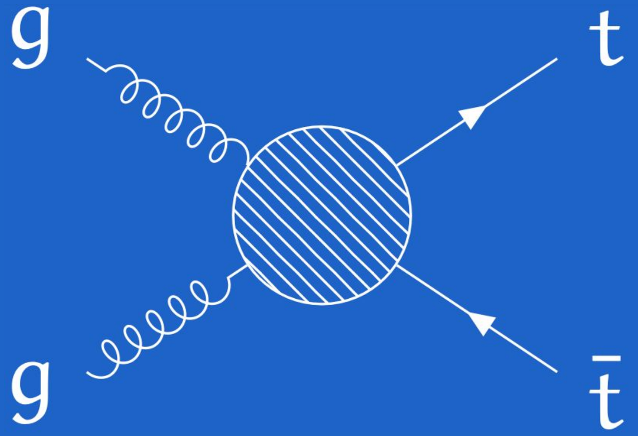
TOP2024 - 17th International Workshop on Top Quark Physics



Recent EFT results from CMS

Niels Van den Bossche on behalf of the CMS Collaboration

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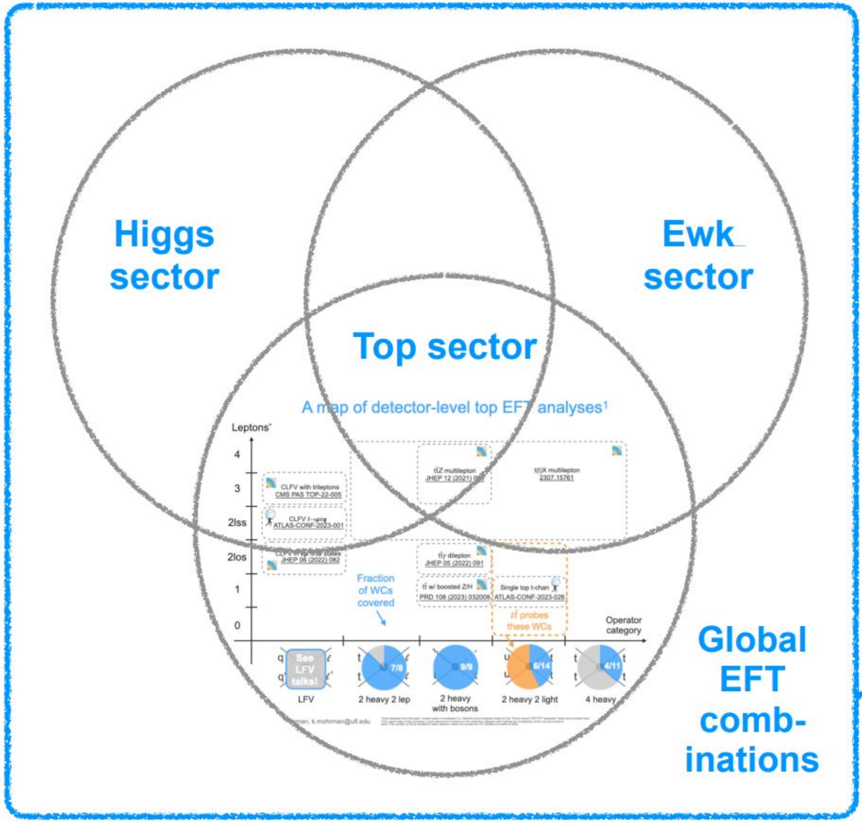
EFT at CMS during TOP2023



Hopefully to new physics discoveries!

- SMEFT: symmetries of SM are valid
- Last year: direct EFT measurement of tt+X processes
- Outlook given by Kelci: combination with Higgs and Electroweak sector

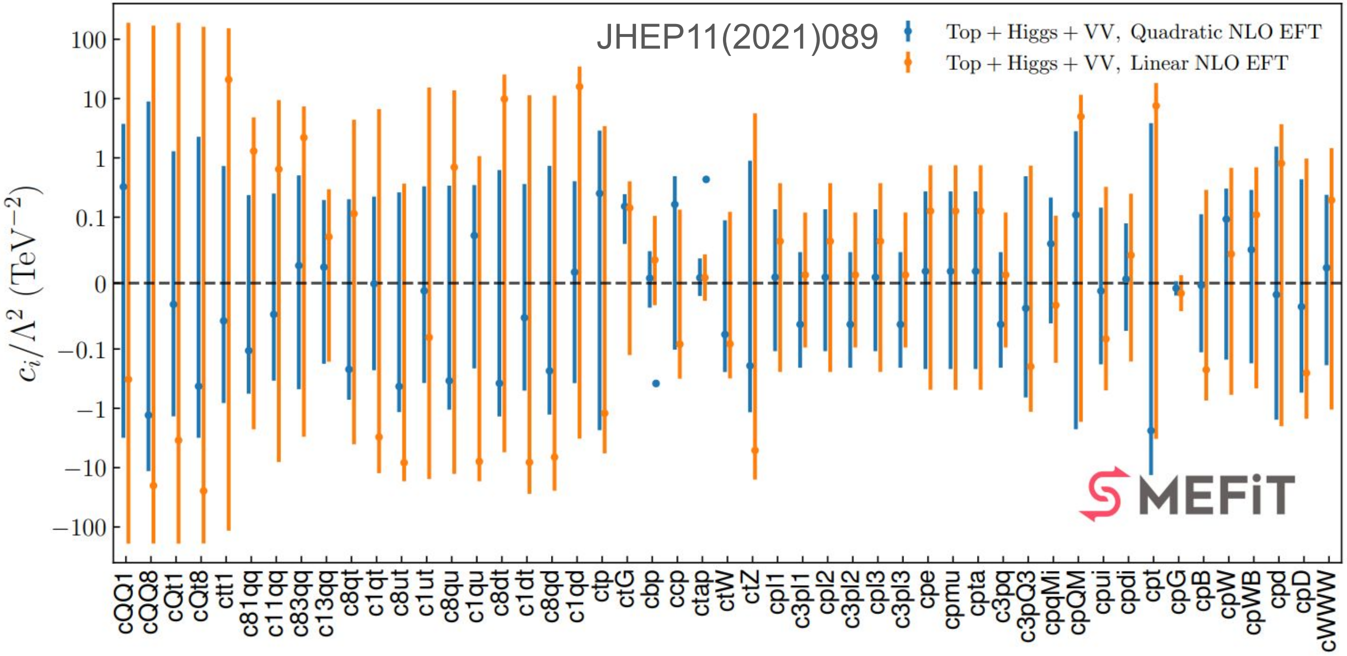
Today, new CMS result:

- Combined EFT interpretation of Higgs, Top, EWK and QCD measurements!
- CMS-PAS-SMP-24-003

Slide by K. Mohrman

Combined EFT interpretation of Higgs, top, EWK and QCD

- Global EFT fits allow to maximize sensitivity and pinpoint excesses to a single operator
- Fits combining multiple measurements have been performed outside experimental collaborations
  - Limited availability of full likelihoods
  - Internal combination allows to modify the analyses



Combined EFT interpretation of Higgs, top, EWK and QCD

- Dimension 6 CP-even operators in the topU3l basis
  - **64 Wilson Coefficients** used in final fit
- The **topU3l basis**:
  - 1st/2nd generation quarks: q, u, d
  - 3rd generation: Q, t, b
  - U(2)q x U(2)u x U(2)d symmetry
  - VCKM= $\mathbb{1}$

Combination of EWPO + 6 CMS analyses in 4 sectors, selection based on:

- **Minimal overlap** in event selection
- Covering a broad set of operators

X^3	
$\mathcal{Q}_{G}$	$\mathcal{Q}_{W}$
H^2D^2	
$\mathcal{Q}_{H\Box}$	$\mathcal{Q}_{HD}$
X^2H^2	
$\mathcal{Q}_{HG}$	$\mathcal{Q}_{HW}$
$\mathcal{Q}_{HB}$	$\mathcal{Q}_{HWB}$
ψ^2H^3	
$\mathcal{Q}_{tH}$	$\mathcal{Q}_{bH}$
ψ^2XH	
$\mathcal{Q}_{tW}$	$\mathcal{Q}_{tB}$
$\mathcal{Q}_{tG}$	
ψ^2H^2D	
$\mathcal{Q}_{Hl}^{(1)}$	$\mathcal{Q}_{Hl}^{(3)}$
$\mathcal{Q}_{He}$	
$\mathcal{Q}_{Hq}^{(1)}$	$\mathcal{Q}_{Hq}^{(3)}$
$\mathcal{Q}_{Hu}$	$\mathcal{Q}_{Hd}$
$\mathcal{Q}_{HQ}^{(1)}$	$\mathcal{Q}_{HQ}^{(3)}$
$\mathcal{Q}_{Ht}$	$\mathcal{Q}_{Hb}$

$\psi^4, (\bar{L}L)(\bar{L}L)$	
$\mathcal{Q}_{lq}^{(1)}$	$\mathcal{Q}_{lq}^{(3)}$
$\mathcal{Q}_{lQ}^{(1)}$	$\mathcal{Q}_{lQ}^{(3)}$
$\mathcal{Q}_{QQ}^{(1)}$	$\mathcal{Q}_{ll}$
$\mathcal{Q}_{qq}^{(1,1)}$	$\mathcal{Q}_{qq}^{(1,8)}$
$\mathcal{Q}_{qq}^{(3,1)}$	$\mathcal{Q}_{qq}^{(3,8)}$
$\mathcal{Q}_{Qq}^{(1,1)}$	$\mathcal{Q}_{Qq}^{(1,8)}$
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$\mathcal{Q}_{uu}^{(1)}$	$\mathcal{Q}_{uu}^{(8)}$
$\mathcal{Q}_{tu}^{(1)}$	$\mathcal{Q}_{tu}^{(8)}$
$\mathcal{Q}_{dd}^{(1)}$	$\mathcal{Q}_{dd}^{(8)}$
$\mathcal{Q}_{ud}^{(1)}$	$\mathcal{Q}_{ud}^{(8)}$
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$\mathcal{Q}_{Qu}^{(1)}$	$\mathcal{Q}_{Qu}^{(8)}$
$\mathcal{Q}_{qt}^{(1)}$	$\mathcal{Q}_{qt}^{(8)}$
$\mathcal{Q}_{Qt}^{(1)}$	$\mathcal{Q}_{Qt}^{(8)}$
$\mathcal{Q}_{qd}^{(1)}$	$\mathcal{Q}_{qd}^{(8)}$
$\mathcal{Q}_{Qd}^{(1)}$	$\mathcal{Q}_{Qd}^{(8)}$

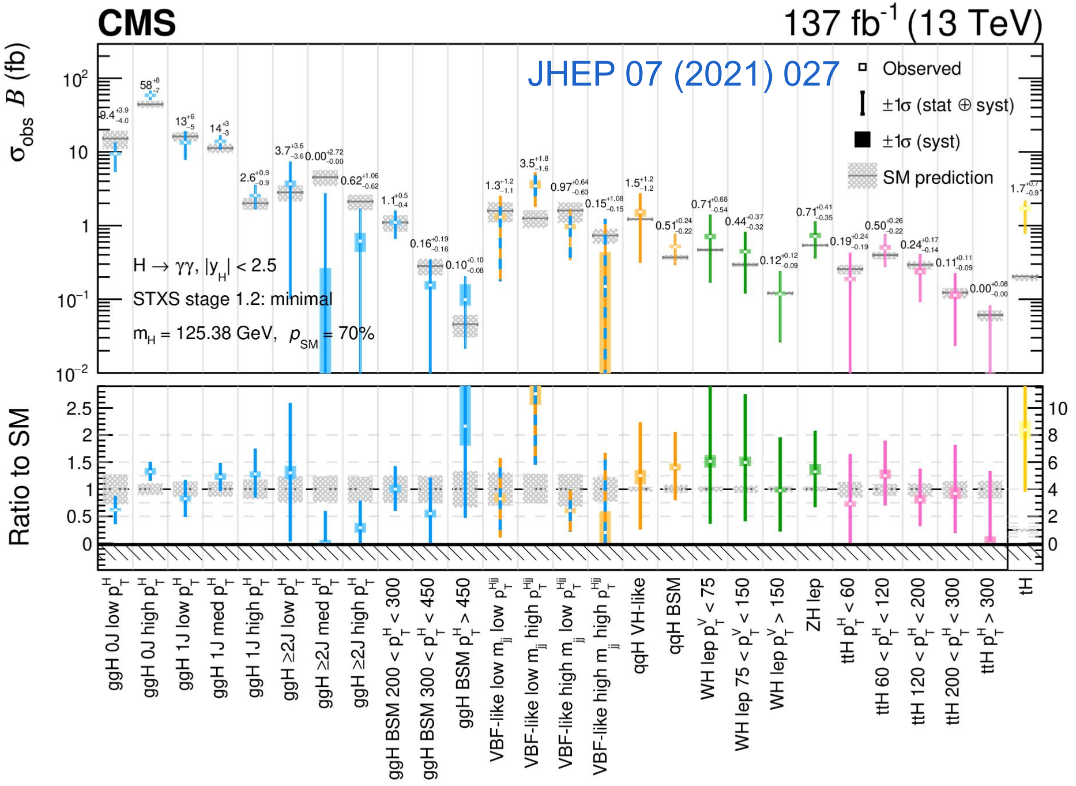
Combined EFT interpretation: Higgs and EWPO input

Measurement of Higgs production cross section in the **H→γγ** decay channel:

- Differential measurement in STXS stage 1.2 binning
- Signal strength parameterized as function of relevant operators
  - SMEFTSim3 and SMEFT@NLO for various production modes
  - Analytically for Higgs decay

EWPO measurements from LEP and SLC:

- Analytic evaluation of SMEFT operators on the observables
- Γ_Z, σ_{had}, R_l, R_c, R_b, $A_{FB}(l)$, $A_{FB}(c)$, $A_{FB}(b)$



Combined EFT interpretation: Wγ, WW, Z

WW differential cross section (PRD 102, 092001 (2020))

- 2016 only
- Observable: m_{ll}

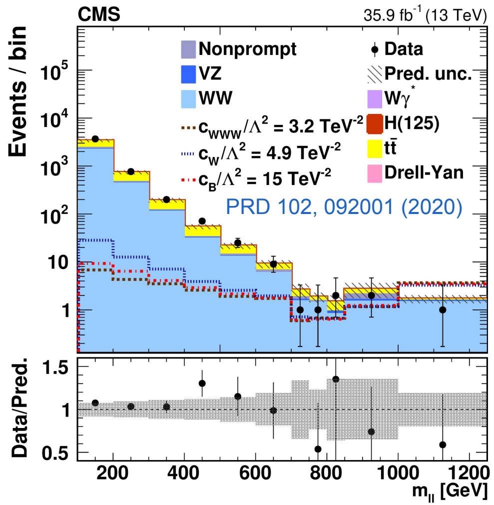
Z $\rightarrow \nu\nu$ differential cross section (JHEP 05 (2021) 205)

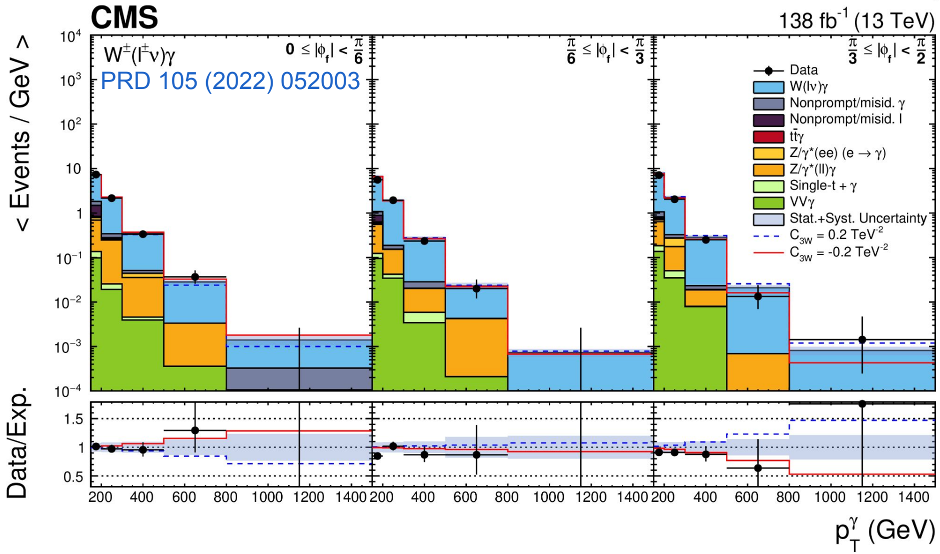
- 2016 only
- Observable: $p_T(Z)$

Wγ double differential cross section (PRD 105 (2022) 052003)

- Full Run 2
- Observable: $p_T(\gamma)$ x $|\phi_f|$

SMEFTSim3 simulation of EFT effects





Combined EFT interpretation: QCD and $t\bar{t}$

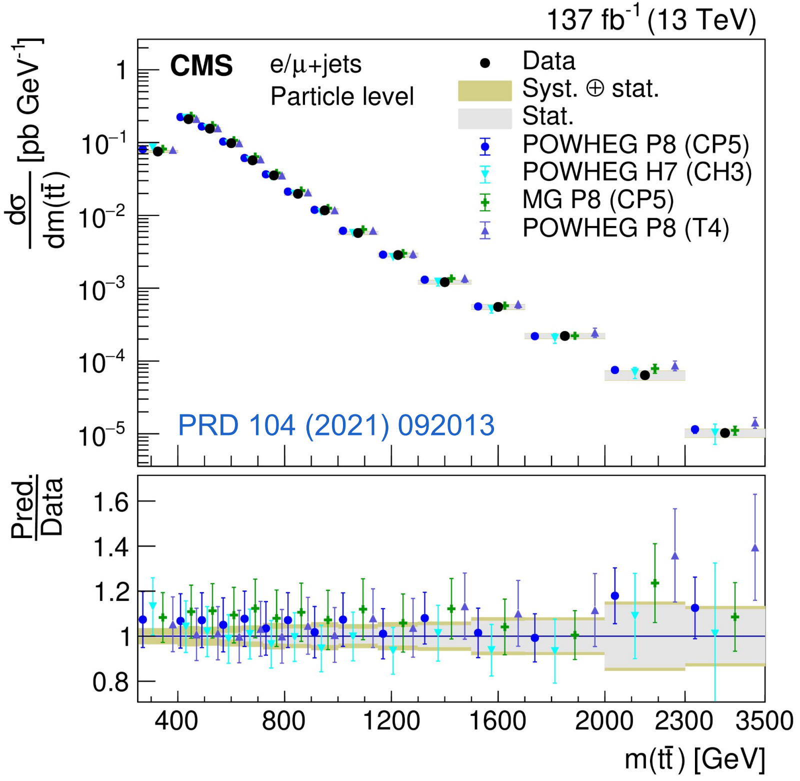
QCD Inclusive jets measurement (JHEP 02 (2022) 142)

- AK7-jets, double differential in p_T, |y| used as input
- New PDF set introduced leading to improved agreement with data (CT18 replaces CT14)

$t\bar{t}$ differential cross section (PRD 104 (2021) 092013)

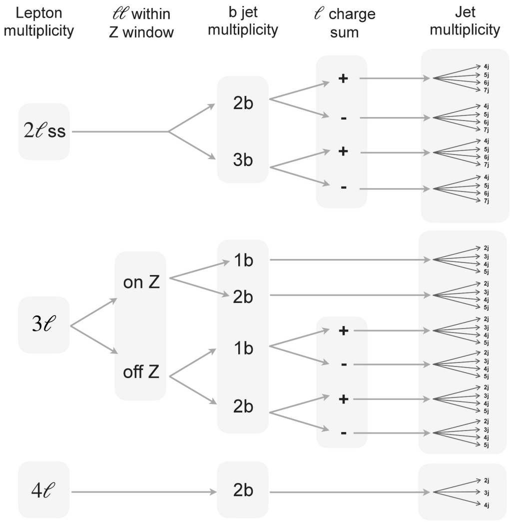
- Single lepton + jets
- Includes boosted top quark reconstruction
- $m(t\bar{t})$ used in combination

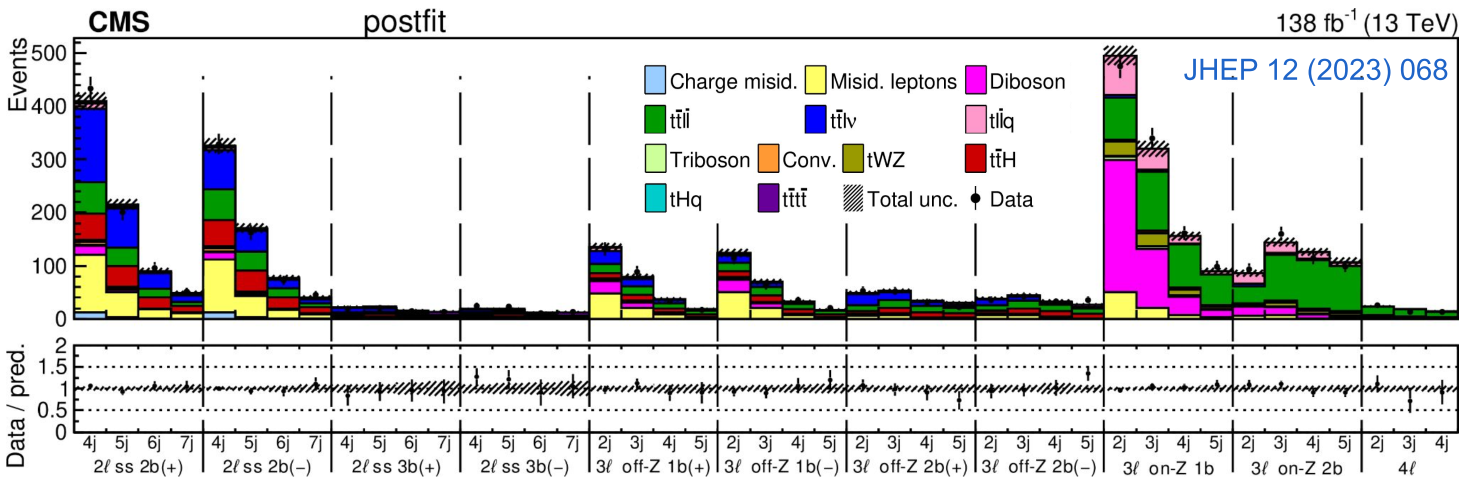
Both are included with a **simplified likelihood (χ^2)**



Combined EFT interpretation: $t\bar{t}X$ multilepton

- Only direct EFT search of all presented results:
  - Expected events in each bin is parameterized as function of WCs
  - Preference over dedicated differential measurements of $t\bar{t}X$ processes due to large overlap in signature
- 26 WCs considered in original analysis in 6 processes:
  - $t\bar{t}W$, $t\bar{t}Z$, tZq (including off-shell)
  - $t\bar{t}H$, tHq, $t\bar{t}t\bar{t}$
- Fit to distribution of max p_T of any combination of 2 leptons and/or jets



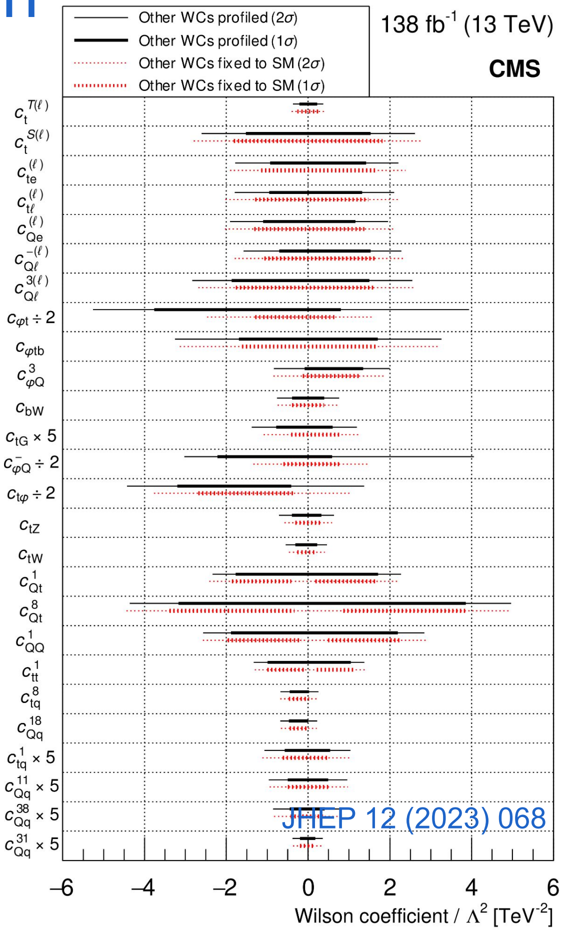


Combined EFT interpretation: tt̄X multilepton

- Only direct EFT search of all presented results:
  - Expected events in each bin is parameterized as function of WCs
  - Preference over dedicated differential measurements of tt̄X processes due to large overlap in signature
- 26 WCs considered in original analysis in 6 processes:
  - tt̄Z, tt̄W, tZq (including off-shell)
  - tt̄H, tHq, tt̄tt̄
- Fit to distribution of max p_T of any combination of 2 leptons and/or jets

In the combination:

- Additional operators have been added:
  - Adding operators is a possibility!
  - Addition of 2-heavy-2-light and $\mathcal{Q}_{H\Box}$
- Basis rotation: dim6top → SMEFTSim3 topU3l



JHEP 12 (2023) 068

Combined EFT interpretation

- Dimension 6 CP-even operators using the topU3l basis
  - 64 Wilson Coefficients considered
- EWPO combined with 6 CMS analyses in 4 sectors

General modifications to analyses:

- Normalization effect of theoretical uncertainties added to all results

Analysis	Type of measurement	Observables used	Experimental likelihood
$H \to \gamma\gamma$	Diff. cross sections	STXS bins [41]	✓
$W\gamma$	Fid. diff. cross sections	$p_T^{\gamma} \times \lvert\phi_f\rvert$	✓
WW	Fid. diff. cross sections	$m_{\ell\ell}$	✓
$Z \to \nu\nu$	Fid. diff. cross sections	p_T^{Z}	✓
$t\bar{t}$	Fid. diff. cross sections	$M_{t\bar{t}}$	×
EWPO	Pseudo-observables	Γ_Z, σ^0_{had}, R_ℓ, R_c, R_b, $A^{0,\ell}_{FB}$, $A^{0,c}_{FB}$, $A^{0,b}_{FB}$	×
Inclusive jet	Fid. diff. cross sections	$p_T^{jet} \times \lvert y^{jet}\rvert$	×
$t\bar{t}X$	Direct EFT	Yields in regions of interest	✓

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$\mathcal{Q}_{H\Box}$	$\mathcal{Q}_{HD}$
X^2H^2	
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$\mathcal{Q}^{(1)}_{qd}$	$\mathcal{Q}^{(8)}_{qd}$
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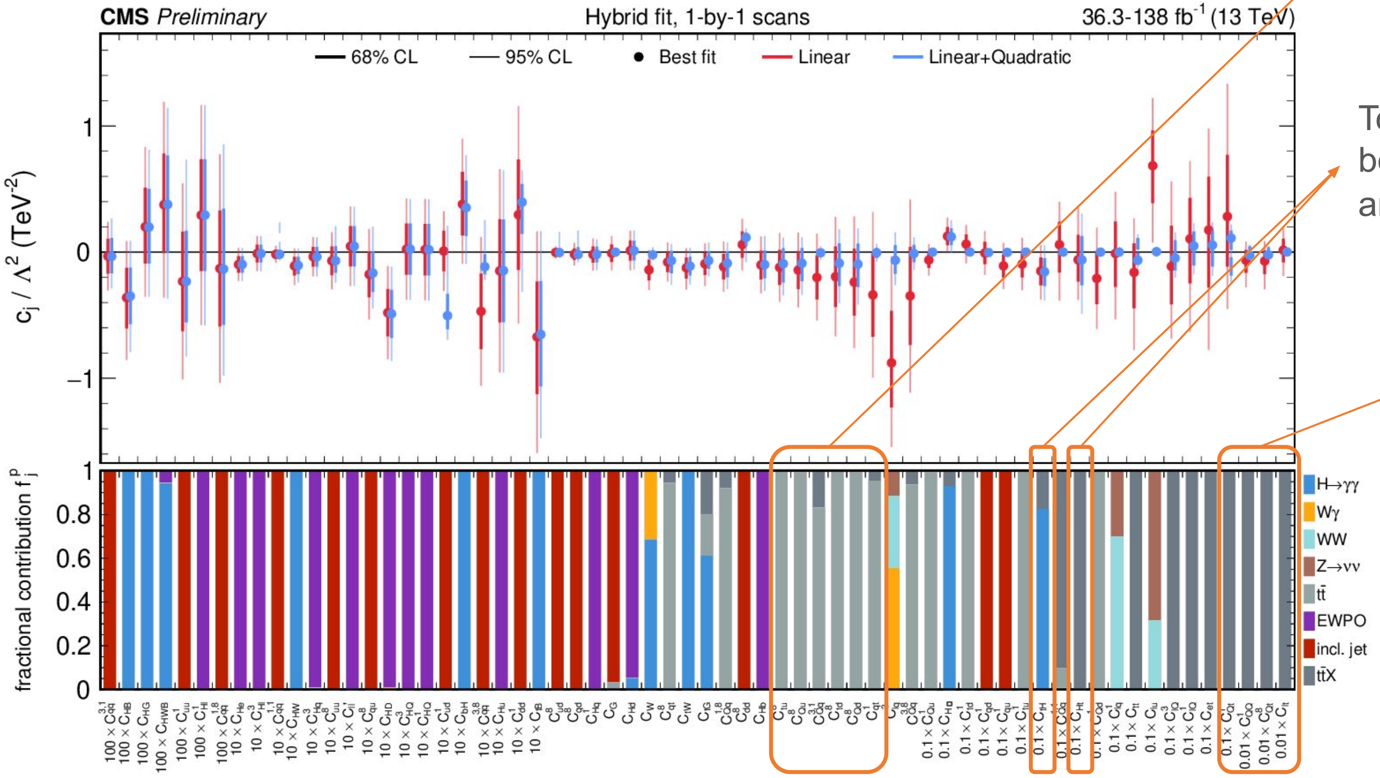
Limits on individual WCs

- In each fit, all WCs set to 0 except the one being profiled
- No significant deviations observed



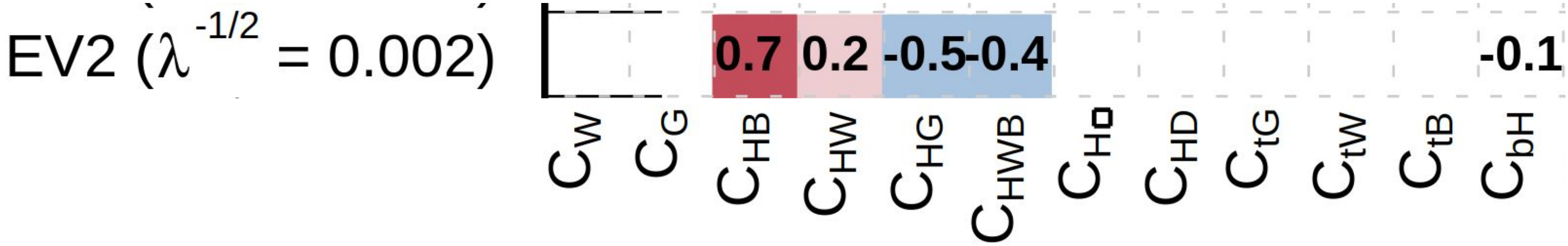
2-heavy-2-light sensitivity from a combination of $t\bar{t}$ and $t\bar{t}X$

Top-Higgs coupling sensitivity boosted by combination of $t\bar{t}X$ and H→γγ

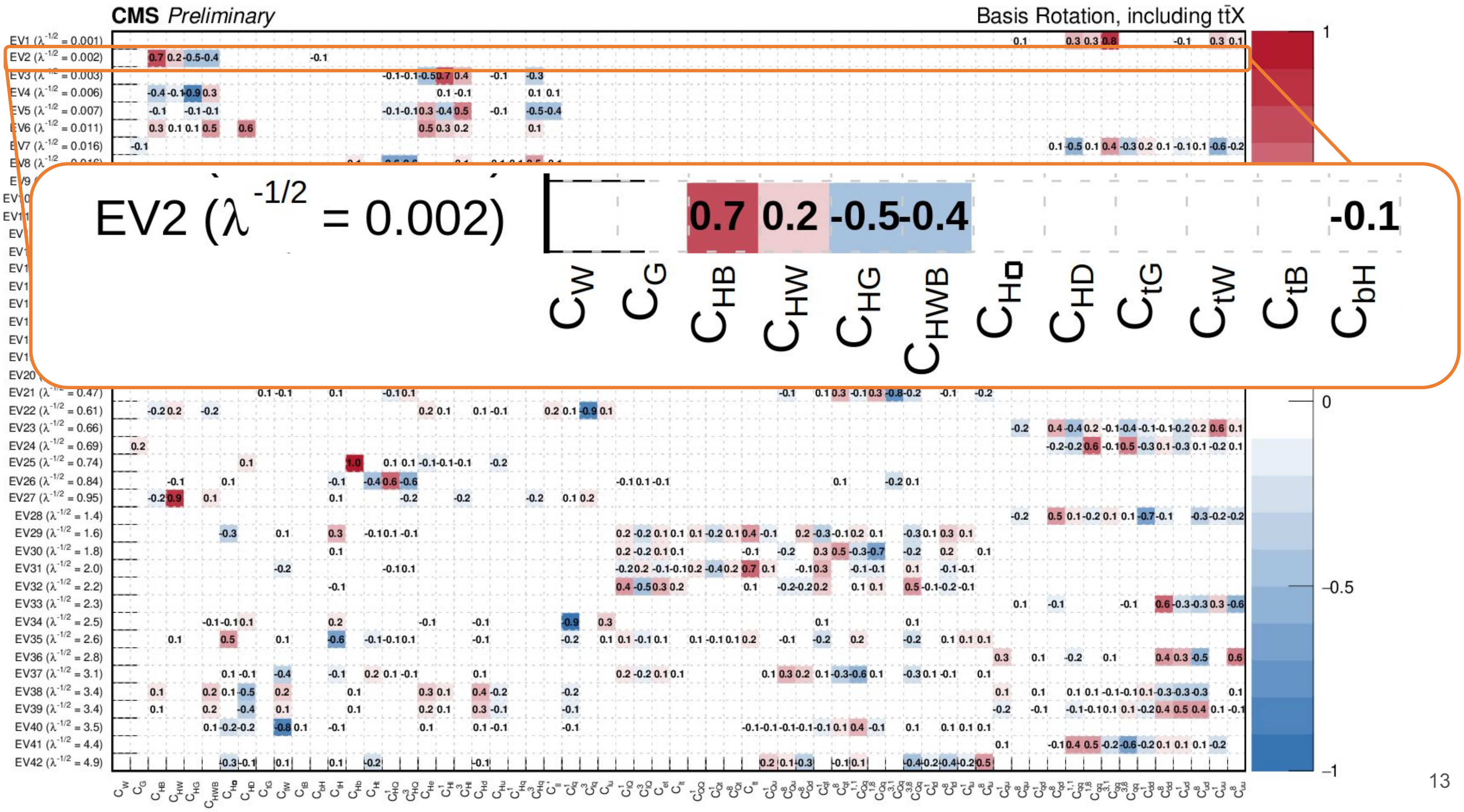
Only sensitivity to 4-heavy operators comes from $t\bar{t}X$

Principal component analysis of considered WCs

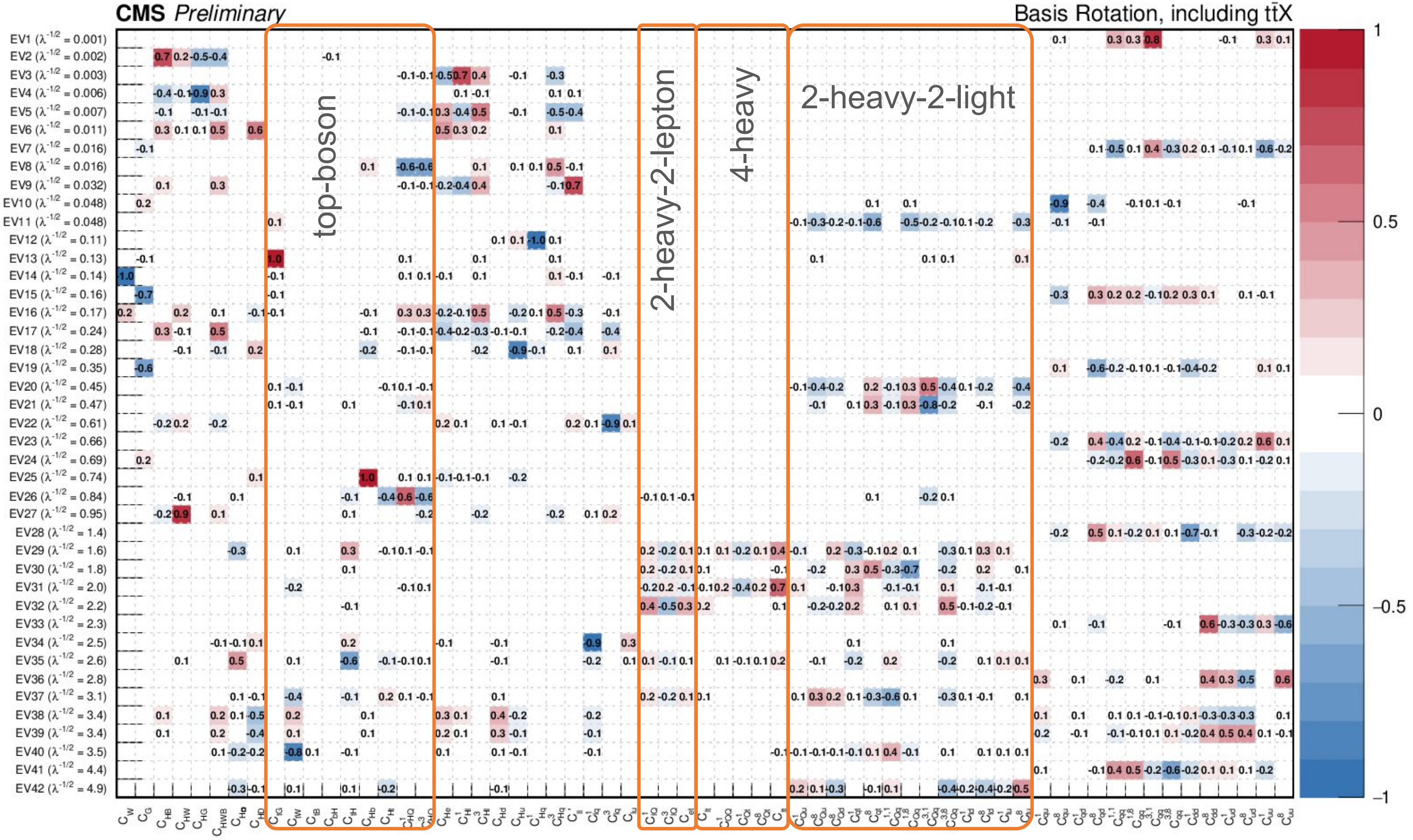
- Not all WCs can be constrained simultaneously due to degeneracies
- PCA allows to identify a basis of linear combinations of WCs
  - Hessian matrix of the measurement parameterized in terms of the WCs: $H_{ij} = \frac{\partial^2 \ln \mathcal{L}}{\partial c_i \partial c_j}$
  - Can be diagonalized to obtain uncorrelated linear combinations of WCs (principal components)
  - Principal components with eigenvalue > 0.04 are kept, the other principal components are set to 0
- Final set of 42 linear combinations is used, others are removed



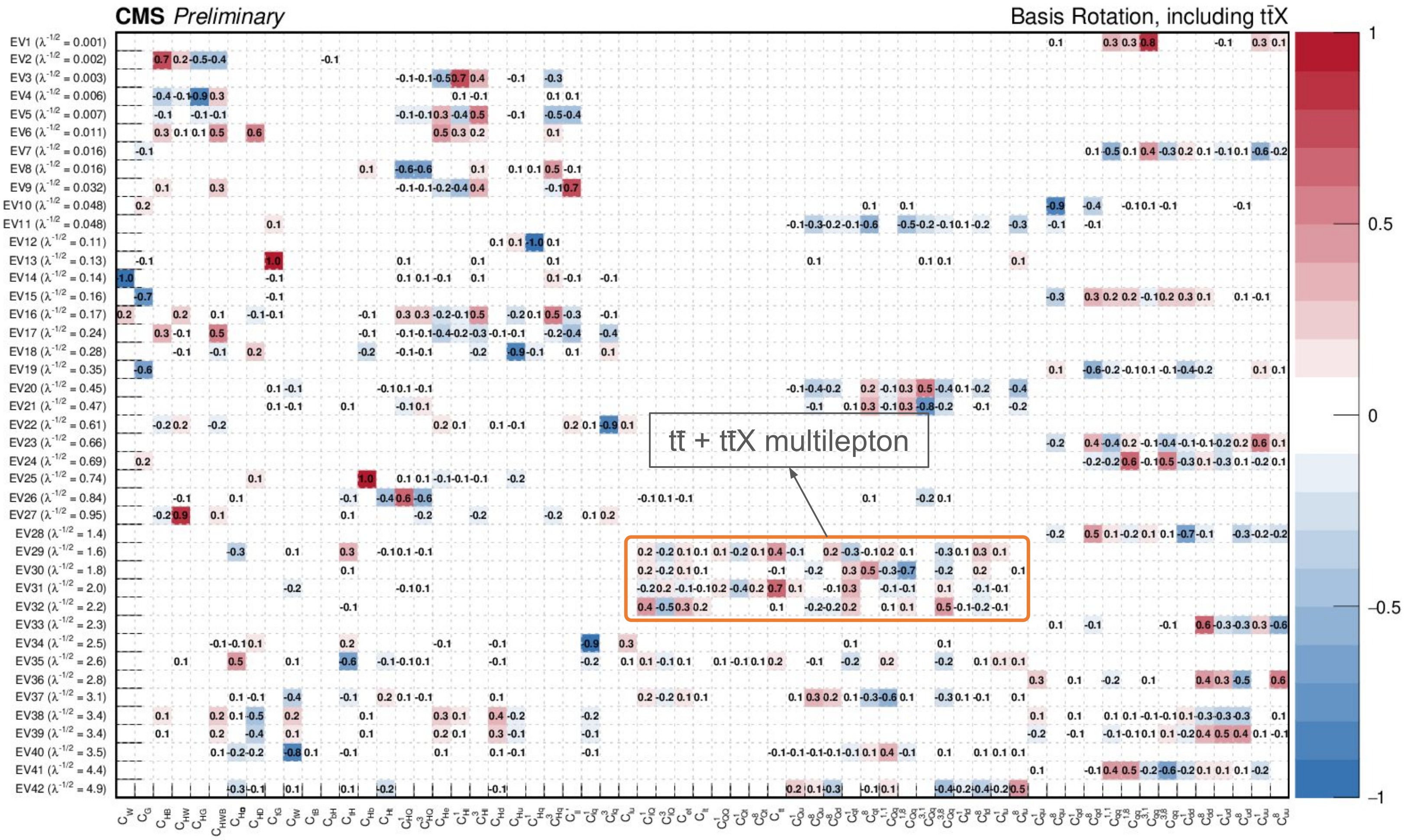
Principal component analysis of considered WCs



Principal component analysis of considered WCs

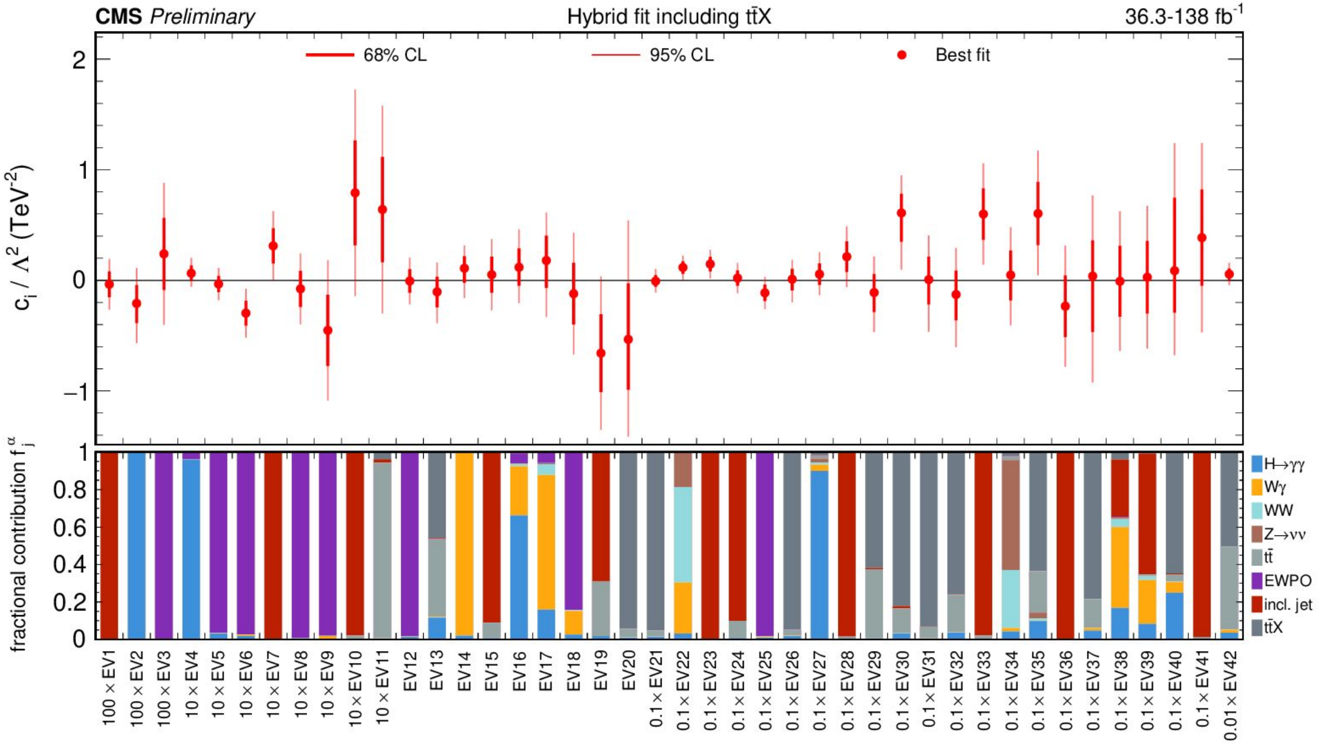


Principal component analysis of considered WCs



Principal component analysis: results

- Less reliant on a single measurement for each fit parameter
- Mix of sensitivity to each linear combination highlights proper treatment of correlations between measurements is needed



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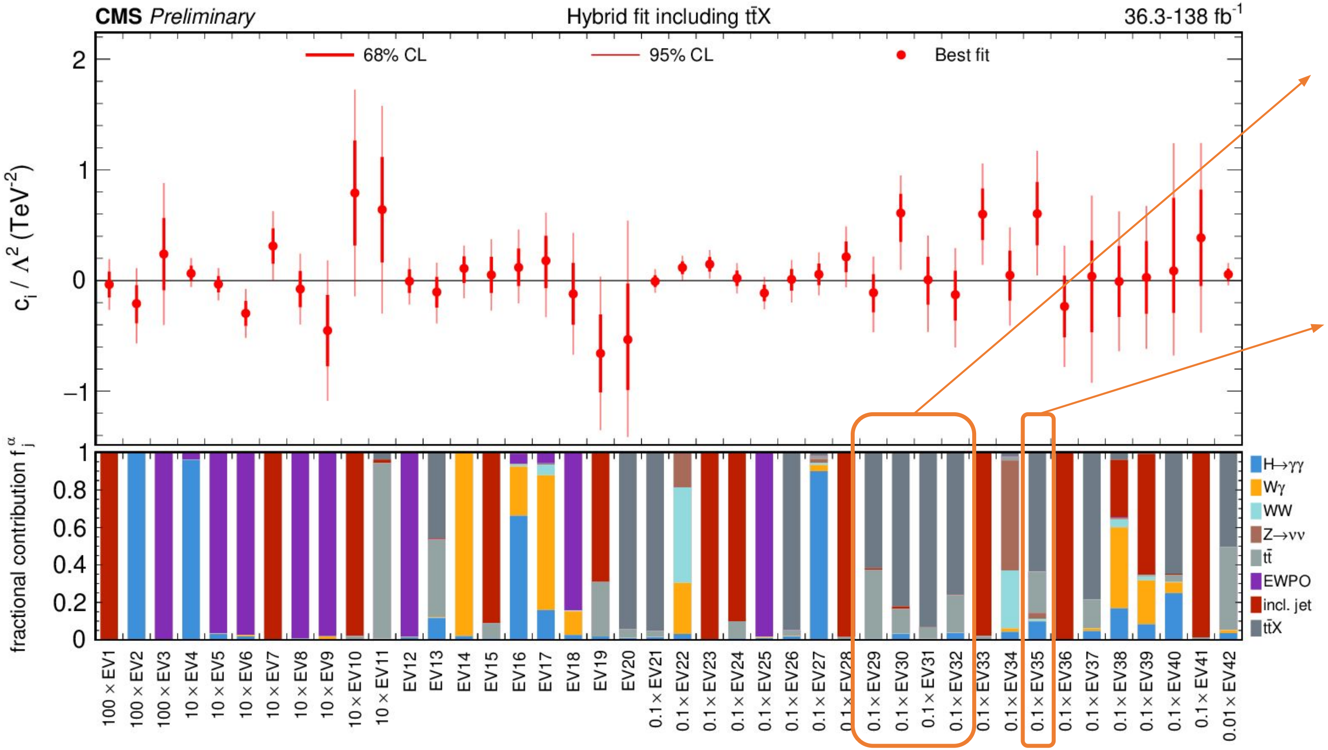
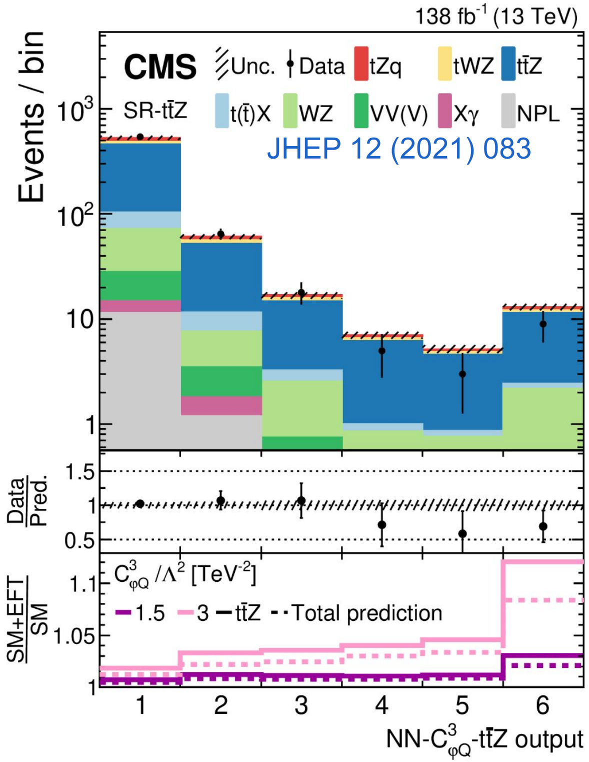


- As expected, dominated by $t\bar{t}X$
- Highlights interplay with $t\bar{t}$

Largest contribution from C_{tH}, $C_{H\Box}$
Mix of $t\bar{t}X$ and $H\rightarrow\gamma\gamma$

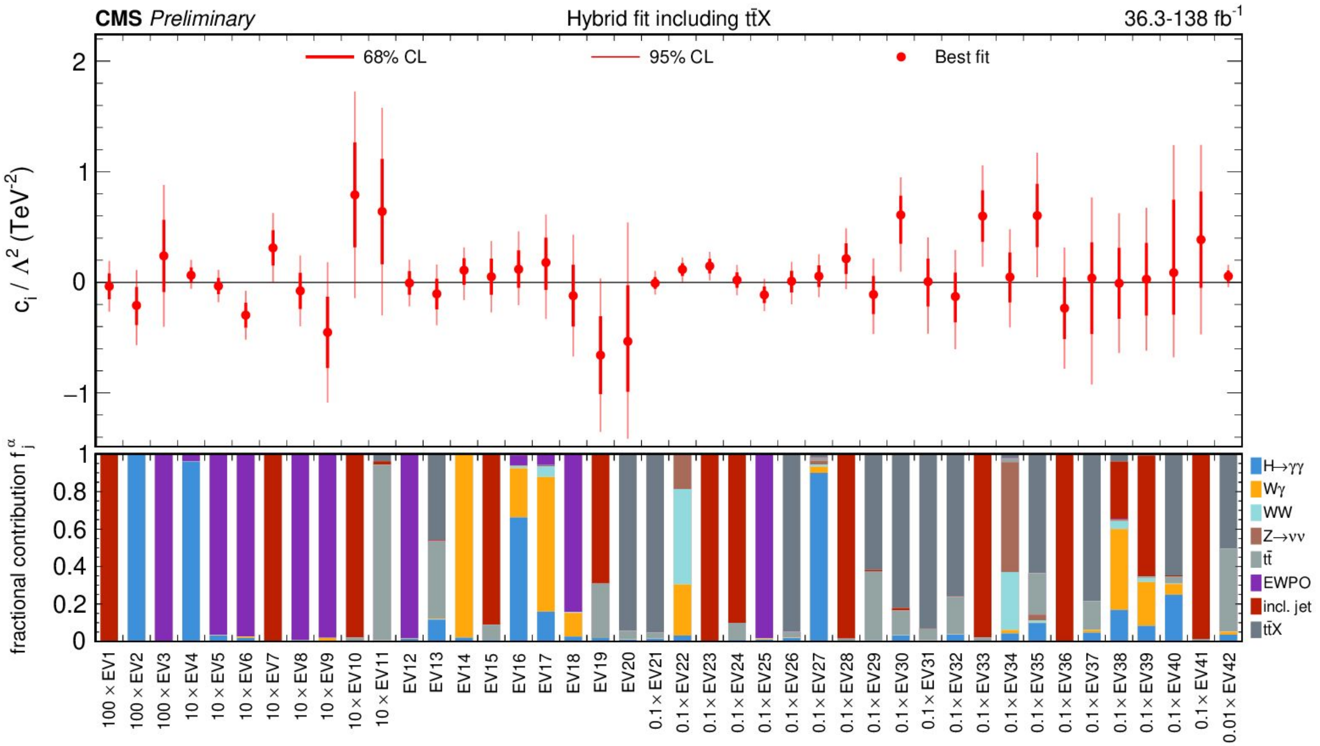
Combined EFT interpretation: what is next?

- There is a full new run of data available!
- Identify analyses to provide sensitivity to the 22 linear combinations that can't be constrained yet!
- How to improve? There are top inputs not (yet) included:
  - Processes with orthogonal signature:
    - $tt\gamma$
    - single top (+ X) with forward jets
  - With modelling advances: tt + HF, tWZ, triple tops
  - Machine learning to increase EFT sensitivity



Conclusions

- New CMS result probing 4 sectors of the SM with EFT: CMS-PAS-SMP-24-003
- Limits on 64 WCs individually (CP-even, topU3l basis) and 42 linear combinations of WCs



Backup

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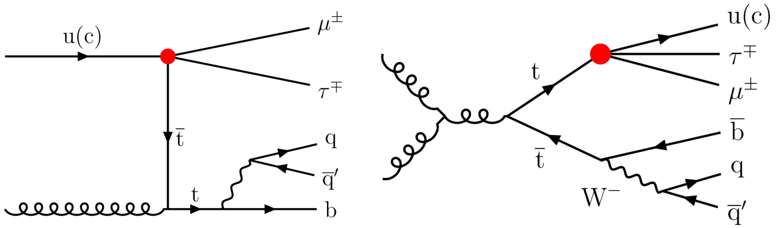
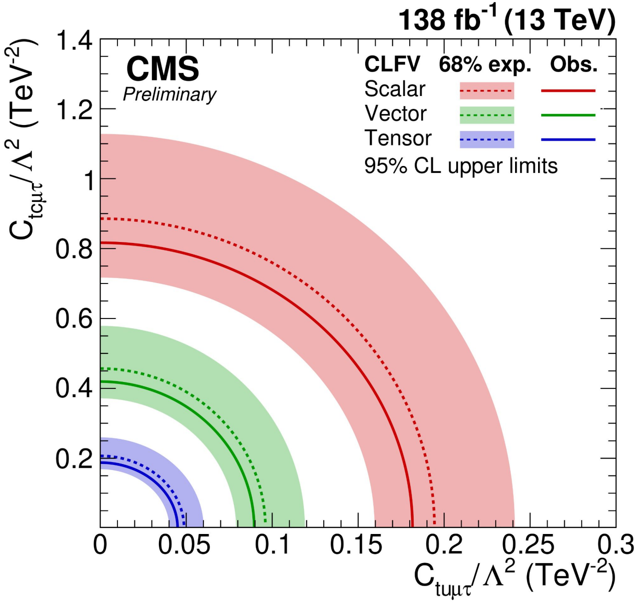
Search for lepton flavor violation

More details in YSF talk Friday by Jiwon Park and ATLAS LFUV talk Wednesday

CMS-PAS-TOP-22-011

- Predicted by many BSM models, EFT used to perform a model-independent search
- New analysis focuses on CLFV with a top quark, muon and **tau** lepton!
- Simulation with SmeftFR, events reweighed to match SMEFTSim predictions
- Signal extraction with a DNN split in 3 categories: Signal Single top, signal ttbar, background
- Limits for a Scalar, Vector and Tensor boson mediator





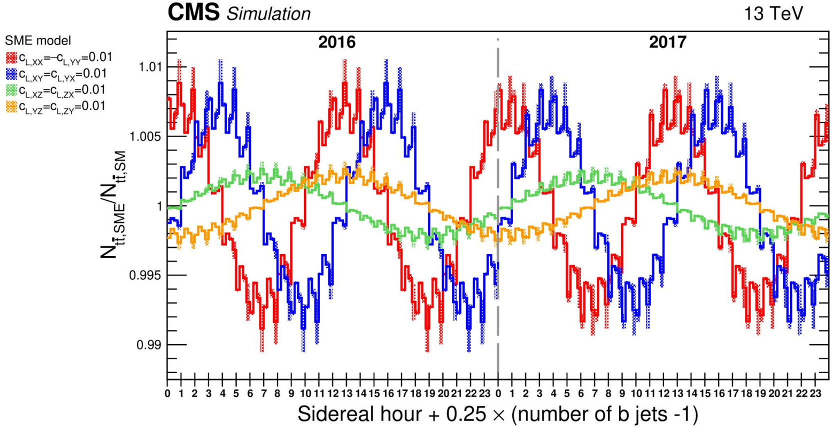
Search for violation of Lorentz invariance

PLB 857 (2024) 138979

- Motivated by String theory or Loop Quantum Gravity
- Only second result testing Lorentz-invariance with top quarks
- All Lorentz-violating operators added to the SM Lagrangian:

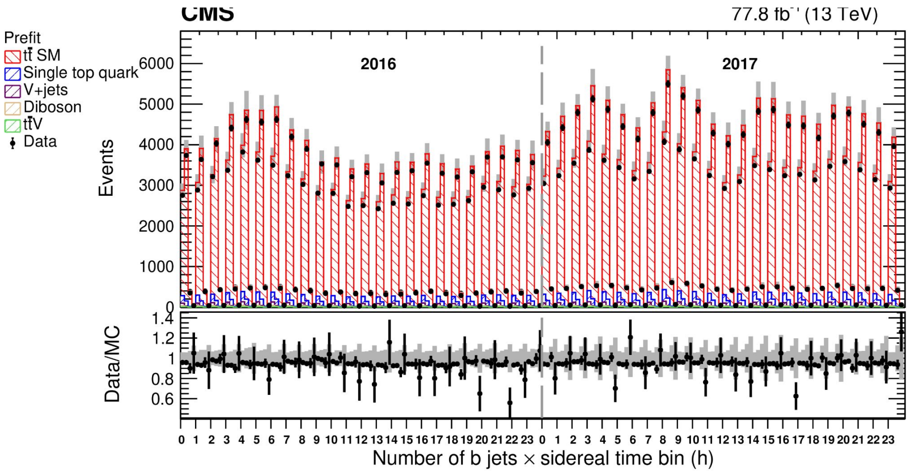
$$\mathcal{L}_{\text{SME}} = \frac{1}{2} i\bar{\psi}(\gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu}) \overleftrightarrow{\partial_{\nu}} \psi - m_t\bar{\psi}\psi$$

- Differential cross section of $t\bar{t}$ as a function of sidereal time



Uncertainties and corrections need to be derived as a function of sidereal time!

- Integrated luminosity and pileup show large dependence on sidereal time



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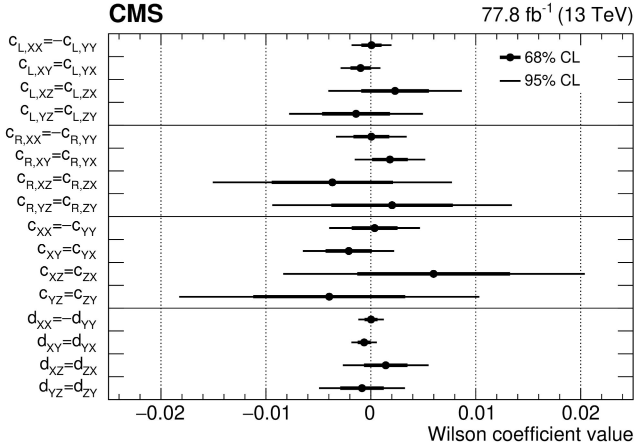
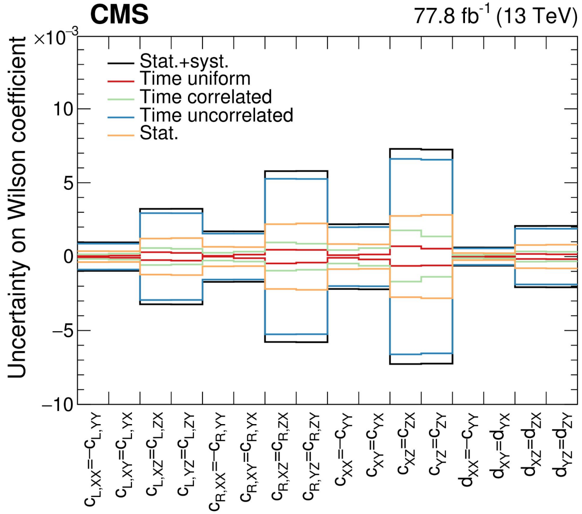




A reminder on EFT

- Most often, we look at SMEFT, where symmetries of the SM are still valid

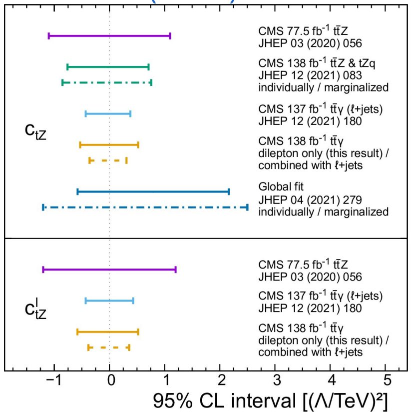
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d,j} \frac{c_j^{(d)}}{\Lambda^{d-4}} Q_j^{(d)}$$

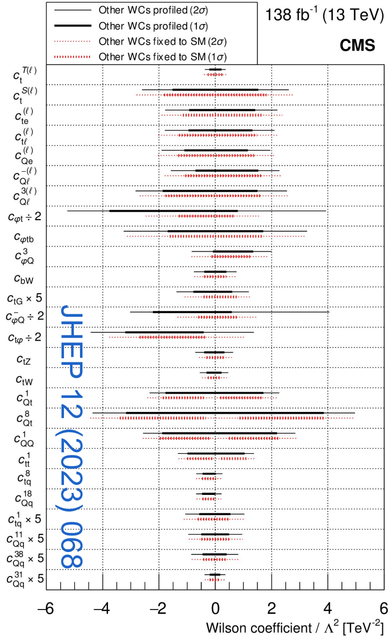
- But this is no strict requirement! Operators can be introduced that lead to:
  - CP violation
  - Lepton flavour universality violation
  - Baryon number conservation violation
  - Violation of Lorentz-invariance

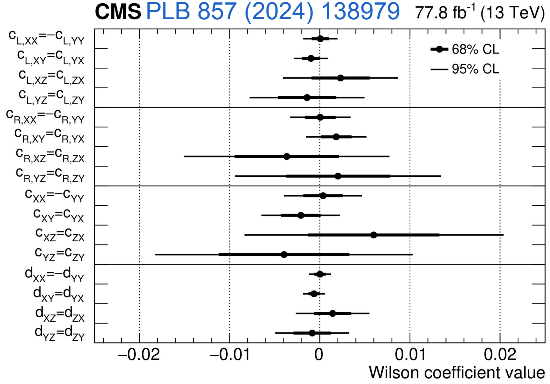
LFUV talk Wednesday by Miriam Watson

YSF talk Friday by Jiwon Park

JHEP 05 (2022) 091







New CMS result since last year:

- Combined EFT interpretation of 4 sectors (CMS-PAS-SMP-24-003)

Definition of 64 WC's (1)

X^3

$\mathcal{Q}_{G} = f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$	$\mathcal{Q}_{W} = \varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	

$H^4 D^2$

$\mathcal{Q}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$	$\mathcal{Q}_{HD} = (D^\mu H^\dagger H)(H^\dagger D_\mu H)$	

$X^2 H^2$

$\mathcal{Q}_{HG} = H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$ $\mathcal{Q}_{HWB} = H^\dagger H W^i_{\mu\nu} B^{\mu\nu}$	$\mathcal{Q}_{HW} = H^\dagger H W^i_{\mu\nu} W^{i\mu\nu}$	$\mathcal{Q}_{HB} = H^\dagger H B_{\mu\nu} B^{\mu\nu}$

$\psi^2 H^3$

$\mathcal{Q}_{tH} = (H^\dagger H)(\bar{Q}\tilde{H}t)$	$\mathcal{Q}_{bH} = (H^\dagger H)(\bar{Q}Hb)$	

$\psi^2 X H$

$\mathcal{Q}_{tW} = (\bar{Q}\sigma^{\mu\nu}t)\sigma^i \tilde{H} W^i_{\mu\nu}$	$\mathcal{Q}_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\tilde{H} B_{\mu\nu}$	$\mathcal{Q}_{tG} = (\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{H} G^a_{\mu\nu}$

$\psi^2 H^2 D$

$\mathcal{Q}^{(1)}_{Hl} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$ $\mathcal{Q}^{(1)}_{Hq} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$ $\mathcal{Q}_{Hd} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$ $\mathcal{Q}_{Ht} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	$\mathcal{Q}^{(3)}_{Hl} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p\sigma^i\gamma^\mu l_r)$ $\mathcal{Q}^{(3)}_{Hq} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$ $\mathcal{Q}^{(1)}_{HQ} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$ $\mathcal{Q}_{Hb} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	$\mathcal{Q}_{He} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$ $\mathcal{Q}_{Hu} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$ $\mathcal{Q}^{(3)}_{HQ} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{Q}\sigma^i\gamma^\mu Q)$

Definition of 64 WC's (2)

$\psi^4, (\bar{L}L)(\bar{L}L)$

$\mathcal{Q}_{lq}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{q}\gamma^\mu q)$	$\mathcal{Q}_{lq}^{(3)} = (\bar{l}_p\sigma^i\gamma_\mu l_r)(\bar{q}\sigma^i\gamma^\mu q)$	$\mathcal{Q}_{lQ}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{Q}\gamma^\mu Q)$
$\mathcal{Q}_{lQ}^{(3)} = (\bar{l}_p\sigma^i\gamma_\mu l_r)(\bar{Q}\sigma^i\gamma^\mu Q)$	$\mathcal{Q}_{QQ}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{Q}\gamma^\mu Q)$	$\mathcal{Q}_{ll} = (\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$\mathcal{Q}_{qq}^{(1,1)} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$	$\mathcal{Q}_{qq}^{(1,8)} = (\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$	$\mathcal{Q}_{qq}^{(3,1)} = (\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$
$\mathcal{Q}_{qq}^{(3,8)} = (\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$	$\mathcal{Q}_{Qq}^{(1,1)} = (\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$	$\mathcal{Q}_{Qq}^{(1,8)} = (\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$
$\mathcal{Q}_{Qq}^{(3,1)} = (\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$	$\mathcal{Q}_{Qq}^{(3,8)} = (\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$	

$\psi^4, (\bar{R}R)(\bar{R}R)$

$\mathcal{Q}_{et} = (\bar{e}_p\gamma_\mu e_r)(\bar{t}\gamma^\mu t)$	$\mathcal{Q}_{tt} = (\bar{t}\gamma_\mu t)(\bar{t}\gamma^\mu t)$	$\mathcal{Q}_{uu}^{(1)} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$
$\mathcal{Q}_{uu}^{(8)} = (\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$	$\mathcal{Q}_{tu}^{(1)} = (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$	$\mathcal{Q}_{tu}^{(8)} = (\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$
$\mathcal{Q}_{dd}^{(1)} = (\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$	$\mathcal{Q}_{dd}^{(8)} = (\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$	$\mathcal{Q}_{ud}^{(1)} = (\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$
$\mathcal{Q}_{ud}^{(8)} = (\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$	$\mathcal{Q}_{td}^{(1)} = (\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$	$\mathcal{Q}_{td}^{(8)} = (\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$

$\psi^4, (\bar{L}L)(\bar{R}R)$

$\mathcal{Q}_{lu} = (\bar{l}_p\gamma_\mu l_r)(\bar{u}\gamma^\mu u)$	$\mathcal{Q}_{lt} = (\bar{l}_p\gamma_\mu l_r)(\bar{t}\gamma^\mu t)$	$\mathcal{Q}_{qu}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$
$\mathcal{Q}_{qu}^{(8)} = (\bar{q}T^a\gamma_\mu q)(\bar{u}T^a\gamma^\mu u)$	$\mathcal{Q}_{Qu}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$	$\mathcal{Q}_{Qu}^{(8)} = (\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$
$\mathcal{Q}_{qt}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$	$\mathcal{Q}_{qt}^{(8)} = (\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$	$\mathcal{Q}_{Qt}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{t}\gamma^\mu t)$
$\mathcal{Q}_{Qt}^{(8)} = (\bar{Q}T^a\gamma_\mu Q)(\bar{t}T^a\gamma^\mu t)$	$\mathcal{Q}_{qd}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$	$\mathcal{Q}_{qd}^{(8)} = (\bar{q}T^a\gamma_\mu q)(\bar{d}T^a\gamma^\mu d)$
$\mathcal{Q}_{Qd}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$	$\mathcal{Q}_{Qd}^{(8)} = (\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$	