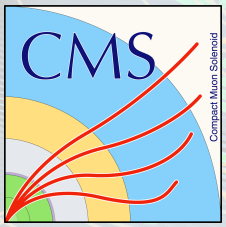
Top quark physics at CMS



Denys Lontkovskyi

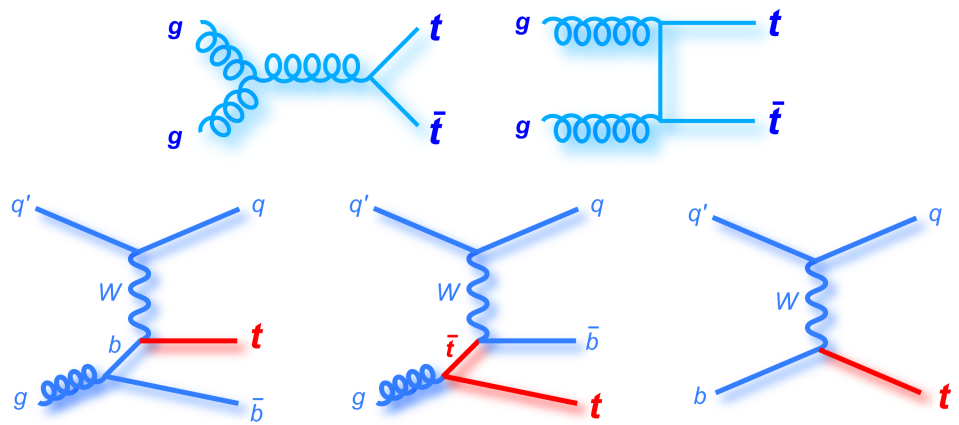
On behalf of the CMS collaboration

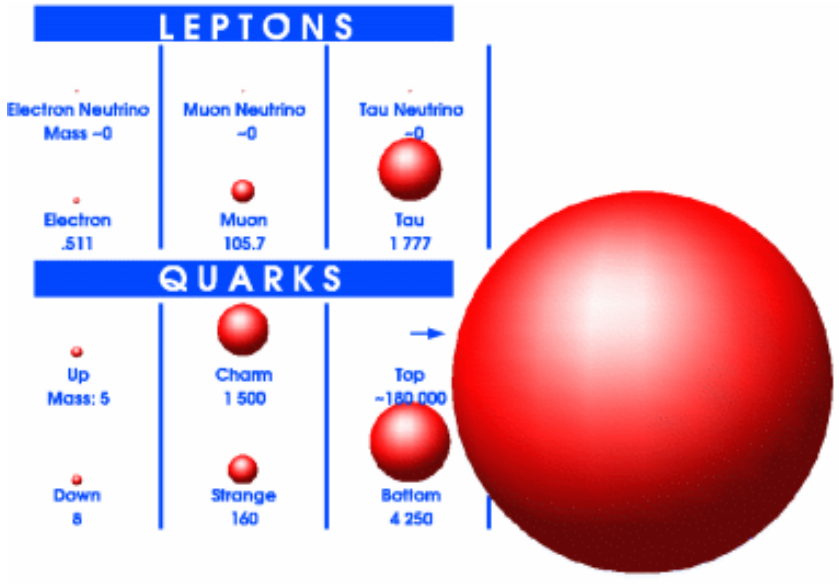
Electroweak and Top Physics

9 March, 2017

▶ Introduction

- The heaviest elementary particle
- Decays before hadron formation
- Main production mechanisms at LHC:

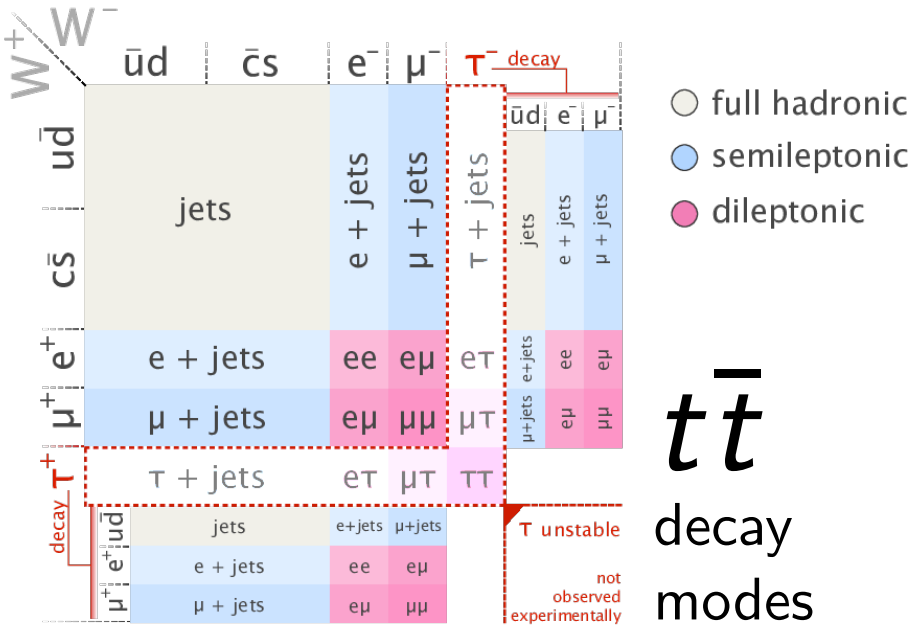


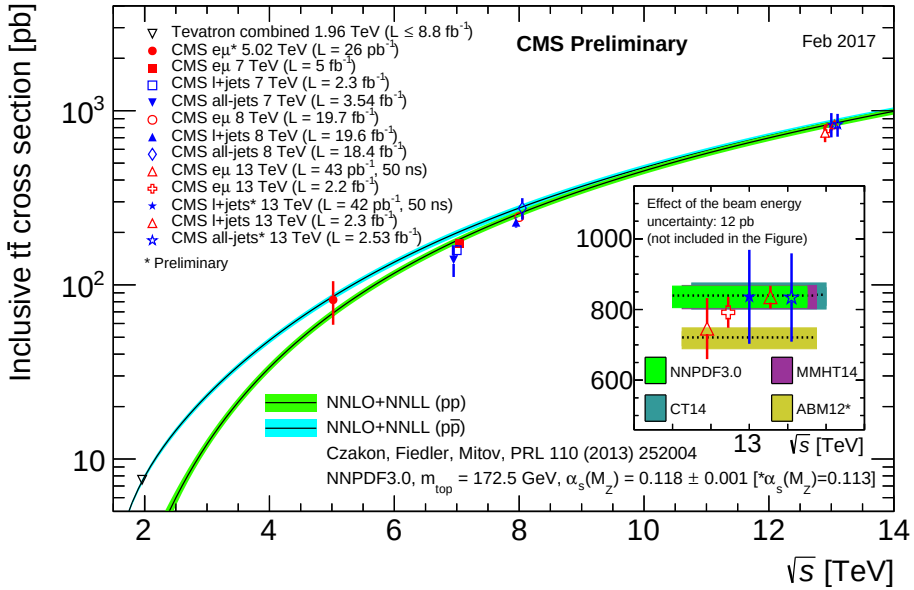


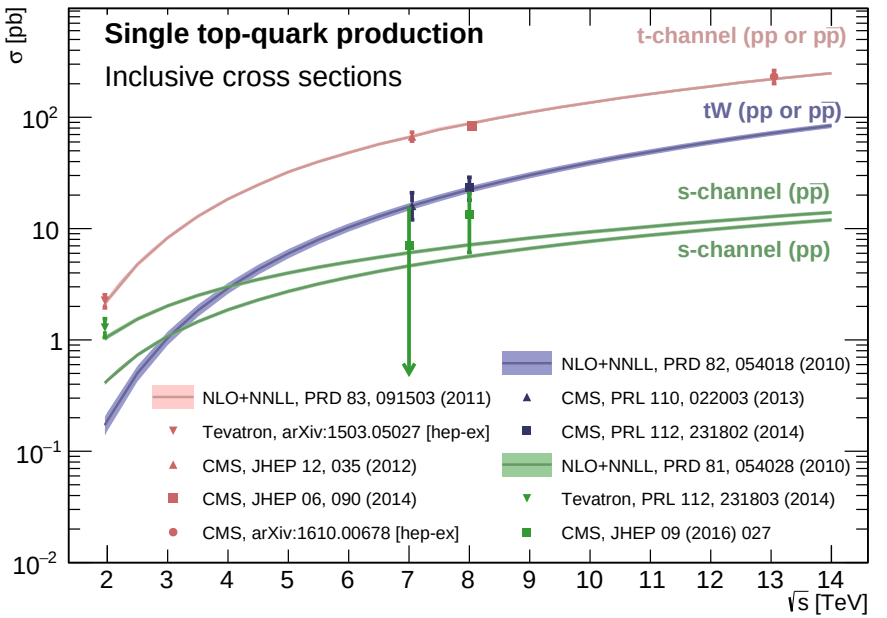
- LHC has extensive top program:
  - Cross sections measurements
  - Mass determination
  - Top properties (asymmetries, spin correlation etc. (**see here**))
  - Searches for rare processes
- Improves understanding of:
  - pQCD predictions
  - PDFs
  - background to many searches

Introduction

- Measurements at $\sqrt{s}$=5,7,8 and 13 TeV
- Total cross section
- Single- and double-differential
- Mass determination
- Top properties







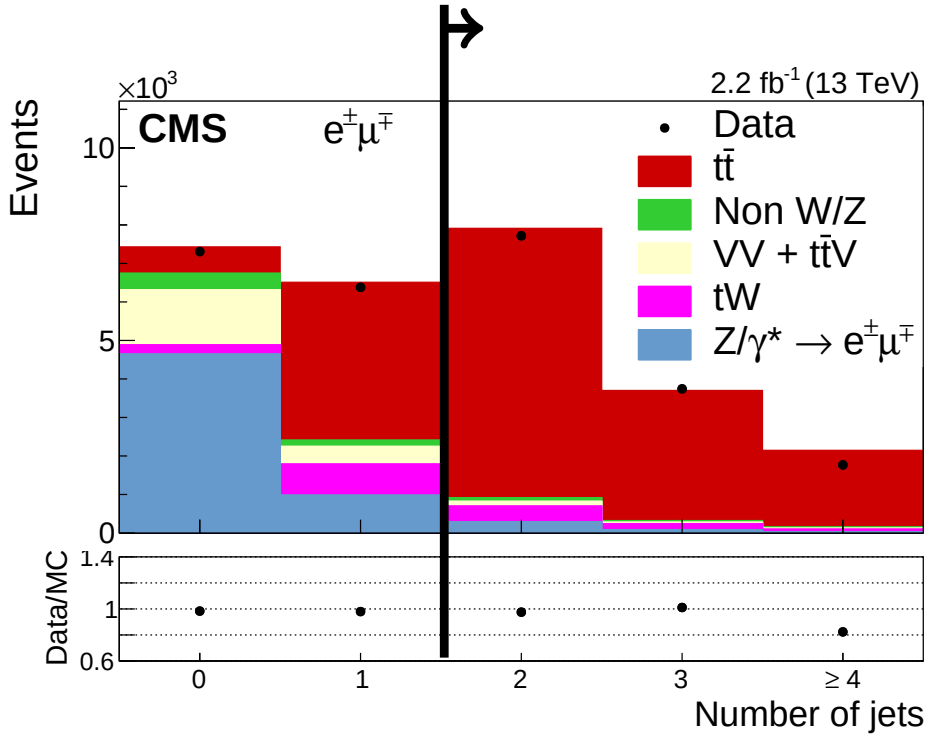
- Different production and decay channels:
  - different background contamination
  - different systematics

Top cross sections

- 2015 data (2.2 fb^{-1})
- Channel with lowest background
- Simple counting experiment

Selection:

- Opposite sign $e\mu$ pair
- $\geq$ 2 jets
- $\geq$ 1 b tag

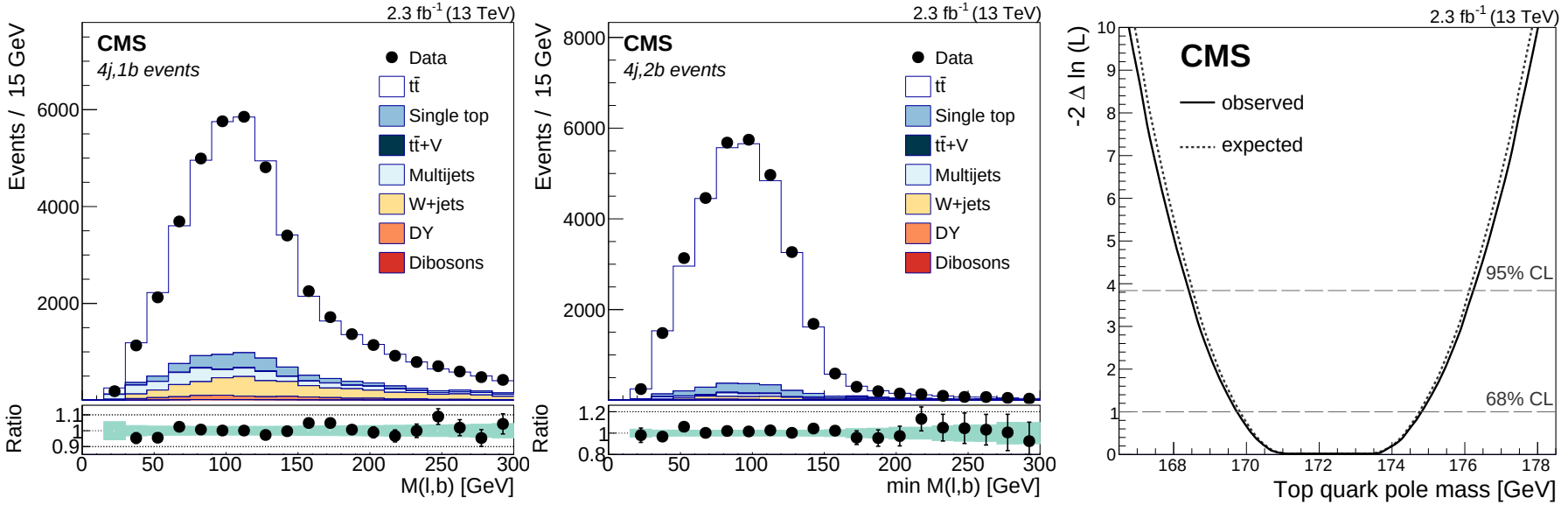


$$\sigma_{t\bar{t}} = 792 \pm 8(\text{stat}) \pm 37(\text{syst}) \pm 21(\text{lumi})\ \text{pb} \quad (\pm 5.5\%)$$

$$\text{SM} : \sigma_{t\bar{t}} = 832^{+40}_{-46}\ \text{pb}$$

- Consistent with other CMS and ATLAS measurements and with the SM predictions

▶ $t\bar{t}$ in single-lepton channel $\sqrt{s}$ =13 TeV (arXiv:1701.06228)



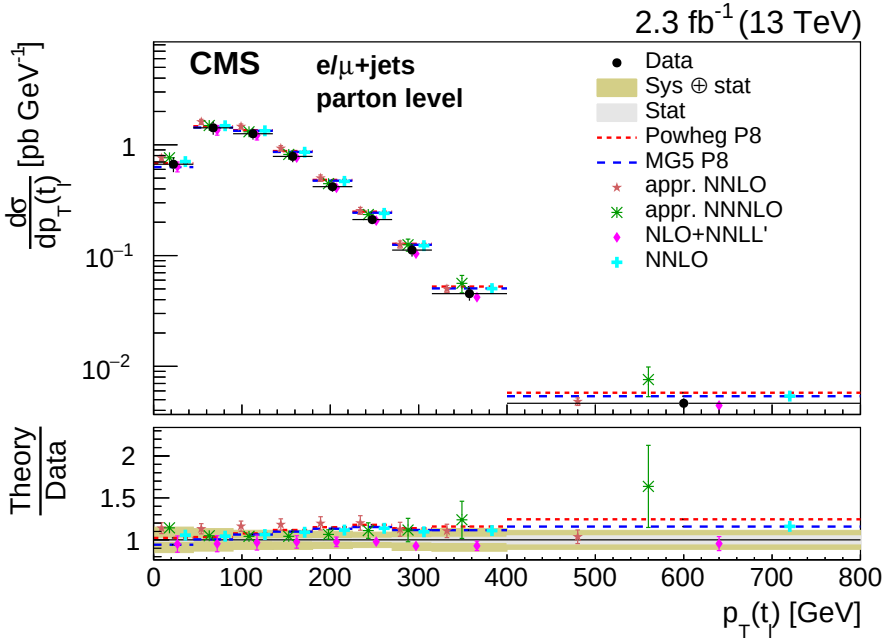
- Simultaneous fit to M_{lb} or min(M_{lb}) in multiple categories (lepton flavour, charge, N_b and N_j)
- Cross section measurement is consistent with previous measurements and with the SM predictions
- Pole mass extracted from the cross section measurement

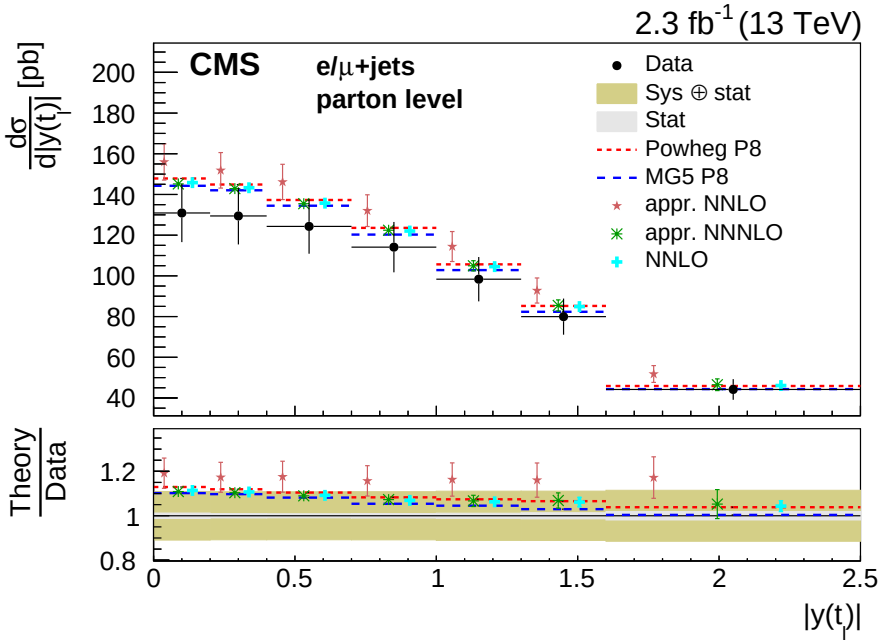
$$\sigma_{t\bar{t}} = 835 \pm 3(\mathrm{st}) \pm 23(\mathrm{sys}) \pm 23(\mathrm{lum})\,\mathrm{pb}\,(\pm 3.9\%)$$

$$m_t = 172.7^{+2.4}_{-2.7}\ \mathrm{GeV} \quad (\,^{+1.4}_{-1.6}\%) \quad (\mathrm{using\ CT14PDF})$$

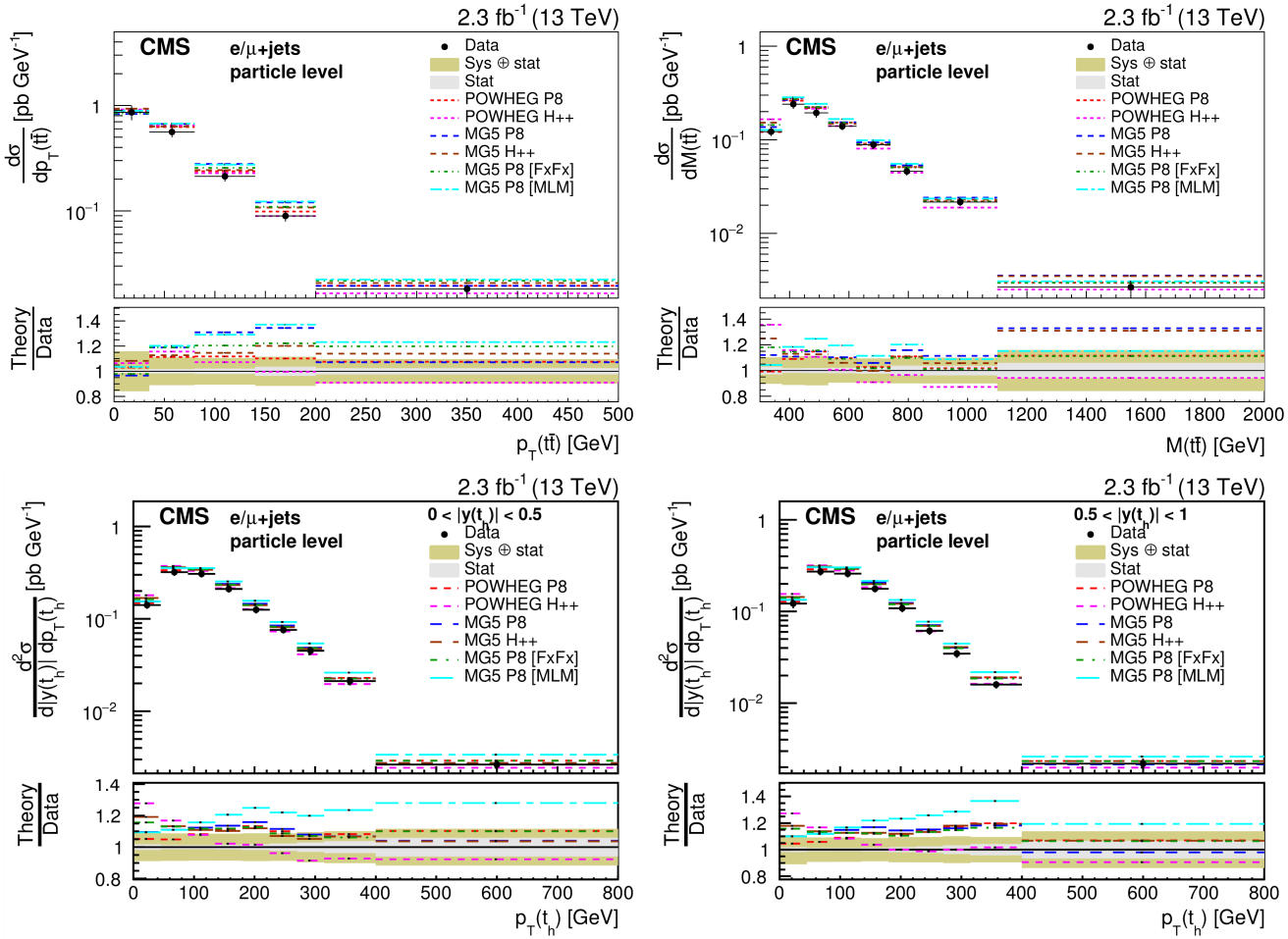
- 2015 data (2.3 fb^{-1})
- Channel with largest branching fraction
- Single differential measurements unfolded to parton level for comparison with analytic predictions.
- Precise test of the validity of QCD at NLO+NLL, NNLO and approximate (N)NNLO

Results at **Parton Level**



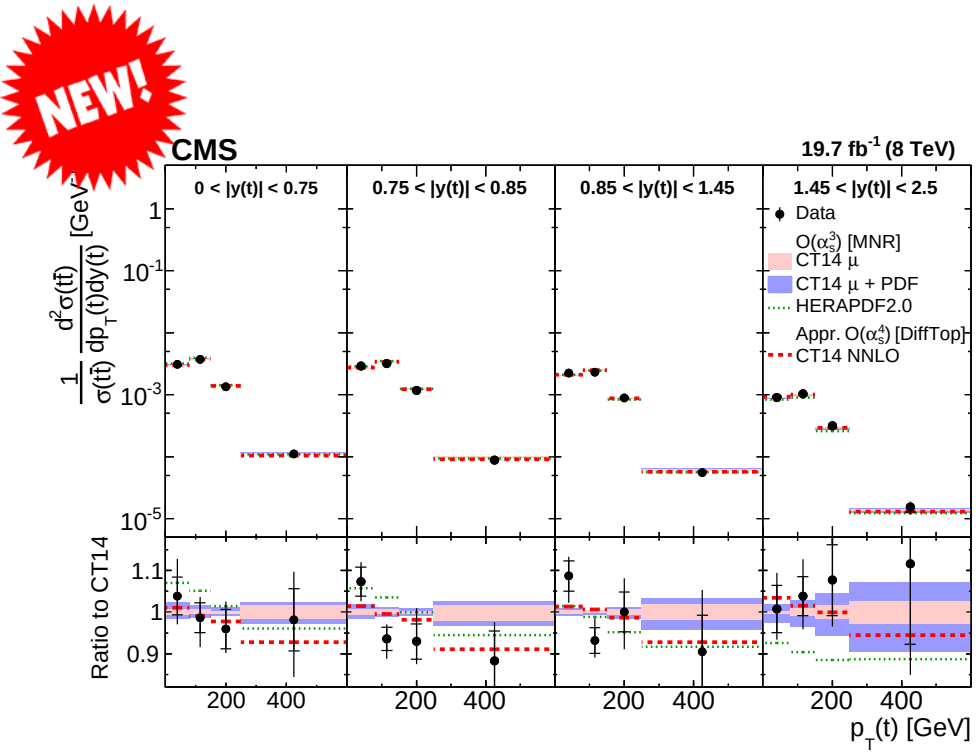


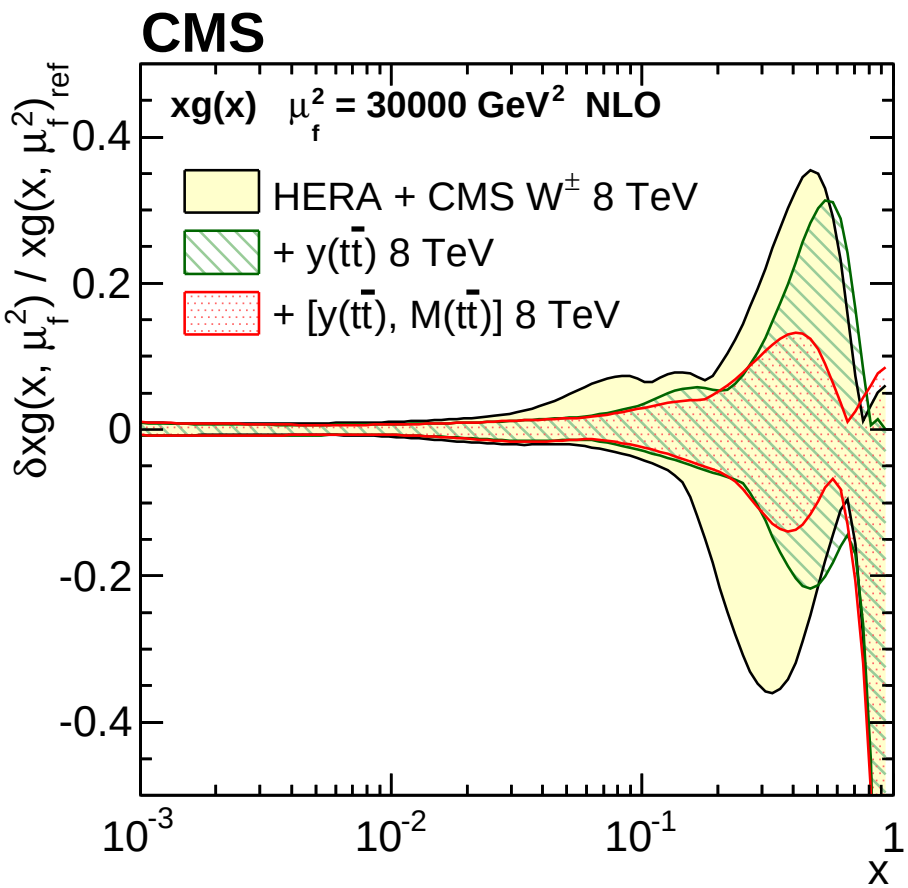
Results at **Particle Level**



- The measured distributions are in agreement with the predictions of the event generators with some exceptions in the $p_T(t\bar{t})$ and $M(t\bar{t})$ distributions
- $p_T(t)$ is softer than predicted by most of the event generators
- The effect seen in RunI and also confirmed by ATLAS

▶ $t\bar{t}$ in dilepton channel $\sqrt{s}$ =8 TeV (arXiv:1703.01630)

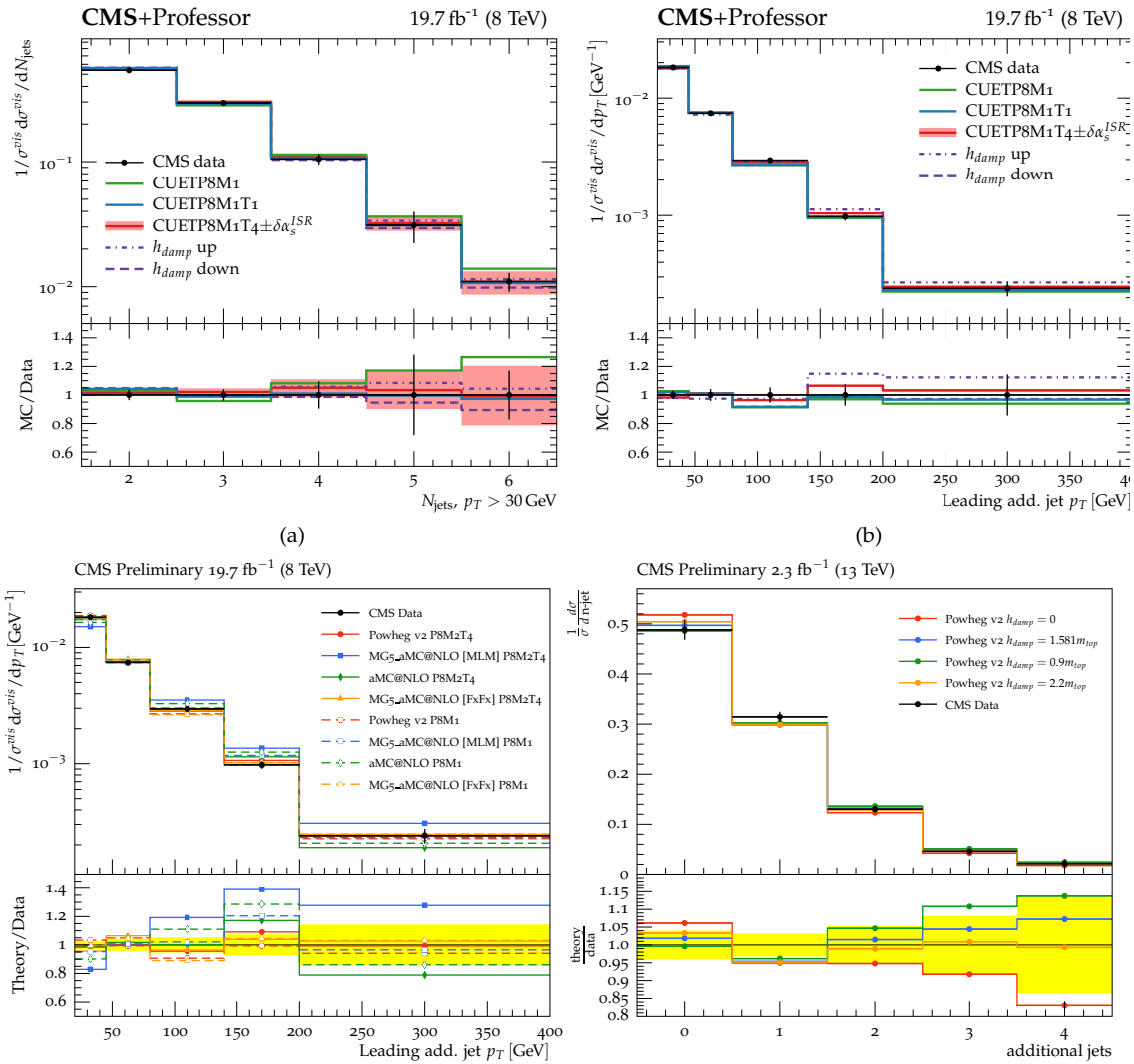




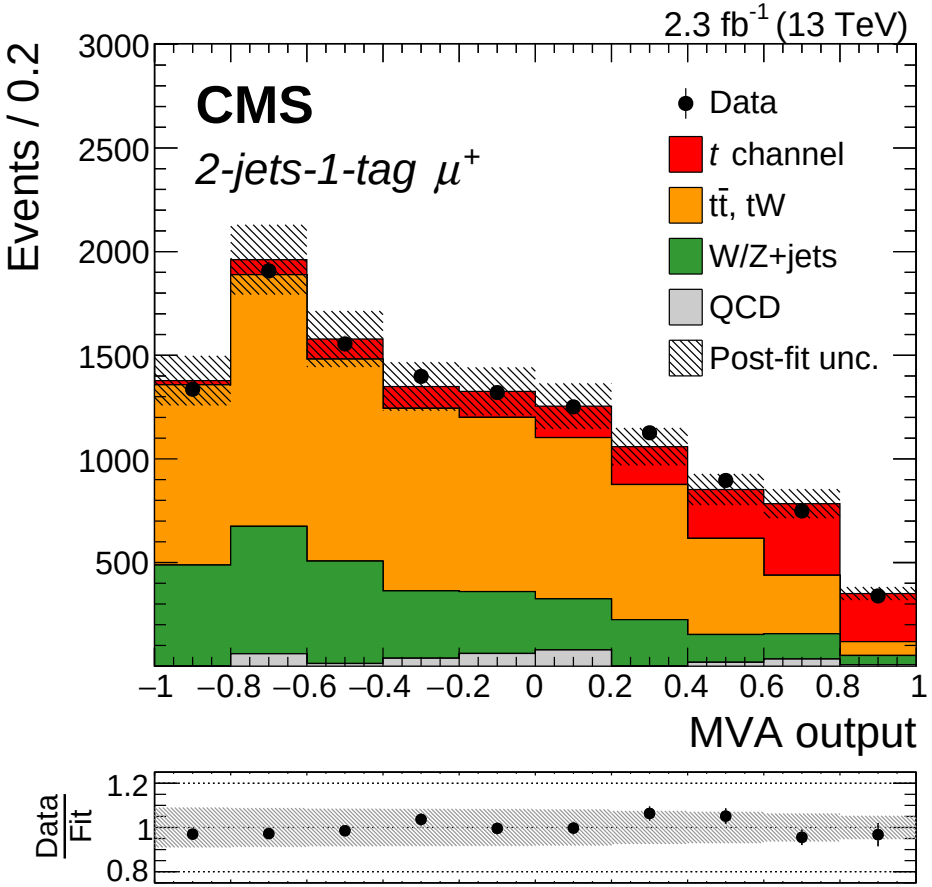
- Single- and double-differential cross section measurements as function of $p_T(t)$, $y(t)$, $M(t\bar{t})$, $y(t\bar{t})$
- Precision test of pQCD and valuable input for pPDF fits

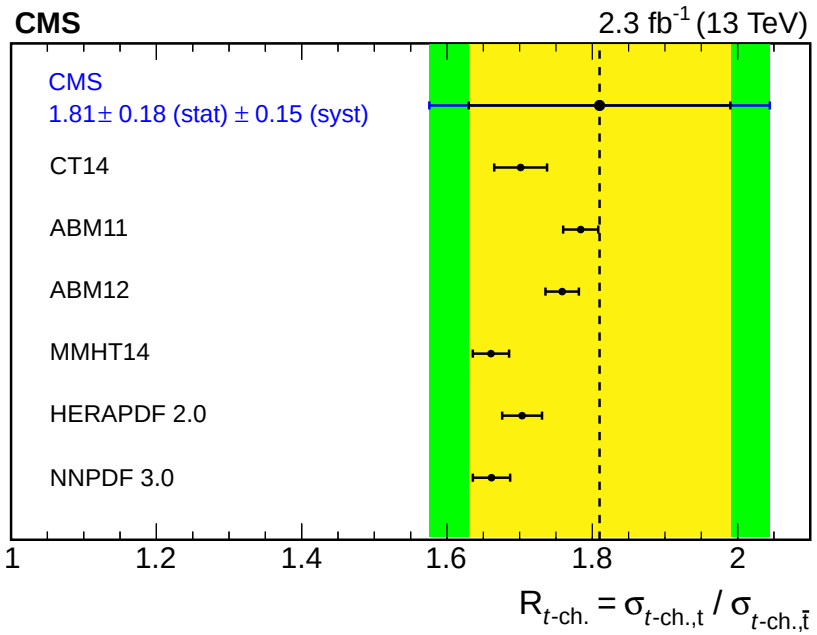
- Double-differential data significantly constrains gluon PDF in medium-x range
- The most powerful constrains come from $M(t\bar{t})$ and $y(t\bar{t})$

- Improve over the baseline NLO+PS MC tuning both the PS scale and the UE
- Data prefer lower α_S^{ISR} and higher h_{damp}
- Tuned α_S^{ISR} and h_{damp} values are found to be consistent with the ATLAS optimized values
- Affects mostly the description of extra jets
- $p_T(t)$, $M(t\bar{t})$, global event variables not significantly affected



▶ $t(\bar{t})$ in single-μ channel $\sqrt{s}$ =13 TeV (arXiv:1610.00678)





- 2015 data (2.3 fb^{-1})
- Channel with lowest systematic uncertainty
- Sensitivity to pPDFs and V_{tb}

$$R_{t-ch} = 1.81 \pm 0.18(\mathrm{stat}) \pm 0.15(\mathrm{syst})$$

- Template fit of the MVA discriminator distribution in multiple categories
- The most precise total cross section at 13 TeV used to extract $|Vtb|$

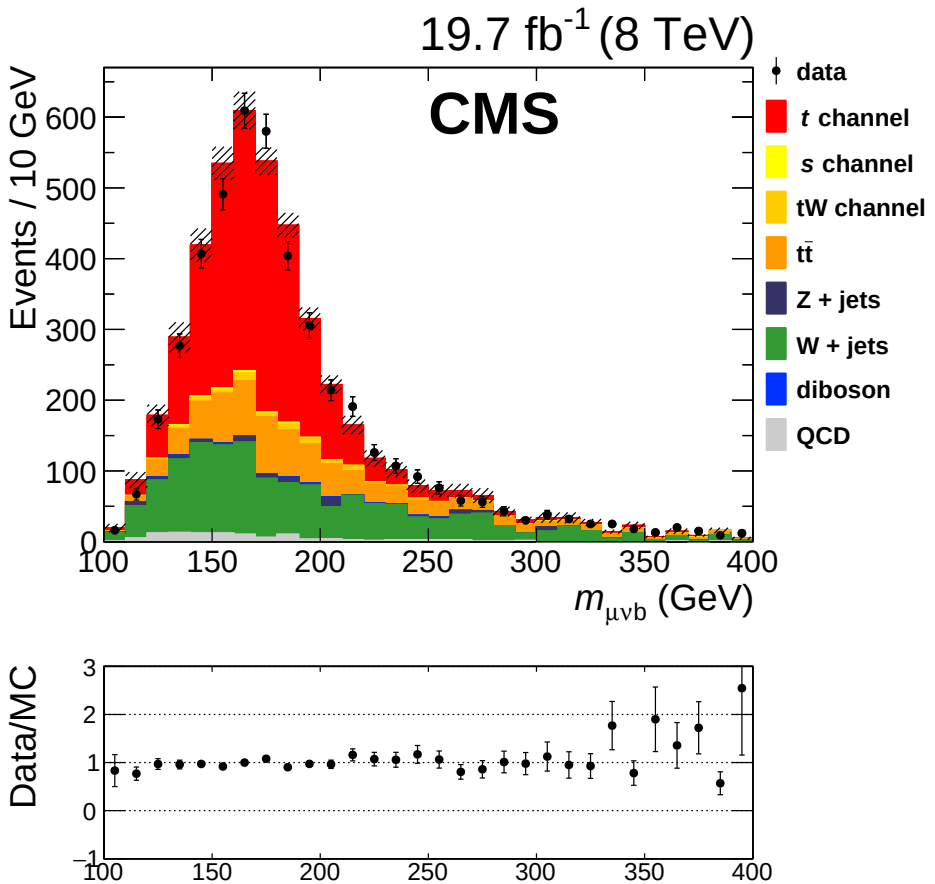
$$\sigma_{t-ch,t} = 150 \pm 8(\mathrm{st}) \pm 4(\mathrm{exp}) \pm 11(\mathrm{th}) \pm 4(\mathrm{lum})$$

$$V_{tb} = 1.03 \pm 0.07(\mathrm{exp}) \pm 0.02(\mathrm{theo})$$

Top mass

▶ m_t from single-μ t production $\sqrt{s}$ =8 TeV (to be submitted to EPJC)

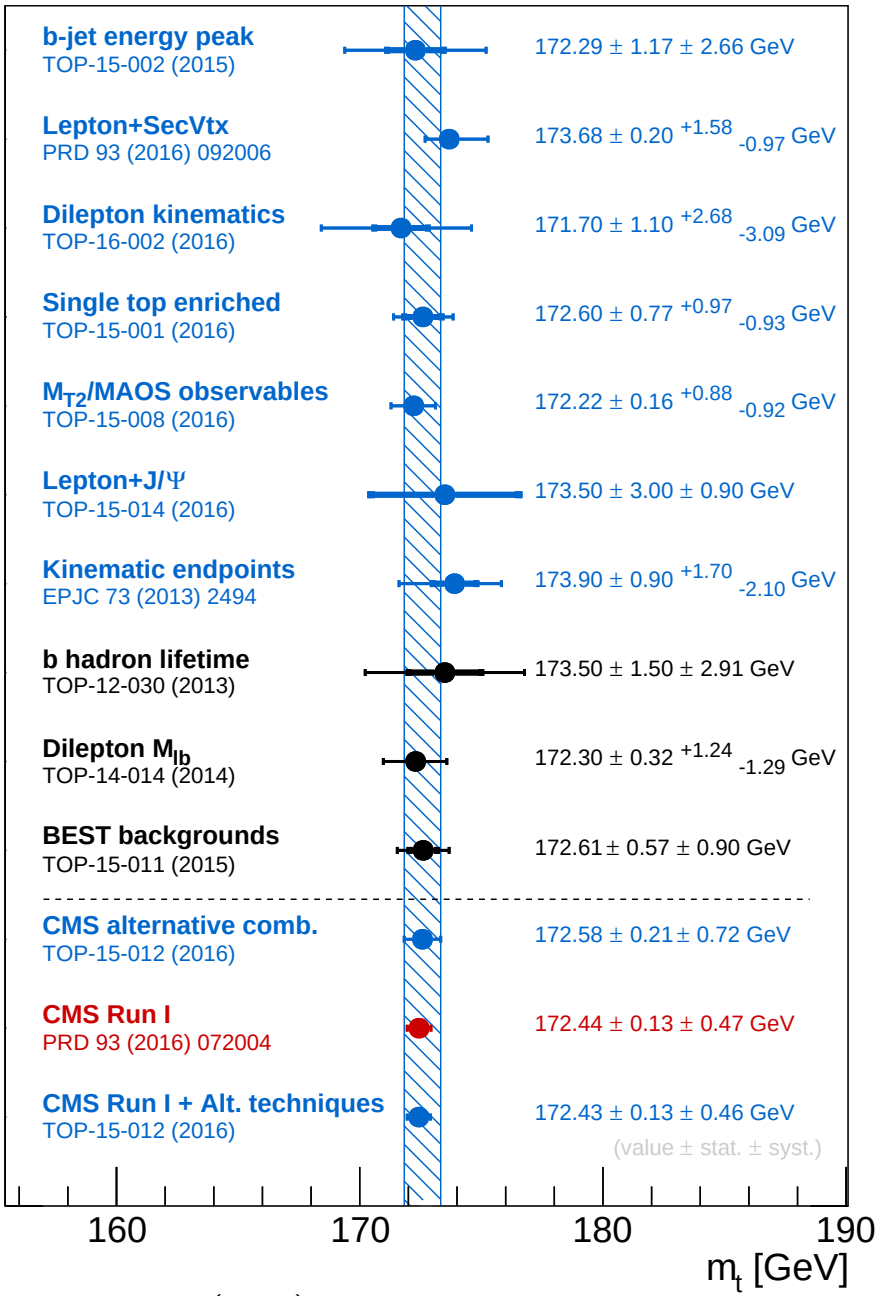
- Top mass measurement in t-channel enriched single-top production (75% purity)
- Different production mechanism featuring different color flow
- Independent cross check of $t\bar{t}$ mass determinations
- The most precise m_t extraction from single-top enriched data



$$m_t = 172.95 \pm 0.77\ (\mathrm{st})^{+0.97}_{-0.93}\ (\mathrm{sys})\mathrm{GeV}$$

▶ Top mass combination

(TOP-15-012)



- A new combination of the measurements using alternative/complementary techniques that were not included in the published CMS Run I result.

$$m_t = 172.58 \pm 0.21\ (\mathrm{st}) \pm 0.72\ (\mathrm{sys})\ \mathrm{GeV} \quad (0.4\%)$$

Legacy combination:

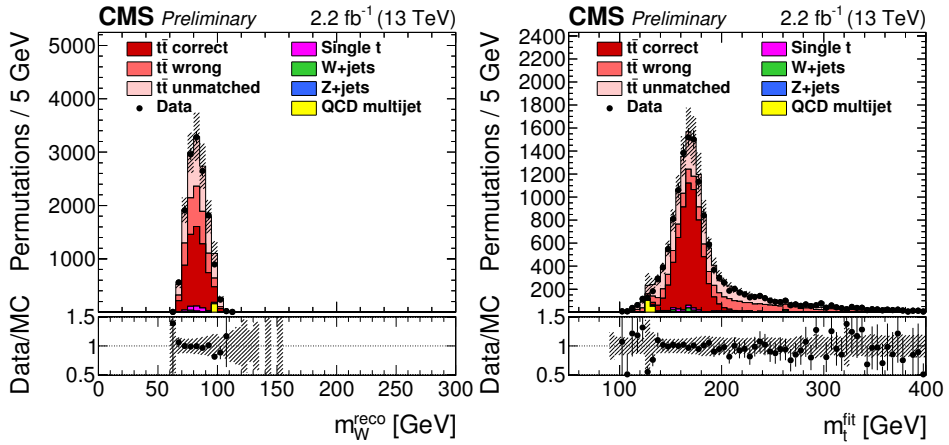
$$m_t = 172.44 \pm 0.13\ (\mathrm{st}) \pm 0.47\ (\mathrm{sys})\ \mathrm{GeV} \quad (0.3\%)$$

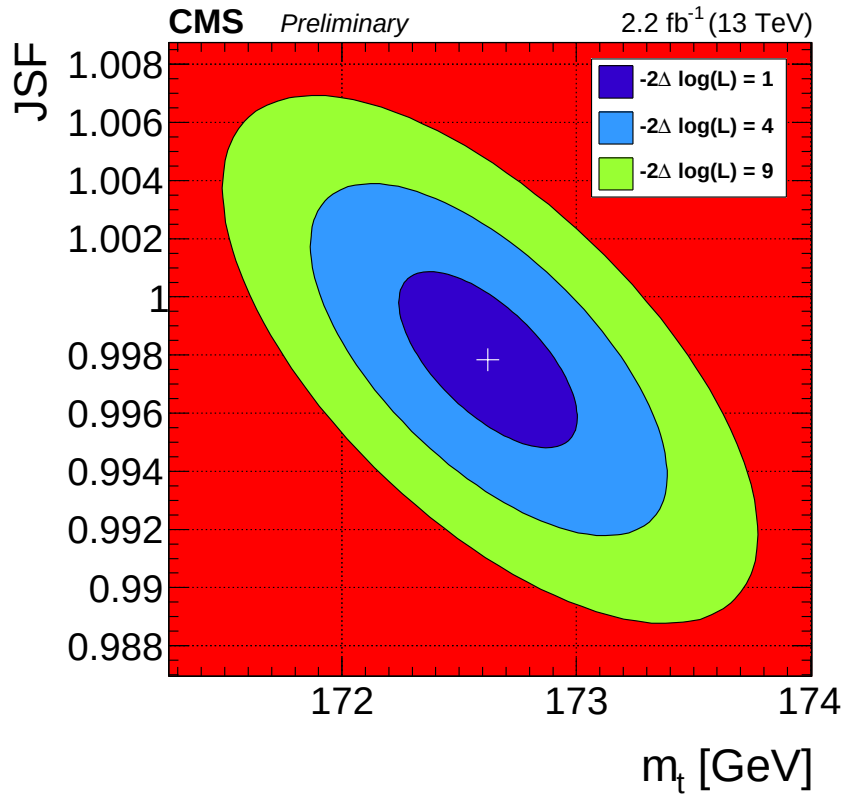
- Good agreement with the CMS Run I combination
- The precision of the new result makes this of the same order as the latest Tevatron and ATLAS combinations

- New preliminary measurement using ideogram method
- Simultaneous mass determination and jet-energy calibration

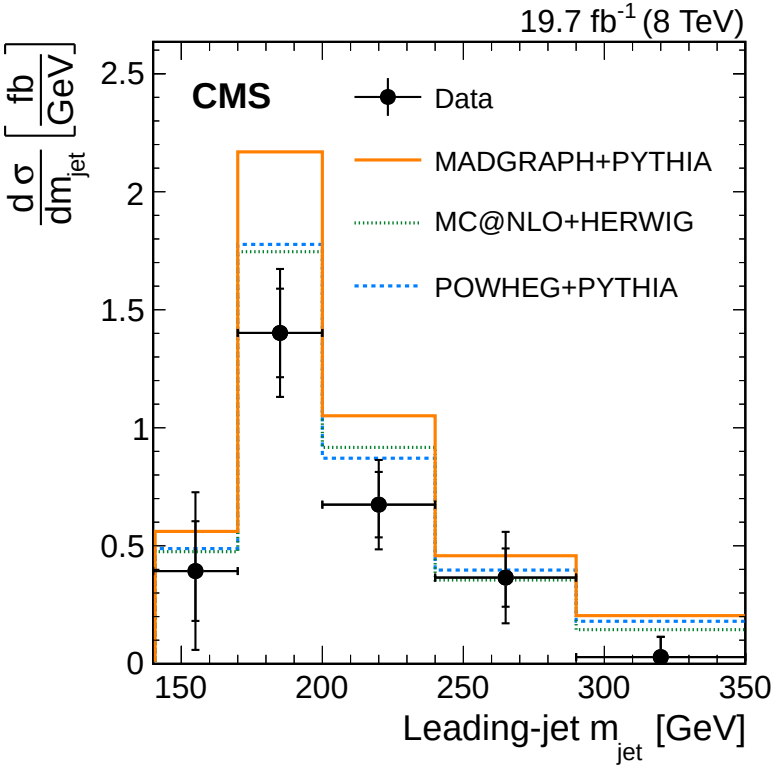
$$m_t = 172.62 \pm 0.38\ (\mathrm{st} + \mathrm{JSF}) \pm 0.70\ (\mathrm{sys})\ \mathrm{GeV}$$
$$JSF = 0.998 \pm 0.003\ (\mathrm{st}) \pm 0.010\ (\mathrm{sys})\mathrm{GeV}$$

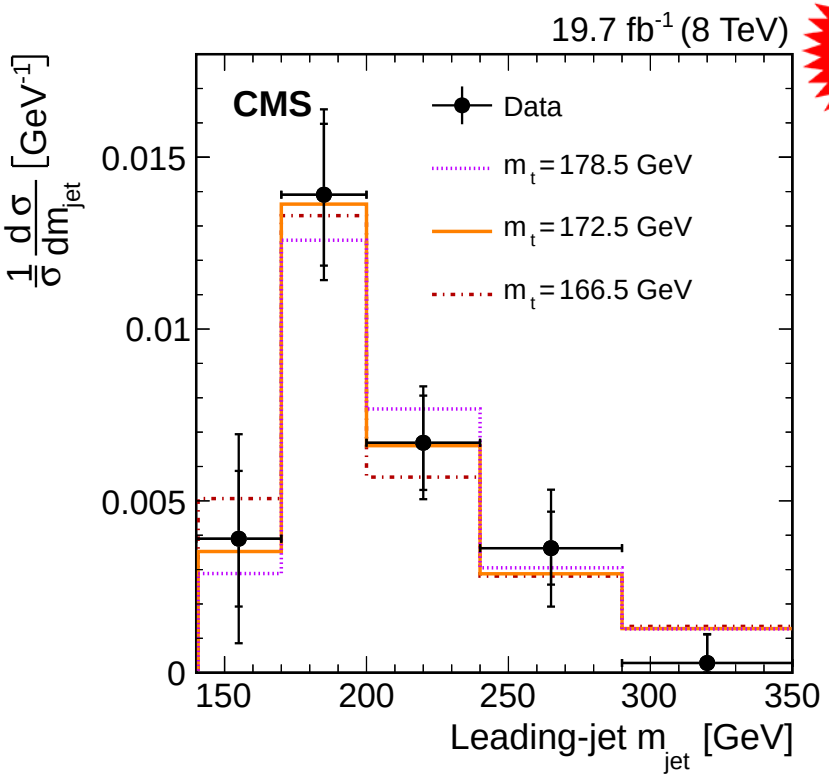
- Simultaneous mass determination and jet-energy calibration
- Systematic uncertainty dominated by effects that cannot be compensated in simultaneous fit: non-$t\bar{t}$ background modelling, PS and hadronization





▶ m_t from boosted top jets $\sqrt{s}$ =8 TeV (to be submitted to EPJC)





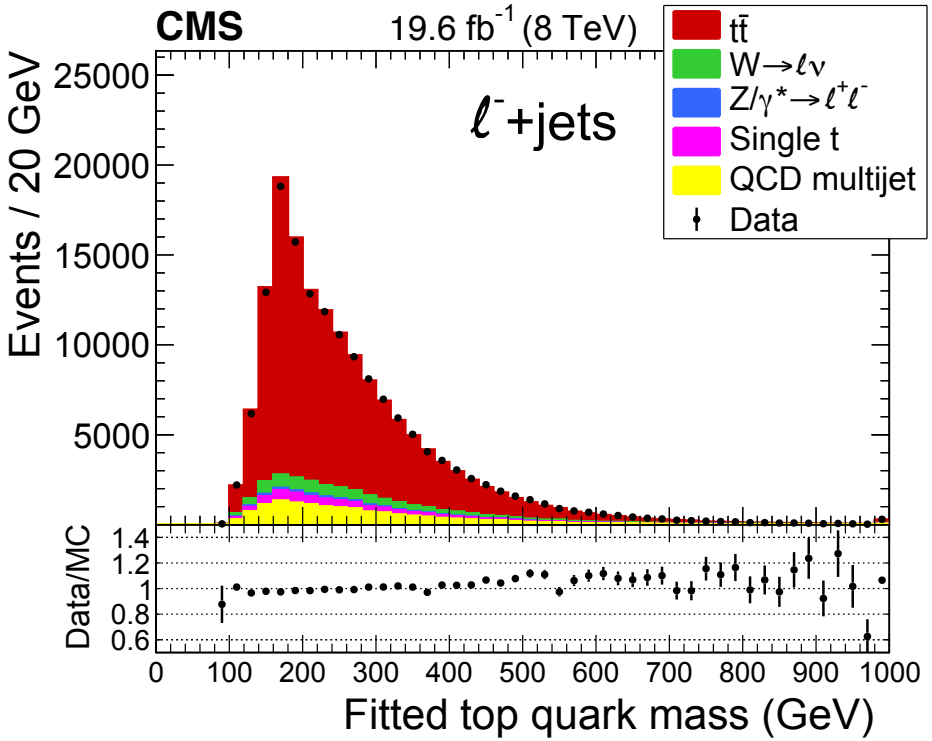
NEW!

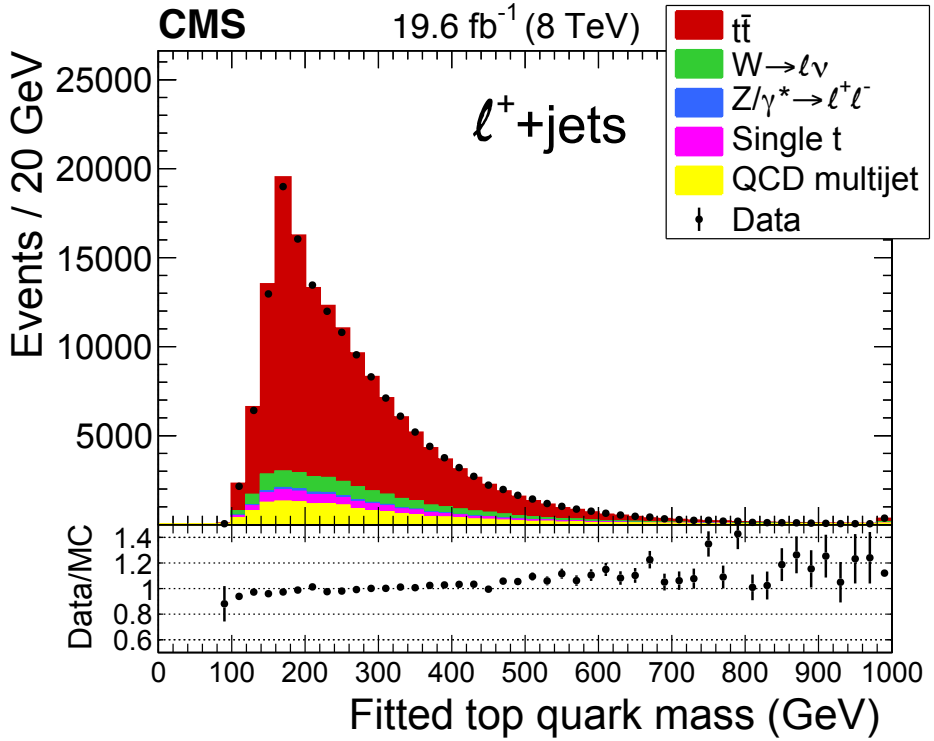
$$m_t = 170.8 \pm 6.0(\mathrm{st}) \pm 2.8\ (\mathrm{sys}) \pm 4.6\ (\mathrm{mod}) \pm 4.0\ (\mathrm{th})\ \mathrm{GeV}$$

- Boosted top decays ($p_T > 400$ GeV)
- Fully merged jet topology

- Test of the modelling of boosted top production
- Assessment of experimental sensitivity to m_t

▶ Measurement of $m_t - m_{\bar{t}}$ $\sqrt{s}$ =8 TeV (arXiv:1610.09551)





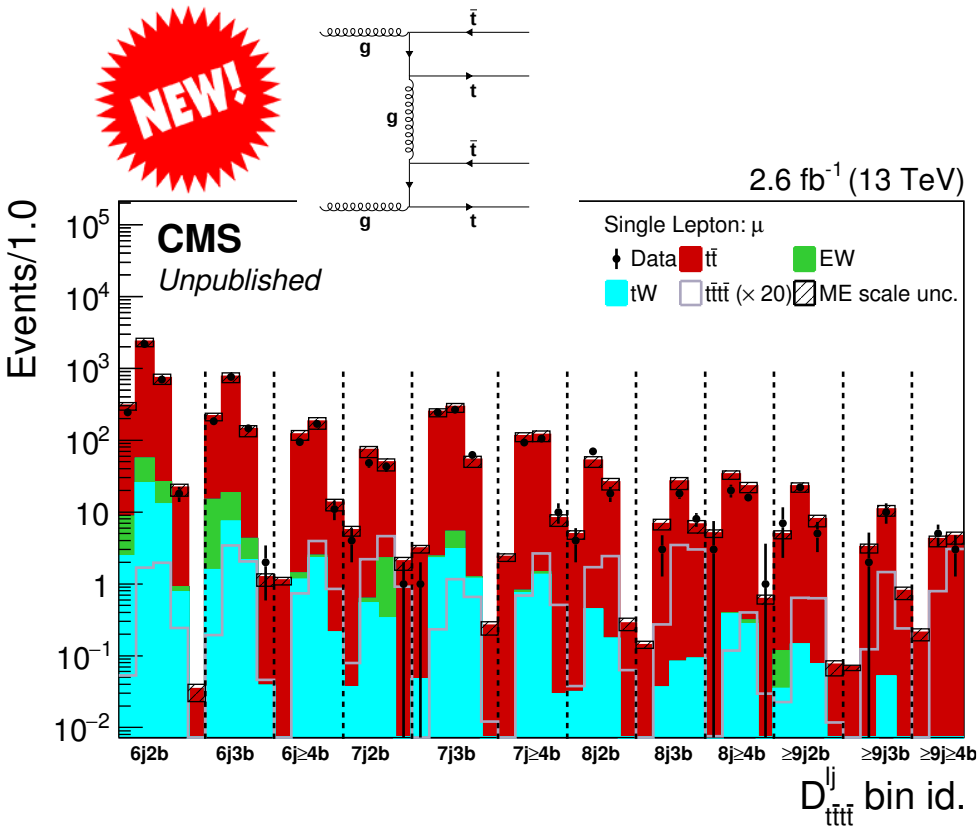
- Measurement of the mass difference between hadronicaly decaying top quark and antiquark
- Systematic uncertainties partially cancel in the difference

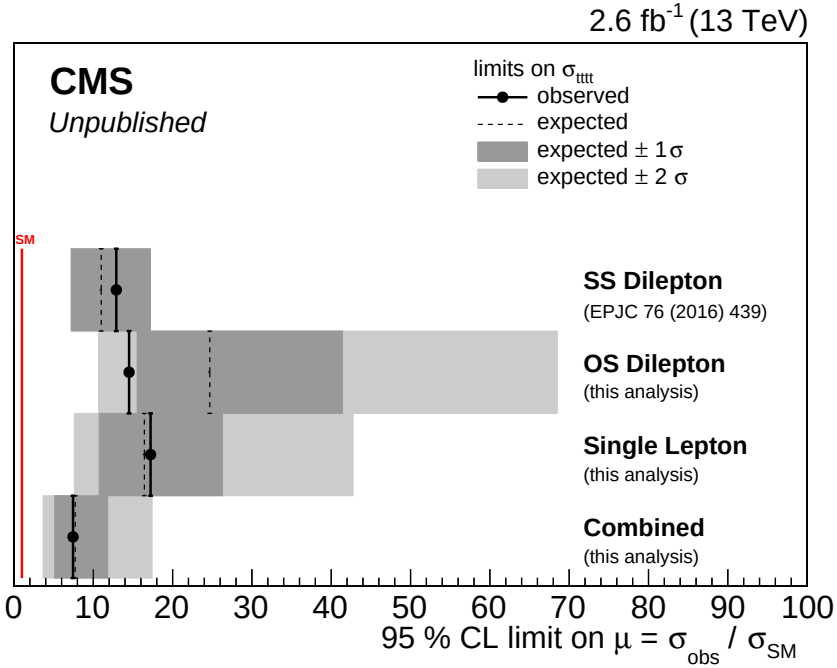
$$\Delta m_t = 0.15 \pm 0.19\,(\mathrm{st}) \pm 0.09\,(\mathrm{sys})\mathrm{GeV}$$

- Consistent with CPT invariance prediction, $\Delta m_t = 0$

Searches for rare processes and BSM phenomena

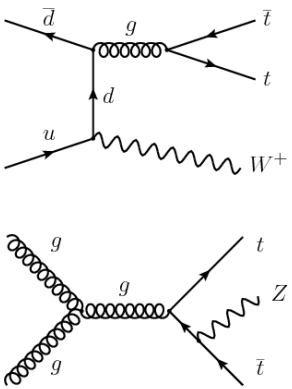
▶ Search for $t\bar{t}t\bar{t}$ production $\sqrt{s}$ =13 TeV (arXiv:1702.06164)

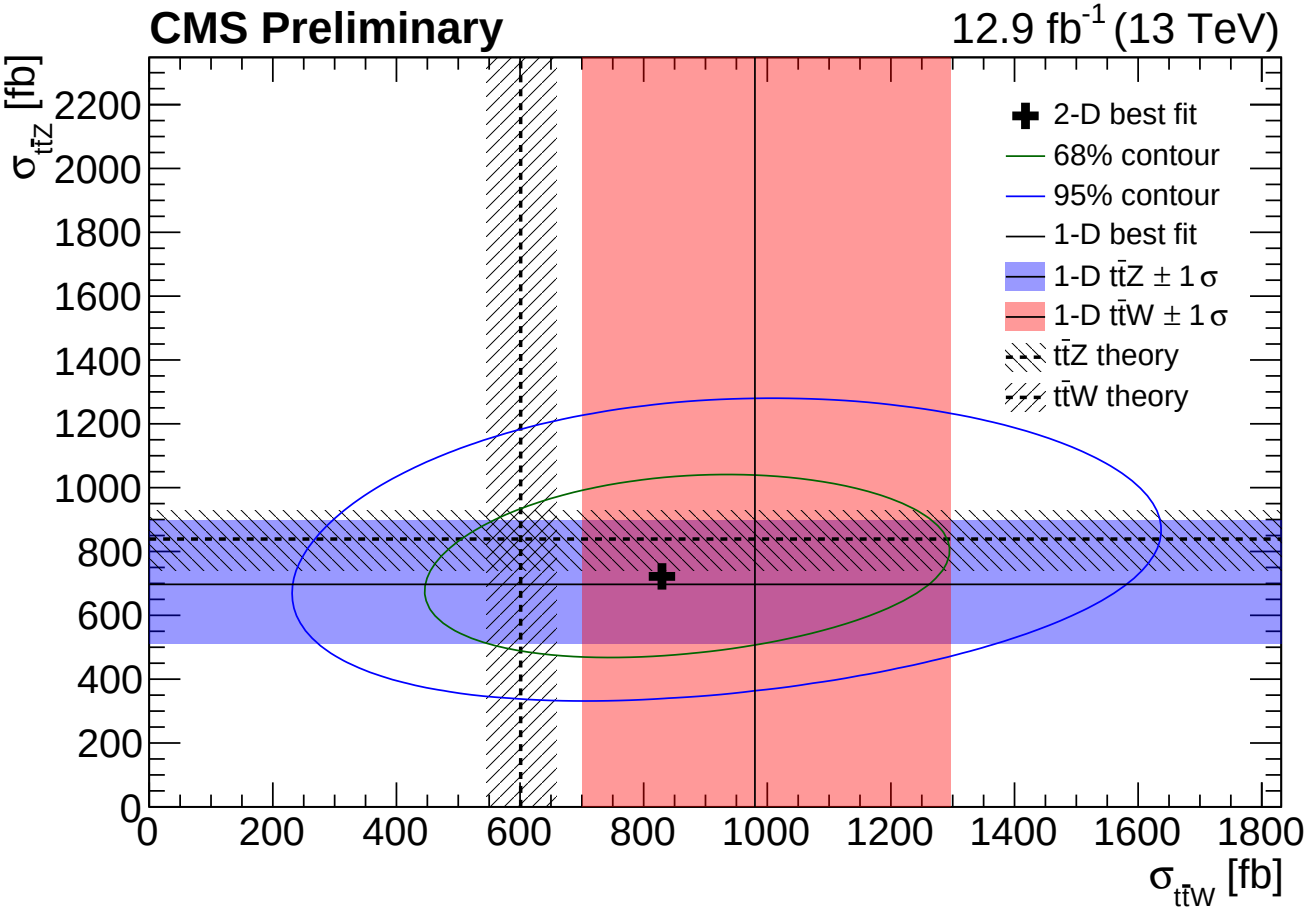




- Important in the context of BSM searches
- Template fit of the MVA discriminator distribution in multiple jet and b-tags categories
- Combination of the search results in three channels

$$95\%\,\mathrm{CL}\ \sigma_{t\bar{t}t\bar{t}} < 69\ (71^{+38}_{-24})\,\mathrm{fb} \quad 7.4\ (7.7^{+4.1}_{-2.6}) \times \sigma^{SM}_{t\bar{t}t\bar{t}}$$



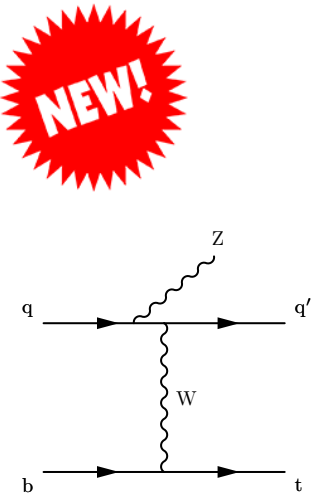


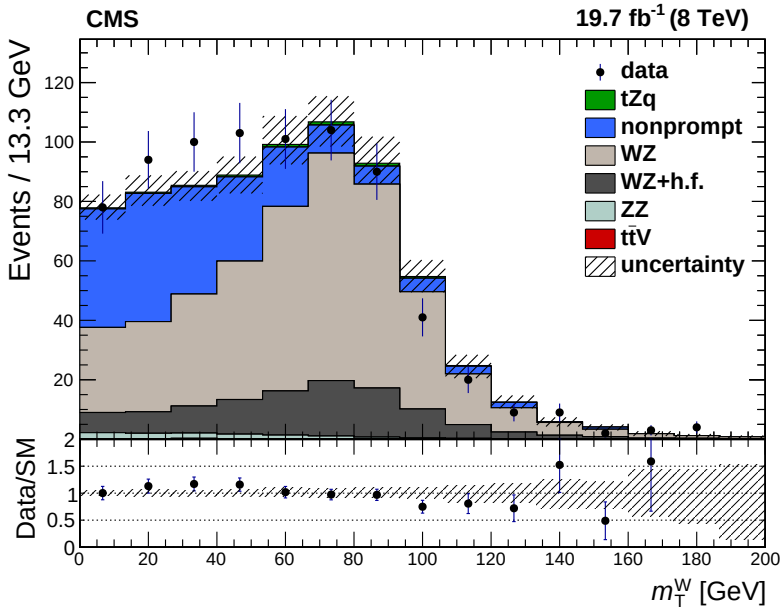
- 2016 data (12.9 fb^{-1})
- Sensitivity to tZ coupling
- Measurements consistent with the SM predictions

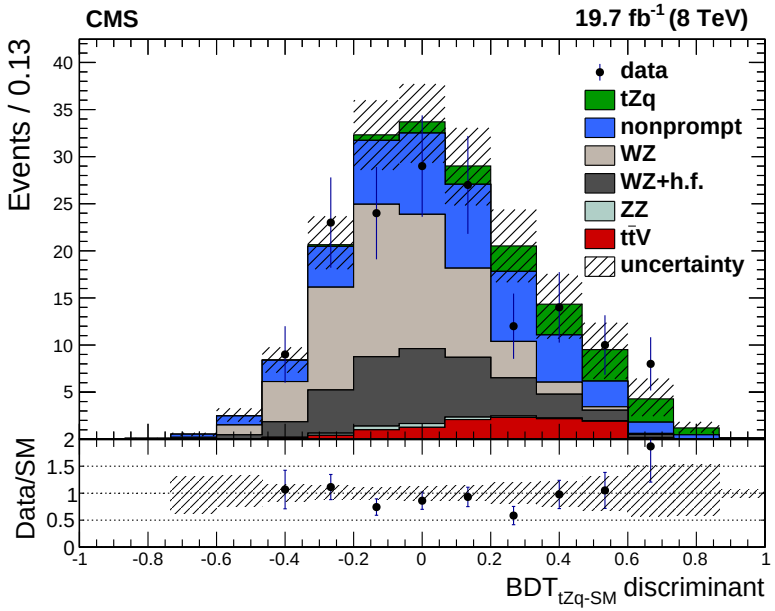
$$\sigma\left(t\bar{t}Z\right) = 0.70^{+0.16}_{-0.15}\,(\mathrm{st})^{+0.14}_{-0.12}\,(\mathrm{sys})\mathrm{pb}$$

$$\sigma\left(t\bar{t}W\right) = 0.98^{+0.23}_{-0.22}\,(\mathrm{st})^{+0.22}_{-0.18}\,(\mathrm{sys})\mathrm{pb}$$

▶ Search for tZ Production $\sqrt{s}$ =8 TeV (arXiv:1702.01404)







- Trilepton final state
- Data-driven estimate of non-prompt background
- 2.4σ SM signal observed

$$\sigma_{tZ} = 10^{+8}_{-7}\,\text{fb}$$

$$\text{SM} : \sigma\left(tl^+l^-q\right)\mathcal{B}\left(t \to l\nu b\right) = 8.2\,\text{fb}$$

- The most stringent limit on Z-mediated FCNC in top sector

$$\mathcal{B}\left(t \to Zu\right) < 0.022\%\ @95\%\,\text{CL}$$

$$\mathcal{B}\left(t \to Zc\right) < 0.049\%\ @95\%\,\text{CL}$$

▶ Summary

- LHC is a top quark factory and has extensive top physics program
- CMS is finalising its 8 TeV results and has new measurements with 13 TeV data
- What has been shown:
  - Precise measurements of total, single- and double-differential top quark pair cross sections and total single top cross section at 8 and 13 TeV
  - New combined top quark mass value from the measurements using alternative techniques

$$m_t = 172.58 \pm 0.21\,(\mathrm{st}) \pm 0.72\,(\mathrm{sys})\mathrm{GeV} \quad (0.4\%)$$

  - New measurements and limits on rare processes involving top quarks

Many new results using 36 fb^{-1} 13 TeV dataset follow soon!

http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP/index.html

BACKUP

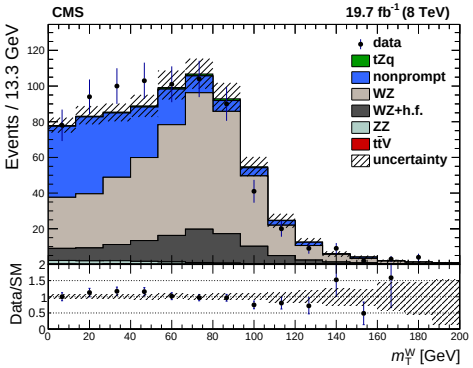
Source	Subcategory	Uncertainty (GeV)
Jet energy scale	In-situ correlation group	$+0.20, -0.21$
	Inter-calibration group	± 0.05
	Flavour-correlation group	± 0.40
	Pileup p_T uncertainty	$+0.18, -0.10$
	Uncorrelated group	$+0.48, -0.40$
	Total	$+0.68, -0.61$
b quark JES and hadronisation model		± 0.15
Jet energy resolution		± 0.05
Muon momentum scale		± 0.05
p_T^{miss}		± 0.15
Pileup		± 0.10
b tagging efficiency		± 0.10
Fit calibration		± 0.39
Background estimate	Shape	± 0.10
	Normalisation	± 0.14
	μ_{R} and μ_{F} scales	± 0.18
	Matching scales	± 0.30
	Total	± 0.39
Generator model		± 0.10
Signal μ_{R} and μ_{F} scales		± 0.23
Underlying event		± 0.20
Colour reconnection		± 0.05
Parton distribution functions		± 0.05
Total		$+0.97, -0.93$

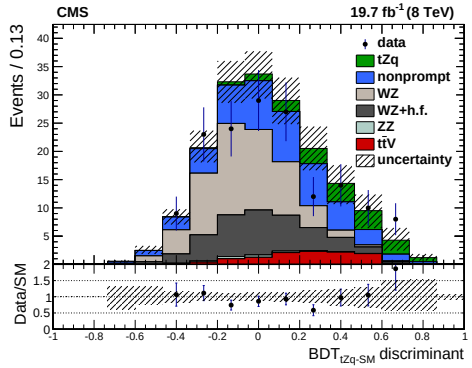
Combined m_t results	Legacy $\delta m_t(GeV)$	Alternative $\delta m_t(GeV)$	Combined $\delta m_t(GeV)$
Experimental uncertainties			
Method calibration	0.03	0.08	0.04
Jet energy corrections			
– JEC: Intercalibration	0.01	0.06	0.02
– JEC: In situ calibration	0.12	0.16	0.12
– JEC: Uncorrelated non-pileup	0.10	0.26	0.10
Lepton energy scale	0.01	0.13	0.01
MET scale	0.03	0.04	0.04
Jet energy resolution	0.03	0.03	0.03
b tagging	0.05	0.02	0.05
Pileup	0.06	0.07	0.06
Secondary vertex mass	n/a	0.04	$<$0.01
Backgrounds	0.04	0.08	0.04
Trigger	$<$0.01	$<$0.01	$<$0.01
Modeling of hadronization			
JEC: Flavor	0.33	0.33	0.31
b jet modeling	0.14	0.22	0.14
Modeling of perturbative QCD			
PDF	0.04	0.11	0.04
Ren. and fact. scales	0.10	0.31	0.10
ME-PS matching threshold	0.08	0.22	0.08
ME generator	0.11	0.08	0.11
Single top modeling	n/a	0.04	0.01
Top quark p_T	0.02	0.23	0.02
Modeling of soft QCD			
Underlying event	0.11	0.11	0.11
Color reconnection modeling	0.10	0.10	0.10
Mass and Uncertainties (GeV)			
m_t	172.44		
Uncertainties (GeV)			
Total systematic	0.47	0.72	0.46
Statistical	0.13	0.21	0.13

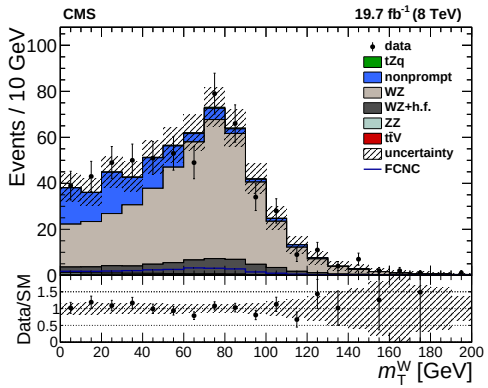
	δm_t	δJSF
Experimental uncertainties		
Method calibration	0.07	<0.001
Jet energy corrections (quad. sum)	(0.30)	(0.006)
– JEC: InterCalibration	0.03	<0.001
– JEC: MPFInSitu	0.12	0.001
– JEC: Uncorrelated non-pileup	0.26	0.004
– JEC: Uncorrelated pileup	0.11	0.004
Muon energy scale	0.03	<0.001
Jet energy resolution	0.04	0.001
b tagging	0.05	<0.001
Pileup	0.01	0.001
Non-$t\bar{t}$ background	0.19	0.001
Modeling of hadronization		
JEC: Flavor-dependent	0.41	0.001
b-jet modeling	0.18	<0.001
Modeling of perturbative QCD		
PDF	0.09	0.001
Ren. and fact. scale	<0.01	<0.001
Parton shower scale	0.23	0.001
ME generator	0.12	0.001
Top quark transverse momentum	0.01	<0.001
Modeling of soft QCD		
Underlying event	0.18	0.007
Color reconnection modeling	0.22	0.001
Systematic	**0.70**	**0.010**
Statistical (expected)	0.38	0.003
Total (expected)	**0.80**	**0.010**

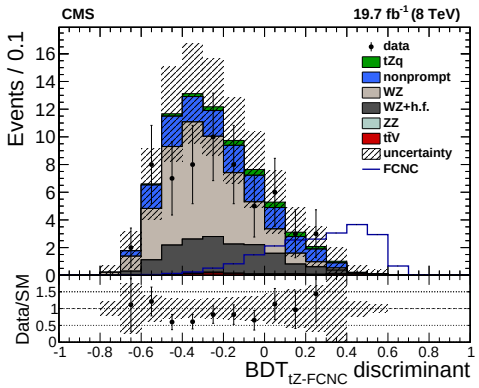
▶ tZ $\sqrt{s}$=8 TeV

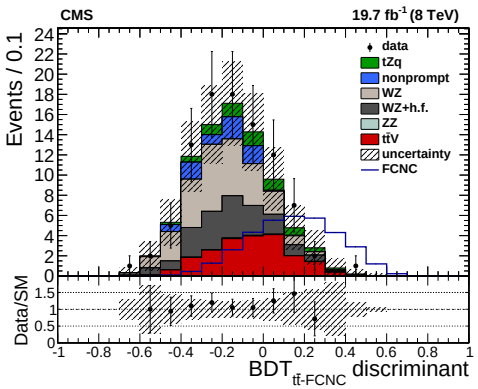
(TOP-12-039/1702.01404)

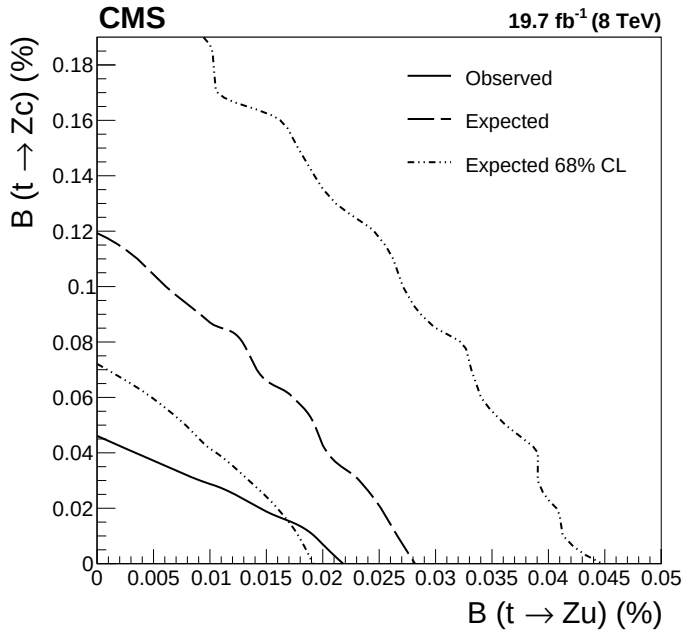










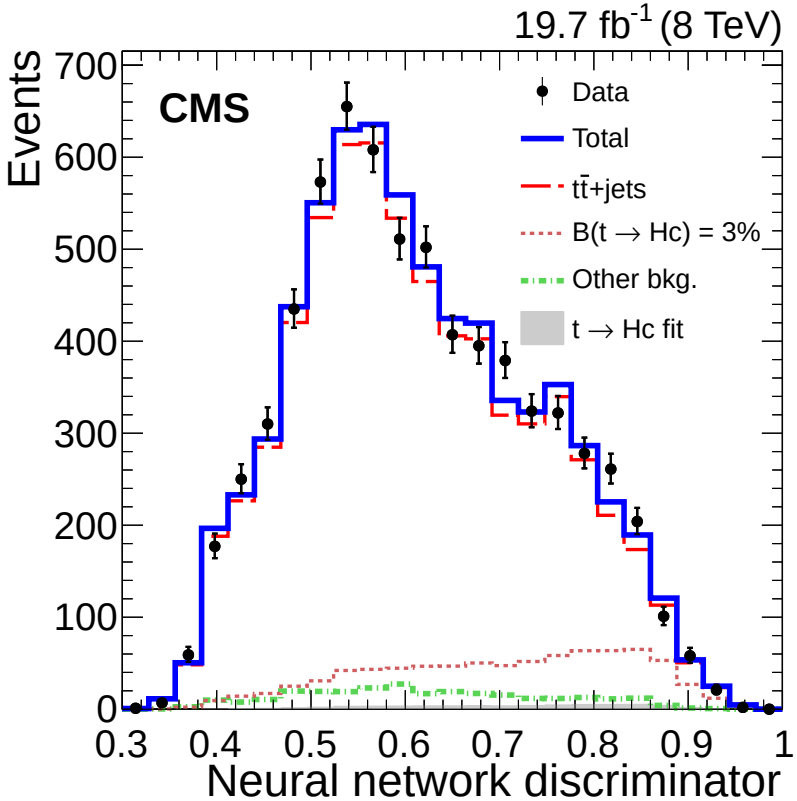


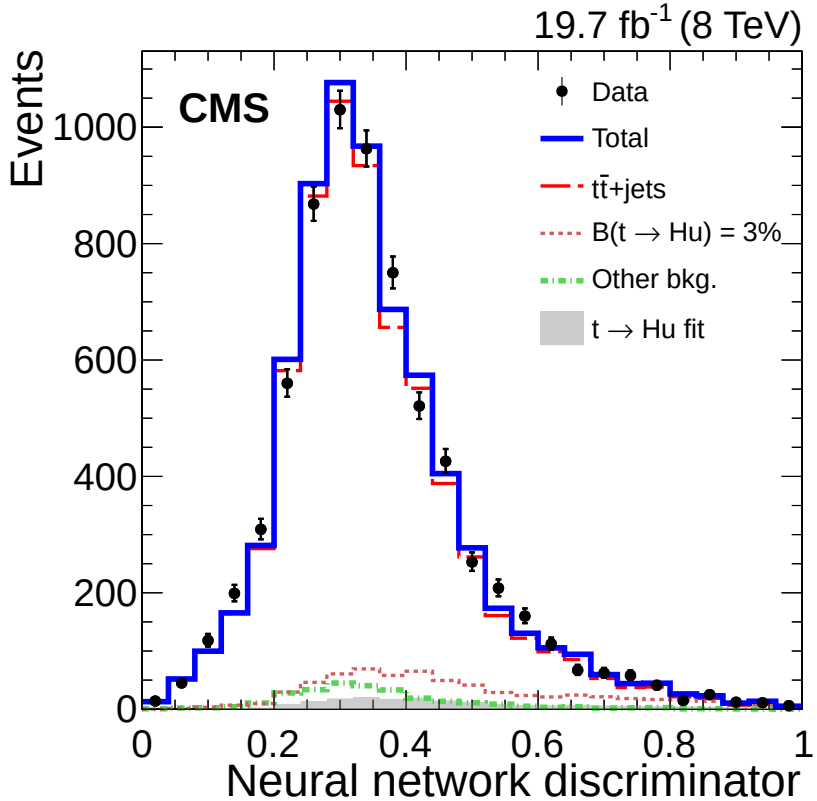
$\sigma_{tZ} = 10^{+8}_{-7}$ fb

$\mathcal{B}(t \to Zu) < 0.022\%$ @95% CL

$\mathcal{B}(t \to Zc) < 0.049\%$ @95% CL

- A search for the production of a single top quark in association with a Z boson
- 2.4 s.d. SM signal observed
- Limits on $t \to Zu$ and $t \to Zc$ decays are established

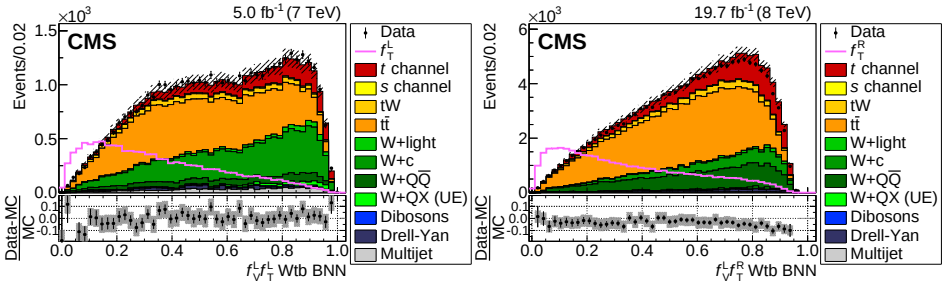


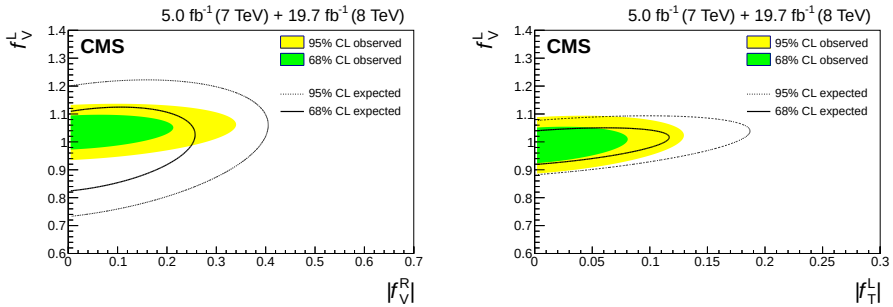


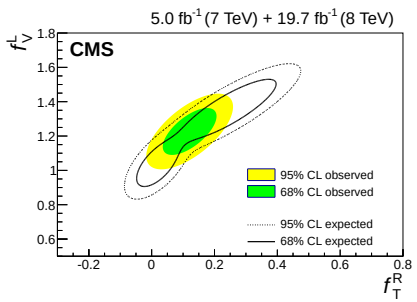
$\mathcal{B}(t \to Hc) < 0.4\% \quad \mathcal{B}(t \to Hu) < 0.55\% \qquad @95\%\,\mathrm{CL}$

- A search is performed for Higgs-boson-mediated flavor-changing neutral currents in the decays of top quarks
- Template fit to ANN discriminant was performed to estimate signal strength
- Observations are consistent with the SM predictions

- Single top channel.
- A Bayesian neural network technique, used to discriminate between the signal and backgrounds.
- Dedicated training to separate SM left-handed interactions from one of the anomalous interactions
- Stringent limits on anomalous couplings

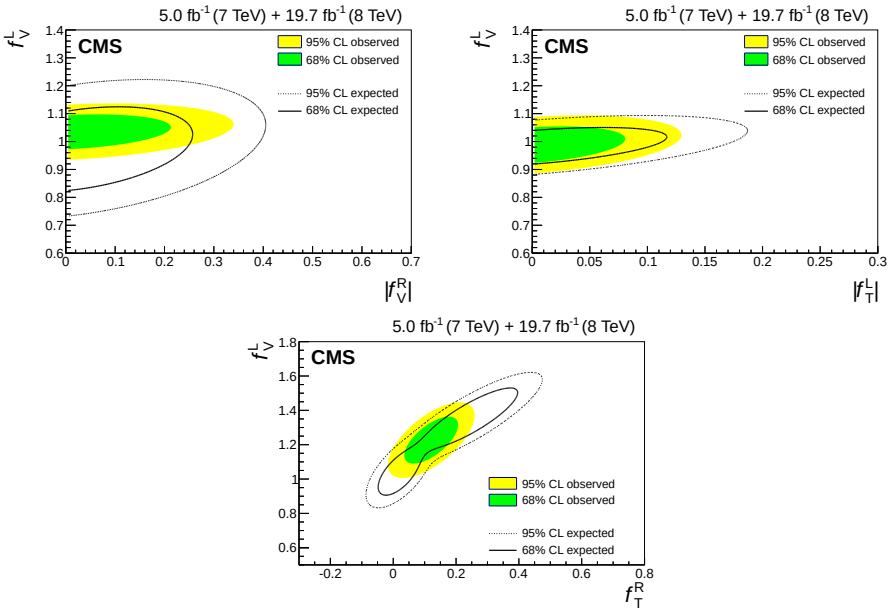


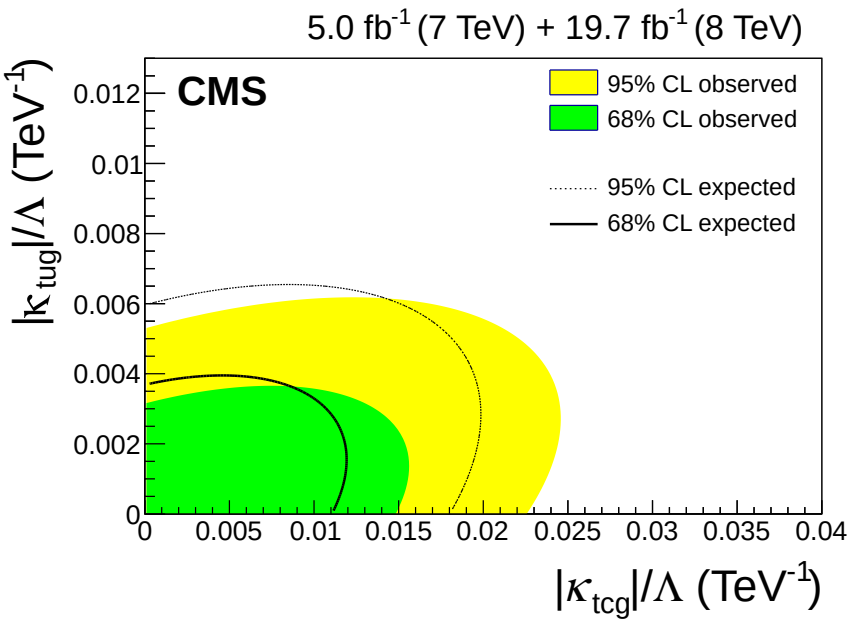




$f_V^L > 0.98,\ |f_V^R| < 0.16$ @95% CL

$f_T^L < 0.057,\ -0.049 < f_V^R < 0.048$ @95% CL





$f_V^L > 0.98,\ |f_V^R| < 0.16$ @95% CL

$f_T^L < 0.057,\ -0.049 < f_V^R < 0.048$ @95% CL

$\mathcal{B}(t \to gu) < 2.0 \times 10^{-5}\%$ @95% CL

$\mathcal{B}(t \to gc) < 4.1 \times 10^{-4}\%$ @95% CL

- Limits on anomalous couplings are established

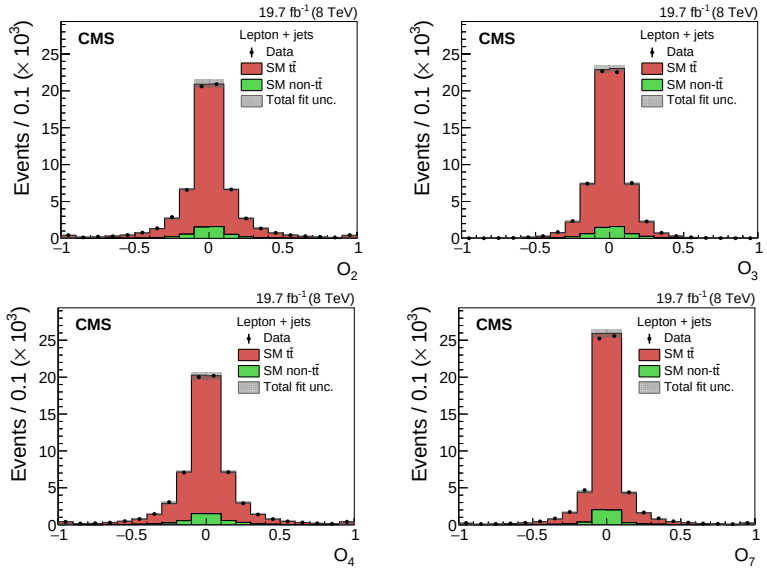
▶ CP violation in $t\bar{t}$ system $\sqrt{s} = 8$ TeV (TOP-16-001/arXiv:1611.08931)

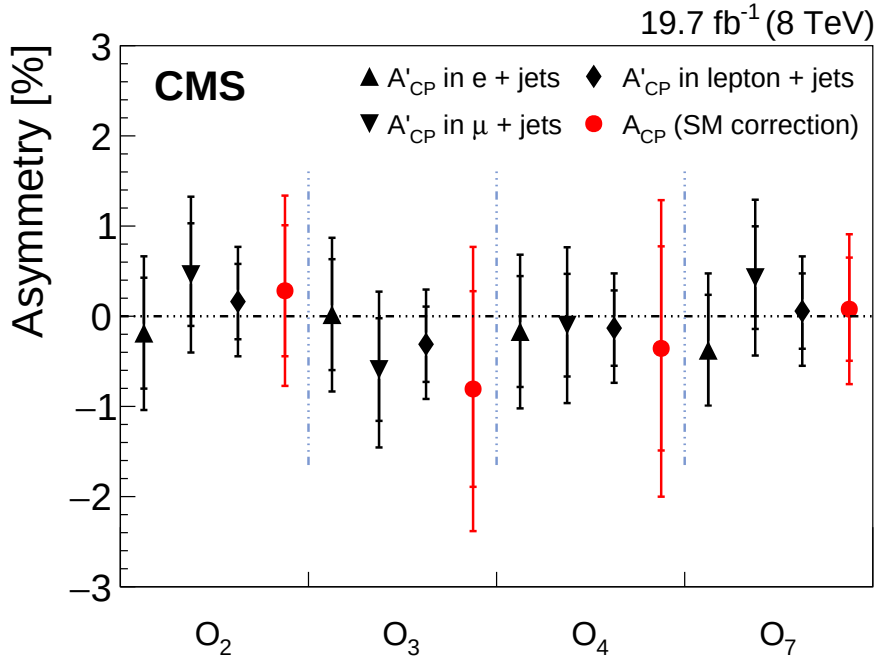
- RunI dataset (19.7 fb^{-1})

$$O_2 = \epsilon\,(P, p_b + p_{\bar{b}}, p_l, p_{j1})\,,$$
$$O_3 = Q_l \epsilon\,(p_b, p_{\bar{b}}, p_l, p_{j_1})\,,$$
$$O_4 = Q_l \epsilon\,(P, p_b - p_{\bar{b}}, p_l, p_{j_1})\,,$$
$$O_2 = q \cdot (p_b - p_{\bar{b}})\,\epsilon\,(P, q, p_l, p_{j_1})\,.$$

$$A_{\mathrm{CP}}(O_i) = \frac{N(O_i > 0) - N(O_i < 0)}{N(O_i > 0) + N(O_i < 0)}$$

- A first search for CP violation in the production and decay of $t\bar{t}$
- No evidence for CP-violating effects
- Consistent with the expectation from the standard model





▶ FCNC searches in top sector

- Searches for H, γ, Z, g-mediated processes in top sector
- Limits approach predictions from various BSM models with FCNC