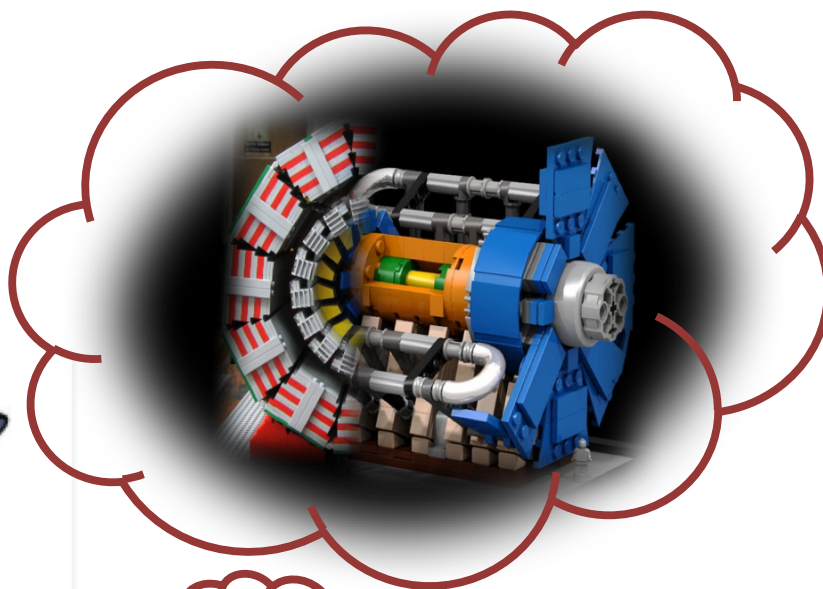


LHC top quark combinations

status and issues for the future



Jan 16-17, 2018
Fermilab
Top quark physics at
the Precision Frontier

Martijn Mulders (CERN)

LHC^{TOP}WG

The Final Legacy

- Often a combination of individual published measurements
- Examples: LEP/SLD, Tevatron, ...

LEP+SLD Run 1 (Z pole) legacy paper

Phys.Rept. 427 (2006) 257-454

<https://inspirehep.net/record/691576>

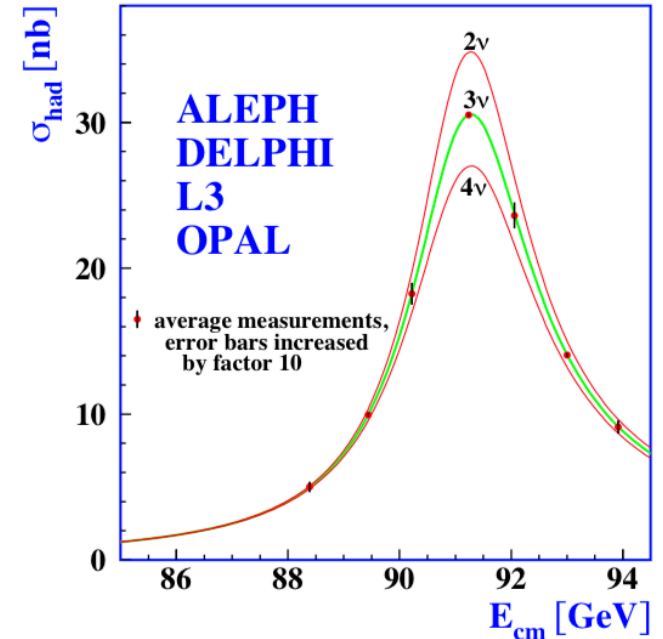
(1712 citations)

LEP Run 2 legacy paper

Phys.Rept. 532 (2013) 119-244

<http://inspirehep.net/record/1219330>

(282 citations)



$$m_Z = 91.1875 \pm 0.0021 \text{ GeV}$$

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$

$$\rho_\ell = 1.0050 \pm 0.0010$$

$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.23153 \pm 0.00016 .$$

$$m_W = 80.376 \pm 0.033 \text{ GeV}$$

$$\Gamma_W = 2.195 \pm 0.083 \text{ GeV}$$

$$B(W \rightarrow \text{had}) = 67.41 \pm 0.27 \%$$

$$g_1^Z = 0.984^{+0.018}_{-0.020}$$

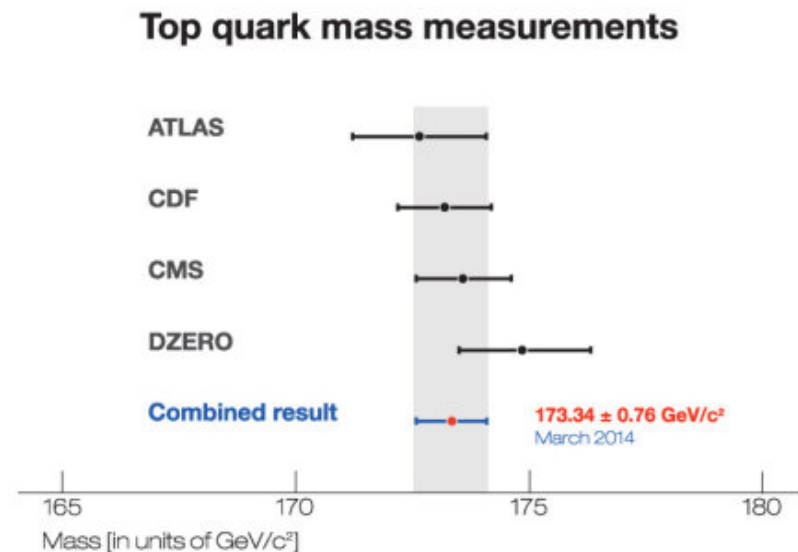
$$\kappa_\gamma = 0.982 \pm 0.042$$

$$\lambda_\gamma = -0.022 \pm 0.019 .$$

Or intermediate combinations...

- At the **Precision Frontier**, even intermediate combinations are useful and can be a ‘big deal’
- Eg. **top mass world average 2014**, ATLAS, CDF, CMS, D0
<https://arxiv.org/abs/1403.4427>
(502 citations)
 - **However:** quickly surpassed by newer measurements..!

LHC and Tevatron scientists announce first joint result



Combinations: Pros and Cons

Advantages (eg combining ATLAS and CMS results)

- **Immediate doubling of statistics!** For “free”... and it gets better:
- **De-correlation** of systematic uncertainties reduces their impact
- Learn from **state-of-the-art discussions** with experts in other experiments + theory
- Contributes to **better understanding and uniformity** of treatment of uncertainties for future rounds of measurements

Potential issues and challenges

- Proper treatment of systematics and correlations far from trivial
- Preparing combinations is often low priority
- Long timescales, lost expertise
- Multiple collaboration review...

LHC Top Working Group



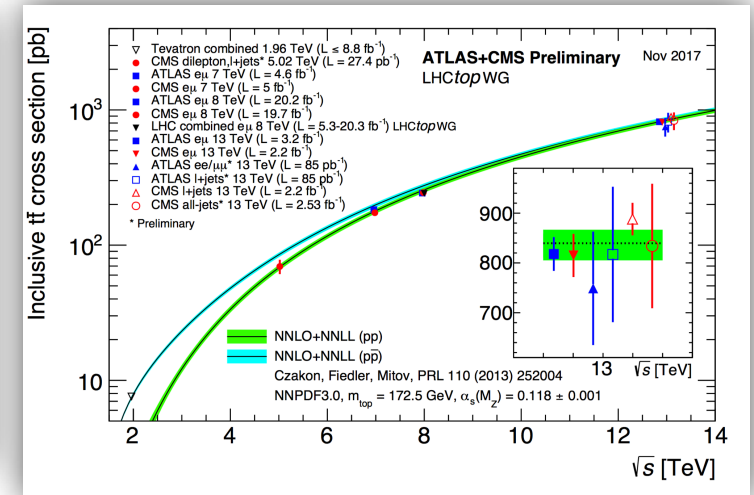
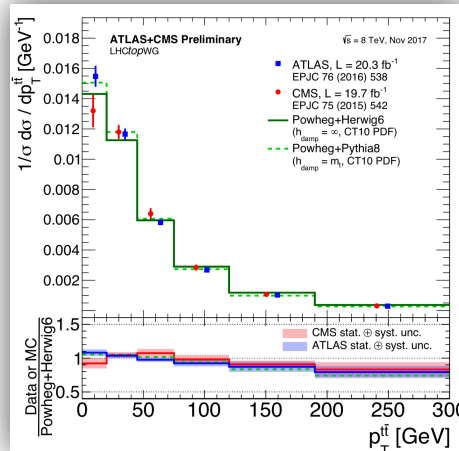
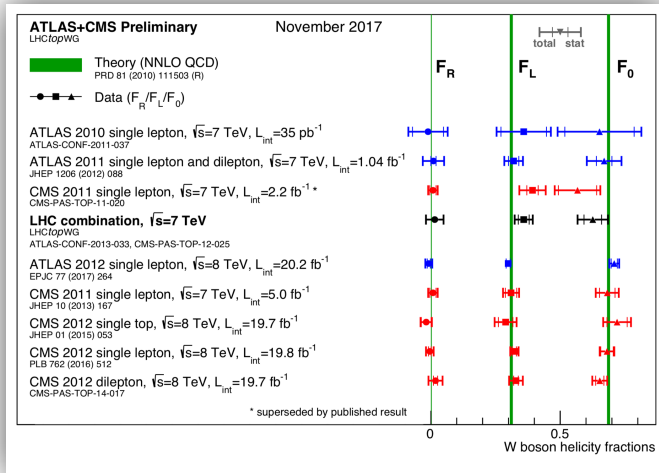
- In the footsteps of LEPEWWG and TeVEWWG
 - Charged by the LHC experiments to [prepare combinations of top quark measurements](#)
 - Where required, allowed to exchange confidential information between experiments in preparation of the combinations
 - [Forum for discussions](#) between experts from the experiments and theory colleagues
- Regular closed meetings between ATLAS+CMS experts to prepare new combination and discuss plans
- [Please join](#) the Open LHCtopWG meetings - twice per year at CERN !!
 - Open discussions of state-of-the-art topics
 - All meetings <https://indico.cern.ch/category/9219/>
 - Mailing list : lhc-toplhwcg@cern.ch

LHC Top Working Group: Status

<https://lpsc.web.cern.ch/lhc-top-wg-wg-top-physics-lhc>

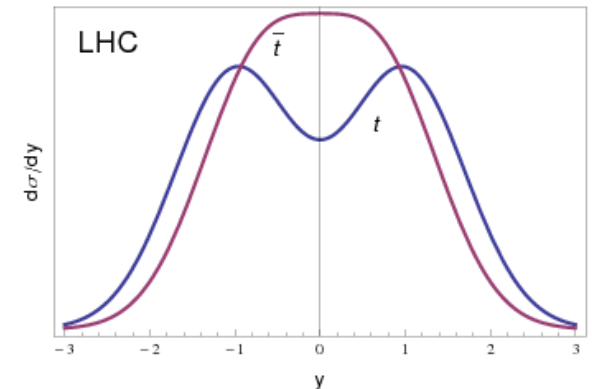
- So far **9 preliminary** and **1 published** combinations
- ATLAS-CMS **agreements** on inter-experiment correlations for Jet Energy Scale and b-tagging uncertainties
- Summary Plots that are regularly updated

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCtopWGSummaryPlots>



First LHC top physics paper: Ac

- Submitted for publication [arXiv:1709.05327](https://arxiv.org/abs/1709.05327) (5098 authors)
- Input measurements: lepton+jets channel
 - ATLAS inclusive (7 and 8 TeV) and differential (8 TeV)
 - CMS unfolding method (7 and 8 TeV) differential
 - CMS template method inclusive (8 TeV)
- Combinations performed (using BLUE: best linear unbiased estimate)
 - 7 TeV inclusive
 - 8 TeV inclusive (using CMS template result)
 - 8 TeV differential in $m_{t\bar{t}}$ (using CMS unfolding method)
 - Binning was agreed upon by both experiments before publication
 - Take into account correlations between bins and experiments



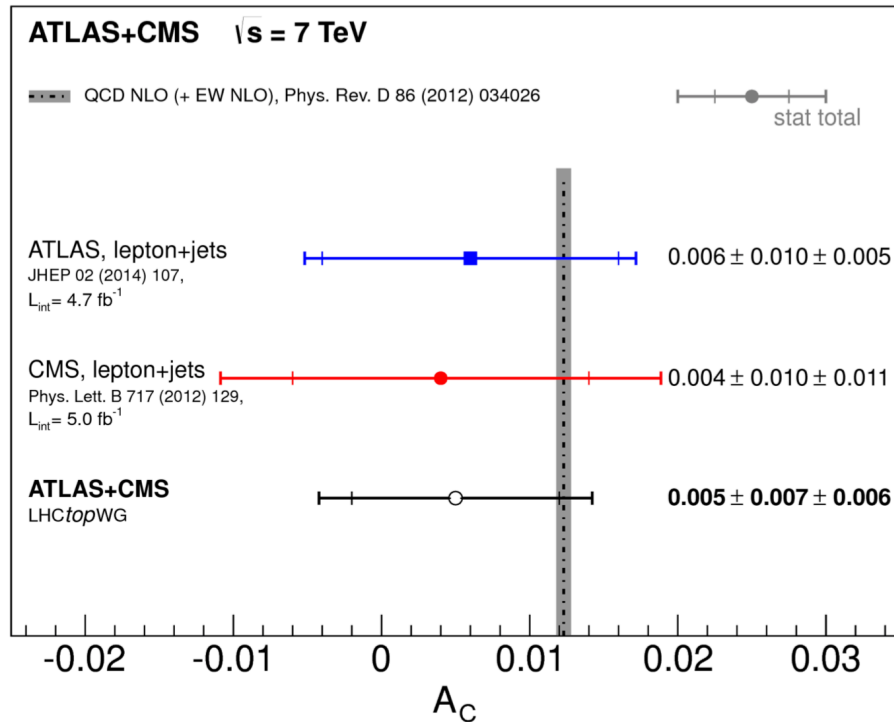
$$A_C = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

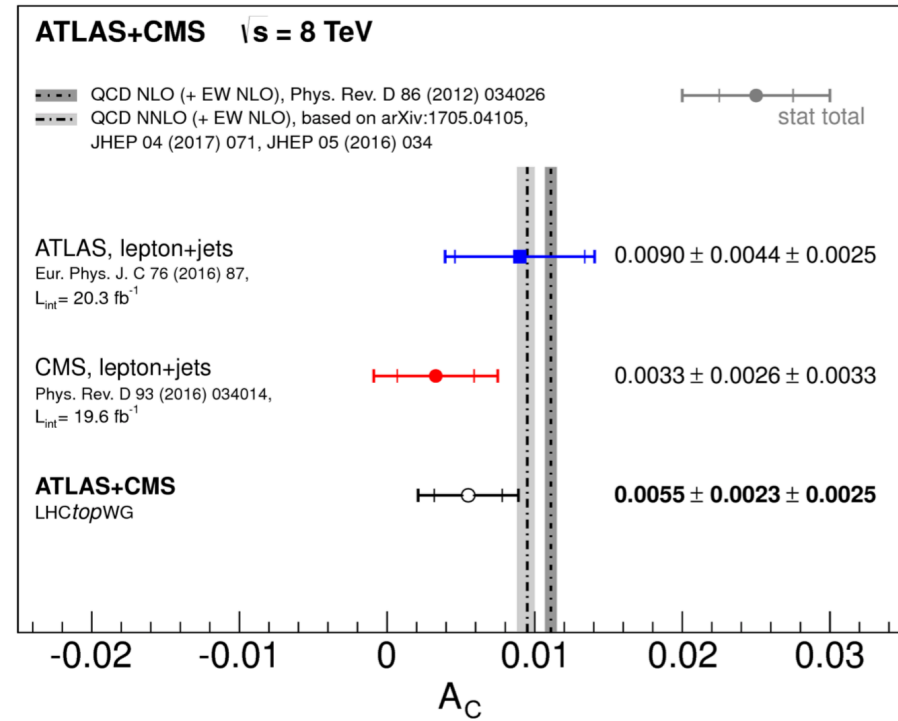
8 TeV inclusive : Systematics

	ATLAS	CMS	ρ	Combined	
A_C	0.0090	0.0033	0.13	0.0055	
Statistical (data)	0.0044	0.0026	0	0.0023	←
Statistical (simulation)	0.0010	0.0015	0	0.0010	←
<i>Detector model (excluding JES)</i>					
Leptons	0.0003	0.0001	0	0.0001	
Jet energy resolution	0.0005	0.0004	0	0.0003	
<i>b</i> -tagging	0.0004	0.0007	0	0.0005	
Missing transverse momentum	0.0002	—	—	0.0001	
Pile-up	—	0.0003	—	0.0002	
<i>Jet energy scale</i>					
Uncorrelated JES	0.0010	0.0004	0	0.0005	
Partially correlated JES	0.0009	0.0010	0.5	0.0008	←
Mostly correlated JES	0.0002	0.0004	1	0.0003	
Fully correlated JES	0.0009	0.0008	1	0.0008	←
<i>Signal modelling</i>					
Event generator	0.0004	0.0002	1	0.0003	
Parton shower and hadronisation	0.0004	—	—	0.0002	
Scale/radiation	0.0009	0.0014	1	0.0012	←
PDF	0.0007	0.0002	1	0.0004	
Integrated luminosity	—	0.0001	—	0.0001	
<i>Backgrounds</i>					
Single-top-quark / <i>Z</i> +jets	0.0001	0.0004	1	0.0003	
Multijet	0.0005	0.0018	0	0.0011	←
<i>W</i> +jets	—	0.0002	—	0.0001	
Method	0.0003	—	—	0.0001	
Systematic uncertainty	0.0025	0.0033		0.0025	
Total uncertainty	0.0051	0.0041		0.0034	

Inclusive combination results

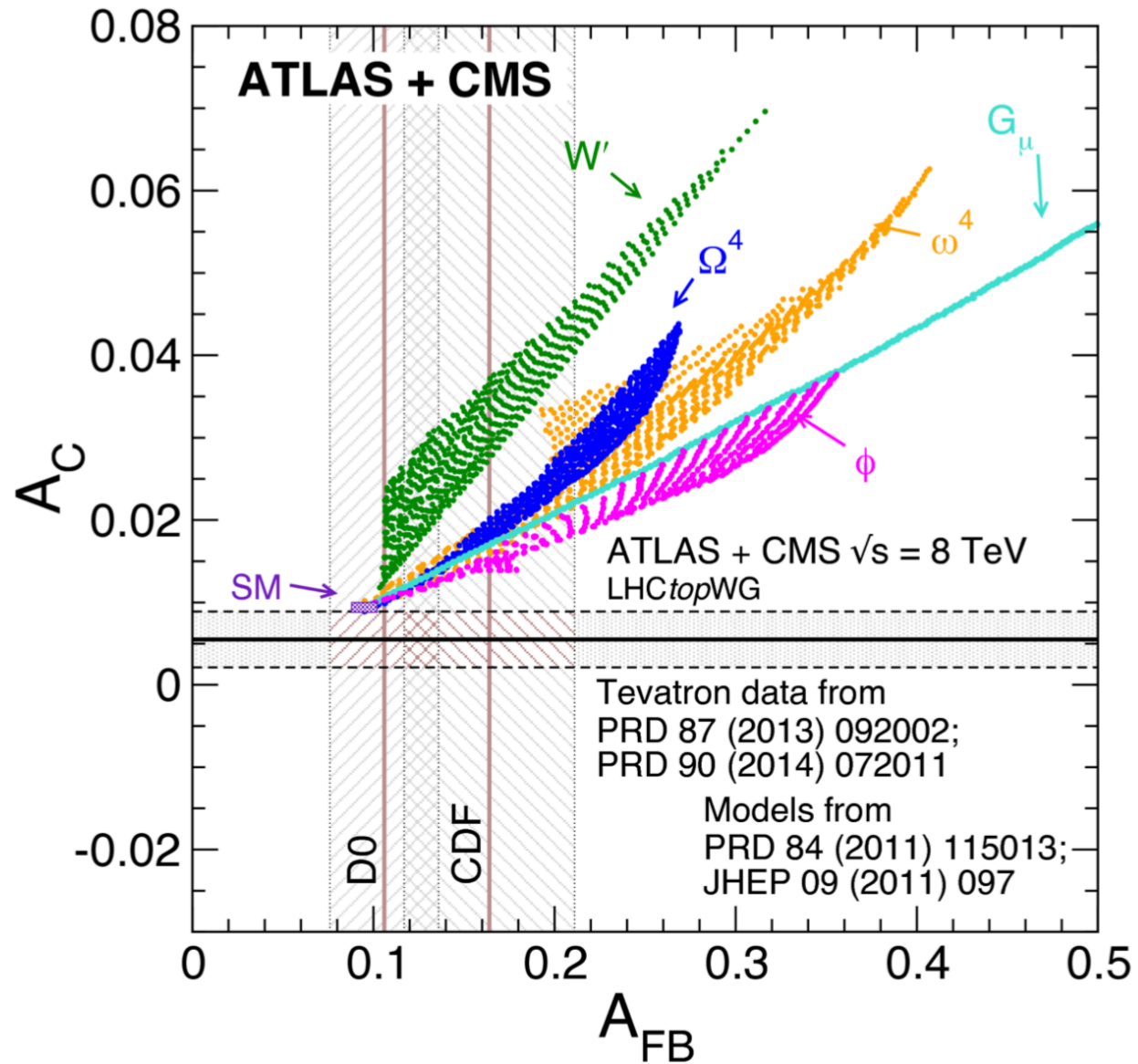


18% improvement over
most precise input (ATLAS)

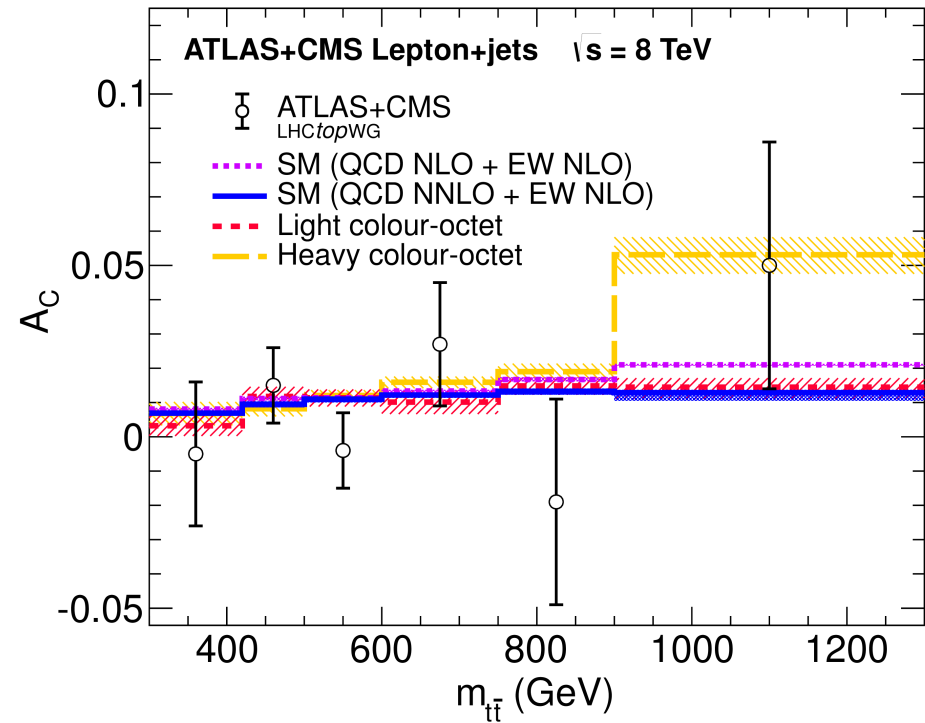
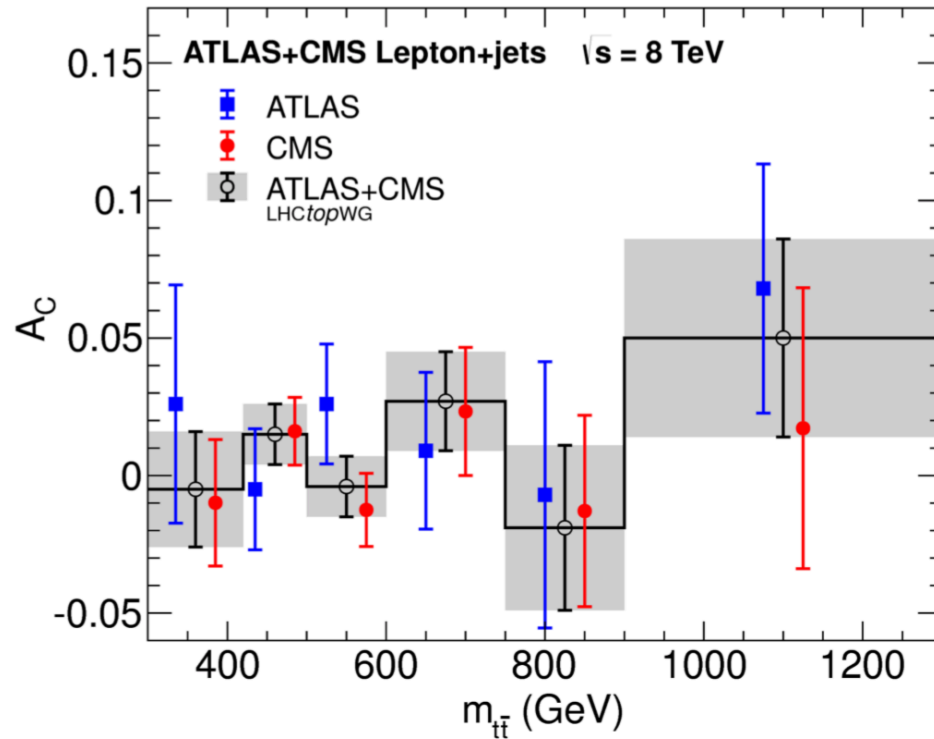


17% improvement over
most precise input (CMS)

8 TeV Inclusive Result



Differential Results

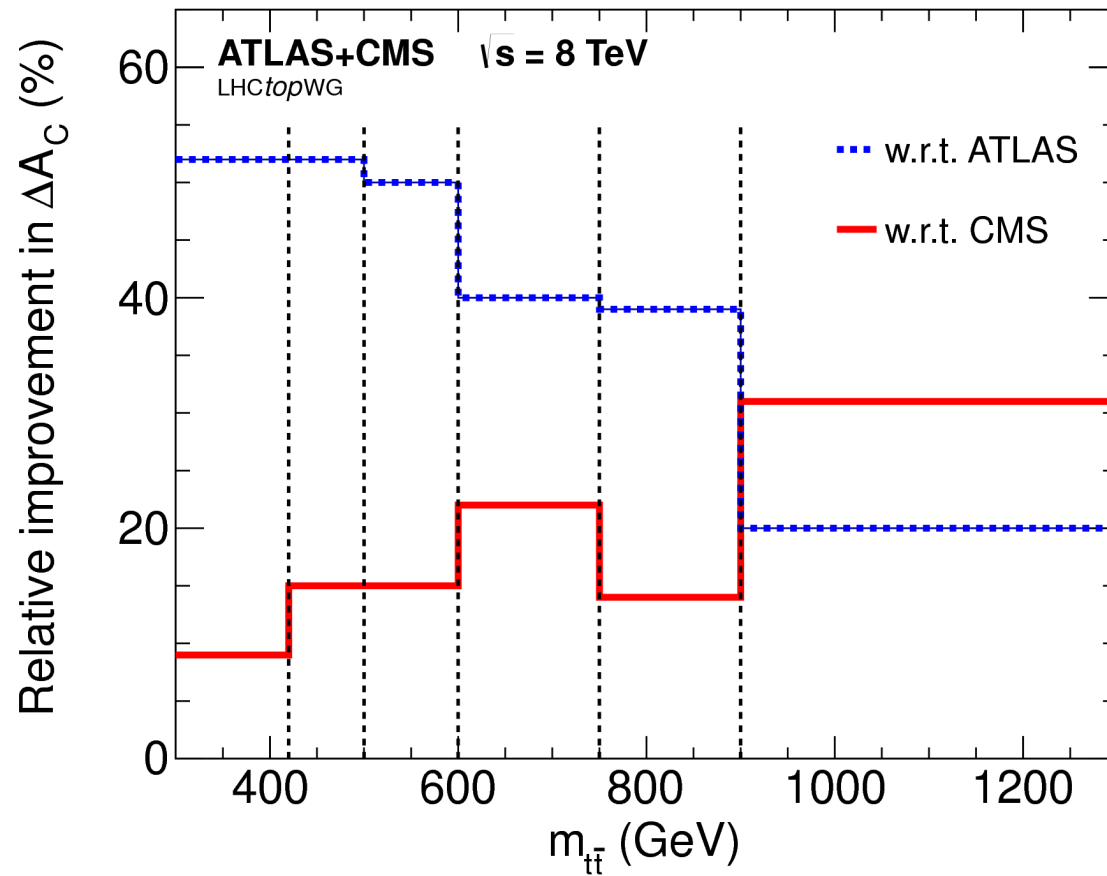


relative uncertainty per bin (input):

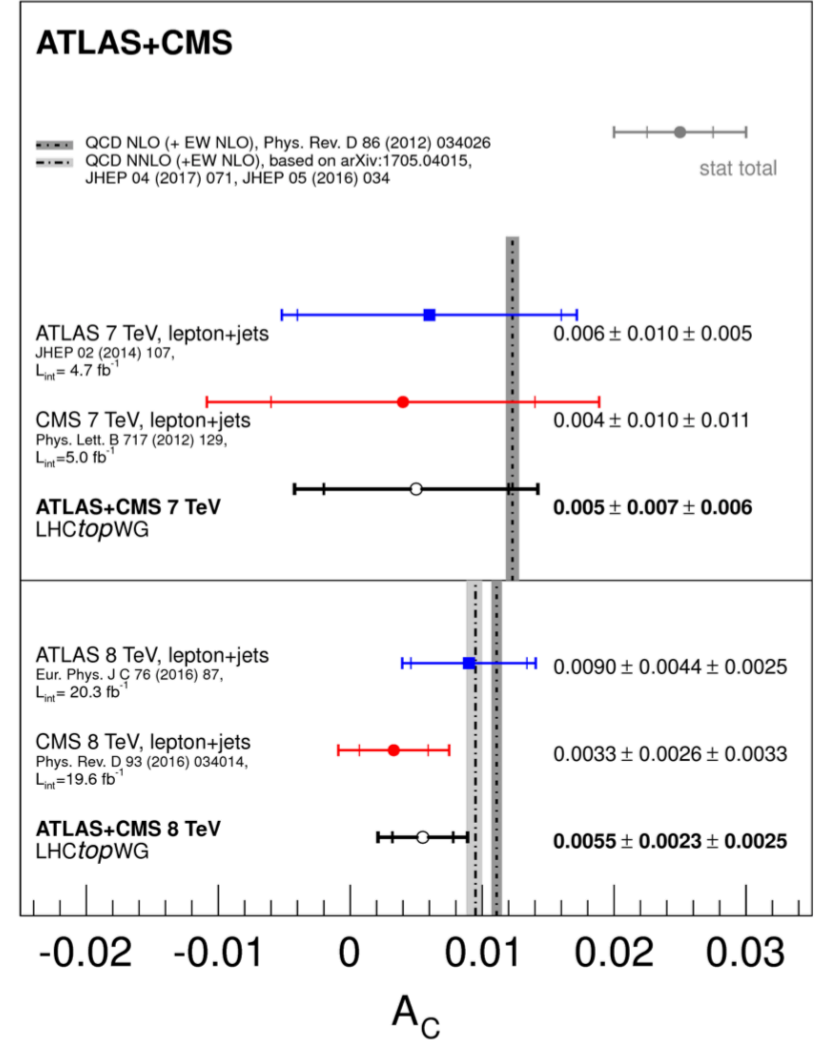
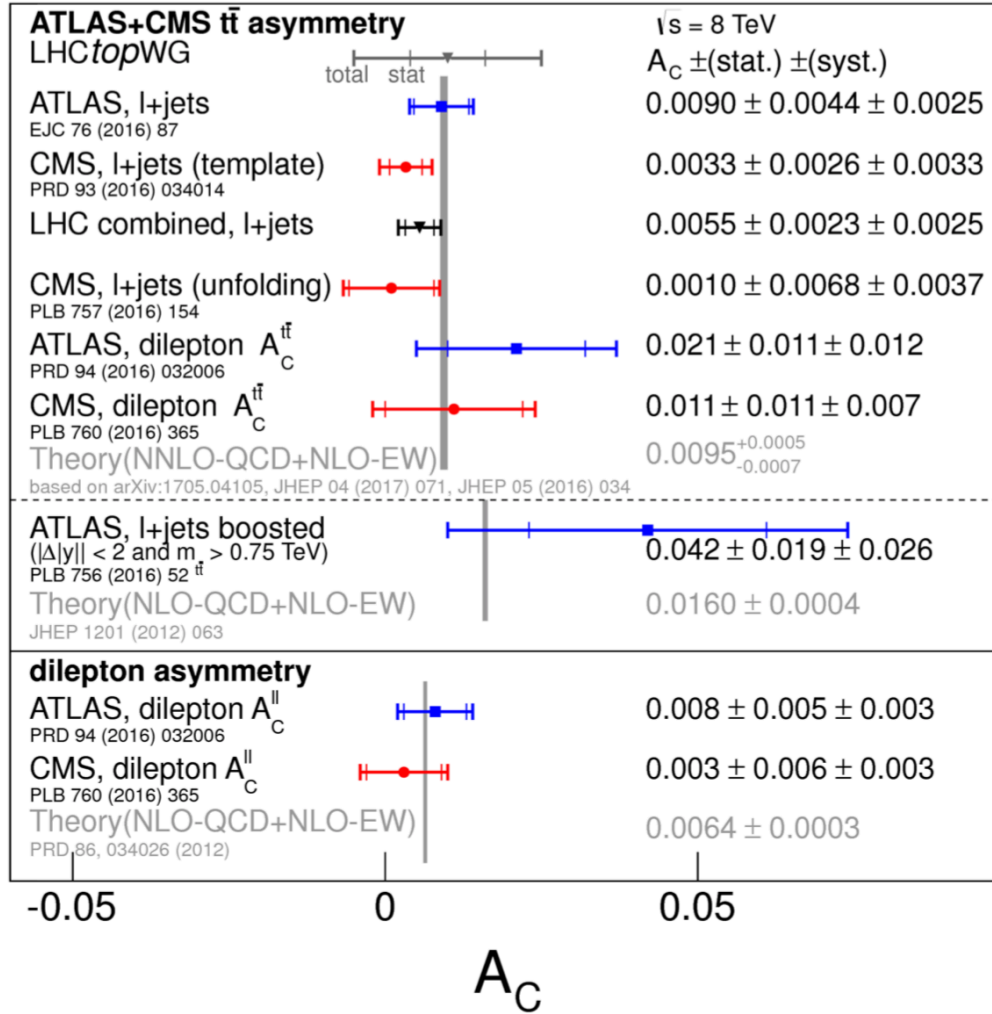
	statistical	systematic
ATLAS	1.7 -- 4.2%	1.2 -- 3.6%
CMS	1.1 -- 3.8%	0.6 -- 3.5%
Comb.	0.9 -- 2.7%	0.6 -- 2.4%

Dedicated NNLO + EW NLO calculation provided for this analysis, in the same binning (thanks !!)

8 TeV differential: relative improvement in bin-by-bin uncertainty



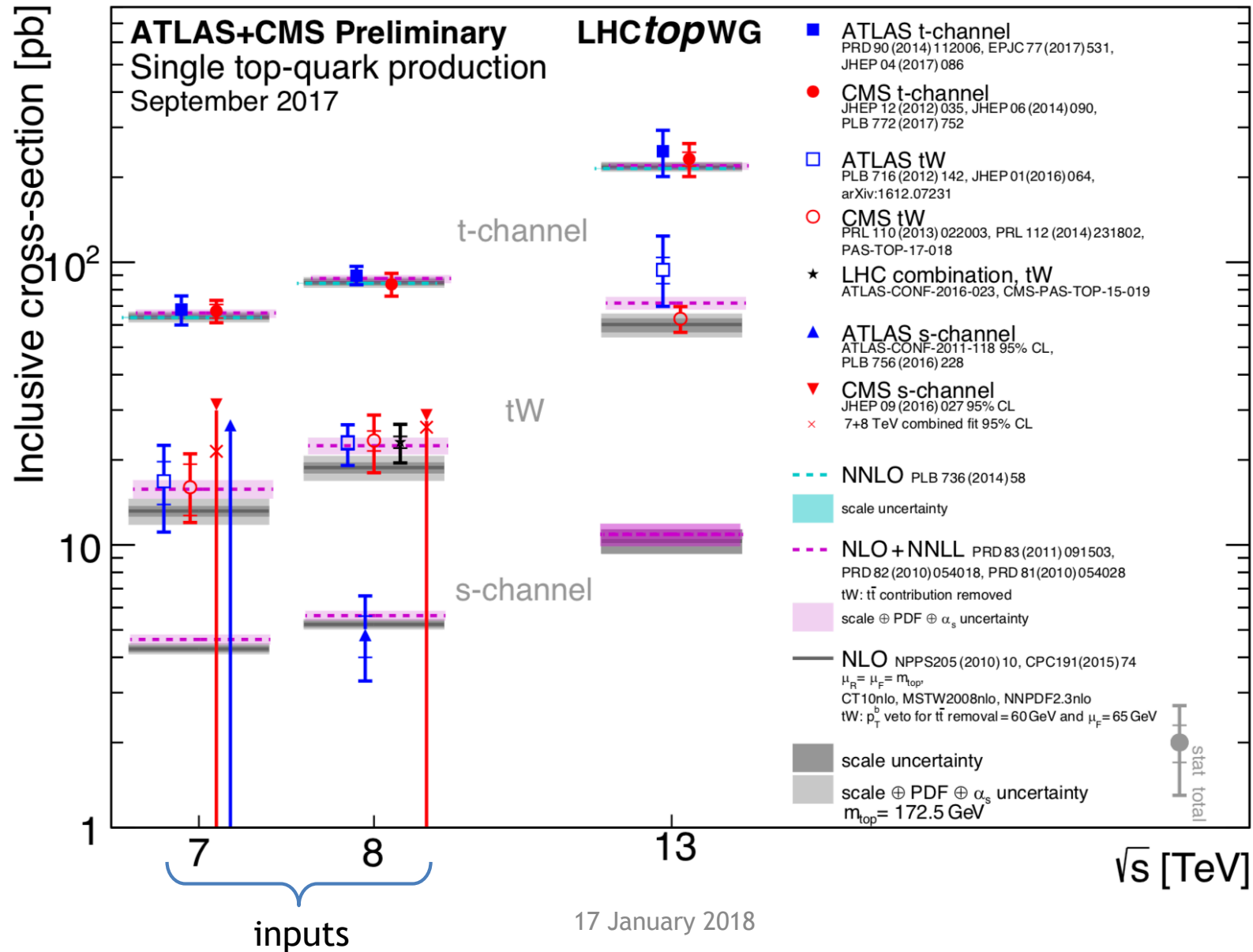
Final Summary Plots Ac



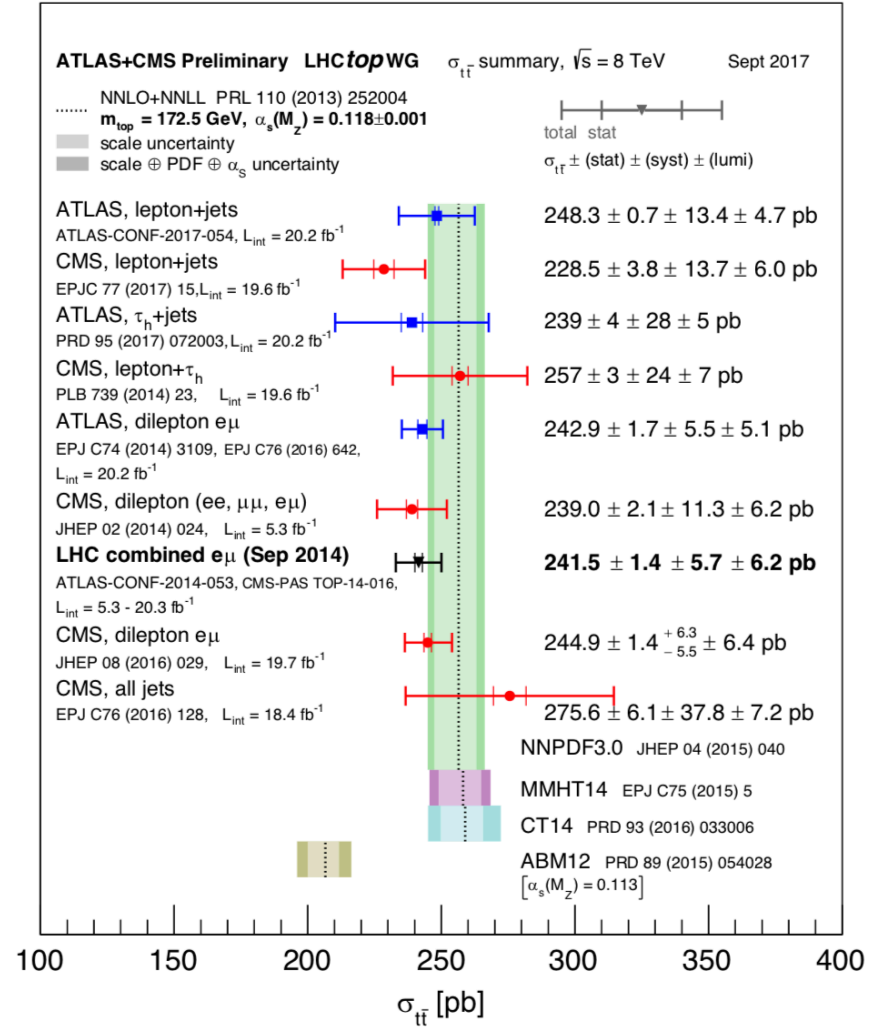
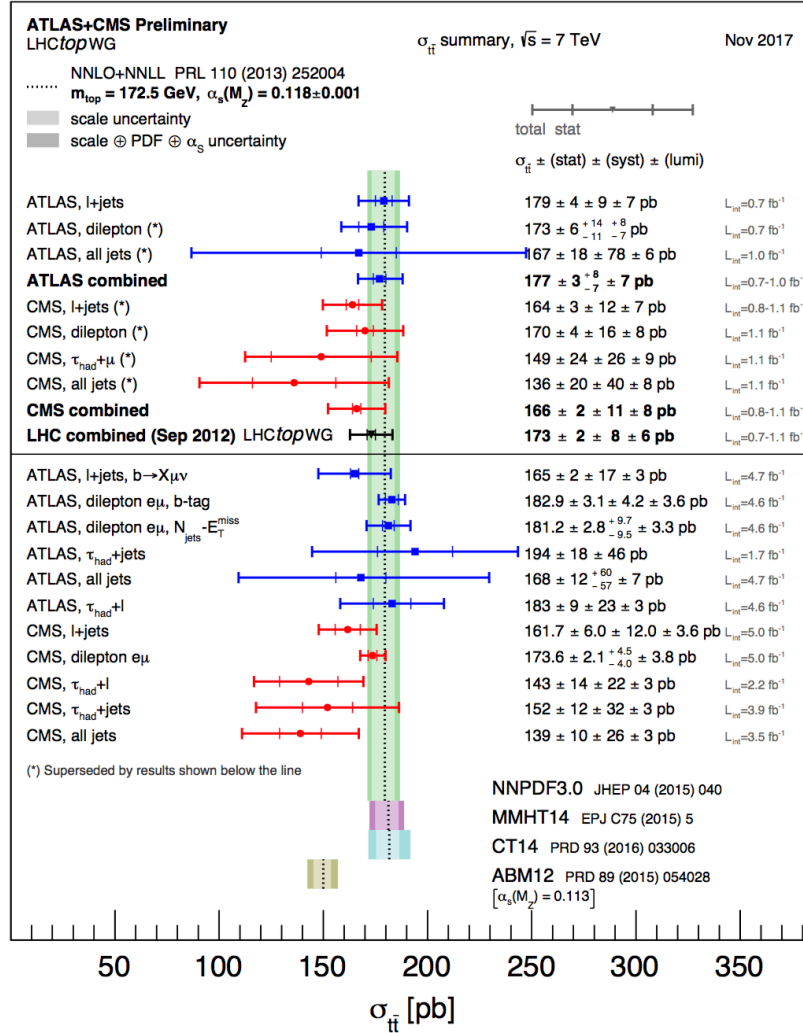
Other planned Run 1 legacy publications

- **Combination analyses in progress:**
 - **Single top channels (t, tW and s) + V_{tb}**
 - To include 7 and 8 TeV combinations per channel
 - V_{tb} from ratio of measured and prediction cross sections
 - Paper in collaboration internal reviews
 - **Inclusive top pair cross sections at 7 and 8 TeV**
 - To include 7 and 8 TeV cross-sections and their ratio
 - Also considering extraction of α_s and top pole mass
 - Paper in preparation
- **Other combinations**
 - **Top mass:** preparatory discussions and studies ongoing
 - **Differential $t\bar{t}$ distributions** (started with comparisons)
 - 8 TeV at parton level
 - 13 TeV at particle level
 - **W helicity** and/or constraints on anomalous couplings and EFTs

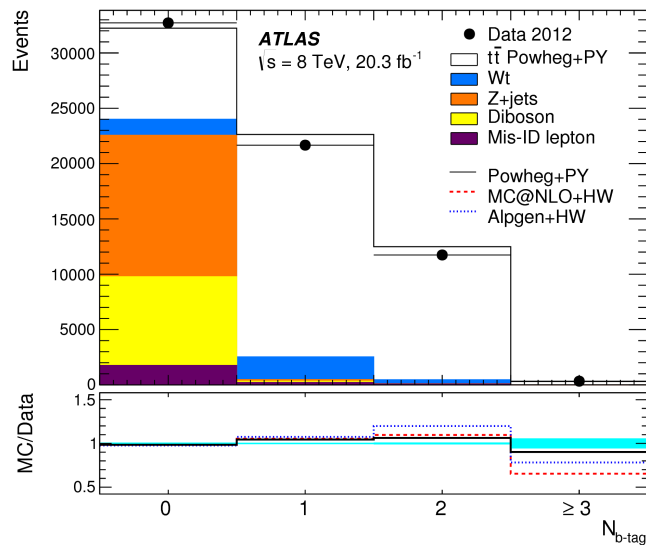
Single Top and Vtb



Top pair cross-section measurements



Top pair inclusive cross-section combination



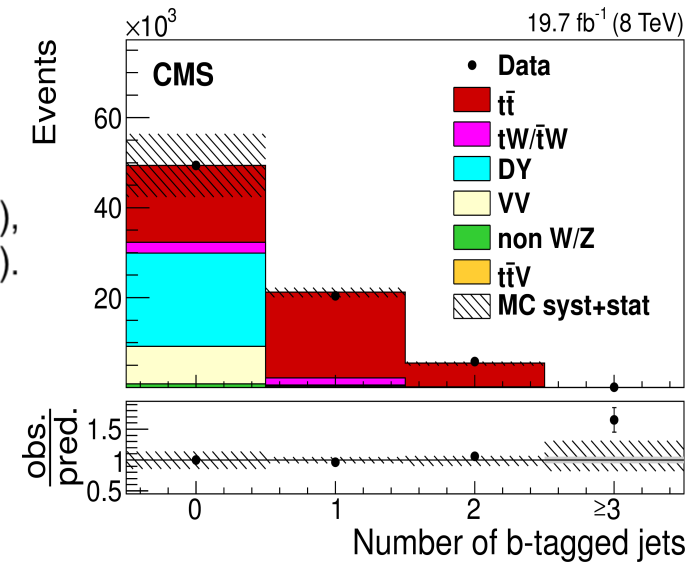
precision:

ATLAS

3.2% (8 TeV),
3.5% (7 TeV).

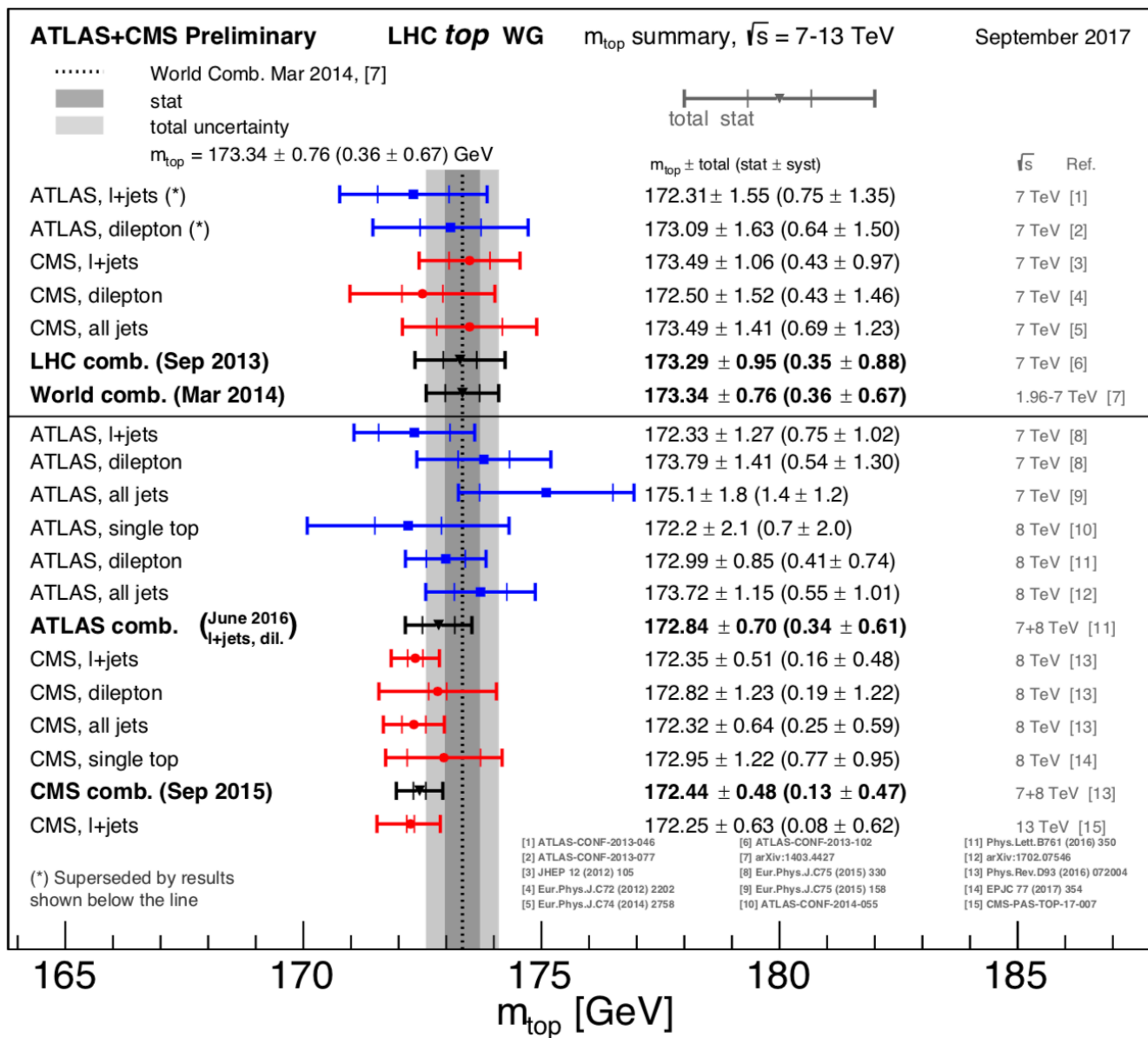
CMS

3.7% (8 TeV),
3.6% (7 TeV).



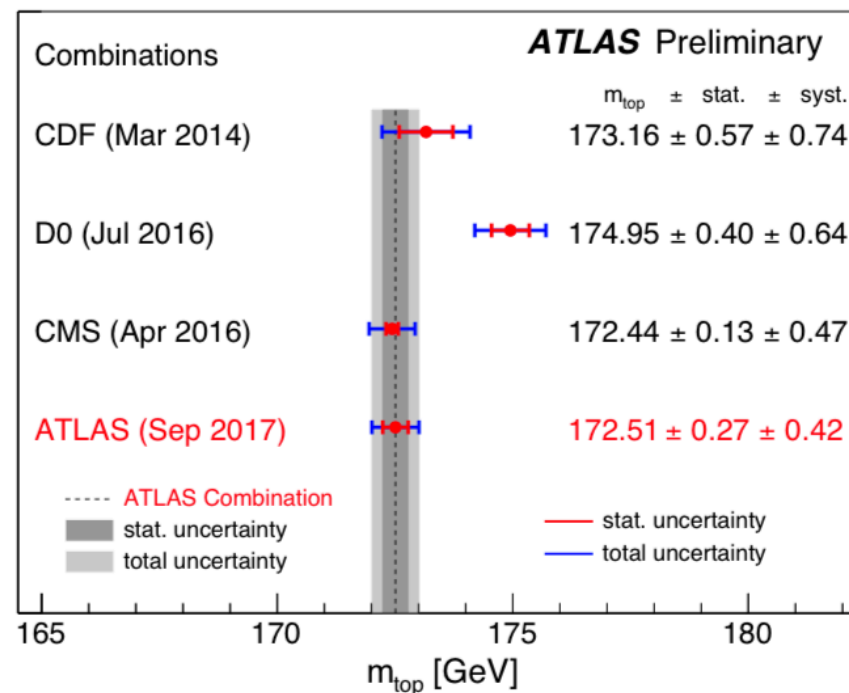
- Combine most precise $t\bar{t}$ cross section results at 7 and 8 TeV ($e\mu$ channel)
- Apart from luminosity, dominant syst unc. different → **gain from combination!**
- **Challenge:** systematics already correlated in input results (from multi-dim fit)
- A new statistics tool was developed for combination *Convino*, that
 - Does combined fit taking into account post-fit covariance matrices of input results
 - Allows any values of correlation assumptions between ATLAS and CMS
 - Accepted by EPJC, see <https://arxiv.org/abs/1706.01681>
- Plan to also extract α_s and $m_{\text{top}}^{\text{pole}}$ from comparison with NNLO+EW predictions

Top Mass



Towards a legacy LHC Run 1 Top Mass

- ATLAS and CMS now both have a **complete set** of Run 1 ‘standard’ measurements
- The **overall precision** of CMS and ATLAS is **comparable**, and the uncertainties only partially correlated
- Expect to gain from LHC combination
- **Goal:** publication of a legacy top mass measurement from the LHC Run 1
 - Including the full set of relevant ‘standard measurements’ from ATLAS and CMS
 - Only using published results as input
 - Hope to be quoted by the PDG
 - Input to future LHC+Tevatron world average
 - **Interpretation** of the measured m_{top} (‘MC mass’); hoping for a statement from theory colleagues that can be cited in our legacy paper



Top Mass correlations

- Detailed treatment for **intra-experiment correlations** in place, developed for CMS legacy paper and ATLAS combinations
 - ATLAS combination shows important gains from anti-correlations
- **Inter-experiment correlations** still to be worked out
- Some harmonization has happened already, and implementation ~trivial
 - **Experimental uncertainties** mostly uncorrelated
 - Jet Energy Scale (and b-tagging) are more subtle, but here an agreed procedure (categorization) exists (in principle)
- **Signal modeling** will require careful definition of correlations
 - Different base MC generator and MC tune (PS); different approaches to estimation of ISR/FSR, b fragmentation, top quark p_T , etc
- CMS uses a very conservative treatment of **statistical uncertainties** on systematic effects (always taking the larger of statistical uncertainty and systematic shift); this may need to be harmonized with ATLAS

The connection with Top SM EFT

(see previous talks)

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

- “BSM Goal” of the SM Precision Frontier: determine (EFT) couplings of the SM Lagrangian up to DIM=6
- **Challenge:** how to constrain (many) higher-order couplings by combining (many) SM measurements
 → this requires a coordinated effort
 - What theoretical definitions to use
 - How to present experimental results to allow optimal re-interpretation and combined fit
 - Take into account correlations ...
- Started a Top EFT Forum to discuss common LHC strategy with theory community in LHCTopWG
- Aim to summarize proposal in public documents

Constraining the SMEFT in the top sector at the LHC

Working document for the TOP LHC WG

Current authors:
 Juan Antonio Aguilar Saavedra, Céline Degrande, Gauthier Durieux,
 Fabio Maltoni, Eleni Vryonidou, Cen Zhang

v0.0: PRELIMINARY
 Thu 12th Oct, 2017, 14:17

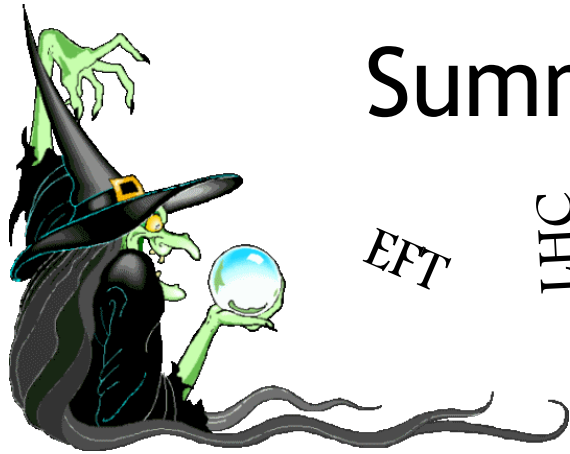
Contents	
1	Introduction
2	Guiding principles
2	Operator definitions
4	Flavour assumptions
4	Degrees of freedom and direct constraints
5	A simple analysis strategy
9	A UFO Model documentation
10	A.1 Some general comments
10	A.2 Syntax
11	A.3 Benchmark results
11	B Degrees of freedom for processes conserving flavour, baryon and lepton numbers
11	B.1 Single top production & hadronic top decay
12	B.2 Top pair production
14	B.3 Four top production
15	B.4 Top pair production in association with a Z boson or a photon
16	B.5 Top pair production in association with a Higgs boson
16	B.6 Top pair production in association with a W-boson

1 Introduction

The aim of this document is to collect the minimal information necessary for experimental collaborations to constrain dimension-six operators in the SMEFT from top-quark measurements at the LHC. It is organised in two main parts followed by several appendices.

In the first part, a minimal class of operators relevant for top-quark processes is presented together with possible extensions. The basic guiding principles are stated and the operators, organised in three main classes—four-quark, two-quark and two-quark-two-lepton—are explicitly written down following a well-defined naming and normalisation convention. In particular, the question of which non-trivial (flavour) symmetries can be employed to reduce the number of independent operators is addressed. The main production (and decay) channels involving a top quark at the LHC are then reviewed, and the relevant degrees of freedom (i.e. linear combination of operators) that can be probed in principle in each process is identified.

In the second part, recommendations on how to proceed in an actual analysis are provided. Limits set on operators in a series of theoretical studies are also presented in this part to provide a guidance for the experimental analyses.



Summary and Outlook

EFT

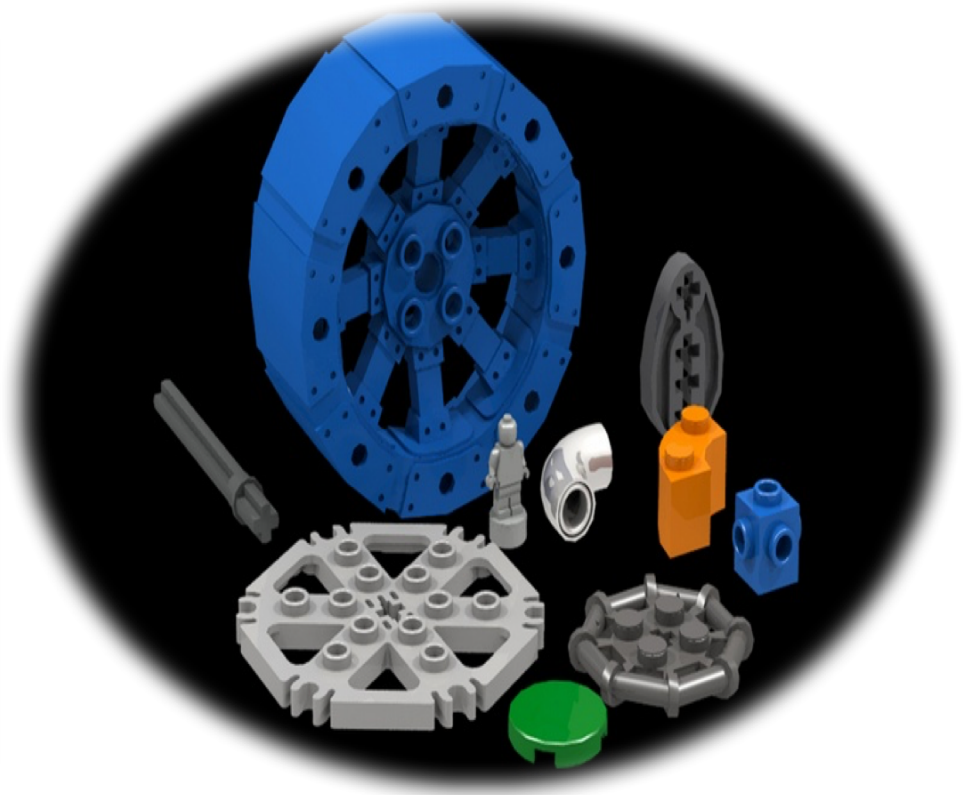
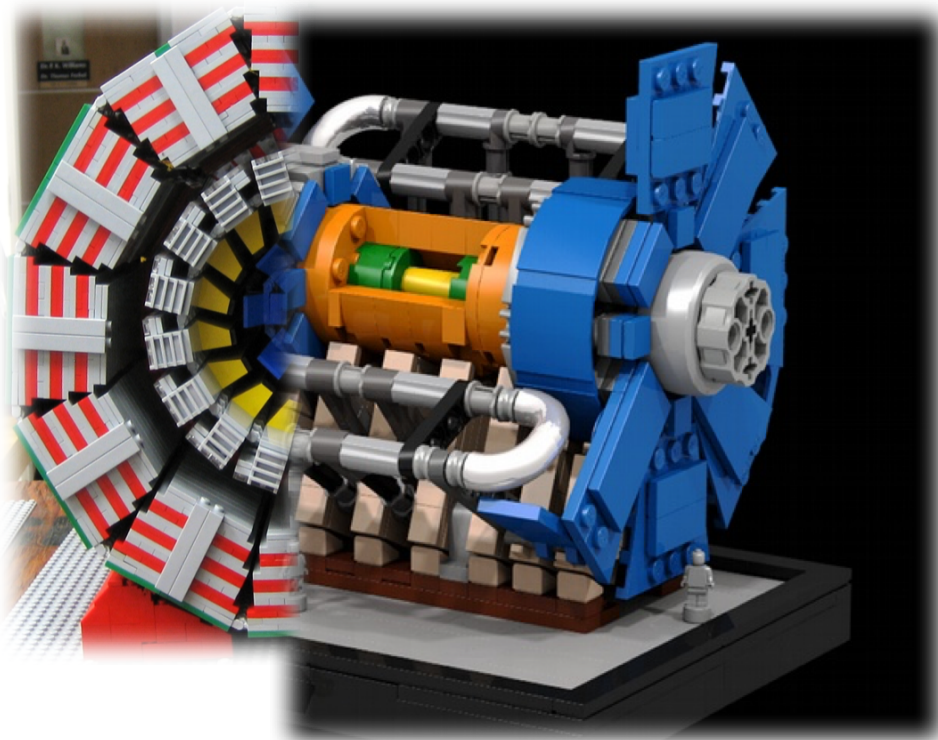
LHC

WG



- The ultimate precision on top quark (SM) properties and EFT operators will come from combinations and/or global fits using all our data and our best theoretical knowledge
- We have published our first LHC top physics combination (A_c) and other papers are in the pipeline (V_{tb} single top, $t\bar{t}$ bar, m_{top} ... for now)
- Hopefully a new LHC+Tevatron world average top mass will follow soon
- This is only the beginning! We are actively preparing the road for future LHC top physics combinations and EFT fits for LHC Run 2, 3, and beyond

BACKUP



LHC*top*WG

LPCC: LHC Physics Centre at CERN

<https://lpcc.web.cern.ch/lhc-working-groups>

- Under umbrella of LPCC
- 2 open meetings per year
- Regular closed meetings
- Summary plots:
<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots>
- Meetings:
<https://indico.cern.ch/category/4463/>

LHC WORKING GROUPS

Dark Matter WG
WG Meetings
WG documents

Electroweak WG
WG Documents
WG meetings

Forward Physics WG
WG TWIKI PAGE
WG documents
WG meetings

Heavy Flavour WG
WG Documents
WG Meetings

MB & UE WG
WG meetings
WG documents

Machine Learning WG
WG meetings
iml web page

Top WG
WG meetings
WG documents
WG plots and twiki

LHC*top*WG organization

Representative for **Theory**:

Michelangelo Mangano

Representative for **LHCb**:

Steve Farry

Representative for **CMS**:

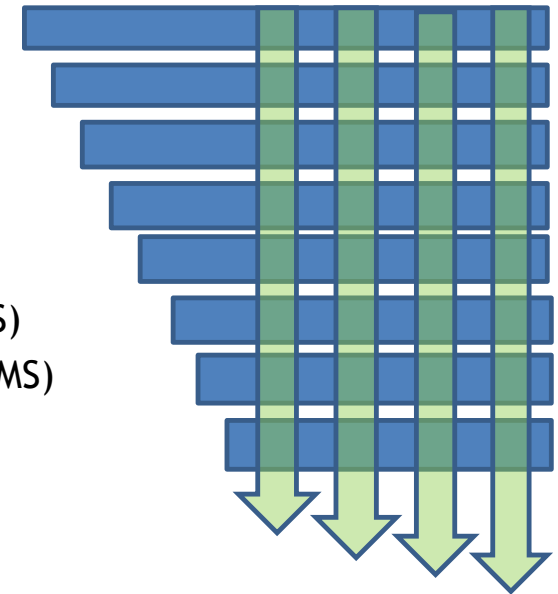
Martijn Mulders

Representative for **ATLAS**:

Mark Owen

Contact persons for combinations:

- **Top pair cross section:** Veronique Boisvert (ATLAS), Jan Kieseler (CMS)
- **Single top cross sections:** Carlos Escobar (ATLAS), Jeremy Andrea (CMS)
- **Top mass:** Mark Owen (ATLAS), Steve Wimpenny (CMS).
- **Charge asymmetry:** Frederic Deliot (ATLAS), Thorsten Chwalek (CMS)
- **ttV :** Markus Cristinziani (ATLAS), Andrew Brinkerhoff (CMS)
- **Top pair diff. cross sec. 8 TeV:** Francesco Spanò (ATLAS), Maria Aldaya (CMS)
- **Top pair diff. cross sec. 13 TeV:** James Howarth (ATLAS), Otto Hindrichs (CMS)
- **W helicity:** Mohammad Kareem (ATLAS), Mara Senghi (CMS)



Task forces for dedicated topics:

- **Jet/MET:** Steven Schramm, Dimitris Varouchas (ATLAS), Mikko Vitoulainen, Henning Kirschenmann (CMS)
- **Common acceptance/PseudoTop:** Kevin Finelli, Dominic Hirschebühl (ATLAS), Junghwan Goh, Orso Iorio (CMS)
- **Radiation/Generators:** James Ferrando, Dominic Hirschebühl (ATLAS), Benedikt Maier, Markus Seidel (CMS)
- **b-Tagging:** Martin zur Nedden and Liza Mijovic (ATLAS), Luca Scodellaro (CMS)
- **Top EFT Forum:** Oliver Maria Kind and Nuno Castro (ATLAS); Alexander Grohsjean and Nadjieh Jafari (CMS)