# Recent progress in SMEFT phenomenology

## 6th LHC EFT WG Annual Meeting

*CERN, Geneva, Switzerland*
*16 November 2023*

**Alejo N. Rossia**
*Department of Physics and Astronomy*
*The University of Manchester*

MANCHESTER 1824
The University of Manchester

# Wilson Coefficients and how to bound them

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \mathcal{O}(\frac{1}{\Lambda^5})$$

**Apologies for not including all relevant papers due to space-time restrictions. Check out the appendix.**

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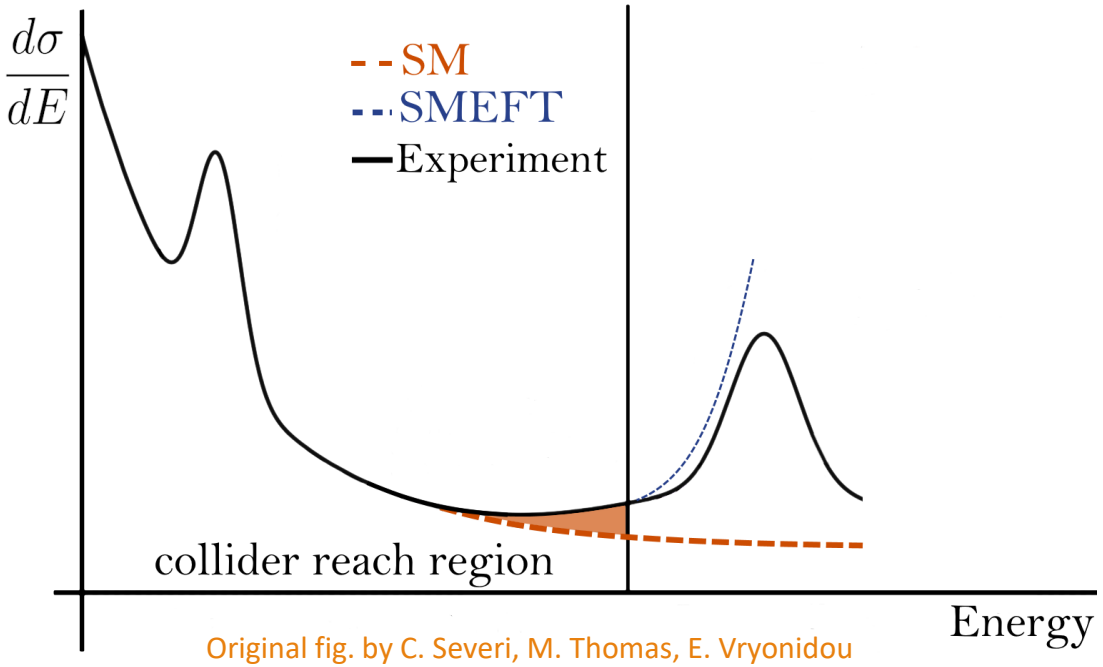


Original fig. by C. Severi, M. Thomas, E. Vryonidou

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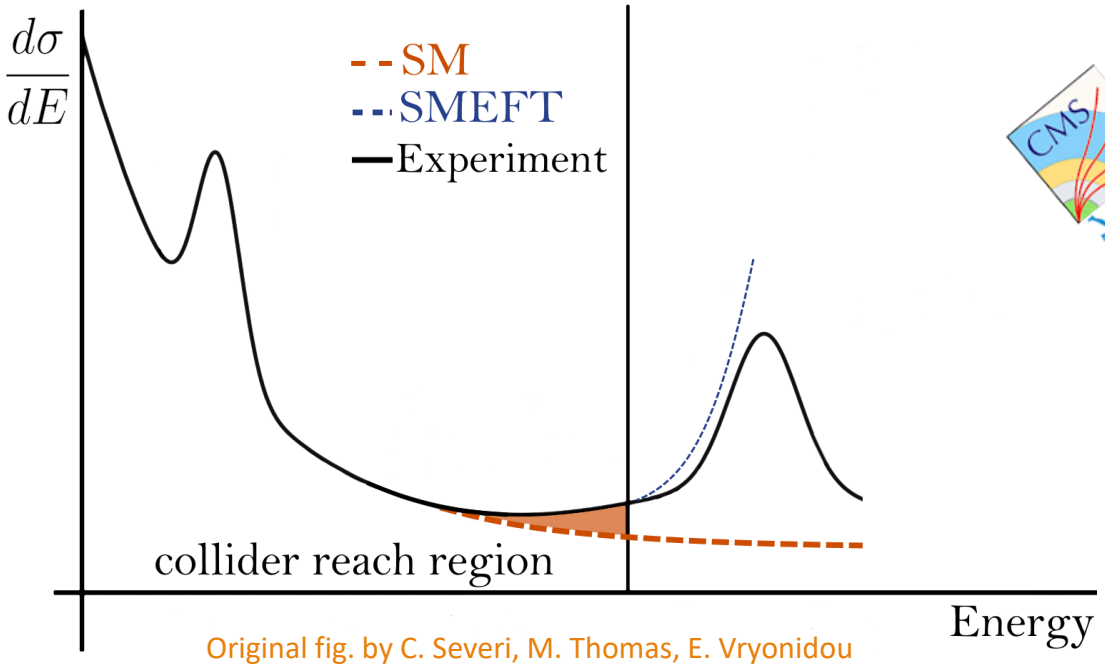


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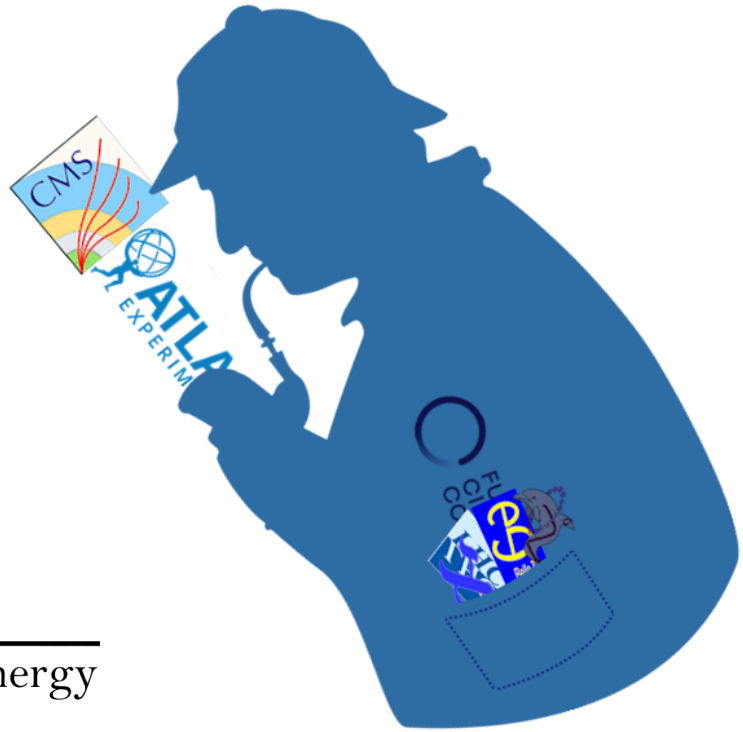


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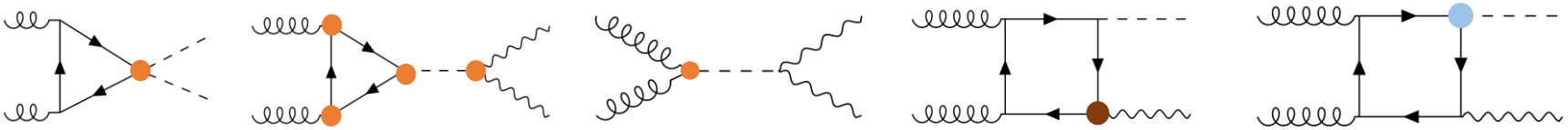
# Diboson and beyond

# Loop-induced processes matter

ANR, M. Thomas, E. Vryonidou [2306.18215]

**Dim-6 SMEFT effects in** $gg \to HH, ZH, ZZ, WW$



See yesterday's
M. Thomas's talk

# Loop-induced processes matter

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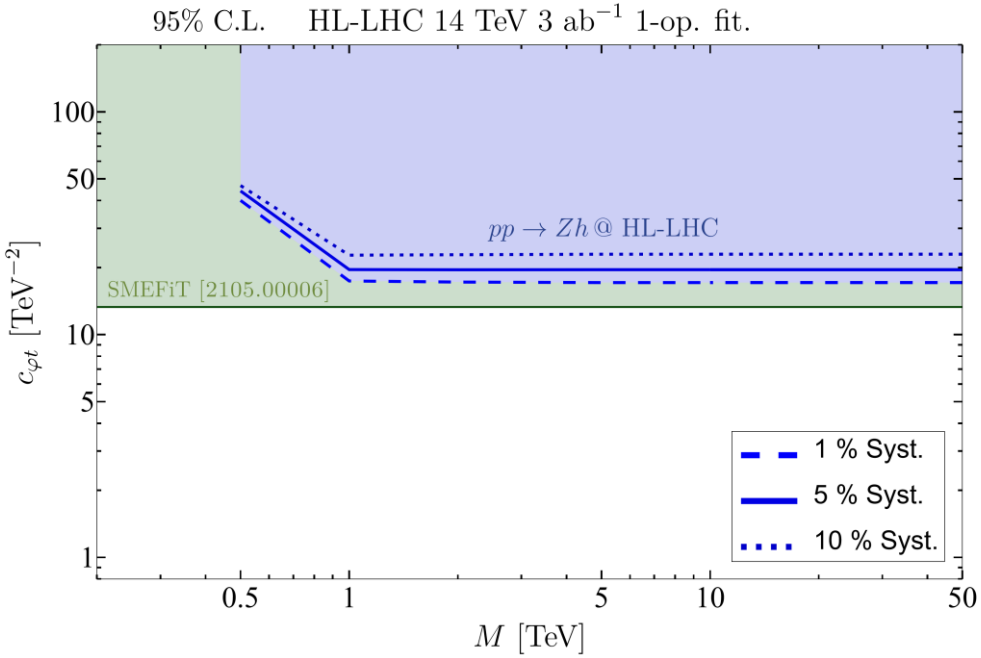
## Dim-6 SMEFT effects in $gg \to HH, ZH, ZZ, WW$

$$\mathcal{M}_{++00} \sim \begin{array}{|c|c|c|} \hline \mathcal{O}_{\varphi t} & \mathcal{O}^{(-)}_{\varphi Q} & \mathcal{O}_{t\varphi} \\ \hline \frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_w\, s_w}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2 & \frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_w\, s_w}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2 & \frac{m_t\, v^2\, e\, g_s^2}{32\sqrt{2}\pi^2\, m_Z\, c_w\, s_w}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2 \\ \hline \end{array} \quad gg \to ZH$$

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# Dimension-8 effects in WW, WZ

C. Degrande, H. Li [2303.10493]

$$q\bar{q} \to WZ$$

| Operator | $2\,\mathrm{Re}(\mathcal{A}^{\mathrm{SM}}\mathcal{A}^{\mathrm{NP}*})$ | $2\int d\Omega\,\mathrm{Re}(\mathcal{A}^{\mathrm{SM}}\mathcal{A}^{\mathrm{NP}*})$ |
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**Several operators generate maximal energy growth**

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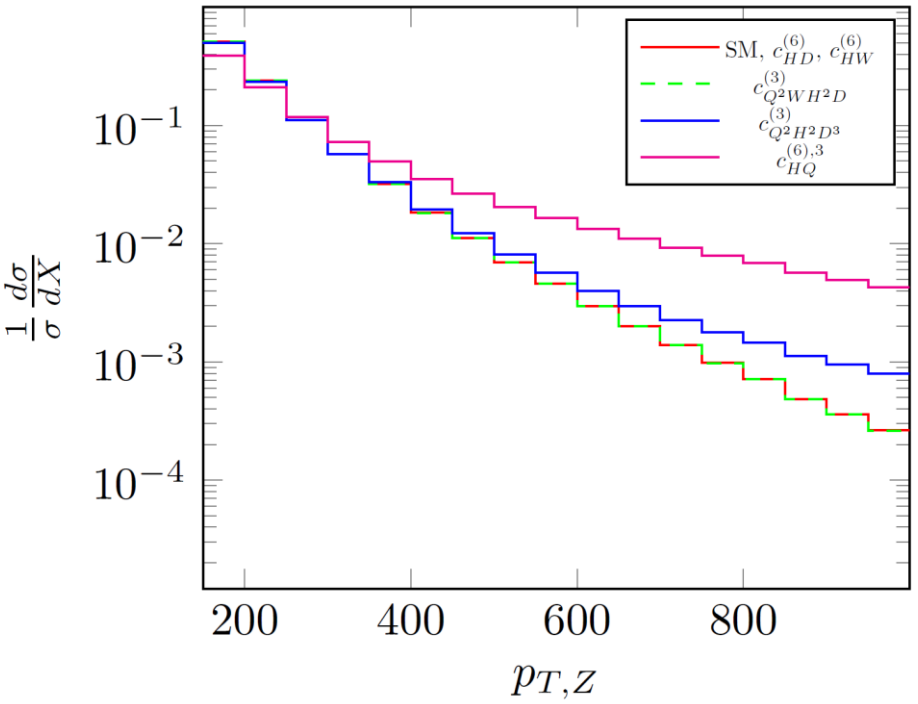


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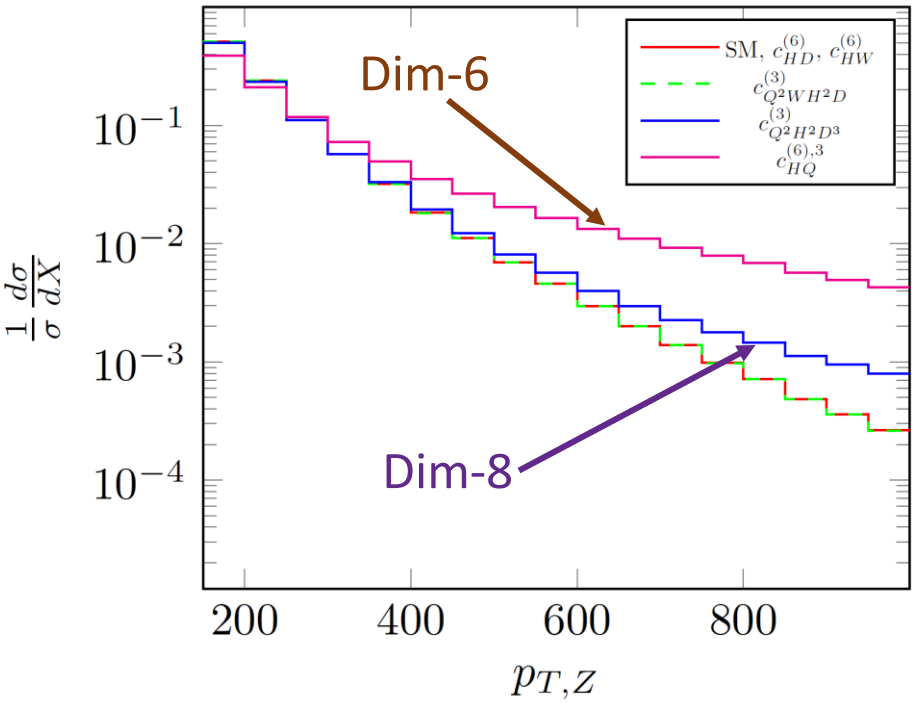


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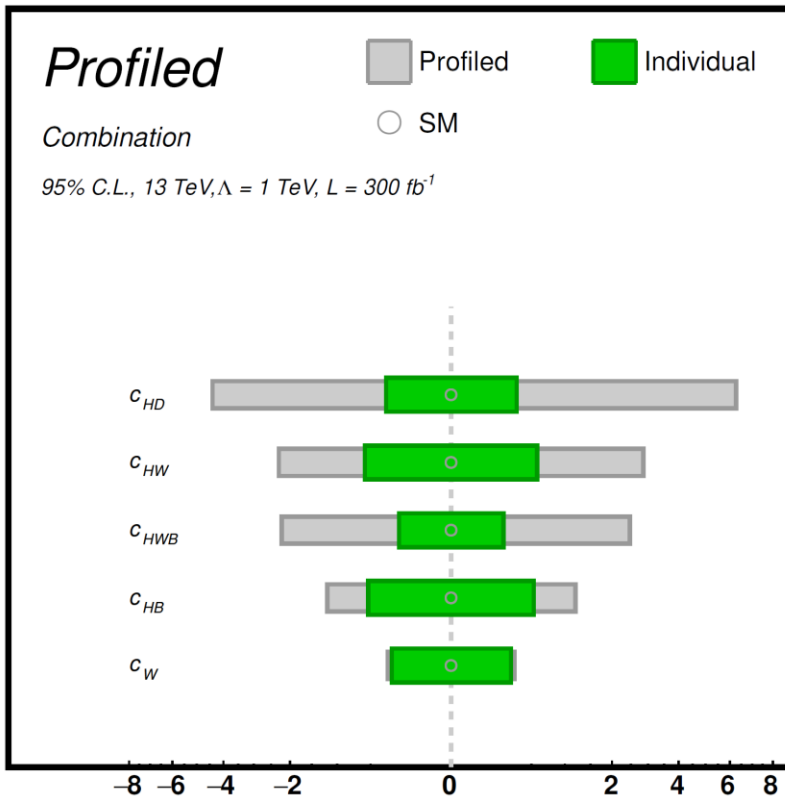
**Mild effect due to SM-suppressed interference**

# Extra bosons for extra fun: Triboson

R. Bellan, S. Bhattacharya, G. Boldrini, F. Cetorelli, P. Govoni [2303.18215]

$WZZ,\ ZZZ,\ WZ\gamma,\ ZZ\gamma$

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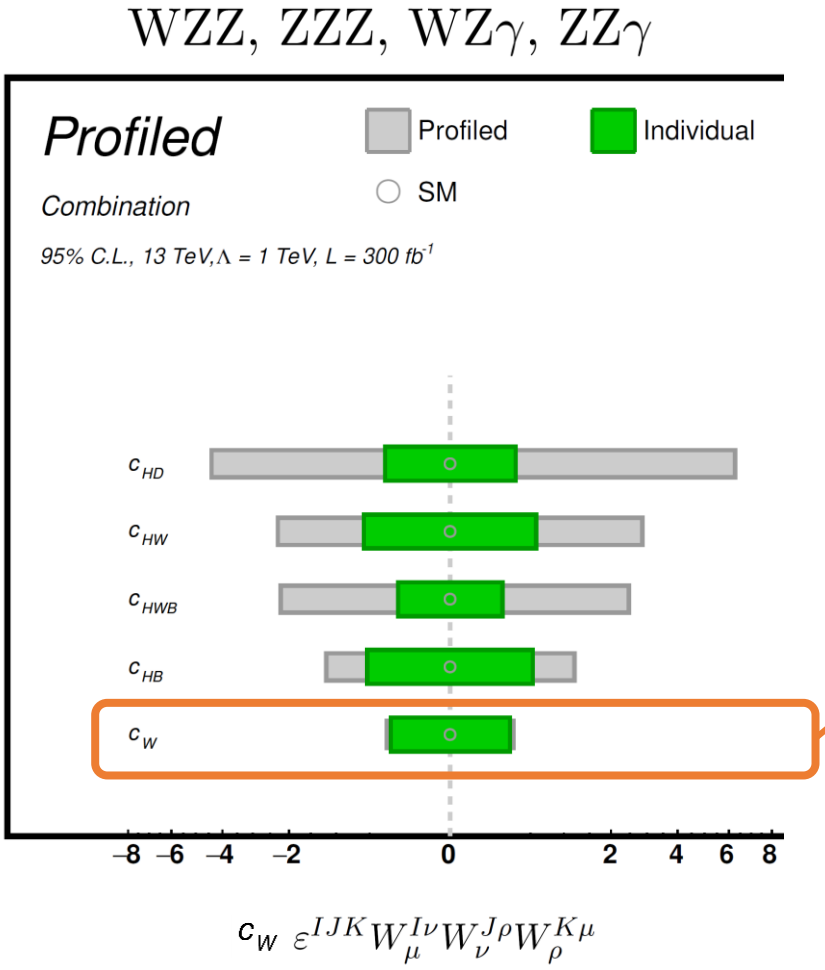


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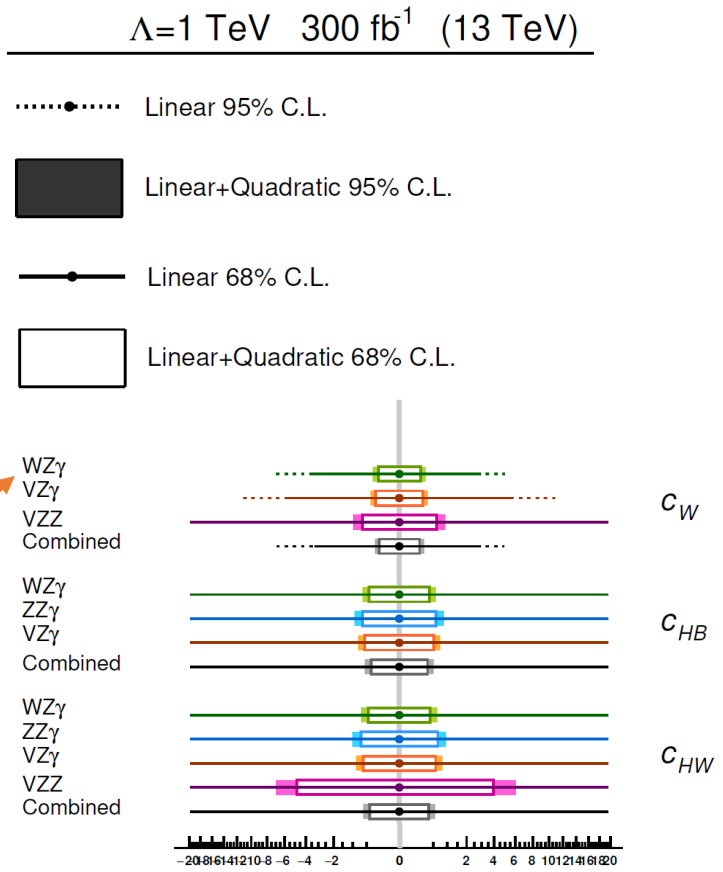


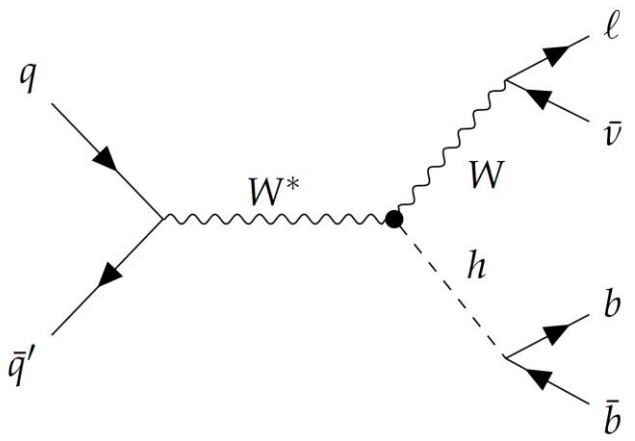

**Stay tuned, more to come!**

# SMEFT in the mirror: CP violation

# WH goes CP-odd at LHC

R. Barrué, P. Conde-Muíño, V. Dao, R. Santos [2308.02882]

$$\tilde{\mathcal{O}}_{HW} = \frac{c_{\tilde{HW}}}{\Lambda^2} H^\dagger H \tilde{W}^I_{\mu\nu} W^{I\mu\nu} = \frac{c_{\tilde{HW}}}{\Lambda^2} H^\dagger H \epsilon_{\mu\nu\rho\sigma} W^{I\rho\sigma} W^{I\mu\nu}$$



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| Observable | Linearized limits | Full limits |
|---|---|---|
| $Q_\ell \cos\delta^+ \in [-1.0, -2/3, -1/3, 0., 1/3, 2/3]$ | $[-0.227, 0.227]$ | $[-0.264, 0.216]$ |
| $m_T^{\ell\nu b\bar{b}} \in [0, 400, 800]$ GeV $\otimes$ $Q_\ell \cos\delta^+ \in [-1.0, -2/3, -1/3, 0., 1/3, 2/3]$ | $[-0.093, 0.093]$ | $[-0.096, 0.096]$ |
| $p_T^W \in [0, 75, 150, 250, 400, 600]$ GeV $\otimes$ $Q_\ell \cos\delta^+ \in [-1.0, -2/3, -1/3, 0., 1/3, 2/3]$ | $[-0.088, 0.088]$ | $[-0.096, 0.072]$ |
| SALLY, w/ $\nu$ 4-vector | $[-0.056, 0.056]$ | $[-0.072, 0.144]$ |
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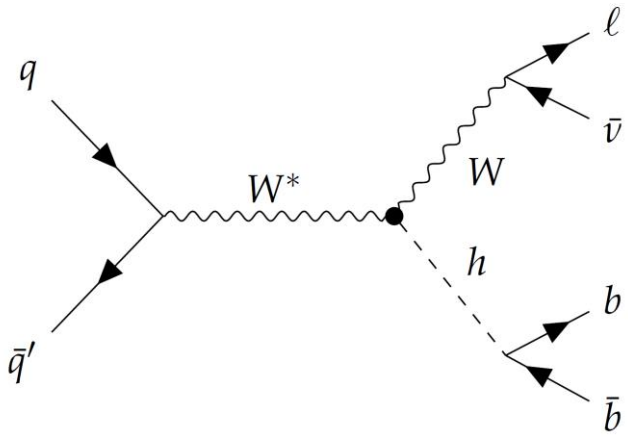
MadMiner



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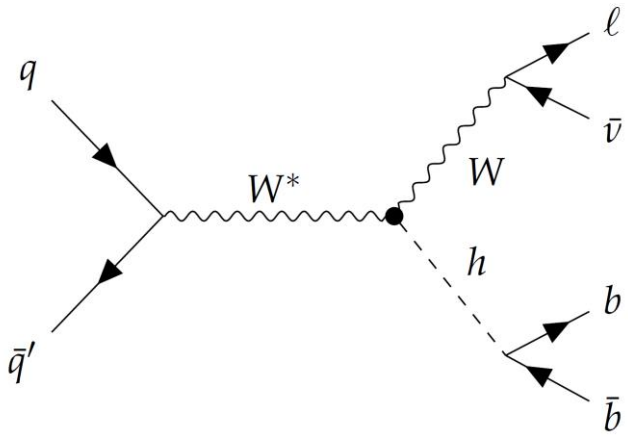



**Not a surprise!** $\longrightarrow$ $\sigma^{int}_{\mathcal{O}_{\varphi\widetilde{W}}} \sim \frac{\sqrt{\hat{s}} M_W}{\Lambda^2} \sin(\phi_W)$

F. Bishara, ANR, et al [2004.06122]

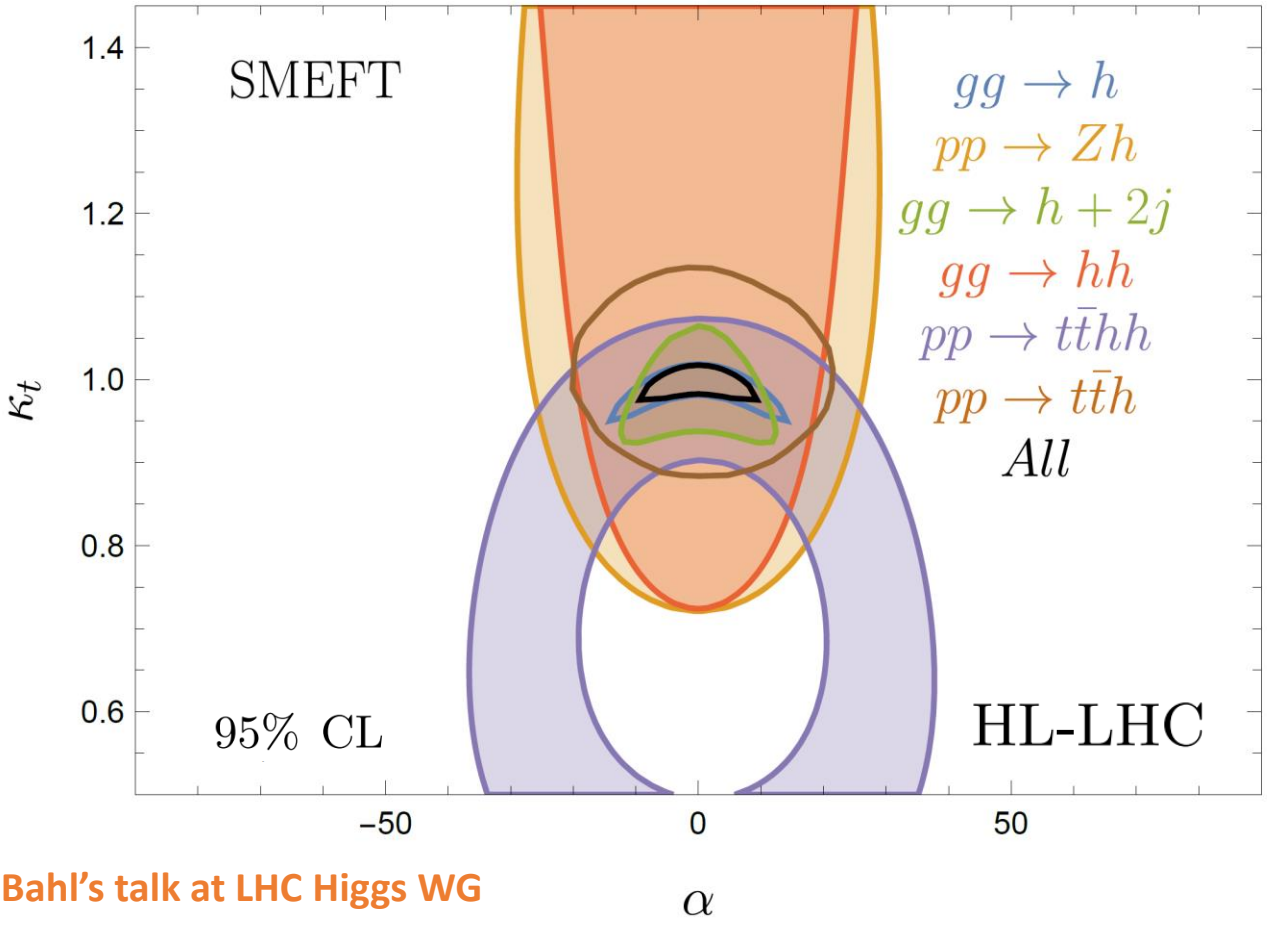
**Other diboson channels are also great CPV probes**

N. Clarke Hall, et al [2209.05143]

# CPV in the top-Higgs interaction

A. Bhardwaj, C. Englert, D. Gonçalves, A. Navarro [2308.11722]

$$\mathcal{O}_{t\Phi} = |\Phi|^2 \bar{Q}_L \Phi^c t_R \qquad \frac{1}{\Lambda^2}\begin{pmatrix}\mathrm{Re}\, C_{t\Phi}\\ \mathrm{Im}\, C_{t\Phi}\end{pmatrix} = -\frac{\sqrt{2}\, m_t}{v^3}\begin{pmatrix}\kappa_t \cos\alpha - 1\\ \kappa_t \sin\alpha\end{pmatrix}$$




See also H. Bahl's talk at LHC Higgs WG

# Four tops

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Eur. Phys. J. C (2023) 83:496
https://doi.org/10.1140/epjc/s10052-023-11573-0

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

## Observation of four-top-quark production in the multilepton final state with the ATLAS detector

**ATLAS Collaboration***

CERN, 1211 Geneva 23, Switzerland

Received: 29 March 2023 / Accepted: 2 May 2023 / Published online: 12 June 2023


**Abstract** This paper presents the observation of four-top-quark ($t\bar{t}t\bar{t}$) production in proton-proton collisions at the LHC. The analysis is performed using an integrated luminosity of 140 fb$^{-1}$ at a centre-of-mass energy of 13 TeV collected using the ATLAS detector. Events containing two leptons with the same electric charge or at least three leptons (electrons or muons) are selected. Event kinematics are used to separate signal from background through a multivariate dis-



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2023-090
2023/05/24

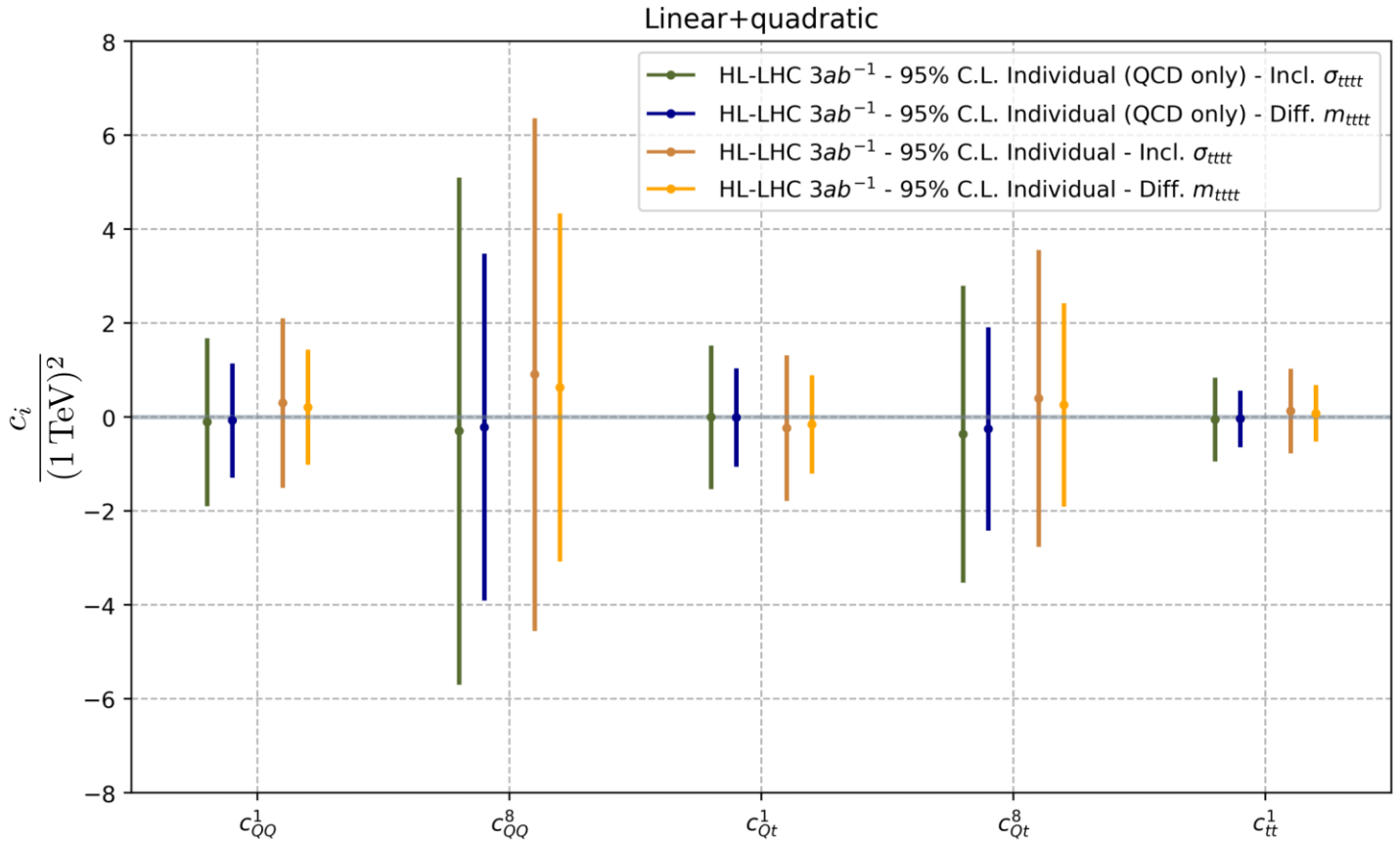
CMS-TOP-22-013

## Observation of four top quark production in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

# Four tops in SMEFT

R. Aoude, H. El Faham, F. Maltoni, E. Vryonidou [2208.04962]



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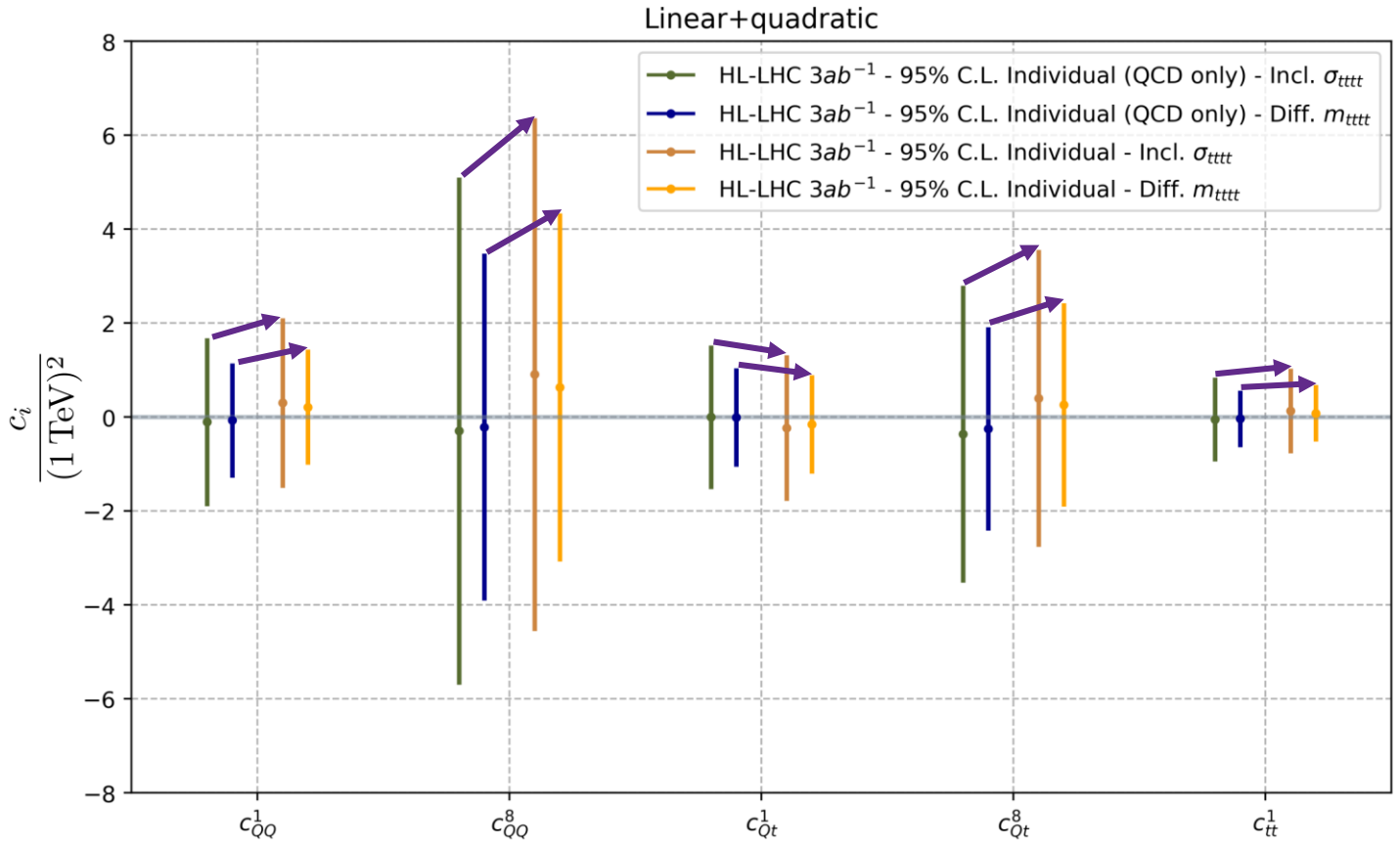
## EW (Yukawa) diagrams important contribution



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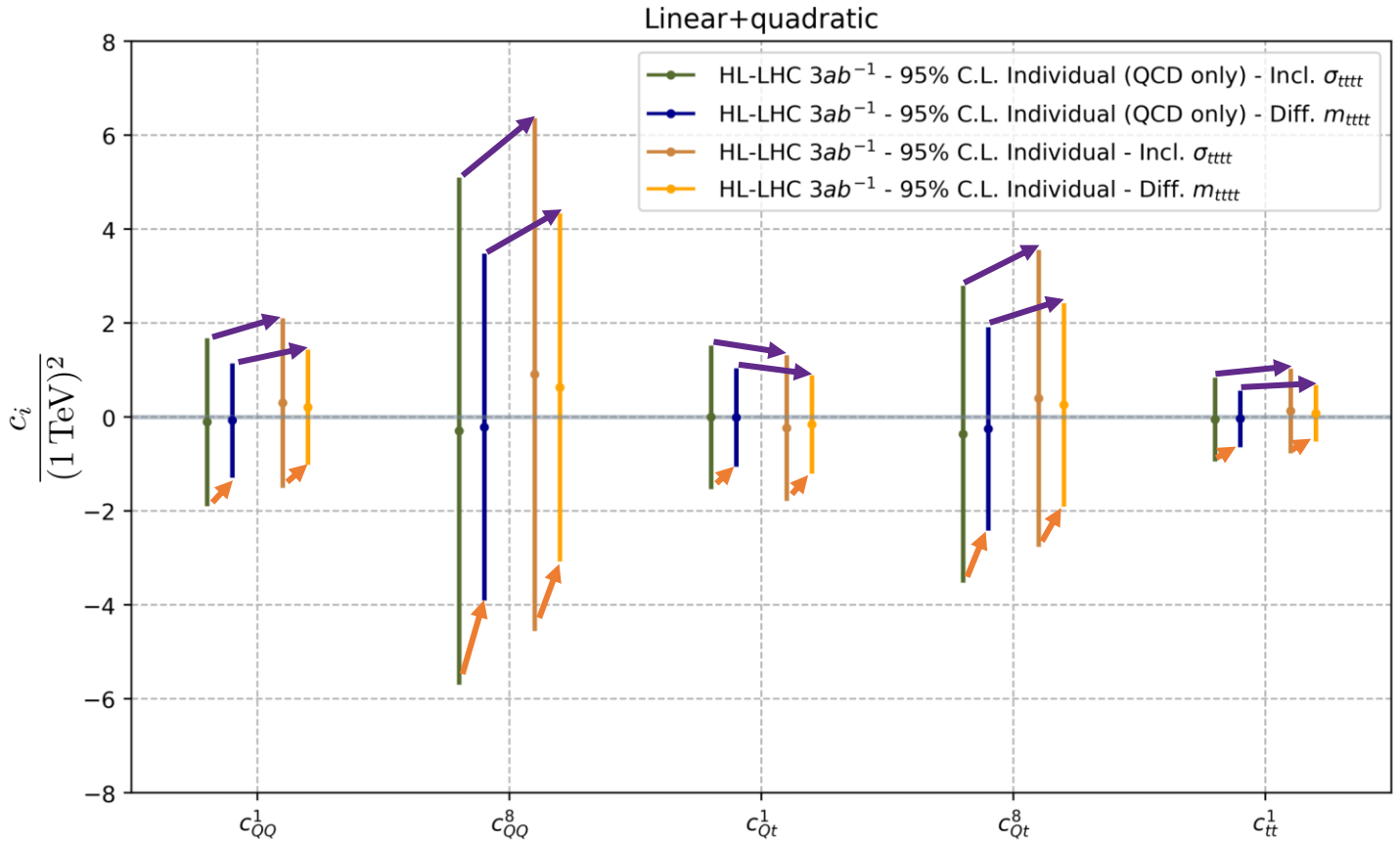



## Improvement with differential information

# Quantum Entanglement

ATLAS EXPERIMENT

**ATLAS CONF Note**

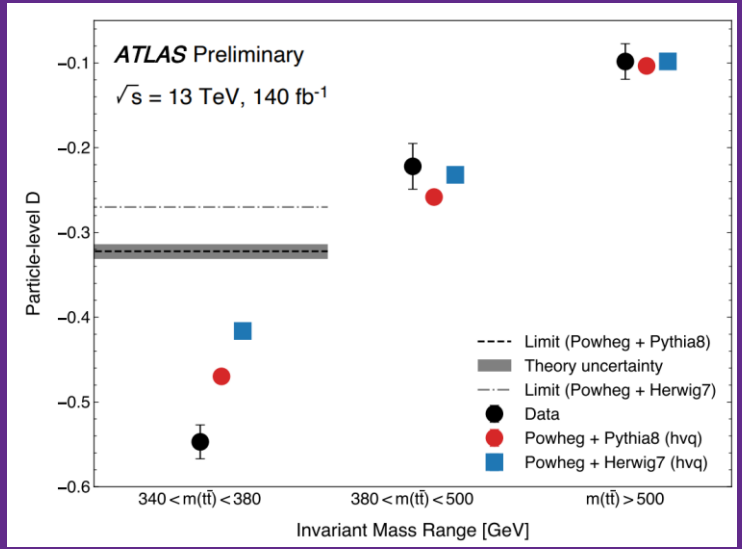
ATLAS-CONF-2023-069

28th September 2023

CERN

**Observation of quantum entanglement in top-quark pair production using $pp$ collisions of $\sqrt{s}$ = 13 TeV with the ATLAS detector**

The ATLAS Collaboration



# Top Entanglement in SMEFT at NLO

C. Severi, E. Vryonidou [2210.09330]

| Operator | Run III Projection $300\,\text{fb}^{-1}$ Differential | Current Global Fit |
|---|---|---|
| $\mathcal{O}_{Qu}^{8}$ | $[-0.7, 0.6]$ | $[-1.0, 0.5]$ |
| $\mathcal{O}_{Qd}^{8}$ | $[-0.9, 0.8]$ | $[-1.6, 0.9]$ |
| $\mathcal{O}_{Qq}^{(1,8)}$ | $[-0.4, 0.3]$ | $[-0.4, 0.3]$ |
| $\mathcal{O}_{Qq}^{(3,8)}$ | $[-1.1, 0.8]$ | $[-0.5, 0.4]$ |

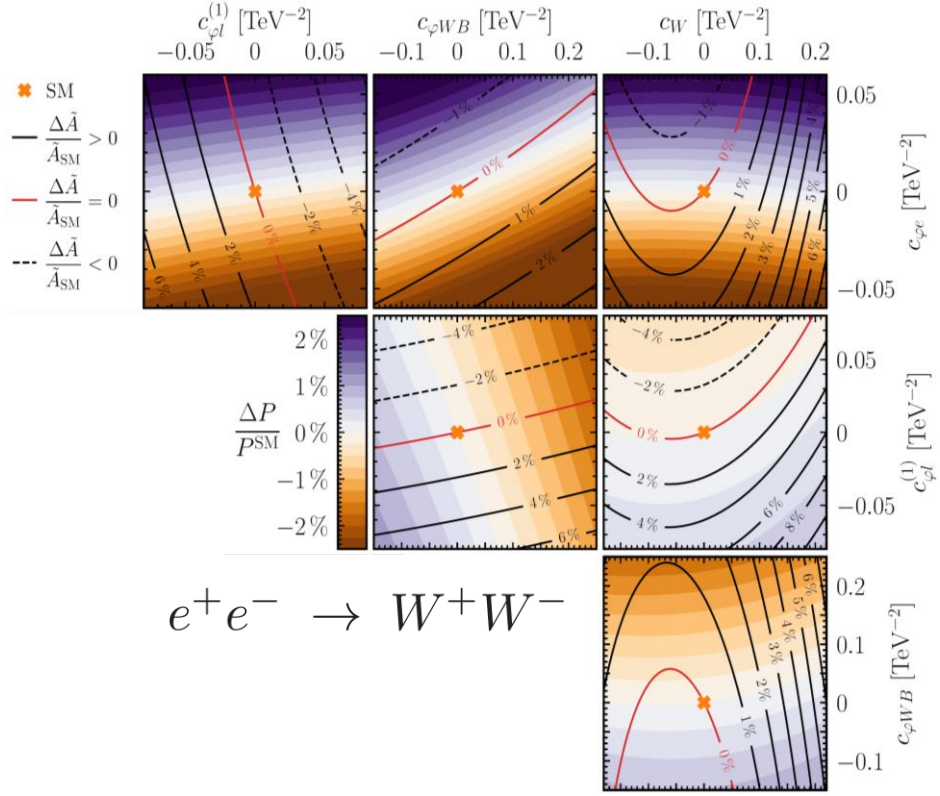
**Differential spin correlation measurements at Run 3**

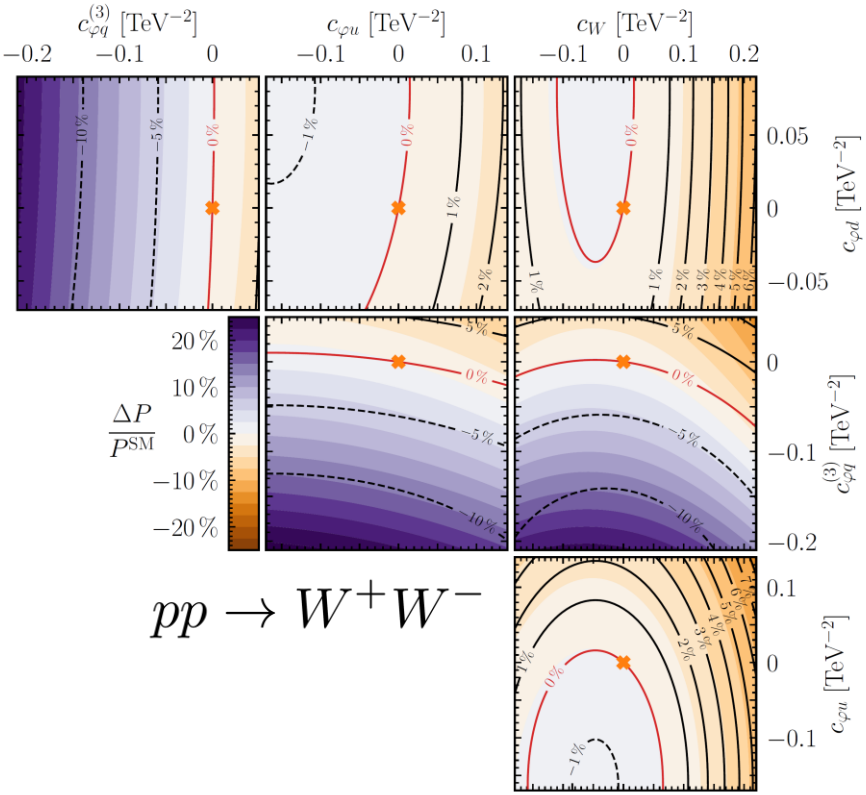
**$\approx$**

**All the current top data**

# Entanglement for Diboson ( $W^+W^-, W^+Z, ZZ$ )

R. Aoude, E. Madge, F. Maltoni, L. Mantani [2307.09675]




$P$: purity

# Towards better (Machine Learned) observables

**See M. Madigan's talk this afternoon**

R. Gómez Ambrosio, J. ter Hoeve, M. Madigan, J. Rojo, V. Sanz [2211.02058]

S. Chen, A. Glioti, G. Panico, A. Wulzer [2308.05704]

# Flavour on top of the energies

# RGE effects in top measurements

R. Aoude, F. Maltoni, O. Mattelaer, C. Severi, E. Vryonidou [2212.05067]

$E = \Lambda = 2\,\text{TeV} \quad c_{Qu}^{8},\ c_{Qq}^{(8,3)}$

# RGE effects in top measurements

R. Aoude, F. Maltoni, O. Mattelaer, C. Severi, E. Vryonidou [2212.05067]

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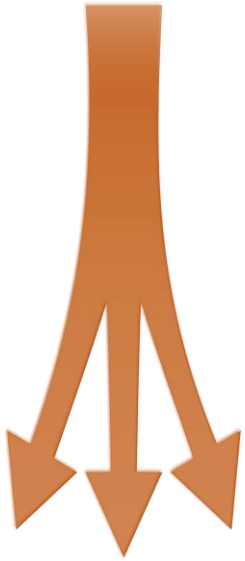


$E = m_t,\ \dfrac{H_T}{2}$

$c_{Qu}^{8},\ c_{Qq}^{(8,3)},\ c_{Qu}^{1},\ c_{Qq}^{(1,3)}$

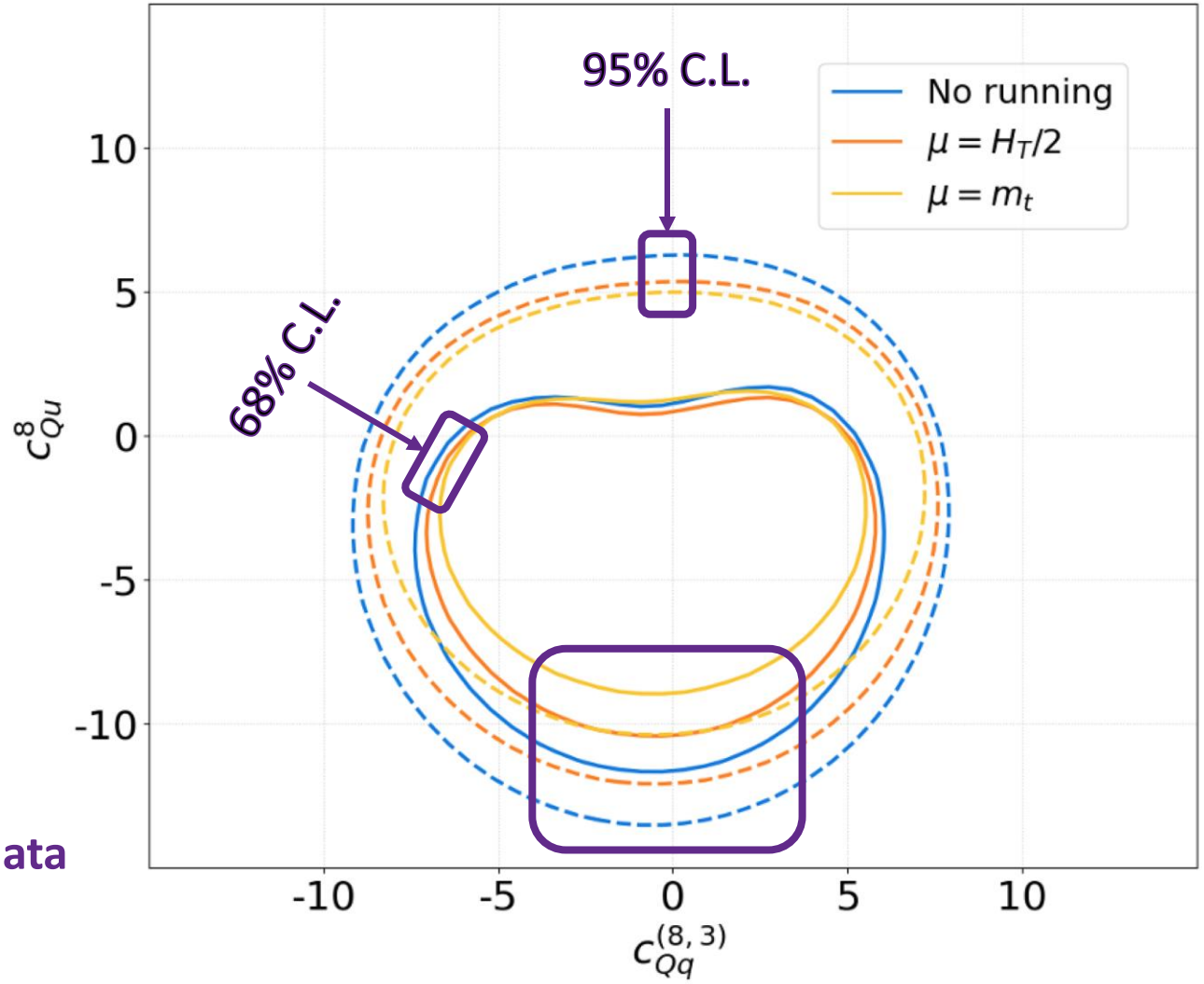
# RGE effects in top measurements

R. Aoude, F. Maltoni, O. Mattelaer, C. Severi, E. Vryonidou [2212.05067]

$E = \Lambda = 2\,\text{TeV}$ $c_{Qu}^{8}$, $c_{Qq}^{(8,3)}$

$E = m_t$, $\frac{H_T}{2}$

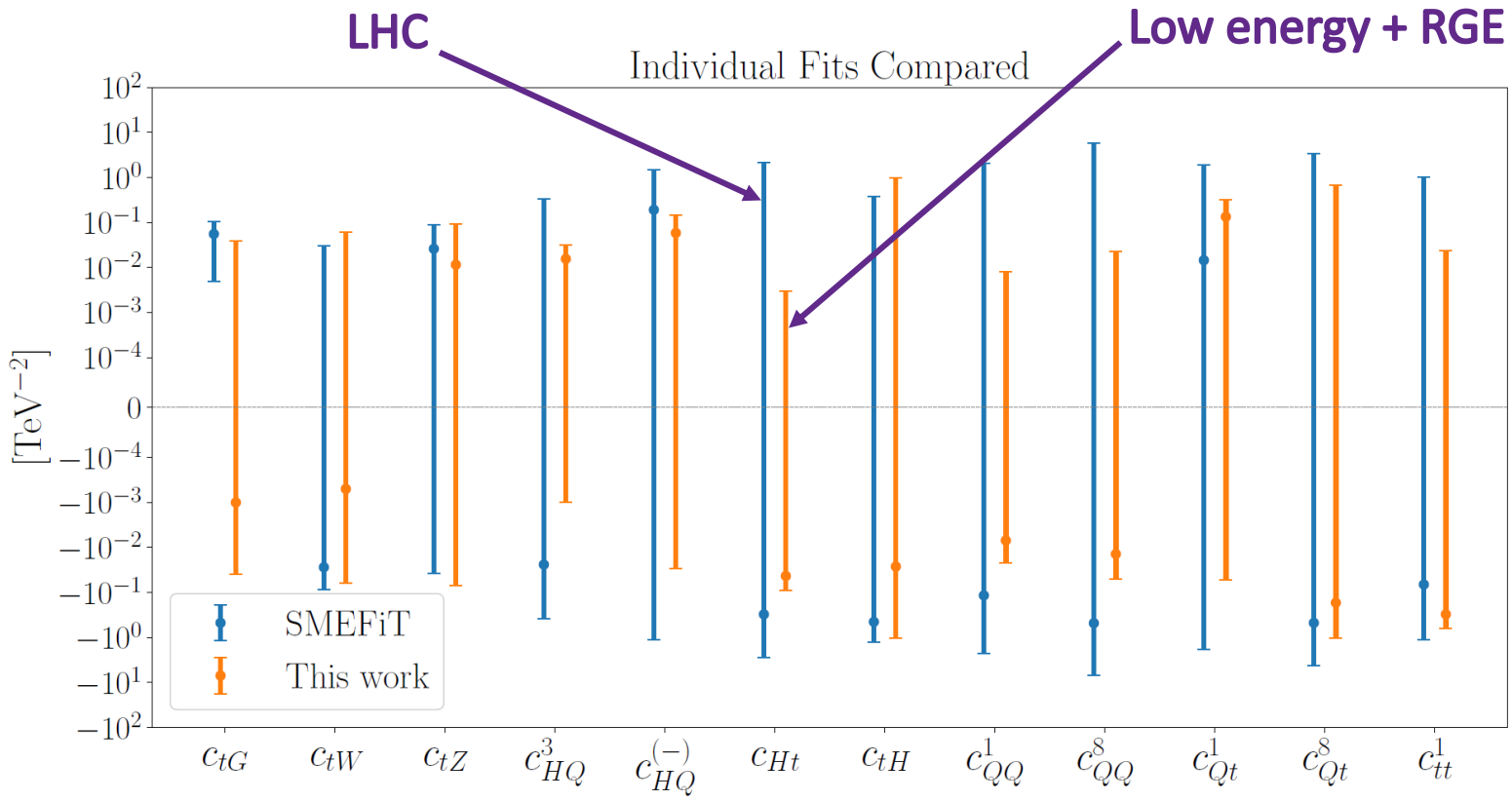
$c_{Qu}^{8}$, $c_{Qq}^{(8,3)}$, $c_{Qu}^{1}$, $c_{Qq}^{(1,3)}$




**Toy fit of current top data**

# Top operators bounded from low energies

F. Garosi, D. Marzocca, A. Rodriguez-Sanchez, A. Stanzione [2310.00047]

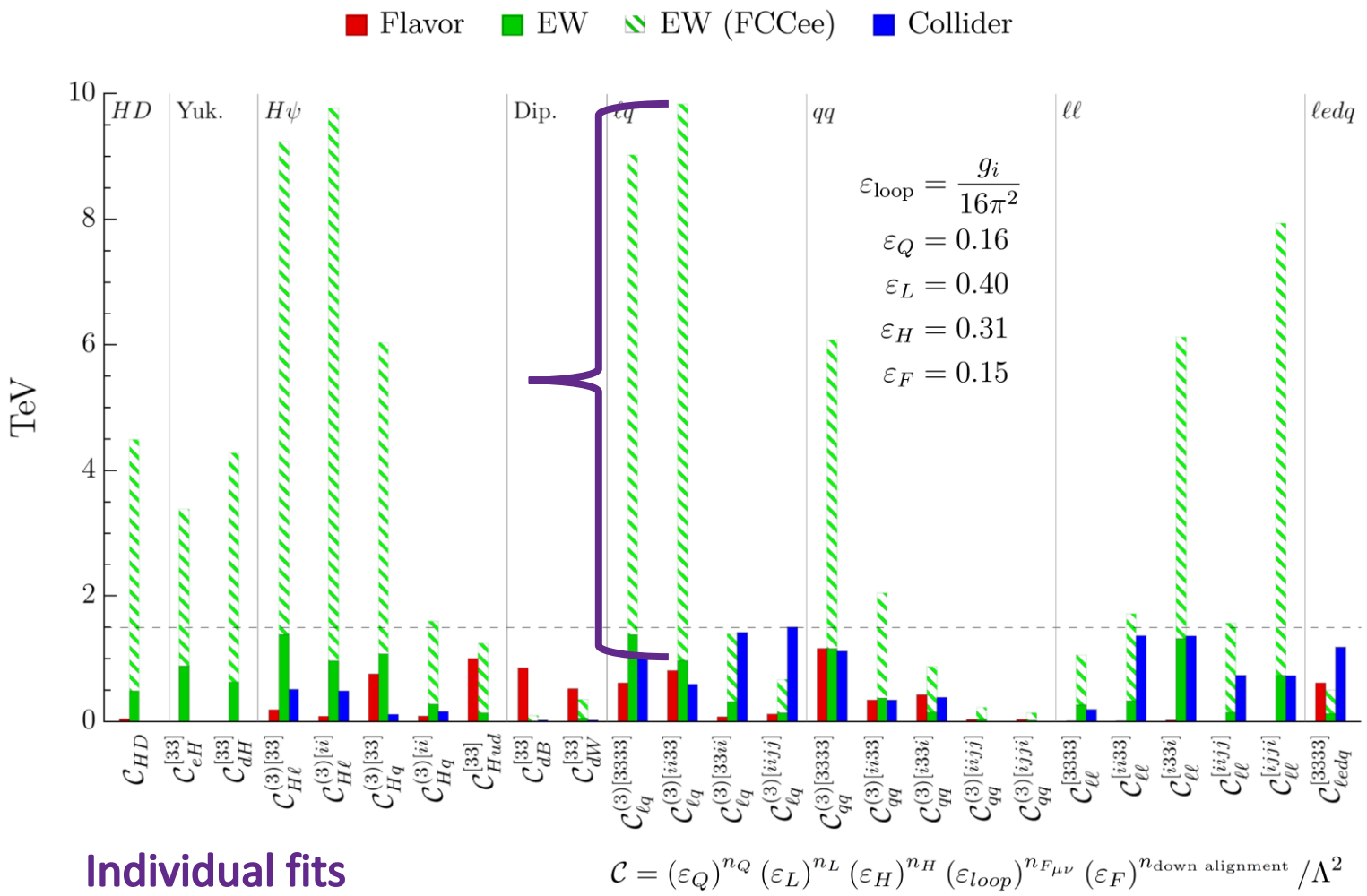



Low energy: B and K phys., $\Delta F=2$, Cabibbo angle, $g_l - 2$, τ and LFV decays, EW and H

See also A. Biekoetter's talk at LHC Higgs WG

# FCC-ee will probe 3rd generation operators

L. Allwicher, C. Cornella, G. Isidori, B. Stefanek [2311.00020]




**Individual fits**

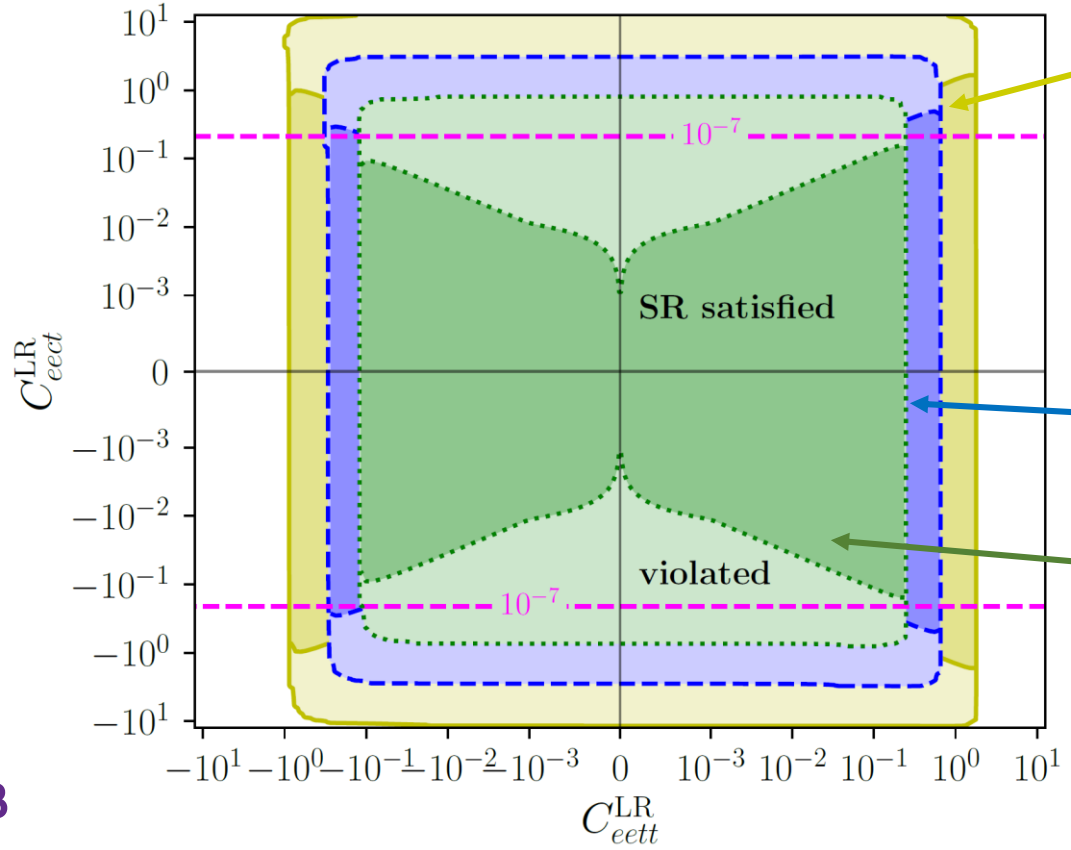
$$\mathcal{C} = (\varepsilon_Q)^{n_Q} (\varepsilon_L)^{n_L} (\varepsilon_H)^{n_H} (\varepsilon_{loop})^{n_{F_{\mu\nu}}} (\varepsilon_F)^{n_{\text{down alignment}}} / \Lambda^2$$

# Theory constraints on fits

**See previous talks by A. Helset and S. Das Bakshi**

# Dim.-6 Sum Rules help experimental bounds

W. Altmannshofer, S. Gori, B. Lehmann, J. Zuo [2303.00781]




Data: top decays, top production, dilepton, parity violation, rare B decays, Z decays.

# Dim.-6 Sum Rules help experimental bounds

W. Altmannshofer, S. Gori, B. Lehmann, J. Zuo [2303.00781]

**Sum rules:**

$$s\left(C_{\alpha\beta}^{\mathrm{LL1}} \pm \tfrac{1}{4} C_{\alpha\beta}^{\mathrm{LL2}}\right) > 0$$

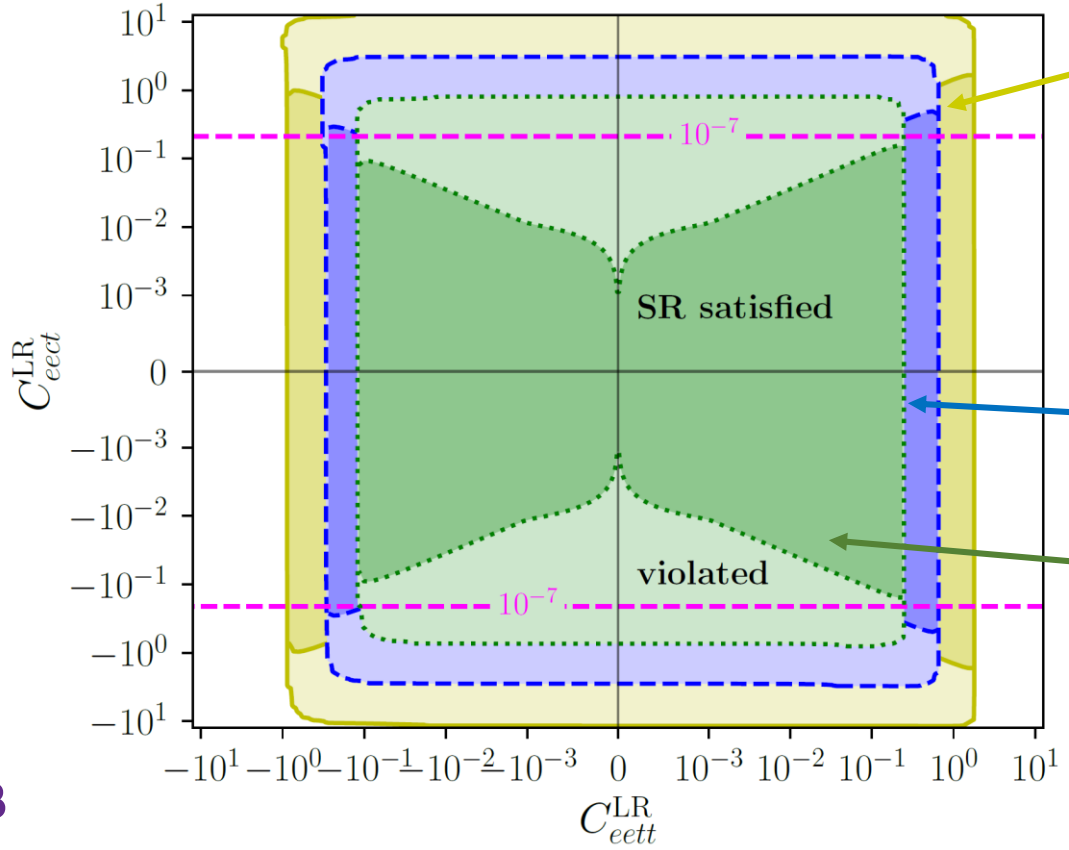
$$s\, C_{\alpha\beta}^{\mathrm{RR}} > 0 \quad s\, C_{\alpha\beta}^{\mathrm{LR}} < 0$$

$$s\, C_{\alpha\beta}^{\mathrm{RL}} < 0$$

$$C_{\alpha\beta} = \alpha_i \alpha_j^* \beta_k^* \beta_l C_{ijkl}$$

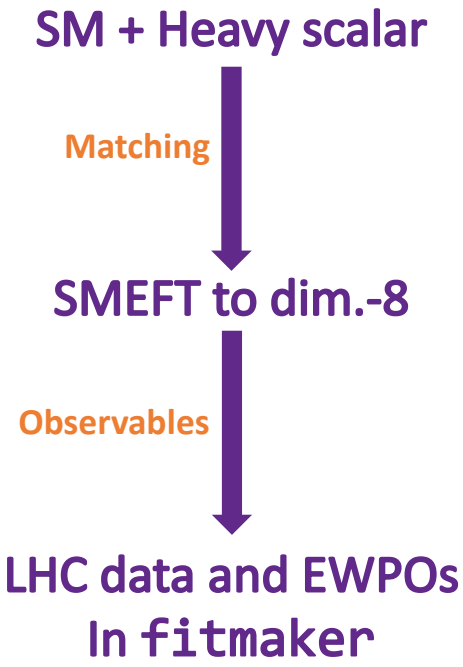
G. Remmen, N. Rodd [2010.04723]

**Data: top decays, top production, dilepton, parity violation, rare B decays, Z decays.**



# Theory constraints and higher orders

J. Ellis, K. Mimasu, F. Zampedri [2304.06663]



# Theory constraints and higher orders

J. Ellis, K. Mimasu, F. Zampedri [2304.06663]

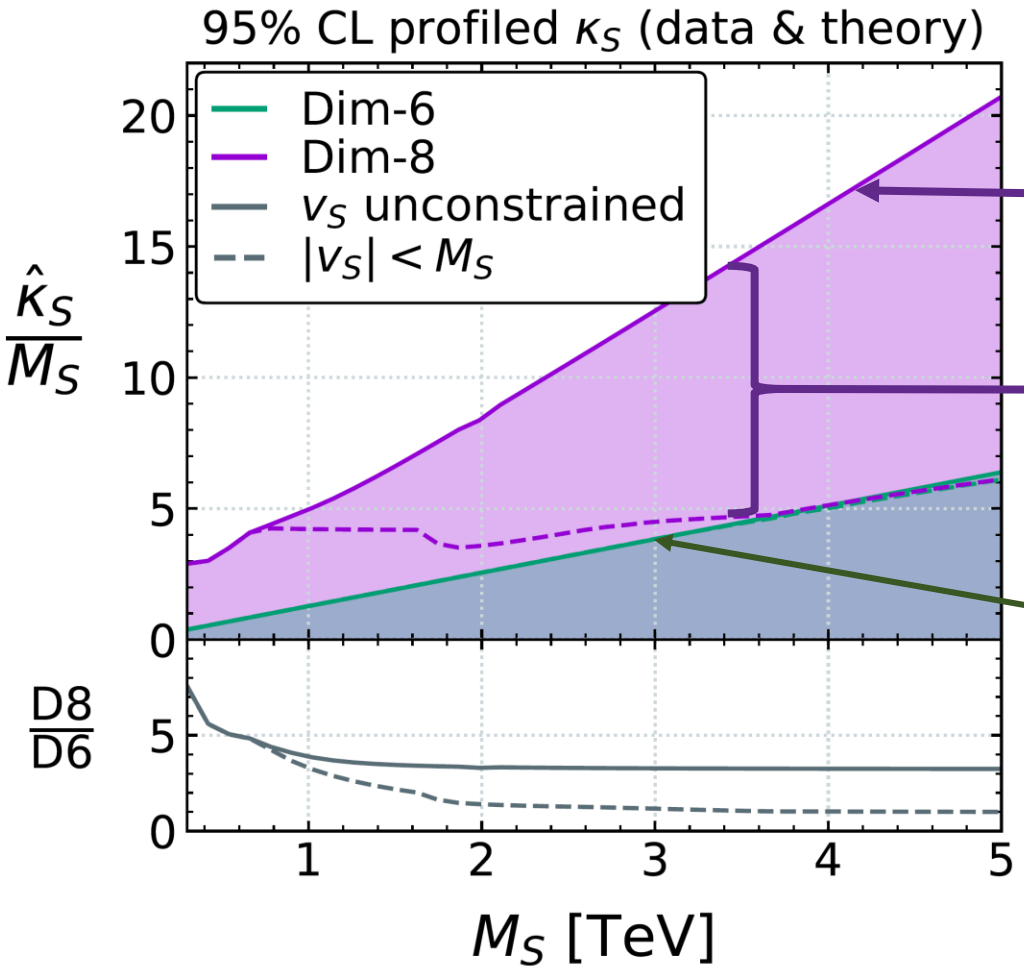
SM + Heavy scalar

Matching

SMEFT to dim.-8

Observables

LHC data and EWPOs
In `fitmaker`



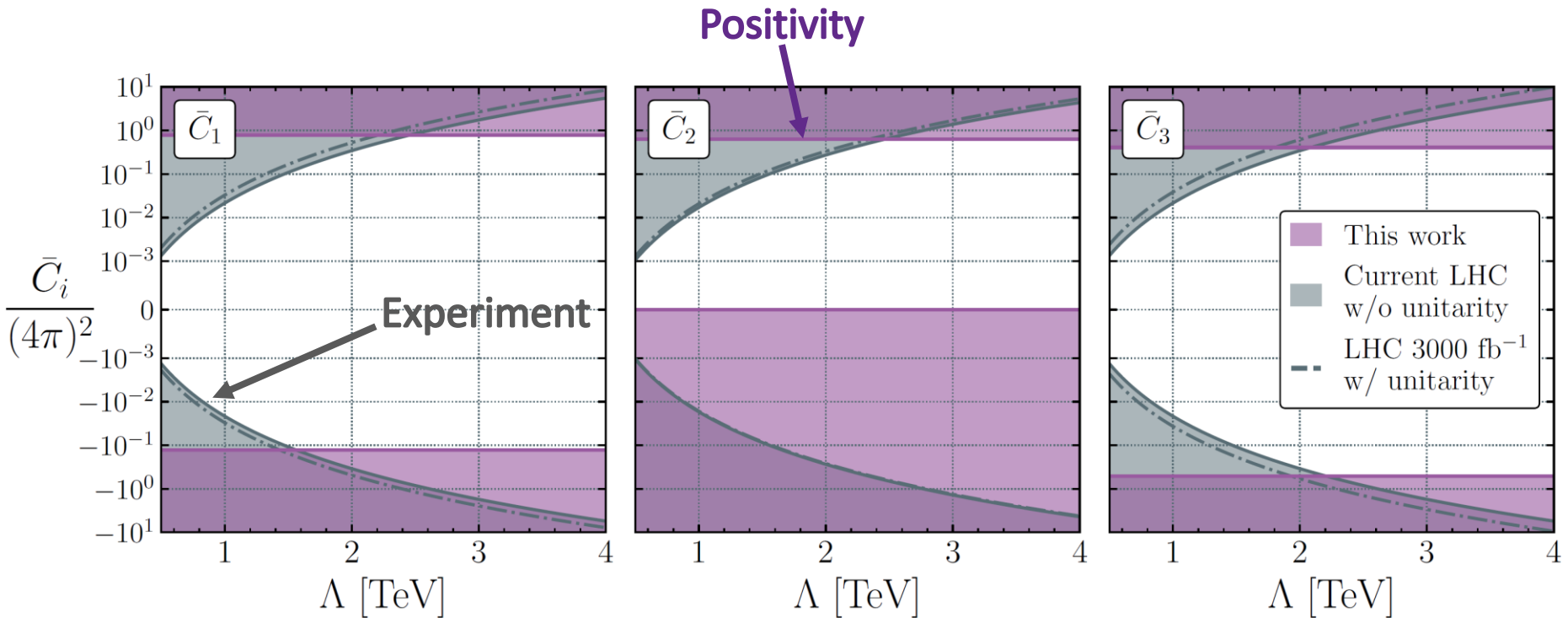

+ (Dim.-6)$^2$ + Dim.-8 interf.

Theoretical constraint

Dim.-6 interf.

# Capped positivity and dim.-8 in VBS

Q. Chen, K. Mimasu, T. Wu, G.-D. Zhan, S.-Y. Zhou [2309.15922]




$$\bar{C}_I = C_I \Lambda^4$$

$$\mathcal{O}_{H^4}^{(1)} = \left(D_\mu H^\dagger D_\nu H\right)\left(D^\nu H^\dagger D^\mu H\right)$$
$$\mathcal{O}_{H^4}^{(2)} = \left(D_\mu H^\dagger D_\nu H\right)\left(D^\mu H^\dagger D^\nu H\right)$$
$$\mathcal{O}_{H^4}^{(3)} = \left(D^\mu H^\dagger D_\mu H\right)\left(D^\nu H^\dagger D_\nu H\right)$$

See M. Riembau's talk tomorrow

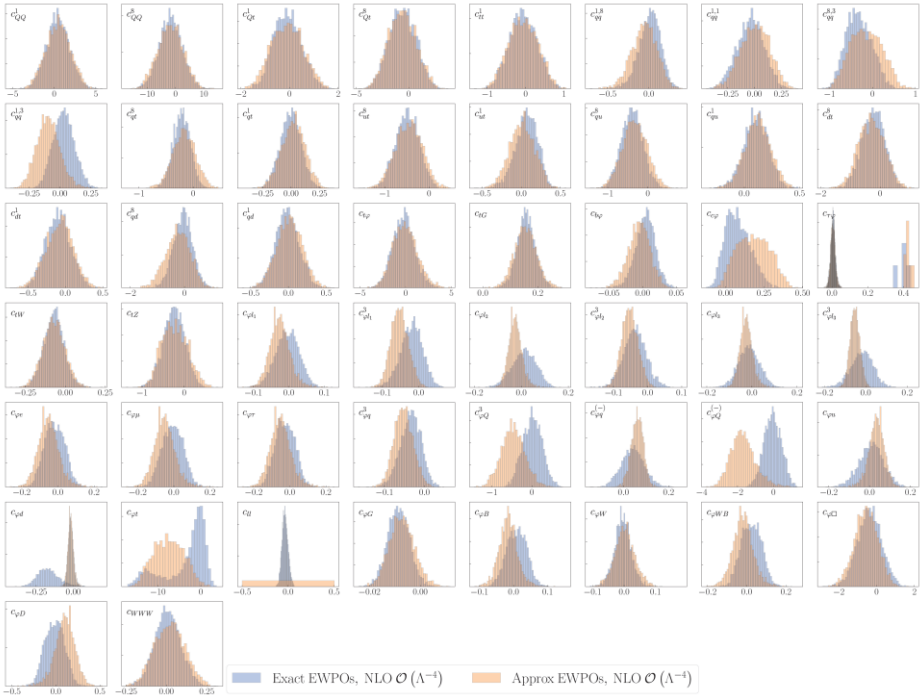
# Global fits

# The SMEFiT framework

T. Giani, G. Magni, J. Rojo [2302.06660]

```
pip install smefit
```

```
smefit NS <path_to_runcard>
```



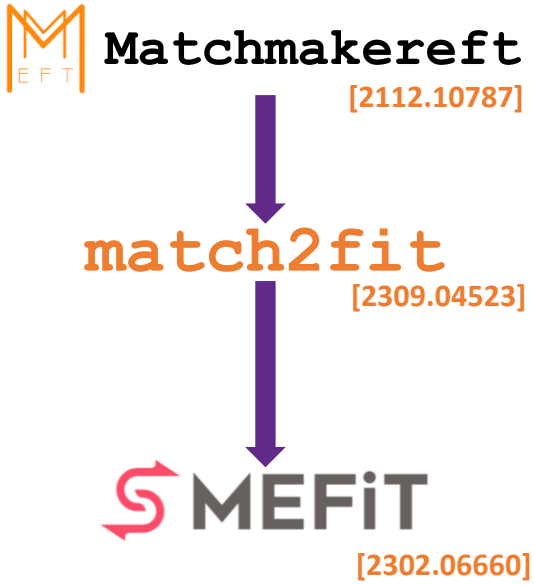

- Open-source and easy-to-use python package for EFT global fits
- Validated against ATLAS framework.
- Large LHC dataset, now includes exact EWPOs
- Support for HL-LHC and FCC-ee projections is around the corner.

SMEFiT Coll., '24

# Automating the matching - global fits connection

J. ter Hoeve, G. Magni, J. Rojo, ANR, E. Vryonidou [2309.04523]

See S. Das Bakshi's talk



# Automating the matching - global fits connection

J. ter Hoeve, G. Magni, J. Rojo, ANR, E. Vryonidou [2309.04523]

See S. Das Bakshi's talk

Matchmakereft [2112.10787]

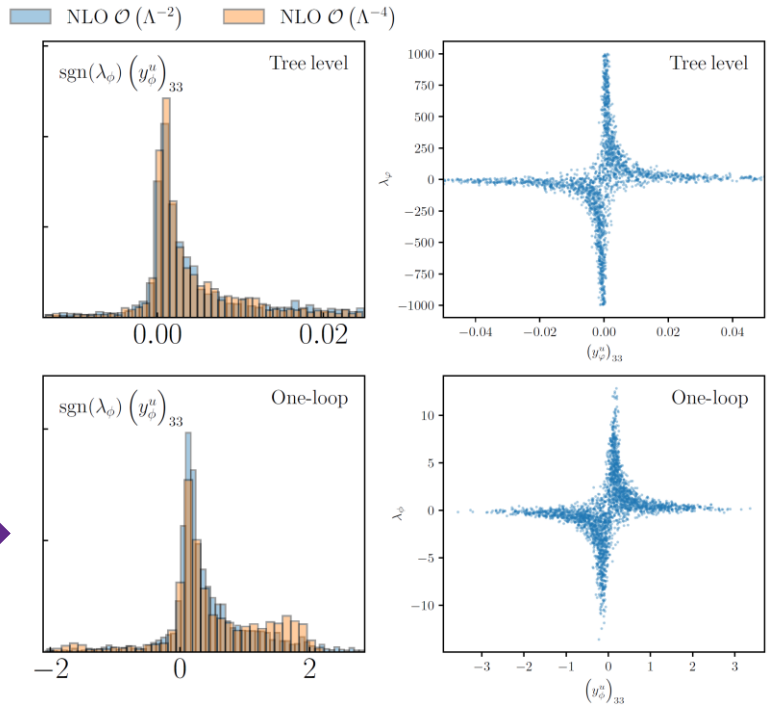
↓

match2fit [2309.04523]

↓

MEFiT [2302.06660]

→




- Automated interface with 1-loop matching support.
- Open-source interface in the form of a Mathematica package.

# The paths ahead

- Ramp up the exploration of rare processes.
- Initial exploration of CPV effects, we need NLO corrections.
- Dim-8 should be incorporated in tools for systematic studies.
  **See M. Ryczkowski's talk tomorrow** **A. Dedes, et al [2302.01353]**
- Automated tools to incorporate theoretical constraints in pheno analysis.
- Systematic way to evaluate EFT validity (clipping method extension).
- Close to full understanding of 1-loop RGE effects. 2-loop RGE?
- More cooperation between theory groups and with experimentalists.

# Thanks for your attention!

**Contact:**

Alejo N. Rossia

HEP Theory Group – Dept. Of Physics and Astronomy

E-mail: alejo dot rossia at manchester dot ac dot uk

http://www.hep.man.ac.uk/

# Appendix: Other interesting papers

- Hide and seek: how PDFs can conceal New Physics
- A global analysis of the SMEFT under the minimal MFV assumption
- Double insertions of SMEFT operators in gluon fusion Higgs boson production
- Exploring SMEFT Couplings Using the Forward-Backward Asymmetry in Neutral Current Drell-Yan Production at the LHC
- Electroweak input schemes and universal corrections in SMEFT
- The importance of flavor in SMEFT Electroweak Precision Fits
- Anomalies in global SMEFT analyses: a case study of first-row CKM unitarity
- Quantum fitting framework applied to effective field theories
- A global analysis of axion-like particle interactions using SMEFT fits
- Resolving the flavor structure in the MFV-SMEFT
- Impact of high invariant-mass Drell-Yan forward-backward asymmetry measurements on SMEFT fits
- Generic Tests of CP Violation in High pT Multilepton Signals at the LHC and Beyond
- SMEFT analysis with LHeC, FCC-eh, and EIC DIS pseudodata
- SMEFT probes in future precision DIS experiments
- To Profile or To Marginalize -- A SMEFT Case Study
- Classifying the CP properties of the ggH coupling in H+2j production

# Appendix: Other interesting papers

- Returning CP-Observables to The Frames They Belong
- Effective Field Theory descriptions of Higgs boson pair production
- EFT, Decoupling, Higgs Mixing and All That Jazz
- Search for the anomalous ZZZ and ZZγ gauge couplings through the process e+e- > ZZ with unpolarized and polarized beams
- Study of HZZ anomalous couplings by angular differential cross sections
- Associated production of Higgs and single top at the LHC in presence of the SMEFT operators
- SMEFT at NNLO+PS: Vh production