EFT Interpretation of Top Quark Measurements at the LHC

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Top Quark Effective Field Theory

- o Expansion of the SM Lagrangian with higher-order operators to model New Physics (NP) at an energy scale, Λ
	- ∞ SM Lagrangian (\mathcal{L}_{SM}) consists of Dimension-4 operators
	- Dimension-5 operators typically excluded as they do not conserve lepton number
	- G The Effective Lagrangian (L_{eff}) is a series of dimension-6 operators (O_i) with dimensionless Wilson coefficients (c_i) to parametrize the NP interaction strength
	- Theoretically consistent, Model independent approach
- os LHCTop Working Group proposal for EFT interpretation:
	- \circ In total, 59 dimension-6

arXiv:1802.07237 [hep-ph]

- operators conserving baryon number
- and lepton numbers
- G Several of them are
- relevant for Top EFT interpretation

 $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum c_i \mathcal{O}_i + \cdots$

$LHCTopWG$ **EFT**Proposal *^µÏ*) © *^Ï†· ^I* (*iDµÏ*)≠(*iDµÏ†*)*· ^I^Ï* where *· ^I* are the Pauli *O*8(*ijkl*) *ud* = (¯*ui"µ^T ^Au^j*)(¯ *dk"µT ^Adl*)*,* (9) *‡O*1(*ijkl*) *quqd* = (¯*qiu^j*) *Á* (¯*qkdl*)*,* (10) *uW* = (¯*qi‡^µ‹· ^Iu^j*) ˜*ÏW^I ‡O*(*ij*) *dW* = (¯*qi‡^µ‹· ^Id^j*) *ÏW^I ‡O*(*ij*)

–—", (29)

matrices; *^T ^A* © *[⁄]^A/*² where *[⁄]^A* are Gell-Mann matrices. 4-Quark Operators \ \ \ \ 2-Quark Operators

Ωæ*^D ^µÏ*) © *^Ï†*(*iDµÏ*)≠(*iDµÏ†*)*Ï*; (*Ï†ⁱ*

 \mathcal{F}

 $O_{aa}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l),$ $O_{aa}^{3(ijkl)} = (\bar{q}_i \gamma^\mu \tau^I q_j)(\bar{q}_k \gamma_\mu \tau^I q_l),$ $O_{au}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{u}_k \gamma_\mu u_l),$ $O_{qu}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{u}_k \gamma_\mu T^A u_l),$ $O_{qd}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{d}_i)$ $O_{qd}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{d}_i)$ $O_{uu}^{(ijkl)} = (\bar{u}_i \gamma^\mu u_i)(\bar{u}_k \gamma_\mu u_l),$ $O_{ud}^{1(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{d}_i)$ $O_{ud}^{8(ijkl)} = (\bar{u}_i \gamma^\mu T^A u_j)(\bar{d}_i)$ ${}^{i}O_{quad}^{1(ijkl)} = (\bar{q}_{i}u_{j}) \varepsilon (\bar{q}_{k}d_{l}),$ ${}^{4}O_{quad}^{8(ijkl)} = (\bar{q}_i T^A u_j) \varepsilon (\bar{q}_k T^A d_l),$ $T_{\rm eff}$ and $T_{\rm eff}$ and $T_{\rm eff}$

*‡O*8(*ijkl*) *quqd* = (¯*qiT ^Au^j*) *Á* (¯*qkT ^Adl*)*,* (11)

 $\bar{d}_k \gamma_\mu d_l$), ${}^{\ddagger}O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^{\dagger} iD_\mu \varphi)(\bar{u}_i \gamma^\mu d_j)$, $O_{eu}^{(ijkl)} = (d_i \gamma^\mu d_l)$ $\bar{d}_k \gamma_\mu T^A d_l$), ${}^{\ddagger} O^{(ij)}_{uW} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j) \; \tilde{\varphi} W^I_{\mu}$ $\bar{d}_k \gamma_\mu d_l$), ${}^{\ddagger}O_{i e d q}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} u_j)$ $\tilde{\varphi} B_{\mu\nu}$, ${}^{\ddagger}O_{i e d q}^{(ijkl)} = (\bar{q}_i \sigma^{\mu\nu} u_j)$ $\bar{d}_k \gamma_\mu T^A d_l$), ${}^{\ddagger} O^{(ij)}_{uG} = (\bar{q}_i \sigma^{\mu\nu} T^A u_j) \; \tilde{\varphi} G^A_{\mu\nu}$ $\partial^{1}_{\mu}O^{(ij)}_{\mu} = \bar{q}_{i}u_{j}\tilde{\varphi}(\varphi^{\dagger}\varphi),$ $O^{1(ijkl)}_{\mu} = (i,j)$ $O_{\varphi q}^{1(ij)} = (\varphi^{\dagger} \overleftrightarrow{D}_{\mu} \varphi)(\overline{q}_i \gamma^{\mu} q_j),$ $O_{\mu}^{3(ijkl)} = (\overline{q}_i \varphi^{\mu} \varphi)(\overline{q}_i \gamma^{\mu} q_j),$ $O_{\varphi q}^{3(ij)} = (\varphi^{\dagger} \overleftrightarrow{D}_{\mu}^{I} \varphi)(\overline{q}_{i} \gamma^{\mu} \tau^{I} q_{j}),$ $O_{\mu}^{(ijkl)} = (Q_{\mu}^{(ijkl)} \varphi)^{i}$ $O_{\varphi u}^{(ij)} = (\varphi^{\dagger} \overleftrightarrow{D}_{\mu} \varphi)(\bar{u}_i \gamma^{\mu} u_j),$ $O_{\varphi a}^{(ijkl)} = (\varphi^{\dagger} \varphi) \overleftrightarrow{D}_{\mu} \varphi^{\dagger} \varphi^{\dagger} u_j),$ ${}^{\ddagger}O_{dW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I d_j) \varphi W^I_{\mu}$ $\frac{A}{\mu\nu}$, $\frac{A}{\mu\nu}$

$\frac{1}{2}$ lenter Operator **2-Quark-2-Lepton Operators**

 ${}^{\dagger}O_{lequ}^{1(ijkl)} = (\bar{l}_ie_j) \varepsilon (\bar{q}_ku_l),$ ${}^{\dagger}O_{lequ}^{3(ijkl)} = (\bar{l}_i \sigma^{\mu\nu} e_j) \varepsilon (\bar{q}_k \sigma_{\mu\nu} u_l),$ $O_{lq}^{1(ijkl)} = (\bar{l}_i \gamma^{\mu} l_j)(\bar{q}_k \gamma^{\mu} q_l),$ $O_{lq}^{3(ijkl)} = (\bar{l}_i \gamma^\mu \tau^I l_j)(\bar{q}_k \gamma^\mu \tau^I q_l),$ $O_{lu}^{(ijkl)} = (\bar{l}_i \gamma^{\mu} l_j)(\bar{u}_k \gamma^{\mu} u_l),$ $O_{eq}^{(ijkl)} = (\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_l),$ $O_{eu}^{(ijkl)} = (\bar{e}_i \gamma^\mu e_i)(\bar{u}_k \gamma^\mu u_l),$ ${}^{i}O_{ledq}^{(ijkl)} = (\bar{l}_{i}e_{j})(\bar{d}_{k}q_{l}),$ Baryon- and lepton-number-violating operators:¹

Example 2.1 Solution 2.1802.07237 [hep-ph]

ⁱ–uj—)(*q^c*

^k"Áll) *'*

‡O(*ijkl*) *duq* = (*d^c*

Two-quark operators: *X* rescriptions for EFT interpretation f *O*3(*ijkl*) *lq* = (¯*li"^µ· ^I ^l^j*)(¯*qk"^µ· ^I ^ql*)*,* (22) *l etation from EHC Top quark ivieasur* ¹In the latest version of Ref. [1], *^O*1*,*³ *qqq* are merged into one single operator with *SU*(2)*^L* indices mixed between o Prescriptions for EFT interpretation from LHC Top quark Measurements

*O*1(*ijkl*)

Ω α ² Number of degrees of freedom $\frac{1}{2}$ *O*(*ijkl*) *eu* = (¯*ei"^µe^j*)(¯*uk"^µul*)*,* (25)

- \circ Four heavy quarks: $11 + 2$ CPV
- *‡O*(*ij*) *^Ïud* = (˜*Ï†iDµÏ*)(¯*ui"^µd^j*)*,* (16) ω ² • (wo nght and two neavy quanks. *‡O*3(*ijkl*) *lequ* = (¯*li‡^µ‹e^j*) *^Á* (¯*qk‡µ‹ul*)*,* (27) \oslash Two light and two heavy quarks: 14 *dkql*)*,* (28)
- *a J*_{*M*} heavy quarks and bosons: 9 μ augres and hosons: $9 + 6$ *‡O*(*ijkl*) *duq* = (*d^c ⁱ–uj—*)(*q^c ^k"Áll*) *' –—",* (29) $C3$ Two heavy quarks and bosons: $9 + 6$ CPV
- *uB* = (¯*qi‡^µ‹u^j*) ˜*ÏBµ‹,* (19) C3 Two heavy quarks and two leptons: (8 + 3 CPV) x 3 lepton flavors

Prolay Kumar Mal 3 *l* op EFT Operators implemented https://feynrules.irmp.ucl.ac.be/wiki/dim6top *O*(*ijkl*) *lu* = (¯*li"^µl^j*)(¯*uk"^µul*)*,* (23) ¹In the latest version of Ref. [1], *^O*1*,*³ *qqq* are merged into one single operator with *SU*(2)*^L* indices mixed between ∞ Top EFT Operators implemented at tree-level in dim6top UFO model:

Top Analyses for EFT Interpretation **the standard model of the standard model (BSM)** ρ

- **▶ Various dimension-6 operators can effect the top quark production** processes at the LHC in different production modes \mathcal{I} sions \mathcal{I} framework, theory (EFT) framework, the contribution of any \mathcal{I}
- Ø **CMS/ATLAS interpretation for the following processes at √s=13 TeV so far** etation for the following processes at Vs=13 TeV so far $\ddot{\sim}$ check at a center-of-mass energy of 13 TeV allows the study of signatures the study of signatures the study of signatures of signatures the study of signatures of signatures and study of signatures of signatures \blacktriangleright civis/ArLAS interpretation io

Interpretation of ttZ measurements $\sqrt{2}$ √√i linterpretation of tt∠ measurer ments ™

- \diamondsuit Same-sign and Opposite sign dilepton, trirepton and tetra-lepton inclusive cross-section

lepton and tetra-lepton inclusive cross-section analysis is associated with a Wilson coecient *Coecient Coecient Coecient Coecient Coecient Coecient Coecient* Coecient Coe T analysis ϵ
- \Diamond 5 operators can modify the ttZ rates: ϕQ^{\prime} ϕQ^{\prime} $\phi' Q^{\prime}$ ϕ'' ϕ'' ϕ'' ϕ'' ϕ'' ϕ'' $O_{\phi \mathcal{Q}}^{(3)}$ $O_{\phi Q}^{(3)}, O_{\phi Q}^{(1)}, O_{\phi t} , O_{tW}, O_{tB}$ φ $\theta^{(3)}$ _{ϕ Q} and $\theta^{(1)}$ _{ϕ Q} are contribute to ttZ vertex as α positive term from the most notable change is the improvement in the improvement in the lower limit for α
- α a linear combination is a linear combination is α $t = \frac{v}{\omega_Q}$
	- \diamond Measurement is sensitive to the $\text{difference: } \mathcal{O}^{(3)}{}_{\text{qO}}$ - $\mathcal{O}^{(1)}{}_{\text{qO}}$ Δ and Δ for the expected and 95% confidence intervals, which include the value of Δ \Diamond Measurement is sensitive to the \leftrightarrow Measurement is sensitive to the γ ivitable chiefit is belisitive to the previous direct constraints at γ and γ at γ

Observed limit at 68% CL [–1.0, 2.7] [–2.0, 3.5] [–3.7, 3.5] [–2.2, 2.1]

4

5

log(L) Δ-

5

1σ

<u>2σ</u>

<u>3σ</u>

\Diamond Only one operator is considered at a time 27 Figure 14: The value of the profile-likelihood test statistic as a function of *^c*/⇤2, for (a) ^C(3) ------|⁰⁰| α and α distributions, and α distributions, and α distributions, α ed at a time that measurements. The vertical axis is the value of the value of the value of the likelihood at the value of the val minimum near *C*ⁱ = 0 is zero. $[-2.6, 2.6]$ Observed limit at 68% CL [-1.0, 2.7] [-2.0, 3.5] [-3.7, 3.5] [-2.2, 2.1]
Observed limit at 95% CL [-3.3, 4.2] [-25, 5.5] [-5.0, 5.0] [-2.9, 2.9] $\frac{[-2.9,]}{2}$ $[-2.1, 1.9]$ $[-3.8, 2.7]$ $\int_{\phi Q}^{(3)}/\Lambda^2$ $C_{\phi t}/\Lambda^2$ C_{tB}/Λ^2 C_{tW}/Λ^2 2 3 $\frac{Q}{\sqrt{Q}}$ and $\frac{Q}{\sqrt{Q}}$ are also constants are also previous direct constraints at $\frac{Q}{\sqrt{Q}}$ and $\frac{1}{\sqrt{Q}}$ 1σ $\frac{1}{2}$ $[-4.2, 4.3]$ Ω ^{14} U_{L} ₁ −30 −25 −20 −15 −10 −5 0 5 10 −1 $C_{\phi t}/\Lambda^2$ 0 1 2 3 4 log(L) Δ $\frac{10}{2}$ <u>2σ</u> <u>3σ</u> $ATLAS$
 $\sqrt{s} = 13$ TeV 36.1 fb **Observed Expected** Phys. Rev D 99, 072009 (2019) \Diamond Only one operator is considered at a tim $\mathsf{m}\mathsf{e}$, we have ref. Eq. (the measurements into limits on the coecients. Limits for the $3\frac{1}{4}$ Coefficients $C_{\phi O}^{(3)}/\Lambda^2$ Expected limit at 68% CL $[-2.1, 1.9]$ $[-3.8, 2.7]$ $[-2.9, 3.0]$ $[-1.8, 1.9]$ $[-2.1, 1.9]$ $[-3.8, 2.7]$ $[-2.9, 3.0]$ $[-1.8, 1.9]$
 $[-4.5, 3.6]$ $[-23, 4.9]$ $[-4.2, 4.3]$ $[-2.6, 2.6]$ Observed limit at 95% CL $[-3.3, 4.2]$ $[-25, 5.5]$ $[-5.0, 5.0]$ $\frac{1}{\sqrt{2}}$ the measurements in the coefficients. Limits for the EFT coefficients with only the $\frac{Q}{\epsilon}$ Coecientis Phys. Rev D 99, 072009 (2019) | Coofficients $C^{(3)}/\Lambda^2$ C/Λ^2 C_1/Λ^2 C_2/Λ^2 $\phi_{\phi Q}^{(1)}$ $\phi_{\phi q}^{(1)}$, $\phi_{\phi q}^{(1)}$, $\phi_{\phi q}^{(1)}$ Expected limit at 95% CL

ATLAS -13 TeV 36.1 s = 13 TeV

$\left| \frac{CMS}{C}\right|$ Interpretation of ttZ measurements. and the presented by the incubarent of the statistical bars in the statistical bars in the statistical vertical vertical statistical vertical vertical vertical vertical vertical vertical vertical vertical vertical vertical

Data 6 T(Z) [fb/GeV] aMC@NLO 5 4 3 dσ/dp 2 \mathbb{Z} 1 0 Pred./Data $\overline{\sigma}$ 1.25 1 0.75 0 100 200 300 400 500 $p_T(Z)$ [GeV] **CMS** Preliminary 77.5 fb⁻¹ (13 TeV) 300 θ* Z) [fb] $\frac{1}{48}$ and the weak mixing and the warsaw basis and the Wilson coefficients in the Warsaw basis are denoted and the Warsaw basis are denoted and the Wilson coefficients in the Wilson coefficient in the Warsaw basis ar 200 dσ/dcos(*f*q 100 Data aMC@NLO Pred./Data 0 Pred./Data 1.25 1 0.75 $-0.8 -0.6 -0.4 -0.2$ 0 0.2 0.4 0.6 $\cos(\theta_{\rm Z}^*)$ **Prolay Kumar Mal 6** Figure 5: Measured differential to the function cross section cross

CMS Preliminary 77.5 fb⁻¹ (13 TeV)

7

- \leftrightarrow ↑ EFT ttZ signal weight estimation at the generator $\frac{2}{3}$ level wrt the SM signal strength
- \Diamond Reconstructed events reweighted to obtain the EFT signal shape

Interpretation of ttZ measurements -. C dashed line shows the best-fit point to the observed result in one of the EFT planes.

negative log-likelihood ratio $\frac{1}{2}$ w.r.t the best-fit value. The year of $\frac{1}{2}$ which lines indicates indicates in distribution of $\frac{1}{2}$

New Physics limits with tW/tt \rightarrow dilepton

arXiv:1903.11144 [hep-ex] submitted to EPJC

- \diamondsuit Final state signature with two isolated leptons and b-jets
- \diamondsuit Signal categorization:

 \diamondsuit tt: 2 leptons + >=2 bjets \diamondsuit tW: 2 leptons + 0-1 bjet

- \Diamond Wilson coefficients sensitive to BSM contributions to the tt and tW production: C_G , $C^{(3)}_{\Phi q}$, C_{tW} , C_{tG} , C_{uG} , and C_{CG} ; C_{LG} can be probed with both tW and tt
- \Diamond Simultaneous fits in different dilepton & b-tagged regions: C_G
- \diamondsuit Neural Network based separation between tt , tW and FCNC signal

 \Diamond tt vs tW: $C^{(3)}$ _{Φq}, C_{tW}, C_{tG}

 \Diamond SM (tt+tW) vs FCNC tW: C_{uG}, and C_{cG}

New Physics limits with $tW/tt\rightarrow$ dilepton

arXiv:1903.11144 [hep-ex] submitted to EPJC

- \Diamond No excess in data have been observed and limits on the 6 coupling constants are set
- \diamondsuit First experimental bound on C_G from top quark results
- \Diamond The limits on C_{uG} and C_{cG} are translated into the FCNC branching ratios at 95% CL:

 \Diamond BR(t \rightarrow ug)<0.12%

Search for 4 top quarks **that state is a unique final state of the state of the provides information** $\mathsf{P} \mathsf{a} \mathsf{r} \mathsf{c} \mathsf{n}$ to the third generators and $\mathsf{P} \mathsf{a} \mathsf{b} \mathsf{r} \mathsf{c} \mathsf{r}$ independent constraints due to small correlation between selected operators. J Carch for T cop quarters. The intervals \bigcup_{noise}

- **[♦] Inclusive cross-section in single**
lepton and opposite sign dilento depton and opposite sign dilepton and right-handed up-type quark singlet of the third generators of th signatures \overline{a} and \overline{b}
	- \diamond In SM, NLO predicted

 $\sigma_{\text{pp}\rightarrow \text{tttt}}$ ≈ 9 fb at Vs=13 TeV

- $\begin{aligned} \nabla_{\text{pp}\rightarrow \text{tttt}} \approx 9 \text{ lb at vs--} \text{ is } 10 \text{ eV} \\ \nabla_{\text{pp}\rightarrow \text{tttt}} \approx 9 \text{ lb at vs--} \text{ is } 10 \text{ eV} \end{aligned}$ number jets and tagged jets
	- \diamondsuit Only relevant EFT dimension-6 operators: \mathcal{O}^1_{tt} , $\mathcal{O}^1_{\mathsf{QQ}}$, $\mathcal{O}^1_{\mathsf{Q}t}$ and $\mathcal{O}^8_{\mathcal{Q}t} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{t}_R \gamma_\mu T^A t_R)$, $\dot{\mathcal{O}}^8$ Qt ∂_{α} ∂_{α} , ∂_{α} and ∂_{α} ∂_{α} ∂_{α} ∂_{α} ∂_{α}
	- \diamondsuit Probe for 4 heavy quark interactions including tttt operator
	- \Diamond Observed cross-section is consistent with the SM and is used to constrain the EFT coupling parameters

only one selected operator \sim CMS-PAS-TOP-17-019 $\rho_{\rm{A}}$ only note to be a small subset of \sim these operators in the EFT per series. In the EFT per series at LO in the EFT per series. In the EFT per series

$$
\mathcal{O}_{tt}^1 = (\bar{t}_R \gamma^\mu t_R) (\bar{t}_R \gamma_\mu t_R),
$$

$$
\mathcal{O}_{QQ}^1 = (\bar{Q}_L \gamma^\mu Q_L) (\bar{Q}_L \gamma_\mu Q_L),
$$

$$
\mathcal{O}_{Qt}^1 = (\bar{Q}_L \gamma^\mu Q_L) (\bar{t}_R \gamma_\mu t_R),
$$

$$
\mathcal{O}_{Qt}^8 = (\bar{Q}_L \gamma^\mu T^A Q_L) (\bar{t}_R \gamma_\mu T^A t_R),
$$

Top Chromo-magnetic Dipole Moment $\mathscr{C}(\mathcal{G})$ T_{Niser}

- \diamondsuit Anomalous Chromo-Magnetic Dipole Moment (CMDM) of the top quark corresponds to the $\mathcal{O}_{\mathsf{tG}}$ operator in EFT $_{\tiny{\textrm{N}}}$ confidence level to 0.06 *< ^C*tG/L² *<* 0.41 TeV² [10]. The results of this work are consistent with these previous results. The sensitivity to *C*tG/L² is improved by about 50% compared to
- \diamondsuit Top pair Spin Density matrix measurement using the dilepton events
- \diamondsuit Simultaneous fit using 20 parton-level differential distributions sensitive to tt spin correlation and top polarization:

 \leftrightarrow -0.07< C_{tG}/ Λ ² < 0.16 at 95% CL

 \Diamond Previous constraints on C_{tG}/ Λ ² using the dσ/dΔφ(l,l) JHEP 02, 149 (2019)

 \leftrightarrow -0.06< C_{tG}/ Λ ² <0.41 at 95% CL

CMS-PAS-TOP-18-006

Figure 13: Left: D*c*² values from the fit to the data are shown in the left plot as a function

Summary & Conclusions

- \Diamond With the 2016 and 2017 datasets both ATLAS and CMS have completed some of the key analyses related to Top quarks
- \Diamond No clear evidence for the New Physics contribution into the Top physics is observed yet
- \Diamond Many top quark results (FCNC, differential cross-section, 4 top) have been interpreted using Effective Field Theory approach using relevant dimension-6 operators (recommended by the LHCTopWG)
	- \diamondsuit For quite a few sensitive channels, Top quark related Wilson Coefficients are best constrained
- \Diamond Many more Top EFT interpretation to follow using Run 2 measurements
	- \diamondsuit Further exploration of different approaches considering consistent treatment of different top production processes

References

² LHCTopWG: <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG> ² ATLAS:<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults> ² CMS: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP>