Interpreting top quark LHC measurements in SMEFT

An introduction & practical guide

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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

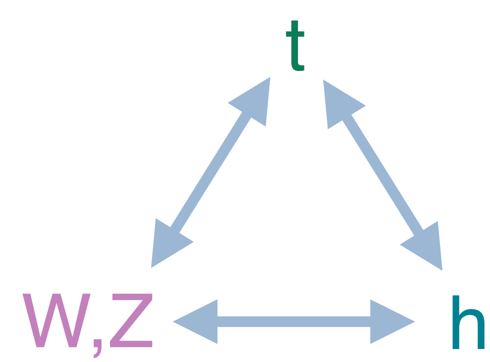
- Tips, tricks & examples for newcomers
- `SMEFTatNLO` model with `MadGraph5_aMC@NLO`
- Key concepts/techniques: coupling orders, reweighting, decays, NLO,…
- Intended as a pedagogical introduction & reference

New physics through tops

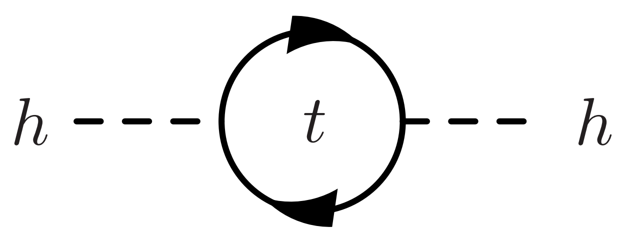
What is the origin of electroweak symmetry breaking?

Who are the main players?

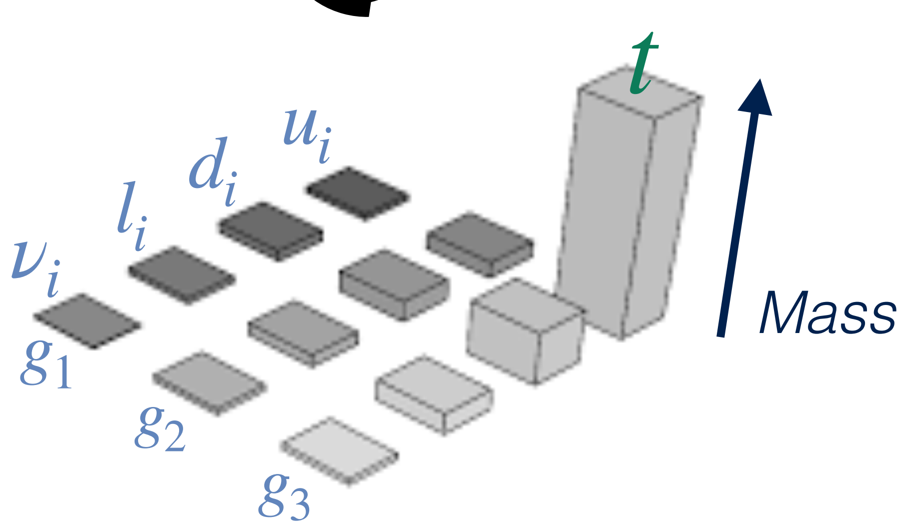
- Higgs boson, EW gauge bosons & **top quark**
- Most **massive** ⇔ **strongly coupled** to the Higgs

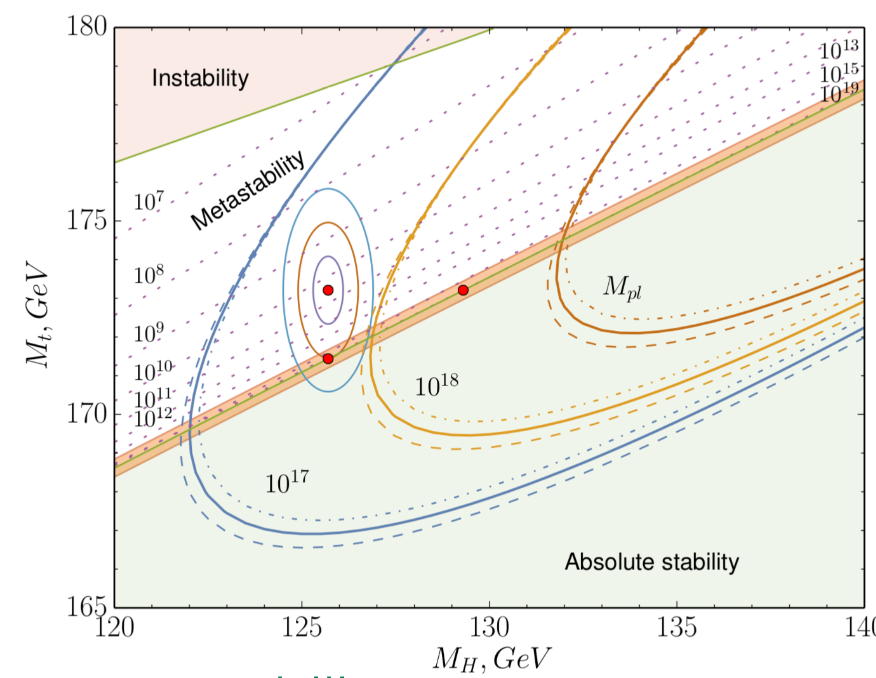


The **top is special** for many reasons



naturalness
&
hierarchies

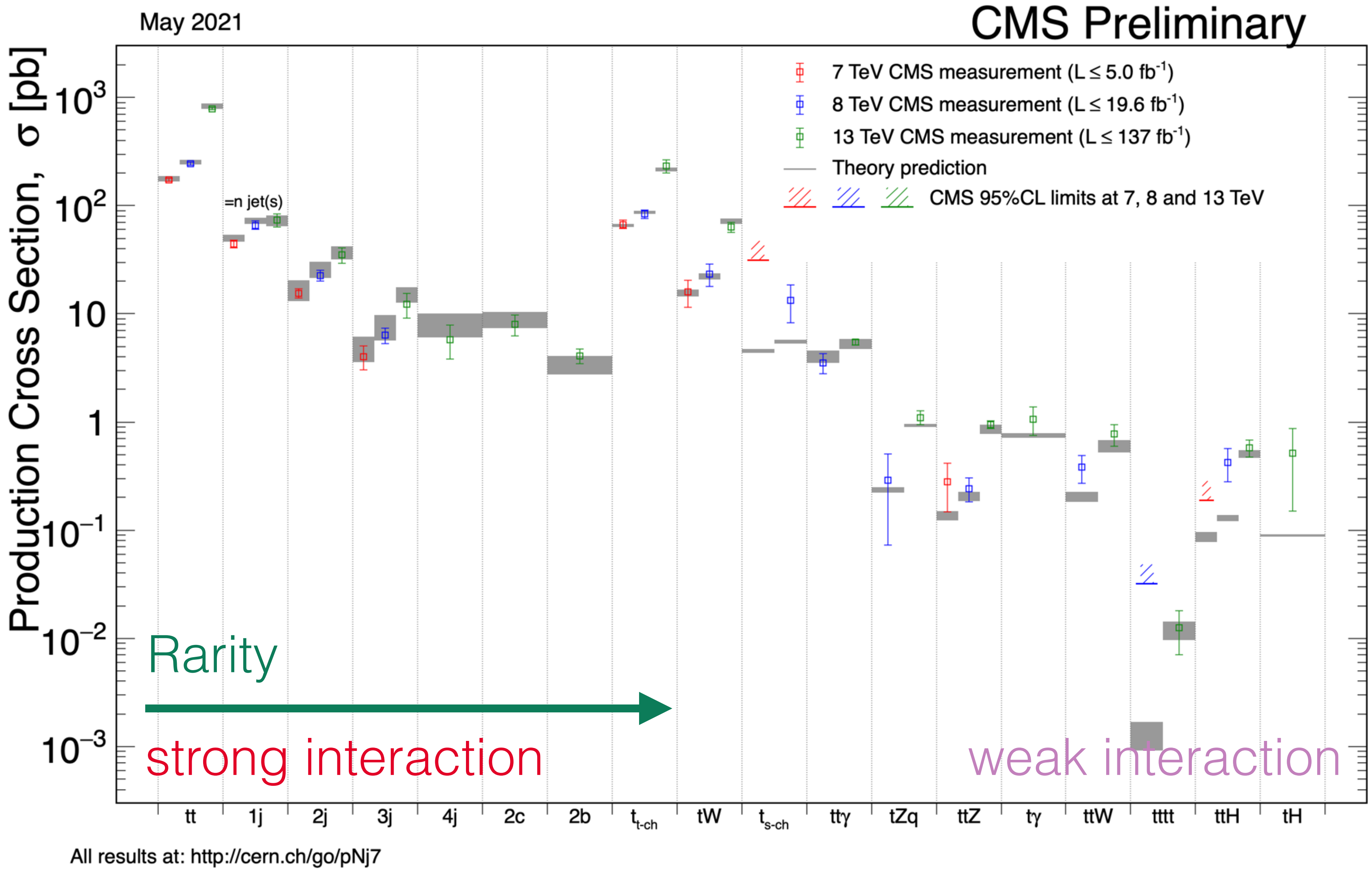




EW vacuum stability

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

The LHC is a top factory



$t\bar{t}:\ 10^9$

$tj, tW, tb:\ 10^8$

$t\bar{t}+Z/W/\gamma:\ 10^7$

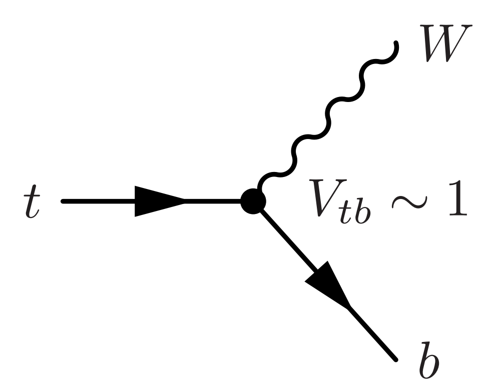
$t\bar{t}H:\ 10^6$

$t\bar{t}t\bar{t}:\ 10^4$

$\mathscr{L}^{\text{int.}} \sim 3\,\text{ab}^{-1}$

Decays before hadronising

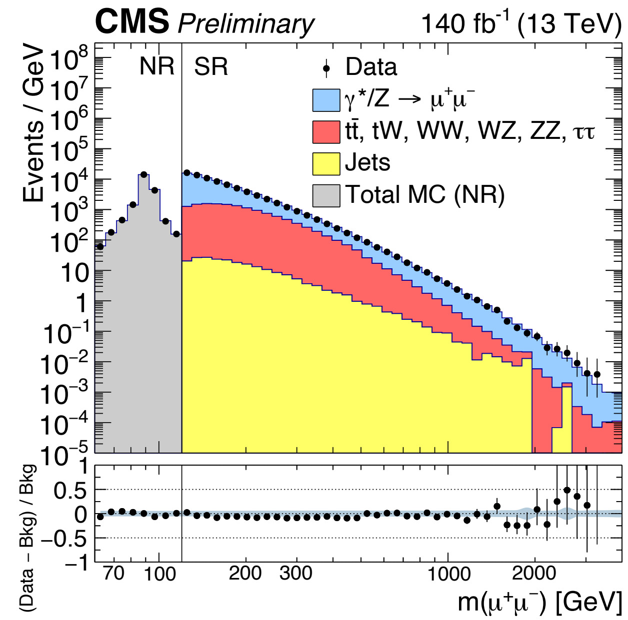
- Spin/helicity information preserved



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

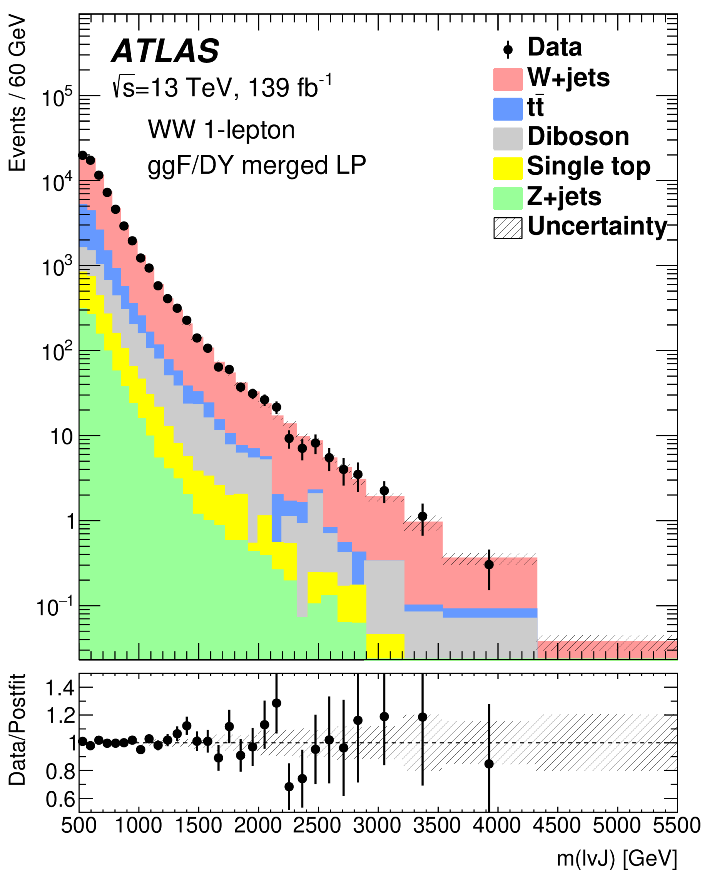
Where are we?

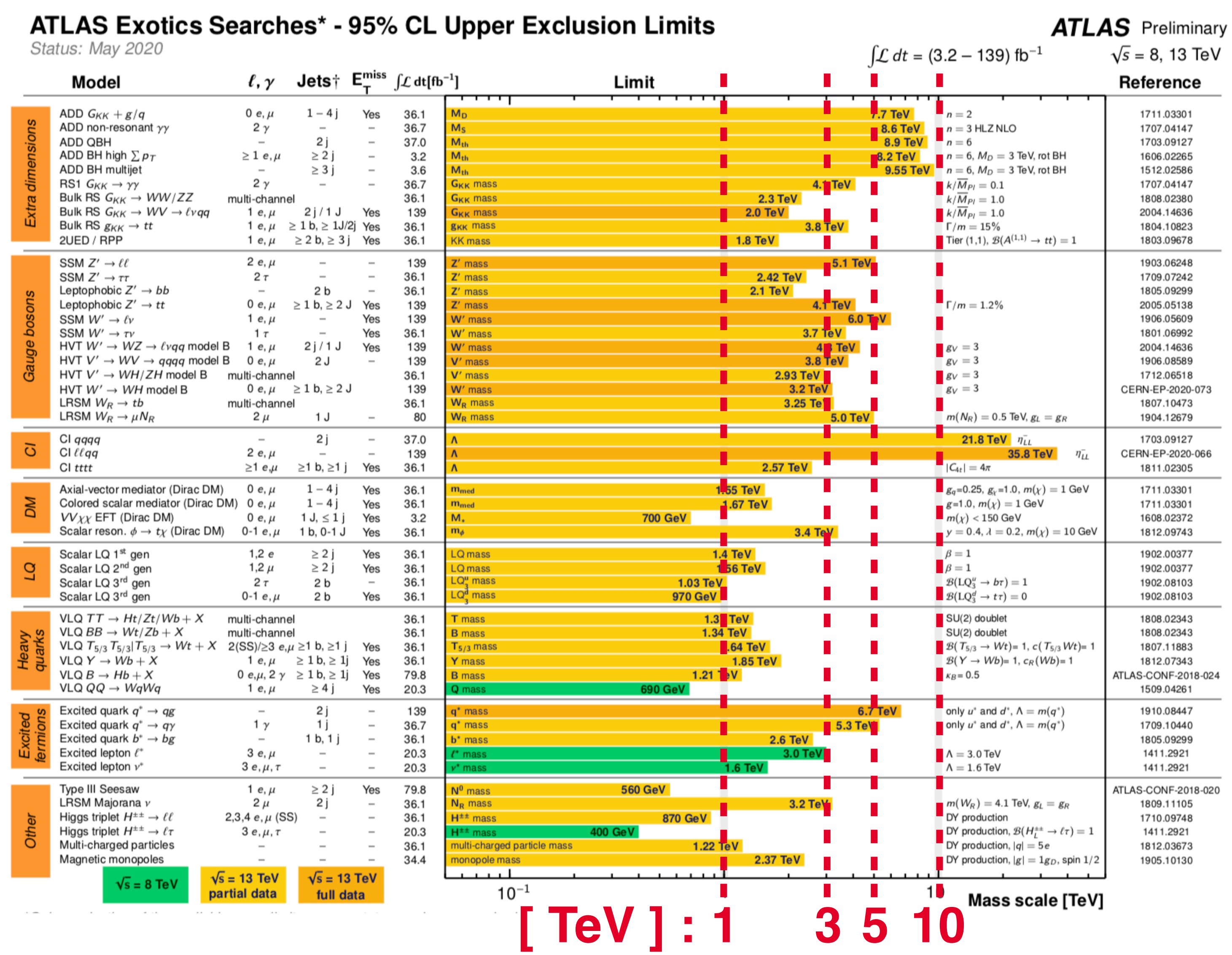
[CMS-PAS-EXO-19-019]



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





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

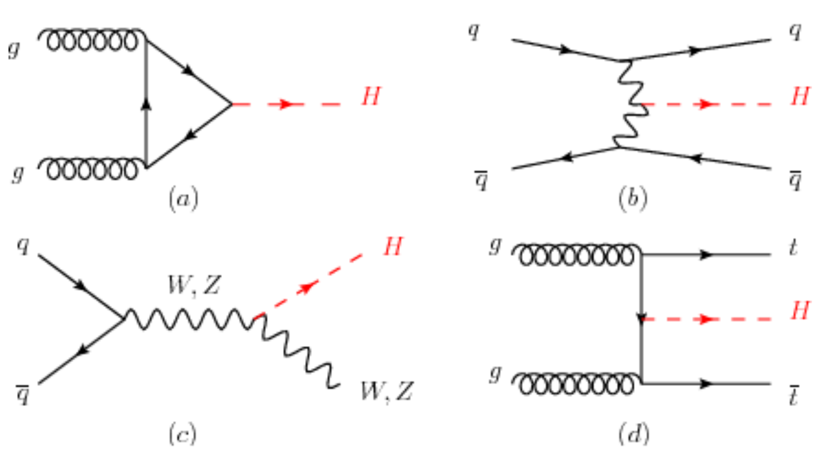
SM: a tremendous amount!

- Higgs discovery & properties $\Rightarrow$ precision LHC programme

The LHC explorer

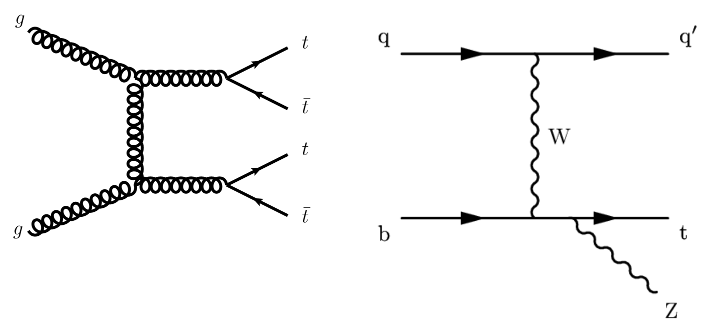
Many new processes observed at the LHC for the first time

Main Higgs production modes



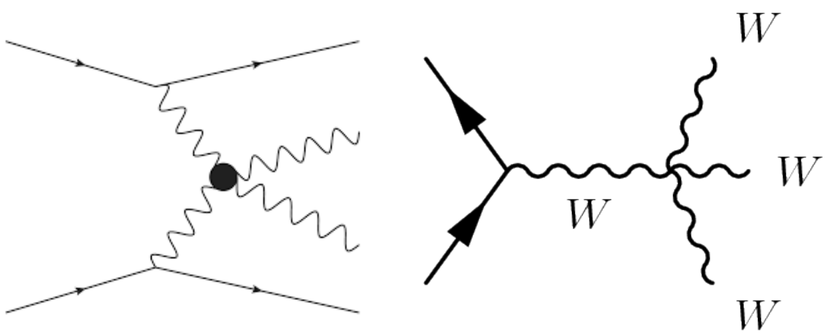
ggF, VH, VBF, ttH

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

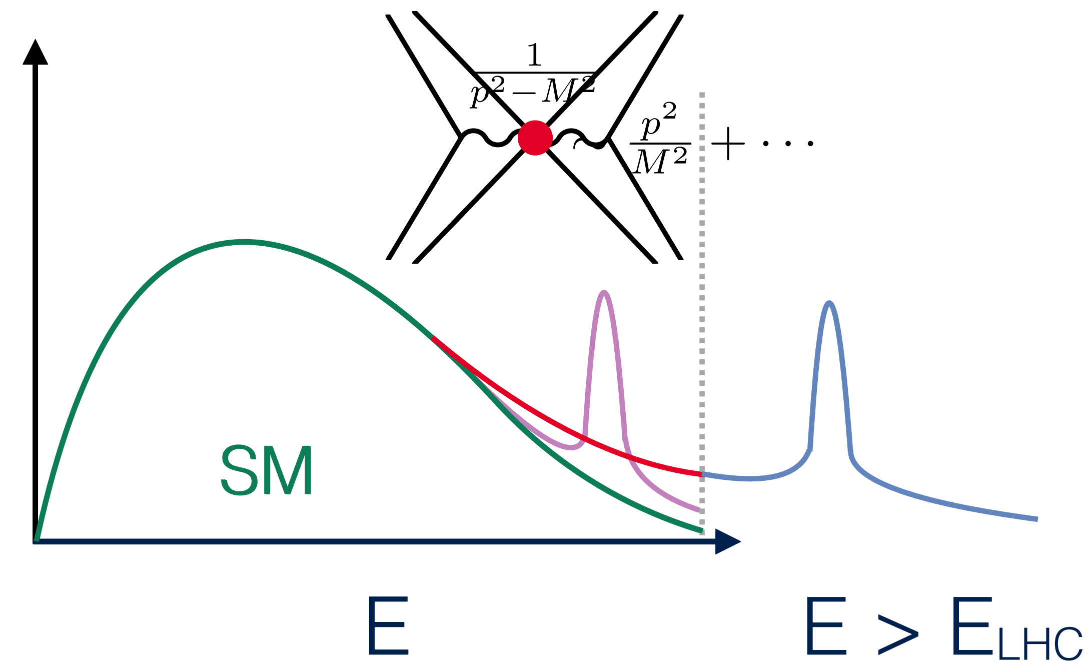
Energy & precision

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

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

SM = low energy effective description

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

SU(3)c x SU(2)L x U(1)Y

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

aTGC	$X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$X^2H^2 : (\varphi^\dagger\varphi)^2 G^a_{\mu\nu} G^{\mu\nu}_a$	ggh(h)
λ_h	$H^6 : (\varphi^\dagger\varphi)^3$	$H^4D^2 : (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D^\mu \varphi)$	δM_Z
y_f	$\psi^2H^3 : (\varphi^\dagger\varphi)^2 (\bar{q}_i\, u_j\, \tilde{\varphi})$	$\psi^2XH : (\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi}) B_{\mu\nu}$	'dipole'
ffV	$\psi^2H^2D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\, \gamma^\mu\, q_j)$	$\psi^4 : (\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l)$	4F

More than 'just' a parametrisation of ignorance

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

SMEFT is…

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

Model independent

- Underlying assumptions

Heavy new physics: $M > E_{exp}$
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…

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

Global nature

As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Sensitivity

Experiment:
Best measurements & understanding of uncertainties and correlations

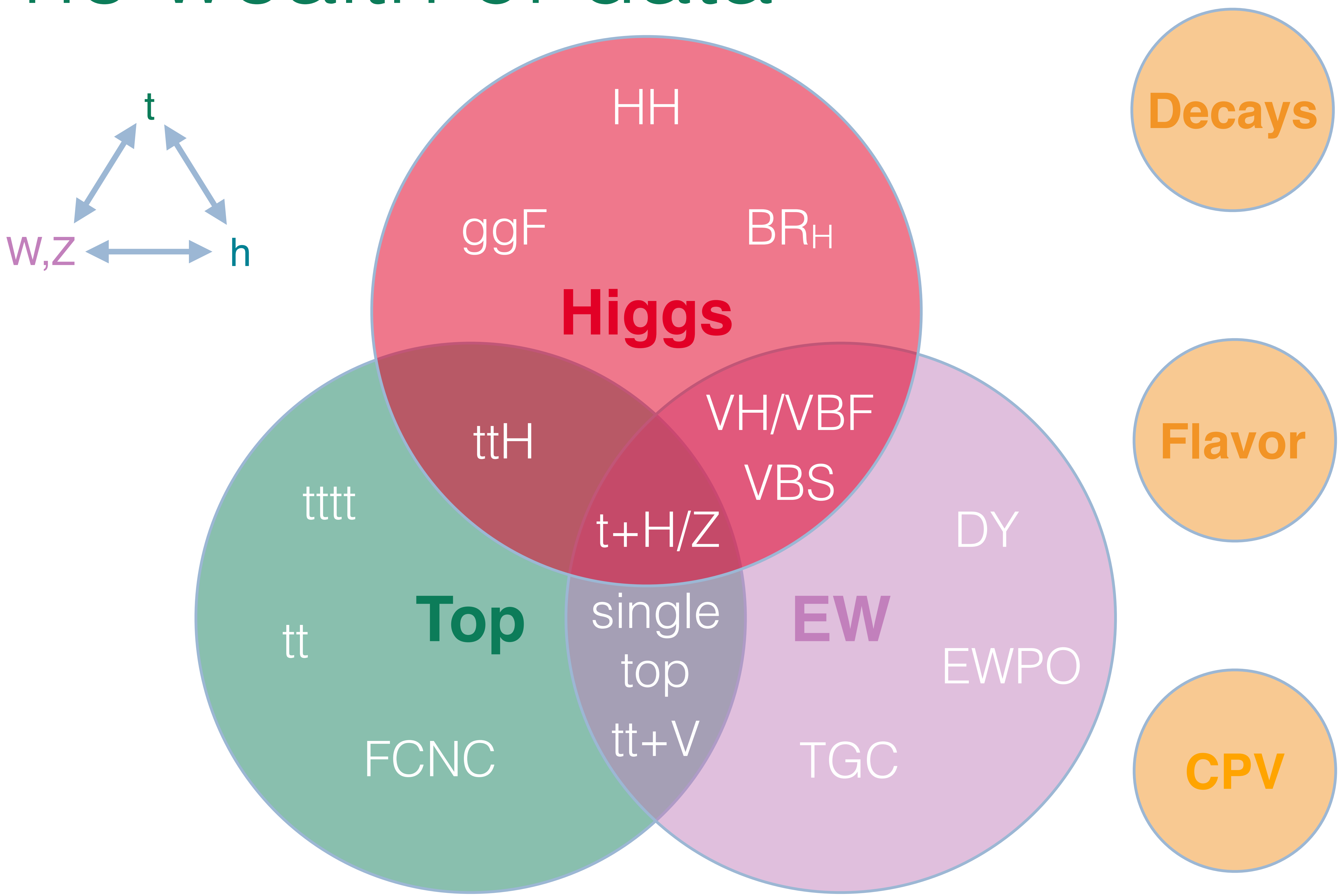
Theory:
Best available predictions for observables (NLO, NNLO, N3LO,…)

Interpretation

Relies on accurate knowledge of the size & correlation among a_i

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

The wealth of data



SMEFT workflow

Basis → Processes & Observables → Sensitivity → Measurement → Global fit

Degeneracies/blind directions

Map to UV models

Flavor assumptions

Hints of new physics?

Universal, diagonal, 3rd gen, general

Constrain classes of models

Validity of EFT

Symmetries

***A posteriori**: depends on sensitivity*

CP, Baryon/Lepton number?

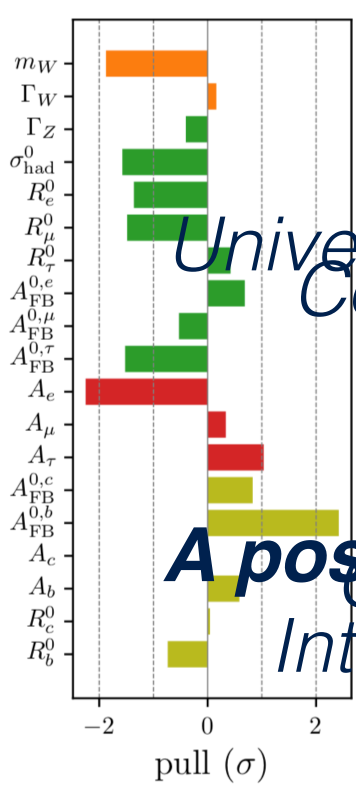
Intrinsically model dependent

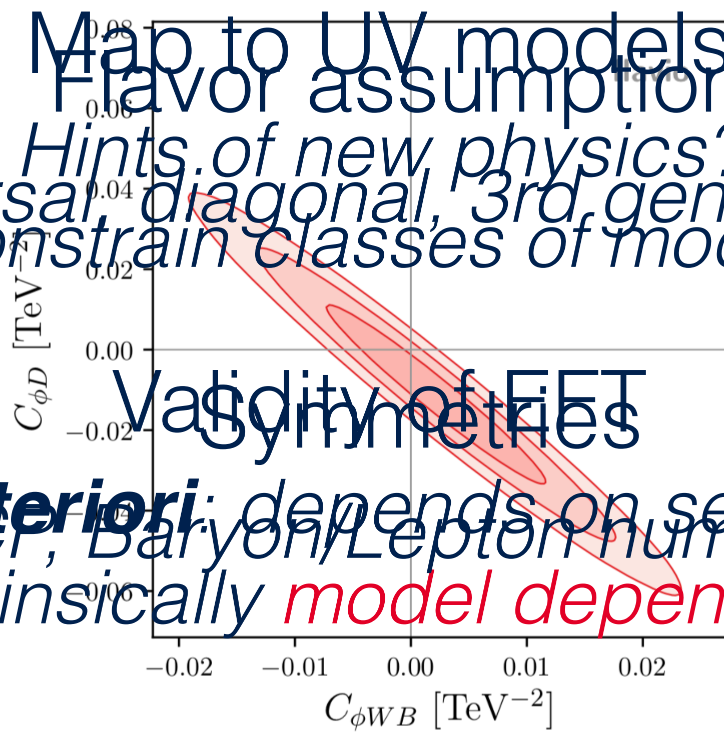
Limits

Marginalised

Pulls, …

Observations/

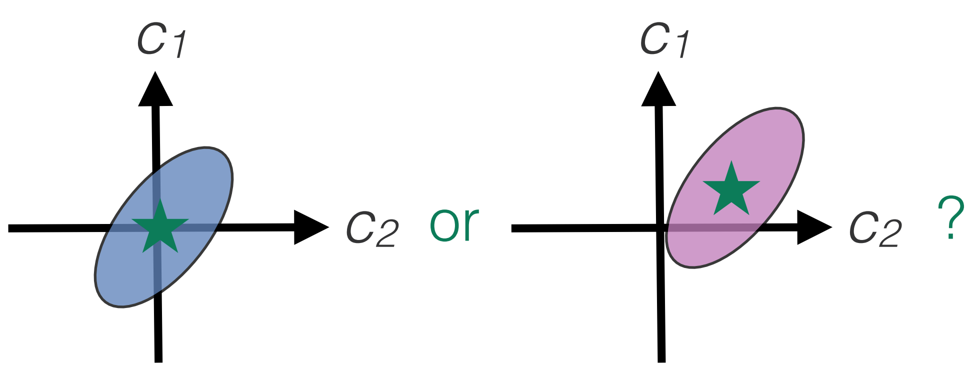




The importance of top data

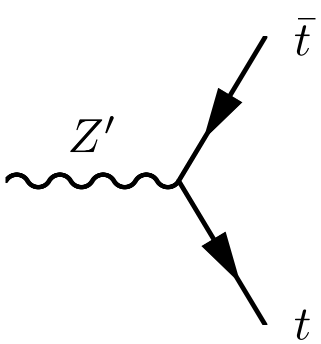
Likelihood ⇔ Fit to the Wilson coefficients

- 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



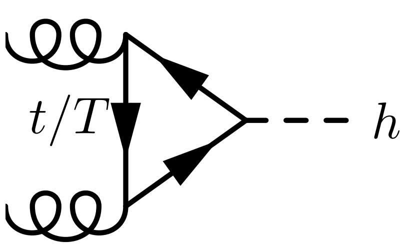
By itself: individual bounds; top data alone

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



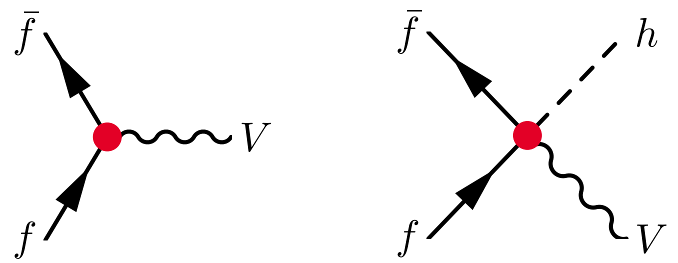
Globally: marginalised; top, Higgs, diboson, LEP, … data

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



Top operator glossary

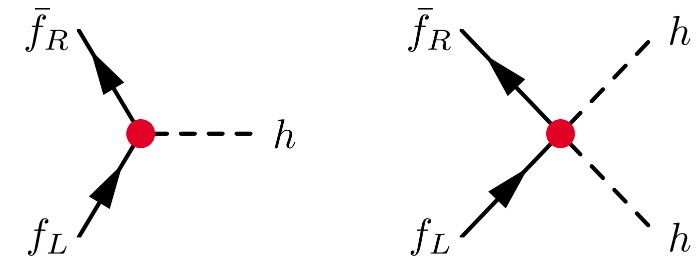
currents $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{Q}\gamma^\mu Q)$



$C_{\phi f}$

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

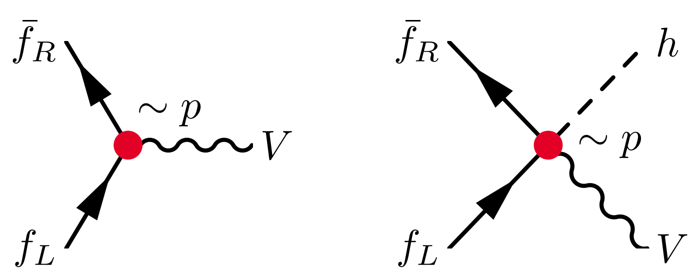
Yukawa $(\bar{q}\, t\, \tilde{\varphi})(\varphi^\dagger \varphi)$



$C_{t\phi}$

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

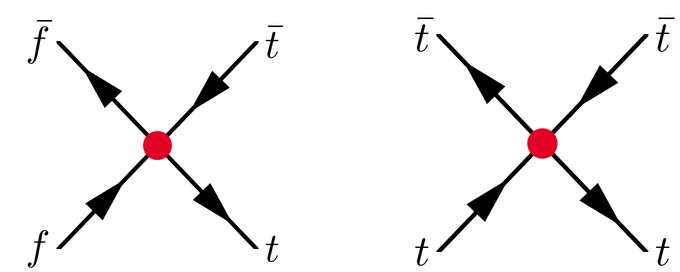
dipole $(\bar{q}\, \sigma_{\mu\nu}\, t\, \tilde{\varphi})V^{\mu\nu}$



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 (~O(20) w/ top)

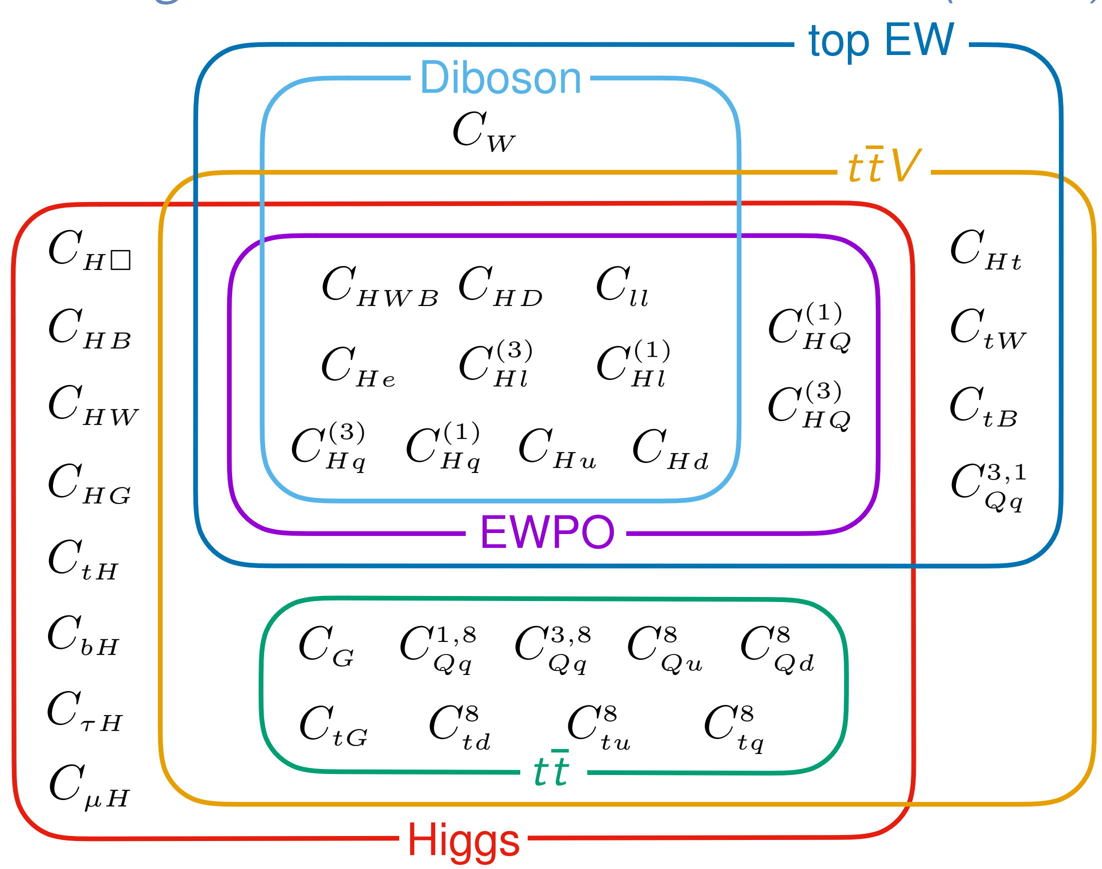
Fits: status & developments

Many SMEFT interpretations in experimental analyses

Global interpretations

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

- **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



Take home message

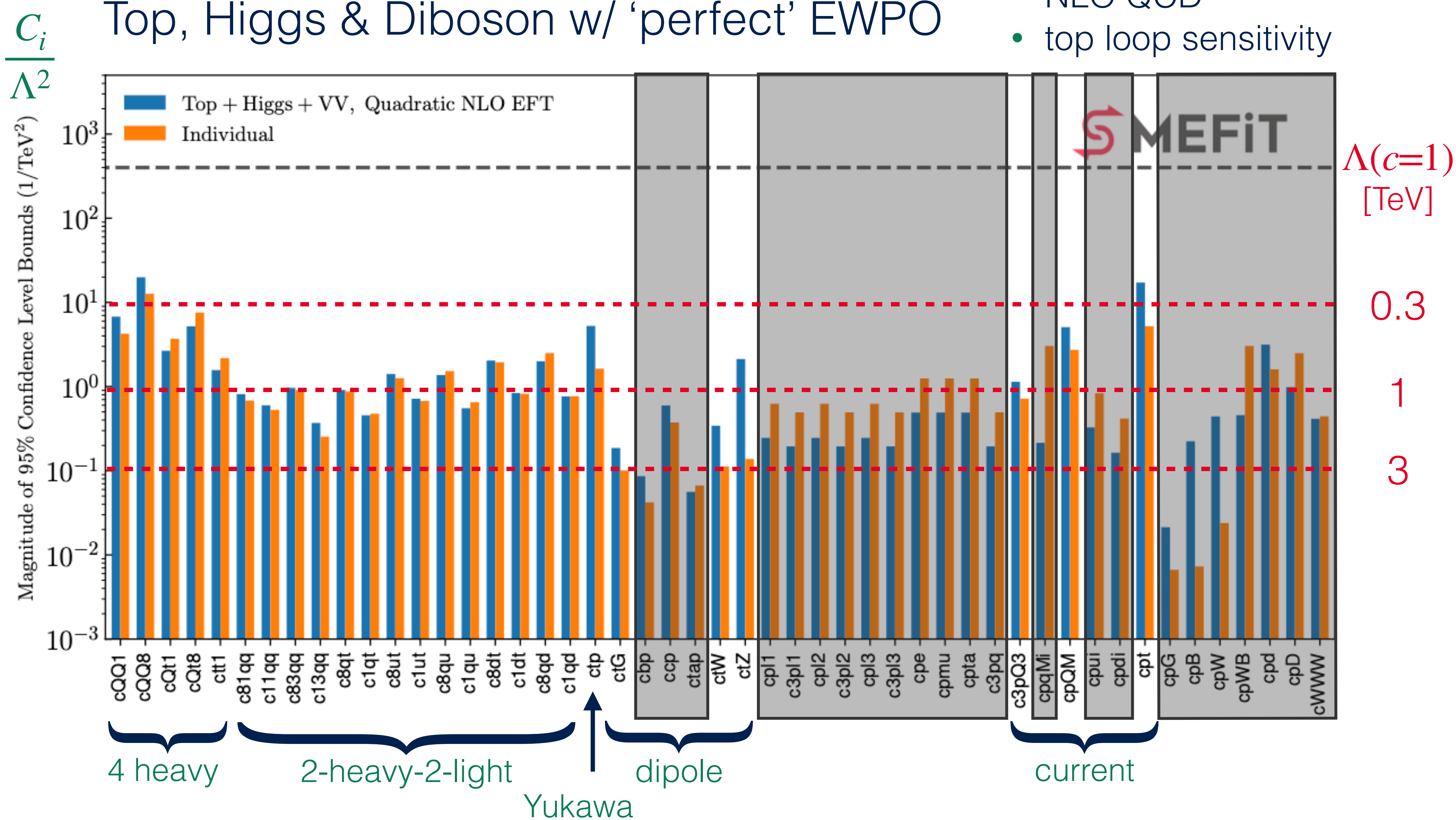
- Top sector probed around TeV scale
- EW top couplings weakly constrained
- NLO effects can be significant
- EFT validity should be studied

Status

[Ethier et al.; JHEP 11 (2021) 089]
see also: [Brivio et al.; JHEP 02 (2020) 131]
[Brown et al.; PoS ICHEP2020 (2021) 322]

Top, Higgs & Diboson w/ ‘perfect’ EWPO

- NLO QCD
- top loop sensitivity



[Ethier et al.; JHEP 11 (2021) 089]

NLO vs LO

SMEFTatNLO

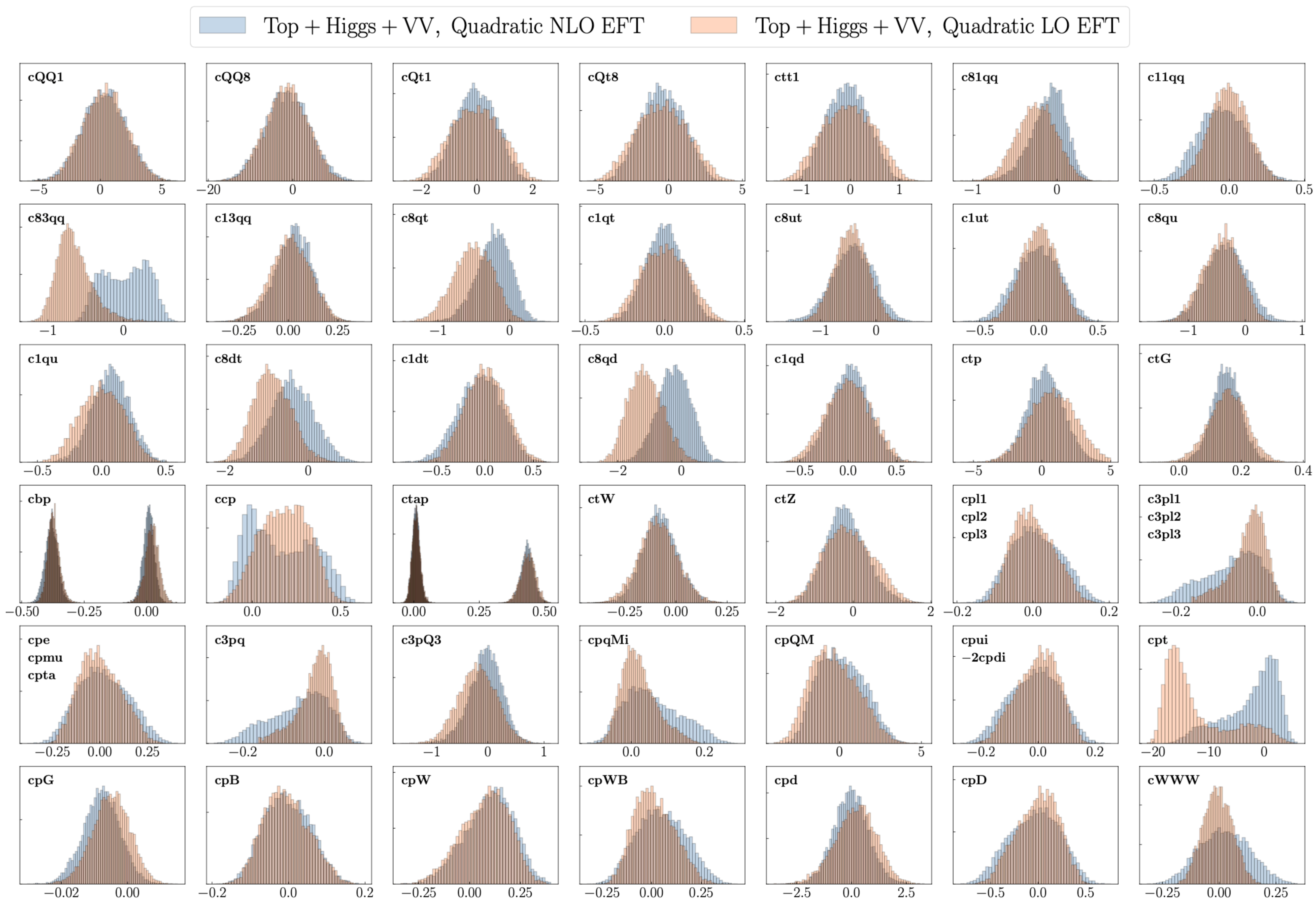
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

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

Top is coloured

Non-trivial QCD corrections

Non-Gaussian posteriors: Quadratic effects important

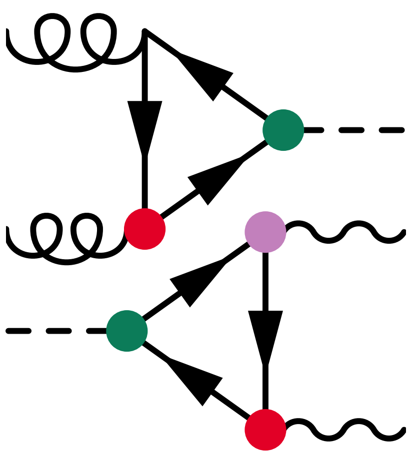


Loop sensitivity

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

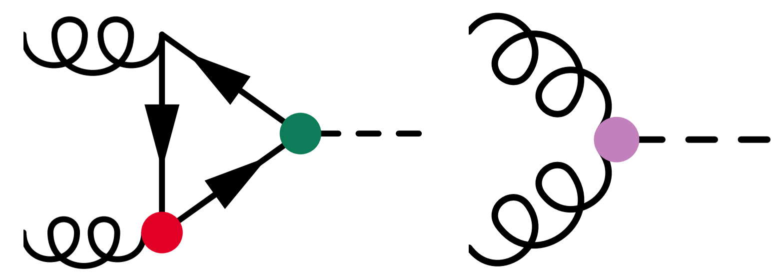
SMEFiT: individual bounds dominated by Higgs data!

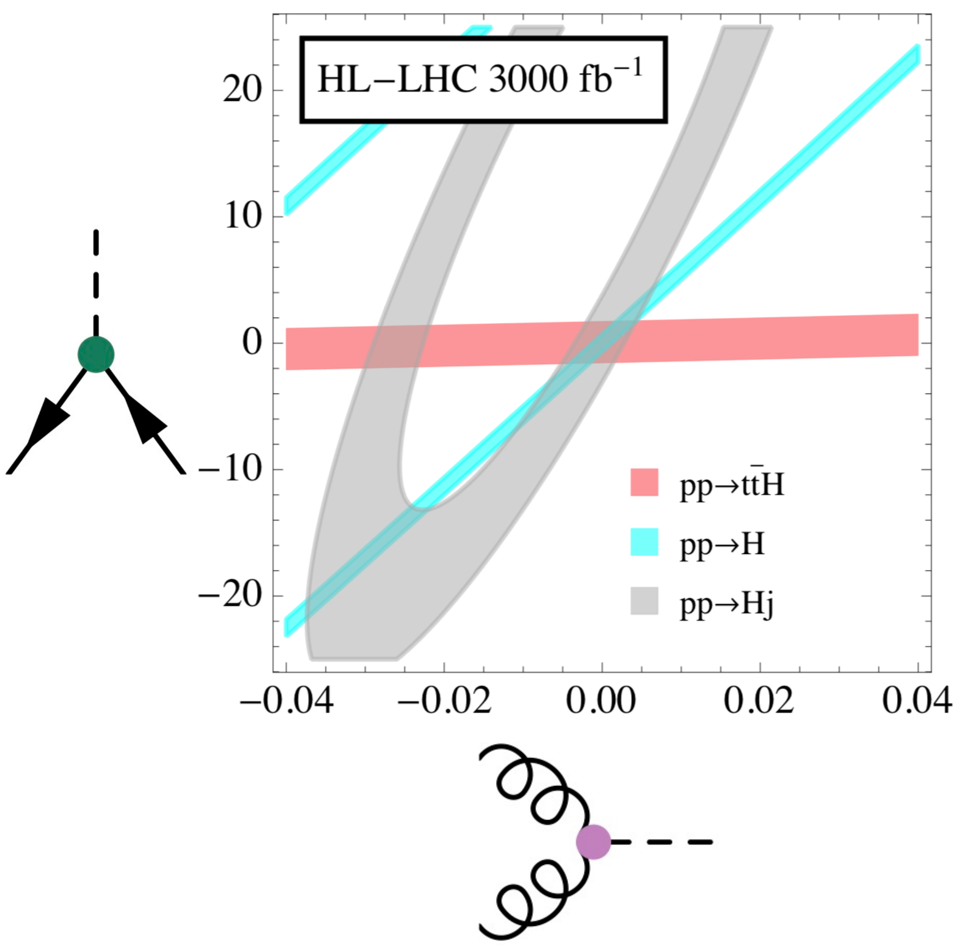
- Weak dipoles & $Z\bar{t}t$ current operators $\left(C_{tW}, C_{tZ}, C^{(-)}_{\varphi Q}, C^{3}_{\varphi Q}, C_{\varphi t}\right)$
- Also contributions to $gg \to Zh/ZZ/Z\gamma/WW$
- Complementary indirect sensitivity from non-top data

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]

ggF is well measured, yet…

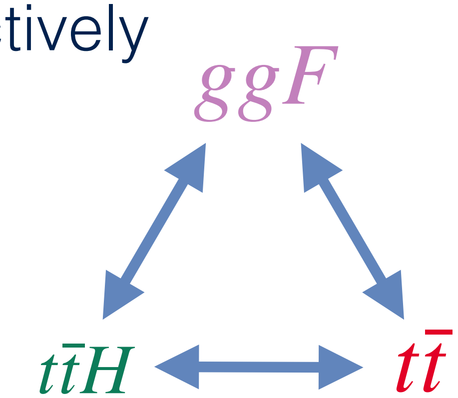
Cannot rule out heavy particles in the loop

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

- Constrain dipole & Yukawa, respectively

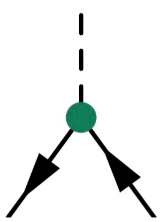
What about 4 fermion ops.?

- Do they limit ultimate sensitivity?

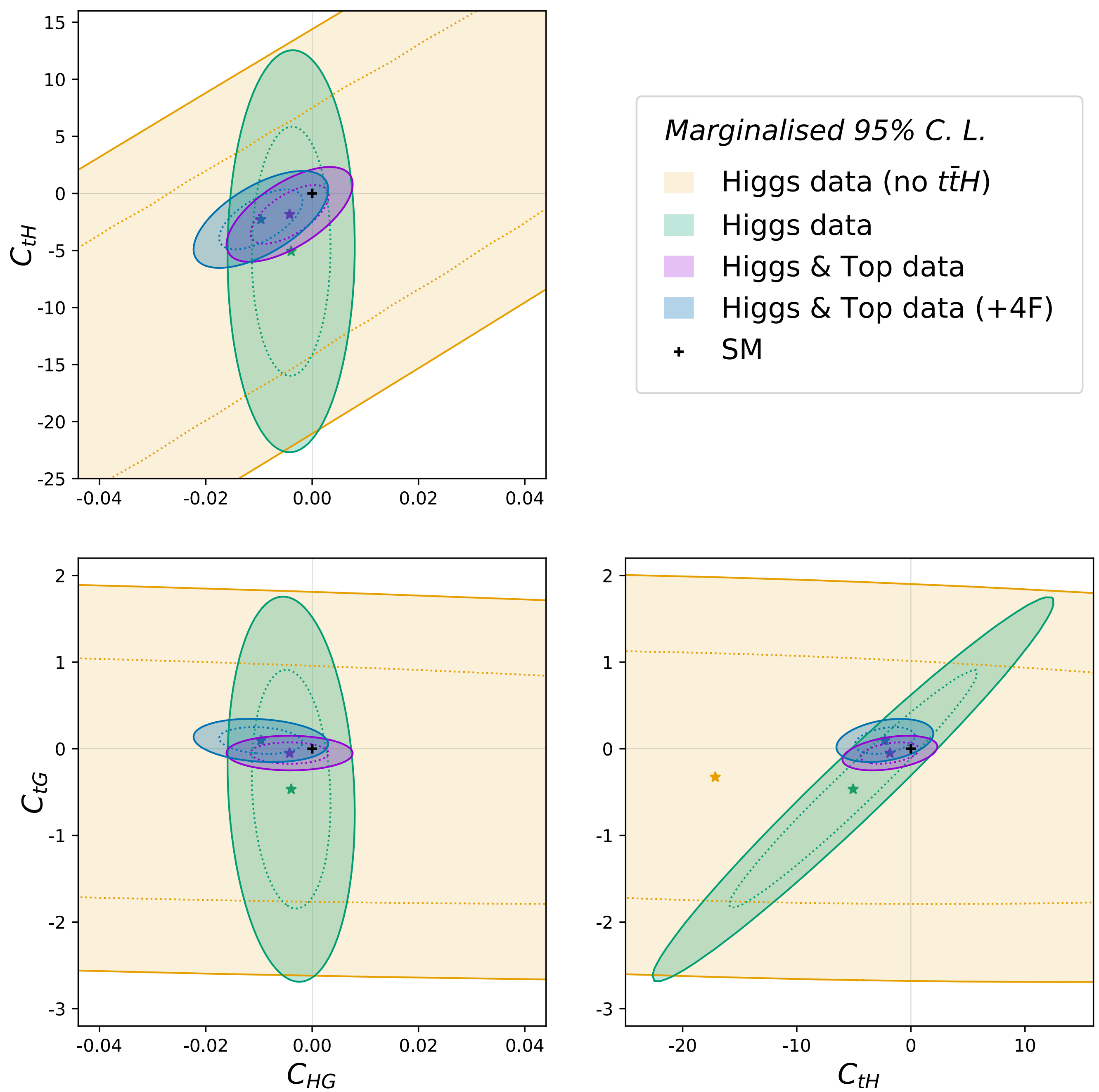


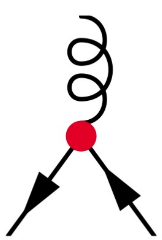
[Ellis, Madigan, KM, Sanz, You; JHEP 04 (2021) 279]

Top-Higgs interplay



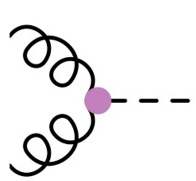
Yukawa



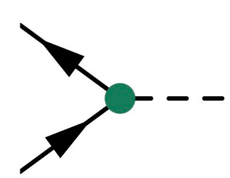


dipole

point-like



Yukawa



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

$$+\ C^{3,8}_{Qq}, C^{1,8}_{Qq}, C^{8}_{Qu}, C^{8}_{Qd}, C^{8}_{tq}, C^{8}_{tu}, C^{8}_{td}$$

- 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!

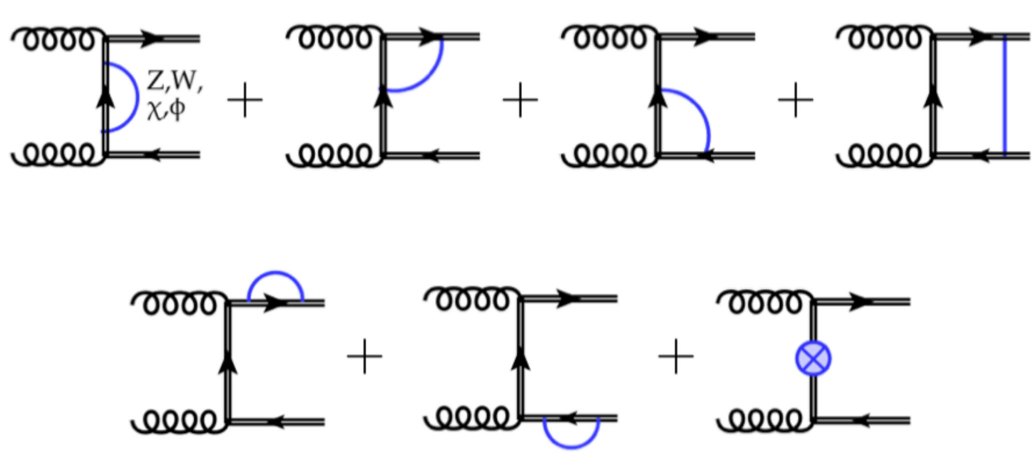
Loop sensitivity in top data

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

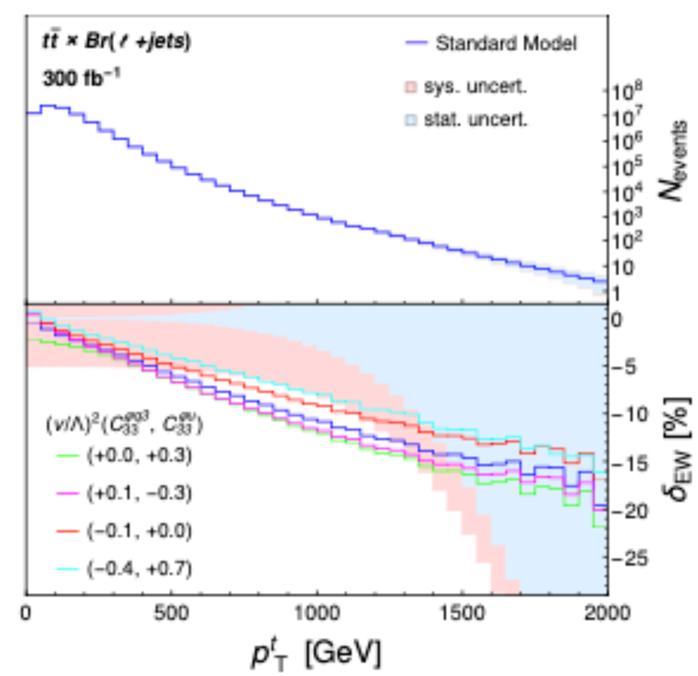
- Few-percent-level precision at LHC

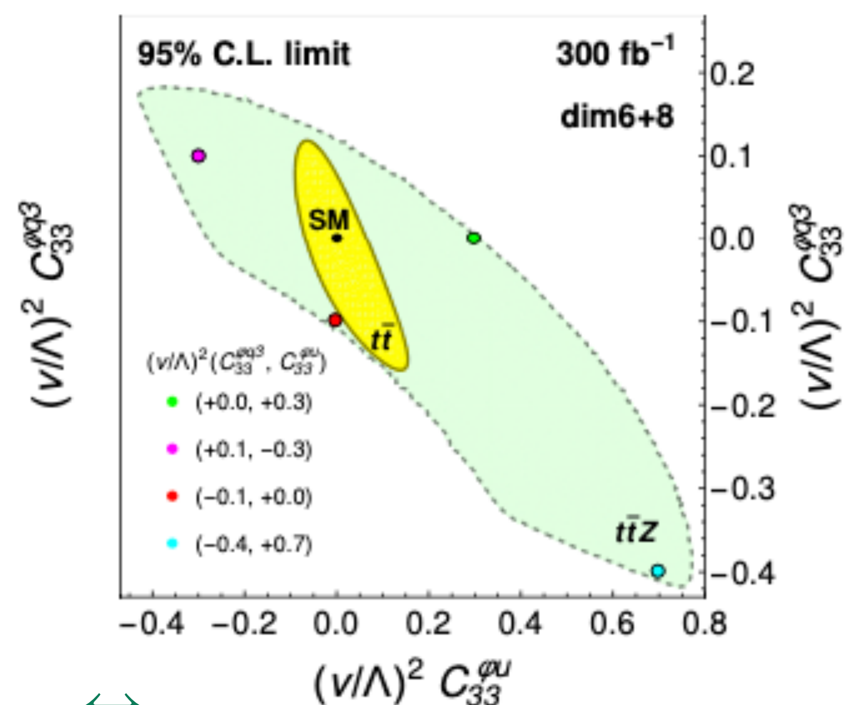
EW top couplings: loops of tops & EW gauge bosons

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



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



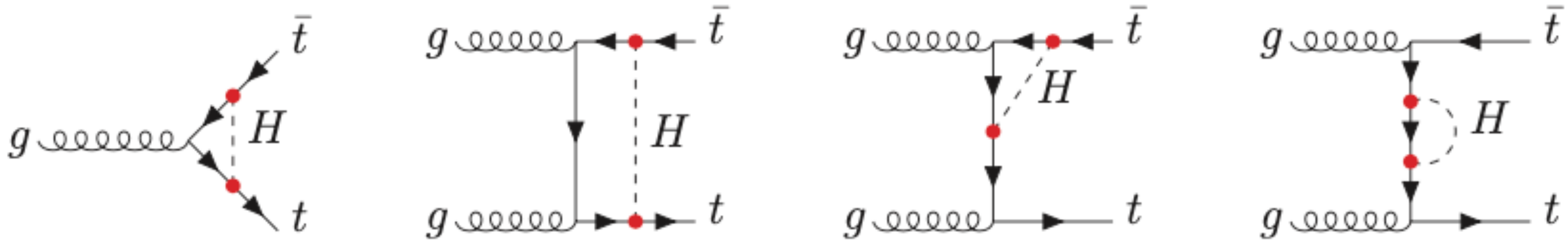


Promising sensitivity to current operators $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{Q}\gamma^\mu Q)$

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

See also [Martini et al.; PRD 104 (2021) 5, 055045]

y_t in $t\bar{t}$



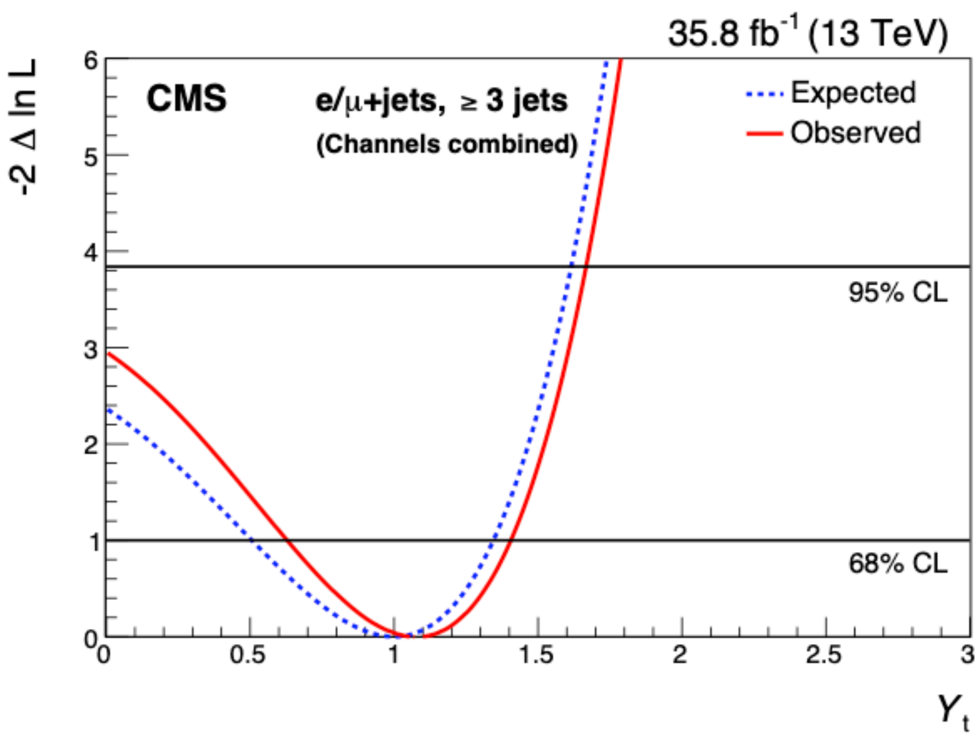
Top Yukawa coupling

- 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)]

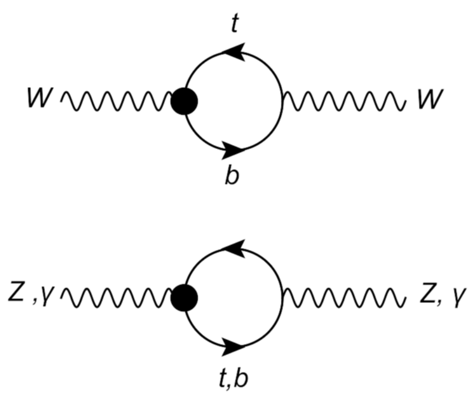
Channel	Best fit Y_t Expected	Best fit Y_t Observed	95% CL upper limit Expected	95% CL upper limit Observed
3 jets	$1.00^{+0.66}_{-0.90}$	$1.62^{+0.53}_{-0.78}$	<2.17	<2.59
4 jets	$1.00^{+0.50}_{-0.72}$	$0.87^{+0.51}_{-0.77}$	<1.88	<1.77
$\geq$5 jets	$1.00^{+0.59}_{-0.83}$	$1.27^{+0.55}_{-0.74}$	<2.03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

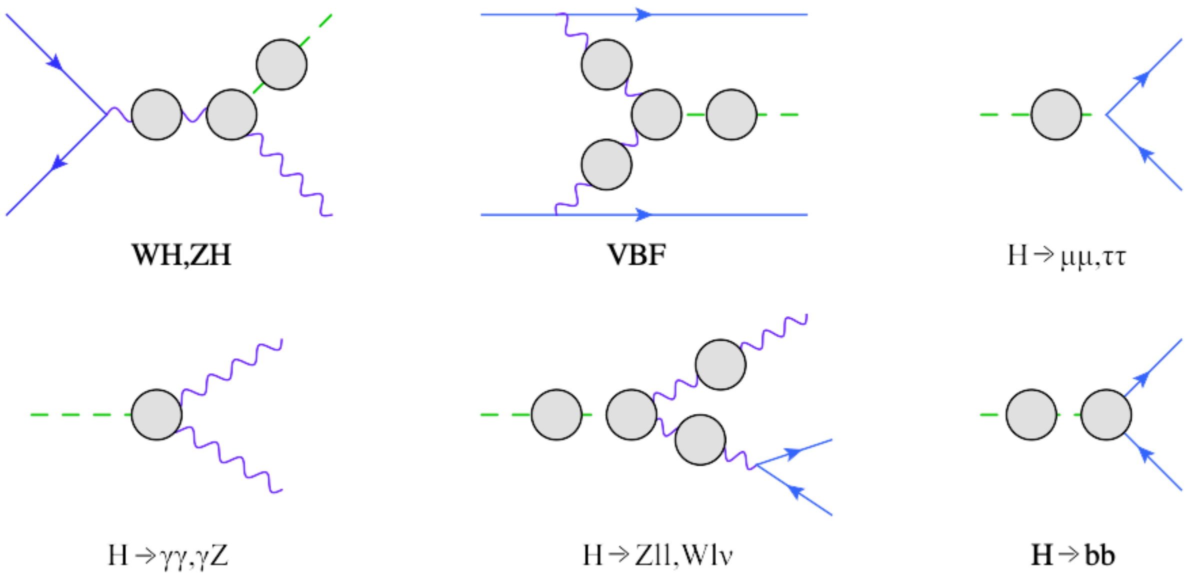
Z-pole observables



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

EW Higgs production & decay

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



Not yet fully combined in a fit

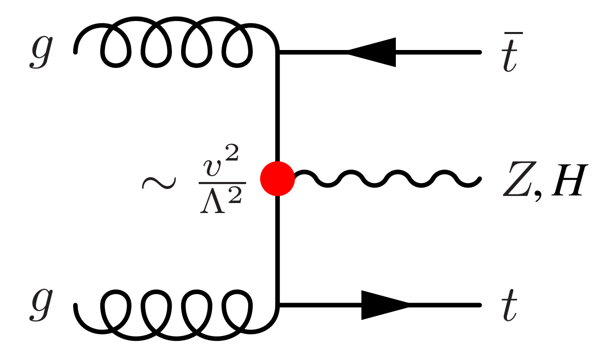
- NLO EW calculations
- Next frontier in precision SMEFT fits
- Impact of 4F operators not calculated
- Automated technology emerging
- Strengthen correlations between top, EWPO & Higgs data

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 × SM interference often suppressed
  [Azatov et al.; PRD 95 (2017) no. 6, 065014]

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

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

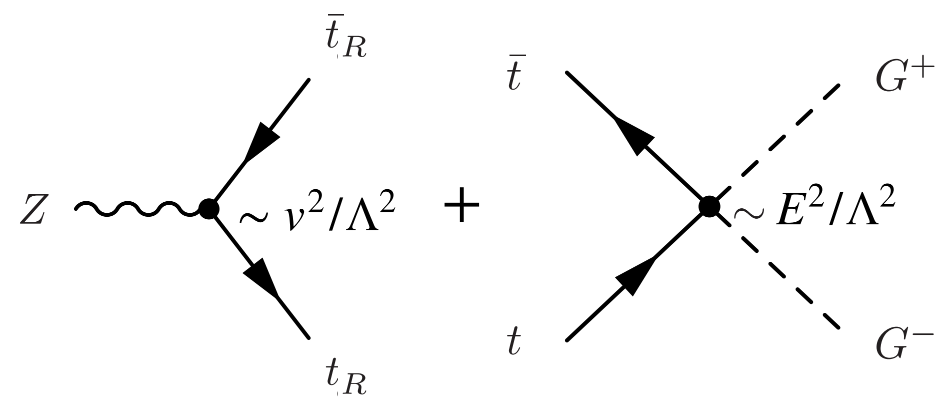
Rate measurements will become systematics dominated
Increasingly high-energy measurements scale with lumi.

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

Finding the right process

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

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

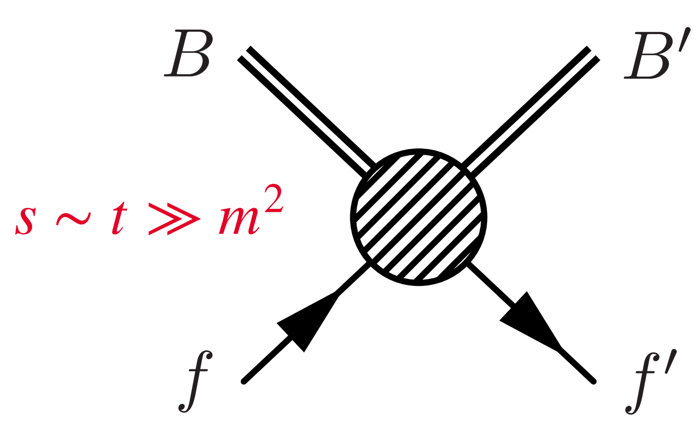


$t\, W_L \to t\, W_L$
$t\, Z_L \to t\, h$
$b\, W_L \to t\, Z_L$
$b\, W_L \to t\, h$

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

Energy-growing interference

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

single-top

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

two-top w/o Higgs

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

two-top w/ Higgs

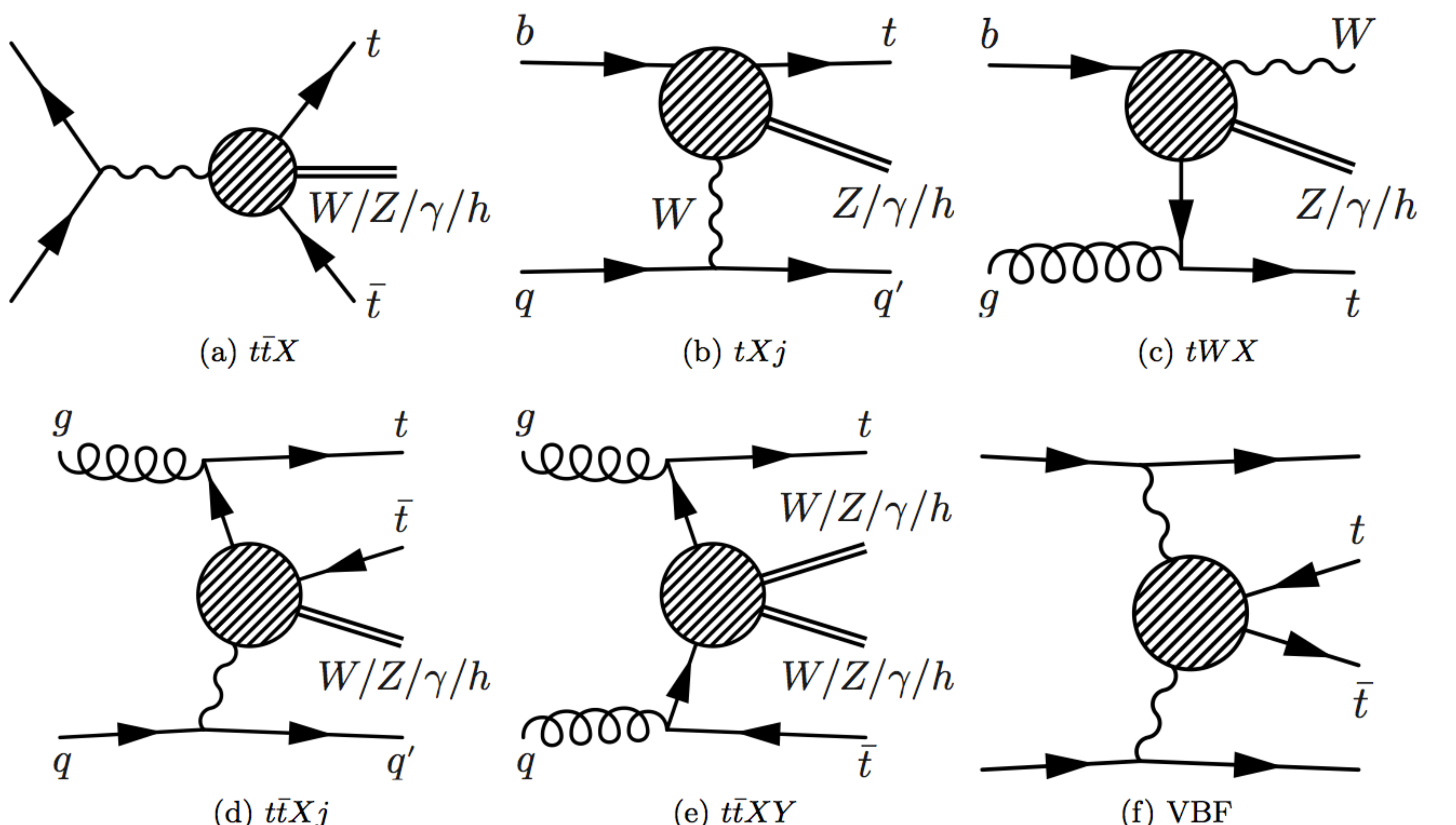
	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$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

Most top operators show max growth somewhere

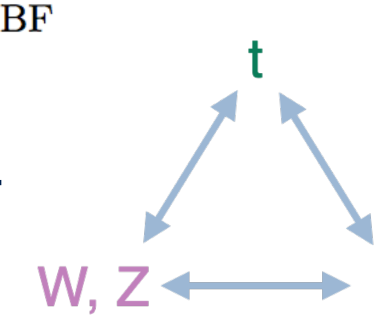
- Interfering growth rare, only in longitudinal configurations (c.f. helicity selection)

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
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

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

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 ($t\bar{t}Wj, tHj, tWZ, \ldots$)
- 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,...
$t\bar{t}t\bar{t}$	$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$,...

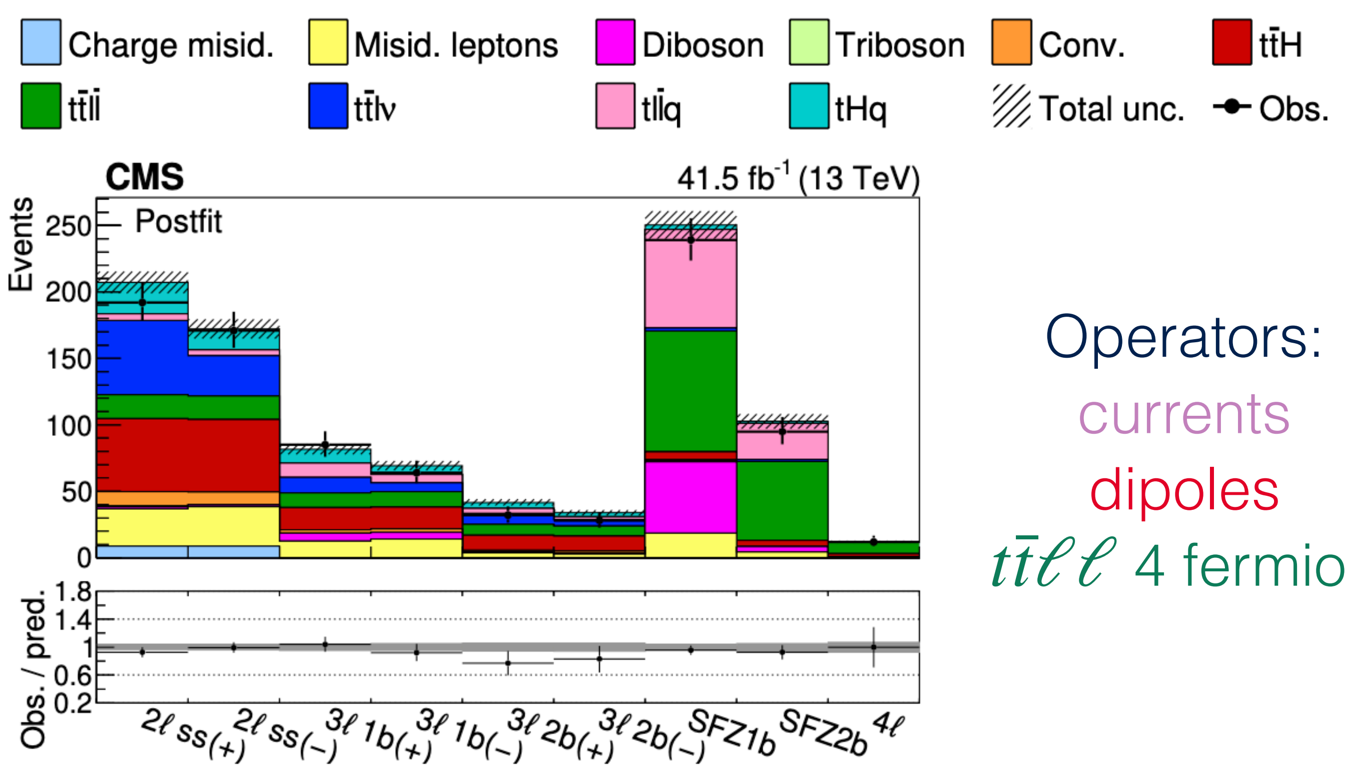
Sig/Bkg. overlap ⇒ global measurements

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

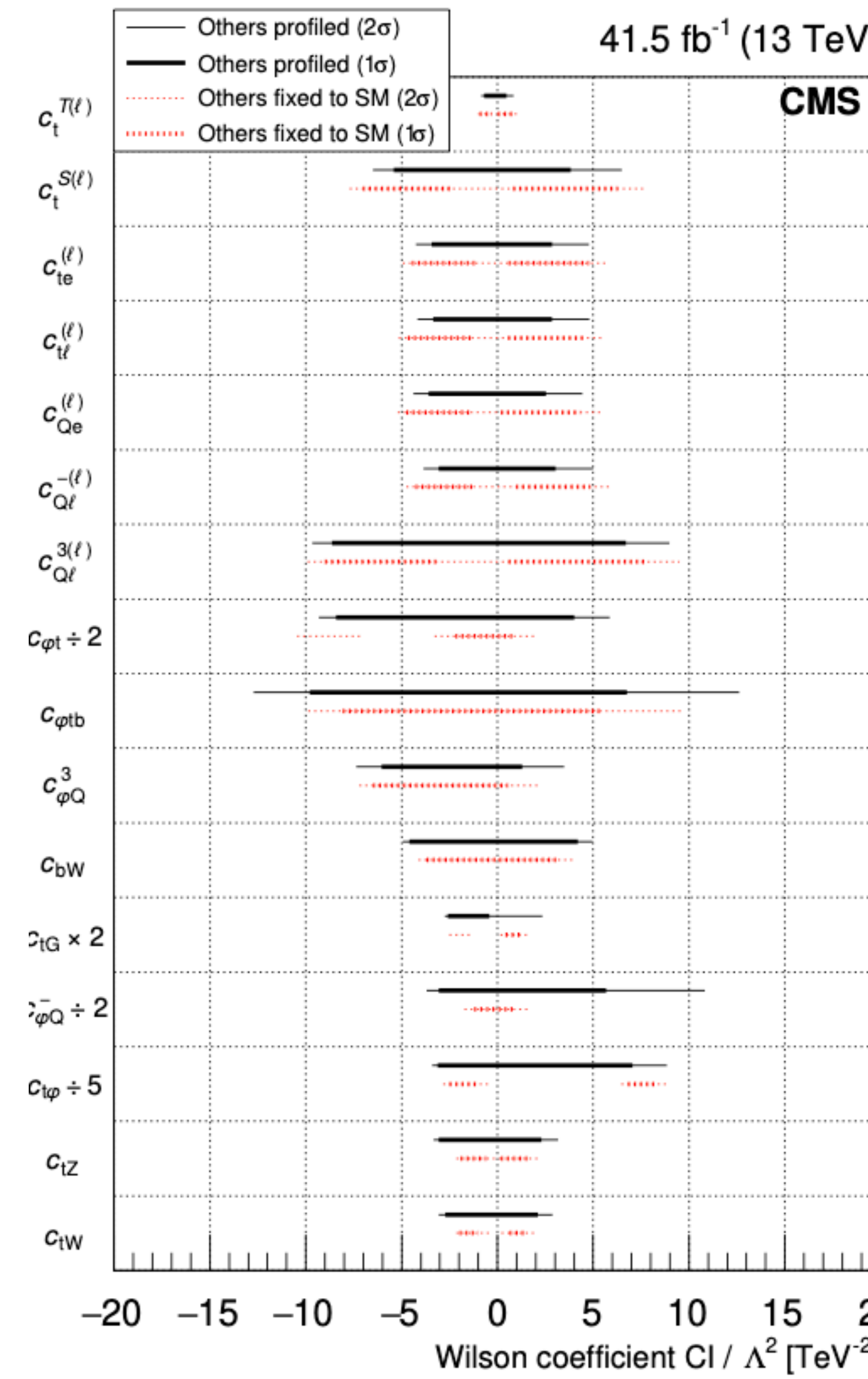
Global measurements

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

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:

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

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

- ‘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`**, …

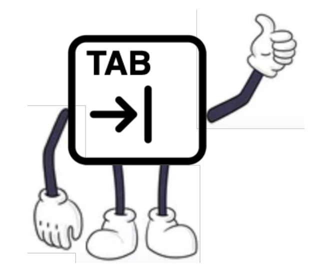
- Generate events: flexible, many distributions & parton shower interface
- Alternative: fixed order (specific observables, needs **`FORTRAN`**)

https://launchpad.net/mg5amcnlo

`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…)



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

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

Standard Model Effective Theory at One-Loop in QCD

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 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 `QQll` operators, with coefficients `ctlS3`, `ctlT3`, and `cblS3`, 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

What's in the box?

'Warsaw' basis

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

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
~~$Q_{\widetilde G}$~~	~~$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$~~	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
~~$Q_{\widetilde W}$~~	~~$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$~~				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
~~$Q_{\varphi\widetilde G}$~~	~~$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$~~	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
~~$Q_{\varphi\widetilde W}$~~	~~$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$~~	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
~~$Q_{\varphi\widetilde B}$~~	~~$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$~~	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
~~$Q_{\varphi\widetilde WB}$~~	~~$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$~~	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	~~Q_{duq}~~	~~$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$~~
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	~~Q_{qqu}~~	~~$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$~~
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	~~$Q_{qqq}^{(1)}$~~	~~$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$~~
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	~~$Q_{qqq}^{(3)}$~~	~~$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$~~
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	~~Q_{duu}~~	~~$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$~~

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]

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

See `dim6top`

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

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: $m_b = 0$

Bosonic			SLHA Block: DIM6		
$\mathcal{O}_i$	UFO	Definition	$\mathcal{O}_i$	UFO	Definition
$\mathcal{O}_G$	cG	$g_S f_{ABC} G^A_{\mu\nu} G^{B,\nu\rho} G^{C,\mu}_{\rho}$	$\mathcal{O}_W$	cWWW	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
$\mathcal{O}_{\varphi G}$	cpG	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) G^{\mu\nu}_A G^A_{\mu\nu}$	$\mathcal{O}_{\varphi W}$	cpW	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W^{\mu\nu}_I W^I_{\mu\nu}$
$\mathcal{O}_{\varphi B}$	cpBB	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$	$\mathcal{O}_{\varphi WB}$	cpWB	$(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W^I_{\mu\nu}$
$\mathcal{O}_{\varphi}$	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, Λ: Lambda (default value 1000 GeV)

- Coupling order: NP (New Physics)
- Dimension-6: $1/\Lambda^2 \Leftrightarrow$ 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. # cWWW
    7 0. # cG
    8 0. # cpG
    9 0. # cpW
   10 0. # cpBB
```

Bosonic

```
###################################
## INFORMATION FOR DIM64F2L
###################################
Block DIM64F2L
    1 0. # cQlM1
    2 0. # cQlM2
    3 0. # cQl31
    4 0. # cQl32
    5 0. # cQe1
    6 0. # cQe2
    7 0. # ctl1
    8 0. # ctl2
    9 0. # cte1
   10 0. # cte2
   13 0. # cQlM3
   14 0. # cQl33
   15 0. # cQe3
   16 0. # ctl3
   17 0. # cte3
   19 0. # ctlS3
   20 0. # ctlT3
   21 0. # cblS3
```

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
```

μ_{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. # cQQ8
   20 0. # cQQ1
   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]
```

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]
```

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!

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`

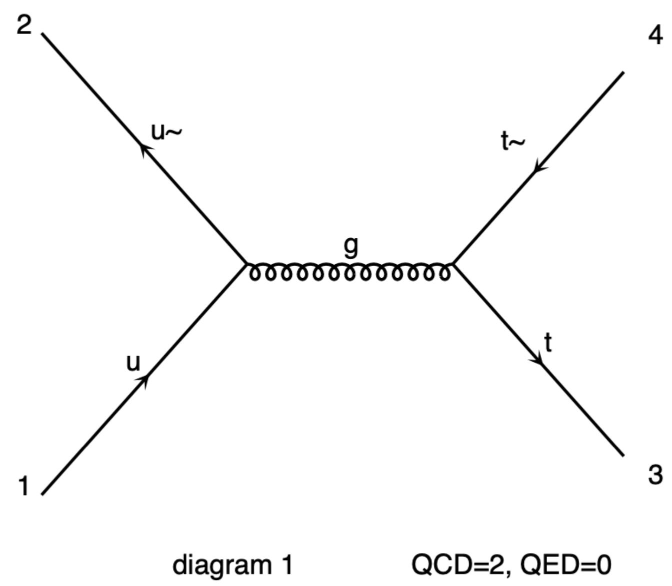
Coupling orders

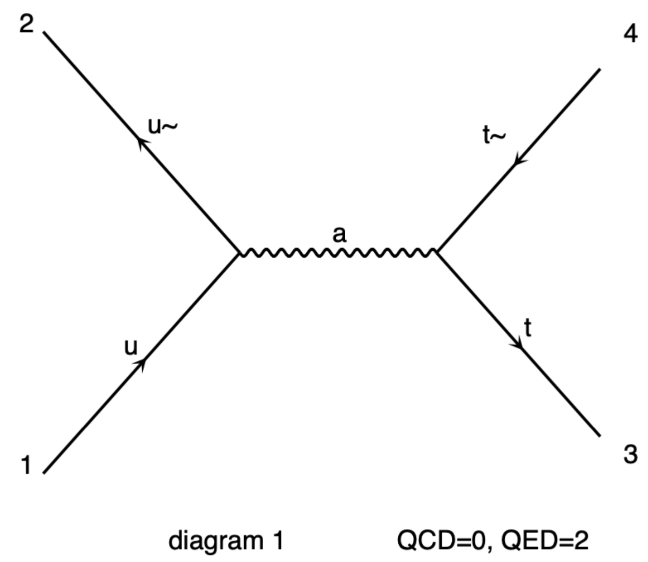
Used to specify desired Feynman diagrams

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

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

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






```
MG5_aMC> display diagrams
```

Open file viewer

```
MG5_aMC> cd SubProcesses/P…
```

After output: access matrix.ps

Coupling orders lvl. 2

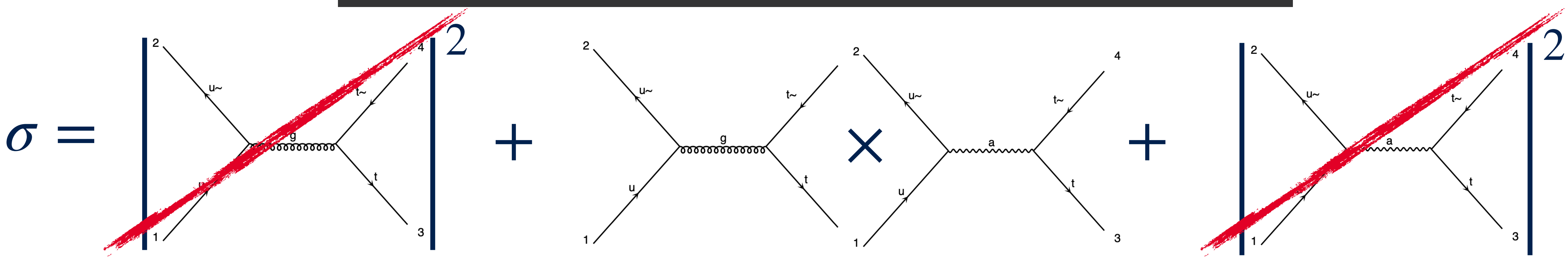
`X=N`: Defined at amplitude level

- `QCD/QED=N`: shorthand for `QCD/QED<=N`
- `QCD/QED==N`: “exactly equal to”
- `MG5`: all possible amplitudes satisfying coupling order constraints

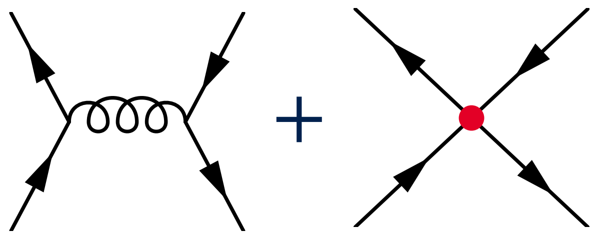
`X^2=N`: Defined at amplitude-squared (cross section) level

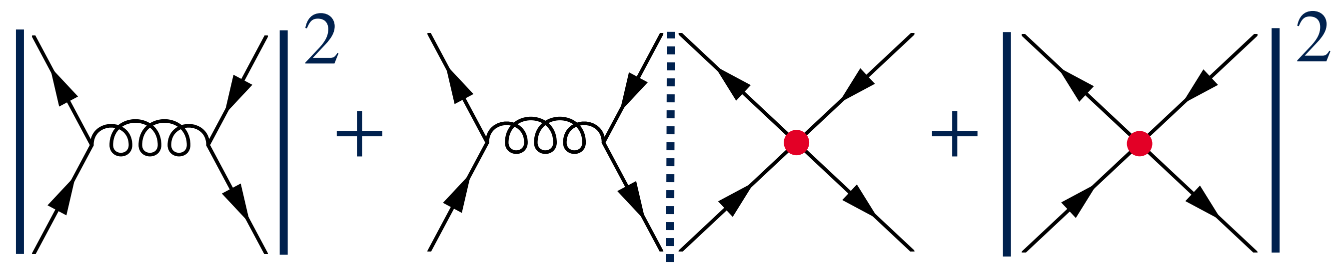
- Can be used in conjunction with above (select diagrams, then fine-tune)
- Fine-tune exact contributions in perturbative (or EFT) expansion
- ! Only fully available in LO (& loop-induced) mode: not NLO !

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



NP coupling orders





$$\mathcal{A}_{D=6} = \underbrace{\mathcal{A}_{SM}}_{\texttt{NP=0}} + \underbrace{\sum_i \frac{c_i}{\Lambda^2}\mathcal{A}_i}_{\texttt{NP=2}} \Rightarrow \sigma_{D=6} = \underbrace{\sigma_{SM}}_{\texttt{NP=0}} + \underbrace{\sum_i \frac{c_i}{\Lambda^2}\sigma_i}_{\texttt{NP=2}} + \underbrace{\sum_{j\leq i} \frac{c_i c_j}{\Lambda^4}\sigma_{i,j}}_{\texttt{NP=4}}$$

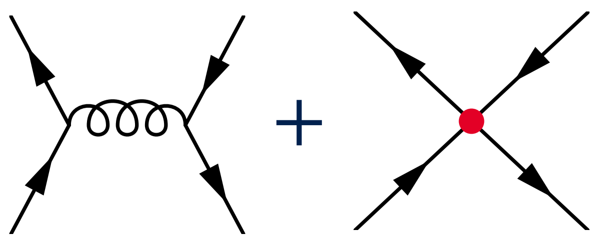
n coefficients $\Rightarrow$ $(n+1)(n+2)/2$ numbers: $\sigma_{SM}, \sigma_i, \sigma_{i,j}$

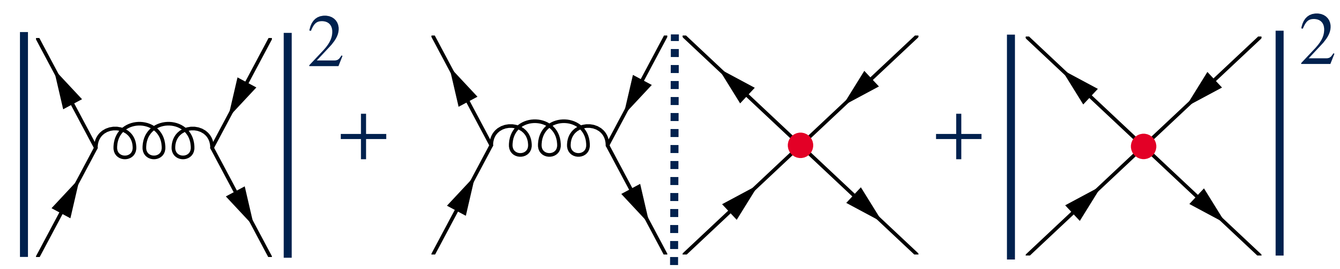
LO mode: select EFT contributions at generation level

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

Full thing	$\lvert\mathcal{A}_{SM} + \mathcal{A}_{EFT}\rvert^2$	`NP=2` or `NP^2=4`
EFT only	$\lvert\mathcal{A}_{EFT}\rvert^2$	`NP==2` or `NP^2==4`
SM + interference	$\lvert\mathcal{A}_{SM}\rvert^2 + 2\mathrm{Re}\left[\mathcal{A}_{SM}\mathcal{A}_{EFT}\right]$	`NP^2=2` or `NP^2<=2`
Interference only	$2\mathrm{Re}\left[\mathcal{A}_{SM}\mathcal{A}_{EFT}\right]$	`NP^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: $\sigma_{SM}, \sigma_i, \sigma_{i,j}$

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

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

Don't worry about Λ, its just a number!

- Sets the effective couplings $\propto c_i/\Lambda^2$

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

- Only physical scale if you fix c_i with UV models (interpretation)

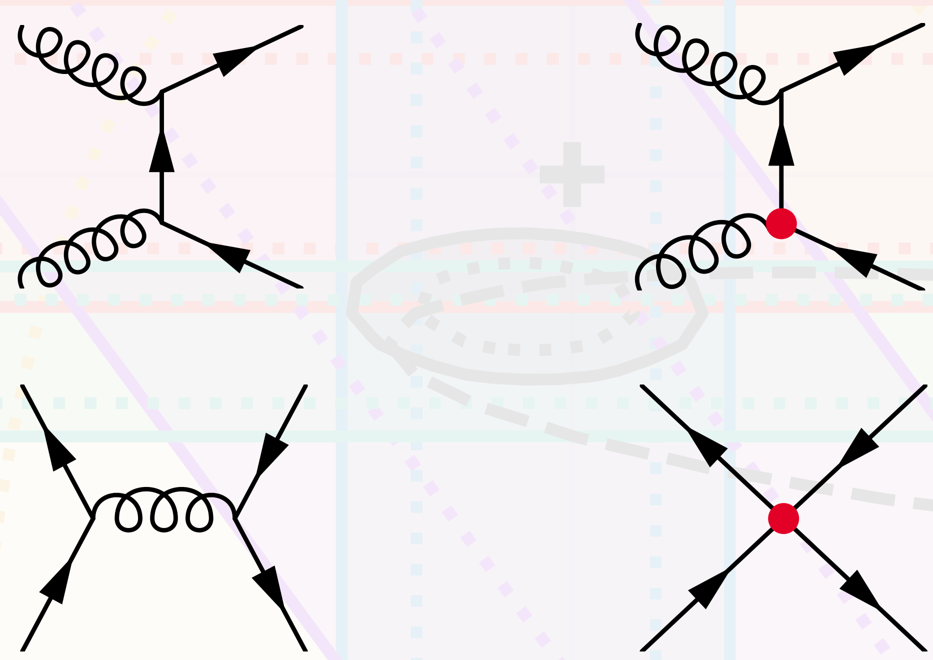
(You may need to do this if using python 3)

```
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

SM



$ig_S\,(\bar{Q}\sigma^{\mu\nu}T_A t)\,\tilde{H}\,G^A_{\mu\nu}$ `ctG`

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

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

… …

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

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

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

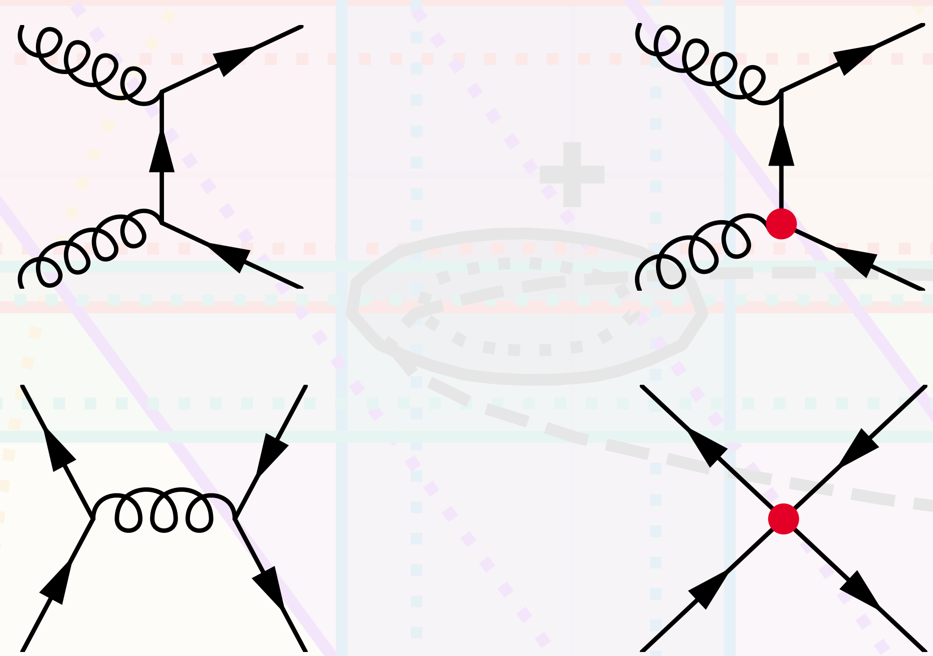
Cons

- 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~`
- Start from SM, get $\bar{\sigma}_i, \bar{\sigma}_{i,j}$
- `set ci 0 / set ci 1`
- `change process… NP^2==2` to get interf.

SM



$ig_S\,(\bar{Q}\sigma^{\mu\nu}T_A t)\,\tilde{H}\,G^A_{\mu\nu}$ — `ctG`

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

$(\bar{u}\gamma^\mu u)\,(\bar{t}\gamma_\mu t)$ — `ctu1`

… …

Production & decay

Often factorise these two effects

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

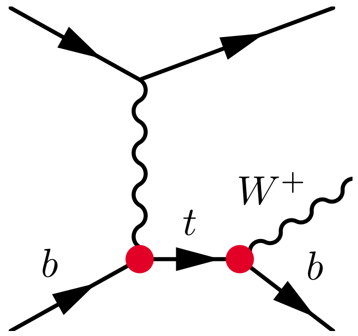
- Narrow width approximation (NWA)
- $\sigma(pp\to X\to ab)=\sigma(pp\to X)\times \mathrm{BR}(X\to ab)$

$$\left(\sigma_{\rm SM}+\sum_i\sigma_i\frac{c_i}{\Lambda^2}+\sum_i\sigma_{i,j}\frac{c_ic_j}{\Lambda^4}\right)\times\frac{\Gamma^{ab}_{\rm SM}+\sum_i\Gamma^{ab}_i\frac{c_i}{\Lambda^2}+\sum_i\Gamma^{ab}_{i,j}\frac{c_ic_j}{\Lambda^4}}{\Gamma^{\rm tot.}_{\rm SM}+\sum_i\Gamma^{\rm tot.}_i\frac{c_i}{\Lambda^2}+\sum_i\Gamma^{\rm tot.}_{i,j}\frac{c_ic_j}{\Lambda^4}}$$

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

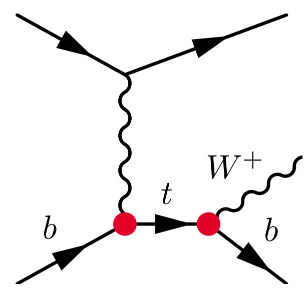
Production & decay

a) Compute separately

✓ Inclusive observables or if no change in decay angular dependence

- Simulate EFT production (+ SM decay) ⇒ rescale by BR

b) Compute whole process



Change UFO!
`expansion_order=4` in `coupling_orders.py`

✓ 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`

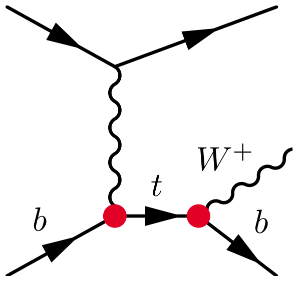
Useful MG5 feature: `MadSpin`

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

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

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
```

factorised: assumes NWA

Decaying with MadSpin

- Undecayed process, modify `madspin_card.dat`
- Madspin syntax:

```
decay t > w+ b
```

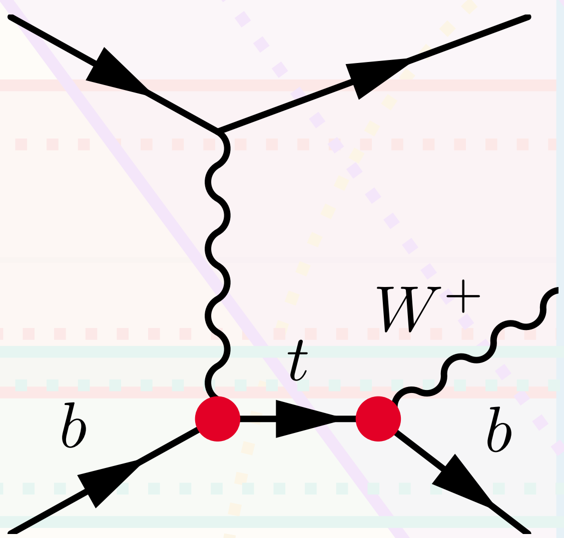
```
decay t > w+ b, w+ > e+ ve
```

⇐ 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

Exercise 3

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



$i(\bar{Q}\sigma^{\mu\nu}\tau_I t)\,\tilde{H}\,W^I_{\mu\nu}$ `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?	✗	✓
Better:	*Reflection of new physics* ***reach***	*Pinpointing of new physics* ***origin***

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` ⇒ access LO/NLO & EFT interference/square
- Propagated through to lhe 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

different scale settings

```
    <weightgroup name='scale_variation          60202   0' 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
```

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  0.00000000000000000E+00  0.00000000000000000E+00
         2 -1    0    0  501    0  0.00000000000000000E+00  0.00000000000000000E+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 0.000
  <rwgt>
   <wgt id='1001'> 0.91941E-01 </wgt>
   <wgt id='1002'> 0.83393E-01 </wgt>
```

id

split order weights

many weights

`

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 (`NP^2==2`)

Possible solutions for NLO

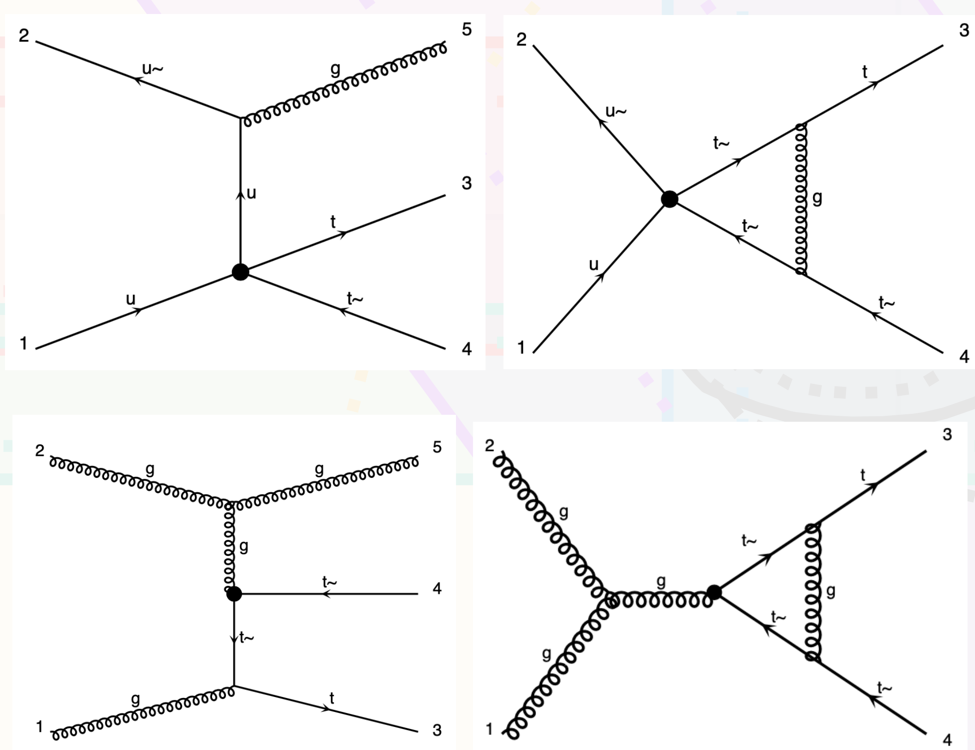
- Pick optimal value of coefficient to maximise relative size of $\mathcal{O}(\Lambda^{-2})$

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

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



$ig_S(\bar{Q}\sigma^{\mu\nu}T_A t)\,\tilde{H}\,G^A_{\mu\nu}$	`ctG`
$(\bar{u}\gamma^\mu T^A u)\,(\bar{t}\gamma_\mu T_A t)$	`ctu8`
$(\bar{u}\gamma^\mu u)\,(\bar{t}\gamma_\mu t)$	`ctu1`
…	…

Merging

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

- No difference to SM case

Example `p p > t t~` (+1 jet)

- 4F operator `ctu8` $(\bar{u}\gamma^{\mu}T^{A}u)\,(\bar{t}\gamma_{\mu}T_{A}t)$

```
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
- …

`SMEFTatNLO` development

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

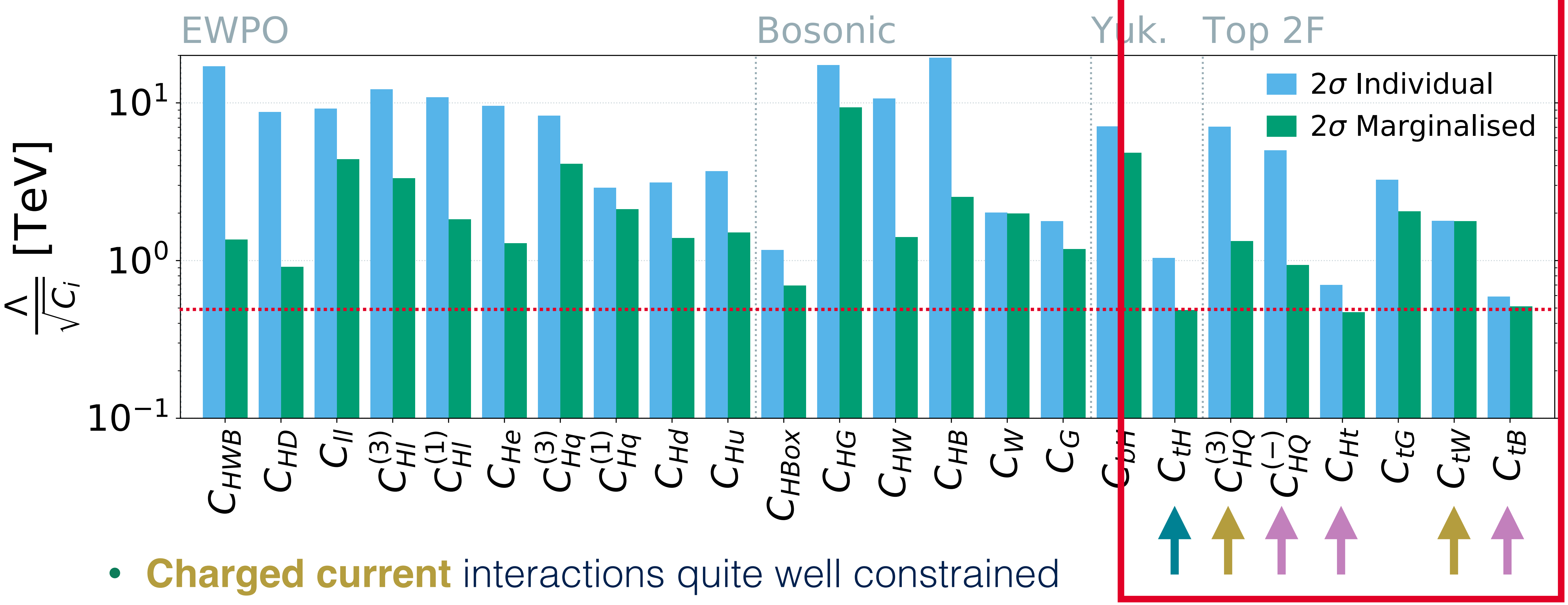
Open to suggestions!

Backup

How poorly?

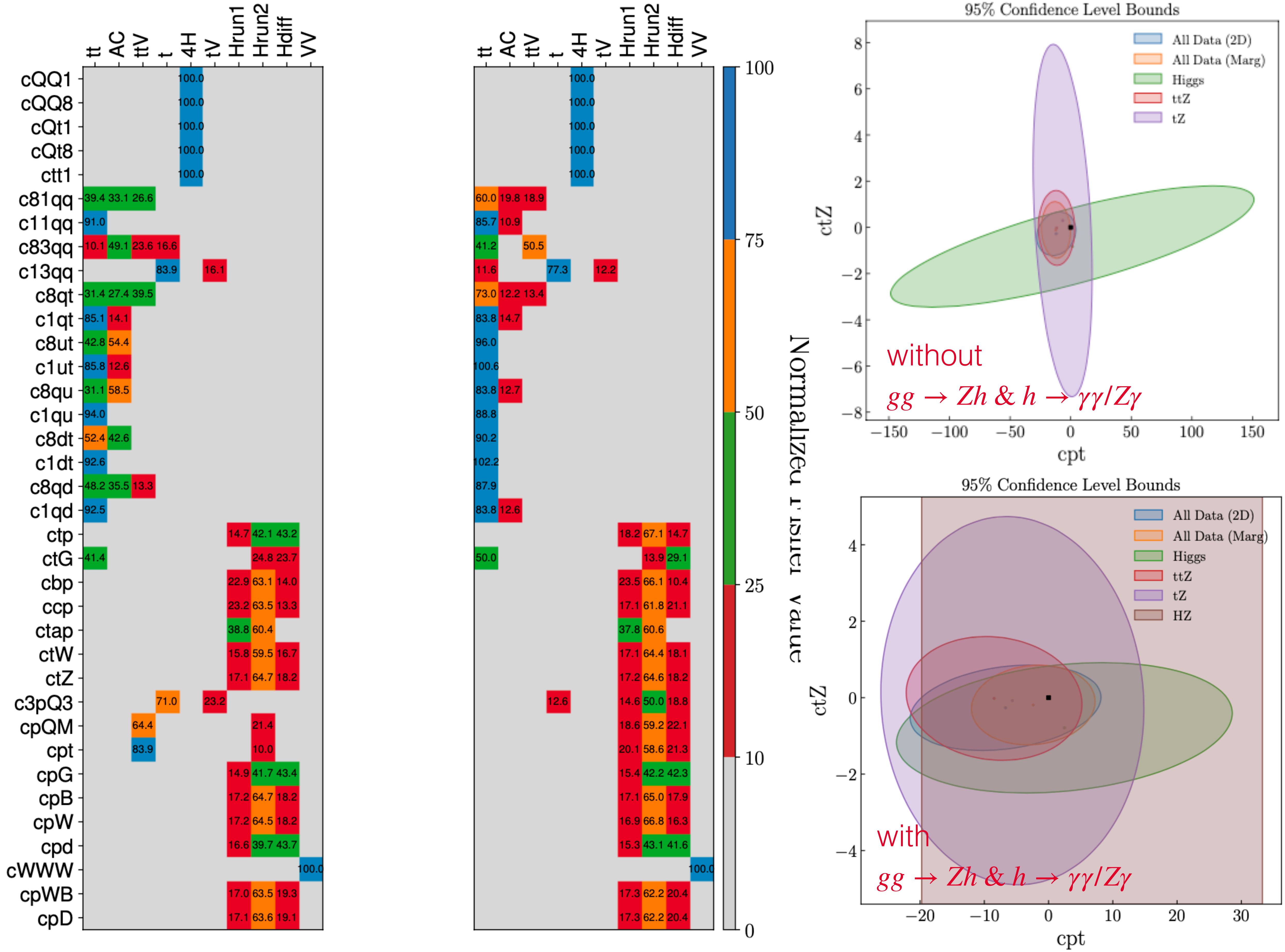
Global SMEFT fit to EWPO, Higgs, Diboson, top (34 d.o.f.)

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

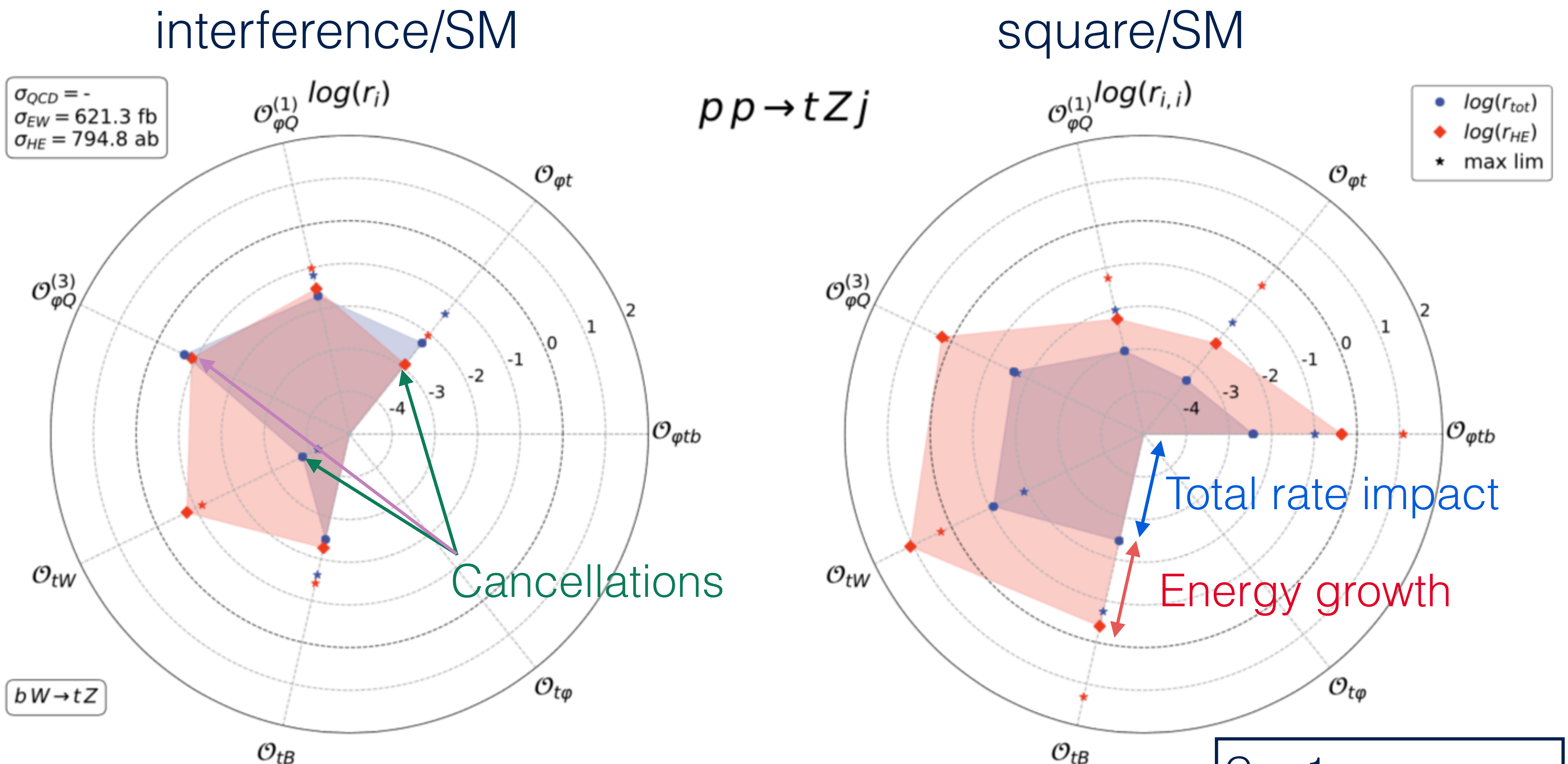


- **Charged current** interactions quite well constrained
- **Yukawa** and **neutral current** are among the worst

How can we improve?


tt AC ttV t 4H tV Hrun1 Hrun2 Hdiff VV
cQQ1 cQQ8 cQt1 cQt8 ctt1 c81qq c11qq c83qq c13qq c8qt c1qt c8ut c1ut c8qu c1qu c8dt c1dt c8qd c1qd ctp ctG cbp ccp ctap ctW ctZ c3pQ3 cpQM cpt cpG cpB cpW cpd cWWW cpWB cpD
Normalized Fisher Value
95% Confidence Level Bounds
All Data (2D)
All Data (Marg)
Higgs
ttZ
tZ
HZ
ctZ
cpt
without
$gg \to Zh$ & $h \to \gamma\gamma/Z\gamma$
with
$gg \to Zh$ & $h \to \gamma\gamma/Z\gamma$

tZ radar plot



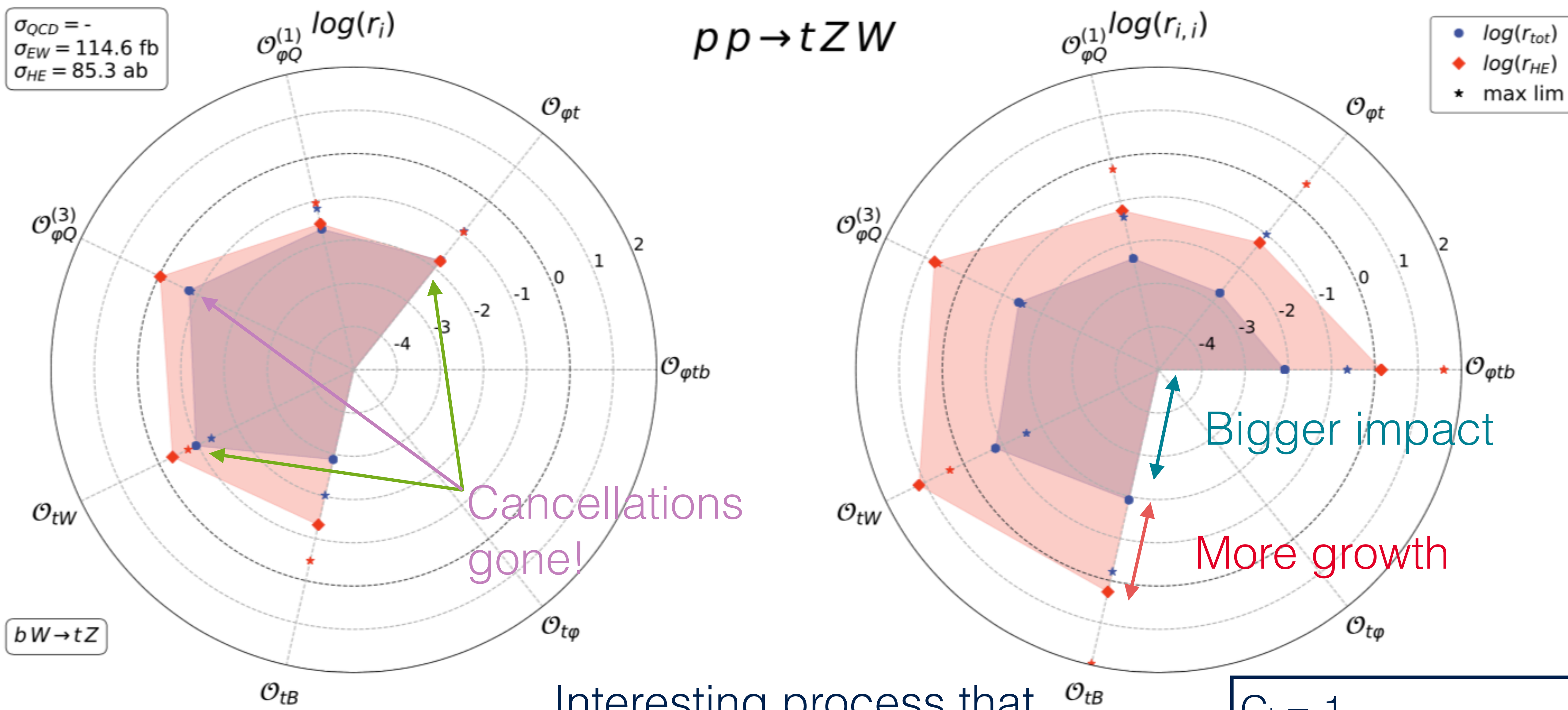
C_i = 1
Inclusive
p_T (Z)> 500 GeV

Expected growth from 2→2 absent!

tZW radar plot

interference/SM

square/SM

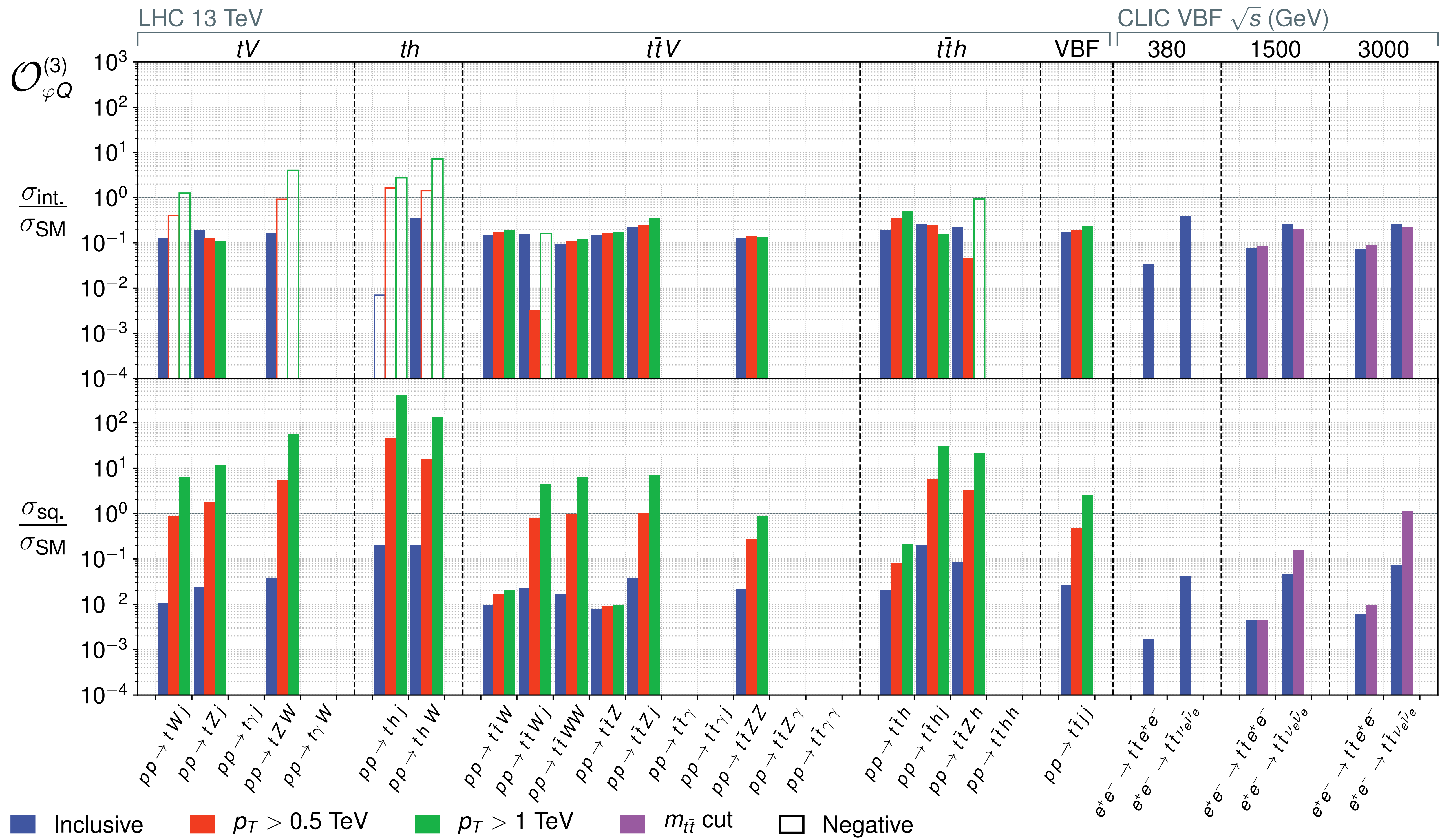


Expected growth is there!

Interesting process that should be accessible at the LHC

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

Charged current operator



Running & mixing

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

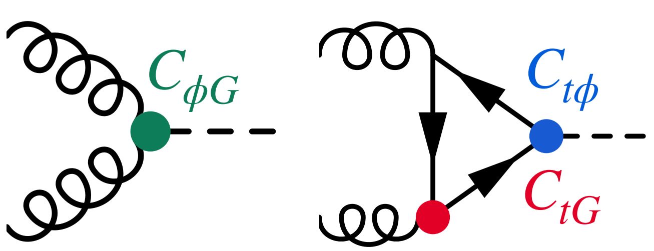
- Coefficients are generated (matching) & measured at different scales
- QFT: couplings depends on the scale at which they are defined
- EFT: couplings run & mix into one another $\Rightarrow$ anomalous dimensions γ_{ij}

$$\frac{dc_i(\mu)}{d\log\mu} = \frac{\alpha(\mu)}{\pi}\gamma_{ij}c_j(\mu)$$

Assuming $c_i = 0$ at low scale is not valid

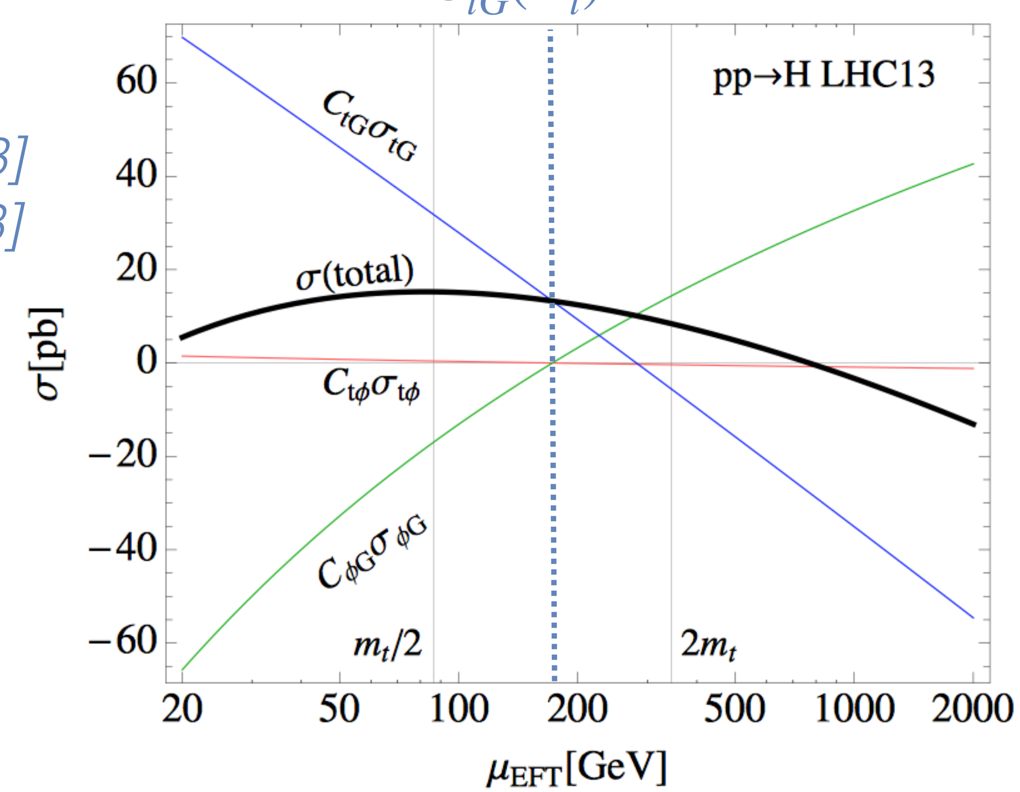
ex: Gluon fusion Higgs production

[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]
[Deutschmann et al.; JHEP 1712 (2017) 063]



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

$C_{tG}(m_t) = 1$



Only **global** approach makes sense

Finite terms

RG structure is universal ⇒ process independent

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

Counterpart: finite terms ⇒ process dependent

- **'Genuine NLO'** & must be studied process-by-process
- Often dominant over RG for LHC energy ($E_{exp.}$) & sensitivity (Λ_{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]