EFT AND TOP: EXPERIMENTAL

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on behalf of the ATLAS & CMS Collaborations

Top LHC France, 6 th April 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

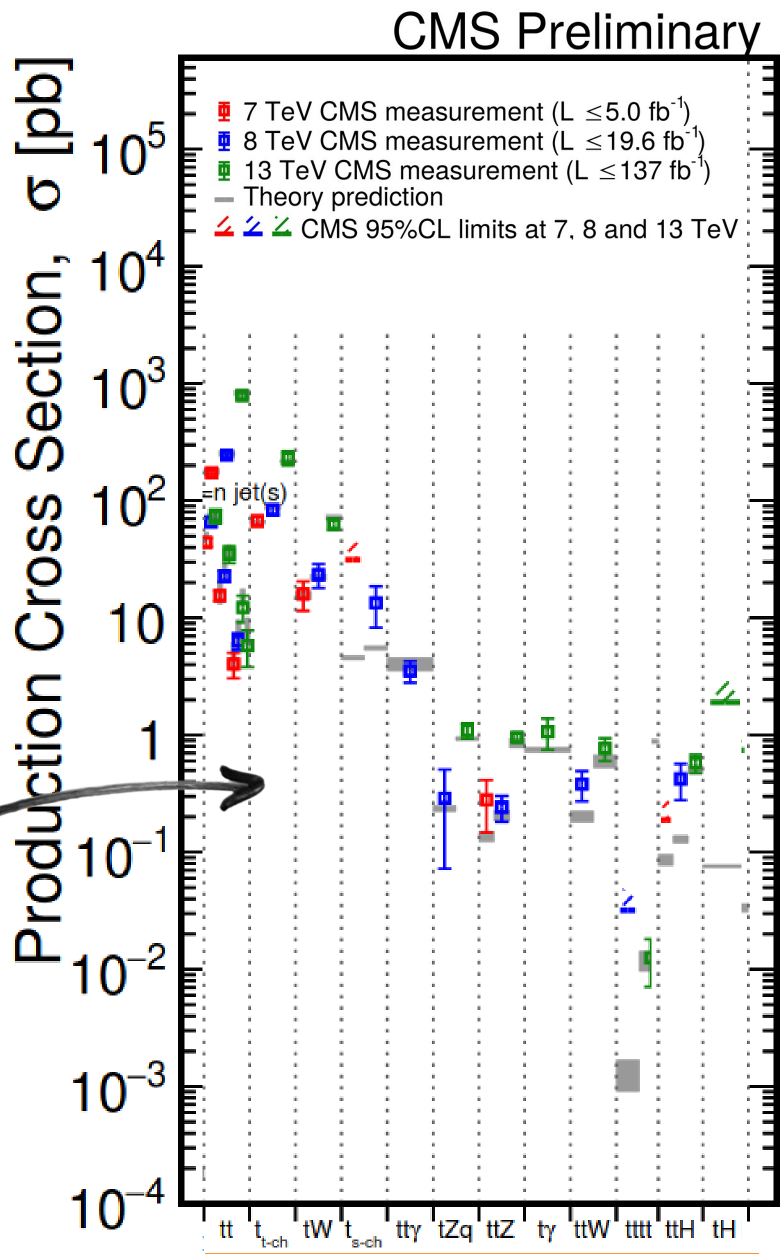
INTRODUCTION

- **No clear sign of new physics** (BSM) at LHC so far…
  - … and future accelerators in coming decade(s) will increase ∫L , not √s

- Many BSM theories predict sizeable **deviations of top quark's couplings** w.r.t. SM predictions

- Most of canonical top quark processes at LHC have reached **precision era** (systematics-limited)

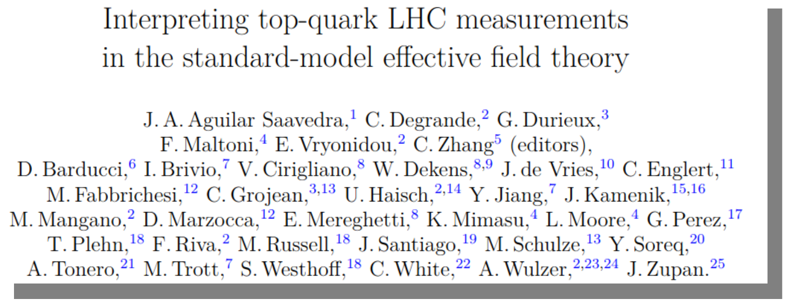
Motivates ambitious top physics programme to **reveal new physics** indirectly **through precision** measurements



Adapted from : http://cern.ch/go/pNj7

EFFECTIVE FIELD THEORY

arXiv:1802.07237


Interpreting top-quark LHC measurements in the standard-model effective field theory

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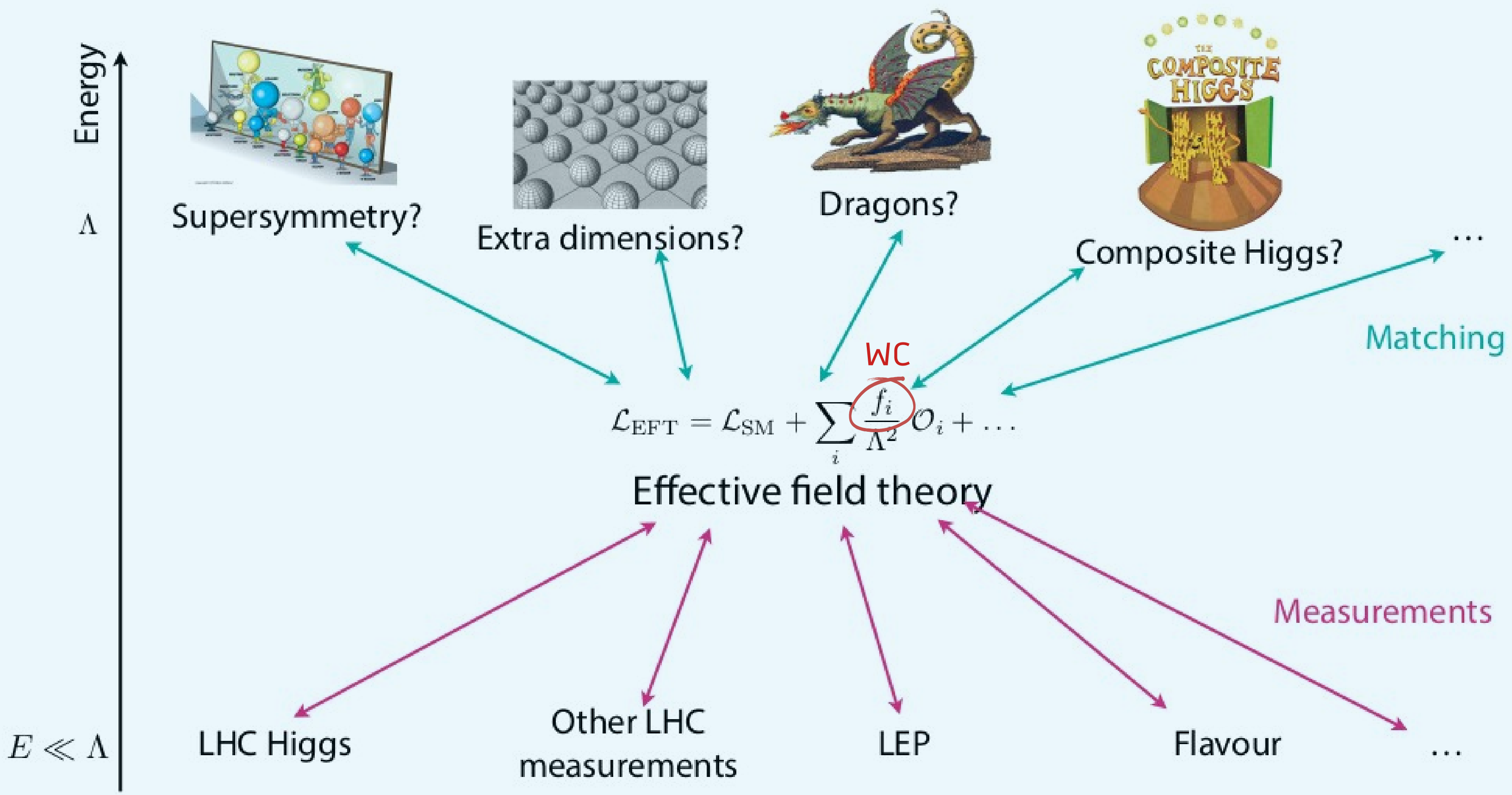
- Interpret potential deviations from SM predictions
  - BSM effects described by **finite number of EFT operators,** whose strengths are encoded into **Wilson coefficients** (WCs) ⇔ **theory parameters**

- Fruitful EXP/TH collaboration within LHCTopWG summarized in EFT note ⇔ **Guiding principles**



APPROACHES TO TOP-EFT

- **Good scalability**
- **Easily combinable** in global fits beyond LHC

…

- ✗ **Treat all backgrounds SM-like**
- ✗ **Many assumptions**, overestimate uncertainties, miss correlations, …

Post-measurement interpretation → Direct measurement at detector-level

- **Optimal sensitivity** to Wilson coefficients
- **Minimal assumptions**
- Can **probe EFT in all sensitive processes**
- In-situ constraint of systematics considering correlations
- Novel approach, less experience with combination

APPROACHES TO TOP-EFT

Reinterpret inclusive measurement

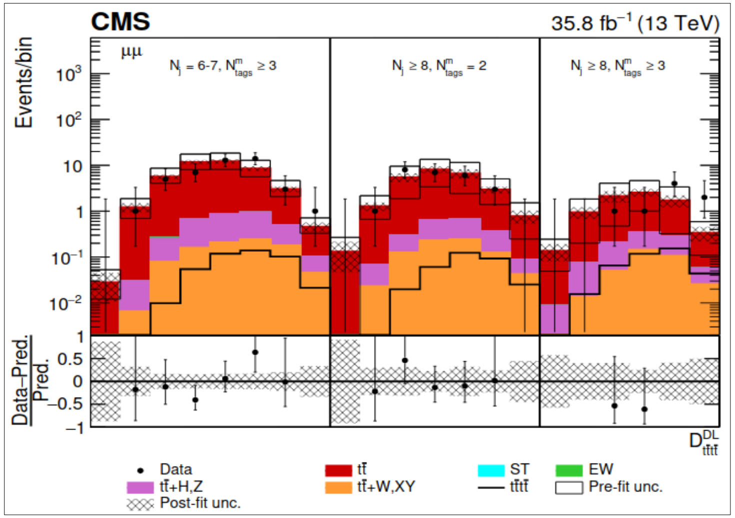
- Wilson coeff. constrained using **straightforward EFT parameterization**
- Scalable & combinable
- **No MC EFT sample required**
- **Maximal assumptions**

Post-measurement interpretation

Direct measurement at detector-level

- **Very rare process**, not yet observed
  - σ(SM) = 9.2 fb, $\mathcal{O}(10^5)$ smaller than $t\bar{t}$ background
- Target 1ℓ and 2ℓ-OS final states with jets
- Train BDTs to assign jets & isolate signal

Post-fit distributions of BDT-2l in eμ channel

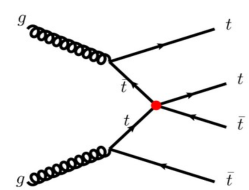


- Results combined with same-sign 2ℓ + 3ℓ analysis
  - Observed limit = 3.6 * σ(SM)
  - Obs. (exp.) significance = 1.4 (1.1) std.dev.

ATLAS Run2 result : [ATLAS-CONF-2021-013]
- Obs. (exp.) significance : 4.7 (2.6) std.dev.

- **Highly sensitive to 4-heavy-quark operators**
- Parameterization derived at gen-level :

$$\sigma_{t\bar{t}t\bar{t}} = \sigma^{\mathrm{SM}}_{t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\sum_k C_k \sigma^{(1)}_k + \frac{1}{\Lambda^4}\sum_{j\leq k} C_j C_k \sigma^{(2)}_{j,k}$$



- 95 % CL upper limits derived on individual operators, marginalizing other operators

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	[−2.0, 1.9]	[−2.2, 2.1]
$\mathcal{O}^1_{QQ}$	[−2.0, 1.9]	[−2.2, 2.0]
$\mathcal{O}^1_{Qt}$	[−3.4, 3.3]	[−3.7, 3.5]
$\mathcal{O}^8_{Qt}$	[−7.4, 6.3]	[−8.0, 6.8]

10.1007/JHEP11(2019)082

TT CHARGE ASYMMETRY

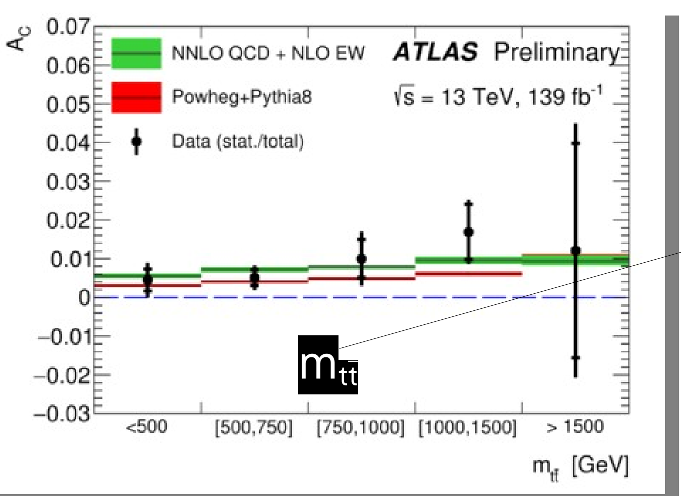
- PDF(q) != PDF($\bar{q}$) → **$t\bar{t}$ charge asymmetry @ pp collider**
  - Asymmetric $q\bar{q}$/qg contributions diluted in dominant gg fusion → Subtle effect
  - A_C altered by several BSM models (anomalous couplings, Z', …)
- ℓ+jets channel ; resolved & boosted topologies
- Inclusive measurement (statistics-limited) :
  - **Evidence for non-zero value (4σ)**
- Differential measurements unfolded at parton-level

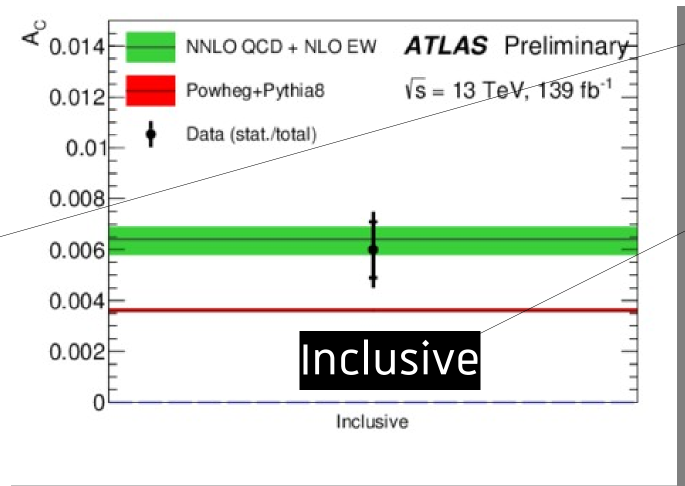
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

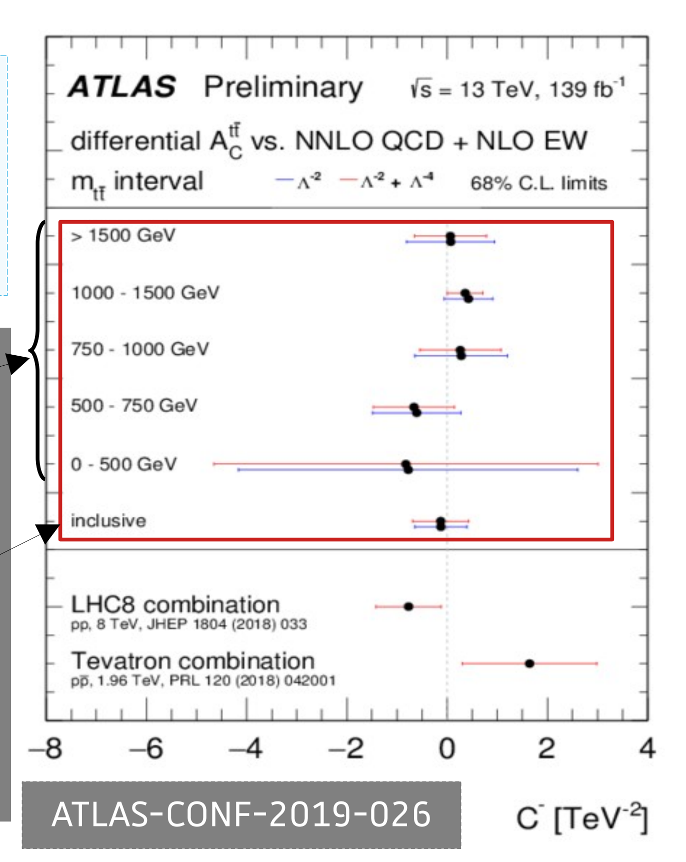
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\boxed{A_C = 0.0060 \pm 0.0015(\text{stat+syst.})}$$

- Sensitive to 7 EFT operators → Flavour assumptions
  → Sensitivity condensed into 1 linear combination (C^-)
- Compare measurements with EFT model → **Tighest bounds**







APPROACHES TO TOP-EFT

Reinterpret inclusive measurement

- Wilson coeff. constrained using straightforward EFT parameterization
- Scalable & combinable
- No MC EFT sample required
- Maximal assumptions

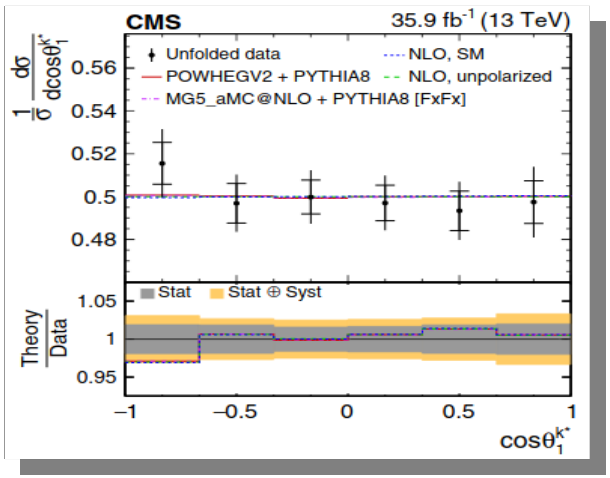
Post-measurement interpretation

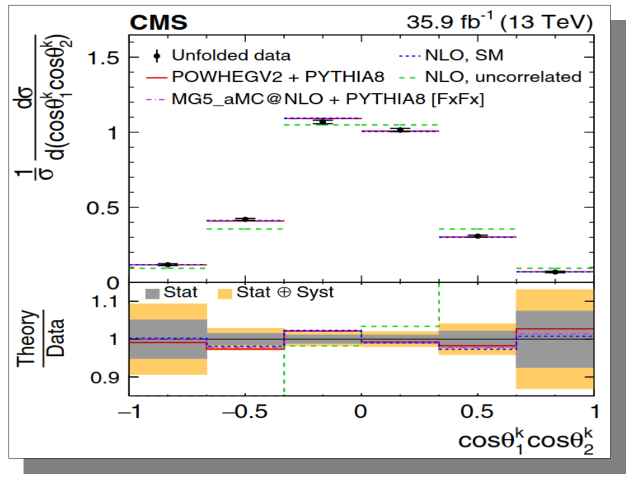
Direct measurement at detector-level

Reinterpret unfolded differential measurement

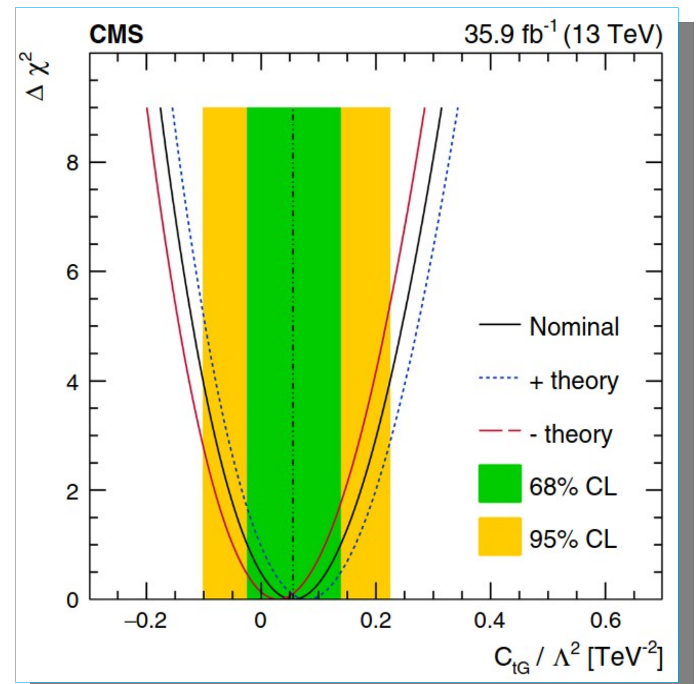
- Quantity(ies) sensitive to EFT are measured at particle/parton-level
- **Need differential MC EFT** at gen-level
- **Combinable** if bin correlations are provided
- Ignore EFT effects on acceptance/efficiency

- 2ℓ OS + b-jets final states
- **Differential $t\bar{t}$ cross section measurement as a function of polarization and spin correl. observables**
  - Unfolded at parton-level, consistent with SM





- Top chromomagnetic dipole moment (**CMDM**) predicted by SM, **modified** in 2HDM/SUSY/technicolor/etc.
  - Related to c_{tG} operator → Modifies yield, kinematics, spin structure
- 95% CL limit on c_{tG} obtained from **simultaneous X^2 fit to several differential spin distributions**
  - **Sensitivity improved by ~ 30 %** w.r.t. previous CMS analysis, mostly due to more powerful observables



10.1103/PhysRevD.100.072002

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Hybrid measurement at detector-level

a) **Parameterize yields with EFT at gen-level**, translate to detector-level assuming SM shapes

Post-measurement interpretation

Direct measurement at detector-level

Reinterpret unfolded differential measurement

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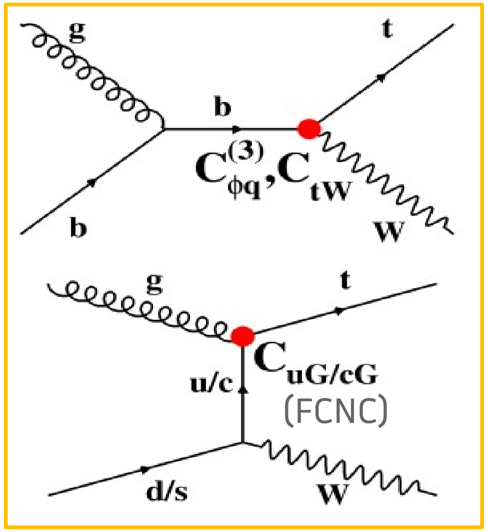
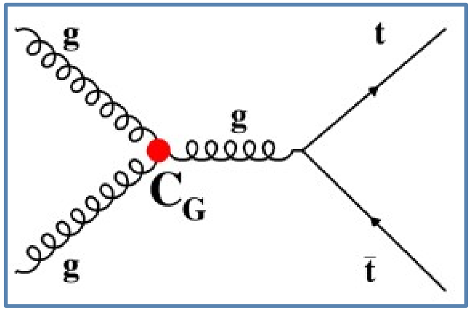
- 2ℓ channel

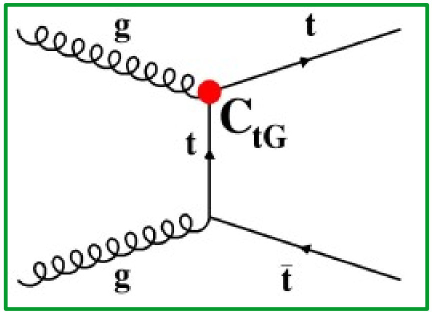
- <u>Event categorized by</u> :
  - lepton channel
  - jet/bjet multiplicities



tW



$t\bar{t}$



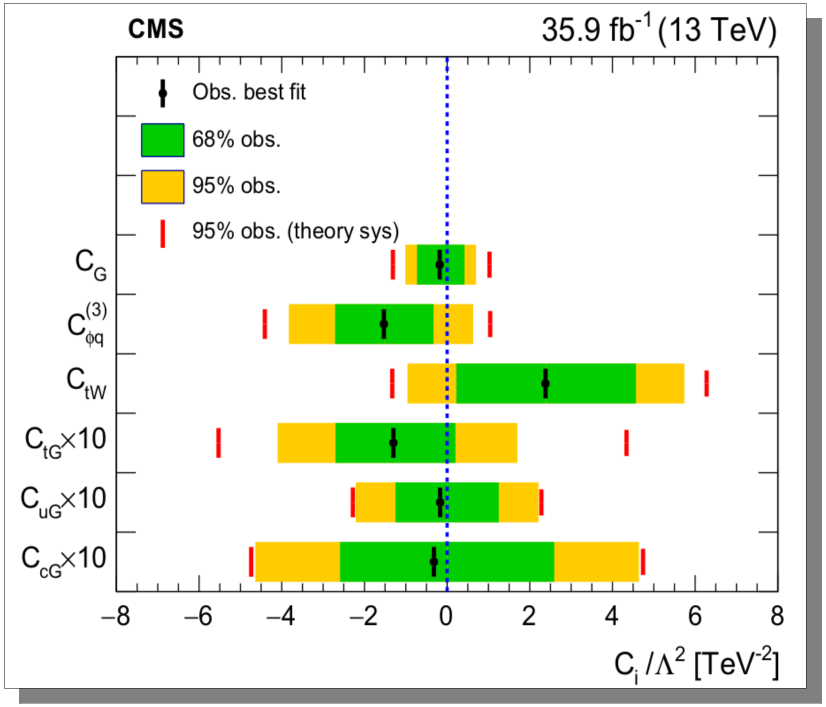
tW + $t\bar{t}$

- Train dedicated **neural networks** to :
  - Isolate the tW process (+ sensitivity)
  - Distinguish FCNC signatures from SM

- EFT contributions estimated at gen-level
  → **extrapolated to detector-level**

- Extract individual limits from simultaneous fit to yields or NN distributions in all categories

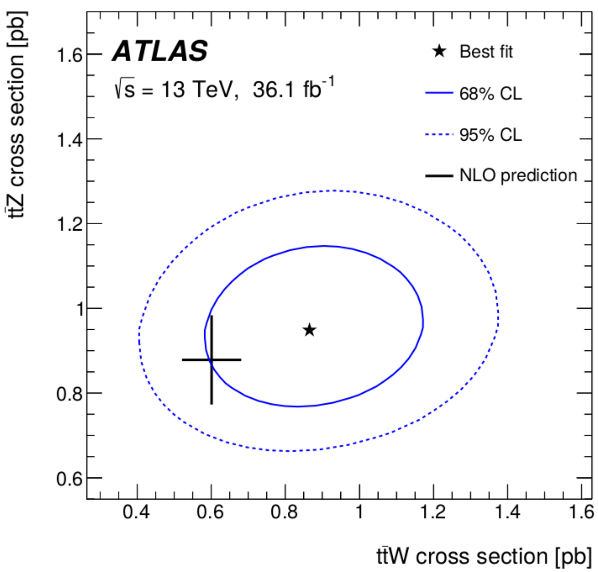
- **First step towards more global fits**



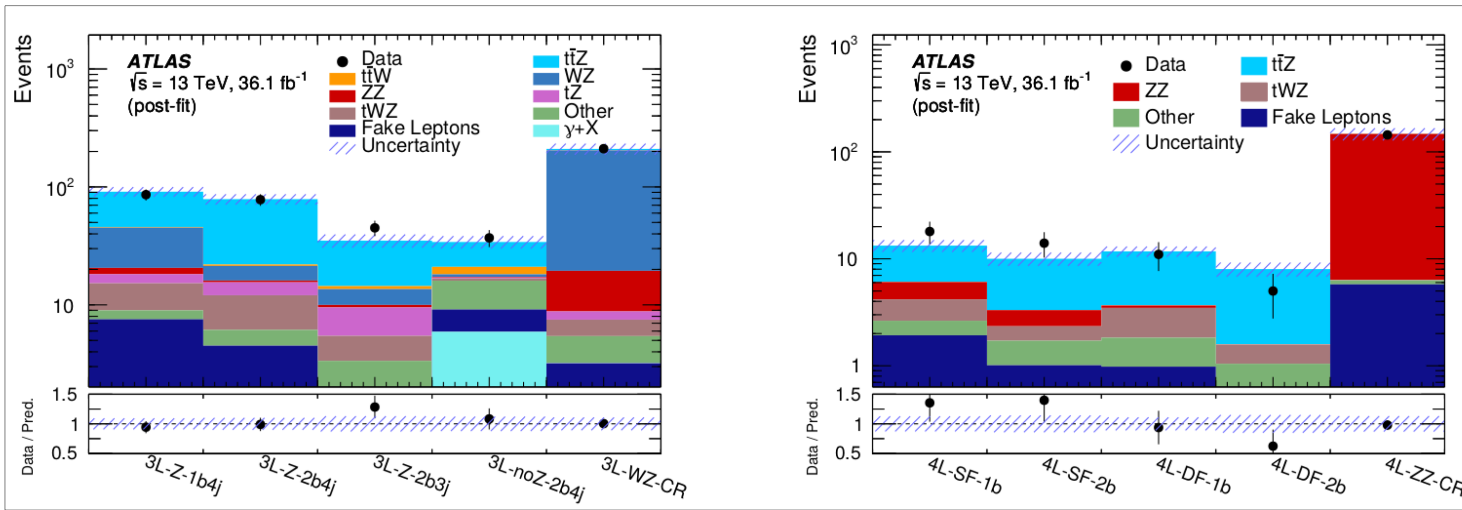
10.1140/epjc/s10052-019-7387-y

10.22323/1.276.0237

- Simultaneous inclusive σ(tt̄Z) & σ(tt̄W) measurements in 2ℓ/3ℓ/4ℓ channels
- Fit to event yields in categories based on object multiplicities / properties



Regions targeting tt̄Z production



$$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08_{\text{stat.}} \pm 0.10_{\text{syst.}}$$

$$\sigma_{t\bar{t}W} = 0.87 \pm 0.13_{\text{stat.}} \pm 0.14_{\text{syst.}}$$

→ Superseded by *CERN-EP-2021-01* (backup)

- Constrain 4 Wilson coefficients separately
  - Fit to 3ℓ/4ℓ categories targeting ttZ

Coefficients	$C^{(3)}_{\phi Q}/\Lambda^2$	$C_{\phi t}/\Lambda^2$	C_{tB}/Λ^2	C_{tW}/Λ^2
Previous indirect constraints at 68% CL	[−4.7, 0.7]	[−0.1, 3.7]	[−0.5, 10]	[−1.6, 0.8]
Previous direct constraints at 95% CL	[−1.3, 1.3]	[−9.7, 8.3]	[−6.9, 4.6]	[−0.2, 0.7]
Expected limit at 68% CL	[−2.1, 1.9]	[−3.8, 2.7]	[−2.9, 3.0]	[−1.8, 1.9]
Expected limit at 95% CL	[−4.5, 3.6]	[−23, 4.9]	[−4.2, 4.3]	[−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]
Expected limit at 68% CL (linear)	[−1.9, 2.0]	[−3.0, 3.2]	–	–
Expected limit at 95% CL (linear)	[−3.7, 4.0]	[−5.8, 6.3]	–	–
Observed limit at 68% CL (linear)	[−1.0, 2.9]	[−1.8, 4.4]	–	–
Observed limit at 95% CL (linear)	[−2.9, 4.9]	[−4.8, 7.5]	–	–

APPROACHES TO TOP-EFT

Reinterpret inclusive measurement

- Wilson coeff. constrained using straightforward EFT parameterization
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- No MC EFT sample required
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Hybrid measurement at detector-level

a) Parameterize yields with EFT at gen-level, translate to detector-level assuming SM shapes

b) **Reweight distributions as (SM+EFT/SM) at gen-level,** translate to detector-level under SM assumption

Post-measurement interpretation

Direct measurement at detector-level

Reinterpret unfolded differential measurement

- Quantity(ies) sensitive to EFT are measured at particle/parton-level
- Need differential MC EFT at gen-level
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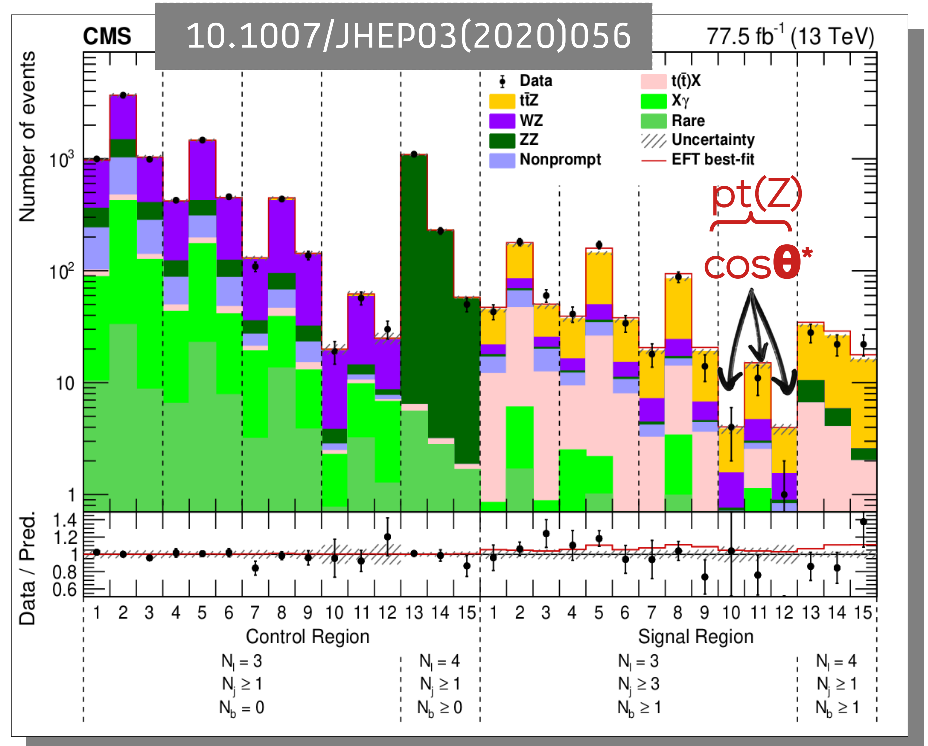
TTZ INCL./DIFFERENTIAL



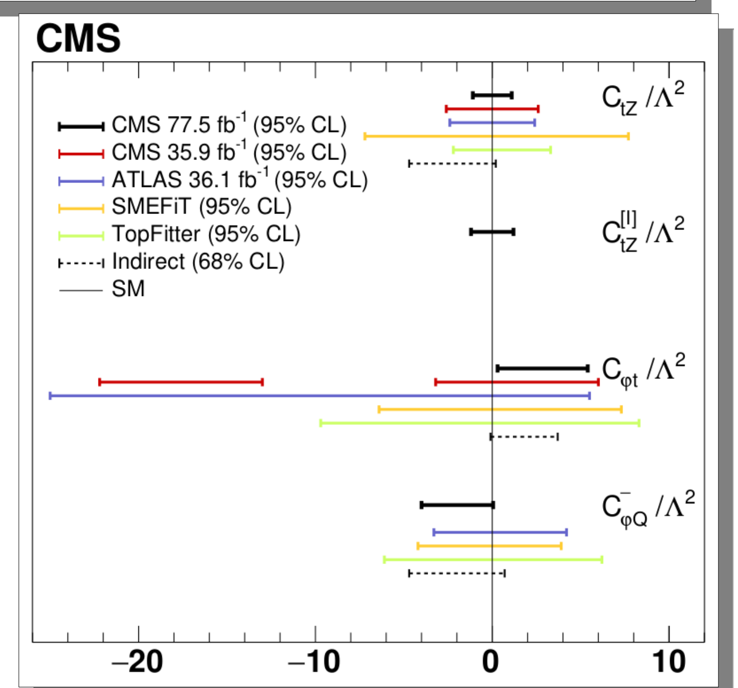
- Procedure :

a) **Produce gen-level samples** for SM & SM+EFT (LO), in fine grid of EFT parameter space

b) **Calculate weights SM+EFT/SM** in bins of both observables, before event selection

c) **Apply weights to detector-level** (NLO) SM sample to emulate EFT contributions

- Inclusive/differential measurements of σ(ttZ) in good agreement with NLO+NNLL predictions
- **Constrain 4 EFT operators impacting t-Z coupling**
- **Up to +20 % sensitivity from shape information**

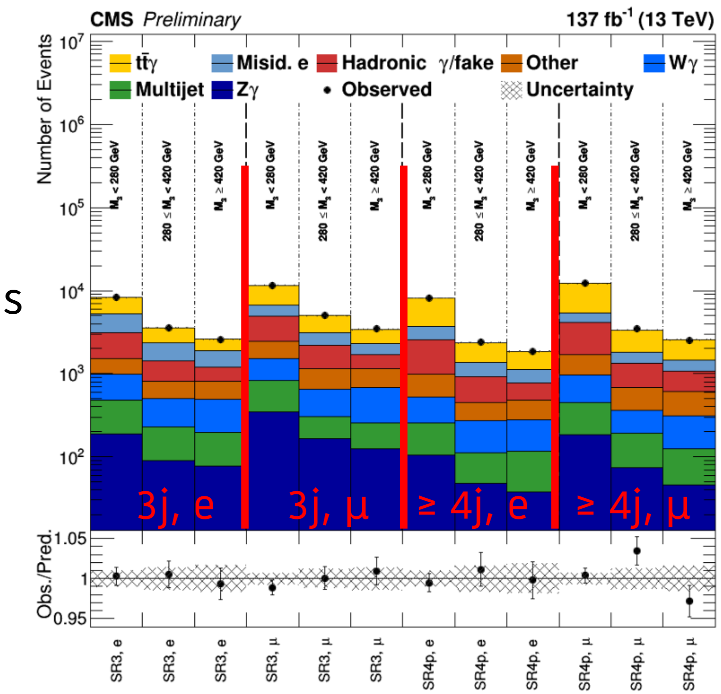


- = 1 e or μ (p_T>25) / = 1 γ (p_T>20) / ≥ 3 j (p_T>30) / ≥ 1 bjet (ε~70 %)
- **Constrain main backgrounds in-situ** with dedicated sidebands
- Simultaneous fit to 12 SR + 34 CR categories

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

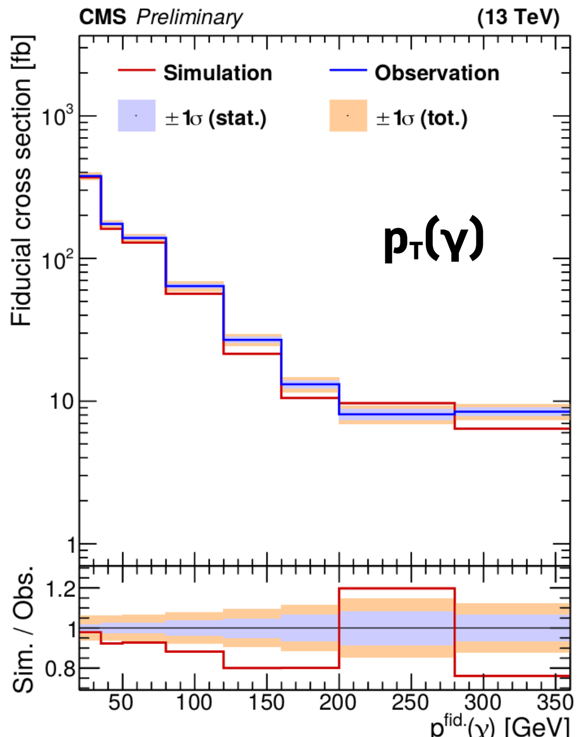
5.8 % precision

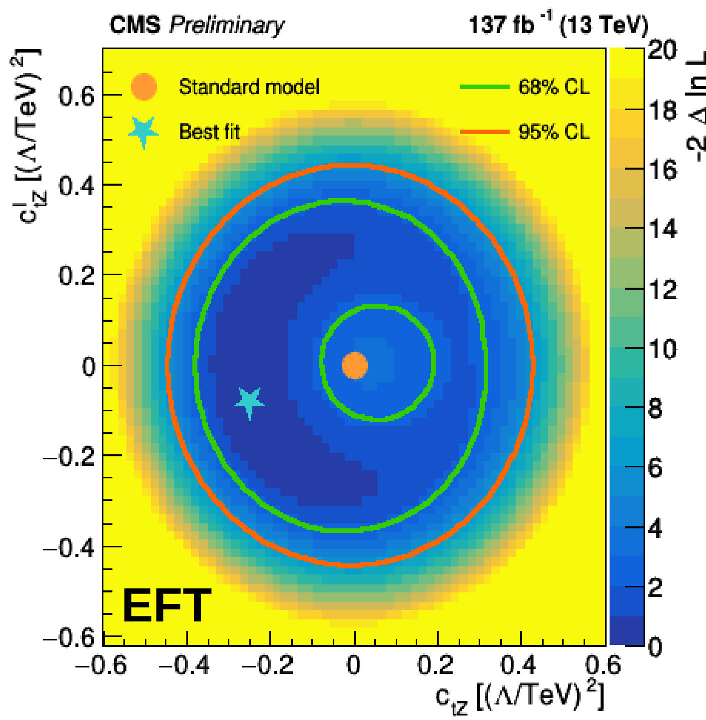
ATLAS Run2 ttγ+tWγ fiducial measurement : JHEP 09 (2020) 049



CMS-PAS-TOP-18-010

- Particle-level unfolding to pt(γ), |η(γ)|, ΔR(ℓ,γ)
- **All results agree with predictions**
- **Constrain 2 EFT operators** impacting t-γ/Z vertices





APPROACHES TO TOP-EFT

Reinterpret inclusive measurement

- Wilson coeff. constrained using straightforward EFT parameterization
- Scalable & combinable
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Hybrid measurement at detector-level

a) **Parameterize yields with EFT at gen-level,** translate to detector-level assuming SM shapes

b) **Reweight distributions as (SM+EFT/SM) at gen-level,** translate to detector-level under SM assumption

Post-measurement interpretation

Direct measurement at detector-level

Reinterpret unfolded differential measurement

- Quantity(ies) sensitive to EFT are measured at particle/parton-level
- Need differential MC EFT at gen-level
- Combinable if bin correlations are provided
- Ignore EFT effects on acceptance/efficiency

Direct EFT measurement

- **~ no SM assumption**
- Consider **EFT in all sensitive processes**
  → Need full SM+EFT sample for each
- Simultaneous fit to multiple regions

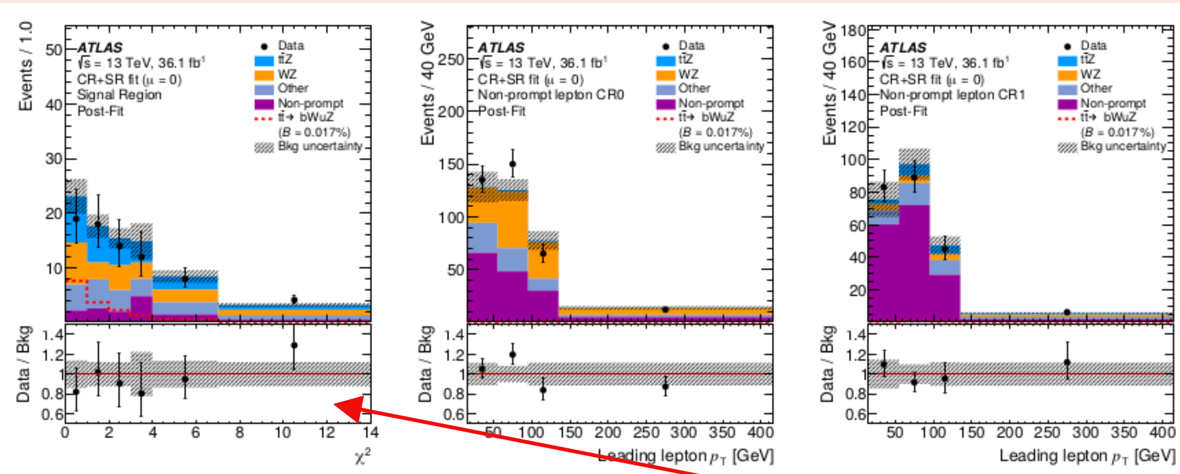
FCNC T→ZQ & T→γQ

36.1 fb^{-1} 81 fb^{-1}

- t → Zq / 3ℓ channel / FCNC in $t\bar{t}$ decay

Model:	SM	QS	2HDM	FC 2HDM	MSSM	RPV SUSY	RS	EMF
$\mathcal{B}(t \to qZ)$:	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}	10^{-6}	10^{-5}	10^{-6}

- Fit to kinematic distributions in several SRs/CRs → Constrain Wilson coefficients

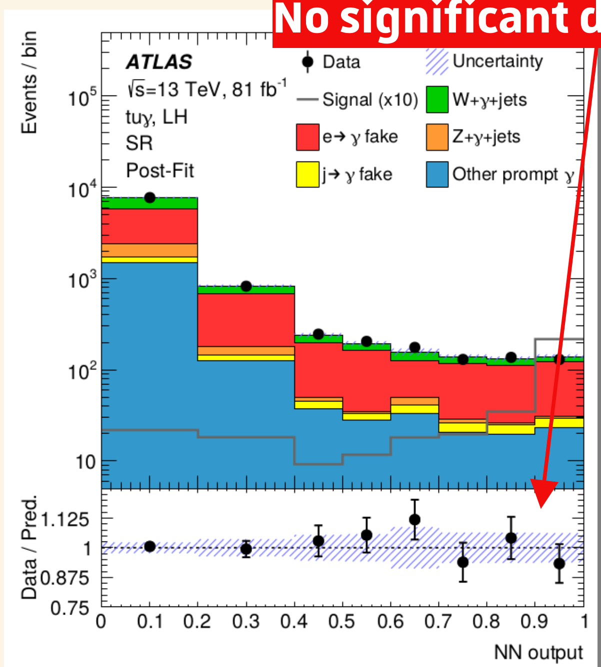


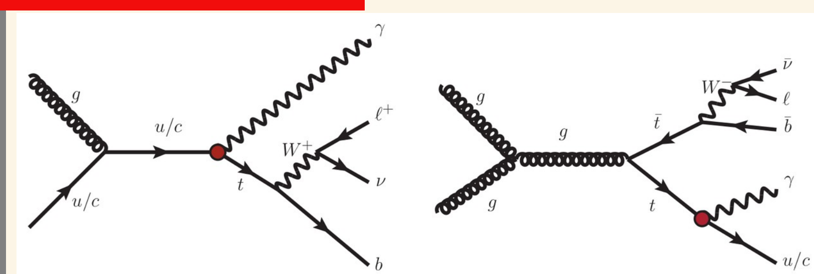
Operator	Observed	Expected
$\lvert C_{uB}^{(31)} \rvert$	0.25	0.30
$\lvert C_{uW}^{(31)} \rvert$	0.25	0.30
$\lvert C_{uB}^{(32)} \rvert$	0.30	0.34
$\lvert C_{uW}^{(32)} \rvert$	0.30	0.34

10.1007/JHEP11(2019)082

No significant deviation from SM

- t → γq / FCNC in top production & decay
- Fit to NN in SR, and to kinematics in CRs





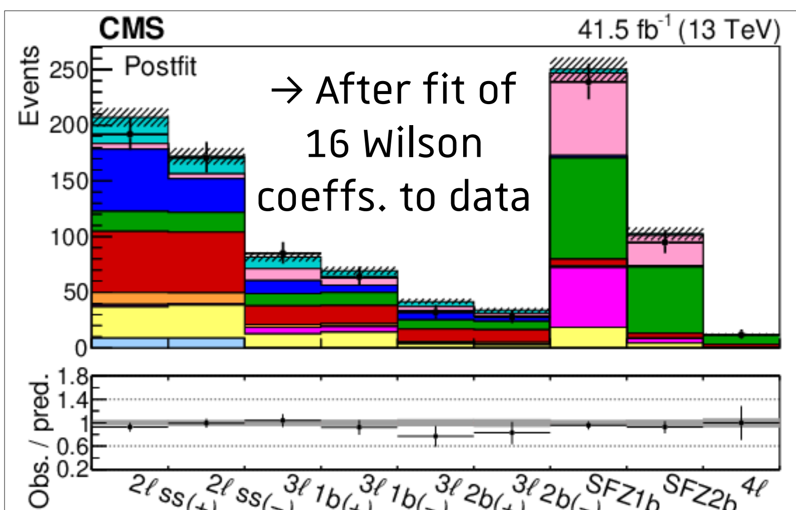
Observable	Vertex	Coupling	Obs.	Exp.
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*} \rvert$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)} \rvert$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*} \rvert$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)} \rvert$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$

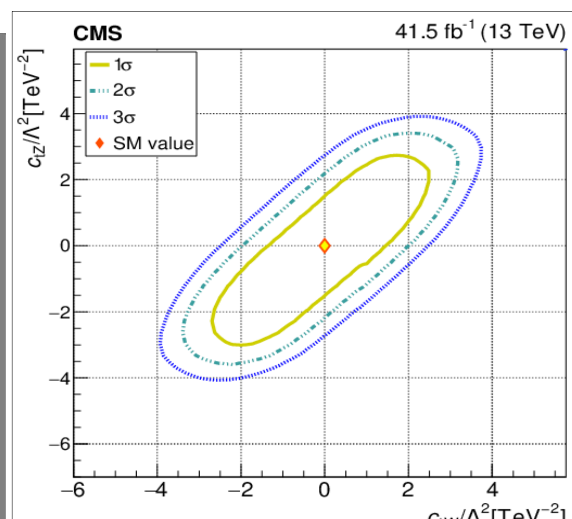
Phys. Lett. B 800 (2019) 135082

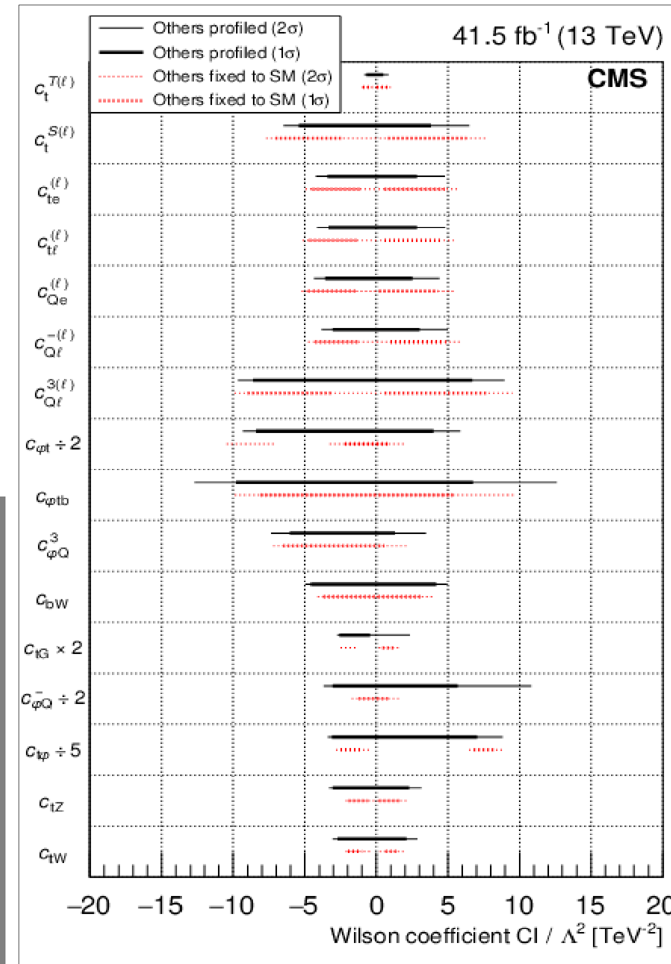
TOP-EFT IN T(T)X PROCESSES

- Target **{$t\bar{t}\ell\ell$/$t\bar{t}\ell\nu$/$t\ell\ell q$/$t\bar{t}H$/tHq}** processes simultaneously in **{2ℓ SS/3ℓ/4ℓ + bjets}** channels
- **Constrain 16 EFT operators impacting top quark vertices**
- Signal event weights parameterized with all Wilson coeffs.
  - Full detector simulation of SMEFT samples
  - Categorization on objects multiplicities & properties

  → Enhance sensitivity to different processes / operators
- Important step towards direct measurements accounting for **EFT in all sensitive processes** !



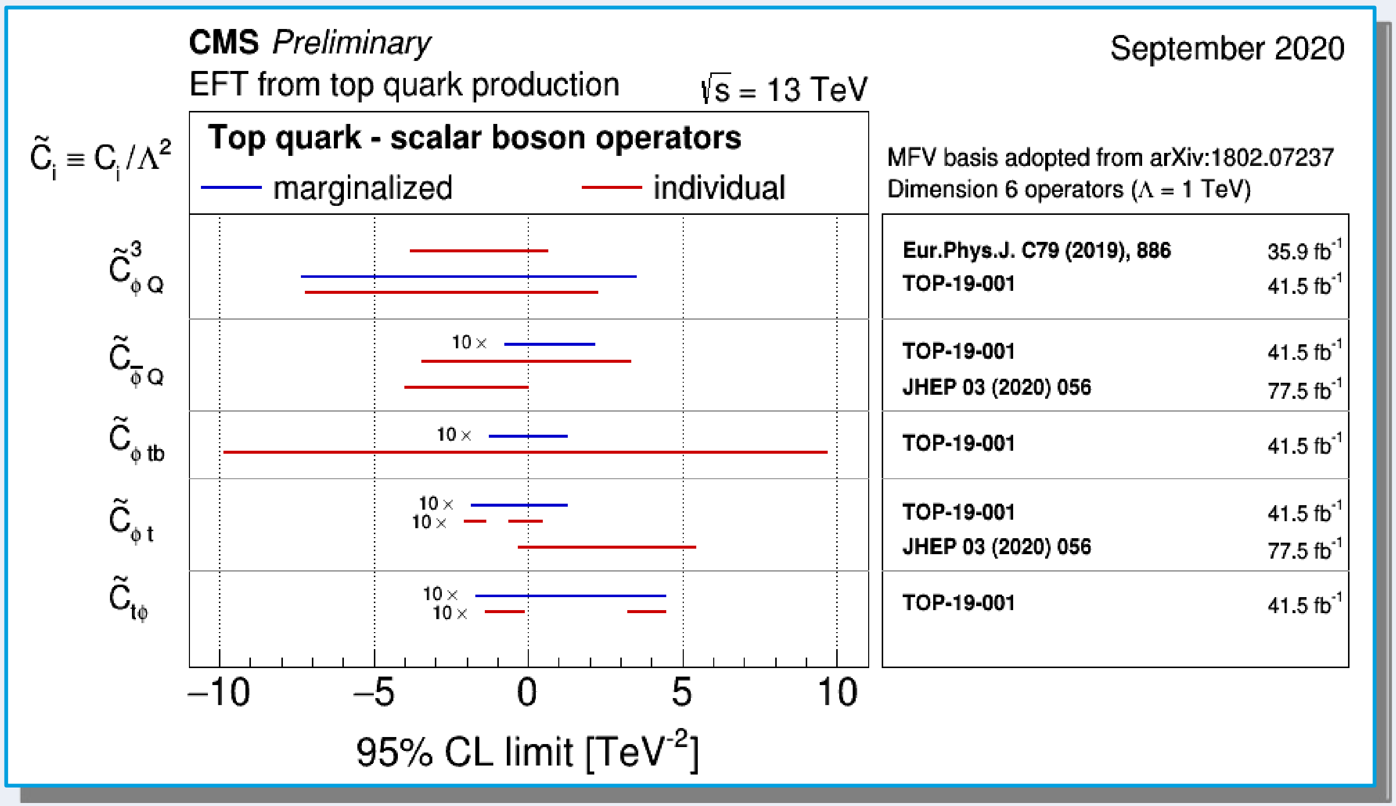




10.1007/JHEP03(2021)095

SUMMARY

- Top physics @ LHC has entered **precision differential era** for good
  - EFT measurements a key part of future physics programme & LHC legacy
- ATLAS & CMS Top groups **continuously improving their EFT strategies**
  - Already numerous publications employing **different approaches** with pros/cons



Other CMS EFT summary plots in backup

TOWARDS RUN 3

Trends

- EFT interpretations are becoming frequent in $t(\bar{t})$+X analyses
- Shifting from reinterpretations of inclusive → differential measurements
- Expect more and more direct EFT measurements in future
- Rares top quark processes (tX, $t\bar{t}t\bar{t}$, …) a crucial component of EFT searches

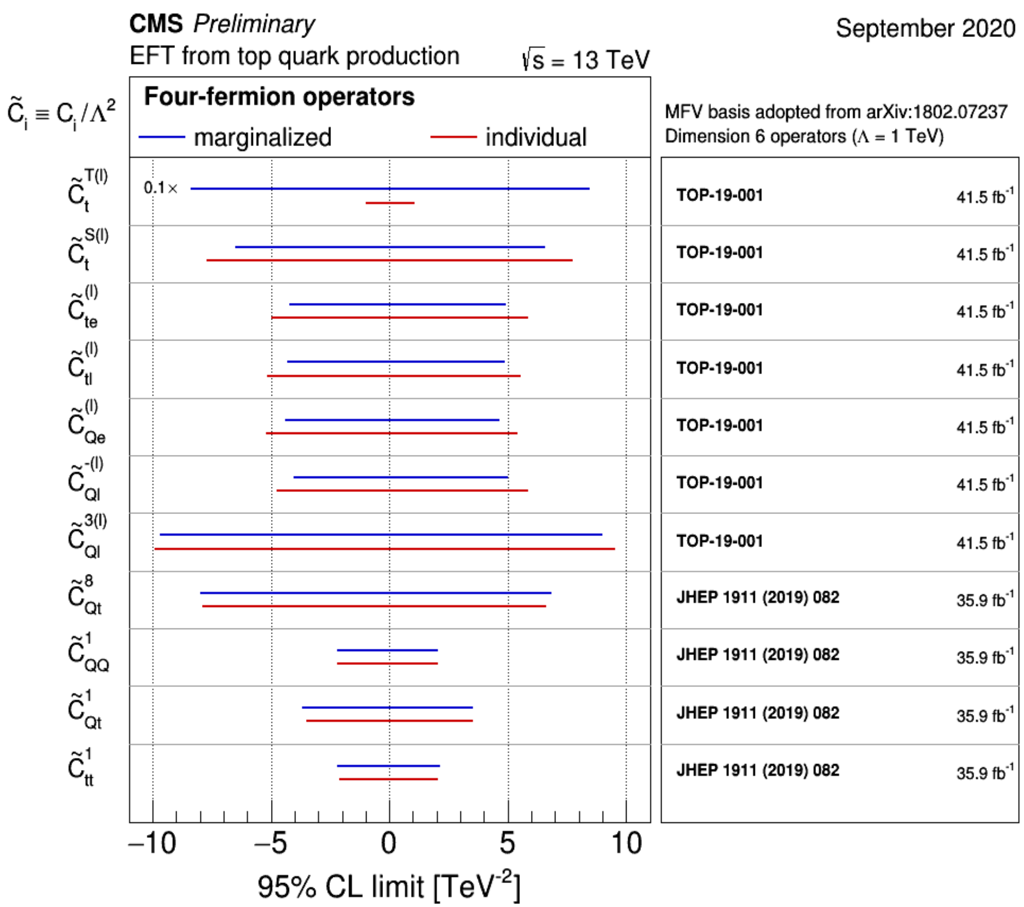
Many avenues to further improve treatment of / sensitivity to EFT

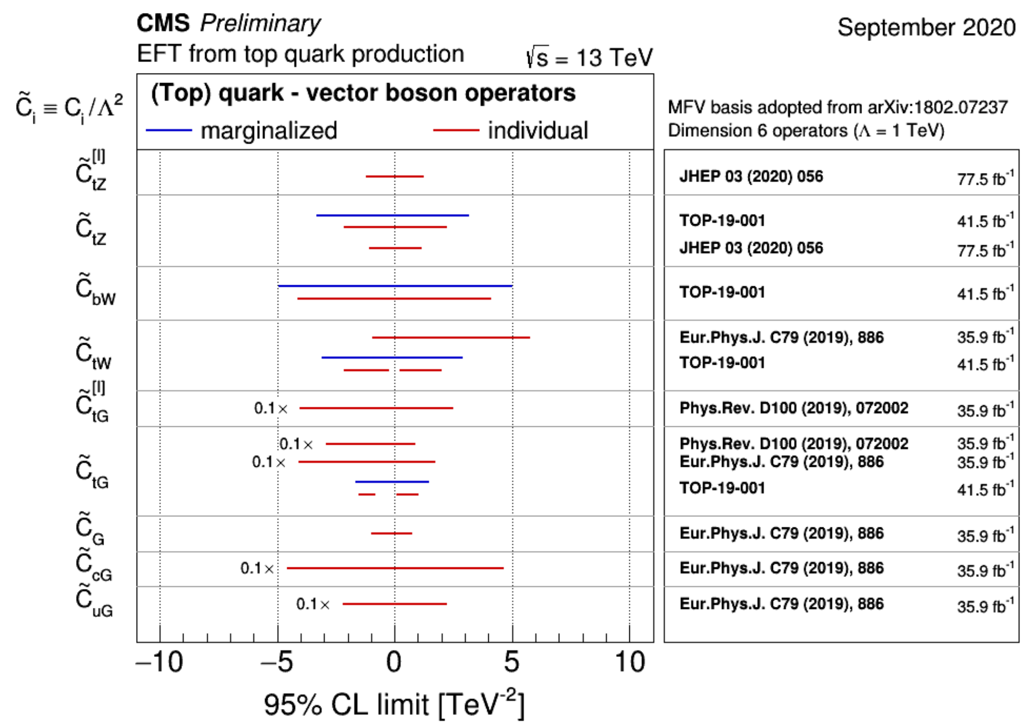
- More studies needed : include EFT effects in top decay, validate/use new NLO models, etc.
- Simultaneous fits to multiple processes & operators ↔ Physics-driven approach
  - Simulation & fits more challenging ! Important to gain experience now
- Make maximal use of available information (→ differential, machine-learning, MEM, etc.)
- Ambitious objective : **global fit in the top quark sector** through combinations between…
  - analyses → orthogonal event selections, unified statistical framework, etc.
  - experiments → common procedures/assumptions (cf.TopLHCWG), etc.

BACKUP

CMS TOP EFT SUMMARY PLOTS

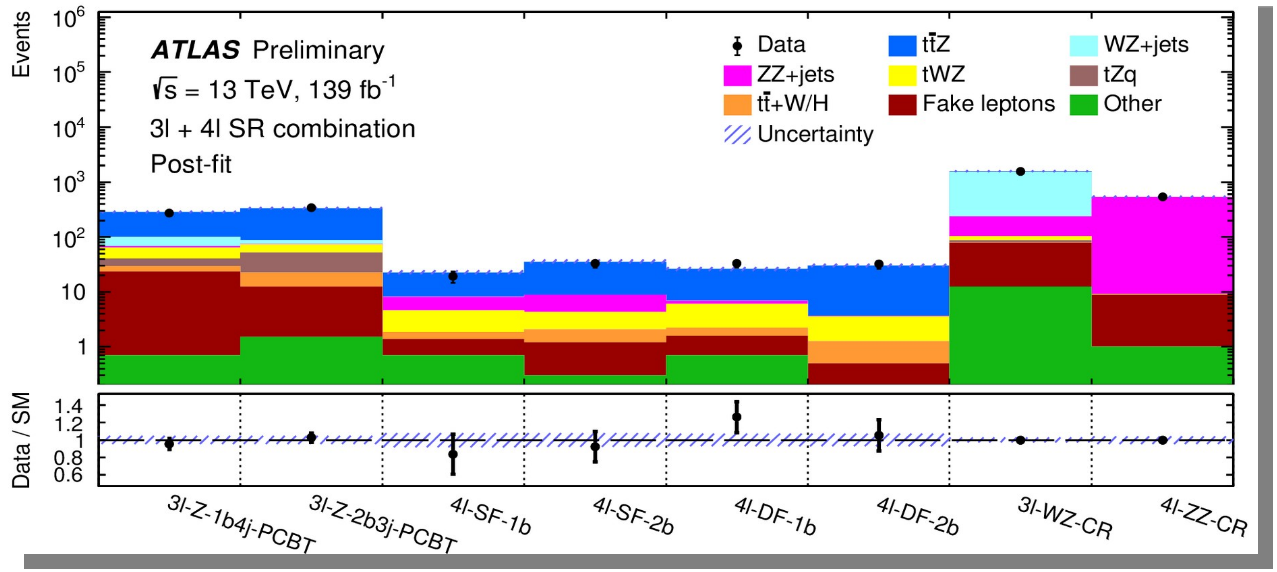
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures





- WZ/ZZ+light jets normalizations free in fit

- Parton shower, tZ/WZ/ZZ modeling, b-tagging



- In agreement (and similar precision) as NLO+NNLL prediction :

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$$\boxed{\sigma_{t\bar{t}Z} = 1.05 \pm 0.05\,(\text{stat.}) \pm 0.09\,(\text{syst.})\ \text{pb}}$$

$$0.86^{+0.07}_{-0.08}\,(\text{scale}) \pm 0.03\,(\text{PDF} + \alpha_S)\ \text{pb}$$

- **Differential measurements versus 9 observables** (↔ Z, tt̄, njets)
  - Parton- & particle-level