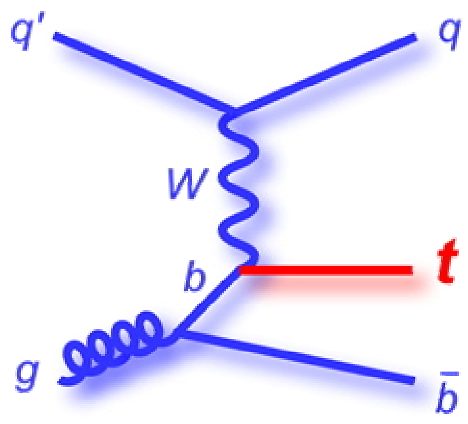
Combination of single top-quark cross-sections measurements in the t-channel

Open TopLHC WG meeting – 28.11.2013



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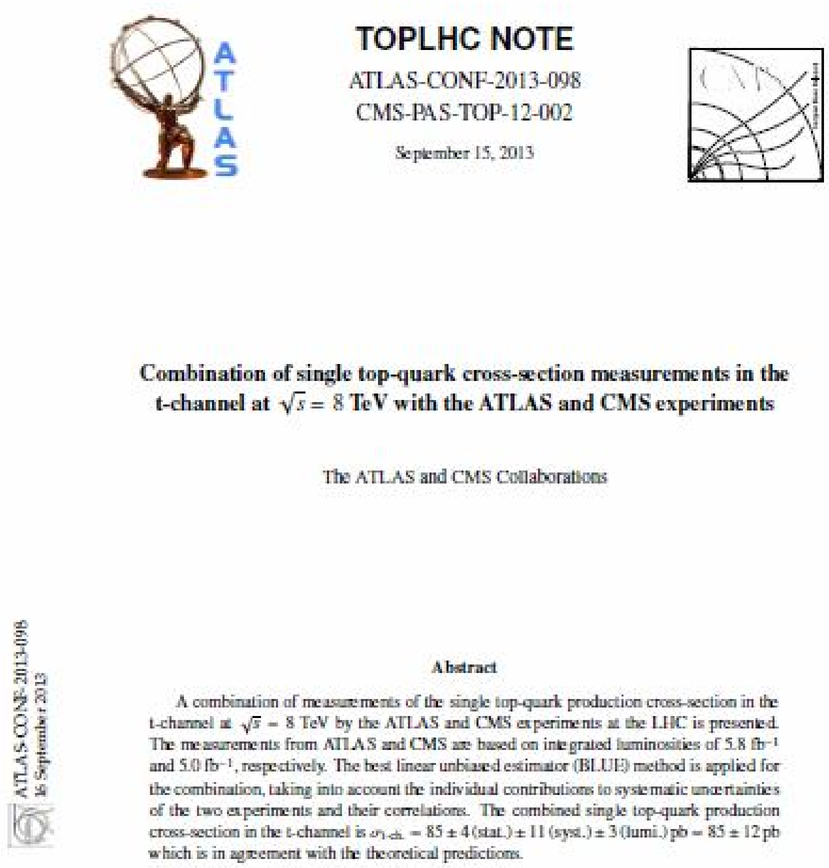
Single-top LHC combination

Overview

- Combination method
- Mapping of uncertainties
- Combined result
- Stability tests
- Conclusion and plans

Preliminary result

- CMS-PAS-TOP-12-002 ; ATLAS-CONF-2013-098
- http://cds.cern.ch/record/1601029



TOPLHC NOTE

ATLAS-CONF-2013-098
CMS-PAS-TOP-12-002

September 15, 2013

Combination of single top-quark cross-section measurements in the t-channel at $\sqrt{s} = 8$ TeV with the ATLAS and CMS experiments

The ATLAS and CMS Collaborations

ATLAS-CONF-2013-098
16 September 2013

Abstract

A combination of measurements of the single top-quark production cross-section in the t-channel at $\sqrt{s} = 8$ TeV by the ATLAS and CMS experiments at the LHC is presented. The measurements from ATLAS and CMS are based on integrated luminosities of 5.8 fb^{-1} and 5.0 fb^{-1}, respectively. The best linear unbiased estimator (BLUE) method is applied for the combination, taking into account the individual contributions to systematic uncertainties of the two experiments and their correlations. The combined single top-quark production cross-section in the t-channel is $\sigma_{t\text{-ch.}} = 85 \pm 4\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 3\,(\text{lumi.})$ pb $= 85 \pm 12$ pb which is in agreement with the theoretical predictions.

Single-top t-channel 8 TeV results

ATLAS [ATLAS-CONF-2012-132, 5.8 fb^{-1}]:

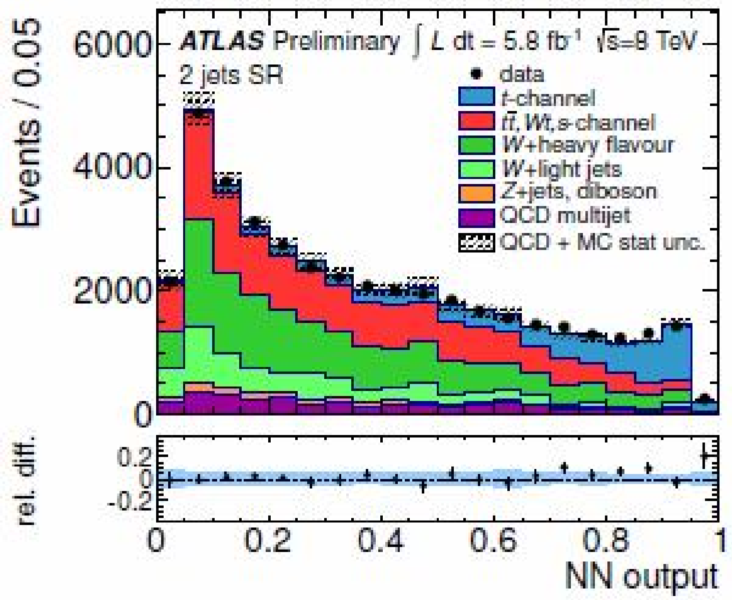
σ_t(t-ch.) = 95 ± 2 (stat.) ± 18 (syst.) pb = 95 ± 18 pb

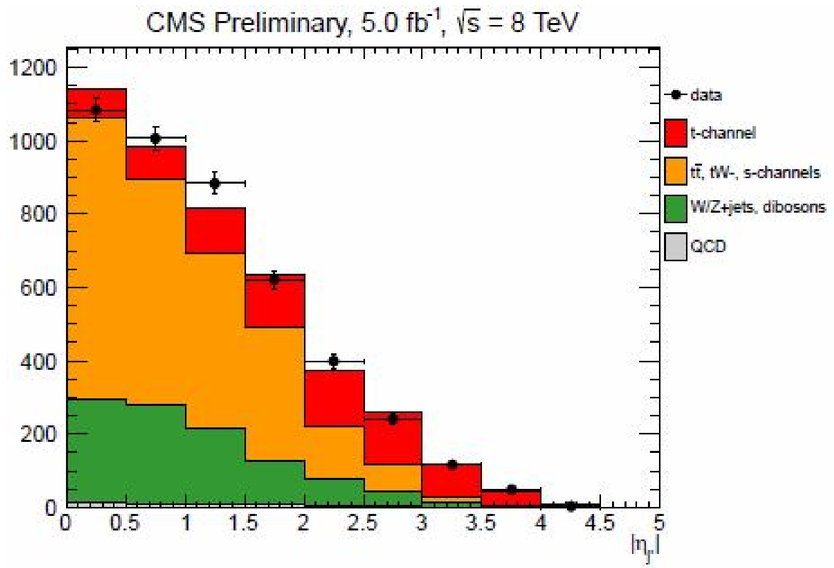
- Multivariate analysis with limited assumptions on simulations
- Fit of **NN distribution** in the data in **e/μ+2/3 jet events, with 1-btag**

CMS [CMS PAS TOP-12-011, 5.0 fb^{-1}]:

σ_t(t-ch.) = 80.1 ± 5.7(stat.) ± 11.0(syst.) ± 4.0(lumi.) pb = 80.1 ± 12.8 pb

- Cut-based analysis, data-driven background estimates (shapes, rates)
- Fit **|η| distribution of forward jet** in **μ+2 jet events, with 1-btag**





Combination method

Based on BLUE (L.Lyons et al. NIM A270 (1988))

- Find linear (unbiased) combination of results: $x = \Sigma\, w_i x_i$
  with weights w_i that give minimum possible variance σ_x^2
- Account properly for correlations between measurements

Iterative method

- Biases could appear when uncertainties depend on central value of each measurement (L. Lyons et al., Phys. Rev. D41 (1990) 982985)
- Reduced if covariance matrix determined as if the central value is the one obtained from combination
  - Rescale uncertainties to combined value

    ex: for measurement 1, and category i: $\sigma_{i,1}^{rescaled} = \sigma_{i,1} \,.\, x_1/x_{blue}$
  - Iterate until central value converges to stable value
  - Method applied for ex. in: CMS, Phys. Rev Lett. 107 (2011) 091802

➔ **See talk from Luca Lista for details and specific studies**

Combination procedure

- Identify common source of uncertainties between CMS and ATLAS
  - Explain/document origin of possible discrepancies
  - If possible adopt common definition of systematic uncertainties
- Regroup common uncertainties in categories
  - Estimate correlation for each uncertainty and category
  - Calculate total covariance matrix
  - Derive combined result and uncertainty
- Stability checks
  - Vary assumptions on correlations
  - Check impact on combined result

Systematic uncertainties

ATLAS

Source	$\Delta\sigma_t/\sigma_t$ [%]
Data statistics	± 2.4
MC statistics	± 2.9
Background normalisation	± 1.5
QCD multijet normalisation	± 3.1
Jet energy scale	± 7.7
Jet energy resolution	± 3.0
Jet reconstruction	± 0.5
Jet vertex fraction	± 1.6
Mistag modeling	± 0.3
c-tagging efficiency	± 0.4
b-tagging efficiency	± 8.5
E_T^{miss}	± 2.3
Lepton efficiencies	± 4.1
Lepton energy resolution	± 2.2
Lepton energy scale	± 2.1
PDF	± 2.8
W+jets shape variation	± 0.3
W+jets extrapolation	± 0.6
t-channel generator	± 7.1
$t\bar{t}$ generator	± 3.3
ISR / FSR	± 9.1
Parton shower	± 0.8
Luminosity	± 3.6
Total systematic	± 18.8
Total	± 19.0

CMS

Uncertainty source	in pb	relative
Statistical	±5.7	±7.2 %
W+jets and $t\bar{t}$modeling	±3.6	± 4.5 %
JES	− 6.2 / + 4.7	− 7.8 / + 5.8 %
JER	− 0.8 / + 0.3	− 1.0 / + 0.4 %
Unclustered $\not{E}_T$	− 0.8 / + 0.7	− 1.0 / + 0.9 %
Pileup	− 0.5 / + 0.3	− 0.6 / + 0.4 %
Muon trigger + reconstruction	− 4.1 / + 4.0	− 5.1 / + 5.1 %
Q^2	±2.5	±3.1 %
$t\bar{t}$, rate	− 1.5 / + 1.7	− 1.9 / + 2.1 %
QCD, rate	±0.7	±0.9 %
$t-$channel generator	±4.4	±5.5 %
Other backgrounds, rate	±0.5	±0.6 %
b-tagging	±3.7	±4.6 %
PDF	± 3.7	±4.6 %
Simulation statistics	±1.8	±2.2 %
Total systematics	±11.0	±13.7 %
Luminosity uncertainty	±4.0	±5.0 %
Total	±13.0	±16.3%

Uncertainties categories and correlations

6 categories of uncertainties. Correlation factor between ATLAS/CMS estimated for each.

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**

Statistical uncertainties

Both measurements based on ~5 fb^{-1}

- Uncorrelated uncertainties
- CMS: muon channel only (ATLAS: e/mu channels)
- CMS has tighter event/object selection
  - CMS: exactly 2-jets events with pt(jet)>60 GeV
  - ATLAS: 2/3-jet events, pt(jet)>25 GeV
  - x10 difference in nb of selected events (with same lumi)

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 uncertainty

Recommendation from lumi-group experts

- Luminosity uncertainty separated in two parts
  - Calibration: correlated (both measurement use April 2012 VdM scans)
  - Long-term stability: uncorrelated (detector specific)
- Added text in the note as suggested by experts

Category	ATLAS		CMS		ρ
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 category

Category	ATLAS		CMS		ρ
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**

Source	ATLAS	CMS
ISR/FSR	Vary AcerMC+Pythia in single-top and ttbar samples, gap fraction constraints	Vary renorm. and fact. Q^2 scales in PowHeg t/Wt samples $Q^2=m_{top}^2$, varied double/half value
PDF	Single-top and ttbar: PDF4LHC rec. (CT10, MSTW2008nlo, NNPDF2)	Included for all simulated processes (CT10 set)
Generator	t-channel: AcerMC vs MCFM ttbar: MC@NLO vs Powheg	t-channel: Powheg vs Comphep ttbar: data-driven modeling
PS + had.	Pythia vs Herwig: ttbar	PS: ttbar shape data-driven Had: accounted in JES, no additional uncertainty due to modeling of signal is assumed

- Common source of uncertainties are assumed fully correlated

Jet category uncertainty

Category	ATLAS		CMS		ρ
Jets	JES Jet res. & reco.	7.7% 3.0%	JES Jet res.	6.8% 0.7%	
Total		**8.3%**		**6.8%**	**0**

Source	ATLAS	CMS
Uncertainties	derive from 2010 single-hadron response measurements	Updated with in-situ calibrations at 8 TeV in 2012
b-JES	Includes specific b-JES uncert.	Systematic derived from ratio in jet response in gluon and lq jets, derived using Pythia/Herwig
Jet reco & res.	Measured separately	Jet reco accounted in JES

- Uncertainties assumed uncorrelated

Background normalization

Category	ATLAS		CMS		ρ
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**

1) Background normalized to theory

- ATLAS: ttbar, single-top (s, Wt), W/Z+jets, dibosons
  - Simulated process, rate uncertainty from theory
  - W+HF rate uncertainty partially derived from data
- CMS: ttbar (rate), single-top (s, Wt), dibosons
  - ttbar shape is data driven, but rate and uncertainty from theory
- Uncertainties assumed 100% correlated

Background normalization

Category	ATLAS		CMS		ρ
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**

2) Background relying on data-derived estimates

- ATLAS: multijet
  - MC dijet sample, rate derived from fit to MET distribution
- CMS: multijet (fit to M_TW), W/Z+jets (sideband), ttbar (shape)
  - All shapes are extracted from data
  - Note: tighter obj/evt. selection result in smaller QCD uncertainty (f_{QCD} is ~5 times smaller in the CMS analysis).
- Uncertainties assumed uncorrelated

Detector modeling

- **Instrumental category**
  - All uncertainties assumed uncorrelated
  - Except b-tagging (conservative 50% correlation)

Category	ATLAS		CMS		ρ
Detector modelling	b-tagging	8.5%	b-tagging	4.6%	0.5
	E_T^{miss}	2.3%	E_T^{miss} (uncl. E_T)	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**

Source	ATLAS	CMS
b-tagging	• JetFitterCombNNc • Preliminary 2012 SF for 8 TeV SF(b):10-15%, SF(light):20-40%	• TCP (~track counting) • SF(b)<5%, SF(light):9-16% x1.5 scale factor uncertainty (7 → 8 TeV extrapolation)

Combined t-channel single-top cross section

Sum covariance matrices in each category to obtain total covariance matrix.

$$\mathbf{C} = \begin{pmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_2^2 \end{pmatrix}$$

$$\downarrow \Sigma$$

$$\mathbf{C} = \begin{pmatrix} 269 & 84 \\ 84 & 182 \end{pmatrix} \mathrm{pb}^2$$

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

Breakdown of uncertainties

$$\sigma_i^2 = w_1^2\sigma_{i,1}^2 + 2w_1w_2\rho_i\sigma_{i,1}\sigma_{i,2} + w_2^2\sigma_{i,2}^2$$

$$\sigma_{\text{t-ch.}} = 85.3 \pm 4.1\,(\text{stat.}) \pm 11.0\,(\text{syst.}) \pm 3.4\,(\text{lumi.})\,\text{pb} = 85.3 \pm 12.2\,\text{pb}$$

With $w_{ATLAS} = 0.35$ and $w_{CMS} = 0.65$, $\chi^2 = 0.79/1$

Overall correlation of measurements is $\rho_{tot} = 0.38$.

Variation of correlation factors (ρ)

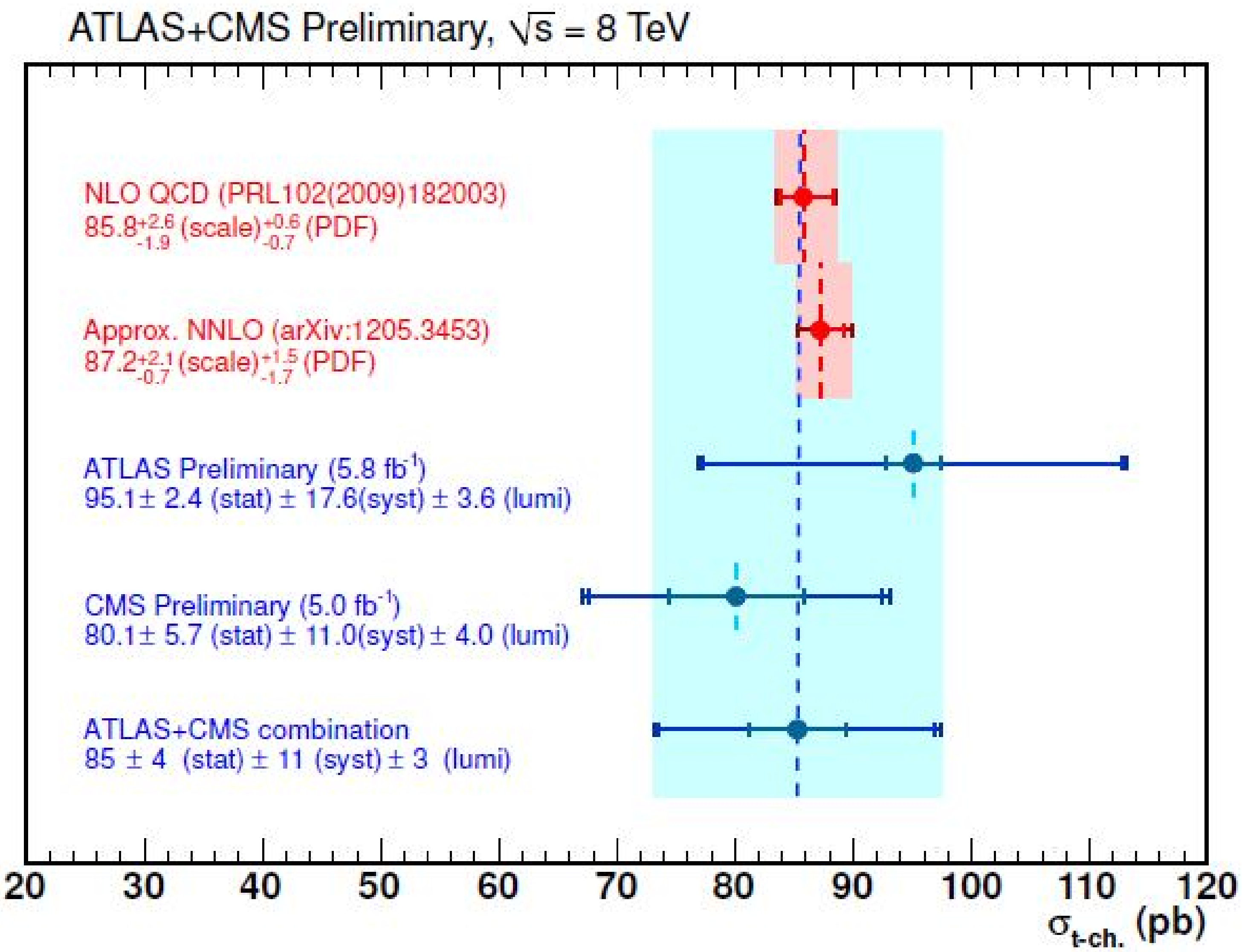
- Fully correlated uncertainties: vary from ρ = 1 to 0.5/0
  - Lumi calibration, ISR/FSR, PDF, t-ch generator, MC norm to theory
- JES: vary from ρ = 0 to 0.5/1
- b-tagging uncertainties: vary from ρ = 0.5 to 0/1
- Test indicate result is stable against our assumptions
  - In all these cases the combined result is improved w.r.t individual result

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

Max variation on central value: 1%

Max variation on uncertainty:
-8% ($\rho_{sim.}$=0)
+5% (ρ_{JES}=1)

Summary plot



(19.0%)

(16.2%)

(14%)

Conclusion

Single-top xs combination in the t-channel at √s = 8 TeV

- 1st LHC combination of single-top measurements
- Based on Iterative-BLUE method
- Mapping of uncertainties, estimate of correlations

Perspectives for future combinations

- Wt cross section
  - Measurements available at √s = 7 and 8 TeV
  - Significance at 8 TeV: 6σ (CMS) and 4.2σ (ATLAS)
  - Similar combination method can be applied
- $R_t = \sigma_{top}/\sigma_{antitop}$: measurements but at different √s
- s-channel: only limits and at different √s
- $|V_{tb}|$: for future updates of (t, Wt) channel measurements

Backup

BLUE method

Best Linear Unbiased Estimator: L.Lyons et al. NIM A270 (1988) 110

- Find linear (unbiased) combination of results: $x = \Sigma w_i x_i$ with weights w_i that give minimum possible variance σ_x^2
- Account properly of correlations between measurements
- For Gaussian errors: method equivalent to χ^2 minimization

- Two measurements: $x_1 \pm \sigma_1$, $x_2 \pm \sigma_2$ with correlation ρ
- The weights that minimize the χ^2:

Cov. matrix

$$\chi^2 = \begin{pmatrix} x_1 - x & x_2 - x \end{pmatrix} \begin{pmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_2^2 \end{pmatrix}^{-1} \begin{pmatrix} x_1 - x \\ x_2 - x \end{pmatrix}$$

are:

$$w_1 = \frac{\sigma_2^2 - \rho\sigma_1\sigma_2}{\sigma_1^2 - 2\rho\sigma_1\sigma_2 + \sigma_2^2} \qquad w_2 = \frac{\sigma_1^2 - \rho\sigma_1\sigma_2}{\sigma_1^2 - 2\rho\sigma_1\sigma_2 + \sigma_2^2} \qquad (w_1 + w_2 = 1)$$

BLUE method

Best Linear Unbiased Estimator: L.Lyons et al. NIM A270 (1988) 110

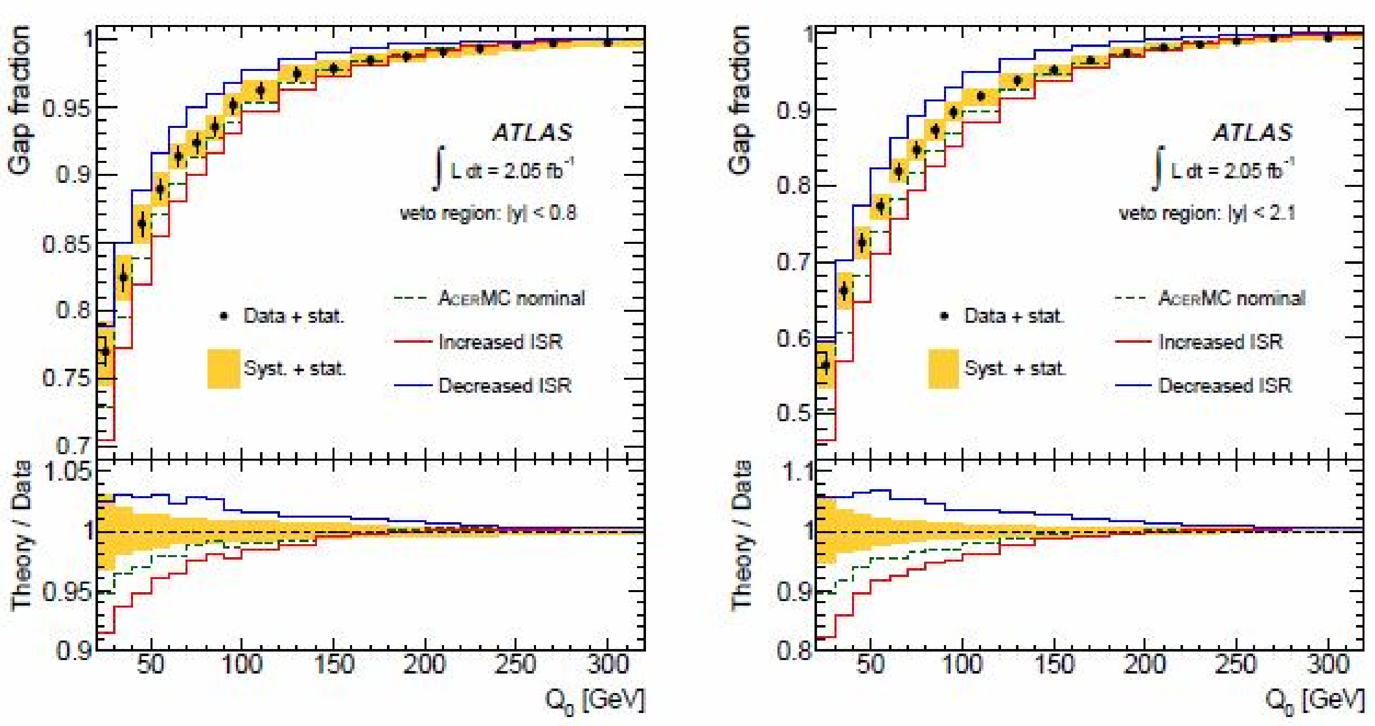
- Find linear (unbiased) combination of results: $x = \Sigma w_i x_i$ with weights w_i that give minimum possible variance σ_x^2
- Account properly of correlations between measurements
- For Gaussian errors: method equivalent to χ^2 minimization

- Two measurements: $x_1 \pm \sigma_1$, $x_2 \pm \sigma_2$ with correlation ρ
- The combined result is: $x = w_1 x_1 + w_1 x_2$
- And the uncertainty on the combined measurement is:

$$\sigma_x = \sqrt{\frac{\sigma_1^2 \sigma_2^2 (1-\rho^2)}{\sigma_1^2 - 2\rho\sigma_1\sigma_2 + \sigma_2^2}}$$

Gap fraction measurement (ATLAS)

ATLAS collaboration, *Measurement of tt production with a veto on additional central jet activity in pp collisions at* ps = 7 *TeV using the ATLAS detector*, Eur. Phys. J. C72 (2012) 2043.

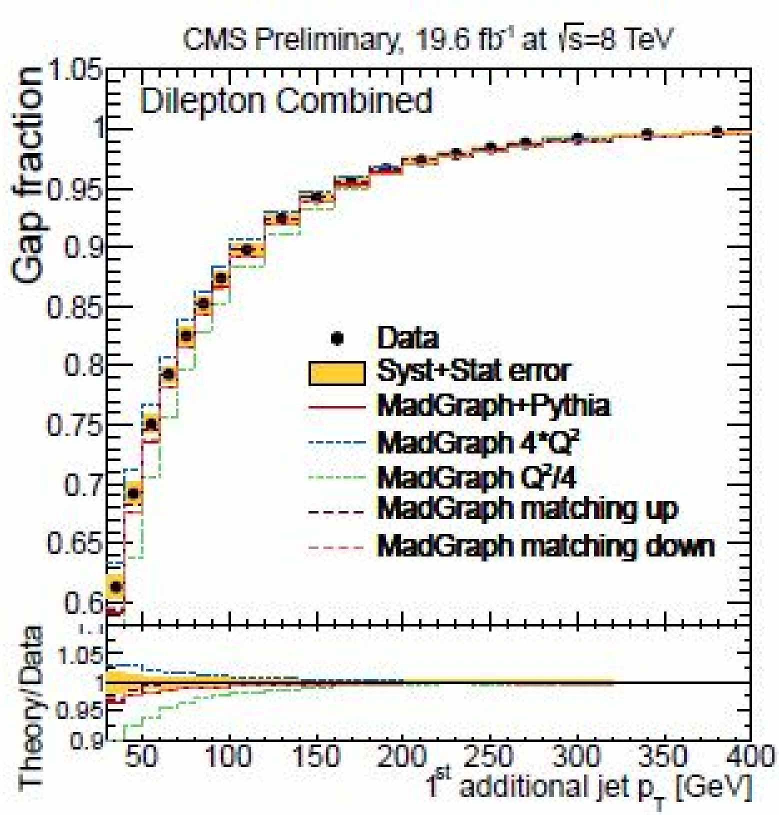


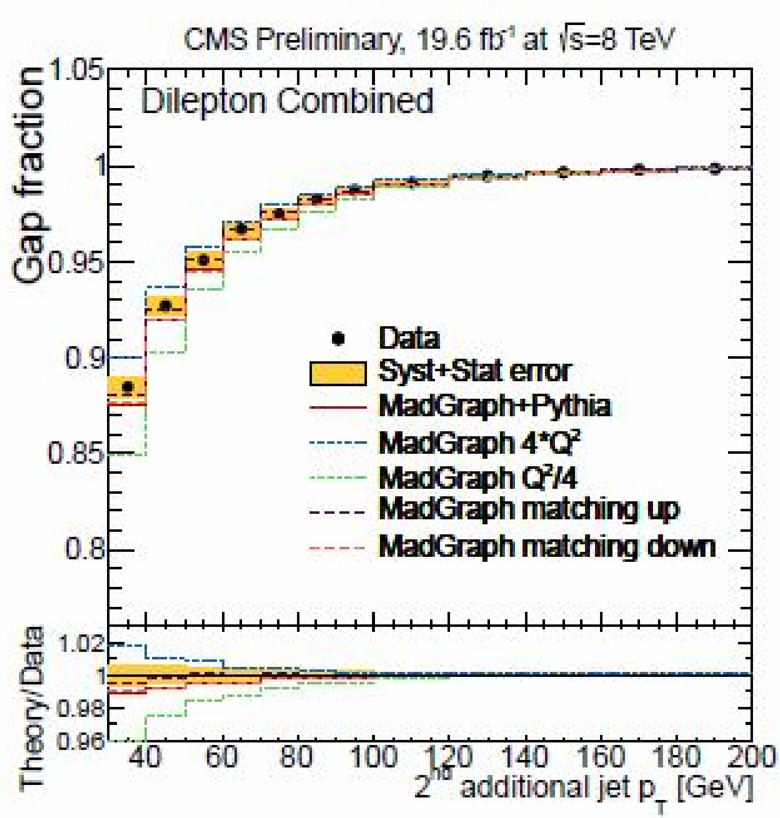
$$f(Q_0) = \frac{n(Q_0)}{N}$$

where N is the number of selected ttbar events and $n(Q_0)$ is the subset of these events that do not contain an additional jet with transverse momentum, pT, above a threshold, Q_0, in a central rapidity interval

Gap fraction measurement (CMS)

CMS collaboration, *Measurement of the Jet Multiplicity in dileptonic Top Quark Pair Events at* 312 ps = *8 TeV*, CMS PAS TOP-12-041 (2013).





Combination method

Iterative method

- Biases could appear when uncertainties depend on central value of each measurement (L. Lyons et al., Phys. Rev. D41 (1990) 982985)
- Reduced if covariance matrix determined as if the central value is the one obtained from combination
  - Rescale uncertainties to combined value

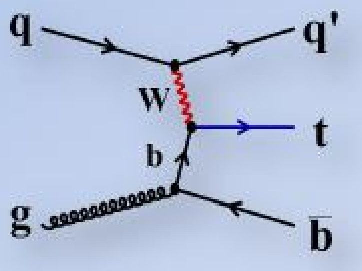
    ex: for measurement 1, and category i: $\sigma_{i,1}^{rescaled} = \sigma_{i,1} \, . \, x_1/x_{blue}$
  - Iterate until central value converges to stable value

  Method applied for ex. in: CMS, Phys. Rev Lett. 107 (2011) 091802

- **Different approaches**

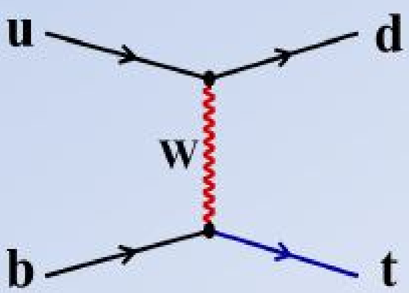
1. 4 flavour ($2 \rightarrow 3$) NLO
   - aMC@NLO: Madgraph5 +NLO techniques/formalism
     Fully automated QCD corrections

     PowHeg $2 \rightarrow 3$



2. Matched samples for $2 \rightarrow 2$ and $2 \rightarrow 3$ process
   - Matching using p_T of second b (Comphep)
   - **ACOT method (AcerMC) → default in ATLAS**

3. 4 flavour ($2 \rightarrow 3$) LO
   - Madgraph, Protos



4. 5 flavour ($2 \rightarrow 2$) NLO
   - **Powheg → default in CMS**
   - MC@NLO (not usable due to bug in fHerwig)

5. 5 flavour ($2 \rightarrow 2$) LO
   - Madgraph, Protos, Pythia
     (second b much too soft)

Calculation available for $2 \rightarrow 2$ & $2 \rightarrow 3$ @ NLO with MCFM

From Dominic Hirschbuehl

Single-top generator systematic

- **ATLAS**
  - Default generator: AcerMC + Pythia (matched $2 \to 2$ & $2 \to 3$ LO)
  - Systematic: compare pt of 2nd b to MCFM $2 \to 3$ NLO
  - Use acceptance difference from truth distributions
- **CMS**
  - Default generator: Powheg $2 \to 2$ NLO
  - Alternative generator: Comphep (matched $2 \to 2$ & $2 \to 3$ LO)
  - Acceptance difference after complete event selection
  - Using half of the difference as systematic variation

Inclusive measurements

Wt measurements

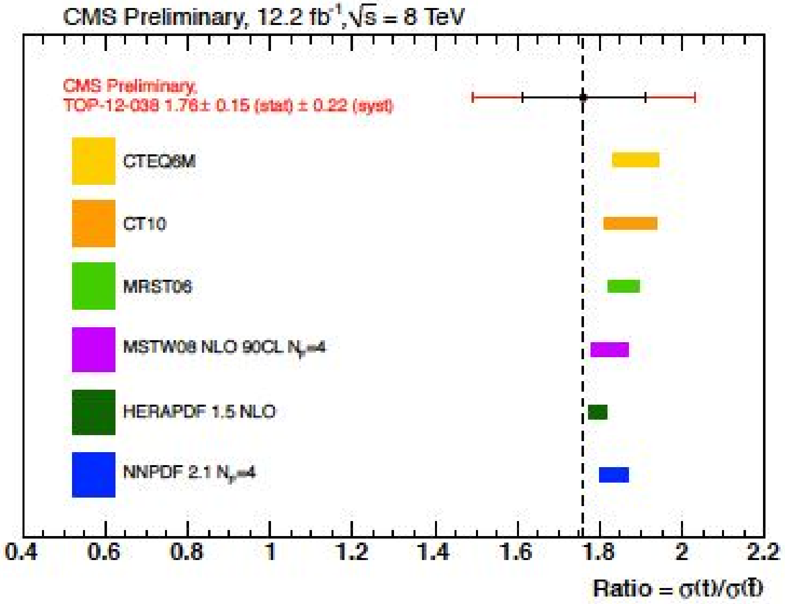
- ATLAS 7 TeV, 2.05 fb^{-1} [PLB717(2012)330]
  σ_{tW} = 83 ± 4(stat.) +20-19(syst) pb
- ATLAS 8 TeV, 20.3 fb^{-1} [ATLAS-CONF-2013-100]
  σ_{tW} = 27.2 ± 5.8 pb (4.2σ)
- CMS 7 TeV, 4.9 fb^{-1} [PRL110(2013)022003]
  σ_{tW} = 16 +5-4 pb (4σ)
- CMS 8 TeV, 12.2 fb^{-1} [CMS-PAS-TOP-12-040]
  σ_{tW} = 23.5 +5.5-5.4 pb (6σ)

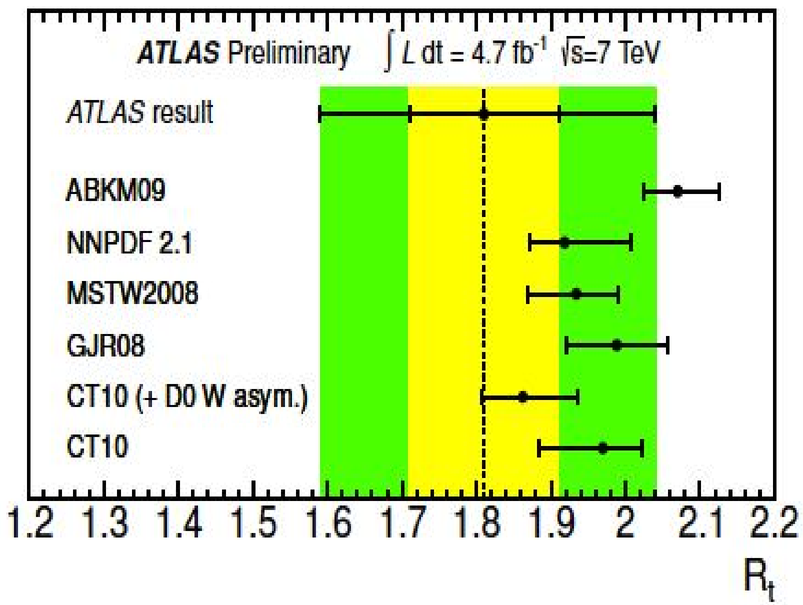
s-channel limits

- ATLAS 7 TeV, 0.7 fb^{-1} [ATLAS-CONF-2011-118]
  $\sigma_{s\text{-}ch.}$ < 26.5 pb @ 95% CL
- CMS 8 TeV, 19.3 fb^{-1} [CMS-PAS-TOP-13-009]
  $\sigma_{s\text{-}ch}$ < 11.5 pb @ 95% CL

Top-antitop ratio

- ATLAS and CMS measured $R_t = \sigma$ top/ σ antitop(*t*-ch.)
  - ATLAS (7TeV): $Rt = 1.81 \pm 0.10(stat.)+0.21-0.20(syst.)$
    [ATLAS-CONF-2012-056, 4.71 fb-1]
  - CMS (8TeV): $Rt = 1.76 \pm 0.15(stat.) \pm 0.22(syst.)$
    [CMS-PAS-TOP-12-038, 12.2 fb-1]





$|V_{tb}|$ combination

- The $|Vtb|$ measurement in single top events provides a unique opportunity to directly probe the top production Wtb vertex
  - Deviations from the SM are potentially sensitive to new physics
- ATLAS:
  - 7 TeV: $|Vtb| = 1.13+0.14-0.13$ (t-ch., 11.9%)
    $|Vtb| = 1.03+0.16-0.19$ (tW-ch., 17.0%)
  - 8 TeV: $|Vtb| = 1.04+0.10-0.11$ (t-ch., 10.1%)
    $|Vtb| = 1.10 \pm 0.12(\text{exp.}) \pm 0.03(\text{th.})$ (tW-ch.,11.2%)
- CMS:
  - 7 TeV: $|Vtb| = 1.020 \pm 0.046(\text{exp.}) \pm 0.017(\text{th.})$ (t-ch. 4.8%)
    $|Vtb| = 1.01+0.16-0.13(\text{exp.})+0.03-0.04(\text{th.})$ (tW-ch., 14.8%)
  - 8 TeV: $|Vtb| = 0.96 \pm 0.08(\text{exp.}) \pm 0.02(\text{th.})$ (t-ch. 8.6%)
    $|Vtb| = 1.03 \pm 0.12(\text{exp.}) \pm 0.04(\text{th.})$ (tW-ch. 12.3%)
- At the moment CMS t-ch.@7 TeV dominates, but with future updates it would be worth to consider the combination of the four t-channel measurements
- Systematic correlation may be non trivial between 7 and 8 TeV