inear *U*nbiased *E*stimate NIM A500 (2003) 391-405, NIM A270 (1988) 110
    - Combined results obtained from a linear weighted sum of the input measurements
    - Weights are determined to minimize the total uncertainty of the combined result, taking into account statistical and systematic uncertainties as well as their correlations
    - Variants using relative uncertainties (iterative BLUE) are used mainly for x-sec measurements.

–» more info in backup slides

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- Inputs:
  - (prel./published) individual results with a detailed breakdown of uncertainties
  - Correlations among corresponding sources of uncertainty (the core of any combination effort). *Correlation coefficients between input measurements are set based on scientific assessments, and the effect of their variation is used to test the stability of the result*

Typical uncertainty categories

- Theory uncertainties:
  - Signal simulation
  - Event modelling and environment
- Experimental uncertainties
  - Physics objects and detector modelling
    - identification, reconstruction, and calibration
  - Energy scales
    - (in particular for jets)

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Combination tasks:

- Finding a mapping between corresponding systematics in different experiments
- understanding (and testing) the correlations in each category

Typical uncertainty categories – 2

- ***Theory and signal modelling*** uncertainties comprise systematics stemming from the modelling of
  - QCD radiation in top quark events (ISR/FSR, μ_R/μ_F scale, ME-PS matching)
  - Hadronization / Parton Shower (Pythia vs. Herwig)
  - Non perturbative effects (Underlying Event, Colour Reconnection)
  - and from the choice of the proton PDF, and of the Monte Carlo generator

–» see also M. Seidel's talk

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- Typically they are assumed to be 100% correlated, although:
  - different MC generators are used as baseline (LO multi-leg vs. NLO)
  - radiation systematics are assessed in different ways (scale variations vs. Pythia radiation parameters tuning)
  - some contributions are under discussion between ATLAS and CMS:
    - *e.g.* (the level of) double counting of the hadronization uncertainty and the corresponding components included in the JES uncertainties (but also in the *b*-tagging calibrations).

Typical uncertainty categories – 3

- ***Jet Energy Scale (JES)*** uncertainties are typically among the dominant systematics.
  - The various JES sub-components are carefully mapped across experiments and their correlation (range) stems from detailed discussions within the Jet/MET liaison group including experts/analysers from both collaborations

–» *see also M. Costa's talk*

Table 4: Range of correlation coefficients to be used when combining measurements between the ATLAS and CMS experiment, for each of the uncertainty categories and respective components.

Description	Component names, CMS	Component name, ATLAS	Correlation range	Default values –»
1a. Statistical	*RelativeStatEC2; RelativeStatHF; AbsoluteStat*	Statistical components for *in situ* calibration	Uncorrelated	
1b. Detector	*AbsoluteScale; RelativeJEREC1; RelativeJEREC2; RelativeJERHF*	Electron/photon energy scale, γ-jet jet energy resolution, Multijet balance components, Closure of the calibration	Uncorrelated	
2. Modelling uncertainties	*AbsoluteMPFBias*	γ-jet and Z-jet: radiation suppression, out-of-cone and MC generator difference; γ-jet photon purity; Z-jet extrapolation; $\eta-$intercalibration modeling	0-50%	0%
3. Modelling uncertainties for relative correction	*RelativeFSR*	$\eta-$intercalibration modeling	50-100%	50%
4. Uncertainties related to jet partonic flavor	*Flavor; AbsoluteFlavorMapping*	Flavor composition and response	0-100%	varying
5. $b-$jet uncertainties	*Flavor*	$b-$jet response	50-100%	50%
6. Pile-up correction	*PileUpDataMC; PileUpPtBB; PileUpBias; PileUpOOT; PileUpJetRate; PileUpPtEC; PileUpPtHF*	Pile-up calibration; effects of pile-up on *in situ* methods	Uncorrelated	
7. High-p_T uncertainties	*HighPtExtra; SinglePion*	High-p_T	Uncorrelated	
8. Close-by jet uncertainties		Close-by	Uncorrelated	

ATL-PHYS-PUB-2014-015 and CMS-PAS-JME-14-003

Typical uncertainty categories – 4

- ***b*-tagging:**
  - the two collaborations use different approaches regarding *b*-jet identification (algorithms, *b*-tagging efficiency working points…)
  - the different approaches have been compared within a dedicated liaison group, and a list of common sources of uncertainty has been identified (see also twiki).

Category of Systematic Uncertainty	Correlation between experiments
General physics modelling (ISR/FSR, parton showering, *b*-frag.)	100%
Specific physics modelling (p_T spectrum for soft muons, light/charm ratio, *b/c* production)	100%
Detector description (JES, pileup, etc.)	0%
Method specific	0%

New!

for correlated sources, breakdowns into several sub-components will be provided and will need to be propagated at the analysis level

→ see also M. Costa's talk

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Category of Systematic Uncertainty	Correlation between experiments	Correlation with physics analyses
General physics modelling (ISR/FSR, parton showering, *b*-frag.)	100%	100%
Specific physics modelling (p_T spectrum for soft muons, light/ charm ratio, *b/c* production)	100%	0%
Detector description (JES, pileup, etc.)	0%	100%
Method specific	0%	0%

New!

for correlated sources, breakdowns into several sub-components will be provided and will need to be propagated at the analysis level

Arise from *b*-tagging calibrations exploiting top quark pair samples
To be addressed within each experiment.

Typical uncertainty categories – 5

- ***Detector modelling (uncorrelated):***
  - trigger
  - lepton identification/reconstruction and energy scales
  - E_T^{miss}/ jet resolution
  - pile-up effects
  - (JES/b-tagging when sub-dominant)

- ***Background:***
  - <u>Fully correlated</u> if estimated from MC (*e.g.* W+jets differential distributions, single top quark / top quark pair norm.)
  - <u>Uncorrelated</u> if estimated from data (*e.g.* fake leptons, W/Z+jets normalization using data driven techniques)

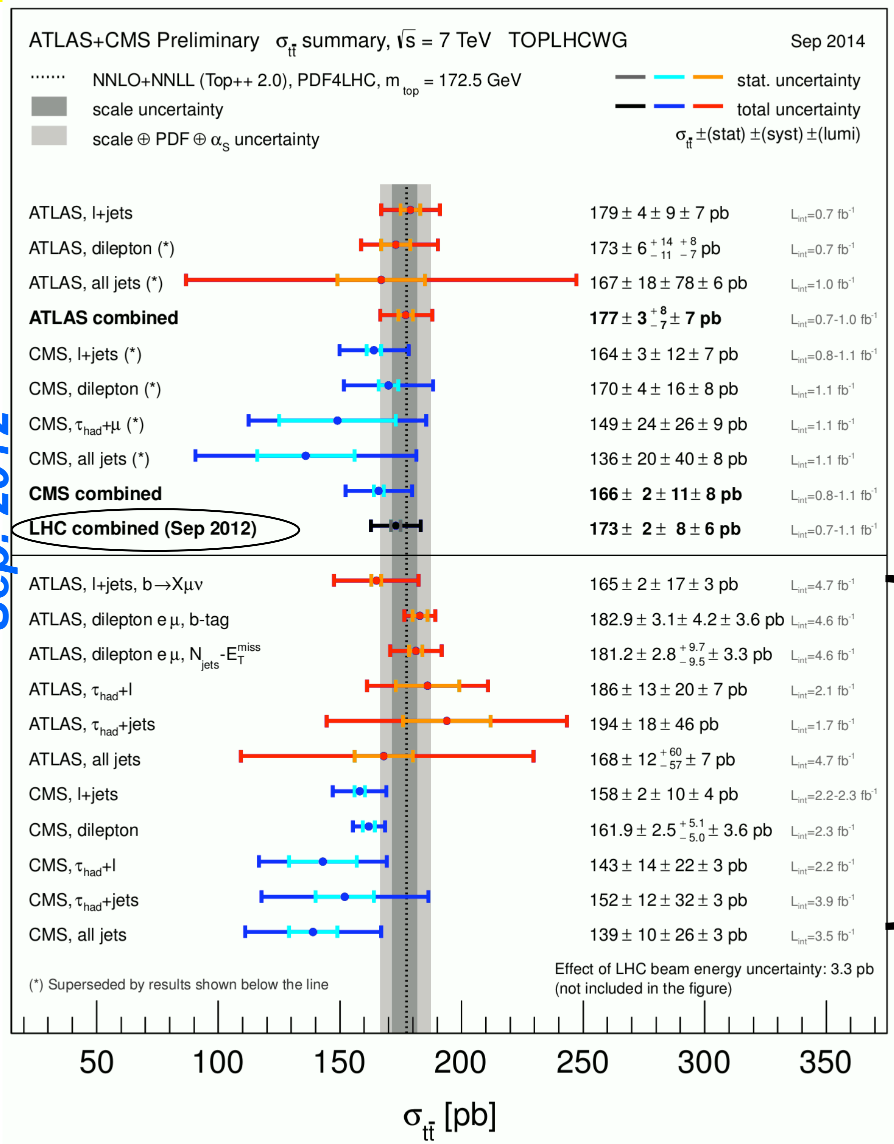
- ***Luminosity:***
  - <u>Fully correlated</u>: Van der Meer scan analysis
  - <u>Uncorrelated</u>: experiment specific luminosity measurements (beam condition, long term stabil. and luminometer calib.)

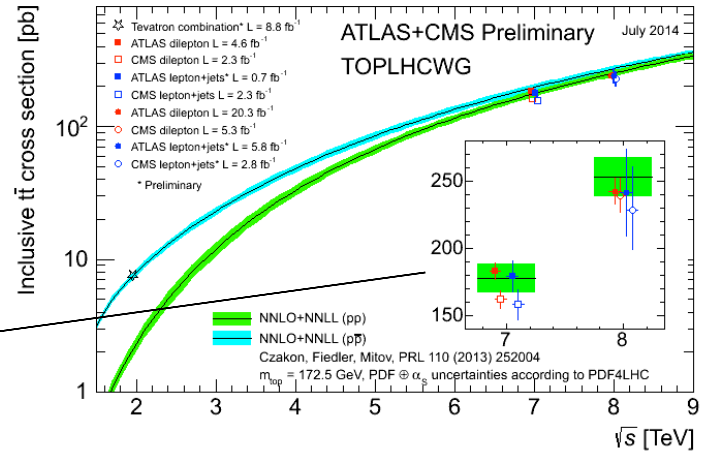
–» *see also M. Costa's talk*

Top quark production cross sections

Top quark pair x-sec. comb. @ 7 TeV

Sep. 2012





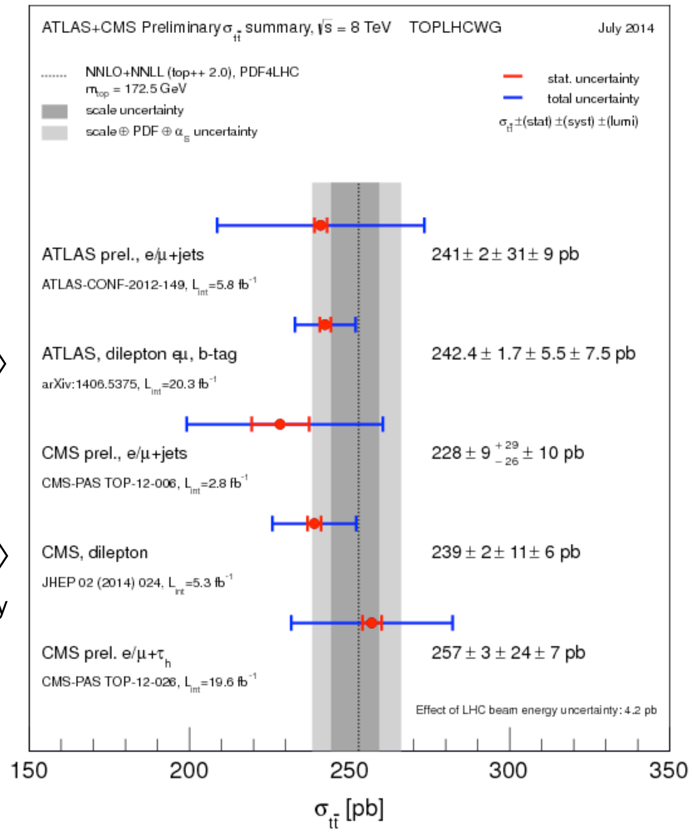
(5.8%)

$$\sigma(t\bar{t} \mid 7\ \text{TeV}) = 173.3 \pm 2.3(\text{stat}) \pm 7.6(\text{syst}) \pm 6.3(\text{lumi})\ \text{pb}$$

- More / newer / updated single measurements are available @ 7 TeV.
- Combination cycles do not keep the pace of the experiments yet:
  - discussions / agreement / harmonization of systematic uncertainties / multi-experiment reviews take time!
- Awaiting final Run-I measurements to perform a new combination…

Top quark pair x-sec @ 8 TeV

- Among available measurements, the most precise are from the eμ channel.



e/μ only

–» see also J. Brochero's talk

$$w_{\text{ATL}} = 72\% \qquad \text{Prob}(\chi^2) = 82\%$$

$$w_{\text{CMS}} = 28\% \qquad \rho_{\text{tot}} = 21\%$$

$$\sigma(t\bar{t} \mid 8\ \text{TeV}) = 241.5 \pm 1.4(\text{stat}) \pm 5.7(\text{syst}) \pm 6.2(\text{lumi})\ \text{pb}$$

(3.5%)

(w/o beam energy unc. 1.7%)

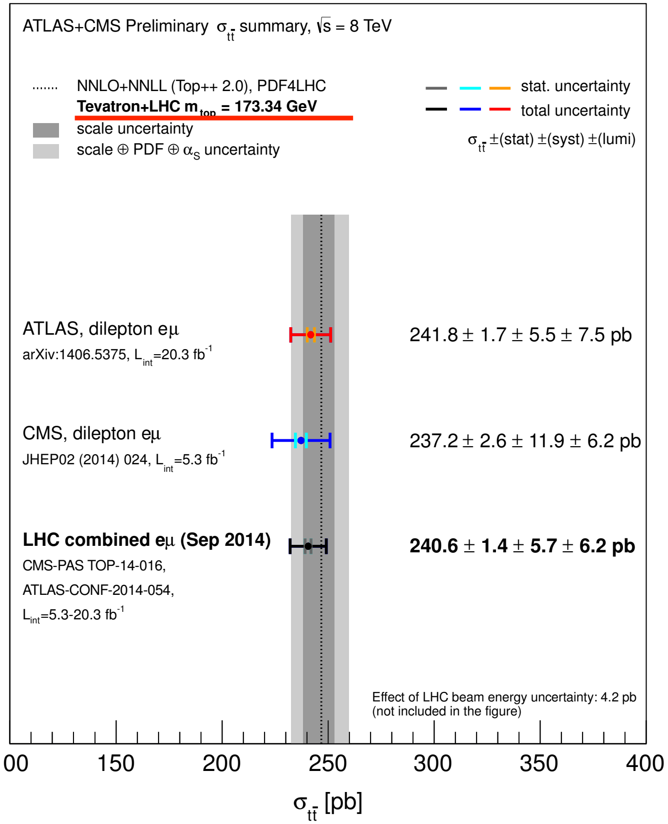
	ATLAS	CMS	Correlation	LHC combination
Cross section (pb)	242.4	239.0		241.5
Uncertainty (pb)				
Statistical	1.7	2.6	0	1.4
Detector model				
Trigger	0.4	3.6	0	1.0
Lepton scale and resolution	1.2	0.2	0	0.9
Lepton identification	1.7	4.0	0	1.6
Jet resolution	1.2	3.0	0	1.2
Jet identification	0.1	–	–	0.1
b-tagging	1.0	1.7	0	0.8
Pileup	–	2.0	–	0.5
Non-JES subtotal	2.6	6.7	0	2.6
UncorrJES	0.6	4.3	0	1.2
InsituJES	0.6	0.6	0	0.5
IntercalibJES	0.3	0.1	0.5	0.2
FlavourJES	0.9	2.9	1	1.4
bJES	0.1	–	–	0.1
JES subtotal	1.3	5.2	0.4	1.9
Class subtotal	2.9	8.5		3.2
Signal model				
Scale	0.7	5.6	0.5	1.9
Radiation	–	3.8	–	1.0
Generator and parton shower	3.0	3.3	0.5	2.7
PDF	2.7	0.5	1	2.1
Class subtotal	4.1	7.5	0.3	4.0
Background from data				
Z+jets	<0.1	1.5	0	0.4
Lepton misidentification	0.8	1.9	0	0.8
Class subtotal	0.8	2.4	0	0.9
Background from simulation				
Dibosons	0.3	0.5	1	0.4
Single top quark	2.0	2.3	1	2.1
Class subtotal	2.0	2.4	1	2.1
Luminosity				
Beam modelling	2.9	5.0	1	3.5
Luminosity determination	6.9	3.6	0	5.1
Class subtotal	7.5	6.2	0.3	6.2
Total systematic	9.3	13.4		8.4
Total	9.4	13.6		8.5

«– Using the recommended JES categories

Top quark pair x-sec @ 8 TeV

Sept. 2014

- Among available measurements, the most precise are from the eμ channel.



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$$\sigma(t\bar{t} \mid 8\ \mathrm{TeV}) = 241.5 \pm 1.4(\mathrm{stat}) \pm 5.7(\mathrm{syst}) \pm 6.2(\mathrm{lumi})\ \mathrm{pb}$$

(3.5%)

$$\frac{d\sigma(t\bar{t})}{dm_t} = -0.46\%/\mathrm{GeV}$$

(w/o beam energy unc. 1.7%)

	ATLAS	CMS	Correlation	LHC combination
Cross section (pb)	242.4	239.0		241.5
Uncertainty (pb)				
Statistical	1.7	2.6	0	1.4
Detector model				
Trigger	0.4	3.6	0	1.0
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Jet identificatio...			–	0.1
b-tagging			0	0.8
Pileup				0.5
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InsituJES				
Intercali...				
Flavou...				
bJES				
JES				
Cla...				
Si...				
S...				
Radiatio...				
Generator and p...				
PDF				
Class subtotal				
Background from data				
Z+jets	<0.1	1...		...4
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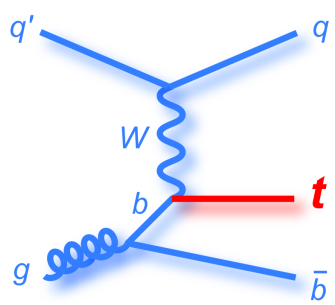
Stability tests are performed changing correlation assumptions as well as the fraction of correlated/uncorrelated luminosity uncertainties. The max observed change 0.4 pb (changing luminosity subcategories. Tough the default treatment corresponds to the most conservative scenario)

Single top t-chan. x-sec. comb. (8 TeV)

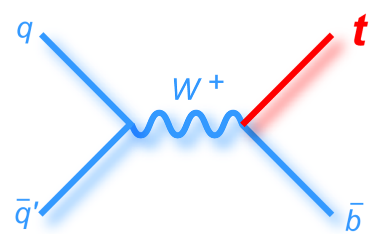
t-chan



LHC:

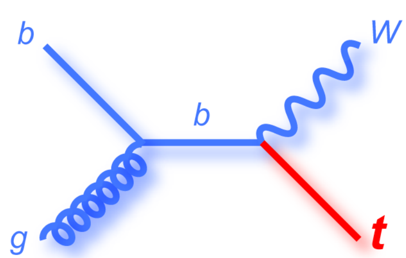
≈ 76 %

s-chan



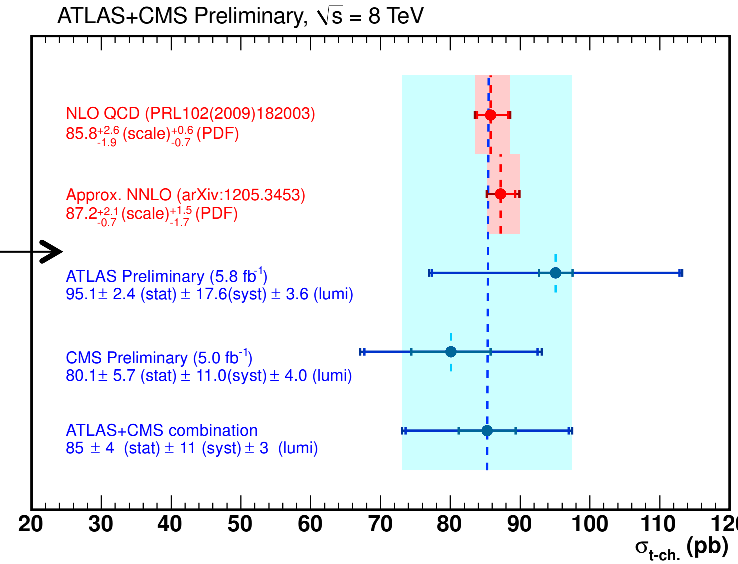
≈ 5 %

tW-chan



≈ 19 %

rule of thumb: $\sum_{\text{ch}} \sigma^{\text{ch}}_{\text{single top}} \sim \frac{1}{2}\sigma_{t\bar{t}}$



Sep. 2013

Performed on preliminary results using partial data samples of 5.8fb^{-1} (ATLAS) and 5.0fb^{-1} (CMS)

(14.8%)

$$\sigma(t \mid 8\ \mathrm{TeV})_{\mathrm{t-ch}} = 85.3 \pm 4.1(\mathrm{stat}) \pm 11.0(\mathrm{syst}) \pm 3.4(\mathrm{lumi})\ \mathrm{pb}$$

Source	Uncertainty (pb)
Statistics	4.1
Luminosity	3.4
Simulation and modelling	7.7
Jets	4.5
Backgrounds	3.2
Detector modelling	5.5
Total systematics (excl. lumi)	11.0
Total systematics (incl. lumi)	11.5
Total uncertainty	12.2

Harmonization efforts in progress for a coherent treatment of t-channel generator uncertainties.

Updated meas. available and awaiting combination:

ATLAS: ATLAS-CONF-2014-007
σ(*t*-ch) = 82.6 ± 12.1 pb

CMS: arxiv:1403.7366
σ(*t*-ch) = 83.6 ± 7.8 pb

Single top tW-chan. x-sec comb. 8 TeV

- Evidence/Observation of associated tW production reported by ATLAS (20.3 fb^{-1}) and CMS (12.2 fb^{-1}) in the dilepton channel using BDT analyses (+ profiling of syst.):
  - ATLAS: 4.2σ obs (4.0σ exp.)
  - CMS: 6.1σ obs (5.4σ exp.)

Source	Uncertainty (%)	Uncertainty (pb)
Data statistics	5.5%	1.4
Simulation statistics	1.8%	0.5
Luminosity	2.7%	0.7
Theory modeling	15.8%	4.0
Background normalization	2.3%	0.6
Jets	5.3%	1.3
Detector modeling	4.9%	1.2
Total systematics (excl. lumi)	17.5%	4.4
Total systematics (incl. lumi)	17.7%	4.4
Total uncertainty	18.6%	4.7

–» see also A. Jafari's talk

Category	ATLAS		CMS		ρ
Data statistics	Data statistics	7.1%	Fit statistics	8.1%	0.0
Category subtotal		**7.1%**		**8.1%**	**0.0**
Simulation statistics	Sim. statistics	2.8%	Sim. statistics	2.4%	0.0
Category subtotal		**2.8%**		**2.4%**	**0.0**
Luminosity		3.7%		3.0%	—
Category subtotal		**3.7%**		**3.0%**	**0.31**
Theory modeling (requires harmonization)	ISR/FSR	5.9%	Ren./fact. scale	12.4%	1.0
	tW gen. and PS	11.0%			—
	$t\bar{t}$ gen. and PS	7.5%	ME/PS match. thr.	14.1%	1.0
	PDF	2.5%	PDF	1.7%	1.0
	$tW/t\bar{t}$ overlap	1.4%	DR/DS scheme	2.1%	1.0
			Top p_T reweight.	0.4%	—
Category subtotal		**14.8%**		**19.0%**	**0.66**
Background normalization	bkg. mod.	3.6%	$t\bar{t}$ cross section	1.7%	0.0
			Z+jets	2.6%	—
Category subtotal		**3.6%**		**3.1%**	**0.0**
Jets (requires harmonization)	JES common	10.0%	JES	3.8%	0.0
	JES flavour	5.0%			—
	Jet id	0.2%			—
	Jet res.	0.7%	Jet resolution	0.9%	0.0
Category subtotal		**11.2%**		**3.9%**	**0.0**
Detector modeling	Lepton modeling	2.4%	Lepton ident.	1.8%	0.0
	MET scale	4.1%	MET modeling	0.4%	0.0
	MET resolution	4.5%			—
	b-tagging	8.4%	b tagging	0.9%	0.5
			Pileup	0.4%	—
Category subtotal		**10.6%**		**2.0%**	**0.17**
Total		**23.3%**		**21.7%**	**0.38**

CMS notes:

lower p_T-jets «–

«–

Not included (effect studied in stab. tests)

«– Constr. using data

Sept. 2014

$$\sigma(t \mid 8\ \mathrm{TeV})_{\mathrm{tW}} = 25.0 \pm 1.4(\mathrm{stat}) \pm 4.4(\mathrm{syst}) \pm 0.7(\mathrm{lumi})\ \mathrm{pb}$$

Single top tW-chan. x-sec comb. 8 TeV

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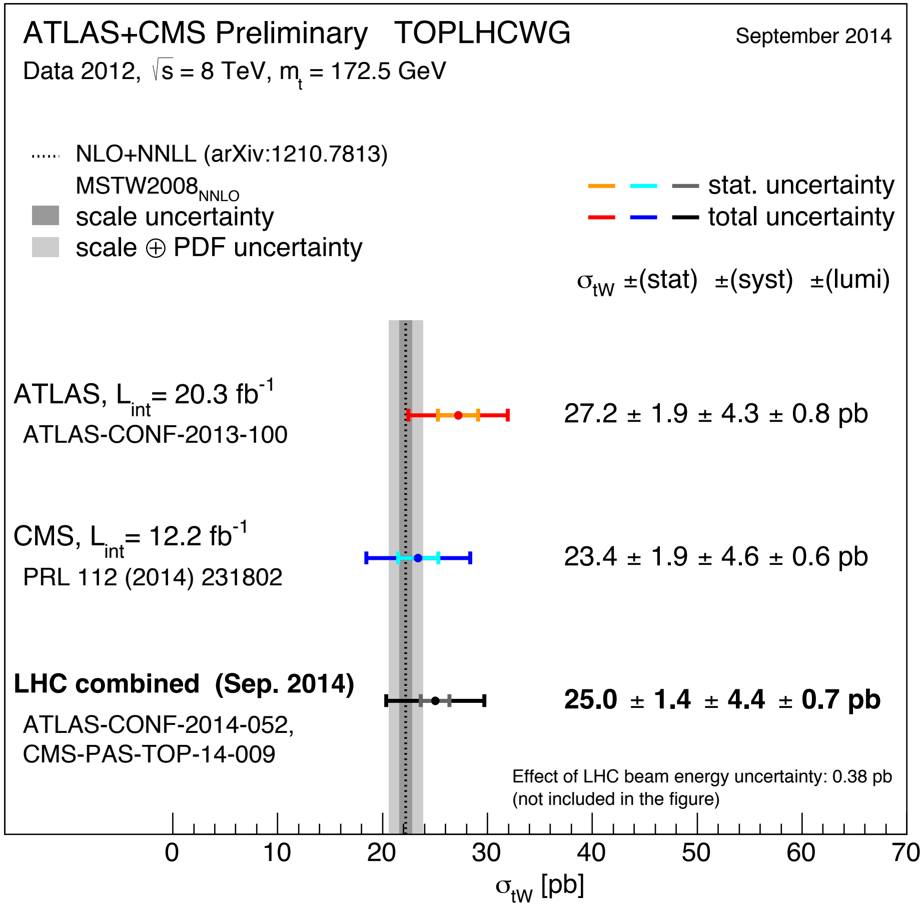


Sept. 2014

$$\sigma(t \mid 8\ \mathrm{TeV})_{\mathrm{tW}} = 25.0 \pm 1.4(\mathrm{stat}) \pm 4.4(\mathrm{syst}) \pm 0.7(\mathrm{lumi})\ \mathrm{pb}$$

$$w_{\mathrm{ATL}} = 43\% \qquad \mathrm{Prob}(\chi^2) = 54\%$$

$$w_{\mathrm{CMS}} = 57\% \qquad \rho_{\mathrm{tot}} = 38\%$$

$$|V_{tb}| > 0.79\ @\ 95\%\ \mathrm{C.L.}$$

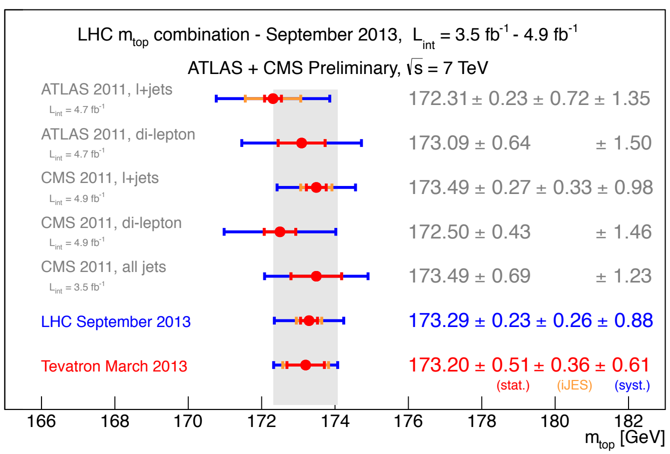
Stability tests are performed changing correlation assumptions.
The max observed change in the combined uncertainty is -0.6 pb (changing theory modelling correlations)

Top quark mass

m_{top} combination(s)

- First combination implementing the recommended JES sub-categories and correlations (triggered the efforts in the TOPLHCWG Jet/MET liaison group).
- Milestone for the subsequent Tevatron+LHC m_{top} combination (using the same input measurements for the LHC)… *–» see Y. Peter's talk*

	Uncertainty Categories: Tevatron	ATLAS	CMS	Size [GeV] ATLAS 2011 l+jets	ATLAS 2011 di-l	CMS 2011 l+jets	CMS 2011 di-l	CMS 2011 all jets	LHC comb	Correlation ρ_{exp}	ρ_{LHC}
	Measured m_{top}			172.31	173.09	173.49	172.50	173.49	173.29		
		Jet Scale Factor		0.27		0.33					
		bJet Scale Factor		0.67							
	iJES	Sum (statistical comp.)		0.72		0.33			0.26	0	0
	dJES	uncorrelated JES comp.		0.61	0.73	0.24	0.69	0.69	0.29	1	0
		in-situ γ/Z JES comp.		0.29	0.31	0.02	0.35	0.35	0.10	1	0
		intercalib. JES comp.		0.19	0.39	0.01	0.08	0.08	0.07	1	0.5
	aJES	flavour JES comp.		0.36	0.02	0.11	0.58	0.58	0.16	1	0.0
	bJES	*b*-jet energy scale		0.08	0.71	0.61	0.76	0.49	0.43	1	0.5
Signal		MC Generator		0.19	0.20	0.02	0.04	0.19			
		Hadronisation		0.27	0.44						
	MC	Sum		0.33	0.48	0.02	0.04	0.19	0.14	1	1
		ISR/FSR		0.45	0.37						
			Q^2-scale			0.24	0.55	0.22			
			Jet-Parton scale			0.18	0.19	0.24			
	Rad	Sum		0.45	0.37	0.30	0.58	0.33	0.32	1	1
	CR	Colour reconnection		0.32	0.29	0.54	0.13	0.15	0.43	1	1
	-	Underlying event		0.12	0.42	0.15	0.05	0.20	0.17	1	1
	PDF	Proton PDF		0.17	0.12	0.07	0.09	0.06	0.09	1	1
		Jet Resolution		0.22	0.21	0.23	0.14	0.15			
		Jet Reco Efficiency		0.05							
		E_T^{miss}		0.03	0.05	0.06	0.12				
	DetMod	Sum		0.23	0.22	0.24	0.18	0.28	0.20	1	0
		b-tagging		0.81	0.46	0.12	0.09	0.06	0.25	1	0.5
	LepPt	Lepton reconstruction		0.04	0.12	0.02	0.14		0.01	1	0
	Background from MC				0.14	0.13	0.05		0.08	1	1
	Background from Data			0.10				0.13	0.04	0	0
	Method			0.13	0.07	0.06	0.40	0.13	0.06	0	0
	Multiple Hadronic Interactions			0.03	0.01	0.07	0.11	0.06	0.05	1	1
			Statistics	0.23	0.64	0.27	0.43	0.69	0.23		
			Systematics	1.53	1.50	1.03	1.46	1.23	0.92		
			Total Uncertainty	1.55	1.63	1.06	1.52	1.41	0.95		
			Comb. Coeff. [%]	22.6	3.6	60.6	-8.4	21.6	χ^2/ndf = 1.8/4		
			Pull	-0.80	-0.15	0.41	-0.67	0.19	χ^2 prob = 77%		

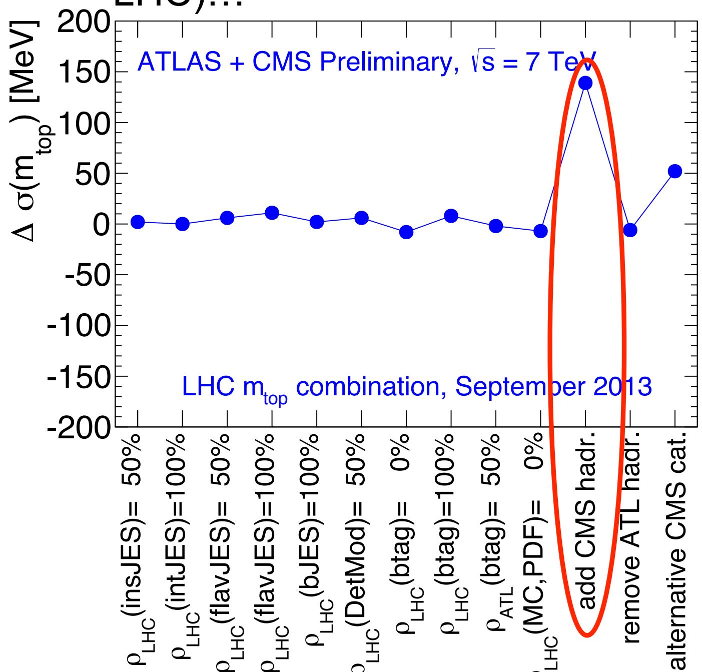


$$m_{top} = 173.29 \pm 0.23(\text{stat}) \pm 0.92(\text{syst})\ \text{GeV}$$ (0.5%)

New measurements awaiting combination, values in GeV: *–» see E. Schieckau's talk*

m_{top} combination(s)

- First combination implementing the recommended JES sub-categories and correlations (triggered the efforts in the TOPLHCWG Jet/MET liaison group).
- Milestone for the subsequent Tevatron+LHC m_{top} combination (using the same input measurements for the LHC)…



Uncertainty Categories			Size [GeV]						Correlation	
			ATLAS		CMS			LHC		
Tevatron	ATLAS	CMS	2011 l+jets	2011 di-l	2011 l+jets	2011 di-l	2011 all jets	comb	ρ_{exp}	ρ_{LHC}
Measured m_{top}			172.31	173.09	173.49	172.50	173.49	173.29		
	Jet Scale Factor		0.27		0.33					
	bJet Scale Factor		0.67							
iJES	Sum (statistical comp.)		0.72		0.33			0.26	0	0
dJES	uncorrelated JES comp.		0.61	0.73	0.24	0.69	0.69	0.29	1	0
	in-situ γ/Z JES comp.		0.29	0.31	0.02	0.35	0.35	0.10	1	0
	intercalib. JES comp.		0.19	0.39	0.01	0.08	0.08	0.07	1	0.5
aJES	flavour JES comp.		0.36	0.02	0.11	0.58	0.58	0.16	1	0.0
bJES	b-jet energy scale		0.08	0.71	0.61	0.76	0.49	0.43	1	0.5
Signal	MC Generator		0.19	0.20	0.02	0.04	0.19			
	Hadronisation		0.27	0.44	(0.58)	(0.76)	(0.93)			
MC	Sum		0.33	0.48	0.02	0.04	0.19	0.14	1	1
	ISR/FSR		0.45	0.37						
		Q^2-scale			0.24	0.55	0.22			
		Jet-Parton scale			0.18	0.19	0.24			
Rad	Sum		0.45	0.37	0.30	0.58	0.33	0.32	1	1
CR	Colour reconnection		0.32	0.29	0.54	0.13	0.15	0.43	1	1
-	Underlying event		0.12	0.42	0.15	0.05	0.20	0.17	1	1
PDF	Proton PDF		0.17	0.12	0.07	0.09	0.06	0.09	1	1
	Jet Resolution		0.22	0.21	0.23	0.14	0.15			
	Jet Reco Efficiency		0.05							
	E_T^{miss}		0.03	0.05	0.06	0.12				
DetMod	Sum		0.23	0.22	0.24	0.18	0.28	0.20	1	0
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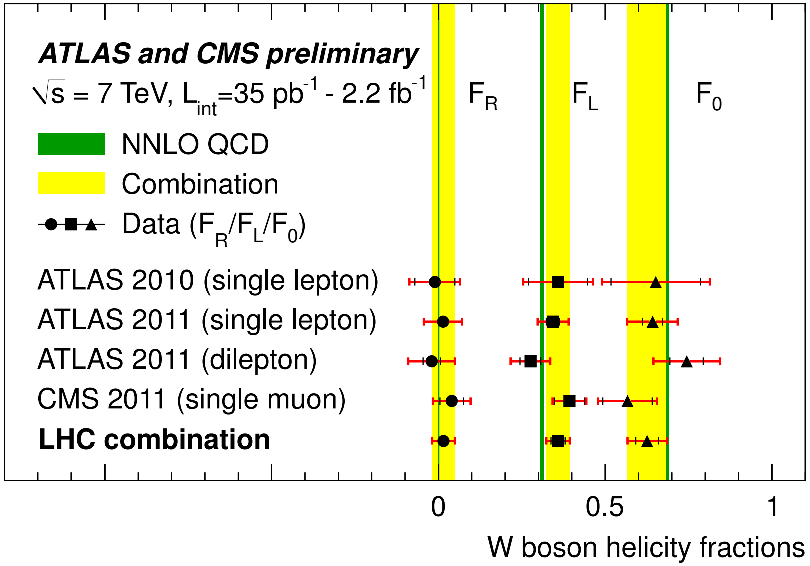
Statistics			0.23	0.64	0.27	0.43	0.69	0.23		
Systematics			1.53	1.50	1.03	1.46	1.23	0.92		
Total Uncertainty			1.55	1.63	1.06	1.52	1.41	0.95		
Comb. Coeff. [%]			22.6	3.6	60.6	-8.4	21.6	χ^2/ndf = 1.8/4		
Pull			-0.80	-0.15	0.41	-0.67	0.19	χ^2 prob = 77%		

- Ongoing discussion on the double counting of the hadronization and JES systematics.
  - Both experiments are at work to get quantitative results on this issue. Expect convergence soon…

Other top quark properties

W boson polarization

- Multi-parameter combination: correlation between F_L and F_0 needs to be taken into account ($F_R = 1 - F_L - F_0$)
- Results used to constrain anomalous couplings in the Wtb vertex (g_R, g_L)



$$F_0 = 0.626 \pm 0.034(\text{stat}) \pm 0.048(\text{syst})$$ (9.5%)

$$F_L = 0.359 \pm 0.021(\text{stat}) \pm 0.028(\text{syst})$$ (9.7%)

- The combination does not include new CMS results:
  - l+jets: JHEP 10 (2013) 167 (7 TeV)
    CMS PAS TOP-13-008 (8 TeV)
  - dilep: CMS PAS TOP-12-015 (7 TeV)
  - single top: CMS PAS TOP-12-020 (8 TeV)

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

Charge asymmetry

—» see R. Hawkings' talk

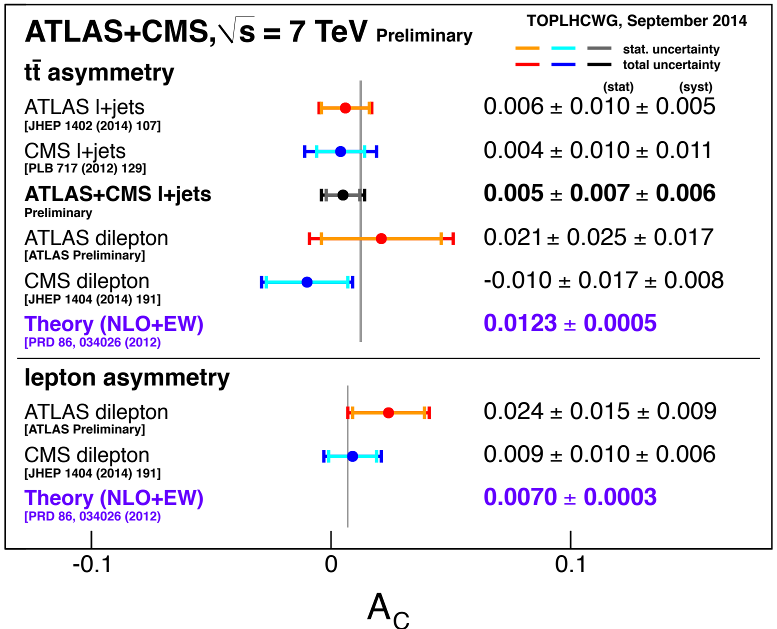
- Input measurements: top-quark based asymmetries obtained from the lepton+jets channel (full event reconstruction)
  - Corrected for detector/acceptance effects (unfolded)
  - Input measurements (and the combination) dominated by statistical uncertainties.

		ATLAS	CMS	Comb.	Corr.
	A_C	0.006	0.004	0.005	0.058
Uncertainties	Statistical	0.010	0.010	0.007	0
	Detector response model	0.004	0.007	0.004	0
	Signal model	< 0.001	0.002	0.001	1
	W+jets model	0.002	0.004	0.003	0.5
	QCD model	< 0.001	0.001	0.000	0
	Pileup+MET	0.002	< 0.001	0.001	0
	PDF	0.001	0.002	0.001	1
	MC statistics	0.002	0.002	0.001	0
	Model dependence				
	Specific physics models	< 0.001	*	0.000	0
	General simplified models	*	0.007	0.002	0
	Systematic uncertainty	0.005	0.011	0.006	
	Total uncertainty	0.011	0.015	0.009	

$$w_{\text{ATL}} = 65\% \qquad \text{Prob}(\chi^2) = 91\%$$
$$w_{\text{CMS}} = 35\% \qquad \rho_{\text{tot}} = 6\%$$

$$A_C = 0.005 \pm 0.007(\text{stat}) \pm 0.006(\text{syst})$$

Total uncertainty improvement of 18% (40%) with respect to the ATLAS (CMS) inputs



LHC combination overview

Overview (Sept. 2014)	$\sigma(t\bar{t})$ [pb] 7 TeV	8 TeV
value	173.3	241.4
statistics ($\star$)	2.8	1.4
MC model/ theory	4.9	4.1
Detector model (†)	4.6	2.7
JES/Jets ($\odot$)	2.1	1.7
Background	2.3	2.3
Luminosity	6.3	6.2
Total uncertainty	10.1	8.5
Relative unc. [%]	5.8	3.5

($\star$) includes data statistics and method calibration uncertainties

(†) when not available separately, includes luminosity and JES

($\odot$) when not available separately includes jet resolution and jet reconstruction systematics

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Detector model ($\dagger$)	4.6	(0.21)	2.7	(0.10)
JES/Jets ($\odot$)	2.1	(0.04)	1.7	(0.04)
Background	2.3	(0.05)	2.3	(0.07)
Luminosity	6.3	(0.39)	6.2	(0.53)
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Values in brackets are defined as: $\sigma_i^2/\sigma_{\mathrm{tot}}^2$

highlights the main contributions

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JES/Jets ($\odot$)	2.1	$(0.04)^{\bullet\circ}$	1.7	$(0.04)^{\times *}$
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$\bullet \; \circ \;\rightarrow\; \rho_{\mathrm{exp}}, \; \rho_{\mathrm{LHC}}$

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i.e.: one input / experiment

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$\circ,\; *,\; \bullet$

stand for uncorrelated, partially correlated and fully correlated uncertainty.

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Background	2.3	$(0.05)^{**}$	2.3	$(0.07)^{\times *}$
Luminosity	6.3	$(0.39)^{\bullet *}$	6.2	$(0.53)^{\times *}$
Total uncertainty	10.1		8.5	
Relative unc. [%]	5.8		3.5	
Best single meas.	$\boxed{182.9 \pm 6.3}$		242.4 ± 9.5	
Ref. (ATLAS, CMS)	arXiv 1406.5375		arXiv 1406.5375	

Values in brackets are defined as: $\sigma_i^2 / \sigma_{\mathrm{tot}}^2$

highlights the main contributions

$\bullet \; \circ$

$\rho_{\mathrm{exp}}, \; \rho_{\mathrm{LHC}}$

$\times \; \circ$

$\cancel{\rho_{\mathrm{exp}}}, \; \rho_{\mathrm{LHC}}$

i.e.: one input / experiment

$\circ, \; *, \; \bullet$

stand for uncorrelated, partially correlated and fully correlated uncertainty.

Single best meas. better than combined result. Combination needs to be updated!

($\star$) includes data statistics and method calibration uncertainties

($\dagger$) when not available separately, includes luminosity and JES

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LHC combination overview

Overview (Sept. 2014)	$\sigma(t\bar{t})$ [pb] 7 TeV		$\sigma(t\bar{t})$ [pb] 8 TeV		$\sigma(t)$ 8 TeV [pb] t − ch		$\sigma(t)$ 8 TeV [pb] tW	
value	173.3		241.4		85.3		25.0	
statistics ($\star$)	2.8	$(0.08)^{\circ\circ}$	1.4	$(0.03)^{\times\circ}$	4.1	$(0.11)^{\times\circ}$	1.5	$(0.10)^{\times\circ}$
MC model/ theory	4.9	$(0.23)^{\bullet\bullet}$	4.1	$(0.23)^{\times *}$	7.7	$(0.40)^{\times *}$	4.0	$(0.72)^{\times *}$
Detector model ($\dagger$)	4.6	$(0.21)^{\bullet\circ}$	2.7	$(0.10)^{\times\circ}$	5.5	$(0.20)^{\times *}$	1.2	$(0.06)^{\times *}$
JES/Jets ($\odot$)	2.1	$(0.04)^{\bullet\circ}$	1.7	$(0.04)^{\times *}$	4.5	$(0.14)^{\times\circ}$	1.3	$(0.08)^{\times\circ}$
Background	2.3	$(0.05)^{**}$	2.3	$(0.07)^{\times *}$	3.2	$(0.07)^{\times *}$	0.6	$(0.02)^{\times\circ}$
Luminosity	6.3	$(0.39)^{\bullet *}$	6.2	$(0.53)^{\times *}$	3.4	$(0.08)^{\times *}$	0.7	$(0.02)^{\times *}$
Total uncertainty	10.1		8.5		12.2		4.7	
Relative unc. [%]	5.8		3.5		14.3		18.8	
Best single meas.	182.9 ± 6.3		242.4 ± 9.5		83.6 ± 7.8		27.2 ± 5.8	
Ref. (ATLAS, CMS)	arXiv 1406.5375		arXiv 1406.5375		JHEP 06 (2014) 090		ATL-CONF 2013-100	

Overview (Sept. 2014)	m_{top} [GeV]		W polarization F_0		W polarization F_L		A_C	
value	173.29		0.626		0.359		0.005	
statistics ($\star$)	0.24	$(0.06)^{\circ\circ}$	0.035	$(0.35)^{\circ\circ}$	0.022	$(0.38)^{\circ\circ}$	0.007	$(0.61)^{\times\circ}$
MC model/ theory	0.59	$(0.38)^{\bullet\bullet}$	0.034	$(0.33)^{\bullet *}$	0.019	$(0.30)^{\bullet *}$	0.002	$(0.07)^{\times *}$
Detector model ($\dagger$)	0.32	$(0.12)^{\bullet\circ}$	0.020	$(0.11)^{\bullet\circ}$	0.011	$(0.11)^{\bullet\circ}$	0.004	$(0.21)^{\times\circ}$
JES/Jets ($\odot$)	0.61	$(0.42)^{\bullet *}$	0.020	$(0.11)^{\bullet\circ}$	0.012	$(0.12)^{\bullet\circ}$		
Background	0.09	$(0.01)^{**}$	0.019	$(0.10)^{\bullet\circ}$	0.010	$(0.09)^{\bullet\circ}$	0.003	$(0.11)^{\times *}$
Luminosity								
Total uncertainty	0.95		0.059		0.035		0.009	
Relative unc. [%]	0.5		9.5		9.7		181	
Best single meas.	172.22 ± 0.73		0.659 ± 0.027		0.350 ± 0.026		0.006 ± 0.011	
Ref. (ATLAS, CMS)	CMS-PAS-TOP 14-001		CMS-PAS-TOP 13-008		CMS-PAS-TOP 13-008		JHEP 1402 (2014) 107	

Comments

- Statistically limited measurements (e.g. W pol., charge asym.)
  - Largest gain in combination precision
    (should keep them up-to-date!)
  - Largely unaffected by variation of systematic uncertainty correlations

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  - Largely unaffected by variation of systematic uncertainty correlations

- Systematics dominated measurements (e.g m_{top}/ top quark pair x-sec)
  - Challenging combination
  - Trigger harmonization efforts (trade-off w.r.t the policies / recommendations within each experiment), further refinements of modelling uncertainties, and MC details
  - Largest gain in understanding complementarities and differences between measurements and approaches to evaluate the uncertainties

Conclusions

- The TOPLHCWG is very successful
  - Combinations: cross sections top-pair and single top (t-ch. Wt-ch.), LHC top mass (x2), first Tevatron+LHC top mass (not covered in this talk), charge asymmetry, W helicity. New results are in the works (differential x-sec…)
  - Progress in JES and *b*-tagging systematics categorisation, work ongoing for the signal modelling and theory uncertainties (radiation, hadronization, ...)
  - Experiments are finalizing their Run-I results, next round of combination to follow…

Conclusions

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  - Progress in JES and *b*-tagging systematics categorisation, work ongoing for the signal modelling and theory uncertainties (radiation, hadronization, ...)
  - Experiments are finalizing their Run-I results, next round of combination to follow…
- Prospects (personal view):

from *"after burner"*

to *"production mode"*

  - proactive planning and coordination of methods, analysis/statistics tools, systematic categorization/treatment (beforehand)
  - Identification of areas/topics needing improvements:
    - Investigate/mitigate double counting effects among different sources
    - Harmonize the sources of uncertainty and their evaluation / understand complementarities
  - Improving on the combination cycles (timely combination, closely following the availability of the inputs)

- Backup -

References

- Combination of ATLAS and CMS top-quark pair cross section measurements using up to 1.1 fb^{-1} of data at 7 TeV
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-134/
- Combination of single top-quark cross-section measurements in the t-channel at √s = 8 TeV with the ATLAS and CMS experiments
  http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-098/
- Combination of ATLAS and CMS results on the mass of the top-quark using up to 4.9 fb^{-1} of √s =7 TeV LHC data
  http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-102/
- Combination of ATLAS and CMS ttbar charge asymmetry measurements using LHC proton-proton collisions at √s = 7 TeV
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2014-012/
- Combination of the ATLAS and CMS measurements of the W-boson polarization in top-quark decays
  http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-033/
- Combination of cross-section measurements for associated production of a single top-quark and a W boson at sqrt(s)=8 TeV with the ATLAS and CMS experiments
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2014-052/
- Combination of ATLAS and CMS top-quark cross-section measurements using proton-proton collisions at sqrt(s)= 8 TeV
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2014-054/
- Jet energy scale uncertainty correlations between ATLAS and CMS
  - To appear :ATL-PHYS-PUB-2014-015 and CMS-PAS-JME-14-003

- Full list of public results and recommendations are available at:
  - http://lpcc.web.cern.ch/LPCC/index.php?page=top_wg_docs
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TopLHCWG

Combination method: BLUE

- We use the BLUE method = *Best Linear Unbiased Estimator*
  - the same techniques employed for
  - the LEPEWWG fits
  - the Tevatron and LHC top mass combinations…
- Advantages of using BLUE for m_{top} combination
  - it allows a directly comparison of the LHC and Tevatron results
  - it 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:

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

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)

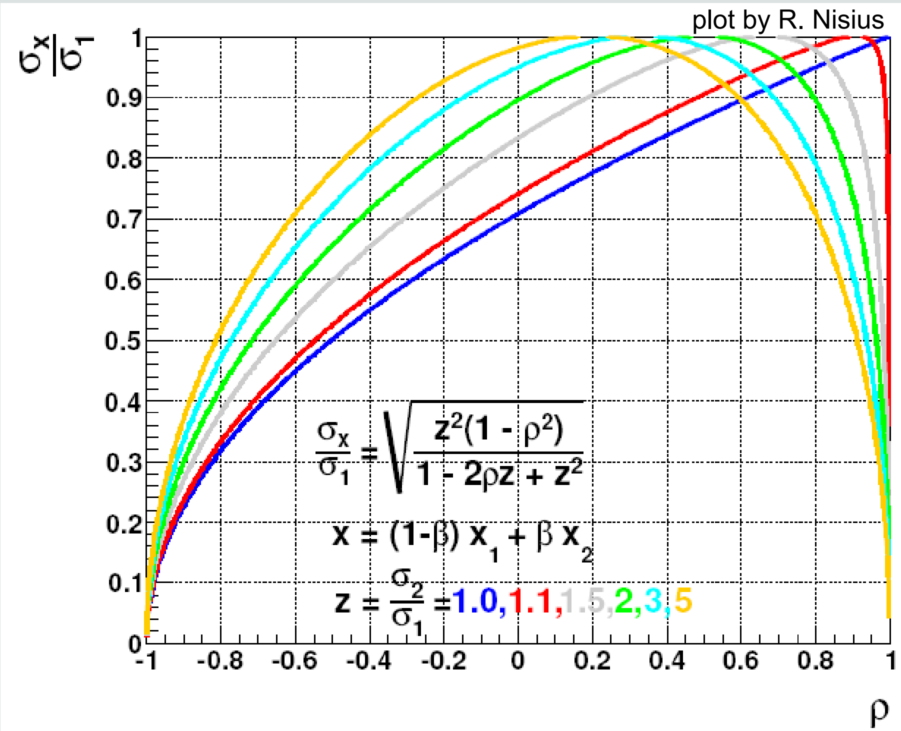
$$\boxed{x = \alpha\, x_1 + \beta\, x_2 \qquad \text{with: } 1 = \alpha + \beta}$$

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

$$\boxed{\begin{aligned} \frac{\sigma_x}{\sigma_1} &= \sqrt{\frac{z^2(1-\rho^2)}{1-2\rho z+z^2}}, \\ \beta &= \frac{1-\rho z}{1-2\rho z+z^2}. \end{aligned}}$$

ρ = correlation between measurements 1 and 2

Combination method: BLUE



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>1 (i.e.: let the second measurement be

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2 with: $1 = \alpha + \beta$

pect

,

s:

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

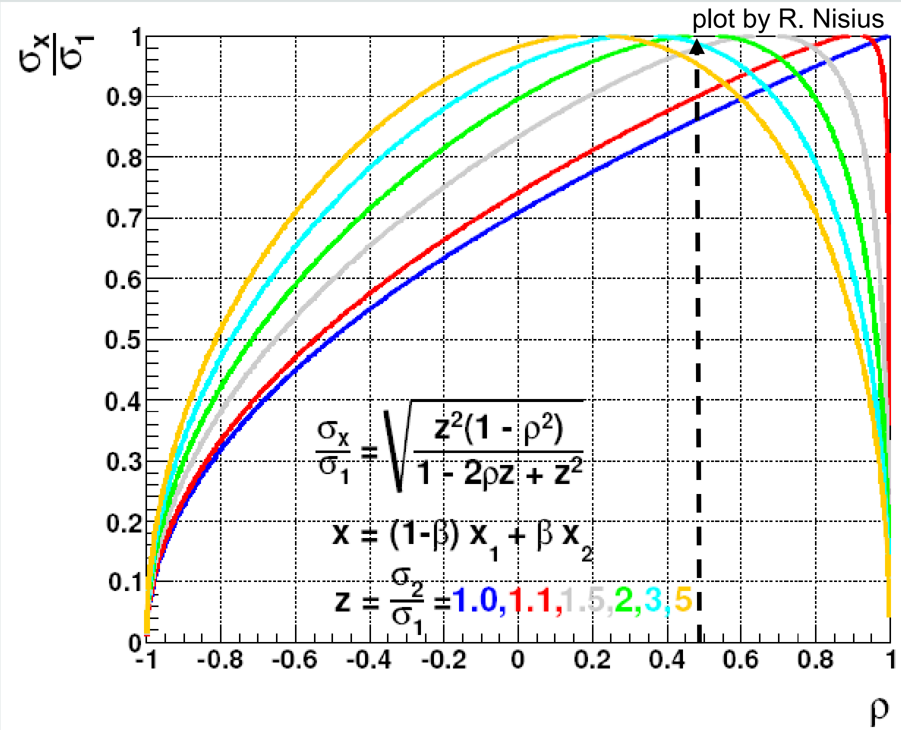
$$\beta = \frac{1-\rho\, z}{1-2\rho\, z+z^2}\,.$$

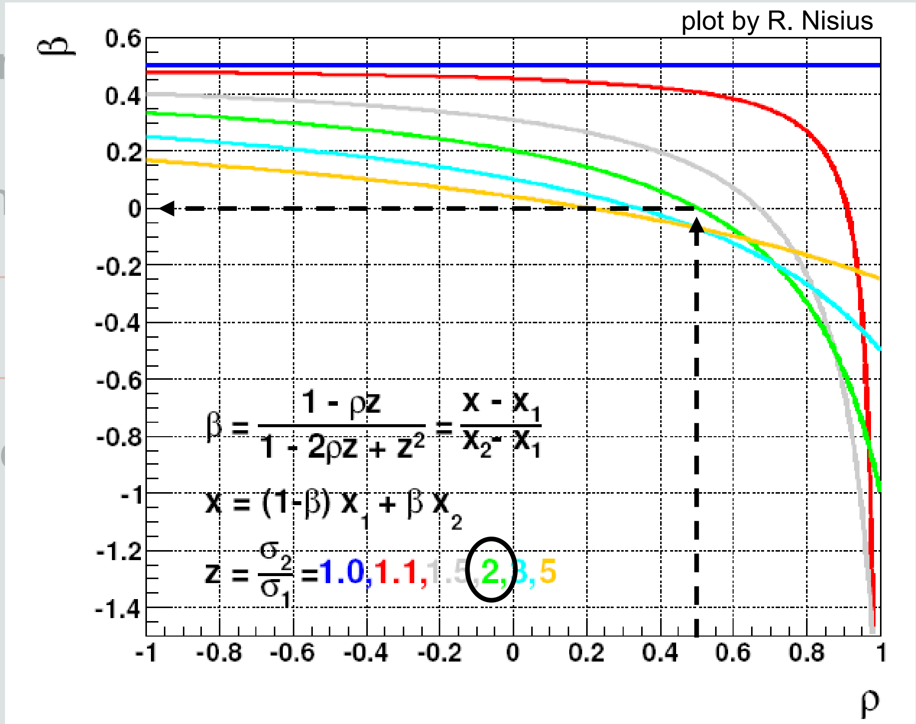
where:
ρ = corr. between x_1 and x_2

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:

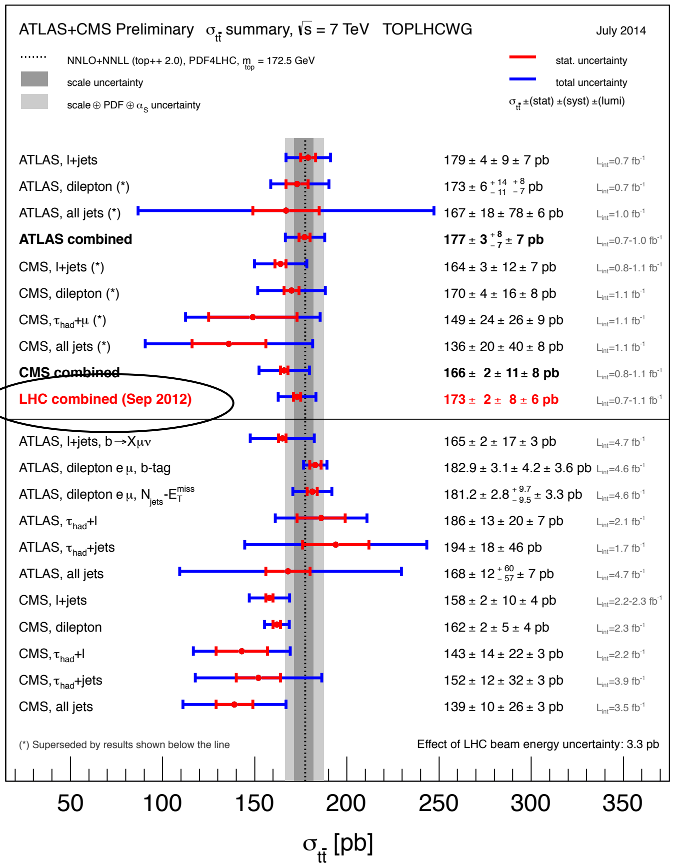
1. The relative improvement of the combination and the weights of the input measurements depend only on their precisions and correlations: they are independent of the actual measured values, x_1 and x_2.

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

Top quark pair x-sec @ 7 TeV

Sep. 2012

ATLAS-CONF-2012-134



	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
Signal model				
Monte Carlo	4.2	1.1	1	3.1
Parton shower	1.3	2.2	1	1.6
Radiation	0.8	4.1	1	1.9
PDF	1.9	4.1	1	2.6
Background from data	1.5	3.4	0	1.6
Background from MC	1.6	1.6	1	1.6
Method	2.4	n/e	0	1.6
W leptonic branching ratio	1.0	1.0	1	1.0
Luminosity				
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

$$w_{\mathrm{ATL}} = 67\% \qquad \mathrm{Prob}(\chi^2) = 47\%$$

$$w_{\mathrm{CMS}} = 33\% \qquad \rho_{\mathrm{tot}} = 30\%$$

- Use as input the individual experiment combinations:

$$\sigma(t\bar{t} \mid 7\ \mathrm{TeV}) = 173.3 \pm 2.3(\mathrm{stat}) \pm 7.6(\mathrm{syst}) \pm 6.3(\mathrm{lumi})$$

Single top t-channel x-sec 8 TeV

$$\sigma(t \mid 8\ \mathrm{TeV})_{\mathrm{t-ch}} = 85.3 \pm 4.1(\mathrm{stat}) \pm 11.0(\mathrm{syst}) \pm 3.4(\mathrm{lumi})$$ 14.8%

Uncertainty breakdown

Source	Uncertainty (pb)
Statistics	4.1
Luminosity	3.4
Simulation and modelling	7.7
Jets	4.5
Backgrounds	3.2
Detector modelling	5.5
Total systematics (excl. lumi)	11.0
Total systematics (incl. lumi)	11.5
Total uncertainty	12.2

Category	ATLAS		CMS		ρ
Statistics	Stat. data	2.4%	Stat. data	7.1%	0
	Stat. sim.	2.9%	Stat. sim.	2.2%	0
Total		**3.8%**		**7.5%**	**0**
Luminosity	Calibration	3.0%	Calibration	4.1%	1
	Long-term stability	2.0%	Long-term stability	1.6%	0
Total		**3.6%**		**4.4%**	**0.78**
Simulation and modelling	ISR/FSR	9.1%	Q^2 scale	3.1%	1
	PDF	2.8%	PDF	4.6%	1
	t-ch. generator	7.1%	t-ch. generator	5.5%	1
	$t\bar{t}$ generator	3.3%			0
	Parton shower/had.	0.8%			0
Total		**12.3%**		**7.8%**	**0.83**
Jets	JES	7.7%	JES	6.8%	0
	Jet res. & reco.	3.0%	Jet res.	0.7%	0
Total		**8.3%**		**6.8%**	**0**
Backgrounds	Norm. to theory	1.6%	Norm. to theory	2.1%	1
	Multijet (data-driven)	3.1%	Multijet (data-driven)	0.9%	0
			W+jets, $t\bar{t}$ (data-driven)	4.5%	0
Total		**3.5%**		**5.0%**	**0.19**
Detector modelling	b-tagging	8.5%	b-tagging	4.6%	0.5
	E_T^{miss}	2.3%	Unclustered E_T^{miss}	1.0%	0
	Jet Vertex fraction	1.6%			0
			pile up	0.5%	0
	lepton eff.	4.1%			0
			μ trigger + reco.	5.1%	0
	lepton res.	2.2%			0
	lepton scale	2.1%			0
Total		**10.3%**		**6.9%**	**0.27**
Total uncert.		**19.2%**		**16.0%**	**0.38**

Updated measurements available:

ATLAS: ATLAS-CONF-2014-007
σ(*t*-channel) = 82.6 ± 12.1 pb

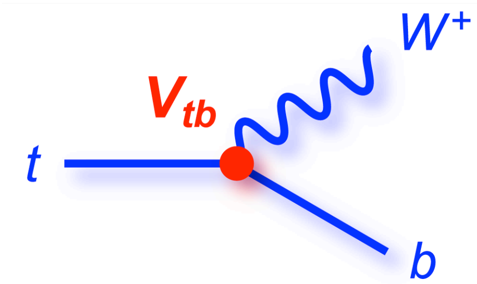
CMS: arxiv:1403.7366
σ(*t*-channel) = 83.6 ± 7.8 pb

Stability tests

Source	Default ρ	Test ρ	Shift: central value (pb)	Shift: uncertainty (pb)
Luminosity calibration	1	0.5/0	+0.1/+0.1	-0.1/-0.2
Simulation and modelling	1	0.5/0	+0.4/+0.7	-0.5/-1.1
JES	0	0.5/1	-0.4/-0.8	+0.3/+0.6
b-tagging	0.5	0/1	+0.2/-0.3	-0.2/+0.2

$$w_{\mathrm{ATL}} = 35\% \quad \mathrm{Prob}(\chi^2) = 37\%$$
$$w_{\mathrm{CMS}} = 65\% \quad \rho_{\mathrm{tot}} = 38\%$$

Probing the Wtb vertex

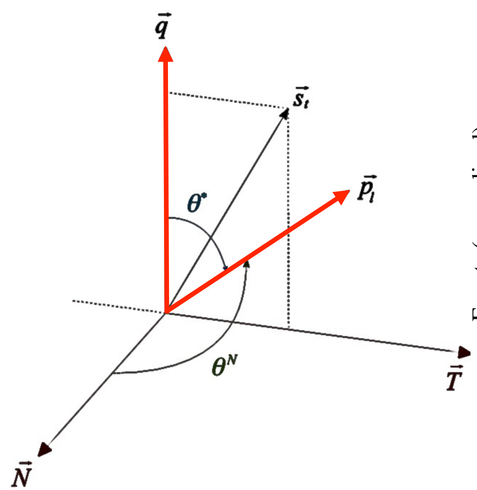


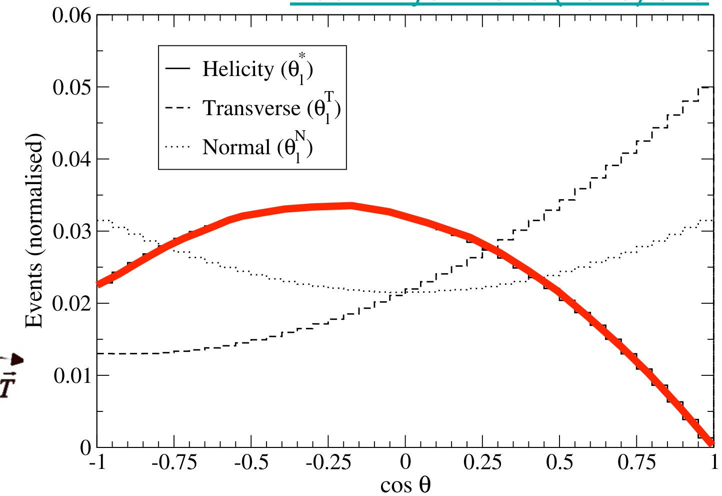
Angular distribution of leptons from W in a given reference frame:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^X} = \frac{3}{8}(1+\cos\theta^X)^2 F_+^X + \frac{3}{8}(1-\cos\theta^X)^2 F_-^X + \frac{3}{4}\sin^2\theta^X) F_0^X$$

$$\text{where}: \ \mathrm{X} = *$$

J.A. Aguilar-Saavedra J. Bernabéu
Nucl. Phys. B 840 (2010) 349





- For un-polarised top quark decays (e.g. top-quark pair production) use the helicity basis, exploit the W boson momentum direction (q) in the top quark rest frame

- In an effective operator framework: W helicity fractions (*) can probe the real part of the couplings

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

$$\mathrm{SM}^{\text{tree level}}: \mathrm{V_L} = \mathrm{V_{tb}} \approx 1 \text{ and } \mathrm{V_R} = \mathrm{g_L} = \mathrm{g_R} = 0$$