Top quark properties

CMS results on: top quark Yukawa coupling
$t\bar{t}$ spin correlations
forward-backward asymmetry
W polarization in top quark decays
CKM elements involving top quark

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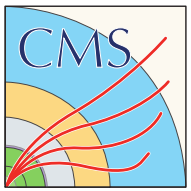
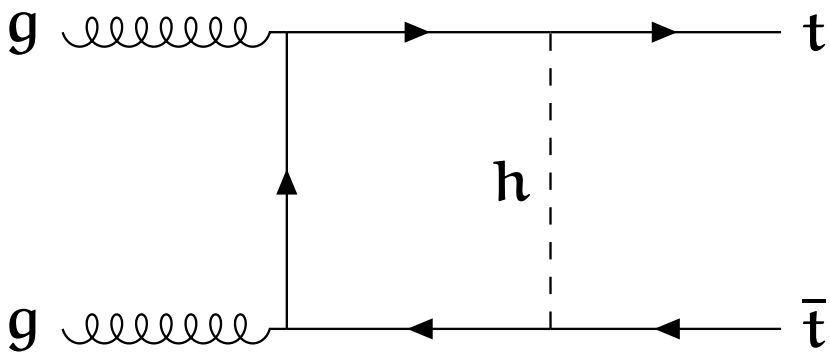
on behalf of the CMS collaboration

Parallel session: Top physics
8th Annual Conference on Large Hadron Collider Physics
May 25th–30th, 2020



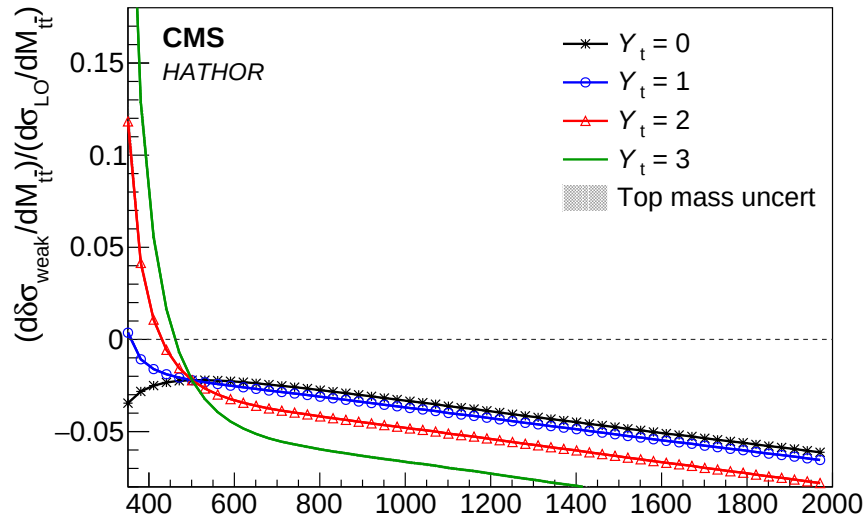
Yukawa coupling from $t\bar{t}$ production

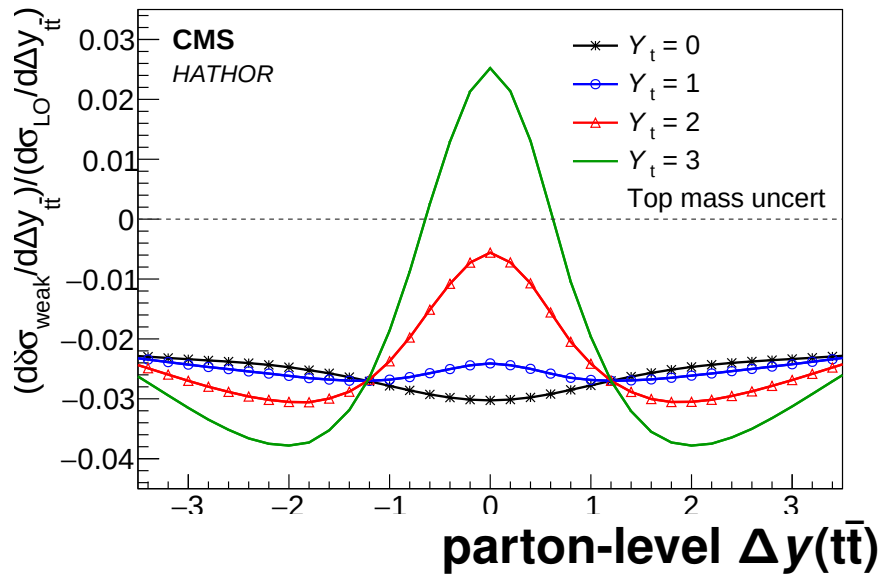
Phys. Rev. D 100 (2019) 072007



- Higgs boson contributes to $t\bar{t}$ production at order $\alpha_s^2\alpha_{\text{weak}}$
- sensitive to top Yukawa coupling, especially in threshold region
- corrections from HATHOR as function of $M(t\bar{t})$ and $\Delta y(t\bar{t})$ for different values of $Y_t = g_t/g_t^{SM}$
- strategy: double-differential $t\bar{t}$ cross section measurement to constrain Y_t

Y_t correction to $\sigma(t\bar{t})$

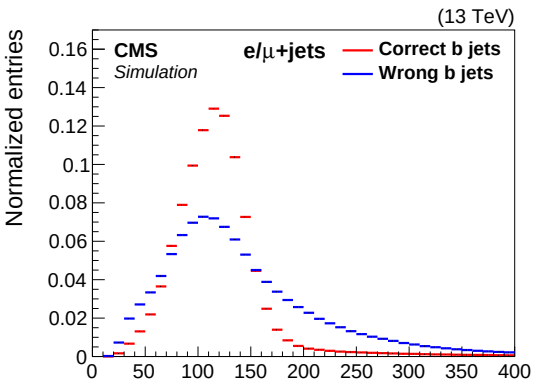




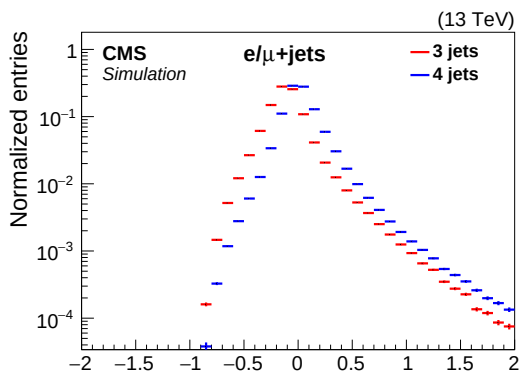
Yukawa coupling: lepton+jets channel

Phys. Rev. D 100 (2019) 072007

- $=$ 1 electron or muon, $\geq$ 3 jets, $\geq$ 2 b-tags
- backgrounds: V+jets, single-top, QCD multijet (shape from control region)
- fulll $t\bar{t}$ reconstruction
  - neutrino momentum constrained from MET
  - m_t, m_W constraints for jet assignment
  - no hadronic W constraint for 3 jet events

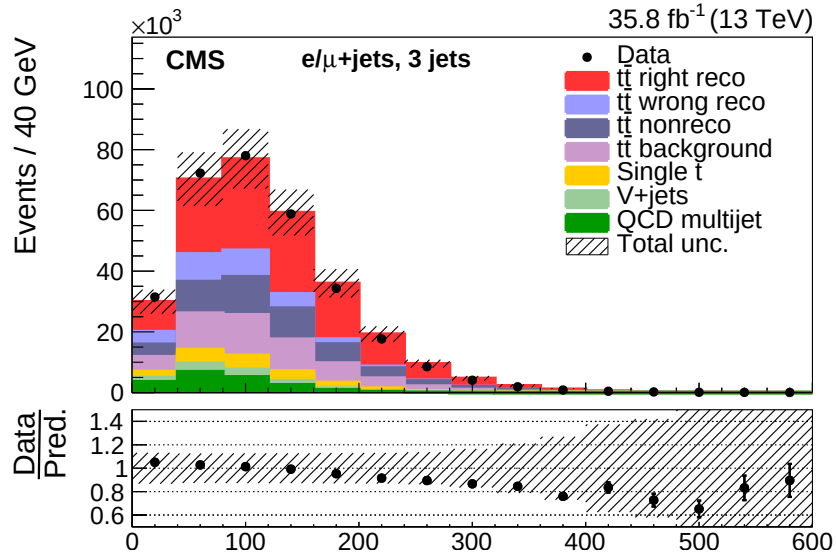


3j: hadronic top mass [GeV]

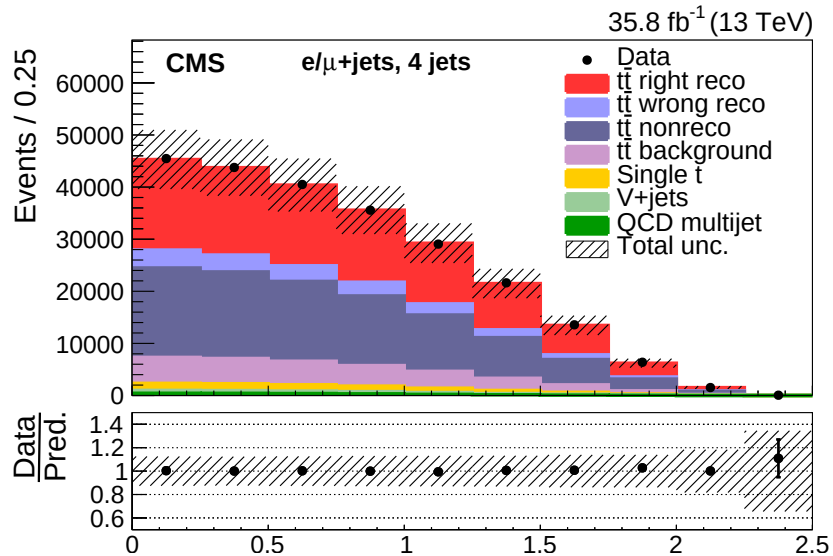


3j/4j: $M(t\bar{t})^{rec}/M(t\bar{t})^{gen} - 1$

- template fit to $[M(t\bar{t}),|\Delta y(t\bar{t})|]$ in 3j, 4j, $\geq$5j
- uncertainties: QCD multijet background, top mass, matrix element scales



3j events: leptonic top p_T [GeV]

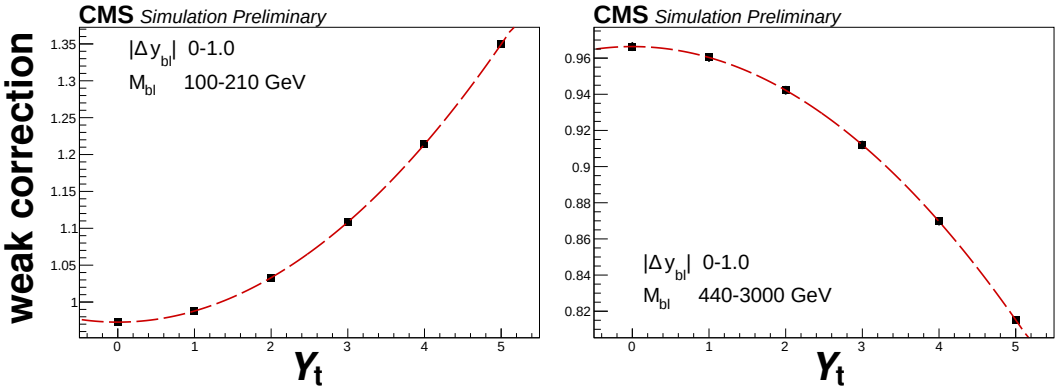


4j events: hadronic top $|y|$

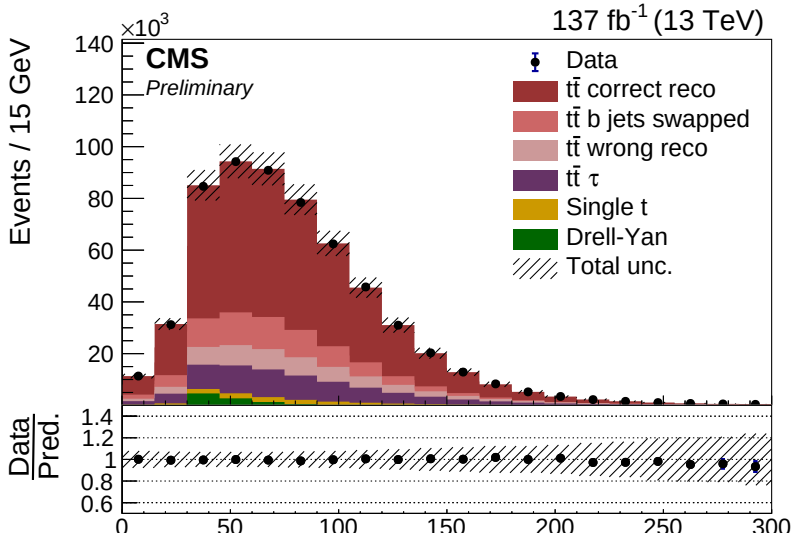
Yukawa coupling: dilepton channel

CMS-PAS-TOP-19-008

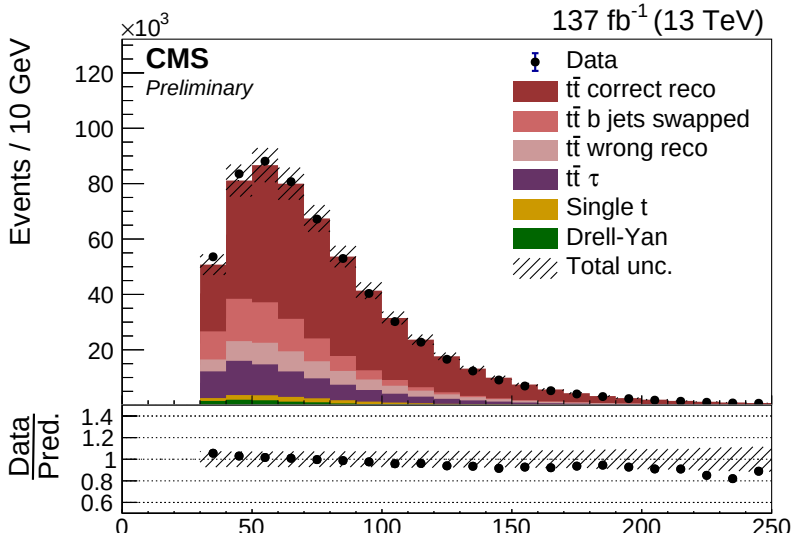
- $=$ 2 electrons and/or muons, $\geq$ 2 jets, $\geq$ 2 b-tags, DY veto in same-flavour events
- backgrounds: V+jets, single-top
- partial $t\bar{t}$ reconstruction for jet assignment
  1. m_t, m_W constraints for both neutrinos
  2. MET constraint for both neutrinos
  3. minimal ΔR between b-jets and leptons
- template fit to [$M(b\ell b\ell)$,$|\Delta y(b\ell,b\ell)|$] per year



- uncertainties: parton shower, EW corrections, matrix element scales



full Run 2: missing p_T



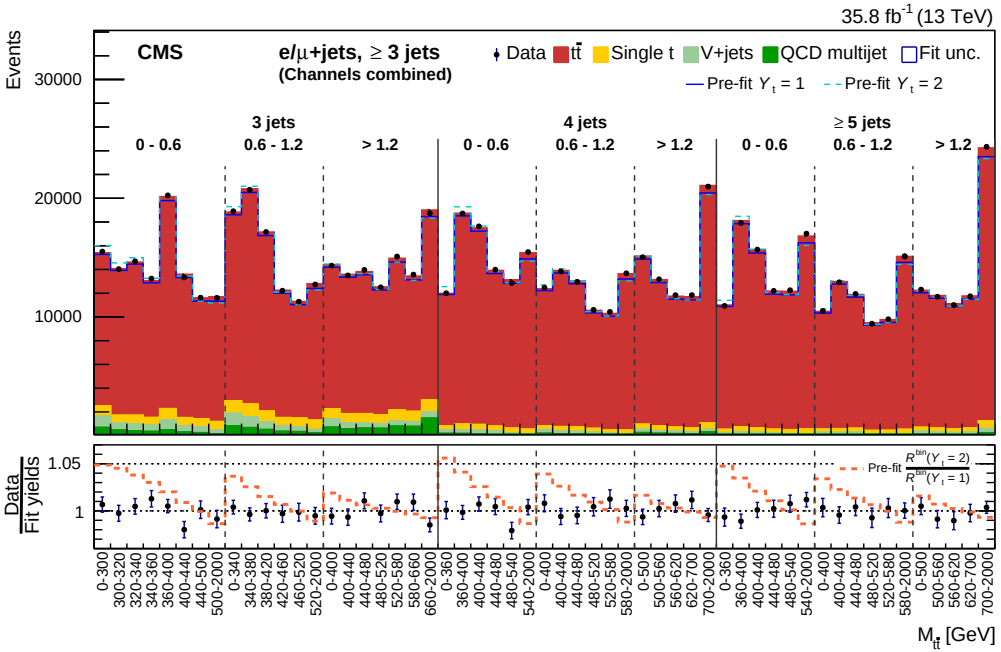
full Run 2: 1st lepton p_T [GeV]

Yukawa coupling: results

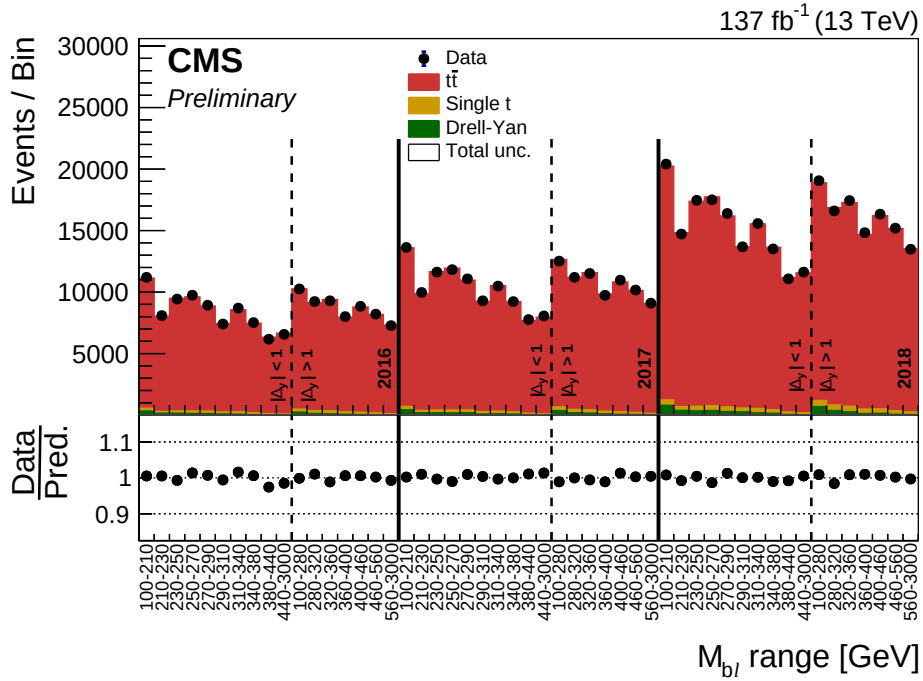
Phys. Rev. D 100 (2019) 072007, CMS-PAS-TOP-19-008

NEW!

lepton+jets



dilepton



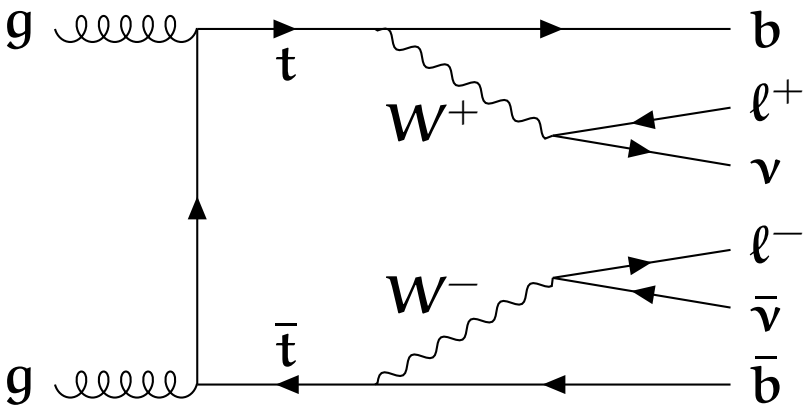
result: $Y_t = 1.07^{+0.34}_{-0.43}$

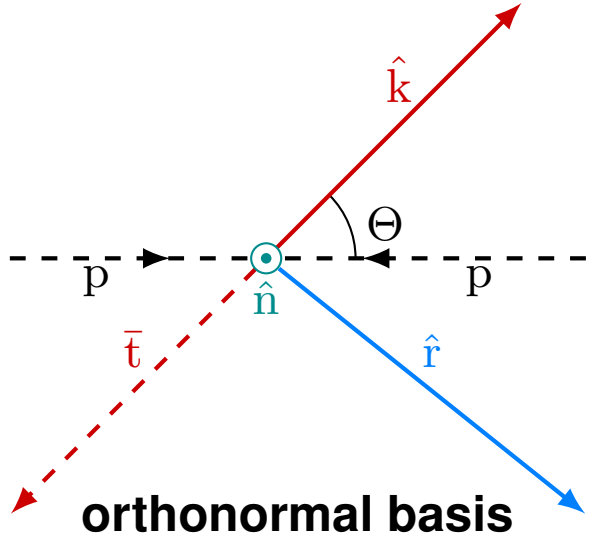
result: $Y_t = 1.16^{+0.24}_{-0.35}$

- Higgs global fit: $Y_t = 0.98 \pm 0.14$ Eur. Phys. J. C 79 (2019) 421
- $t\bar{t}t\bar{t}$ measurement: $Y_t < 1.7$ (95% CL) Eur. Phys. J. C 80 (2020) 75

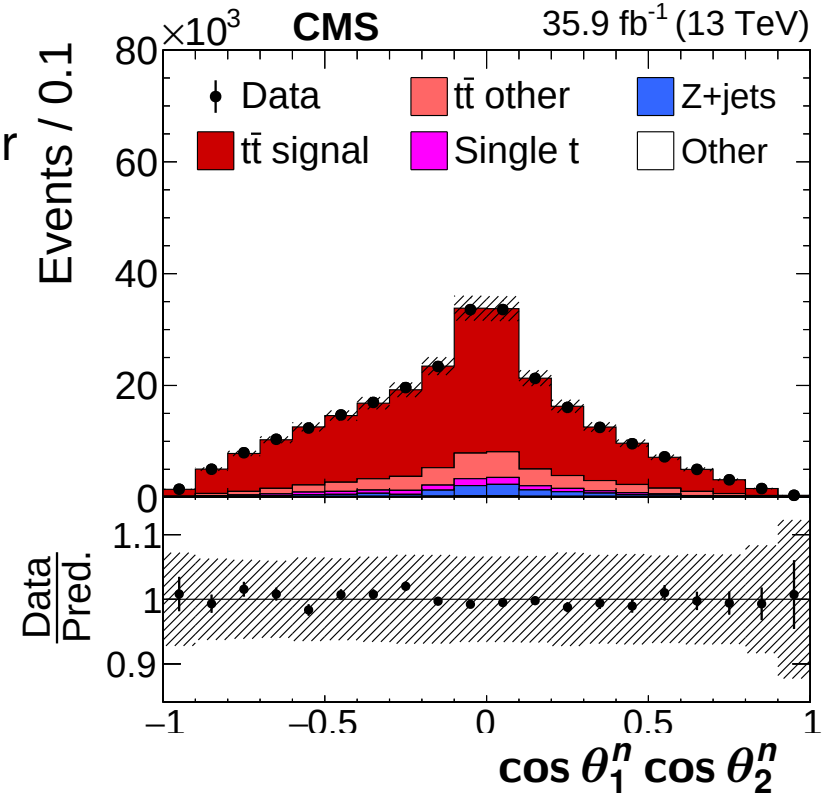
$t\bar{t}$ spin correlations

Phys. Rev. D 100 (2019) 072002





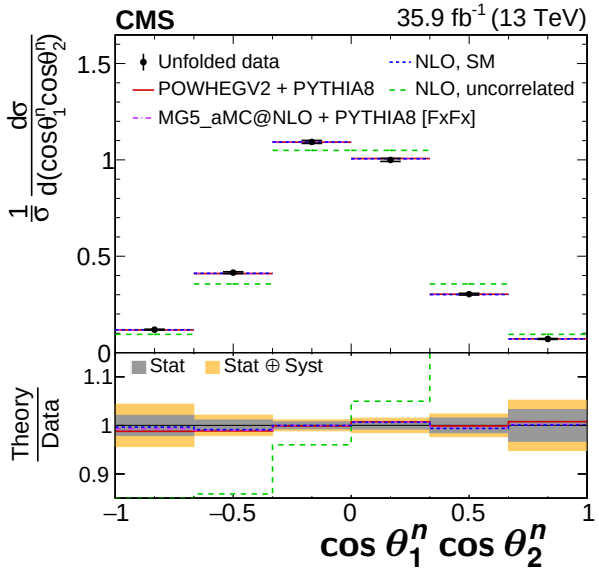
- lepton from top decay is optimal spin analyzer
- measured coefficients from angular distributions in $t\bar{t}$ rest frame, unfolded to parton-level:
  - polarization coefficients, B_1^i, B_2^i
  - "diagonal" spin correlation coefficients, C_{ii}
  - "cross" spin correlation coefficients, C_{ij}
- measured lab-frame observables:
  - $\cos\varphi_{\text{lab}} = \hat{\ell}_1 \cdot \hat{\ell}_2$
  - $|\Delta\phi_{\ell\ell}|$



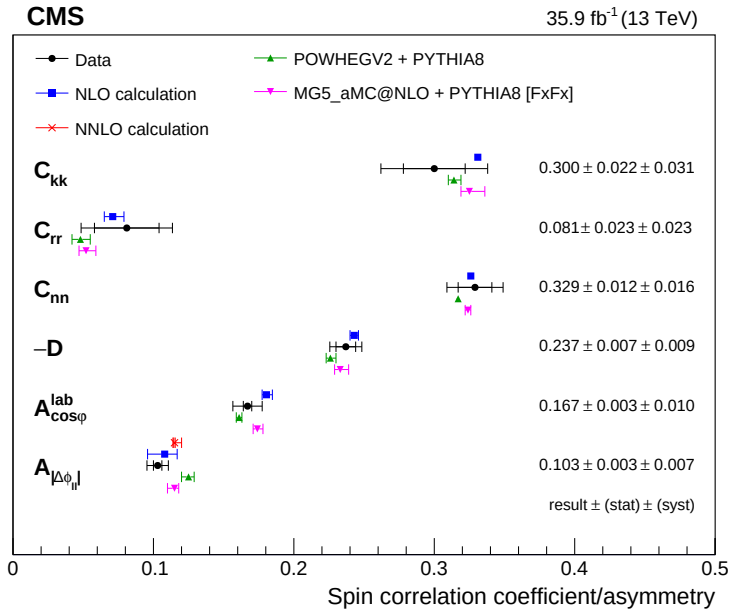
$t\bar{t}$ spin correlations: results

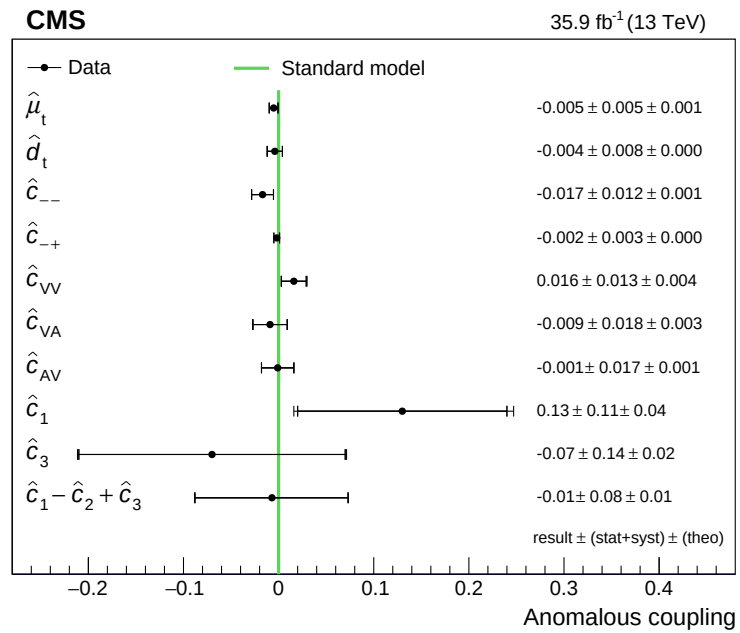
Phys. Rev. D 100 (2019) 072002

- $=$ 2 electrons and/or muons, $\geq$ 2 jets, $\geq$ 1 b-tag, DY veto in same-flavor events
- backgrounds: $t\bar{t}$ with τ leptons, single-top, V+jets, diboson, $t\bar{t}V$
- kinematic reconstruction of $t\bar{t}$ system
- regularized unfolding with TUnfold



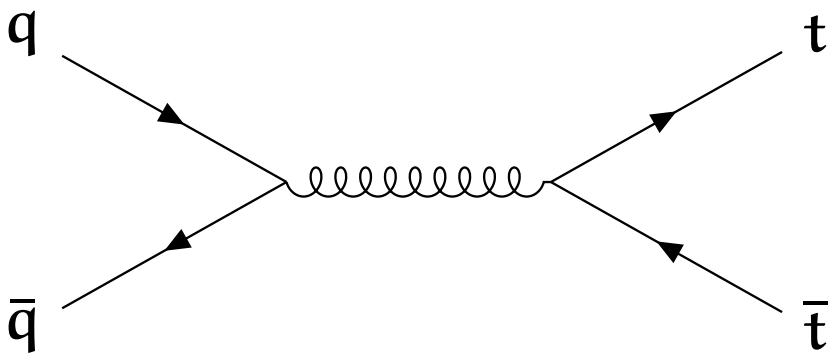
- unfolded results in agreement with SM, use to constrain anomalous couplings



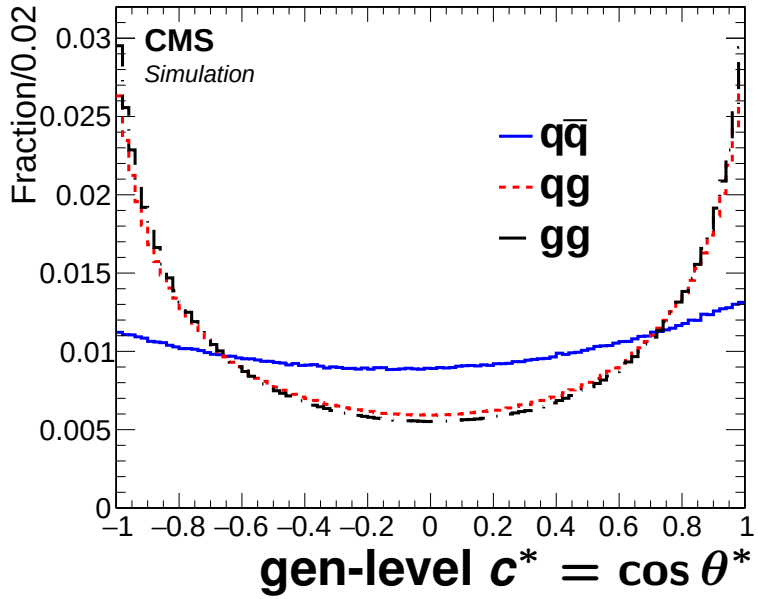


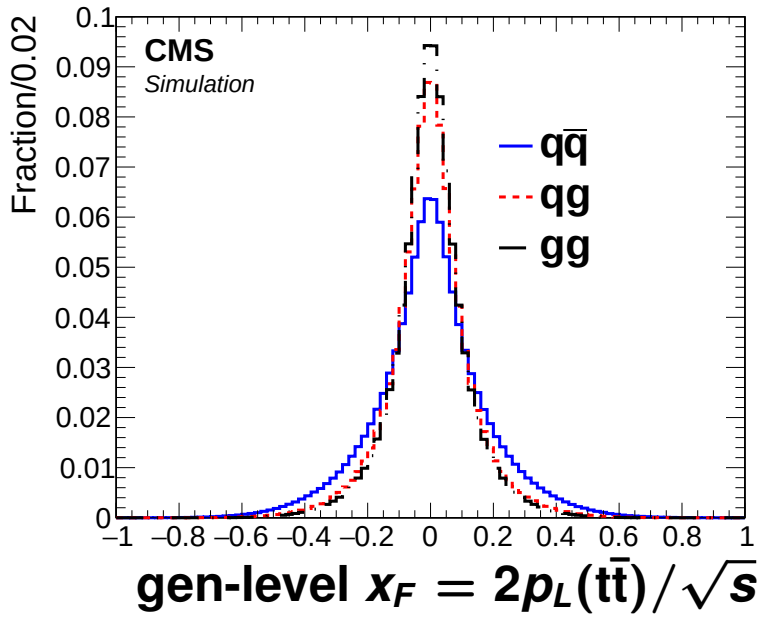
Forward-backward asymmetry

arXiv:1912.09540 (accepted by JHEP)



- $q\bar{q}$ initial state generates forward-backward asymmetry in $t\bar{t}$ production
- production angle θ^* of top quark w.r.t. initial-state quark, in $t\bar{t}$ rest frame
- $A_{FB} = \dfrac{\sigma(\cos\theta^* > 0) - \sigma(\cos\theta^* < 0)}{\sigma(\cos\theta^* > 0) + \sigma(\cos\theta^* < 0)}$
- strategy: triple-differential $t\bar{t}$ cross section measurement to extract $q\bar{q} \rightarrow t\bar{t}$ cross section as a function of $c^* = \cos\theta^*$
  - $A_{FB}^{(1)}$ from linear terms
  - anomalous dipole moments from c^*-even terms





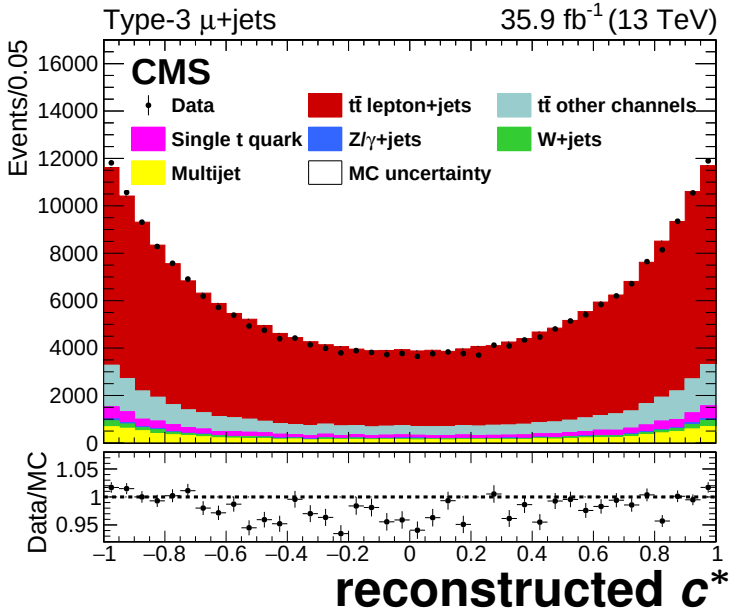
Forward-backward asymmetry: results

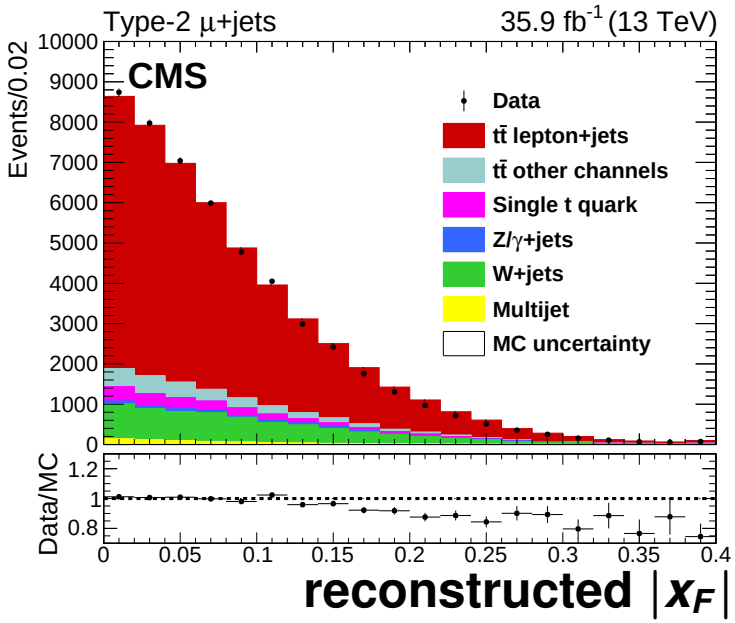
arXiv:1912.09540 (accepted by JHEP)

- $t\bar{t}$ events in lepton+jets channel
  - $=$ 1 isolated electron or muon
  - type-1: top-tagged AK8 jet, additional b-tagged AK4 jet, highly boosted
  - type-3: no AK8 jet, $\geq$ 4 AK4 jets, $\geq$ 2 b-tags, resolved
  - type-2: AK8 jet not top-tagged, $\geq$ 4 AK4 jets, $\geq$ 1 b-tag, transition region
- backgrounds: V+jets, single-top, QCD multijet
- kinematic fit of $t\bar{t}$ system
- template fit to $[c^*, |x_F|, M(t\bar{t})]$, separately for categories, lepton flavour & charge
- $A_{FB}^{(1)} = 0.048^{+0.095}_{-0.087}(\text{stat})^{+0.020}_{-0.029}(\text{syst})$
  - NNLO QCD prediction: $A_{FB} = 0.095 \pm 0.007$

    Phys. Rev. Lett. 115 (2015) 052001
  - Tevatron combination: $A_{FB} = 0.128 \pm 0.025$

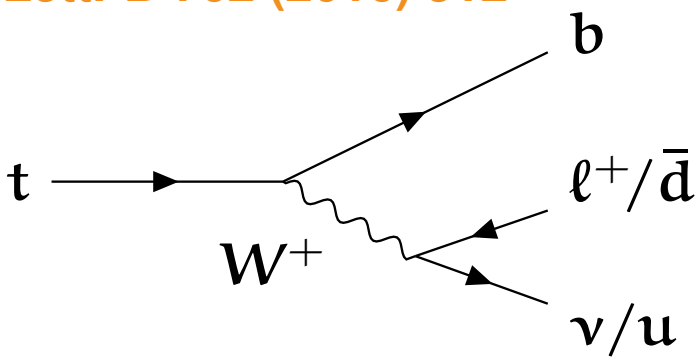
    Phys. Rev. Lett. 120 (2018) 042001



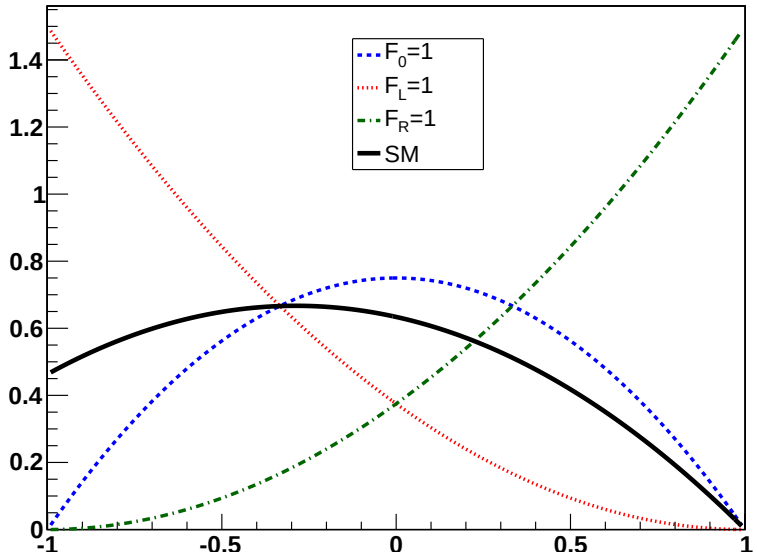


W polarization in top quark decays

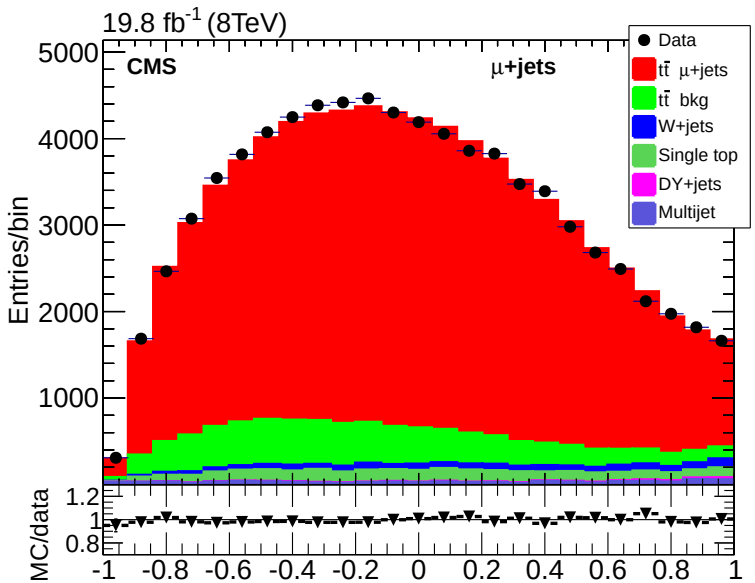
Phys. Lett. B 762 (2016) 512



- $V - A$ structure of tWb vertex determines polarization fractions of W boson in top quark decays
  - longitudinal polarization F_0
  - left-handed polarization F_L
  - right-handed polarization F_R
  - constraint: $F_0 + F_L + F_R = 1$
- polarization angle θ^* between directions of lepton (down-type quark) and reversed b quark in W rest frame
- strategy: combine 8 TeV measurements of ATLAS and CMS contributions



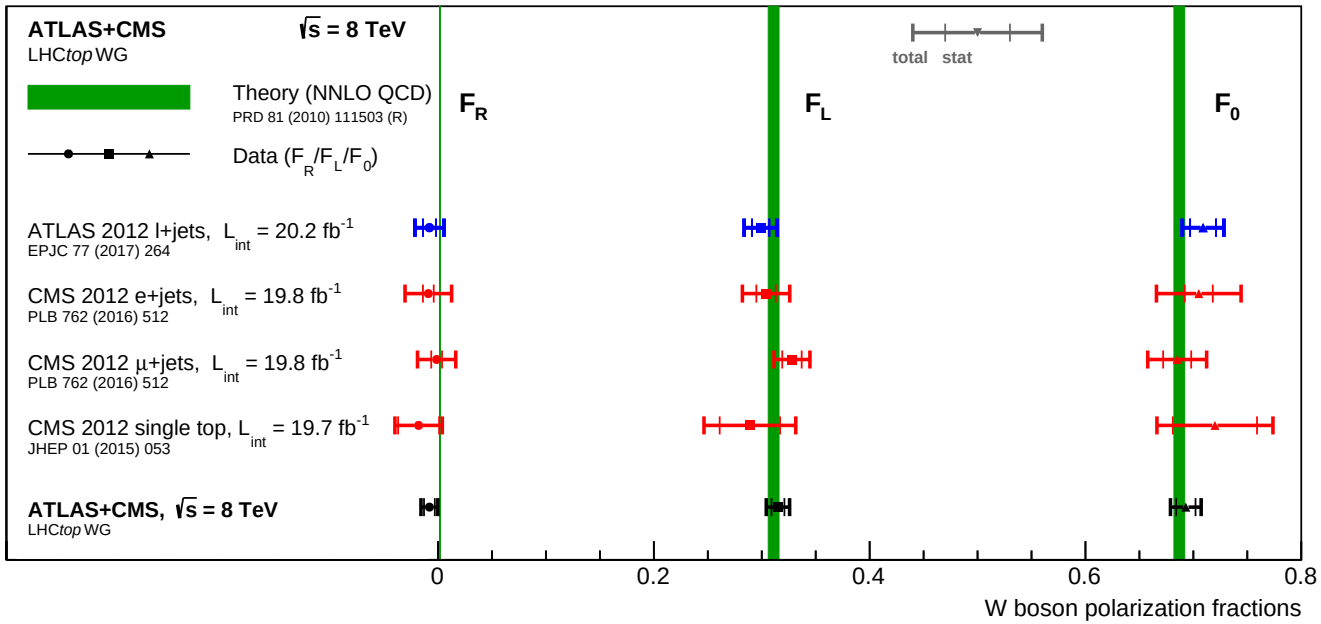
prediction for cos θ^*



tt̄ lepton+jets events: cos θ^*

W polarization: 8 TeV combination

arXiv:2005.03799 (submitted to JHEP)



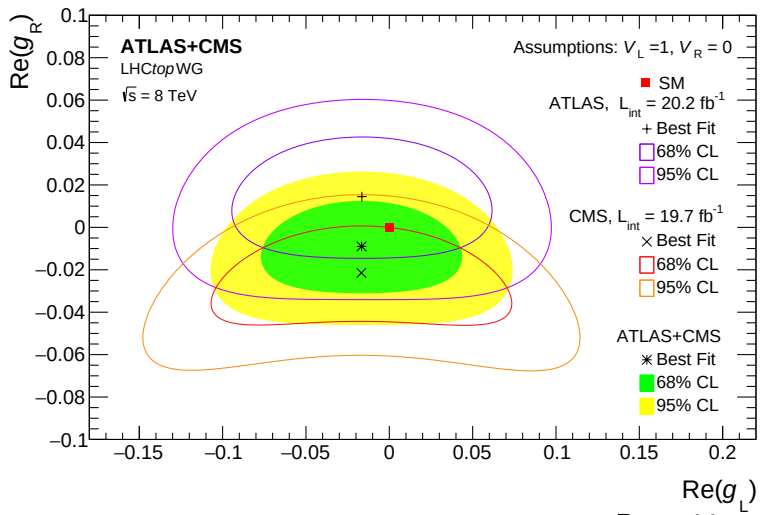
- harmonize uncertainty treatment
- study correlations between observables, within CMS, between CMS & ATLAS
- BLUE combination
- evaluate limits on anomalous couplings

$$F_0 = 0.693 \pm 0.009\,(\text{stat+bkg}) \pm 0.011\,(\text{syst})$$

$$F_L = 0.315 \pm 0.006\,(\text{stat+bkg}) \pm 0.009\,(\text{syst})$$

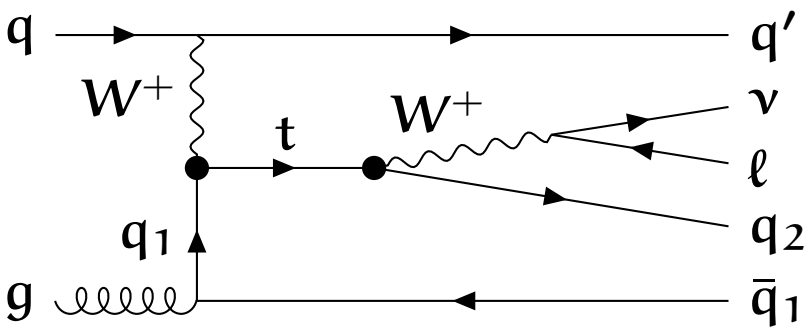
$$F_R < 0.007 \text{ at } 95\%\text{ CL}$$

$\Rightarrow$ in agreement with NNLO SM prediction

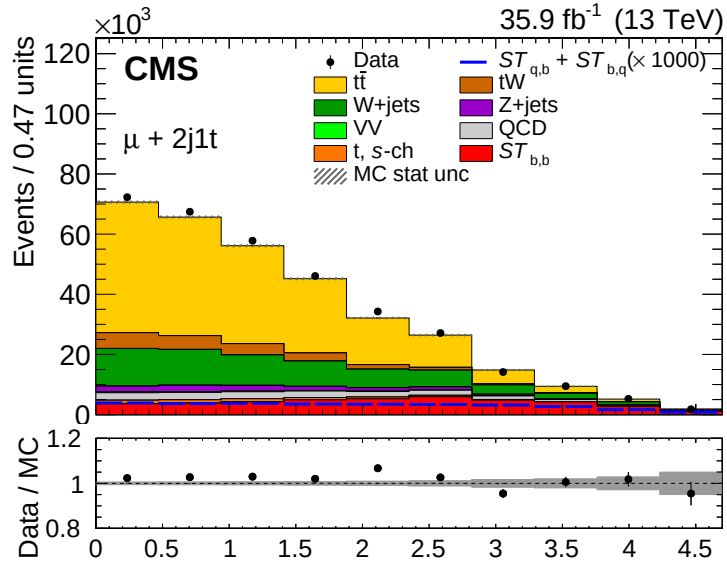


CKM elements involving top quark

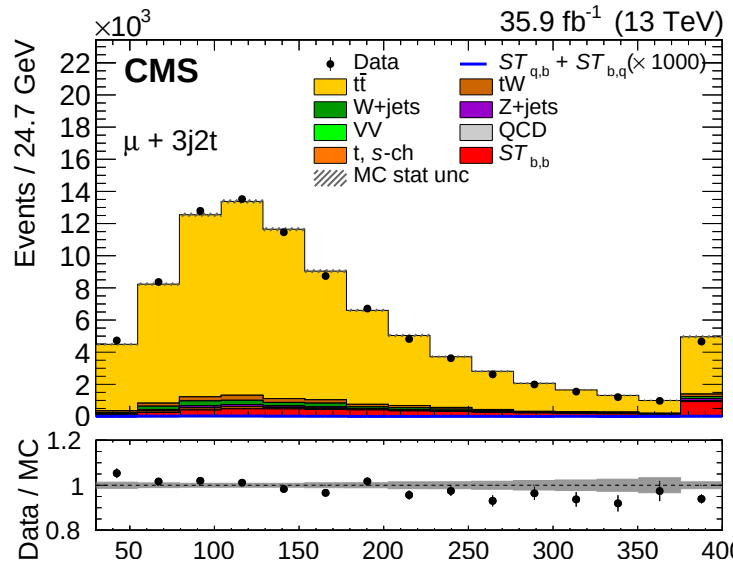
arXiv:2004.12181 (submitted to PLB)



- measure *t*-channel single-top production to probe CKM elements both in production and decay of top quarks
  - $ST_{b,b}$: tWb vertex in production and decay, $\sigma \times \mathcal{B} \approx 220\,\text{pb}$
  - $ST_{q,b}$: tWs or tWd vertex in production, tWb vertex in decay, $\sigma \times \mathcal{B} \approx 1\,\text{pb}$
  - $ST_{b,q}$: tWb vertex in production, tWs or tWd vertex in decay, $\sigma \times \mathcal{B} \approx 0.4\,\text{pb}$
- strategy: multivariate discrimination between both signal and background processes



η of non-b-tagged jet



inv. mass of lepton & non-b-tagged jet

CKM elements: results

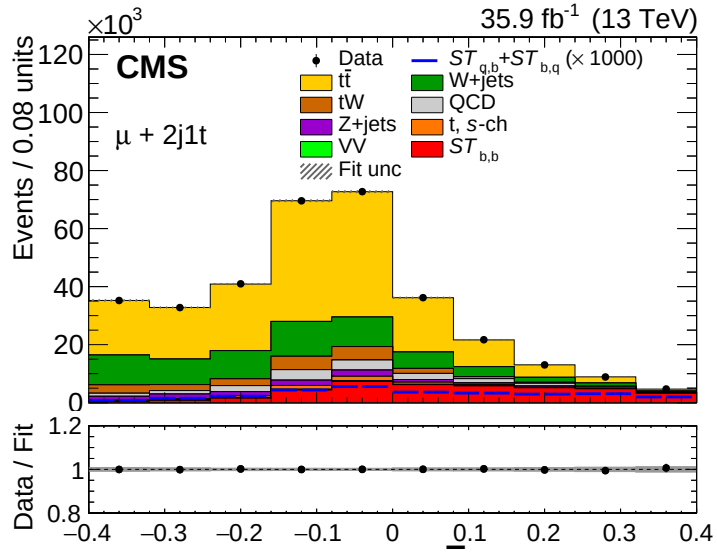
arXiv:2004.12181 (submitted to PLB)

- $=1$ electron or muon, ≥ 2 jets
- backgrounds: $t\bar{t}$, V+jets, VV, other single-top, QCD multijets (from data)
- three BDT discriminants trained:
  - $=2$ jets, $=1$ b-tag: $ST_{b,b}$ vs. $t\bar{t}$, W+jets
  - $=3$ jets, $=1$ b-tag: $ST_{q,b}$ vs. $ST_{b,b}$, $t\bar{t}$, W+jets
  - $=3$ jets, $=2$ b-tags: $ST_{b,b}$ vs. $t\bar{t}$
- template fit to BDT output distributions
- uncertainties: jet energy scale, parton shower
- CKM results with no assumptions on quark number or top quark decay channels:

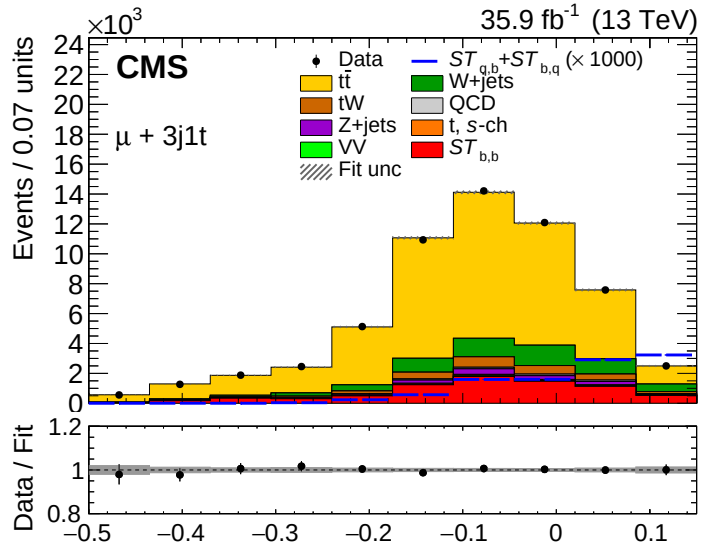
$$|V_{tb}| = 0.988 \pm 0.011\,(\text{stat+prof}) \pm 0.021\,(\text{nonprof})$$

$$|V_{td}| + |V_{ts}| = 0.06 \pm 0.05\,(\text{stat+prof}) \pm 0.04\,(\text{nonprof})$$

$$\Gamma_t/\Gamma_t^{SM} = 0.99 \pm 0.42\,(\text{stat+prof}) \pm 0.03\,(\text{nonprof})$$



2j1t: $ST_{b,b}$ vs. $t\bar{t}$, W+jets



3j1t: $ST_{q,b}$ vs. $ST_{b,b}$, $t\bar{t}$, W+jets

Summary

- Huge number of $t\bar{t}$ and single-top events produced at the CMS experiment allows for precise measurements of top quark properties.
- Highlights shown here:
  - top quark Yukawa coupling with full Run 2 dataset
  - spin correlations in $t\bar{t}$ production
  - LHC's first A_{FB} in $q\bar{q} \rightarrow t\bar{t}$ measurement
  - Run 1 combination of W boson polarization
  - first direct measurement of CKM elements in single-top production and decay
- Measured properties used to evaluate constraints on new physics models.
- More results are underway $\Rightarrow$ stay tuned!

- For discussion afterwards, I am available at: https://cern.zoom.us/j/95370667298

References

- CMS Collaboration, *Measurement of the top quark Yukawa coupling from $t\bar{t}$ kinematic distributions in the lepton+jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV*, Phys. Rev. D 100 (2019) 072007 [arXiv:1907.01590].
- CMS Collaboration, *Measurement of the top quark Yukawa coupling from $t\bar{t}$ kinematic distributions in the dilepton final state at $\sqrt{s} = 13$ TeV*, CMS-PAS-TOP-19-008, CERN 2020.
- CMS Collaboration, *Measurement of the top quark polarization and $t\bar{t}$ spin correlations using dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV*, Phys. Rev. D 100 (2019) 072002 [arXiv:1907.03729].
- CMS Collaboration, *Measurement of the top quark forward-backward production asymmetry and the anomalous chromoelectric and chromomagnetic moments in* pp *collisions at $\sqrt{s} = 13$ TeV*, arXiv:1912.09540 (accepted by JHEP).
- ATLAS & CMS Collaborations, *Combination of the* W *boson polarization measurements in top quark decays using ATLAS and CMS data at $\sqrt{s} = 8$ TeV*, arXiv:2005.03799 (submitted to JHEP).
- CMS Collaboration, *Measurement of CKM matrix elements in single top quark t-channel production in proton-proton collisions at $\sqrt{s} = 13$ TeV*, arXiv:2004.12181 (submitted to Phys. Lett. B).