An overview of the ongoing ATLAS & CMS combination efforts

Open LHC*top*WG meeting

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Nov 14th, 2019

Why combining results?

- To improve the measurements precision
- To improve our understanding about the differences in the implemented methods
- To test the consistency ATLAS and CMS results

Ongoing combinations & contacts

- **Top pair cross-section:** Veronique Boisvert (ATLAS), Jan Kieseler (CMS)
- **Top mass:** Mark Owen (ATLAS), Steve Wimpenny (CMS)
- **W helicity:** Mohammad Kareem (ATLAS), Mara Senghi (CMS)
- **Top pair differential cross-section:** Francesco Spanò (ATLAS), Maria Aldaya (CMS),

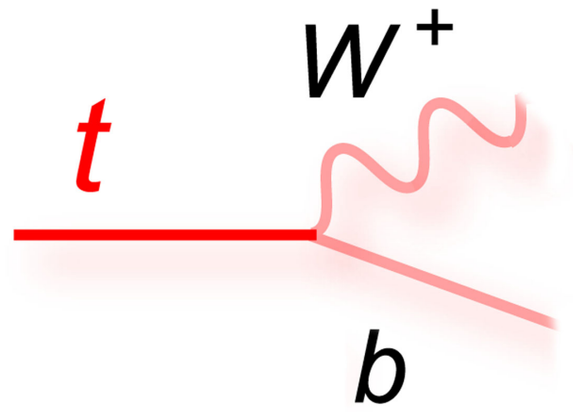
Jan Kieseler (CMS)

All are run 1 combinations

Run 1 combination of W helicity measurements in top quark decay

W Helicity in top quark decay

- **The top quark decay vertex Lagrangian with minimum generalization:**



Vector couplings

Tensor couplings

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})\,t\,W_{\mu}^{-} + \mathrm{h.c.}\,,$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

(≈ 1 in SM)

Anomalous couplings (≈ 0 in SM at tree level)

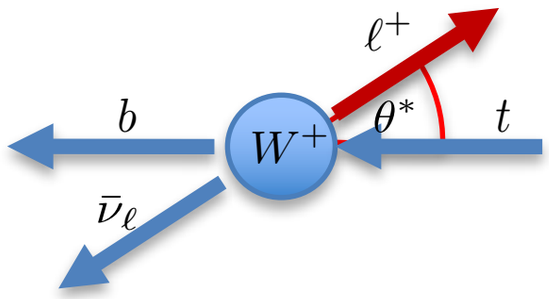
Direct impact on the W boson polarization

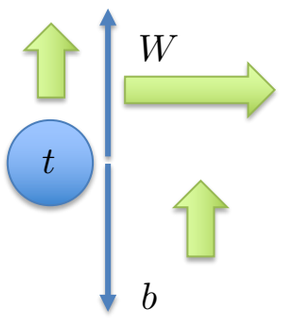
- **Measuring W boson polarization with high precision:**
  - ✤ **Good test of the Standard Model prediction**
  - ✤ **Probe for new physics processes**

W Helicity in top quark decay

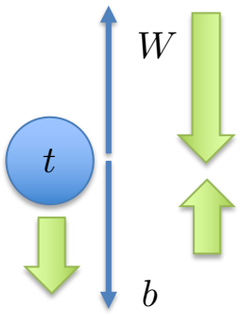
- W polarization in top quark decay is sensitive to **cosθ^*** distribution

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

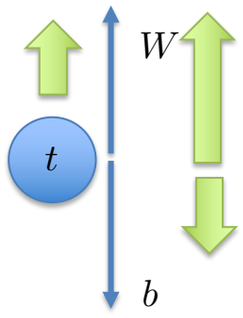




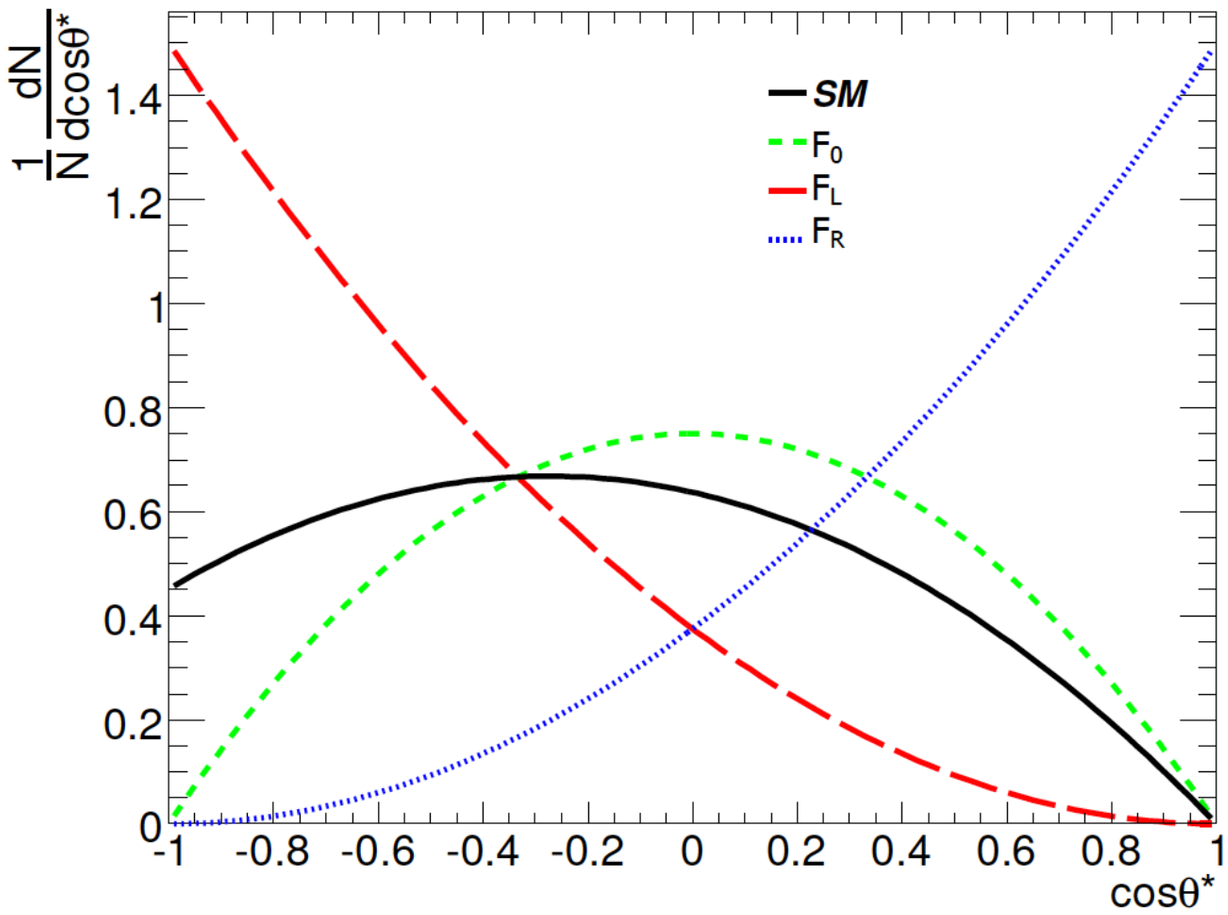
F_0=0.687±0.005



F_L=0.311±0.005

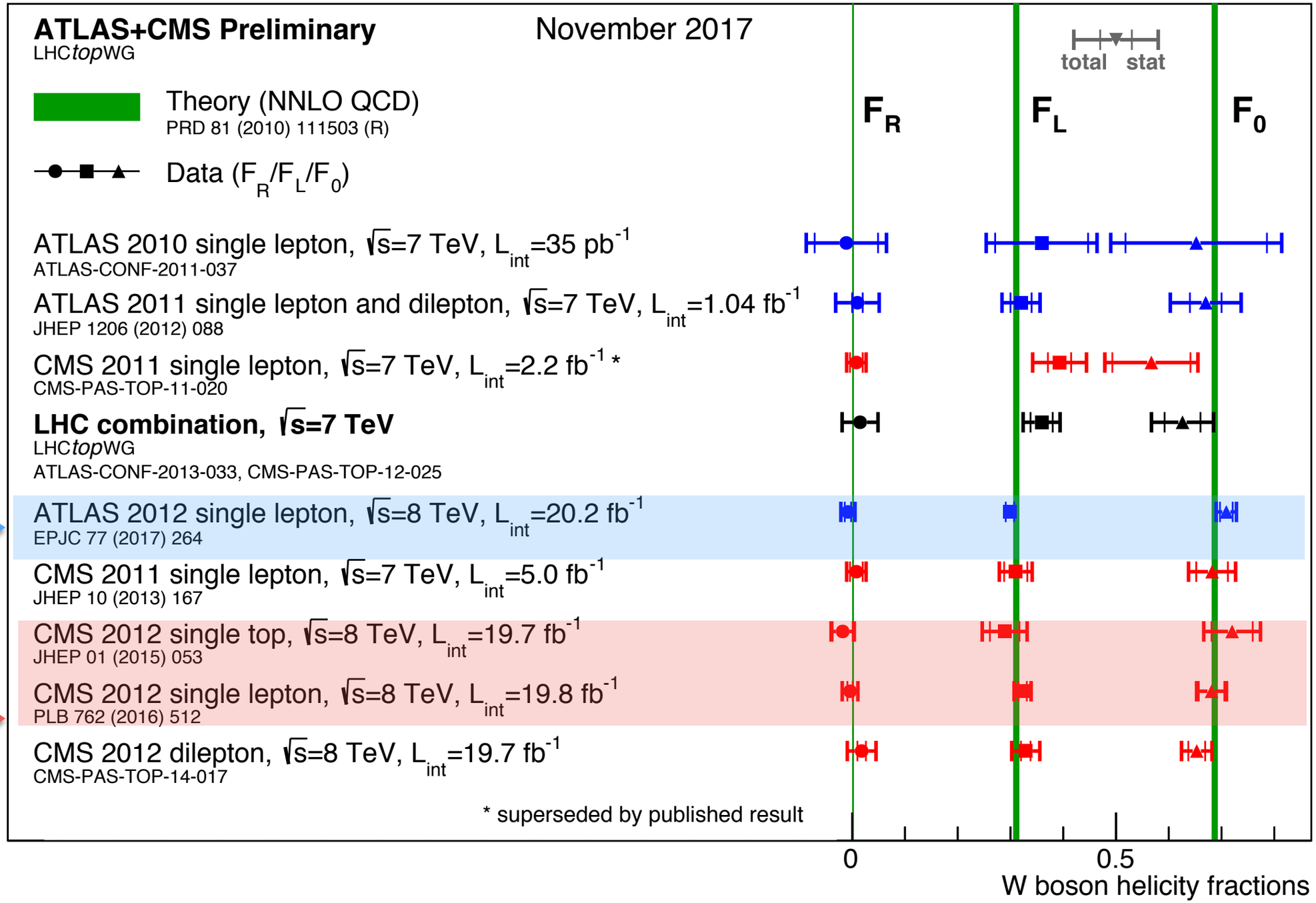


F_R0=0.0017±0.0001



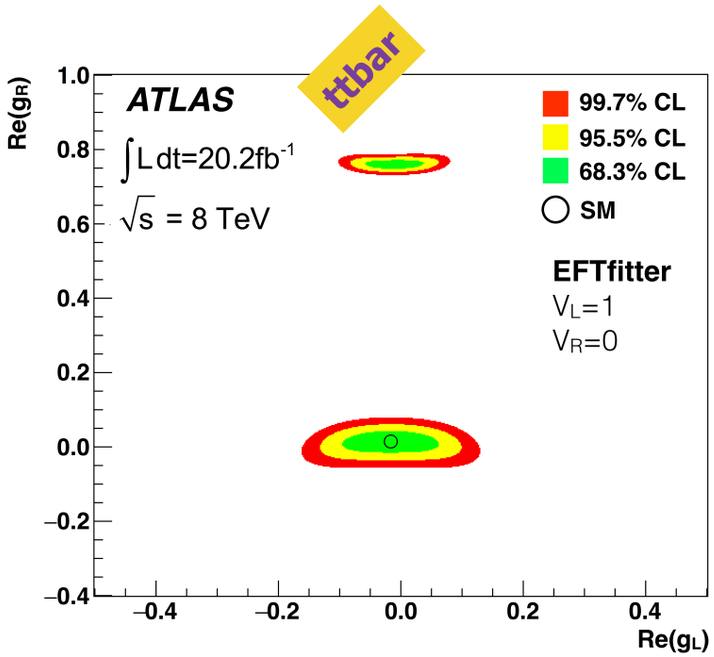
SM NNLO calculation: Phys. Rev. D81, 111503 (2010)

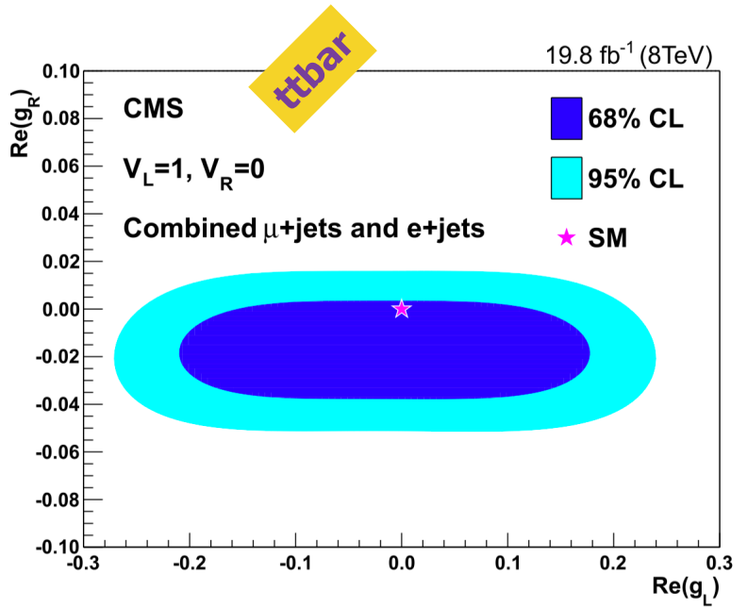
W Helicity @run 1

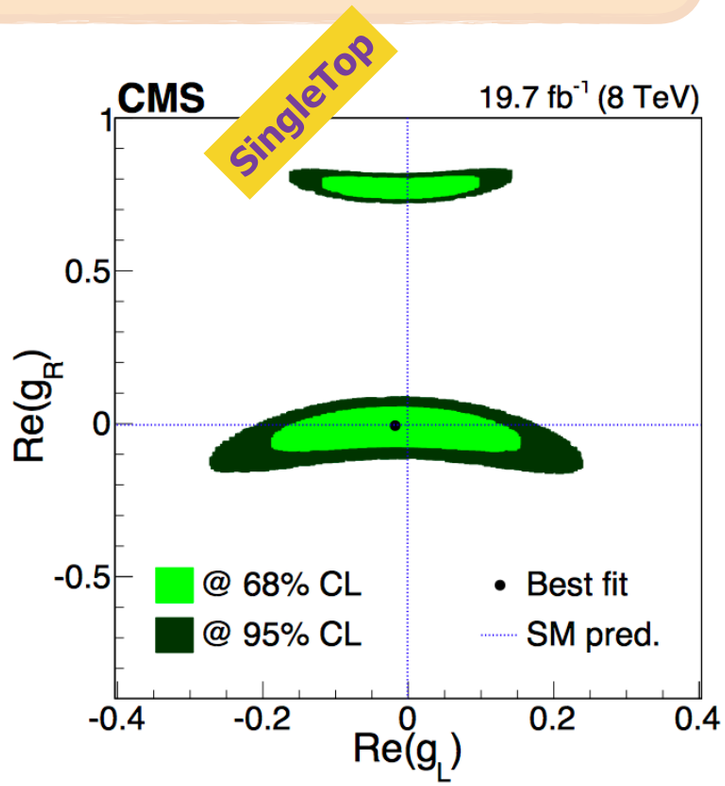


W Helicity combination

- The combination is performed using Best Linear Unbiased Estimat (BLUE) method
- The systematics and correlations are studied
  - a) Correlations between the observables (F0 & FL) in each measurement
  - b) Correlations between CMS input measurements (e+jets, mu+jets, singleTop)
  - c) Correlations between ATLAS & CMS experiments
- The result will be used to derive constraints on the anomalous couplings / Willson coefficients in EFT framework





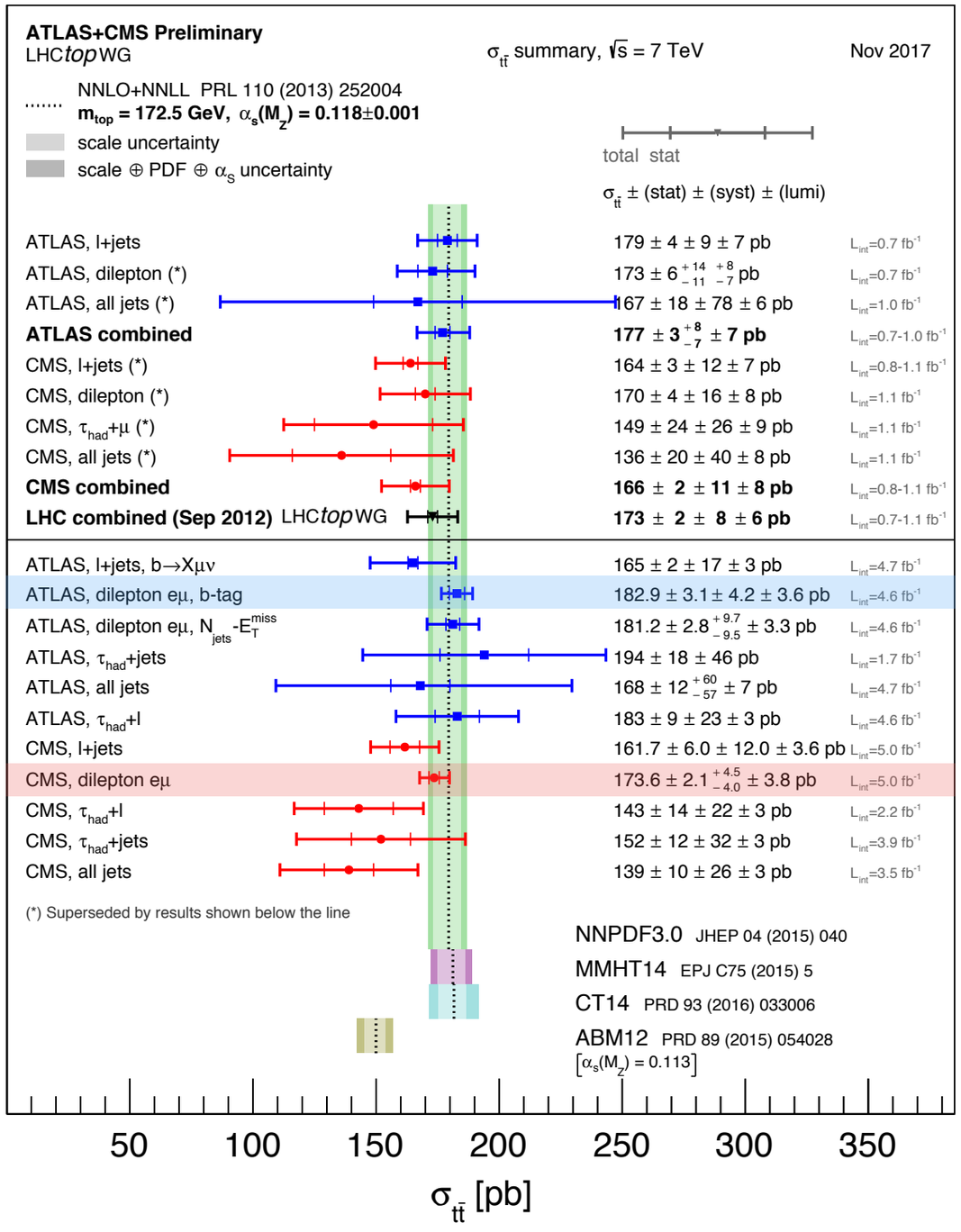


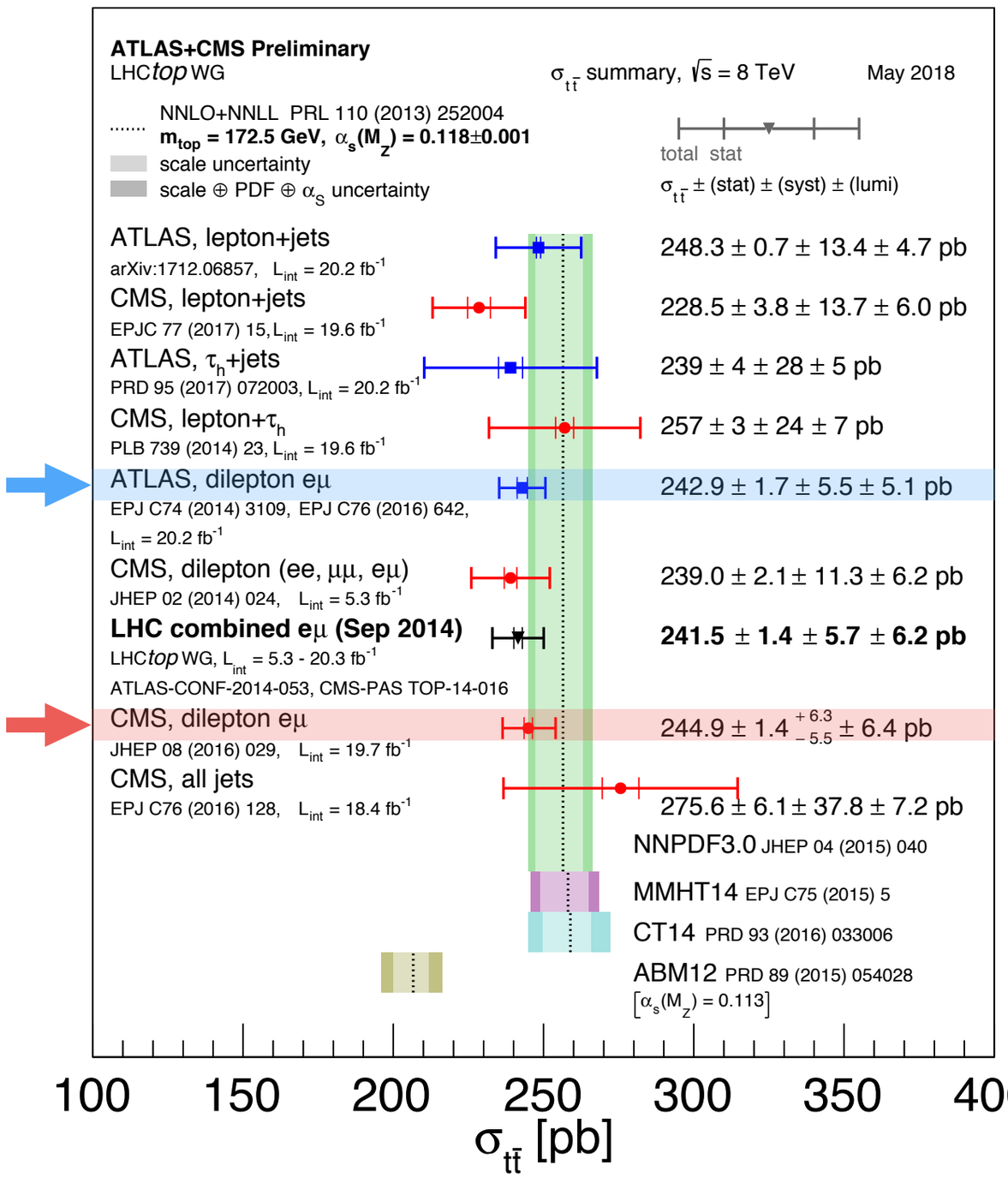
W Helicity combination status

- The analysis is **APPROVED** by both collaborations Top Working groups
- Paper's draft is currently under review by both collaborations
  - CMS Wide Review started last week
  - ATLAS 1st circulation started today

Run 1 combination of
Inclusive tt cross-section, pole top quark mass and α_s measurements

Inclusive tt x-section @run 1





Inclusive tt x-section @run 1

- **Input measurements: most precise ATLAS and CMS measurements**

ATLAS (EPJC 76 (2016) 642)

7TeV: 182.9±3.1(stat)±4.2(syst)±3.6(lumi) pb (3.5%)
8TeV: 242.9±1.7(stat)±5.5(syst)±5.1(lumi) pb (3.2%)

CMS (JHEP 08 (2016) 029)

7TeV: 173.6 ± 2.1 (stat) ± 4.5 (syst) ± 3.8 (lumi) pb (3.6%)
8TeV: 244.9 ± 1.4 (stat) ± 6.3 (syst) ± 6.4 (lumi) pb (3.7%)

Dominant uncertainties

- ✣ Luminosity
- ✣ Statistics (mostly @ 7TeV)
- ✣ Signal modeling
- ✣ PDF
- ✣ tW background

- ✣ Luminosity
- ✣ Lepton ID/Isolation
- ✣ Z+jets background
- ✣ Trigger
- ✣ Statistics (mostly @ 7TeV)

- **Highly precise inputs**
- **Improvement is expected from the combination**

Inclusive tt x-section combination

- **Challenge:**

  - Different uncertainty evaluation treatments used by ATLAS and CMS
  - ATLAS: uncorrelated uncertainties, group of individual uncertainties
  - CMS: post-fit the uncertainties are correlated (nuisance parameters) , can not be easily grouped together
  - BLUE technique can not be used due to this issue

- **Convino combination tool[1] is introduced to perform the combination**
  - Accounts for all uncertainty correlations via maximization of a combined likelihood

- **Current status and next steps**

  - Pre-approved in the collaborations sub-groups
  - The analysis /paper draft is under review in both collaborations
  - The result will be used to extract top-quark pole mass and α_s using the following PDF: CT14, MMHT2014 and NNPDF3.1_ascorr_notop[2]

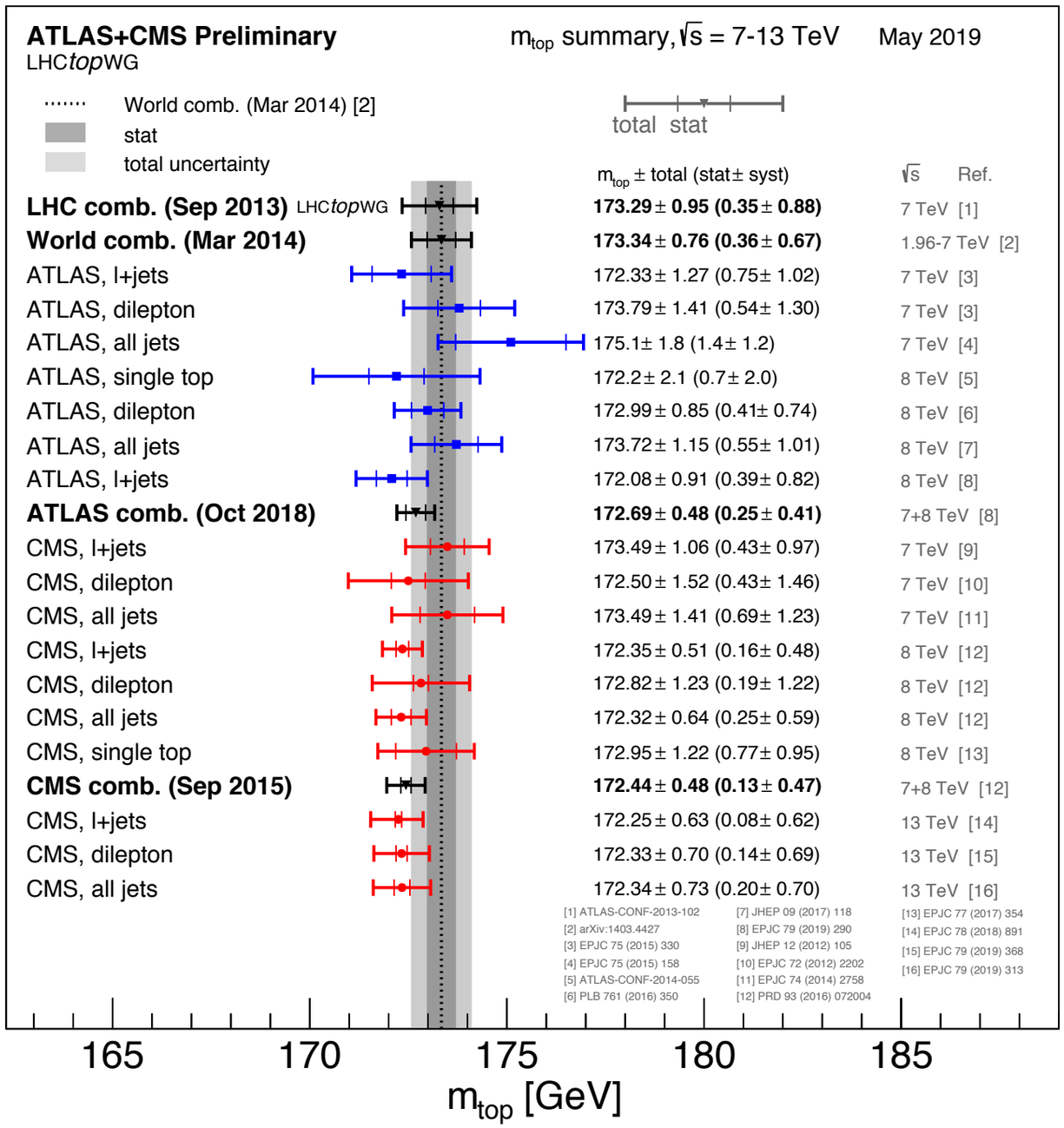
1- Eur. Phys. J. C (2017) 77:792
2- Eur. Phys. J. C (2018) 78:408

Run 1 combination of

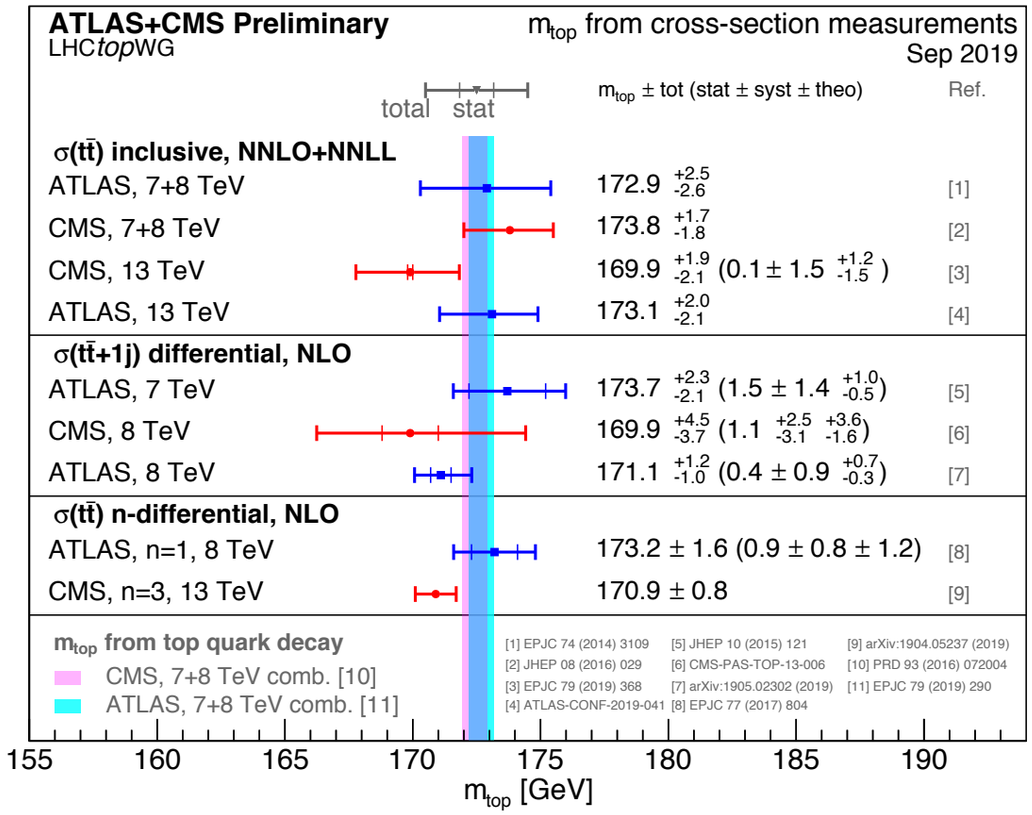
Top quark mass measurements

Top quark mass @run 1

Direct measurements



Indirect measurements



Top quark mass combination status

- Aiming to have an updated LHC average result
- Method:
  - ✣ Baseline technique: BLUE
- Available Inputs:
  - ✣ Indirect results are <u>not considered</u> for combination
  - ✣ ATLAS: 6 published results from different channels
  - ✣ CMS: 12 published from different channels

- Current status and next steps
  - ✣ Coherent mapping scheme for the ATLAS and CMS systematics has been developed
  - ✣ All of the measurements have been mapped onto a common grid
  - ✣ Baseline studies of the correlation factors is completed
  - ✣ Reference sets of combinations have been performed and checked
  - ✣ Draft paper is in preparation
  - ➡ Still to complete:
    - ✣ studies of the effects of anti-correlations between the ATLAS and CMS systematic terms
    - ✣ selection of which combinations to include and to best describe the systematics of the final result(s)

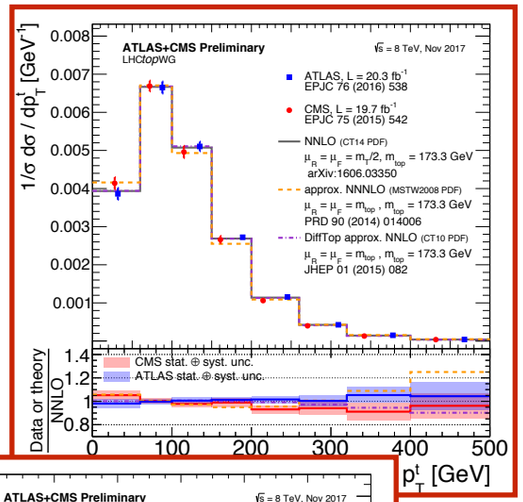
8 TeV combination of
tt differential cross-section

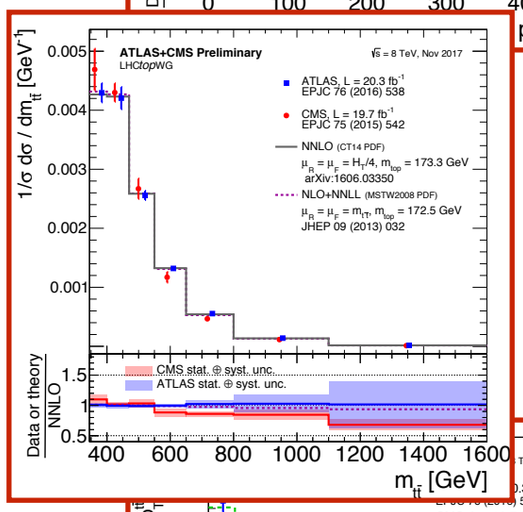
tt differential cross-section @8TeV

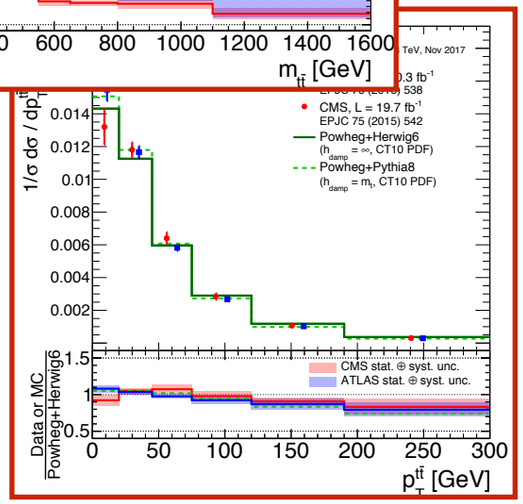
- **Combining parton-level, full phase space (l+jets): p_T(top), m(tt), p_T(tt)**
  - **ATLAS: EPJC 76 (2016) 538,**
  - **CMS : EPJC 75 (2015) 542**
  - **Results used same binning and phase space**

- **Combination technique: BLUE method**
- **Correlation classifications adopted from "differential ttbar charge asymmetry" combination[3]**
  - **Between bins in the same experiments ⇦ determined by each experiment**
  - **Between same bins in different experiments ⇦ from inclusive x-sec combination**
  - **Between different bins of different experiments ⇦ average of estimates from each experiment:**

$$\mathrm{corr}^{u}(a_i, c_j) = \rho_u \frac{\mathrm{corr}^{u}(c_i, c_j) + \mathrm{corr}^{u}(a_i, a_j)}{2}$$







- **Current status and next steps**
  - **A Common set of uncertainty categories is developed**
  - **Combinations are developed for all variables of interest**
  - **Testing Convino tool (BLUE limitation in handling highly correlated inputs from normalized differential cross sections)**

3- JHEP 04 (2018) 033

Summary & Outlook

- **Combination:**
  - ✤ **Is the key to achieve more precise results**
  - ✤ **Helps to better understand and compare ATLAS and CMS results**
  - ✤ **The combined run 1 results will challenge run 2 measurements**

- **What's next at 13 TeV ? Open for discussion.**
  - ✤ **Exiting results from top quark properties measurements? EFT interpretations?**
  - ✤ **Run 1 + Run 2 combinations?**

Thanks to all contacts and conveners for the help preparing this talk

Backup

W helicity @ 8TeV

- **ATLAS**:
  - Analysis method= template fitting:
    - 3 signal templates (obtained from reweighting the SM Cosθ* distribution) + 5 bkg. Cosθ* distributions
    - Binned likelihood fit:

$$\mathscr{L} = \prod_{k=1}^{N_{\text{bins}}} \text{Poisson}(n_{\text{data},k}, n_{\text{exp},k}) \prod_{j=1}^{N_{\text{bkg}}} \frac{1}{\sqrt{2\pi}\sigma_{\text{bkg},j}} \exp\left(\frac{-(n_{\text{bkg},j} - \hat{n}_{\text{bkg},j})^2}{2\sigma^2_{\text{bkg},j}}\right)$$

$$n_{\text{exp}} = n_0 + n_{\text{L}} + n_{\text{R}} + n_{W+\text{light}} + n_{W+c} + n_{W+bb/cc} + n_{\text{fake}} + n_{\text{rem. bkg.}}$$

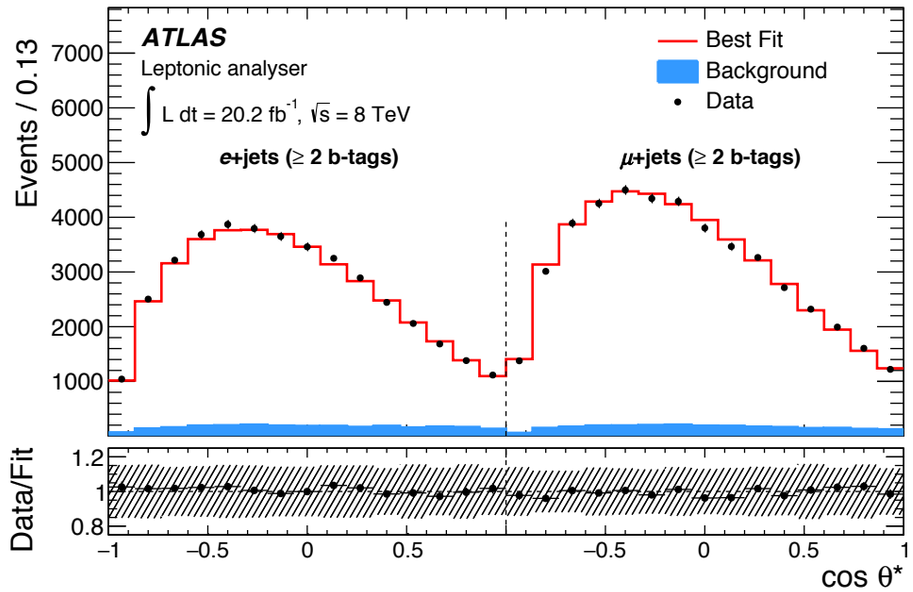
  - Fit parameters:
    - Yields of signal (**n0, nL, nR**) and background (W+jets, Lepton fakes, Remaining backgrounds)
  - Normalization uncertainties used as Gaussian priors to constrain background normalization
  - Background normalization uncertainty effect is reflected in the statistical uncertainty
  - W boson polarization extracted as:

$$F_{\text{i}} = \frac{N_i}{N_0 + N_L + N_R}, \qquad n_i = \epsilon_i^{\text{sel}} N_i \qquad \text{for i= 0, L, R.}$$

EPJC 77(2017) 264

top pair (l+jets)

Leptonic analyser (≥2 *b*-tags)
$F_0 = 0.709 \pm 0.012$ (stat. + bkg. norm.) $^{+0.015}_{-0.014}$ (syst.)
$F_L = 0.299 \pm 0.008$ (stat. + bkg. norm.) $^{+0.013}_{-0.012}$ (syst.)
$F_R = -0.008 \pm 0.006$ (stat. + bkg. norm.) ± 0.012 (syst.)



W helicity @ 8TeV

- **CMS**:
  - Analysis method: event-by-event reweighting of the SM value of Cosθ* in Monte Carlo

  - Binned likelihood fit:

$$\mathcal{L}(\vec{F}) = \prod_i \frac{N_{\mathrm{MC}}(i;\vec{F})^{\,N_{\mathrm{data}}(i)}}{\left[N_{\mathrm{data}}(i)\right]!}\,\exp\left[-N_{\mathrm{MC}}(i;\vec{F})\right]$$

  - Number of expected **t** events in($\mathbf{N_{MC}}$) in each bin is modified as:

$$w_{t\bar{t}/t,}\left(\cos\theta^*_{gen};\vec{F}\right) \equiv \frac{\frac{3}{8}F_L\left(1-\csc\theta^*_{gen}\right)^2 + \frac{3}{4}F_0\sin^2\theta^*_{gen} + \frac{3}{8}F_R\left(1+\csc\theta^*_{gen}\right)^2}{\frac{3}{8}F_L^{SM}\left(1-\csc\theta^*_{gen}\right)^2 + \frac{3}{4}F_0^{SM}\sin^2\theta^*_{gen} + \frac{3}{8}F_R^{SM}\left(1+\csc\theta^*_{gen}\right)^2}$$

  - N_{MC}= $\mathbf{N_{tt}}$ + $\mathbf{N_{sing\text{-}t}}$ + N_{bkg}

$$N_{t\bar{t}}(i;\vec{F}) \propto \mathcal{F}_{t\bar{t}}\left[\sum_{t\bar{t}\ \text{in bin i}} w_{t\bar{t}}\left(\cos\theta^*_{gen};\vec{F}\right)\right] \qquad N_{sing-t}(i;\vec{F}) \propto \sum_{sing-t\ \text{in bin i}} w_t\left(\cos\theta^*_{gen};\vec{F}\right)$$

- Fit parameters: $\mathbf{F_{tt}}$(normalization of the ttbar yield), $\mathbf{F_0}$ and $\mathbf{F_R}$.
- Background normalizations are fixed —> normalization uncertainty taken as separate systematic
- Final result (l+jets) is **BLUE** combination of **e+jets** and **μ+jets**

JHEP 01 (2015) 053

top pair (l+jets)

Channel	$F_0 \pm (\text{stat}) \pm (\text{syst})$	$F_L \pm (\text{stat}) \pm (\text{syst})$	$F_R \pm (\text{stat}) \pm (\text{syst})$
e + jets	$0.705 \pm 0.013 \pm 0.037$	$0.304 \pm 0.009 \pm 0.020$	$-0.009 \pm 0.005 \pm 0.021$
μ + jets	$0.685 \pm 0.013 \pm 0.024$	$0.328 \pm 0.009 \pm 0.014$	$-0.013 \pm 0.005 \pm 0.017$
ℓ + jets	$0.681 \pm 0.012 \pm 0.023$	$0.323 \pm 0.008 \pm 0.014$	$-0.004 \pm 0.005 \pm 0.014$

+

PLB 762 (2016) 512

single top t-chan. (l+jets)

$F_L = 0.298 \pm 0.028\,(\text{stat}) \pm 0.032\,(\text{syst}),$
$F_0 = 0.720 \pm 0.039\,(\text{stat}) \pm 0.037\,(\text{syst}),$
$F_R = -0.018 \pm 0.019\,(\text{stat}) \pm 0.011\,(\text{syst}),$