Searches for new physics with top quarks

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HQL2021

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HQL2021 - The XV International Conference on Heavy Quarks and Leptons

Sep 13-17, 2021

Where do we stand?

- So far, no evidence for new physics (NP) in direct searches at the energy frontier

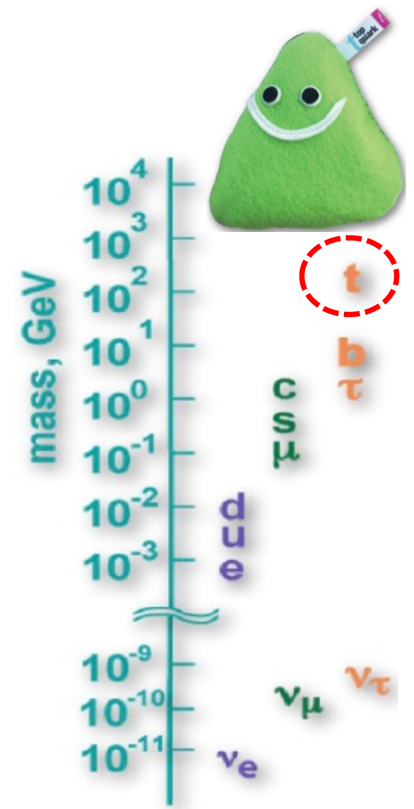
GeV → 100 GeV → Where ???

QCD scale | EW scale | New scales for new phenomena?

dark matter, neutrino mass, matter-antimatter asymmetry, gravity, …

- Concentrate on precision measurements of vector bosons, Higgs boson, and top quark at the LHC
  - ❑ Unprecedented scrutiny of SM (model parameters, particle properties, gauge structure, rare processes…)
  - ❑ Indirect sensitivity to NP (anomalous couplings, loop effects…)
- LHCb and Belle II have a special appetite for bottom and charm quarks as well as for tau leptons
  - ❑ Intriguing hints for the lepton family universality violation in certain B-meson decays

arXiv:2103.11769

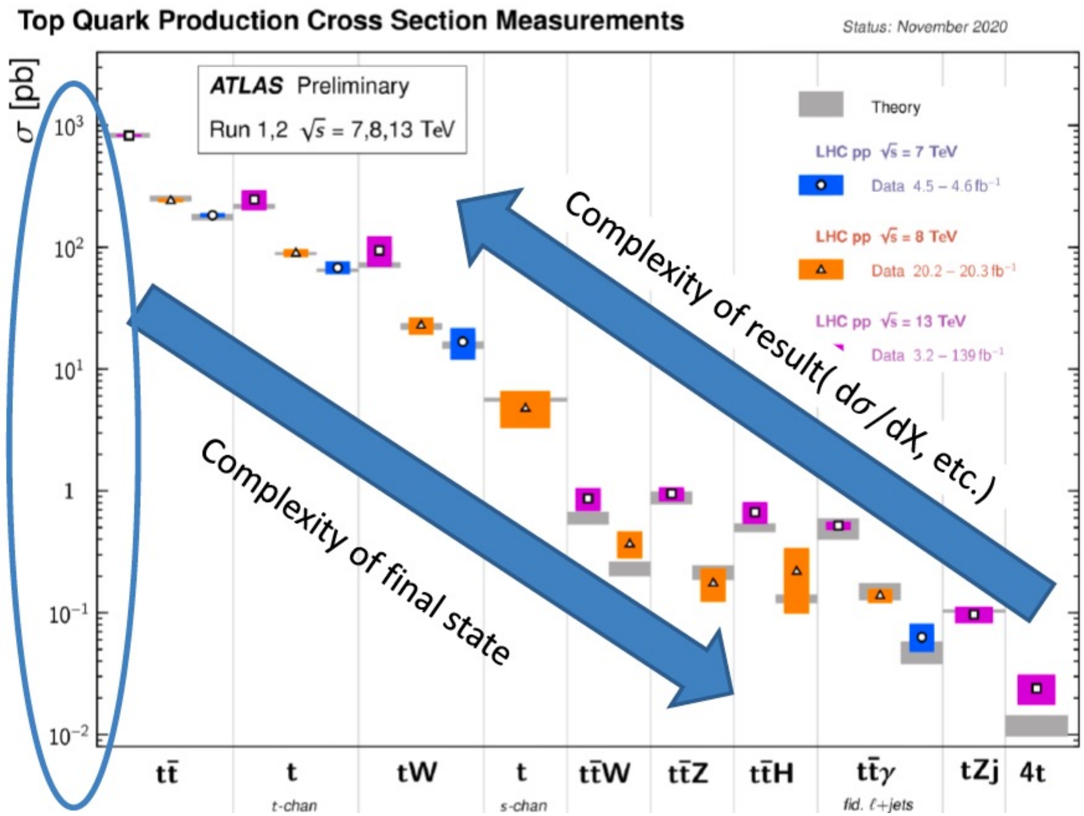


☞ Focus of my talk on the heaviest known elementary particle

How can the top quark help?

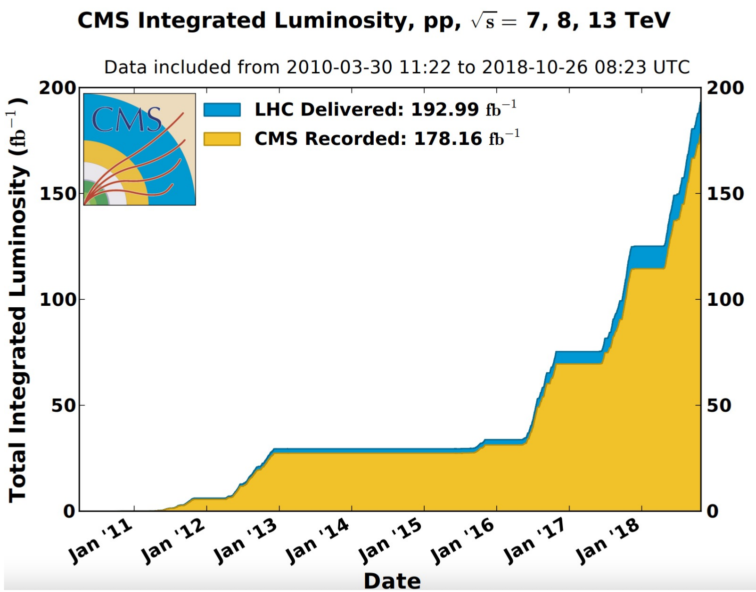
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{\text{QCD}}}}_{\substack{\text{hadronization}\\10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\10^{-21}\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

- Unique properties:
  - ❑ Extremely short lifetime ⇒ access to bare properties
  - ❑ Largest Yukawa coupling to the Higgs ⇒ key role in EW symmetry breaking
  - ❑ Spin information preserved in the angular distribution of its decay products ⇒ provides an ideal setting for spin measurements
- Produced in large numbers at the LHC with its Run-2 accumulating
  - ❑ About 120M top quark pairs (~15 pairs per sec)
  - ❑ About 30M single top-quark events (~5 events per sec)
- Rare top-quark processes are produced with a cross section of ≤ 1 pb ⇒ see talk by Matis



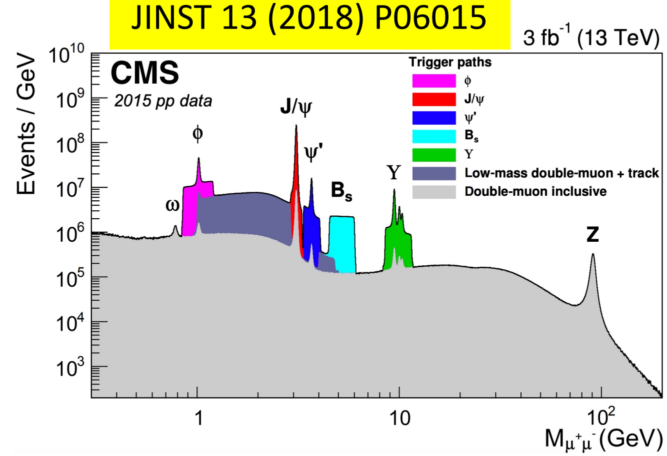
☞ Present a suite of NP sensitive measurements related to the top quark

Need data: both quantity & quality

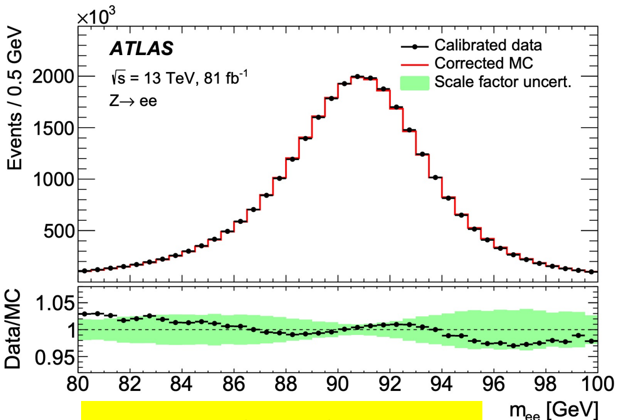


- Incredible performance by the machine crew
- Detector teams make the data collection as smooth as it can get

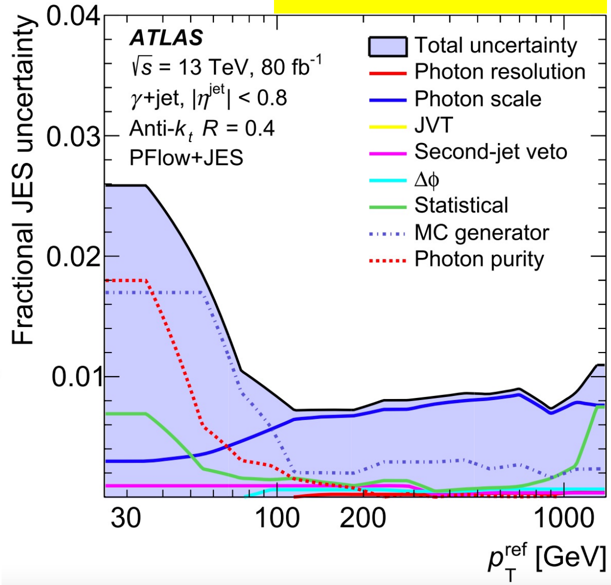
JINST 13 (2018) P06015



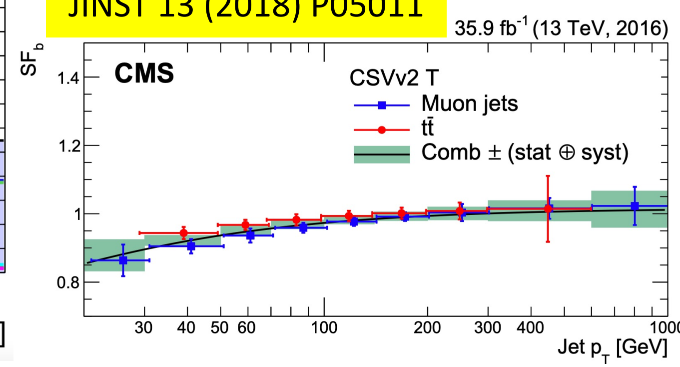
EPJC 81:689 (2021)



JINST 14 (2019) P12006



JINST 13 (2018) P05011



- Successful data harvesting owes to a precise understanding of physics objects

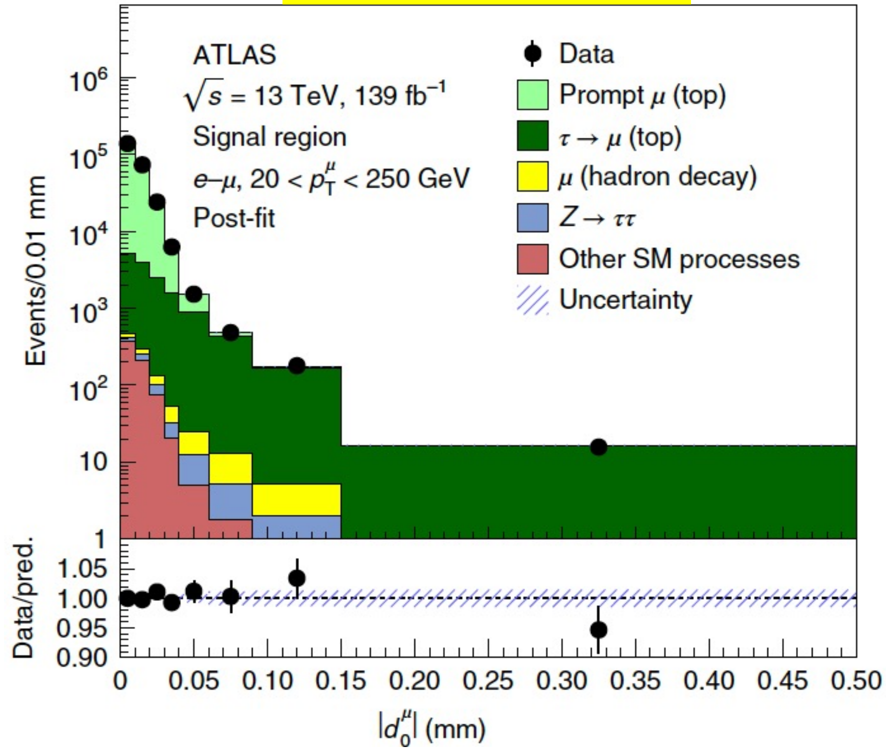
Test of lepton universality in $t\bar{t}$ events

- Utilize top quark pair events as a copious source of on-shell W bosons
- Determine lepton flavor universality ratio:

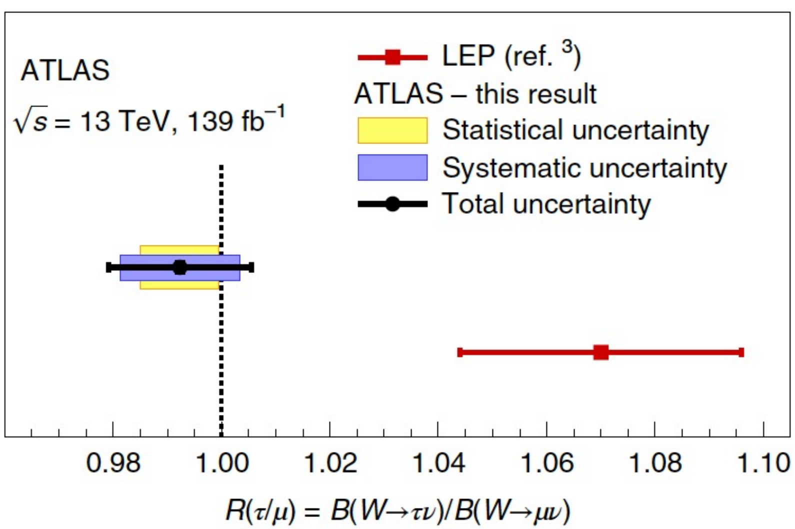
$$R(\tau/\mu) = \frac{\mathcal{B}(W\to\tau\nu_\tau)}{\mathcal{B}(W\to\mu\nu_\mu)}$$

by comparing transverse impact parameter (d_0) of prompt μ and $\tau \to \mu$ arising from W decays

Nat. Phys. 17 (2021) 813



- Challenge: modeling of d_0 distributions
- Care in obtaining d_0 resolution correction and data-driven background contribution

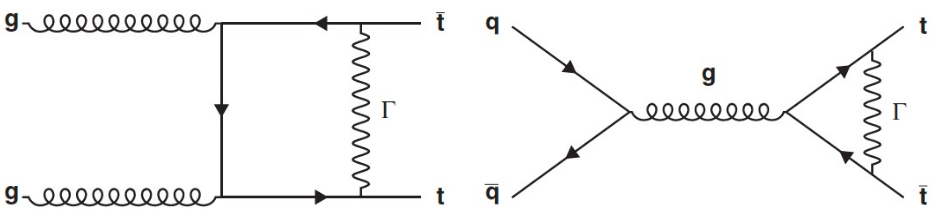


$$\boxed{R(\tau/\mu) = 0.992 \pm 0.013\,[\pm 0.007\,(\text{stat}) \pm 0.011\,(\text{syst})]}$$

☞ Record precision surpassing LEP as well as resolves the longstanding 2.7σ discrepancy

Probe NP via top Yukawa coupling

- Measure the top Yukawa coupling ($Y_t = g_t/g_t^{SM}$) exploiting loop effects in the dilepton channel of $t\bar{t}$ events



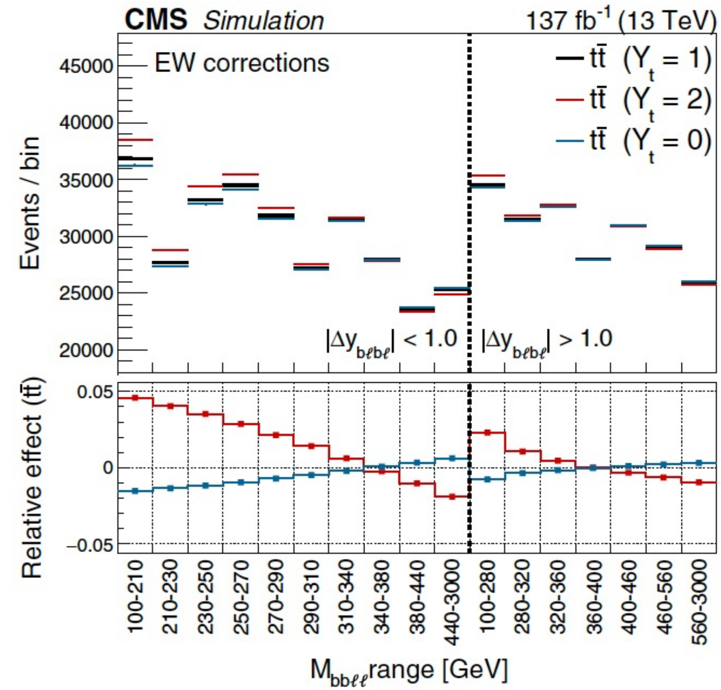
Γ denotes a neutral scalar (H) or vector boson

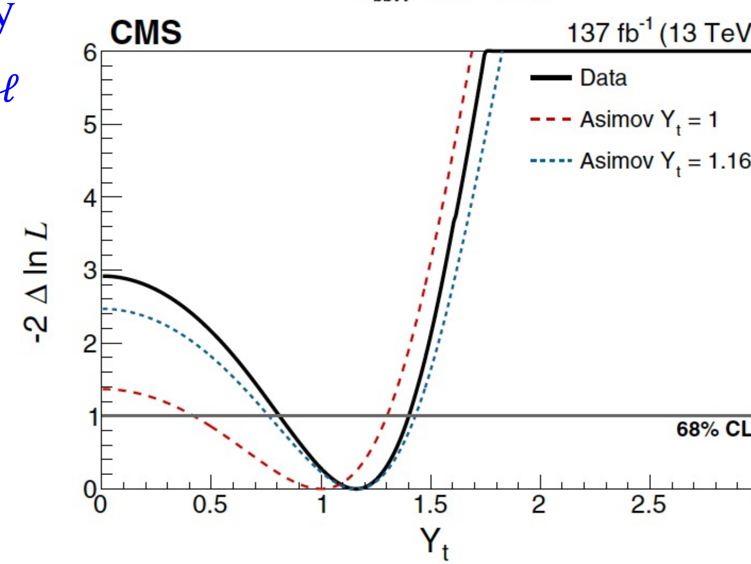
- Invariant mass of the $t\bar{t}$ system and the rapidity difference between the top quark and antiquark are sensitive to the Y_t value
- Avoid the p_T^{miss} dependence using $b\ell$ as a proxy for top quark and do binned fit in $M_{bb\ell\ell} \times \Delta y_{b\ell b\ell}$

PRD 102 (2020) 092013

$$\boxed{Y_t = 1.16^{+0.07}_{-0.08}(\text{stat})^{+0.23}_{-0.34}(\text{syst})}$$

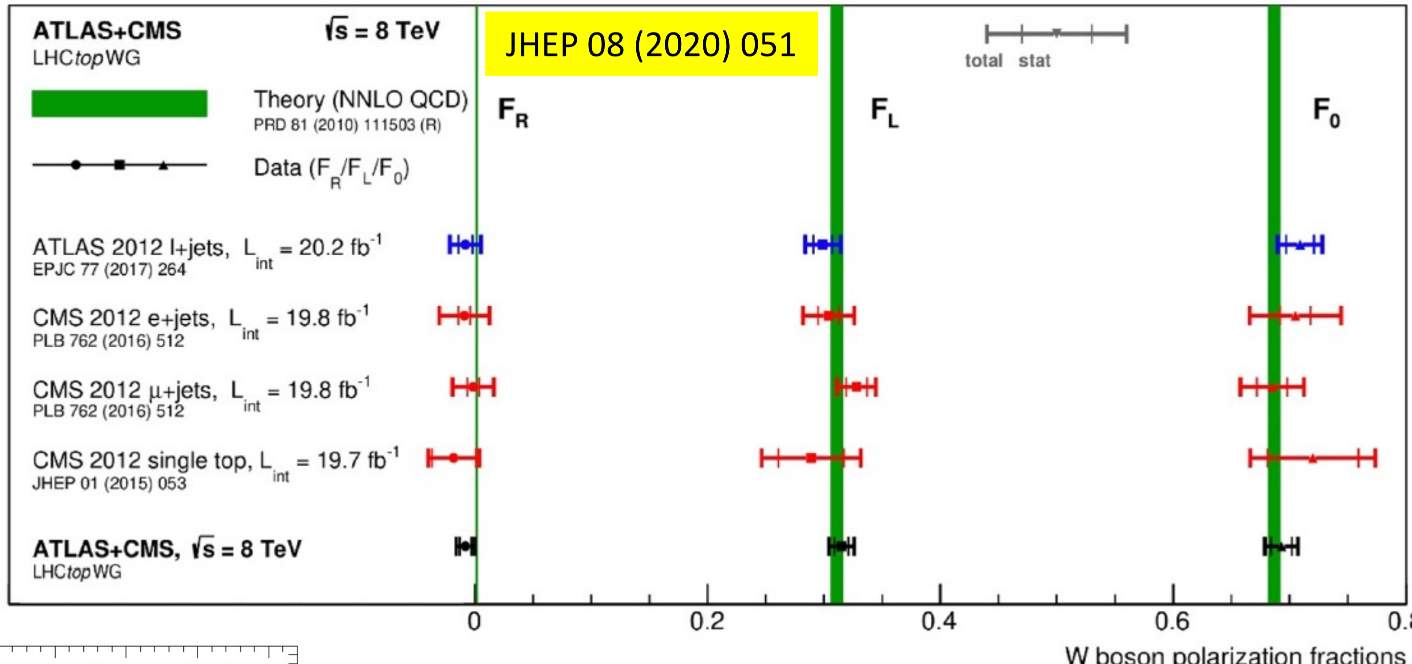
- ❑ Dominant systematic sources: EW corrections, signal modeling, and flavor JES
- ☞ New complementarity to the on-shell Higgs boson studies EPJC 79, 421 (2019)

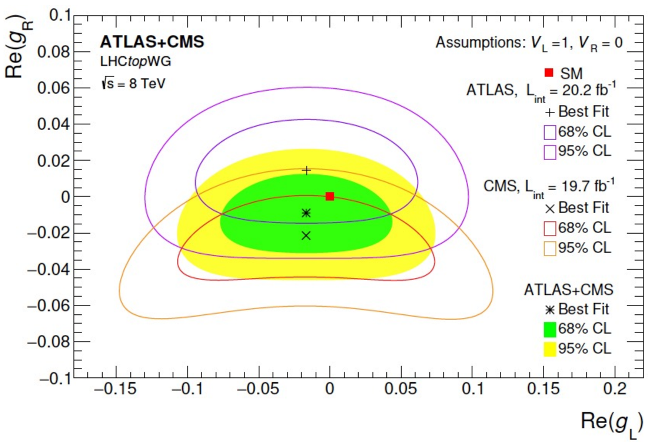




W boson polarization in top quark decays

- Information on the W boson polarization in top quark decays can shed light on the nature of tWb weak interaction
- Combine 8 TeV measurements from both experiments ⇒ record precision





- ➢ Interpreted as constraints in anomalous couplings, e.g., left plot shows limit on anom. tensor coupling
- ➢ Also set limits on the Wilson coefficients:

	ATLAS	CMS	Comb.
$C^*_{\phi\phi}$	$[-5.64, 7.68]$	$[-3.84, 4.92]$	$[-3.48, 5.16]$
C^*_{bW}	$[-1.30, 0.96]$	$[-1.06, 0.72]$	$[-0.96, 0.67]$
C_{tW}	$[-0.34, 0.67]$	$[-0.62, 0.19]$	$[-0.48, 0.29]$

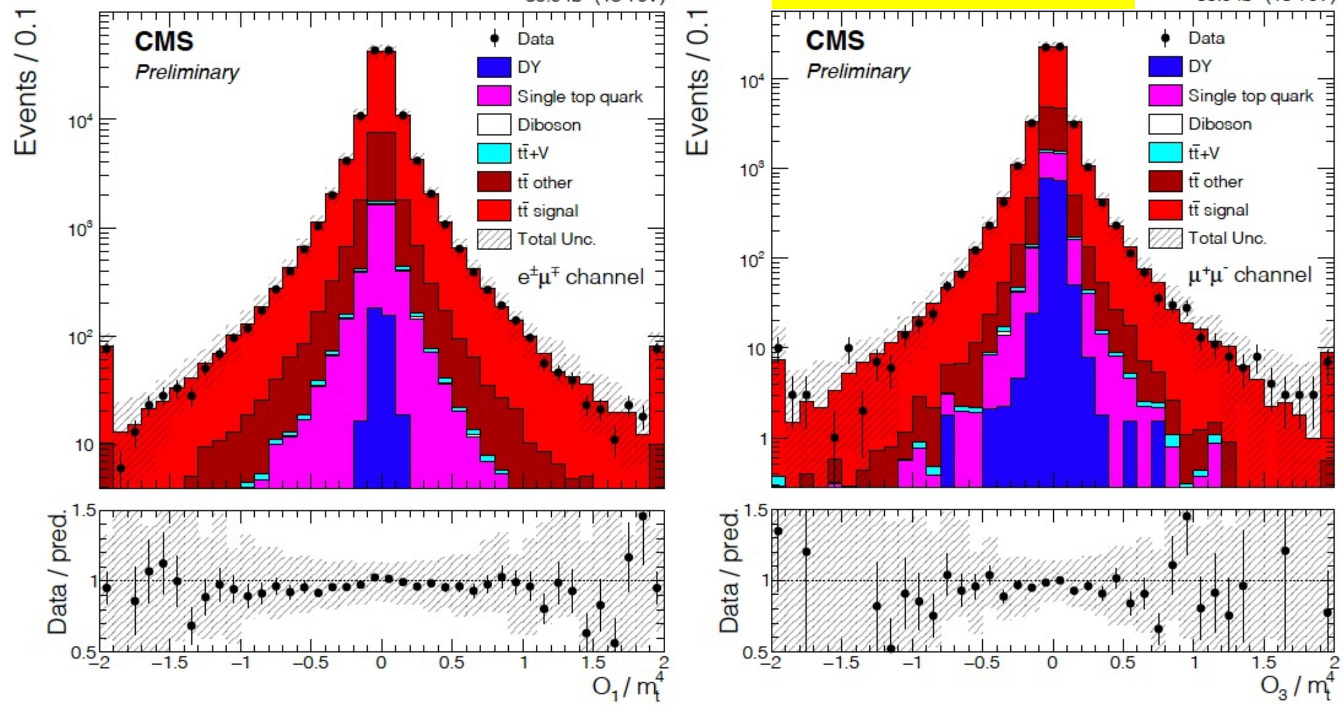
CP violating anomalous top quark coupling

- Search for CP violation in the dilepton final state of $t\bar{t}$ events based on two CP-odd observables $\mathcal{O}_1$ and $\mathcal{O}_3$ ⇒ determinants of 4×4 matrices having the four-momenta of charged leptons, b jets, and top quarks as components
- The chromoelectric dipole moment (CEDM) of top quark is extracted from these observables

CMS PAS TOP-19-007

➢ $\mathcal{O}_1$ and $\mathcal{O}_3$ may be as large as 15% and 9% in some NP models with a CEDM

Hayreter and Valencia, PRD 93 (2016) 014020

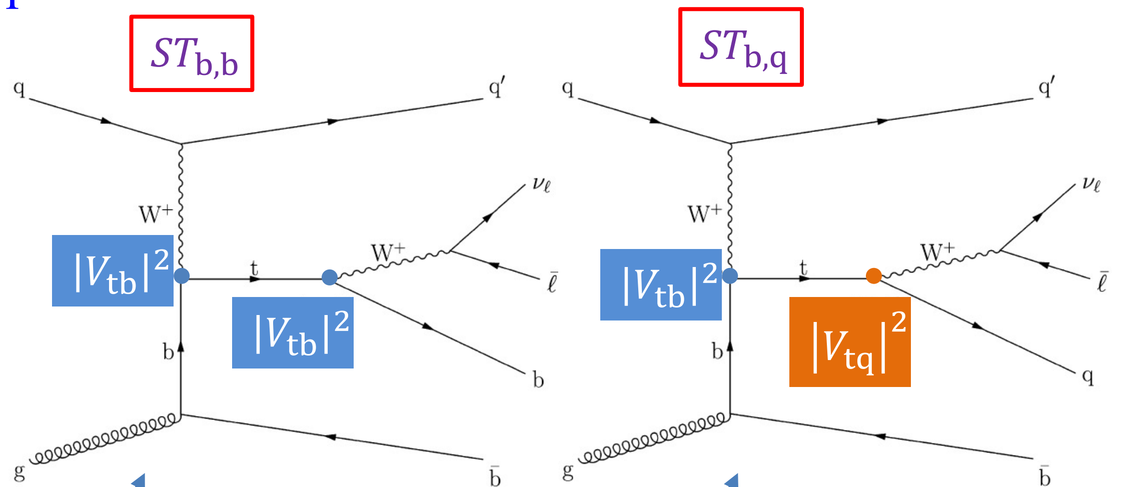


☞ Results consistent with the SM

Physics observable	d_{tG}	CEDM (10^{-18} $g_s \cdot$ cm)
$\mathcal{O}_1$	$0.10 \pm 0.12(\text{stat}) \pm 0.12(\text{syst})$	$0.58 \pm 0.69(\text{stat}) \pm 0.70(\text{syst})$
$\mathcal{O}_3$	$0.00 \pm 0.13(\text{stat}) \pm 0.10(\text{syst})$	$-0.01 \pm 0.72(\text{stat}) \pm 0.58(\text{syst})$

CKM matrix elements in top sector

- First direct, model-independent measurement of CKM matrix elements $|V_{td}|$, $|V_{ts}|$, and $|V_{tb}|$ in *t*-channel single top quark events
- Distinguish various signals via a simultaneous fit to data in different event categories



➢ Assuming unitarity

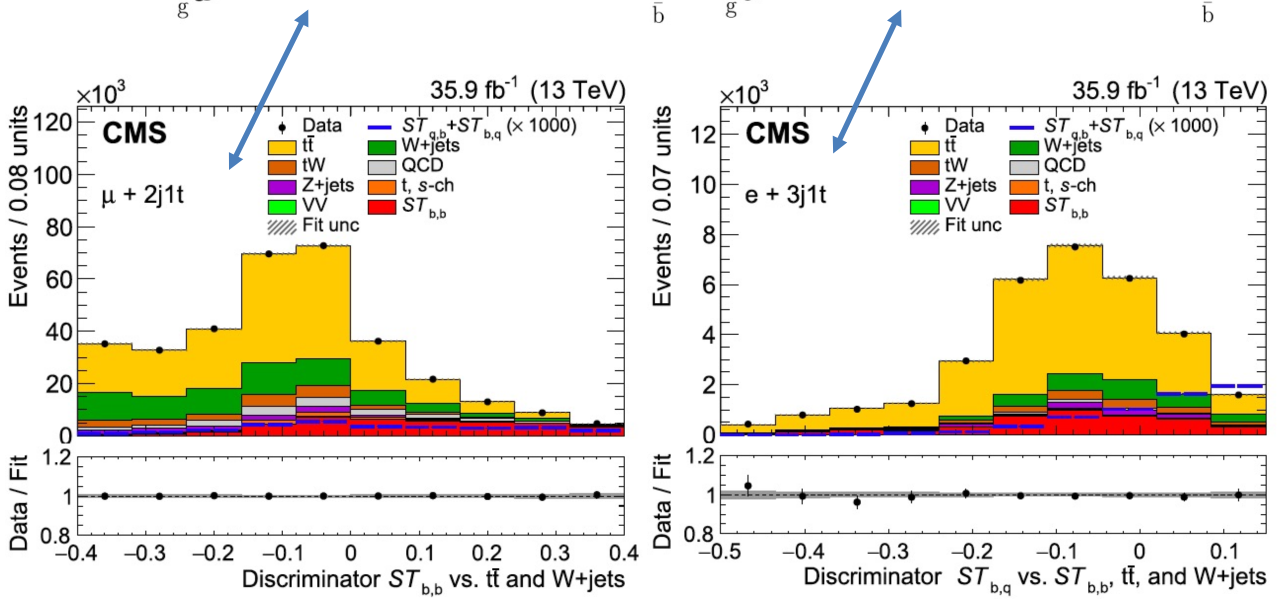
$|V_{td}|^2 + |V_{ts}|^2 < 0.057$, $|V_{tb}| > 0.97$

➢ Allowing for ≥ 3 quark families

$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$

$|V_{tb}| = 0.988 \pm 0.051$

PLB 808 (2020) 135609



☞ Best determination of these SM parameters via single top quark measurements

Novel approach to probe NP in top sector

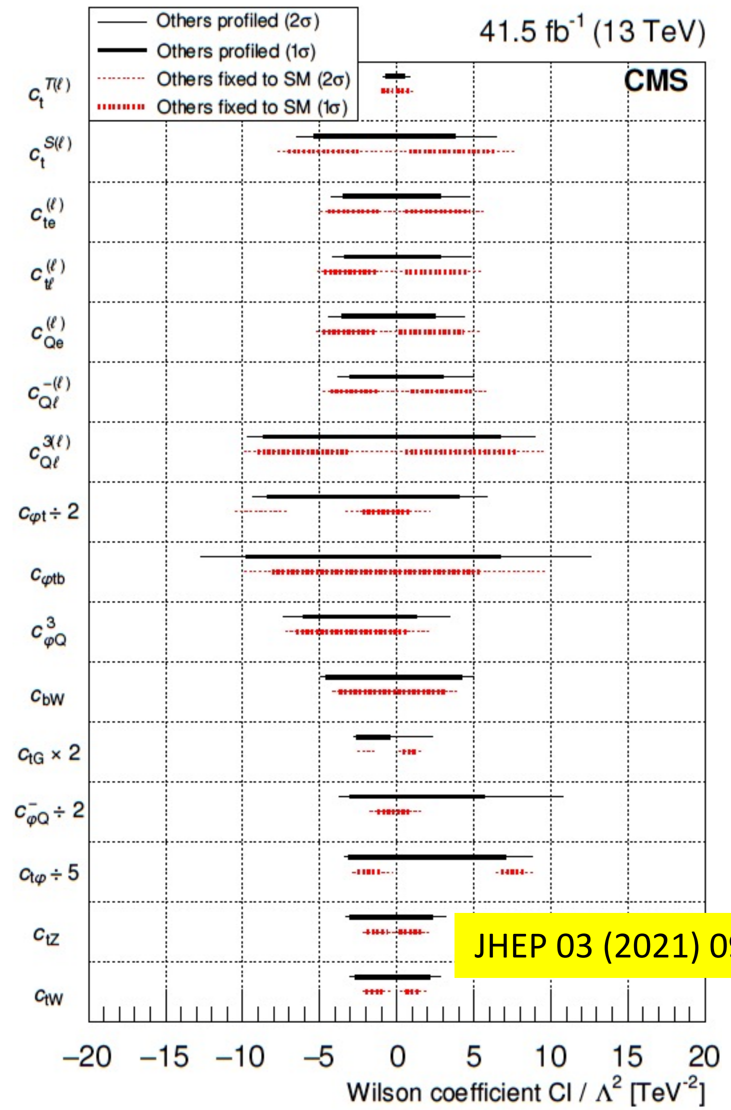
- Events containing at least one top quark produced with extra prompt leptons are used for NP search within the framework of an effective field theory

$$\boxed{\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d}$$

$\mathcal{O}_i^d$ are EFT operators of dimension d and c_i^d are the Wilson coefficients (WCs) that describe interaction strengths of $\mathcal{O}_i^d$

- Study in total 16 contributing dim-6 operators
- Observed signal yields are modeled in terms of the WCs of EFT operators
- Simultaneously extract these WCs with ttZ, ttW, tHq, tZq, and ttH events

➢ All results consistent with SM predictions



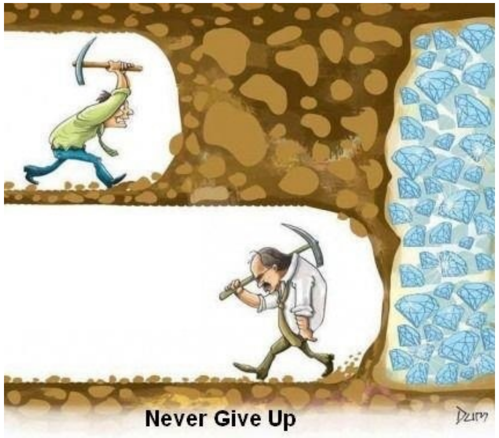
JHEP 03 (2021) 095

☞ First attempt of a global analysis considering all processes relevant for a given EFT operator

Closing words

- Discussed a number of recent measurements probing NP in the top quark sector
- Large data sample, exhaustive work, and deployment of novel techniques have led to unprecedented sensitivity in most of the channels
- Interpretation of measurements is being more vigorously pursued, e.g., using the EFT framework
- Further results with the full Run-2 data are on the way

☞ History has shown that we must continue digging



Bonus material

Systematics uncertainty in $R(\tau/\mu)$

Source	Impact on $R(\tau/\mu)$
Prompt d_0^{μ} templates	0.0038
μ_{prompt} and $\mu_{\tau(\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
μ_{had} normalization	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_{T} spectrum variation	0.0026
μ_{had} parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{\tau(\to\mu)}$ and μ_{had} d_0^{μ} shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalization	0.0009
Other sources	0.0004
$B(\tau\to\mu\nu_{\tau}\nu_{\mu})$	0.0023
Total systematic uncertainty	0.0109

- Not a single major one, rather several almost similar contributors