Interpreting top quark LHC measurements in SMEFT

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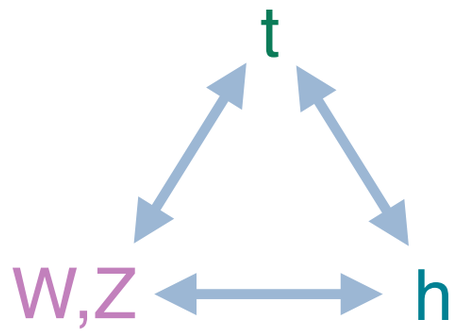
New physics through tops

What is the origin of electroweak symmetry breaking?

Who are the main players?

- Higgs boson, EW gauge bosons & **top quark**
- Most **massive** ⇔ **strongly coupled** to the Higgs



see Andrea's keynote talk

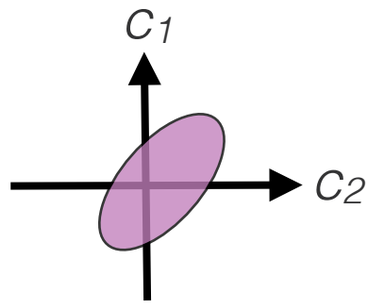
Indirect: new physics is heavy ⇒ modifies top "properties"

- Precision measurements seeking new physics via new interactions
- Complementary to direct searches

Established framework: **SMEFT** $\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^D$

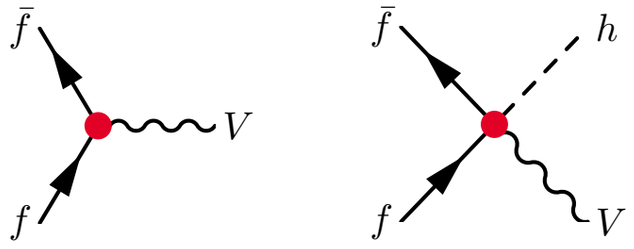
Wealth of top quarks produced at the LHC

- Measure the parameters of the SM up to dimension 6



Top operator glossary

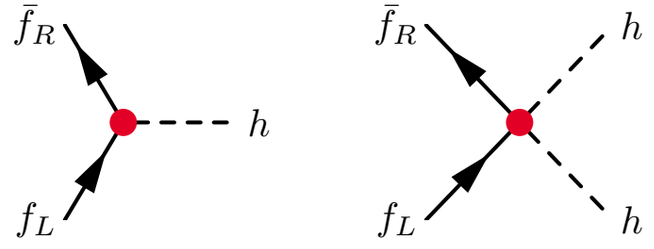
currents $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{Q}\gamma^\mu Q)$



$C_{\phi f}$

- Shift SM $f\bar{f}V$ couplings
- $f\bar{f}Vh$ contact interactions

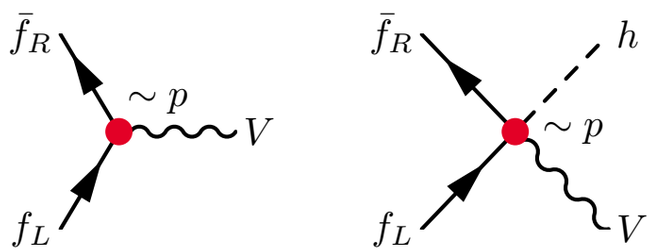
Yukawa $(\bar{q}\, t\, \tilde{\varphi})(\varphi^\dagger \varphi)$



$C_{t\phi}$

- Decouple m_t & y_t
- $t\bar{t}hh(h)$ contact interactions

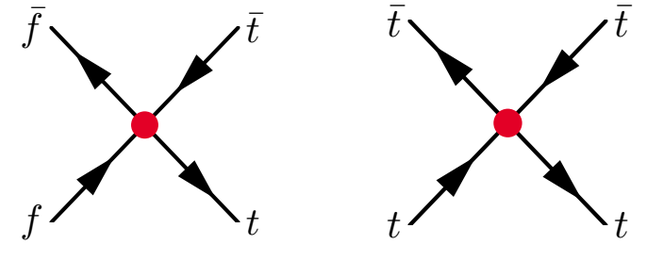
dipole $(\bar{q}\, \sigma_{\mu\nu}\, t\, \tilde{\varphi})V^{\mu\nu}$



C_{tV}

- Chirality flipping $f\bar{f}V$ couplings
- $f\bar{f}V(V)h$ contact interactions
- W, B & G fields

4 fermion $(\bar{q}\gamma_\mu q)(\bar{Q}\gamma^\mu Q)$



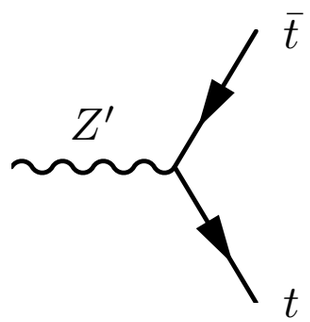
C_{ft}

- Contact interactions
- 2-heavy-2-light or 4-heavy
- Numerous (~O(20) w/ top)

The importance of top data

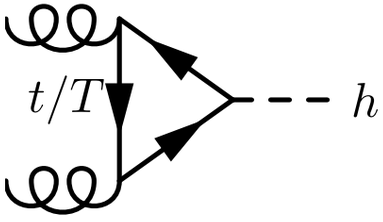
By itself: individual bounds; top data alone

- Determine top quark properties/interactions
- Probe heavy new physics that couples preferentially to tops



Globally: marginalised; top, Higgs, diboson, LEP, … data

- Influence determination of other couplings in EW sector,…
- Probe more realistic models connected to the EWSB puzzle



Model independence ⇔ Global approach

- We don’t know what operators new physics will generate
- Patterns & correlations among operators/observables are key
- Ultimate goal: complete SMEFT likelihood confronted with all HEP data
- Interpret in UV models (Z’, MSSM,…)/scenarios (top-philic, composite t_R…)

see Ilaria's talk later

Fits: status & developments

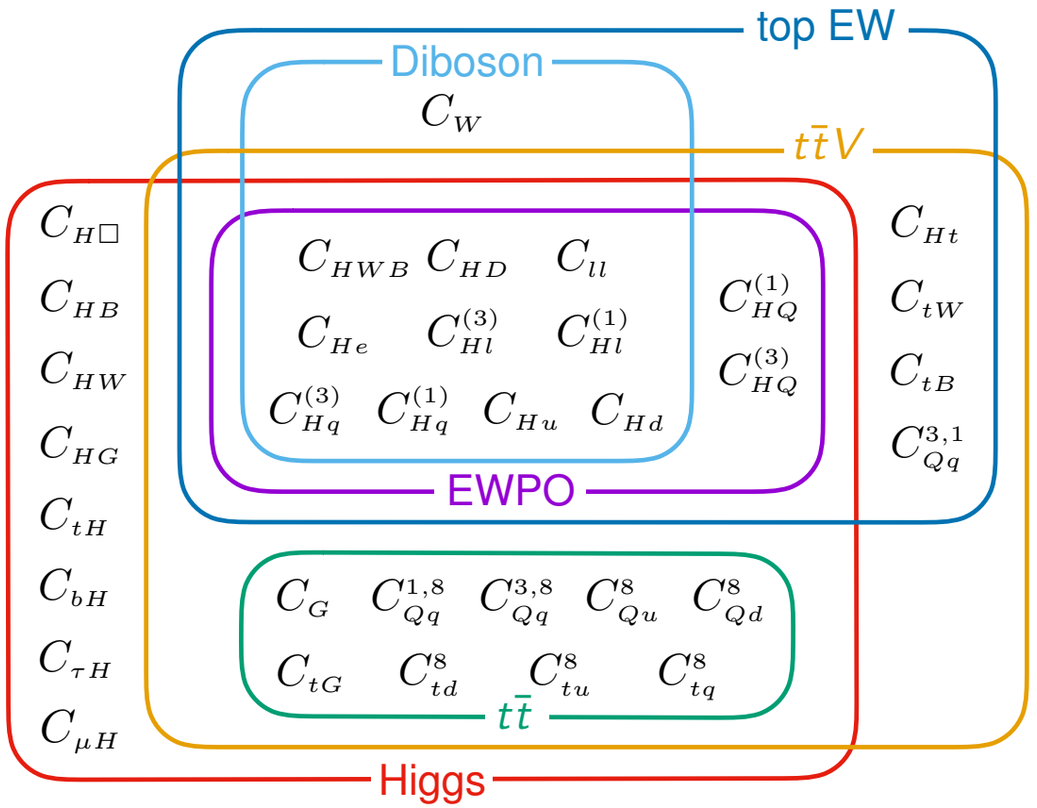
Many SMEFT interpretations in experimental analyses

- Almost every experimental talk so far in this workshop!

Global interpretations

- **Size:** 100s of data points & 10s of operators
- **Precision:** Inclusion of NLO QCD corrections & loop sensitivity
- **Breadth:** First combinations of top, Higgs & EW precision data

[Ellis, Madigan, KM, Sanz, You; JHEP 04 (2021) 279]



Take home message

- Top sector probed around TeV scale
- EW top couplings weakly constrained
- NLO effects can be significant
- EFT validity should be studied

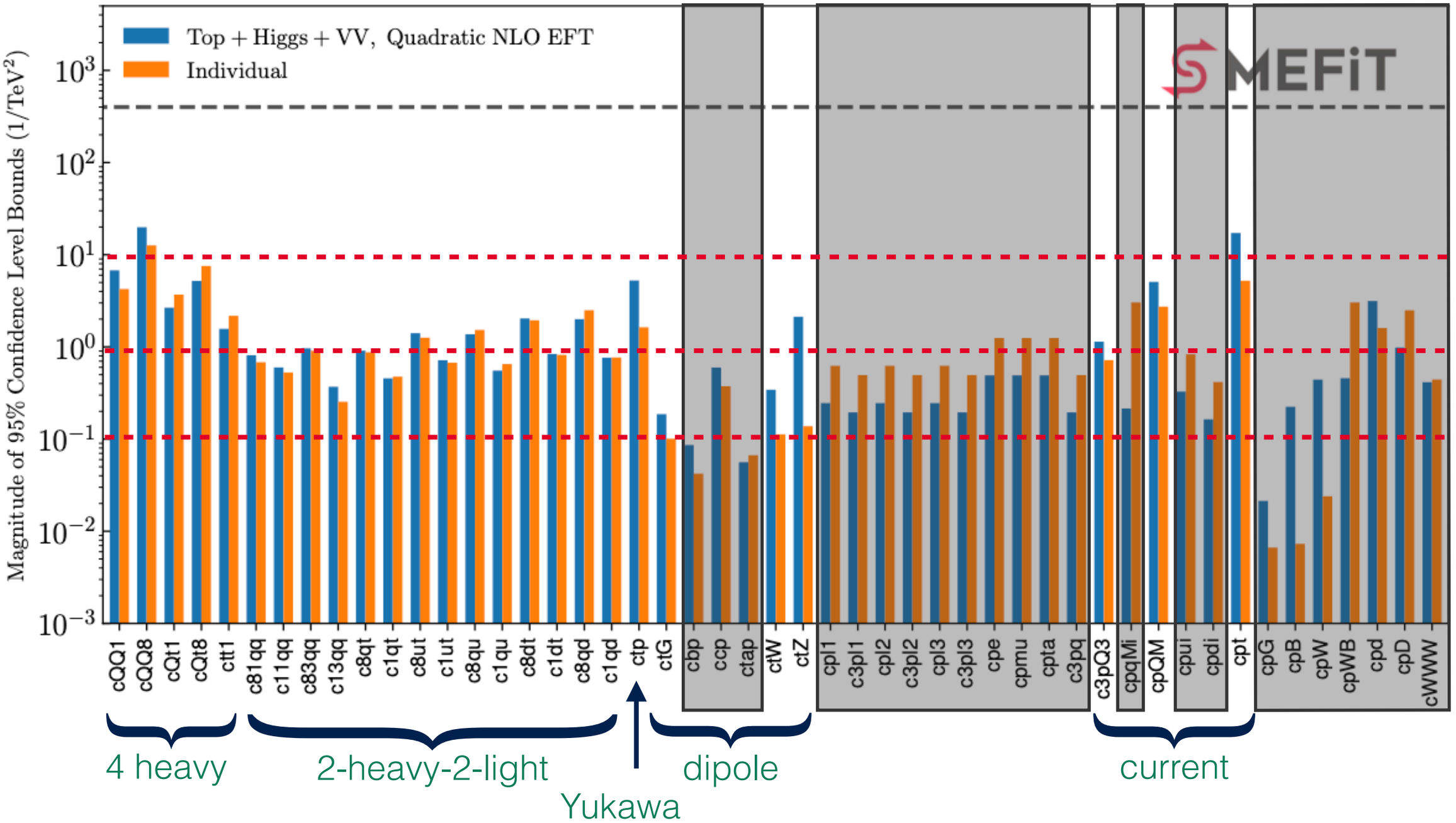
see poster by Luca Mantani today *[Ethier et al.; arXiv:2105.00006]*

see also: [Brivio et al.; JHEP 02 (2020) 131]
[Brown et al.; PoS ICHEP2020 (2021) 322]

Status

Top, Higgs & Diboson w/ ‘perfect’ EWPO

- NLO QCD
- top loop sensitivity



NLO vs LO

[Ethier et al.; arXiv:2105.00006]

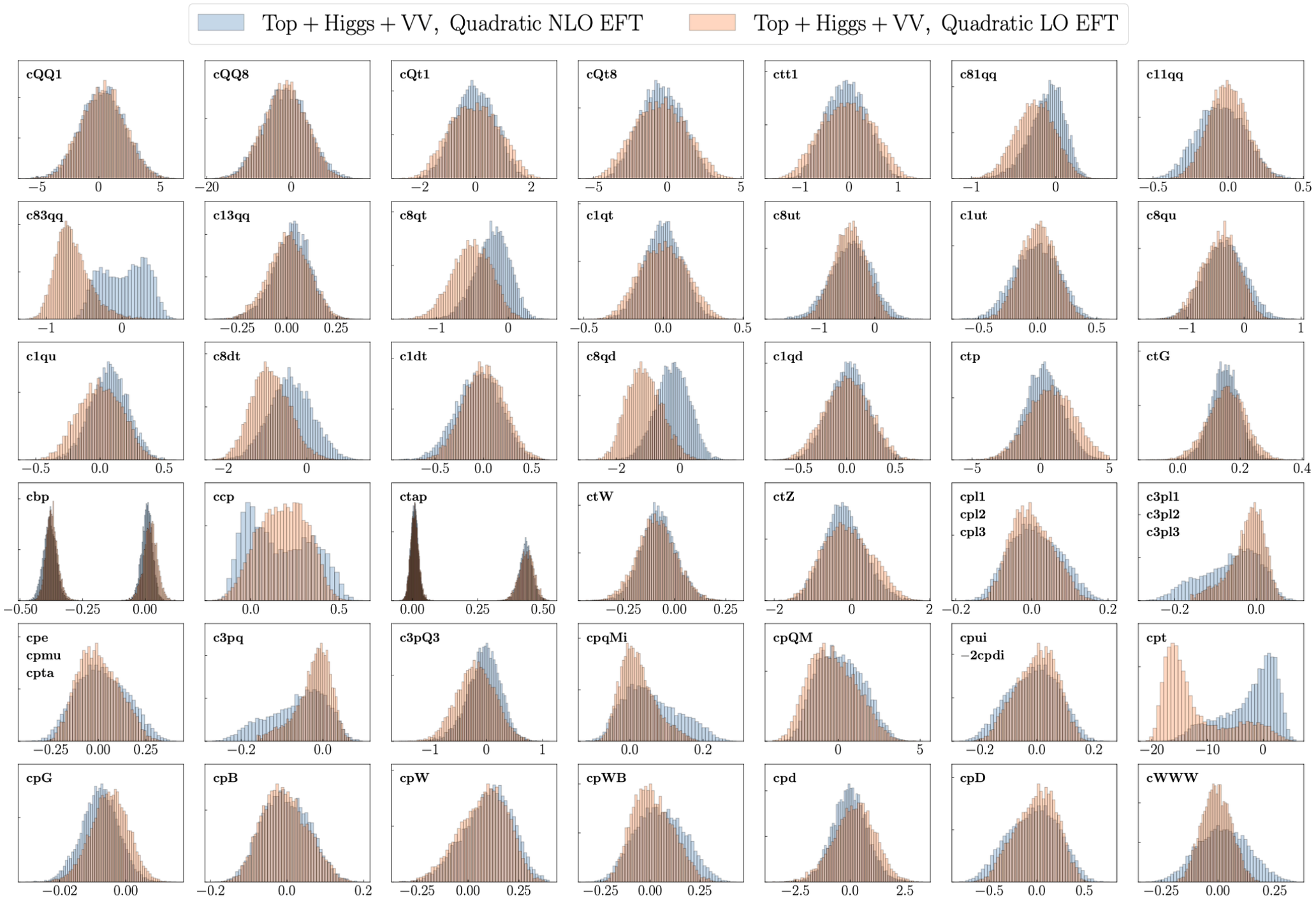
SMEFTatNLO

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

[Degrande et al.; PRD 103 (2021) 9, 096024]

Top is coloured

Non-trivial QCD corrections



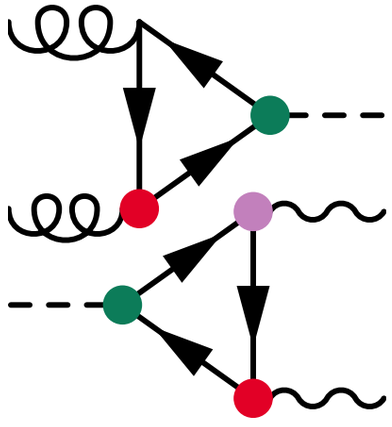
Loop sensitivity

Not just higher precision: new loop-induced sensitivity

- Especially relevant for top loops: most strongly coupled particle
- Weakly constrained directions meet precisely measured observables
- Large allowed Wilson coefficients overcome loop factors

Example: top couplings in hVV vertex

- Yukawa, current & dipole couplings in $gg \to h$ & $h \to \gamma\gamma/Z\gamma$
- (Weakly) constrained at tree-level by $t\bar{t}\gamma/Z/H$ & $t\bar{t}$



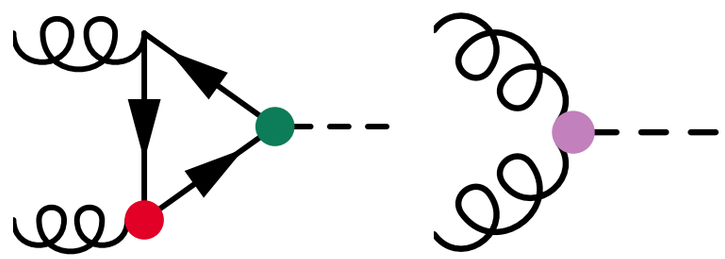
SMEFiT: individual bounds dominated by Higgs data!

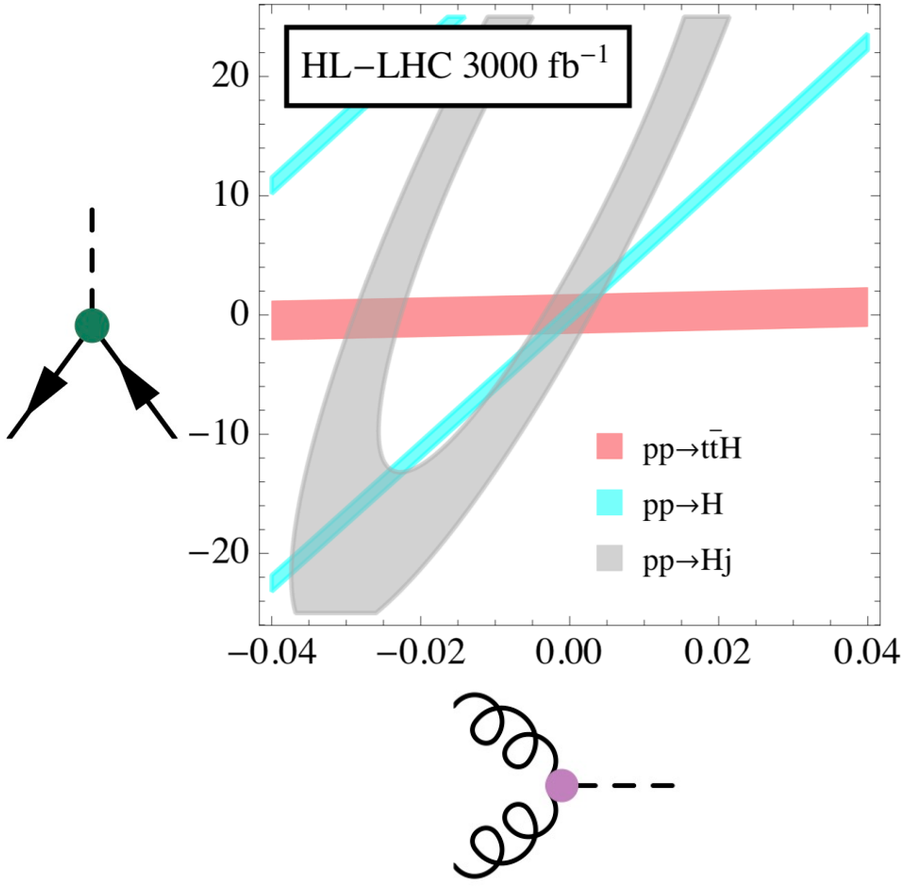
- Weak dipoles & $Z\bar{t}t$ current operators $\left(C_{tW}, C_{tZ}, C_{\varphi Q}^{(-)}, C_{\varphi Q}^{3}, C_{\varphi t}\right)$
- Also contributions to $gg \to Zh/ZZ/Z\gamma/WW$
- Complementary direct sensitivity from non-top data

Top-Higgs interplay

Top data indirectly improves Higgs coupling measurements

- $gg \to h$ has 3 relevant new interactions
- Yukawa, dipole & contact term
- Degeneracy in coefficient/theory space





[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

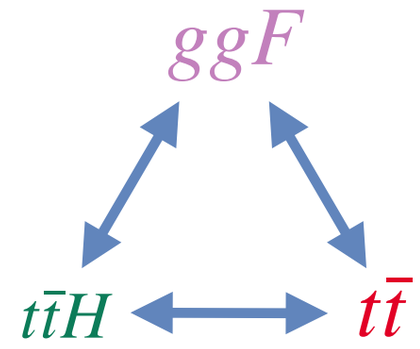
Cannot rule out heavy particles in the loop

$t\bar{t}$ and $t\bar{t}h$ data can help

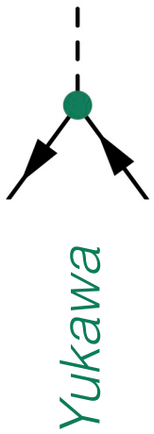
- Constrain dipole & Yukawa, respectively

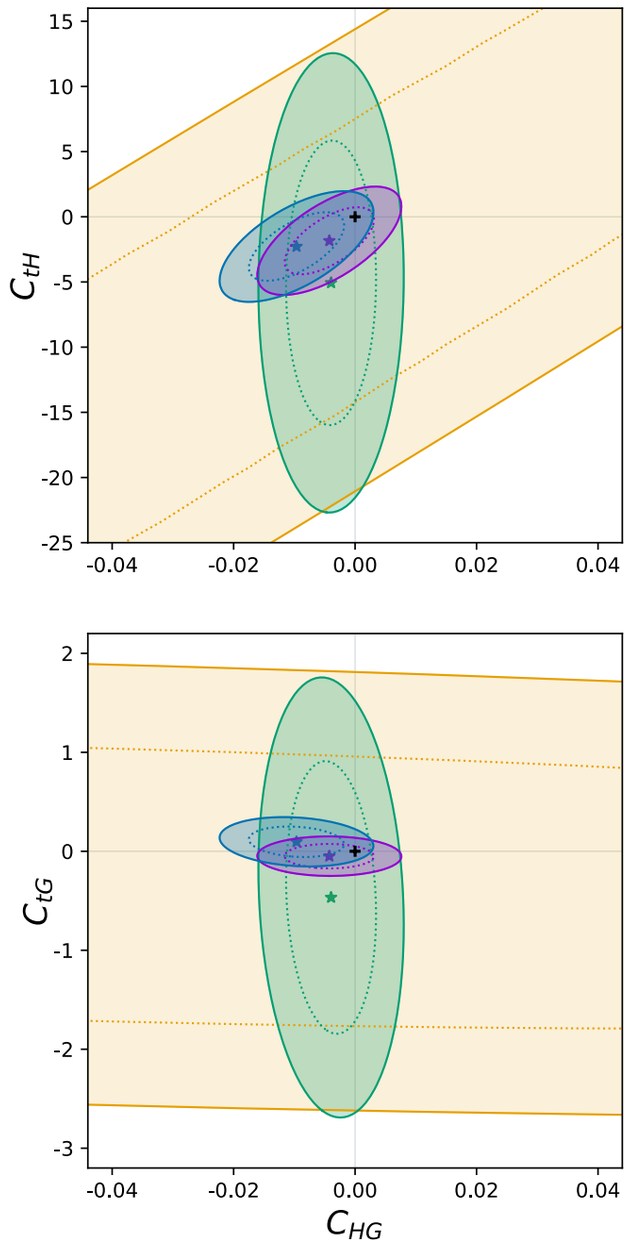
What about 4 fermion ops.?

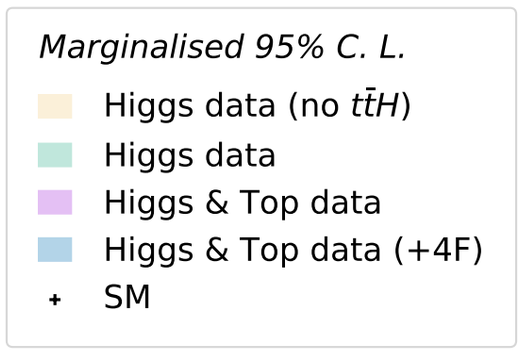
- Do they limit ultimate sensitivity?

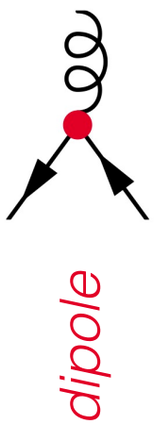


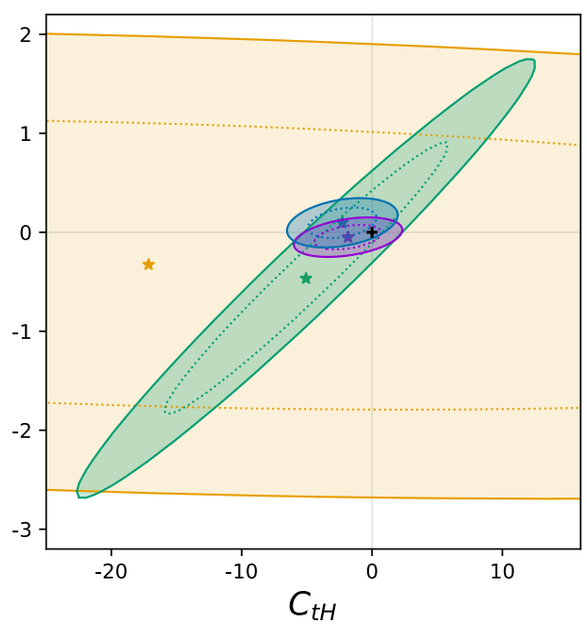
Top-Higgs interplay

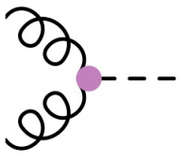


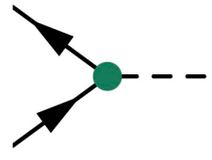












Fit: Higgs SS & STXS $\mathcal{O}(\Lambda^{-2})$

8 Higgs operators + C_{tG}

- Marginalised confidence regions
- Significant impact of $t\bar{t}H$ & $t\bar{t}(V)$

Now add in $t\bar{t}$ 4F operators

+ $C_{Qq}^{3,8}, C_{Qq}^{1,8}, C_{Qu}^{8}, C_{Qd}^{8}, C_{tq}^{8}, C_{tu}^{8}, C_{td}^{8}$

- Relatively mild impact
- Preferred $t\bar{t}$ phase space is different

C_{tG} : low $m_{t\bar{t}}$ *J. Erdmann's talk today*

$4F$: high $m_{t\bar{t}}$

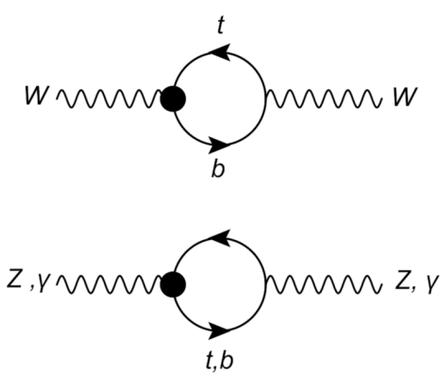
- Able to constrain them independently

Top data is crucial!

More loop sensitivity

Several other processes have been studied

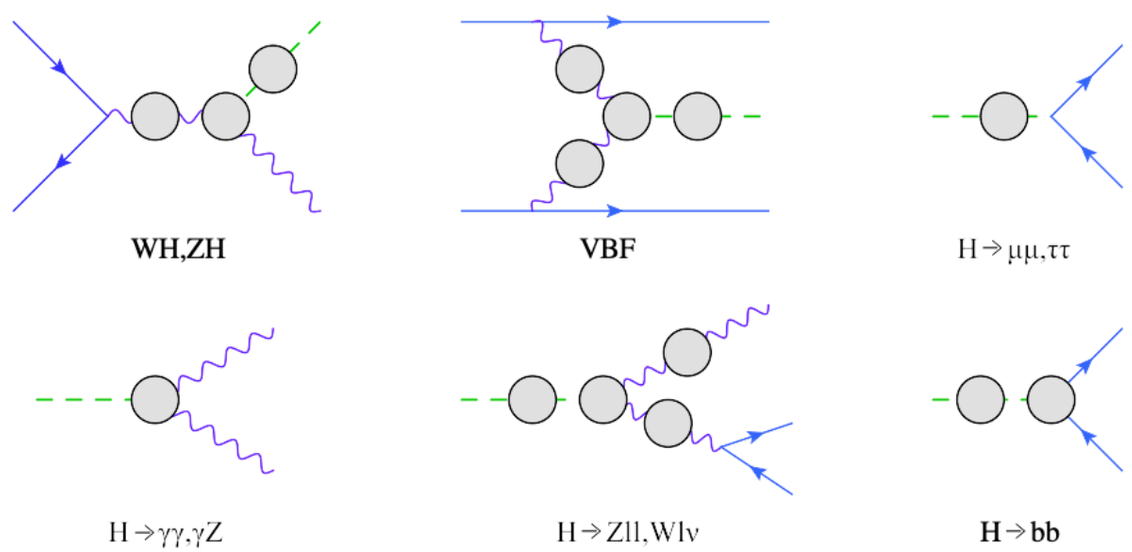
Z-pole observables



[Zhang, Greiner & Willenbrock; PRD 86 (2012) 014024]

EW Higgs production & decay

[Zhang & Vryonidou; JHEP 08 (2018) 036]



Not yet fully combined in a fit

- NLO EW calculations
- Next frontier in precision SMEFT fits
- Impact of 4F operators not calculated
- Automated technology emerging
- Strengthen correlations between top, EWPO & Higgs data

Others? Diboson, Drell-Yan, …

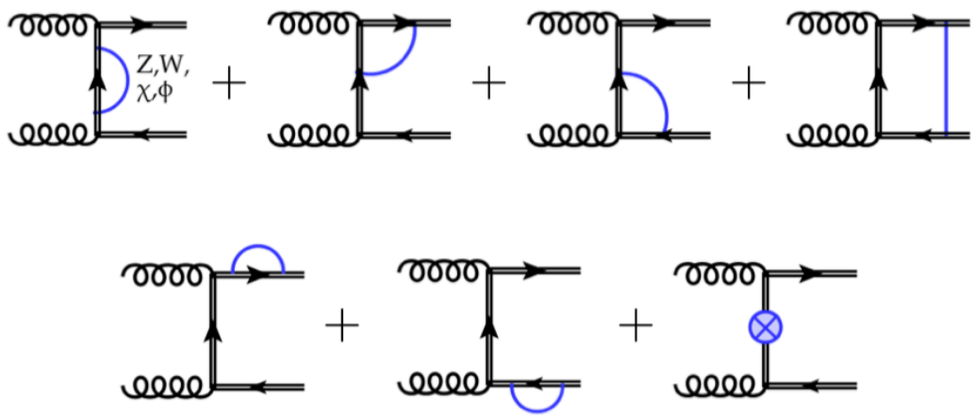
Loop sensitivity in top data

Need precision measurements ⇒ $t\bar{t}$ production

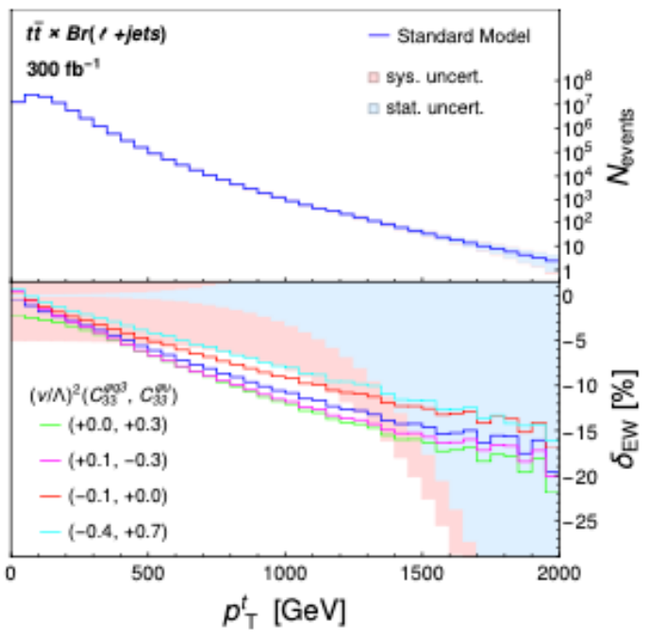
- Few-percent-level precision at LHC

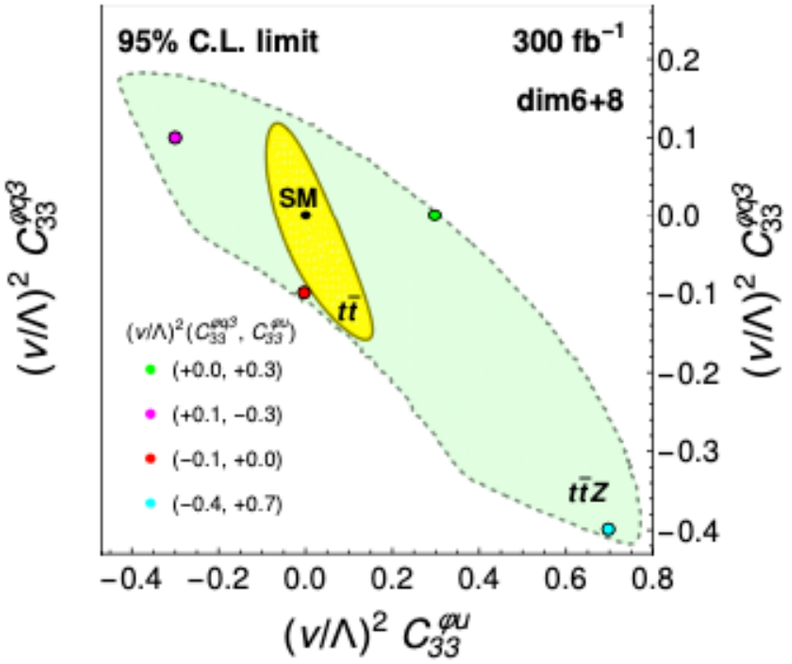
EW top couplings: loops of tops & EW gauge bosons

- Enhanced at high energy by logarithms of $\hat{s}/m_V^2$



[Martini & Schulze; JHEP 04 (2020) 017]

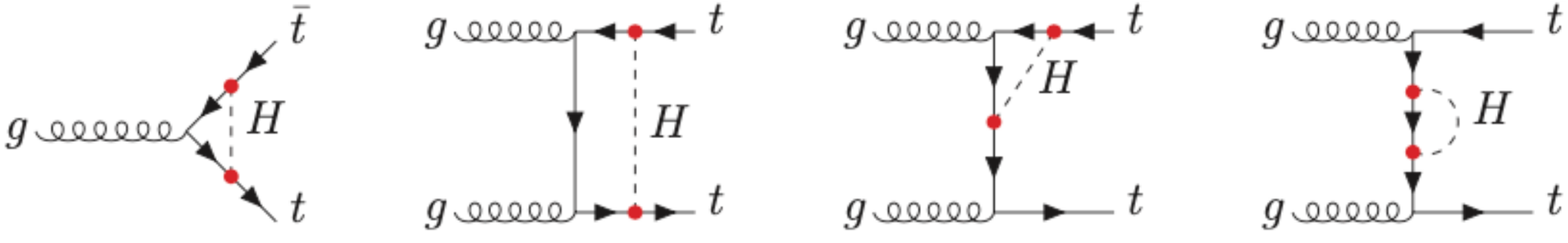




Promising sensitivity to current operators

- Better than $t\bar{t}Z$ prospects using $\Delta\phi_{\ell\ell}$ distribution with 300 fb^{-1}

y_t in $t\bar{t}$

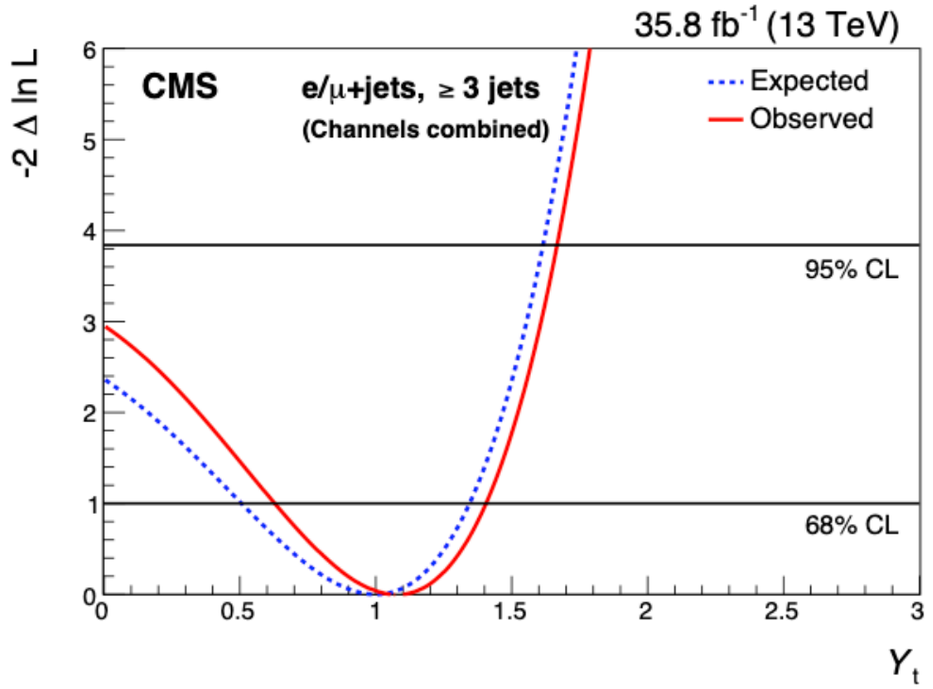


Top Yukawa coupling

- Electroweak corrections to $t\bar{t}$ known for ~ 15 years
- Proposal to constrain y_t recently carried out by CMS
- Double differential $\left(m_{t\bar{t}}, |\Delta y_{t\bar{t}}|\right)$ measurement

[Kühn, Scharf & Uwer; PRD 91 (2015) 1, 014020]
[PRD 100, 072007 (2019)]

Channel	Best fit Y_t		95% CL upper limit	
	Expected	Observed	Expected	Observed
3 jets	$1.00^{+0.66}_{-0.90}$	$1.62^{+0.53}_{-0.78}$	<2.17	<2.59
4 jets	$1.00^{+0.50}_{-0.72}$	$0.87^{+0.51}_{-0.77}$	<1.88	<1.77
≥5 jets	$1.00^{+0.59}_{-0.83}$	$1.27^{+0.55}_{-0.74}$	<2.03	<2.23
Combined	$1.00^{+0.35}_{-0.48}$	$1.07^{+0.34}_{-0.43}$	<1.62	<1.67

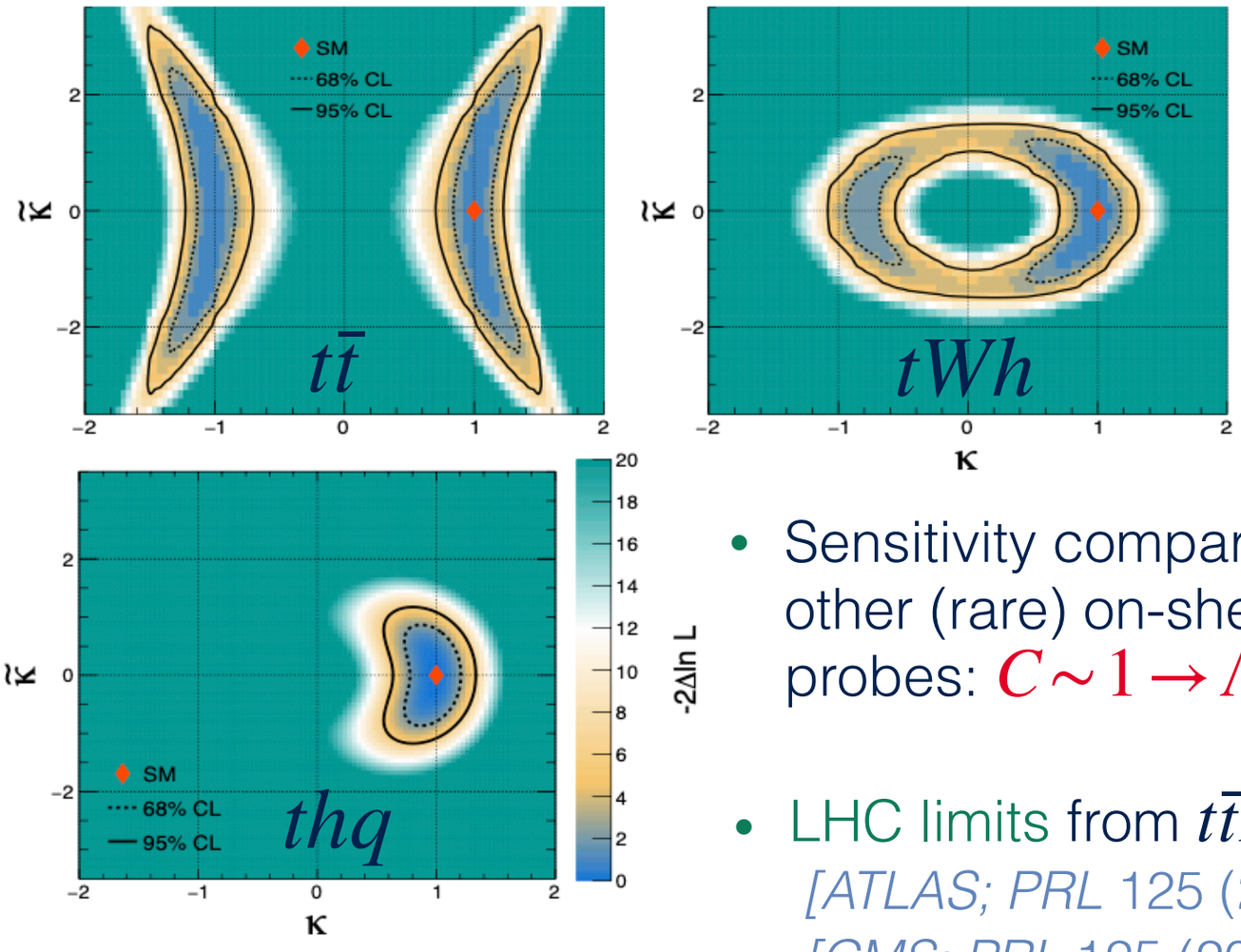


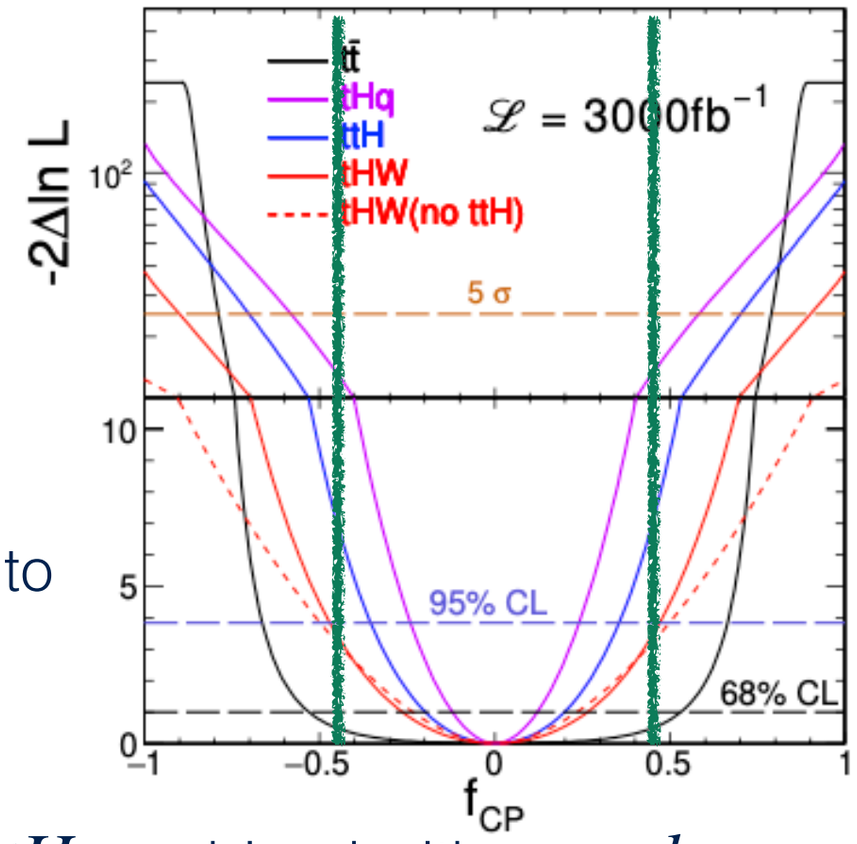
[Martini et al.; arXiv:2104.04277]

$\tilde{y}_t$ in $t\bar{t}$

Recently extended to include CP-odd component

$$-\frac{m_t}{v}\bar{\psi}_t\left(\kappa + \mathrm{i}\,\tilde{\kappa}\gamma_5\right)\psi_t\, H \Leftrightarrow \kappa = 1 - \frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Re}\left[C_{tt}^{u\varphi}\right], \quad \tilde{\kappa} = -\frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Im}\left[C_{tt}^{u\varphi}\right]$$





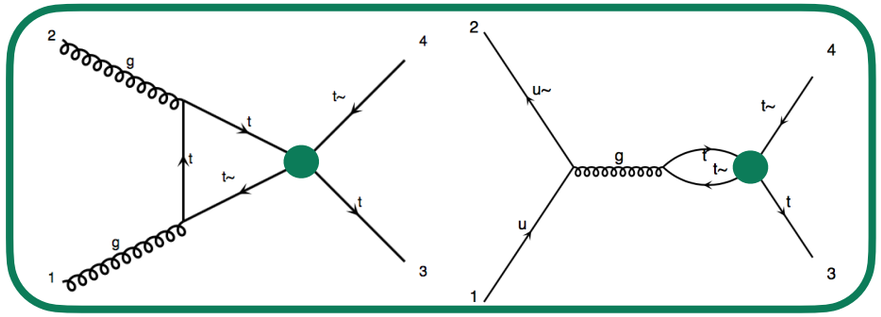
- Sensitivity comparable to other (rare) on-shell probes: $C \sim 1 \rightarrow \Lambda \sim v$
- LHC limits from $t\bar{t}H + tH$ combined with $gg \rightarrow h \rightarrow \gamma\gamma$

[ATLAS; PRL 125 (2020) 6, 061802]
[CMS; PRL 125 (2020) 6, 061801]

only 139 fb^{-1}!

[Degrande et al.; PRD 103 (2021) 9, 096024]

4 tops in $t\bar{t}$



$\sigma(pp \to t\bar{t})$ [pb], $c_i/\Lambda^2 = 1\,\text{TeV}^{-2}$

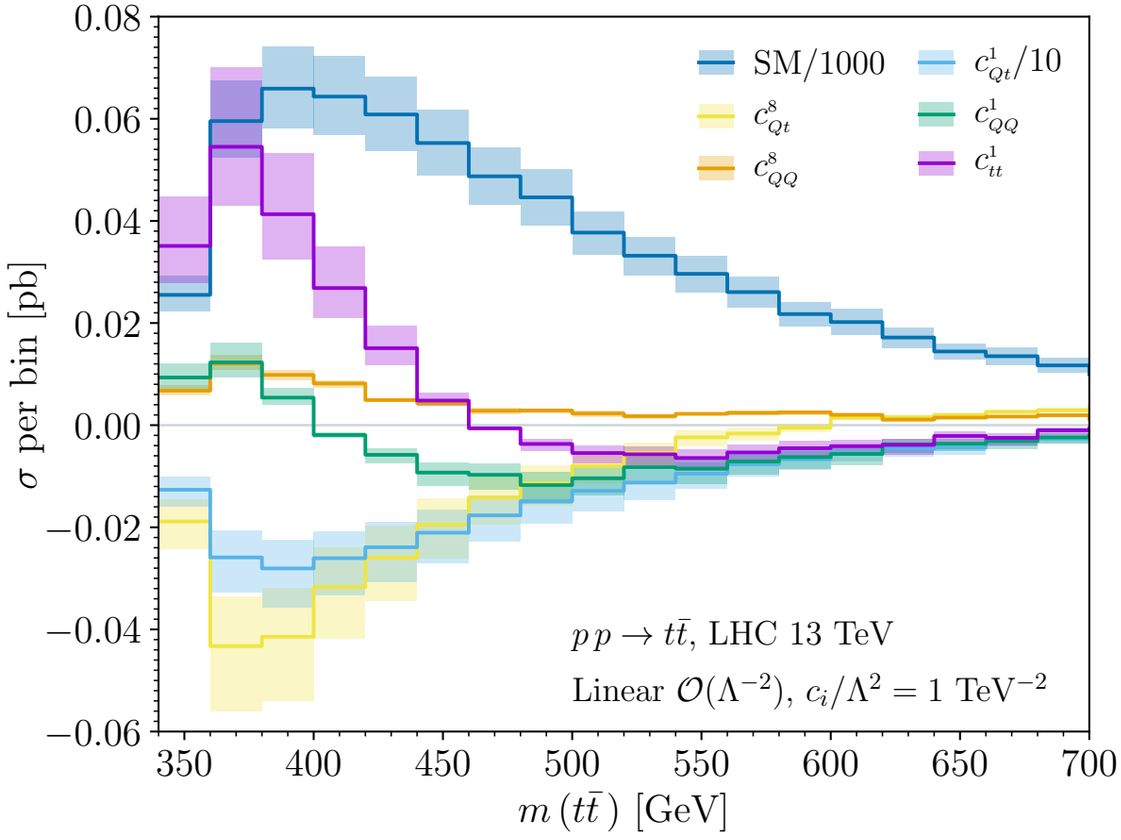
c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO		$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO
c^8_{QQ}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c^8_{Qt}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c^1_{QQ}	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-38\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
c^1_{Qt}	$[-0.068^{+16\%}_{-18\%}]$	$-2.51^{+29\%}_{-21\%}$	$[-0.12^{+3\%}_{-6\%}]$	$0.0283^{+13\%}_{-16\%}$	$0.066^{+5\%}_{-6\%}$
c^1_{tt}	×	$0.215^{+23\%}_{-18\%}$		×	×

Weakly constrained by $t\bar{t}t\bar{t}$

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

[CMS; JHEP 11 (2019) 082]

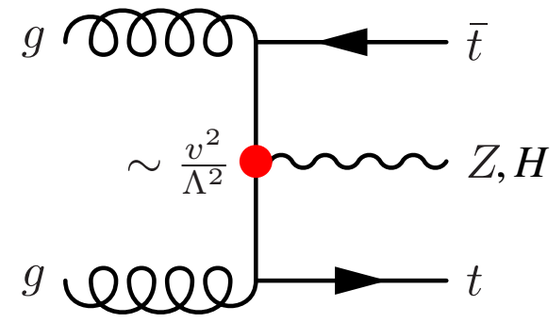
- $q\bar{q} \to t\bar{t}$: mixing with $q\bar{q}t\bar{t}$ ops.
  $(\bar{t}\gamma^\mu t)(\bar{t}\gamma_\mu t) \to (\bar{t}\,\gamma^\mu\, T_A D^\nu\, t)\, G^A_{\mu\nu}$
- $gg(b\bar{b}) \to t\bar{t}$: finite(small) contribution
- 1-2 orders smaller than $q\bar{q}t\bar{t}$ (tree) ops.
- Large contribution for c^1_{Qt} -
  similar size to $q\bar{q}t\bar{t}$ operators!
- Main effect near threshold ~ percent level
  effect assuming current bound ~ 3.5



High energy & multiplicity

Improving sensitivity = collect more data. Is it enough?

$t\bar{t}X$ for Yukawa & neutral current operators



- EFT effect $\propto v^2/\Lambda^2$, no energy growth (SM-kinematics)
- EFT × SM interference often suppressed
  [Azatov et al.; PRD 95 (2017) no. 6, 065014]

$$\mathcal{A} \sim \mathcal{A}_{SM}\left(1 + c_i\frac{v^2}{\Lambda^2} + c_j\frac{v\,E}{\Lambda^2} + c_k\frac{E^2}{\Lambda^2}\right)$$

'Energy helps accuracy'
[Farina et al.; PLB 772 (2017) 210-215]

Rate measurements will become systematics dominated

Increasingly high-energy measurements scale with lumi.

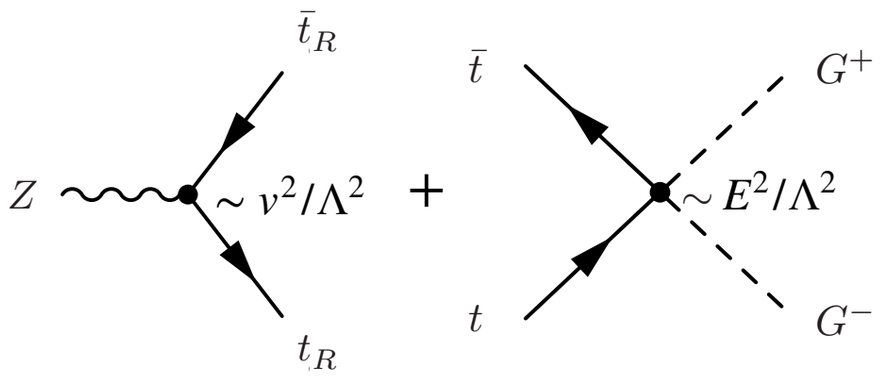
There will always be some scattering amplitude that displays maximal (E^2) growth w.r.t the SM

[Dror et al.; JHEP 01 (2016) 071]
[Mantani, Maltoni & KM; JHEP 10 (2019) 004]

Finding the right process

Exploit Goldstone equivalence theorem: $\partial^\mu G \leftrightarrow V_L^\mu$

$C_{Ht}\, i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R) \Rightarrow$

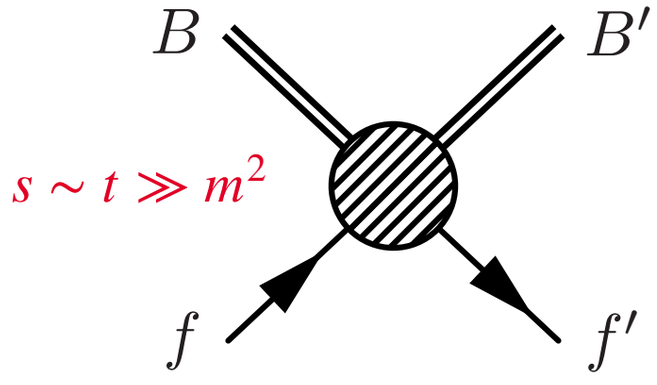


$$
\begin{aligned}
t\,W_L &\to t\,W_L \\
t\,Z_L &\to t\,h \\
b\,W_L &\to t\,Z_L \\
b\,W_L &\to t\,h
\end{aligned}
$$

Unitarity non-cancellations in scattering amplitudes ⇔ **Non-renormalisable contact interactions with Goldstones**

c.f. 'Higgs without Higgs' [Henning et al.; PRL 123 (2019) 181801]

Less vevs, more legs! (AKA multiplicity)



High energy EW top scattering

	Single-top	Two-top ($t\bar{t}$)
w/o Higgs	$b\,W \to t\,(Z/\gamma)$	$t\,W \to t\,W$ $t\,(Z/\gamma) \to t\,(Z/\gamma)$
w/ Higgs	$b\,W \to t\,h$	$t\,(Z/\gamma) \to t\,h$ $t\,h \to t\,h$

EW top scattering

gauge/higgs operators $\Longleftarrow \quad \Longrightarrow$ *top operators*

Energy-growing interference

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

single-top

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

two-top w/o Higgs

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

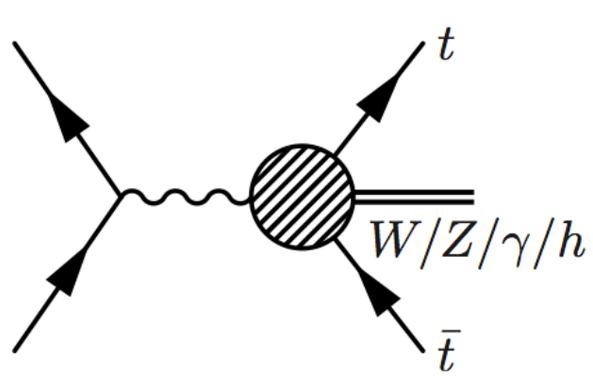
two-top w/ Higgs

Most top operators show max growth somewhere

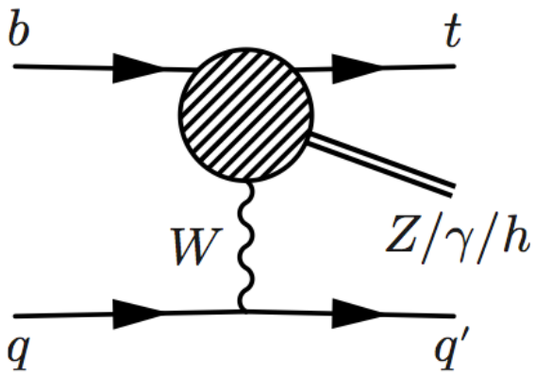
- Interfering growth rare, only in longitudinal configurations (c.f. helicity selection)

Embedding the amplitudes

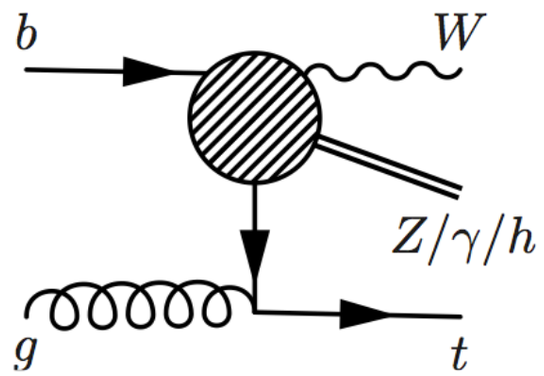
Collider processes: **high multiplicity, EW top production**



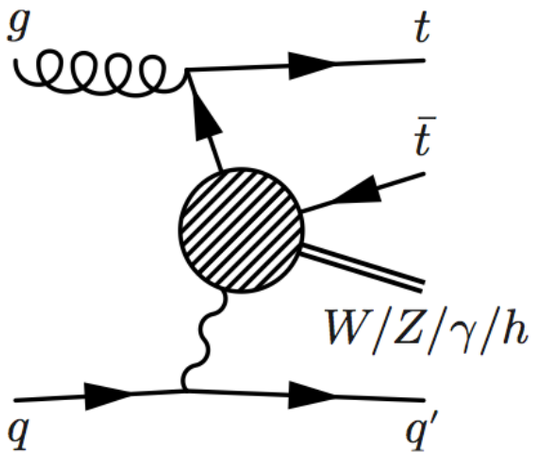
(a) $t\bar{t}X$



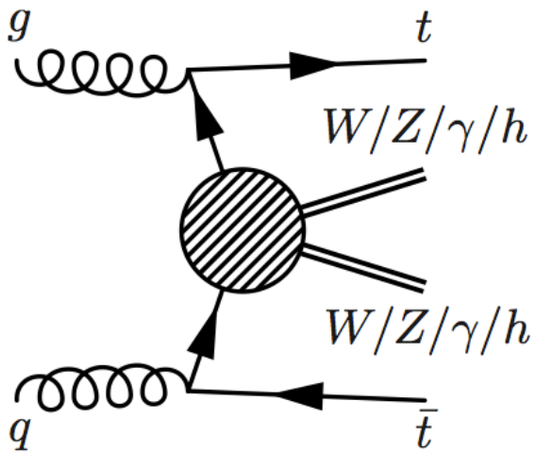
(b) tXj



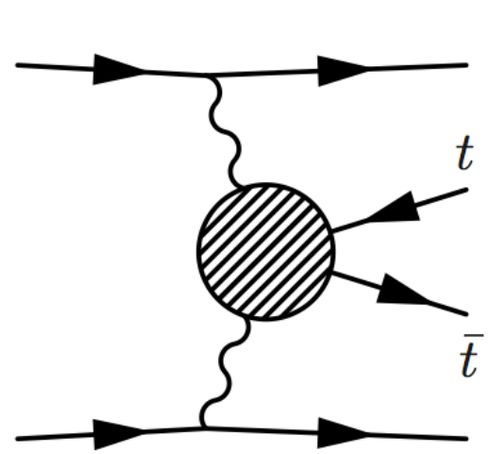
(c) tWX



(d) $t\bar{t}Xj$

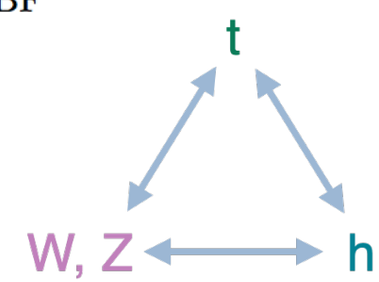


(e) $t\bar{t}XY$



(f) VBF

Couplings { top EW, Higgs, triple gauge } ⇒ Heart of EWSB sector



Top EW scattering pheno

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

single-top

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

two-top w/o Higgs

	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

two-top w/ Higgs

Talk by Hesham El Faham in YSF on Friday

Prospects & challenges

EW top scattering: promising avenue for fingerprinting EWSB

- Go beyond rate measurements & access energy growth/unitarity violation
- Increasingly high energy & multiplicity processes: future-proof
- Rare EW top modes: probe complimentary directions in SMEFT space
- Some already measured or within LHC reach ($t\bar{t}Wj, tHj, tWZ, \ldots$)
- Others challenging, dedicated pheno studies required

Sig.	Bkg.
$t\bar{t}Z(\ell^+\ell^-)$	$t\bar{t}W$, $t\bar{t}H$, tZj, WZ,...
$t\bar{t}H(b\bar{b})$	$t\bar{t}Z$, $t\bar{t}b\bar{b}$, $t\bar{t}W$, tZj,...
$t\bar{t}H(\gamma\gamma)$	$t\bar{t}$, $b\bar{b}H$, tHj, tHW
$t\bar{t}H(\tau^+\tau^-)$	$t\bar{t}W(W)$, $t\bar{t}Z$,...
tZj	$t\bar{t}V$, tHj, tHW, tZW,...
tHj	$t\bar{t}H$, $t\bar{t}Z$, $t\bar{t}b\bar{b}$, $t\bar{t}W$, tZj,...
$t\bar{t}t\bar{t}$	$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$,...

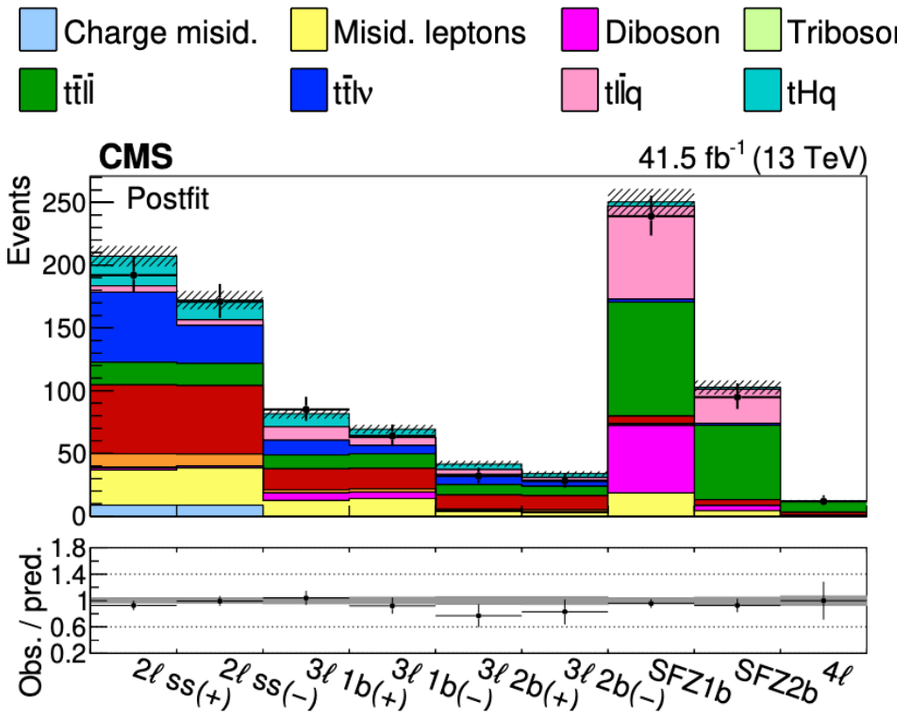
Sig/Bkg. overlap ⇒ global measurements

- SMEFT contributes everywhere… blurs the lines
- Challenging to incorporate into global likelihood
- From individual to simultaneous measurements
- Signal regions based on final state properties

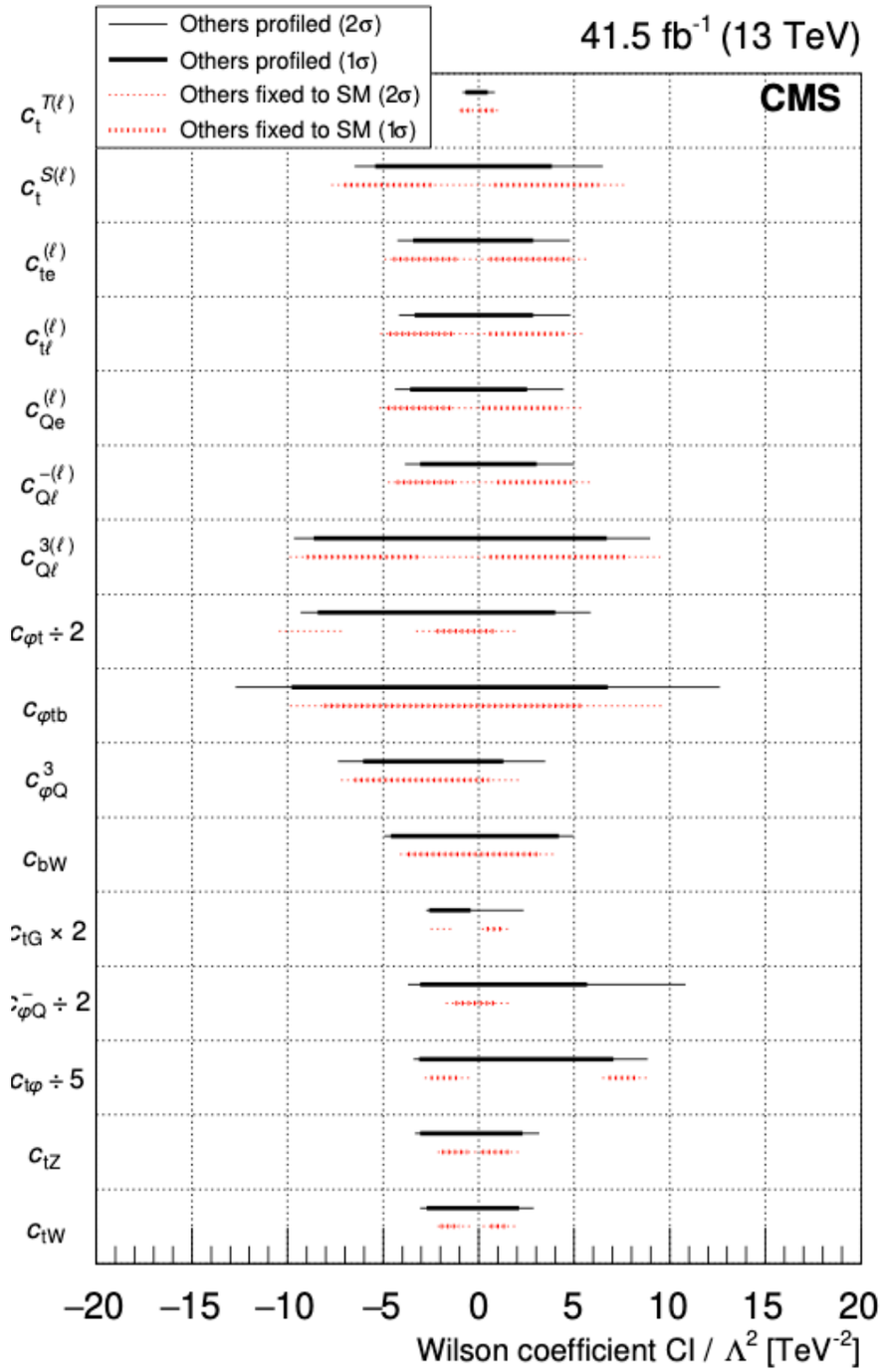
Global measurements

Several examples in top analyses

- $t\bar{t}H + tH(+tWH)$, $t\bar{t}\gamma + tW\gamma$, …
- The first truly global measurement:



Operators:
currents
dipoles
$t\bar{t}\ell\ell$ 4 fermion



- Signal categories: # leptons, SS/SF, # b-jets,…
- Future: expand categories & probe high energy region

Conclusions

The future is bright for top physics in SMEFT

- Global SMEFT analyses are rapidly expanding & probing model space
- New precision tools available (**`SMEFTatNLO`**): NLO & loop-induced effects
- Being incorporated into experimental interpretations
- Rare EW top production: high energy & high multiplicity
- Towards global measurements for global fits

Things I couldn't mention!

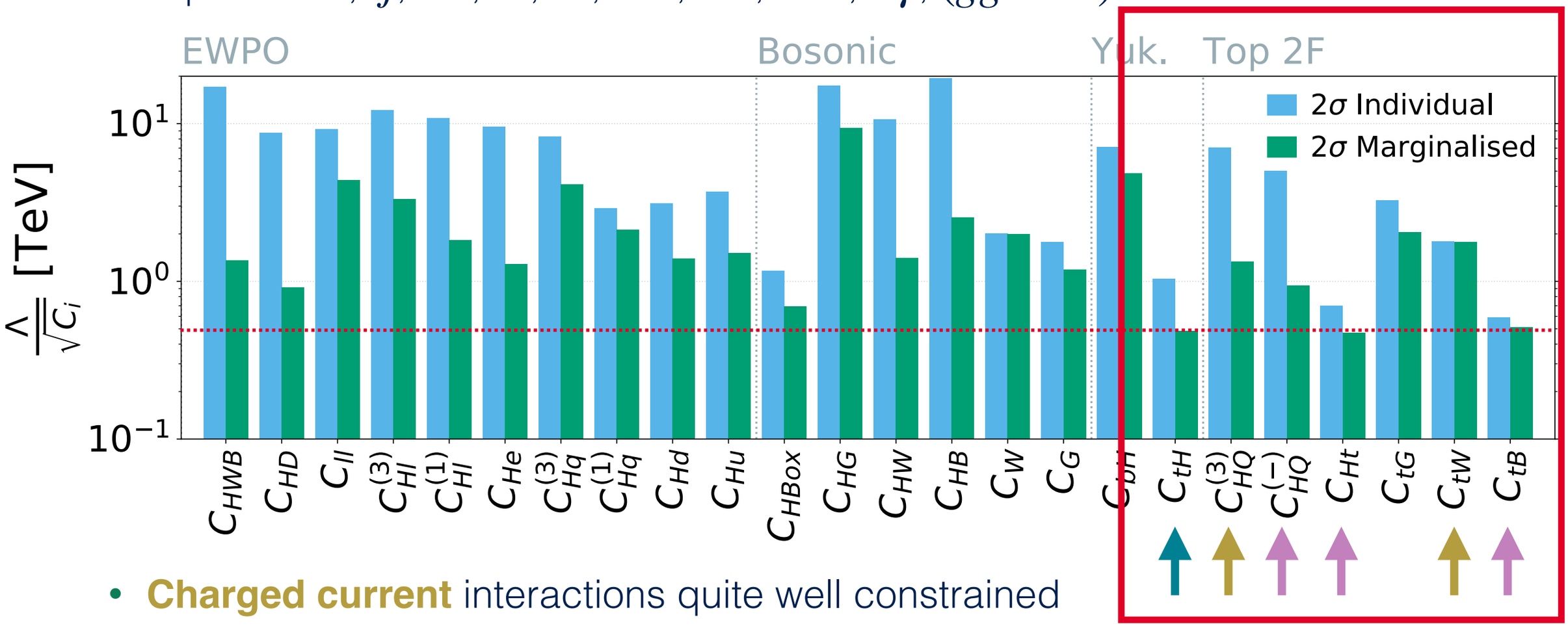
- Future direction: global study on CP violating operators in top data
- Fantastic progress in UV model interpretations of global fits
- Automated matching tools available *[Ethier et al.; arXiv:2105.00006]*
- Very important for testing validity *[Ellis, Madigan, KM, Sanz, You; JHEP 04 (2021) 279]*
  [Brivio et al.; arXiv:2108.01094]

Backup

How poorly?

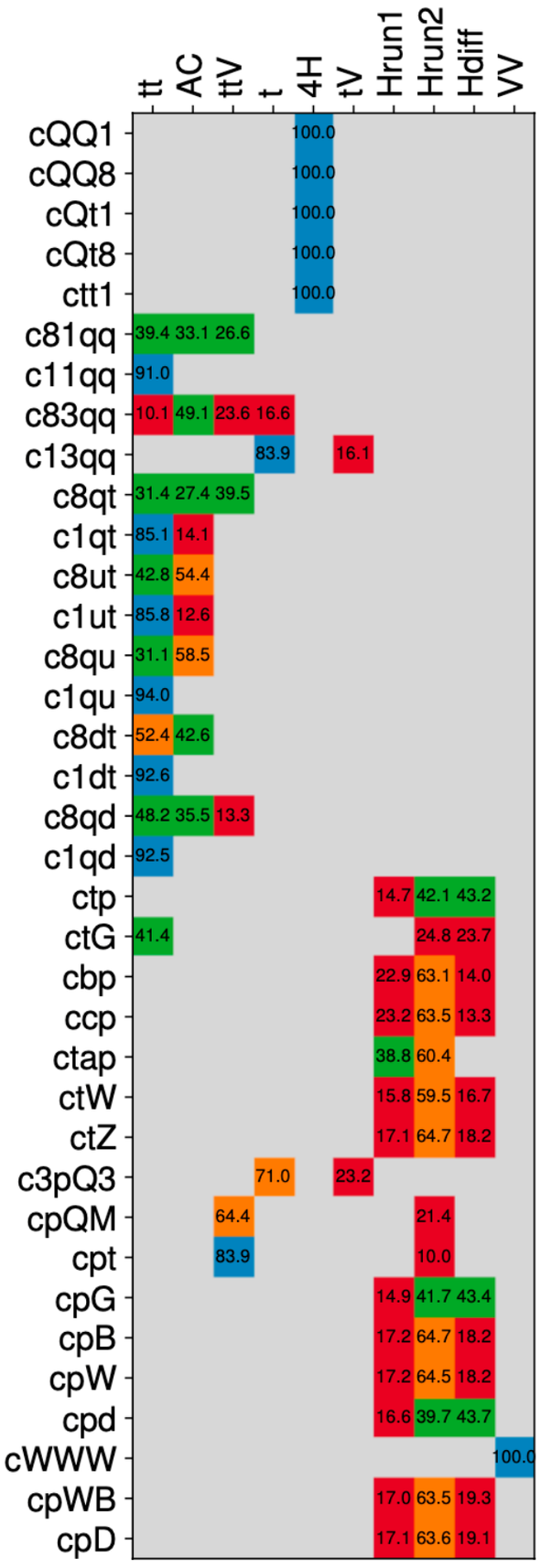
Global SMEFT fit to EWPO, Higgs, Diboson, top (34 d.o.f.)

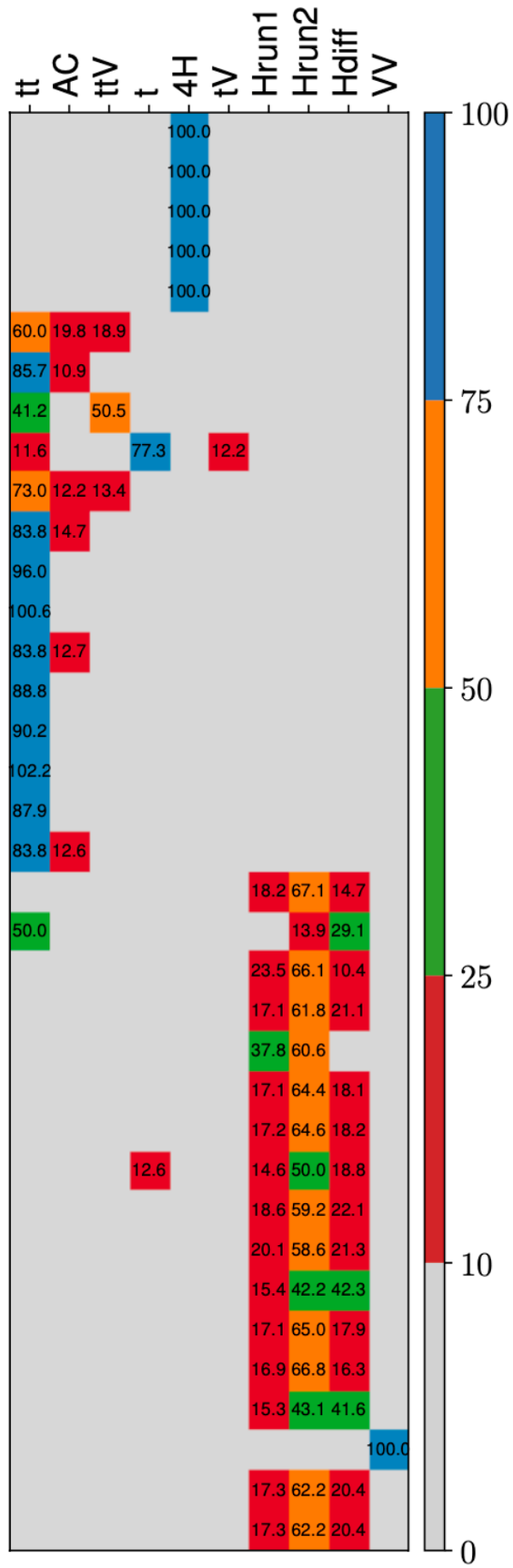
- Top data: $t\bar{t}$, tj, tW, $t\bar{b}$, tZ, $t\bar{t}H$, $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}\gamma$, $(gg \to h)$



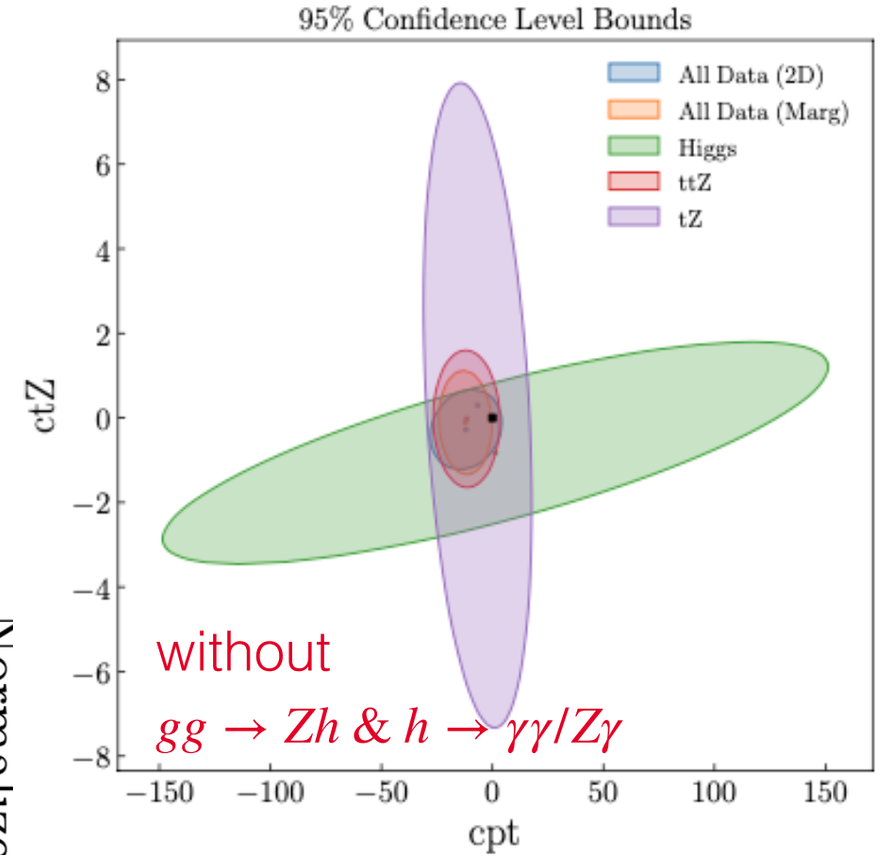
- **Charged current** interactions quite well constrained
- **Yukawa** and **neutral current** are among the worst

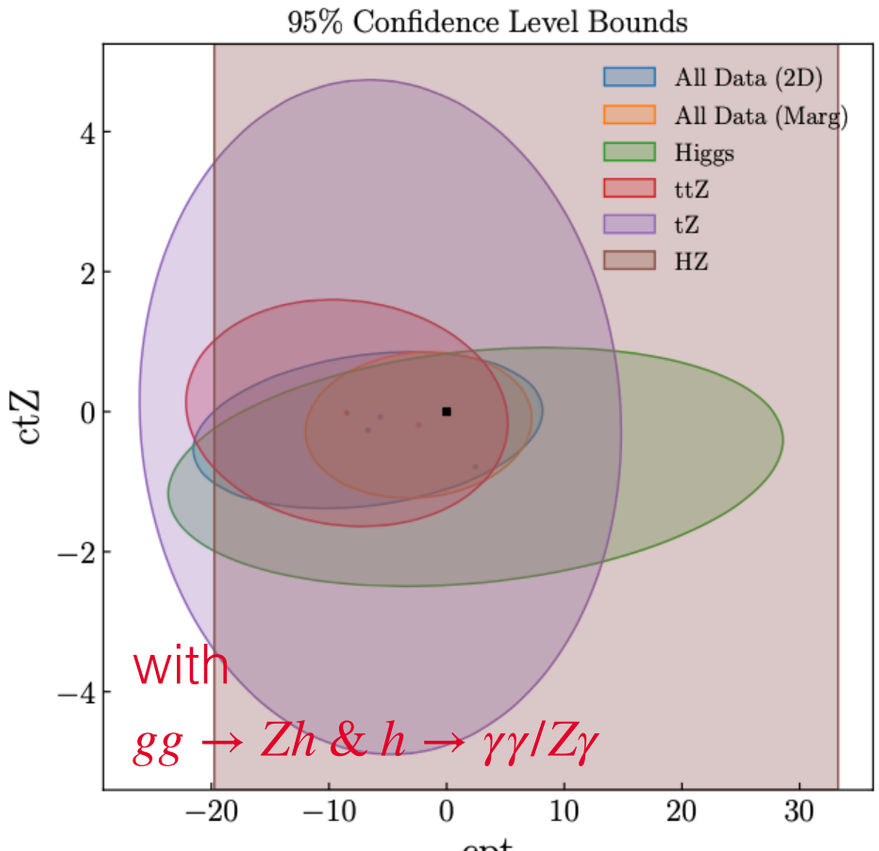
How can we improve?





Normalized value

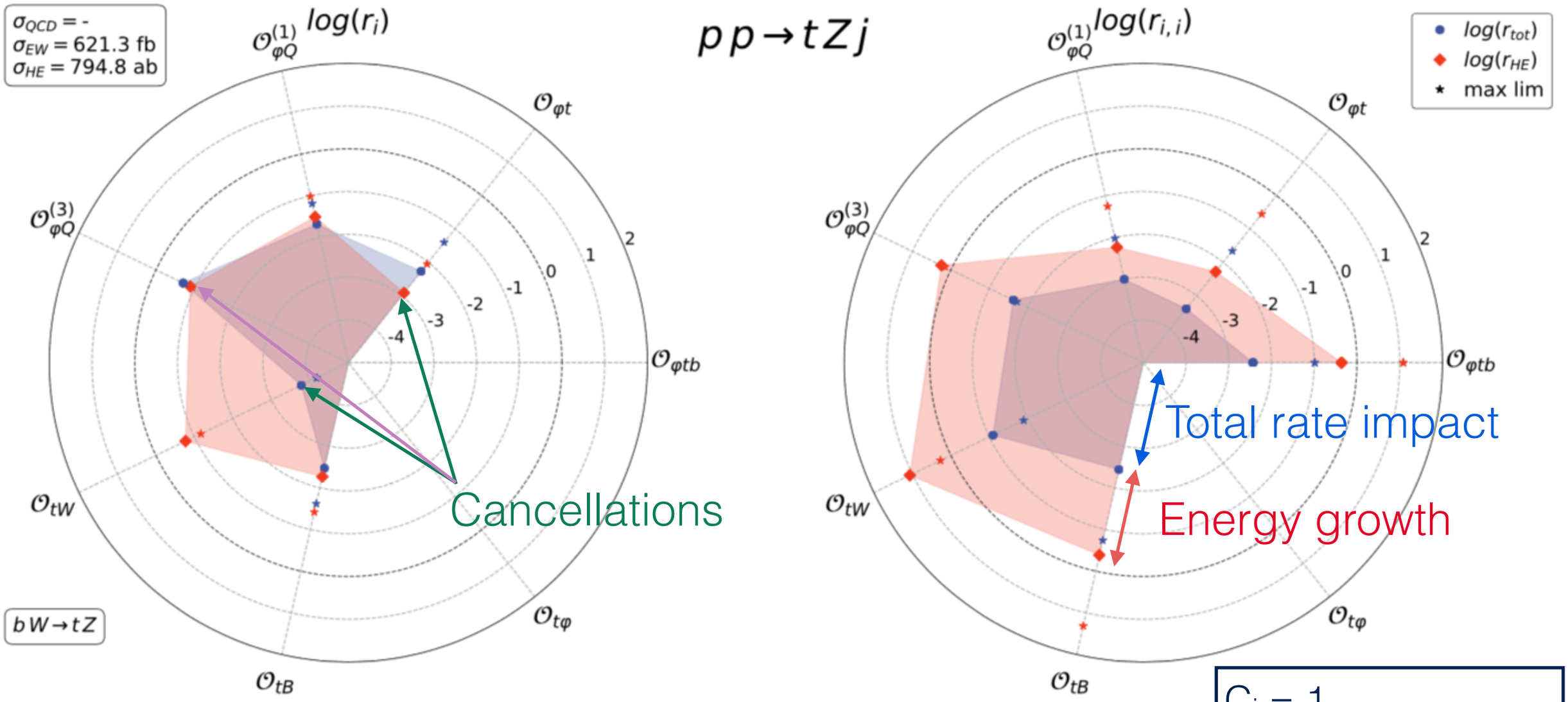




tZ radar plot

interference/SM

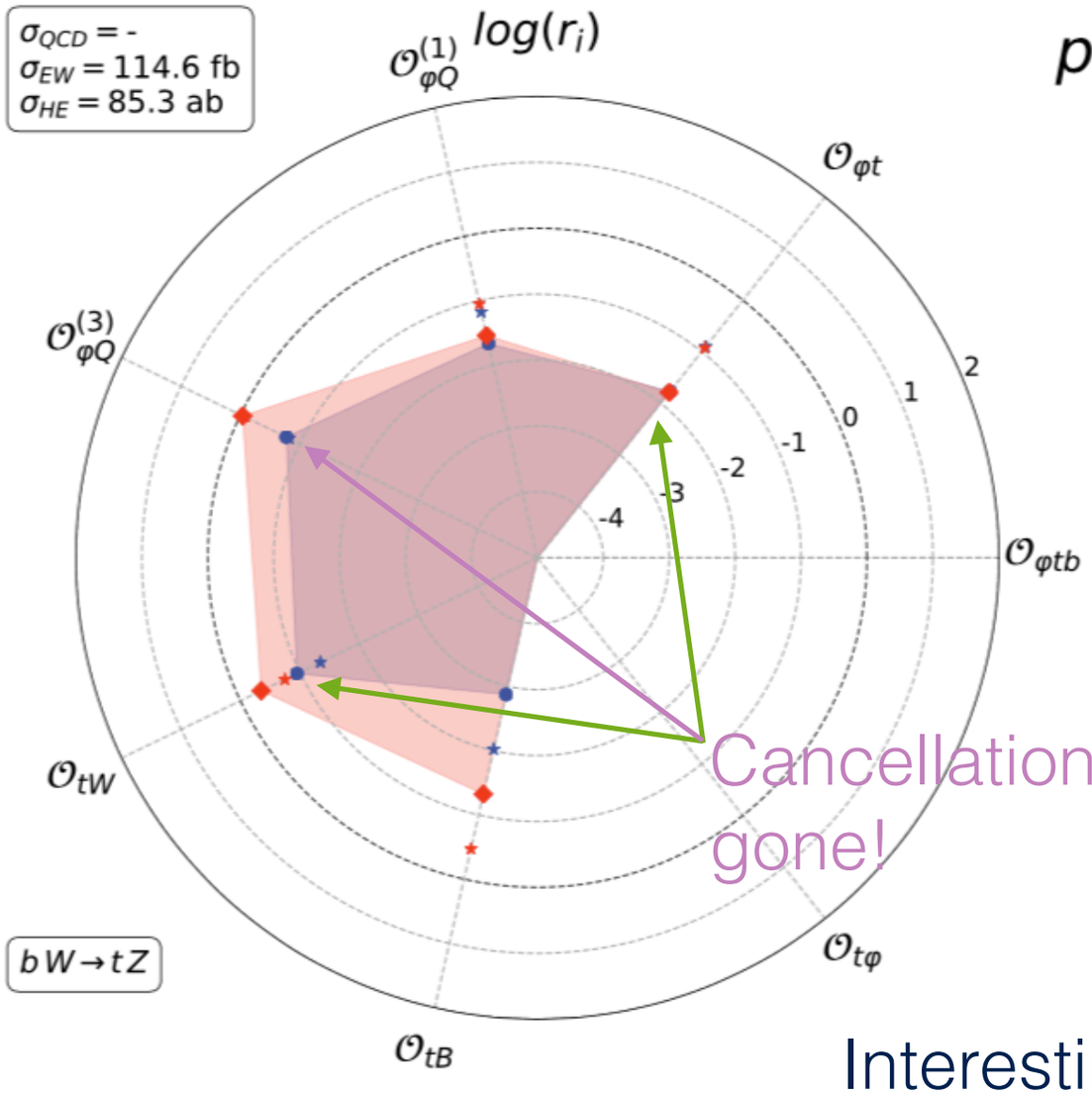
square/SM



Expected growth from 2→2 absent!

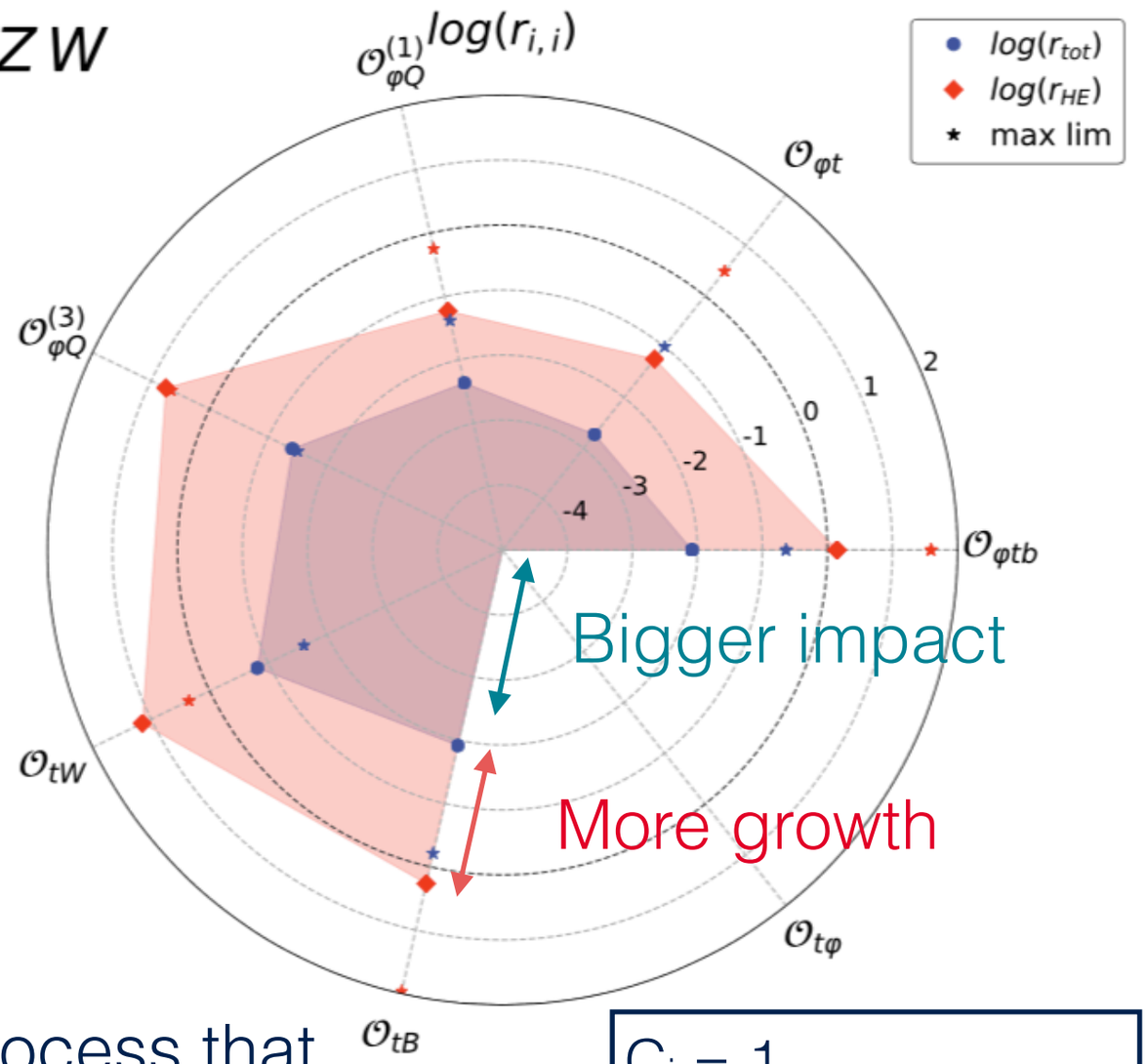
tZW radar plot

interference/SM



$pp \to tZW$

square/SM



Expected growth is there!

Interesting process that should be accessible at the LHC

$C_i = 1$
Inclusive
p_T (W,Z)> 500 GeV

Charged current operator