Top measurements from CMS

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on behalf of the CMS Collaboration

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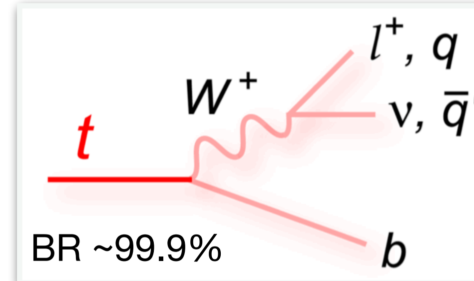
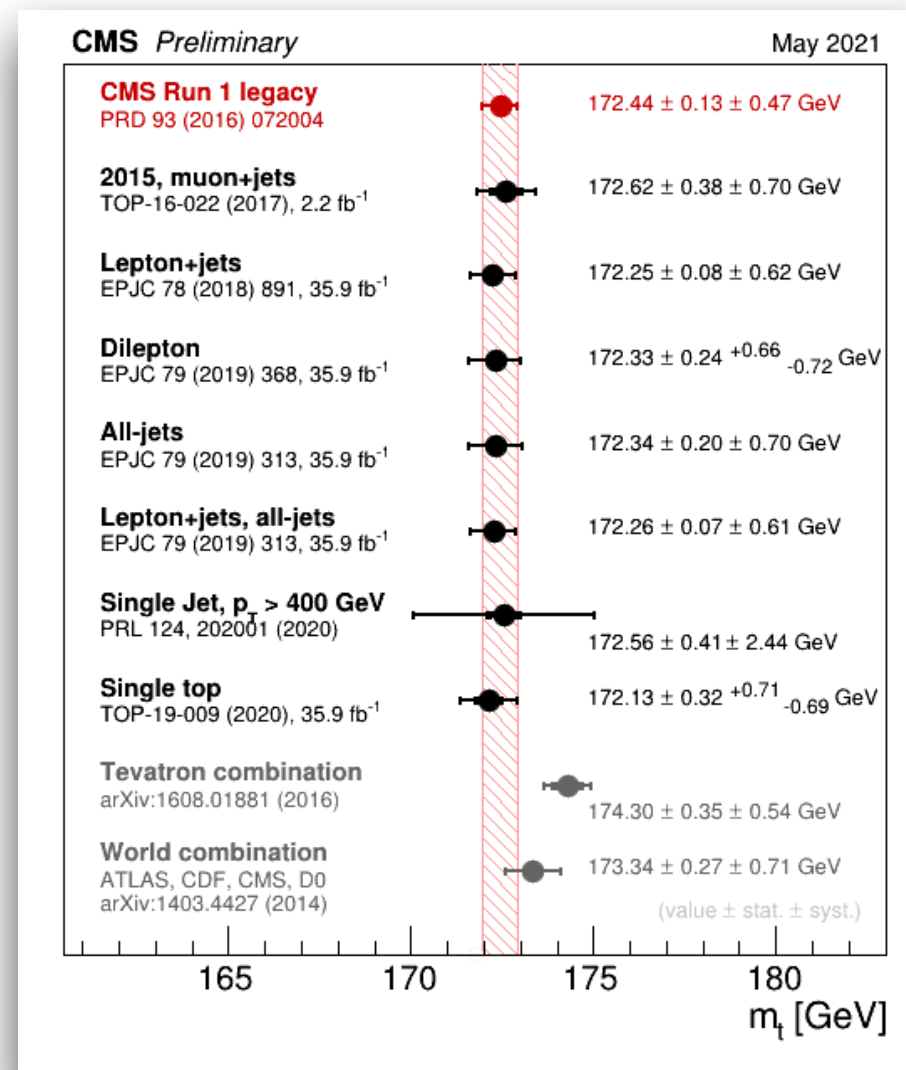
The Top Quark

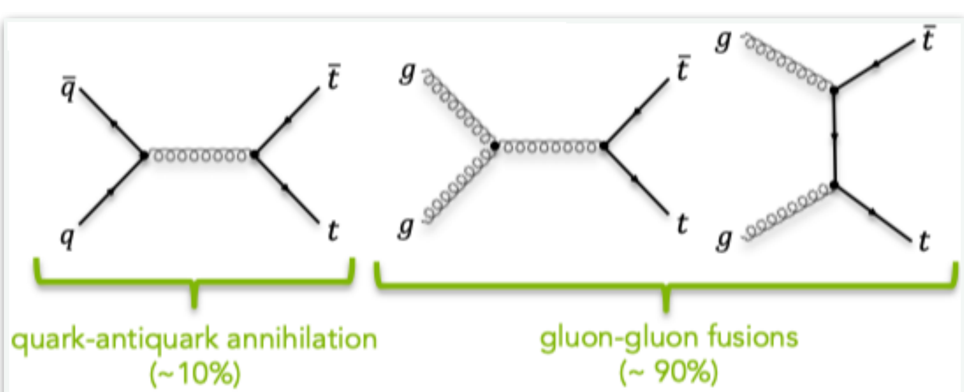
- Heaviest elementary particle discovered so far
- **Extremely short lifetime** → bare quark properties
- **Large Yukawa coupling** to Higgs boson → important for EW symmetry breaking
- **Spin information preserved** in the angular distribution of its decay products → **ideal candidate for spin measurements**



$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\10^{-27}\,\text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\10^{-25}\,\text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\10^{-24}\,\text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\10^{-21}\,\text{s}}}$$

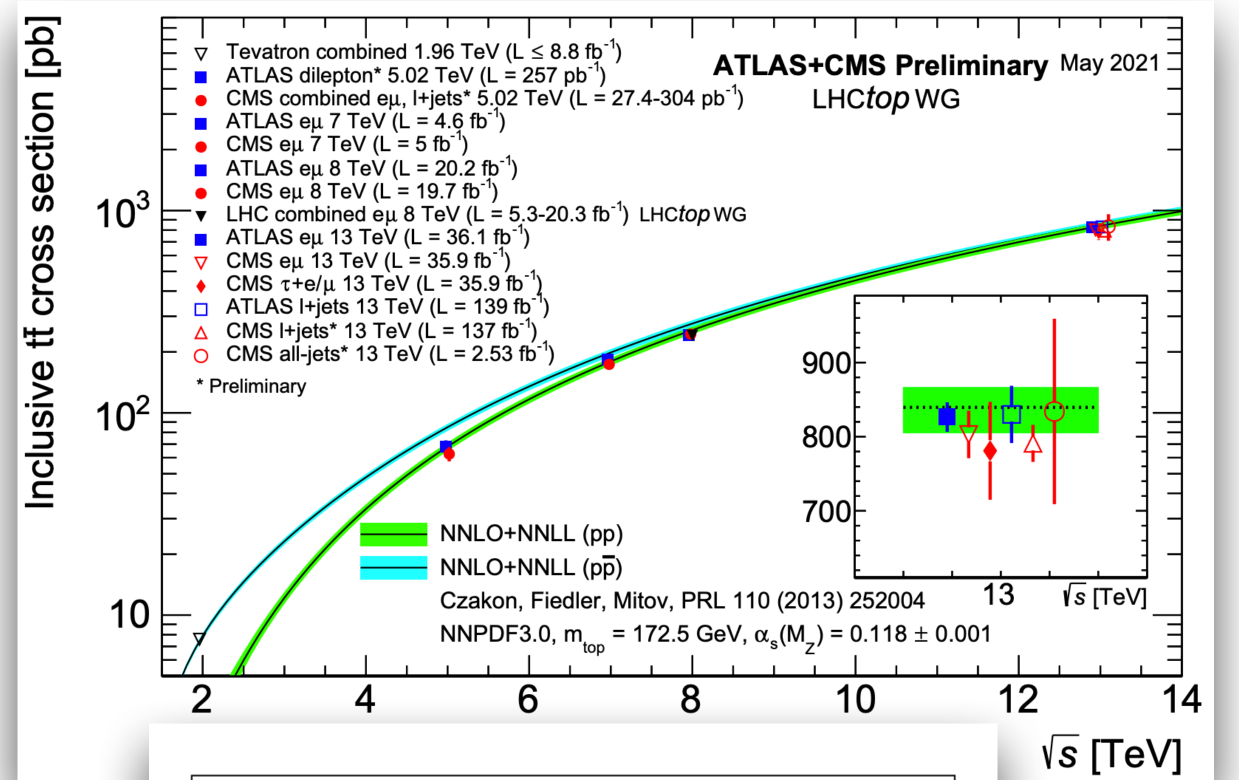
- Studies of its properties provide crucial info to:
  - test internal consistency of SM
  - search for new phenomena (BSM physics)
- Top quark pairs production:
  - dominated by gluon fusion (~90%) @LHC
  - constraint of fundamental SM parameters (e.g. PDF, α_S, m_t^{pole})
- Single top production:
  - constraint of EWK sector of SM (direct sensitivity to V_{tb})

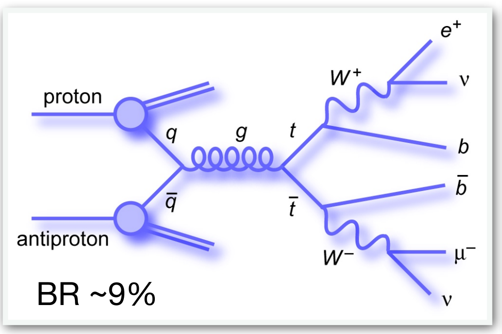


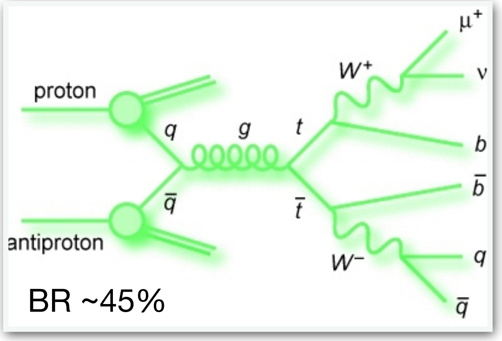


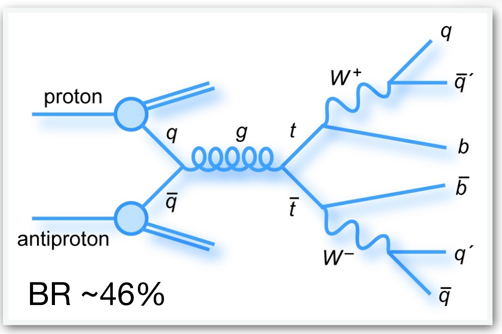
Top quark pair production

- Many measurements performed at 7, 8 and 13 TeV
  - impressive agreement with predictions
- Inclusive production cross sections can be calculated up to NNLO+NNLL in QCD:
  - test of perturbative QCD
- Differential cross sections can be used to test fixed-order predictions and MC generators:
  - indirect search for new physics (e.g. EFT framework)
- 3 main investigation channels:





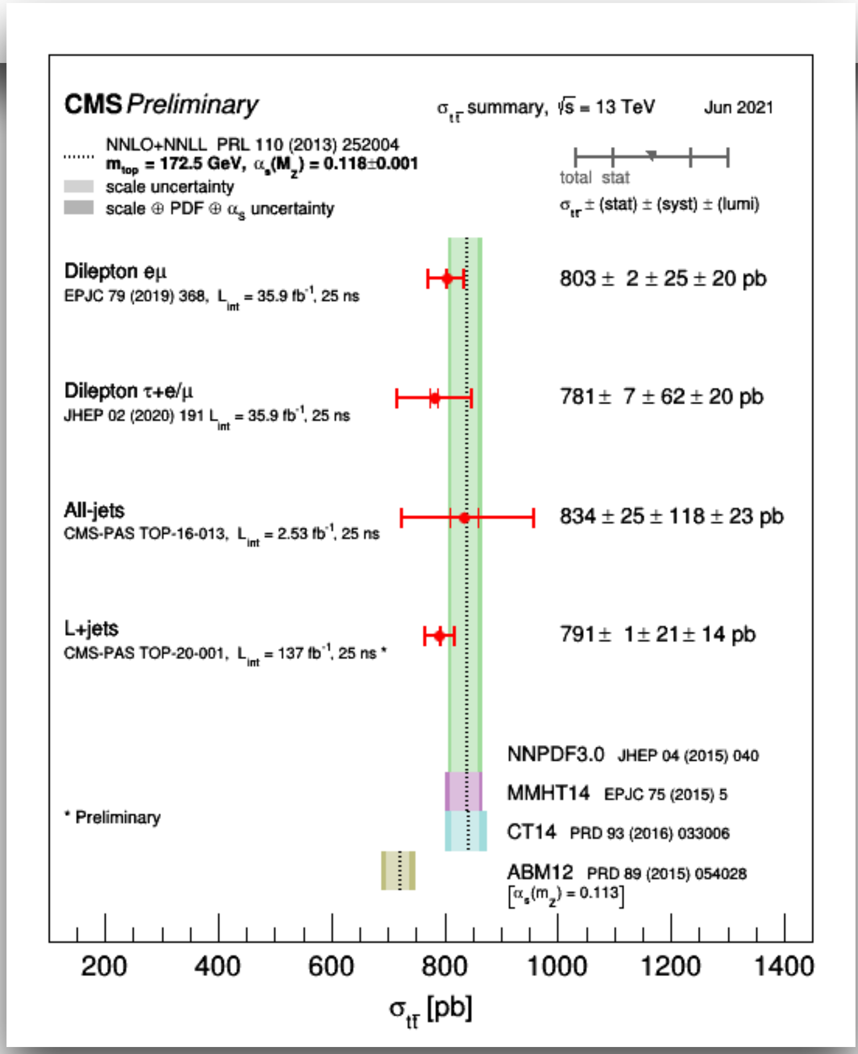




dilepton
cleanest signature but small BR

lepton+jets
compromise between signal statistic & bkg contamination

full hadronic
significantly less precise (large multijet bkg)



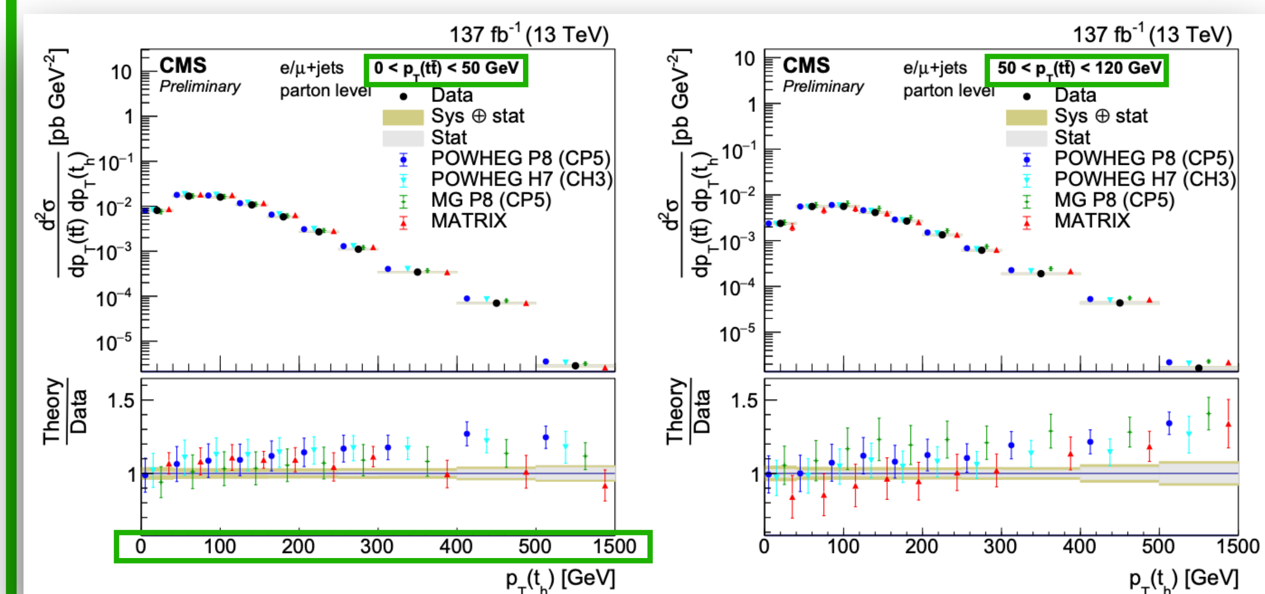
Dominant syst. unc.:
$t\bar{t}$ modeling, objects efficiencies and calibrations, bkg estimates, luminosity (~2%)

$t\bar{t}$: inclusive & differential

CMS-PAS-TOP-20-001

Full Run2 data

- First **combined fit of resolved and boosted topology** in l+jets channel
- Boosted top identified with **NN approach**
- Profiled nuisance parameters
  - significant reduction of uncertainties
- Observed softer top pT spectrum wrt predictions
  - improved description with NNLO



$$\sigma_{\mathrm{tot}} = 791 \pm 25\,\mathrm{pb}$$

Most precise result in l+jets channel

$$\frac{\Delta\sigma}{\sigma} \sim 3.1\,\%$$

Dominant syst. unc.: JES, b-tagging

CMS-PAS-TOP-20-004

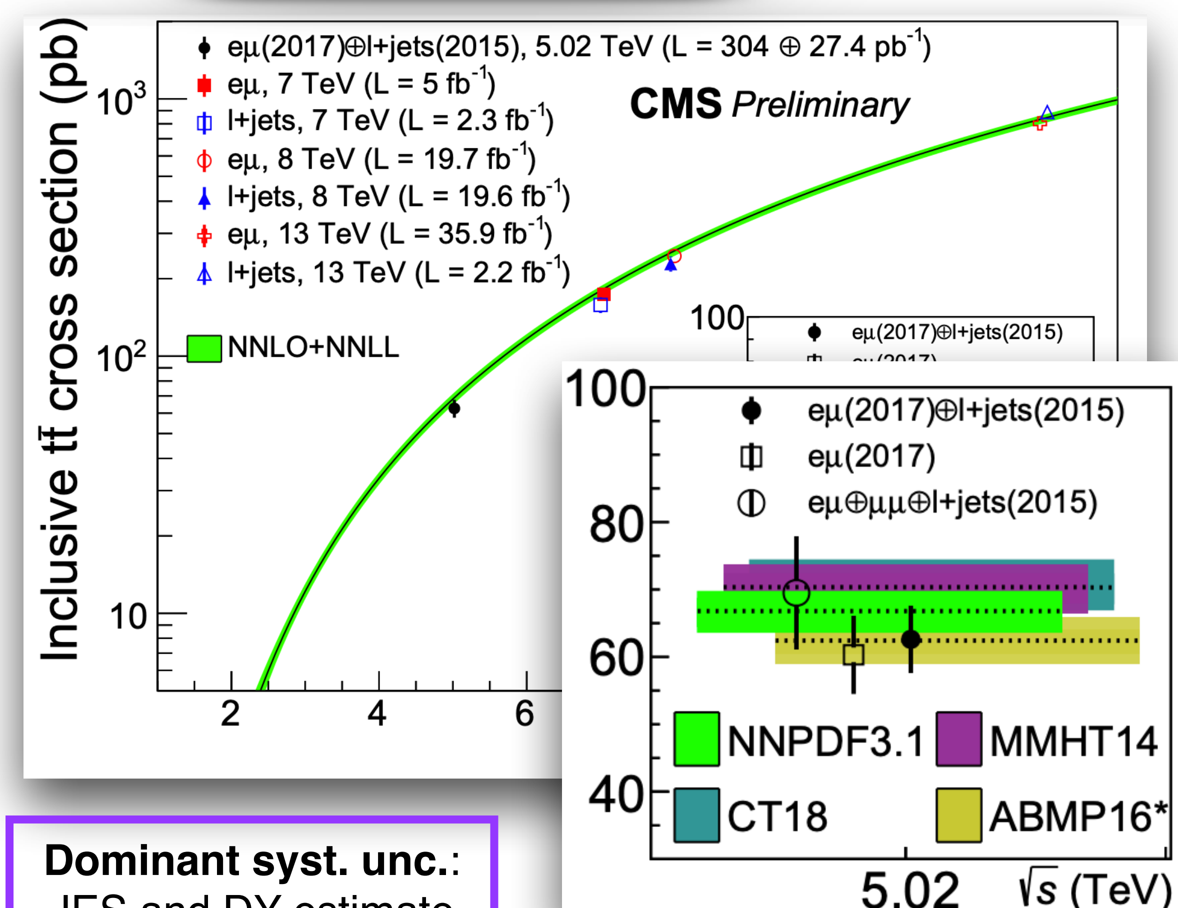
Small dataset **@5.02 TeV**

- Event count in eμ channel (2017) combined with measurement in l+jets channel (2015)
  - both limited by statistical uncertainty
  - good agreement with NNLO + NNLL prediction

$$\sigma_{t\bar{t}} = 62.6 \pm 4.1\ (\mathrm{stat}) \pm 3.0\ (\mathrm{syst{+}lumi})\ \mathrm{pb}$$

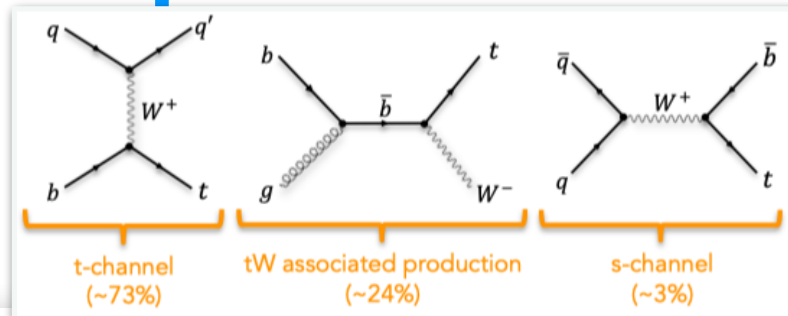
Precision improved wrt previous results (~12%)

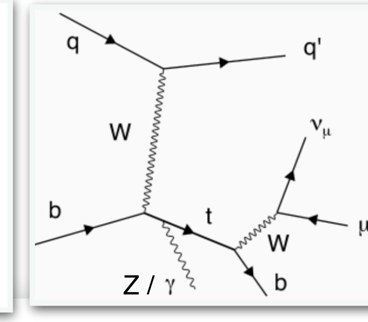
$$\frac{\Delta\sigma}{\sigma} \sim 7.9\,\%$$



Dominant syst. unc.: JES and DY estimate

Single top quark production





- Many measurements performed at 7,8 and 13 TeV
  - impressively in agreement with predictions
  - 3 main investigation channels

- Used to measure different parameters, e.g.:
  - **charge ratio**: improvement of precision (3.0%) wrt 2015 analysis (12.9%)

$$R_{t-ch} = 1.68 \pm 0.02(\text{stat.}) \pm 0.05(\text{syst.})$$

PLB 800 (2020) 135042

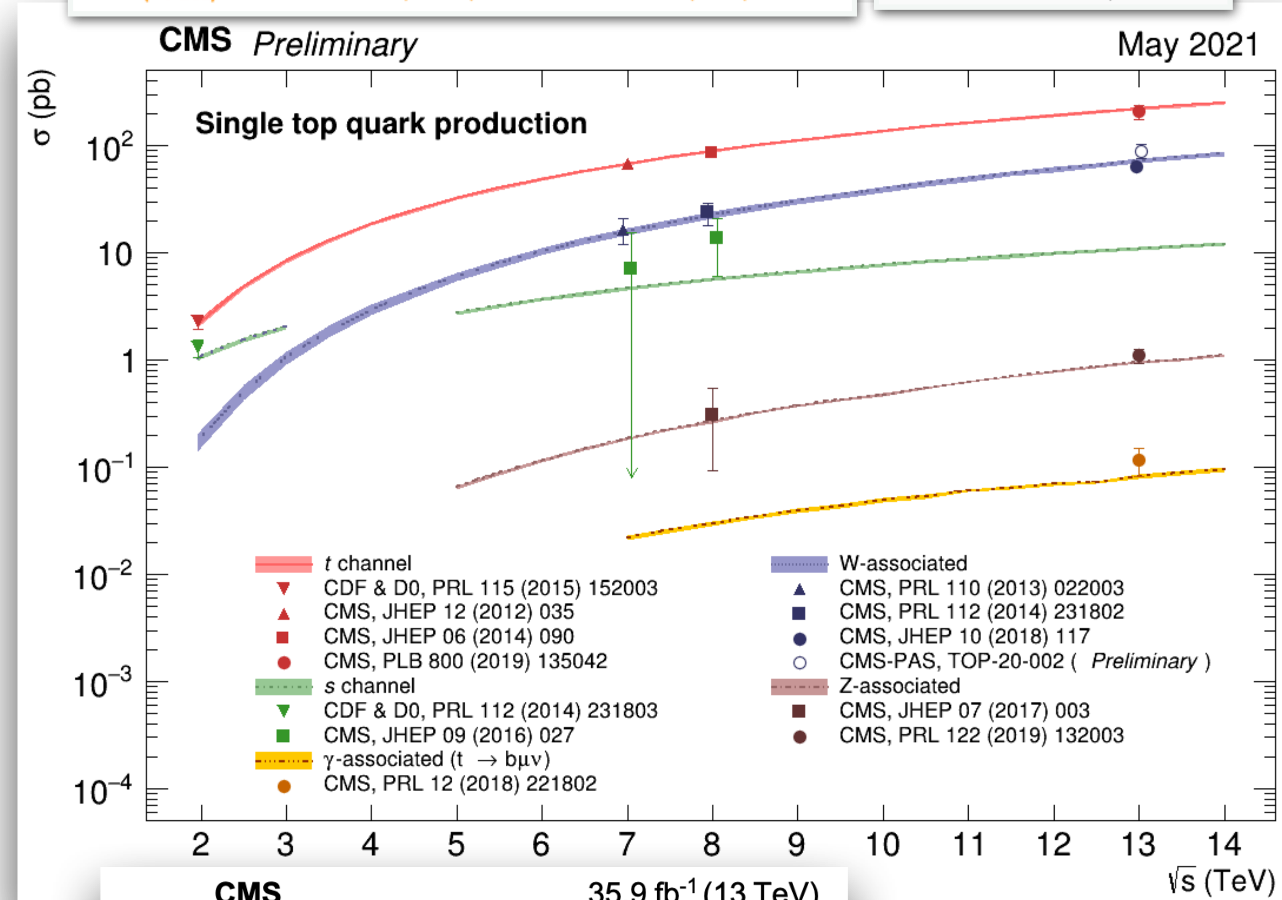
  - **spin asymmetry**: estimated from differential distribution of polarisation angle

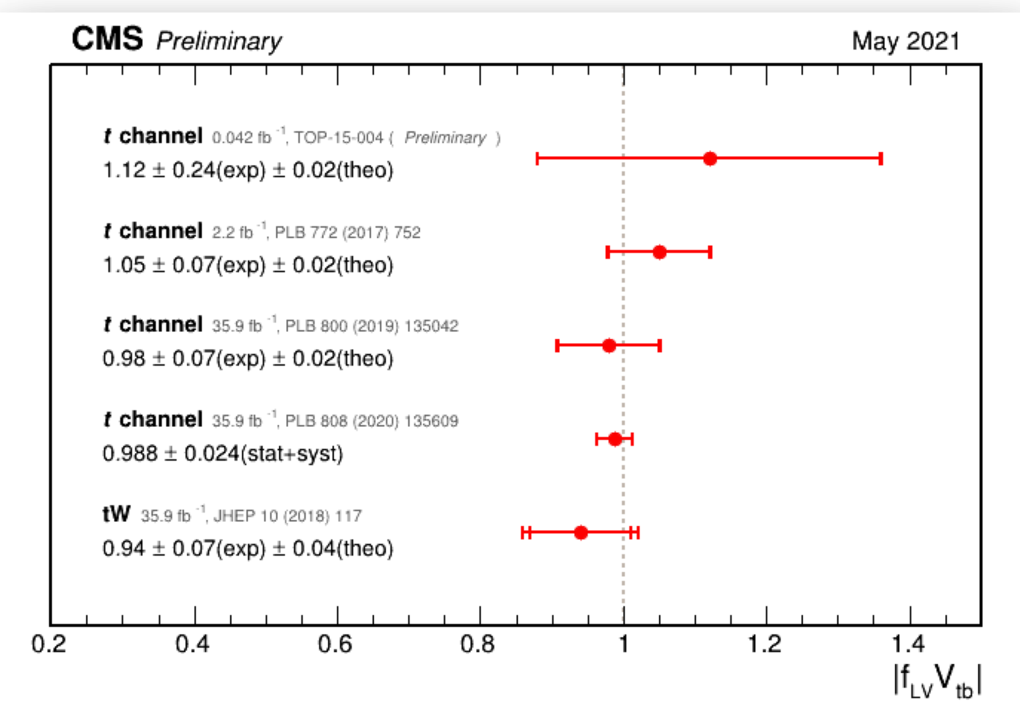
	A_μ	A_e	$A_{\mu+e}$
Central values	0.403	0.446	0.440

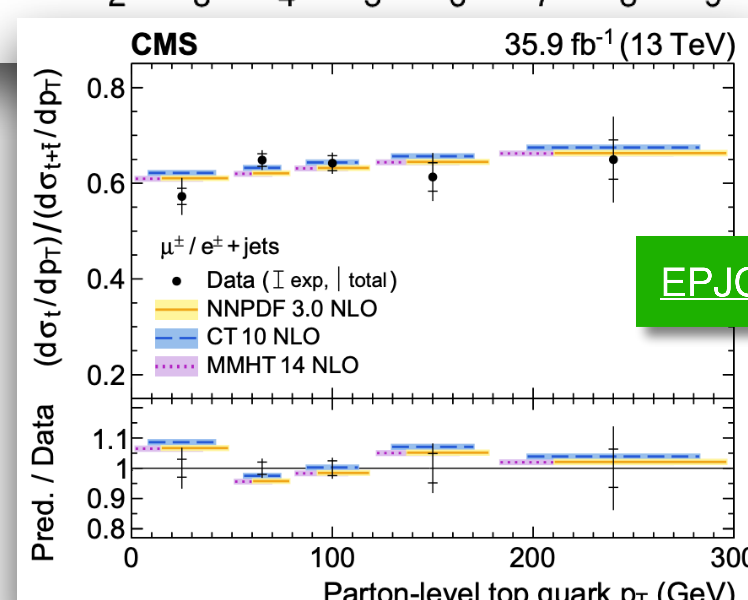
EPJC 80 (2020) 370

in agreement with SM predictions: 0.436

  - **V_{tb}** : from $|f_{LV}V_{tb}| = p\sigma_{meas}/\sigma_{theo}$







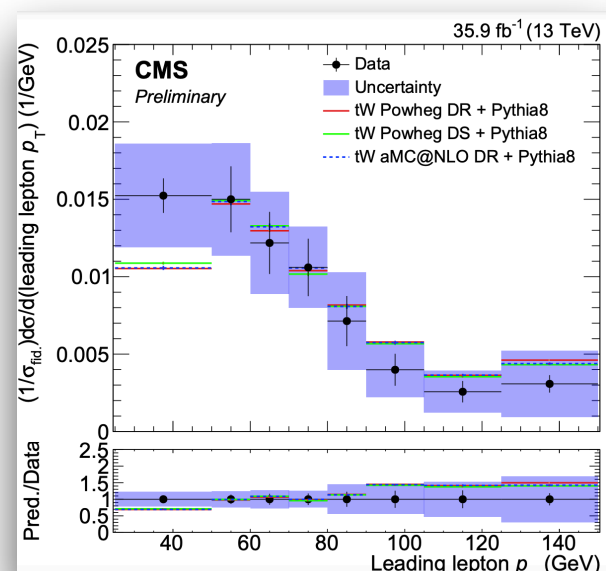
EPJC 80 (2020) 370

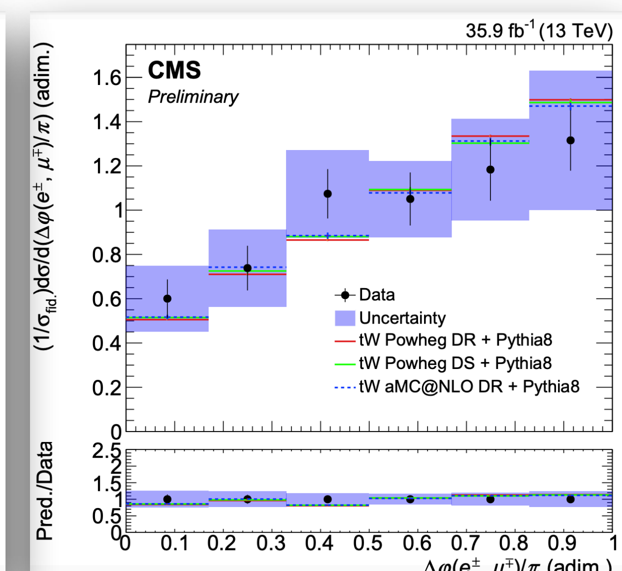
shapes overall compatible with theory

Single top: tW channel

CMS-PAS-TOP-19-003 | **2016 data**

- **Differential** cross section in dilepton ($e\mu$) events
- **Cut & count analysis**:
  - signal extraction performed by subtracting bkg (estimated through MC simulations)
- Absolute and normalised results at particle level in fair agreement with POWHEG and MADGRAPH5_aMC@NLO predictions





Dominant syst. unc.:
jet reconstruction and theoretical modeling, driven by overwhelming $t\bar{t}$ background

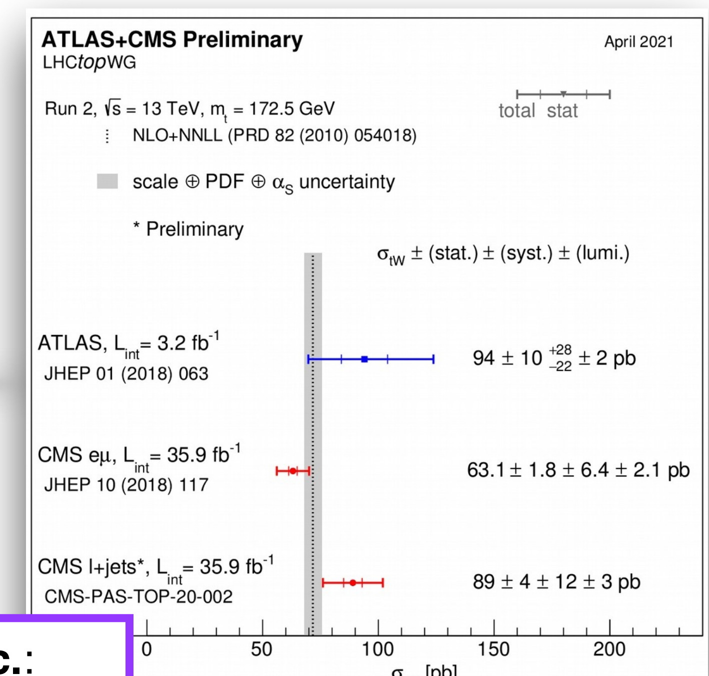
CMS-PAS-TOP-20-002 | **2016 data**

- **Inclusive** cross section in lepton+jets channel
- **Binned likelihood fit on BDT discriminants**
- Measured cross-section in agreement with SM predictions within 2σ:

$$\sigma_{tW} = 89 \pm 4\,(\text{stat.}) \pm 12\,(\text{syst.})\text{ pb}$$

$$\sigma_{tW}^{SM} = 71.7 \pm 1.8\,(\text{scale}) \pm 3.4\,(\text{PDF})\text{ pb}$$

First observation ($> 5\sigma$) of tW in lepton+jets channel!

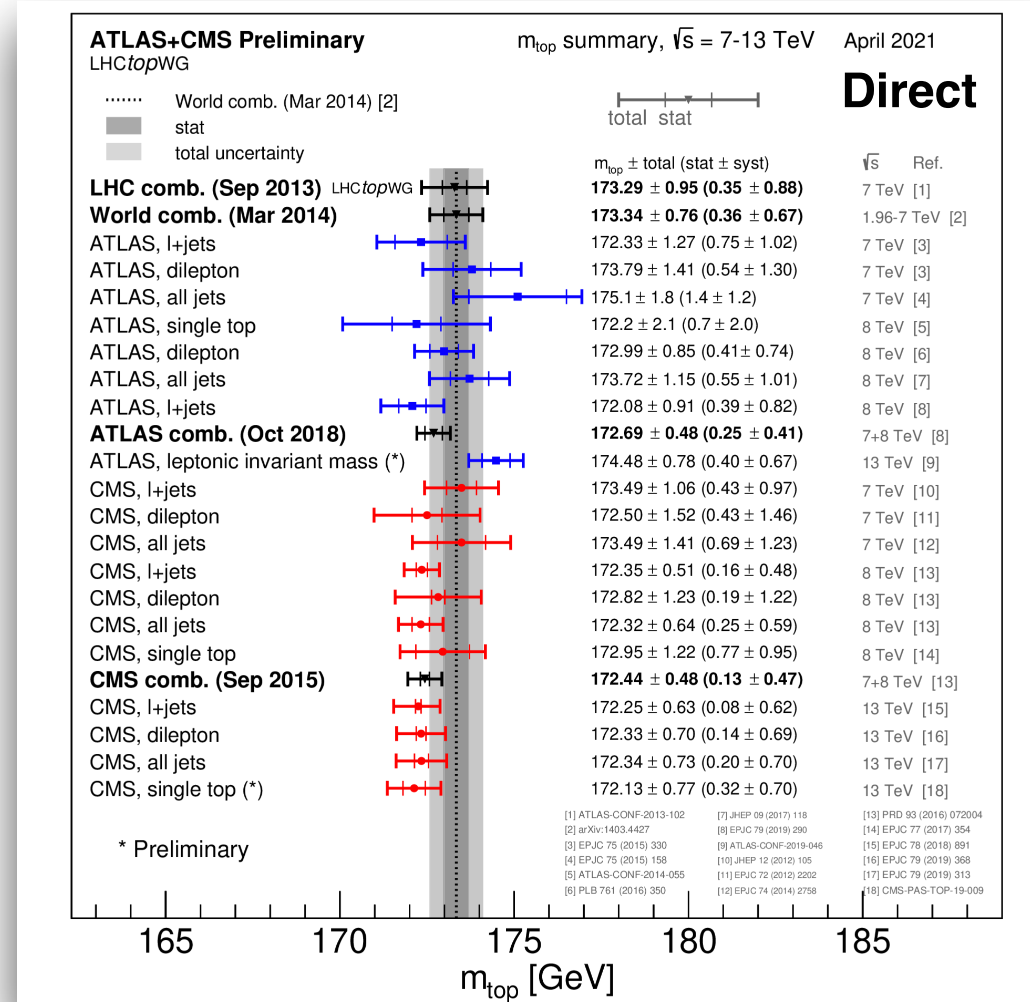


Dominant syst. unc.:
multi-jet and W+jets background normalisation, jet energy scale and $t\bar{t}$ modelling

Top mass: direct measurements

- From kinematic reconstruction of invariant mass of top quark decay products
  - data compared to MC simulations with different input values of m_t
- Precision (~ 500 MeV) improved with combined measurements → 0.28% with ATLAS & CMS combination

Dominant syst. unc.: jet energy scale calibration, b-tagging and modeling



CMS-PAS-TOP-19-009

2016 data

- Mass from **single top t-channel** in lepton + jets events
  - multivariate technique to increase signal purity
  - simultaneous ML fit to $\ln(m_t)$ distributions
  - combined and separate measurement of top and antitop quark mass → **stringent test of CPT invariance:** no violation observed

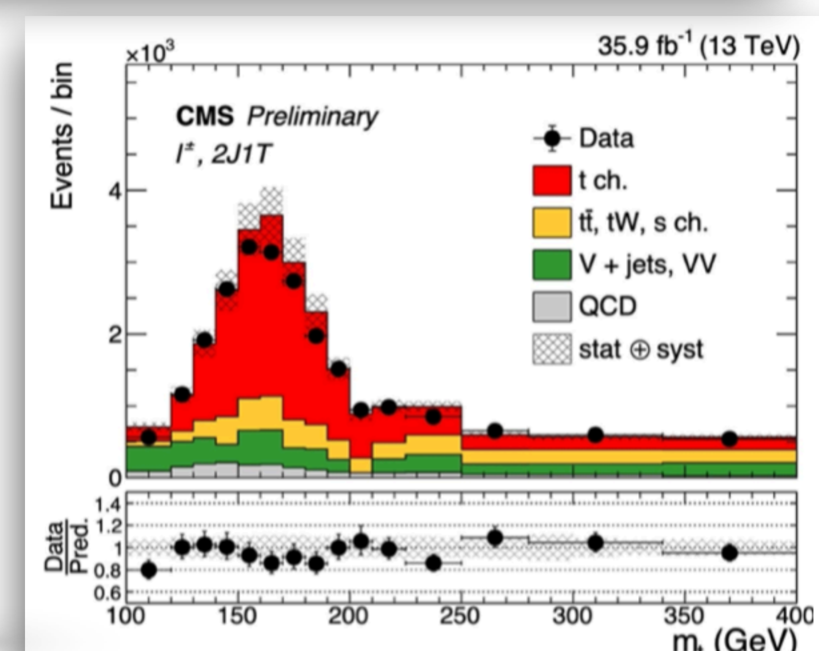
$$m_t = 172.13 \pm 0.32\,(\text{stat} + \text{prof})\,^{+0.69}_{-0.70}\,(\text{syst})\ \text{GeV} = 172.13^{+0.76}_{-0.77}\ \text{GeV}$$

$$\frac{\Delta m_t}{m_t} < 0.5\ \%$$

$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.995 \pm 0.004\,(\text{stat} + \text{prof})\,^{+0.002}_{-0.004}\,(\text{syst}) = 0.995^{+0.005}_{-0.006}$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83 \pm 0.69\,(\text{stat} + \text{prof})\,^{+0.35}_{-0.74}\,(\text{syst})\ \text{GeV} = 0.83^{+0.77}_{-1.01}\ \text{GeV}$$

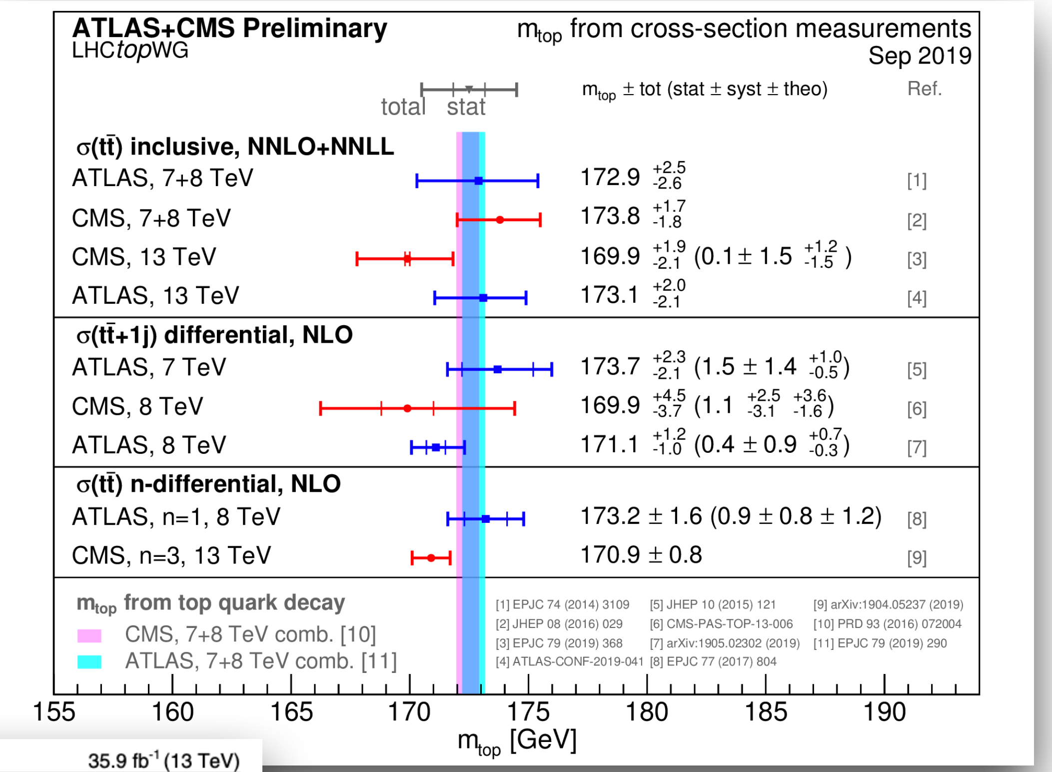
First R_{m_t} and Δm_t measurement in single top events



Top mass: indirect measurements

- From inclusive/differential cross-sections in a well defined renormalization scheme (pole, MS)

Dominant syst. unc.:
PDFs and higher order corrections



- Simultaneous measurement of α_S, m_t^{pole}, PDFs at NLO from **triple-differential cross sections** in dilepton channel

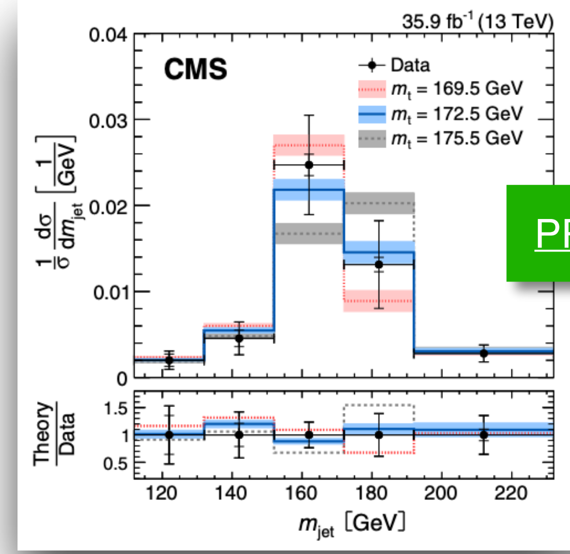
$$m_t^{pole} = 170.5 \pm 0.8\,\text{GeV}$$

EPJC 80 (2020) 658

Most precise determination of m_t^{pole}!

$$\frac{\Delta m_t}{m_t} < 0.5\,\%$$

- Measurement of hadronic decays of **boosted top quarks** in lepton+jets channel:
  - m_t extracted from normalized $t\bar{t}$ cross section as function of m_{jet}: $m_t = 172.6 \pm 2.5\,\text{GeV}$

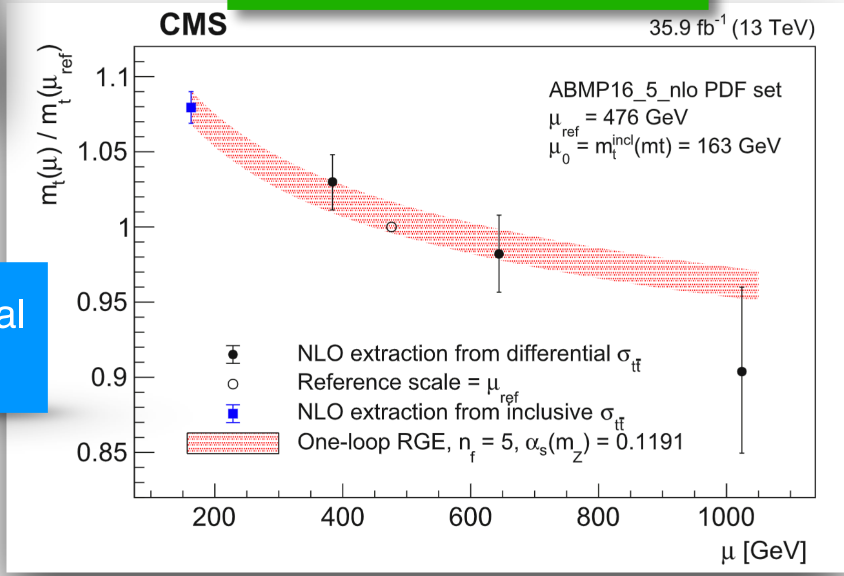


PRL 124 (2020) 202001

PLB 803 (2020) 135263

- **Running of top quark mass**:
  - extracted by comparing NLO predictions to differential cross section measured vs $m_{t\bar{t}}$ in $e\mu$ channel
  - in agreement with prediction of QCD renormalization group equations (1 loop RGE)
  - no-running scenario excluded at > 95% C.L.

First experimental investigation!



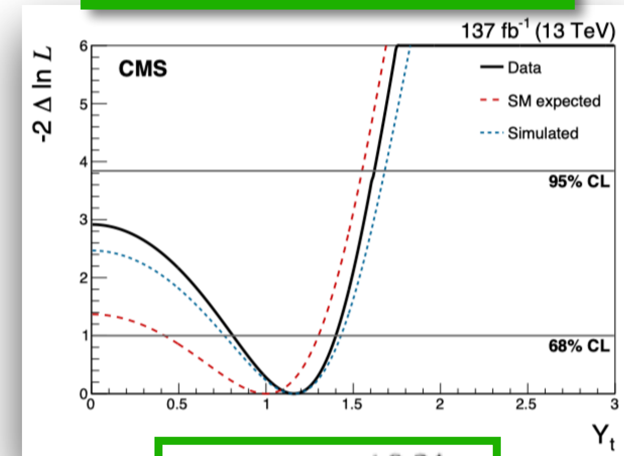
Top quark properties

- First analysis to measure **Yukawa coupling** with top pair production in lepton+jets channel (2016 data):
  - results in agreement with Full Run2 data measurement in dilepton channel

PRD 100 (2019) 072007

Best fit Y_t		95% CL upper limit	
Expected	Observed	Expected	Observed
$1.00^{+0.35}_{-0.48}$	$1.07^{+0.34}_{-0.43}$	<1.62	<1.67

PRD 102 (2020) 092013



$Y_t = 1.16^{+0.24}_{-0.36}$

68% CI: [0.80, 1.40]

95% CI: [0.00, 1.62]

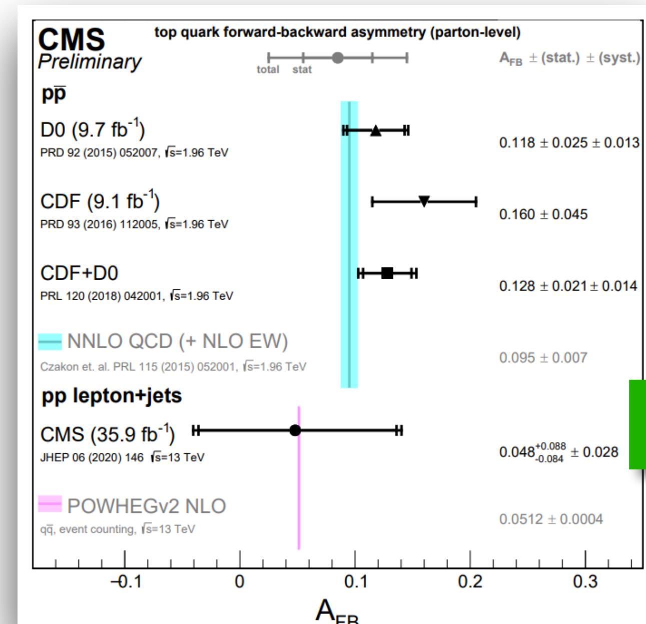
- First direct model-independent measurement of **CKM elements** in single top t-channel events

$|V_{tb}| > 0.970$

$|V_{td}|^2 + |V_{ts}|^2 < 0.057$

PLB 808 (2020) 135609

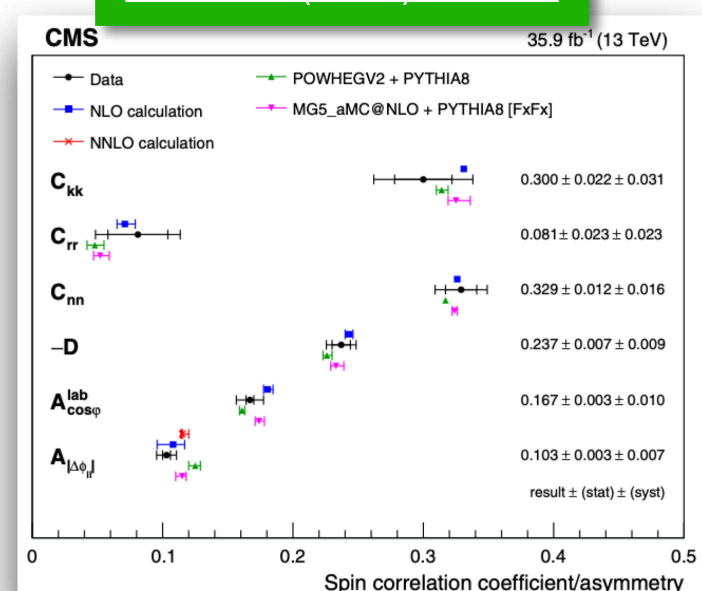
- First measurement @LHC of **Forward-Backward asymmetry**:
  - values consistent with SM expectations and in good agreement with previous measurements

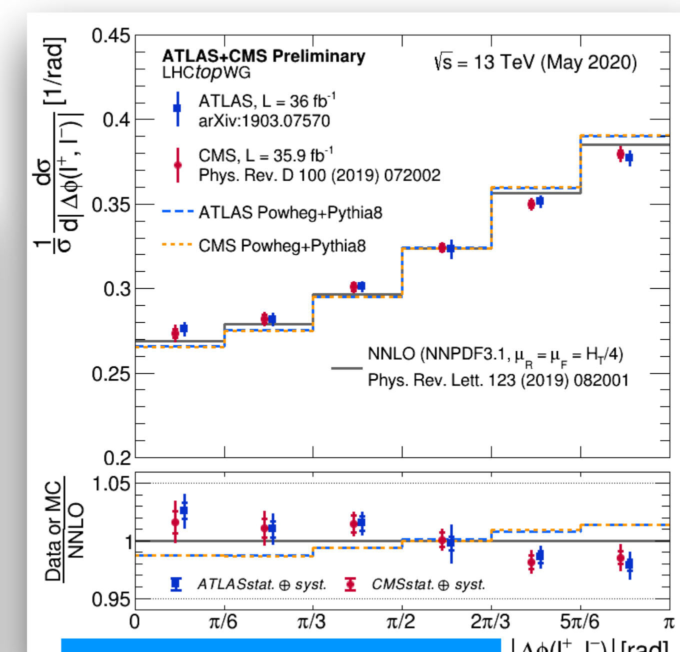


JHEP 06 (2020) 146

- **Spin correlations**:
  - all distributions and extracted parameters in close agreement with SM predictions
  - tension between data and predictions in $\Delta\phi$
  - very good agreement between ATLAS and CMS data and main MC predictions

PRD 100 (2019) 072002





First ATLAS+CMS comparison @13 TeV within *LHCtopWG*

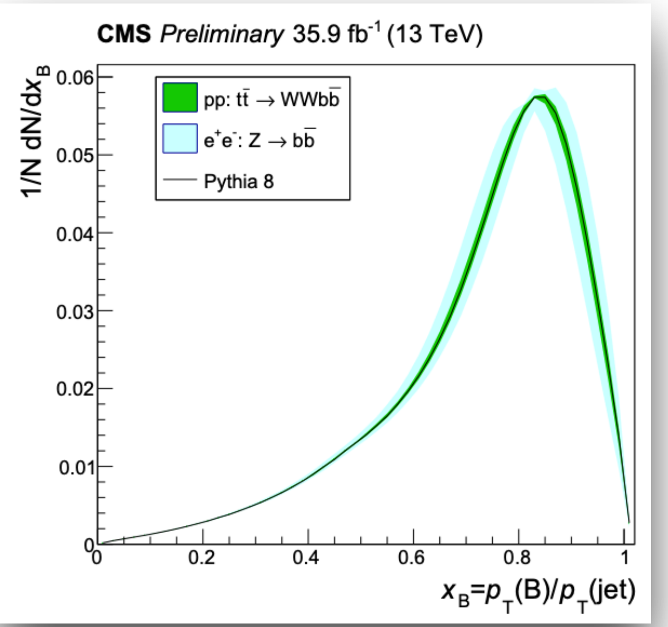
Other top quark properties

CMS-PAS-TOP-18-012 **2016 data**

- Measurement of **b-fragmentation** shape parameter in lepton + jets and dilepton decay channels
- Simultaneous fit to J/Ψ, muon tagged and un-tagged D^0 samples
- Extraction of r_b from template fit to fragmentation proxy distributions x_b of parent b quark:

$$r_b = 0.858 \pm 0.037\,(\text{stat}) \pm 0.031\,(\text{syst})$$

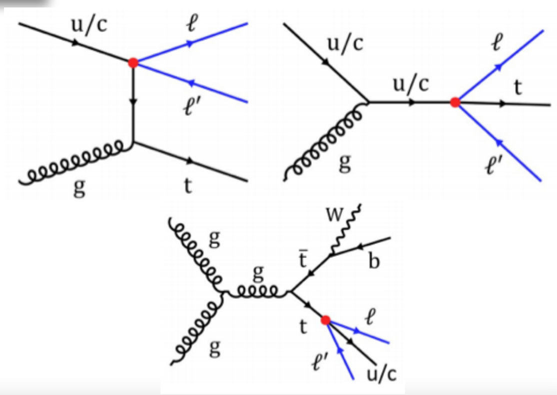
- Results compared with the ones obtained at the Z pole in e^+e^- data:
  - agreement between results
  - significant improvement in experimental precision



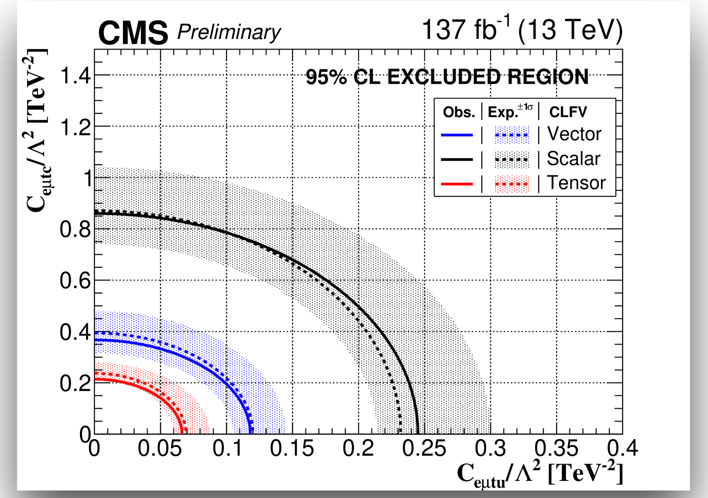
First measurement in $t\bar{t}$ events at LHC!

CMS-PAS-TOP-19-006 **Full Run2 data**

- Search for **charged lepton flavor violation** in oppositely charged $e\mu$ final states with up and charm quarks



- CLFV interactions parametrized with **EFT approach**
- Used BDT to maximize signal sensitivity

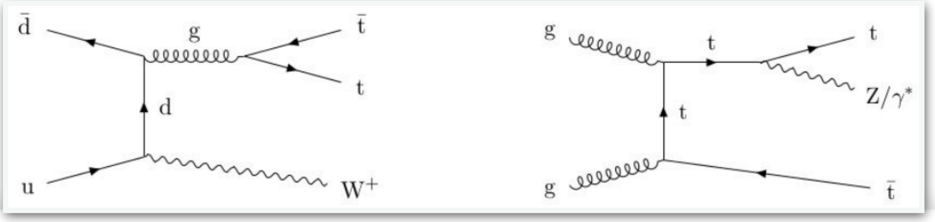


Vertex	Int. type	Cross section [fb] Exp.	Cross section [fb] Obs.	$C_{e\mu tq}/\Lambda^2$ [TeV^{-2}] Exp.	$C_{e\mu tq}/\Lambda^2$ [TeV^{-2}] Obs.	$\mathcal{B} \times 10^{-6}$ Exp.	$\mathcal{B} \times 10^{-6}$ Obs.
	Vector	7.02	6.78	0.12	0.12	0.14	0.13
		[5.33,10.21]		[0.10,0.14]		[0.11,0.20]	
		(3.39,12.33)		(0.08,0.16)		(0.07,0.24)	
$e\mu tu$	Scalar	5.63	6.25	0.23	0.24	0.06	0.07
		[4.79,9.38]		[0.21,0.33]		[0.05,0.11]	
		(3.75,12.12)		(0.19,0.34)		(0.04,0.14)	
	Tensor	10.01	9.18	0.07	0.06	0.27	0.25
		[7.51,15.90]		[0.06,0.09]		[0.20,0.43]	
		(4.59,19.24)		(0.04,0.09)		(0.12,0.52)	
	Vector	11.21	9.73	0.39	0.37	1.49	1.31
		[7.21,16.63]		[0.32,0.48]		[0.96,2.21]	
		(4.33,21.61)		(0.24,0.55)		(0.58,2.89)	
$e\mu tc$	Scalar	9.11	8.88	0.87	0.86	0.91	0.89
		[6.58,13.10]		[0.74,1.04]		[0.65,1.31]	
		(3.54,17.41)		(0.54,1.21)		(0.35,1.74)	
	Tensor	21.02	17.22	0.24	0.21	3.16	2.59
		[16.52,29.21]		[0.21,0.28]		[2.48,4.41]	
		(10.51,42.02)		(0.17,0.33)		(1.58,6.32)	

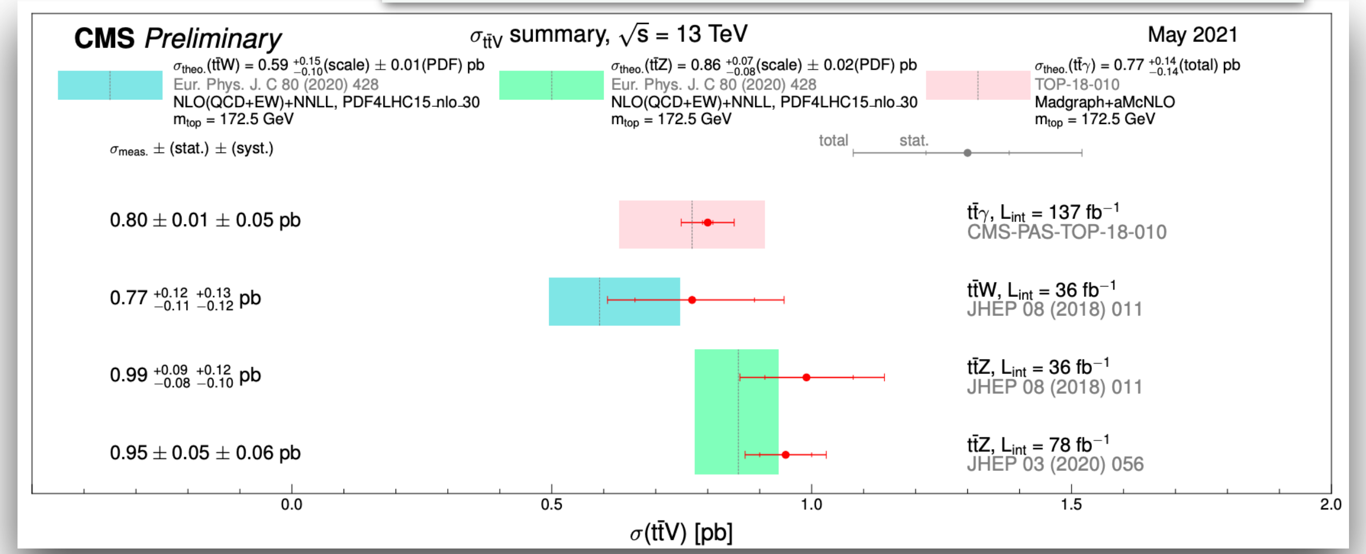
Most stringent limits to date on all couplings

Top quark rare production

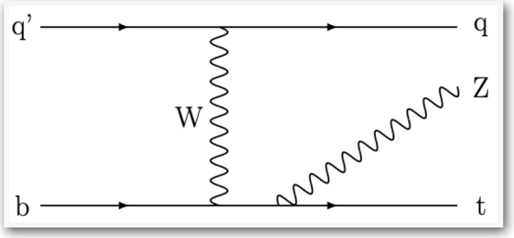
- Rare top production modes become fully accessible with Run2 data



- **ttW/ttZ/ttγ production**:
  - among the most massive signatures that can be studied with high precision
  - important backgrounds for searches and measurements such as ttH in multilepton final states
  - ttZ production: JHEP 03 (2020) 056
    - most sensitive process for directly measuring the coupling of the top quark to the Z boson

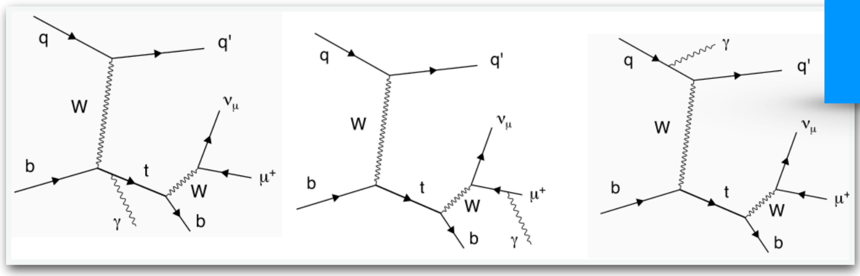


- **tZq production**: PRL 122 (2019) 132003
  - sensitive to top-Z and triple gauge boson WWZ couplings

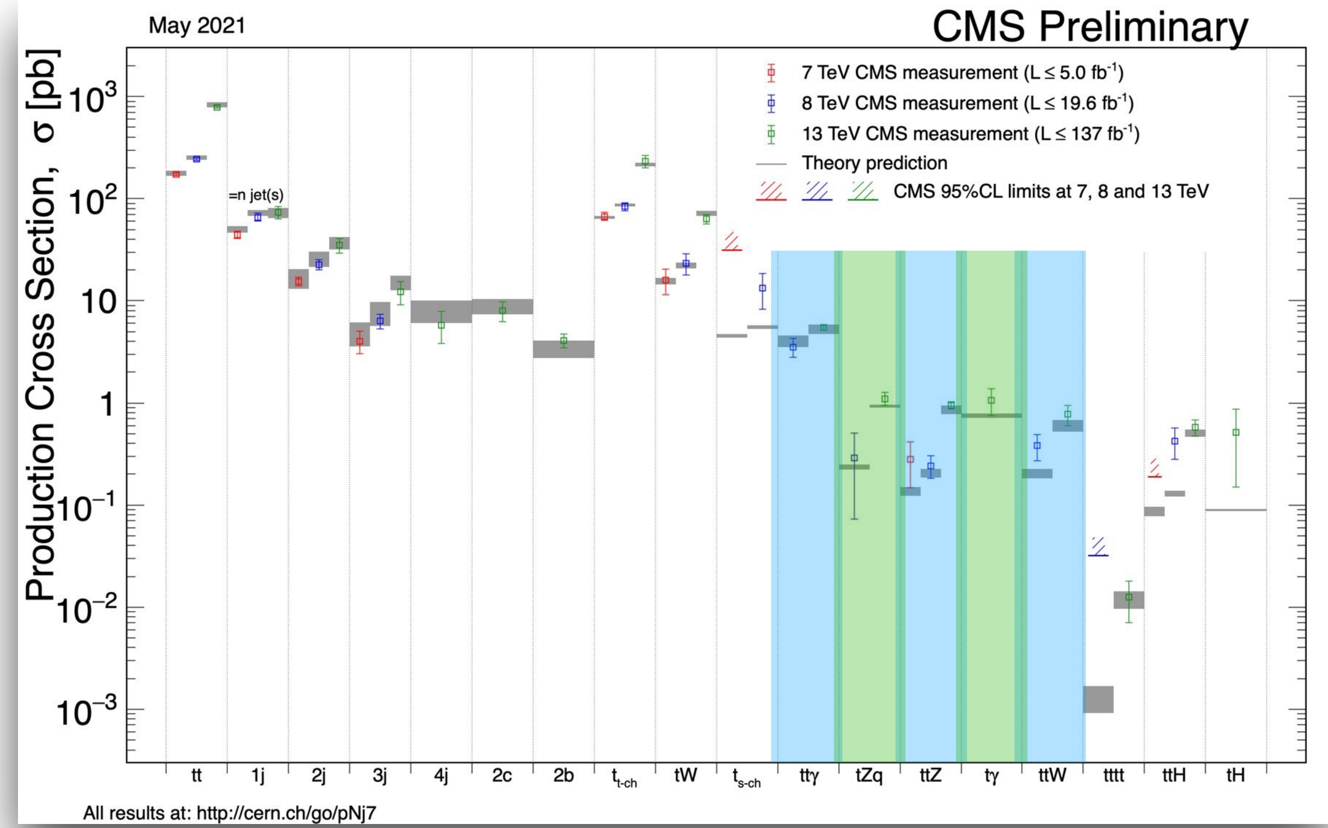


PRL 121 (2018) 221802

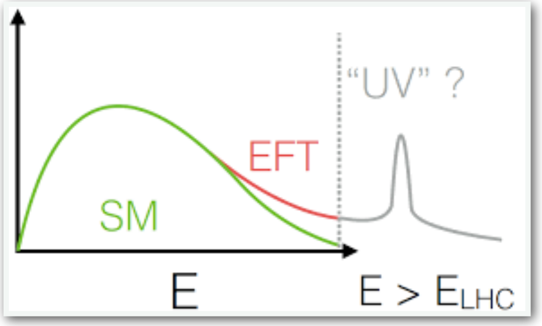
- **tγq production**:
  - sensitive to top quark charge and top quark electric and magnetic dipole moments



First evidence of this process !



EFT in rare processes



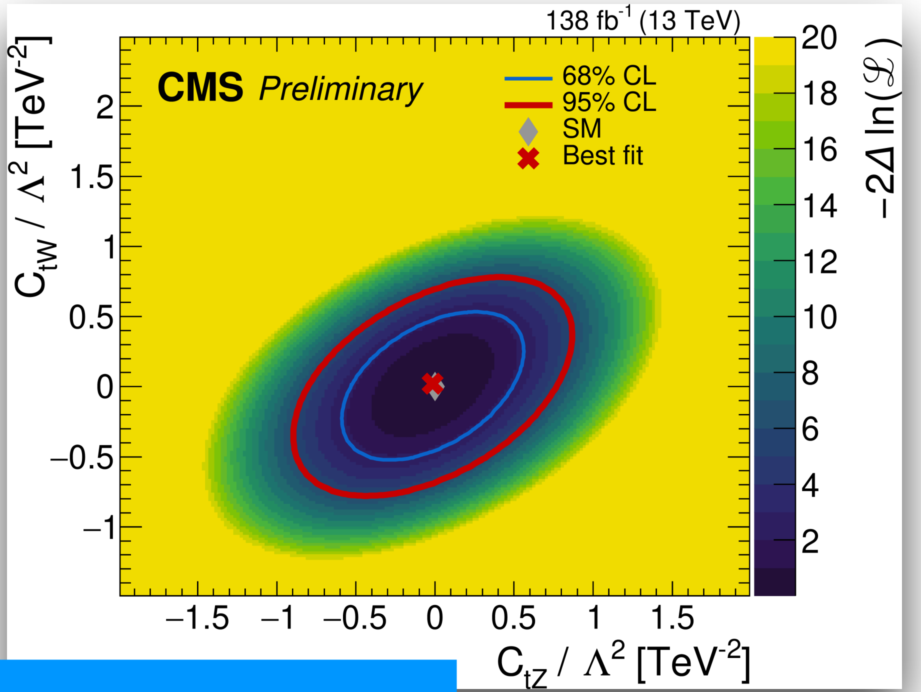
- **EFT framework**: model-independent and coherent interpretation of potential deviations in interactions between SM fields
  - new physics characterized by BSM energy scale (>> E_{LHC})
  - SM Lagrangian expanded with higher-order operators
  - Wilson coefficients describe interaction strengths of operators

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_x \frac{C_x}{\Lambda^2} O_x + \dots$$

CMS-PAS-TOP-21-001

Full Run2 data

- **Constrain top-electroweak EFT operators** with ttZ and tZq production in multileptons (3l and 4l) final states
  - distributions used for signal extraction parametrized in terms of Wilson coefficients
  - use novel **ML techniques** to improve sensitivity to WCs
  - single and global WCs fit in signal and control regions
  - confidence intervals computed at 95% C.L.



	Other WCs fixed to SM		5D fit	
	Expected	Observed	Expected	Observed
WC / Λ^2 [TeV^{-2}]	95% CL confidence intervals			
c_{tZ}	$[-0.97, 0.96]$	$[-0.76, 0.71]$	$[-1.24, 1.17]$	$[-0.85, 0.76]$
c_{tW}	$[-0.76, 0.74]$	$[-0.52, 0.52]$	$[-0.96, 0.93]$	$[-0.69, 0.70]$
$c^3_{\varphi Q}$	$[-1.39, 1.25]$	$[-1.10, 1.41]$	$[-1.91, 1.36]$	$[-1.26, 1.43]$
$c^-_{\varphi Q}$	$[-2.86, 2.33]$	$[-3.00, 2.29]$	$[-6.06, 14.09]$	$[-7.09, 14.76]$
$c_{\varphi t}$	$[-3.70, 3.71]$	$[-21.65, -14.61] \cup [-2.06, 2.69]$	$[-16.18, 10.46]$	$[-19.15, 10.34]$

Best direct constraints to date from multilepton final states on several WCs

Rare processes: tZq, $t\bar{t}\gamma$

CMS-PAS-TOP-20-010

Full Run2 data

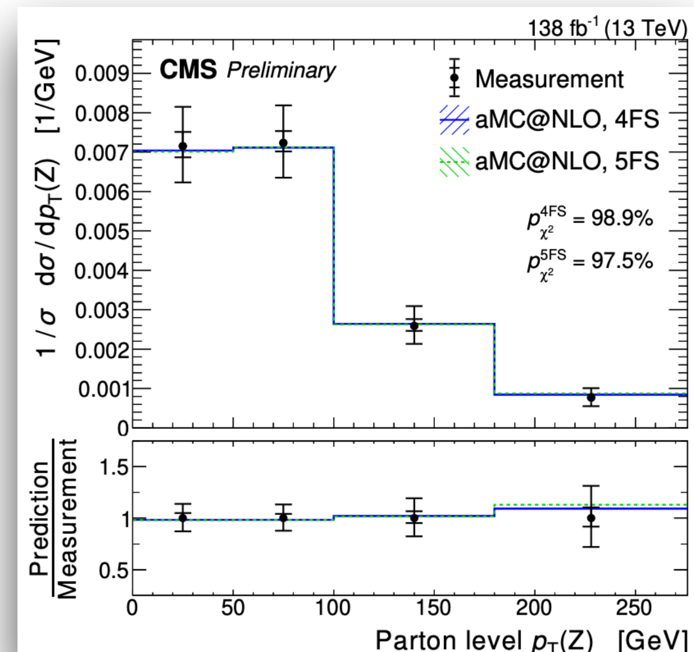
- **Inclusive and differential tZq** cross section in leptons+jets channel
- Simultaneous fit to BDT outputs in multiple regions:

$$\sigma_{tZq} = 87.9^{+7.5}_{-7.3}\,(\text{stat.})^{+7.3}_{-6.0}\,(\text{syst.})\ \text{fb}$$

Most precise measurement to date!

  - result consistent with SM prediction

- Good agreement in differential measurement of t/Z observables and angular distributions



- Spin asymmetry measurement in agreement with SM:

$$A_l = 0.58^{+0.15}_{-0.16}\,(\text{stat.}) \pm 0.06\,(\text{syst.})$$

First differential measurement!

Dominant syst. unc.:
bkg normalization, signal renormalization and factorization, b-tagging

CMS-PAS-TOP-18-010

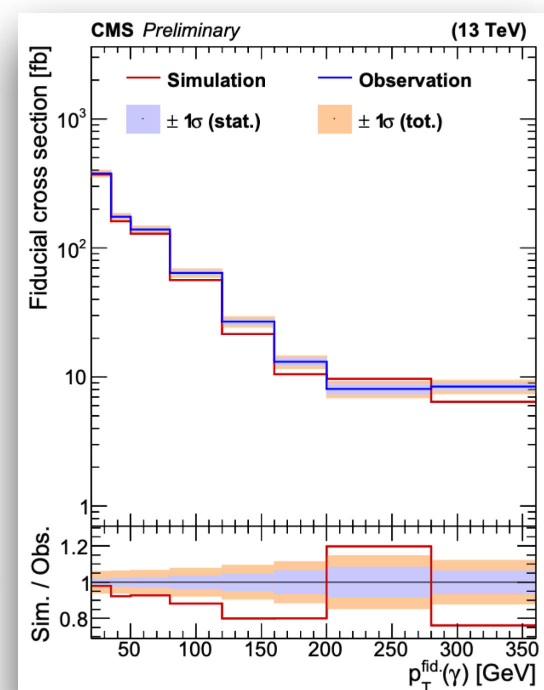
Full Run2 data

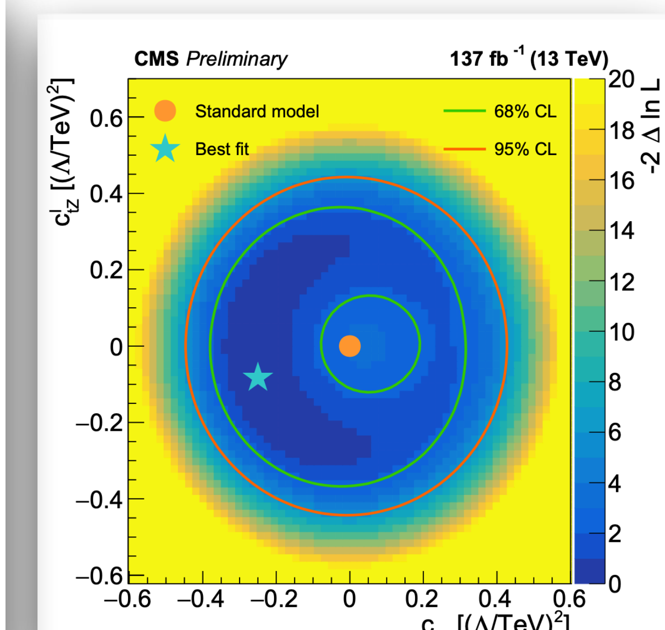
- **Inclusive and differential $t\bar{t}\gamma$** cross section in leptons+jets channel
- Simultaneous likelihood fits in 12 SRs and 34 CRs

$$\sigma(t\bar{t}\gamma) = 800 \pm 46\,(\text{syst.}) \pm 7\,(\text{stat.})\ \text{fb}$$

Dominant syst. unc.:
ttγ modeling, background estimation, JES

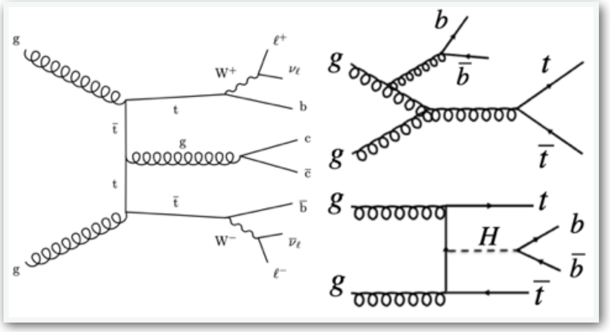
- Results in good agreement with NLO predictions
- Constrain 2 EFT operators impacting t-γ/Z vertices

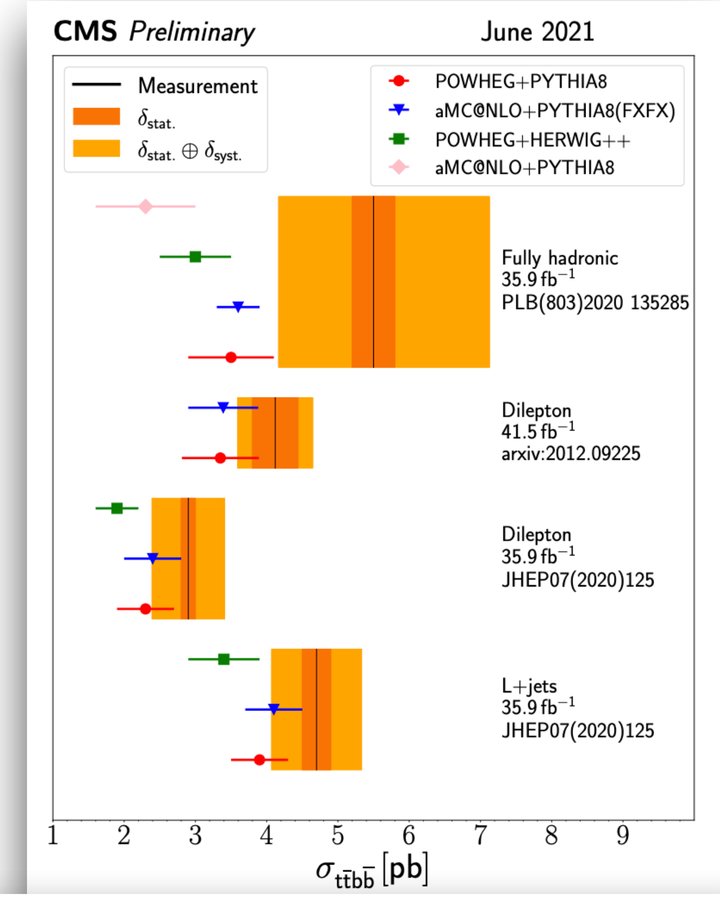




Top quark rare production

- Rare top production modes become fully accessible with Run2 data
- **ttjj, ttbb, ttcc**:
  - important background for ttH and BSM events
  - precise measurements needed to improve tt+jets MC simulation
  - NLO calculations are affected by large uncertainties associated to μ_R/μ_F scales



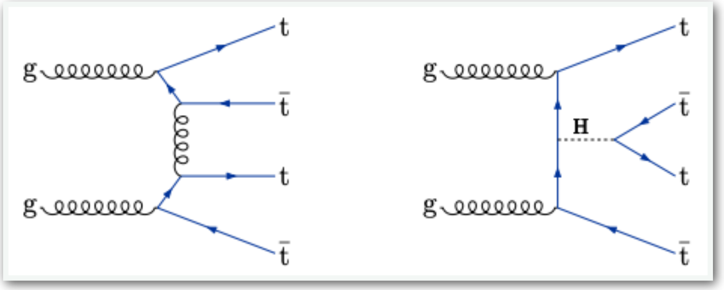


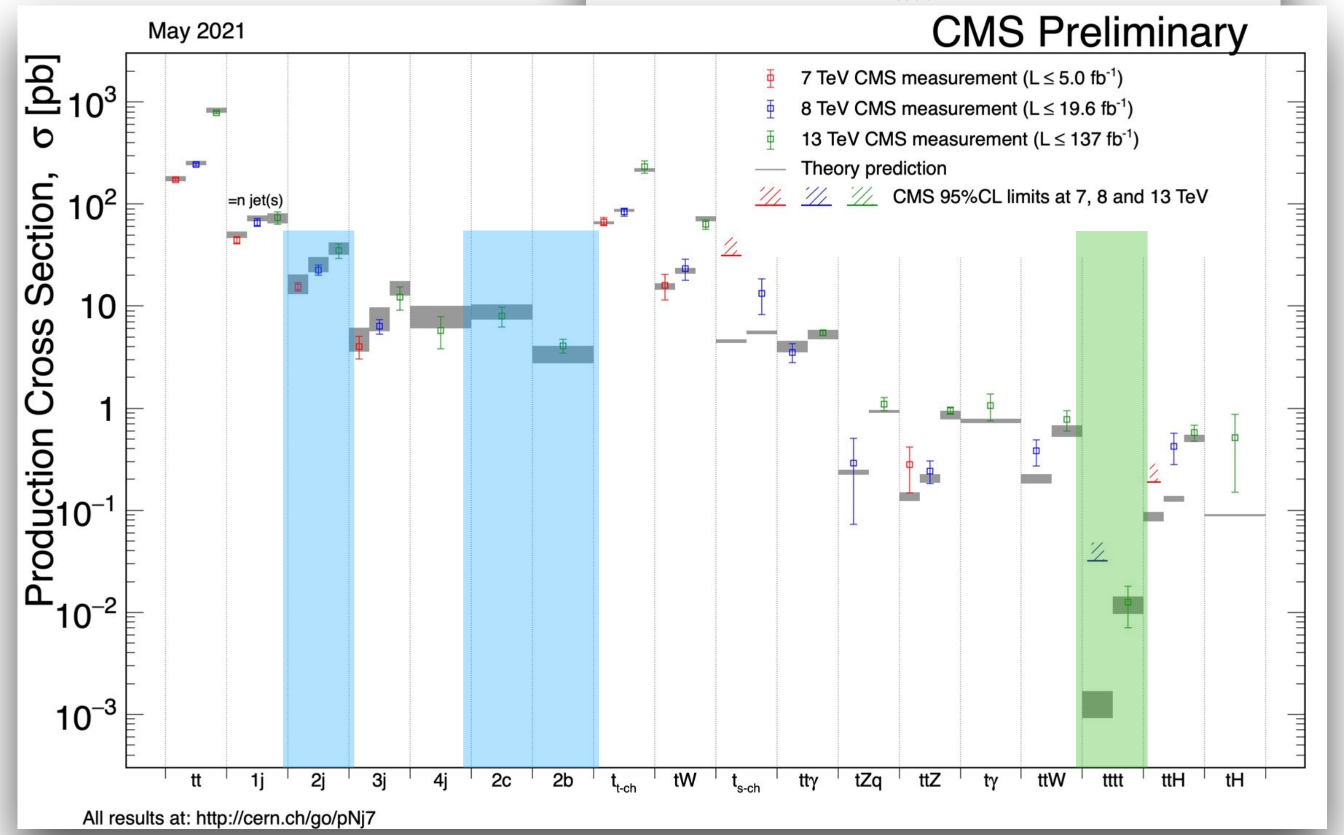
EPJC 80 (2020) 75

JHEP 11 (2019) 082

- **tttt**:
  - constrain t-H Yukawa coupling (but less precisely than ttH)
  - not observed yet, but expected in SM
  - very tiny cross section at NLO QCD + NLO QED at 13 TeV:

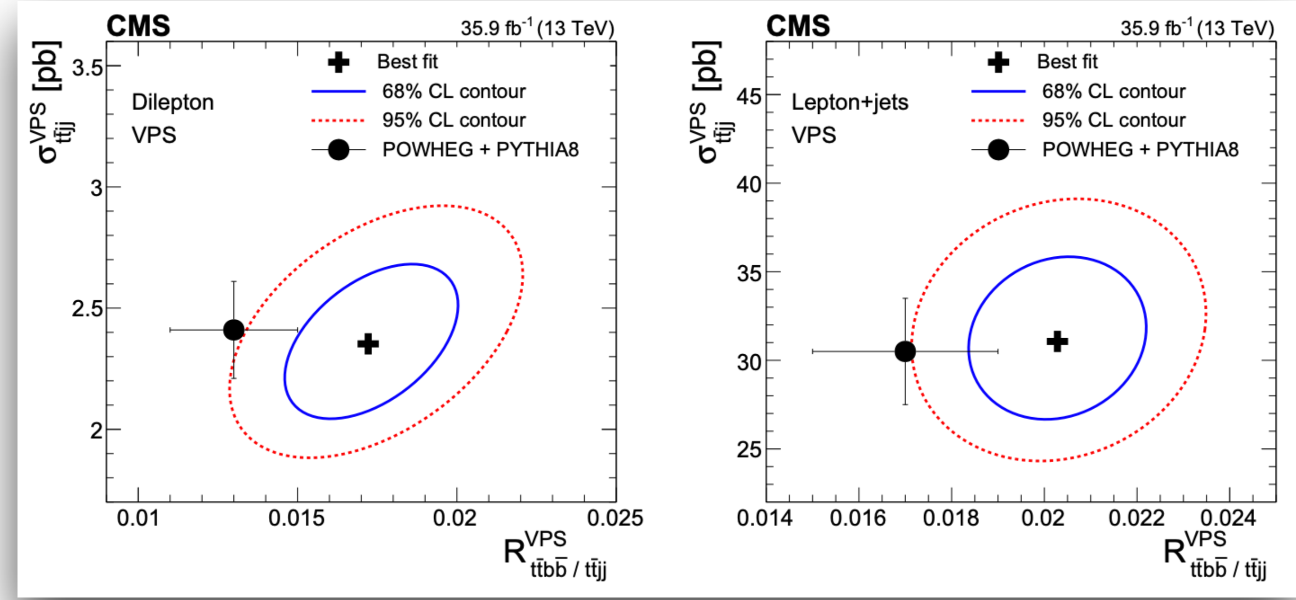
$$\sigma(tttt) = 11.97\,\text{fb}$$





ttjj+ttbb+ttcc production

- 2 separate analyses to measure **ttbb cross sections:**
  - dilepton/leptons+jets — JHEP 07 (2020) 125 — **2016 data**
  - all-hadronic — PLB 803 (2020) 135285 — **2016 data**



- **Simultaneous measurement of $\sigma(t\bar{t}+c\bar{c})$, $\sigma(t\bar{t}+b\bar{b})$,** $\sigma(t\bar{t}+\mathrm{LL})$ and $R_{c/b} = \sigma(t\bar{t}+c\bar{c}/b\bar{b})\big/\sigma(t\bar{t}+jj)$ in fiducial and full phase space in dilepton events:
  - **c-tagging** exploiting new c-jet tagger
  - ML techniques with template fit to 2D distribution

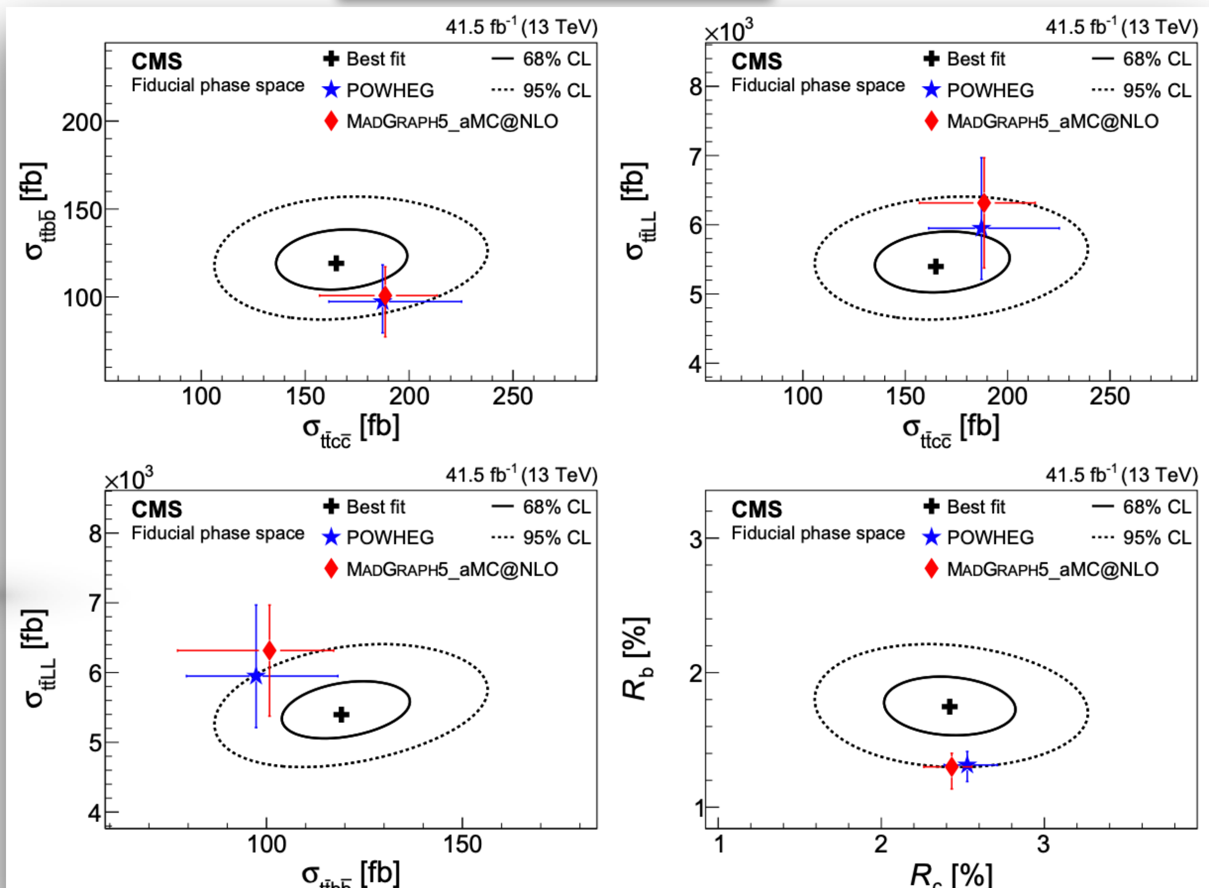
CMS-PAS-TOP-20-003 submitted to PLB — **2017 data**

	Result	POWHEG	MadGraph5_aMC@NLO
Fiducial phase space			
$\sigma_{t\bar{t}c\bar{c}}$ [pb]	$0.165 \pm 0.023 \pm 0.025$	0.187 ± 0.038	0.189 ± 0.032
$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$0.119 \pm 0.010 \pm 0.015$	0.097 ± 0.021	0.101 ± 0.023
$\sigma_{t\bar{t}LL}$ [pb]	$5.40 \pm 0.11 \pm 0.45$	5.95 ± 1.02	6.32 ± 0.94
R_c [%]	$2.42 \pm 0.32 \pm 0.29$	2.53 ± 0.18	2.43 ± 0.17
R_b [%]	$1.75 \pm 0.14 \pm 0.18$	1.31 ± 0.12	1.30 ± 0.16
Full phase space			
$\sigma_{t\bar{t}c\bar{c}}$ [pb]	$8.0 \pm 1.1 \pm 1.3$	9.1 ± 1.8	8.9 ± 1.5
$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$4.09 \pm 0.34 \pm 0.55$	3.34 ± 0.72	3.39 ± 0.66
$\sigma_{t\bar{t}LL}$ [pb]	$231 \pm 5 \pm 21$	255 ± 43	261 ± 37
R_c [%]	$2.69 \pm 0.36 \pm 0.32$	2.81 ± 0.20	2.72 ± 0.19
R_b [%]	$1.37 \pm 0.11 \pm 0.14$	1.03 ± 0.08	1.03 ± 0.09

~19% ($\sigma_{t\bar{t}c\bar{c}}$)

~17% (R_c)

First measurement of ttcc !



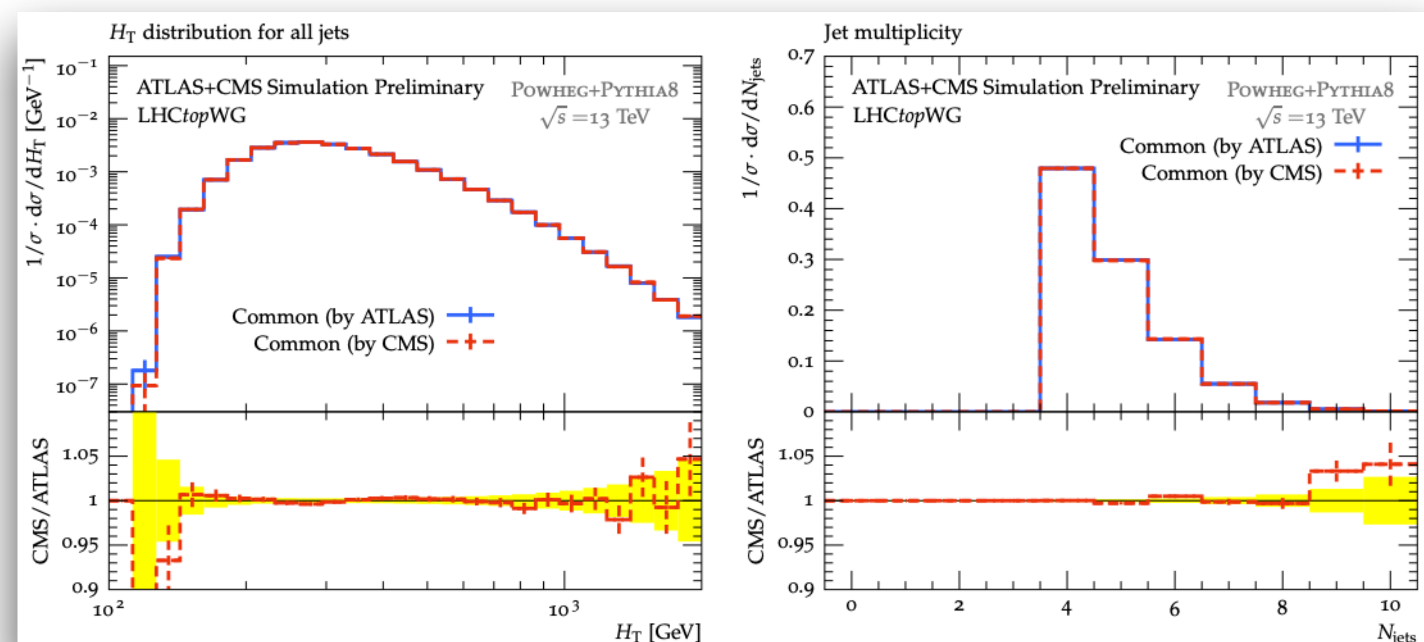
Dominant syst. unc.:
JES, c-tagging calibration, renormalization and factorization scales in ME, matching ME-PS (hdamp)

ATLAS-CMS common MC

CMS-NOTE-2021-005

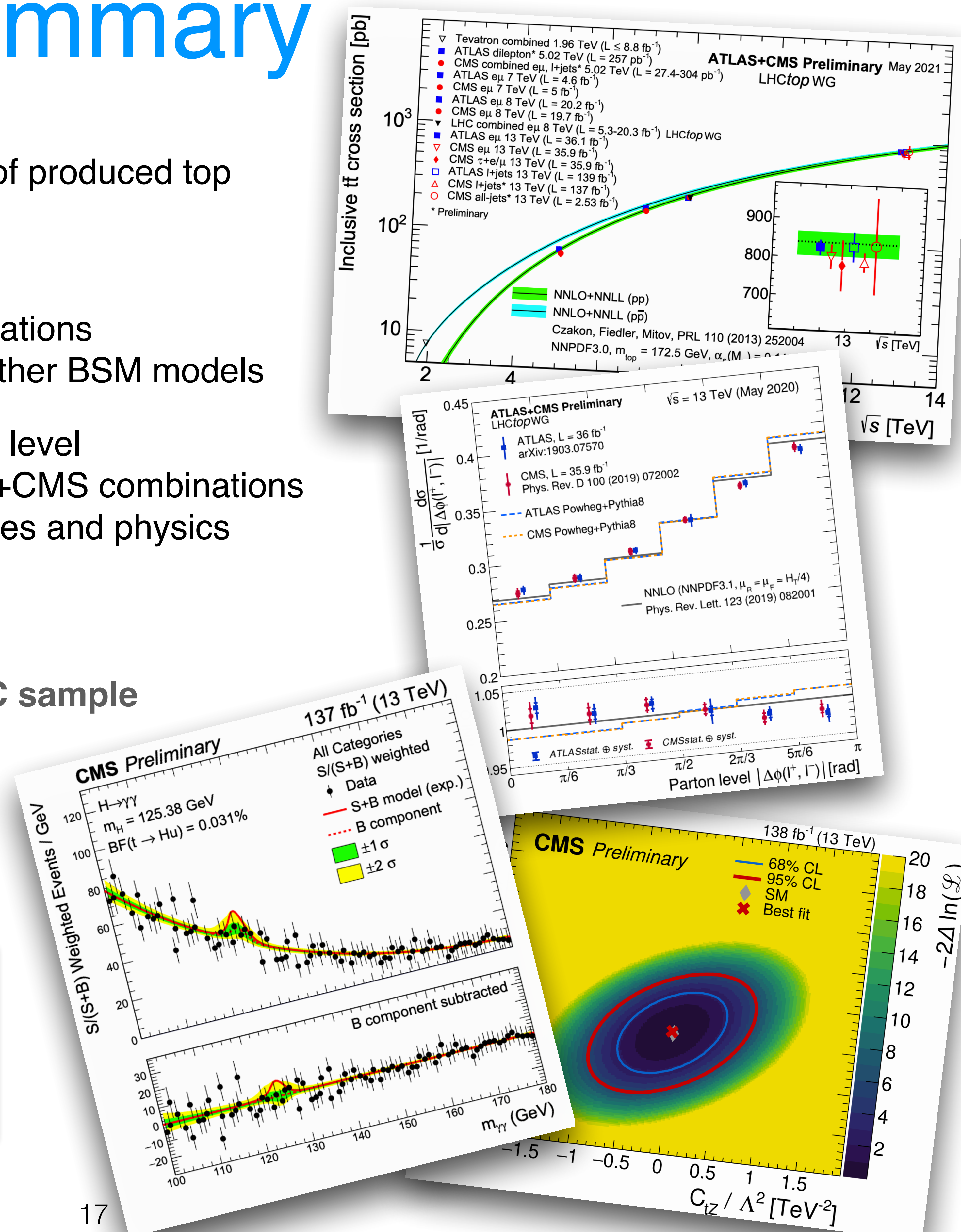
- ATLAS and CMS use different nominal MC samples: **POWHEG-BOX (hvq) + Pythia8 with different parameters**
  - understand similarities and differences can be crucial to reduce modeling systematics in analysis combination
  - a common $t\bar{t}$ MC sample would make combinations and comparisons easier
- **Identified a first set of common settings:**
  - average of ATLAS and CMS settings
  - Monash tune
- **First common sample** with 10M inclusive events **successfully produced** by both experiments
  - great agreement between samples produced in separate frameworks
- Discussion ongoing for *real* common sample:
  - decide new settings to have **sample tuned on data**

Setting name	Setting description	CMS default	ATLAS default	Common Proposal
Powheg				
qmass	top-quark mass [GeV]	172.5	172.5	172.5
twidth	top-quark width [GeV]	1.31	1.32	1.315
hdamp	first emission damping parameter [GeV]	237.8775	258.75	250
wmass	$W^{\pm}$ mass [GeV]	80.4	80.3999	80.4
wwidth	$W^{\pm}$ width [GeV]	2.141	2.085	2.11
bmass	b-quark mass [GeV]	4.8	4.95	4.875
Pythia 8				
	Pythia 8 version	v240	v230	v240 (CMS) v244 (ATLAS)
	Tune	CP5	A14	Monash
PDF:pSet	LHAPDF6 parton densities to be used for proton beams	NNPDF31_nnlo _as_0118	NNPDF23_lo _as_0130_qed	NNPDF23_lo _as_0130_qed
TimeShower:alphaSvalue	Value of α_s at Z mass scale for Final State Radiation	0.118	0.127	0.1365
SpaceShower:alphaSvalue	Value of α_s at Z mass scale for Initial State Radiation	0.118	0.127	0.1365
MPI:alphaSvalue	Value of α_s at Z mass scale for Multi-Parton Interaction	0.118	0.126	0.130
MPI:pT0ref	Reference p_T scale for regularizing soft QCD emissions	1.41	2.09	2.28
ColourReconnection:range	Parameter controlling colour reconnection probability	5.176	1.71	1.80



Summary

- LHC Run1 and Run2 provided huge number of produced top quark events
- Several measurements with **Run2 data**
  - confirm good agreements with SM expectations
  - allow to explore parameters of EFT and other BSM models
- **Increased precision** up to NNLO+NLO EWK level
  - allowed by large statistics and via ATLAS+CMS combinations
  - better understanding of top quark properties and physics modeling
  - constraints on new physics
- Production of **first common ATLAS-CMS MC sample**
  - new version tuned on data coming soon!



Focus only on a selection of recent measurements.. for more results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

BACKUP

tt differential in l+jets

CMS-PAS-TOP-20-001

Full Run2 data

- High precision measurements of differential and double differential cross sections of t¯t production in e/mu + jets (2 b-tagged jets) channel
  - results at both parton and particle level
  - both resolved and boosted regimes
- Boosted top identified with NN approach:
  - NN to discriminate leptonically decaying top from bkg candidates
  - NN with 21 input variables to identify hadronically decaying top
- Most of the predictions are in good agreement with the measurement
- Ratio |y(¯t)|/|y(t)| calculated from double differential cross section |y(t)| vs |y(¯t)| taking into account bin-by-bin correlations:
  - no significant observation of a charge asymmetry is observed
- Precise inclusive t¯t production cross section obtained from integration of differential distributions:

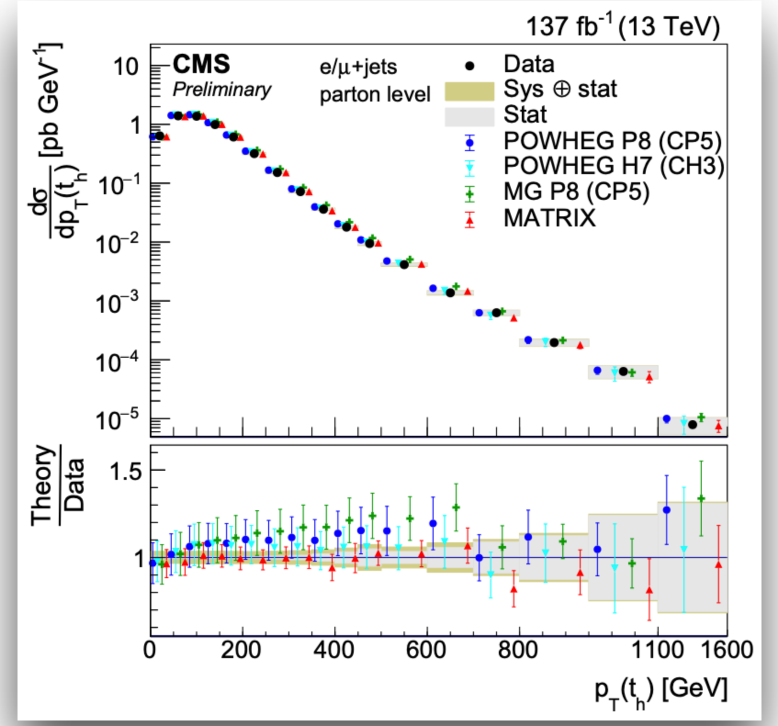
$$\sigma_{e/\mu+jets} = 227.6 \pm 6.8\,\mathrm{pb}$$

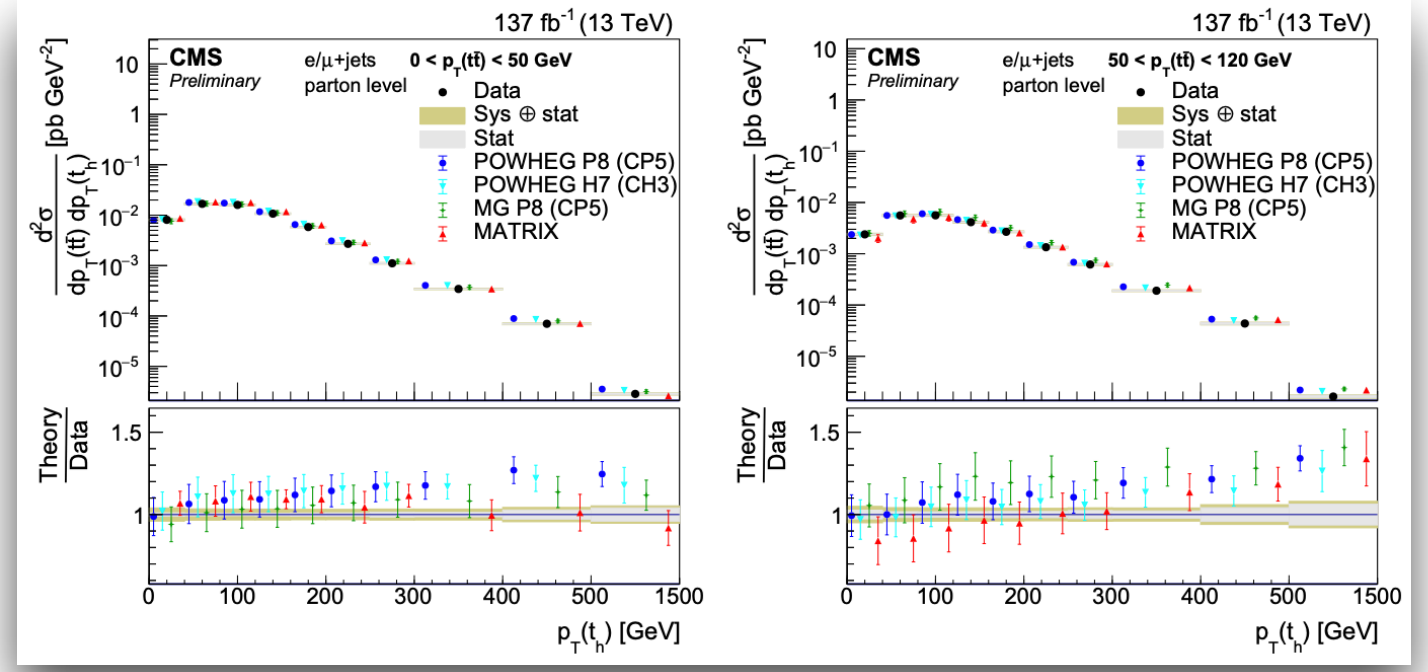
- With a branching fraction of 28.77 ± 0.32% to e/μ+jets the total tt production cross section becomes:

$$\sigma_{tot} = 791 \pm 25\,\mathrm{pb}$$

  - in good agreement with the SM expectation

$$\sigma_{SM} = 832^{+40}_{-46}\,\mathrm{pb}$$



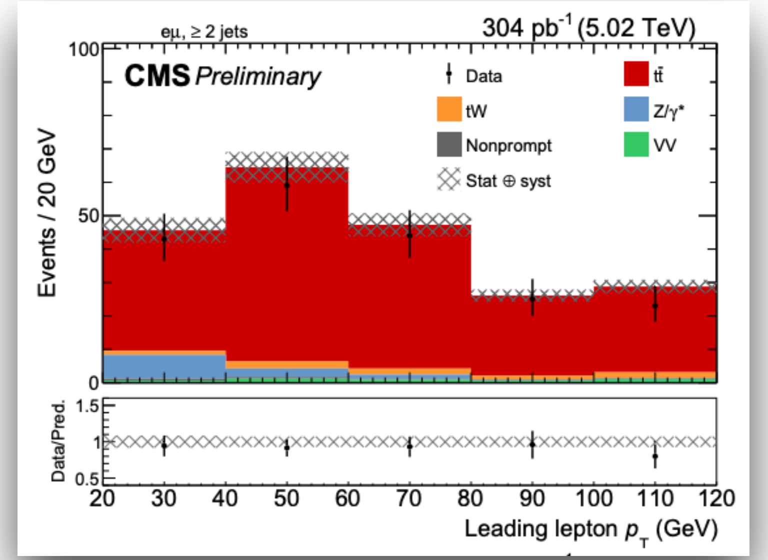


$t\bar{t}$ inclusive @5.02 TeV

CMS-PAS-TOP-20-004

Small dataset @5.02 TeV

- Measurement of $t\bar{t}$ production cross section at 5.02 TeV using ~300 pb-1 recorded in 2017
  - sensitive to gluon PDFs and top quark mass
- Cross section extracted by counting experiment in dilepton (emu) channel, in a region with high tt purity
- Already measured in 2015 with 27.4 pb-1:
  - at first only $e\mu$ channel (TOP-16-015): ~25% uncertainty
  - then $e\mu$, $\mu\mu$, e/μ+jets combination (TOP-16-023): total uncertainty of ~12%



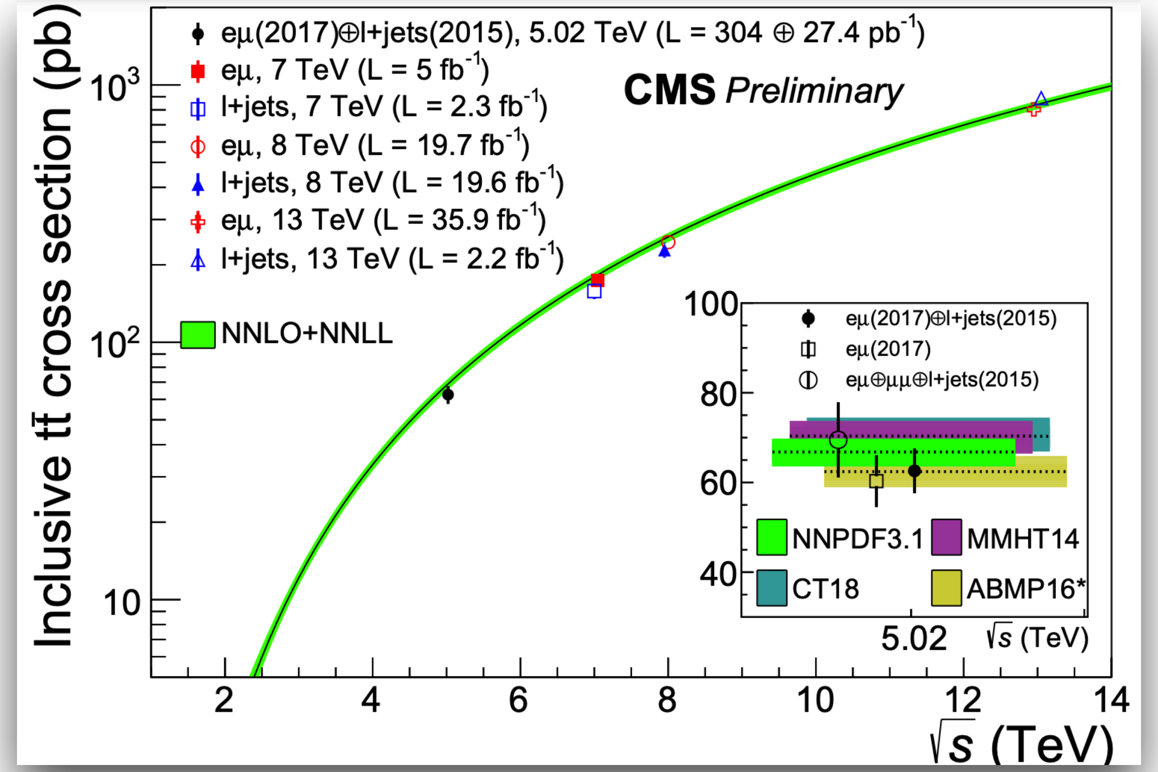
- Current measurement improves precision of previous CMS measurements at 5.02 TeV:
  - total uncertainty of ~ 9.1%

$$\sigma_{t\bar{t}} = 60.3 \pm 5.0\ (\text{stat}) \pm 2.8\ (\text{syst}) \pm 0.9\ (\text{lumi})\ \text{pb} = 60.3 \pm 5.5\ (\text{tot})\ \text{pb}.$$

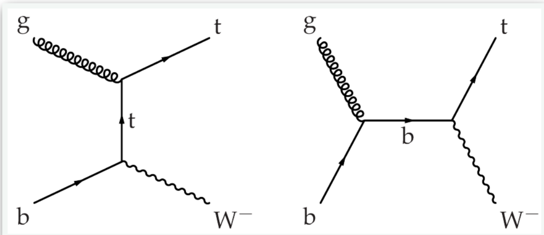
(prediction : $\sigma_{t\bar{t}}^{\text{NNLO}} = 66.8^{+1.9}_{-2.3}(\text{scale}) \pm 1.7(\text{PDF})^{+1.4}_{-1.3}(\alpha_S)\ \text{pb}$)
using NNPDF3.1

- A combination with the previous measurement in the l+jets channel is performed:
  - total uncertainty decreased to 7.9%

$$\sigma_{t\bar{t}} = 62.6 \pm 4.1\ (\text{stat}) \pm 3.0\ (\text{syst+lumi})\ \text{pb}$$



Single top: tW channel



CMS-PAS-TOP-20-002

2016 data

- Inclusive cross section in lepton+jets channel
- Data-driven background estimation
- BDT used to discriminate tW from leading $t\bar{t}$ background
- Binned likelihood fit performed on BDT discriminants:
  - final result calculated using all regions (with different Njets) for both e/mu channels
  - fit checked in each region individually and in combination with signal region
  - expected signal strength and associated uncertainty extracted from each fit
- Measured (expected) signal strength:

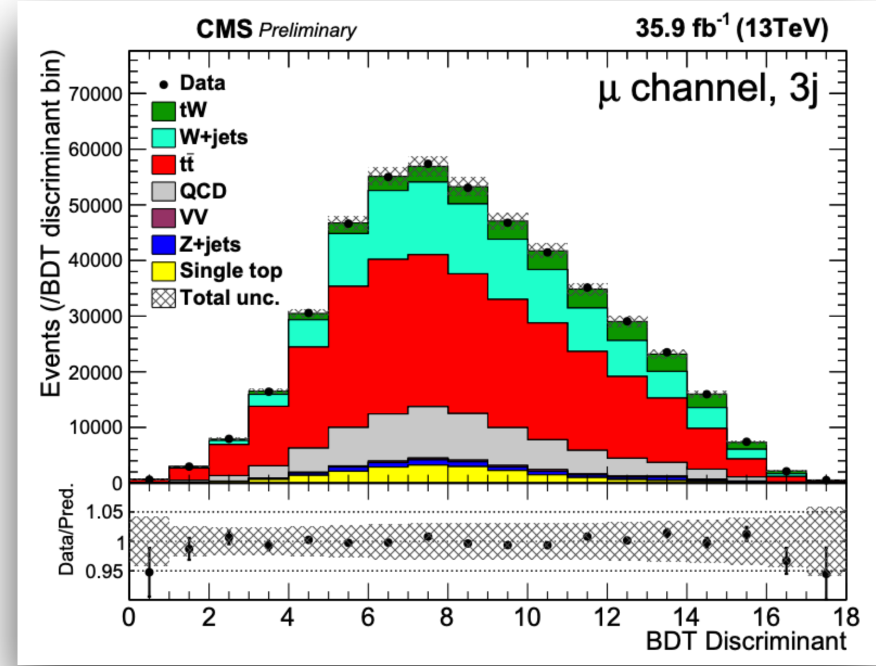
$$\mu = 1.24 \pm 0.18\,(1 \pm 0.17)$$

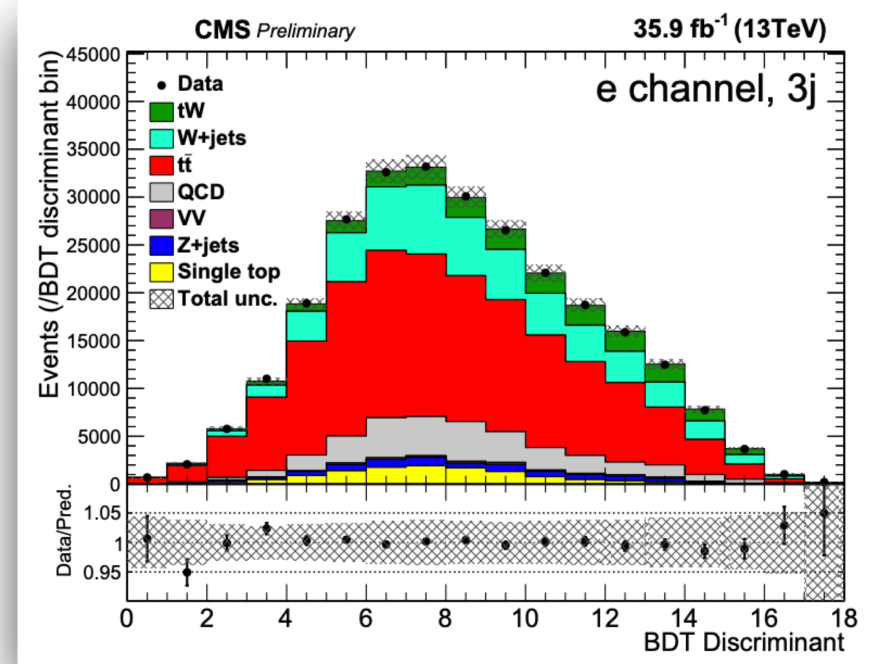
- Cross section:

$$\sigma_{tW} = 89 \pm 4\,(\text{stat.}) \pm 12\,(\text{syst.})\,\text{pb}$$

$$\sigma_{tW}^{SM} = 71.7 \pm 1.8\,(\text{scale}) \pm 3.4\,(\text{PDF})\,\text{pb}$$

→ corresponds to an observed (expected) significance of 7.4 (6.8) σ





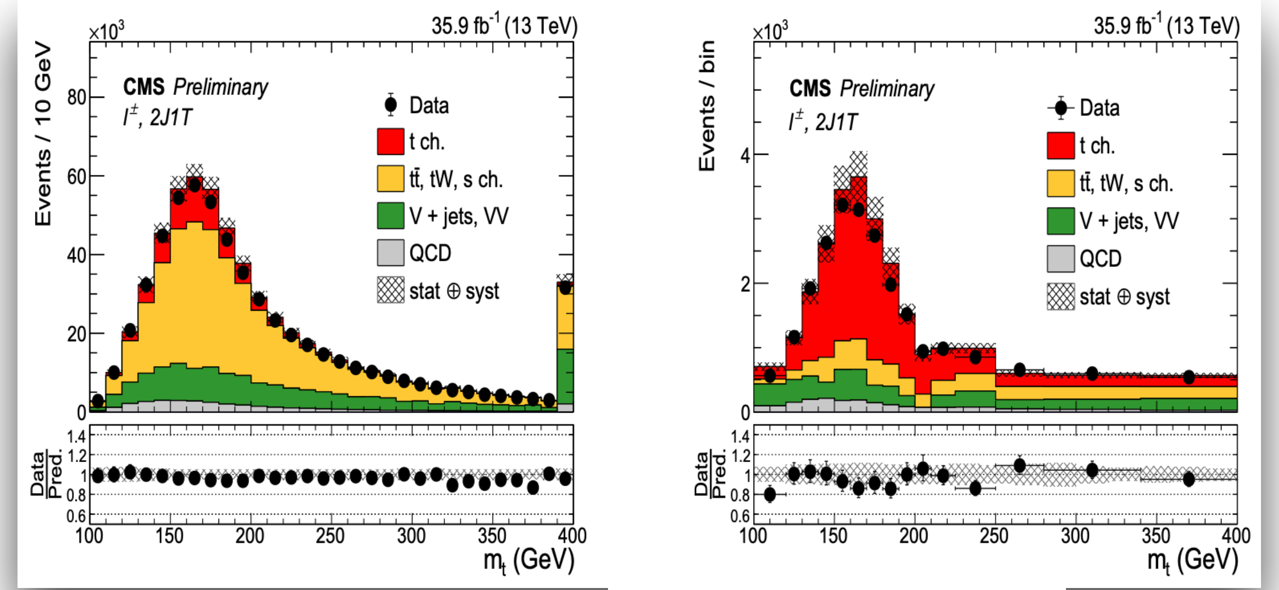
Top mass from ST t-channel

2016 data

CMS-PAS-TOP-19-009

- Traditionally mt measurements performed with $t\bar{t}$ events
- Single top provides statistically independent sample:
  - enhances the range of available measurements
  - partially uncorrelated systematics from $t\bar{t}$ measurements
- Data-driven estimation of QCD multijet bkg
- BDT discriminators to increase signal purity
- Extraction of mt:
  - QCD contribution is subtracted from data
  - simultaneous ML fit using y = ln(mt) distributions in μ and e final states
  - signal and bkg. rates added as nuisance parameters to the fit → constrained using log-normal priors based on unc. on respective cross sections
  - 3 separate fits performed in l+, l-, l± final states
  - peak region well-modeled by fit

Before and after BDT selection

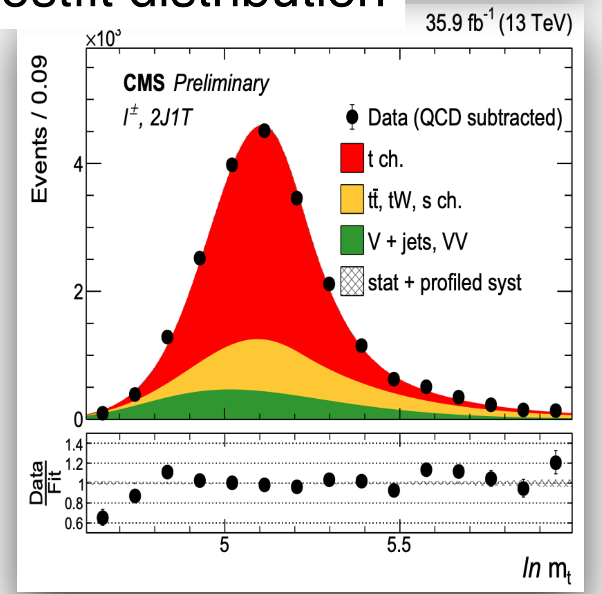


$$m_t = 172.13 \pm 0.32\,(\text{stat}+\text{prof})\ ^{+0.69}_{-0.70}\,(\text{syst})\ \text{GeV} = 172.13^{+0.76}_{-0.77}\ \text{GeV}$$

Dominant syst. unc.: JES, signal FSR scale, Color reconnection, b-quark had. model

First mt measurement to achieve sub-GeV precision in single top enriched event sample

Postfit distribution

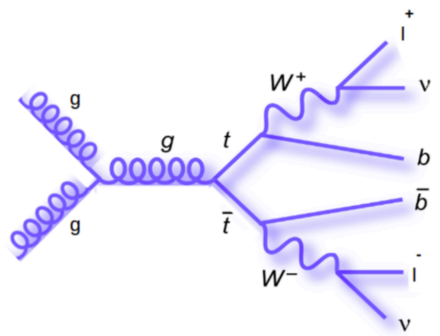


- Masses of top quark and antiquark determined separately by requiring positively and negatively charged leptons in the final state:

$$m_t = 172.62 \pm 0.37\,(\text{stat}+\text{prof})\ ^{+0.97}_{-0.65}\,(\text{syst})\ \text{GeV} = 172.62^{+1.04}_{-0.75}\ \text{GeV},$$
$$m_{\bar{t}} = 171.79 \pm 0.58\,(\text{stat}+\text{prof})\ ^{+1.32}_{-1.39}\,(\text{syst})\ \text{GeV} = 171.79^{+1.44}_{-1.51}\ \text{GeV}.$$

- Estimated values of Rmt and Δmt agree with unity and zero within uncertainties → consistent with no violation of CPT invariance

$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.995 \pm 0.004\,(\text{stat}+\text{prof})\ ^{+0.002}_{-0.004}\,(\text{syst}) = 0.995^{+0.005}_{-0.006}$$
$$\Delta m_t = m_t - m_{\bar{t}} = 0.83 \pm 0.69\,(\text{stat}+\text{prof})\ ^{+0.35}_{-0.74}\,(\text{syst})\ \text{GeV} = 0.83^{+0.77}_{-1.01}\ \text{GeV}$$

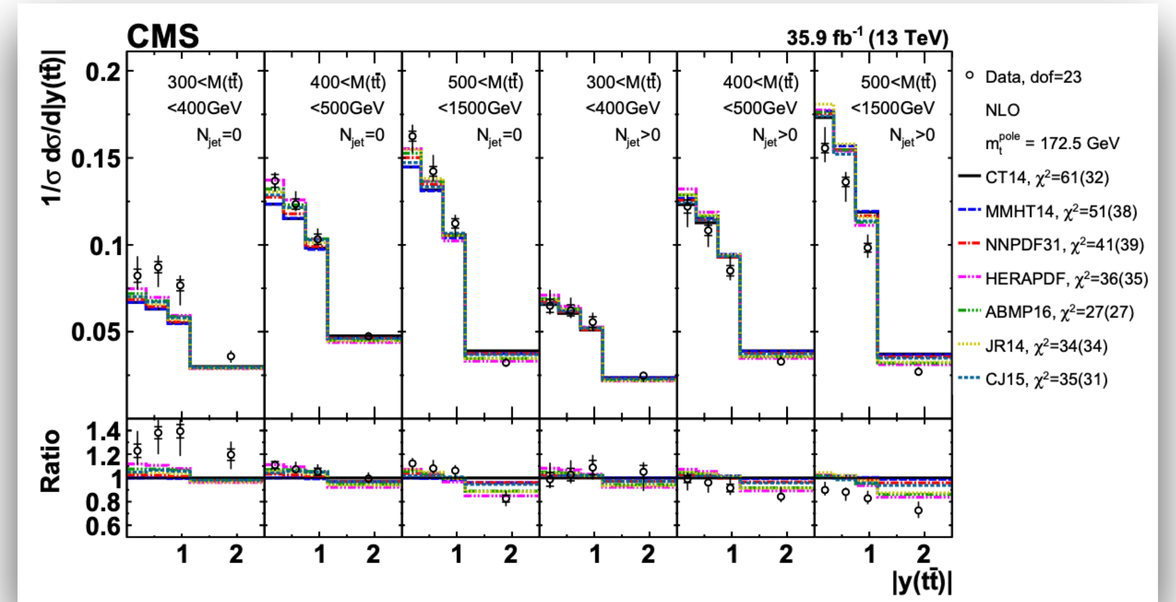


Mass from multidifferential

EPJC 80 (2020) 658

2016 data
@13 TeV: 35.9 fb[-1]

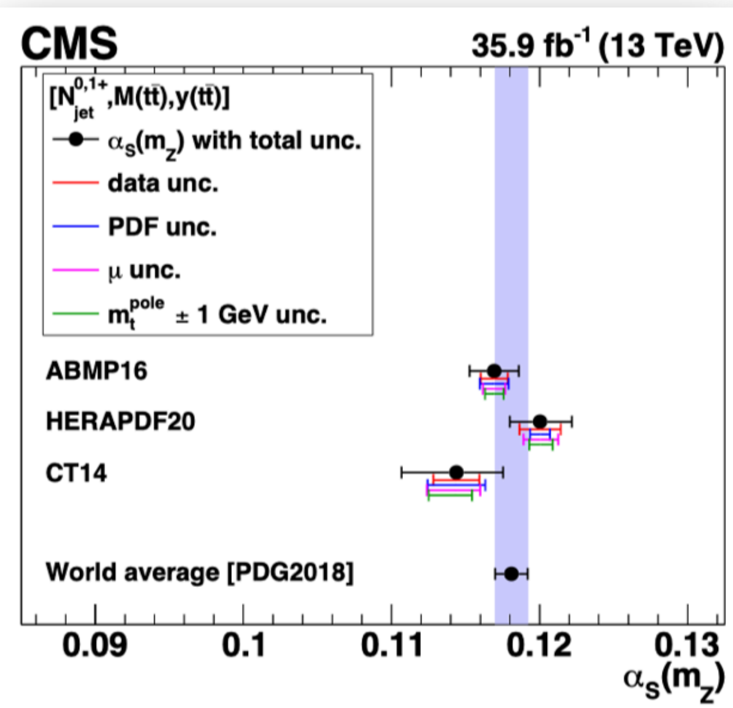
- **Normalized 3D cross sections** vs $m_{t\bar{t}}$, $y_{t\bar{t}}$, N(extra jets) in dilepton channel
- Extraction of α_S and m_t^{pole}:
  - cross sections compared to NLO predictions with different PDFs
  - simultaneous fit of PDF+α_S+m_t^{pole} at NLO + HERA DIS data

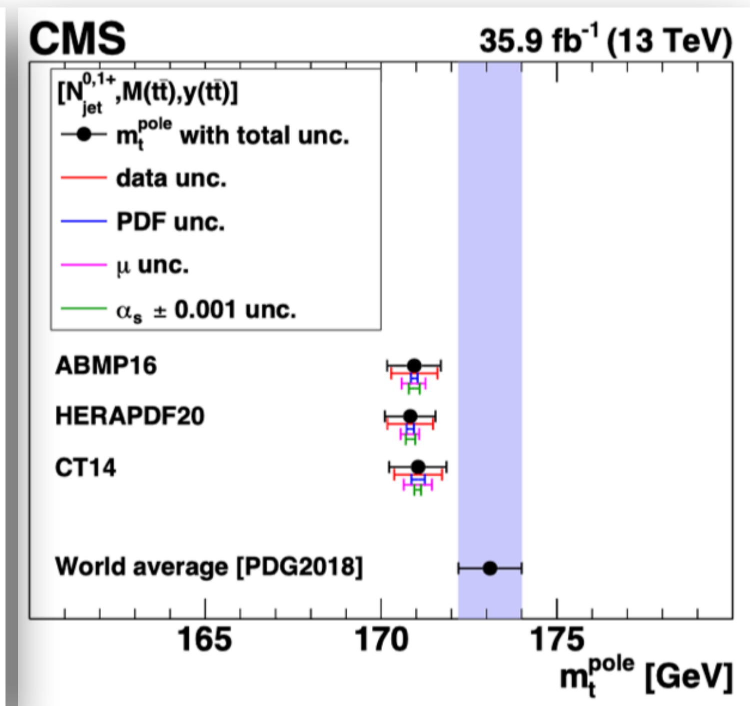


$$\alpha_S(m_Z) = 0.1135^{+0.0021}_{-0.0017}$$
$$= 0.1135 \pm 0.0016\,(\text{fit})^{+0.0002}_{-0.0004}\,(\text{model})^{+0.0008}_{-0.0001}\,(\text{param})^{+0.0011}_{-0.0005}\,(\text{scale})$$
$$m_t^{pole} = 170.5 \pm 0.8\,\text{GeV}$$
$$= 170.5 \pm 0.7\,(\text{fit}) \pm 0.1\,(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3\,(\text{scale})\,\text{GeV}$$

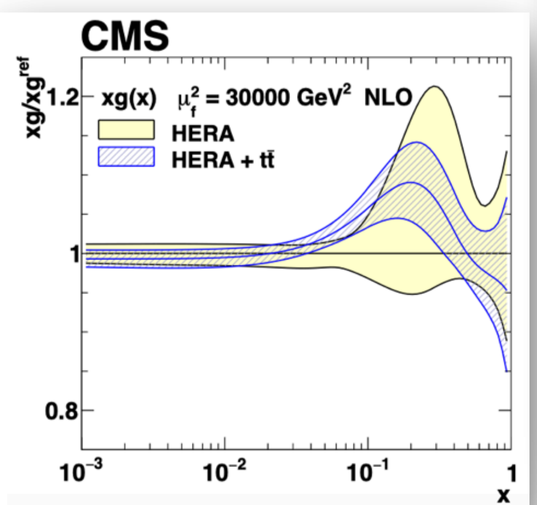
Most precise result on m_t^{pole} from single analysis!

$$\frac{m_t}{\Delta m_t} < 0.5\,\%$$

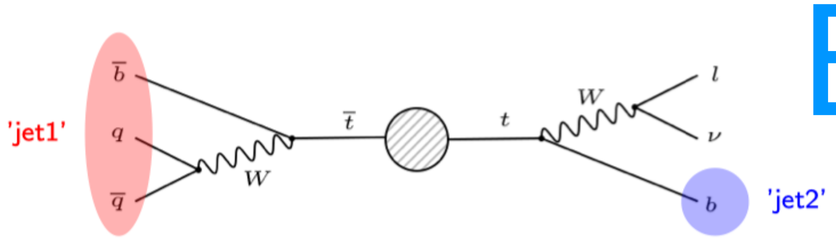




- Constraint on PDFs:
  - significant impact on gluon PDF at large values of x



Dominant syst. unc.:
JES and signal modeling



Boosted mass

PRL 124, 202001 (2020)

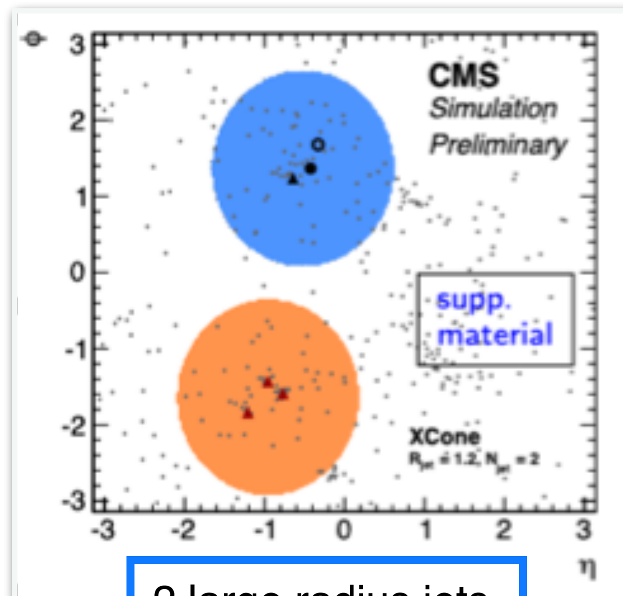
2016 data
@13 TeV: 35.9 fb^{-1}

- Measurement of top quark mass in hadronic decays of boosted top quarks in **lepton+jets** channel
- Novel jet reconstruction technique, XCone:
  - excellent m_{jet} resolution
- m_t extracted from normalized $t\bar{t}$ cross section as function of m_{jet} unfolded at particle level:

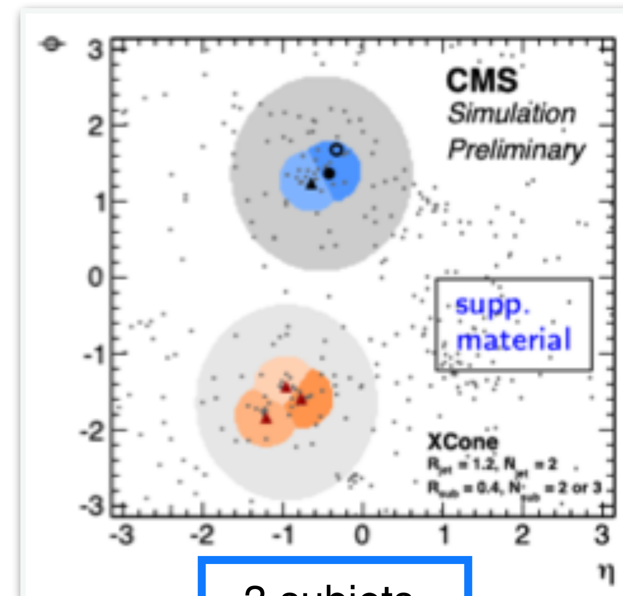
$$m_t = 172.6 \pm 2.5\,\text{GeV}$$
$$= 172.6 \pm 0.4\,(\text{stat}) \pm 1.6\,(\text{exp}) \pm 1.5\,(\text{model}) \pm 1.0\,(\text{theo})\ \text{GeV}$$

$$\frac{m_t}{\Delta m_t} \sim 0.7\,\%$$

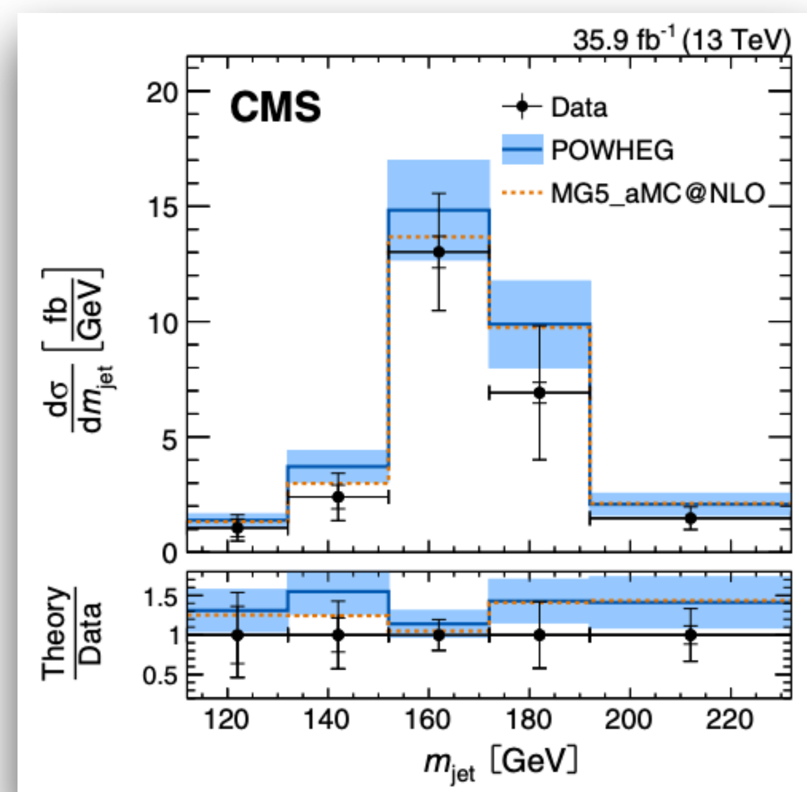
Dominant syst. unc.:
JES, JER, XCone jet energy correction, signal modeling FSR, color reconnection, UE tune, top mass value)

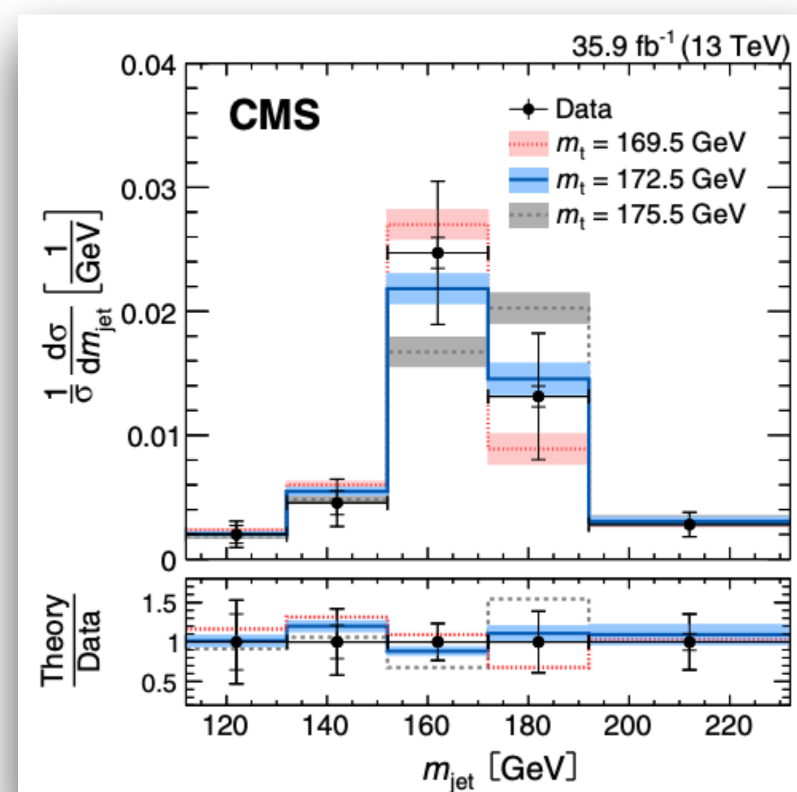


2 large radius jets, p_T > 400 GeV



3 subjets, p_T > 30 GeV





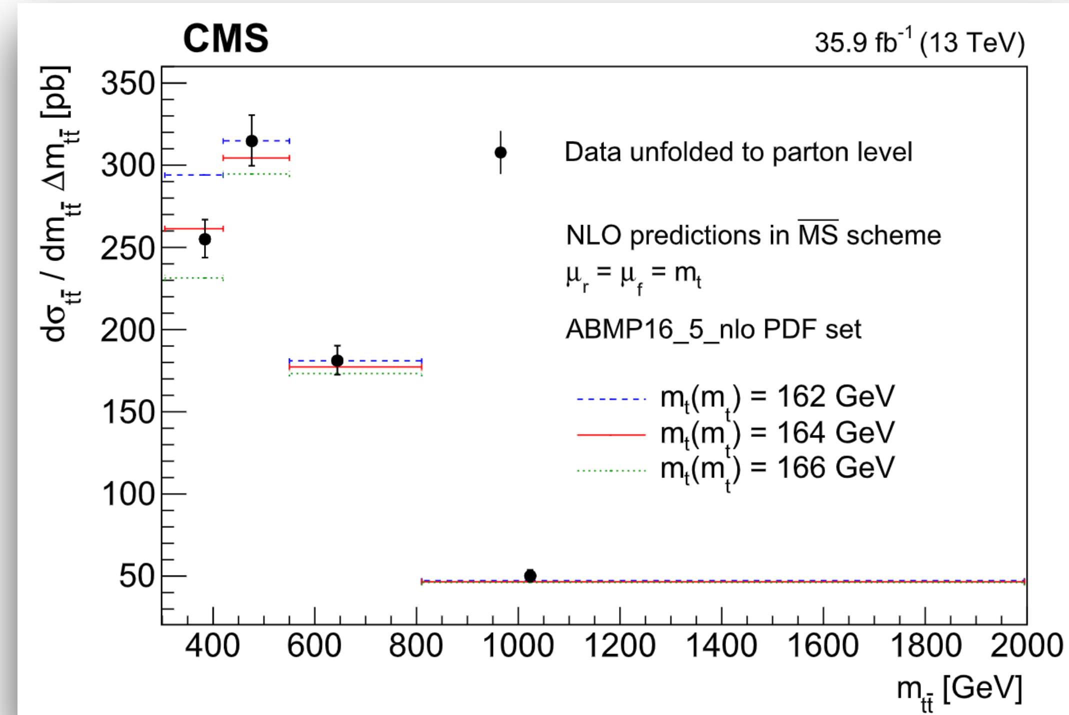
First experimental investigation!

Running of top mass

PLB 803 (2020) 135263

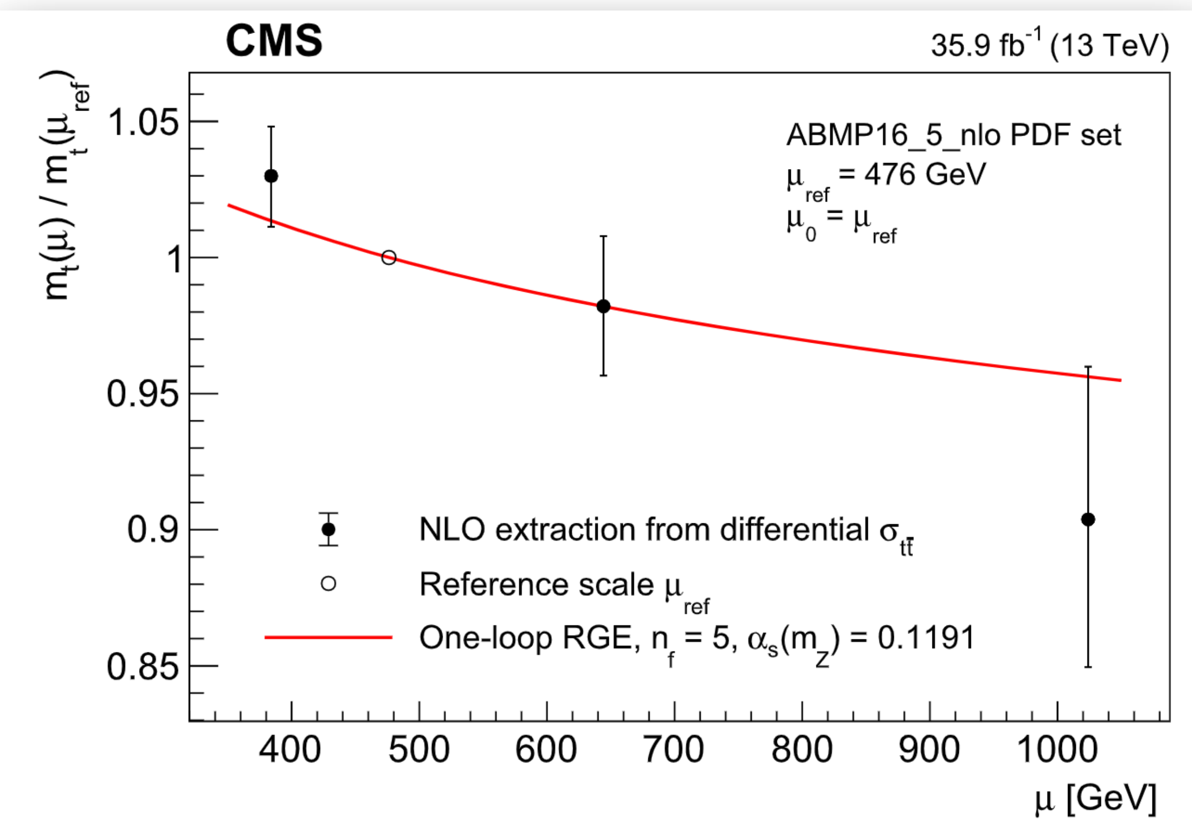
2016 data
@13 TeV: 35.9 fb^{-1}

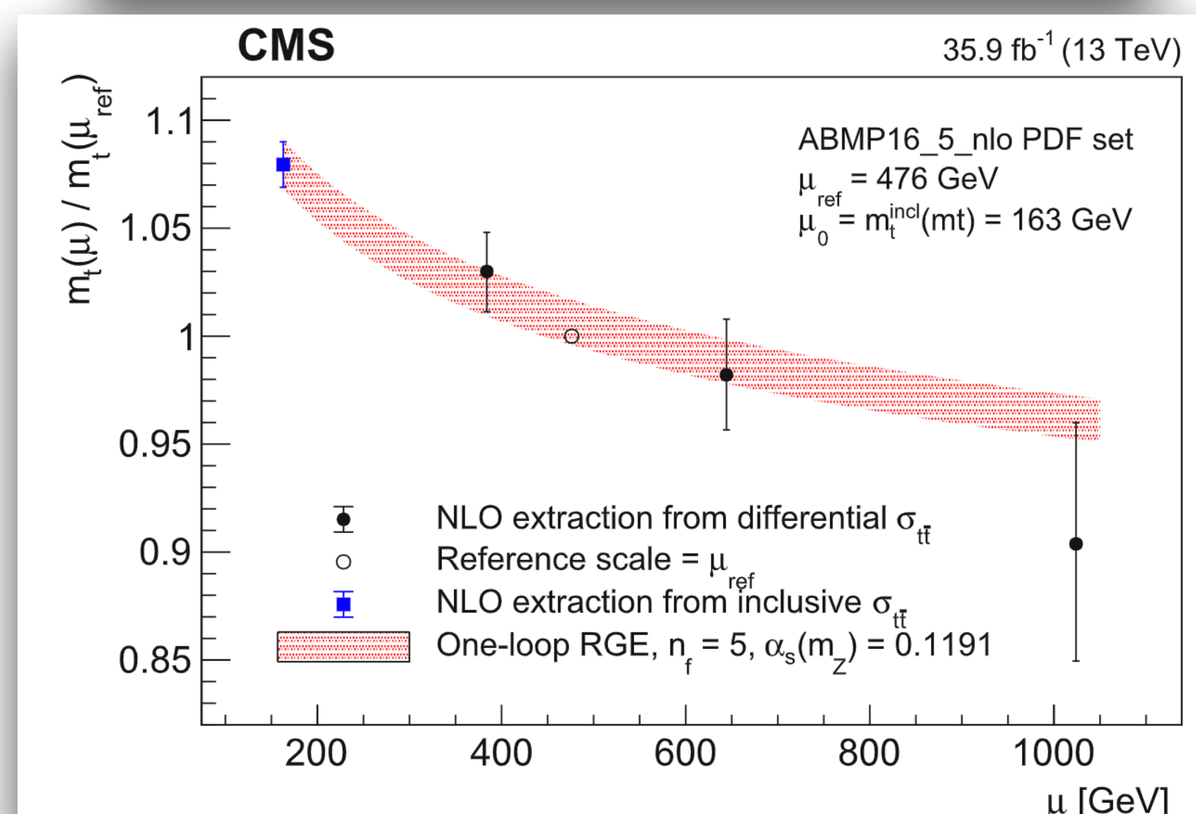
- Extracted by comparing NLO predictions to differential cross section measured vs $m_{t\bar{t}}$ in ***eμ* channel**
- Simultaneous measurement of $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$ and m_t^{MC} by means of maximum- likelihood fit to multi-differential distributions
- Running of m_t in agreement with prediction of corresponding RGE within 1.1 σ
- No-running scenario excluded at > 95% C.L.



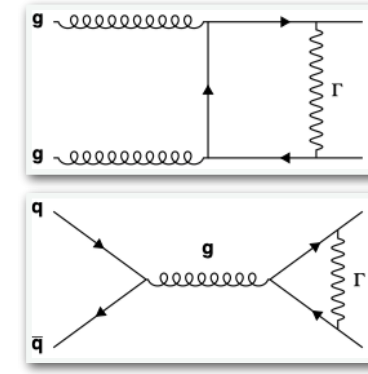
Dominant syst. unc.: luminosity, lepton id, JES/ JER and signal modeling

Based on EPJC 79 (2019) 368's strategy





Top Yukawa coupling



$$Y_t = \frac{g_t}{g_t^{SM}}$$

- **Weak corrections** affect cross sections at $\alpha_S^2\alpha_w$ order → may lead to large distortions of $t\bar{t}$ differential distributions near the production threshold region
- Virtual Higgs exchange depends on the top-Higgs Yukawa coupling g_t

PRD 100 (2019) 072007

2016 data
@13 TeV: 35.8 fb^{-1}

- Full kinematic reconstruction in **lepton+jets** channel
- 2D likelihood fit in $(M_{t\bar{t}}, \Delta y_{t\bar{t}})$ to constrain Y_t

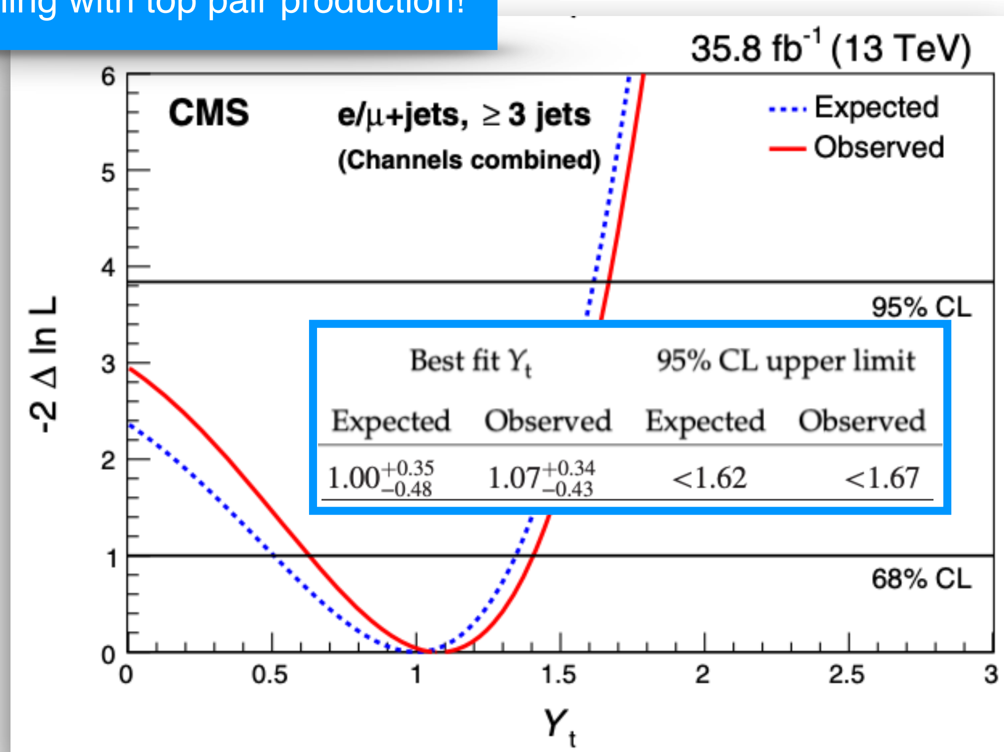
First analysis to measure Yukawa coupling with top pair production!

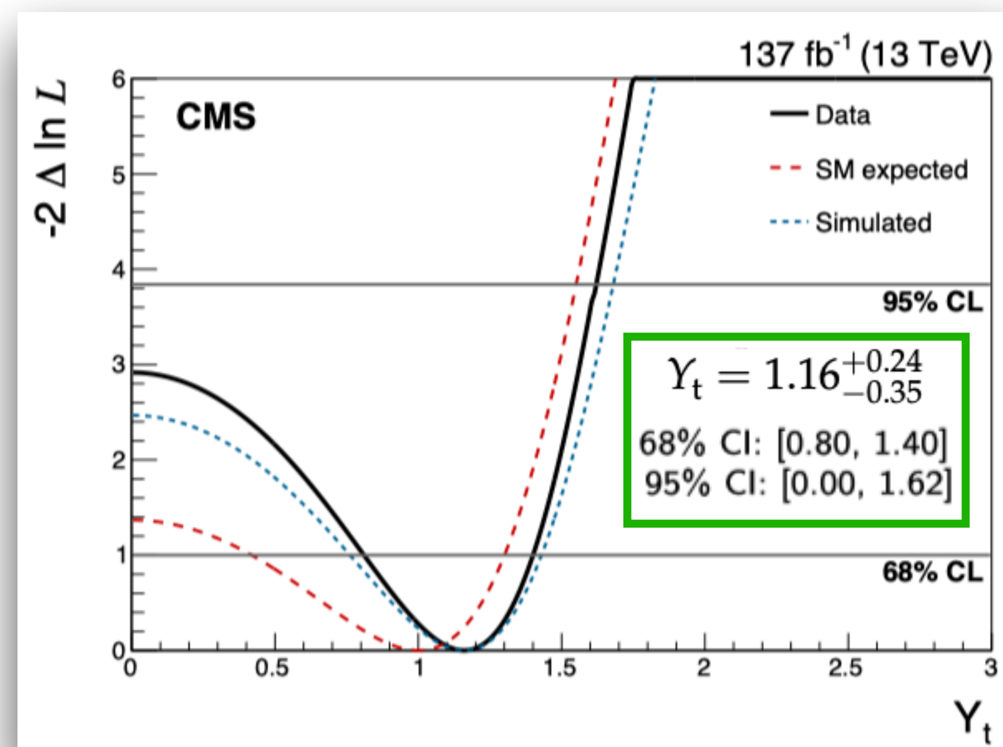
PRD 102 (2020) 092013

Full Run2 data
@13 TeV: 137 fb^{-1}

- Partial kinematic reconstruction in **dilepton** channel
- 2D likelihood fit in $(M_{b\ell}, \Delta y_{b\ell})$ to constrain Y_t

Upper limit extraction on top quark Yukawa coupling





Results in agreement between 2 channels

- More sensitive than 4t production: $Y_t < 1.7$ @ 95% C.L.
- Less sensitive than model-dependent Higgs combination: $Y_t = 0.98 \pm 0.14$

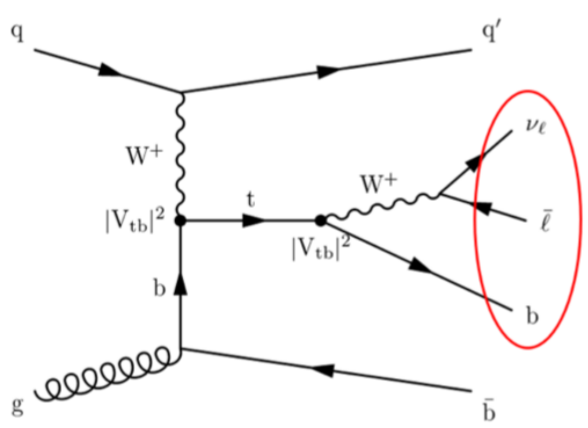
Top CKM elements

PLB 808 (2020) 135609

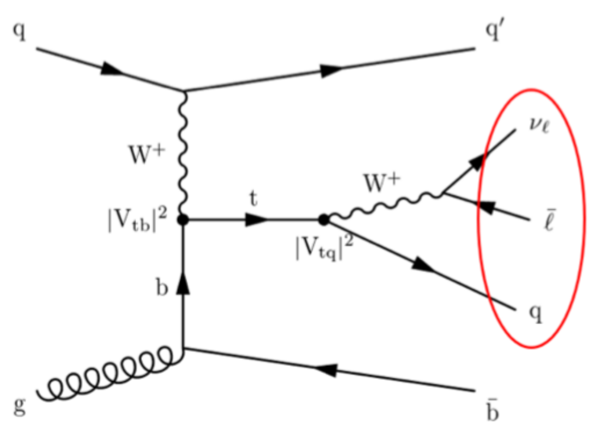
2016 data
@13 TeV: 35.9 fb^{-1}

- Processes directly sensitive to $|V_{tb}|$, $|V_{td}|$, and $|V_{ts}|$ are considered at both the production and decay vertices of the top quark:

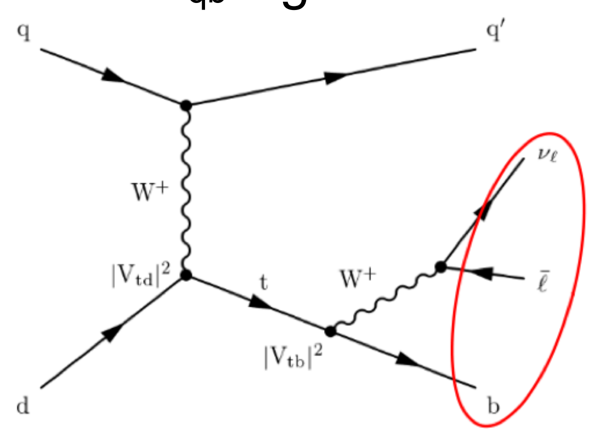
ST_{bb} signal



ST_{bq} signal



ST_{qb} signal



- BDT discriminant trained for each category to separate signal and background processes
- Multivariate discriminators used in a simultaneous fit to the 3 event categories to discriminate between ST_{bb}, ST_{bq}, and ST_{qb}

Category	Enriched in
2j1t	$ST_{b,b}$
3j1t	$ST_{b,q}$, $ST_{q,b}$
3j2t	$ST_{b,b}$

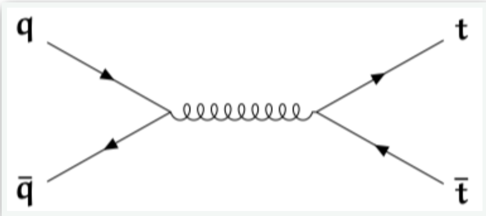
- CKM matrix elements extracted by signal strengths
  - **in SM** assuming CKM unitarity (@ 95% C.L.):
  - also **BSM scenarios** are probed

$$|V_{tb}| > 0.970$$
$$|V_{td}|^2 + |V_{ts}|^2 < 0.057$$

- All results are consistent with each other
- Best determination of these parameters w.r.t. latest measurements of single top quark in Run2

Dominant syst. unc.:
modeling

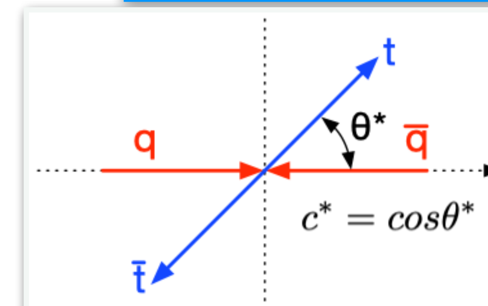
First direct model-independent measurement in single top t-channel events



Top Forward-Backward Asymmetry

JHEP 06 (2020) 146

2016 data @13 TeV: 35.9 fb^{-1}



- Lepton+jets events with "boosted" and "resolved" topologies
- Asymmetry in $t\bar{t}$ production due to NLO interference terms between $q\bar{q}$ initial states
- Search for anomalies in the angular distribution of produced $t\bar{t}$ pairs:

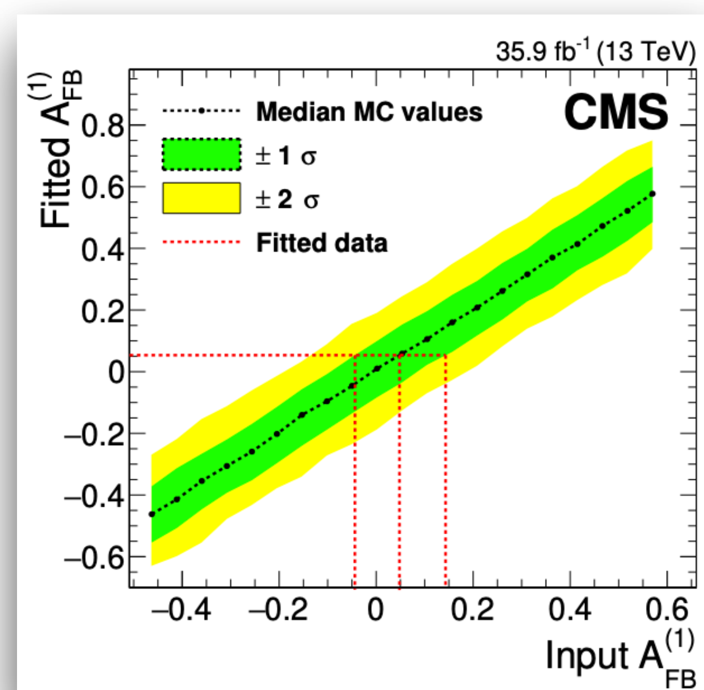
$$\frac{d\sigma}{dc^*}(q\bar{q}) \approx f_{\rm sym}(c^*) + \left[\int_{-1}^{1} f_{\rm sym}(x)dx\right] c^* A_{\rm FB}^{(1)}(m_{t\bar{t}})$$

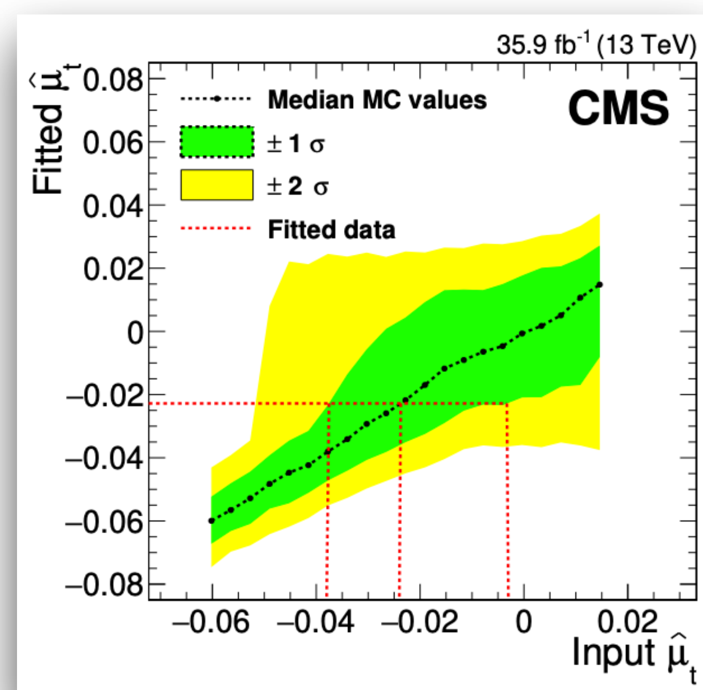
anomalous chromoelectric (d_t) + chromomagnetic (μ_t) dipole moments

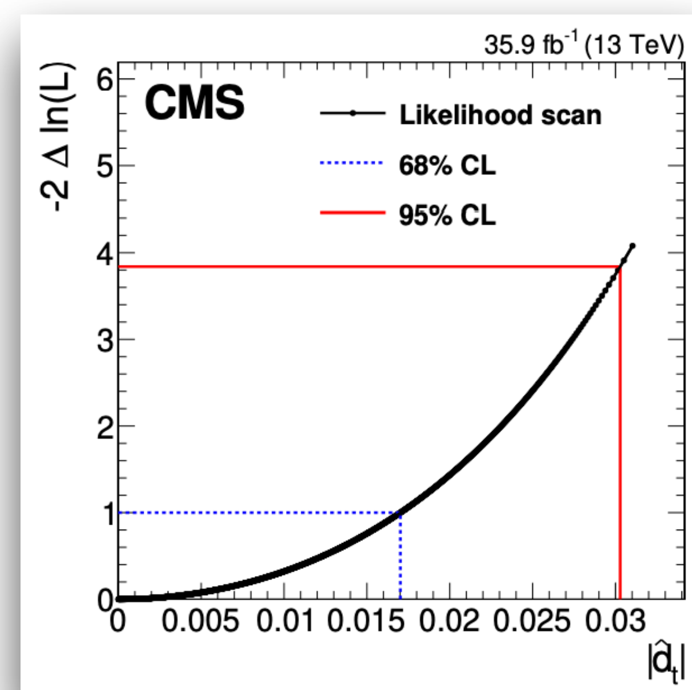
$$A_{\rm FB} = \frac{\sigma(c^*>0) - \sigma(c^*<0)}{\sigma(c^*>0) + \sigma(c^*<0)}$$

- Multi-dimensional template fit for each category
- Parameters independently extracted from a linear combination of the 3D templates fitted to data
- Values consistent with SM expectations and in good agreement with previous measurements like CMS spin correlation measurements in dilepton channel

First measurement @LHC !



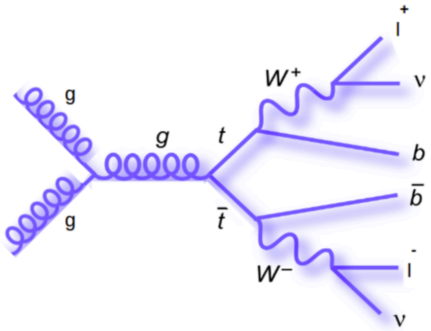




$$A_{\rm FB}^{(1)} = 0.048^{+0.095}_{-0.087}\,({\rm stat})^{+0.020}_{-0.029}\,({\rm syst})$$

$$\hat{\mu}_t = -0.024^{+0.013}_{-0.009}\,({\rm stat})^{+0.016}_{-0.011}\,({\rm syst})$$

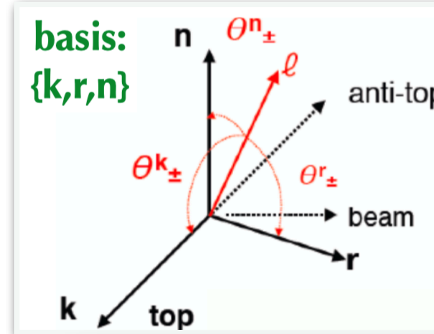
$$|\hat{d}_t| < 0.03 \text{ at } 95\% \text{ C.L.}$$



Spin correlations

PRD 100 (2019) 072002

2016 data
@13 TeV: 35.9 fb^{-1}



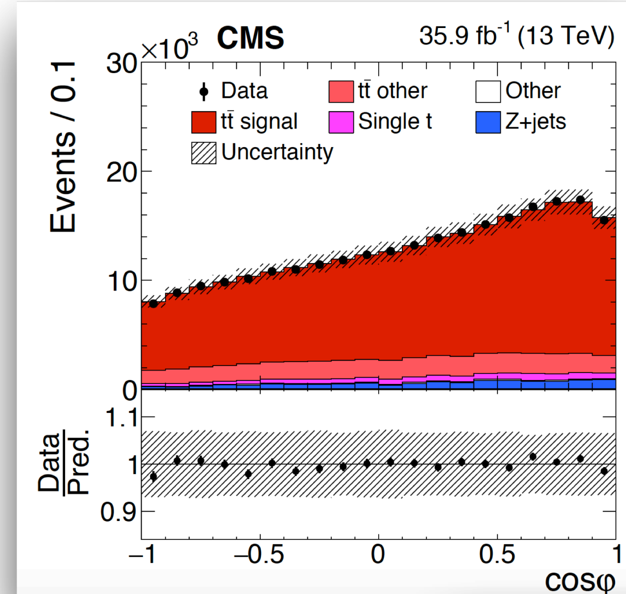
$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}\left(1 + [\text{Coef.}]\, x\right) f(x)$$

- Measurement of full spin density production matrix in dilepton channel
- Angular distributions in $t\bar{t}$ rest frame (**direct measurement**):
  - full reconstruction of $t\bar{t}$ system required

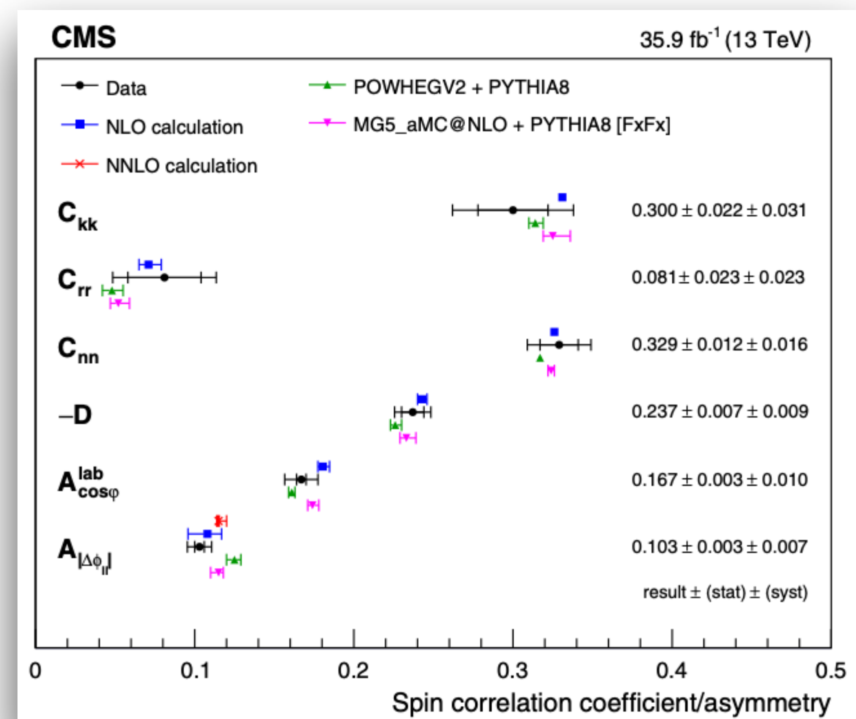
$$\frac{1}{\sigma}\frac{d\sigma}{dcos\theta_1^i dcos\theta_2^j} = \frac{1}{4}(1 + B_1^i cos\theta_1^i + B_2^i cos\theta_2^i - C_{ii} cos\theta_1^i cos\theta_2^i)$$

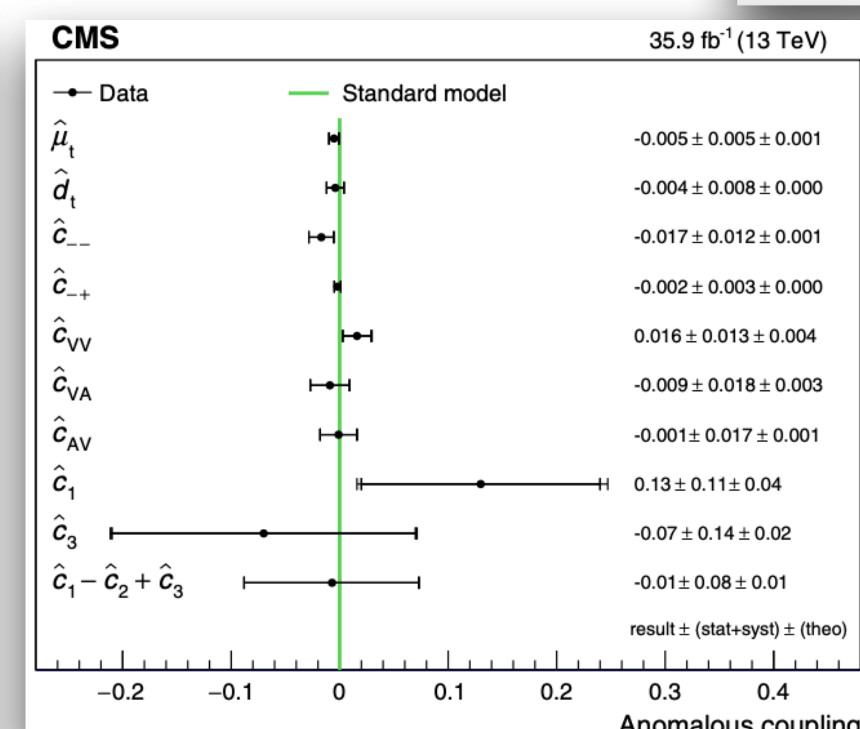
Polarizations   Spin correlations

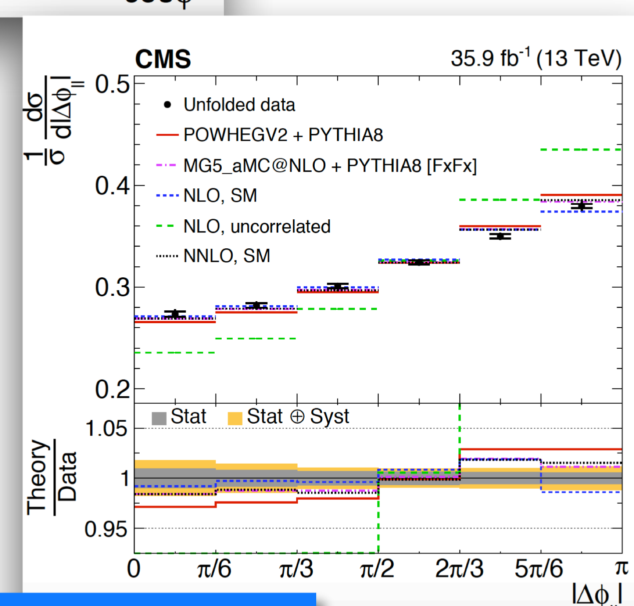
- Coefficients individually probed by 1D angular distribution
- Lab-frame observables (**indirect measurement**)
- All distributions and extracted parameters in close agreement with SM predictions
- Unfolded results used to constrain anomalous couplings



Opening angle between leptons most precise measurement



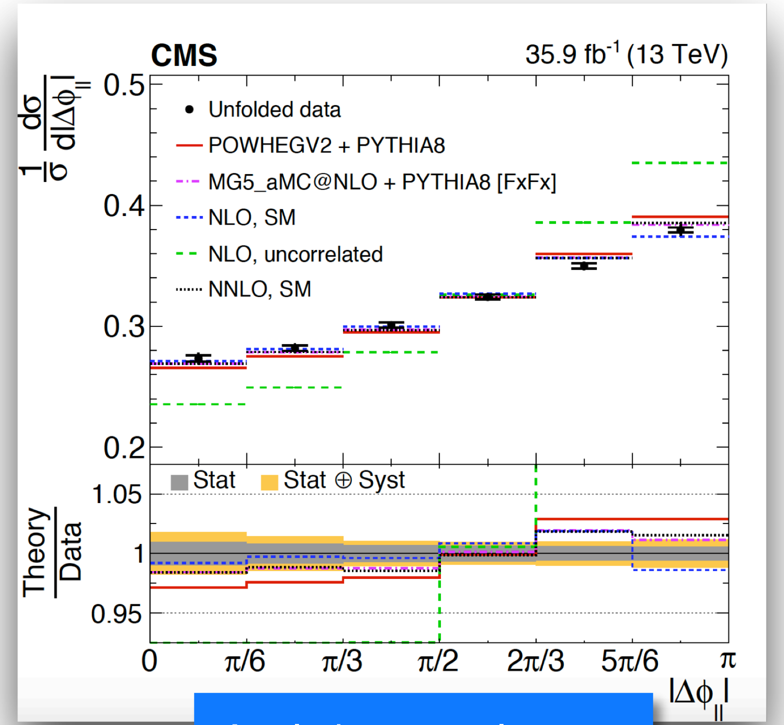




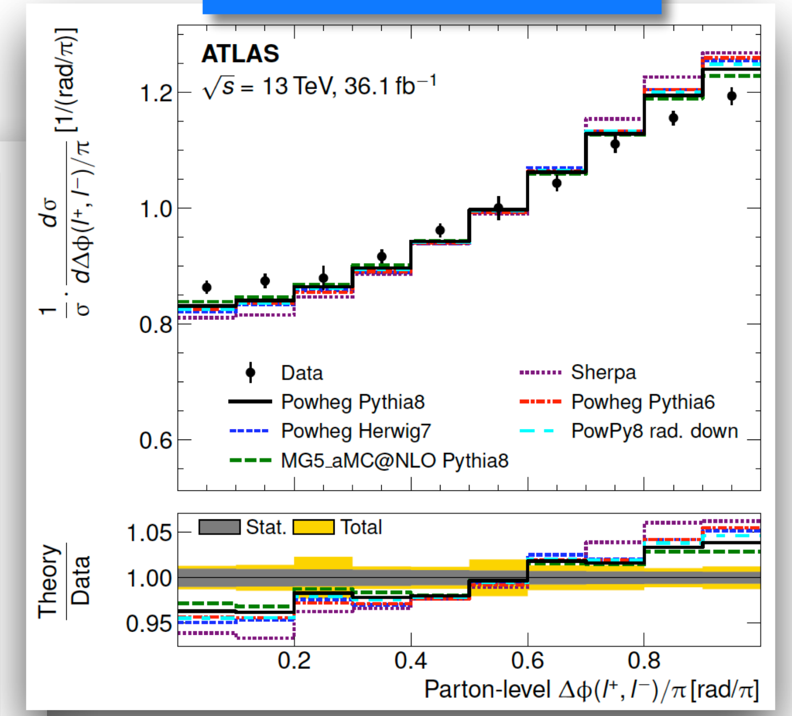
angle between leptons in transverse plane

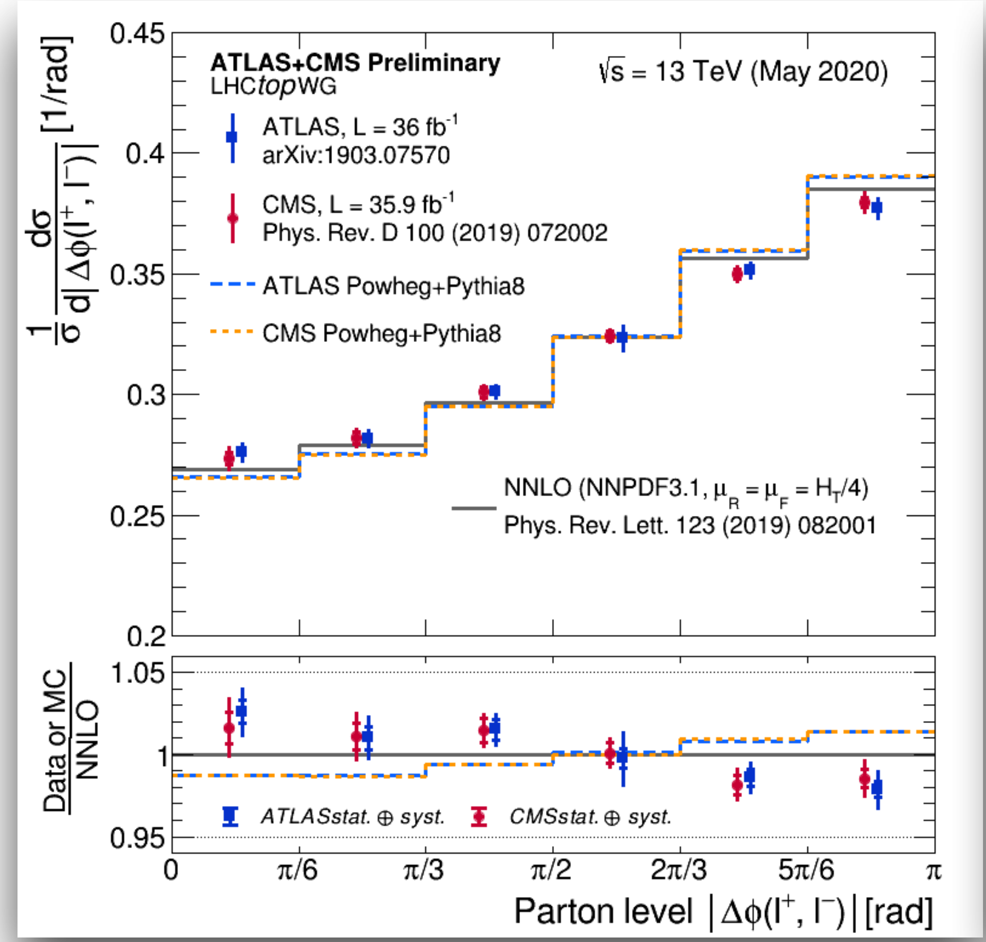
Δϕ distribution

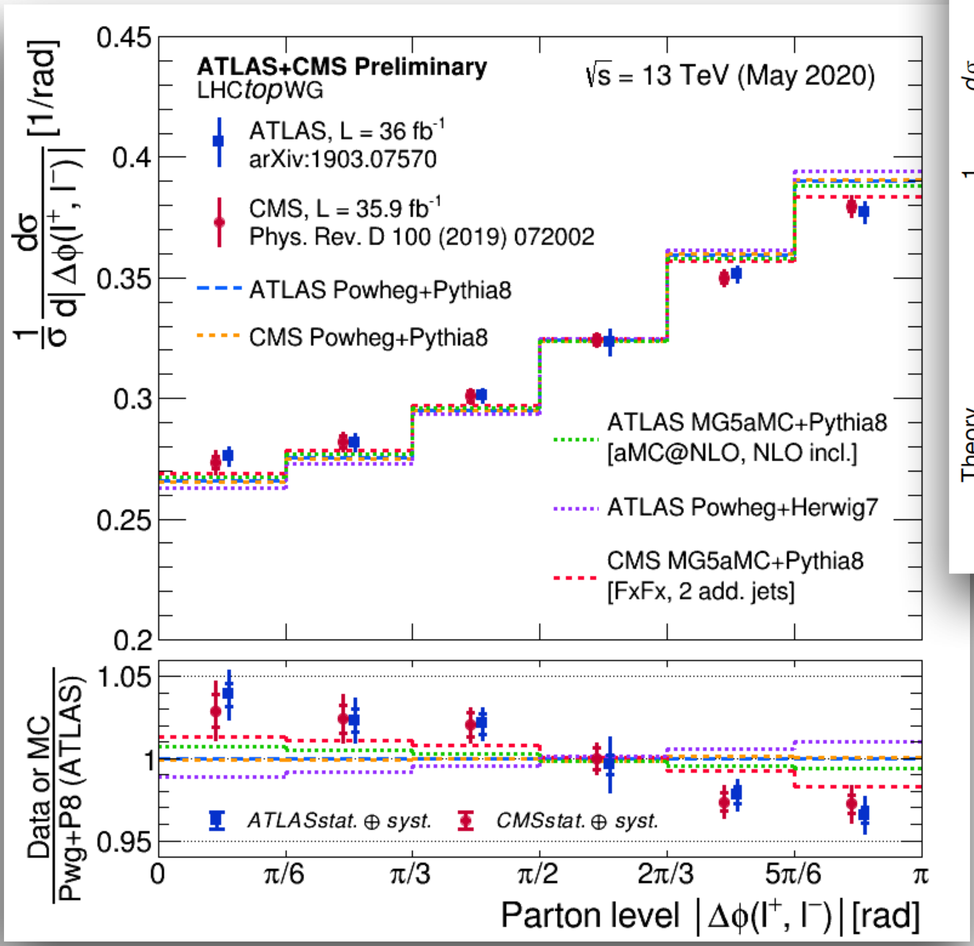
- Tension between data and predictions in both ATLAS (3.2σ) and CMS (1σ)
- First **ATLAS+CMS comparison** @13 TeV within *LHCtopWG*:
  - normalized cross sections at parton level
  - very good agreement between ATLAS and CMS data and between ATLAS and CMS main MC predictions
  - good agreement between data and MG5_aMC@NLO with FXFX merging (2 additional jets from the matrix element)
  - fair agreement with NNLO calculation



Angle between leptons in transverse plane







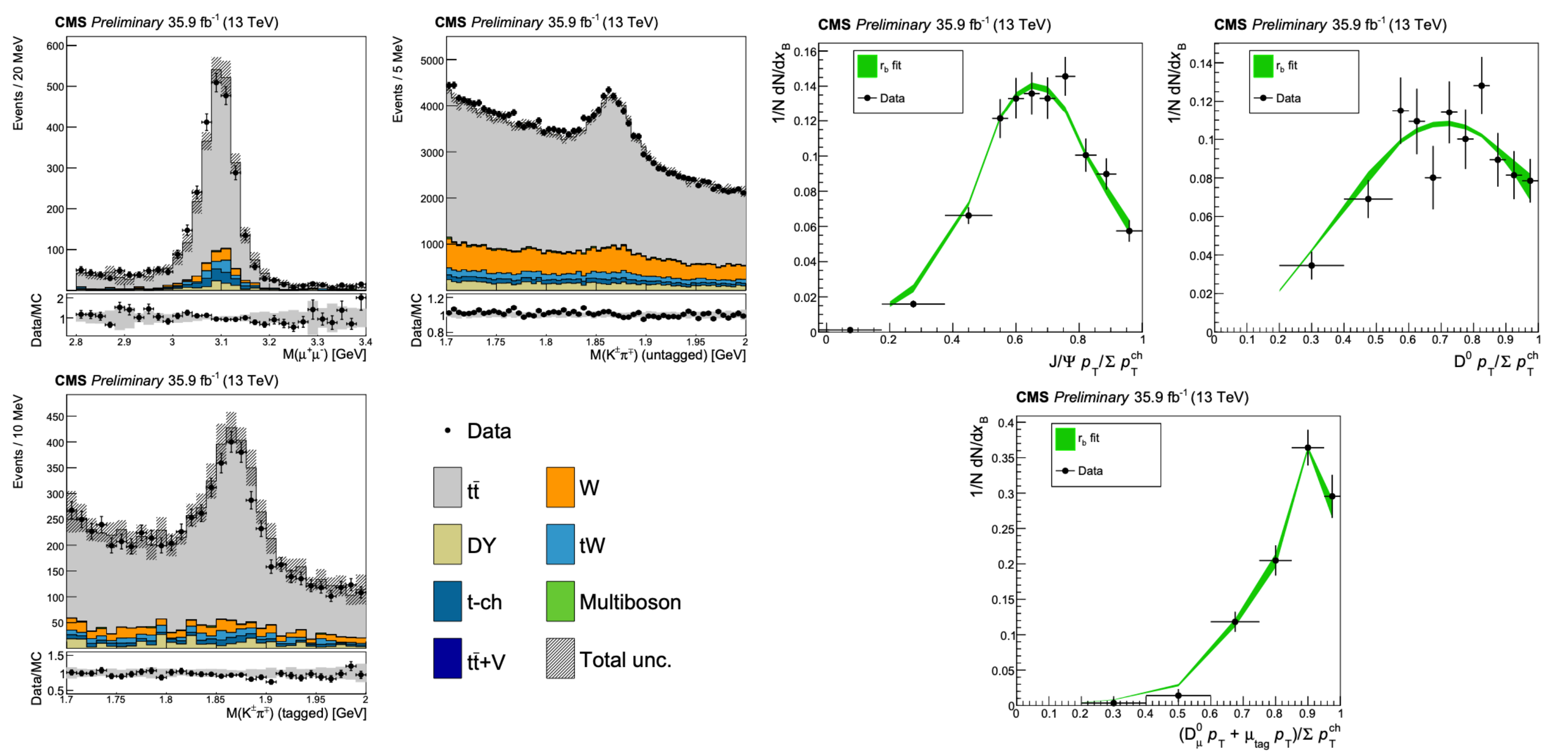
First measurement in tt and at LHC!

B-fragmentation

CMS-PAS-TOP-18-012

2016 data @13 TeV:
35.9 fb -1

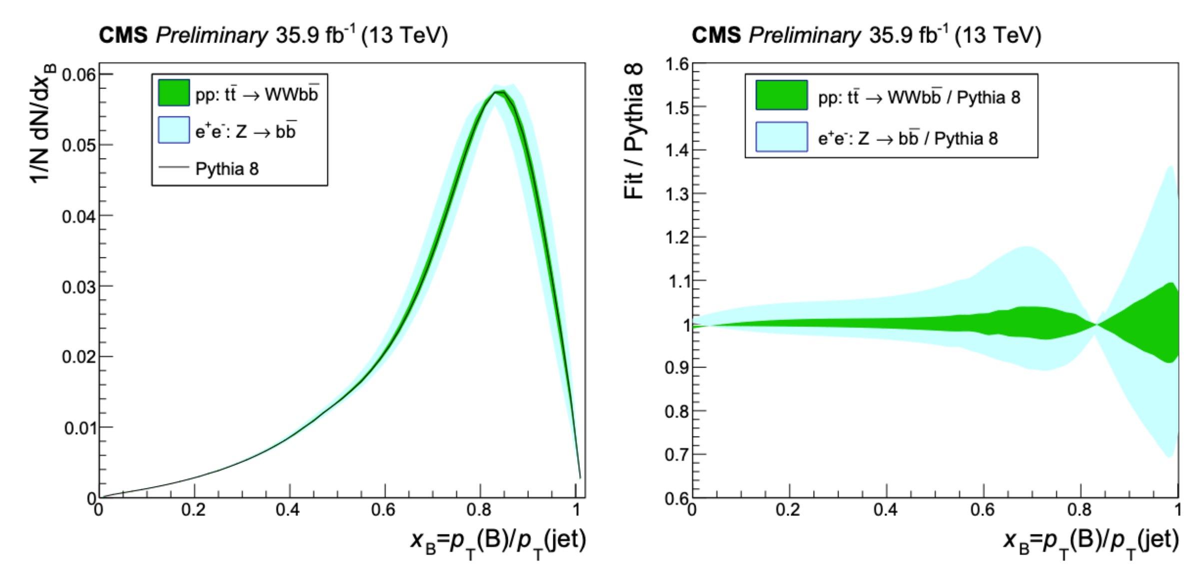
- In lepton + jets and dilepton decay channels
- Lund–Bowler fragmentation function with fixed mb
- 3 samples of charm mesons (J/ψ, Untagged D0, Muon tagged D0 (D0mu)) produced inside b jets and reconstructed from the D0 → K± π ∓ and J/ ψ → μ+μ- decays
- Signal and background contributions for each meson sample:
    - extracted by negative log likelihood fit on invariant mass distribution
    - used to produce fragmentation proxy distributions xb of parent b quark
- Extraction of rb from template fit to xb distribution:
    - best fit value of rb determined from the minimum of a χ2 scan over 0.655 < rb < 1.055
- Final result determined from simultaneous fit to the 3 meson samples:
    - systematic uncertainties assumed to be uncorrelated between the channels
    - uncertainties are statistically limited in all channels
- Results compared with the ones obtained at the Z pole in e^+e^- data:
    - agreement between results → no evidence for an environmental dependence of the fragmentation function
    - significant improvement in experimental precision
    - PYTHIA 8 function (rb = 0.855) is also in good agreement with the result presented here



$$f(z) = \frac{1}{z^{1+r_q b m_q^2}}(1-z)^a \exp\left(-\frac{b m_T^2}{z}\right)$$

$$x_B = \frac{\text{charm meson } p_T}{\sum p_T^{ch}}$$

$$r_b = 0.858 \pm 0.037\,(\text{stat}) \pm 0.031\,(\text{syst})$$



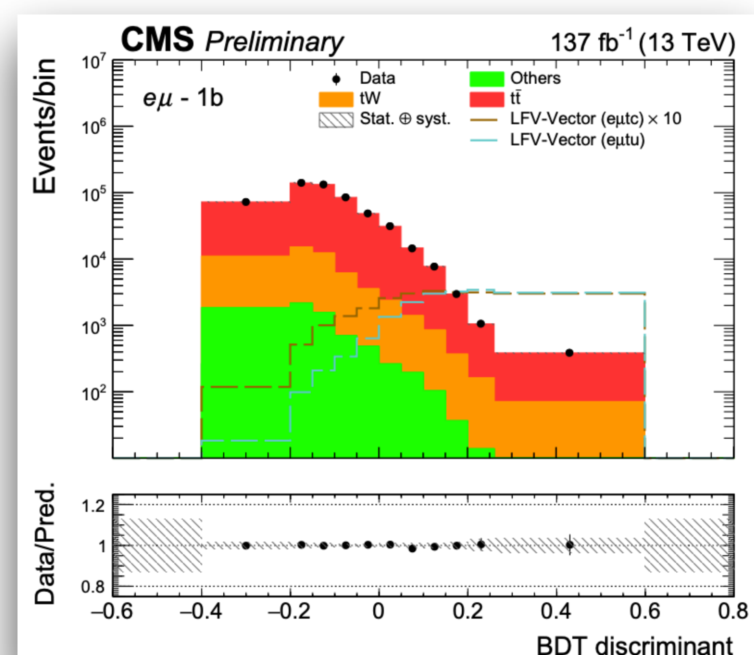
Lepton flavour violation

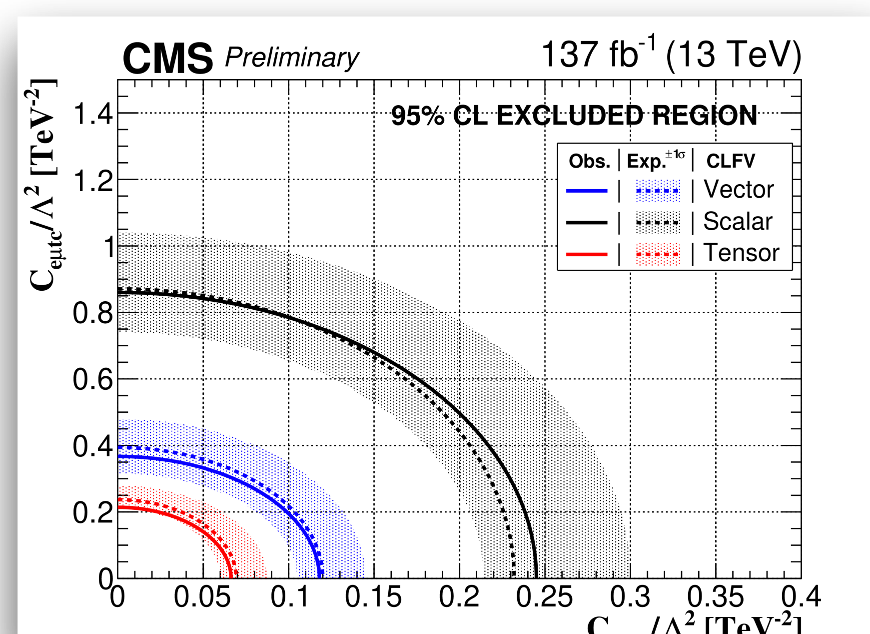
CMS-PAS-TOP-19-006

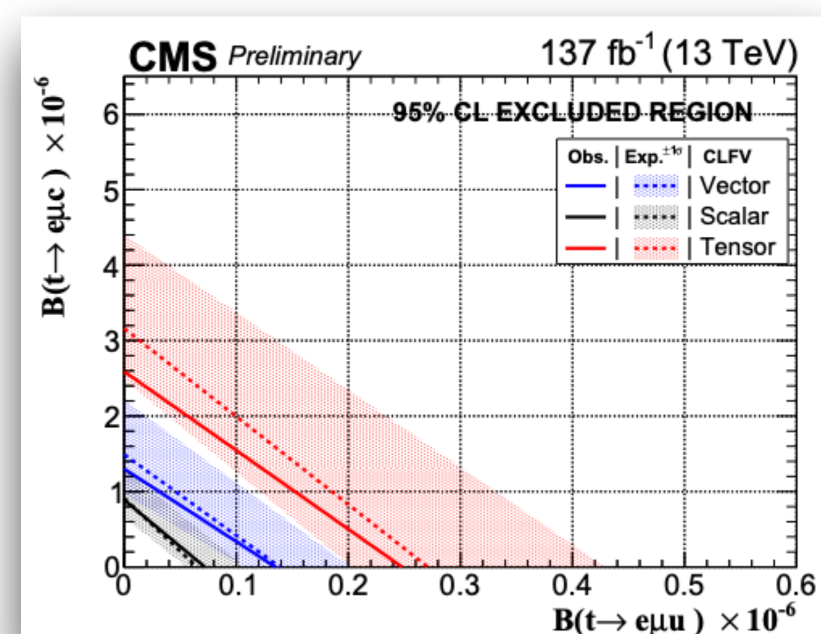
Full Run2 data

- Single top quark production signal is added to the top decay signal
- A model independent effective field theory approach is followed for modeling the CLFV signal: dim6 EFT operators
- Vector, tensor and scalar Lorentz structures are probed separately
- eμtc and eμtu LFV interactions are probed separately
- A BDT is used to maximize signal sensitivity
- Data are consistent with the SM predictions within the uncertainties
- We set upper limits on the signal production cross section using the modified frequentist CLs method
- Limits are translated into upper limits on the related Wilson coefficient and top quark LFV branching fractions
- These results are the most stringent limits on the top CLFV branching fraction to date

Vertex	Int. type	Cross section [fb] Exp.	Cross section [fb] Obs.	$C_{e\mu tq}/\Lambda^2$ [TeV^{-2}] Exp.	$C_{e\mu tq}/\Lambda^2$ [TeV^{-2}] Obs.	$\mathcal{B}\times10^{-6}$ Exp.	$\mathcal{B}\times10^{-6}$ Obs.
	Vector	7.02	6.78	0.12	0.12	0.14	0.13
		[5.33,10.21]		[0.10,0.14]		[0.11,0.20]	
		(3.39,12.33)		(0.08,0.16)		(0.07,0.24)	
$e\mu tu$	Scalar	5.63	6.25	0.23	0.24	0.06	0.07
		[4.79,9.38]		[0.21,0.33]		[0.05,0.11]	
		(3.75,12.12)		(0.19,0.34)		(0.04,0.14)	
	Tensor	10.01	9.18	0.07	0.06	0.27	0.25
		[7.51,15.90]		[0.06,0.09]		[0.20,0.43]	
		(4.59,19.24)		(0.04,0.09)		(0.12,0.52)	
	Vector	11.21	9.73	0.39	0.37	1.49	1.31
		[7.21,16.63]		[0.32,0.48]		[0.96,2.21]	
		(4.33,21.61)		(0.24,0.55)		(0.58,2.89)	
$e\mu tc$	Scalar	9.11	8.88	0.87	0.86	0.91	0.89
		[6.58,13.10]		[0.74,1.04]		[0.65,1.31]	
		(3.54,17.41)		(0.54,1.21)		(0.35,1.74)	
	Tensor	21.02	17.22	0.24	0.21	3.16	2.59
		[16.52,29.21]		[0.21,0.28]		[2.48,4.41]	
		(10.51,42.02)		(0.17,0.33)		(1.58,6.32)	



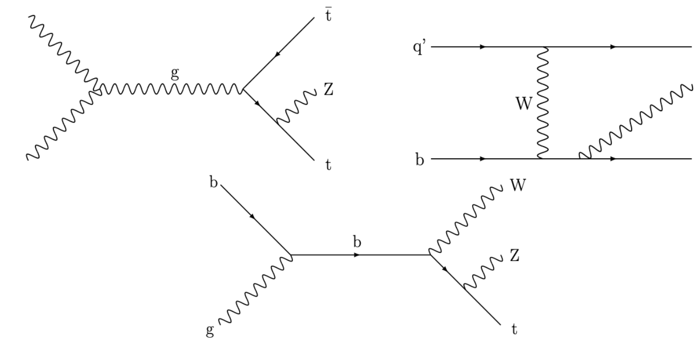




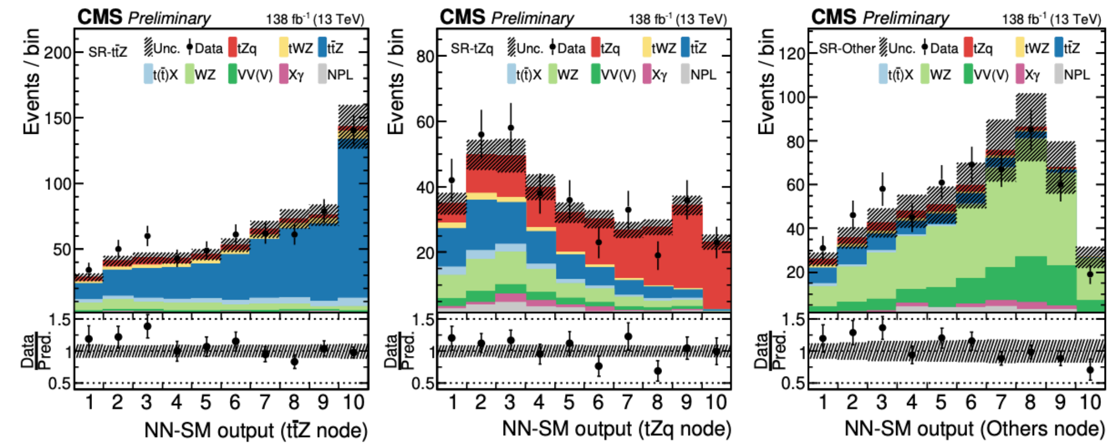
CMS-PAS-TOP-21-001

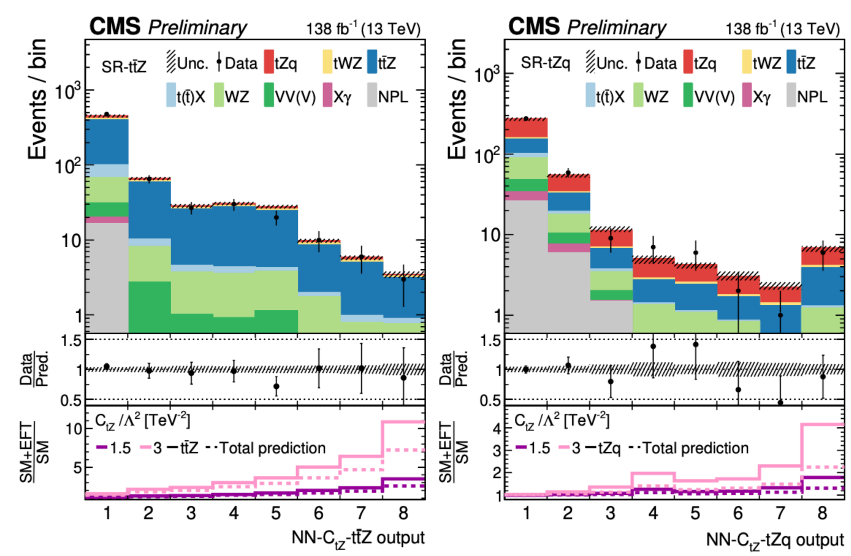
Full Run2 data

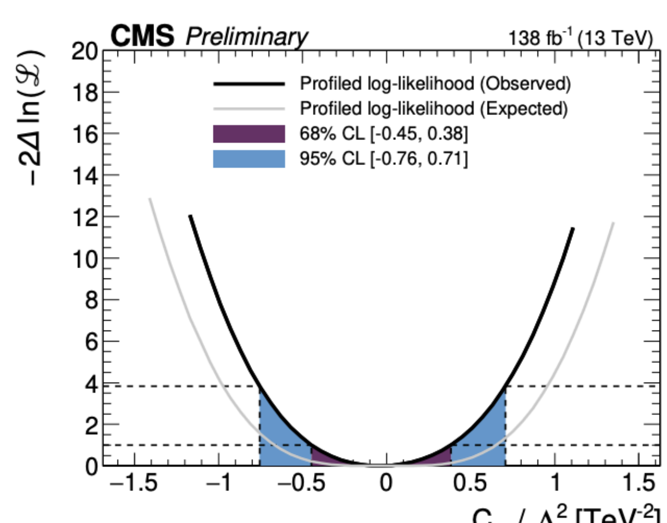
EFT using ML

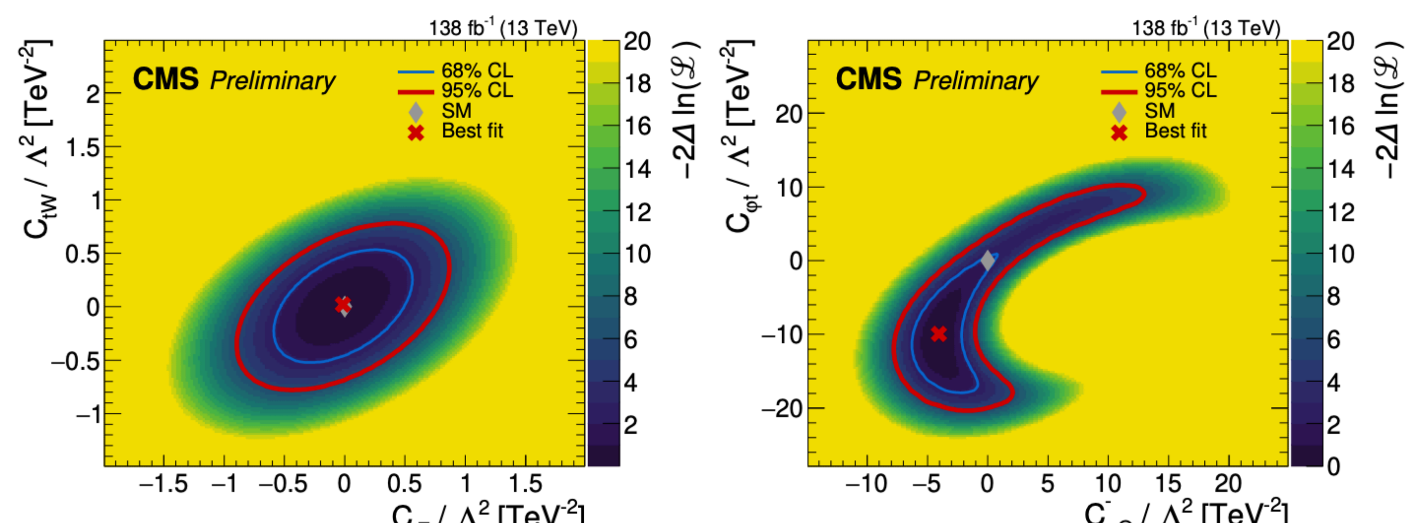


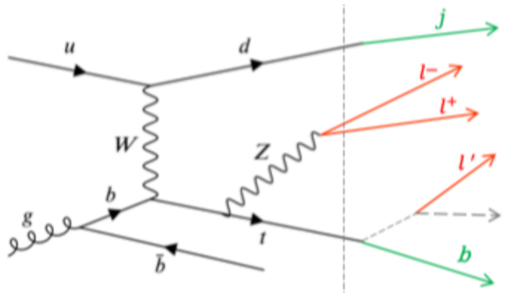
- Probing EFT operators in t(t)Z production in multilepton final states
- Target 3 t-Z associated production modes:
    - complementary, probe similar dim-6 EFT operators
- Analysis strategy entirely optimized to search for EFT effects
- Cross sections & kinematics of signals are parameterized with WCs with reweighting procedure
    - reweight any distribution according to any EFT scenario
- Use novel ML techniques to improve sensitivity to WCs:
    - NN multi class classifier trained to separate physics processes
    - NN binary classifiers trained to separate SM/EFT scenarios
- Signal extraction with simultaneous fits in 6 regions
    - signal yields parameterized with EFT in each bin
    - constrain WCs directly in the fits
- Extract 1D and 5D confidence intervals at 95 % CL for each WC
    - best direct constraints to date from multilepton final states on several WCs
- 1D likelihood scan as a function of each WC (other WCs fixed to 0)
- 2D likelihood scans illustrate correlations of pairs of WCs (other WCs fixed to 0)









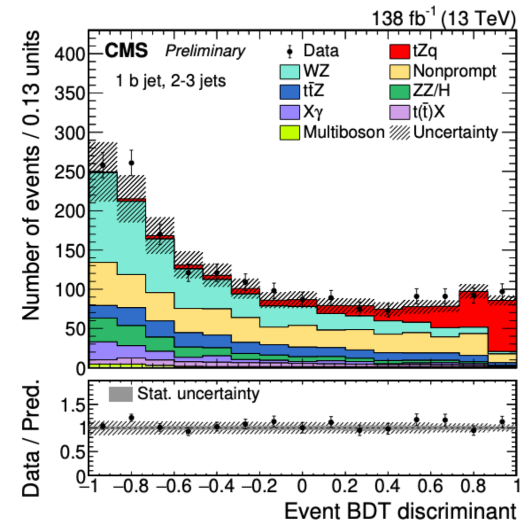


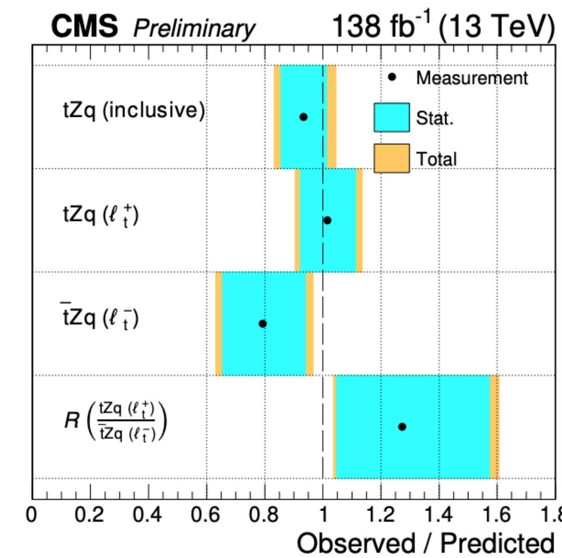
tZq cross section

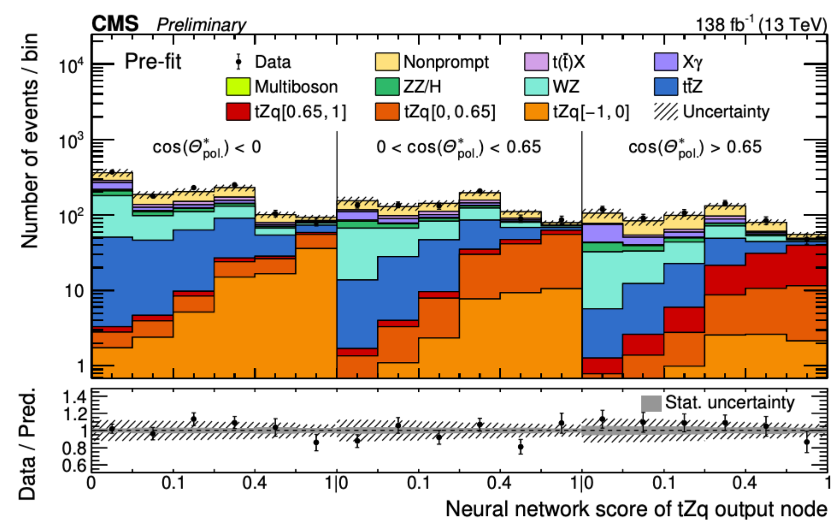
CMS-PAS-TOP-20-010

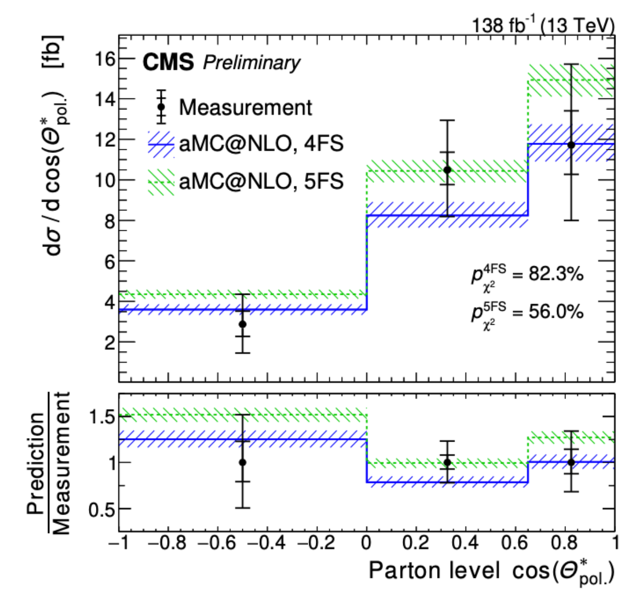
Full Run2 data

- tZq is a probe for new physics (sensitive to top quark polarization and to proton PDFs via top quark-antiquark ratio)
- Inclusive measurement:
  - BDT trained in 3 signal categories based on number of jets and b-jets
  - total unc. improved from 15% to ~11%
- Differential measurement:
  - signal region inclusive in jets and b-jets
  - multiclass NN discrimination between different backgrounds
  - absolute and normalized diff xsec at particle and parton level
- Simultaneous maximum-likelihood fit to output distribution of MVA classifier trained to separate tZq signal: observed good agreement between measurement and prediction
- First measurement of top charge ratio measuring separately top and anti-top associated with Z
- In tZq, top quark is highly polarized: consequence of V-A nature of electroweak coupling→ deviation could point to anomalous coupling structure
- Measured polarization using 'spin asymmetry' variable
  - related to diff. xsec as function of polarization angle
  - fit is reparametrized to extract A directly, with full likelihood and uncertainties









$$\frac{d\sigma}{d\cos(\theta^\star_{\text{pol}})} = \sigma_{\text{tZq}} \cdot \left(\frac{1}{2} + A_\ell \cos(\theta^\star_{\text{pol}})\right)$$

Prediction (for 4FS and 5FS):

$$A_\ell^{4FS} = 0.437^{+0.004}_{-0.003} \qquad A_\ell^{5FS} = 0.454^{+0.004}_{-0.005}$$

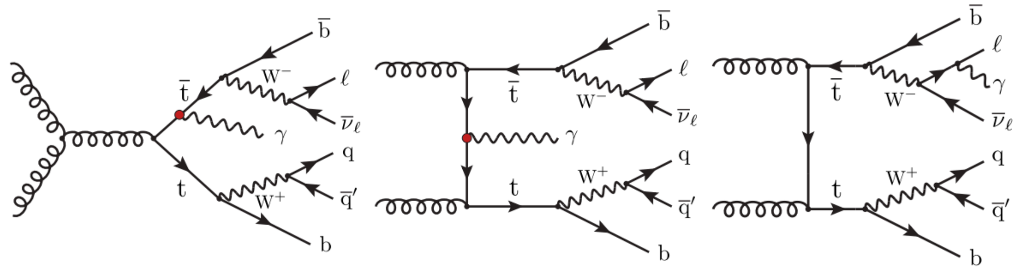
Measurement result:

$$A_\ell = 0.58^{+0.15}_{-0.16}\,(\text{stat}) \pm 0.06\,(\text{syst})$$

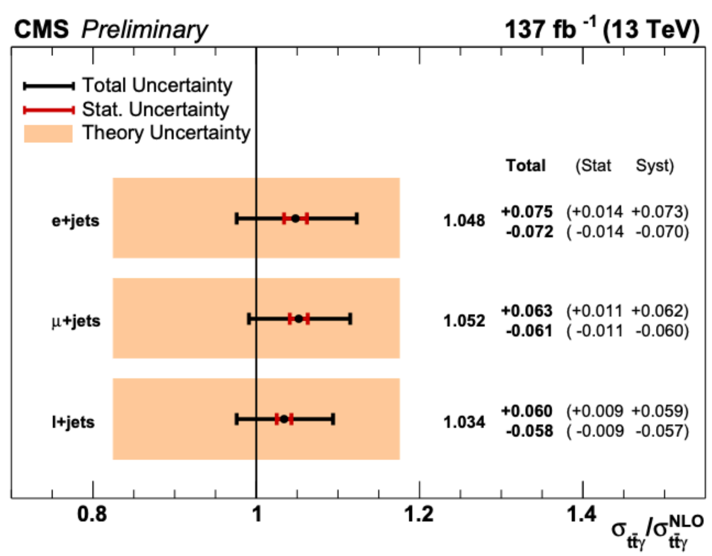
ttγ cross section

CMS-PAS-TOP-18-010

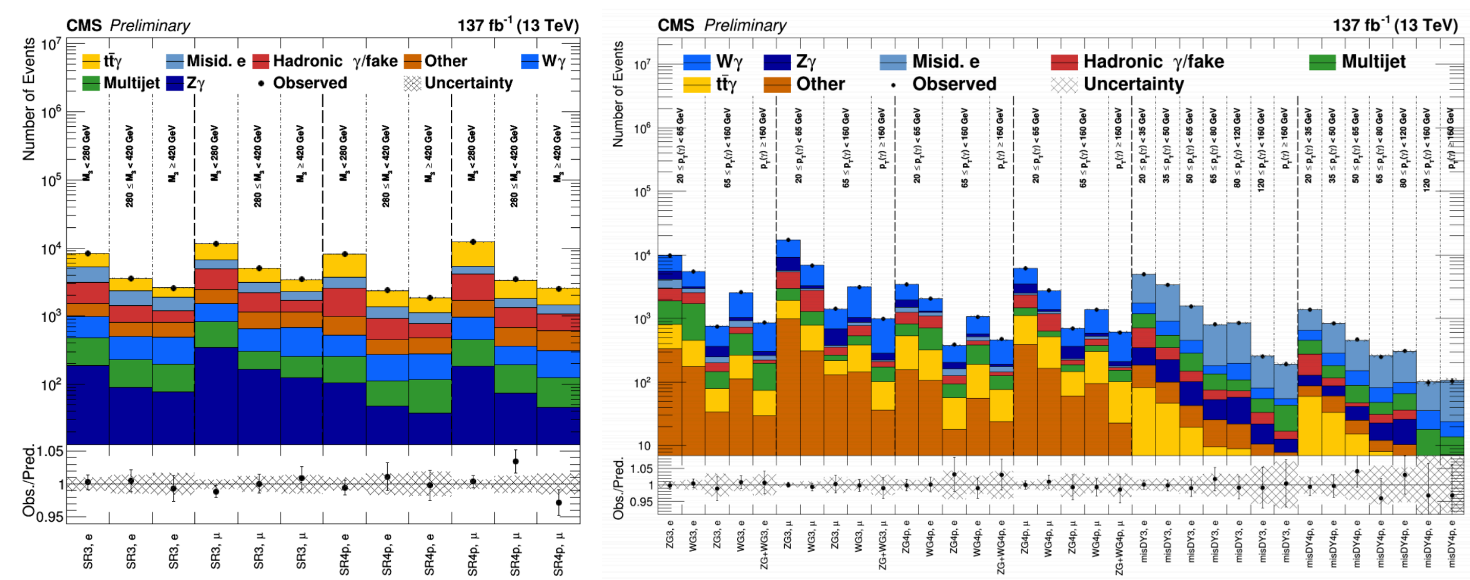
Full Run2 data

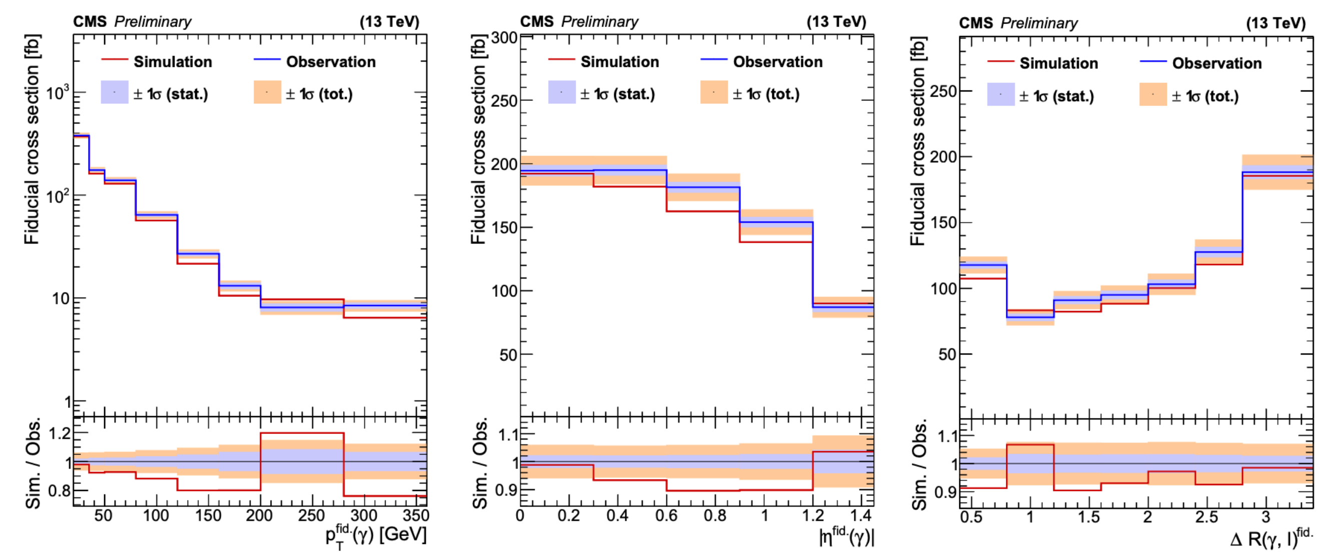


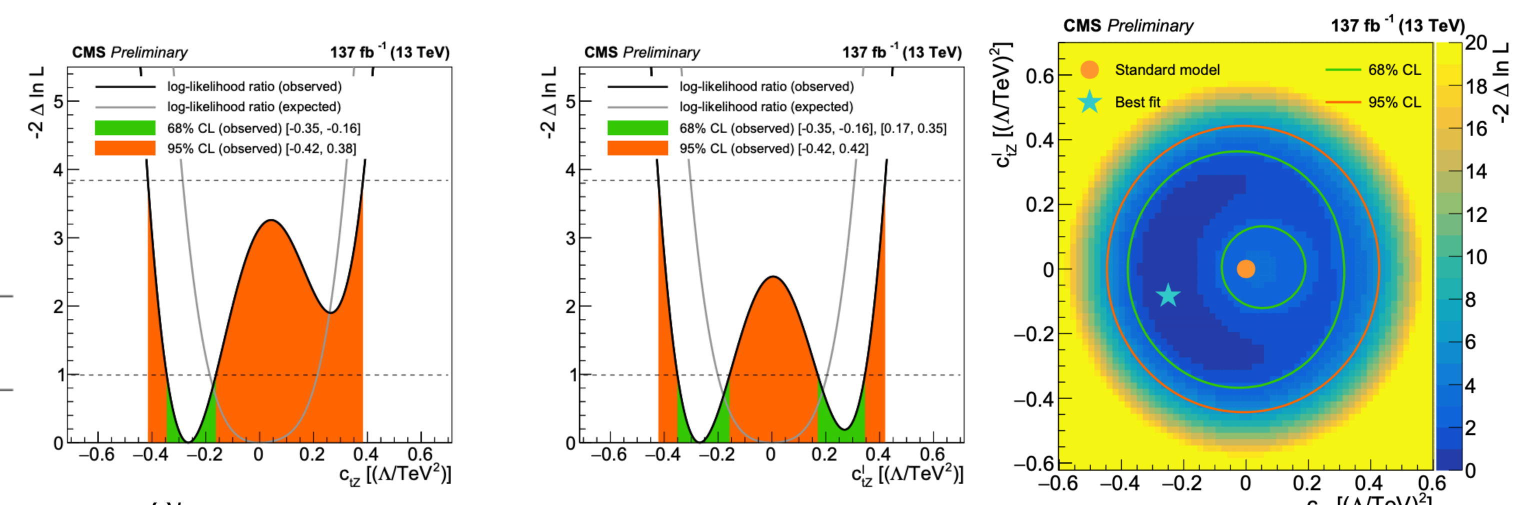
- Constrain main bkgs in-situ with dedicated sidebands (data-driven estimation)
- Inclusive xsec extracted from simultaneous likelihood fits in 12 SRs and 34 CRs
- Differential cross section measured as a function of pT(γ), |η(γ)|, and ΔR(l, γ), unfolded to particle level
- Profiled maximum likelihood scan on Wilson coefficients



Data set	Wilson coefficient	68% CL interval	95% CL interval
expected	c_{tZ}	[-0.19, 0.21]	[-0.29, 0.32]
	c^{I}_{tZ}	[-0.20, 0.20]	[-0.30, 0.31]
observed	c_{tZ}	[-0.35, -0.16]	[-0.42, 0.38]
	c^{I}_{tZ}	[-0.35, -0.16], [0.17, 0.35]	[-0.42, 0.42]





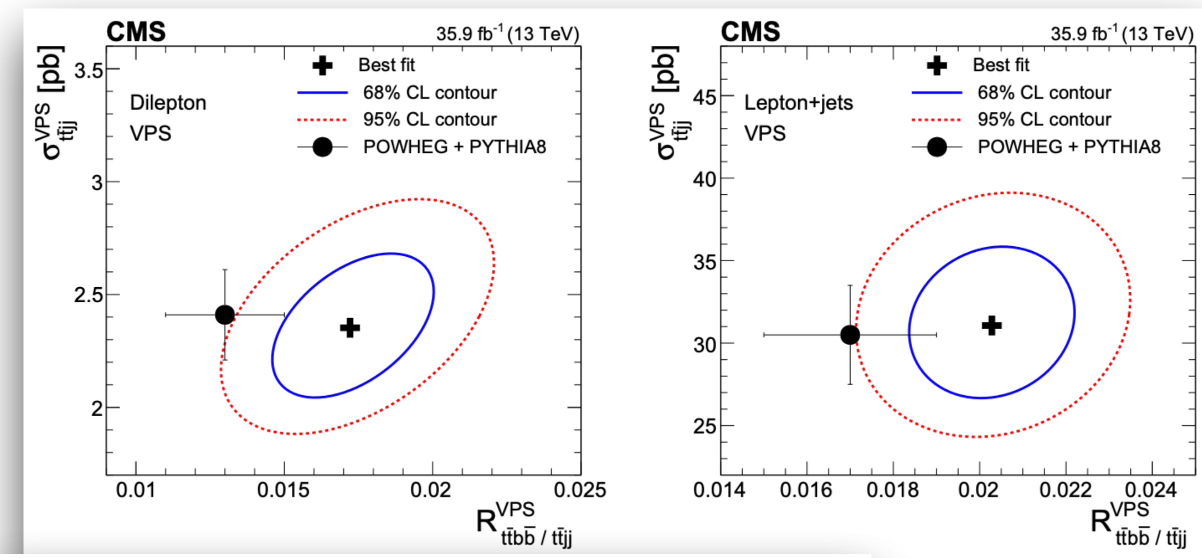


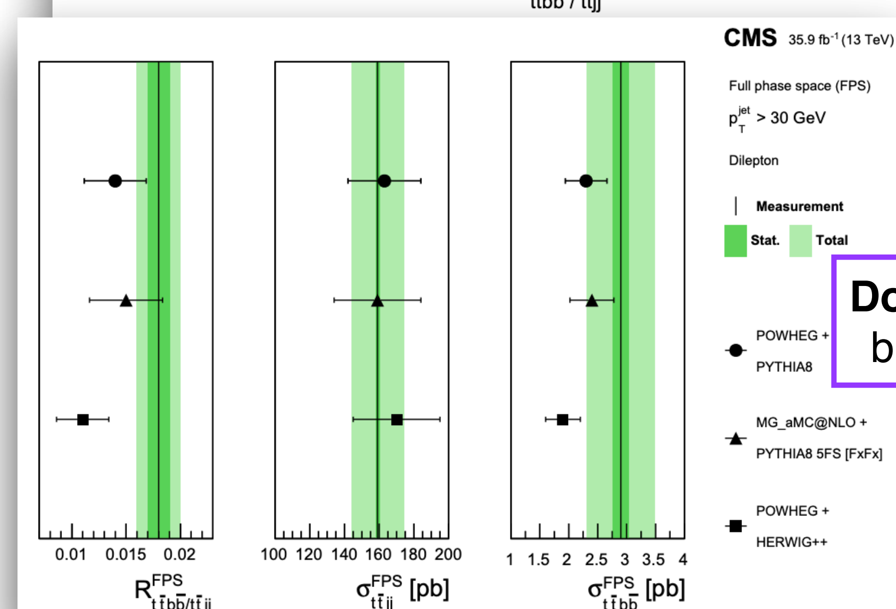
ttjj+ttbb production

JHEP 07 (2020) 125

2016 data
@13 TeV: 35.8 fb^{-1}

- **Dilepton**: 2 e/μ + ≥4 jets (≥2 b-jets)
- **Single lepton**: 1 e/μ + ≥6 jets (≥2 b-jets)
- Extraction of cross sections / ratio from max likelihood binned fit in VPS independently for the 2 channels
  - extrapolated to FPS using acceptances from MC
  - $\sigma_{obs}(ttjj)$ and R_{obs} higher but consistent with different MCs $\sigma_{obs}(ttjj) \simeq \sigma_{SM}(ttjj)$





Dominant syst. unc.: b-tagging, JES, ISR

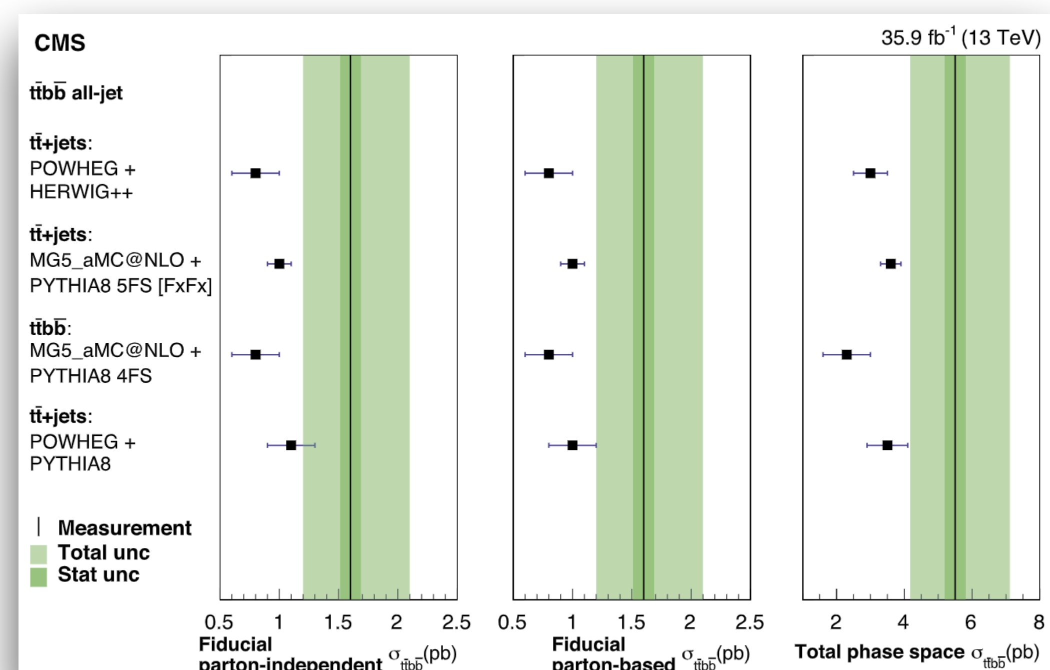
PLB 803 (2020) 135285

2016 data
@13 TeV: 35.9 fb^{-1}

- **Full hadronic**: ≥8 jets (≥4 b-jets)
- Data fitted with profiled ML technique
- Predictions underestimate measurements by a 1.5 - 2.4 factor (1-2 σ)
- Consistent with previous results

	Fiducial, parton-independent (pb)	Fiducial, parton-based (pb)	Total (pb)
Measurement	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$5.5 \pm 0.3^{+1.6}_{-1.3}$
POWHEG ($t\bar{t}$)	1.1 ± 0.2	1.0 ± 0.2	3.5 ± 0.6
POWHEG ($t\bar{t}$) + HERWIG++	0.8 ± 0.2	0.8 ± 0.2	3.0 ± 0.5
MADGRAPH5_aMC@NLO (4FS $t\bar{t}b\bar{b}$)	0.8 ± 0.2	0.8 ± 0.2	2.3 ± 0.7
MADGRAPH5_aMC@NLO (5FS $t\bar{t}$+jets, FxFx)	1.0 ± 0.1	1.0 ± 0.1	3.6 ± 0.3

Dominant syst. unc.:
b-tagging, quark/gluon likelihood, renorm. and fact. scales, MC stat.

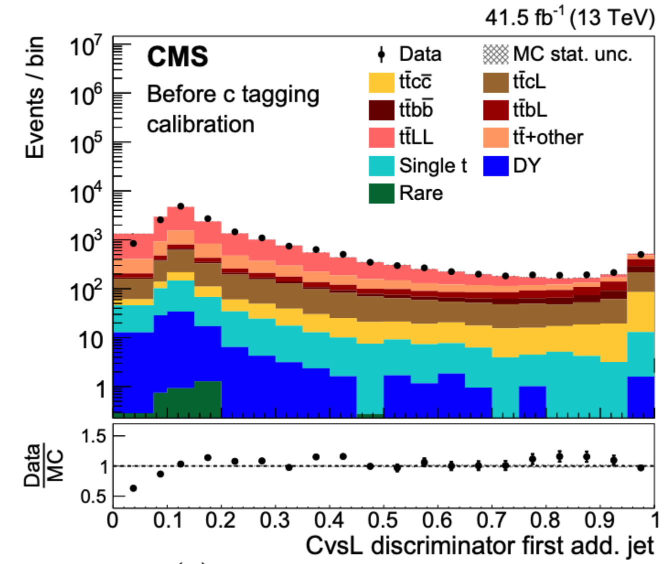


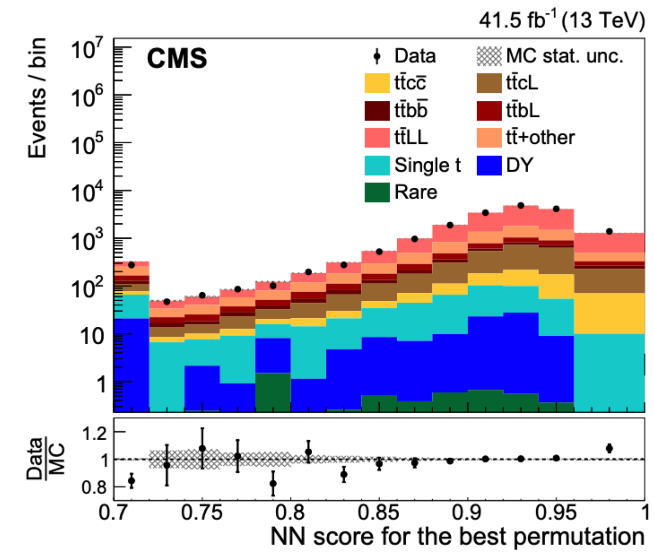
ttcc production

CMS-PAS-TOP-20-003
submitted to PLB

2017 data

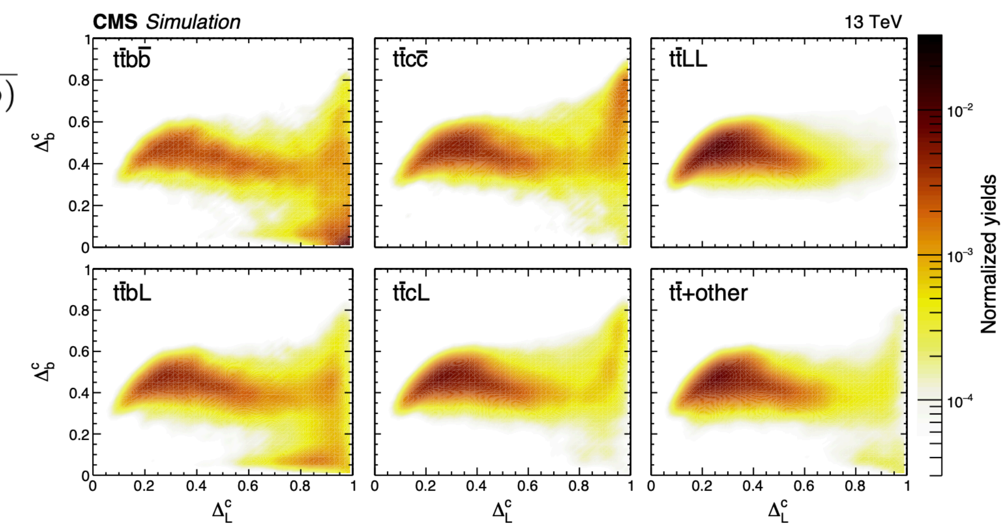
- c, b, and t quarks require jets and heavy flavor tagging (new c-tagger)
  - improved ML techniques for HF tagging (DeepCSV)
  - c-tagger shape calibration using NN discriminants
- Selection and reconstruction of tt+HF topology with jet-parton match:
  - pick best permutations from NN -> clear improvement in matching efficiency
- ML classifier trained to differentiate tt+HF categories (ttbb, ttbL, ttcc, ttcL, ttLF, tt+other)
  - clear separation between the $t\bar{t}b\bar{b}$, $t\bar{t}c\bar{c}$ and ttLF contributions
- Simultaneous fit of event-based NN discriminators in ee, mumu and emu channels
  - 2D distributions will be unrolled to 1D histogram -> 4x4 binning results in 16 bins with varying flavor composition
  - systematic uncertainties as nuisance parameters in the fit
  - scaling factors represent the signal strength and are related to the cross section





$$\mathrm{CvsL} = \frac{P(c)}{P(c) + P(udsg)},$$

$$\mathrm{CvsB} = \frac{P(c)}{P(c) + P(b) + P(bb)}$$



$$\sigma = \frac{\mu \times N^{MC}}{\mathcal{L}^{int} \times \epsilon}$$

$$\Delta_L^c \otimes \Delta_b^c : [0, 0.45, 0.6, 0.9, 1.0] \otimes [0, 0.3, 0.45, 0.5, 1.0]$$

- Some tension observed but overall agreement within 1-2 sigma with Powheg predictions:
  - ttbb comes out higher, ttcc and ttLF come out a bit lower in the data
  - Rc is in very good agreement with theory prediction
  - largest tension observed for Rb

$$\Delta_b^c = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c}) + P(t\bar{t}b\bar{b})}$$

$$\Delta_L^c = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c}) + P(t\bar{t}LL)}$$

Dominant syst. unc.:
Jet energy scale, c-tagging calibration, renormalization and factorization scales in ME, matching ME-PS (hdamp)