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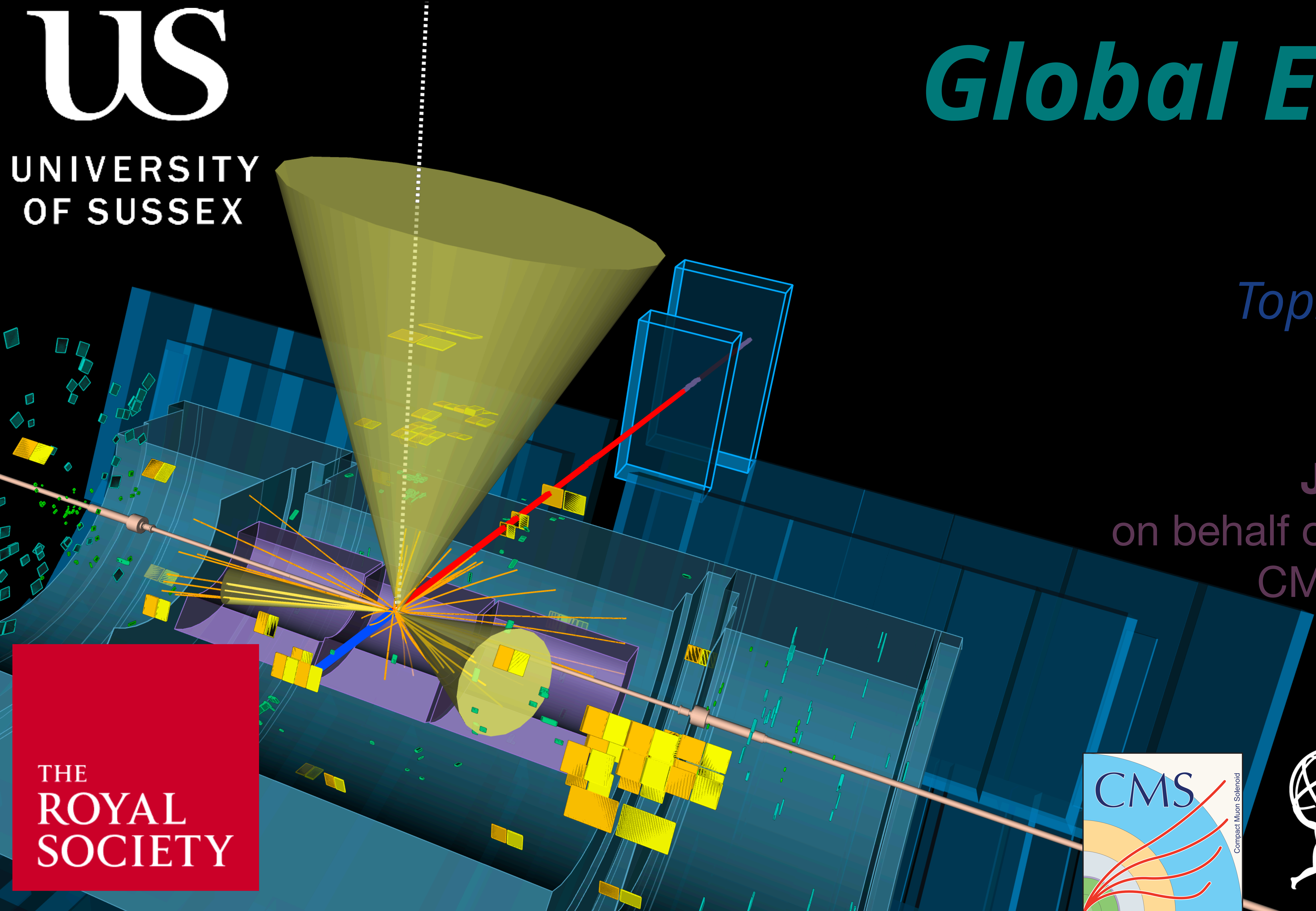
Global EFT Fits



Top2022 Durham

6/9/2022

Josh McFayden,
on behalf of the ATLAS and CMS collaborations

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cern.ch/mcfayden

THE ROYAL SOCIETY

CMS

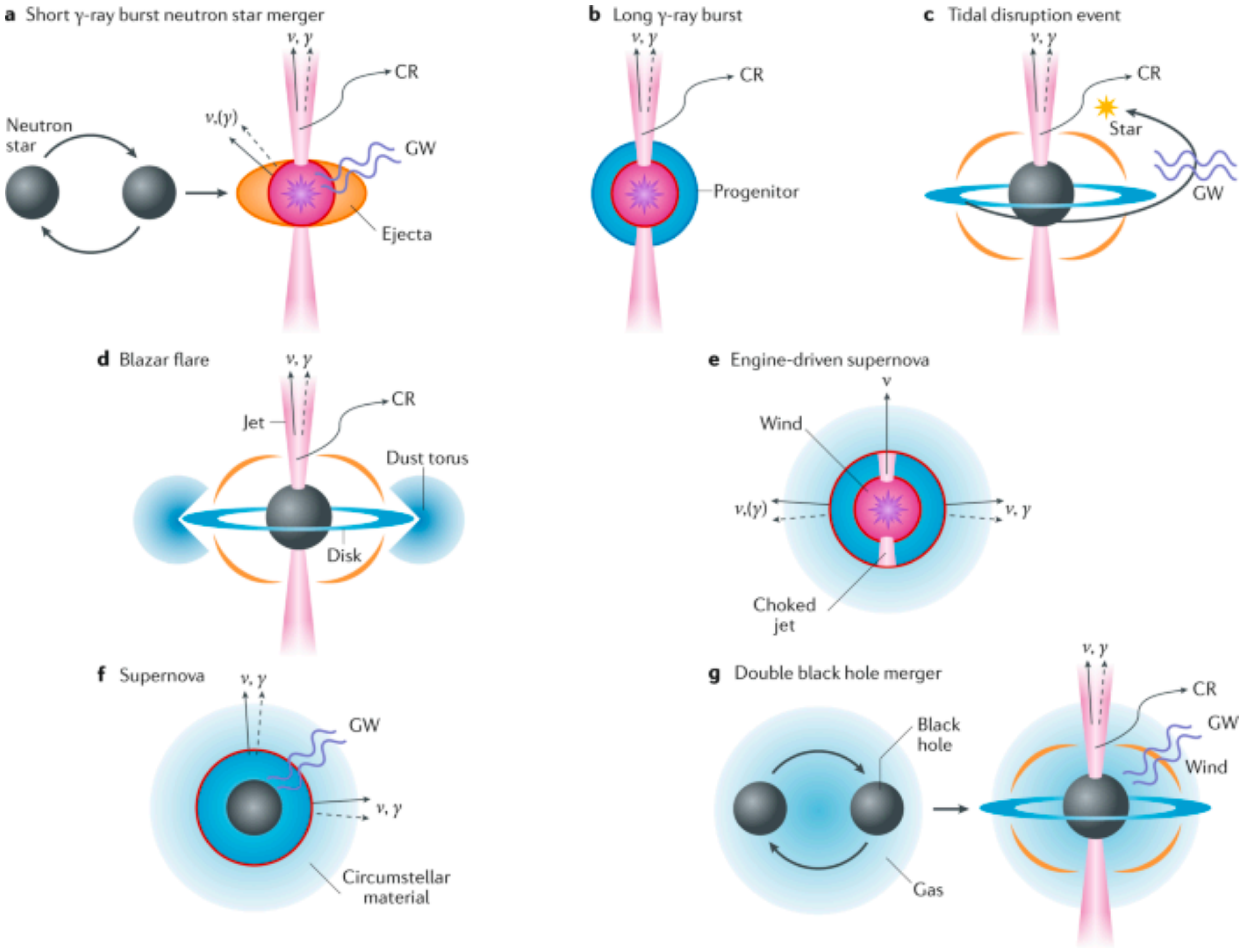
ATLAS EXPERIMENT

Review Article | Published: 03 October 2019

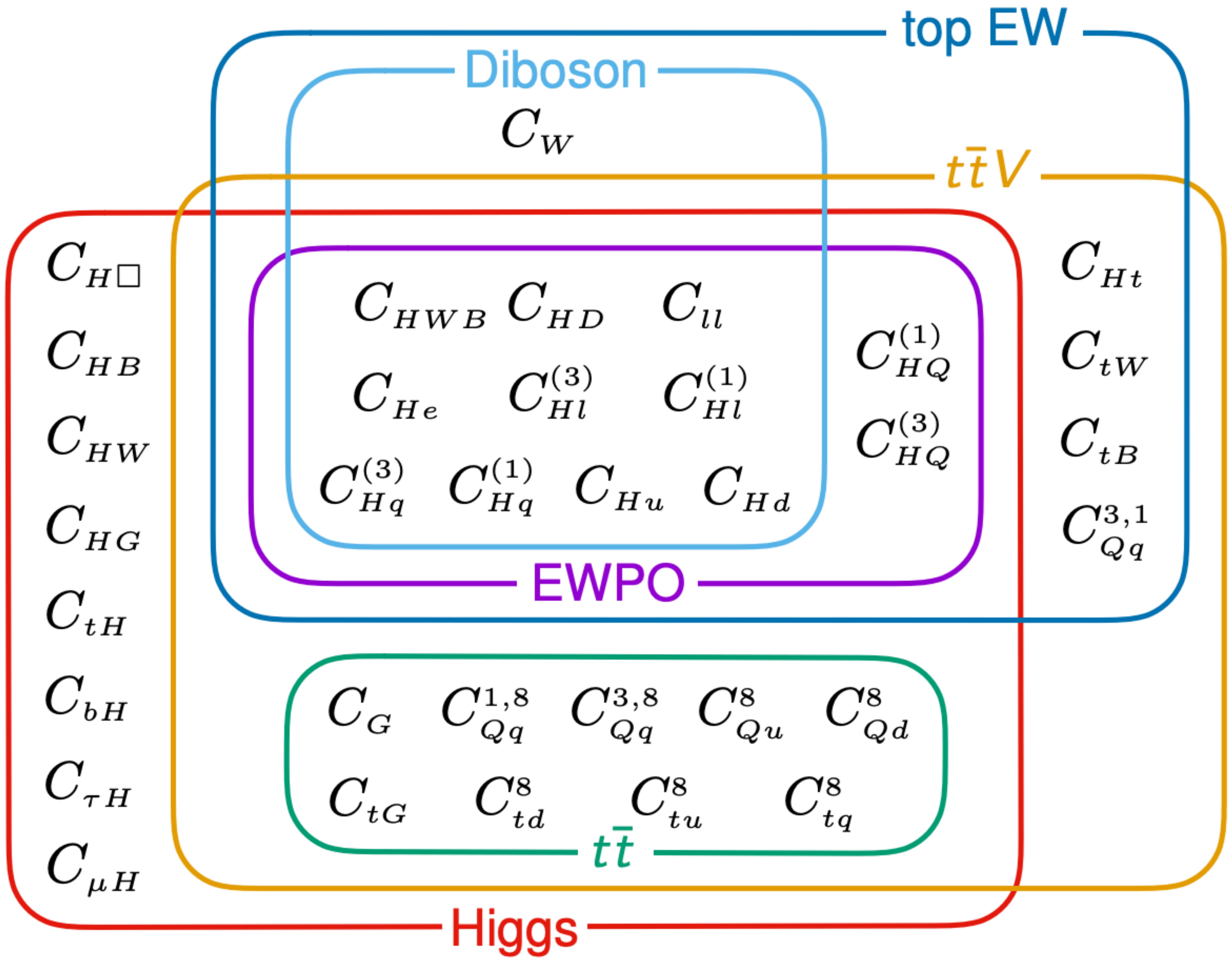
Multi-messenger astrophysics

Péter Mészáros, Derek B. Fox, Chad Hanna & Kohta Murase

Nature Reviews Physics **1**, 585–599 (2019) | Cite this article

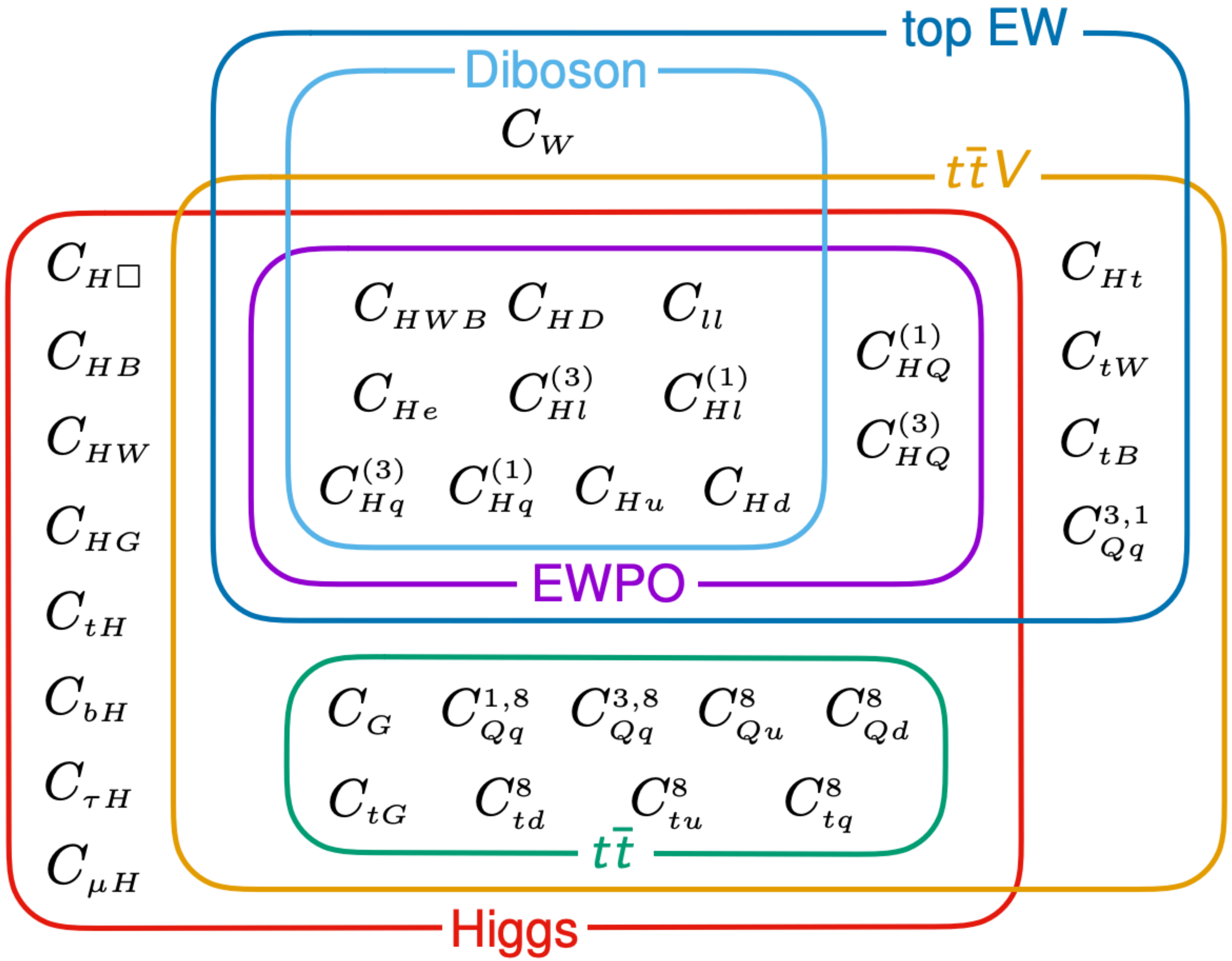


Multi-messenger particle physics



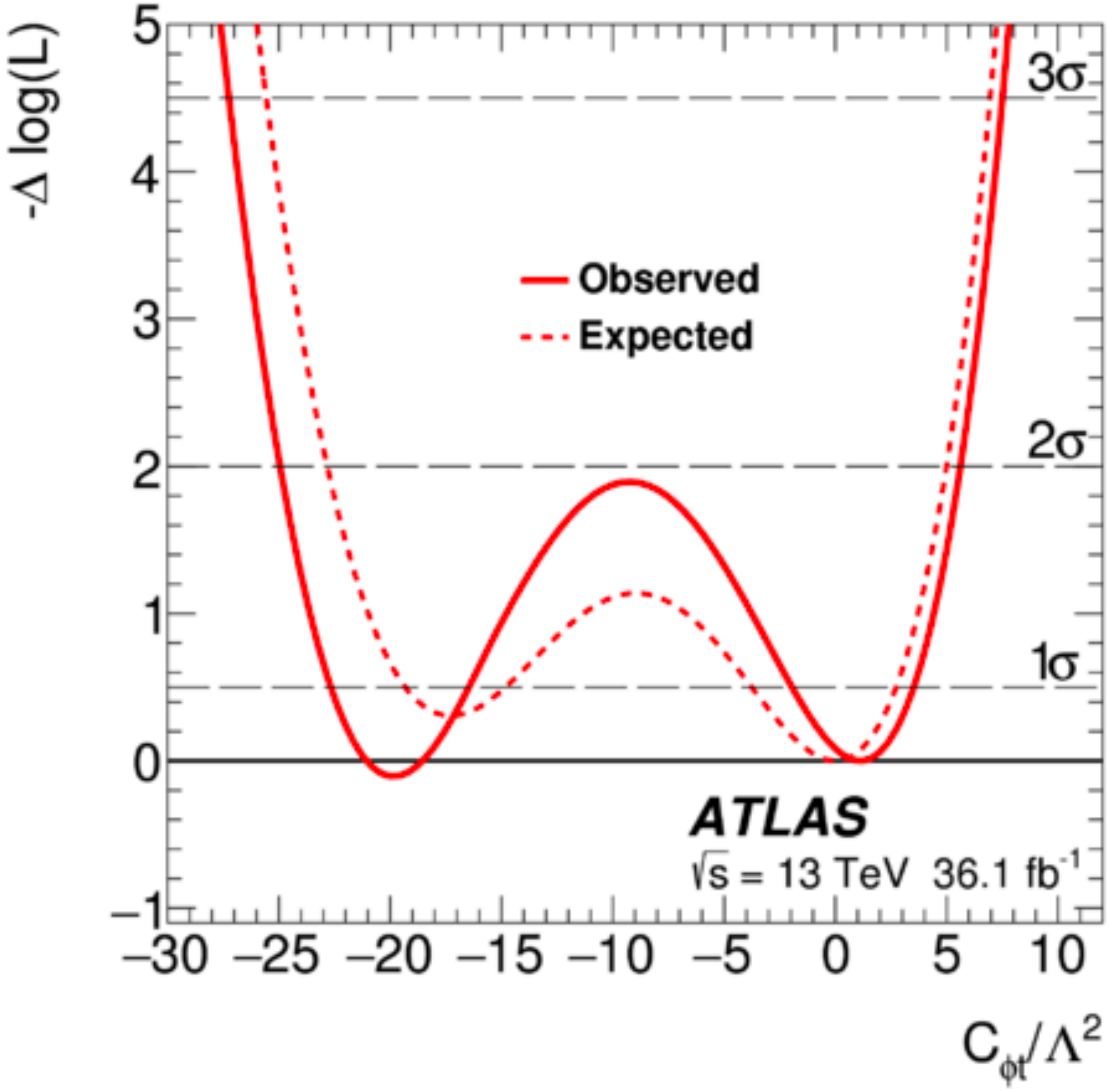
Multi-messenger particle physics

- Global EFT approaches offer a multi messenger approach to searching for new physics



Mini history of EFT in top

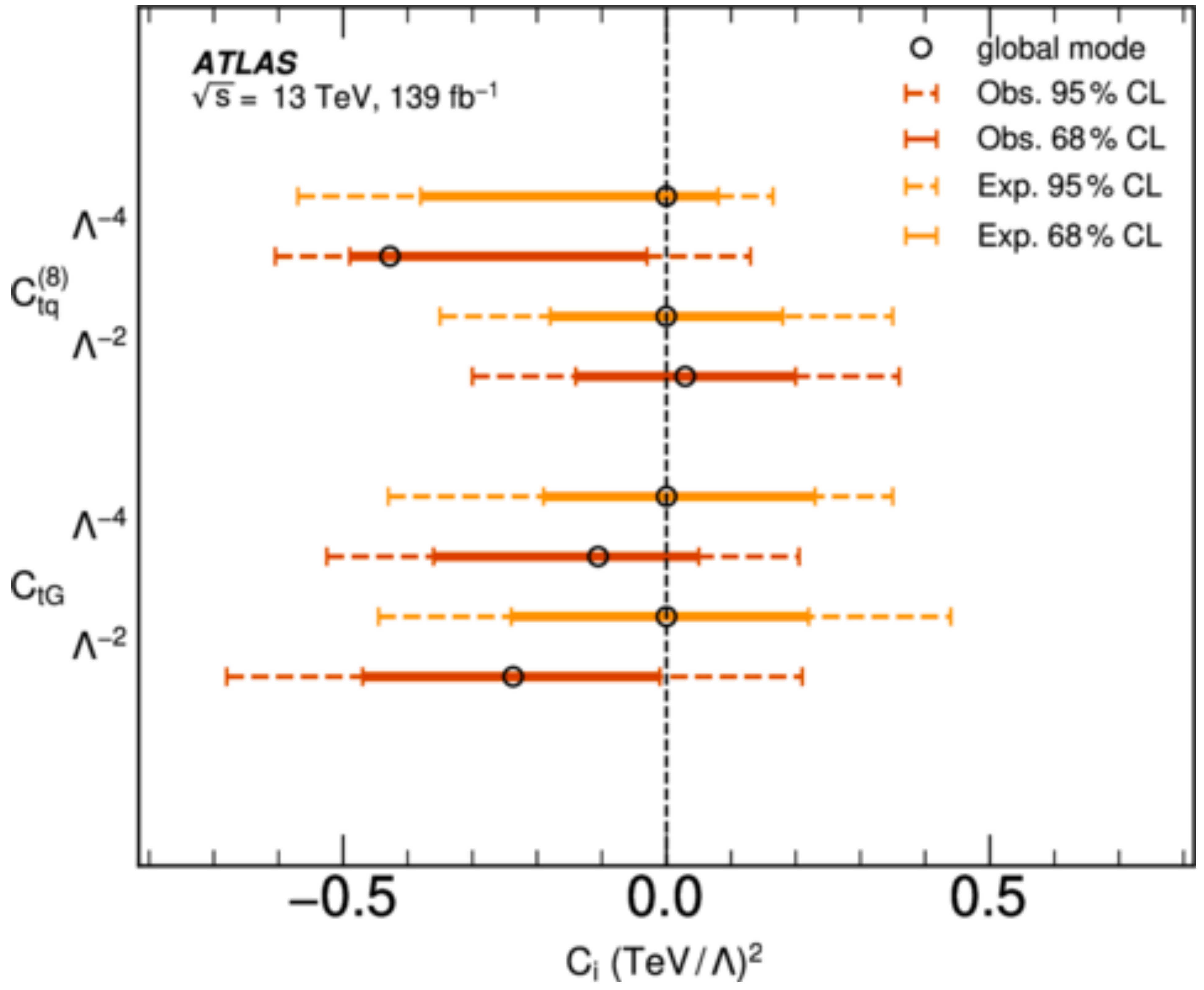
- Single process one operator at a time



[TOPQ-2016-11]

Mini history of EFT in top

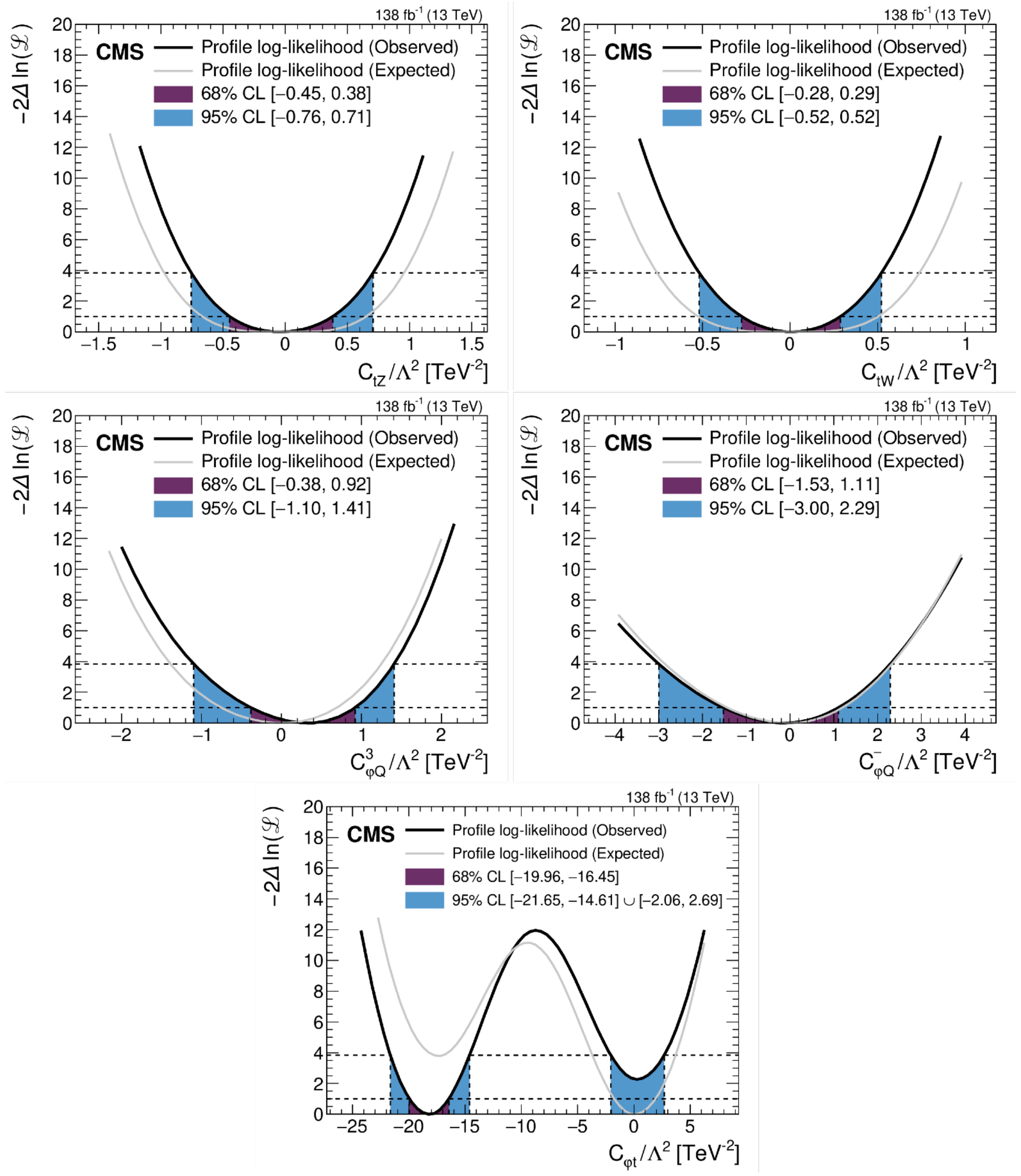
- Single process one operator at a time
- Single process multiple operators



[TOPQ-2019-23]

Mini history of EFT in top

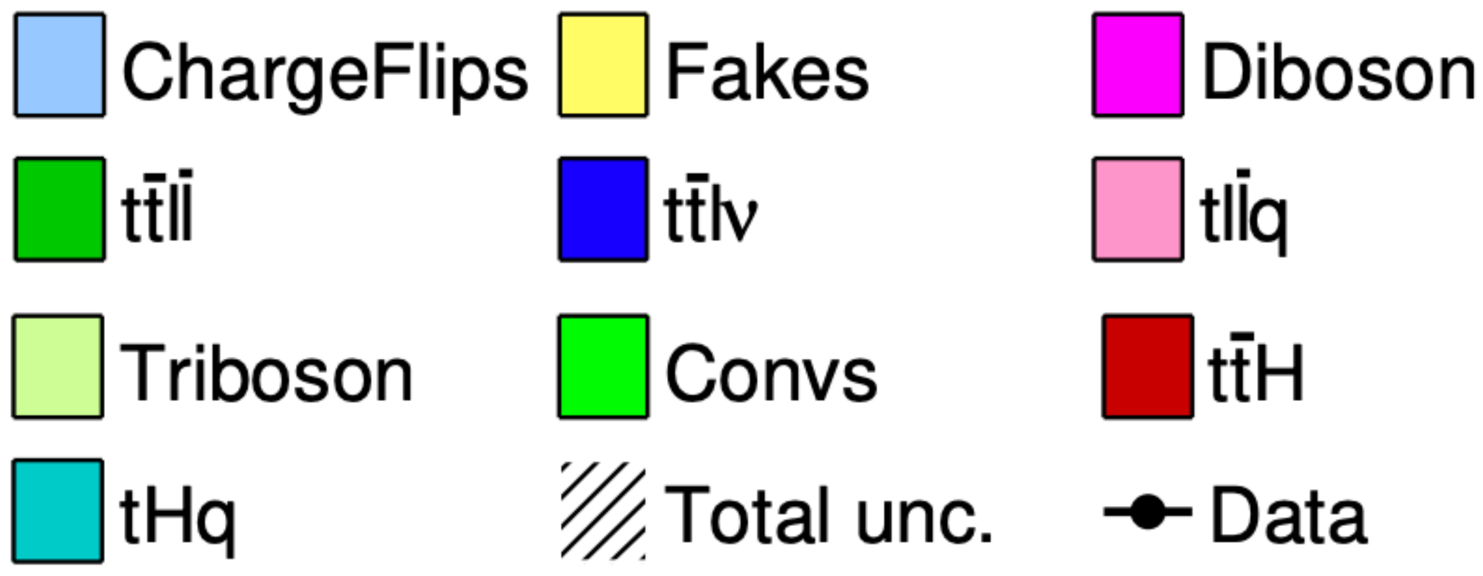
- Single process one operator at a time
- Single process multiple operators
- Multiple processes single operators

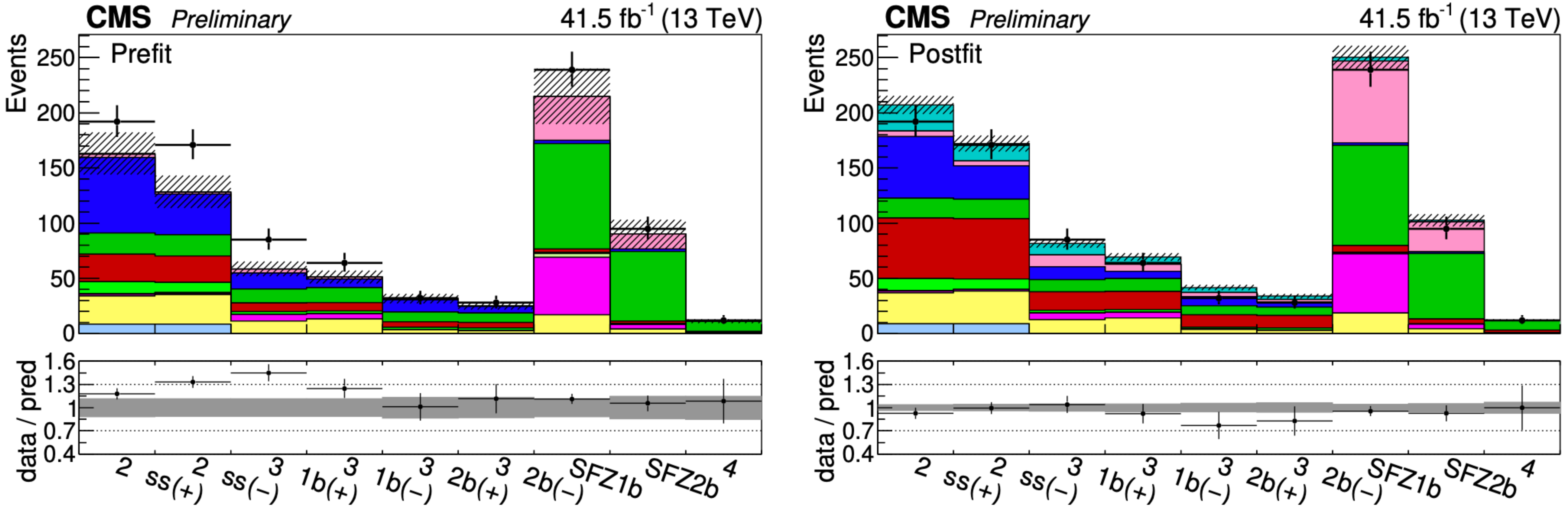


[TOP-21-001]

Mini history of EFT in top

- Single process one operator at a time
- Single process multiple operators
- Multiple processes single operators
- Multiple processes multiple operators





[TOP-19-001]

Mini history of EFT in top

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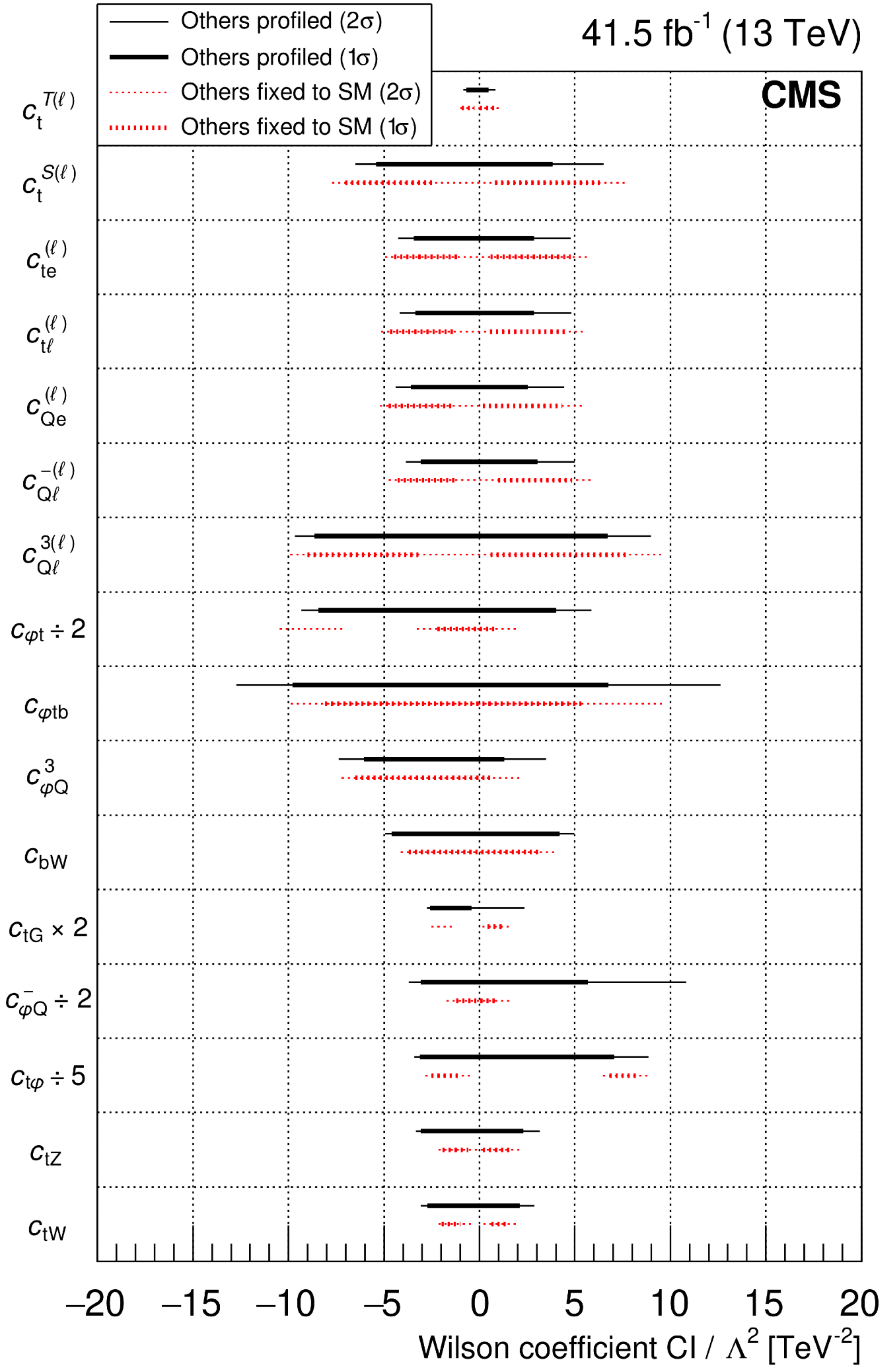
- Single process multiple operators
- Multiple processes single operators
- Multiple processes multiple operators

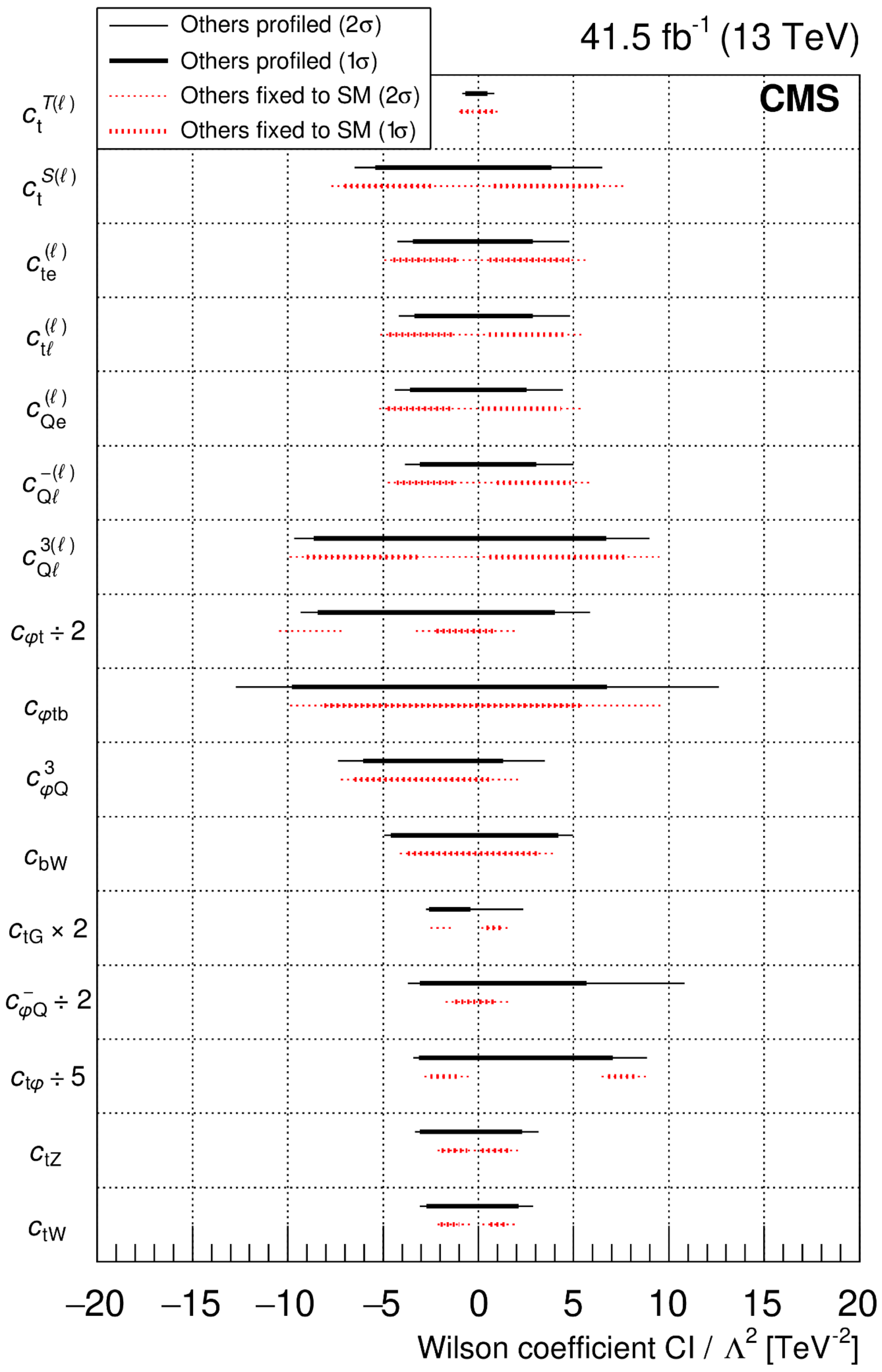


[TOP-19-001]

Mini history of EFT in top

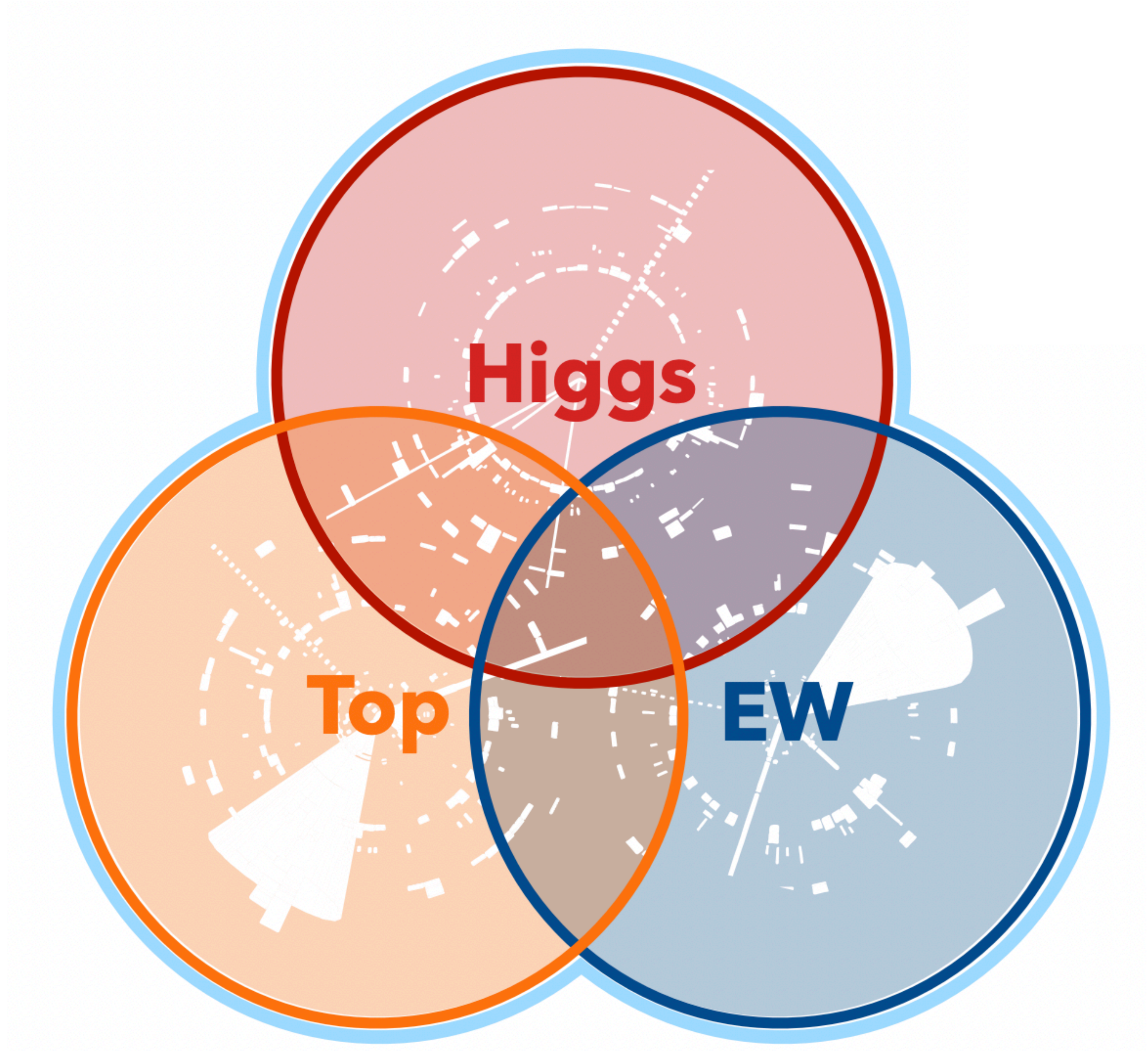
- Single process one operator at a time
- Single process multiple operators
- Multiple processes single operators
- Multiple processes multiple operators

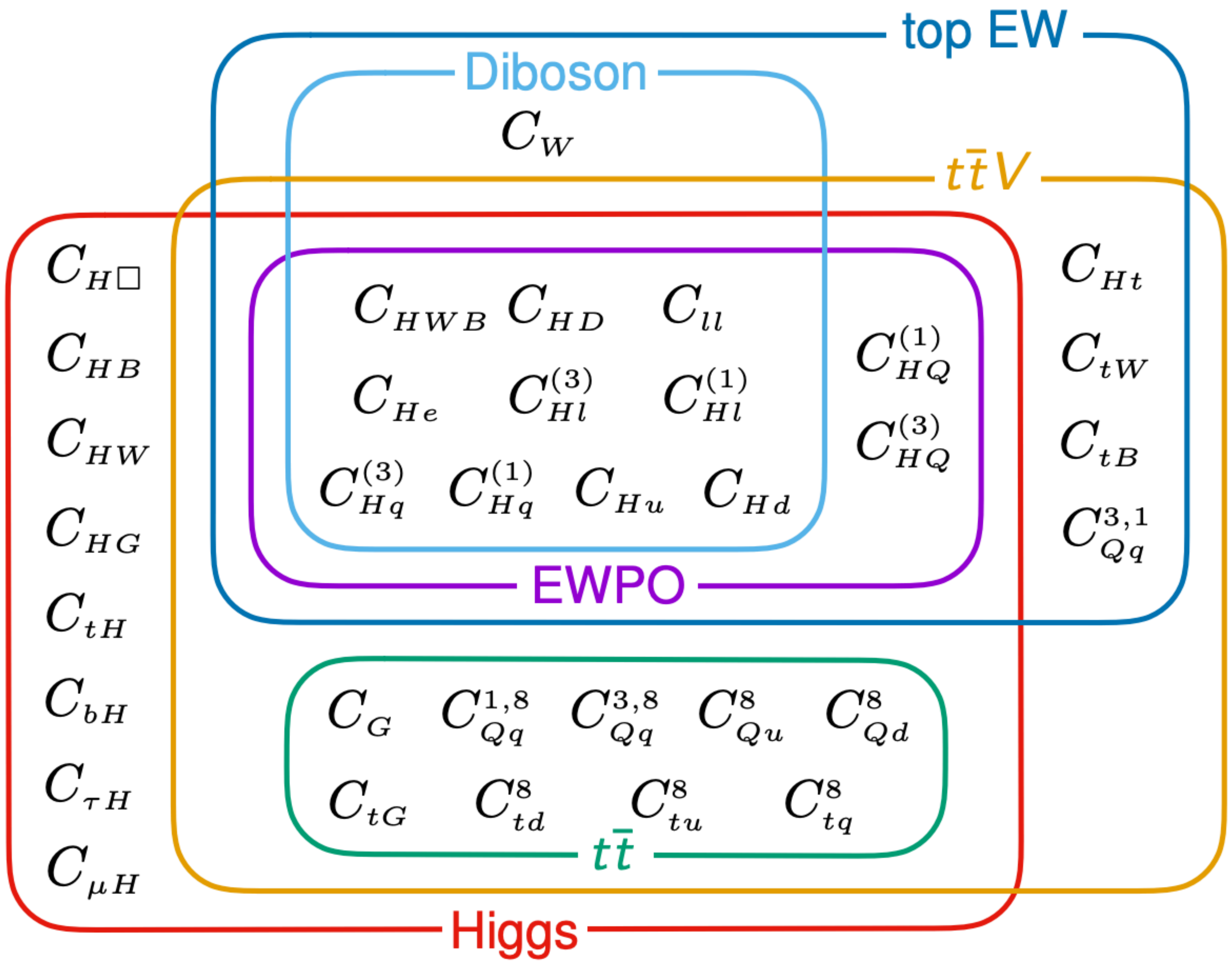
- Next steps?
  - A more global Top fit
  - A fully global fit



[TOP-19-001]

Global Fits



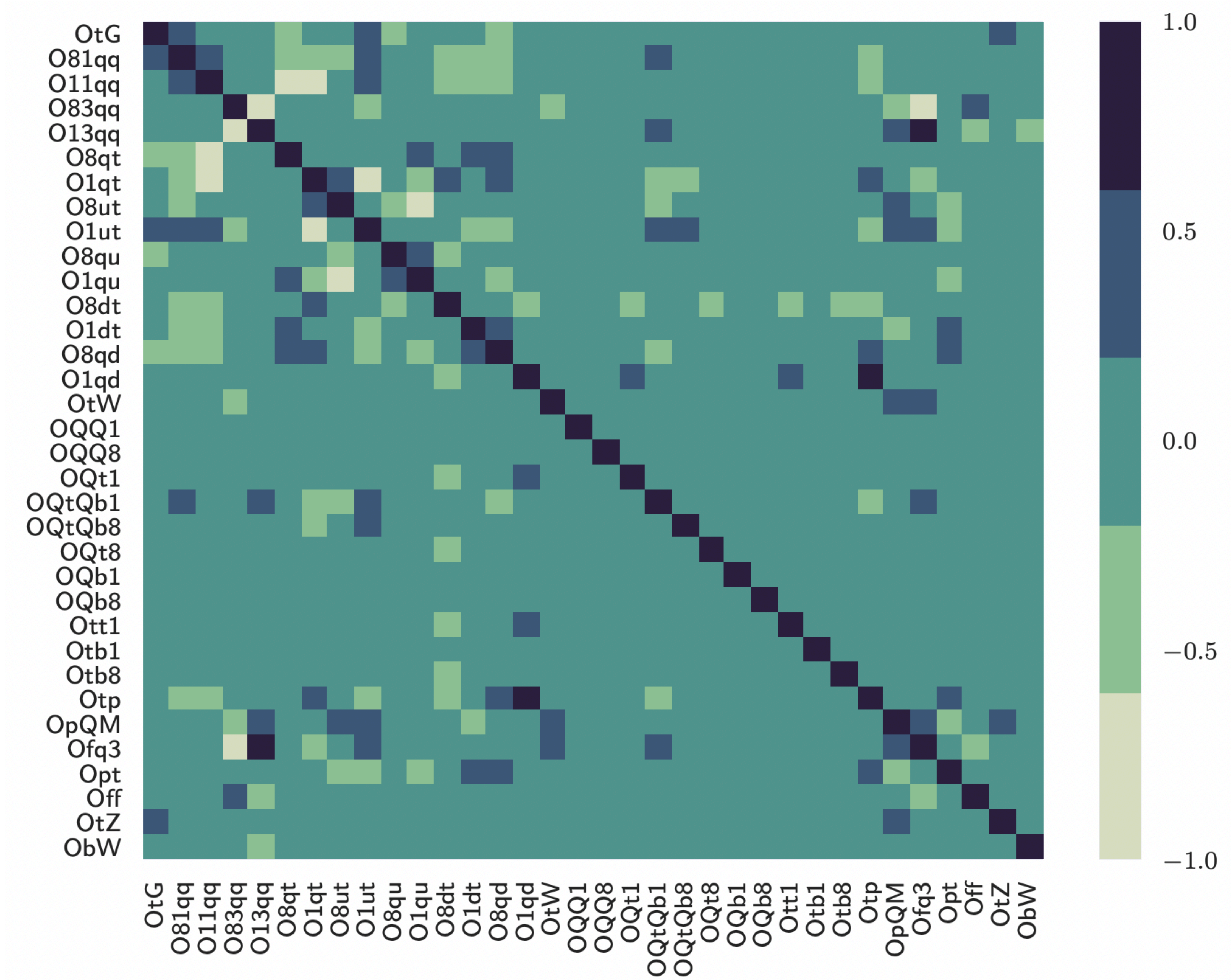


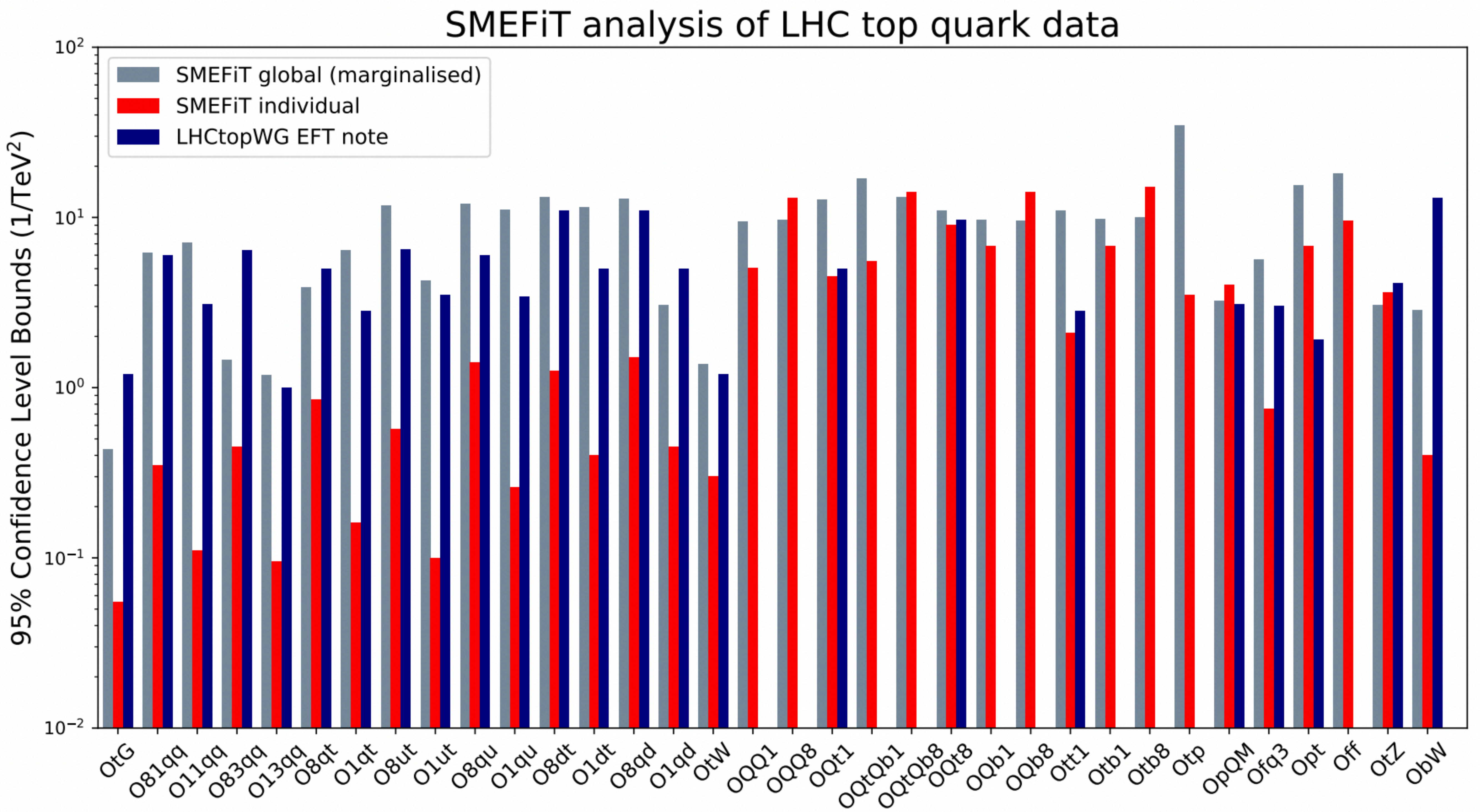
- Measurements of several processes
  - Including from different experiments
- Many operators
- Complementarity improves sensitivity
- Currently performed mainly in pheno community
  - Using available experimental data/information

[arXiv:2012.02779]

SMEFit | Top Sector "global" fit

- SMEFiT framework "proof-of-concept" analysis of top quark production measurements from LHC 8 TeV and 13 TeV data





[1901.05965]

SMEFit | Top+Higgs+VV fit

[2105.00006]

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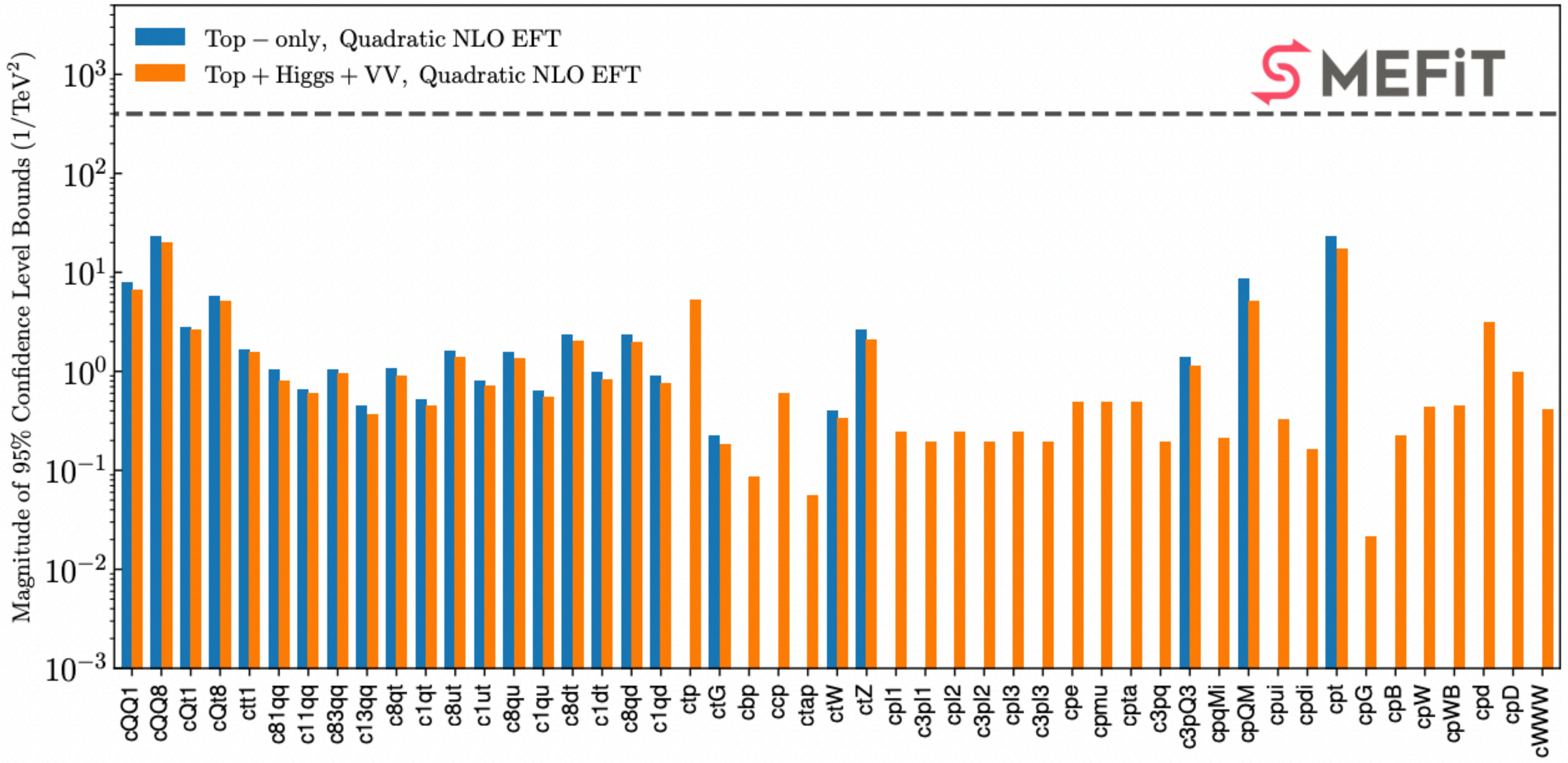
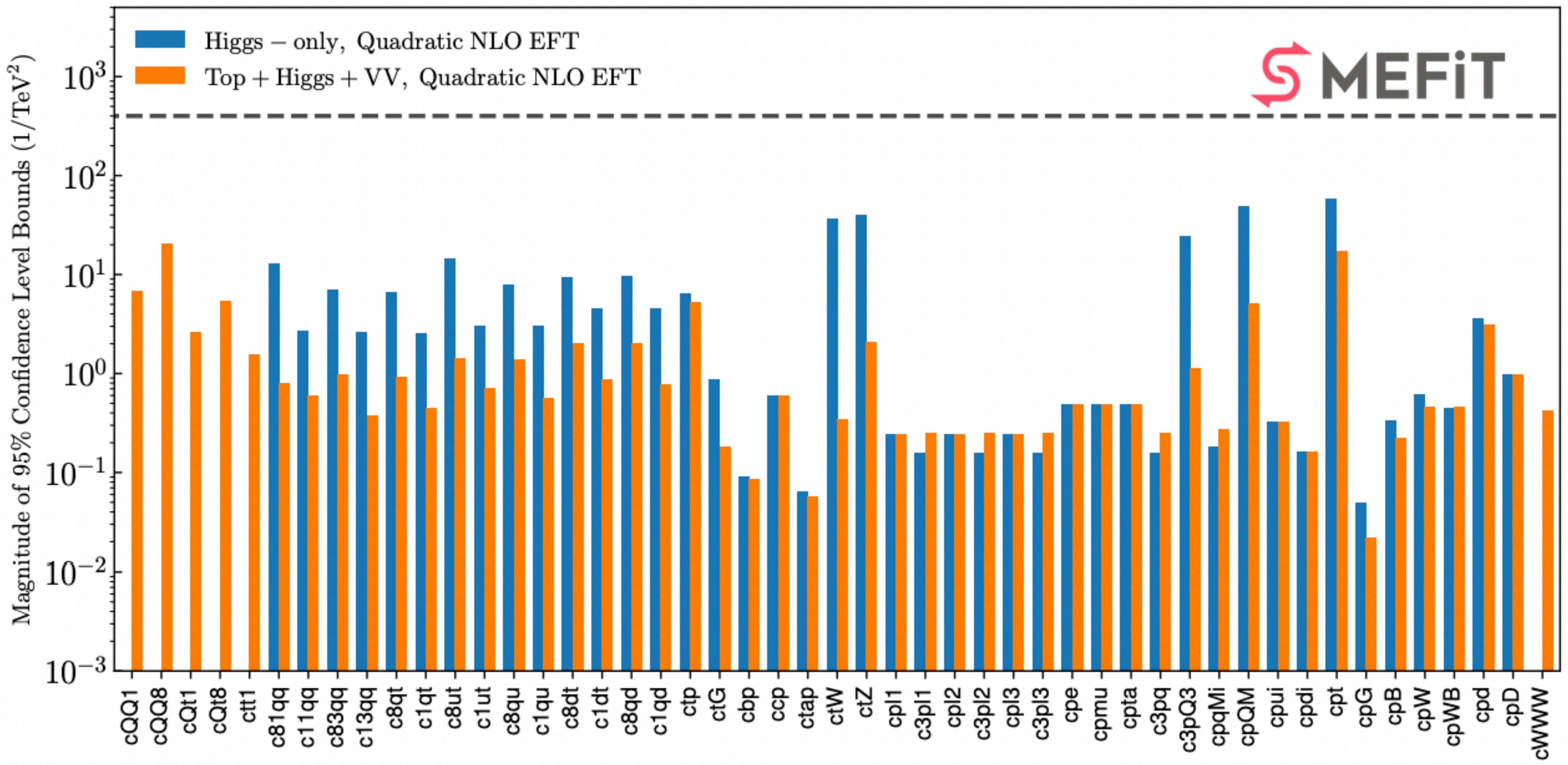
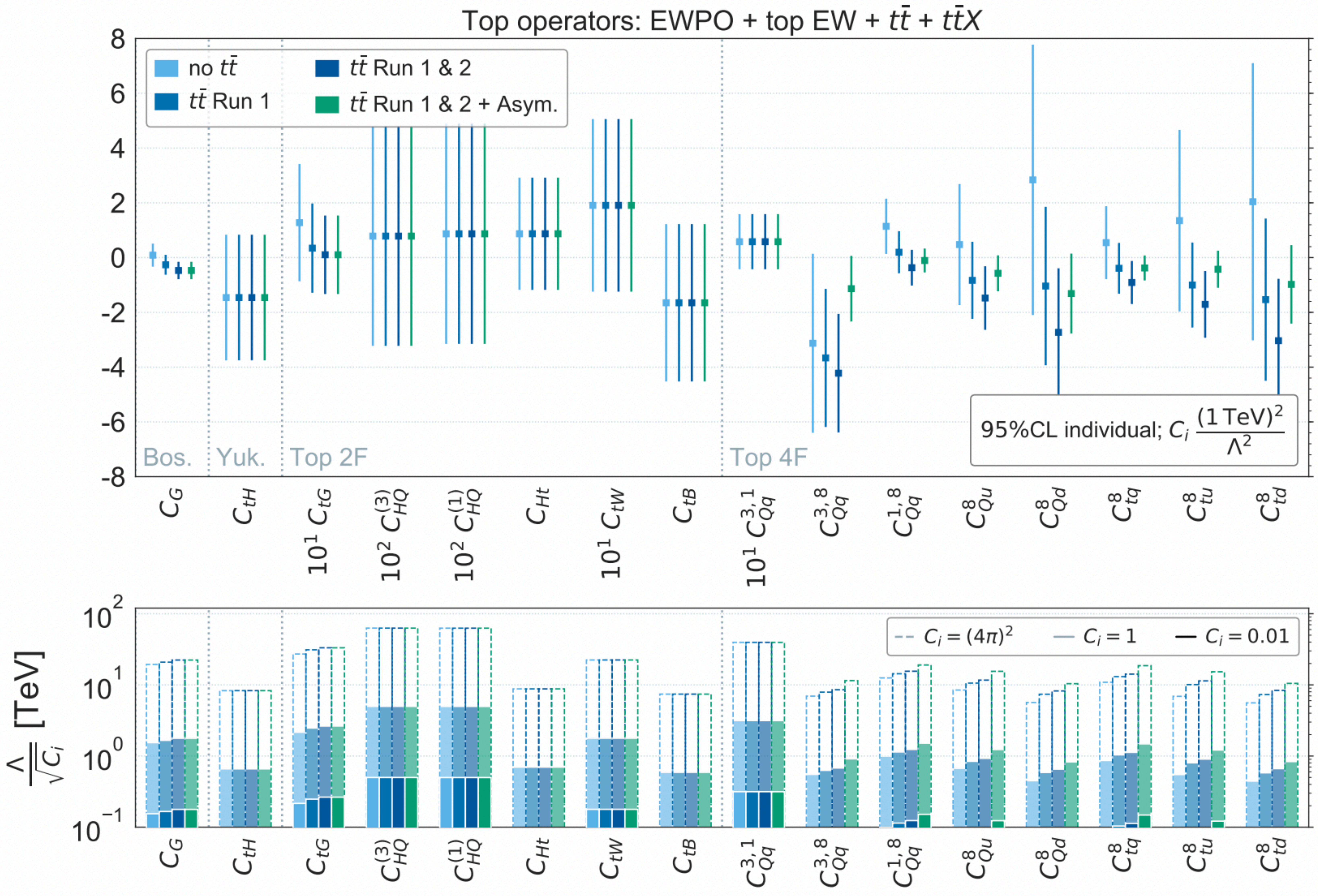
- Global fit bounds more stringent for all EFT coefficients than either top- or Higgs-only fit
- Cross-talk of the top and Higgs data leads to significant improvement in sensitivity
  - E.g. $c_{\phi t}$ and $c^{(-)}_{\phi Q}$ bounds improved by ~factor 2
- Few operators unconstrained in top-only fit
  - E.g. $c_{\phi G}$
- In a Higgs-only fit a large number of EFT coefficients are poorly constrained
- Gain information in the global fit by breaking degeneracies
  - Sometimes in unexpected directions in the parameter space (such as for $c_{\phi G}$)





Fitmaker | Global fit

- Global fit using several datasets:
  - LEP+EWPO, Tevatron, LHC Run1, LHC Run 2
- Top-only fit
  - Shows impact of different datasets for individual fits



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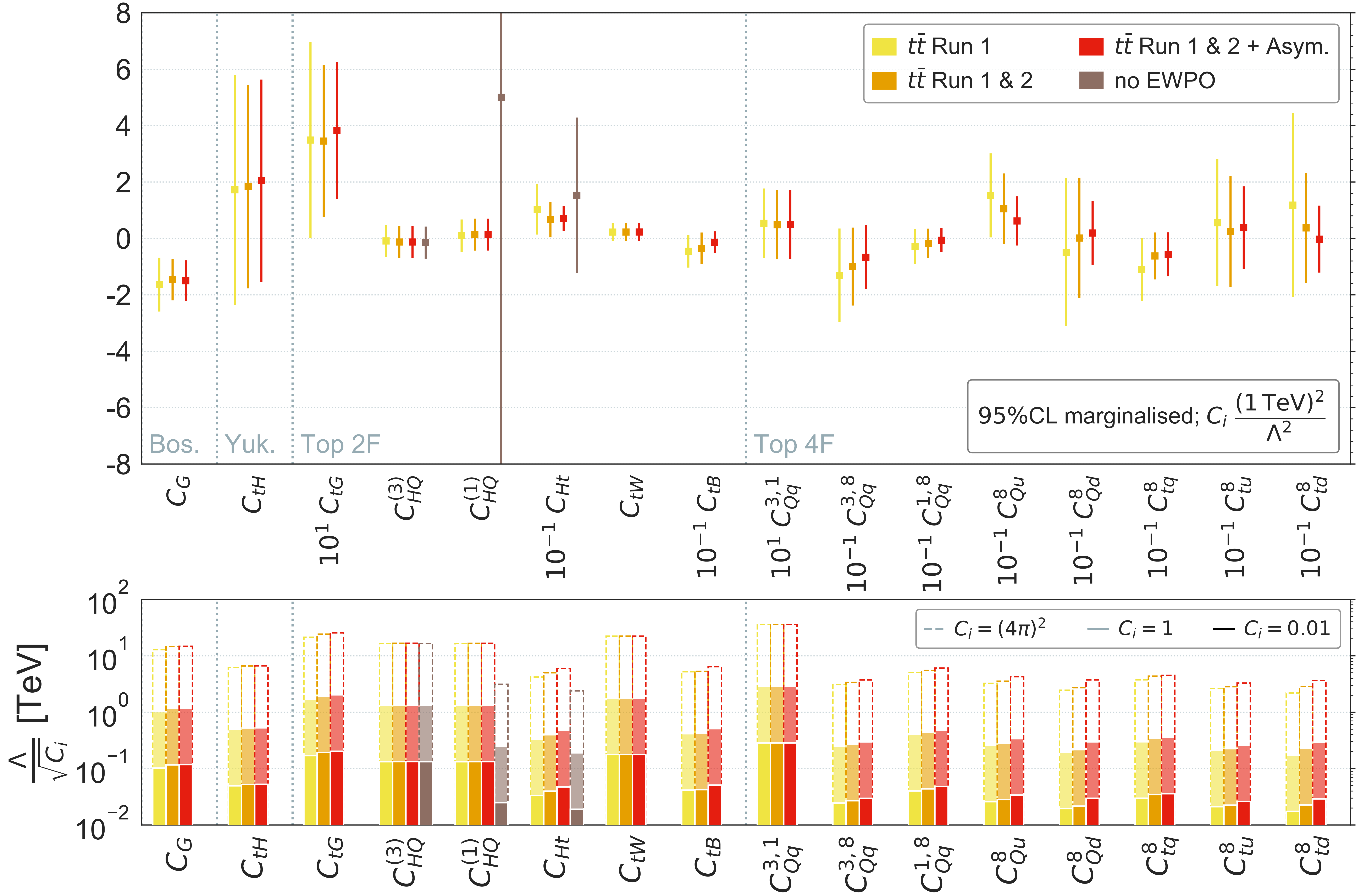
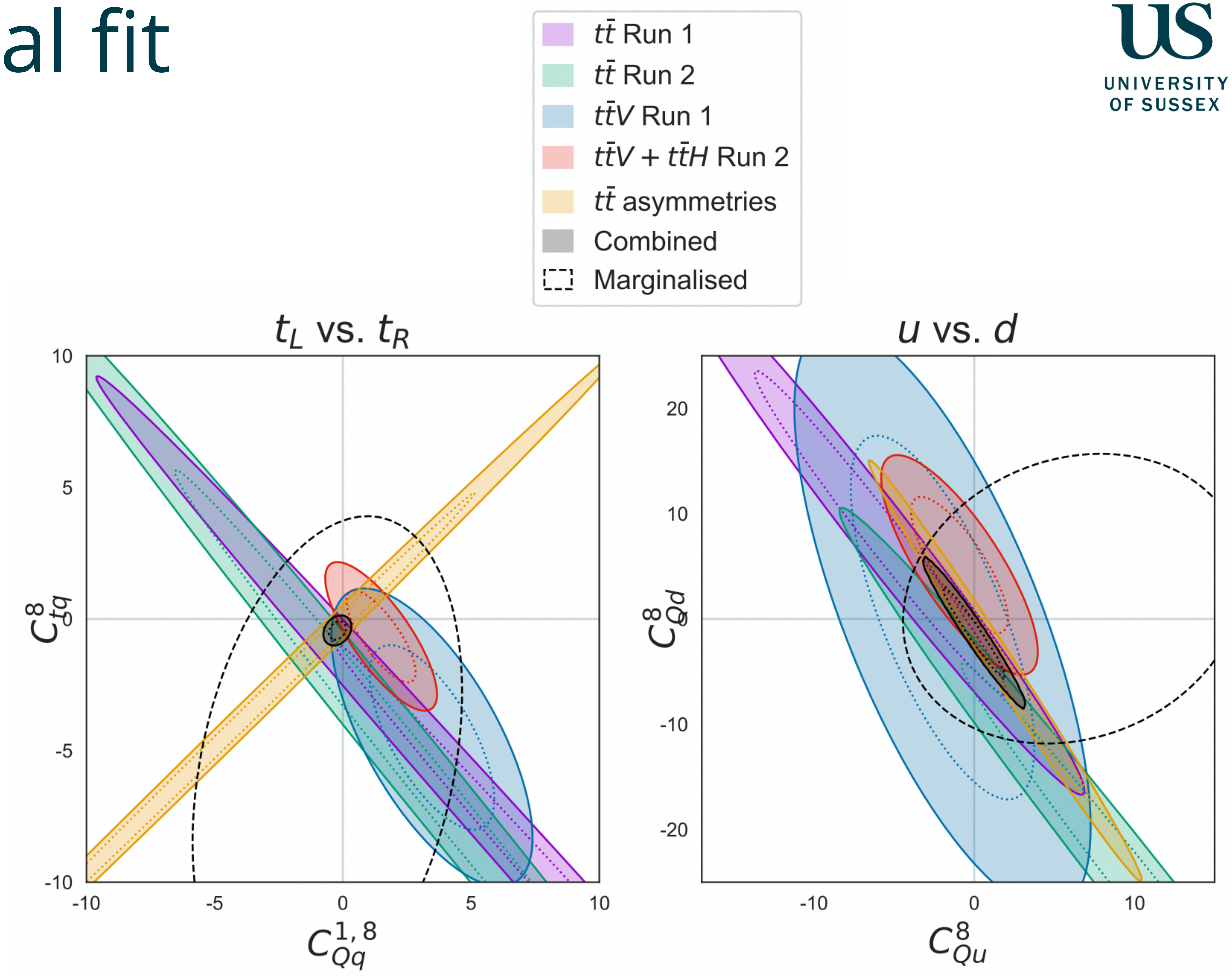
  - Shows impact of different datasets for individual fits
  - Marginalised fit



[arXiv:2012.02779]

Fitmaker | Global fit

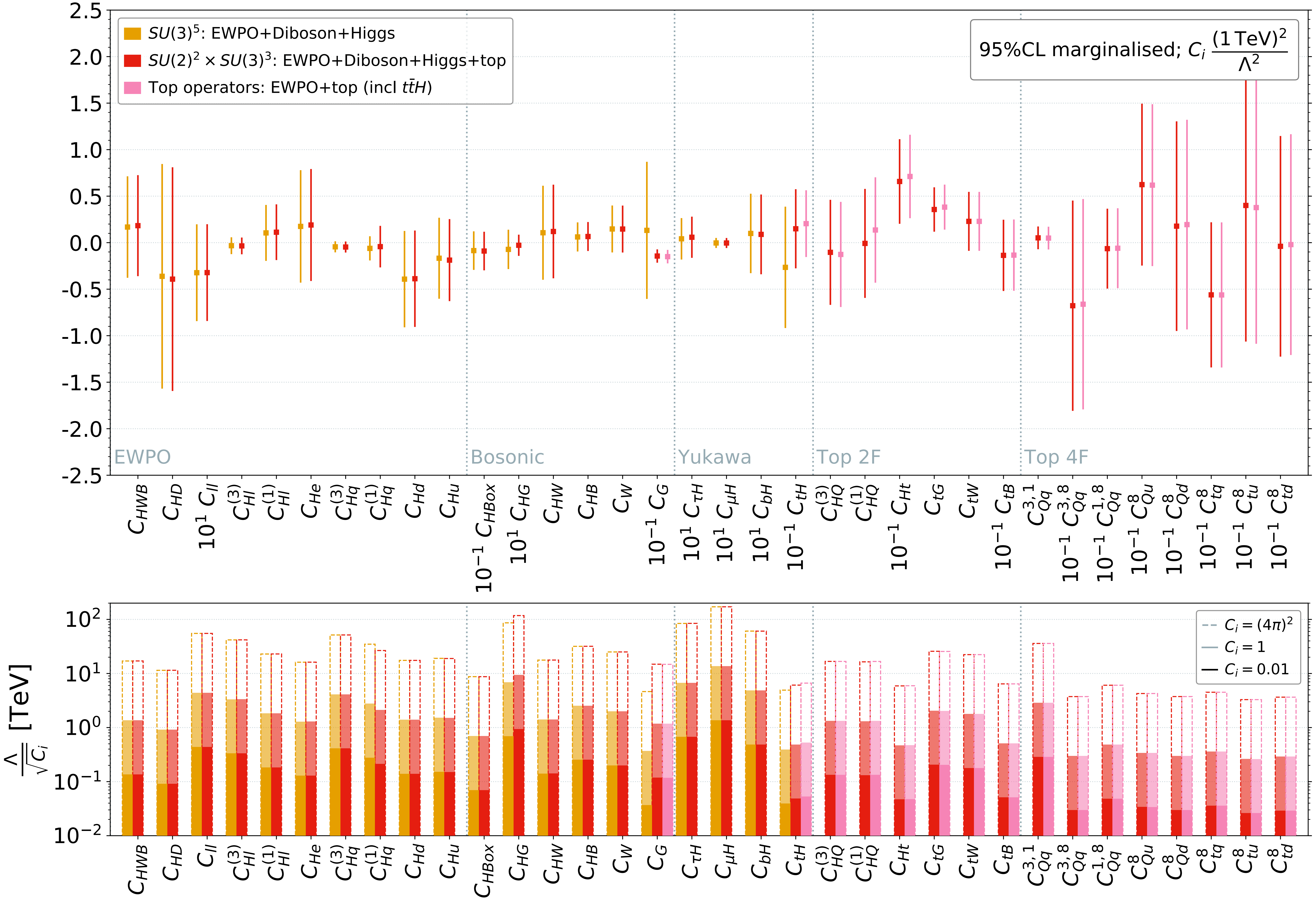
- Global fit using several datasets:
  - LEP+EWPO, Tevatron, LHC Run1, LHC Run 2
- Top-only fit
  - Shows impact of different datasets for individual fits
  - Marginalised fit
  - Detailed impact of different measurements to constrain fit directions for some operators



[arXiv:2012.02779]

Fitmaker | Global fit

- Global fit
  - Shows impact of different datasets
    - **All data except top**
    - **Full global fit**
    - **Top data alone**



- In some cases worsened sensitivity
  - More freedom in the fit

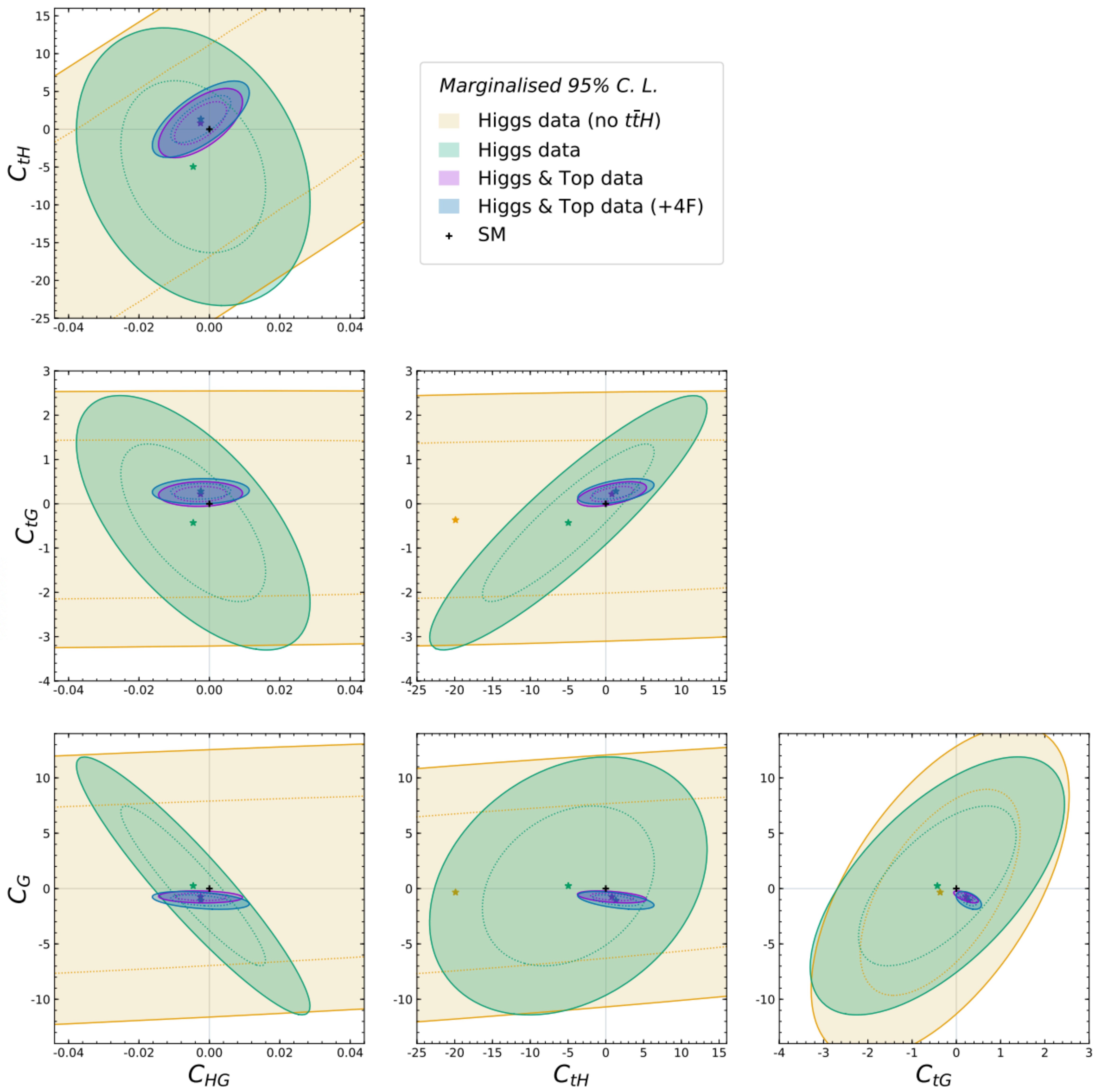
[arXiv:2012.02779]

Fitmaker | Global fit

- Some correlations between Top vs Higgs and EWKPO observables.
- Interesting to see e.g. Higgs and Top complementarity
- Fit to subset of operators:

$$\{C_{H\Box}, C_{HG}, C_{HW}, C_{HB}, C_{tH}, C_{bH}, C_{\tau H}, C_{\mu H}\, C_G \text{ and } C_{tG}\}$$

  - Effect of including both Higgs and top data clearly reduces the allowed parameter space and reduces correlations

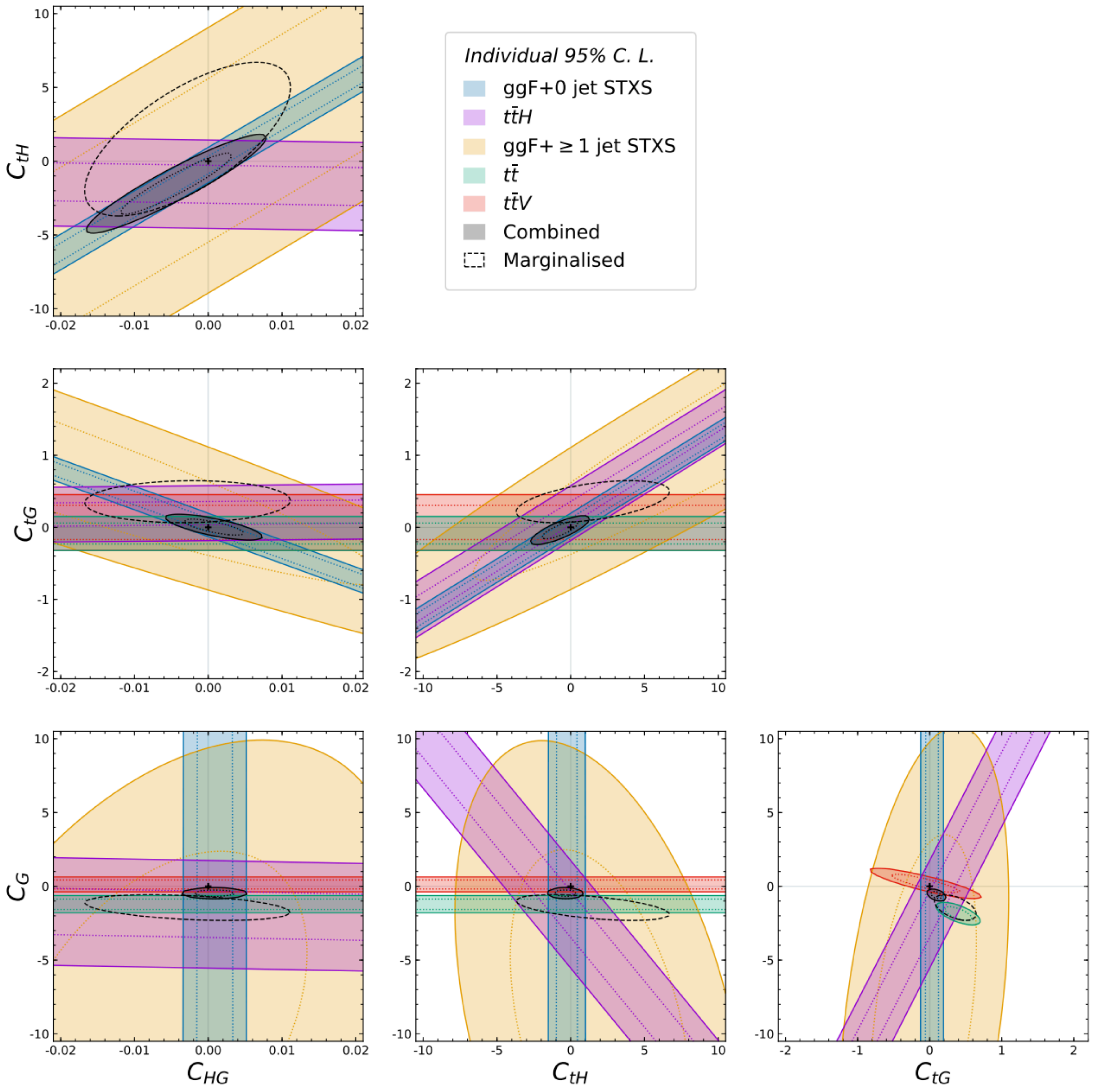


[arXiv:2012.02779]

Fitmaker | Global fit

- Some correlations between Top vs Higgs and EWKPO observables.
- Interesting to see e.g. Higgs and Top complementarity

- Fit only 2 operators at a time:
  - 2D fits show what is driving the marginalised constraints
  - Shows contribution of individual measurements
  - STXS on its own not yet very sensitive
  - **Including top data helps a lot**



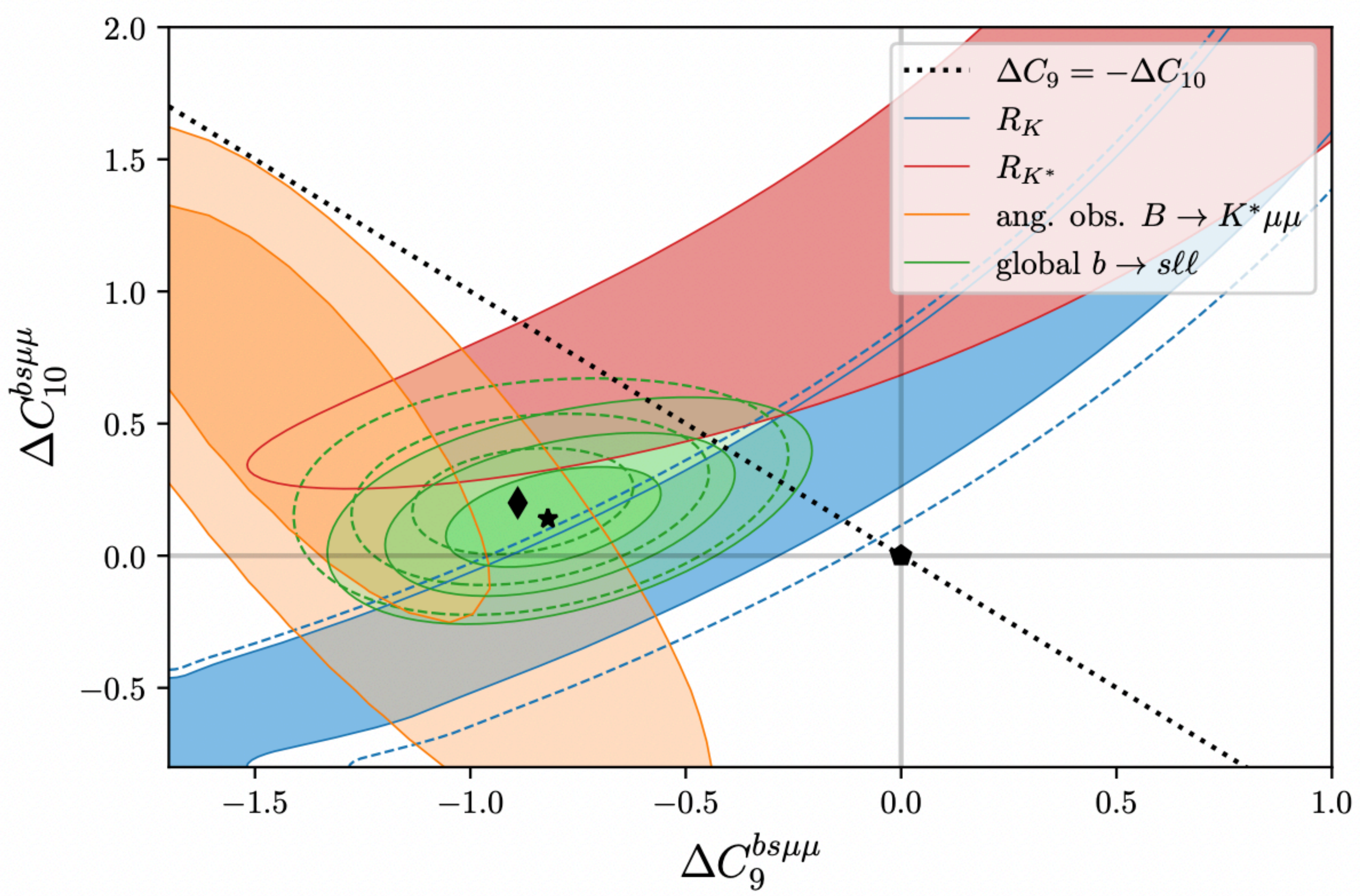
[arXiv:2012.02779]

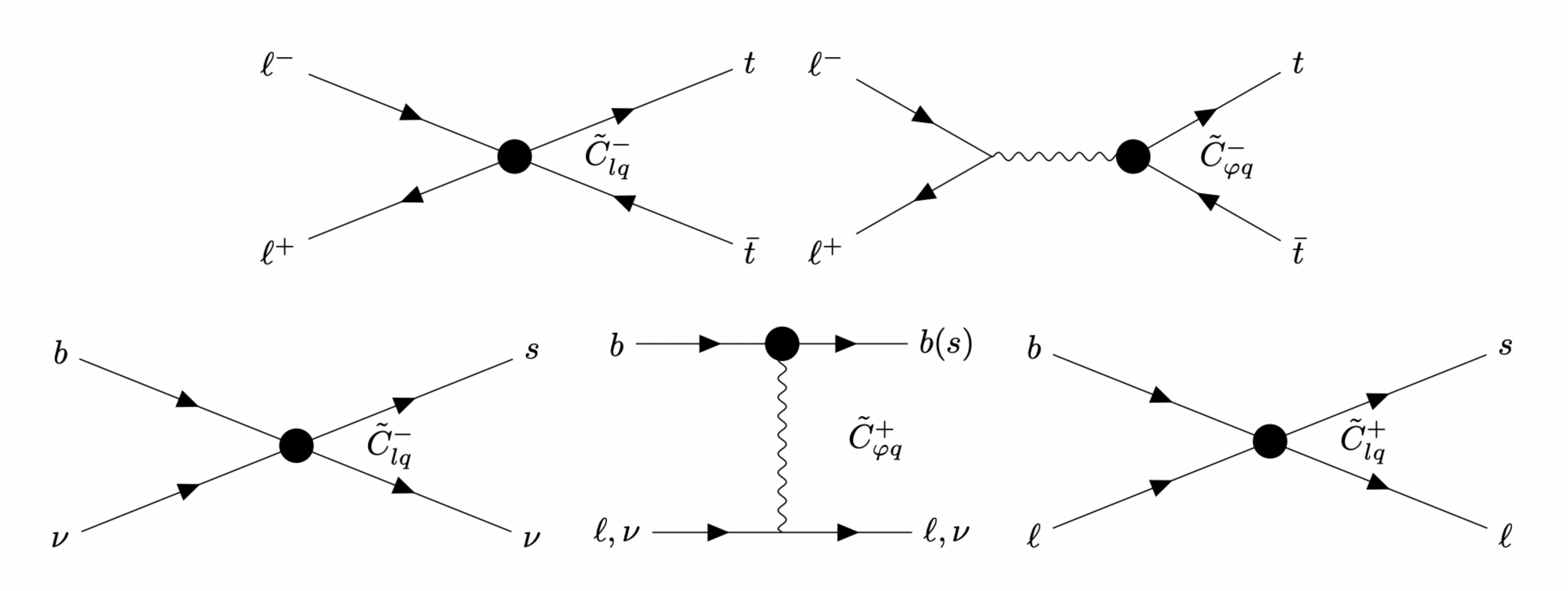
Link to B-anomalies

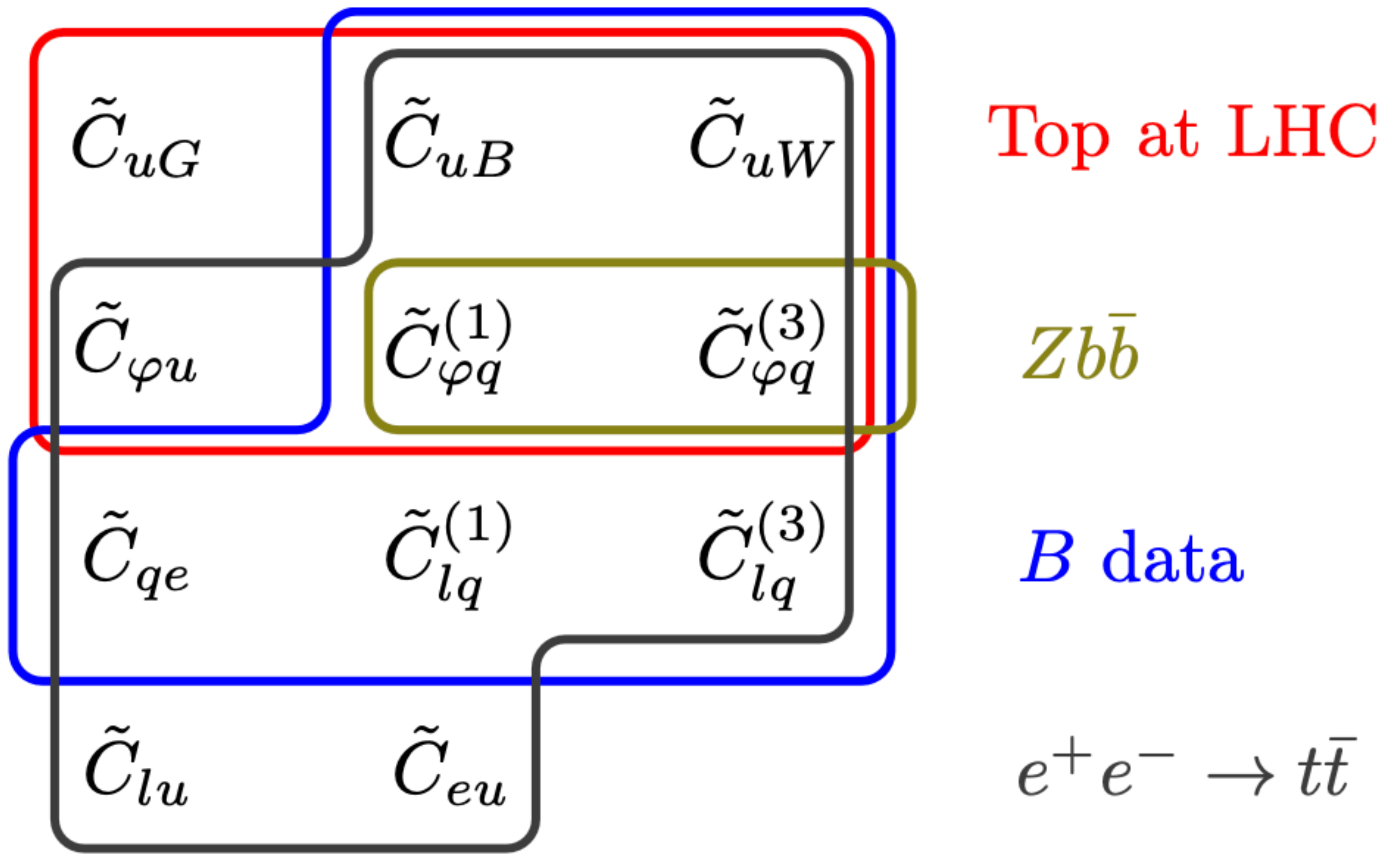
- EFT already used in interpretation of B-anomalies
- Links between b and top:
  - B-anomalies require NP in semileptonic 4-fermion operators
  - Can also use SMEFT to include tops:

$$\bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L \quad \Rightarrow \quad \begin{aligned} O_{lq}^{(1)} &= \bar{Q}\gamma_\mu Q \bar{L}\gamma^\mu L, \\ O_{lq}^{(3)} &= \bar{Q}\gamma_\mu \tau^I Q \bar{L}\gamma^\mu \tau^I L \end{aligned}$$

[2104.00015]







[2012.10456]

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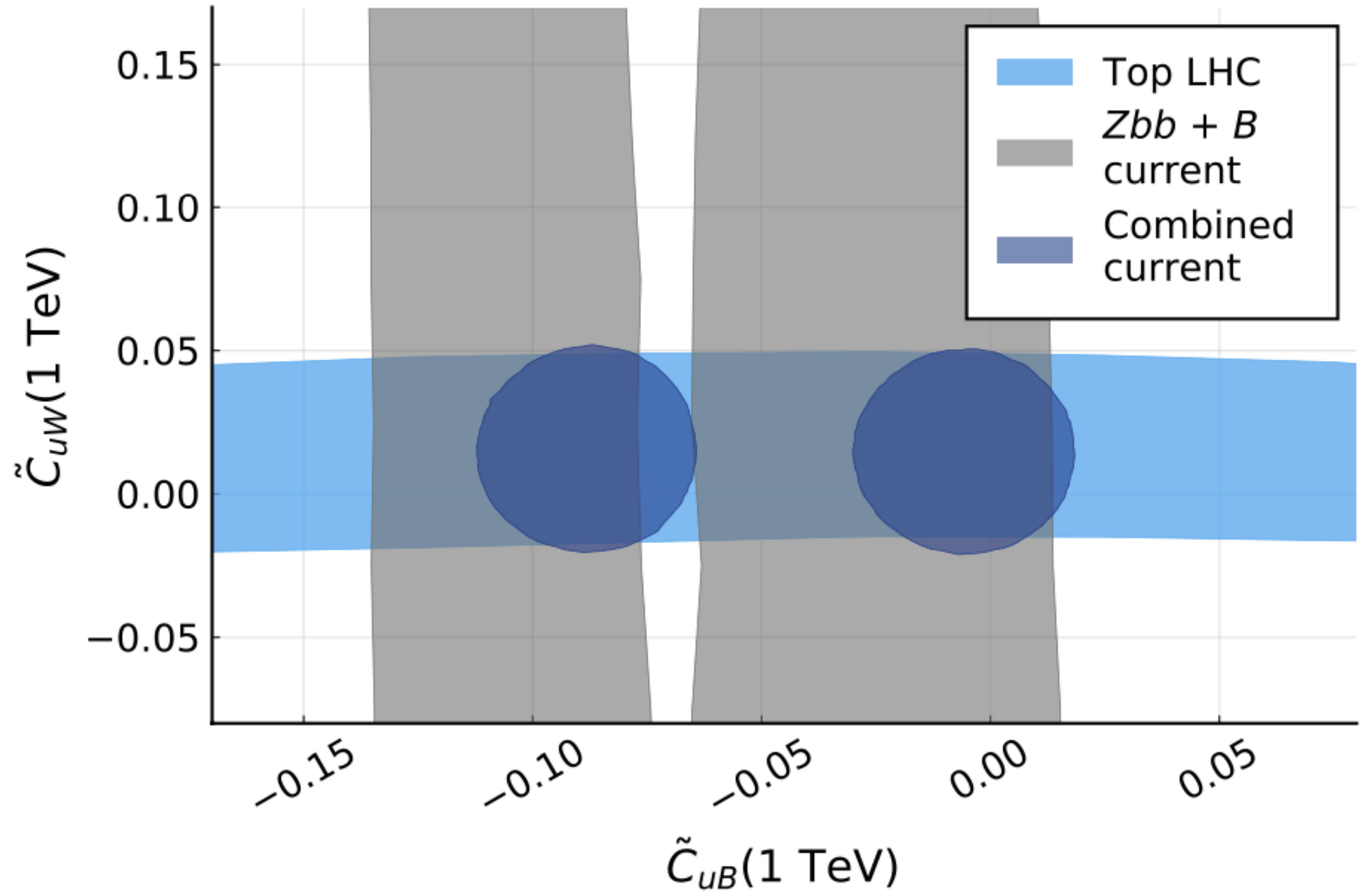
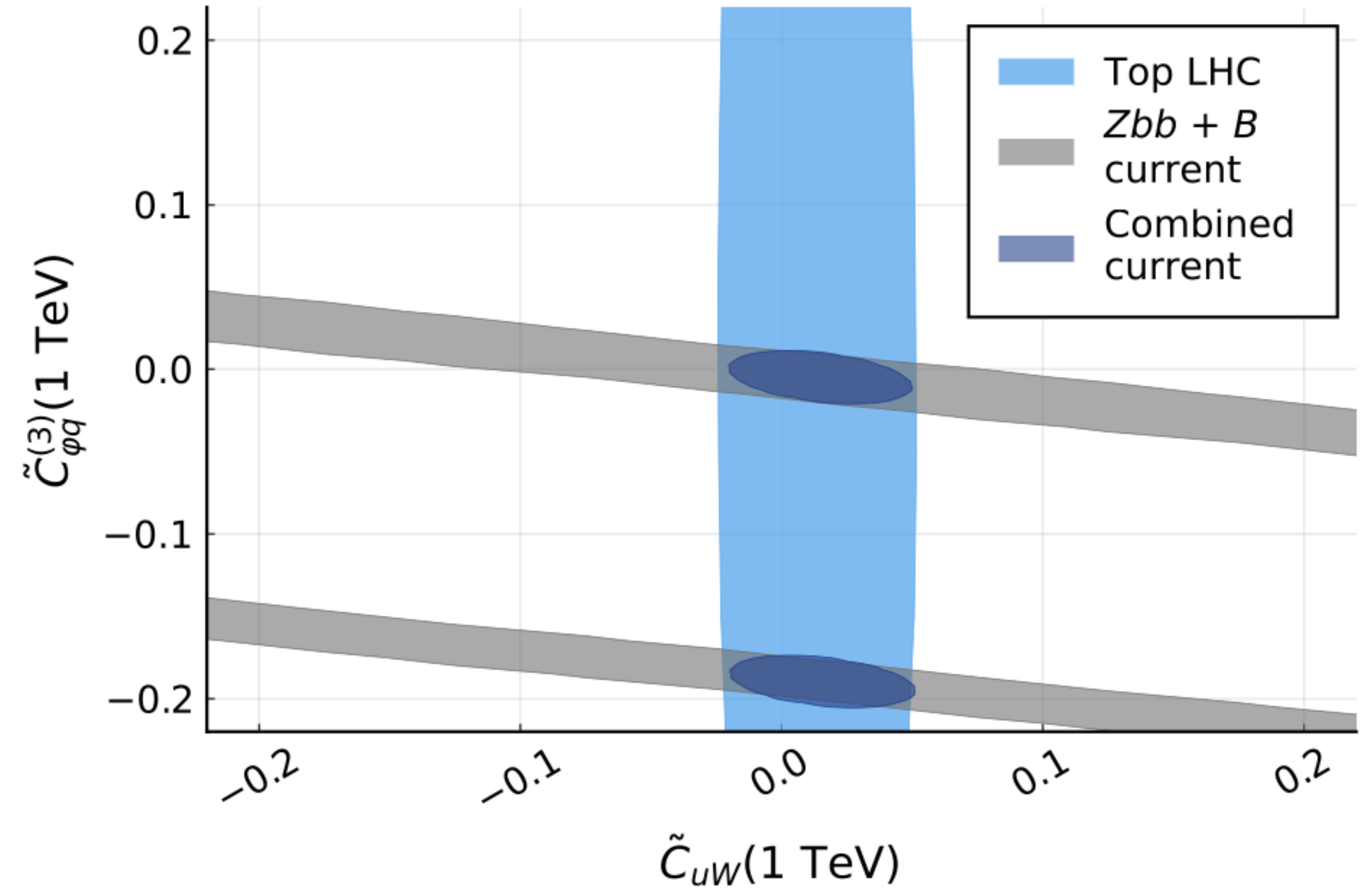
- Top data particularly complementary wrt B + Zbb for some coefficients





[2012.10456]

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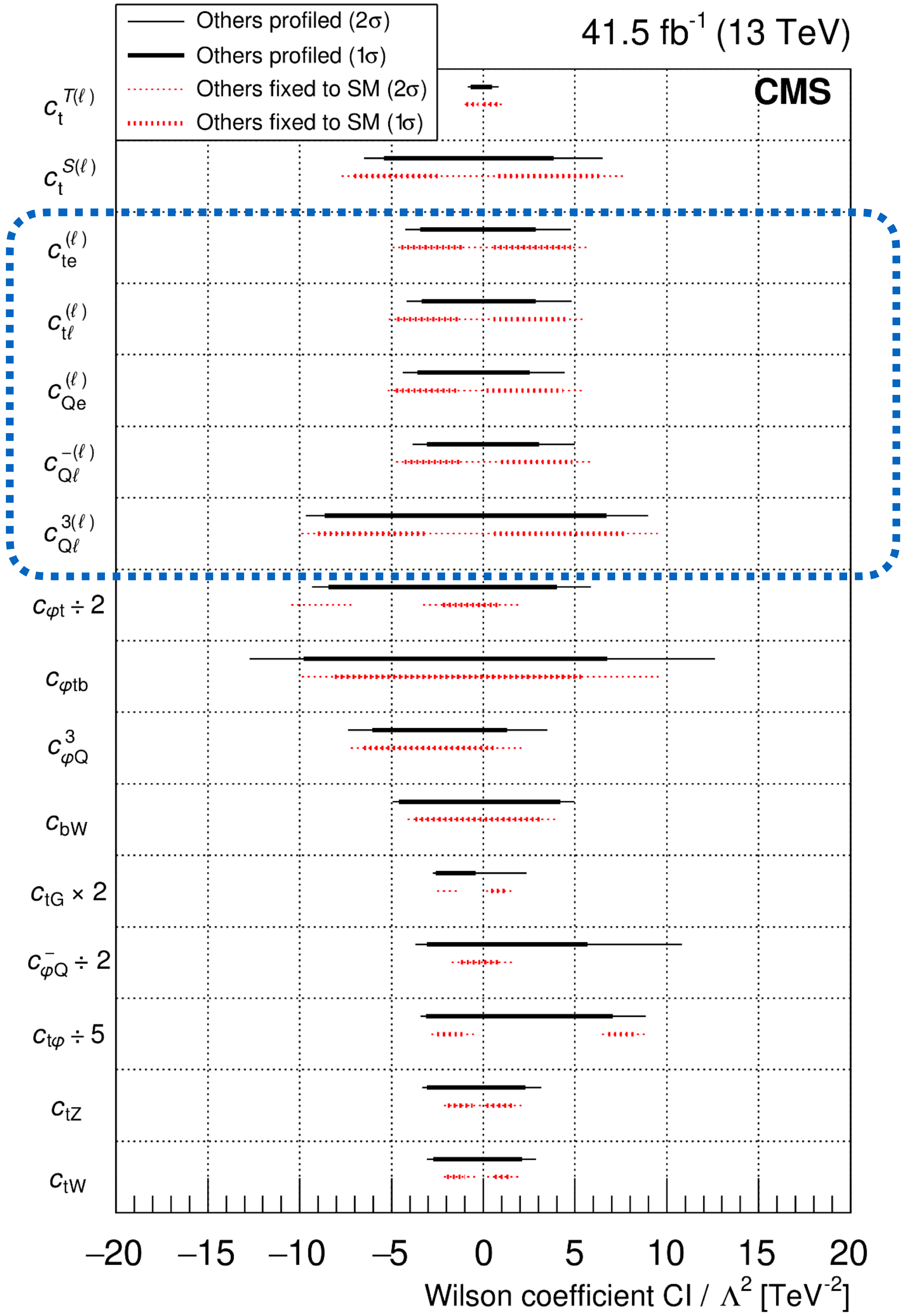
- CMS Top+X fit already gives constraints on semileptonic four-fermion operators



[TOP-19-001]

Link to B-anomalies

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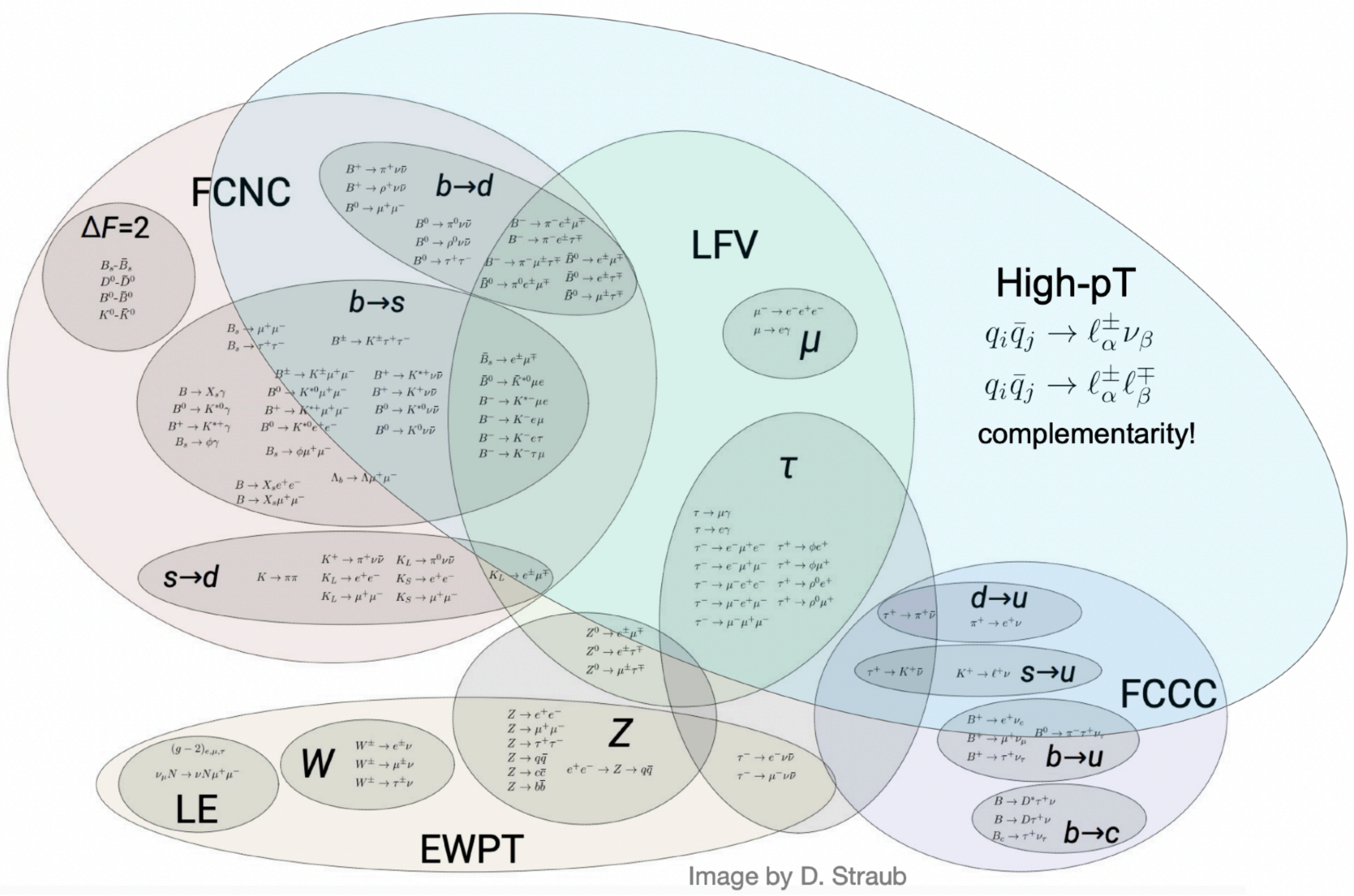

- Top data particularly complementary wrt B + Zbb for some coefficients
- CMS Top+X fit already gives constraints on semileptonic four-fermion operators
- Need agreement on EFT flavour assumptions: [LHC EFT WG Meeting]

Global fit from experiments

- What about global fits from the experiments?
- Global *"Top+X"* fit seem from CMS already
- ATLAS has started looking at first steps to a global EFT fit including Higgs, EW and EW precision measurements
  - Builds on previous efforts to perform fits with multiple datasets (e.g. [ATL-PHYS-PUB-2021-010])
  - Adds LEP and SLC EW precision data for the first time
- LHC Top WG combining ATLAS+CMS data
- LHC EFT WG combining ATLAS+CMS+LEP
  - Including Top data

Wilson coefficient and operator		Affected process group: LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		✓	
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$		✓	✓
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$		✓	✓
c_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$		✓	✓
c_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$		✓	
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$		✓	
c_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$		✓	
c_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	✓	✓	✓
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$		✓	
c_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u\widetilde{H})$		✓	
c_{tH}	$(H^\dagger H)(\bar{Q}\widetilde{H}t)$		✓	
c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$		✓	
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	✓	✓	✓
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}\tau^I\gamma^\mu l)$	✓	✓	✓
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	✓	✓	✓
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	✓	✓	✓
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)$	✓	✓	✓
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	✓	✓	✓
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	✓	✓	✓
$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	✓	✓	
$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{Q}\tau^I\gamma^\mu Q)$	✓	✓	
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	✓		
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	✓	✓	
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\, G_{\mu\nu}^A$		✓	
c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\widetilde{H}\, W_{\mu\nu}^I$		✓	
c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\widetilde{H}\, B_{\mu\nu}$		✓	
c_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	✓		✓

[ATL-PHYS-PUB-2022-037]

ATLAS Global EFT fit

[ATL-PHYS-PUB-2022-037]

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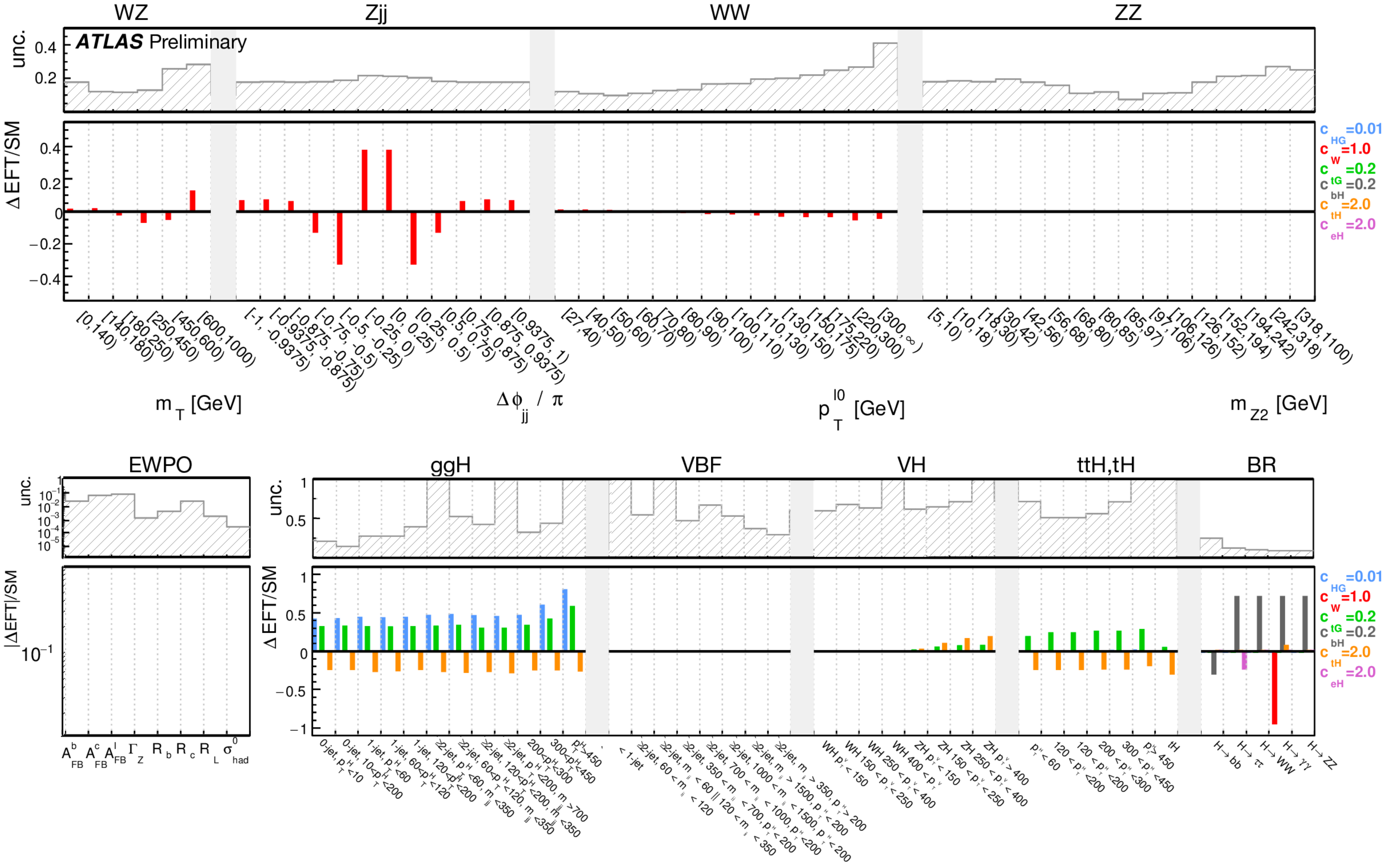
- Sensitivity to numerous EFT operators
- Complementarity between different observables



ATLAS Global EFT fit

[ATL-PHYS-PUB-2022-037]

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- Sensitivity to numerous EFT operators
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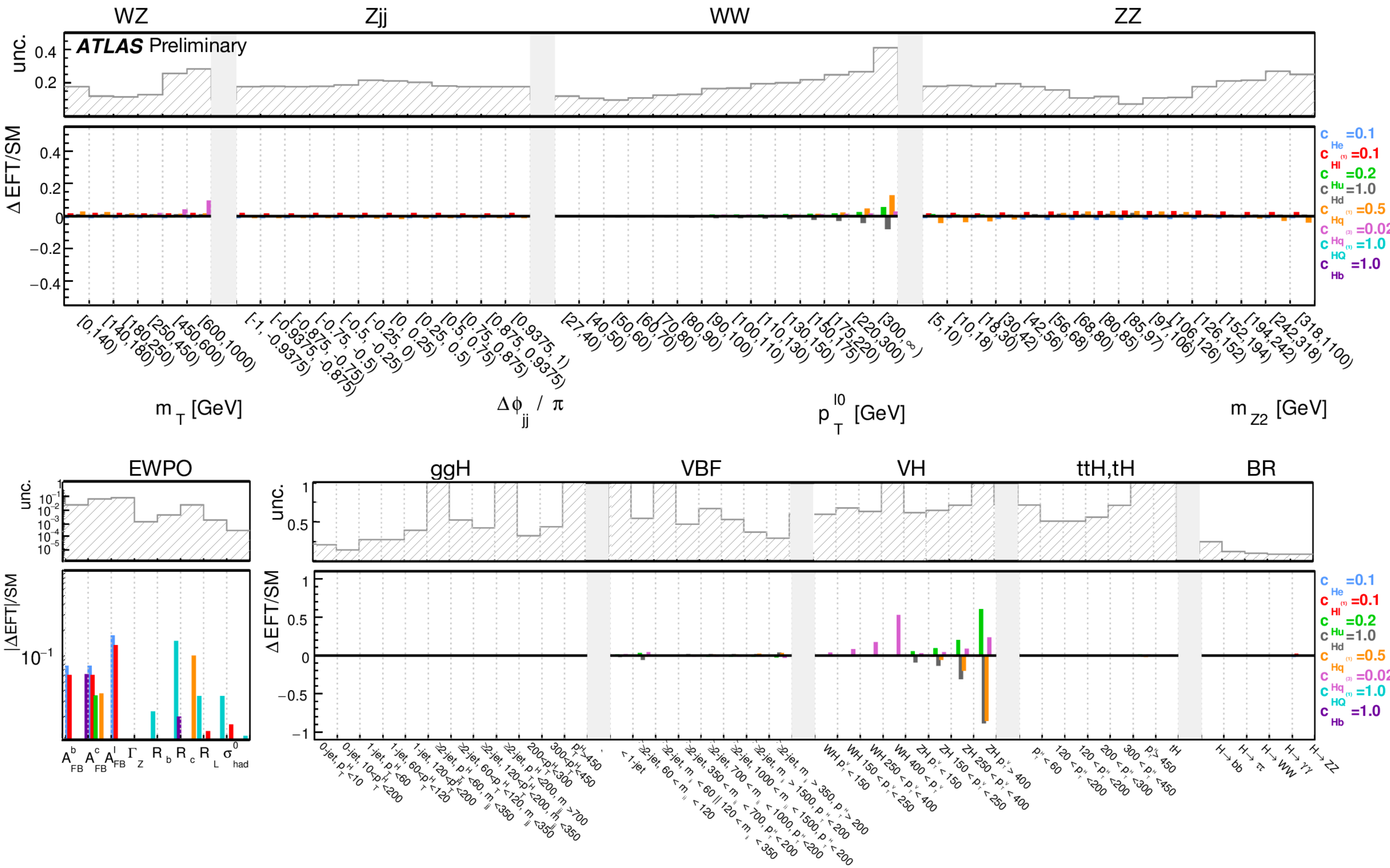

ATLAS Global EFT fit

[ATL-PHYS-PUB-2022-037]

- Sensitivity to numerous EFT operators
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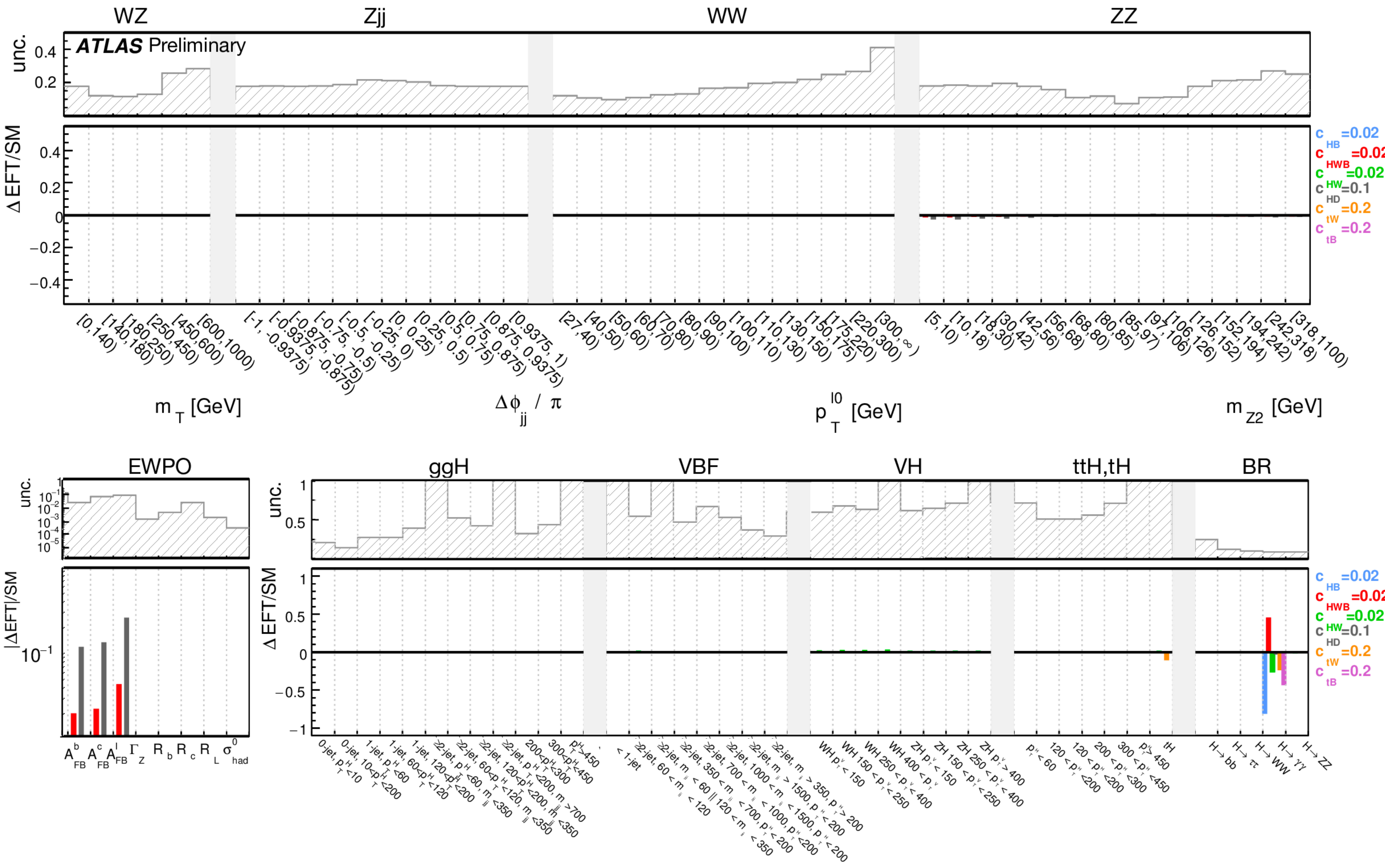
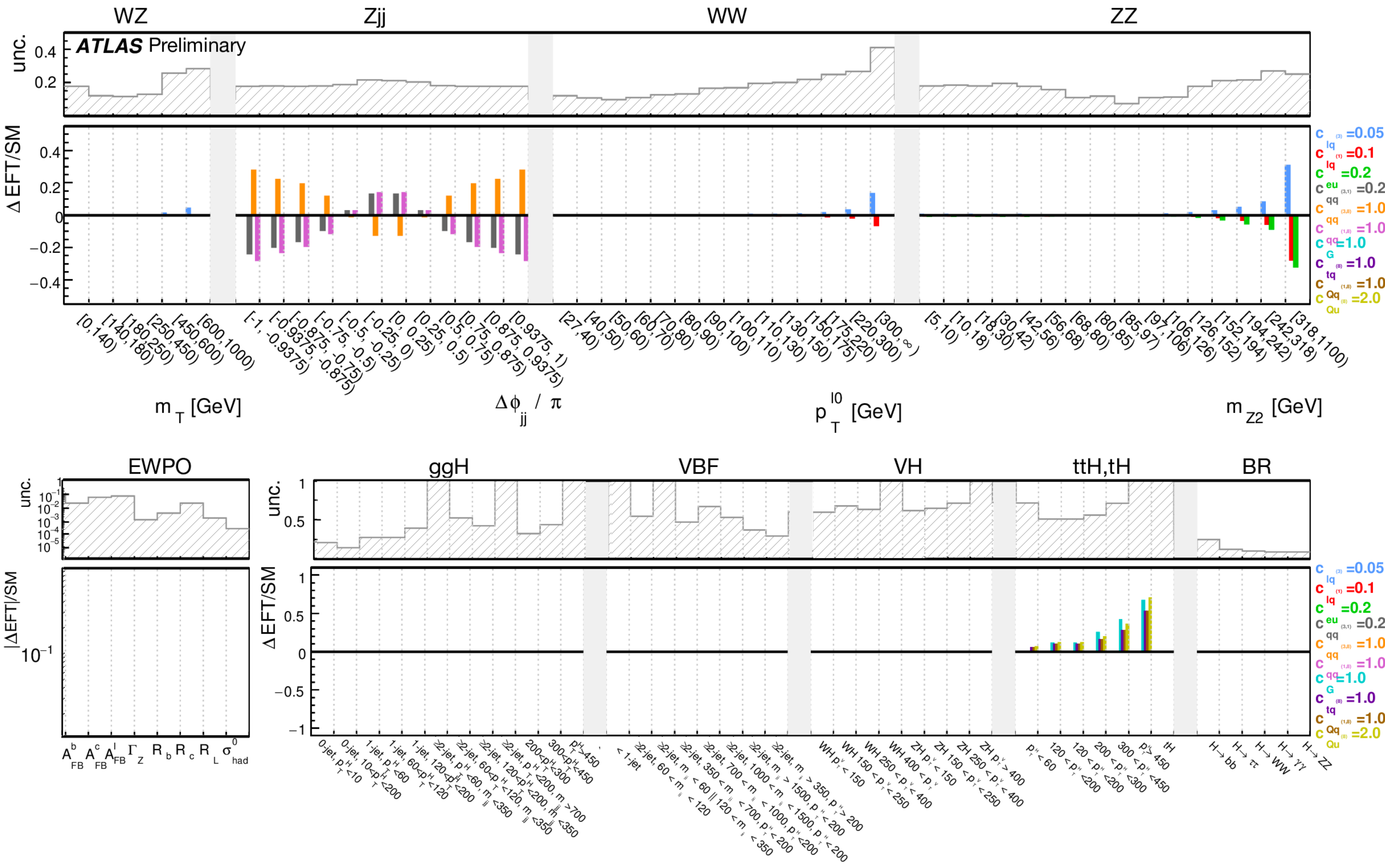


ATLAS Global EFT fit

[ATL-PHYS-PUB-2022-037]

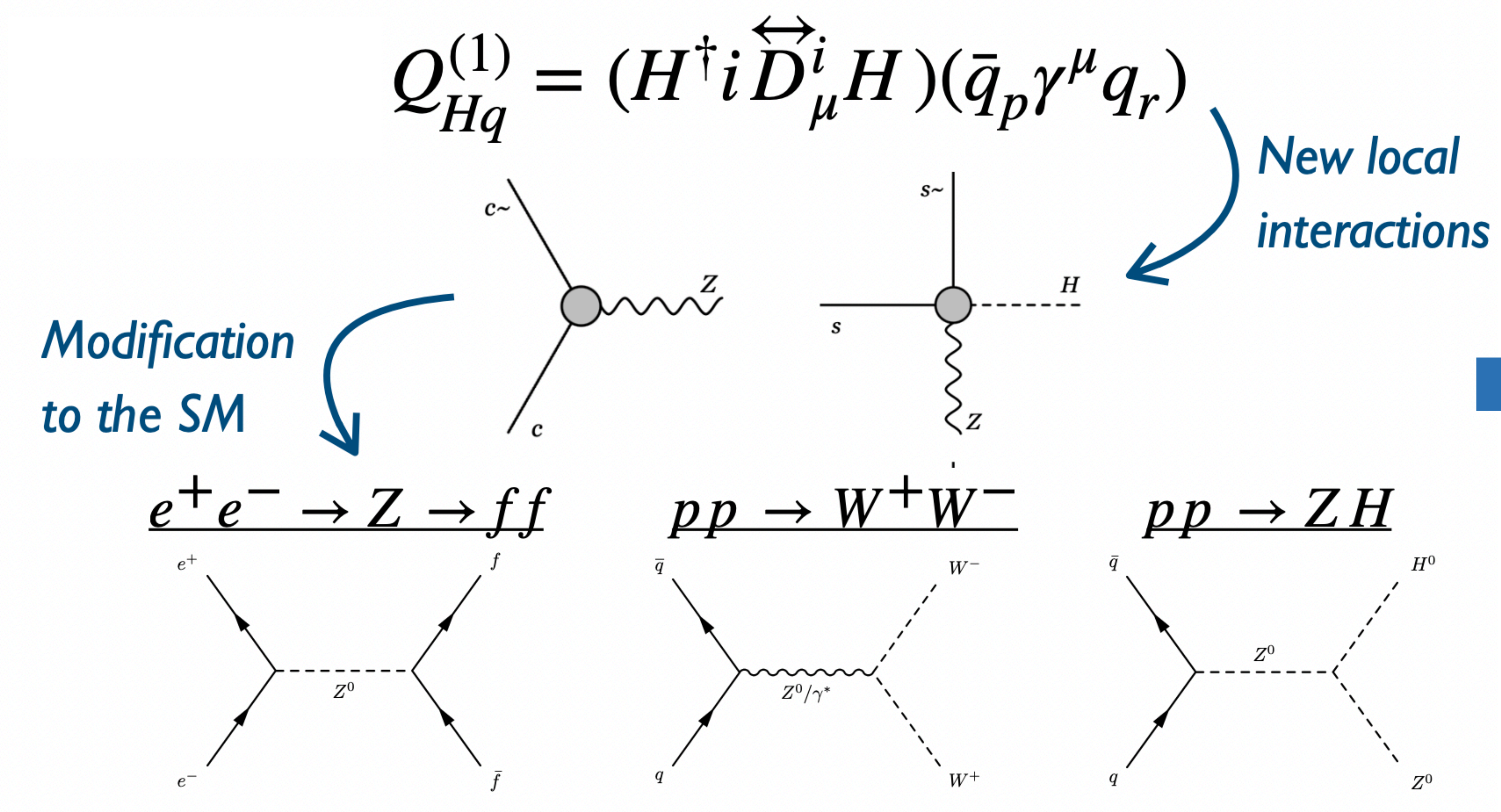
- Sensitivity to numerous EFT operators
- Complementarity between different observables

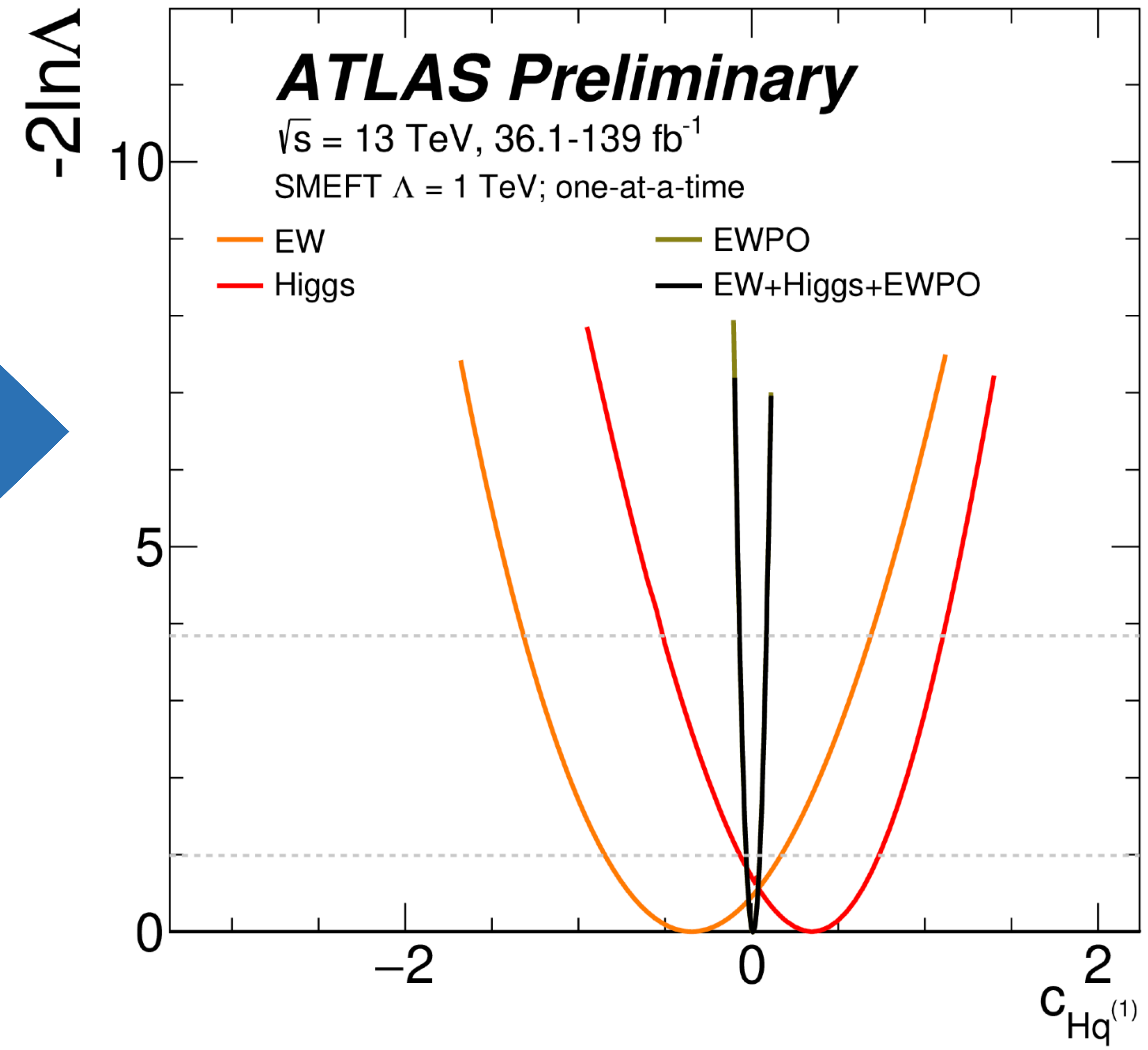


ATLAS Global EFT fit

[ATL-PHYS-PUB-2022-037]

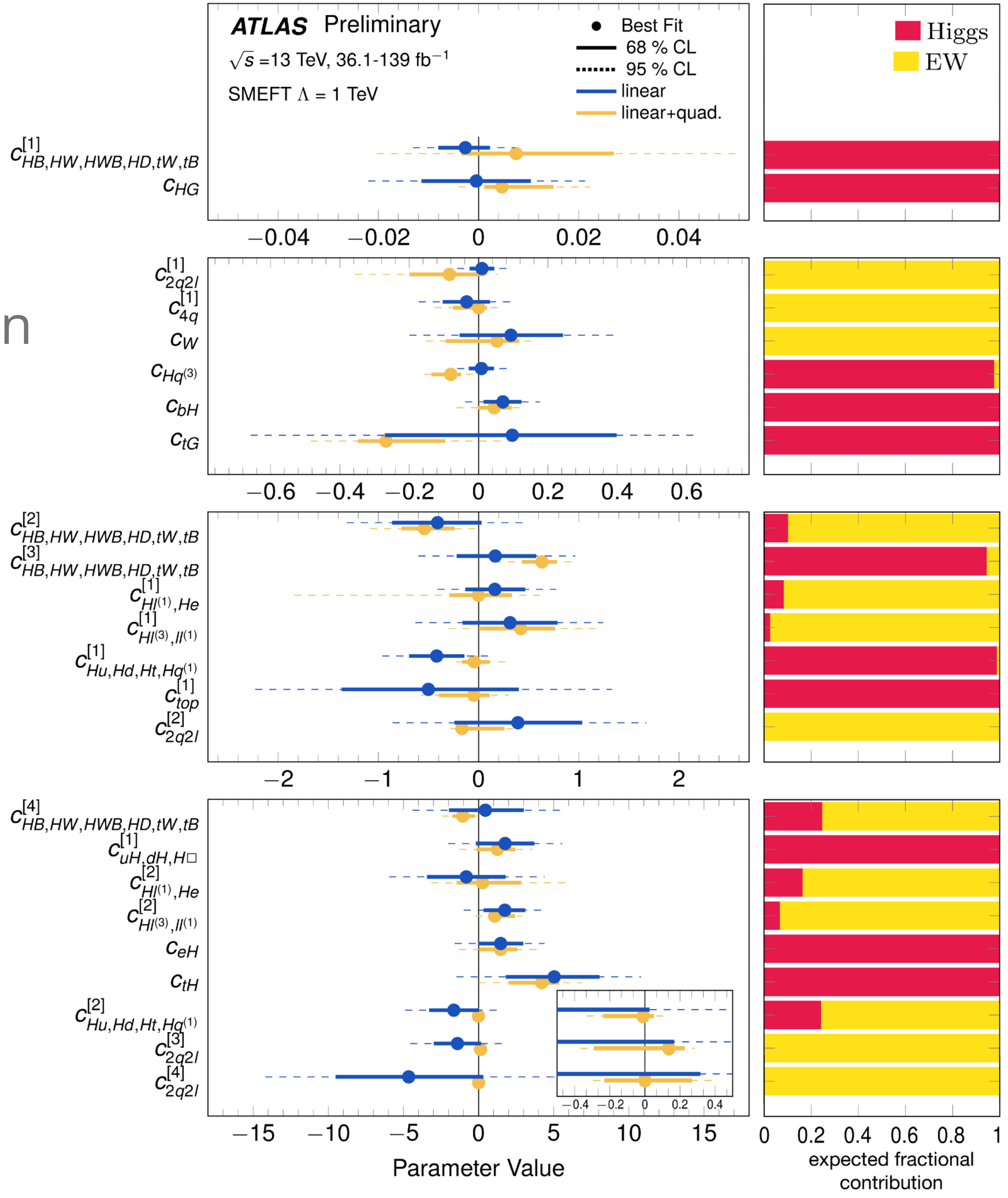
- Single operator fits used to assess impact of different datasets
  - For example O_{Hq}:





ATLAS Global EFT fit

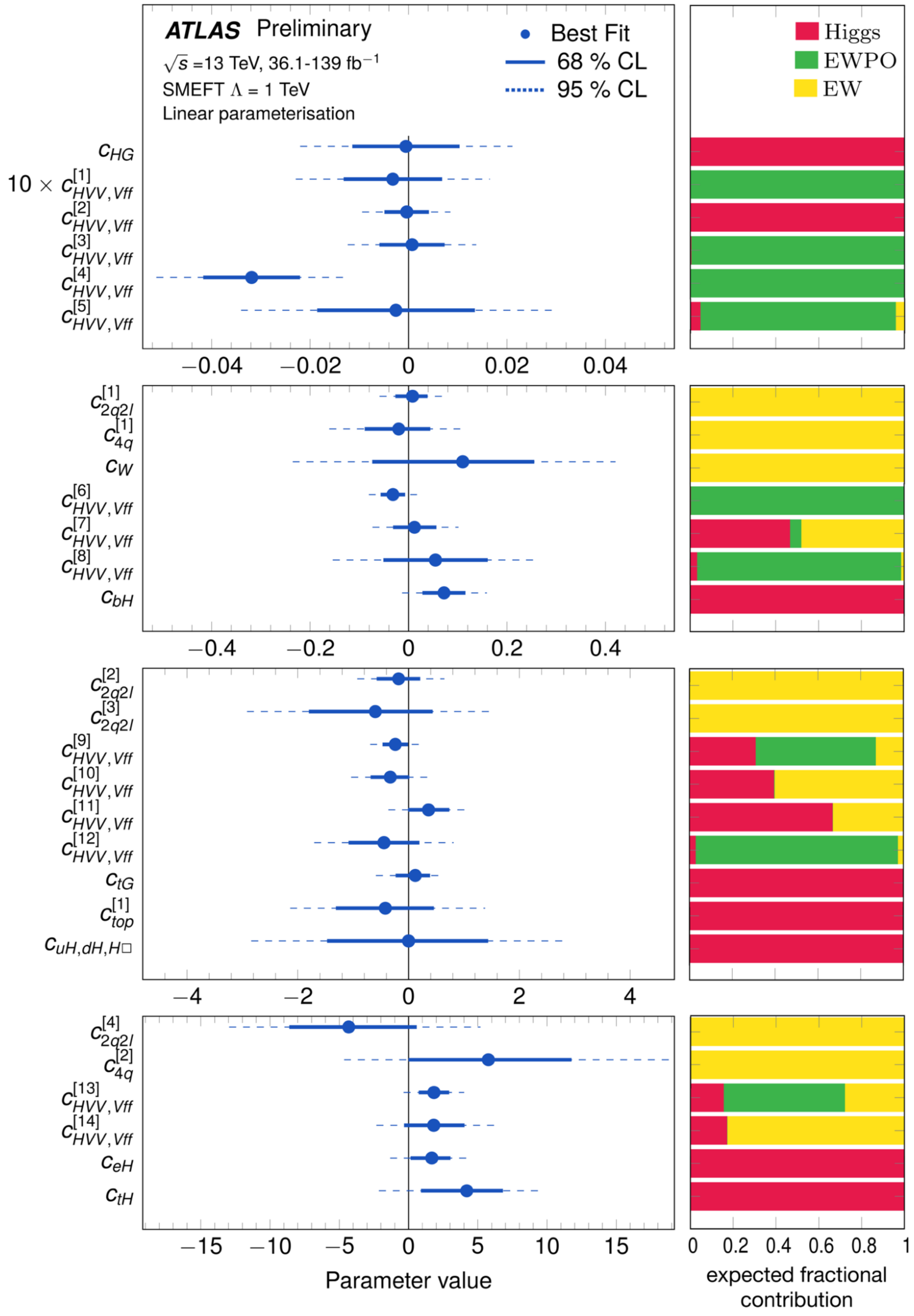
- Start by looking at Higgs+EW fit
  - Linear and quadratic parameterisations
  - Expected contribution to sensitivity shown



[ATL-PHYS-PUB-2022-037]

ATLAS Global EFT fit

- Start by looking at Higgs+EW fit
  - Linear and quadratic parameterisations
  - Expected contribution to sensitivity shown
- Full fit to EWPO+EW+Higgs
  - Results largely compatible with SM
  - σ^0_{had}, $H\rightarrow\gamma\gamma$, Γ_Z, A_{fb}, and $gg\rightarrow H$ giving largest constraints
  - In some cases significant constraints come EWPD with important contributions from VH, VBF Higgs and VV production
    - Contributions of the Higgs and EW measurements expected to become more important with larger datasets

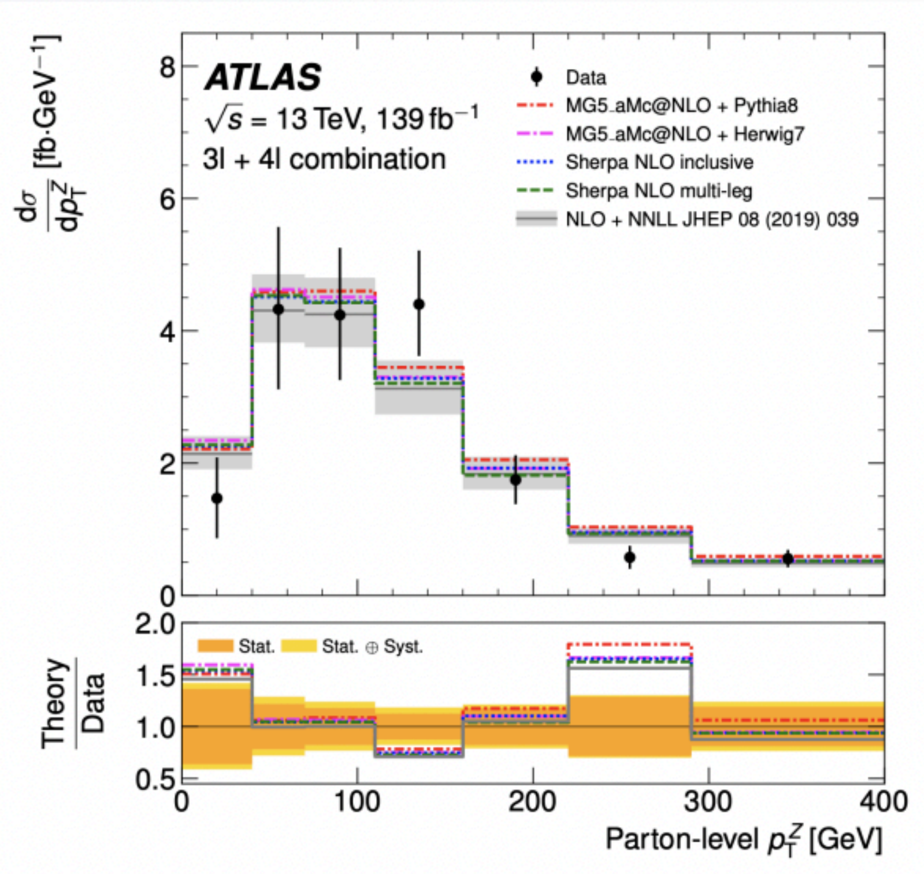
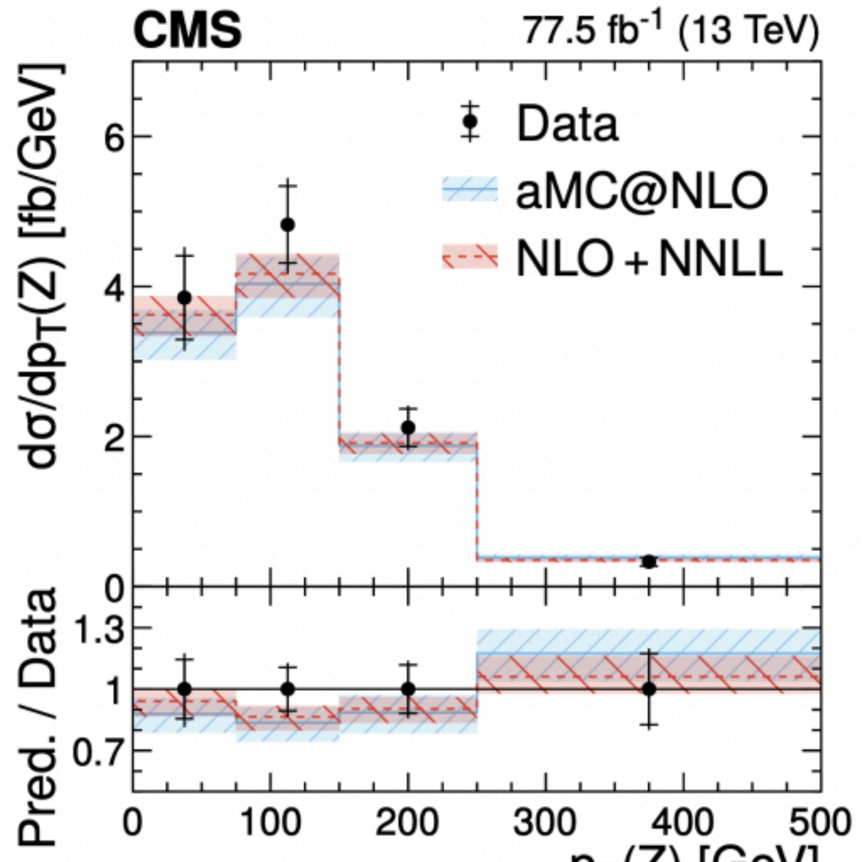
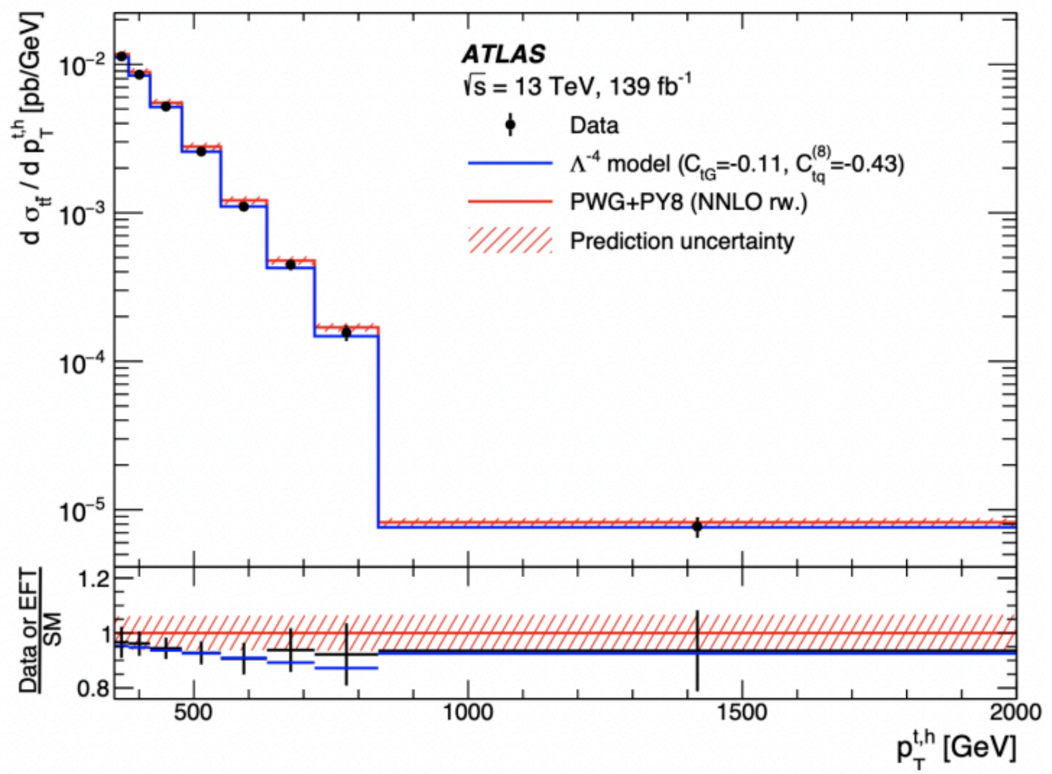
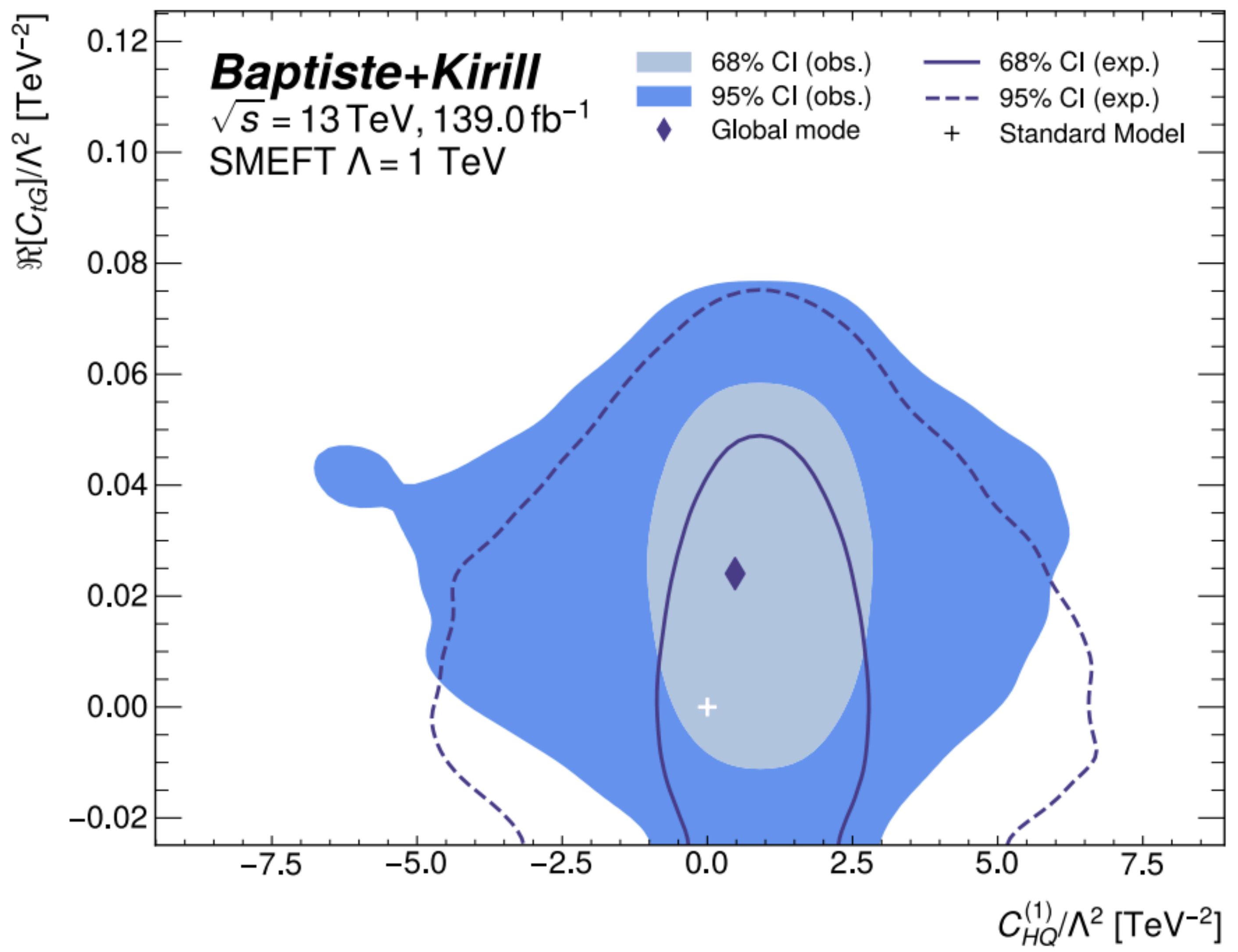
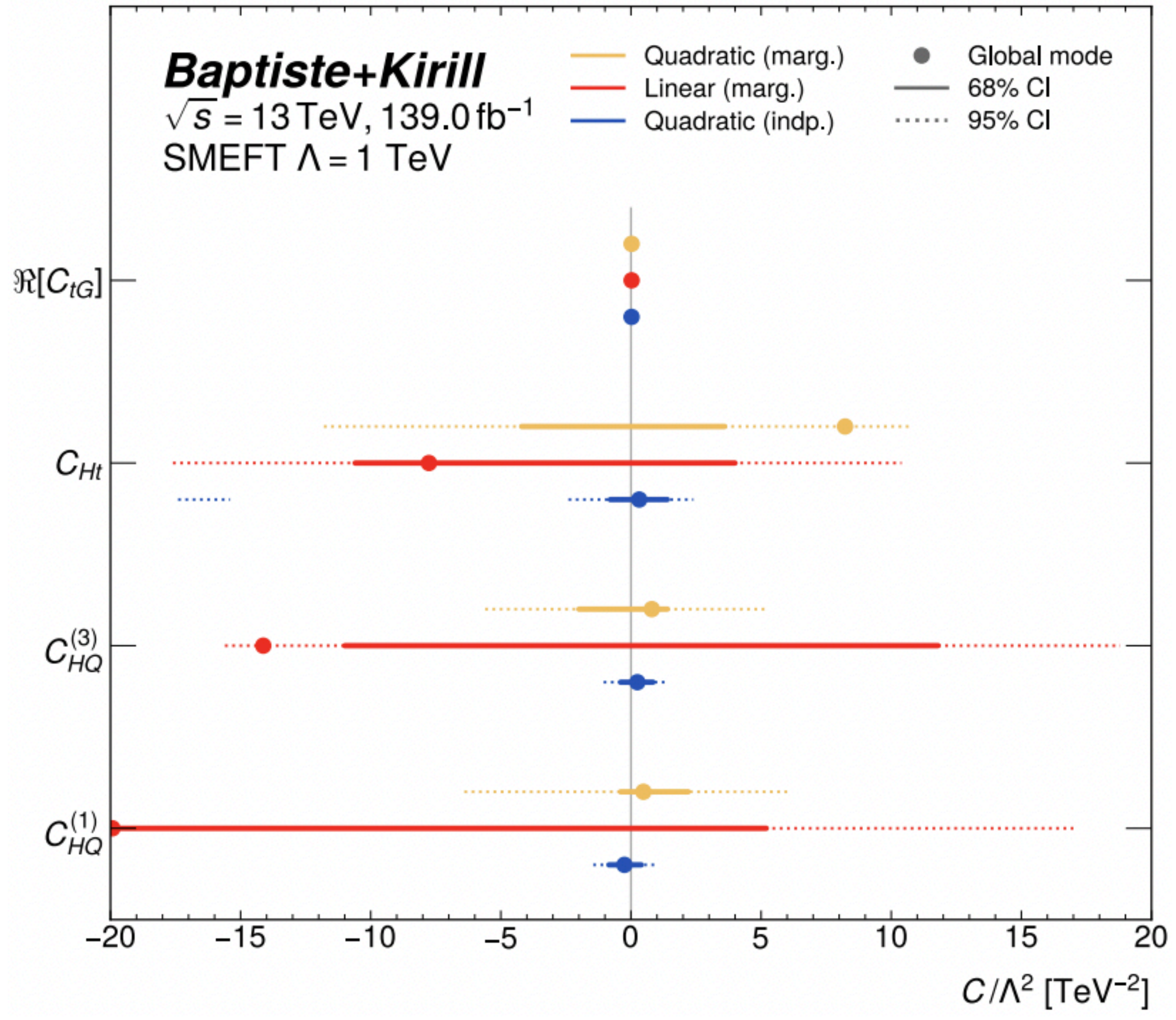


[ATL-PHYS-PUB-2022-037]

LHC Top WG efforts

- ATLAS+CMS combination of top measurements and EFT interpretation

- Using unfolded data:

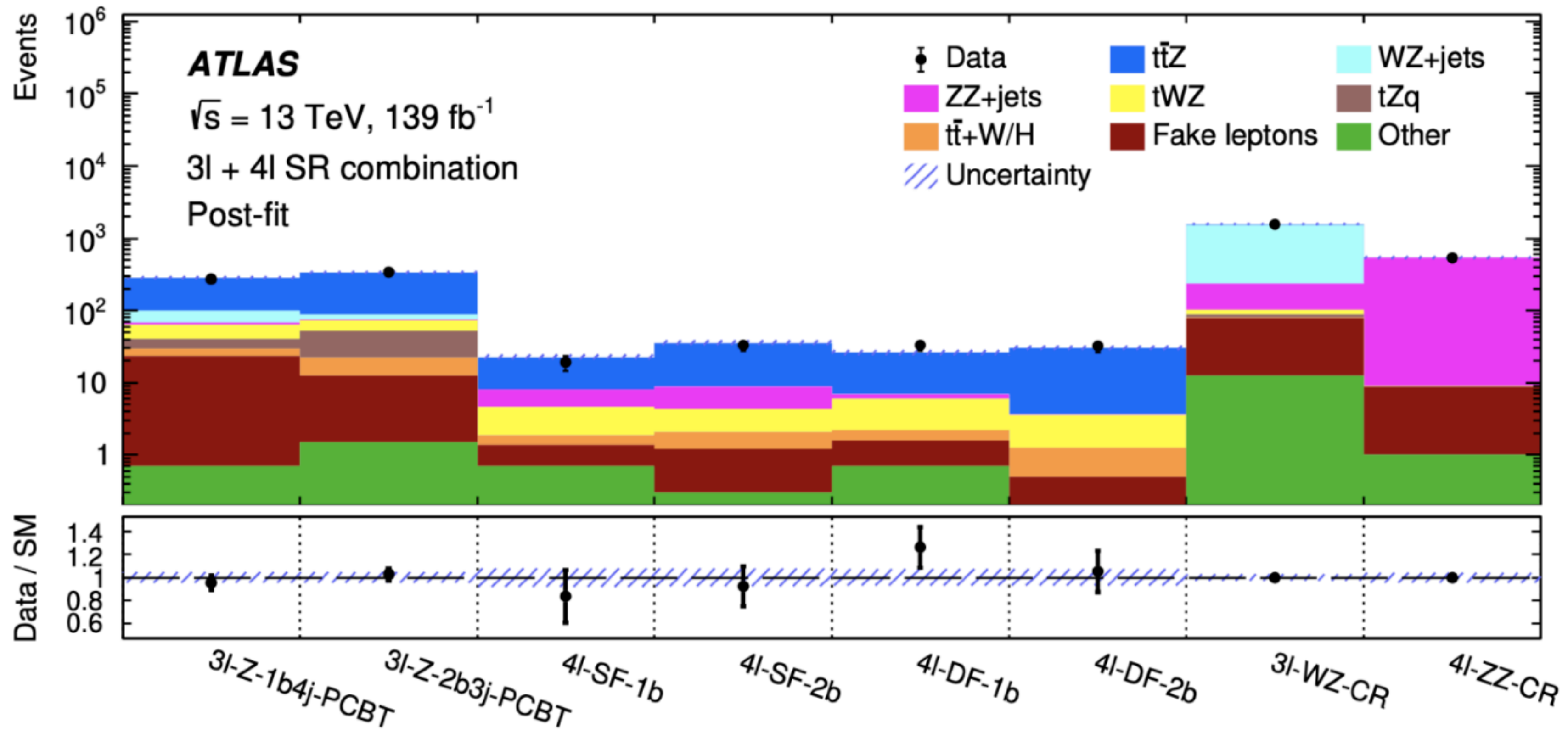
[LHCtopWG: Ravina+Skovpen]

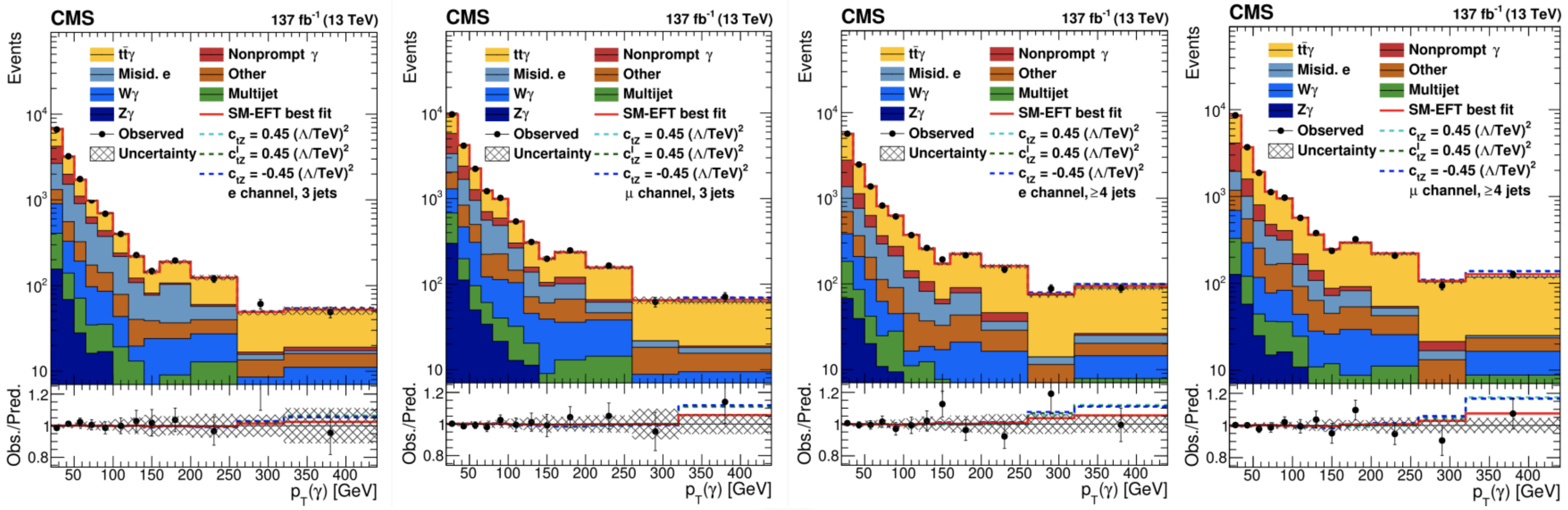
LHC Top WG efforts

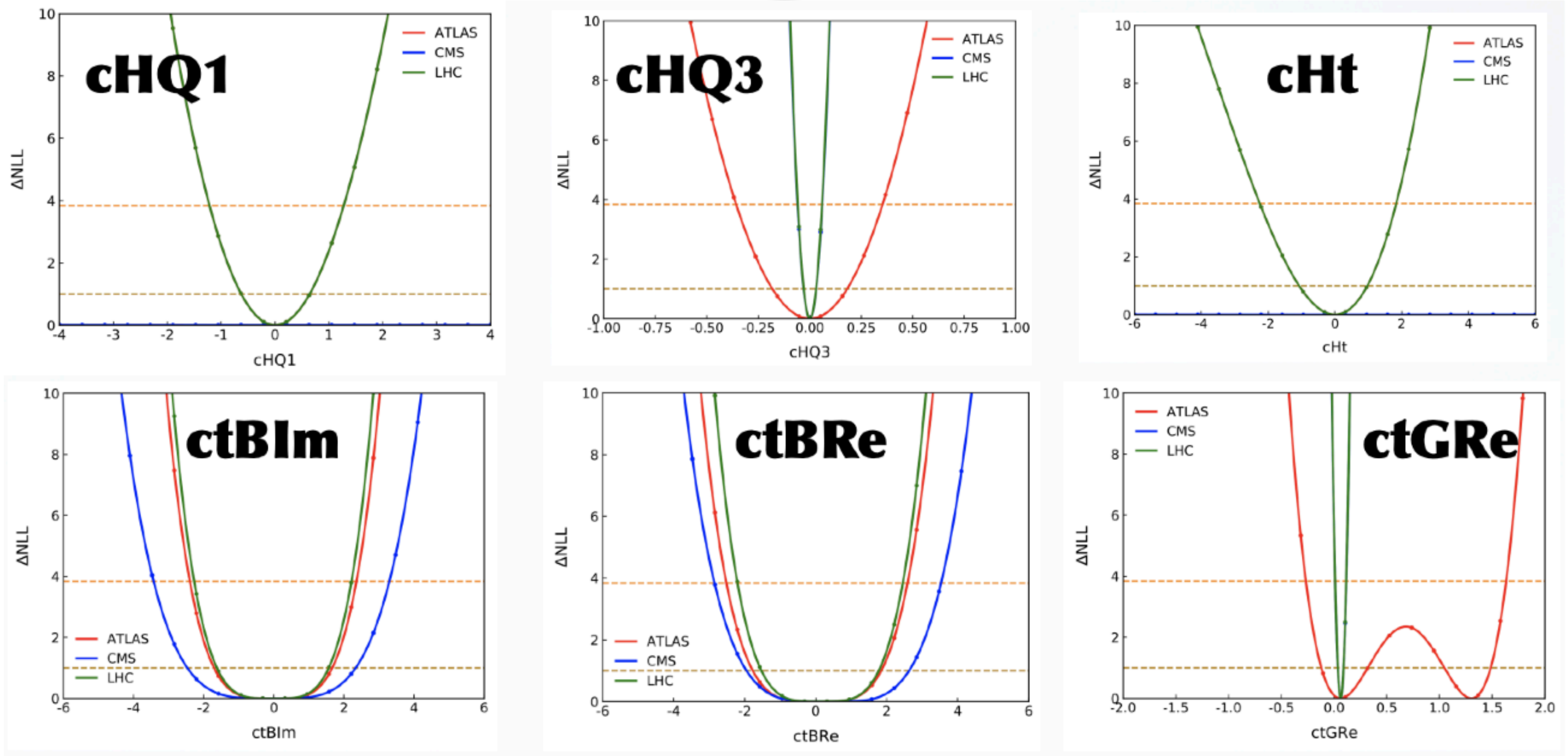
- ATLAS+CMS combination of top measurements and EFT interpretation

- Using unfolded data

- Using reconstruction-level information:



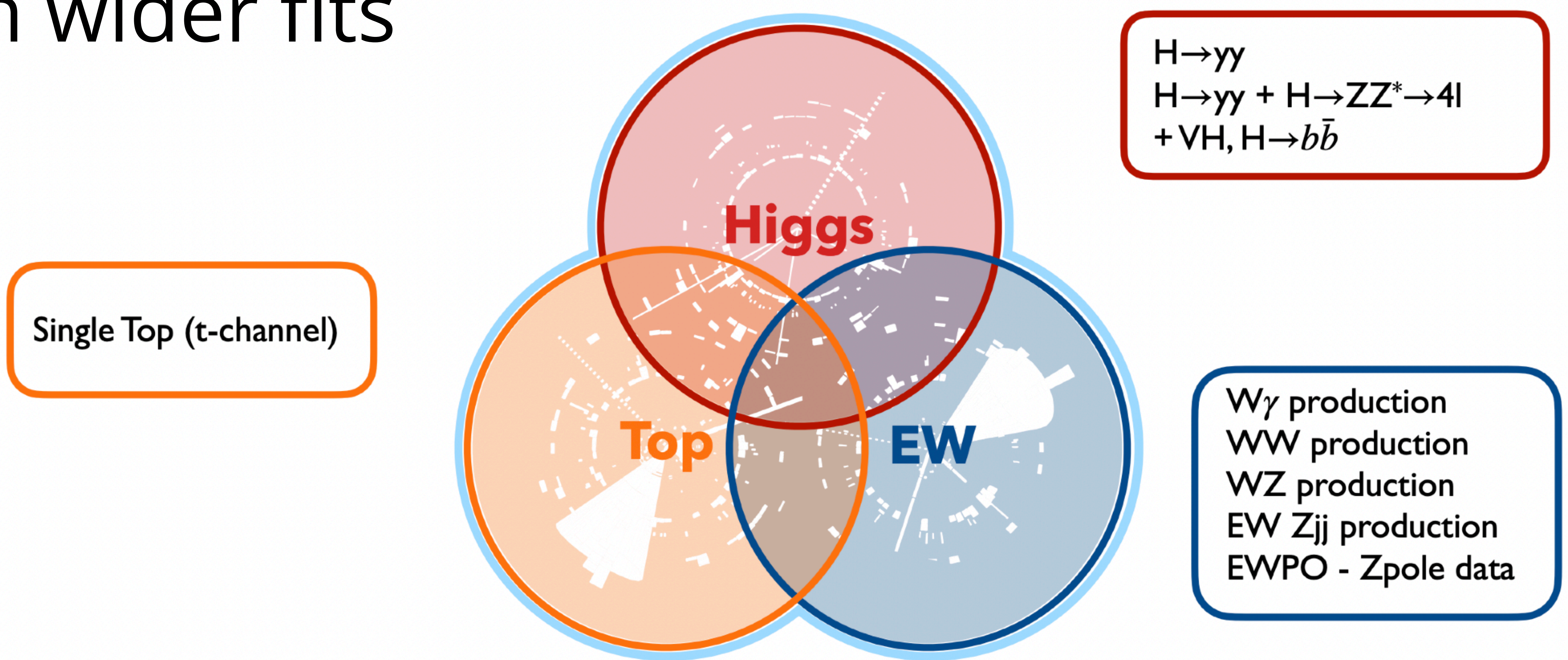




[LHCtopWG: Ravina+Skovpen]

LHC EFT WG Efforts

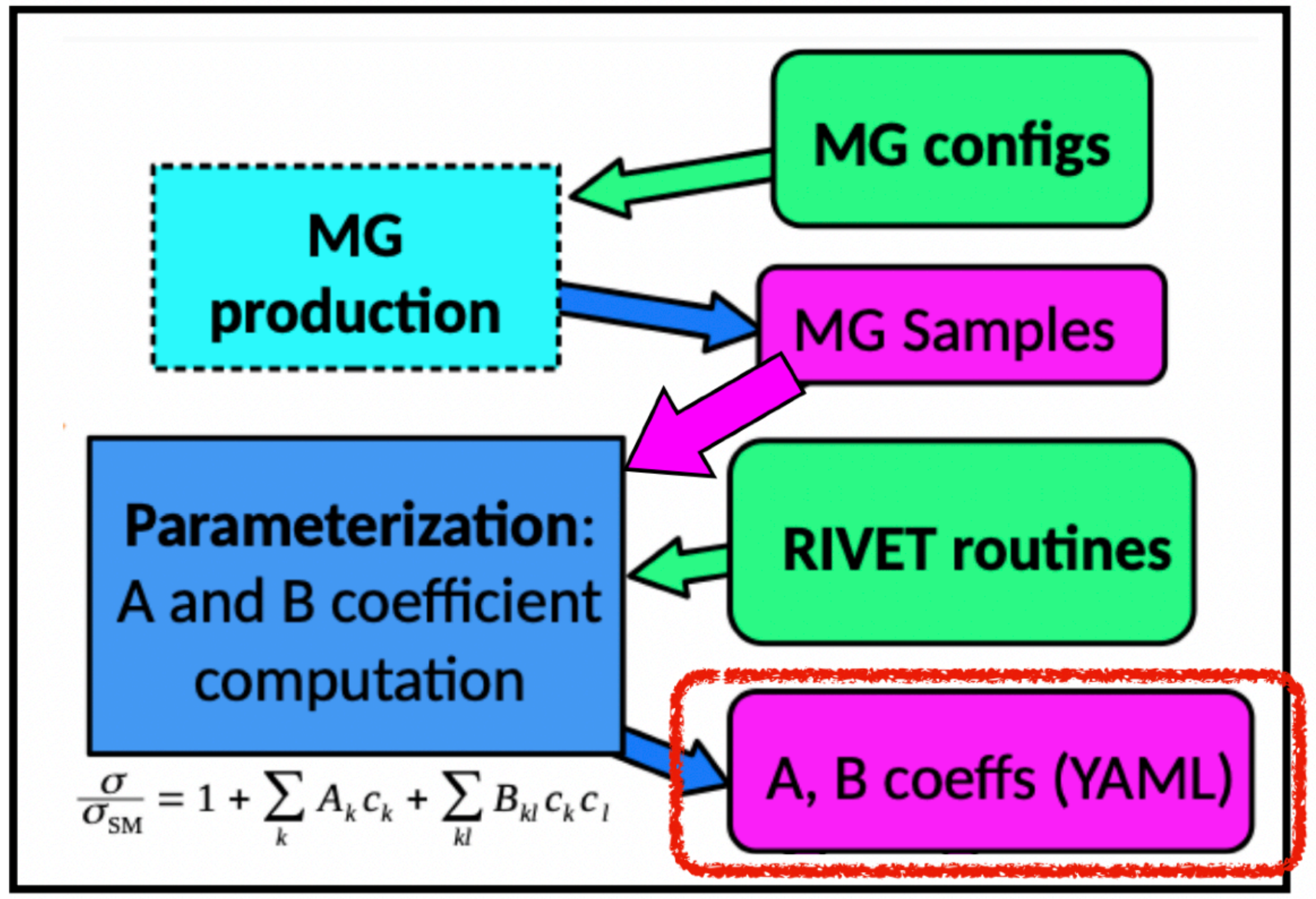
- LHC EFT WG already staring work on wider fits
  - WG to provide EFT recommendations
  - Currently looking at ATLAS+CMS fitting exercise (latest update here)
  - Includes Top data!



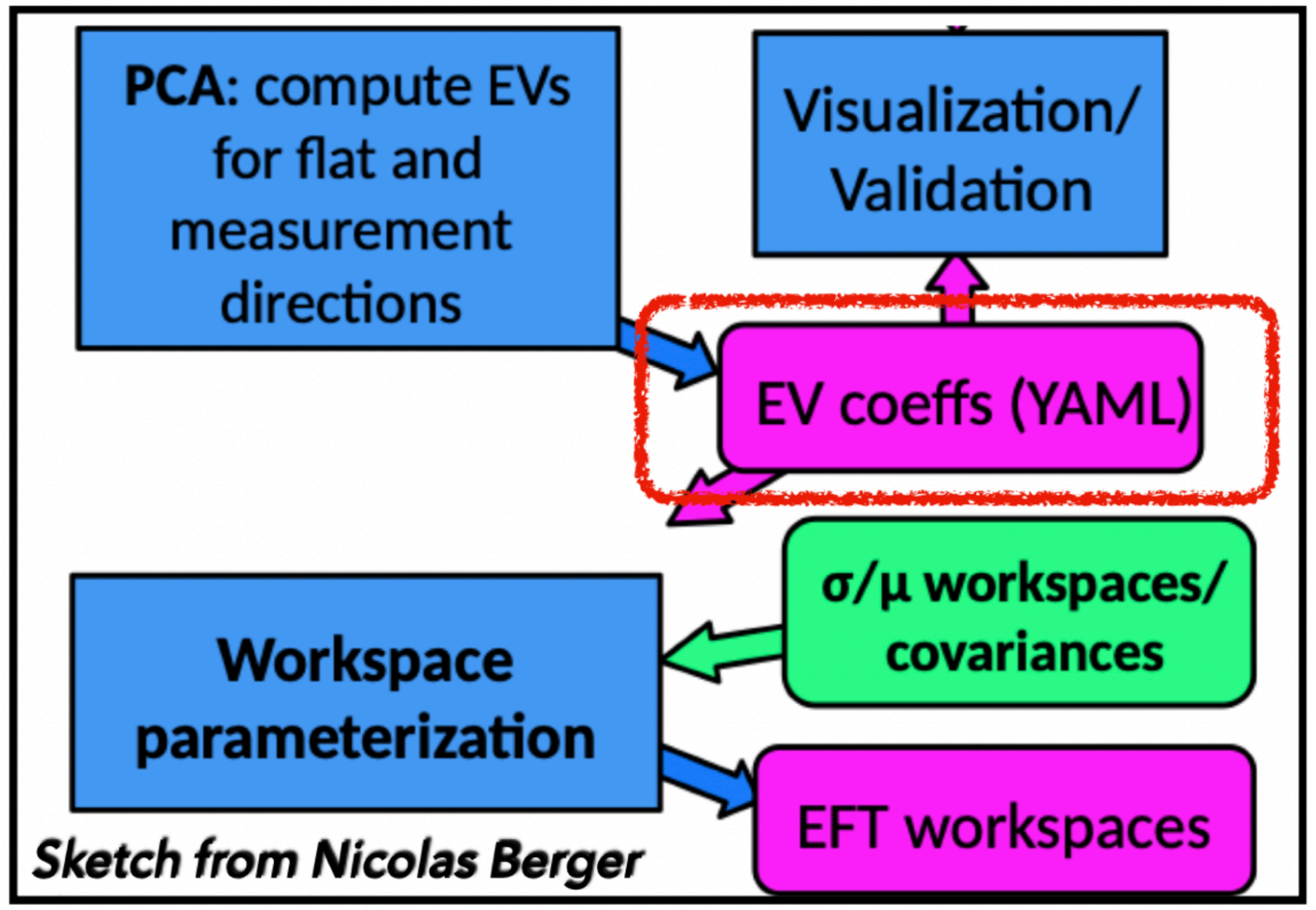
Sketch inspired from Ken Mimasu

- Workflow defined
  - Rivet used to extract parameterisation
  - Input based on YAML
  - Fit performed with Roofit

Parameterisation



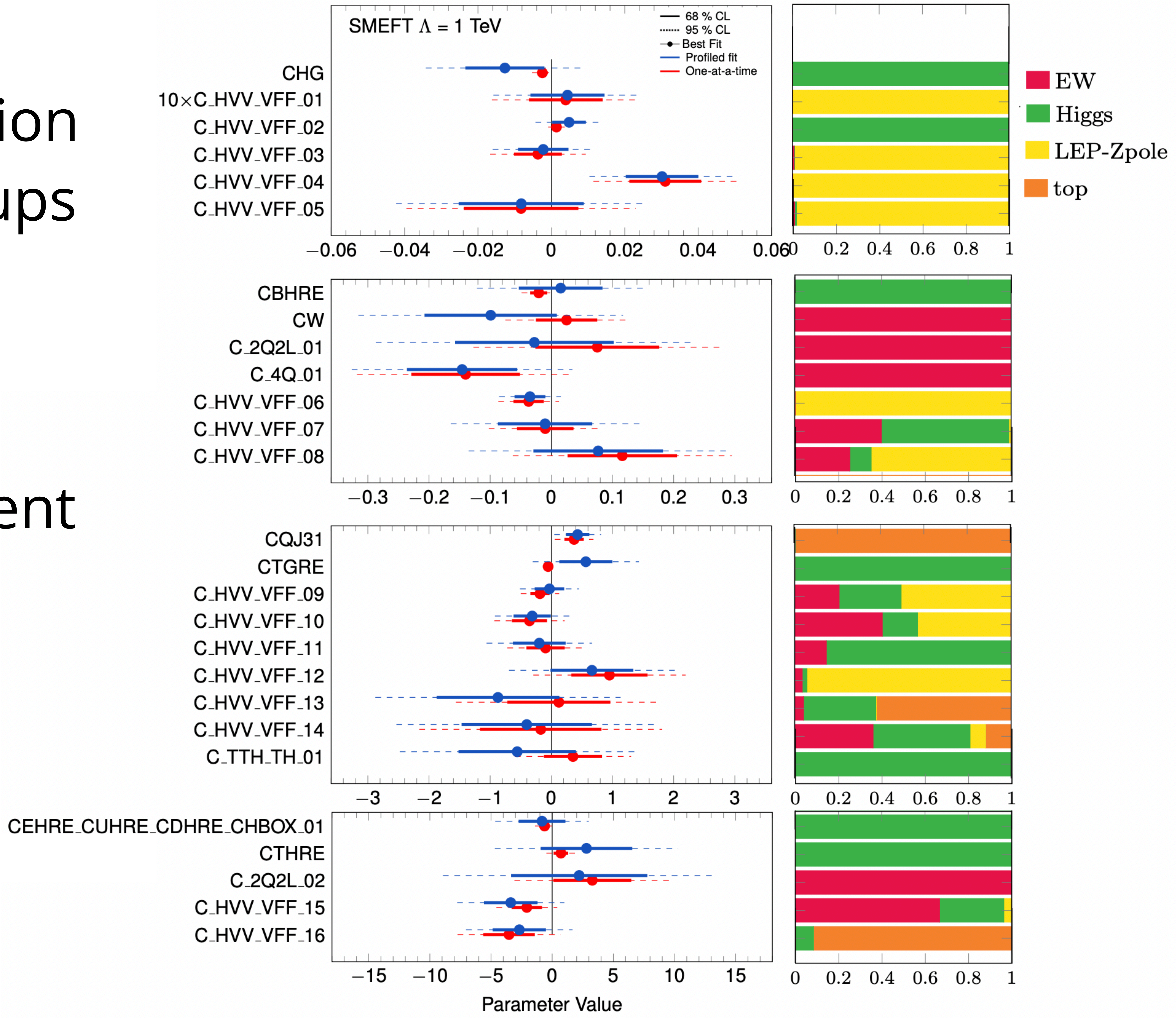
Statistical model



 [LHC EFT WG: R. Balasubramanian et al.]

LHC EFT WG Efforts

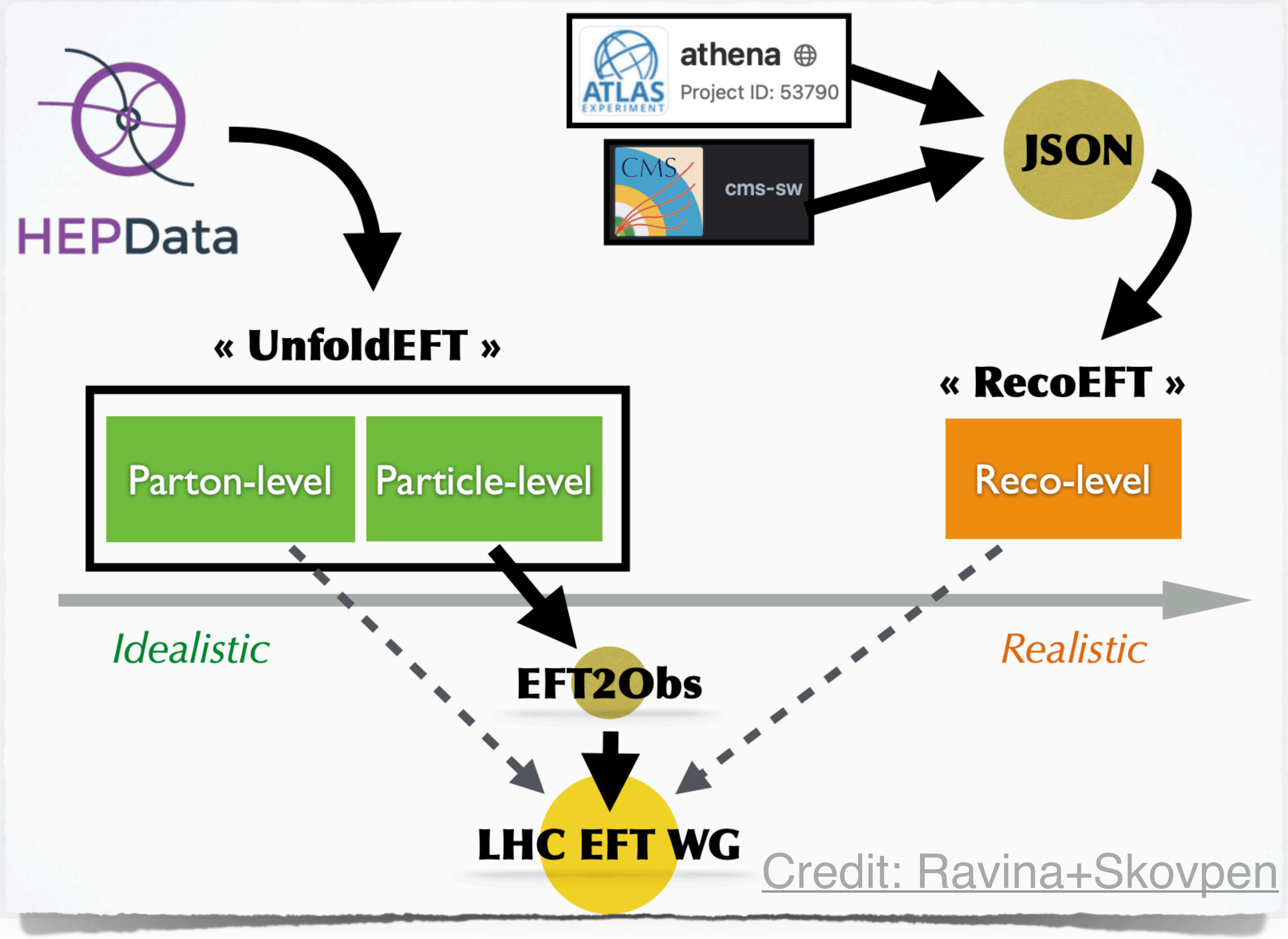
- Perform eigenvector decomposition and PCA to identify operator groups
  - Small correlation between groups
- Able to identify expected contributions of each measurement
- Fitting exercise in a good shape
  - Everything in place to perform the different steps in a flexible manner



 [LHC EFT WG: R. Balasubramanian et al.]

Coordination/Organisational Challenges

- General approach
  - Combine input measurements & interpret or directly interpret simultaneous fit of measurements?
  - Detector level fits vs unfolded data?
- Practical difficulties
  - Different statistical methods (IBU vs FBU, PL vs toys, ...)
  - Proper treatment of statistical and systematic correlations
  - Measurements delivered on different timelines
  - Interpretations: different assumptions on "backgrounds" → EFT effects - Hard without coordination!



Credit: Ravina+Skovpen

- What to store?
  - Store bootstrap replicas for data - estimate stat. correlations
  - Stat only results
  - Impact of systematic uncertainties:
    - Full likelihood (at least: full ranking and NPs correlations), cov. matrix for each unc. incl. stat only. Metadata.
- Signal model
  - SMEFT@LO or @NLO? Which operators? Linear/quadratic terms. EFT uncs & validity constraints.

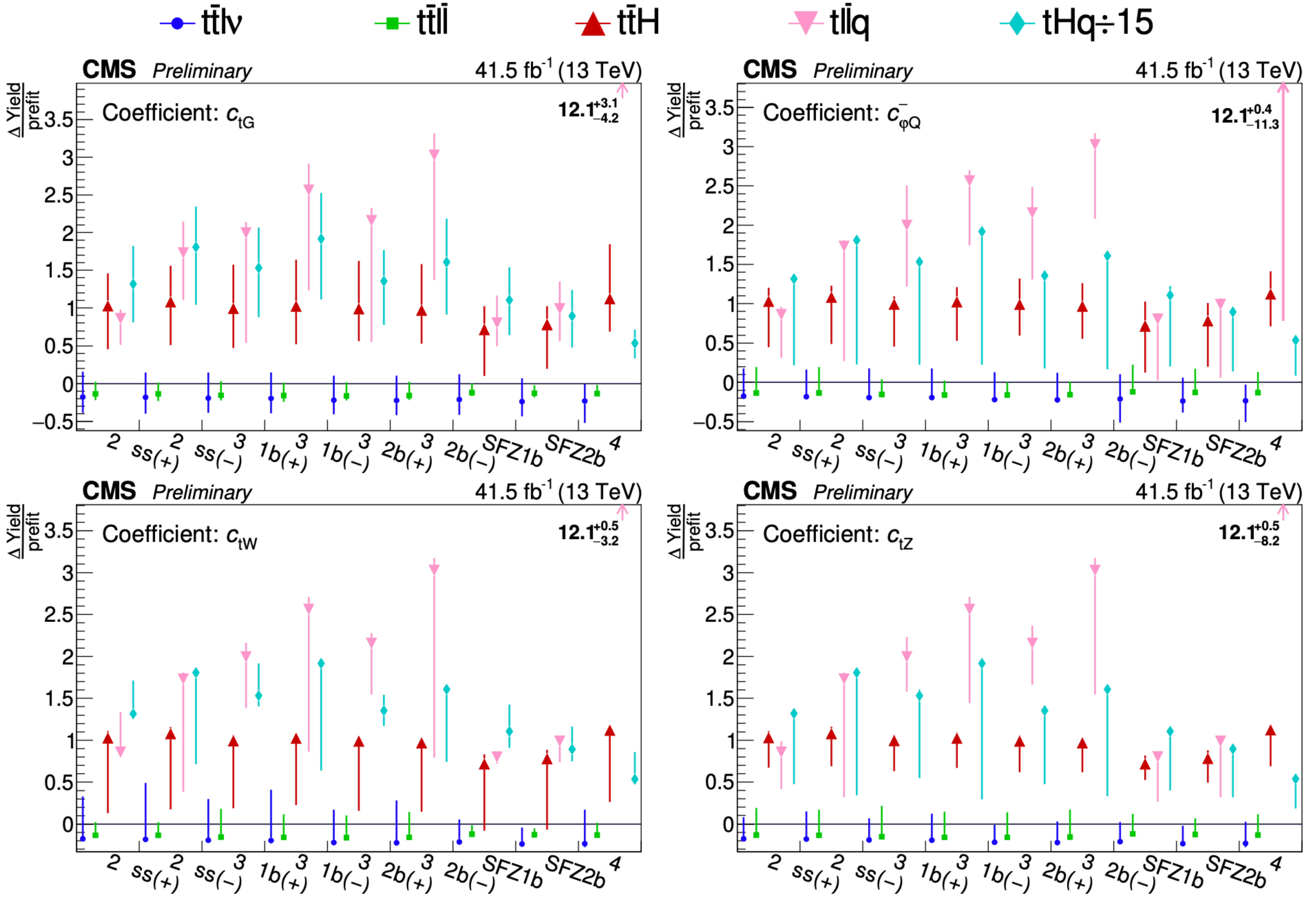
Summary

- Quite comprehensive global fits exist from the theory/pheno community
  - The importance of including Top data in these is clear
- Now it's time to think about next steps for adding Top data to experimental global fits
  - CMS has published a "global" Top+X fit
  - ATLAS has a recent PUB note on a "global" EWPO/Higgs/EW fit
  - LHC Top WG exercise looking at unfolded at detector level combinations
  - LHC EFT WG fitting exercise includes LEP+ATLAS+CMS EWPO/Higgs/EW/**Top** fit
- Many coordination/organisational challenges
  - Much of the technical machinery is there and existing fits can serve as starting point

Back-ups

CMS Top+X “global” fit

- Complicated interplay of many “signals” all allowed to “float” at once.
- Some small processes get very large effective normalisation factors
- One of the complexities of such a fit!



[TOP-19-001]

ATLAS Global EFT fit

[ATL-PHYS-PUB-2022-037]

- Input datasets

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]	Ref.
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	[10]
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139	[11]
$H \to WW^*$	ggF, VBF	139	[12]
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139	[13]
	WH, ZH	139	[14–16]
$H \to b\bar{b}$	VBF	126	[17]
	$t\bar{t}H$	139	[18]

Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R^0_ℓ	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R^0_c	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R^0_b	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ^0_{had} [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]	Ref.
$pp \to e^\pm\nu\mu^\mp\nu$	$m_{\ell\ell} > 55$ GeV, $p_{\text{T}}^{\text{jet}} < 35$ GeV	$p_{\text{T}}^{\text{lead. lep.}}$	36	[19]
$pp \to \ell^\pm\nu\ell^+\ell^-$	$m_{\ell\ell} \in (81, 101)$ GeV	m_{T}^{WZ}	36	[20]
$pp \to \ell^+\ell^-\ell^+\ell^-$	$m_{4\ell} > 180$ GeV	m_{Z2}	139	[21]
$pp \to \ell^+\ell^- jj$	$m_{jj} > 1000$ GeV, $m_{\ell\ell} \in (81, 101)$ GeV	$\Delta\phi_{jj}$	139	[22]

ATLAS Global EFT fit

[ATL-PHYS-PUB-2022-037]

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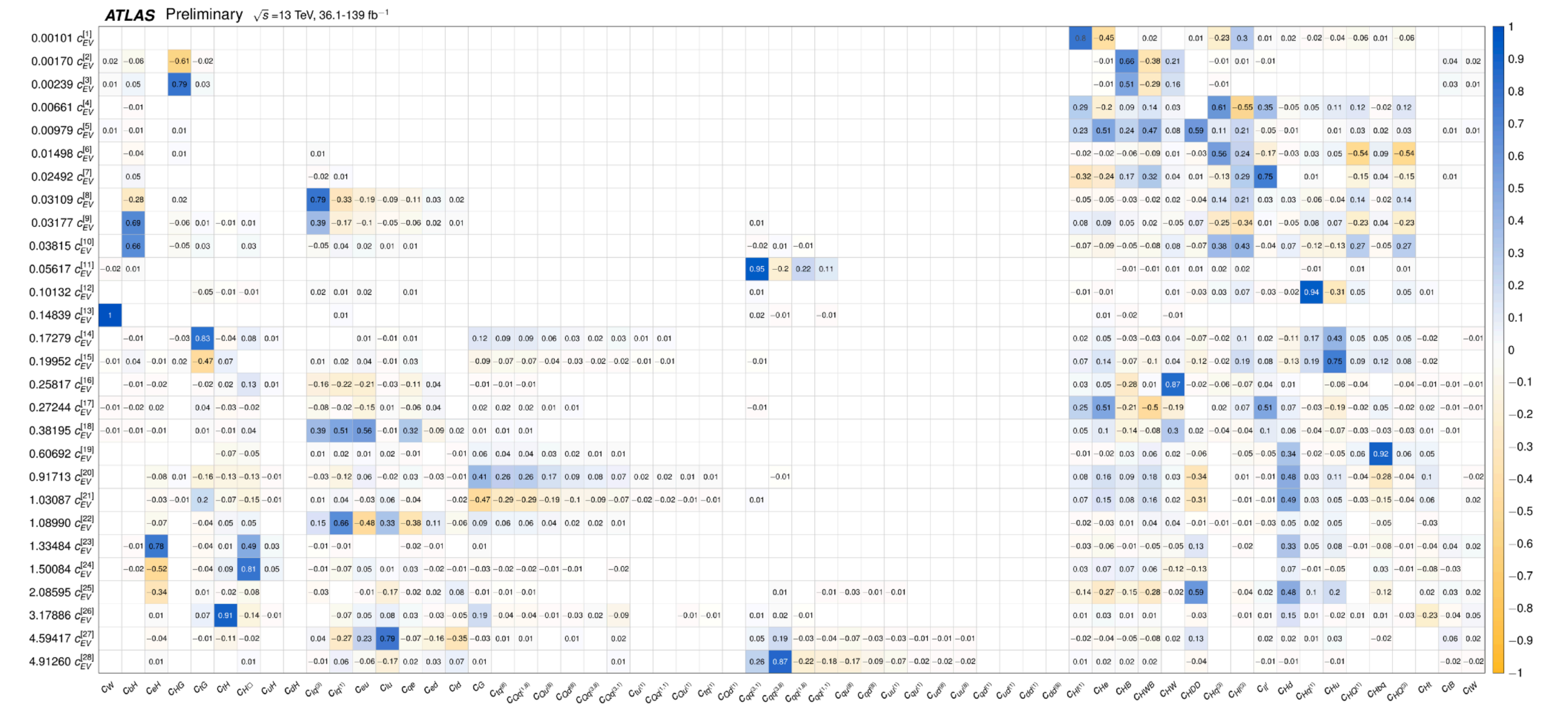
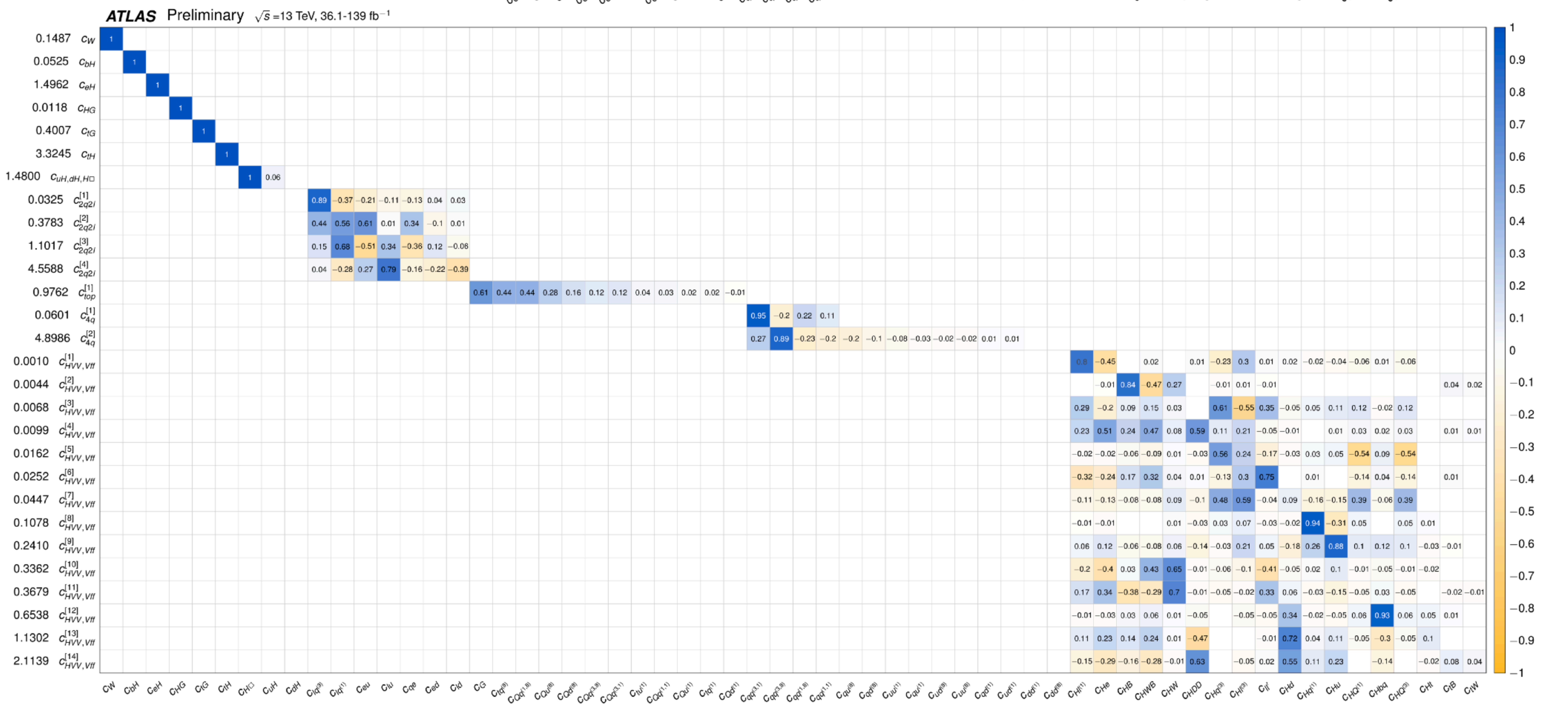
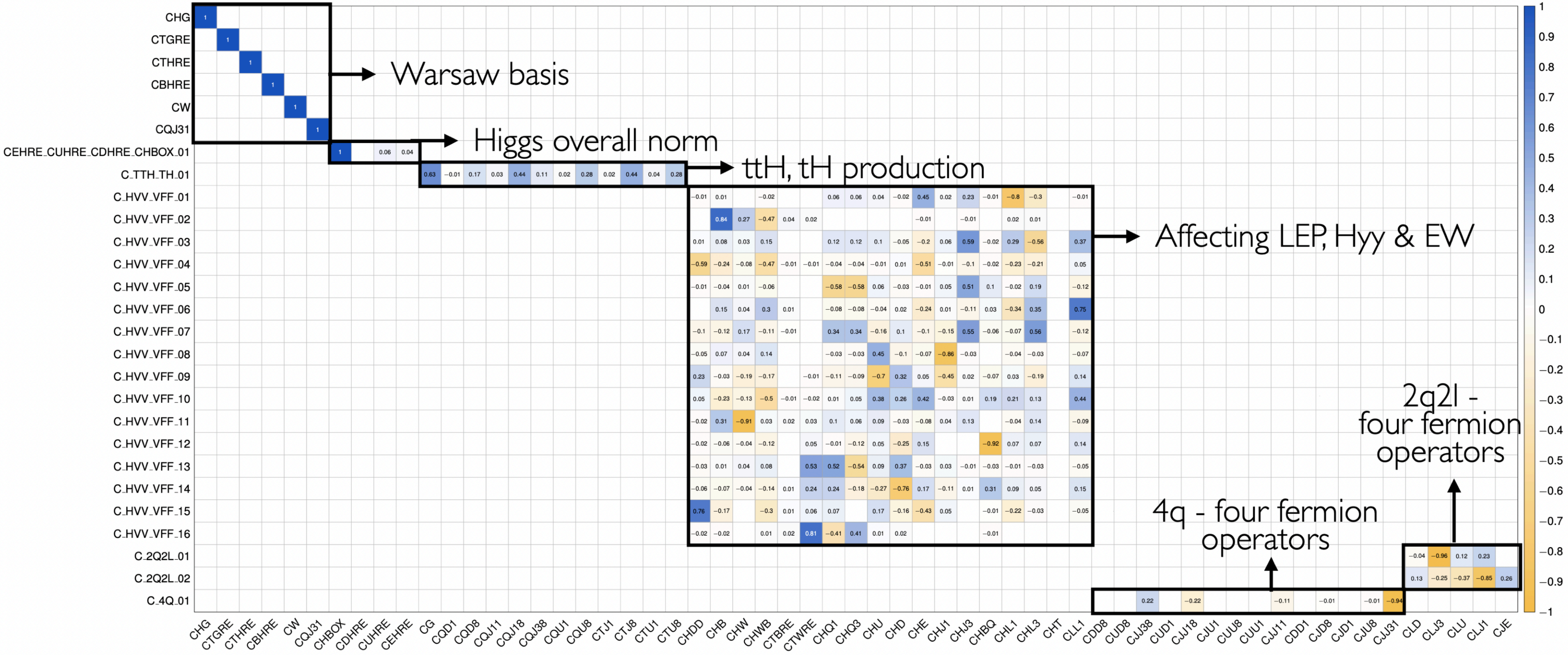
- Not enough information in the measurements to constrain all EFT coeffs
- Use eigenvector decomposition and PCA to identify most sensitive directions
- Choose physics driven groupings for most useful interpretation





LHC EFT WG Efforts

- Perform eigenvector decomposition and PCA to identify operator groups
  - Small correlation between groups



SMEFit

[2105.00006]

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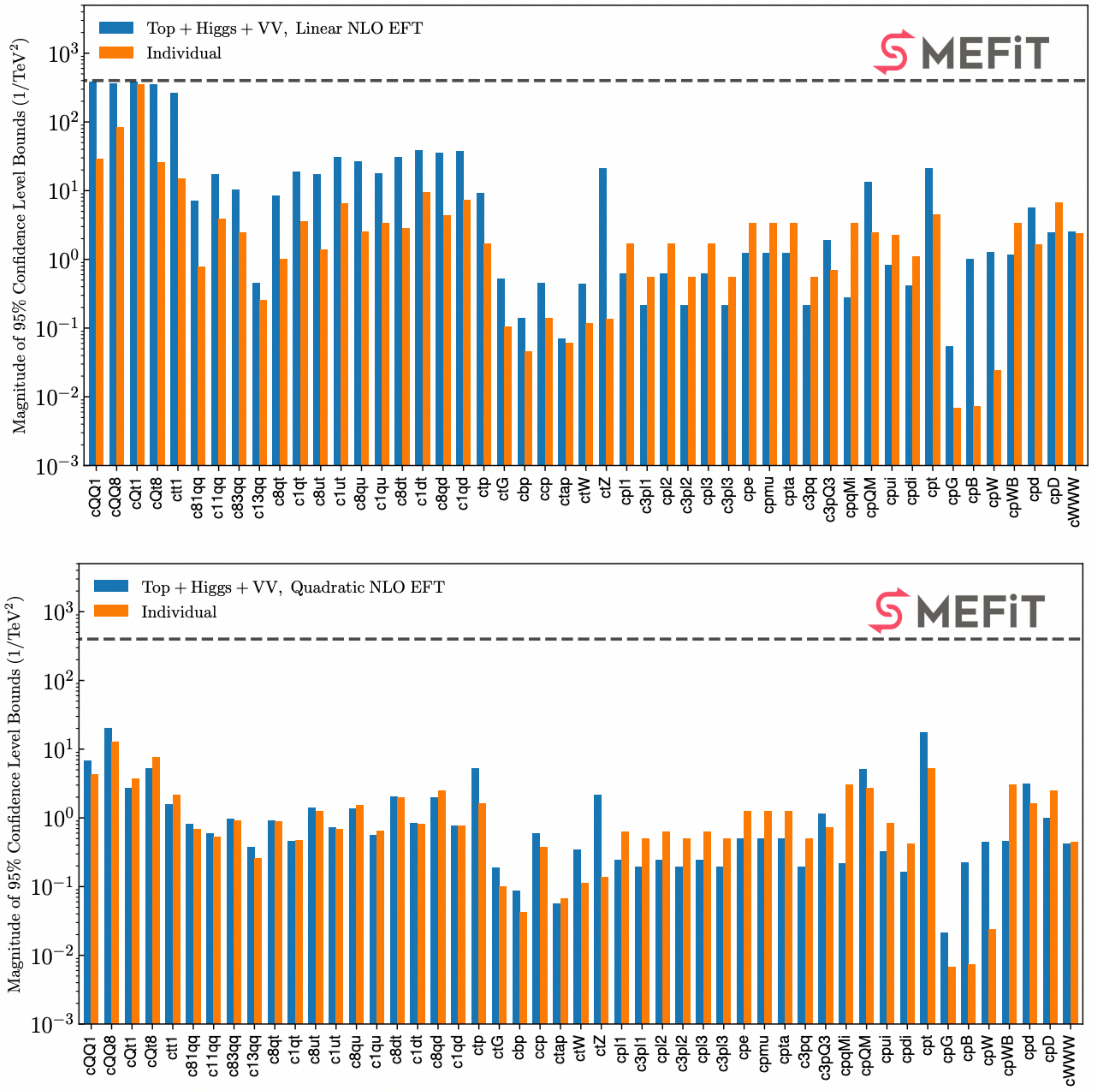


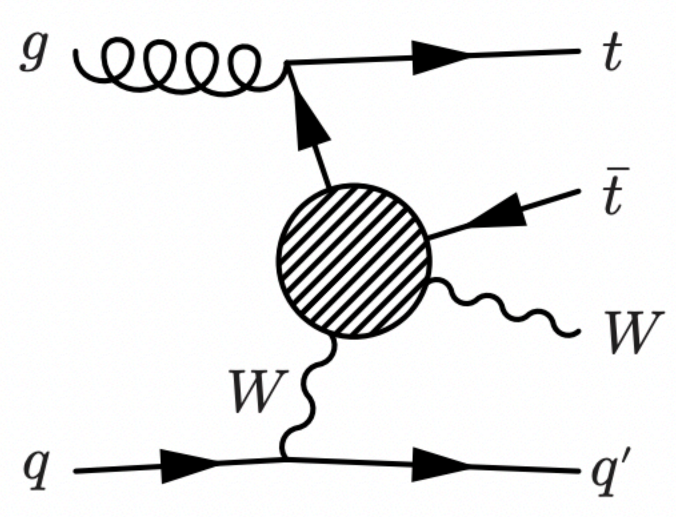
ATLAS Global EFT fit

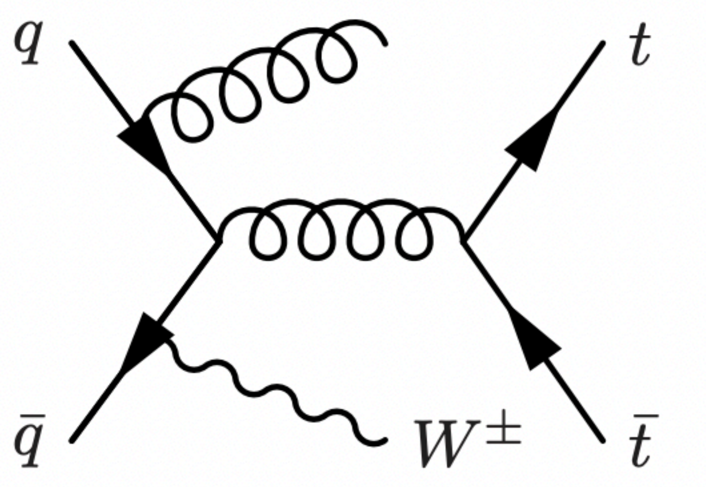
[ATL-PHYS-PUB-2022-037]

- Input measurements:
  - ATLAS Higgs boson data: A combined measurement of Higgs boson production and decay in exclusive kinematic regions of the production phase space, defined within the Simplified Template Cross-Section (STXS) framework [ATLAS-CONF-2021-053]
  - ATLAS electroweak data: Differential cross-section measurements for diboson production and Z boson production via vector boson fusion (VBF) [ATL-PHYS-PUB-2021-022] .
  - Electroweak precision data (EWPD): A combined measurements of electroweak precision observables (EWPO) on the Z resonance [arXiv:0509008] that were performed at LEP and SLC.

Wilson coefficient and operator		Affected process group: LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		✓	
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$		✓	✓
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$		✓	✓
c_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$		✓	✓
c_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$		✓	
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$		✓	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$		✓	
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	✓	✓	✓
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$		✓	
c_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u\widetilde{H})$		✓	
c_{tH}	$(H^\dagger H)(\bar{Q}\widetilde{H}t)$		✓	
c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$		✓	
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	✓	✓	✓
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l)$	✓	✓	✓
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	✓	✓	✓
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	✓	✓	✓
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$	✓	✓	✓
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	✓	✓	✓
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	✓	✓	✓
$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	✓	✓	
$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$	✓	✓	
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	✓		
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	✓	✓	
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\, G^A_{\mu\nu}$		✓	
c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\widetilde{H}\, W^I_{\mu\nu}$		✓	
c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\widetilde{H}\, B_{\mu\nu}$		✓	
c_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	✓		✓

High pT Top+X





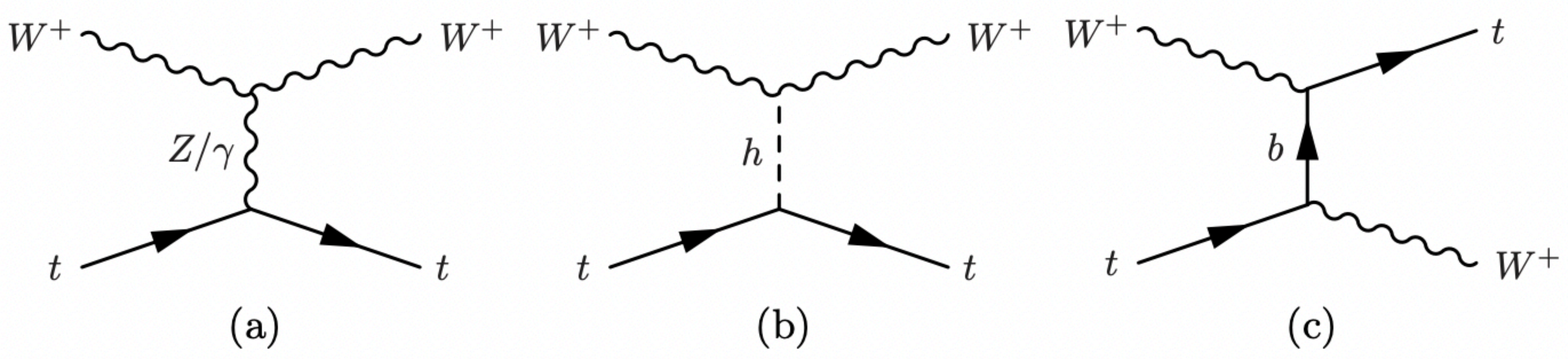


Figure 17: SM diagrams for the $tW \to tW$ subprocess.

	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

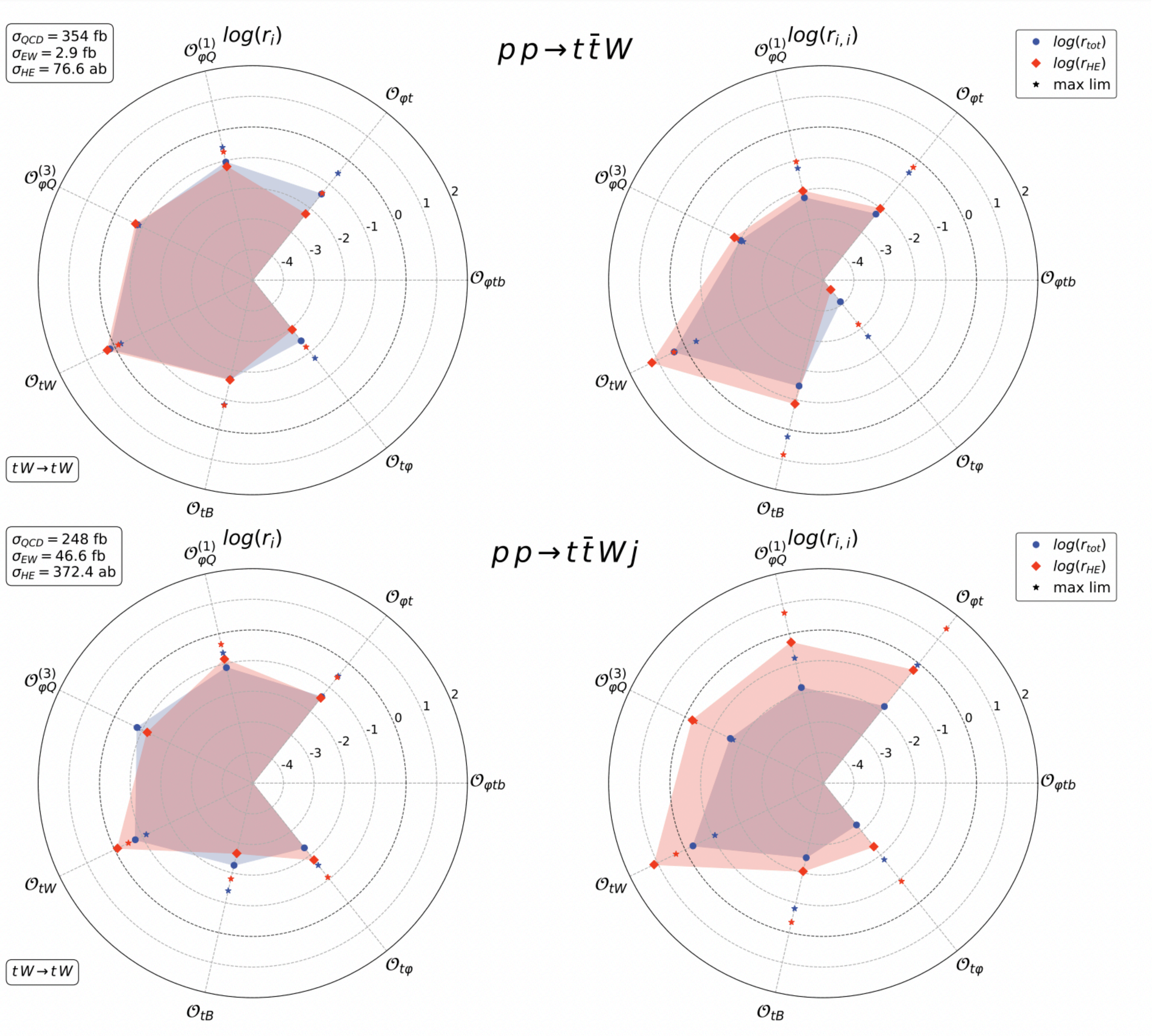
Table 6: The set of two-top $2 \to 2$ scattering amplitudes without Higgs bosons considered in this work mapped to the collider processes in which they are embedded.

A summary of the maximal energy growths obtained in our helicity amplitude computations, taken from Tables 13–16, is shown in Table 7. A clear favourite emerges in $tW \to tW$ scattering, which displays maximal and interfering energy growth for all current operators. It has equal or better energy growth for all other operators apart from $\mathcal{O}_{\varphi B}$. In contrast, the other two amplitudes show at most linear growth in all cases barring the dipole operators, which have a tendency to grow maximally everywhere.

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi \Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$
$tW \to tW$	E	E	–	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \to tZ$	E	E	E	E	E	–	E	E^2	E^2	E	E	E
$tZ \to t\gamma$	–	–	E	E	E	–	–	E^2	E^2	–	–	–
$t\gamma \to t\gamma$	–	–	E	E	E	–	–	E	E	–	–	–

[1904.05637]

High pT Top+X



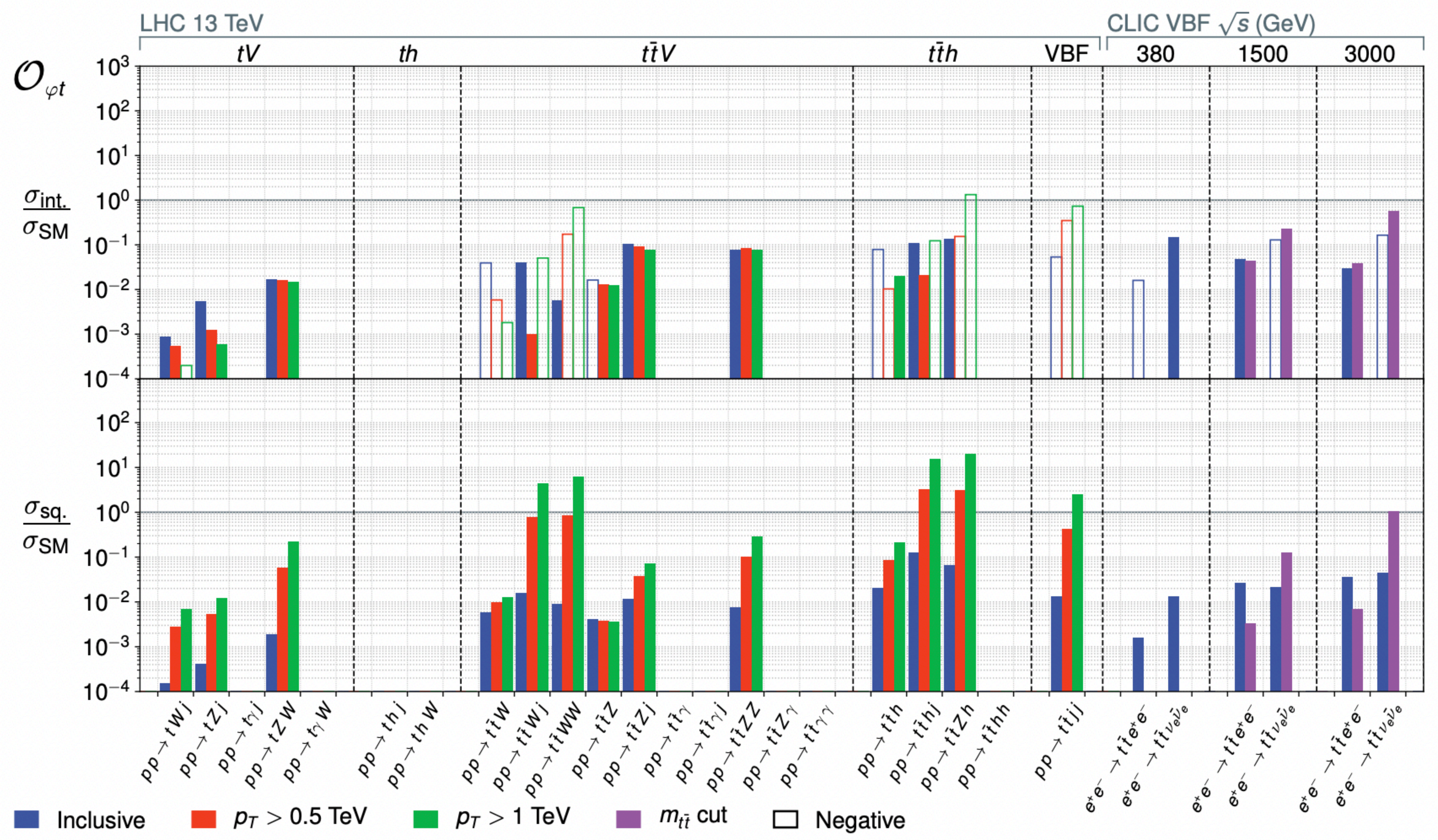


Figure 42: Same as Figure 40 for $\mathcal{O}_{\varphi t}$

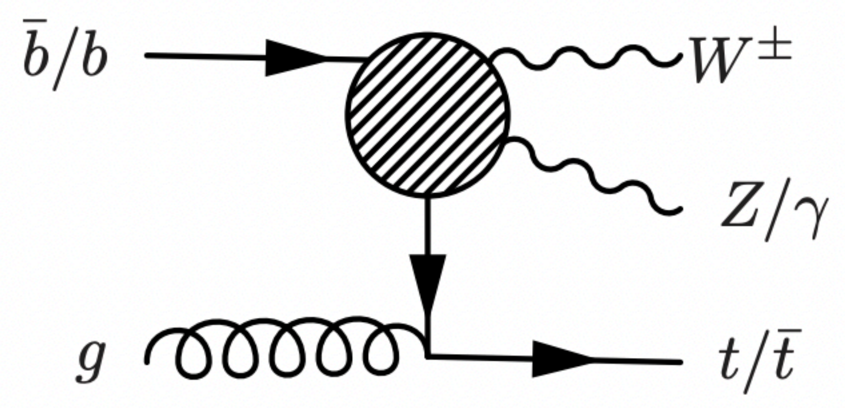
[1904.05637]

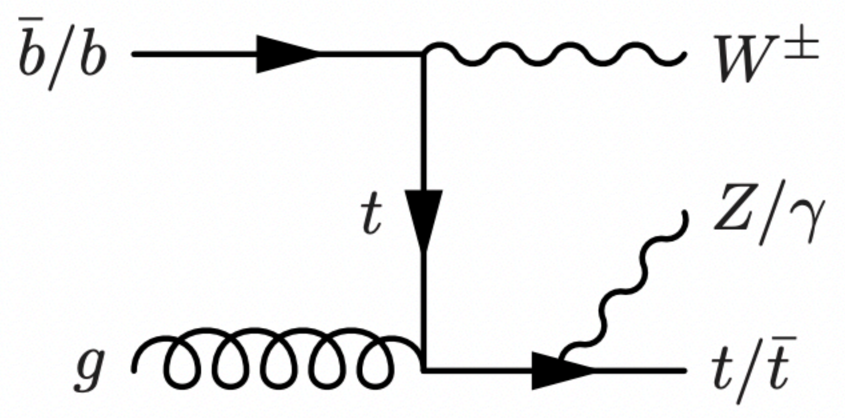
High pT Top+X

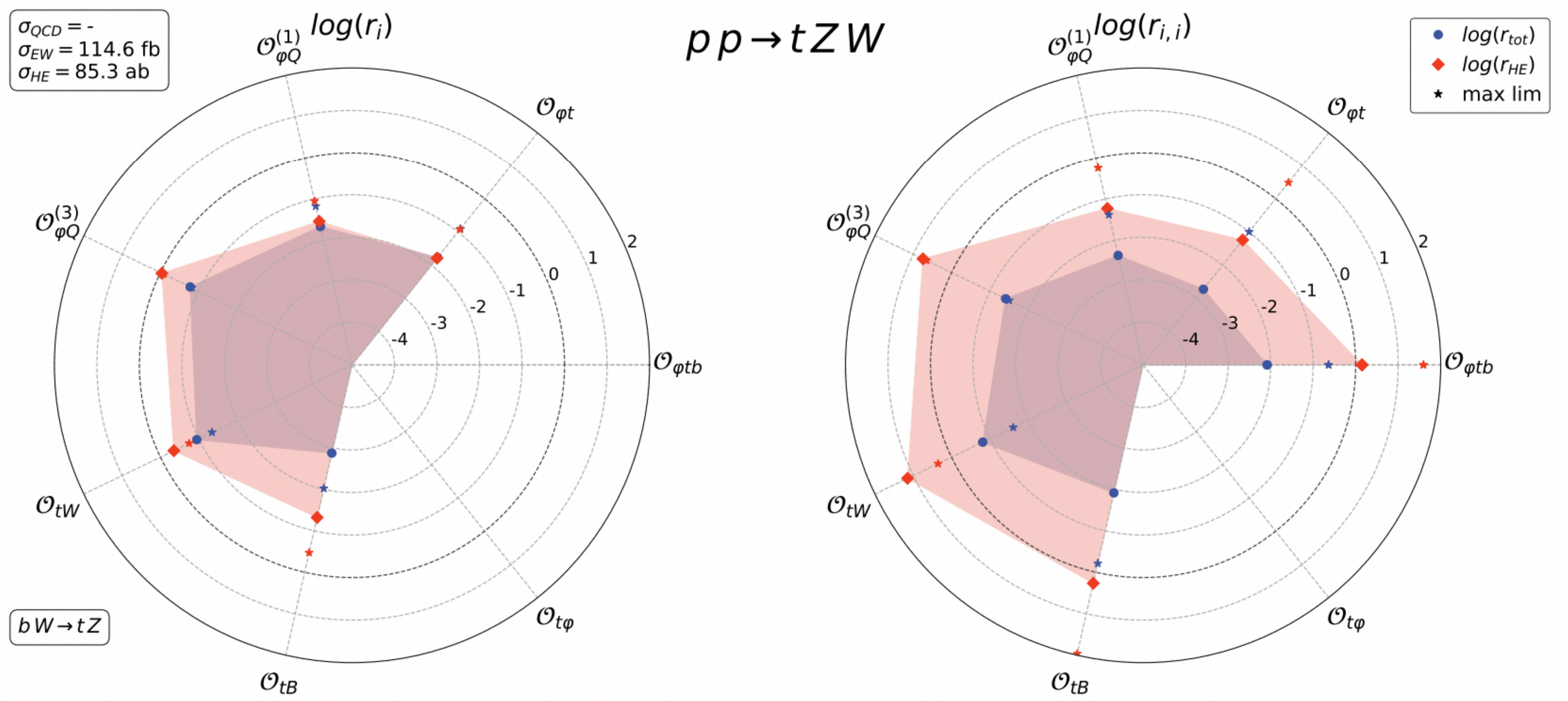
	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi \Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$bW \to tZ$	E	–	–	–	E	E^2	–	E^2	E^2	E	E^2	E	E^2
$bW \to t\gamma$	–	–	–	–	E	E^2	–	E^2	E^2	–	–	–	–
$bW \to th$	–	–	–	E	–	–	E	–	E^2	–	E^2	–	E^2

able 5: Maximal energy growths induced by each operator on the set of single top attering amplitudes considered. '–' denotes either no contribution or no energy growth ıd the red entries denote the fact that the interference between the SMEFT and the SM nplitudes also grows with energy.

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓



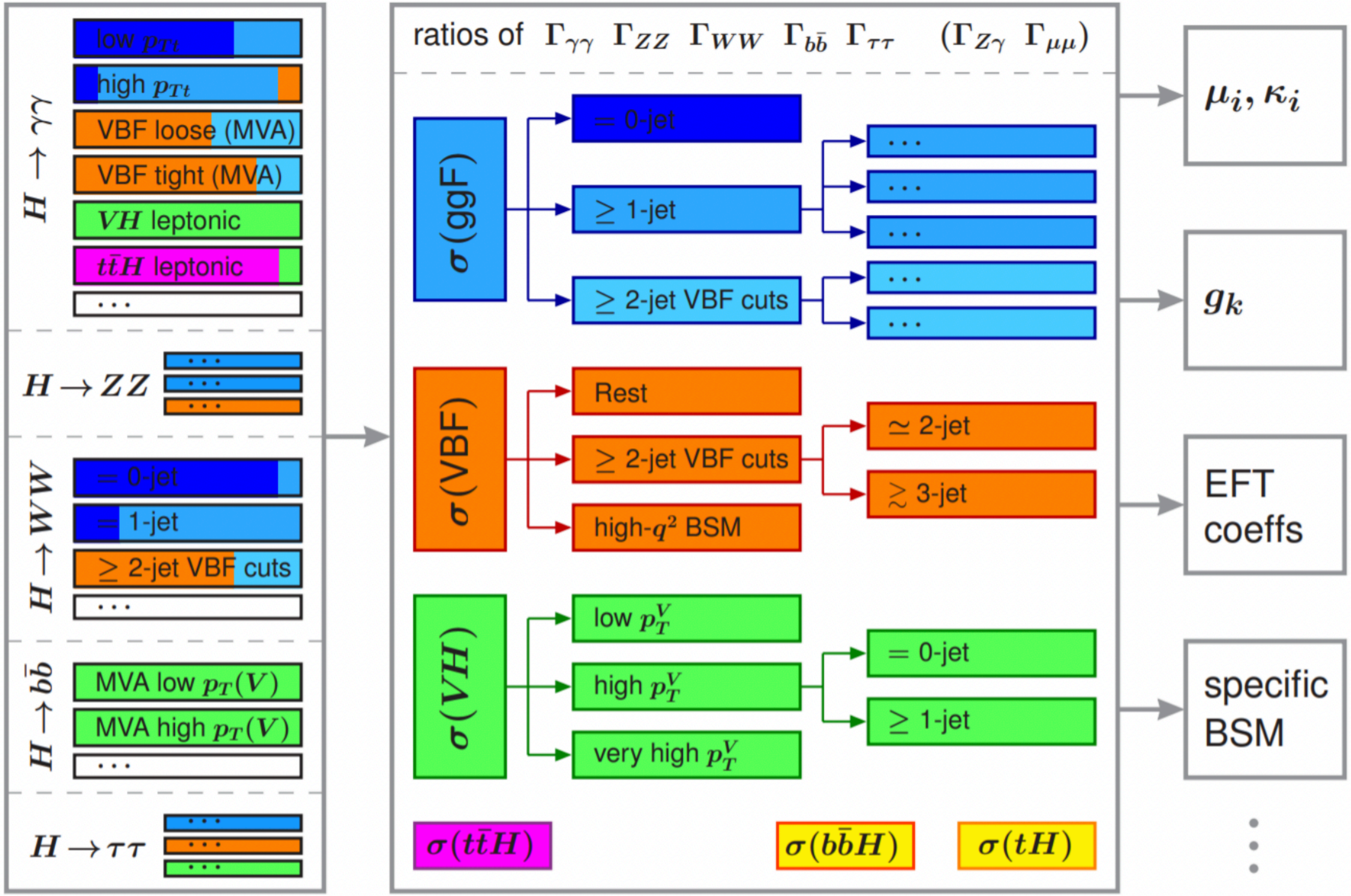




[1904.05637]

EFT | Extending to differential Higgs

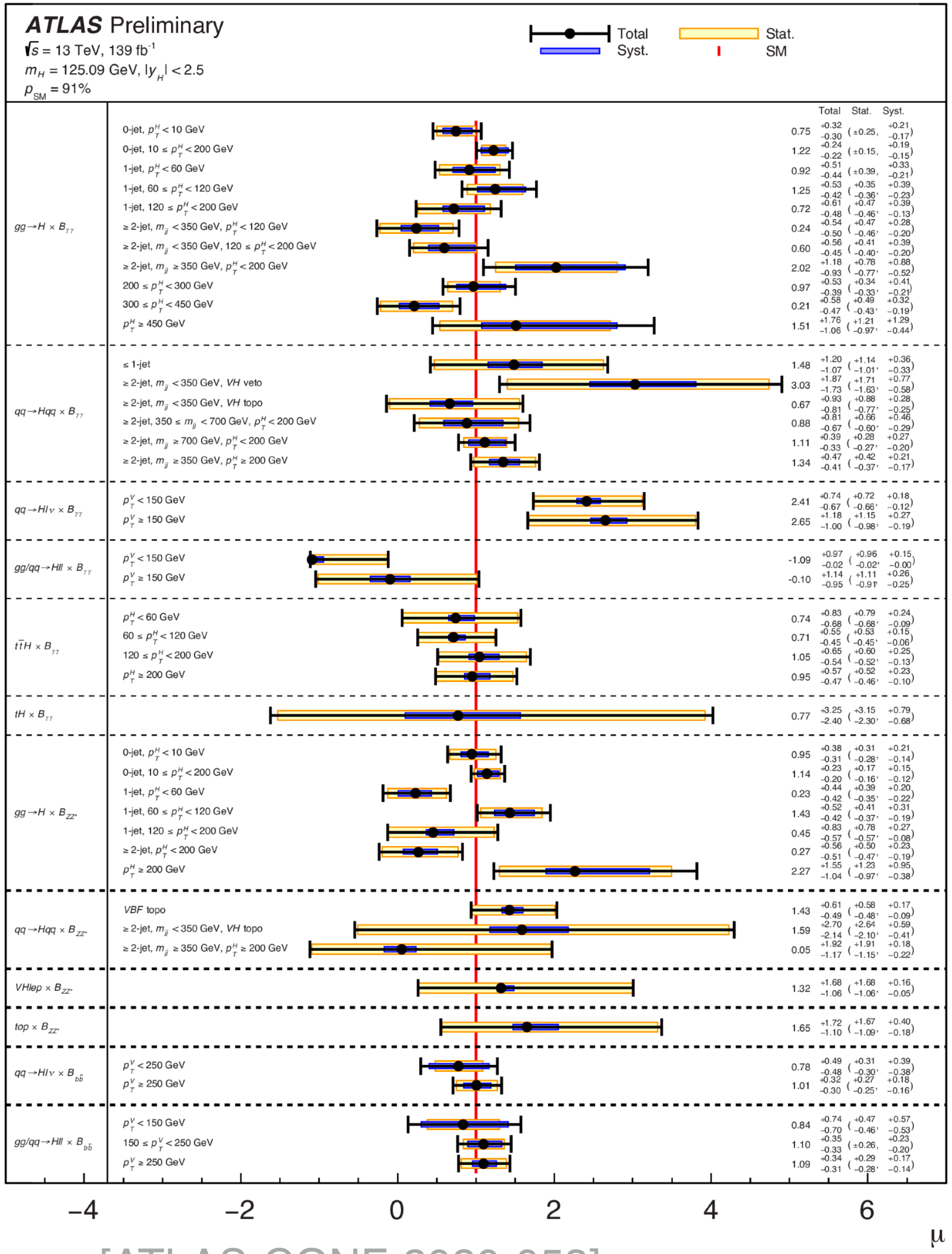
- Simplified Template Cross section (STXS)
  - Going beyond kappa framework
  - Compromise for channels without stats for fiducial cross-section.
- Key features:
  - Regions defined inclusively in Higgs decay & kinematics
  - Specific to Higgs prod. mode, topology and kinematics
- Enables:
  - Combination of multiple Higgs decays to extract STXS bins in prod. mode/event topology
  - Permits use of MVA techniques.



[arXiv:1605.04692, arXiv:1610.07922, arXiv:1906.02754]

EFT | In practise… Higgs

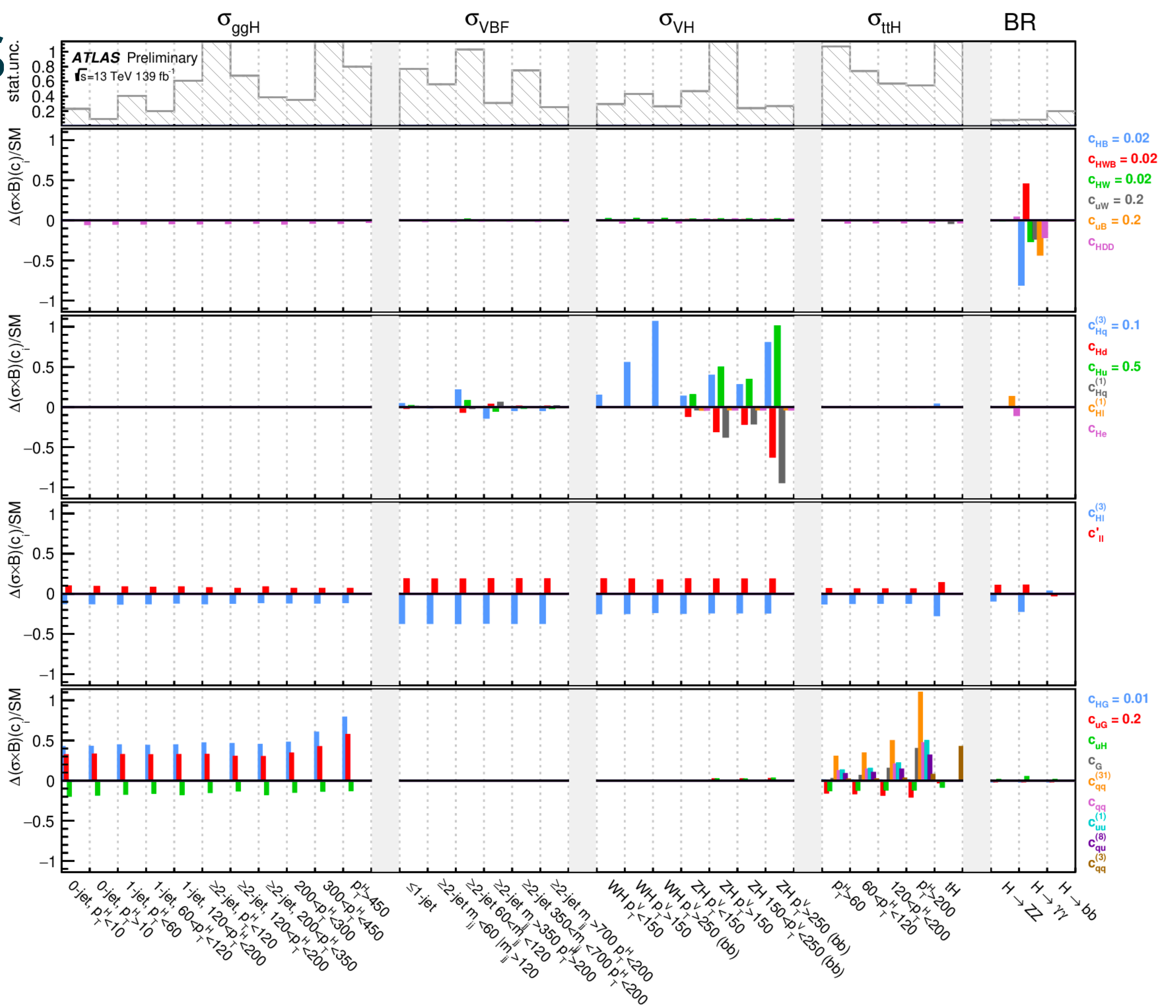
- ATLAS Higgs combination



[ATLAS-CONF-2020-053]

EFT | Higgs

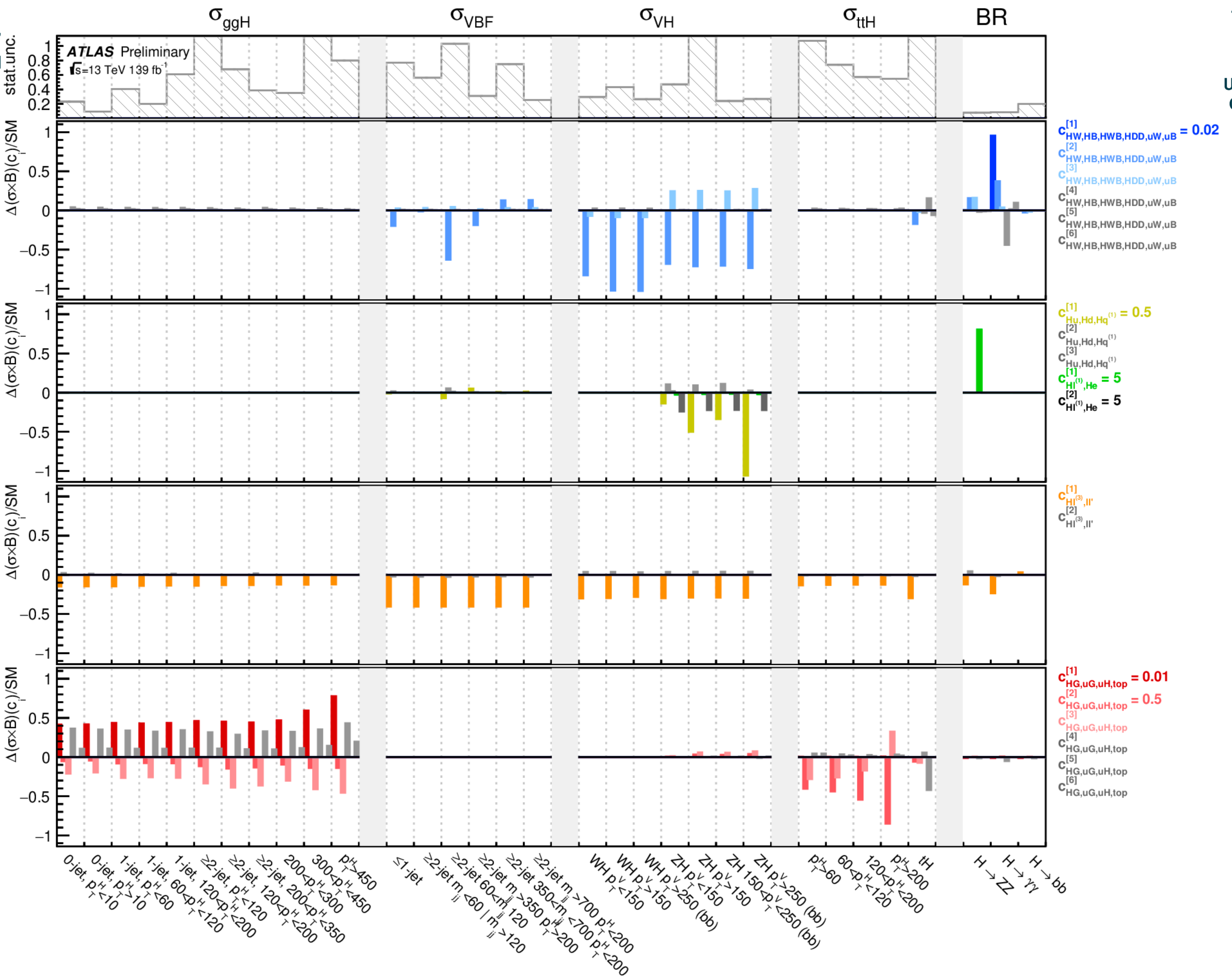
- ATLAS Higgs combination
  - EFT parameter sensitivity



[ATLAS-CONF-2020-053]

EFT | Higgs

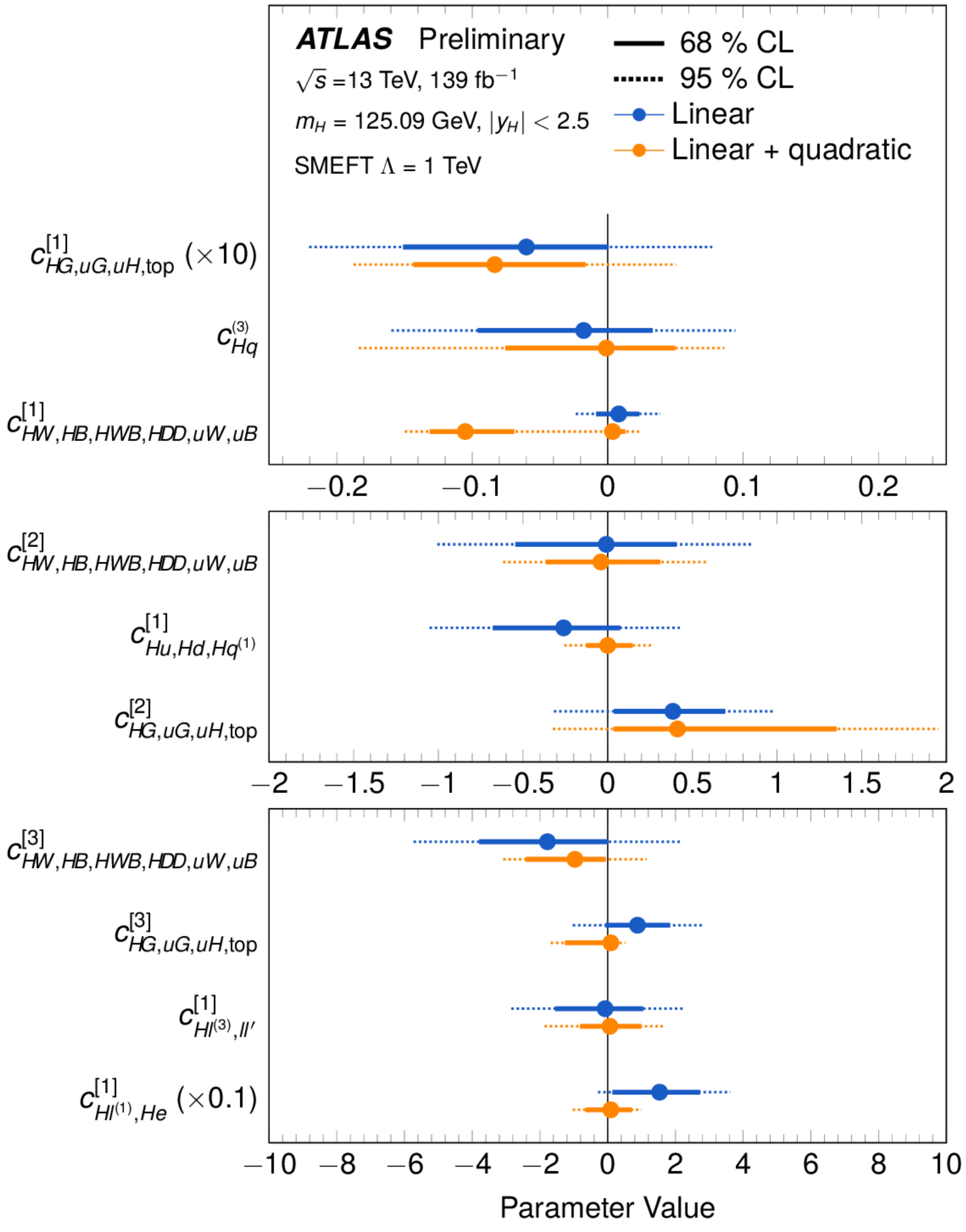
- ATLAS Higgs combination
  - EFT parameter sensitivity
  - Same parameter decomposition as before



[ATLAS-CONF-2020-053]

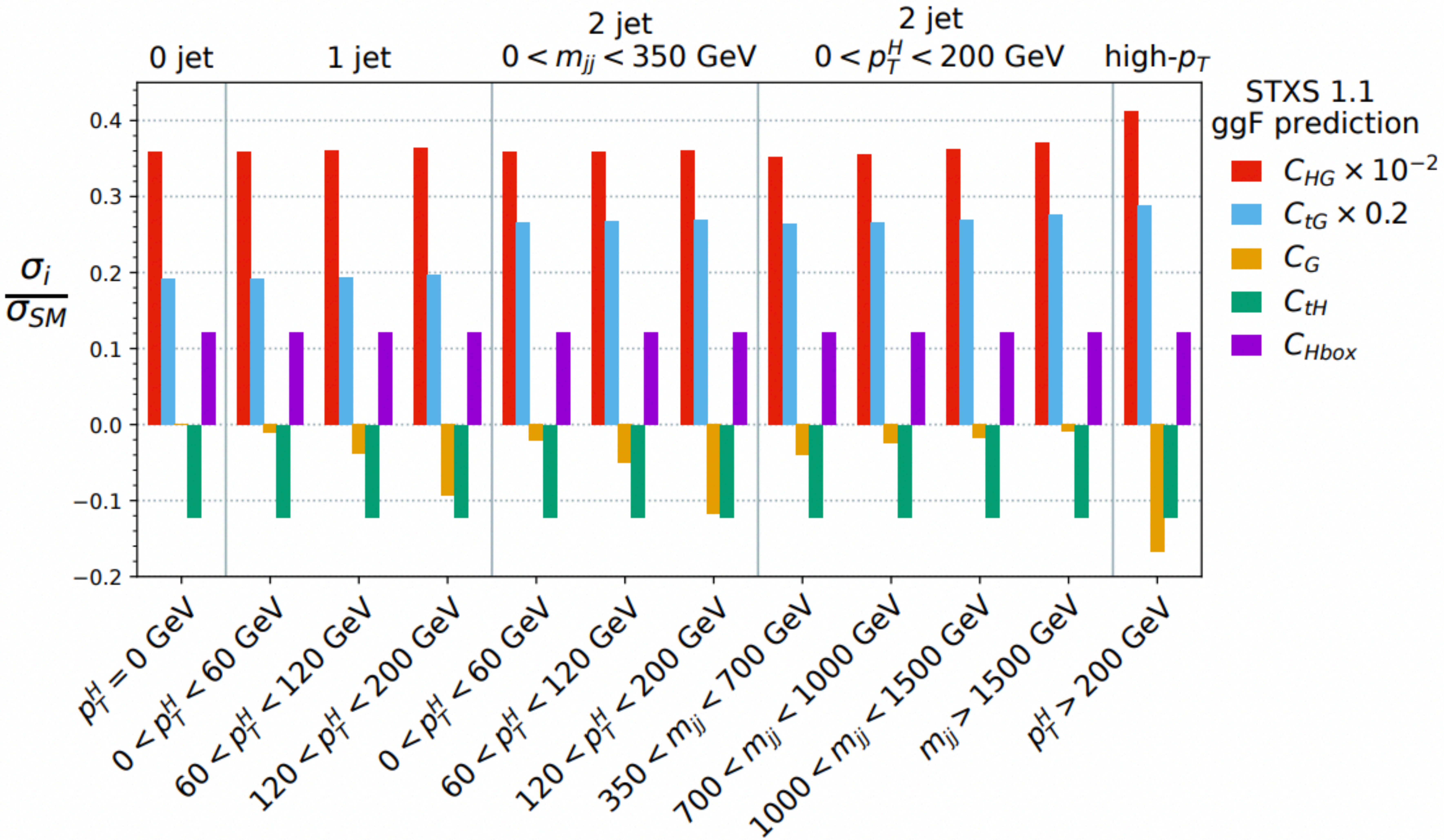
EFT | Higgs

- ATLAS Higgs combination
  - EFT parameter sensitivity
  - Same parameter decomposition as before
- Results
  - All parameters consistent with SM expectation
  - Somewhat tighter tighter constraints from lin+quad fit
    - Implies non-negligible influence of these terms.



[ATLAS-CONF-2020-053]

- STXS also lends itself to wider interpretation

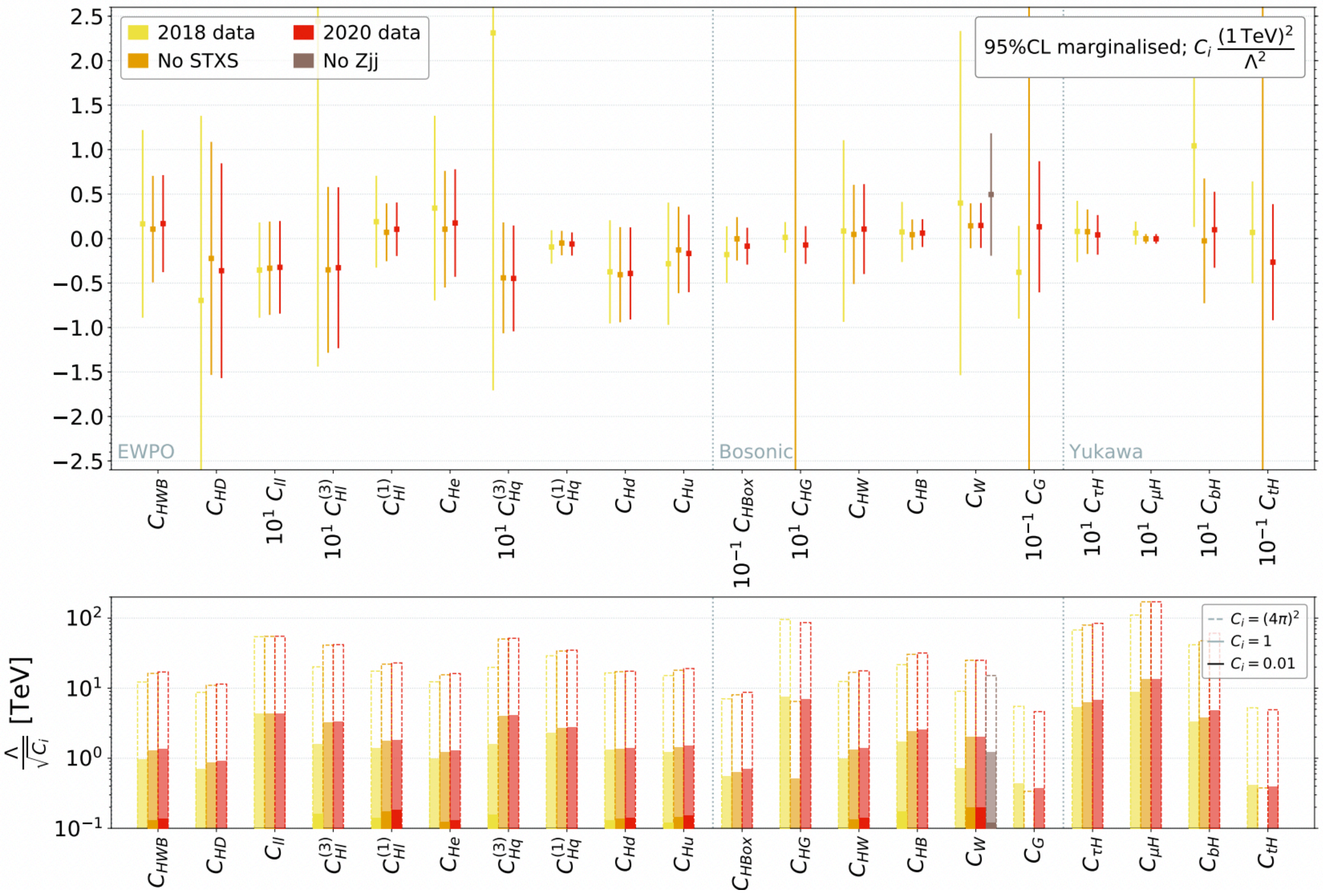


[arXiv:2012.02779]

EFT | Higgs

- STXS also lends itself to wider interpretation

- Significant impact of STXS measurements in global fits
  - More on this later…



[arXiv:2012.02779]

EFT Flavour Assumptions

Starting-point proposal

[LHC EFT WG Meeting]

more restrictive **Top-philic** (extending the 'universal' scenario)

- new physics couples dominantly to bosons+tops
  - e.g. realized in composite Higgs scenarios
- $\mathcal{O}(30)$ CP-even + $\mathcal{O}(10)$ CP-odd d.o.f.
- not radiatively stable

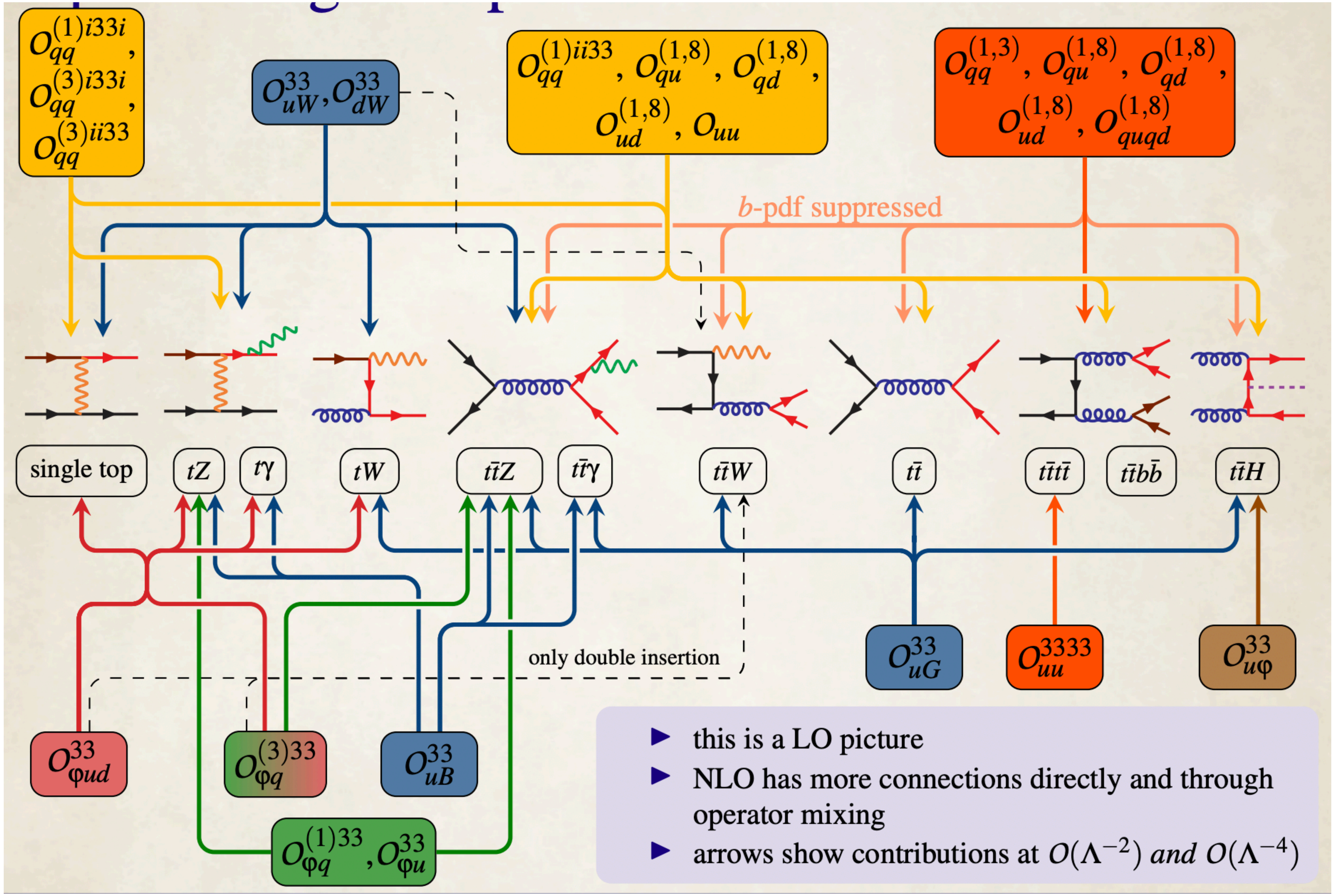
baseline $SU(2)^2_{u,q} \times SU(3)^3_{d,l,e}$

- basically MFV with all breakings neglected apart from y_t
- $\mathcal{O}(100)$ d.o.f. [$\mathcal{O}(180)$ for $SU(2)^3_{q,u,d} \times SU(3)^2_{l,e}$]
- reasonable approx. for dim≤4 too
  - radiatively stable then
  - massless b (5F scheme), no $h \to b\bar{b}$ or $\mu^+\mu^-$

less restrictive **LFU-violating**

- separating e, μ, τ (e.g. $U(1)^3_e \times U(1)^3_l$, $[U(1)_{l+e}]^3$, $U(2)^5$, etc.)
- not needed, a priori, given the limited interplay with B anomalies (only in high-mass Drell-Yan)
- $\mathcal{O}(15)$ Warsaw operators with leptons

Gauthier Durieux – Flavour assumptions – 25 January 2022


$O_{qq}^{(1)i33i}$, $O_{qq}^{(3)i33i}$, $O_{qq}^{(3)ii33}$
O_{uW}^{33}, O_{dW}^{33}
$O_{qq}^{(1)ii33}$, $O_{qu}^{(1,8)}$, $O_{qd}^{(1,8)}$, $O_{ud}^{(1,8)}$, O_{uu}
$O_{qq}^{(1,3)}$, $O_{qu}^{(1,8)}$, $O_{qd}^{(1,8)}$, $O_{ud}^{(1,8)}$, $O_{qudq}^{(1,8)}$
b-pdf suppressed
single top
tZ
$t\gamma$
tW
$t\bar{t}Z$
$t\bar{t}\gamma$
$t\bar{t}W$
$t\bar{t}$
$t\bar{t}t\bar{t}$
$t\bar{t}b\bar{b}$
$t\bar{t}H$
only double insertion
O_{uG}^{33}
O_{uu}^{3333}
$O_{u\varphi}^{33}$
$O_{\varphi ud}^{33}$
$O_{\varphi q}^{(3)33}$
O_{uB}^{33}
$O_{\varphi q}^{(1)33}$, $O_{\varphi u}^{33}$
this is a LO picture
NLO has more connections directly and through operator mixing
arrows show contributions at $O(\Lambda^{-2})$ and $O(\Lambda^{-4})$

EFT | Basics

- SMEFT describes ~all BSM models characterised by a scale Λ ($\gg v(E)$)
- Additions to the SM built from dim>4 operators based on SM fields
- Schematically the Lagrangian is:

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \mathscr{L}_8 + \ldots$$

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SM (dim 4)

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1 lepton number violating parameter

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~100-1000 parameters depending on flavour structure

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30 operators violating lepton/baryon number

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~1000 operators
for N_f=1 scenario

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Scale-suppressed terms

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- In terms of operators and coefficients

$$\frac{\mathscr{L}_6}{\Lambda^2} = \sum_i \frac{C_i \mathscr{O}_i^{d=6}}{\Lambda^2}$$

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- In terms of operators and coefficients
  - **Scale of new physics**
  - **Wilson coefficients**
  - **Dimension 6 operators**

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- Given these Lagrangian terms

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$$\frac{C_i a_i}{\Lambda^2}$$

"Interference terms"

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$$\frac{C_i a_i}{\Lambda^2} \qquad \frac{C_i C_j b_{ij}}{\Lambda^4}$$

"Interference terms" "Quadratic terms"

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  - (For a given Λ, conventionally set to 1 TeV)