

# Interpreting top quark LHC measurements in SMEFT

An introduction & practical guide

Ken Mimasu

King's College London

Top LHC France, IP2I Lyon

9<sup>th</sup> May 2022

# Plan

## **Part 1:** Top physics & SMEFT, status & prospects

- Why tops?
- Indirect approach through SMEFT
- Importance of top data: direct (tree) & indirect (loop)
- Top quark EW interactions: high energy & multiplicity
- Global analyses = global measurements

## **Part 2:** MC simulations for SMEFT, practical guide

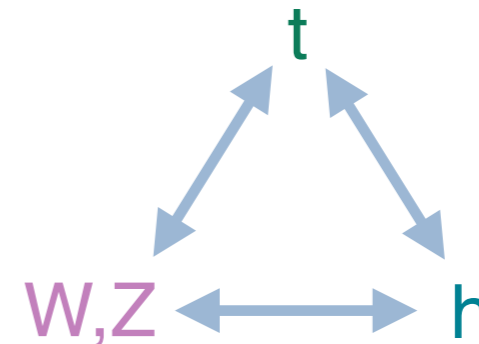
- Tips, tricks & examples for newcomers
- `SMEFTatNLO` model with `MadGraph5_aMC@NLO`
- Key concepts/techniques: coupling orders, reweighting, decays, NLO,...
- Intended as a pedagogical introduction & reference

# New physics through tops

## What is the origin of electroweak symmetry breaking?

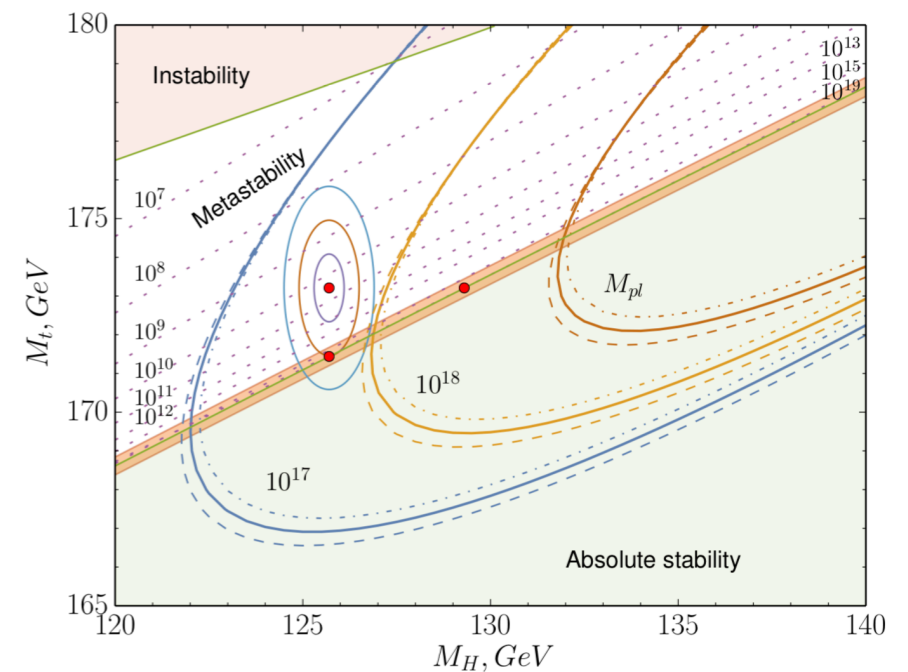
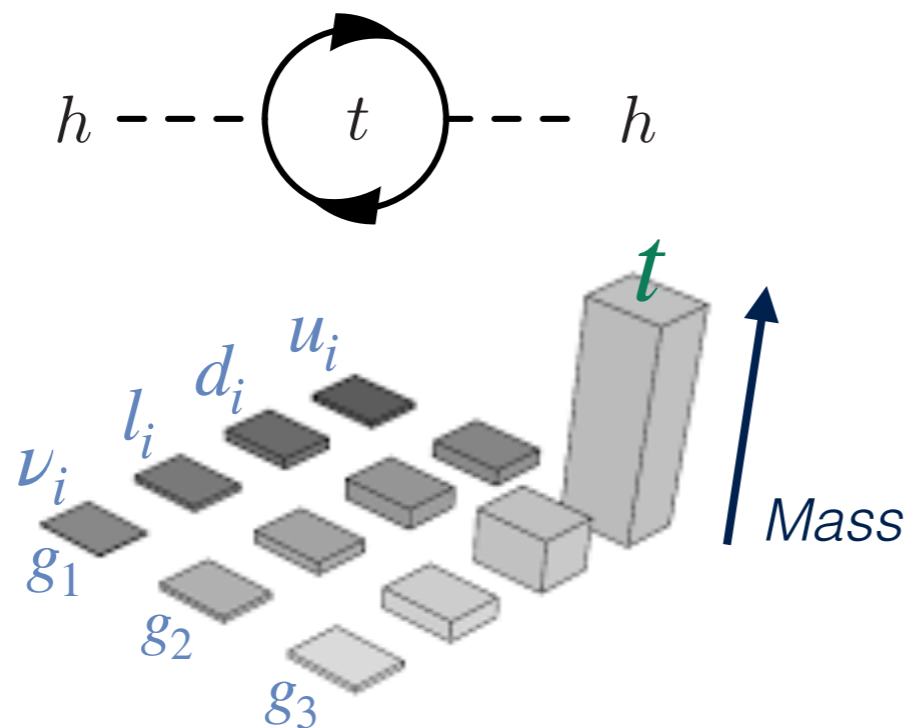
Who are the main players?

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



The **top is special** for many reasons

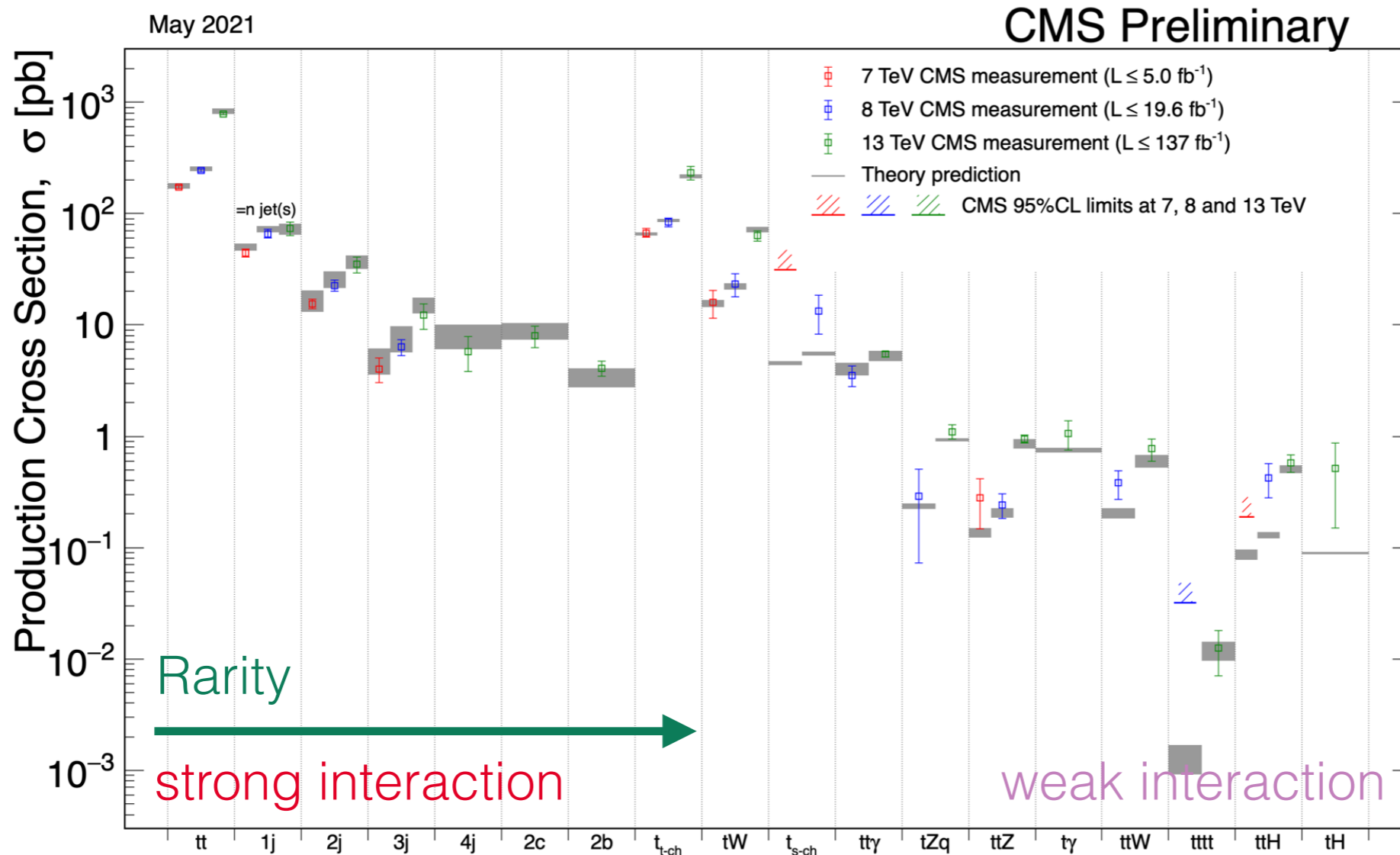
*naturalness  
&  
hierarchies*



*EW vacuum stability*

*[Bednyakov et al.; PRL 115 (2015) 201802],...*

# The LHC is a top factory

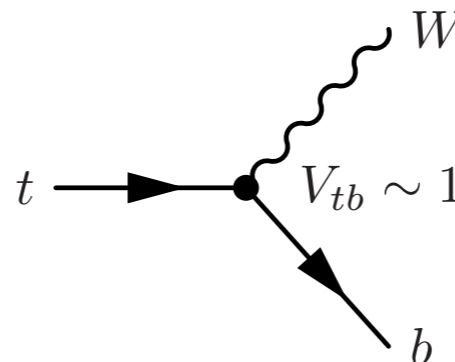


$t\bar{t} : 10^9$   
 $tj, tW, tb : 10^8$   
 $t\bar{t} + Z/W/\gamma : 10^7$   
 $t\bar{t}H : 10^6$   
 $t\bar{t}t\bar{t} : 10^4$   
 $\mathcal{L}^{int.} \sim 3 \text{ ab}^{-1}$

All results at: <http://cern.ch/go/pNj7>

## Decays before hadronising

- Spin/helicity information preserved

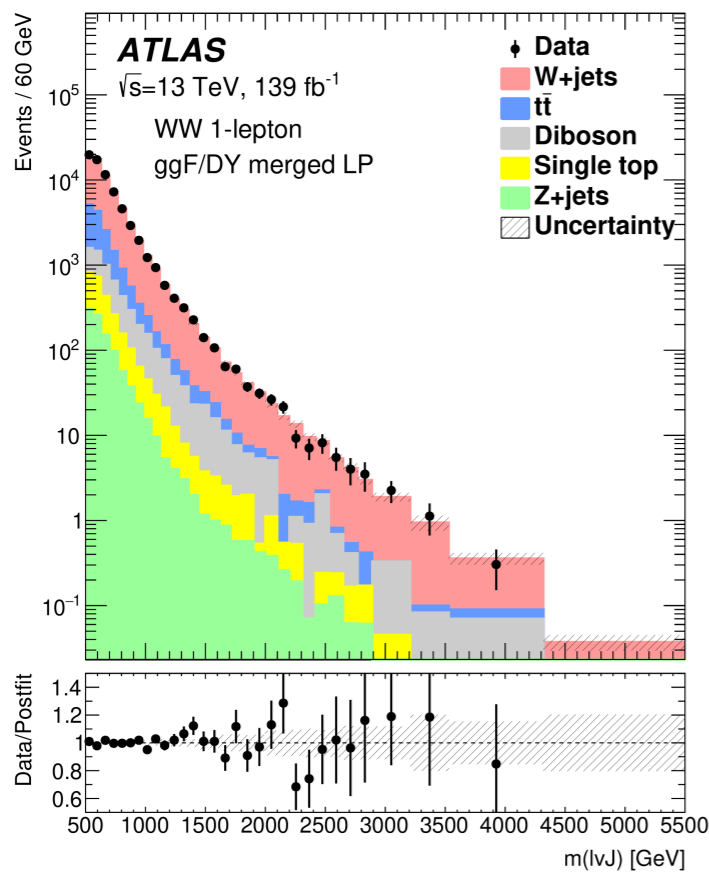
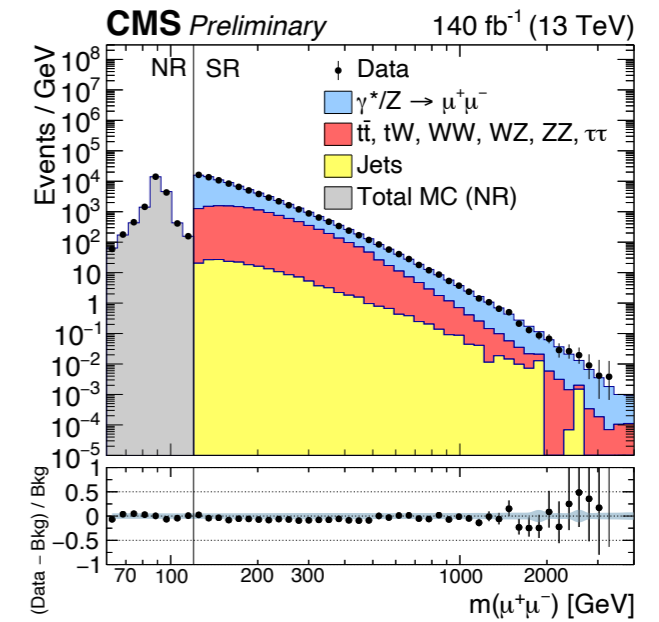


$$\frac{1}{\Gamma_t} \frac{d\Gamma_{t\pm}}{d \cos \theta_\ell} \propto (1 \pm \cos \theta_\ell)$$

# Where are we?

10 years since the start of LHC Run 1

- No clear sign of new physics at the TeV scale
- Direct searches are saturating the energy frontier



ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits  
Status: May 2020

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
<b>Extra dimensions</b>	ADD $G_{KK} + g/q$	0 $e, \mu$	1-4 j	Yes	36.1	$M_D$ 7.7 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	2 $\gamma$	-	-	36.7	$M_S$ 8.6 TeV $n=3$ HLZ NLO
	ADD QBH	-	2 j	-	37.0	$M_{\text{th}}$ 8.9 TeV $n=6$
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	$M_{\text{th}}$ 8.2 TeV $n=6, M_D = 3 \text{ TeV, rot BH}$
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{th}}$ 9.55 TeV $n=6, M_D = 3 \text{ TeV, rot BH}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 $\gamma$	-	-	36.7	$G_{KK}$ mass 4.1 TeV $k/\overline{M}_{\text{pl}} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK}$ mass 2.3 TeV $k/\overline{M}_{\text{pl}} = 1.0$
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu q\bar{q}$	1 $e, \mu$	2 j / 1 J	Yes	139	$G_{KK}$ mass 2.0 TeV $k/\overline{M}_{\text{pl}} = 1.0$
	Bulk RS $G_{KK} \rightarrow t\bar{t}$	1 $e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$G_{KK}$ mass 3.8 TeV $\Gamma/m = 15\%$
	2UED / RPP	1 $e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	$KK$ mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow t\bar{t}) = 1$
<b>Gauge bosons</b>	SSM $Z' \rightarrow \ell\ell$	2 $e, \mu$	-	-	139	$Z'$ mass 5.1 TeV $\Gamma/m = 1.2\%$
	SSM $Z' \rightarrow \tau\tau$	2 $\tau$	-	-	36.1	$Z'$ mass 2.42 TeV
	Leptophobic $Z' \rightarrow b\bar{b}$	-	2 b	-	36.1	$Z'$ mass 2.1 TeV
	Leptophobic $Z' \rightarrow t\bar{t}$	0 $e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$Z'$ mass 4.1 TeV
	SSM $W' \rightarrow \ell\nu$	1 $e, \mu$	-	Yes	139	$W'$ mass 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	1 $\tau$	-	Yes	36.1	$W'$ mass 3.7 TeV
	HVT $W' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B	1 $e, \mu$	2 j / 1 J	Yes	139	$W'$ mass 4.0 TeV
	HVT $V' \rightarrow WV \rightarrow qq\bar{q}\bar{q}$ model B	0 $e, \mu$	2 J	-	139	$V'$ mass 3.8 TeV
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	$V'$ mass 2.93 TeV
	HVT $W' \rightarrow WH$ model B	0 $e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$W'$ mass 3.2 TeV
	LRSM $W_R \rightarrow t\bar{b}$	multi-channel	-	-	36.1	$W_R$ mass 3.25 TeV
	LRSM $W_R \rightarrow \mu N_R$	2 $\mu$	1 J	-	80	$W_R$ mass 5.0 TeV $m(N_R) = 0.5 \text{ TeV, } g_L = g_R$
<b>CI</b>	CI $qq\bar{q}\bar{q}$	-	2 j	-	37.0	$\Lambda$ 21.8 TeV $\eta_{LL}$
	CI $\ell\ell q\bar{q}$	2 $e, \mu$	-	-	139	$\Lambda$ 35.8 TeV $\eta_{LL}$
	CI $t\bar{t}t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\Lambda$ 2.57 TeV $ C_{41}  = 4\pi$
<b>DM</b>	Axial-vector mediator (Dirac DM)	0 $e, \mu$	1-4 j	Yes	36.1	$m_{\text{med}}$ 1.65 TeV $g_q = 0.25, g_\tau = 1.0, m(\chi) = 1 \text{ GeV}$
	Colored scalar mediator (Dirac DM)	0 $e, \mu$	1-4 j	Yes	36.1	$m_{\text{med}}$ 1.67 TeV $g = 1.0, m(\chi) = 1 \text{ GeV}$
	$VV\chi\chi$ EFT (Dirac DM)	0 $e, \mu$	1 j, $\leq 1 j$	Yes	3.2	$M, m_\chi$ 700 GeV $m(\chi) < 150 \text{ GeV}$
	Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	0-1 $e, \mu$	1 b, 0-1 j	Yes	36.1	$m_\phi$ 3.4 TeV $y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$
<b>LQ</b>	Scalar LQ 1 <sup>st</sup> gen	1,2 $e$	$\geq 2 j$	Yes	36.1	LQ mass 1.4 TeV $\beta = 1$
	Scalar LQ 2 <sup>nd</sup> gen	1,2 $\mu$	$\geq 2 j$	Yes	36.1	LQ mass 1.6 TeV $\beta = 1$
	Scalar LQ 3 <sup>rd</sup> gen	2 $\tau$	2 b	-	36.1	LQ mass 1.03 TeV $\mathcal{B}(LQ_3^+ \rightarrow b\bar{r}) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	0-1 $e, \mu$	2 b	Yes	36.1	LQ mass 970 GeV $\mathcal{B}(LQ_3^+ \rightarrow t\bar{r}) = 0$
<b>Heavy quarks</b>	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.3 TeV SU(2) doublet
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	2(SS) $\geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	
	VLQ $Y \rightarrow Wb + X$	1 $e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$
	VLQ $B \rightarrow Hb + X$	0 $e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV $x_B = 0.5$
	VLQ $QQ \rightarrow WqWq$	1 $e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV
<b>Excited fermions</b>	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	$q^*$ mass 6.7 TeV only $u'$ and $d'$ , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	1 $\gamma$	1 j	-	36.7	$q^*$ mass 5.3 TeV only $u'$ and $d'$ , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow b\gamma$	-	1 b, 1 j	-	36.1	$b^*$ mass 2.6 TeV
	Excited lepton $\ell^*$	3 $e, \mu$	-	-	20.3	$\ell^*$ mass 3.0 TeV $\Lambda = 3.0 \text{ TeV}$
	Excited lepton $\nu^*$	3 $e, \mu, \tau$	-	-	20.3	$\nu^*$ mass 1.6 TeV $\Lambda = 1.6 \text{ TeV}$
<b>Other</b>	Type III Seesaw	1 $e, \mu$	$\geq 2 j$	Yes	79.8	$N^0$ mass 560 GeV
	LRSM Majorana $\nu$	2 $\mu$	2 j	-	36.1	$N_R$ mass 3.2 TeV $m(W_R) = 4.1 \text{ TeV, } g_L = g_R$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 $e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV DY production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 $e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV DY production, $ q  = 1 g_D, \text{spin } 1/2$
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV

[ TeV ] : 1 3 5 10

# What have we learnt?

**BSM:** new states are too...

## **Weakly coupled**

*rate limited*

Room for improvement

With increasing integrated luminosity

## **Exotic**

*we aren't looking in  
the right place*

Limited by our creativity

Work for theorists & experimentalists:  
Motivate & enable searches for new  
signatures

## **Heavy**

*kinematically  
out of reach*

Worst-case scenario

...from direct search point of view

Complemented by indirect searches

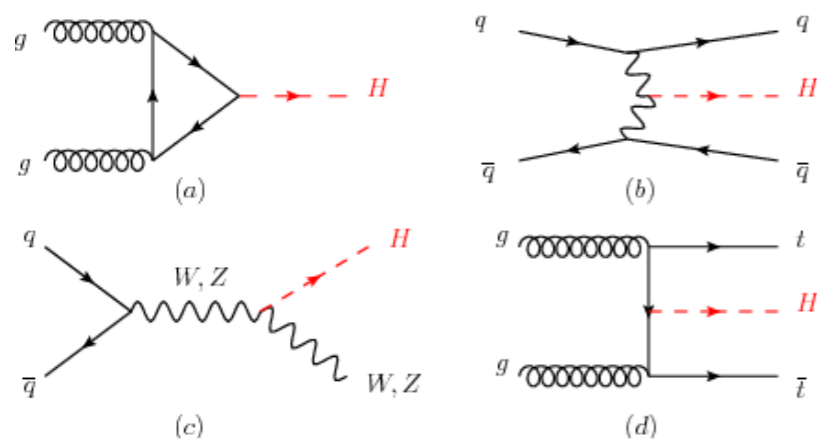
**SM:** a tremendous amount!

- Higgs discovery & properties ⇒ precision LHC programme

# The LHC explorer

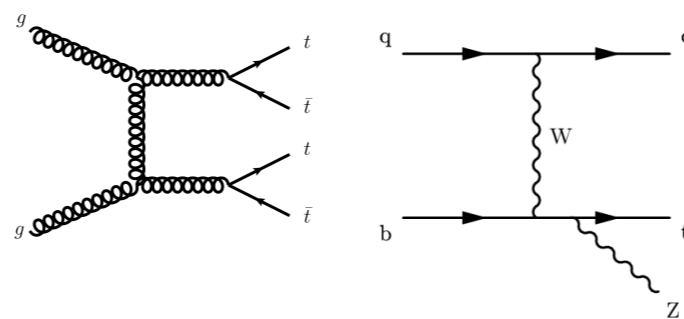
Many new processes observed at the LHC for the first time

*Main Higgs production modes*



*ggF, VH, VBF, ttH*

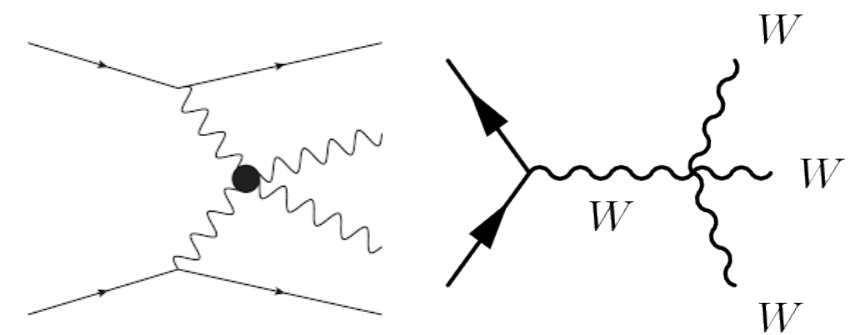
*Rare top production*



*tttt, ttbb*

*ttV, tW, tZ*

*Weak boson scattering*



*VBS, VVV*

Each opens a new window, through which we can

Improve our understanding of the SM

- Search for new physics via new interactions

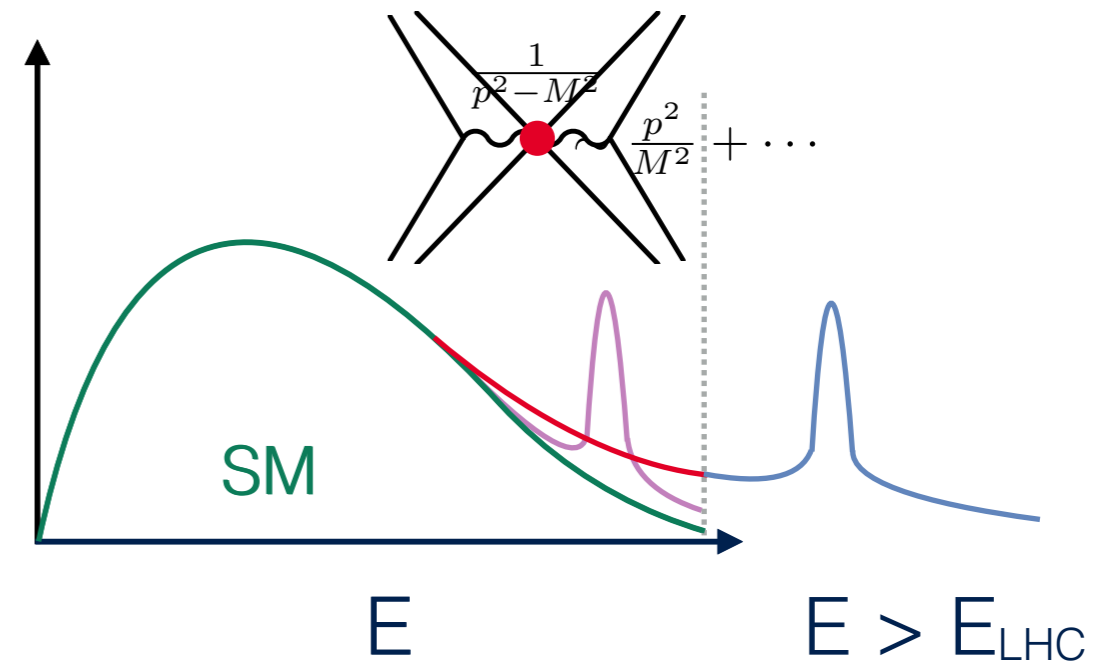
# Energy & precision

Paradigm shift at the energy frontier for BSM searches

Direct (bumps)

Indirect (tails)

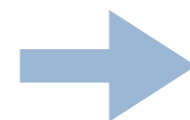
⇒ New physics is heavy



Heavy new physics

Precision measurements

High energy



**Standard Model  
Effective Field Theory  
(SMEFT)**

A QFT parameter space for BSM interactions between SM particles



# SMEFT: SM v2.0

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

## SM = low energy effective description

- New physics = tower of irrelevant ( $D > 4$ ) operators
- Respecting low energy field content & symmetries

$$\text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y$$

$$\varphi = \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} : \mathbf{2}_{\frac{1}{2}}$$

aTGC

$$X^3 : \epsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W_{\rho}^{K,\mu}$$

$$X^2 H^2 : (\varphi^\dagger \varphi)^2 G_{\mu\nu}^a G_a^{\mu\nu}$$

ggh(h)

$\lambda_h$

$$H^6 : (\varphi^\dagger \varphi)^3$$

$$H^4 D^2 : (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D^\mu \varphi)$$

$\delta M_Z$

$y_f$

$$\psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{q}_i u_j \tilde{\varphi})$$

$$\psi^2 XH : (\bar{q}_i \sigma^{\mu\nu} u_j \tilde{\varphi}) B_{\mu\nu}$$

'dipole'

ffV

$$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi) (\bar{q}_i \gamma^\mu q_j)$$

$$\psi^4 : (\bar{q}_i \gamma^\mu q_j) (\bar{q}_k \gamma_\mu q_l)$$

4F

## More than 'just' a parametrisation of ignorance

- Unlike anomalous couplings
- Renormalisable QFT (order-by-order)
- Finite energy range ( $\sim \Lambda$ )
- Well defined matching procedure

# SMEFT is...

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

## Model independent

- Underlying assumptions

*Heavy new physics:  $M > E_{\text{exp}}$   
SM field content & gauge symmetries  
Linear EWSB: Higgs = doublet*

## Systematically improvable

- Double expansion *higher dim.*  $\frac{E^2}{\Lambda^2}$  &  $\{g_s, g, g'\}$  *more loops*

## Global

- **Model independence:** we don't know what operators NP will generate
- *Patterns & correlations* among observables are key
- **Ultimate goal:** complete *SMEFT likelihood* confronted with HEP data

EWPO, *Higgs*, *multiboson*, *top*, DY, *flavor*,...

- ➔ **Interpretation:** bounds on masses/couplings of heavy new physics models

# SMEFT interpretation

Improving new physics reach means improving...

$$\Delta o_n = o_n^{\text{EXP}} - o_n^{\text{SM}} = \sum_i \frac{a_{n,i}^{(6)}(\mu) c_i^{(6)}(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

## Global nature

As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

## Sensitivity

*Experiment:*

Best measurements & understanding of uncertainties and correlations

*Theory:*

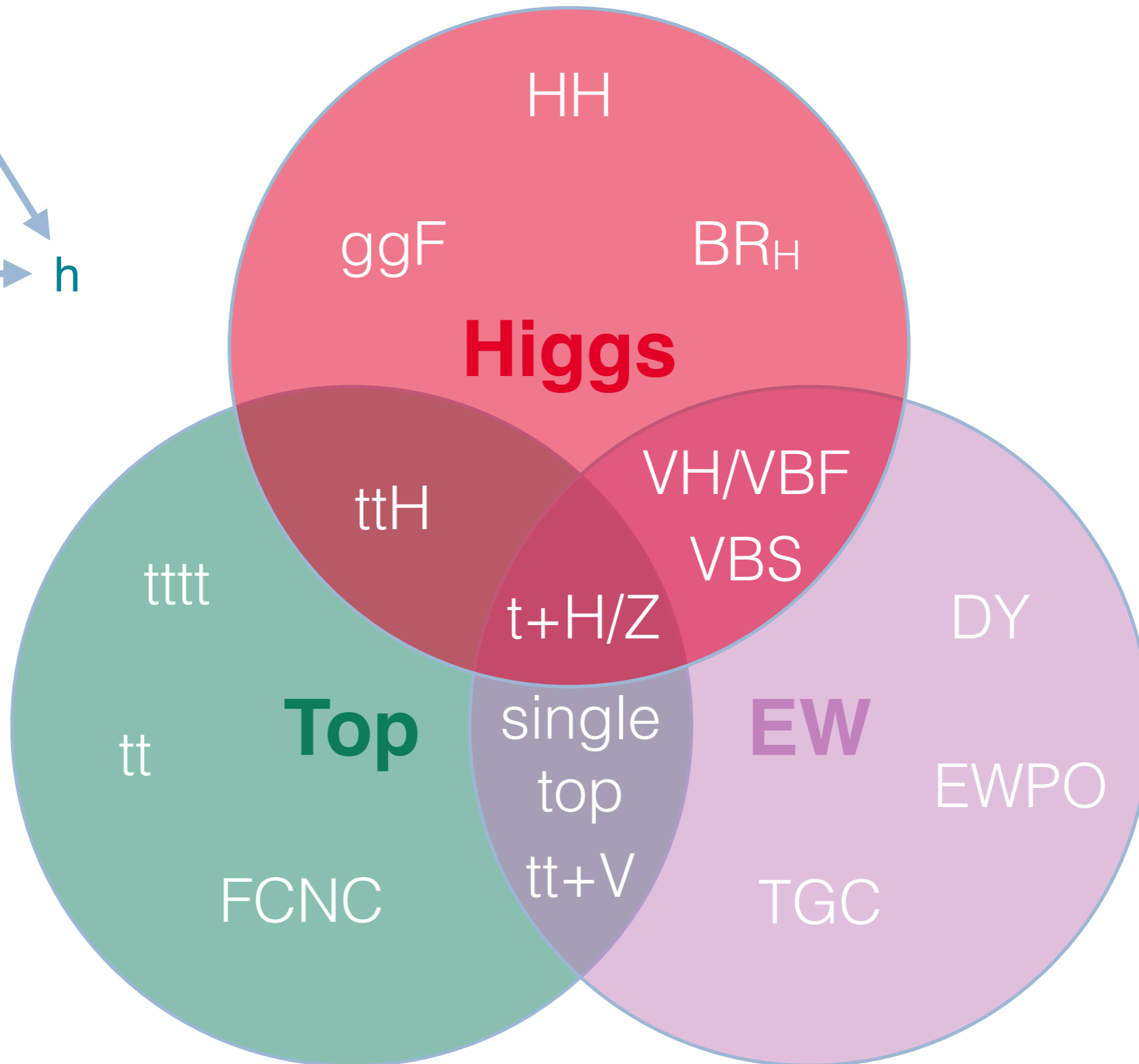
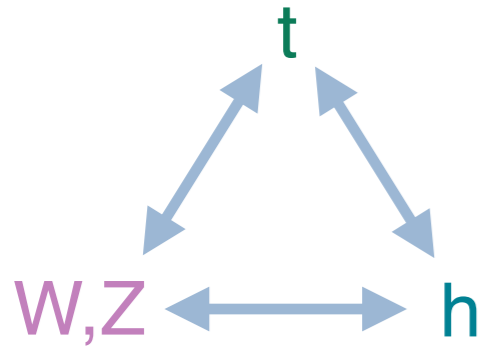
Best available predictions for observables (NLO, NNLO, N3LO,...)

## Interpretation

Relies on accurate knowledge of the size & correlation among  $a_i$

Determining  $c_i^{(6)}$  requires most precise available SMEFT predictions  $\Rightarrow$  **NLO**

# The wealth of data



Decays

Flavor

CPV

# SMEFT workflow

# SMEFT workflow



Basis

*Warsaw, SILH, HISZ, Higgs Basis*

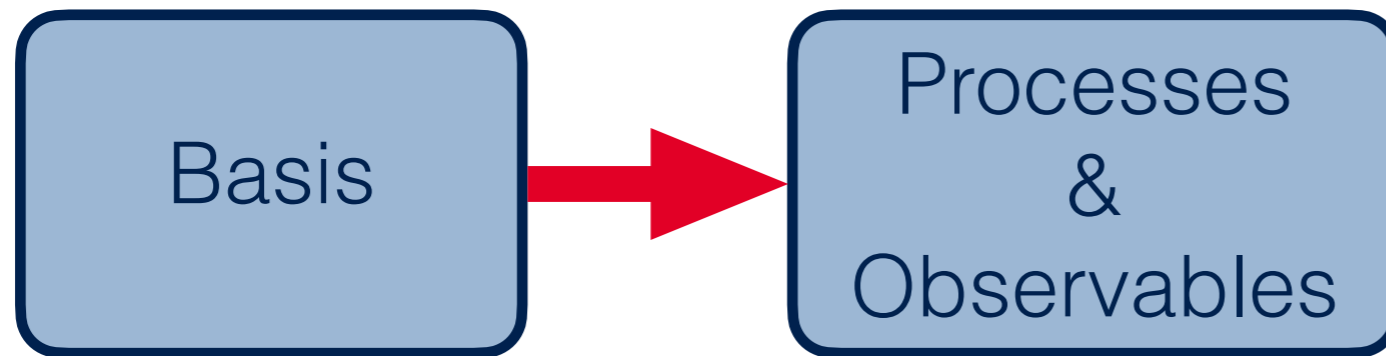
Flavor assumptions

*Universal, diagonal, 3rd gen, general?*

Symmetries

*CP, Baryon/Lepton number?*

# SMEFT workflow



Rate measurements

$$\sigma_{\text{tot.}}, \quad \mu = \frac{\sigma}{\sigma_{\text{SM}}}$$

Differential

$$\frac{d\sigma}{dM_{XX}}$$

*energy, angular*

*asymmetries*

High-level

*optimal  
observables*

*NN-output*

# SMEFT workflow



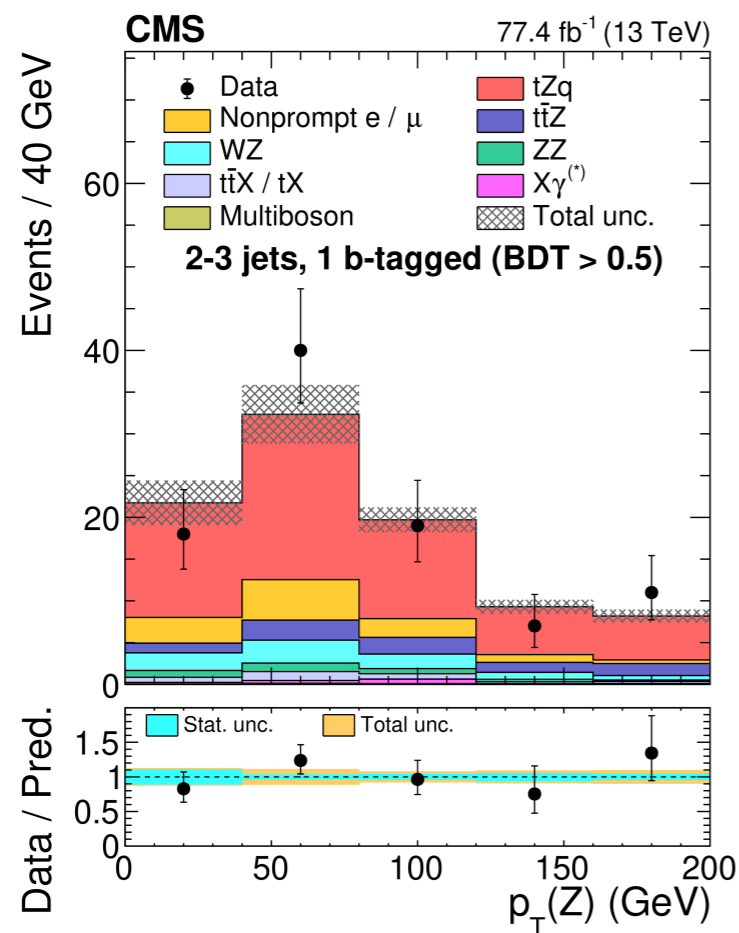
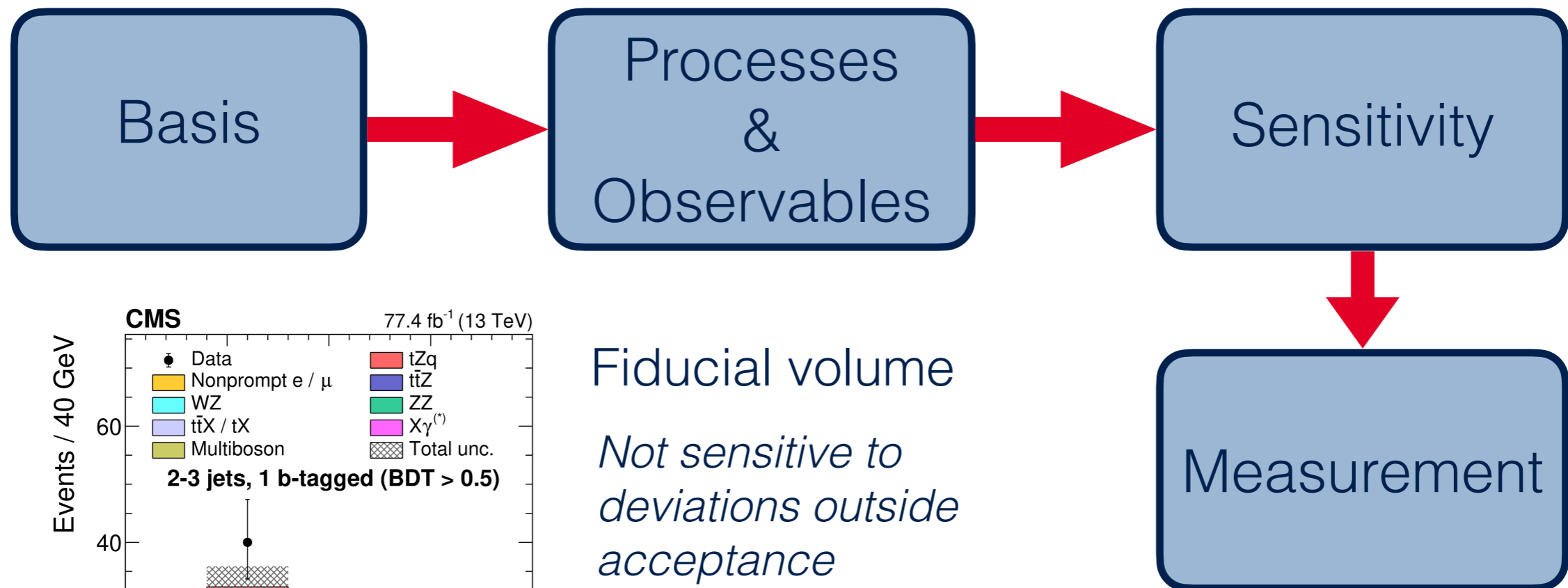
Determine dependence on  
Wilson coefficients

$$\mathcal{O} = \mathcal{O}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_{\text{int}}^i + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} \mathcal{O}_{\text{sq}}^{ij}$$

Precise Monte Carlo tools



# SMEFT workflow



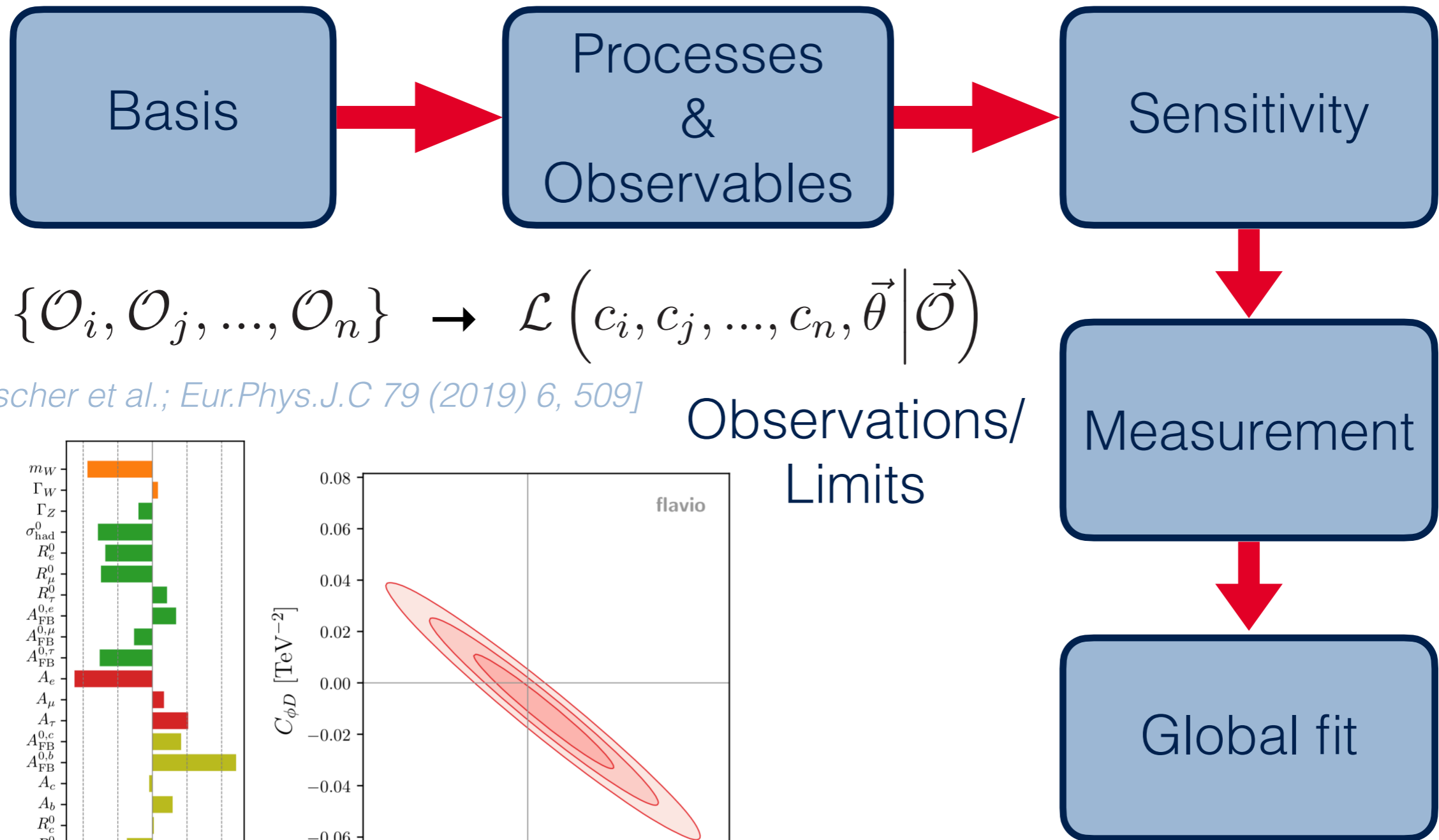
Fiducial volume  
*Not sensitive to deviations outside acceptance (model dependent)*

Extract limits

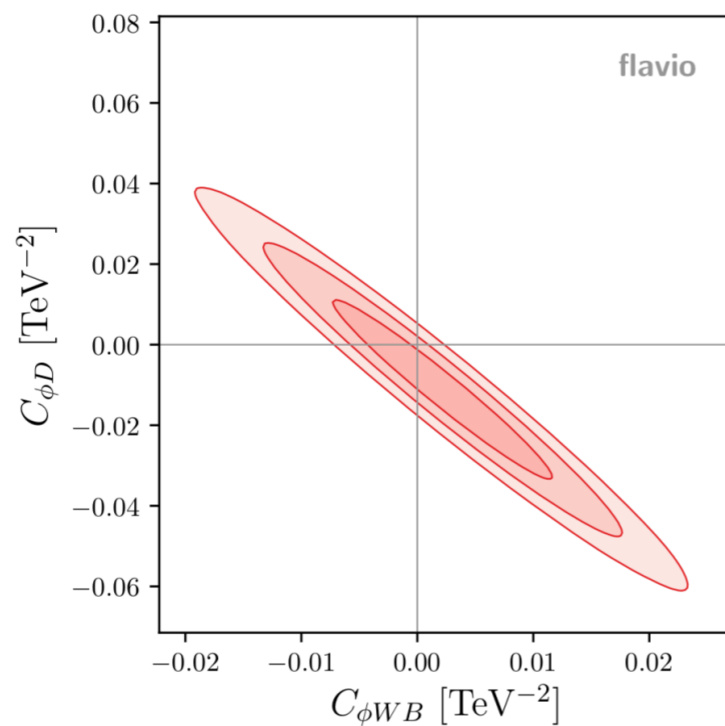
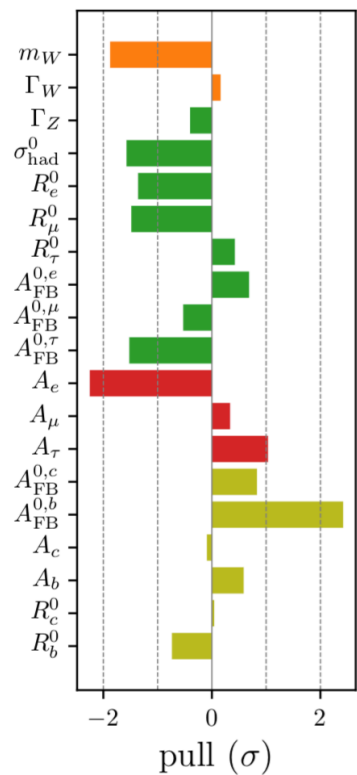
$$c_i \subset [a, b] [\text{TeV}^{-2}]$$

[CMS.; PRL 122 (2019) 132003]

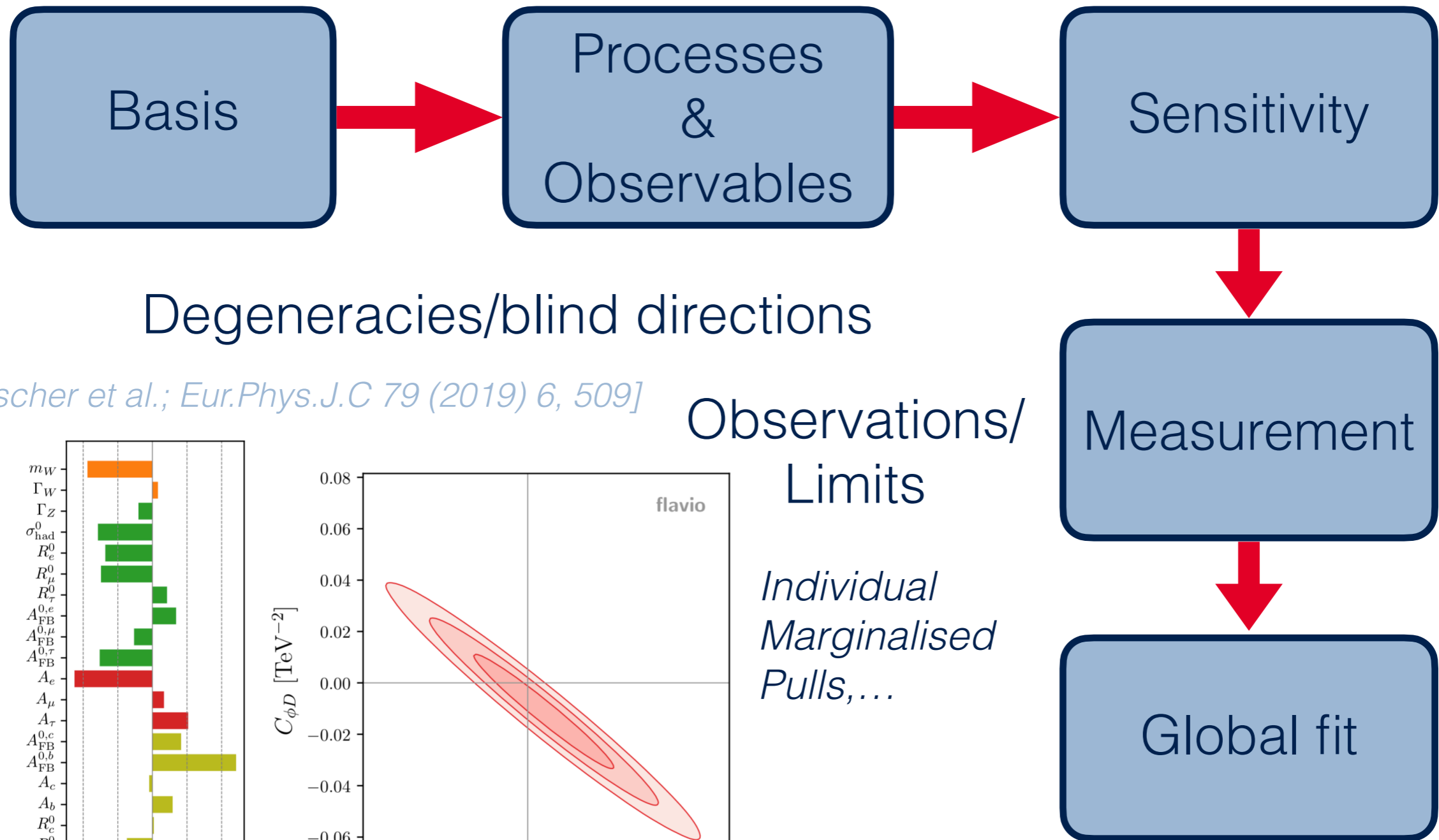
# SMEFT workflow



[Aebischer et al.; Eur.Phys.J.C 79 (2019) 6, 509]

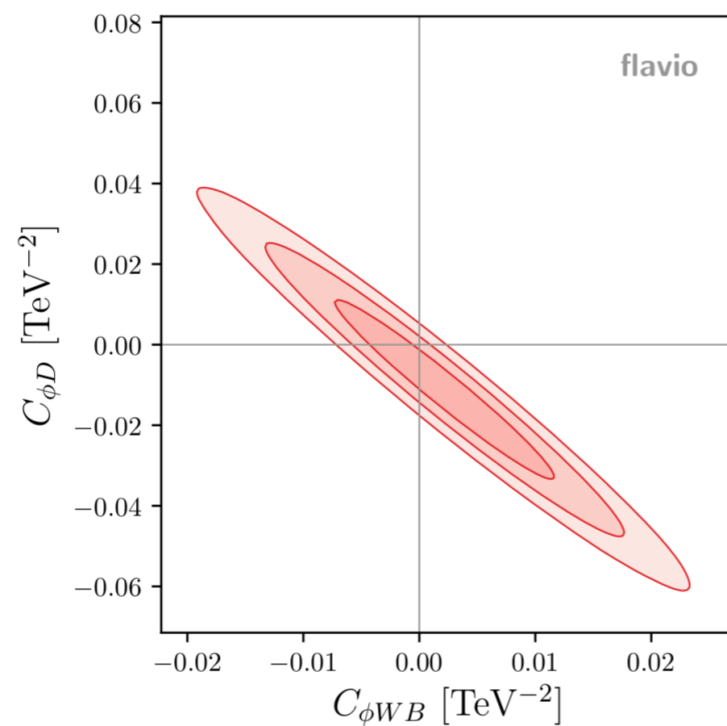
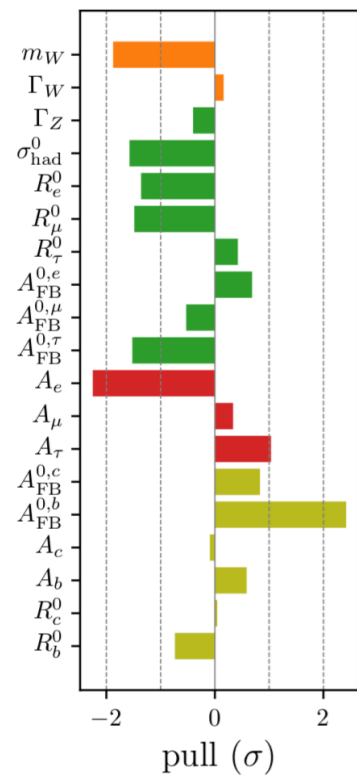


# SMEFT workflow



Degeneracies/blind directions

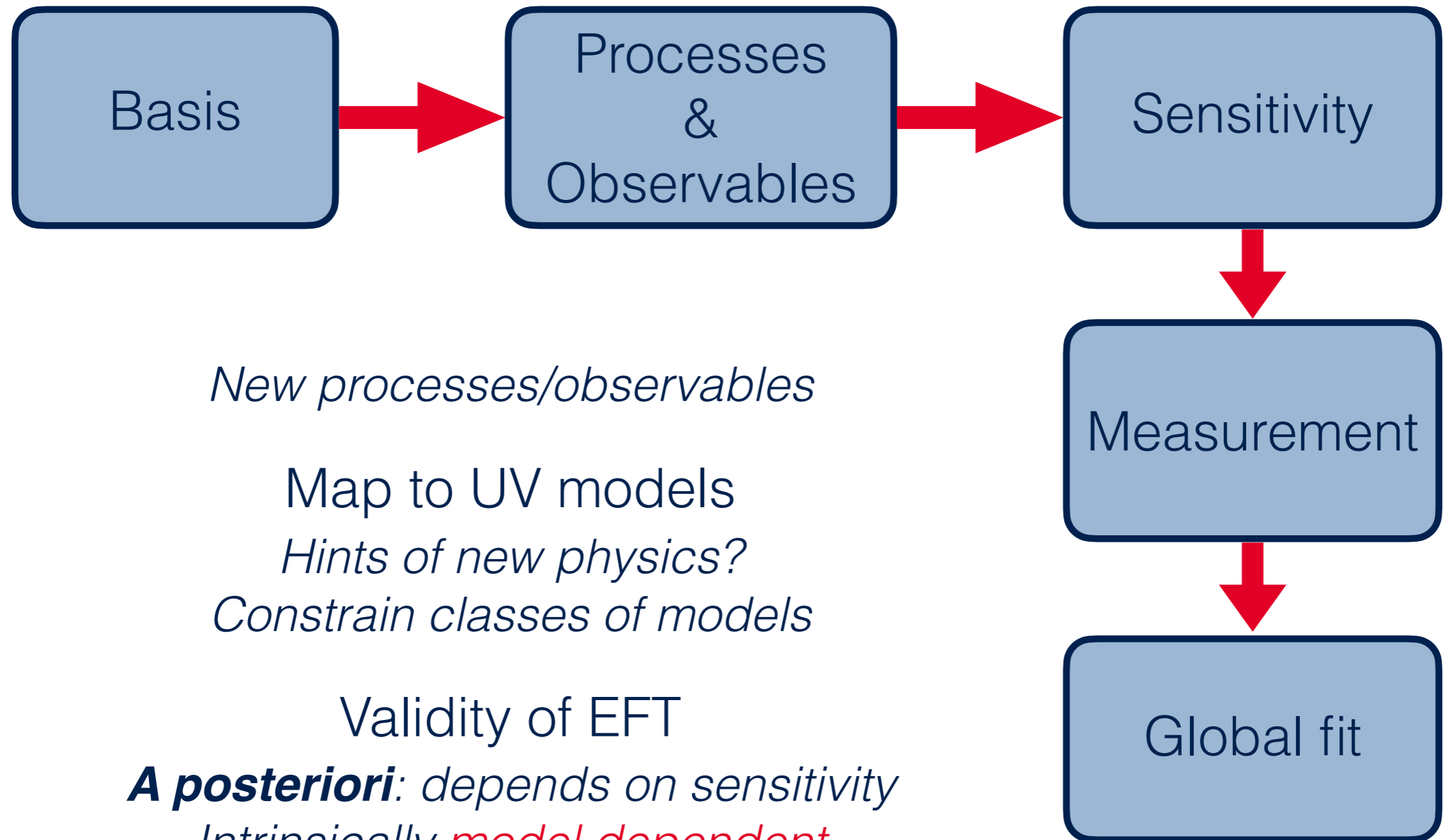
[Aebischer et al.; Eur.Phys.J.C 79 (2019) 6, 509]



Observations/  
Limits

*Individual  
Marginalised  
Pulls,...*

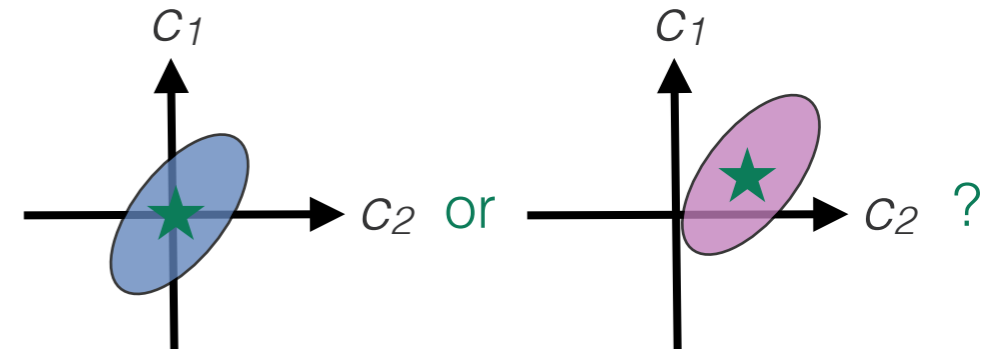
# SMEFT workflow



# The importance of top data

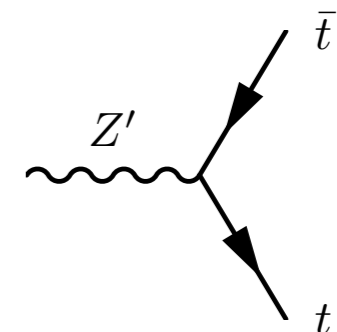
## Likelihood $\Leftrightarrow$ Fit to the Wilson coefficients

- Search for deviations from the SM:  $\frac{C_i}{\Lambda^2} = 0$
- Find **hints** for heavy new physics
- LHC top data has a vital role in this programme



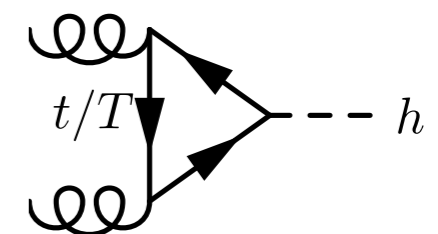
## By itself: individual bounds; top data alone

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



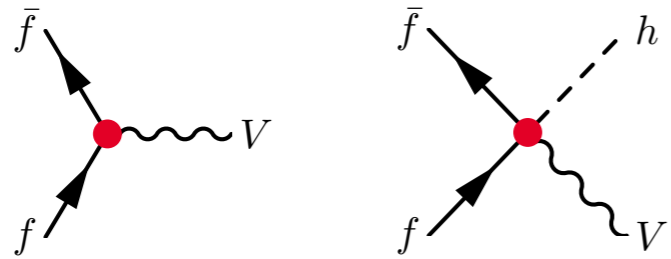
## Globally: marginalised; top, Higgs, diboson, LEP, ... data

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



# Top operator glossary

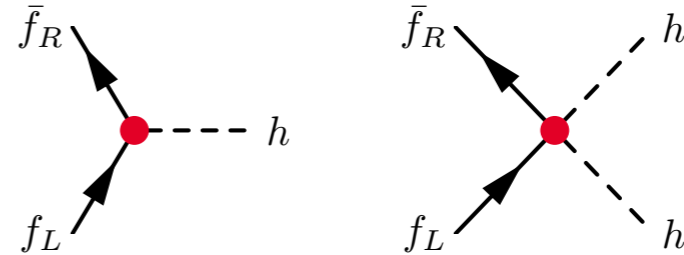
currents  $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{Q}\gamma^\mu Q)$



$C_{\phi f}$

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

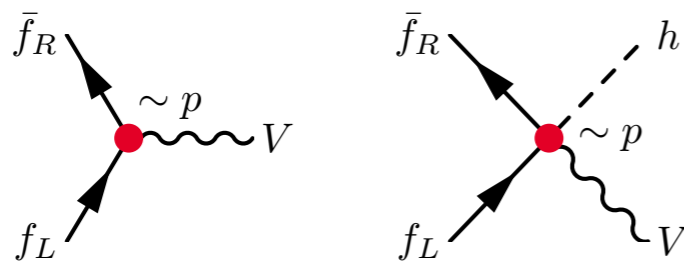
Yukawa  $(\bar{q} t \tilde{\varphi})(\varphi^\dagger \varphi)$



$C_{t\phi}$

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

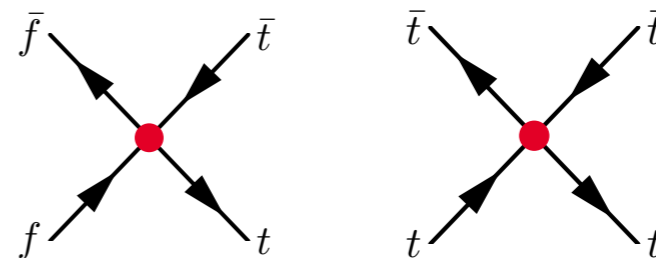
dipole  $(\bar{q} \sigma_{\mu\nu} t \tilde{\varphi})V^{\mu\nu}$



$C_{tV}$

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

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



$C_{ft}$

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

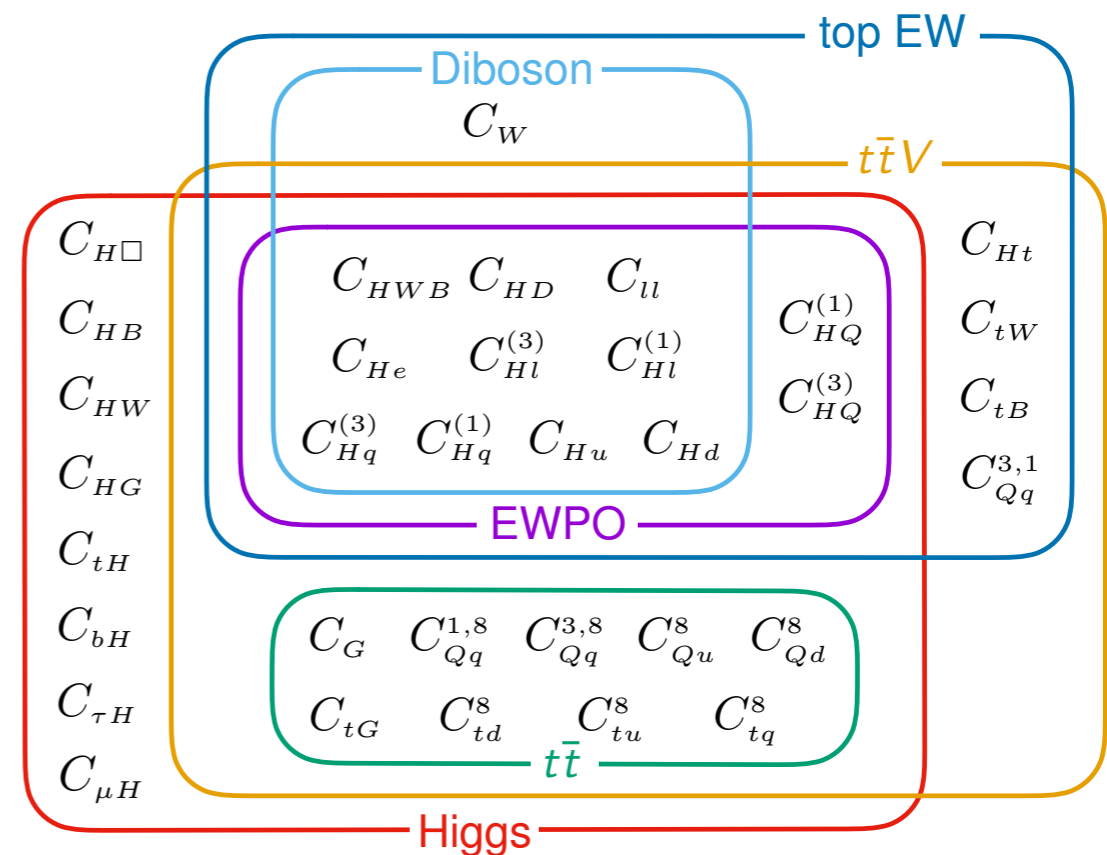
# Fits: status & developments

Many SMEFT interpretations in experimental analyses

## 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
- NLO effects can be significant
- EW top couplings weakly constrained
- EFT validity should be studied

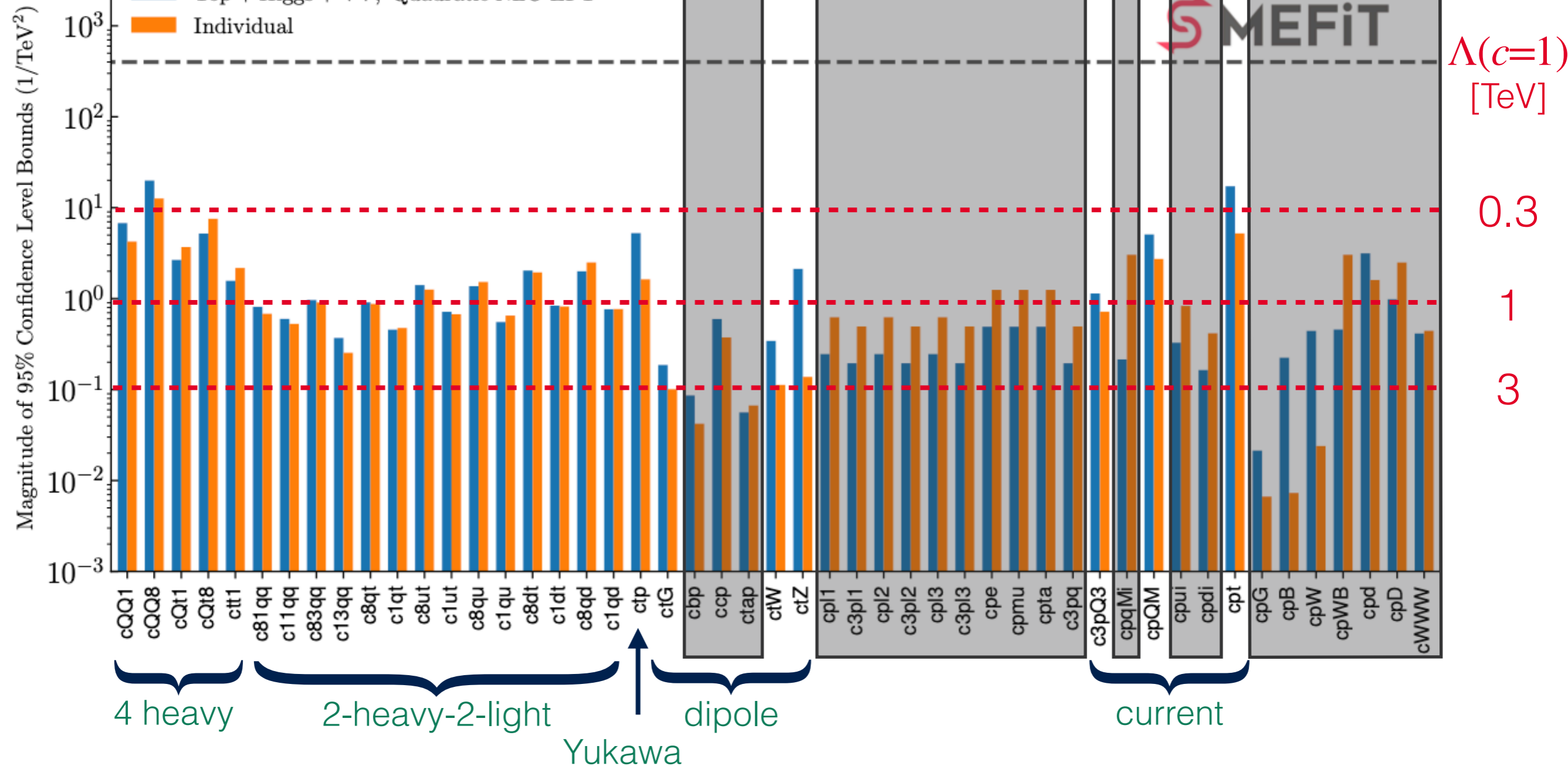
# Status

$C_i$

Top, Higgs & Diboson w/ 'perfect' EWPO

- NLO QCD
- top loop sensitivity

$\Lambda^2$





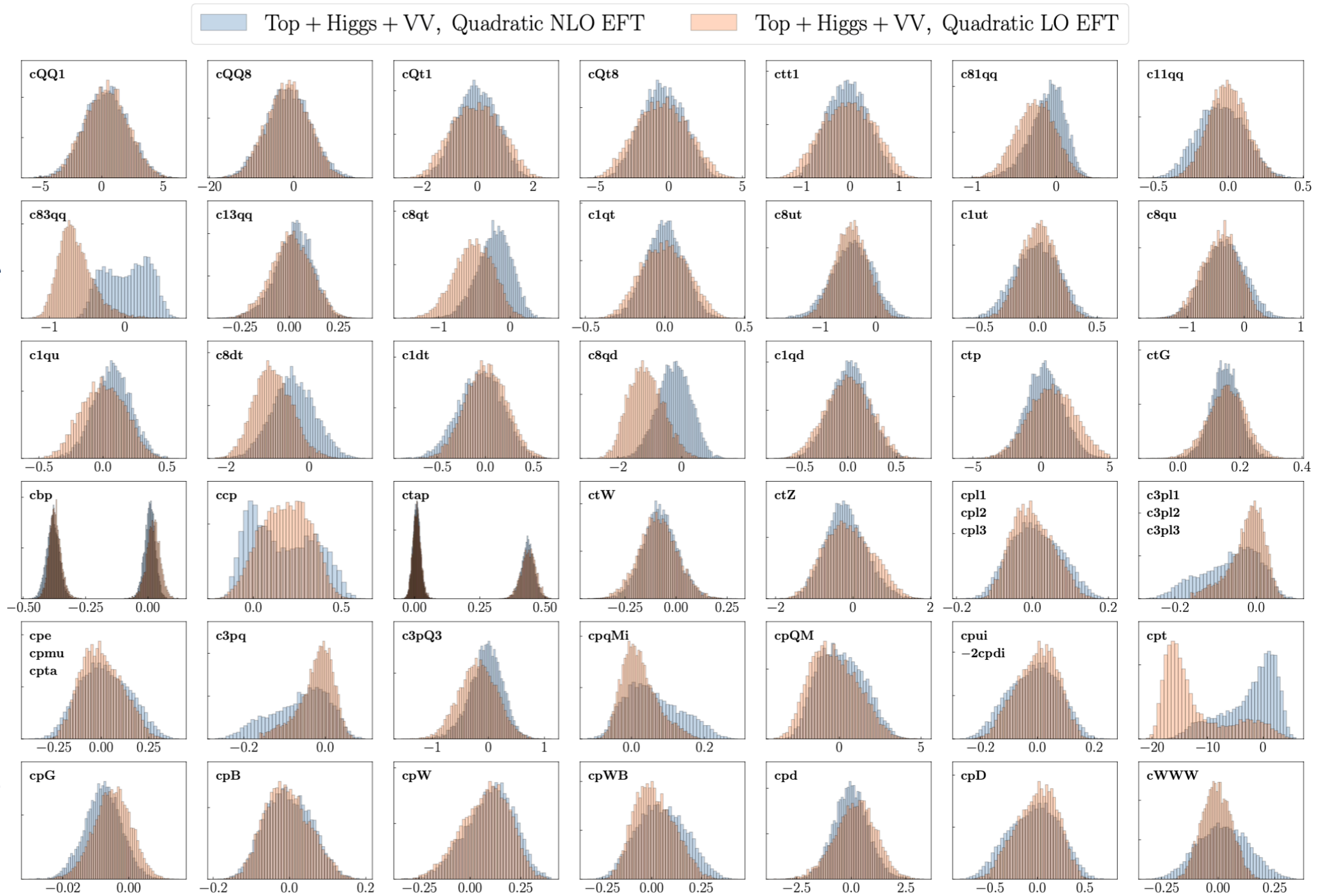
# NLO vs LO

Top is coloured

Non-trivial  
QCD corrections

Non-Gaussian  
posteriors:

Quadratic effects  
important



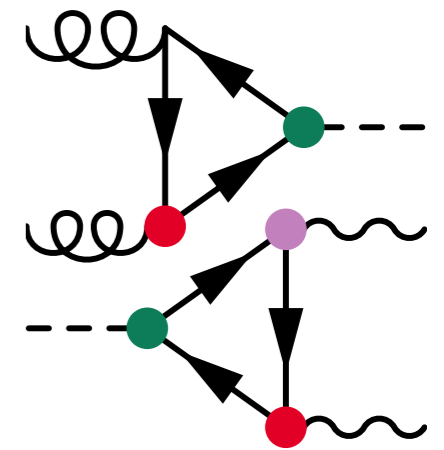
# Loop sensitivity

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  $gg \rightarrow h$  &  $h \rightarrow \gamma\gamma/Z\gamma$
- (Weakly) constrained at tree-level by  $t\bar{t}\gamma/Z/H$  &  $t\bar{t}$



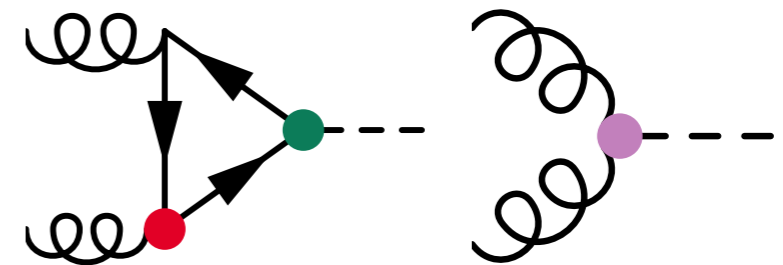
SMEFiT: individual bounds dominated by Higgs data!

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

# Top-Higgs interplay

Top data indirectly improves Higgs coupling measurements

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



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

**ggF is well measured, yet...**

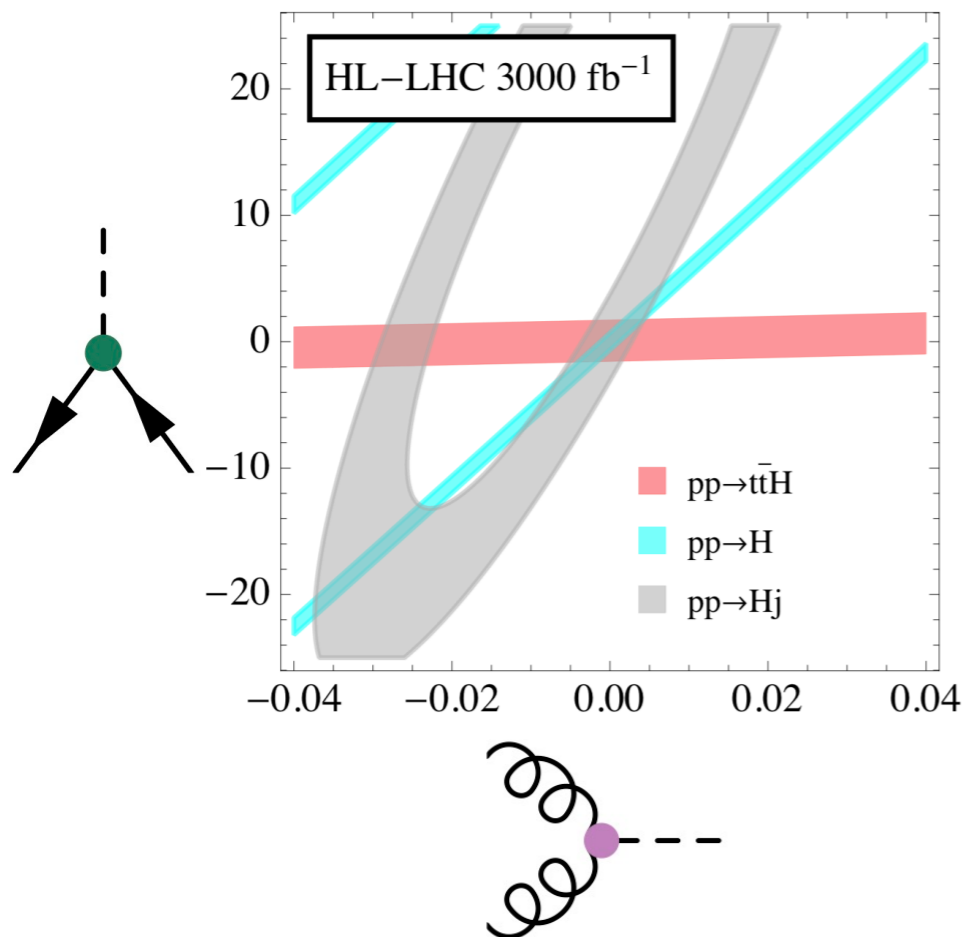
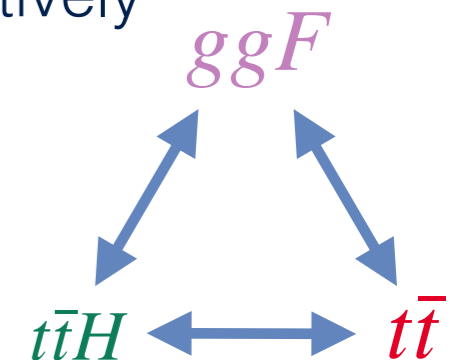
**Cannot rule out heavy particles in the loop**

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

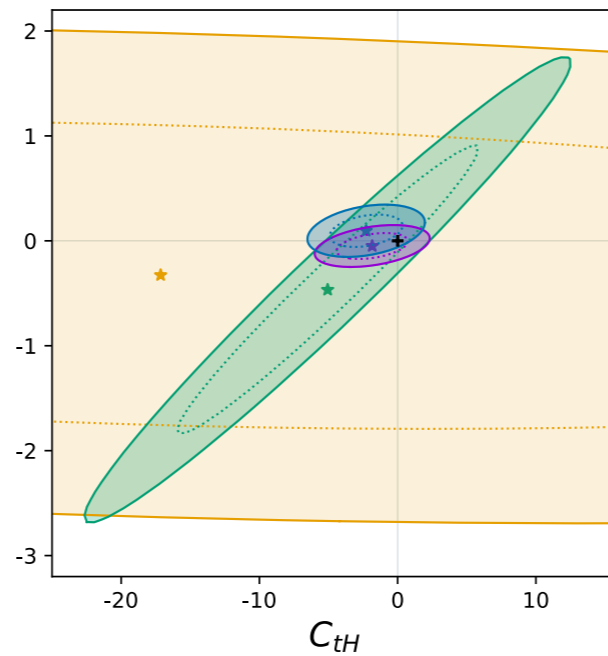
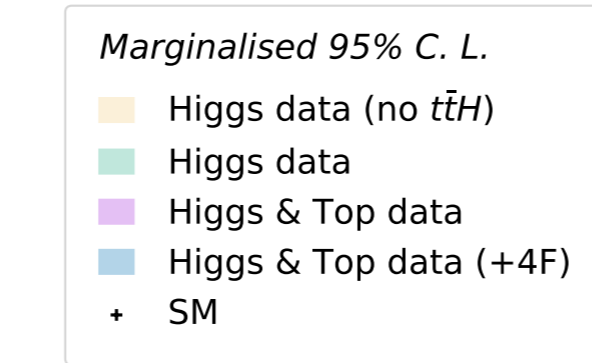
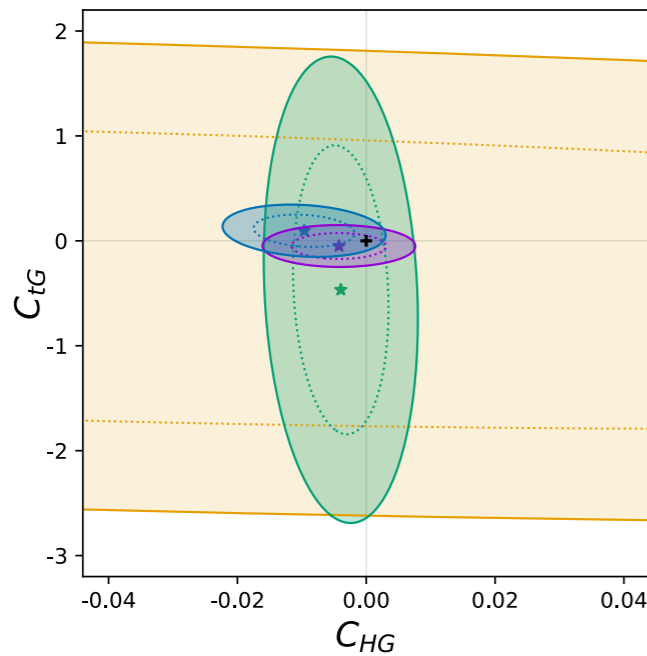
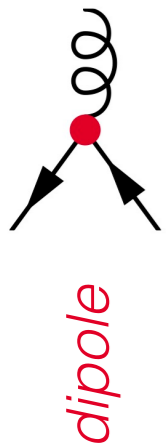
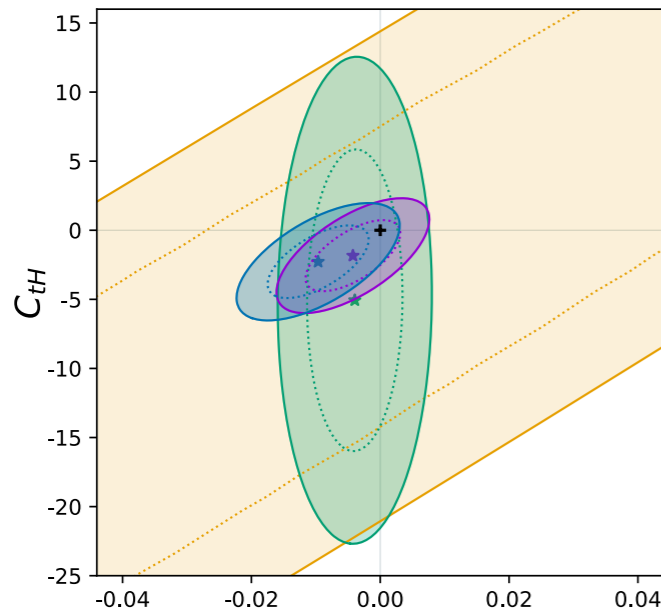
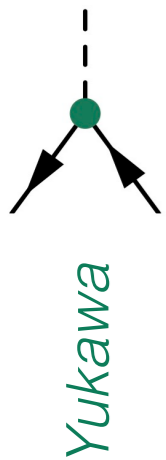
- Constrain **dipole** & **Yukawa**, respectively

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  $m_{t\bar{t}}$

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

- Able to constrain them independently

**Top data is crucial!**

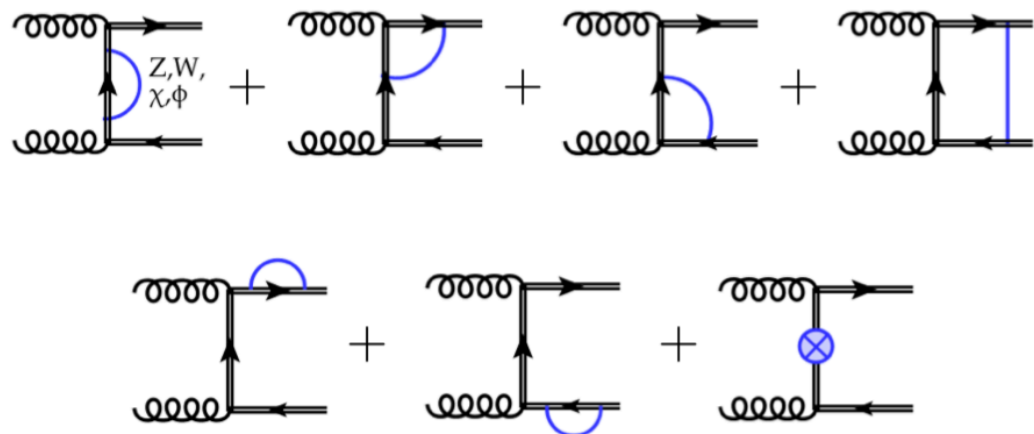
# Loop sensitivity in top data

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

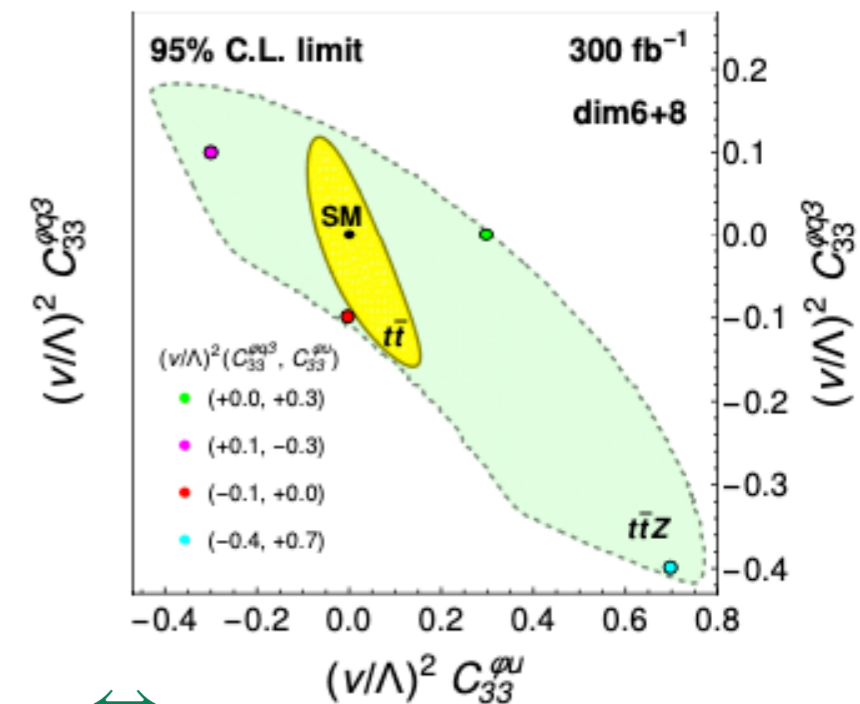
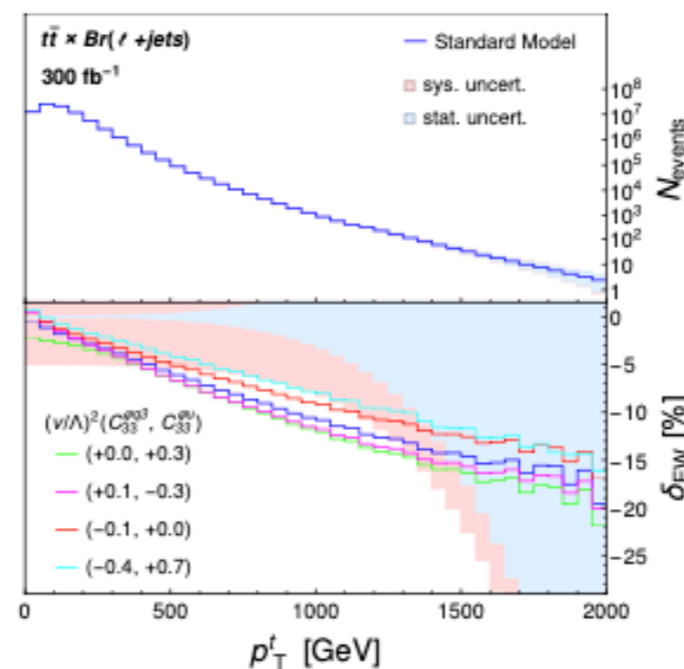
- Few-percent-level precision at LHC

EW top couplings: loops of tops & EW gauge bosons

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



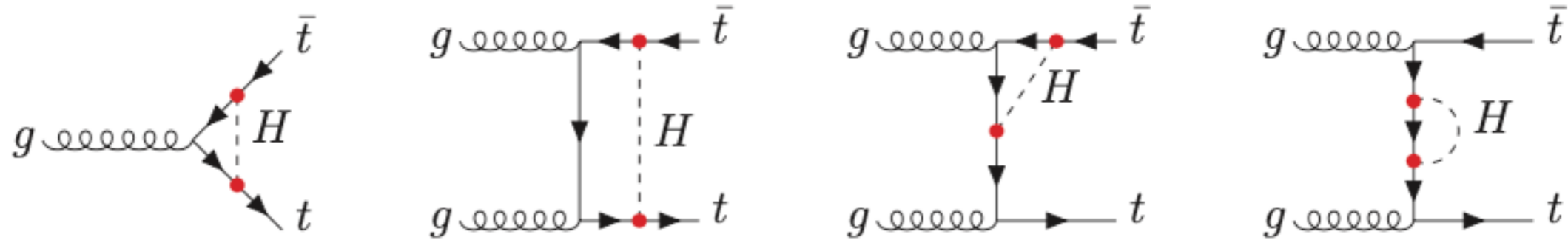
[Martini & Schulze; JHEP 04 (2020) 017]



Promising sensitivity to current operators  $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{Q}\gamma^\mu Q)$

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

# $y_t$ in $t\bar{t}$

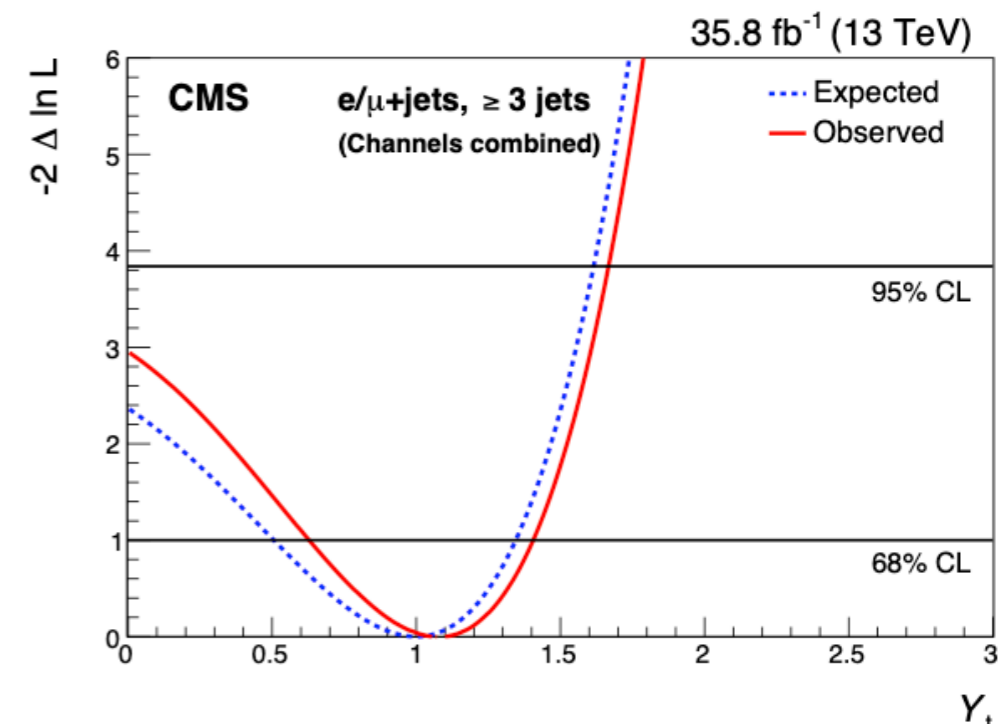


## Top Yukawa coupling

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

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

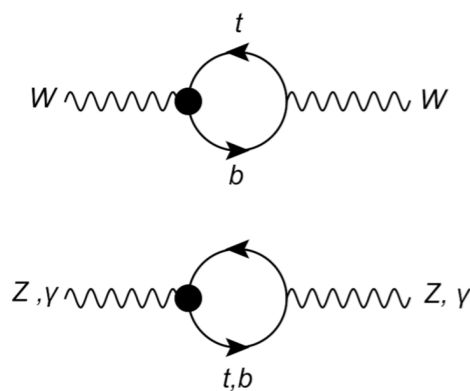
Channel	Best fit $Y_t$		95% CL upper limit	
	Expected	Observed	Expected	Observed
3 jets	$1.00^{+0.66}_{-0.90}$	$1.62^{+0.53}_{-0.78}$	$<2.17$	$<2.59$
4 jets	$1.00^{+0.50}_{-0.72}$	$0.87^{+0.51}_{-0.77}$	$<1.88$	$<1.77$
$\geq 5$ jets	$1.00^{+0.59}_{-0.83}$	$1.27^{+0.55}_{-0.74}$	$<2.03$	$<2.23$
Combined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



# More loop sensitivity

Several other processes have been studied

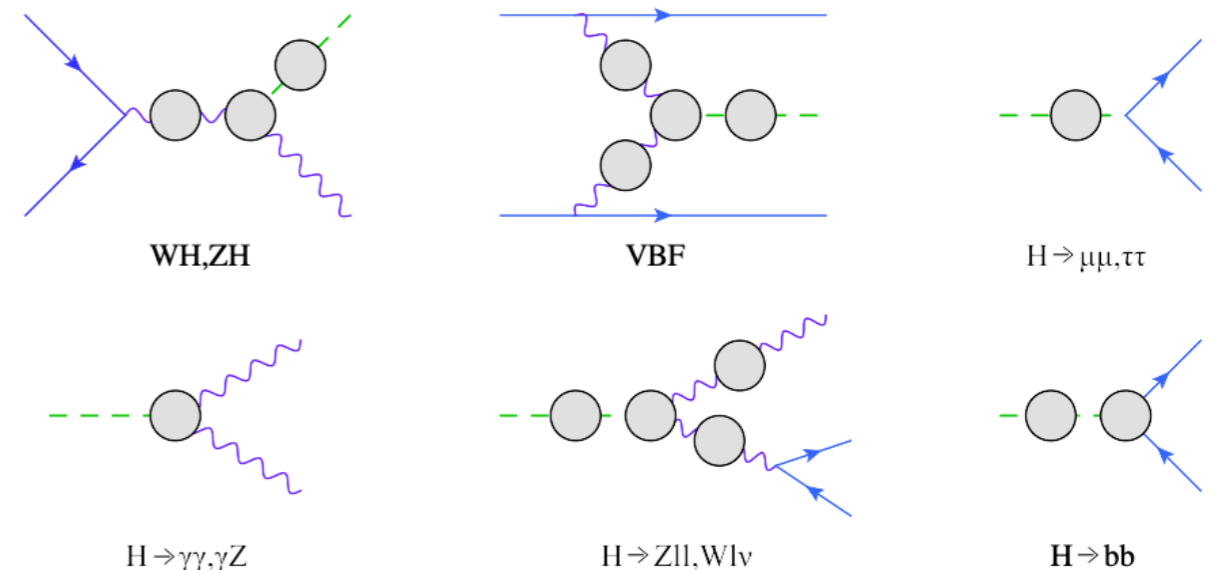
## Z-pole observables



[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

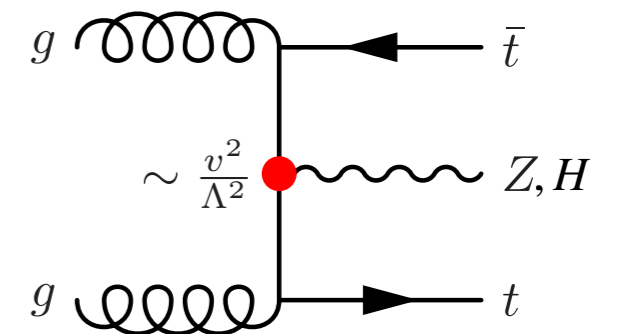
Others? Diboson, Drell-Yan, ...

# 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  $\times$  SM interference often **suppressed**  
[Azatov et al.; PRD 95 (2017) no. 6, 065014]



$$\mathcal{A} \sim \mathcal{A}_{SM} \left( 1 + c_i \frac{v^2}{\Lambda^2} + c_j \frac{v E}{\Lambda^2} + c_k \frac{E^2}{\Lambda^2} \right) \quad \text{'Energy helps accuracy'}$$

[Farina et al.; PLB 772 (2017) 210-215]

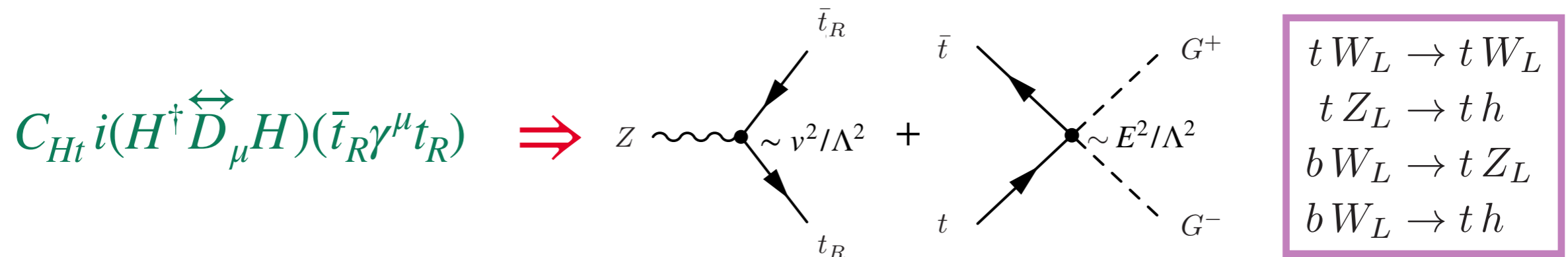
Rate measurements will become systematics dominated  
Increasingly high-energy measurements scale with lumi.

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



# Finding the right process

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



**Unitarity non-cancellations in scattering amplitudes**

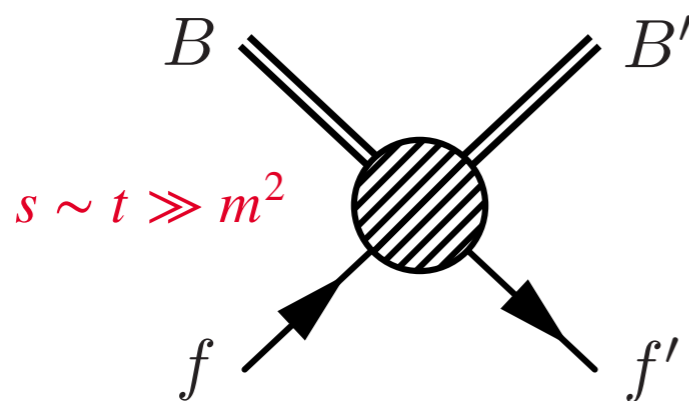


**Non-renormalisable contact interactions with Goldstones**

*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	$b W \rightarrow t (Z/\gamma)$	$t W \rightarrow t W$ $t (Z/\gamma) \rightarrow t (Z/\gamma)$
w/ Higgs	$b W \rightarrow t h$	$t (Z/\gamma) \rightarrow t h$ $t h \rightarrow t h$

# EW top scattering

Energy-growing  
interference

*gauge/higgs operators*  $\Leftarrow \Rightarrow$  *top operators*

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

*single-top*

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

*two-top  
w/o Higgs*

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

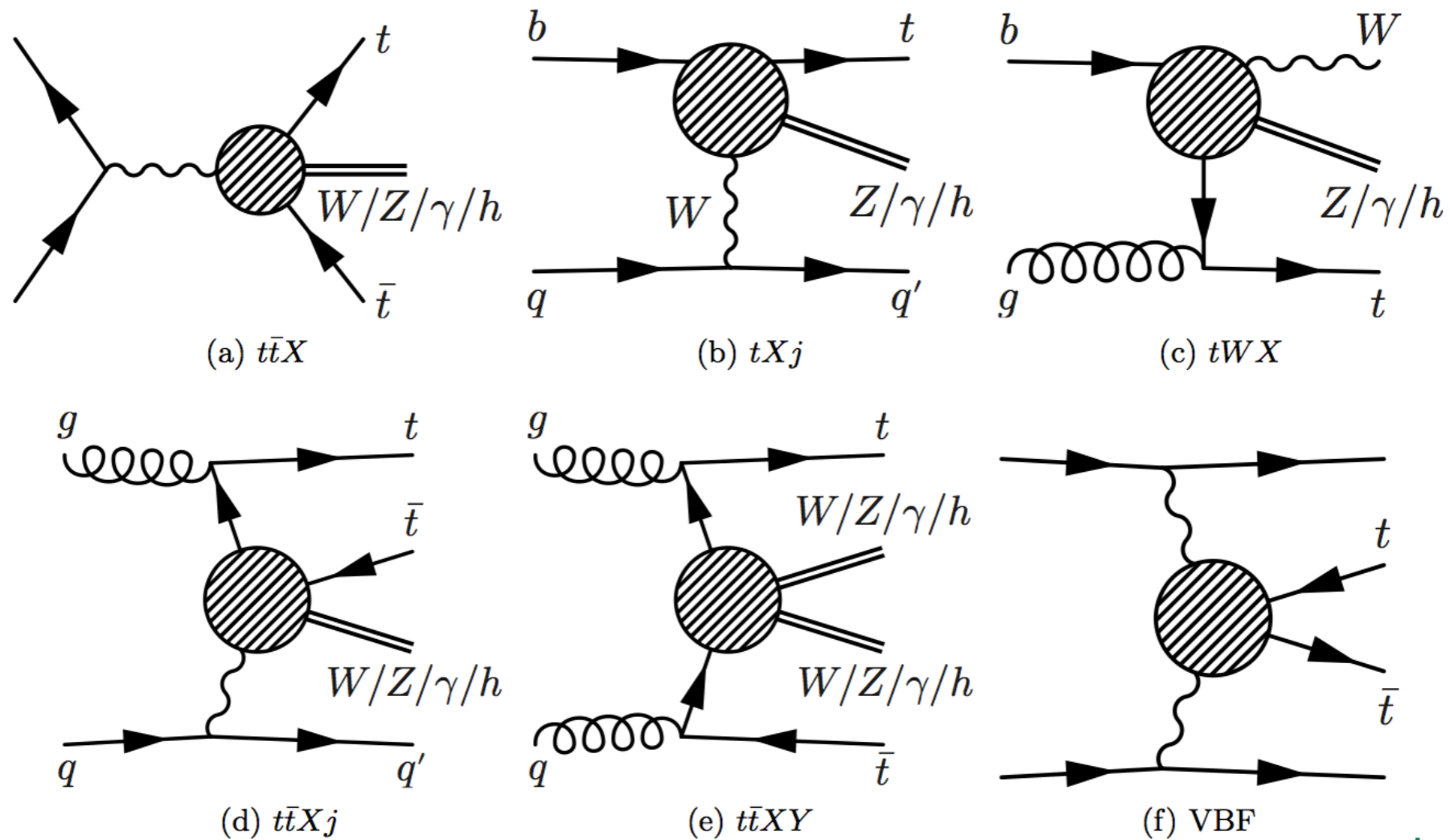
*two-top  
w/ Higgs*

Most top operators show max growth somewhere

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

# Embedding the amplitudes

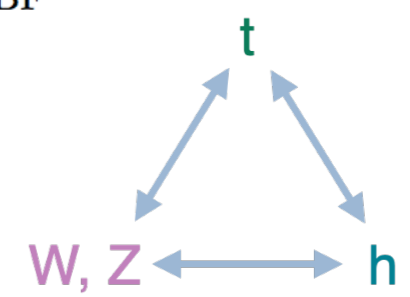
Collider processes: **high multiplicity, EW top production**



Couplings { top EW  
Higgs  
triple gauge



Heart of EWSB sector



# Top EW scattering pheno

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

*single-top*

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

*two-top  
w/o Higgs*

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

*two-top  
w/ Higgs*

See, e.g.,  $tZj/tHj$  [Degrande, Maltoni, KM, Vryonidou & Zhang; JHEP 01 (2022) 100]  
 $tWZ$  [El Faham, Maltoni, KM & Zaro; JHEP 01 (2022) 100]

# Prospects & challenges

EW top scattering: promising avenue for EW top couplings

- 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 ( $t\bar{t}Wj$ ,  $tHj$ ,  $tWZ$ , ...)
- Others challenging, dedicated pheno studies required...

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

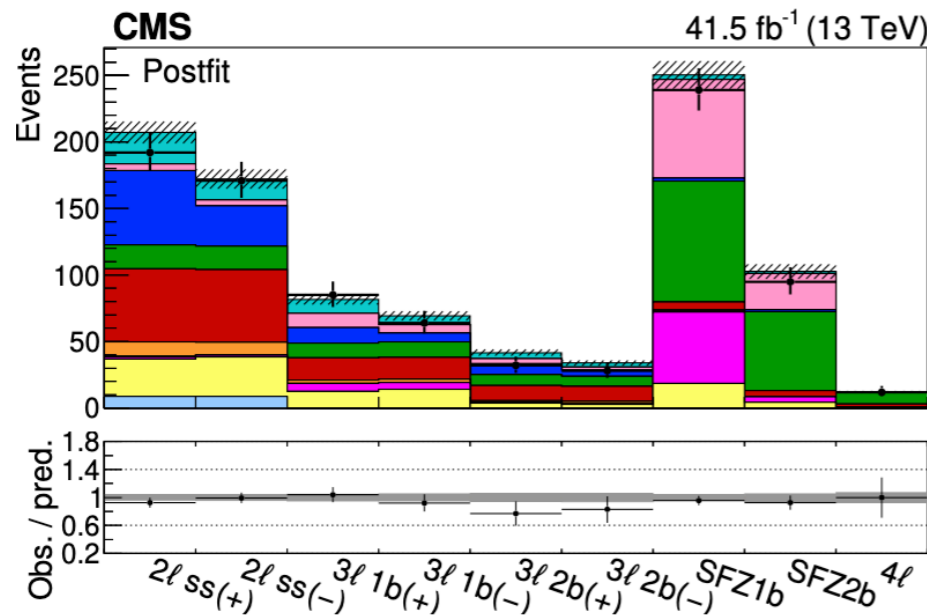
Sig/Bkg. overlap  $\Rightarrow$  global measurements

- 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

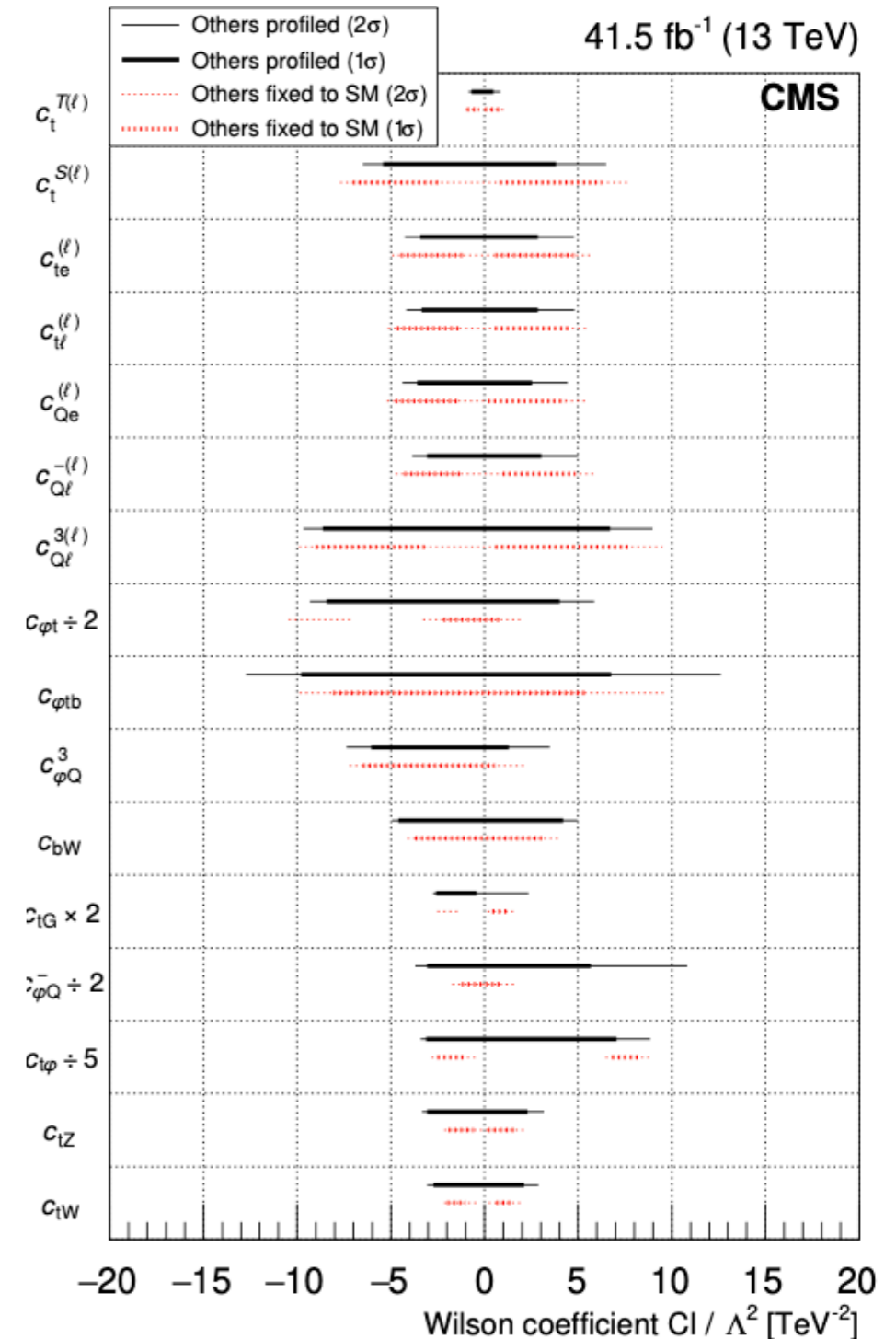
Several examples in top analyses

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



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

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



# Part 1: 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
- Very important for testing validity

# Part 2: practical guide

How to get predictions for SMEFT interpretations

- Basic techniques, tips & tricks for newcomers
- Based on `MadGraph5_aMC@NLO` & `SMEFTatNLO`
- Assumes some experience in using `MG5`
- Key topics & suggested exercises
- Probably too much to cover in remaining time
- Hopefully the slides can be a useful reference to return to

## Topics

- What do we need to calculate?
- What is `SMEFTatNLO`?
- Example commands
- Restriction cards
- Coupling orders
- Reweighting
- Production & decay
- NLO mode



# Getting SMEFT predictions

Any observable at dim-6:

$$\mathcal{O} = \mathcal{O}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_{\text{int}}^i + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} \mathcal{O}_{\text{sq}}^{ij}$$

Goal: determine  $\mathcal{O}_{\text{SM}}$ ,  $\mathcal{O}_{\text{int}}^i$  &  $\mathcal{O}_{\text{sq}}^{i,j}$

- ‘sq’: formally higher order, same as dim-8 ‘int’
- Generally not considered & no generic tools to estimate
- Relevant for validity: question of interpretation

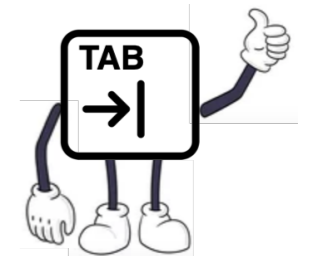
MC tools: **MG5\_aMC@NLO**, POWHEG, Sherpa, Whizard, ...

- Generate events: flexible, many distributions & parton shower interface
- Alternative: fixed order (specific observables, needs FORTRAN)

# mg5\_aMC top tips

## Top tips:

- `Tab completion` (start typing then press tab) to view suggestions/possibilities
- `help` (very useful!)
- `help COMMAND` (e.g. `generate`, `display`, `set`)
- `tutorial`
- `display diagrams` (make sure you are generating the desired process)
- Google is your friend: many users worldwide with similar problems ;)
- You can communicate with developers on Launchpad (questions, bugs...)



MadGraph5\_aMC@NLO

Overview Code Bugs Blueprints Translations **Answers**

Questions for MadGraph5\_aMC@NLO

by relevancy

Get Involved

[Report a bug](#) →

[Ask a question](#) →

*a) check if a similar question & answer exist*

*b) report issue*

# SMEFT UFOs

General-purpose MC: process-independent codes

- Models implement the SM+BSM Lagrangian
- Fast & efficient MC generation for pheno/experimental studies

Today: **SMEFTatNLO** *[Degrande et al.; PRD **103**, 096024]*  
<http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO>

- `dim6top`, `SMEFTsim`, `HELatNLO`,...


Implements dim-6 SMEFT in top-specific flavor limit

- 75 operator coefficients relevant for Higgs, top, EW physics
- Allows calculation of tree- & (QCD) loop-level predictions
- Cross-validated with `SMEFTsim` *[Durieux et al.; arXiv:1906.12310]*

Applications in pheno papers, global fits & exp. analyses

Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou & Cen Zhang, [arXiv:2008.11743](#)

The implementation is based on the Warsaw basis of dimension-six SMEFT operators, after canonical normalization. Electroweak input parameters are taken to be  $G_F$ ,  $M_Z$ ,  $M_W$ . The CKM matrix is approximated as a unit matrix, and a  $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_l \times U(1)_e)^3$  flavor symmetry is enforced. It forbids all fermion masses and Yukawa couplings except that only of the top quark. The model therefore implements the five-flavor scheme for PDFs.

A new coupling order, `NP=2`, is assigned to SMEFT interactions. The cutoff scale `Lambda` takes a default value of  $1 \text{ TeV}^{-2}$  and can be modified along with the Wilson coefficients in the `param_card`. Operators definitions, normalisations and coefficient names in the UFO model are specified in [definitions.pdf](#) . The notations and normalizations of top-quark operator coefficients comply with the LHC TOP WG standards of [1802.07237](#). Note however that the flavor symmetry enforced here is slightly more restrictive than the baseline assumption there (see the [dim6top page](#) for more information). This model has been validated at tree level against the `dim6top` implementation (see [1906.12310](#) and the [comparison details](#)).

### Current implementation

UFO model: [SMEFTatNLO\\_v1.0.tar.gz](#) 

The current implementation imposes CP conservation. In the quark sector, it focuses primarily on top-quark interactions. The light-quark current operator, qqHDH, uuHDH, ddHDH, with coefficients `cpq3i`, `cpqMi`, `cpu`, `cpd` are however included. The triple-gluon operator, with coefficient `cG`, is currently not available (see the loop-capable `GGG` implementation). Vertices including more than four scalars or four leptons are not included. Scalar and tensor `QQ11` operators, with coefficients `ct1S3`, `ct1T3`, and `cb1S3`, break our flavor symmetry assumption and are not available for one-loop computations. Top-quark flavor-changing interactions, not compatible with the imposed flavor symmetry, are not included (see the loop-capable [TopFCNC](#) implementation).

Unlike prescribed by the LHC TOP WG, the top quark chromomagnetic-dipole operator coefficient `ctG` is normalized with a factor of the strong coupling,  $g_s$ . This normalization factor temporarily ensures compatibility with the 2.X.X series of MadGraph5\_aMC@NLO but may be dropped in the future. As with every other appearance of this coupling in MadGraph5\_aMC@NLO, its value is renormalisation-group evolved to the QCD renormalization scale (set in the `run_card`).

```
MG5_aMC>import model SMEFTatNLO
```

```
MG5_aMC>generate p p > t t~ NP=2
```

```
MG5_aMC>output
```

```
MG5_aMC>launch
```

[support: smeftatnlo-dev@cern.ch](mailto:smeftatnlo-dev@cern.ch)

# What's in the box?

'Warsaw' basis

[Grzadkowski et al.; JHEP 1010 (2010) 085]

$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$		$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$	$Q_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$Q_{ee}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$Q_{le}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
<del><math>Q_{\tilde{G}}</math></del>	<del><math>f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}</math></del>	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$	$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$Q_{lu}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$	$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{ld}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
<del><math>Q_{\tilde{W}}</math></del>	<del><math>\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}</math></del>					$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$Q_{qe}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
						$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_{ed}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
								$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
								$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
										$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$		$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$	$Q_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$Q_{duq}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jkl} [(d_p^\alpha)^T C u_r^\beta] [(q_s^\gamma)^T C l_t^k]$		
<del><math>Q_{\varphi \tilde{G}}</math></del>	<del><math>\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}</math></del>	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jkl} (\bar{q}_s^k d_t)$	$Q_{qqu}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jkl} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(u_s^\gamma)^T C e_t]$		
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$	$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jkl} (\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jkl} \varepsilon_{mnp} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^\gamma)^T C l_t^p]$		
<del><math>Q_{\varphi \tilde{W}}</math></del>	<del><math>\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}</math></del>	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \varepsilon_{jkl} (\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jkl} (\tau^I \varepsilon)_{mnp} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^\gamma)^T C l_t^p]$		
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jkl} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$	$Q_{duu}$	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$		
<del><math>Q_{\varphi \tilde{B}}</math></del>	<del><math>\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}</math></del>	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$						
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$						
<del><math>Q_{\varphi \tilde{W}B}</math></del>	<del><math>\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}</math></del>	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$						

Some symmetries imposed to control parameter space

- CP, B and flavor conservation
- Top-specific flavour structure of 2 & 4 fermion operators

# Flavor symmetry

## Approximate flavor symmetry in the SM

- SM: broken by Yukawa interactions
- SMEFT: broken by  $\psi^2 X \varphi$ ,  $\psi^2 \varphi^3$ ,  $(\bar{L}R)(\bar{L}R)$ ,  $(\bar{L}R)(\bar{R}L)$  &  $\mathcal{O}_{\varphi ud}$
- + any off-diagonal or non-universal entries of other 2F operators

## SMEFTatNLO: minimal extension to single out top quark

universal  $U(3)_L \times U(3)_e \times U(3)_Q \times U(3)_u \times U(3)_d$   
 top  $U(3)_L \times U(3)_e \times U(2)_Q \times U(2)_u \times U(3)_d$

*cf. Minimal flavor violation*

*[Buras et al.; PLB 500 (2001) 161]*

*[D'Ambrosio et al.; NPB 645 (2002) 155]*

See **dim6top**

*[Aguilar-Saavedra et al.; arXiv:1802.07237]*

Yukawa	$\psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{Q} t \tilde{\varphi})$
Dipoles	$\psi^2 X H : (\bar{Q} \sigma^{\mu\nu} t \tilde{\varphi}) B_{\mu\nu} [W_{\mu\nu}^I, G_{\mu\nu}^a]$
3rd gen. currents	$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi) (\bar{Q} \gamma^\mu Q) [(\bar{Q} \gamma^\mu \tau^I Q), (\bar{t} \gamma^\mu t), \dots]$
3rd gen. 4F	$\psi^4 : (\bar{Q} \gamma^\mu Q) (\bar{q} \gamma_\mu q), (\bar{Q} \gamma^\mu Q) (\bar{Q} \gamma_\mu Q), \dots$

# SMEFTatNLO UFO

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

Check out [definitions.pdf](#) on FeynRules webpage

- Conventions, operator & coefficient definitions, flavor assumption
- $(M_W, M_Z, G_F)$  input scheme details re: EFT effects
- Flavor symmetry dictates 5 flavor scheme:  $m_b = 0$

<i>Bosonic</i>			SLHA Block: DIM6		
$\mathcal{O}_i$	UFO	Definition	$\mathcal{O}_i$	UFO	Definition
$\mathcal{O}_G$	cG	$g_S f_{ABC} G_{\mu\nu}^A G^{B,\nu\rho} G_{\rho}^{C,\mu}$	$\mathcal{O}_W$	cWWW	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W_{\rho}^{K,\mu}$
$\mathcal{O}_{\varphi G}$	cpG	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) G_A^{\mu\nu} G_{\mu\nu}^A$	$\mathcal{O}_{\varphi W}$	cpW	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W_{\mu\nu}^I$
$\mathcal{O}_{\varphi B}$	cpBB	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$	$\mathcal{O}_{\varphi WB}$	cpWB	$(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W_{\mu\nu}^I$
$\mathcal{O}_\varphi$	cp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$	$\mathcal{O}_{\varphi d}$	cdp	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi D}$	cpDC	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$			

*example:*  
*bosonic operators*

match **dim6top**  
conventions

Cutoff parameter,  $\Lambda$ : **Lambda** (default value 1000 GeV)

- Coupling order: **NP** (New Physics)
- Dimension-6:  $1/\Lambda^2 \Leftrightarrow \text{NP}=2$  ! different from **SMEFTsim** (NP=1) !

# Parameter card

```
#####
## INFORMATION FOR DIM6
#####
Block DIM6
  1 1.000000e+03 # Lambda
  2 0. # cpDC
  3 0. # cpWB
  4 0. # cdp
  5 0. # cp
  6 0. # cWW
  7 0. # cG
  8 0. # cpG
  9 0. # cpW
 10 0. # cpBB
```

Bosonic

```
#####
## INFORMATION FOR DIM64F2L
#####
Block DIM64F2L
  1 0. # cQ1M1
  2 0. # cQ1M2
  3 0. # cQ131
  4 0. # cQ132
  5 0. # cQe1
  6 0. # cQe2
  7 0. # ct11
  8 0. # ct12
  9 0. # cte1
 10 0. # cte2
 13 0. # cQ1M3
 14 0. # cQ133
 15 0. # cQe3
 16 0. # ct13
 17 0. # cte3
 19 0. # ct1s3
 20 0. # ct1t3
 21 0. # cb1s3
```

2 quark  
2 lepton

```
#####
## INFORMATION FOR DIM62F
#####
Block DIM62F
  1 0. # cpl1
  2 0. # cpl2
  3 0. # cpl3
  4 0. # c3pl1
  5 0. # c3pl2
  6 0. # c3pl3
  7 0. # cpe
  8 0. # cpmu
  9 0. # cpta
 10 0. # cpqMi
 11 0. # cpq3i
 12 0. # cpQ3
 13 0. # cpQM
 14 0. # cpu
 15 0. # cpt
 16 0. # cpd
 19 0. # ctp
 22 0. # ctZ
 23 0. # ctW
 24 0. # ctG
```

2 fermion

```
#####
## INFORMATION FOR RENOR
#####
Block Renor
  1 9.118800e+01 # mueft
```

$\mu_{EFT}$  renormalisation scale

```
#####
## INFORMATION FOR DIM64F
#####
Block DIM64F
  1 0. # cQq83
  2 0. # cQq81
  3 0. # cQu8
  4 0. # ctq8
  6 0. # cQd8
  7 0. # ctu8
  8 0. # ctd8
 10 0. # cQq13
 11 0. # cQq11
 12 0. # cQu1
 13 0. # ctq1
 14 0. # cQd1
 16 0. # ctu1
 17 0. # ctd1
 19 0. # cQ08
 20 0. # cQ01
 21 0. # cQt1
 23 0. # ctt1
 25 0. # cQt8
```

4 quark

```
#####
## INFORMATION FOR DIM64F4L
#####
Block DIM64F4L
  1 0. # cll1111
  2 0. # cll2222
  3 0. # cll3333
  4 0. # cll1122
  5 0. # cll1133
  6 0. # cll2233
  7 0. # cll1221
  8 0. # cll1331
  9 0. # cll2332
```

4 lepton



# Example commands

## Higgs production

### loop-induced

```
> g g > H          QED=1 QCD=2 NP=2 [QCD]
> g g > H H         QED=2 QCD=2 NP=2 [QCD]
> g g > H H H       QED=3 QCD=2 NP=2 [QCD]
> g g > H j         QED=1 QCD=3 NP=2 [QCD]
```

## Top quark production

```
> e+ e- > t t~      QED=2 QCD=0 NP=2 [QCD]
> p p > t t~        QED=0 QCD=2 NP=2 [QCD]
> p p > t t~ h      QED=1 QCD=2 NP=2 [QCD]
> p p > t t~ Z      QED=1 QCD=2 NP=2 [QCD]
> p p > t t~ W+     QED=1 QCD=2 NP=2 [QCD]
> p p > t W- $$ t~  QED=1 QCD=1 NP=2 [QCD]
> p p > t W- j     $$ t~ QED=1 QCD=2 NP=2 [QCD]
> p p > t j        $$ W- QED=2 QCD=0 NP=2 [QCD]
> p p > t h j      $$ W- QED=3 QCD=0 NP=2 [QCD]
> p p > t Z j      $$ W- QED=3 QCD=0 NP=2 [QCD]
> p p > t a j      $$ W- QED=3 QCD=0 NP=2 [QCD]
```

## Generation tips

- Specify **QCD**, **QED** & **NP** coupling orders as much as possible
- Always use a restriction card (`'import model SMEFTatNLO'` has 0 ops.)
- Check diagrams!

## QCD

```
> p p > j j          QED=0 QCD=2 NP=2 [QCD]
```

## Drell Yan

```
> p p > mu+ mu-      QCD=0 QED=2 NP=2 [QCD]
> p p > mu+ vm       QCD=0 QED=2 NP=2 [QCD]
> p p > W+ j $$ t     QCD=1 QED=1 NP=2 [QCD]
> p p > W- j $$ t~    QCD=1 QED=1 NP=2 [QCD]
> p p > Z j          QCD=1 QED=1 NP=2 [QCD]
```

## Multi-boson production

### quark-initiated

```
> p p > W+ W-        QED=2 QCD=0 NP=2 [QCD]
> p p > W+ Z          QED=2 QCD=0 NP=2 [QCD]
> p p > Z Z           QED=2 QCD=0 NP=2 [QCD]
```

### loop-induced

```
> g g > W+ W-        QED=2 QCD=2 NP=2 [QCD]
> g g > Z Z           QED=2 QCD=2 NP=2 [QCD]
> g g > W+ W- Z      QED=3 QCD=2 NP=2 [QCD]
> g g > Z Z Z        QED=3 QCD=2 NP=2 [QCD]
```

# Restriction cards

SMEFT has many parameters

- Only a subset relevant for a given process
- Recommended to remove unused operators before generation

Place card inside model folder: `restrict_XYZ.dat`

- Copy of `param_card` with e.g. `unused=0`



```
MG5_aMC> import model SMEFTatNLO-XYZ
```

- Use `python ./write_param_card.py` to generate template

1. Parameters set to 0 will be **removed**

2. Parameters set to 1 will be **fixed** to 1

3. Those set to the same value will be **tied together**

Helper command line script: `write_restrict_card.py`

- `python ./write_restrict_card.py --info or --help`

# Coupling orders

Used to specify desired Feynman diagrams

- SM: **QCD** (strong coupling  $g_S$ ) & **QED** (weak couplings  $g, g', e$ )
- **SMEFTsim** & **SMEFTatNLO**: **NP** (new physics,  $\Lambda^2, \Lambda$ )

```
generate p p > t t~ QCD=2 QED=0
```

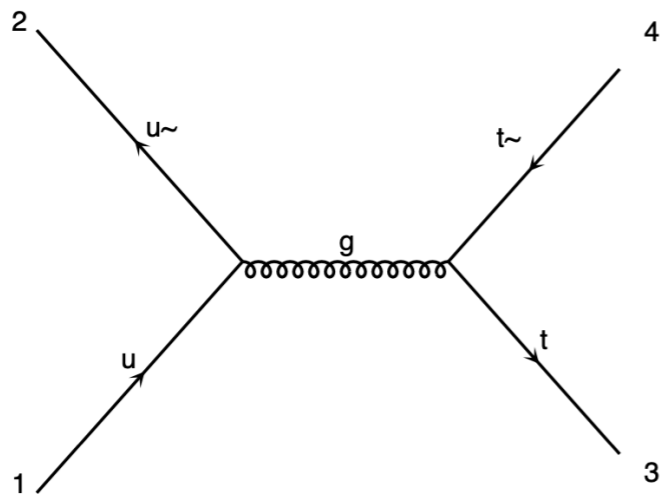


diagram 1 QCD=2, QED=0

```
generate p p > t t~ QCD=0 QED=2
```

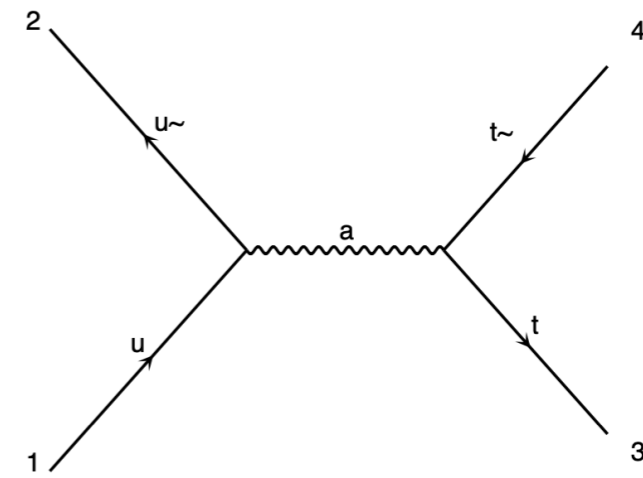


diagram 1 QCD=0, QED=2

```
MG5_aMC> display diagrams
```

Open file viewer

```
MG5_aMC> cd SubProcesses/P...
```

After output: [access matrix.ps](#)

# Coupling orders |v. 2

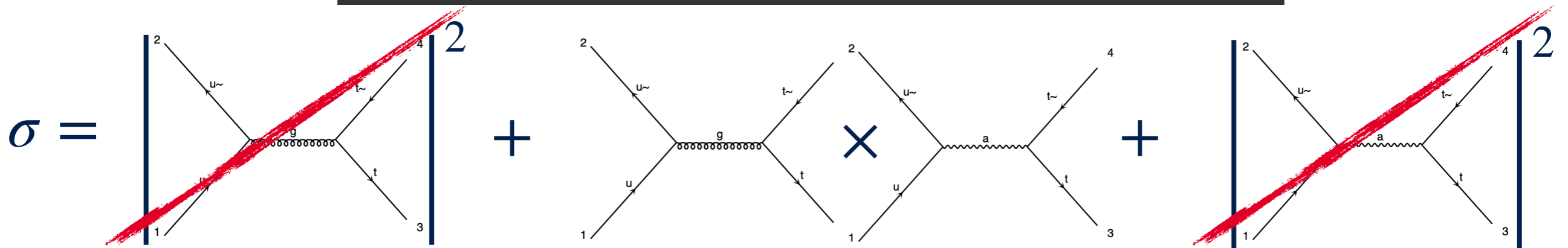
$X=N$ : Defined at **amplitude** level

- $QCD/QED=N$ : shorthand for  $QCD/QED \leq N$
- $QCD/QED==N$ : “exactly equal to”
- **MG5**: all possible amplitudes satisfying coupling order constraints

$X^2=N$ : Defined at **amplitude-squared** (cross section) level

- Can be used in conjunction with above (select diagrams, then fine-tune)
- Fine-tune exact contributions in perturbative (or EFT) expansion
- **!** Only fully available in LO (& loop-induced) mode: not NLO **!**

generate p p > t t~ QCD=2 QED=2 QCD^2=2 QED^2=2



# NP coupling orders

$$\mathcal{A}_{D=6} = \mathcal{A}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{A}_i \quad \Rightarrow \quad \sigma_{D=6} = \sigma_{SM} + \sum_i \frac{c_i}{\Lambda^2} \sigma_i + \sum_{j \leq i} \frac{c_i c_j}{\Lambda^4} \sigma_{i,j}$$

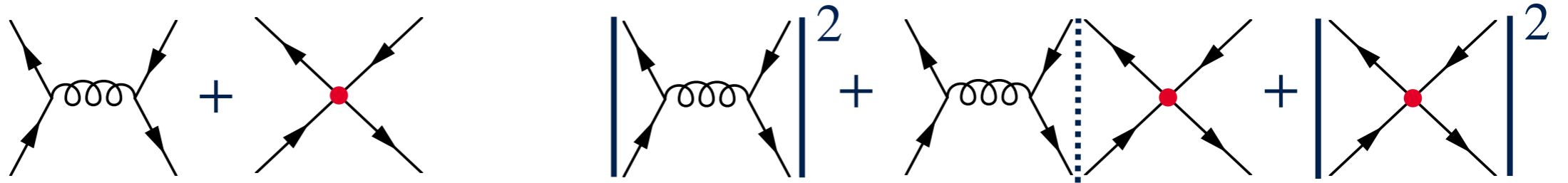
NP=0
NP=2
NP=0
NP=2
NP=4

$n$  coefficients  $\Rightarrow (n + 1)(n + 2)/2$  numbers:  $\sigma_{SM}, \sigma_i, \sigma_{i,j}$

LO mode: select EFT contributions at generation level

generate p p > t t~ QCD=2 QED=0 NP...		
Full thing	$ \mathcal{A}_{SM} + \mathcal{A}_{EFT} ^2$	NP=2 or NP <sup>2</sup> =4
EFT only	$ \mathcal{A}_{EFT} ^2$	NP <sup>2</sup> =2 or NP <sup>2</sup> =4
SM + interference	$ \mathcal{A}_{SM} ^2 + 2\text{Re}[\mathcal{A}_{SM}\mathcal{A}_{EFT}]$	NP <sup>2</sup> =2 or NP <sup>2</sup> ≤2
Interference only	$2\text{Re}[\mathcal{A}_{SM}\mathcal{A}_{EFT}]$	NP <sup>2</sup> =2

# NP coupling orders



$$\mathcal{A}_{D=6} = \mathcal{A}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{A}_i \quad \Rightarrow \quad \sigma_{D=6} = \sigma_{SM} + \sum_i \frac{c_i}{\Lambda^2} \sigma_i + \sum_{j \leq i} \frac{c_i c_j}{\Lambda^4} \sigma_{i,j}$$

NP=0
NP=2
NP=0
NP=2
NP=4

$n$  coefficients  $\Rightarrow (n+1)(n+2)/2$  numbers:  $\sigma_{SM}, \sigma_i, \sigma_{i,j}$

Simple strategy: set  $\Lambda = 1000$  GeV,  $c_i = 1$

- Compute cross section:  $\bar{\sigma}_{i,j}(\Lambda = 1 \text{ TeV})[\text{fb}]$
- Determine  $\sigma_i = \bar{\sigma}_i [\text{fb} \cdot \text{TeV}^2]$  &  $\sigma_{i,j} = \bar{\sigma}_{i,j} [\text{fb} \cdot \text{TeV}^4]$

Don't worry about  $\Lambda$ , its just a number!

- Sets the effective couplings  $\propto c_i/\Lambda^2$
- Only physical scale if you fix  $c_i$  with UV models (interpretation)

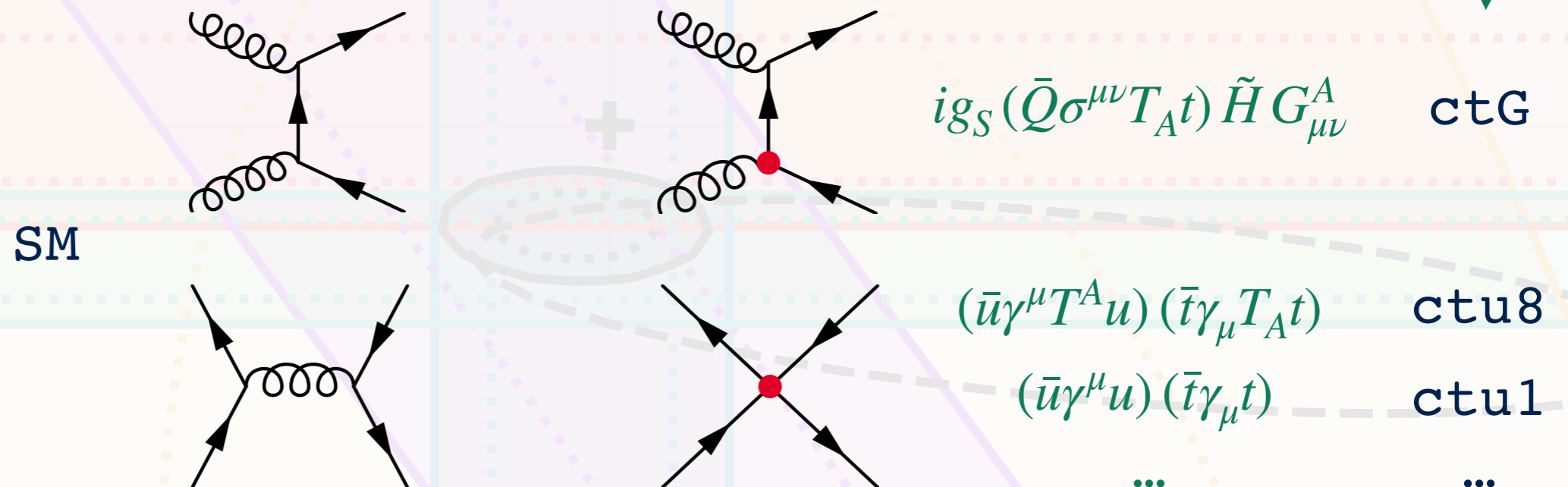
large coupling high scale  $\Leftrightarrow$  small coupling low scale

(You may need to do this if using python 3)

```
MG5_aMC> import model SMEFTatNLO
MG5_aMC> convert model ...
MG5_aMC> quit()
```

# Exercise 1

- SMEFTatNLO: download, contents, write\_param\_card.py
- restrict\_card: parameters, write\_restrict\_card.py
- Generate: ttbar example, remember display diagrams
- Coupling orders: selecting different pieces of the EFT contribution



# Reweighting

Alternative way to get multi-dimensional EFT dependence

- Generate one (big) sample for a baseline hypothesis (e.g. SM)
- Calculate new weights for alternative hypotheses ( $c_i = 1$ )
- Repeat at least  $(n + 1)(n + 2)/2$  times

$$w_i^{new} = w_i^{old} \frac{|M_{new}|^2}{|M_{old}|^2}$$

Extract: 
$$w^k = w_{SM} + \sum_i w_i^k \frac{c_i}{\Lambda^2} + \sum_i w_{i,j}^k \frac{c_i c_j}{\Lambda^4}$$

Instructions specified in `reweight_card.dat`

- Change parameter values: `set param 0.`
- `change process p p > ...`
- `change model SMEFTatNLO-...`

```
launch --rwgt_name=cpGxcpG # cpG = 1
set cpG 1.
set ctp 0.
```

- Documentation: <https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/Reweight>



# Reweighting

$$w^k = w_{SM} + \sum_i w_i^k \frac{c_i}{\Lambda^2} + \sum_i w_{i,j}^k \frac{c_i c_j}{\Lambda^4}$$

## Pros

- **Efficient**: one sample only - saves time & space
- **Fully differential**:  $w^k$  predicts dependence of any observable/binning
- Parton shower, ... : can propagate  $w^k$  to hadron/reco level events

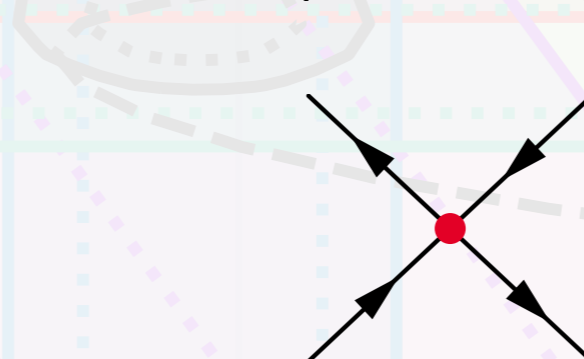
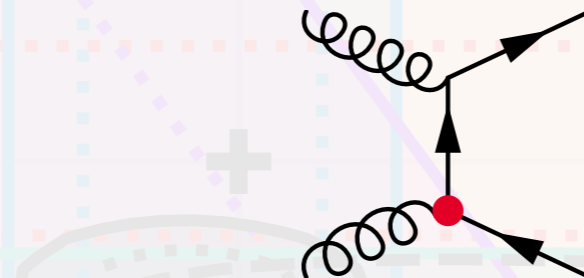
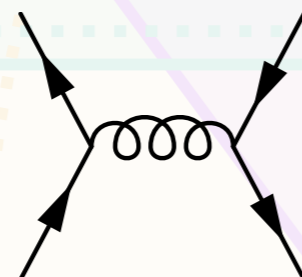
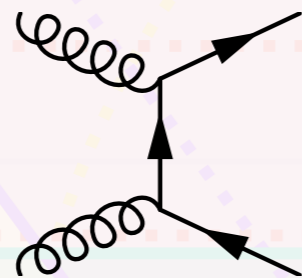
## Cons

- Need to parse `.lhe` file and extract & store  $w^k$
- Sensitive to 'baseline' generation point & its phase space population
- Can lead to **large weights** when extrapolating too far from baseline
- MC uncertainties become unclear
- **Worst case** - baseline scenario doesn't populate a part PS at all:  $0 \times \left| \frac{M_f}{M_i} \right|^2 = 0!$
- Requires making good baseline choices and careful validation

# Exercise 2

- Reweight  $p p > t t \sim$
- Start from SM, get  $\bar{\sigma}_i, \bar{\sigma}_{i,j}$
- set  $c_i = 0$  / set  $c_i = 1$
- change process...  $NP^2 \Rightarrow 2$  to get interf.

SM



$$ig_S (\bar{Q} \sigma^{\mu\nu} T_A t) \tilde{H} G_{\mu\nu}^A \quad ctG$$

$$(\bar{u} \gamma^\mu T^A u) (\bar{t} \gamma_\mu T_A t) \quad ctu8$$

$$(\bar{u} \gamma^\mu u) (\bar{t} \gamma_\mu t) \quad ctu1$$

...

...

# Production & decay

Often factorise these two effects

- Narrow width approximation (NWA)

$$\lim_{M\Gamma \rightarrow 0} \frac{1}{(s - M^2)^2 + (M\Gamma)^2} = \delta(s - M^2) \frac{\pi}{M\Gamma}$$

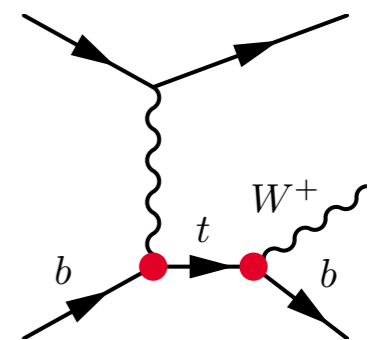
- $\sigma(pp \rightarrow X \rightarrow ab) = \sigma(pp \rightarrow X) \times \text{BR}(X \rightarrow ab)$

$$\left( \sigma_{\text{SM}} + \sum_i \sigma_i \frac{c_i}{\Lambda^2} + \sum_i \sigma_{i,j} \frac{c_i c_j}{\Lambda^4} \right) \times \frac{\Gamma_{\text{SM}}^{ab} + \sum_i \Gamma_i^{ab} \frac{c_i}{\Lambda^2} + \sum_i \Gamma_{i,j}^{ab} \frac{c_i c_j}{\Lambda^4}}{\Gamma_{\text{SM}}^{\text{tot.}} + \sum_i \Gamma_i^{\text{tot.}} \frac{c_i}{\Lambda^2} + \sum_i \Gamma_{i,j}^{\text{tot.}} \frac{c_i c_j}{\Lambda^4}}$$

Non-linear (quadratic) dependence

a) Compute pieces separately & combine

b) Compute full process



“double insertion”

OK as far as NWA holds

Should be similar if EFT valid

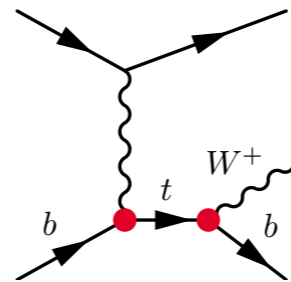
# Production & decay

## a) Compute separately

- ✓ Inclusive observables or if no change in decay angular dependence
- Simulate EFT production (+ SM decay)  $\Rightarrow$  rescale by BR

## b) Compute whole process

- ✓ Correct angular dependence
- Choice of whether or not to include double insertions (**NP=2** or **NP=4**)
- Total width correction can be computed by setting width to **Auto**



*Change UFO!*  
*expansion\_order=4 in*  
*coupling\_orders.py*

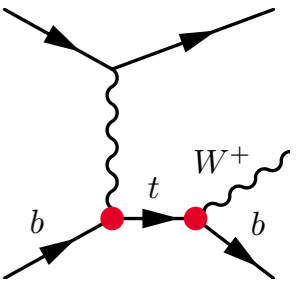
## Useful MG5 feature: **MadSpin**

- Generates events assuming stable particles first
- Decays after, using full process matrix element

```
#####  
## INFORMATION FOR DECAY-  
#####  
DECAY · 6 · Auto ·  
DECAY · 23 · 2.495200e+00 ·  
DECAY · 24 · 2.085000e+00 ·  
DECAY · 25 · 5.753088e-03 ·
```

<https://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO#MadSpin>

# SMEFTatNLO + MadSpin



t-channel single top: `generate p p > t j $$ w+ QED=2 QCD=0 NP=2`

## Decaying without MadSpin

- Full process: `p p > t > b w+ j $$ w+ QED=3 QCD=0 NP=2`
- Decay syntax: `p p > t j $$ w+ QED=2 QCD=0 NP=2, t > w+ b NP=2`

## Decaying with MadSpin

- Undecayed process, modify `madspin_card.dat`

• Madspin syntax: `decay t > w+ b`

`decay t > w+ b, w+ > e+ ve`

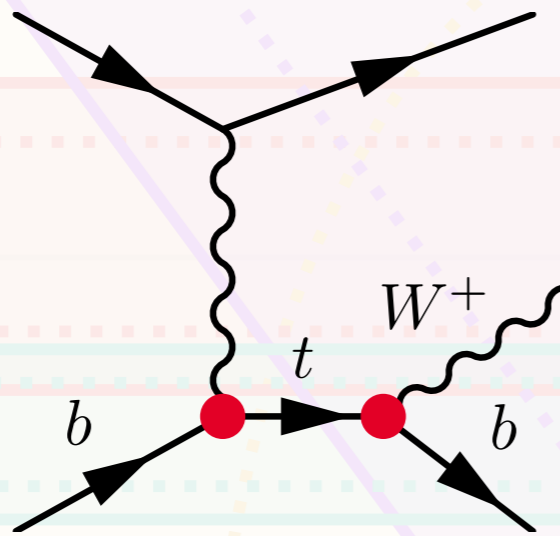
← decay chains

- Will run automatically if `madspin_card.dat` exists
- Or decay existing sample in `bin/madevent`: `decay_events RUN_NAME`
- Creates new directory in `Events/` with decayed sample

factorised:  
assumes NWA

# Exercise 3

- Generate t-channel single-top w/ decays
- Try/compare different options:
- Stable, full, decay syntax & MadSpin



$$i(\bar{Q}\sigma^{\mu\nu}\tau_{It})\tilde{H}W_{\mu\nu}^I \quad \text{ctW}$$

# Why NLO?

In general: improve precision/accuracy of predictions

- Correct **normalisations** & **shapes**, better scale & PDF **uncertainties**

Old reasons: same as for SM predictions

- **QCD** corrections: a minimum to control hadron collider uncertainties
- **EW** corrections: for extra accuracy and in specific phase space regions

New reasons: specific to (SM)EFT interpretation

- First order where non-trivial effects come in: **running & mixing** of coefficients
- Opportunities for **loop-induced** sensitivity: **new contributions at loop level**
- Best possible understanding of patterns & correlations among coefficients

Deviations?	<b>x</b>	<b>✓</b>
Better:	<i>Reflection of new physics <b>reach</b></i>	<i>Pinpointing of new physics <b>origin</b></i>

# SMEFTatNLO in NLO mode

Same syntax + `[QCD]` to enable NLO mode

- Can also access NLO mode for LO generation: `[LOonly=QCD]`
- Important to specify coupling orders & check diagrams
- **!Warning! Do not** set c's to 0 in param\_card, use e.g. `1e-5` (else crash)
- Use restriction cards as much as possible to remove parameters entirely
- `mueft` parameter: **fixed** SMEFT coefficient renormalisation scale
- **We recommend fixed scale generation** (MG5 doesn't run coefficients)

Runs takes longer!

- Get LO events first: `launch aMC@LO`
- Testing: generate events without showering: `--parton` (unphysical!)

Limited squared-order syntax: `NP^2=` OK, `NP^2==` not OK

✓ `MG5 aMC> generate ... [QCD] NP^2=2`

✗ `MG5_aMC> generate ... [QCD] NP^2==2`



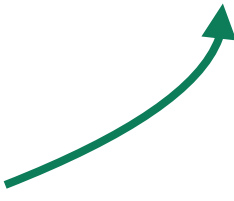
# Coupling orders at NLO

New MG5 version 3 feature: `orders_tag_plot`

- Now splits different coupling order contributions to cross section
- `QED, QCD, NP`  $\Rightarrow$  access LO/NLO & EFT interference/square
- Propagated through to the events!
- `SMEFTatNLO`: only 1 run gives you SM, interference & square

```
INFO: orders_tag_plot is computed as: ..... + NP * ..... 1 ..... + QCD * ..... 100 ..... + QED * ..... 10000
orders_tag_plot= ..... 60000 for NP,QCD,QED, = ..... 0, ..... 0, ..... 6,
AMP_SPLIT: ..... 1 correspond to S.O. .... 0 ..... 0 ..... 6
orders_tag_plot= ..... 60002 for NP,QCD,QED, = ..... 2, ..... 0, ..... 6,
```

Each order is assigned an integer value

- Recorded in output: `Events/*/alllogs_*.html` 
- e.g. `NP*1 + QCD*100 + QED*10000`
- Can access them in fortran analysis of Fixed Order mode (for 'experts'!)
- Each weight stored separately in `<rwgt>` info per event

# Coupling orders in .lhe

weight ids

order tag

central scale

```
... <weightgroup name='scale_variation' tag='60202' combine='envelope'>
... <weight id='1046' tag='60202' dyn='0' muR=0.10000E+01
muF=0.10000E+01 </weight>
... <weight id='1047' tag='60202' dyn='0' muR=0.20000E+01
muF=0.10000E+01 </weight>
... <weight id='1048' tag='60202' dyn='0' muR=0.50000E+00
muF=0.10000E+01 </weight>
... <weight id='1049' tag='60202' dyn='0' muR=0.10000E+01
muF=0.20000E+01 </weight>
... <weight id='1050' tag='60202' dyn='0' muR=0.20000E+01
```

different scale settings

Many of these blocks in <initrwgt> header before events

event

```
<event>
6 0 0.91938860E-01 0.15346304E+03 0.78185903E-02 0.11601516E+00
-2 -1 0 0 0 501 0.000000000000000000E+00 0.000000000000000000E+00
2 -1 0 0 501 0 0.000000000000000000E+00 0.000000000000000000E+00
23 2 1 2 0 0 0.11462519274438232E+03 0.17434816792678109E+02
25 1 1 2 0 0 -0.11462519274438232E+03 -0.17434816792678109E+02
11 1 3 3 0 0 0.12159577903331332E+03 0.27038977374790313E+02
-11 1 3 3 0 0 -0.69705862889310026E+01 -0.96041605821122040E+01
#aMcatNLO 1 0 0 0 0 0.00000000E+00 0.00000000E+00 9 6 0 0.00000000E+00 0.00
<rwgt>
<wgt id='1001'> 0.91941E-01 </wgt>
<wgt id='1002'> 0.83393E-01 </wgt>
```

split order weights

many weights

# Extracting interferences

Trouble getting good precision for interference terms?

- Sometimes  $\mathcal{O}(\Lambda^{-2})$  contributions can be relatively **suppressed**
- Helicity (non-interference), colour (symmetry), small mass, ...
- Squared,  $\mathcal{O}(\Lambda^{-4})$ , terms can swamp MC predictions
- Non-issue for LO generation, can compute interference only ( $\text{NP}^2=2$ )

Possible solutions for NLO

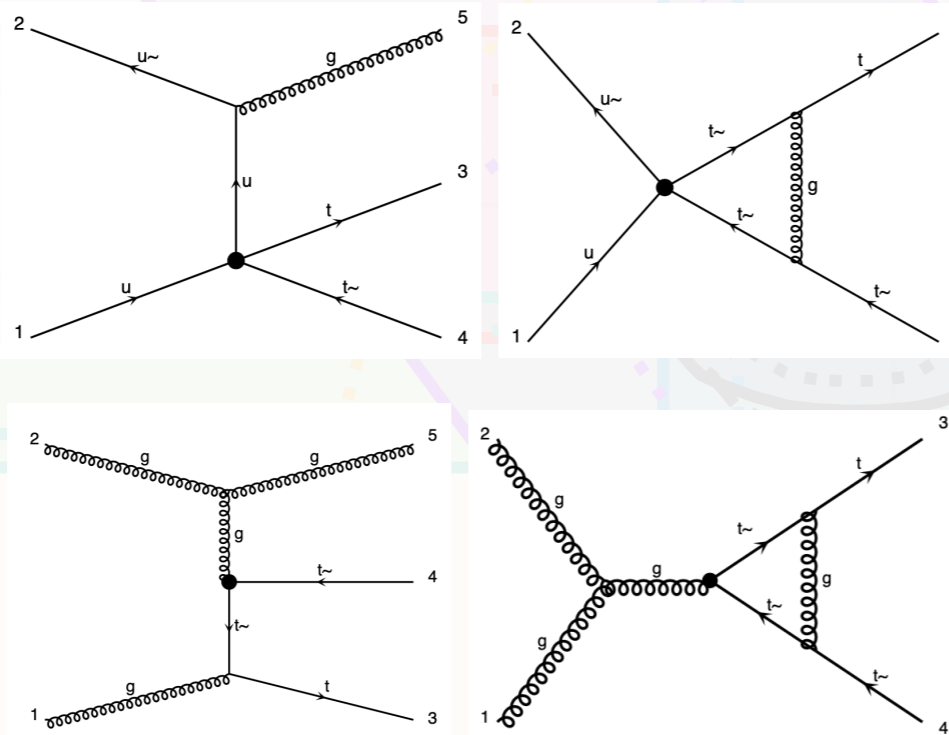
- Pick optimal value of coefficient to maximise relative size of  $\mathcal{O}(\Lambda^{-2})$

$$\frac{\partial}{\partial c} \left( \frac{\sigma_{\text{INT}} c}{\sigma_{\text{SM}} + \sigma_{\text{INT}} c + \sigma_{\text{SQ}} c^2} \right) = 0 \quad \Rightarrow \quad c_{\text{opt.}} = \sqrt{\frac{\sigma_{\text{SM}}}{\sigma_{\text{SQ}}}}$$

- Best value depends on phase space
- Version 3: remove  $\mathcal{O}(\Lambda^{-4})$  altogether: ( $\text{NP}^2=2$ )

# Exercise 4

- Generate ttbar events @ NLO
- Same as Exercise 1 + [QCD]
- Get interference contribution for the operators
- Evaluate NLO/LO 'k-factors': quantify importance of QCD corrections



$$ig_S (\bar{Q}\sigma^{\mu\nu}T_A t) \tilde{H} G_{\mu\nu}^A \quad \text{ctG}$$

$$(\bar{u}\gamma^\mu T^A u) (\bar{t}\gamma_\mu T_A t) \quad \text{ctu8}$$

$$(\bar{u}\gamma^\mu u) (\bar{t}\gamma_\mu t) \quad \text{ctu1}$$

...

...

# Merging

SMEFTatNLO compatible with LO merging (e.g. MLM)

- No difference to SM case

Example  $p p > t t^{\sim}$  (+1 jet)

- 4F operator  $c_{tu8} (\bar{u}\gamma^{\mu}T^A u) (\bar{t}\gamma_{\mu}T_A t)$

```
generate p p > t t~ QCD=2 QED=0 NP=2 @0
add process p p > t t~ j QCD=3 QED=0 NP=2 @1
```

Proceed as usual!

NLO merging (FxFx) has not been tested yet

- Possible issues with mixed coupling orders
- Stay tuned!

# More topics...

- Fixed-order mode analysis & HwU format
- Propagating split orders info through parton shower
- Reweighting@NLO - testing in progress
- ...

## SMEFT@NLO development

- CP violating operators
- Extended flavor structure ( $U(2)^5$ )
- Triple gluon operator  $C_G$
- 4-light fermion operators:  $qqqq$  &  $qqll$

Open to suggestions!

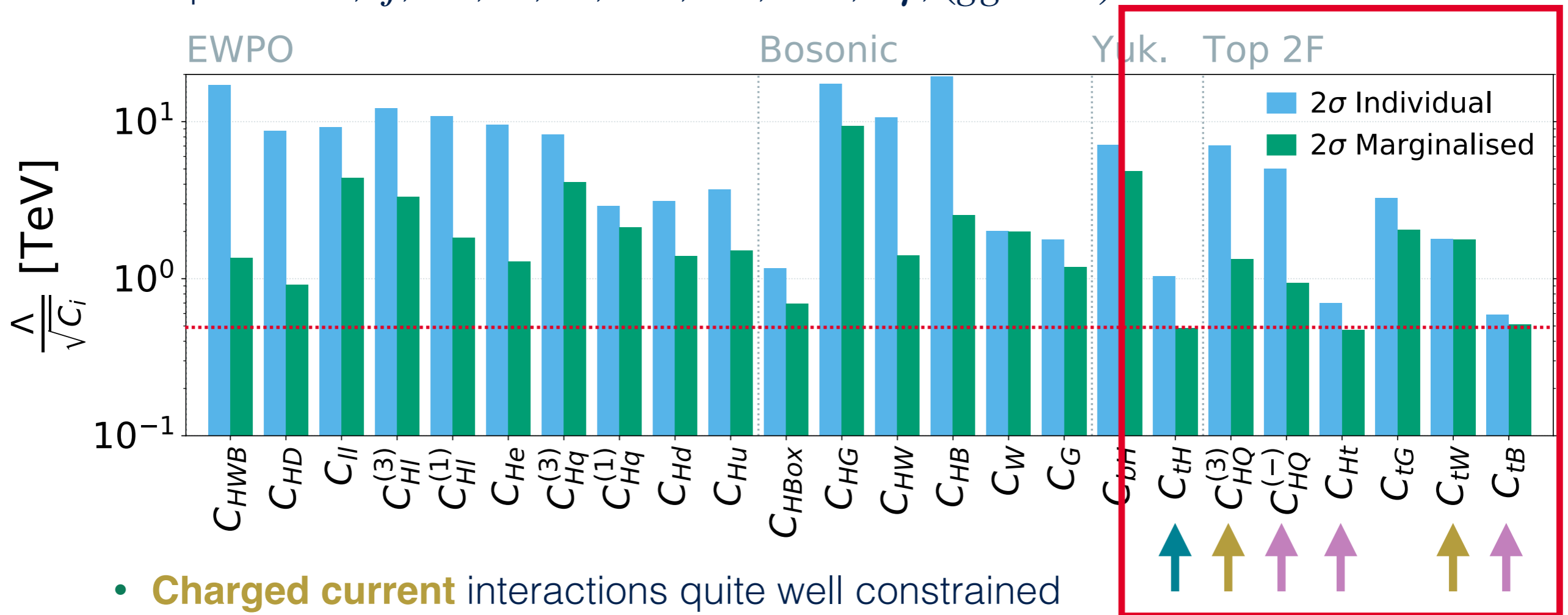
Backup



# How poorly?

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

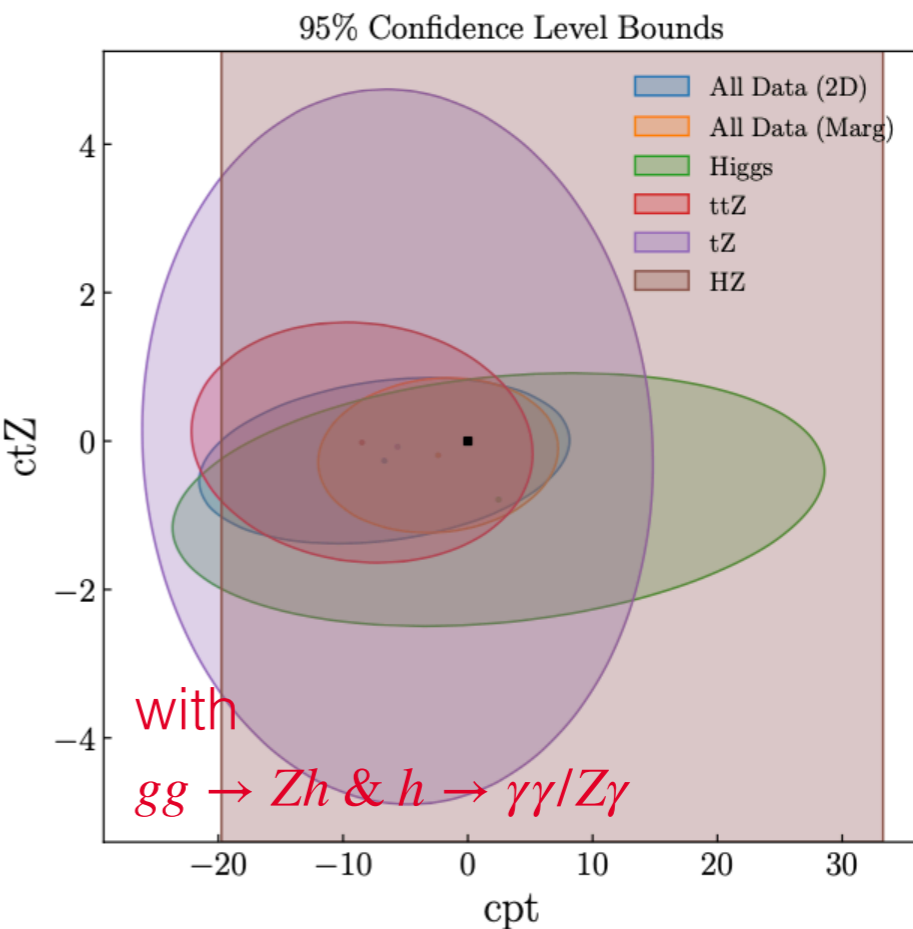
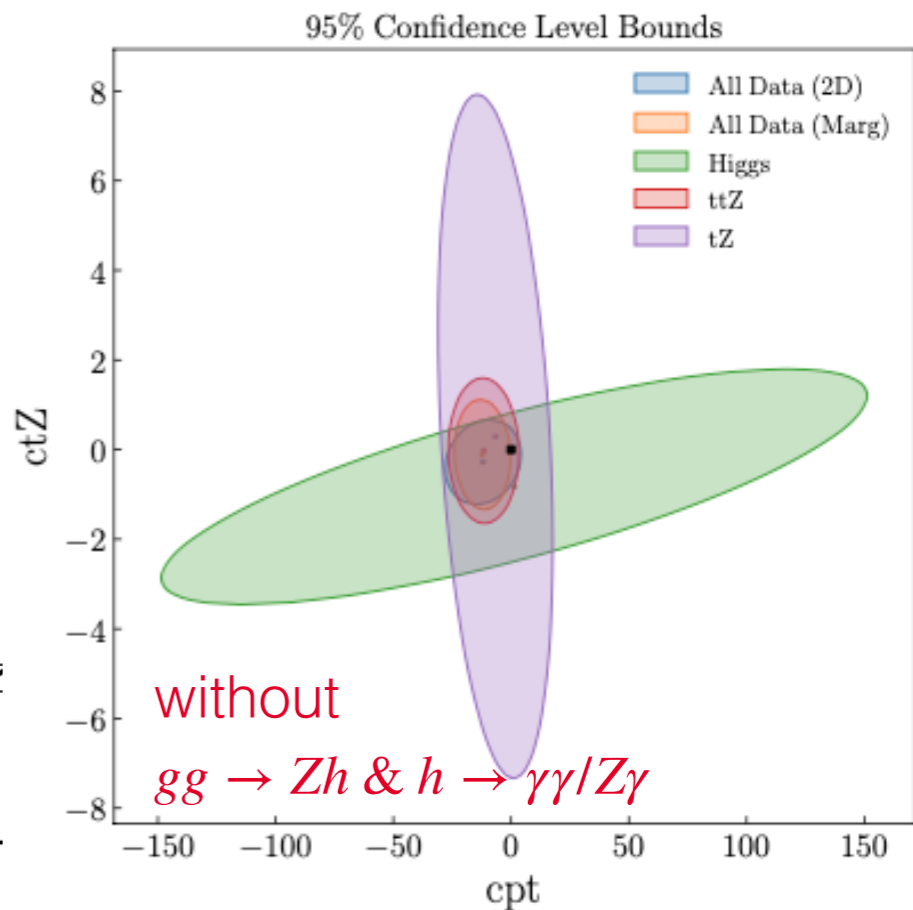
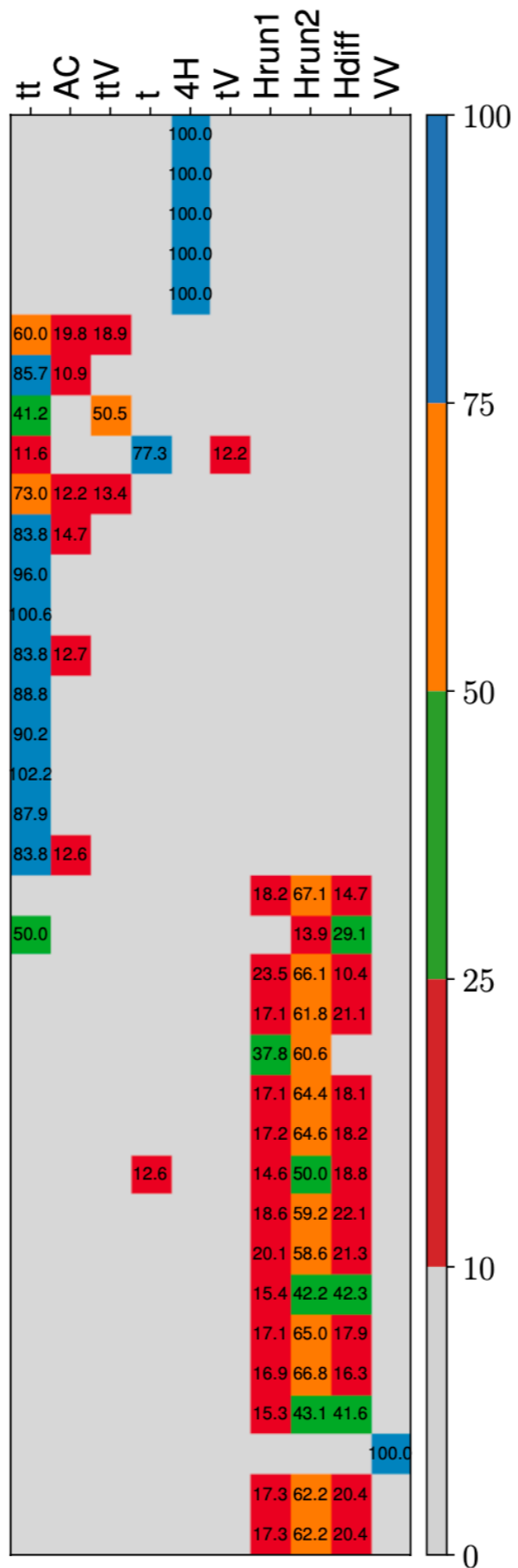
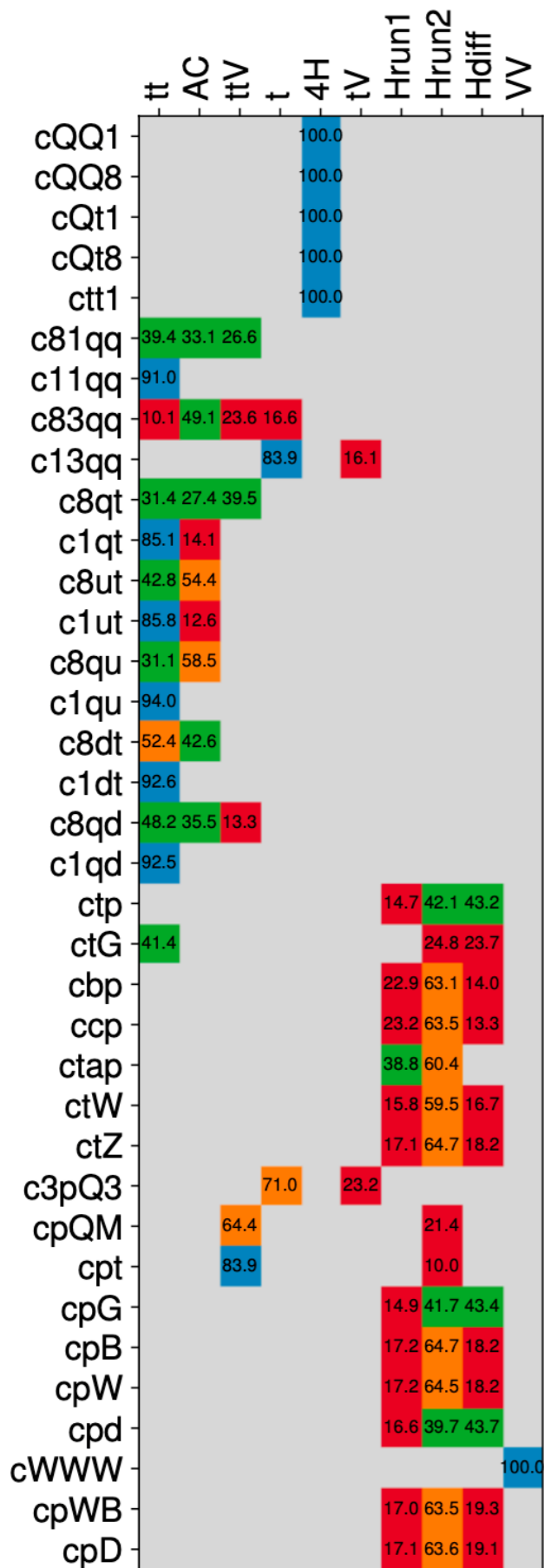
- Top data:  $t\bar{t}$ ,  $tj$ ,  $tW$ ,  $t\bar{b}$ ,  $tZ$ ,  $t\bar{t}H$ ,  $t\bar{t}Z$ ,  $t\bar{t}W$ ,  $t\bar{t}\gamma$ , ( $gg \rightarrow h$ )



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

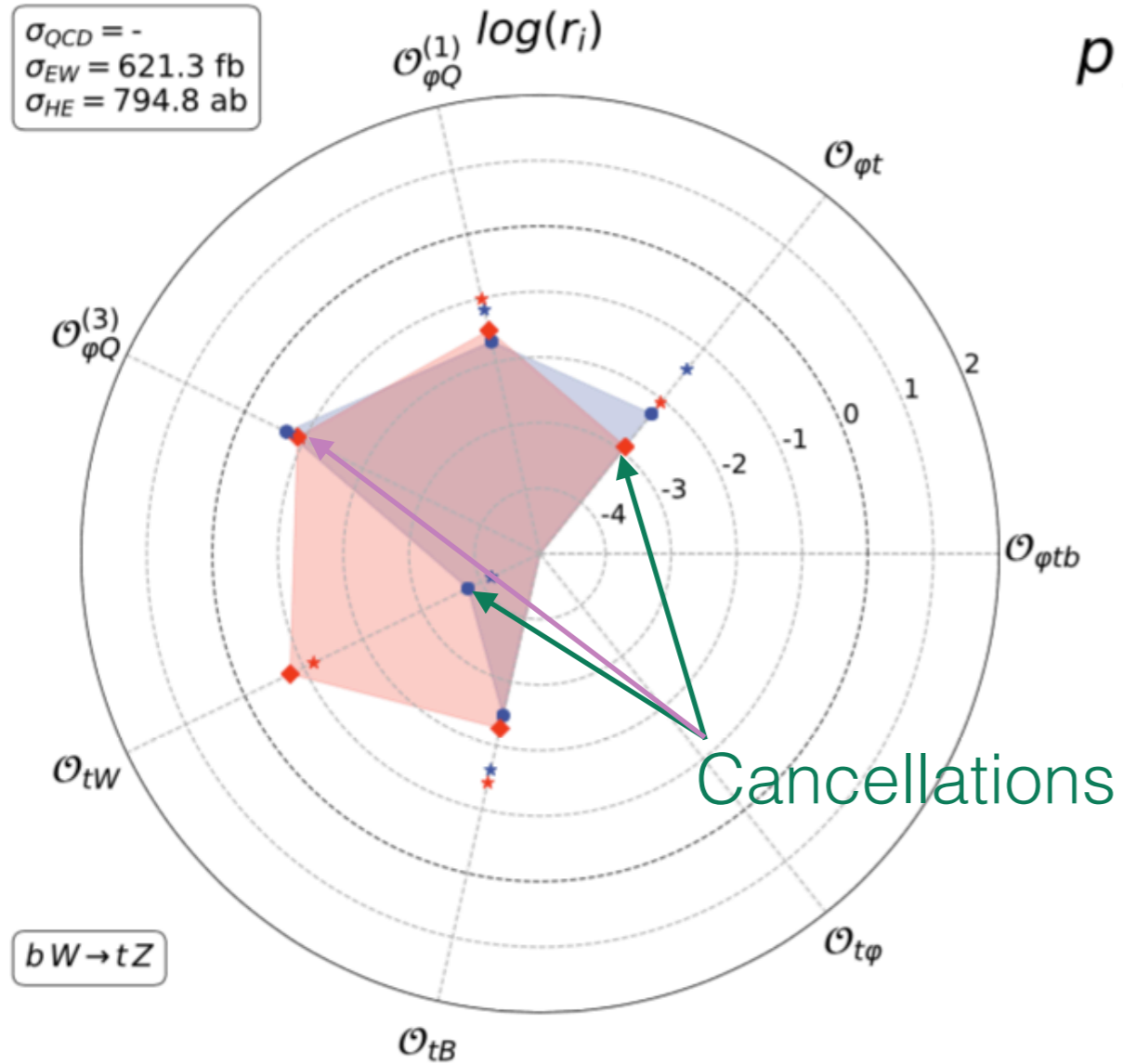
**How can we improve?**





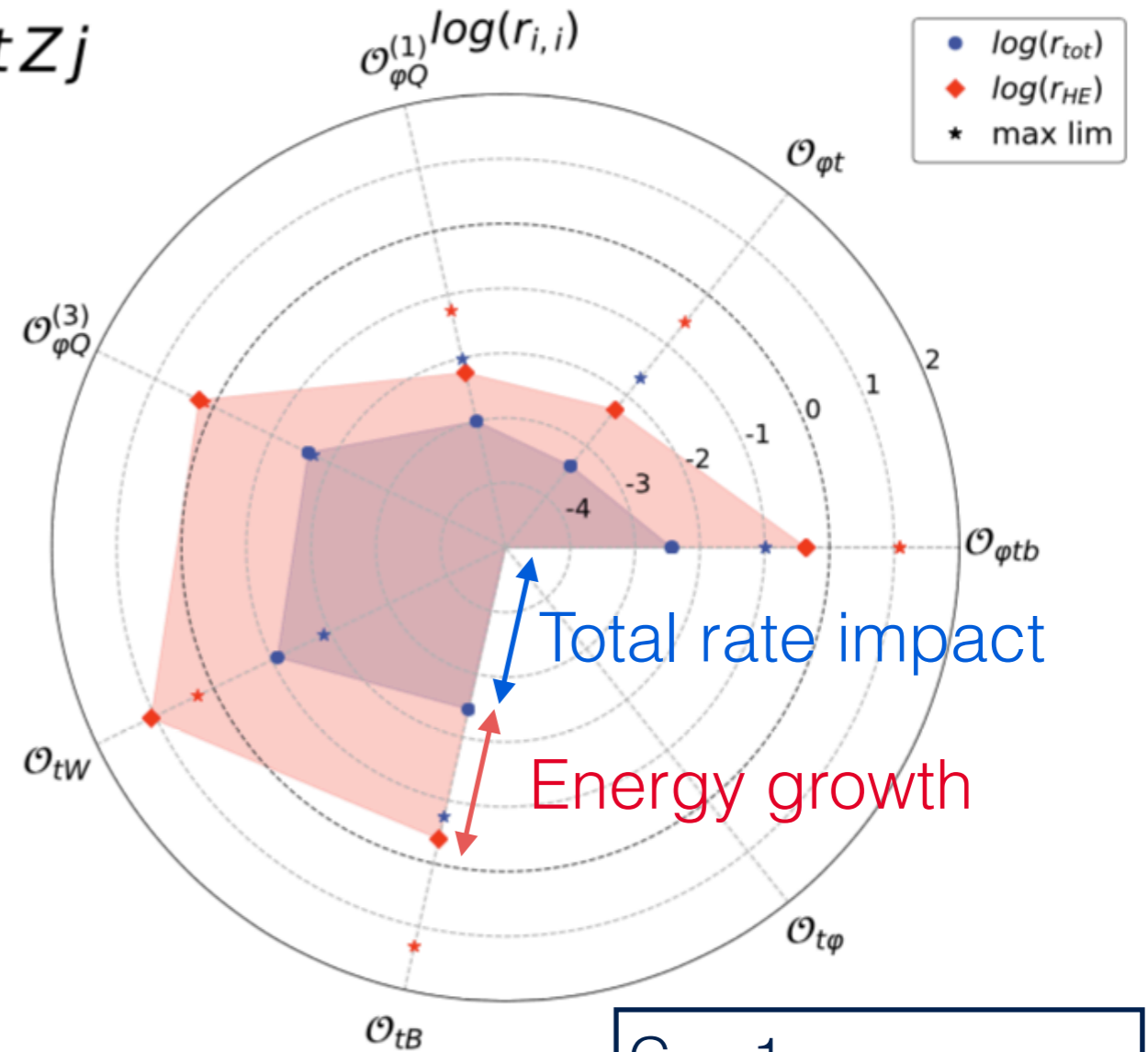
# $tZ$ radar plot

interference/SM



square/SM

$pp \rightarrow tZj$

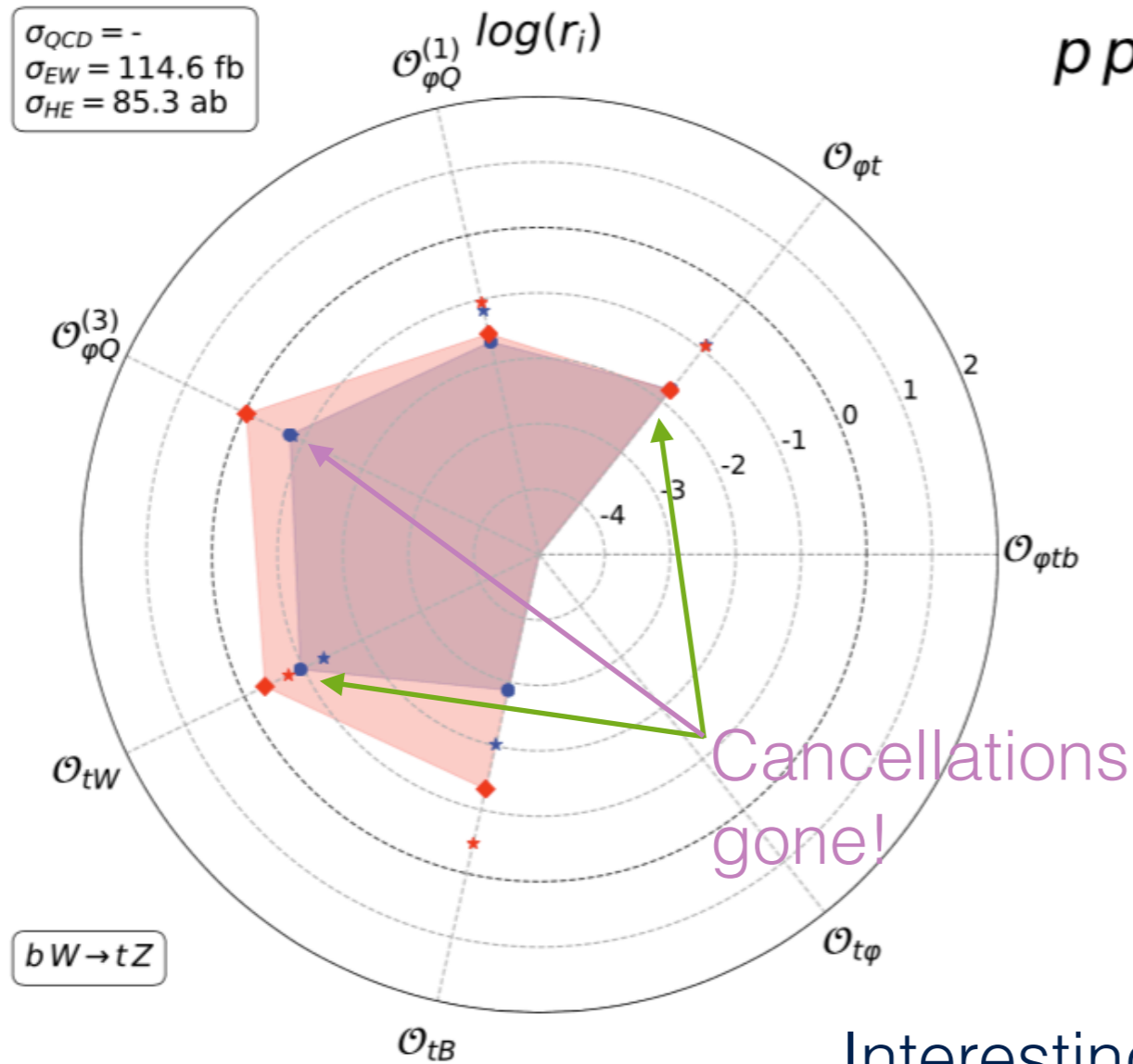


Expected growth from  $2 \rightarrow 2$  absent!

$C_i = 1$   
 Inclusive  
 $p_T(Z) > 500 \text{ GeV}$

# $tZ$ radar plot

interference/SM

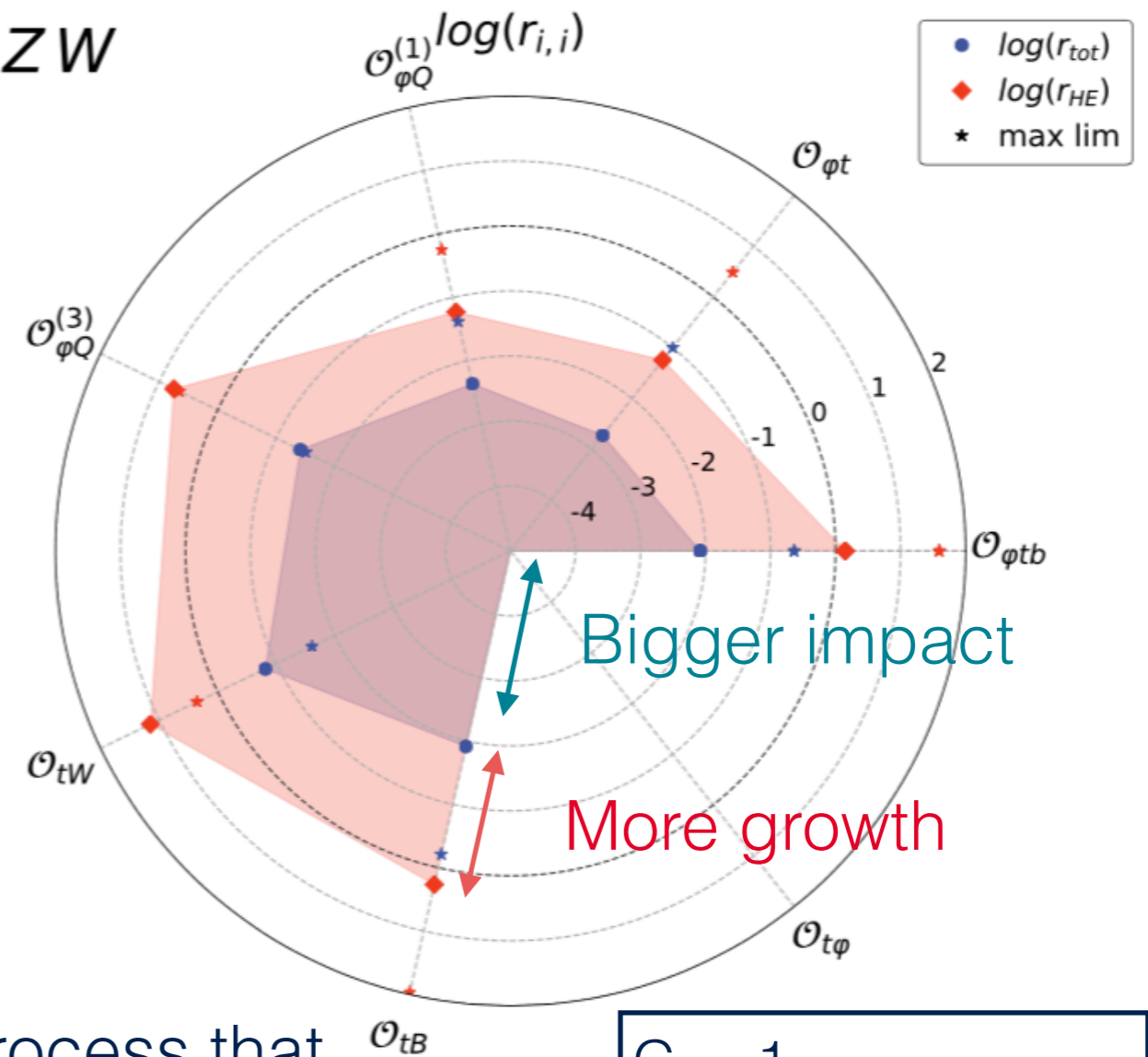


Expected growth is there!

Cancellations gone!

square/SM

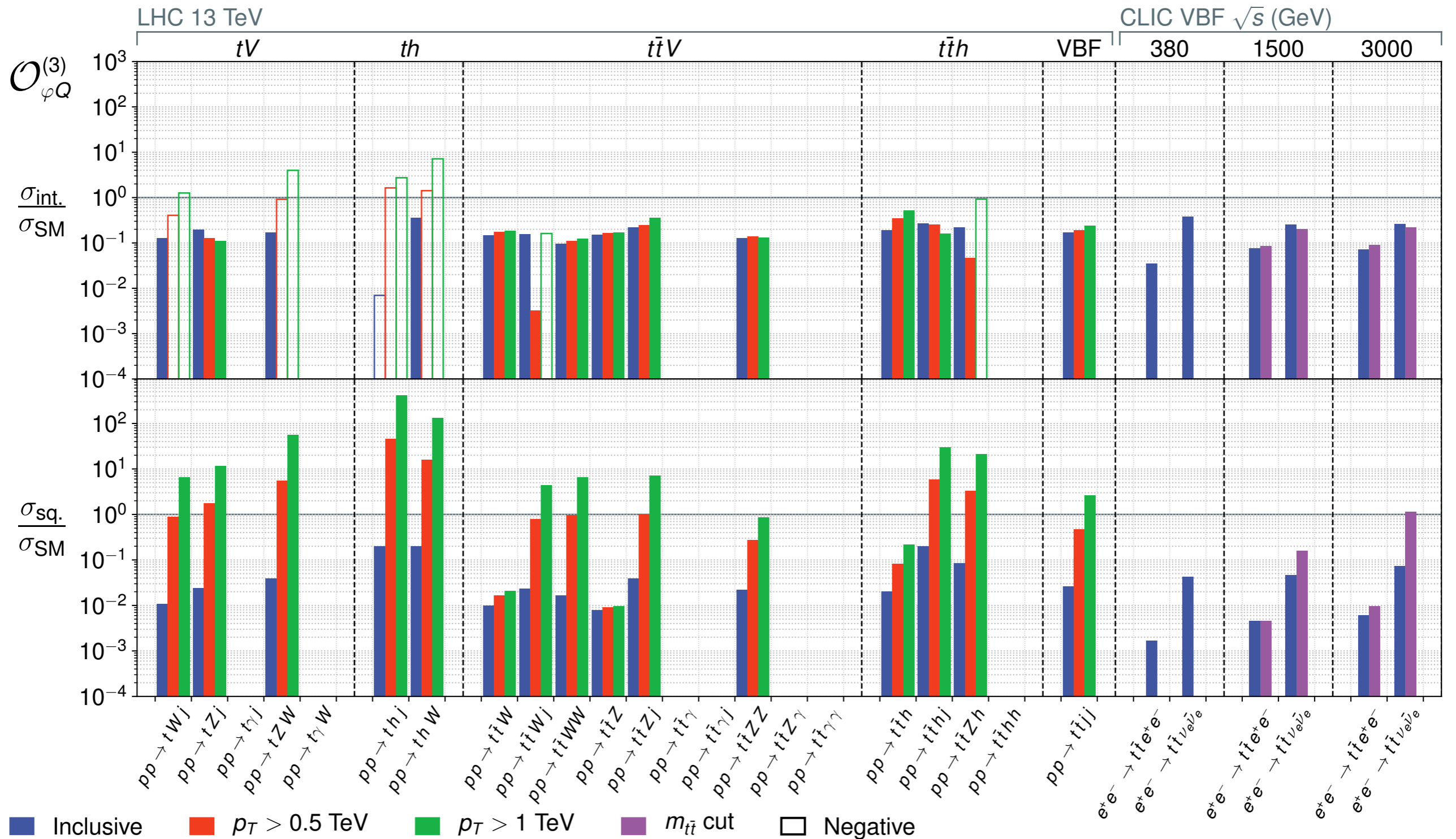
$pp \rightarrow tZW$



Interesting process that should be accessible at the LHC

$C_i = 1$   
 Inclusive  
 $p_T(W,Z) > 500 \text{ GeV}$

# Charged current operator



# Running & mixing

EFT based on existence of scale separation:  $\Lambda_{BSM} \gg E_{exp}$ .

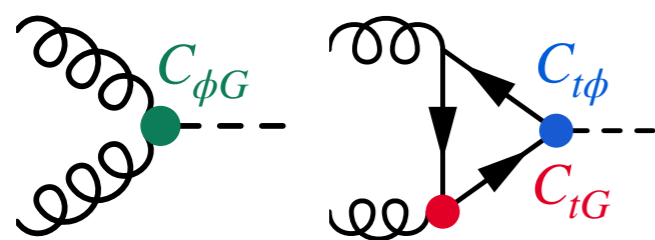
- Coefficients are **generated** (matching) & **measured** at different scales
- QFT: couplings depends on the scale at which they are defined
- EFT: couplings run & mix into one another  $\Rightarrow$  anomalous dimensions  $\gamma_{ij}$

$$\frac{dc_i(\mu)}{d \log \mu} = \frac{\alpha(\mu)}{\pi} \gamma_{ij} c_j(\mu) \quad \text{Assuming } c_i = 0 \text{ at low scale is not valid}$$

ex: Gluon fusion Higgs production

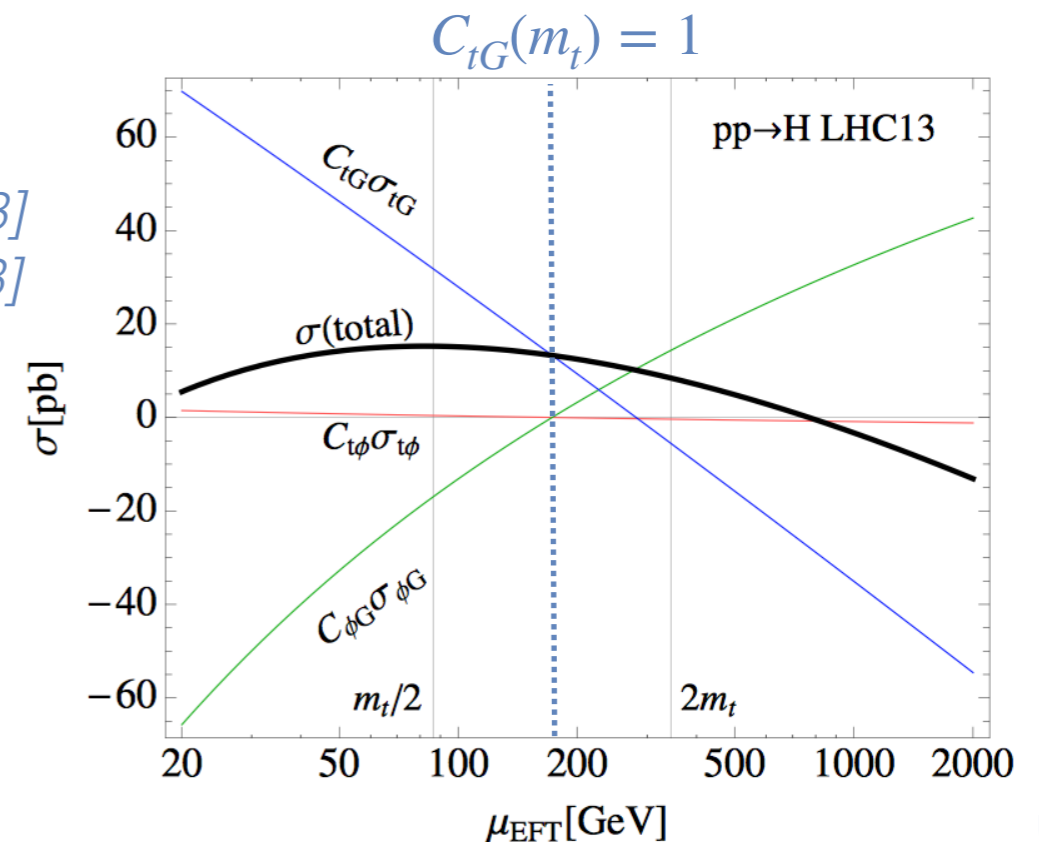
[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

[Deuschmann et al.; JHEP 1712 (2017) 063]



$C_{\phi G}$  (LO) scale dep.  
cancelled by  
running  $C_{tG}$  (NLO)

Only **global** approach makes sense



# Finite terms

RG structure is universal  $\Rightarrow$  process independent

- Only encodes a part of the NLO corrections
- ‘**LO-like**’ & only relevant when a measurement probes very different scales

Counterpart: finite terms  $\Rightarrow$  process dependent

- ‘**Genuine NLO**’ & must be studied process-by-process
- Often dominant over RG for LHC energy ( $E_{exp.}$ ) & sensitivity ( $\Lambda_{BSM}$ )

ex:  $t\bar{t}H$  production

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

- RG severely underestimates NLO
- Similar observations in other calculations, e.g., Higgs & Z boson decays

[Gauld, Pecjak & Scott; PRD 94 (2016) 7, 074045]

[Hartmann, Shepherd & Trott; JHEP 03 (2017) 060]

