SMEFT (at NLO) : EW, Higgs, and Top

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Plan for today's lecture

- SMEFT essentials
- The SMEFT precision frontier
- Example: Fitting in the Top (with Higgs/EW) sector
- Bringing lessons home

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SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

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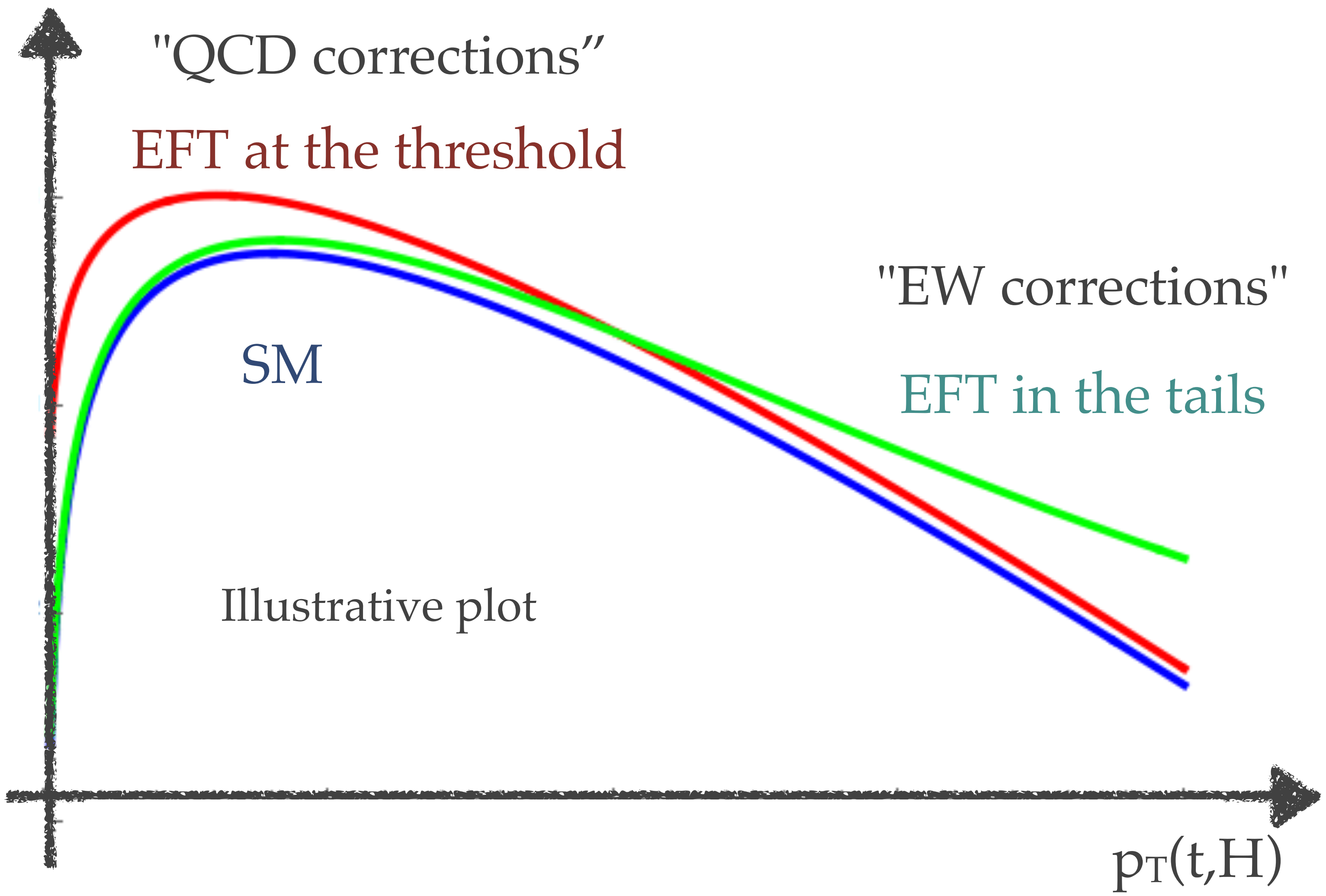
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

The EFT approach: managing unknown unknowns

- Very powerful model-independent approach.
- A **global constraining strategy** needs to be employed:
  - assume all* couplings not be zero at the EW scale.
  - identify the operators entering predictions for each observable (LO, NLO,..)
  - find enough observables (cross sections, BR's, distributions,…) to constrain all operators.
  - solve the linear (+quadratic)* system.
- Use to constrain UV-complete* models.
- The final reach on the scale of New Physics crucially depends on the THU.

SMEFT at the LHC



The expected effects can be both at threshold as well as in the tails. Some operators can affect distributions at the threshold. Some operators just lead to global rescaling of the distributions. Other induce an energy growth in the tails. The latter are the most characteristic EFT effects that are looked for.

The sensitivity to new interactions depends on a crucial way to our ability to make accurate/ precise predictions for the SM observables. The reach of our interpretations will also depend on the accuracy/precision on the SMEFT predictions.

SMEFT at the LHC

S is a generic scale, which is process and operator dependent

- Large number of operators, yet a plethora of observables and final states to measure.
- Precision observables in the bulk of the distributions while tails provide sensitivity through the energy growth.
- Validity issues arise, as well as for the interpretation in terms of models.

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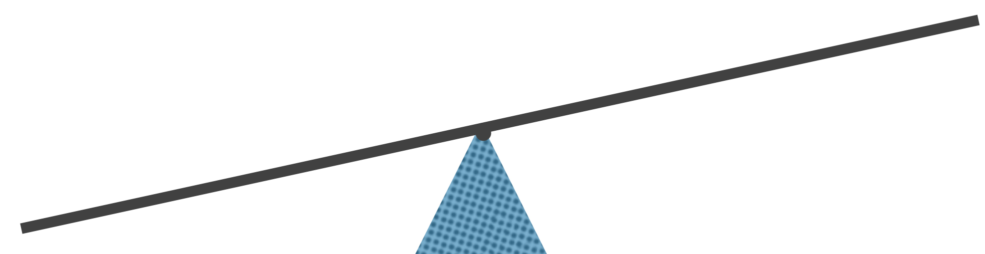
$$\Lambda > \sqrt{s}\sqrt{|c_i|/\delta}$$



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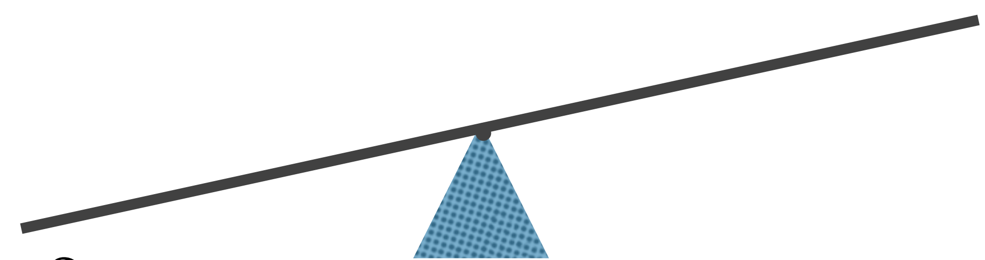

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$$\sqrt{s} < \Lambda$$

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu\varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

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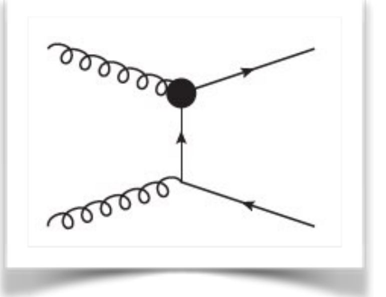

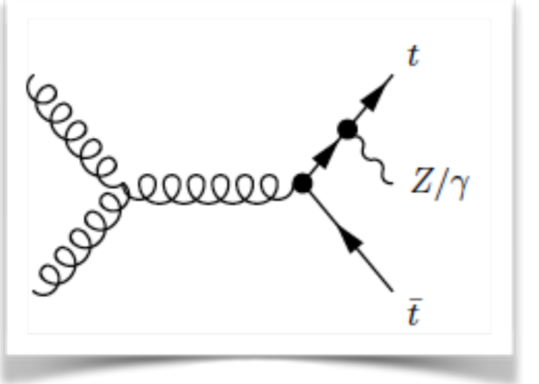

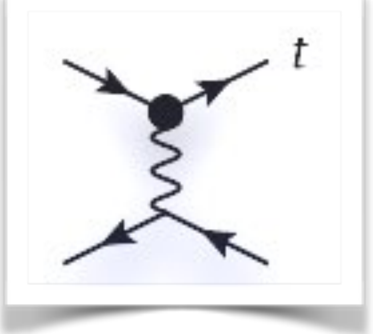

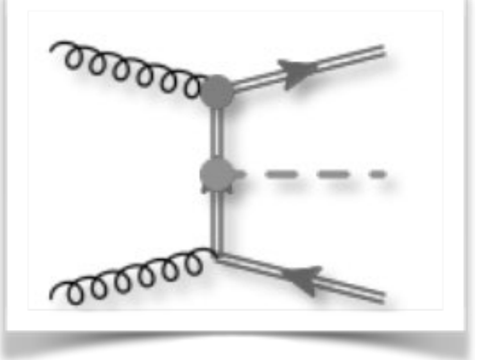

+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

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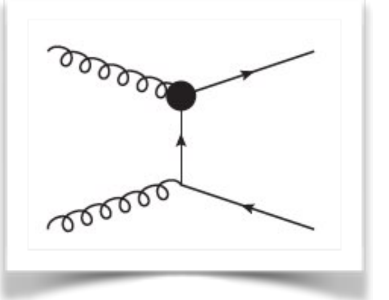

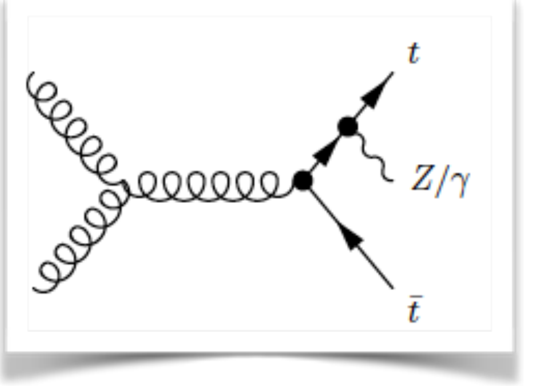

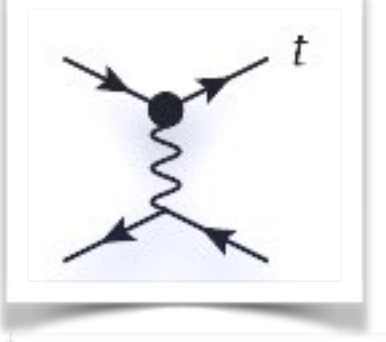

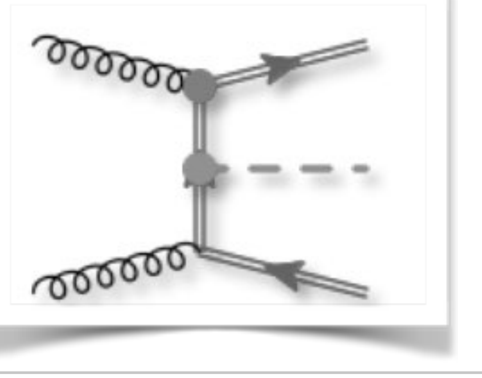

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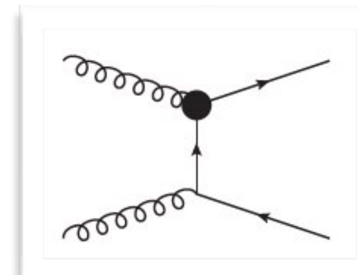

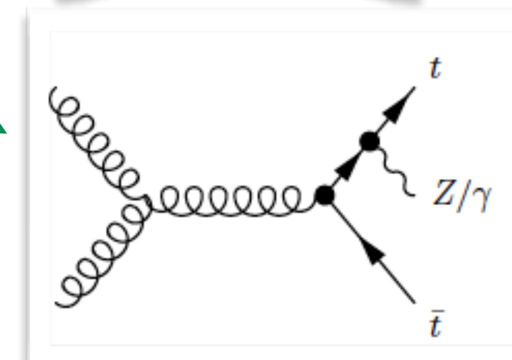

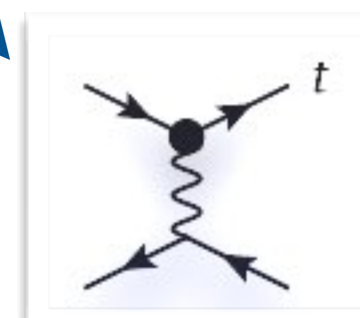

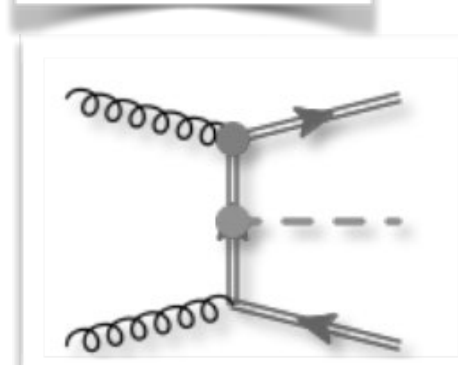

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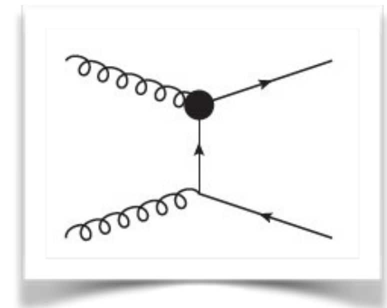

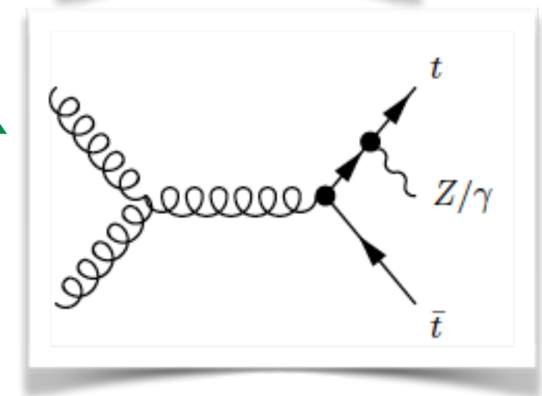

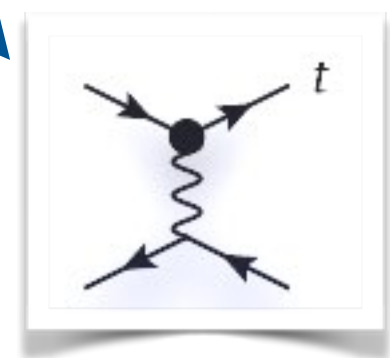

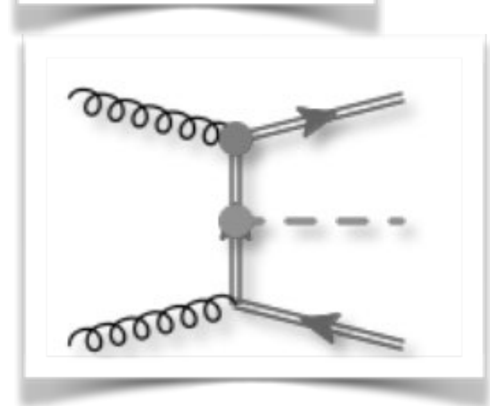

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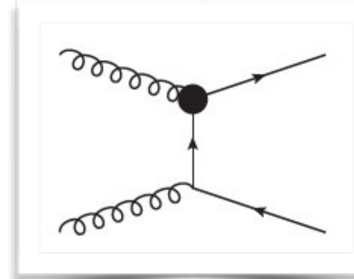

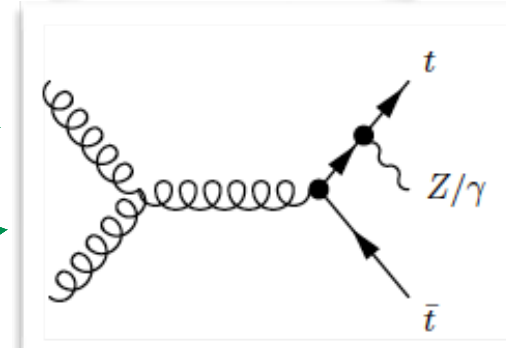

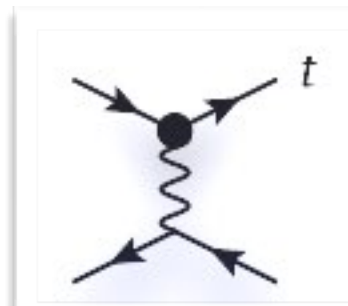

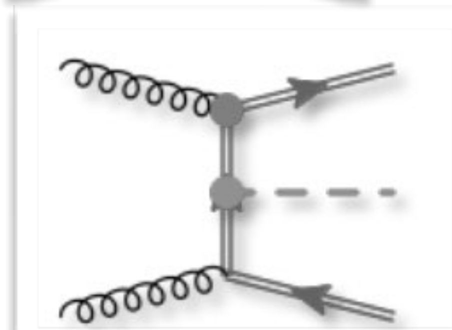

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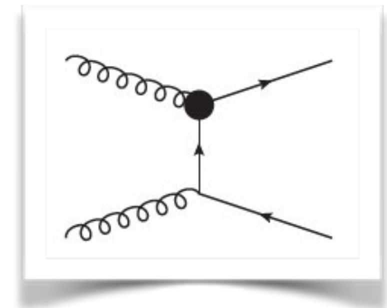
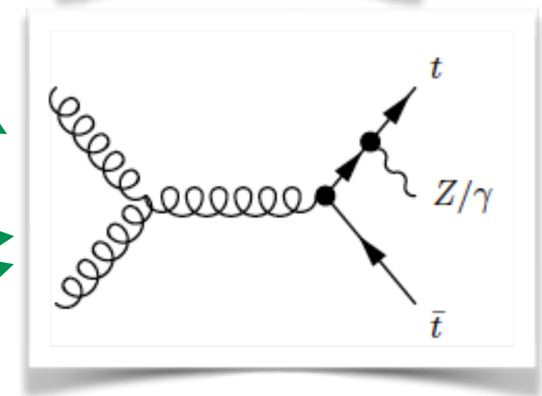
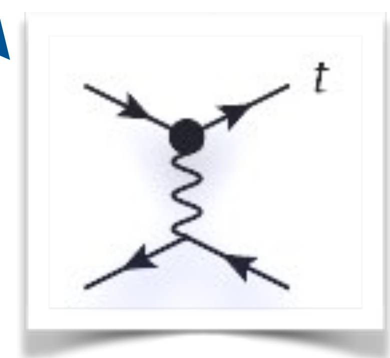
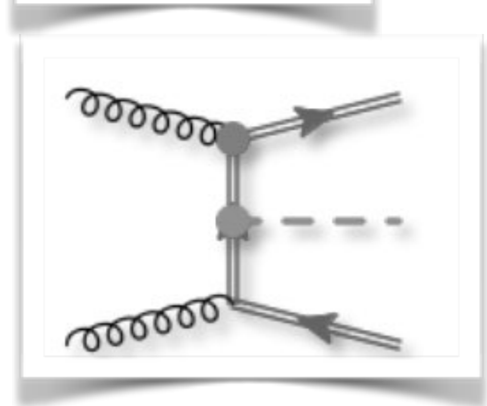
$$O_{t\varphi} = y_t^3(\varphi^\dagger\varphi)\bar{Q}\tilde{\varphi}t$$









+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

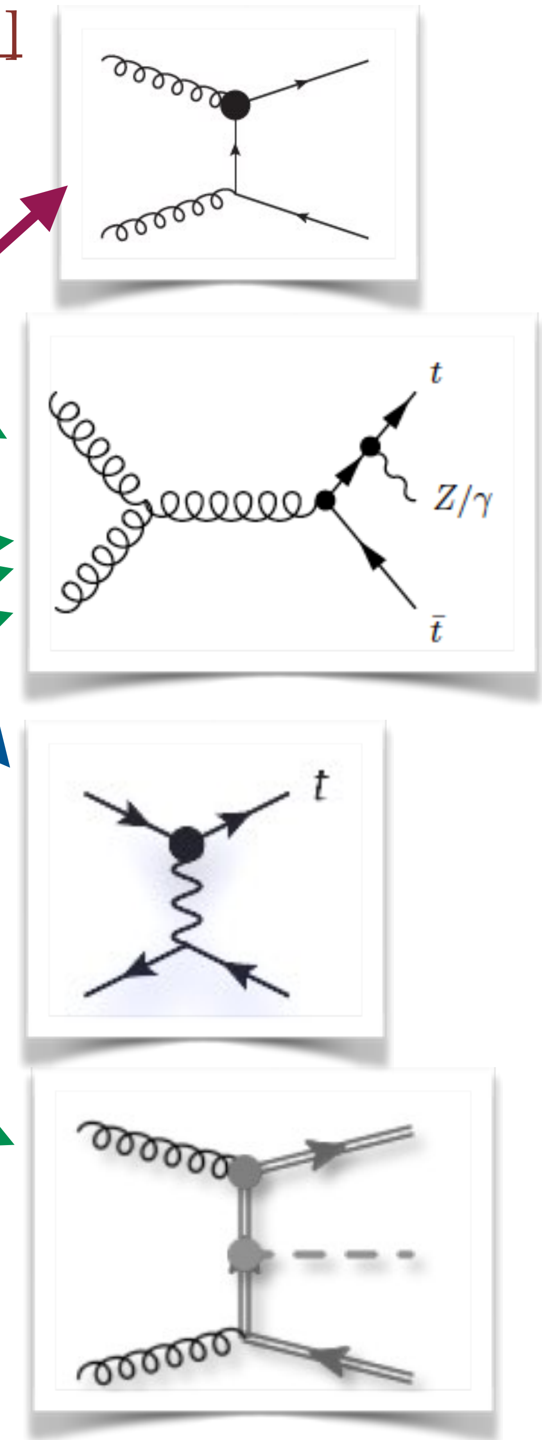
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

$$O_{t\varphi} = y_t^3(\varphi^\dagger\varphi)\bar{Q}\tilde{\varphi}t$$



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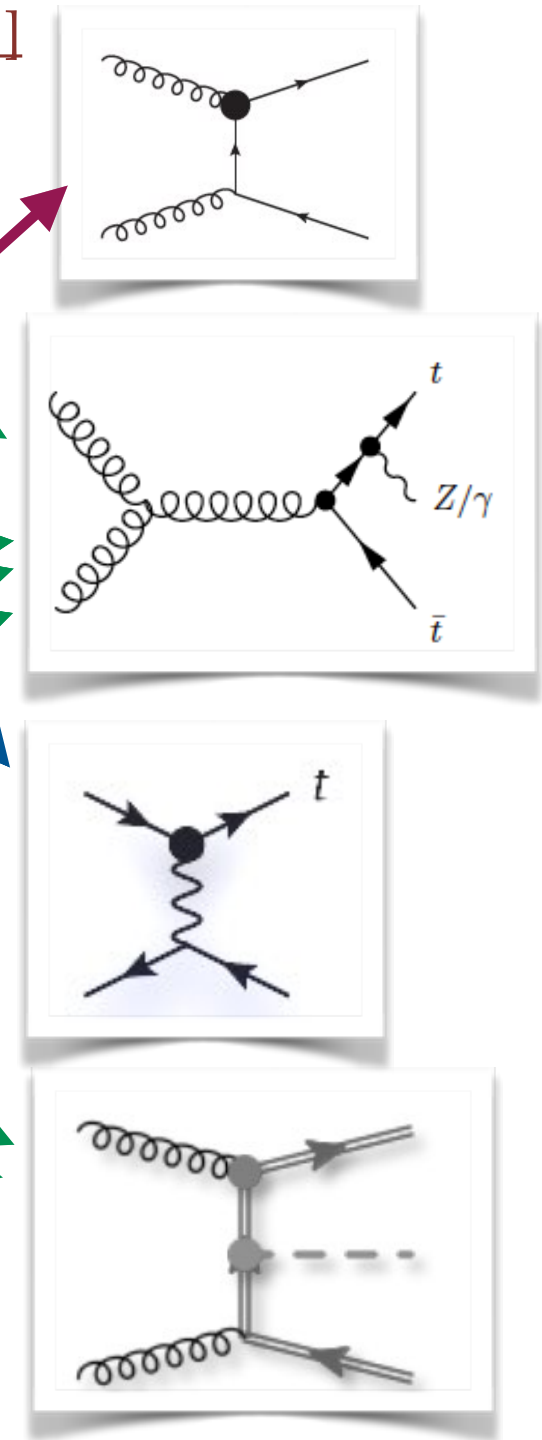


+four-fermion operators

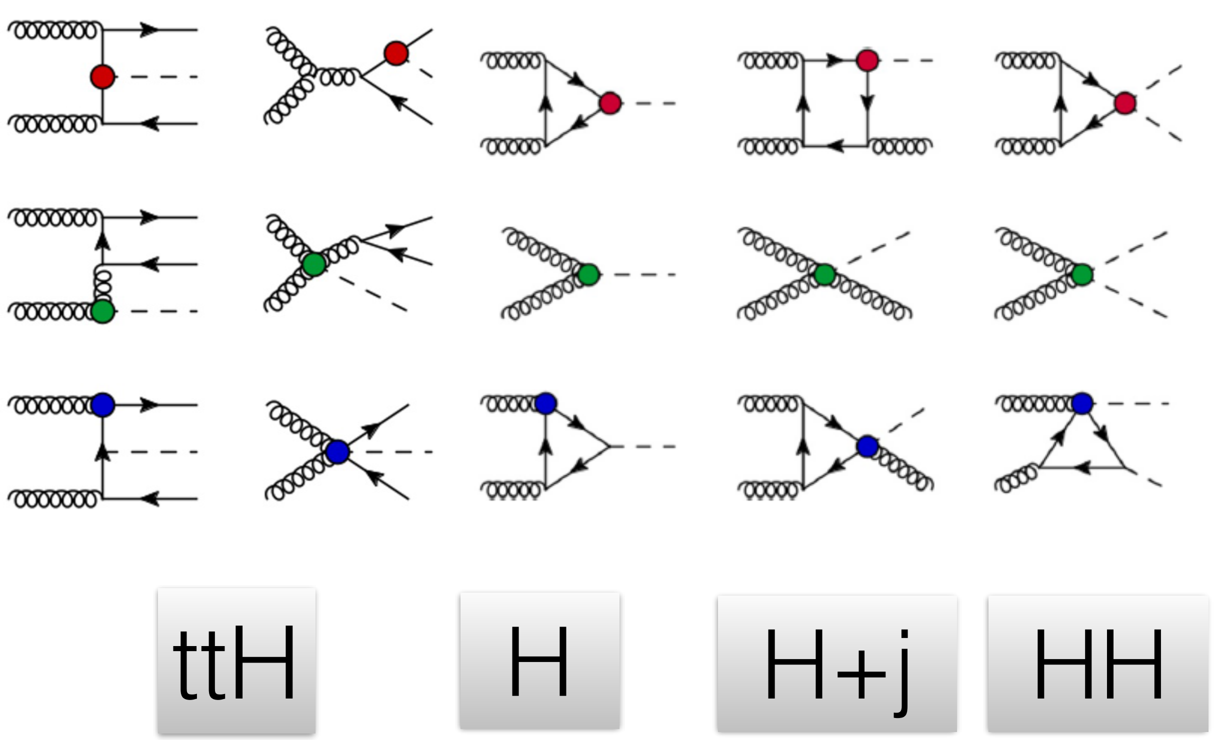
+ operators that do not feature a top, but contribute to the procs…

Top/Higgs operators and processes

Several operators typically enter each process at LO (or at LO^2) and

NLO (no	Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
✓	$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	1L^2		
✓	$pp \to tj$	N		L	L				L^2	L^2	1L		
✓	$pp \to tW$	L		L	L				L^2	L^2	1N	N	
✓	$pp \to t\bar{t}$	L									2L-4N	L	
✓	$pp \to t\bar{t}j$	L									2L-4N	L	
✓	$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
✓	$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
✓	$pp \to t\bar{t}W$	L								L	1L-2L		
✓	$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
✓	$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
✓	$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
✓	$pp \to t\bar{t}H$	L						L			2L-4L	L	L
✓	$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N
O ✓	$gg \to H$	L						L				N	L
O ✗	$gg \to Hj$	L						L				L	L
O ✗	$gg \to HH$	L						L				N	L
O ✗	$gg \to HZ$	L			L	L	L	L				N	L

Top/Higgs operators and processes



$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G_{\mu\nu}^A G^{A\mu\nu}$$

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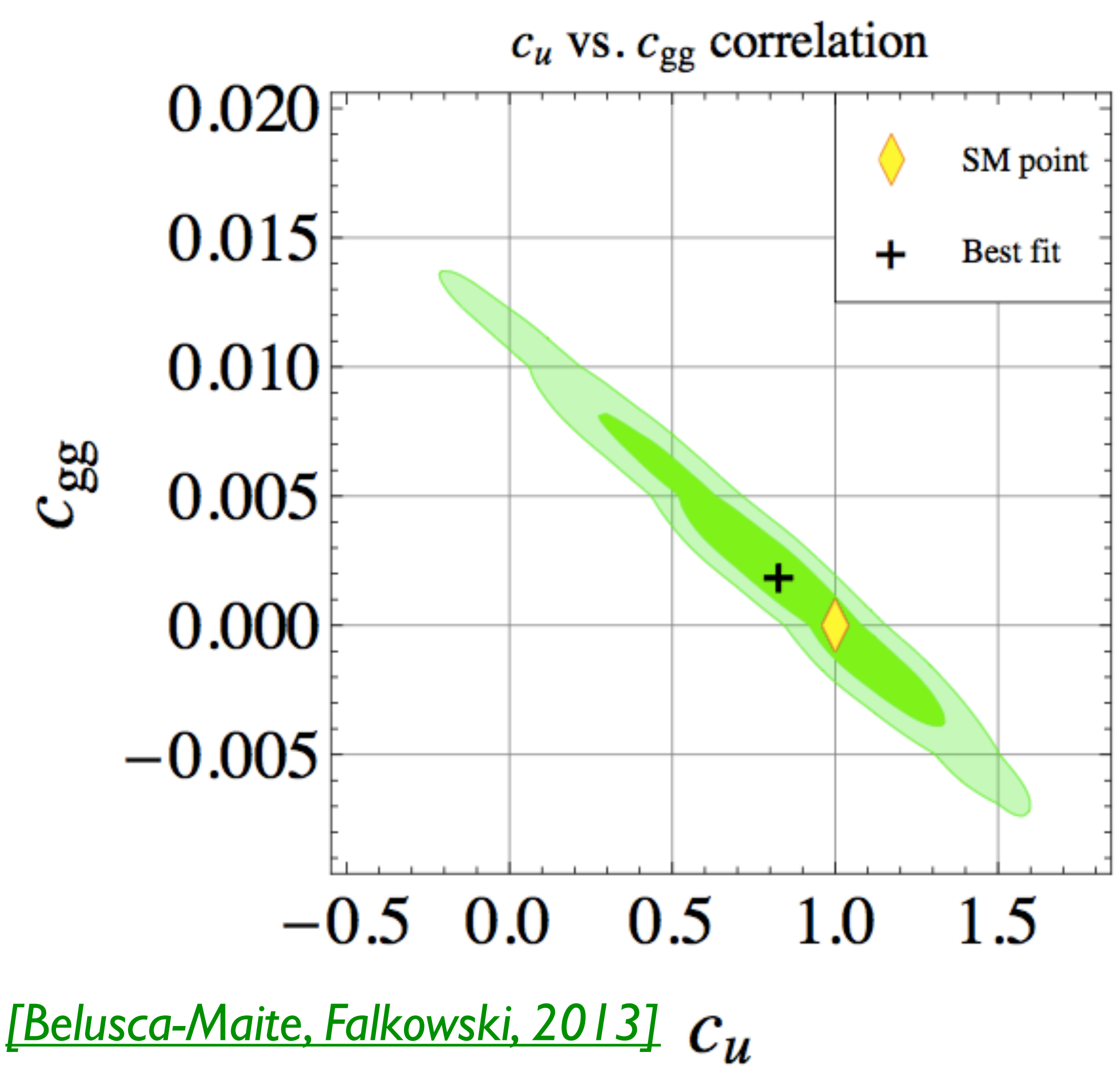
Top-Higgs interactions: constraints

From a global fit the coupling of the higgs to the top is poorly determined.

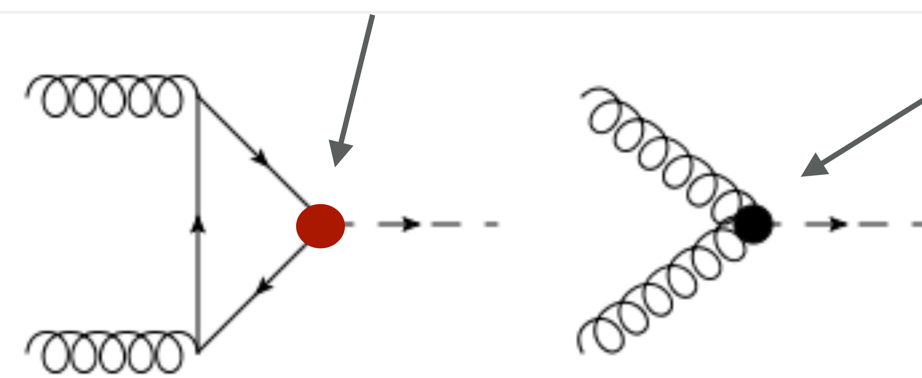
$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq \left|1+\frac{\hat{c}_{gg}}{c_{gg}^{\rm SM}}\right|^2$$

$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq 1+237 c_{gg}+2.06\delta y_u-0.06\delta y_d.$$



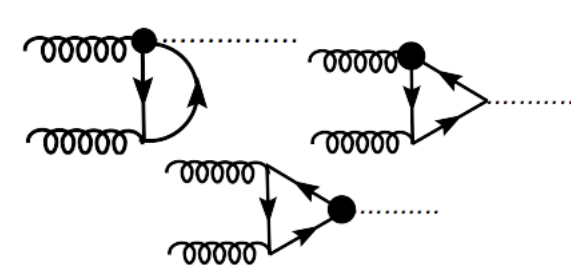
[Belusca-Maite, Falkowski, 2013]

$$\mathcal{O}_{Hy}=H^\dagger H\left(H\bar{Q}_L\right)t_R \qquad \mathcal{O}_{HG}=\frac{1}{2}H^\dagger H G^a_{\mu\nu}G_a^{\mu\nu}$$



the loop could still be dominated by np.

THE EFFECT OF THE CM OPERATOR NOT INCLUDED

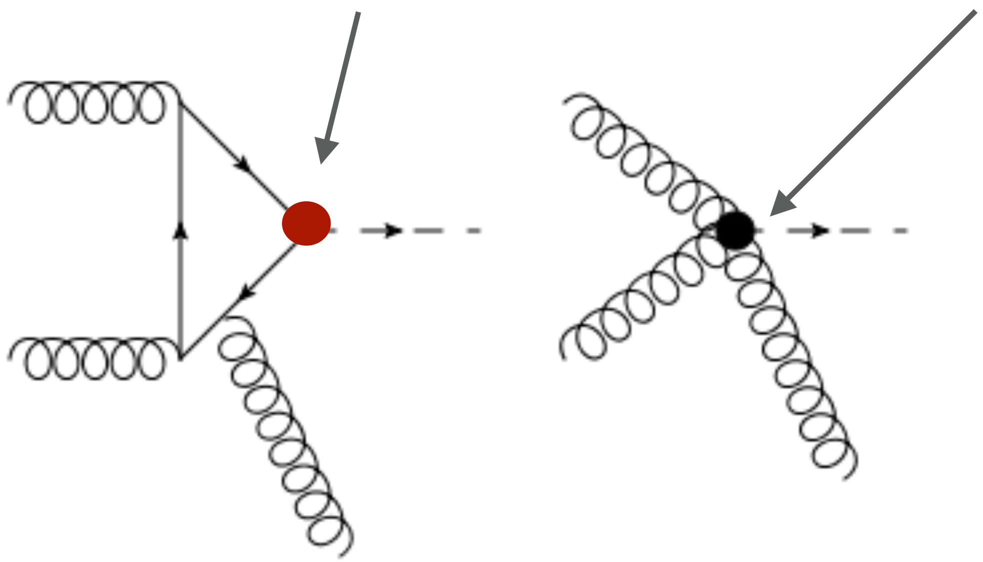


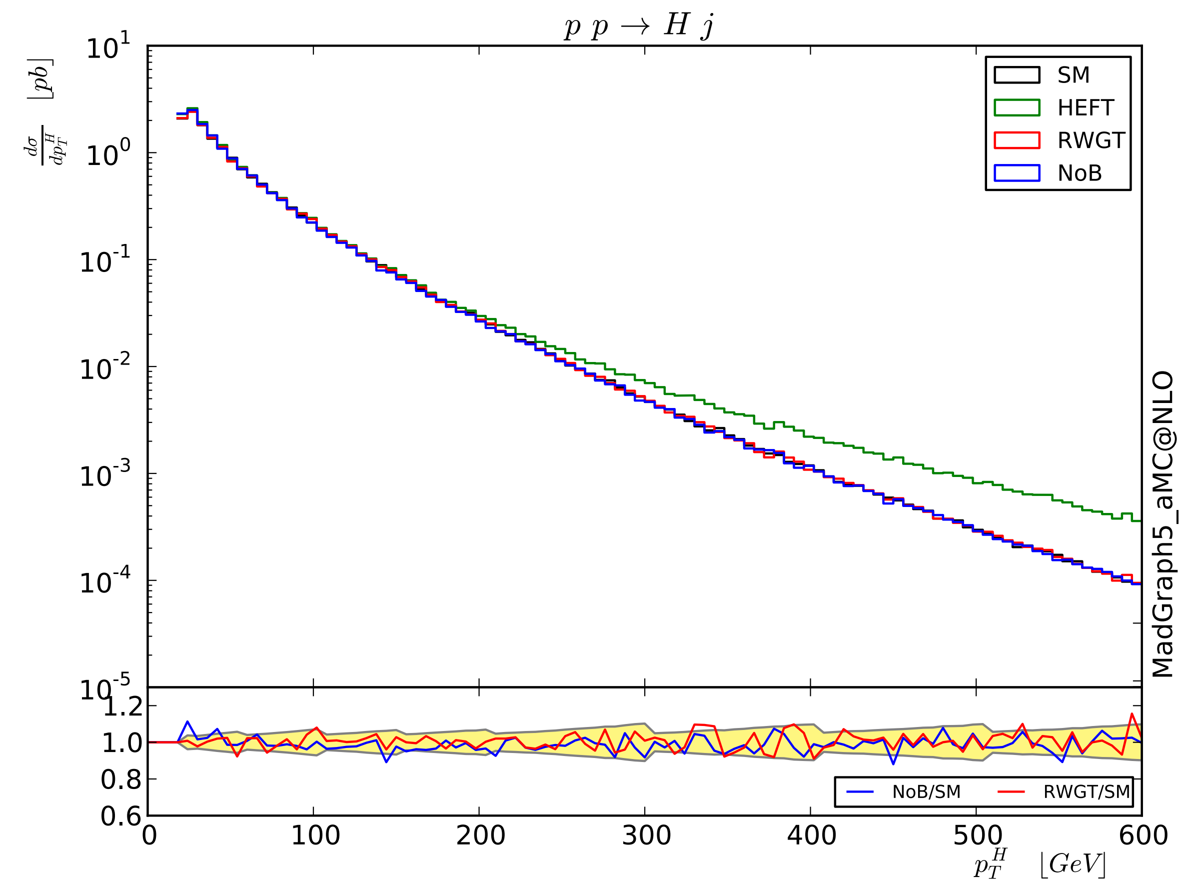
Top-Higgs interactions: high-pt

From a global fit the coupling of the higgs to the top is poorly determined: the loop could still be dominated by np.

[Grojean et al., 2013] [Banfi et al. 2014] [Buschmann, et al. 2014]

$$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$





EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy a precision.

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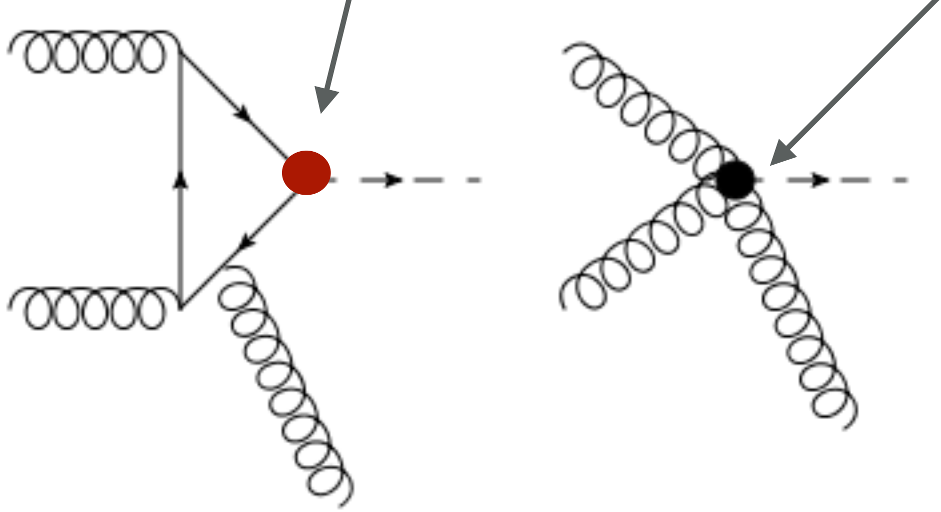
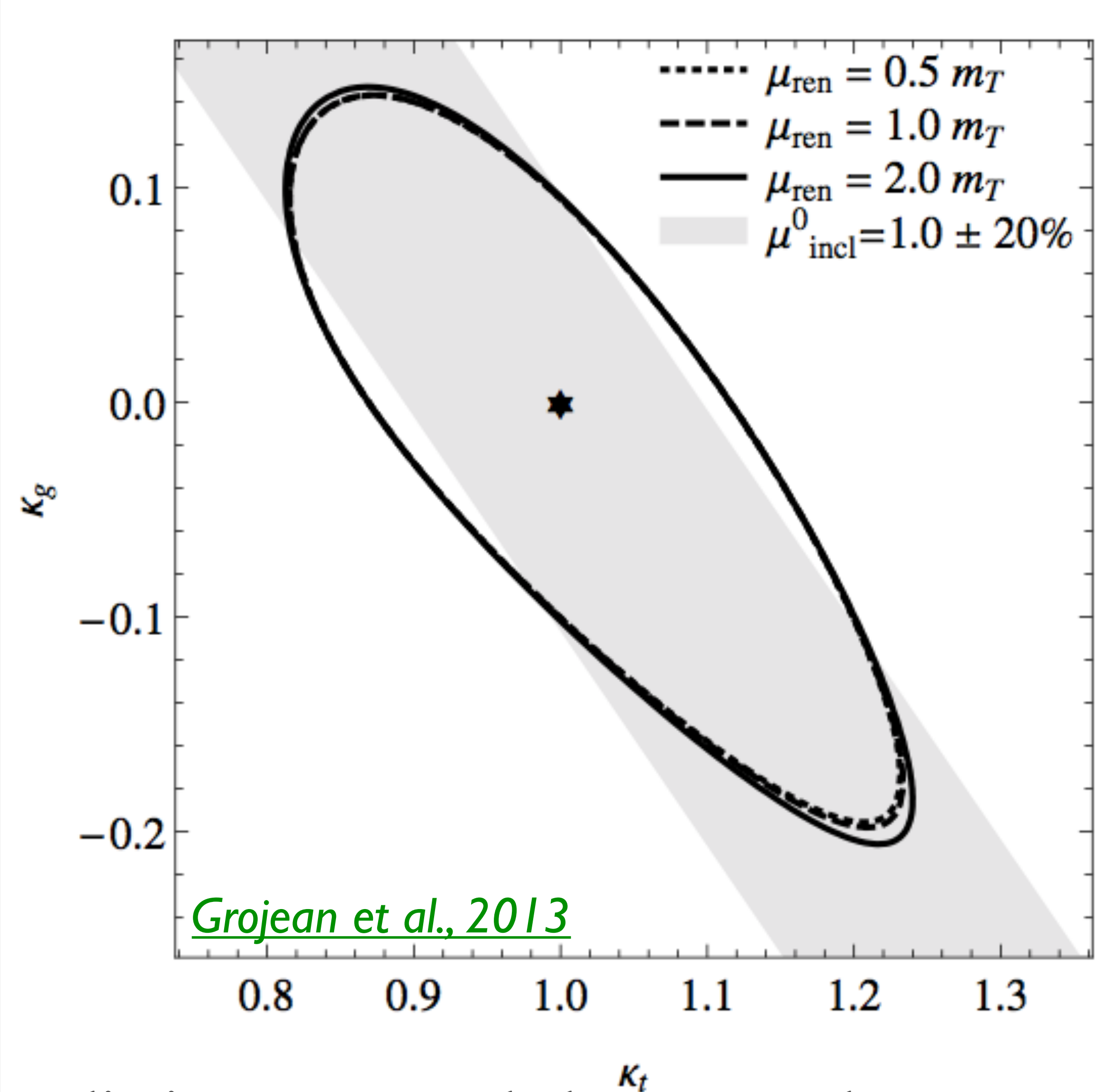
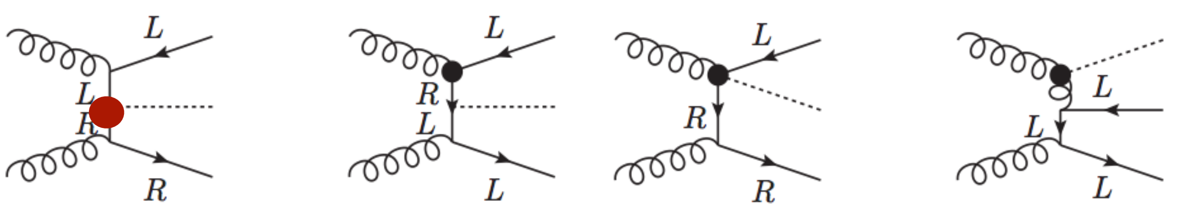


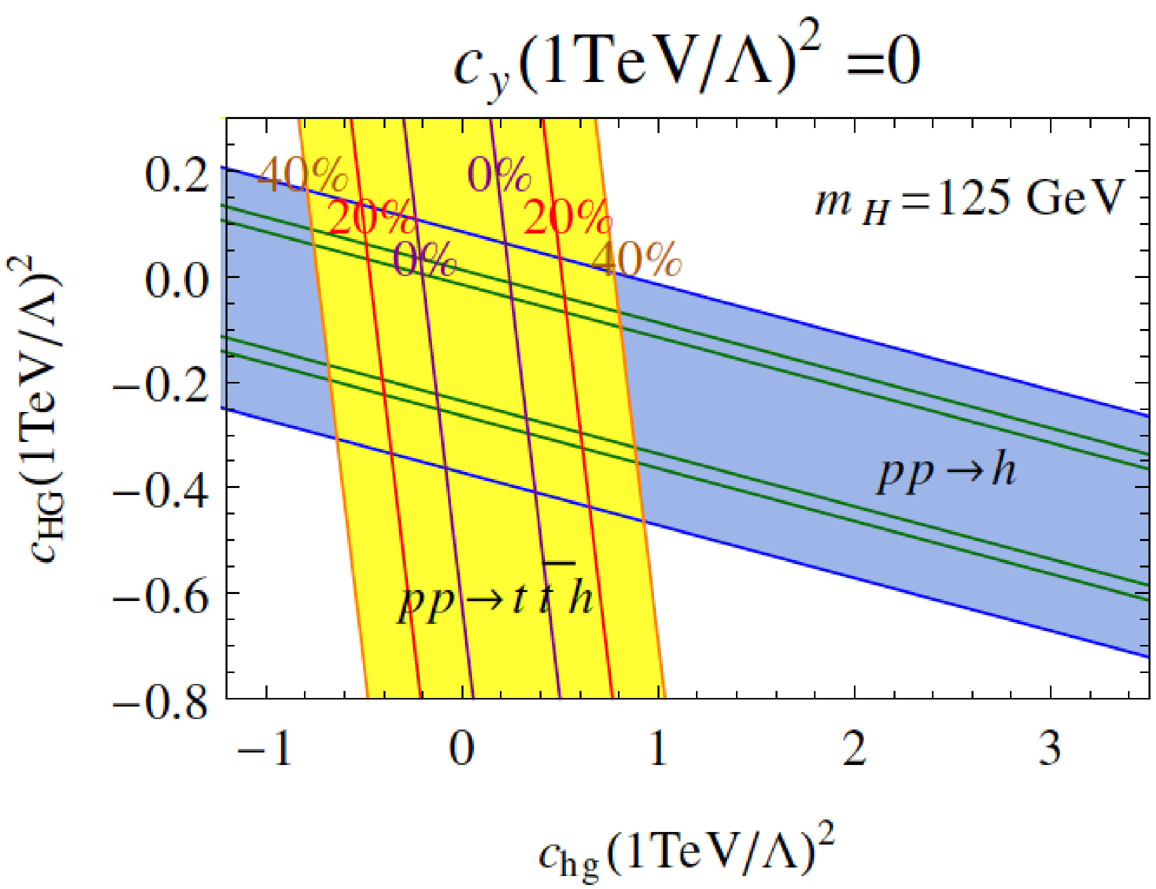


EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy and precision.

Top-Higgs interactions: ttH

[Degrande et al. 2012]





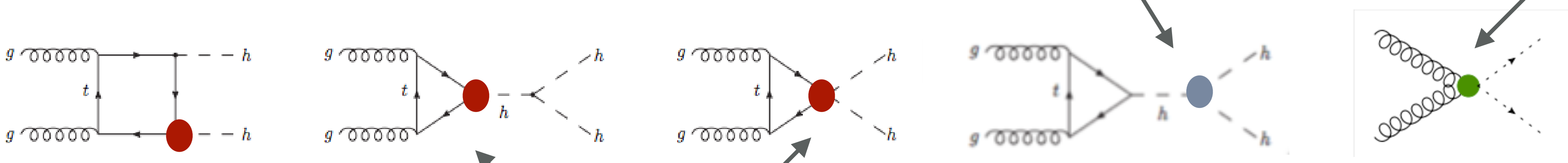
$$
\begin{aligned}
\frac{\sigma(pp\to t\bar{t}h)}{\mathrm{fb}} = {} & 611^{+92}_{-110} + \left[457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10} c_G\right. \\
& \left. + 147^{+55}_{-32} c_{HG} - 67^{+23}_{-16} c_y\right]\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \\
& + \left[543^{+143}_{-123}(\Re c_{hg})^2 + 1132^{+323}_{-232} c_G^2\right. \\
& + 85.5^{+73}_{-21} c_{HG}^2 + 2^{+0.7}_{-0.5} c_y^2 \\
& + 233^{+81}_{-144}\Re c_{hg} c_{HG} - 50^{+16}_{-14}\Re c_{hg} c_y \\
& \left. - 3.2^{+8}_{-8}\Re c_{Hy} c_{HG} - 1.2^{+8}_{-8} c_H c_{HG}\right]\left(\frac{\mathrm{TeV}}{\Lambda}\right)^4
\end{aligned}
$$

Top-Higgs interactions: HH

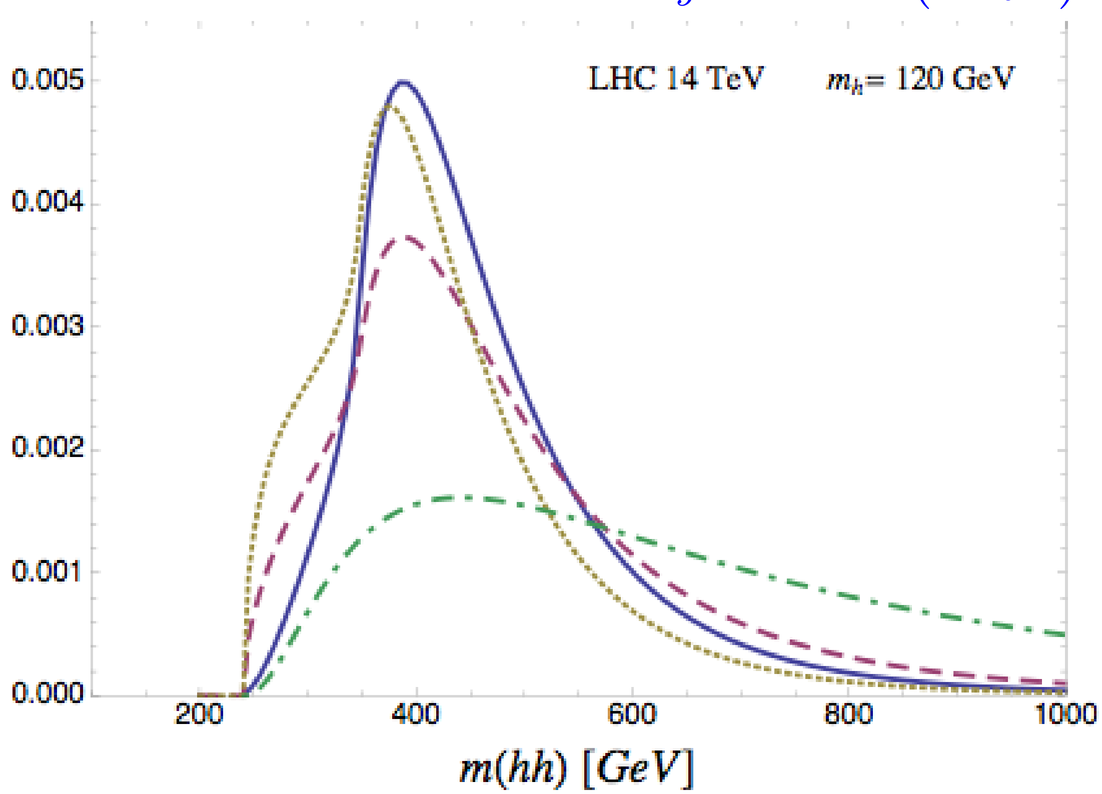
$pp \to hh$

$\mathcal{O}_6 = (H^\dagger H)^3$

$\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$



$\mathcal{O}_{Hy} = H^\dagger H \left(H \bar{Q}_L \right) t_R$



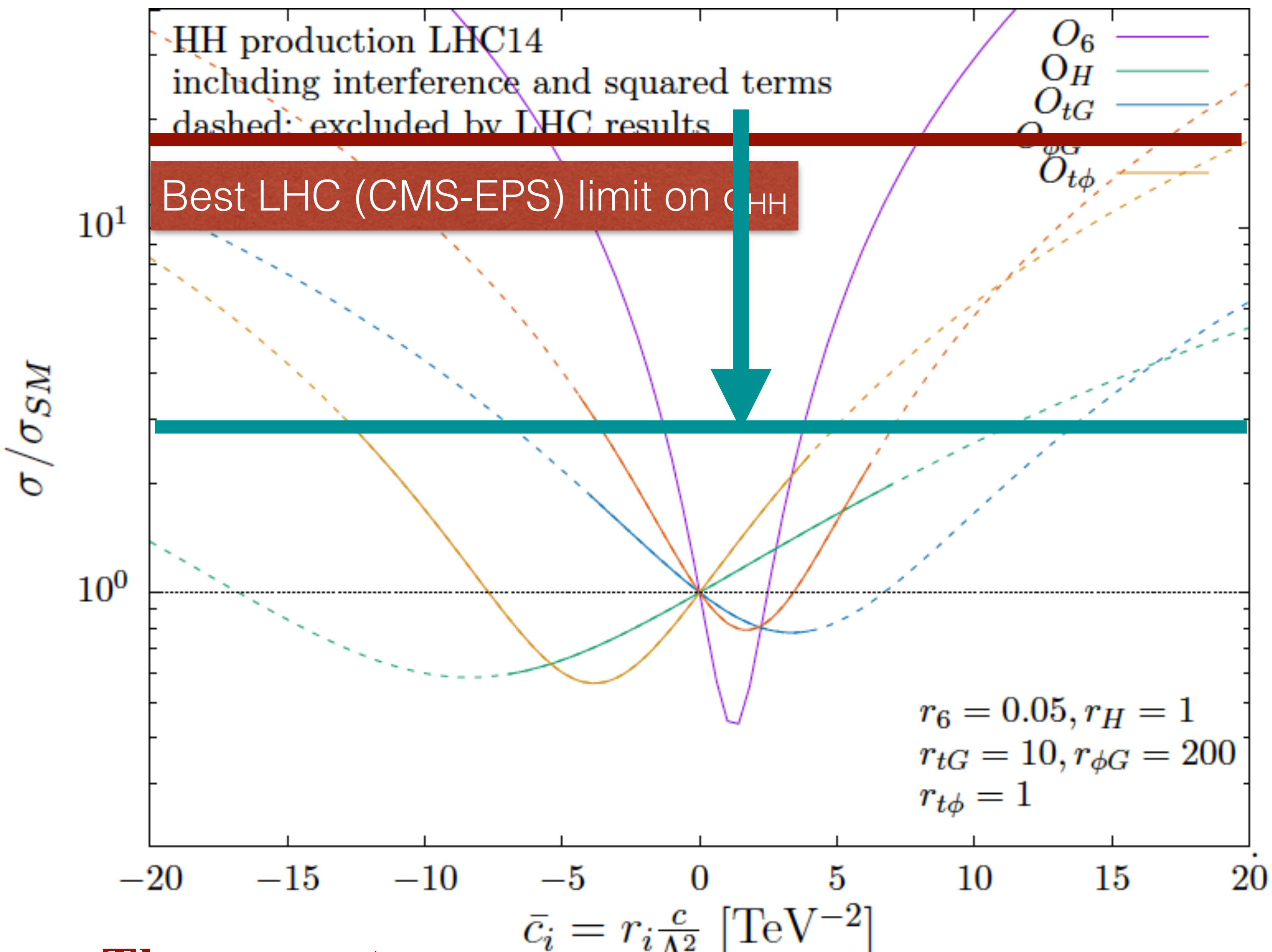
[Contino et al. 2012]

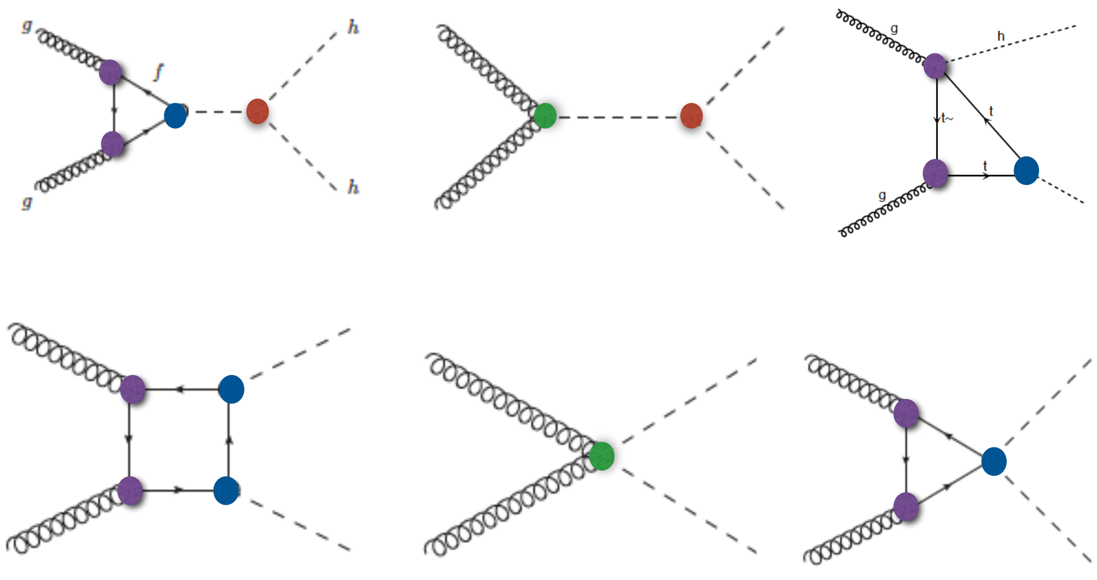
The strong destructive interference gives extra sensitivity of pp→HH to dim=6 operators.

The HHH coupling is modified by two operators of dim=6.

Only a global approach will allow to accurately measure the HHH coupling from HH.

How to extract λ_{HHH} from HH?





Other couplings enter in the same process: top Yukawa, ggh(h) coupling, top-gluon interaction

The present

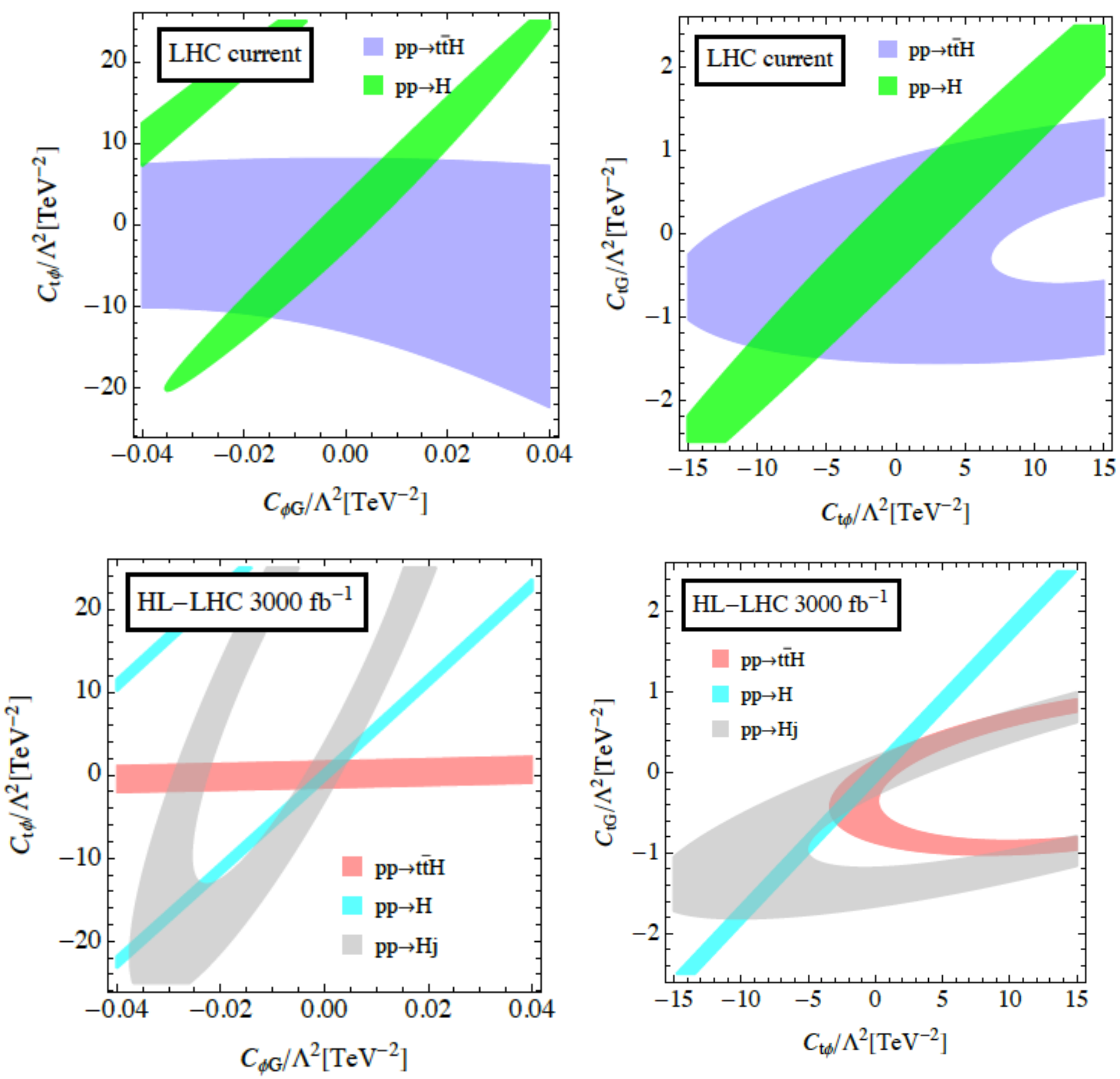
Given the current constraints on σ(HH), σ(H) and the fresh ttH measurement, the Higgs self-coupling can be currently constrained “ignoring” other couplings

The future

Precise knowledge of other Wilson coefficients will be needed to bound λ as the bound gets closer to SM. Differential distributions will also be necessary

Constraints from ttH and Higgs production

[FM, Vryonidou, Zhang, 16]



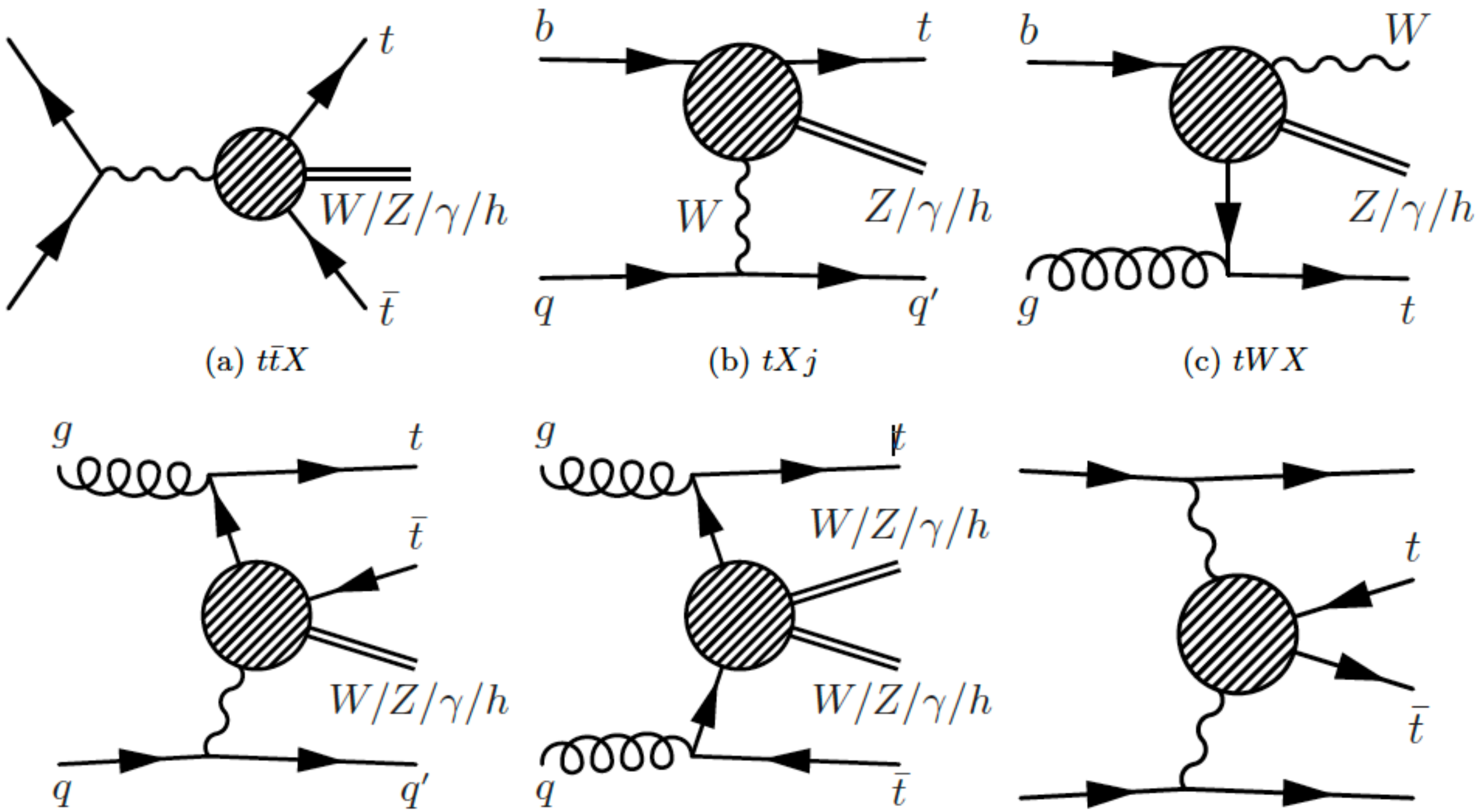
Current limits using LHC measurements

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right) (\bar{Q}t)\,\tilde{\phi}$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

14TeV projection

3000 fb-1

EW/Higgs top couplings sensitivity



(a) $t\bar{t}X$ (b) tXj (c) tWX

(d) $t\bar{t}Xj$ (e) $t\bar{t}XY$ (f) VBF

See work at e+e- : [Durieux et al. 2018] [Durieux, Matsedonsky, 2018] [Riva, Grojean et al., 2018] wip.

Energy growths

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	–	–	–	–	–	–

Energy growths

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

Energy-growing interference

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	–	–	–

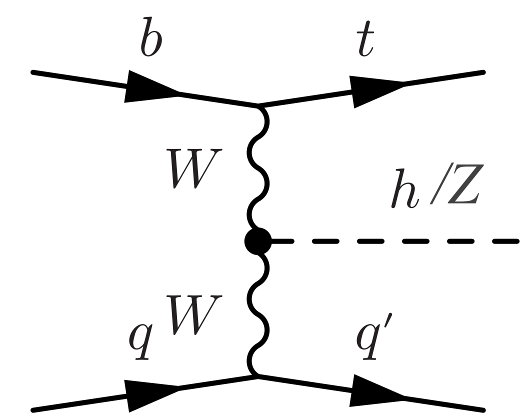
two-top w/ Higgs

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

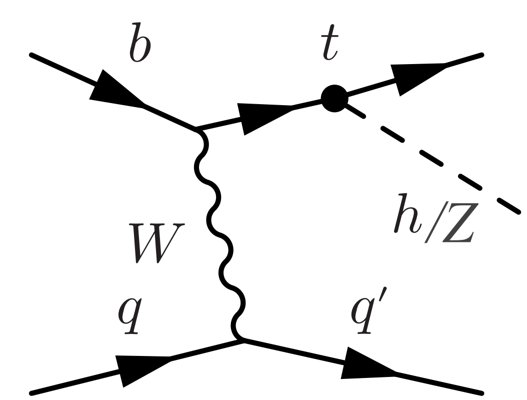
- Interfering growth rare, only in longitudinal configurations (c.f. helicity selection)

Example: tZj/tHj

- Single top rate about 1/4 of QCD tt
- Purely EW processes => no QCD contribution
- Sensitive to 2 four-fermion and 3 top/EW operators that modify tbW vertex

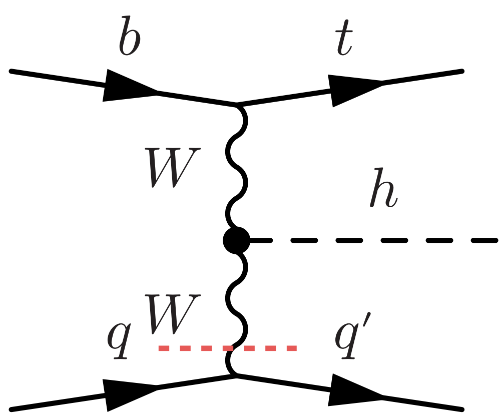


- Requiring the presence of an additional Z or Higgs
  - Unique possibility of probing full set of top/Higgs/EW operators at once
  - Higher thresholds may enhance EFT effects
  - Recent LHC measurement of tZj cross section at 4.2σ



Example: tZj/tHj

tHj (tZj = h→Z) : classes of operators

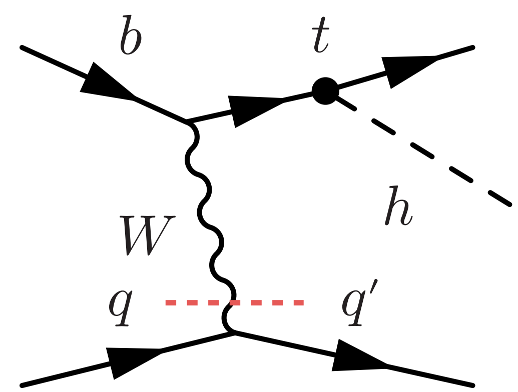


$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi \, W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

$\mathcal{O}_W \; : \; \epsilon^{ijk} W_{i,\,\mu\nu} W_j^{\nu\rho} W^{\mu}_{k,\,\rho}$

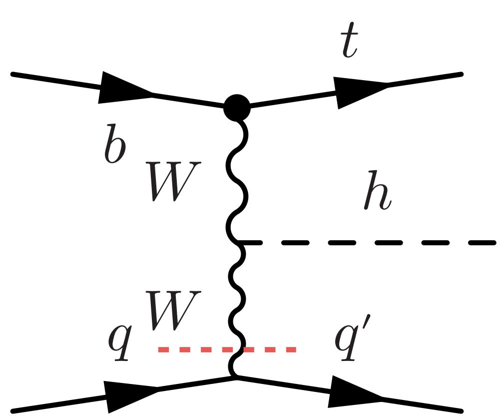


$\mathcal{O}_{t\varphi} \; : \; (\varphi^\dagger \varphi)\,(\bar{Q}\,t)\,\tilde{\varphi}$

top Yukawa

ttZ coupling

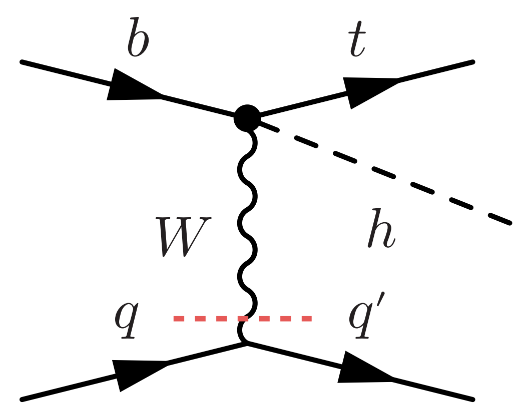
$\mathcal{O}_{\varphi t} : i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$



$\mathcal{O}^{(3)}_{\varphi Q} : i(\varphi^\dagger \overleftrightarrow{D}^i_\mu \varphi)(\bar{Q}\gamma^\mu \sigma_i Q)$

Wtb vertex

$\mathcal{O}_{\varphi tb} : i(\tilde{\varphi}\, D_\mu \varphi)(\bar{b}\gamma^\mu t)$

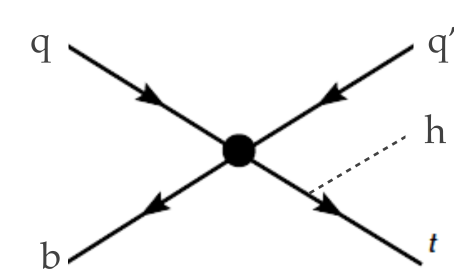


$\mathcal{O}^{(3)}_{\varphi Q} : i(\varphi^\dagger \overleftrightarrow{D}^i_\mu \varphi)(\bar{Q}\gamma^\mu \sigma_i Q)$

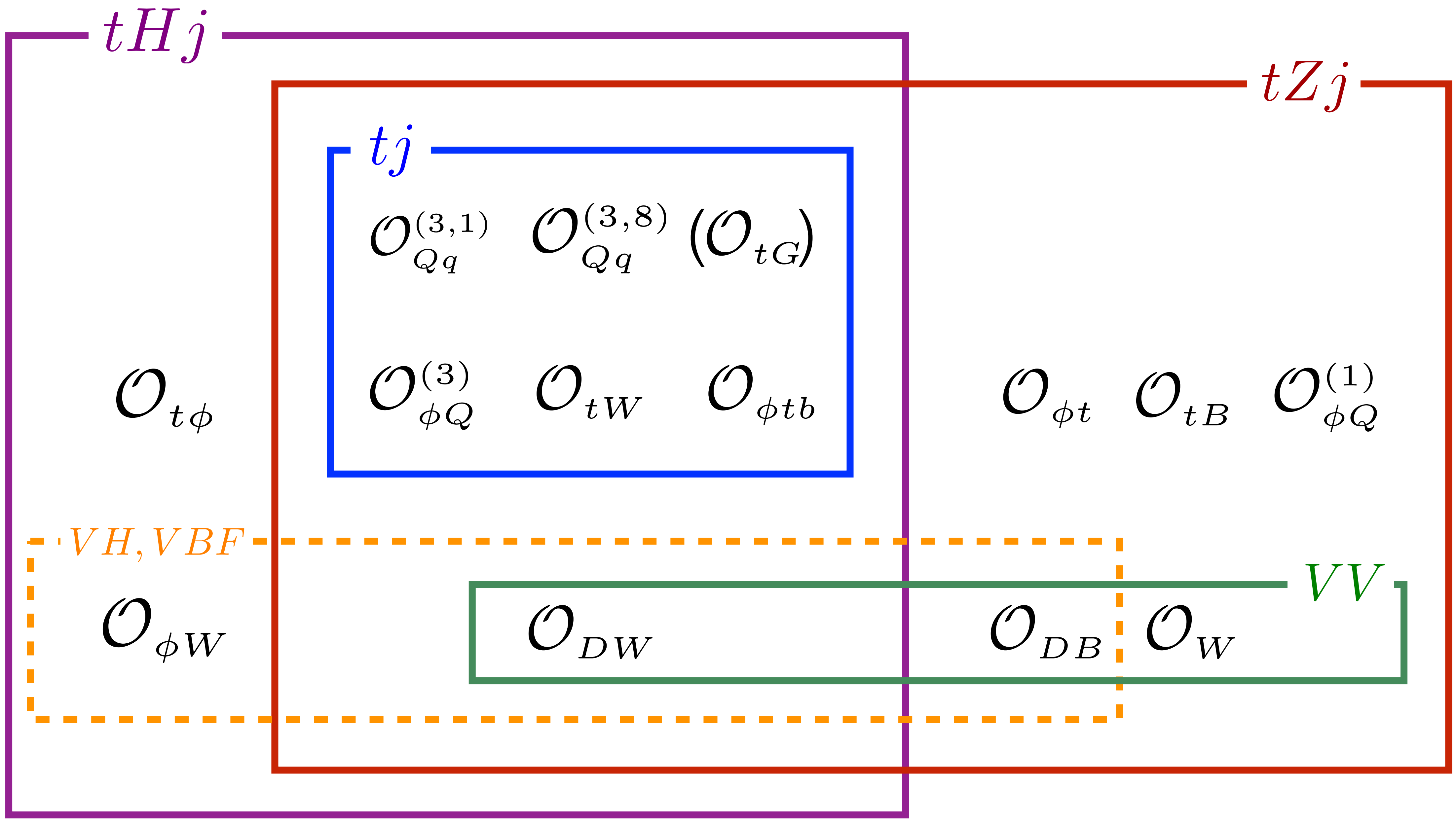
Contact terms

$\mathcal{O}_{tB} \; : \; (\bar{Q}\,\sigma_{\mu\nu}\,t)\,\tilde{\varphi}\,B^{\mu\nu}$

- Accessing the bW→tH & bW→tZ sub-amplitudes
  - Rich interplay between EFT operators from different sectors
  - Different energy growth and interference with the SM
  - Four fermion interactions also present

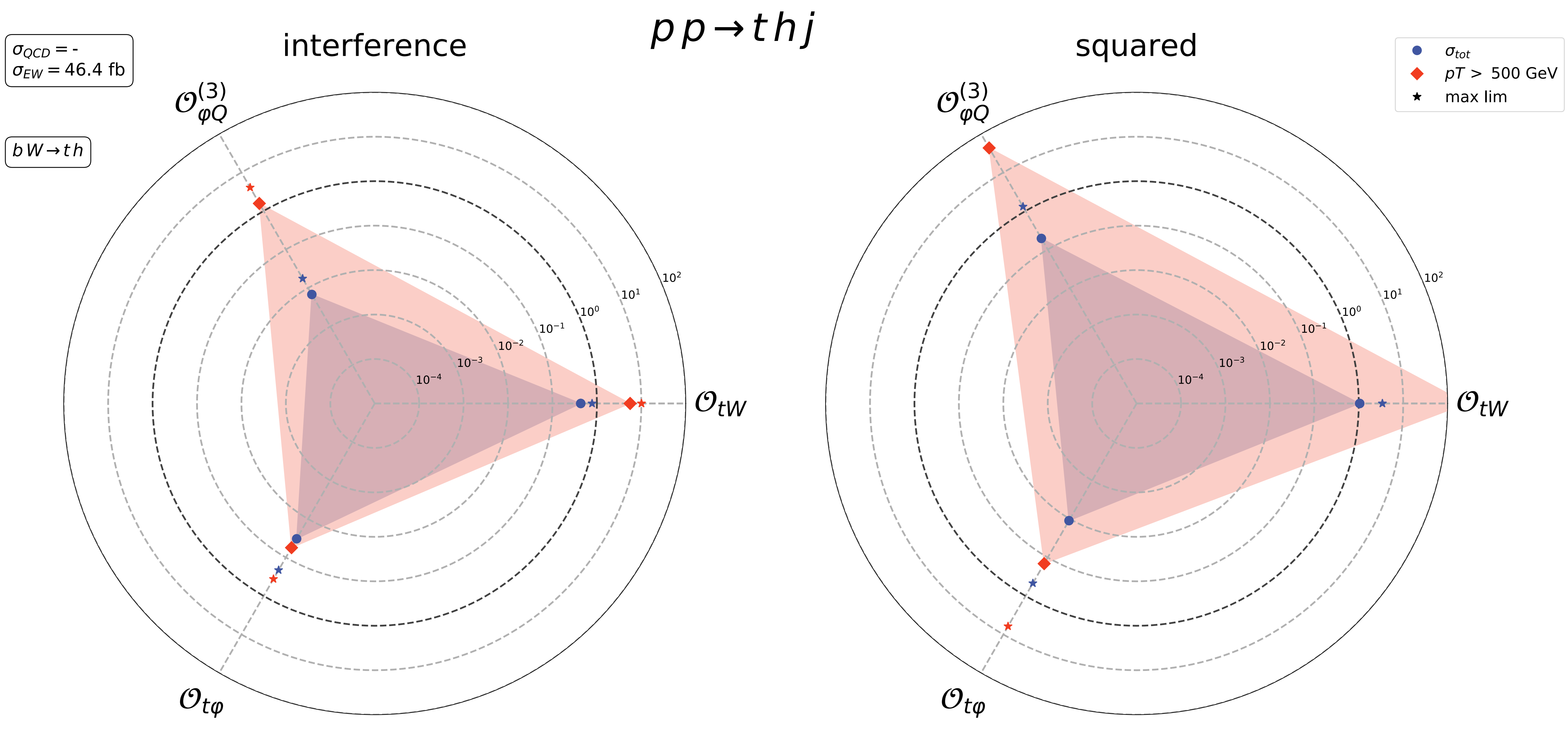


Example: tZj/tHj

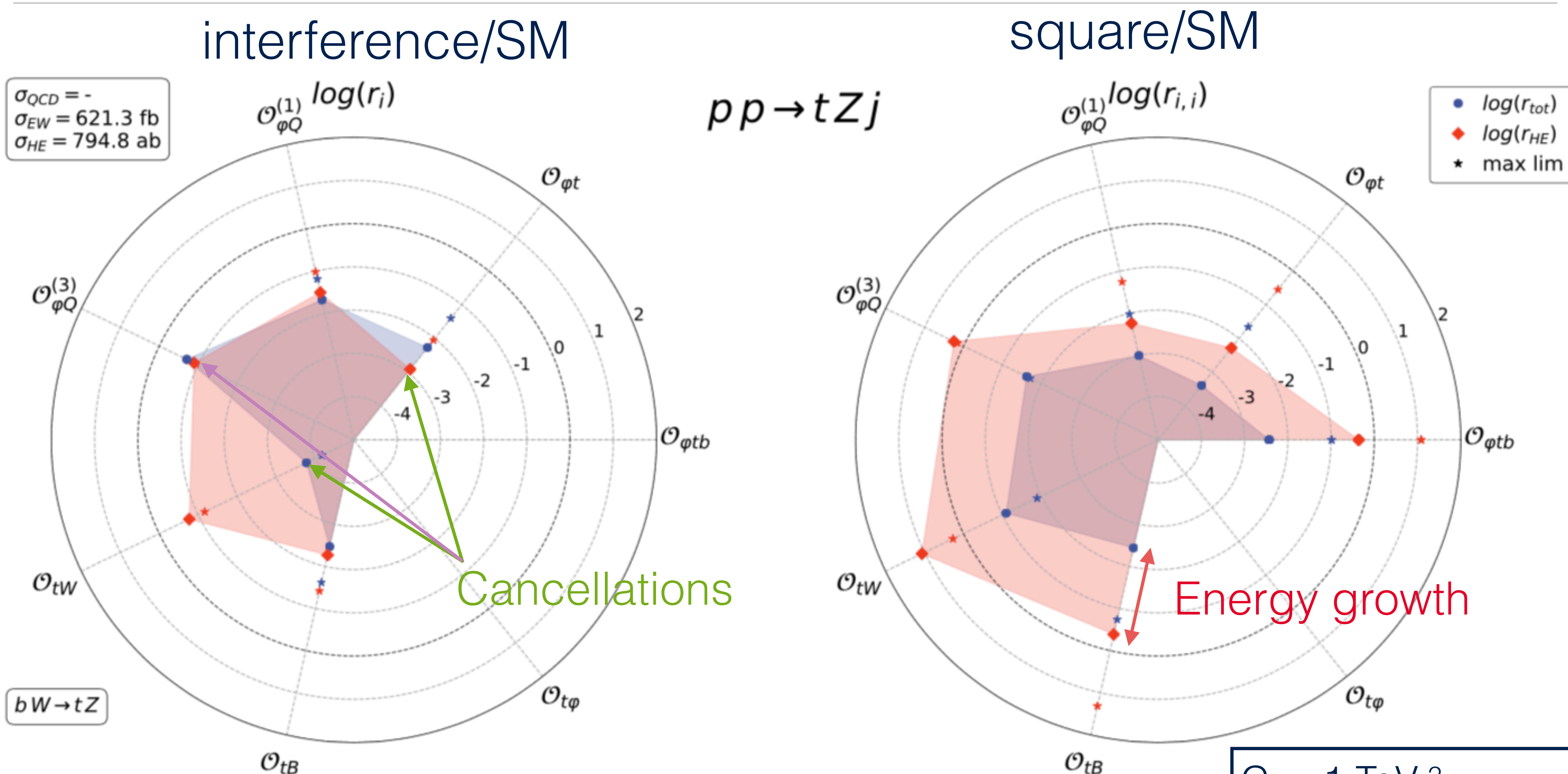


tHj

[FM, Mantani, Mimasu, 2018]



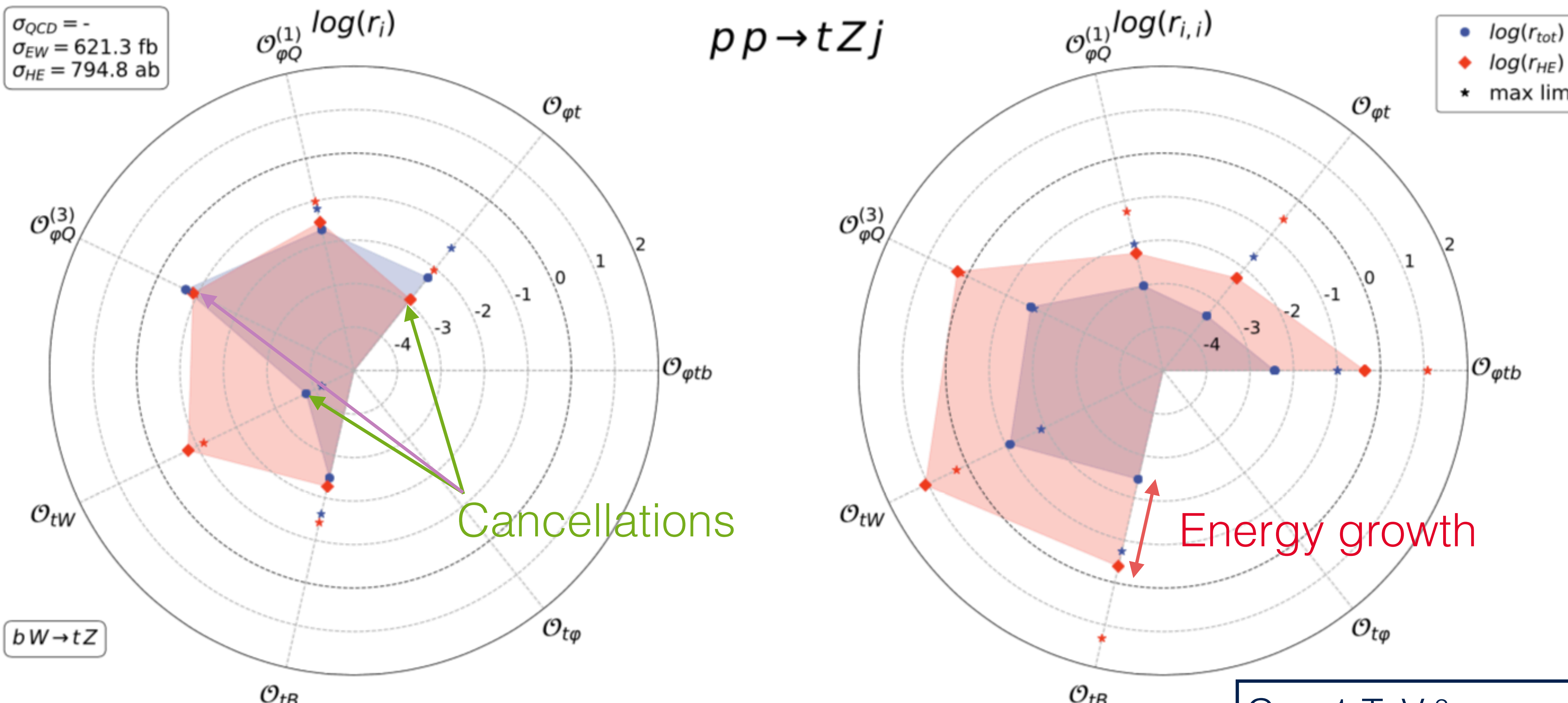
tZj



C_i = 1 TeV^{-2}
Inclusive
p_T (Z)> 500 GeV

tZj

interference/SM | square/SM

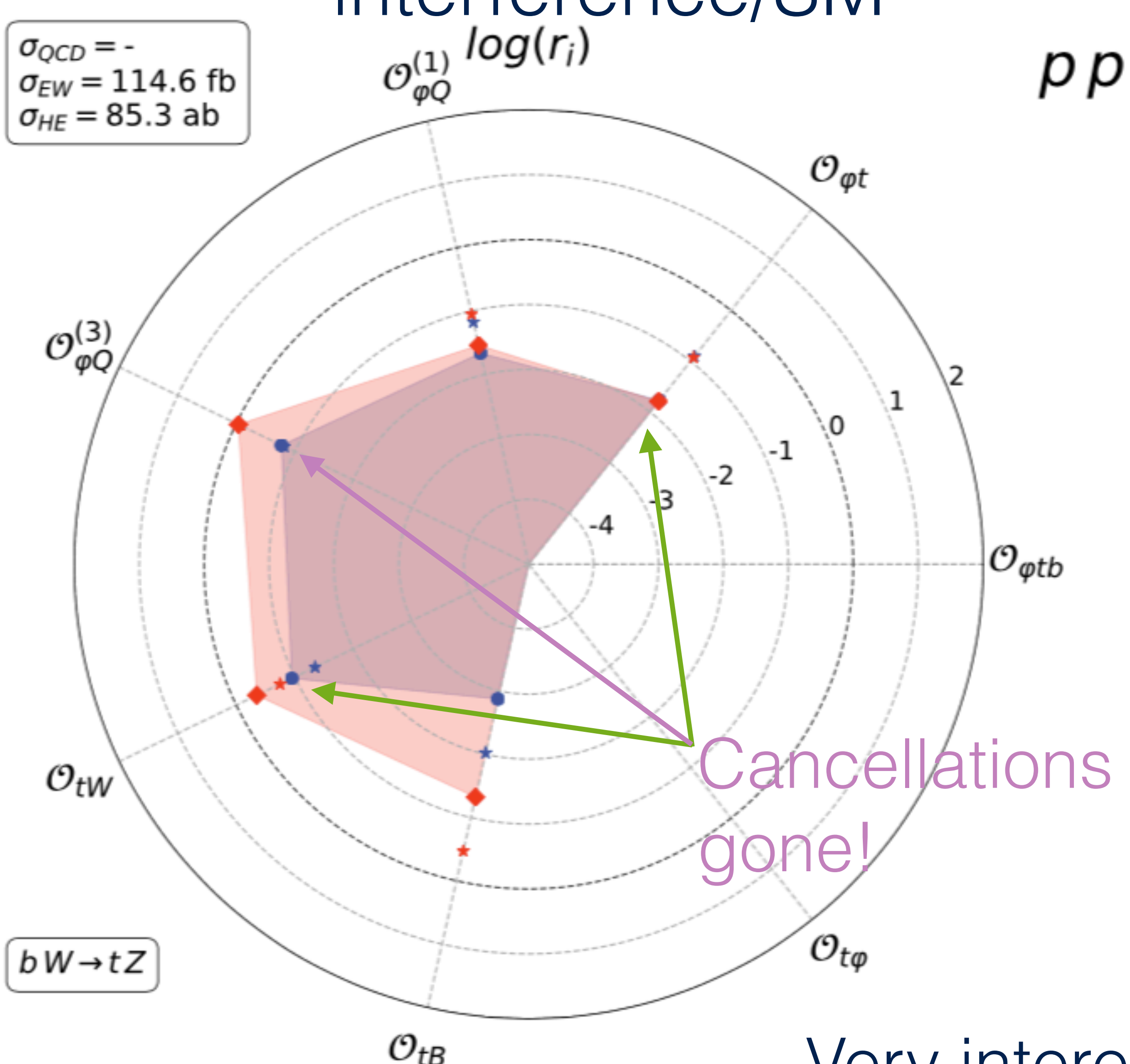


C_i = 1 TeV^{-2}
Inclusive
p_T (Z)> 500 GeV

Expected growth from 2→2 absent!

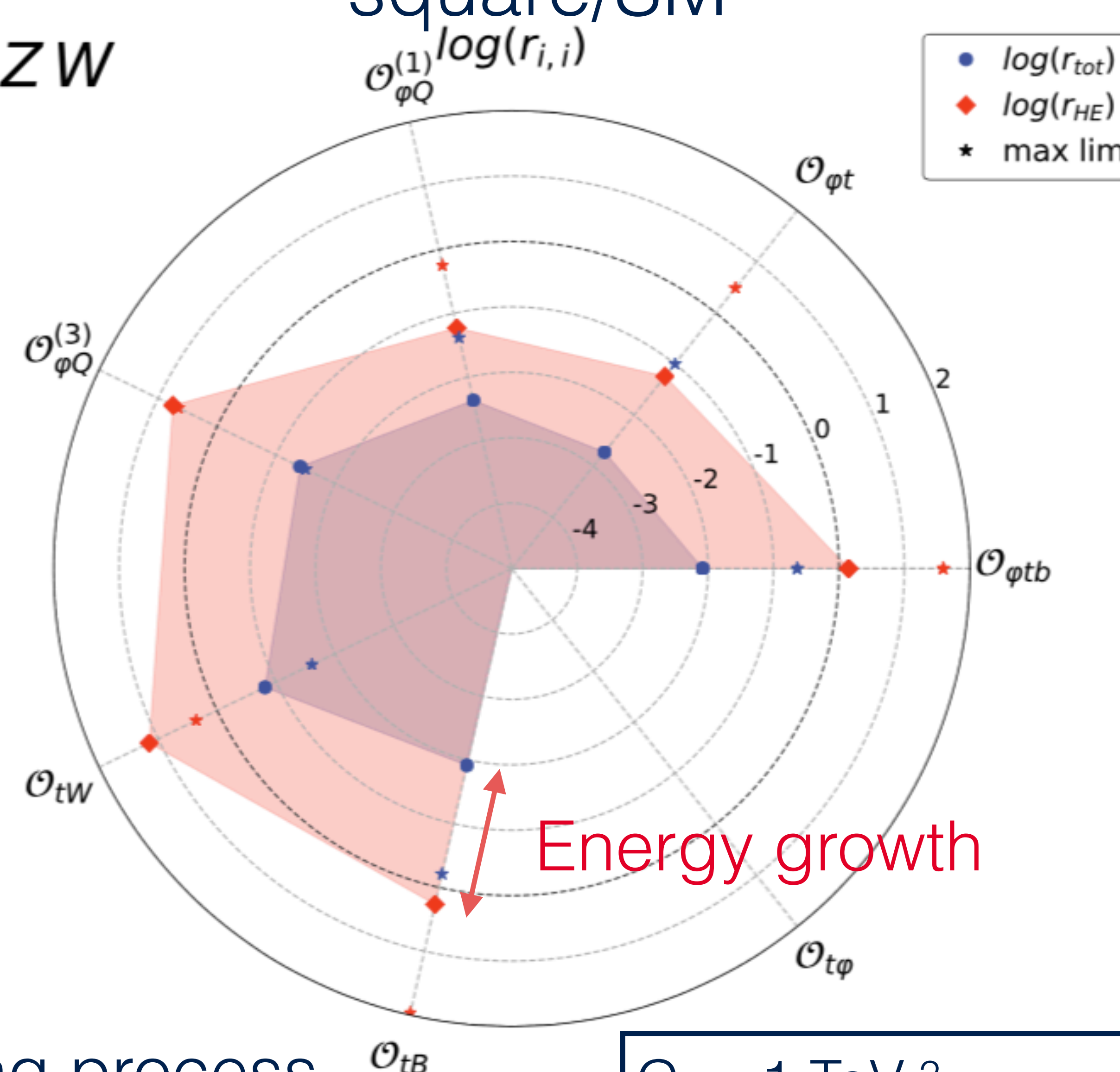
tZW

interference/SM



$pp \to tZW$

square/SM



Expected growth is there!

Very interesting process that should be measured at the LHC

C_i = 1 TeV^{-2}
Inclusive
p_T (W,Z)> 500 GeV

Plan for today's lecture

- SMEFT essentials
- The SMEFT precision frontier
- Example: Fitting in the Top (with Higgs/EW) sector
- Bringing the lesson home

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Need for NLO

1. **Operators run and mix under RGE**

2. **EFT scale dependence**

3. **Genuine NLO corrections (finite terms) are important**

4. **New operators arise**

Need for NLO

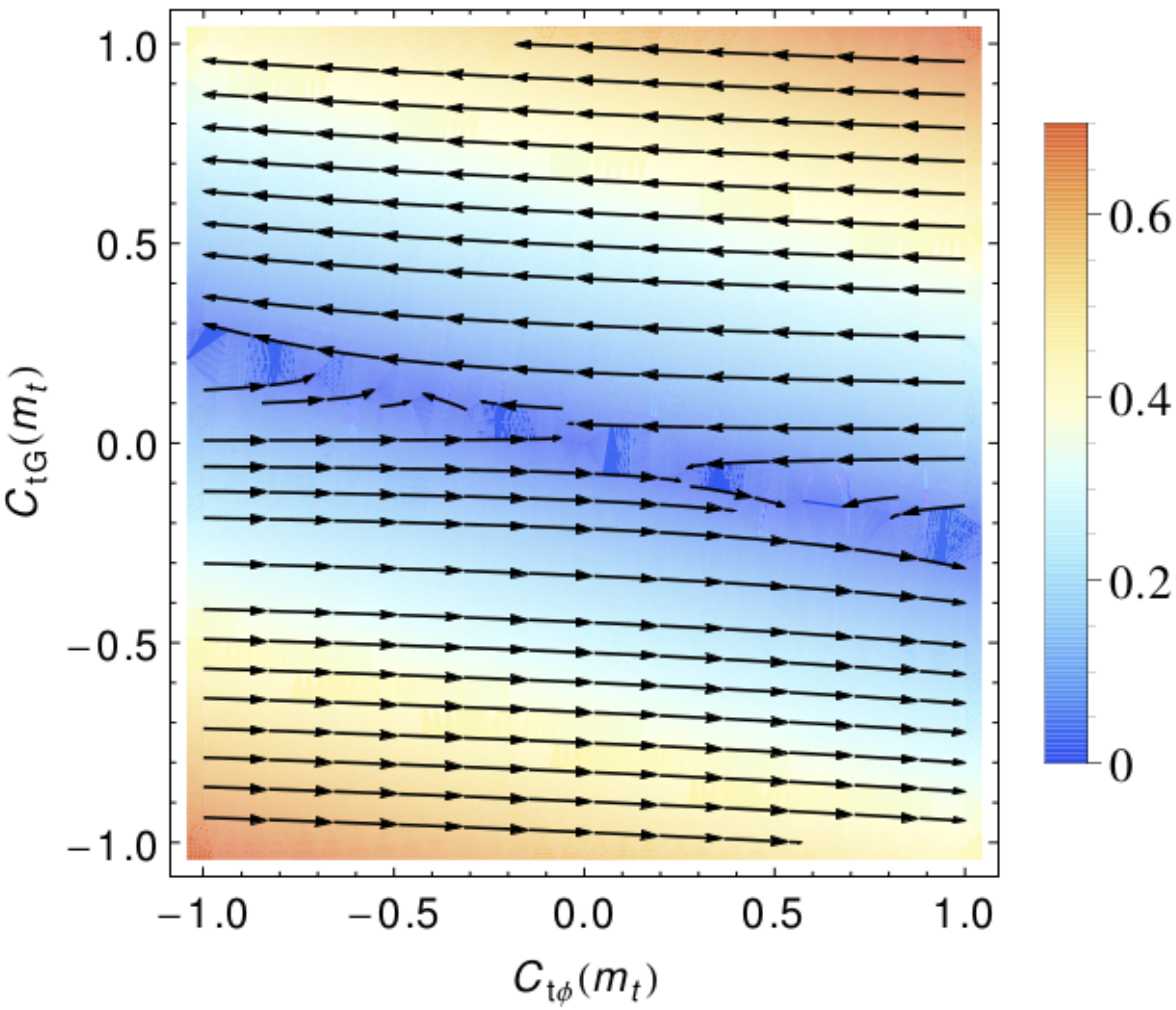
1. Operators run and mix under RGE

Running means that the Wilson coefficients depend on the scale where they are measured (as the couplings in the SM). Note that this introduces also an additional uncertainty in the perturbative computations.

Mixing means that in general the Wilson coefficients at low scale (=where the measurements happen) are related. One immediate consequence is that assumptions about some coefficients being zero at low scales are in general not valid (and in any case have to be consistent with the RGEs). Note also that operator mixing is not symmetric: Op1 can mix into Op2, but not viceversa.

Need for NLO

1. Operators run and mix under RGE



Scale corresponds to the change from mt to 2 TeV.

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}\,,$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu}G^{A\mu\nu}\,,$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}\,.$$

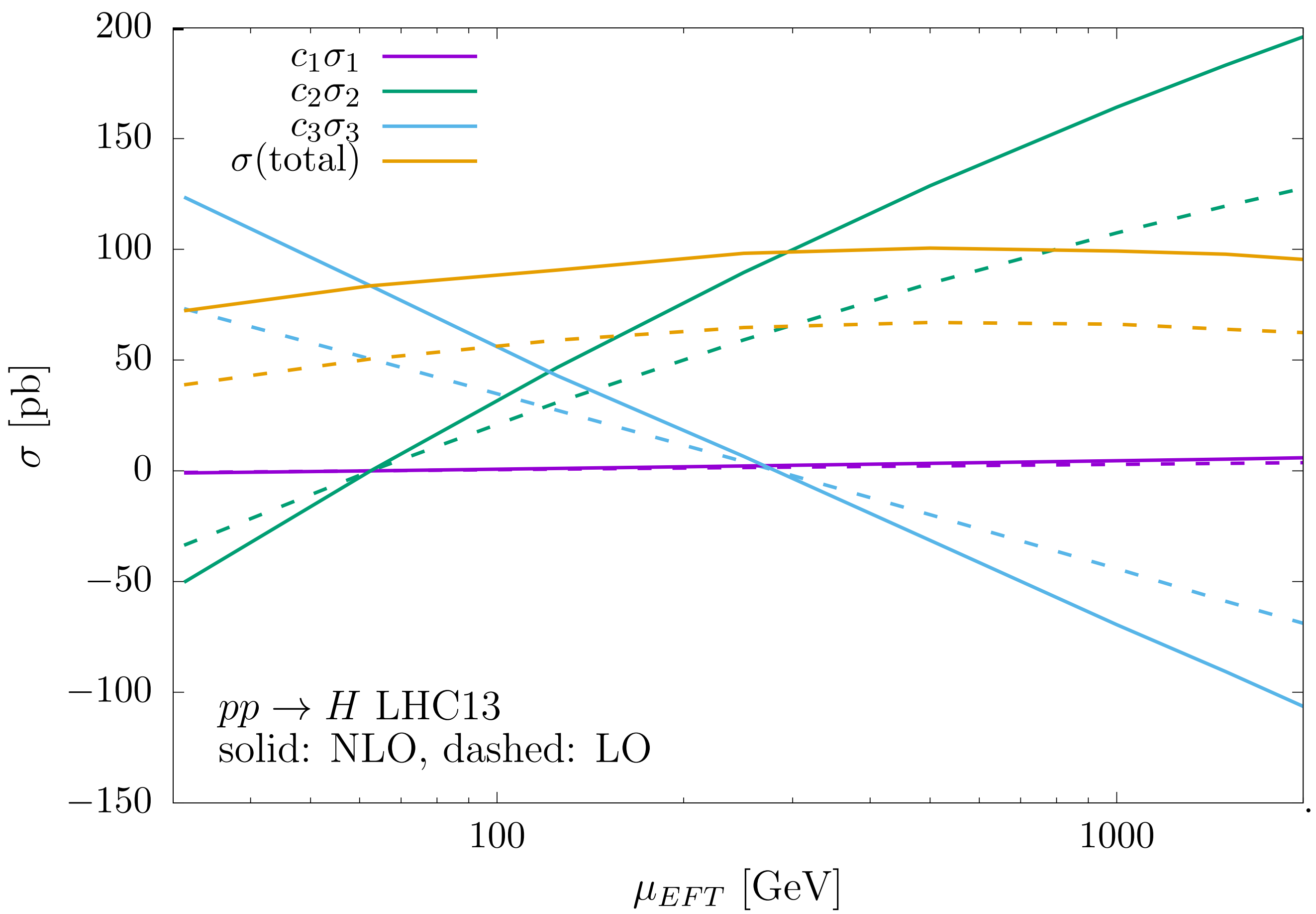
$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij}C_j(\mu), \quad \gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

At = 1 TeV: $C_{tG} = 1$, $C_{t\varphi} = 0$;

At = 173 GeV: $C_{tG} = 0.98$, $C_{t\varphi} = 0.45$

Need for NLO

2. EFT scale dependence



$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}\,,$$

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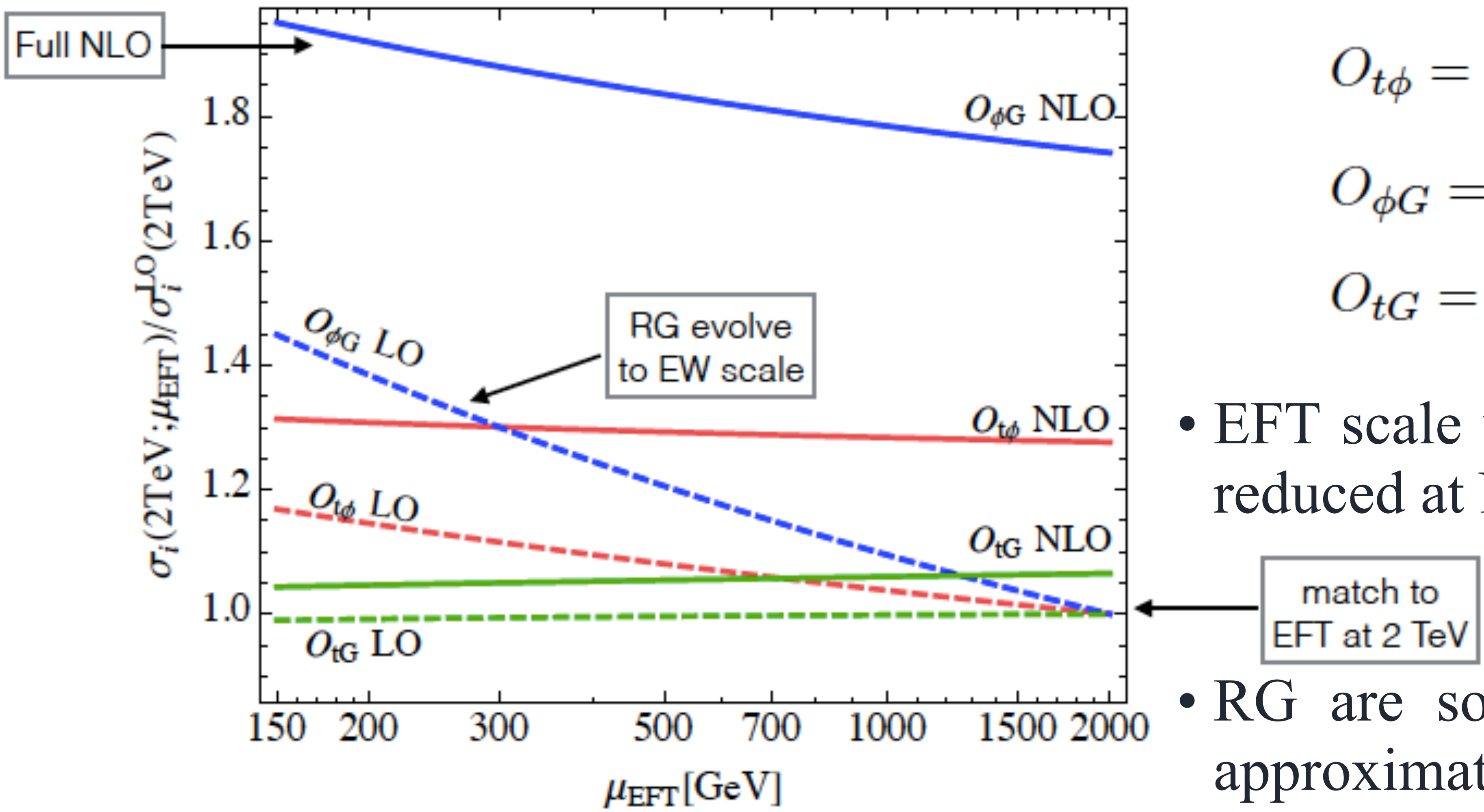
By including the mixing, the overall scale dependence at LO, is very much reduced with respect to the single ones. A global point of view is required: contribution from each coupling may not make sense; only their sum is meaningful.

Need for NLO

3. Genuine NLO corrections (finite terms) are important



- pp → ttH

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}\,,$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}\,.$$

- EFT scale uncertainties are very much reduced at NLO.
- RG are sometimes thought to be an approximation for full NLO, but it is often not the case.

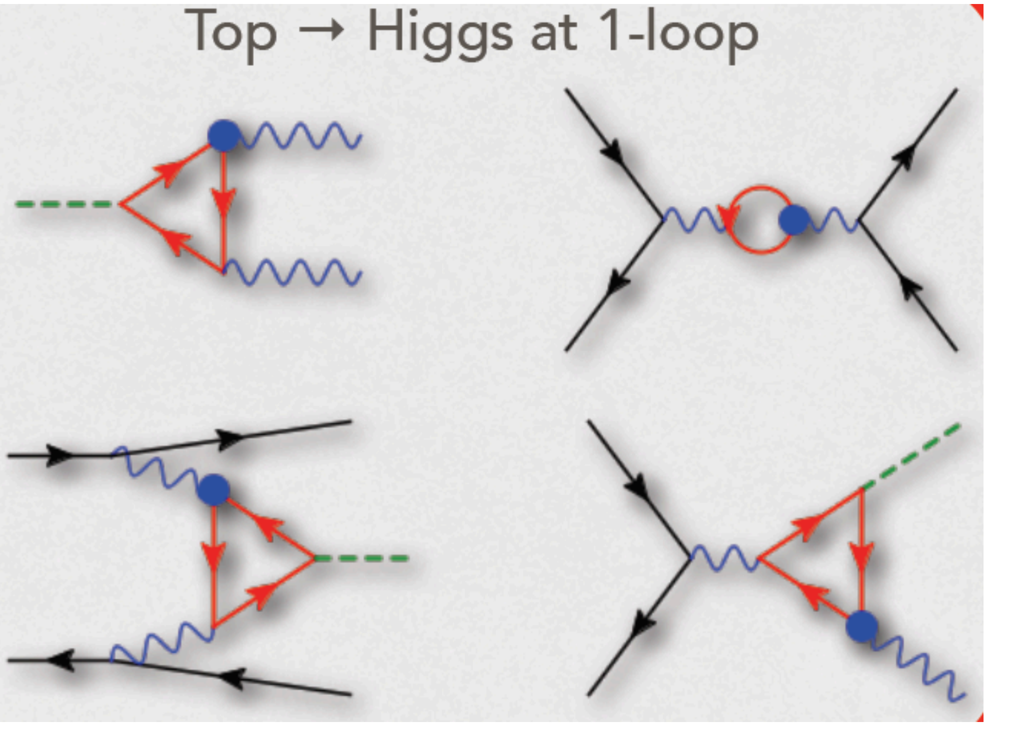
Need for NLO

4. New operators arise

[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15a]
[Hartmann and Trott, 15]
[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15b]
[Dawson, Giardino, 2018, 2019]
[Dedes et al, 2018]
[Vryonidou and Zhang, 2018]

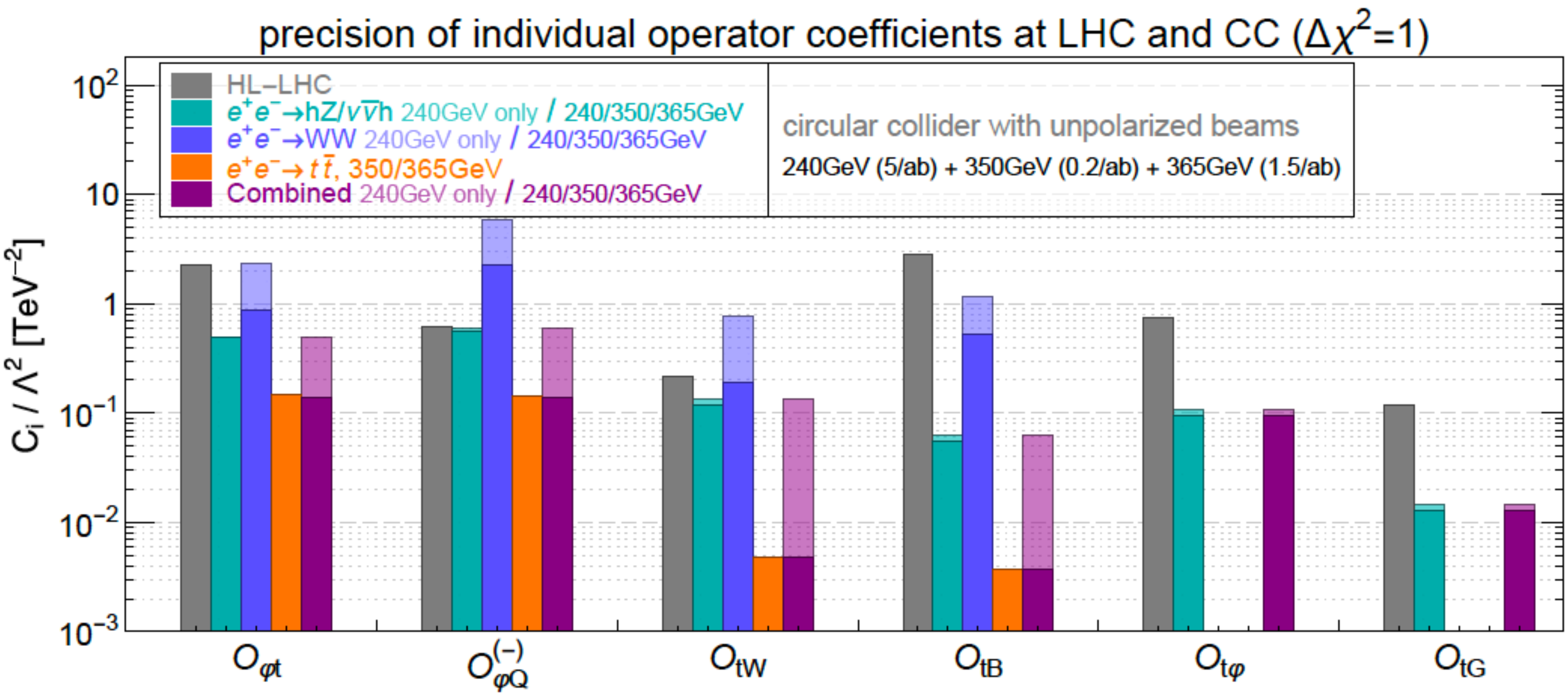
New operators can arise at one-loop or via real corrections.

- At variance with the SM, loop-induced processes might not be finite.
- Including the full set of operators at a given order implies that no extra UV divergences appear (closure check).
- Use tree-level, loop-level, hierarchy but not gauge couplings.



Need for NLO

4. New operators arise



[Durieux, Gu, Vryonidou and Zhang, 2018]

SMEFT codes

[Spira; arXiv:hep-ph/9510347]
[Harlander, Liebler & Mantler; arXiv: 1605.03190]
[Dawson, Dittmaier & Spira; Phys. Rev. D58:115012]
[Goertz et al.; JHEP 1504 (2015) 167]

- Single & double Higgs (partial SMEFT)
  - HiGlu, SusHi, HPAIR, HiggsPair

[Contino et al.; Comp. Phys. Comm. 185 (2014) 3412-3423]
https://www.itp.kit.edu/~maggie/eHDECAY/

- eHDECAY for BR

[Denner et al.; JHEP 1203 (2012) 075]
http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk

- HAWK
  - VBF and VH @ NLO in QCD & EW for SM + 2 anomalous couplings

[Baglio et al.; arXiv:1404.3940]
https://www.itp.kit.edu/vbfnlo

- VBFNLO
  - General (FO) tool for Higgs/weak boson production @ NLO in QCD

http://powhegbox.mib.infn.it

- POWHEG-BOX/MCFM
  - VH NLO QCD + PS for Higgs/EW operators (SILH) [KM et al.; JHEP 1608 (2016) 039]
  - Drell-Yan & EW Higgs production with more operators [Alioli et al.; JHEP 08 (2018) 205]
  - WW with TGC & quark vertex operators [Baglio et al.; PRD 99 (2019) 035029]

SMEFT models

- HEL
  [Alloul et al.; JHEP 1404 (2014) 110]
  http://feynrules.irmp.ucl.ac.be/wiki/HEL
  [Degrande, et al.; EPJC 77 (2017) 4, 262]
  http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO
  - Flavor universal SILH basis @ LO
  - Higgs/EW operators in SILH basis @ NLOQCD (HELatNLO)
- SMEFTsim
  [Brivio et al.; JHEP 1712 (2017) 070]
  http://feynrules.irmp.ucl.ac.be/wiki/SMEFT
  - Complete Warsaw basis (2499!) @ LO with flavor restriction options
- SMEFTfr
  [Dedes et al.; JHEP 1706 (2017) 143]
  [Misiak et al.; JHEP 1902 (2019) 051]
  htttps://www.few.edu.pl/smeft
  - FeynRules for Warsaw basis @ LO in R_ξ-gauge
- dim6top
  [Aguilar-Saavedra et al.; arXiv:1802.07237]
  http://feynrules.irmp.ucl.ac.be/wiki/dim6top
  - top sector @ LO, several flavor symmetry scenarios (LH top WG)
- SMEFTatNLO
  [Degrande et al.; in preparation]
  http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO
  - top/Higgs/EW sector @ NLOQCD (4F operators now validated)

SMEFT at NLO

Aim to fully automate NLO calculations in the SMEFT within public Monte Carlo generators based on:

- Warsaw basis of dimension-6 operators

Current status:

- 73 degrees of freedom (top, Higgs, gauge):
  - CP-conserving
  - Flavour assumption: $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$
- Successful validation with LO implementations
- 0/2F@NLO operators validated (with previous partial NLO implementations)
  http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO
- 4F@NLO operators validation: completed

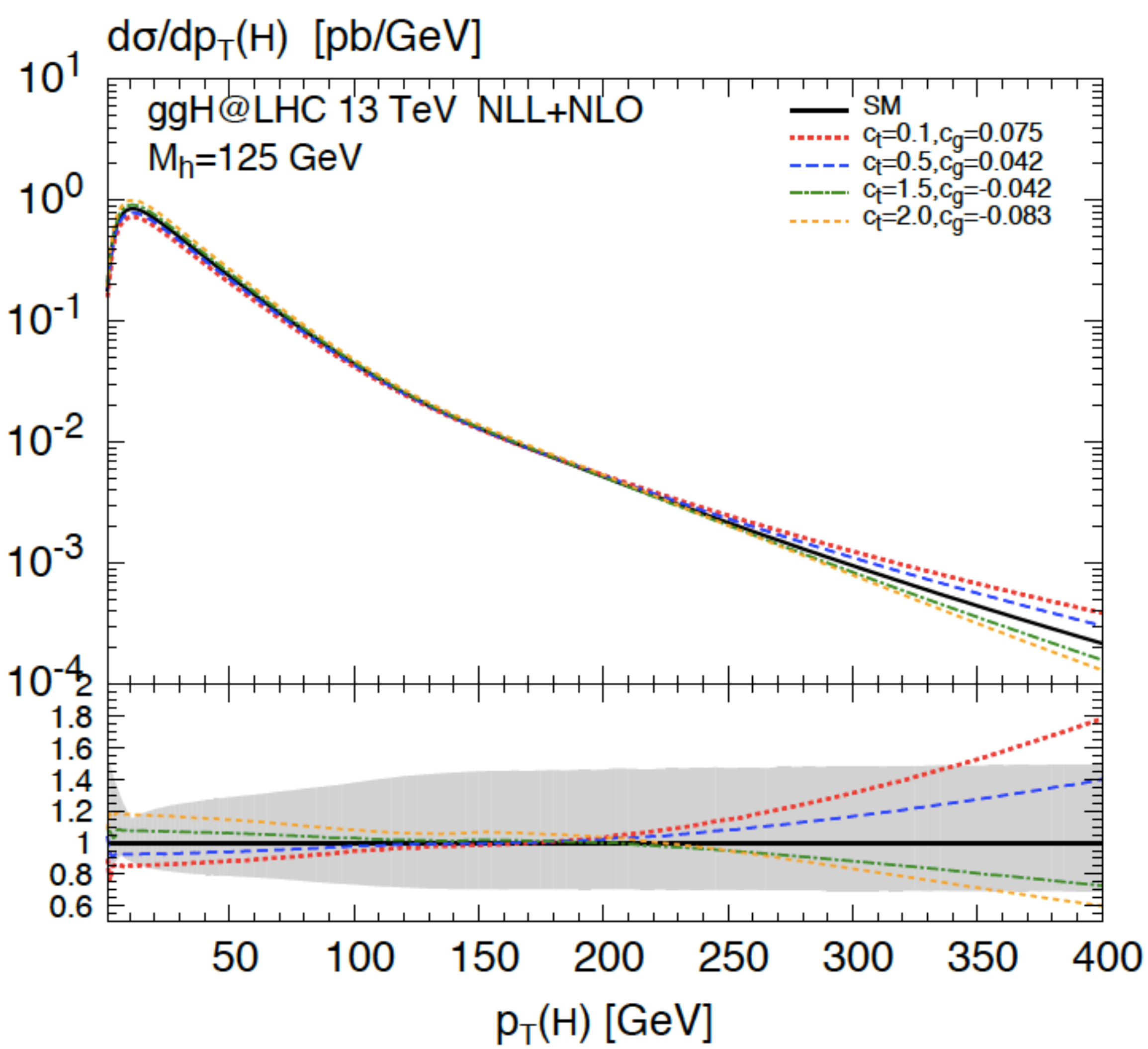
Paves the way for a precise SMEFT programme at the LHC

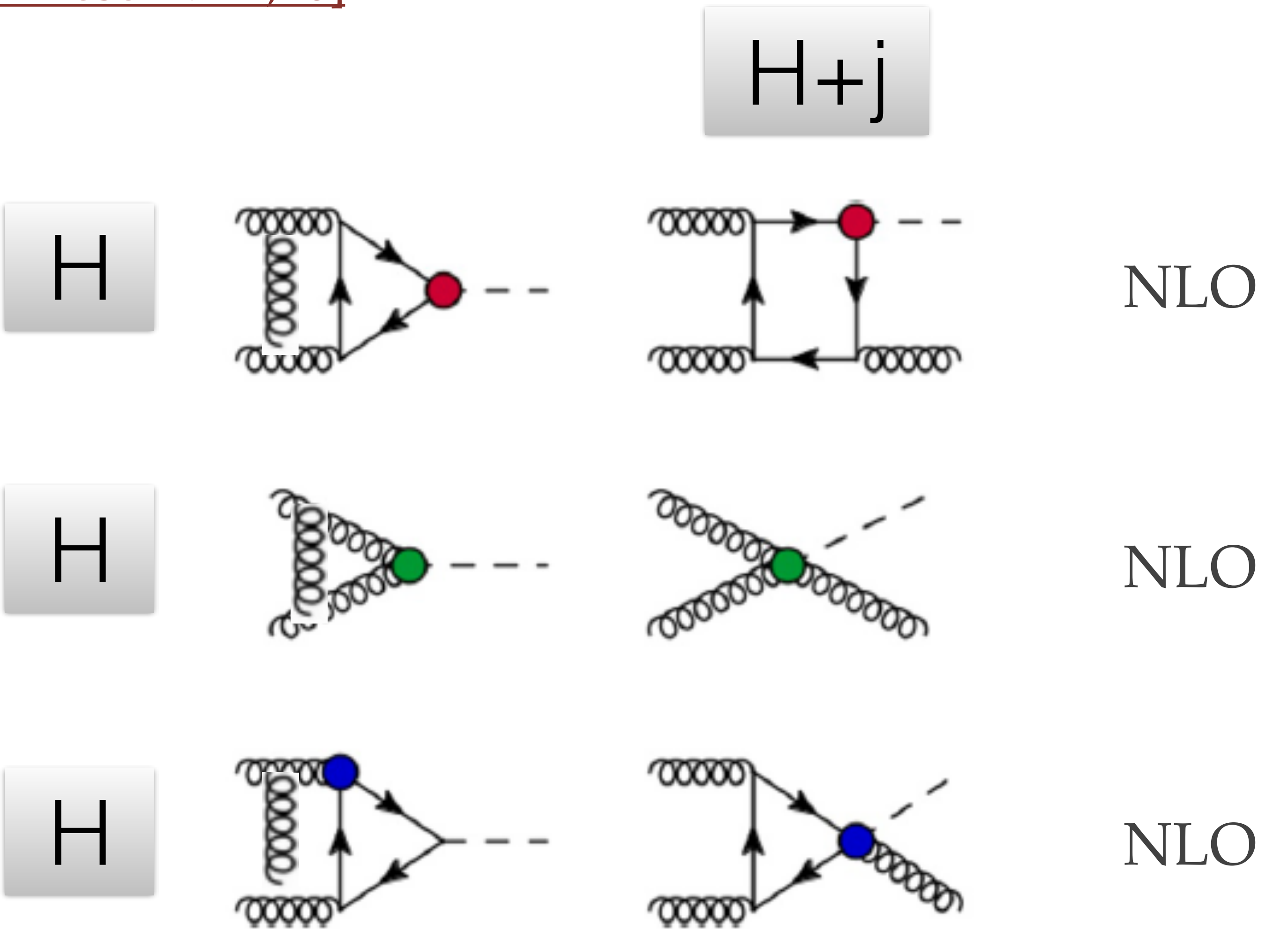
[In collaboration with: C. Degrande, G. Durieux, K. Mimasu, E. Vryonidou, C. Zhang]

ggH at NLO

Earlier studies of ggH in the SMEFT [Degrande et al. 12] [Grojean et al. 13]

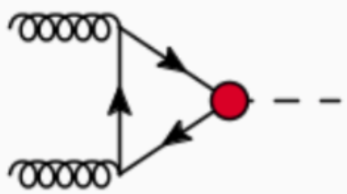
More recently, [Grazzini, Ilnicka, Spira, Wiesemann,16]



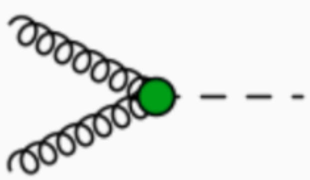


[Deutschmann, Duhr, FM, Vryonidou, 17]

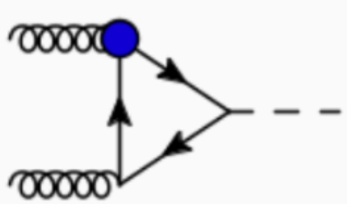
ggH at NLO



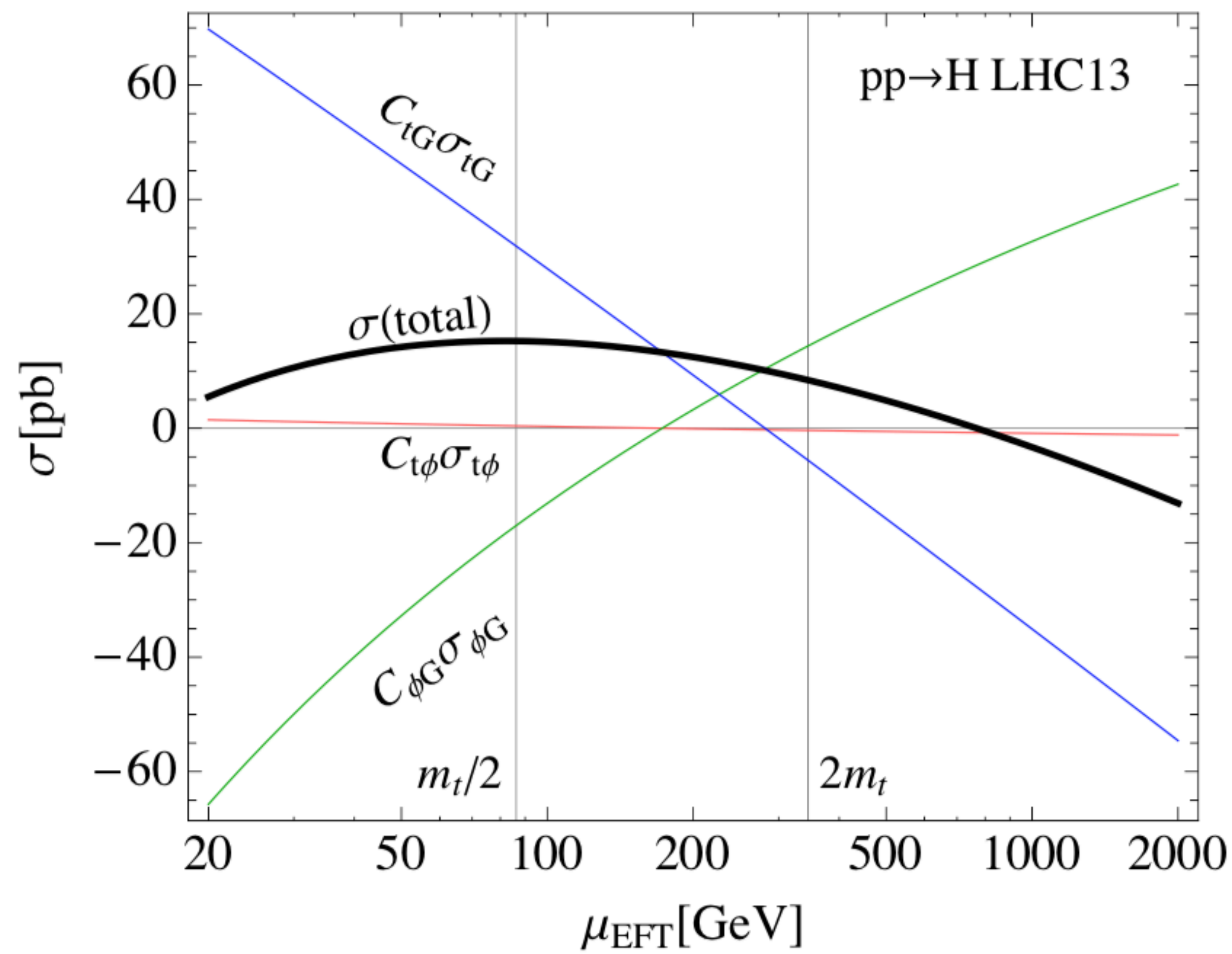
(NLO)
$O_{t\varphi} = y_t^3 \left(\varphi^\dagger \varphi\right) (\bar{Q} t) \tilde{\varphi}$



(LO)
$O_{\varphi G} = y_t^2 \left(\varphi^\dagger \varphi\right) G^A_{\mu\nu} G^{A\mu\nu}$



(NLO)
$O_{tG} = y_t g_s \left(\bar{Q} \sigma^{\mu\nu} T^A t\right) \tilde{\varphi} G^A_{\mu\nu}$

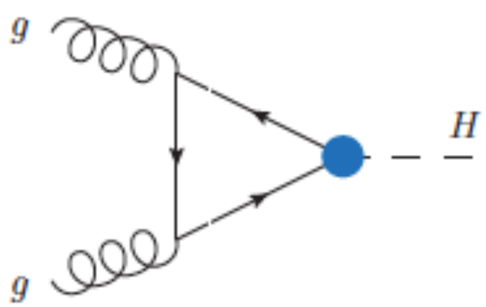


$C_{tG} = 1,\ C_{t\varphi} = C_{\varphi G} = 0$ at m_t

- Scale dependence of (LO) OφG, from running coef., cancels that of (NLO) OtG, from the loop.
- Only global point of view could make sense. To estimate TH uncertainty, must sum all operators.

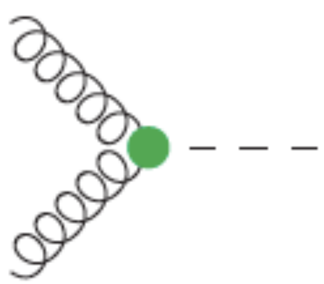
ggH at NLO

σ1



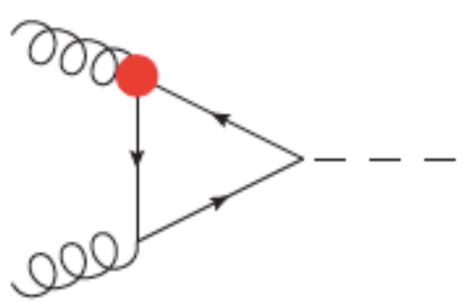
$(\Phi^\dagger\Phi)\,\bar{Q}_L\Phi\, q_R$

σ2



$(\Phi^\dagger\Phi)\, GG$

σ3

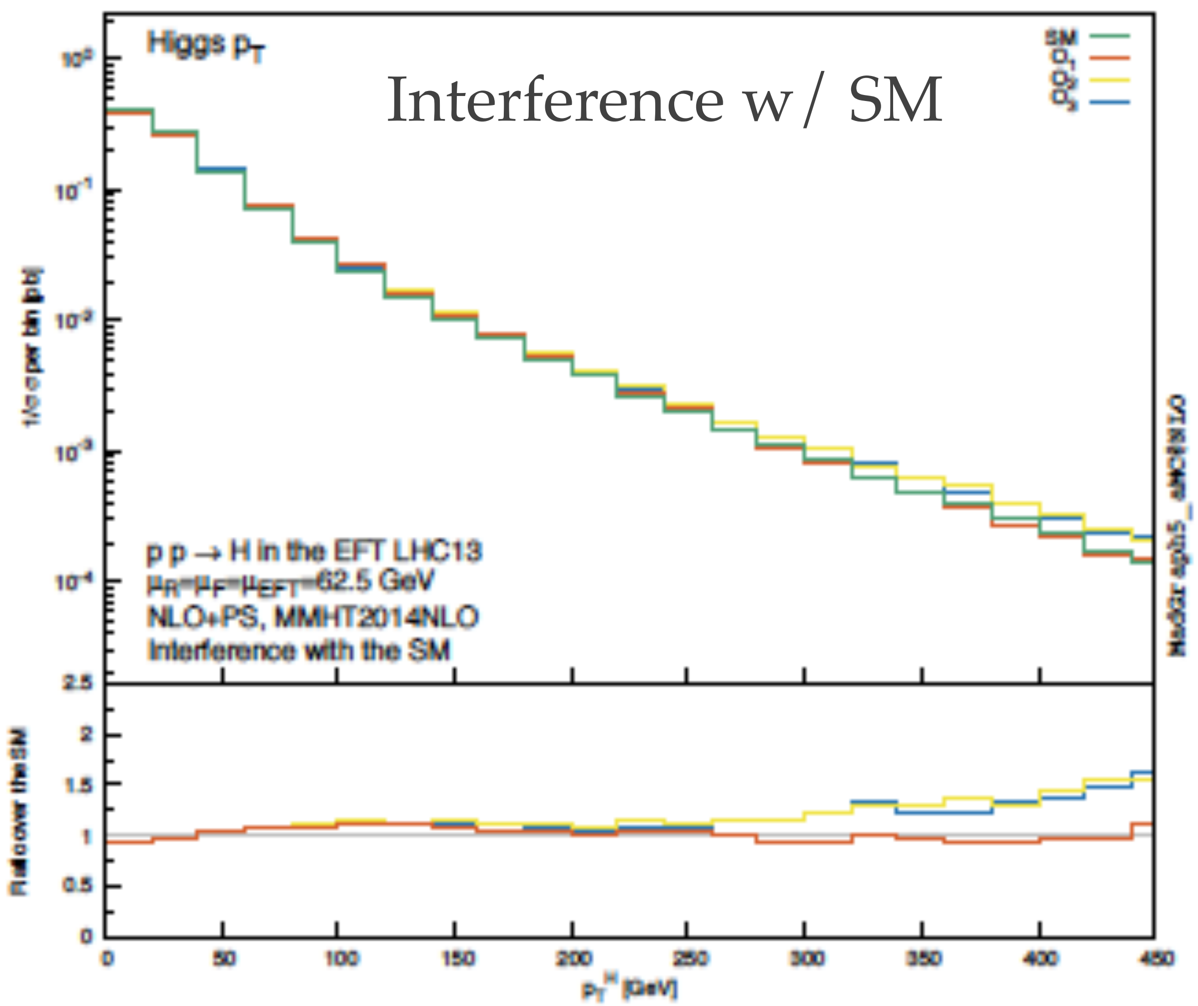


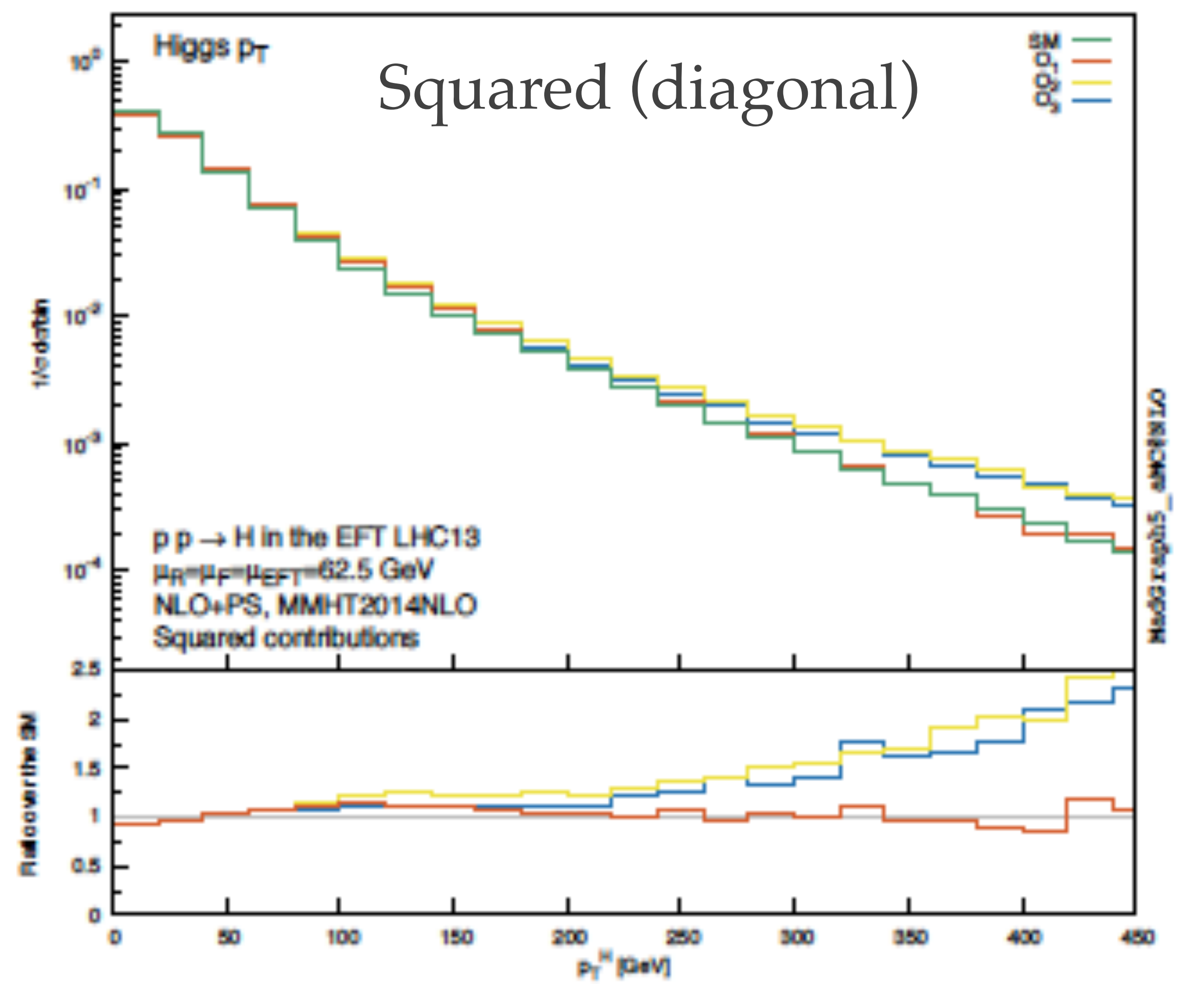
$\bar{Q}_L\Phi\,\sigma q_R G$

13 TeV	σ LO	σ/σ_{SM} LO	σ NLO	σ/σ_{SM} NLO	K
σ_{SM}	$21.3^{+34.0+1.5\%}_{-25.0-1.5\%}$	1.0	$36.6^{+26.4+1.9\%}_{-20.0-1.6\%}$	1.0	1.71
σ_1	$-2.93^{+34.0+1.5\%}_{-25.0-1.5\%}$	-0.138	$-4.70^{+24.8+1.9\%}_{-20.0-1.6\%}$	-0.127	1.61
σ_2	$2660^{+34.0+1.5\%}_{-25.0-1.5\%}$	125	$4130^{+23.9+1.9\%}_{-19.6-1.6\%}$	114	1.55
σ_3	$50.5^{+34.0+1.5\%}_{-25.0-1.5\%}$	2.38	$83.5^{+26.0+1.9\%}_{-20.6-1.6\%}$	2.28	1.65

$$\sigma = \sigma_{SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i\le j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}$$

ggH at NLO





The effects of the chromo are "degenerate" with those of the $O_{\varphi G}$ operator in the interference and diagonal squared terms.

VH, VBF, DY at NLO

[Alioli et al.; JHEP 08 (2018) 205]
http://powhegbox.mib.infn.it

Most operators don't run under QCD

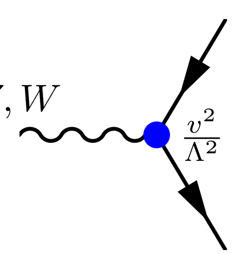
- Only Yukawa and scalar 4F
- Mostly SM counterterms

VH, VBF	VH, VBF / DY	DY
$(\varphi^\dagger\varphi)W^I_{\mu\nu}W_I^{\mu\nu}$	$(\varphi^\dagger\tau_I\varphi)W^I_{\mu\nu}B^{\mu\nu}$	$\bar{q}_i q_j \bar{\ell}_k \ell_l$
$(\varphi^\dagger\varphi)B_{\mu\nu}B^{\mu\nu}$	$(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi)(\bar{f}_i\gamma^\mu f_j)$	
$(\varphi^\dagger\varphi)\tilde{\varphi}\,\bar{Q}_i\,u_j$	$\varphi\,(\bar{F}^i_L\tau_I\sigma^{\mu\nu}f^j_R)W^I_{\mu\nu}$	
	$\varphi\,(\bar{F}^i_L\sigma^{\mu\nu}f^j_R)B_{\mu\nu}$	

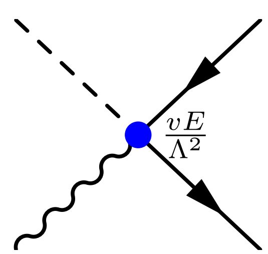
	$pp\to\ell\nu$	$pp\to\ell^+\ell^-,\,\nu\bar{\nu}$	WH	ZH	VBF
$C_{\varphi W}, C_{\varphi\tilde{W}}$	–	–	✓	✓	✓
$C_{\varphi B}, C_{\varphi\tilde{B}}$	–	–	–	✓	✓
$C_{\varphi WB}, C_{\varphi\tilde{W}\tilde{B}}$	–	–	–	✓	✓
$\Gamma^{u,d}_\gamma$	✓	✓	–	✓	✓
$\Gamma^{u,d}_W$	✓	✓	✓	✓	✓
$\Gamma^e_{\gamma,W}$	✓	✓	×	×	–
$c_{Q\varphi,U}, c_{Q\varphi,D}$	✓	✓	✓	✓	✓
$c_{U\varphi}, c_{D\varphi}$	–	✓	–	✓	✓
ξ	✓	–	✓	–	✓
$c^{(1,3)}_{L\varphi},\, c_{e\varphi}$	×	×	×	×	–
$Y'_u,\, Y'_d$	–	–	✓	✓	–
$C_{LQ,U}, C_{LQ,D}$	✓	✓	–	–	–
C_{eu}, C_{ed}	–	✓	–	–	–
$C_{Lu}, C_{Ld,Qe}$	–	✓	–	–	–
$C_{LedQ}, C^{(1,3)}_{LeQu}$	✓	✓	–	–	–

Current operators interesting

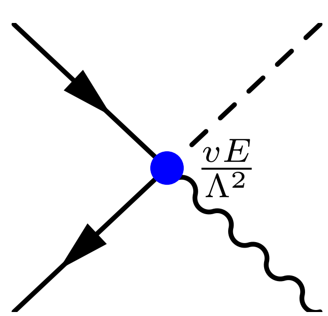
$$(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi)(\bar{f}_i\gamma^\mu f_j)$$

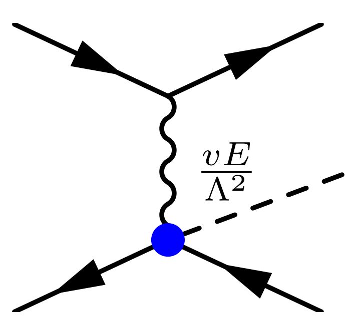


D=4



D=5





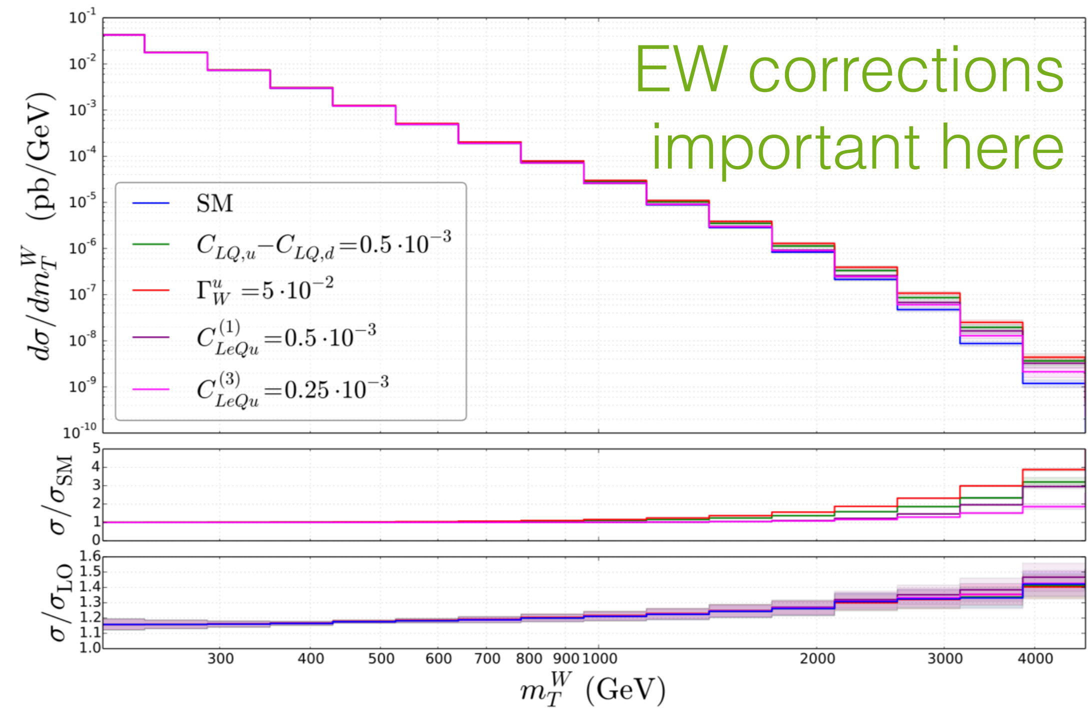
VH,VBF, DY at NLO

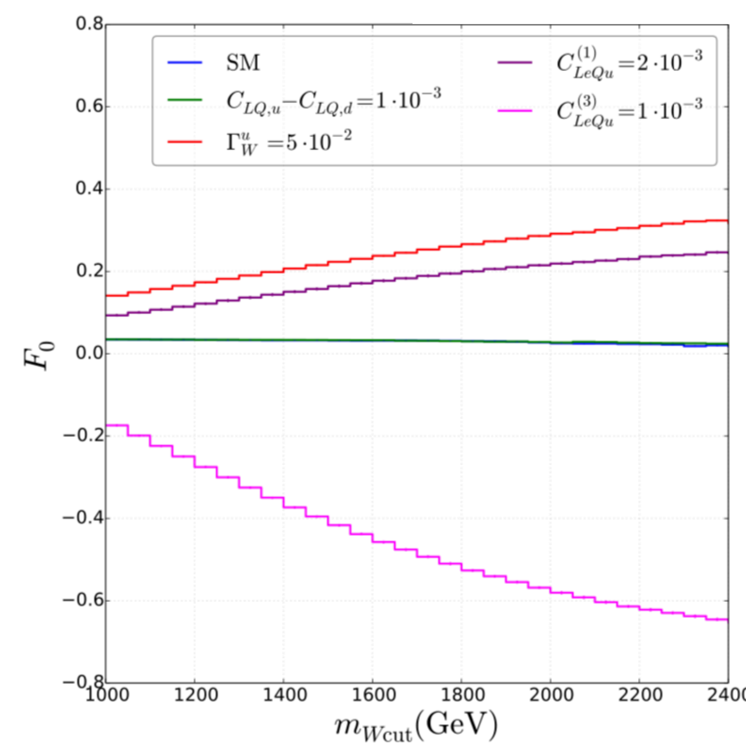
Drell-Yan

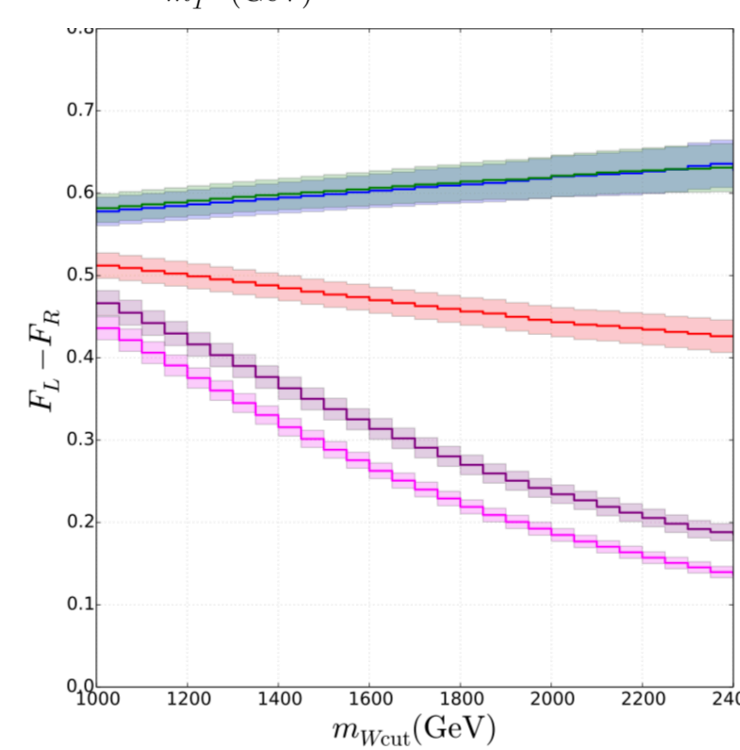
- Large effects in high energy tails, saturating existing limits
- K-factors increase with energy ~1.4
- Dominated by PDF uncertainty
- Set limits by recasting high mass NC & CC measurements
  [ATLAS; EPJ C78 (2018) no.5 401 & JHEP 10 (2017) 182]

(pseudo)scalar & tensor 4F limits competitive with pion & β-decays

W-helicity fractions (challenging measurement) can distinguish operators

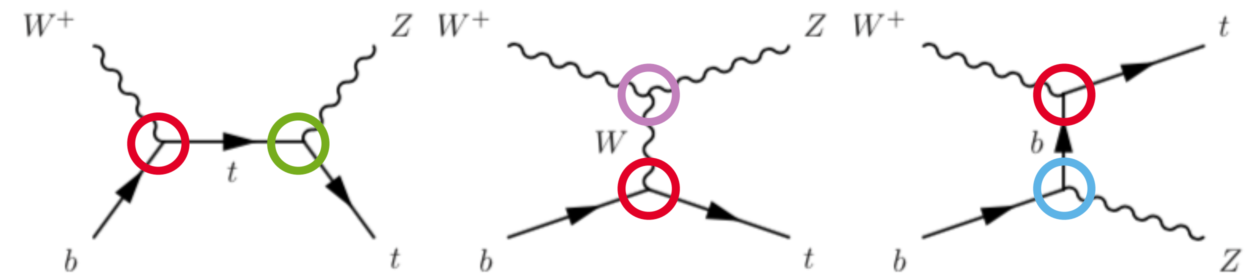






tZj/tHj

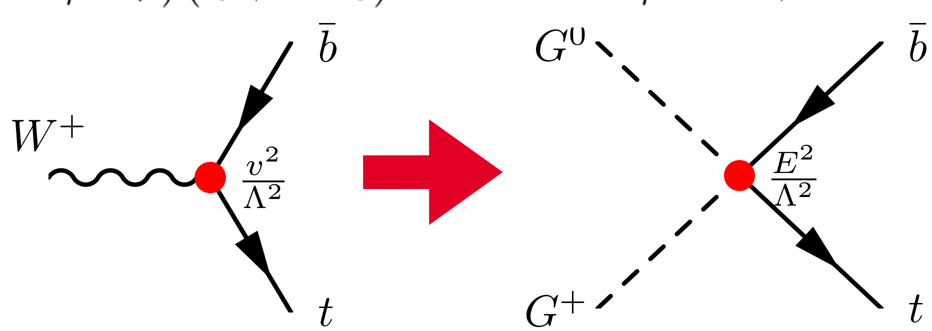
SMEFT@NLO

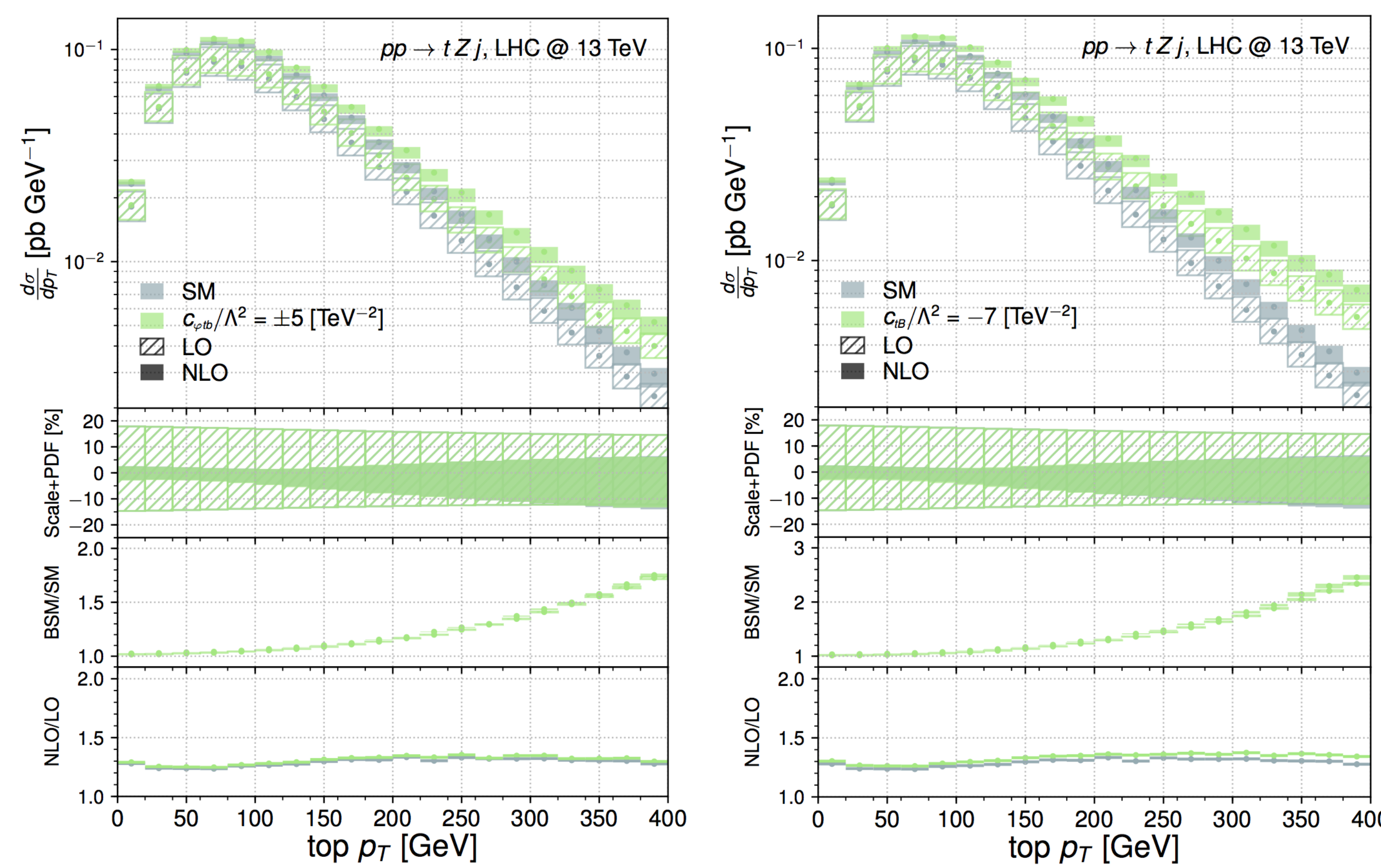


- tZj/tHj: case study of EW-top scattering
- Interplay of many top/higgs/EW couplings
- Energy growth from new Lorentz structures & unitarity non-cancellations

$$i(\tilde{\varphi}D_\mu\varphi)(\bar{t}\gamma^\mu b) + \text{h.c.} \quad \rightarrow \quad G^0\,\partial_\mu G^+\,\bar{t}_R\gamma^\mu b_R$$

$$i(\varphi^\dagger \overleftrightarrow{D}_\mu\,\tau_I\varphi)(\bar{Q}\,\gamma^\mu\,\tau^I Q) \quad \rightarrow \quad G^0\,\overleftrightarrow{\partial}_\mu G^+\,\bar{t}_L\gamma^\mu b_L$$





tZj/tHj

Useful inputs to global interpretations

←tZj

σ [fb]	LO	NLO	K-factor
σ_{SM}	$660.8(4)^{+13.7\%}_{-9.6\%} \pm 9.7\%$	$839.1(5)^{+1.1\%}_{-5.1\%} \pm 1.0\%$	1.27
σ_{W}	$-7.87(7)^{+8.4\%}_{-12.6\%} \pm 9.7\%$	$-8.77(8)^{+8.5\%}_{-4.3\%} \pm 1.1\%$	1.12
$\sigma_{W,W}$	$34.58(3)^{+8.2\%}_{-3.9\%} \pm 13.0\%$	$43.80(4)^{+6.6\%}_{-15.1\%} \pm 2.8\%$	1.27
σ_{tB}	$2.23(2)^{+14.7[0.9]\%}_{-10.7[1.0]\%} \pm 9.4\%$	$2.94(2)^{+2.3[0.4]\%}_{-3.0[0.7]\%} \pm 1.1\%$	1.32
$\sigma_{tB,tB}$	$2.833(2)^{+10.5[1.7]\%}_{-6.3[1.9]\%} \pm 11.1\%$	$4.155(3)^{+4.7[0.9]\%}_{-10.1[1.4]\%} \pm 1.7\%$	1.47
σ_{tW}	$2.66(4)^{+18.8[0.9]\%}_{-15.3[1.0]\%} \pm 11.4\%$	$13.0(1)^{+15.8[2.1]\%}_{-22.8[0.0]\%} \pm 1.2\%$	4.90
$\sigma_{tW,tW}$	$48.16(4)^{+10.0[1.7]\%}_{-5.8[1.9]\%} \pm 11.3\%$	$80.00(4)^{+7.9[1.3]\%}_{-14.7[1.6]\%} \pm 1.9\%$	1.66
$\sigma_{\varphi dtR}$	$4.20(1)^{+14.9\%}_{-10.9\%} \pm 9.3\%$	$4.94(2)^{+3.4\%}_{-6.7\%} \pm 1.0\%$	1.18
$\sigma_{\varphi dtR,\varphi dtR}$	$0.3326(3)^{+13.6\%}_{-9.5\%} \pm 9.6\%$	$0.4402(5)^{+3.7\%}_{-9.3\%} \pm 1.0\%$	1.32
$\sigma_{\varphi Q}$	$14.98(2)^{+14.5\%}_{-10.5\%} \pm 9.4\%$	$18.07(3)^{+2.3\%}_{-1.6\%} \pm 1.0\%$	1.21
$\sigma_{\varphi Q,\varphi Q}$	$0.7442(7)^{+14.1\%}_{-10.0\%} \pm 9.5\%$	$1.028(1)^{+2.8\%}_{-7.3\%} \pm 1.0\%$	1.38
$\sigma_{\varphi Q^{(3)}}$	$130.04(8)^{+13.8\%}_{-9.8\%} \pm 9.5\%$	$161.4(1)^{+0.9\%}_{-4.8\%} \pm 1.0\%$	1.24
$\sigma_{\varphi Q^{(3)},\varphi Q^{(3)}}$	$17.82(2)^{+11.7\%}_{-7.5\%} \pm 10.5\%$	$23.98(2)^{+3.7\%}_{-9.3\%} \pm 1.4\%$	1.35
$\sigma_{\varphi tb}$	0	0	–
$\sigma_{\varphi tb,\varphi tb}$	$2.949(2)^{+10.5\%}_{-6.2\%} \pm 11.1\%$	$4.154(4)^{+5.1\%}_{-11.2\%} \pm 1.8\%$	1.41
σ_{HW}	$-5.16(6)^{+7.8\%}_{-12.0\%} \pm 10.5\%$	$-6.88(8)^{+6.4\%}_{-2.0\%} \pm 1.4\%$	1.33
$\sigma_{HW,HW}$	$0.912(2)^{+9.4\%}_{-5.2\%} \pm 12.0\%$	$1.048(2)^{+5.2\%}_{-12.8\%} \pm 2.1\%$	1.15
σ_{HB}	$-3.015(9)^{+9.9\%}_{-13.9\%} \pm 9.5\%$	$-3.76(1)^{+5.2\%}_{-1.0\%} \pm 1.0\%$	1.25
$\sigma_{HB,HB}$	$0.02324(6)^{+12.7\%}_{-8.5\%} \pm 9.9\%$	$0.02893(6)^{+2.3\%}_{-7.5\%} \pm 1.1\%$	1.24
σ_{tG}	$0.45(2)^{+93.0\%}_{-148.8\%} \pm 4.9\%$		–
$\sigma_{tG,tG}$	$2.251(4)^{+20.9\%}_{-30.0\%} \pm 2.5\%$		–
$\sigma_{Qq^{(3,1)}}$	$-393.5(5)^{+8.1\%}_{-12.3\%} \pm 10.0\%$	$-498(1)^{+8.9\%}_{-3.2\%} \pm 1.2\%$	1.26
$\sigma_{Qq^{(3,1)},Qq^{(3,1)}}$	$462.25(3)^{+8.4\%}_{-4.1\%} \pm 12.7\%$	$545.50(5)^{+7.4\%}_{-17.4\%} \pm 2.9\%$	1.18
$\sigma_{Qq^{(3,8)}}$	0	$-0.9(3)^{+23.3\%}_{-26.3\%} \pm 19.2\%$	–
$\sigma_{Qq^{(3,8)},Qq^{(3,8)}}$	$102.73(5)^{+8.4\%}_{-4.1\%} \pm 12.7\%$	$111.18(5)^{+9.3\%}_{-18.4\%} \pm 2.8\%$	1.08

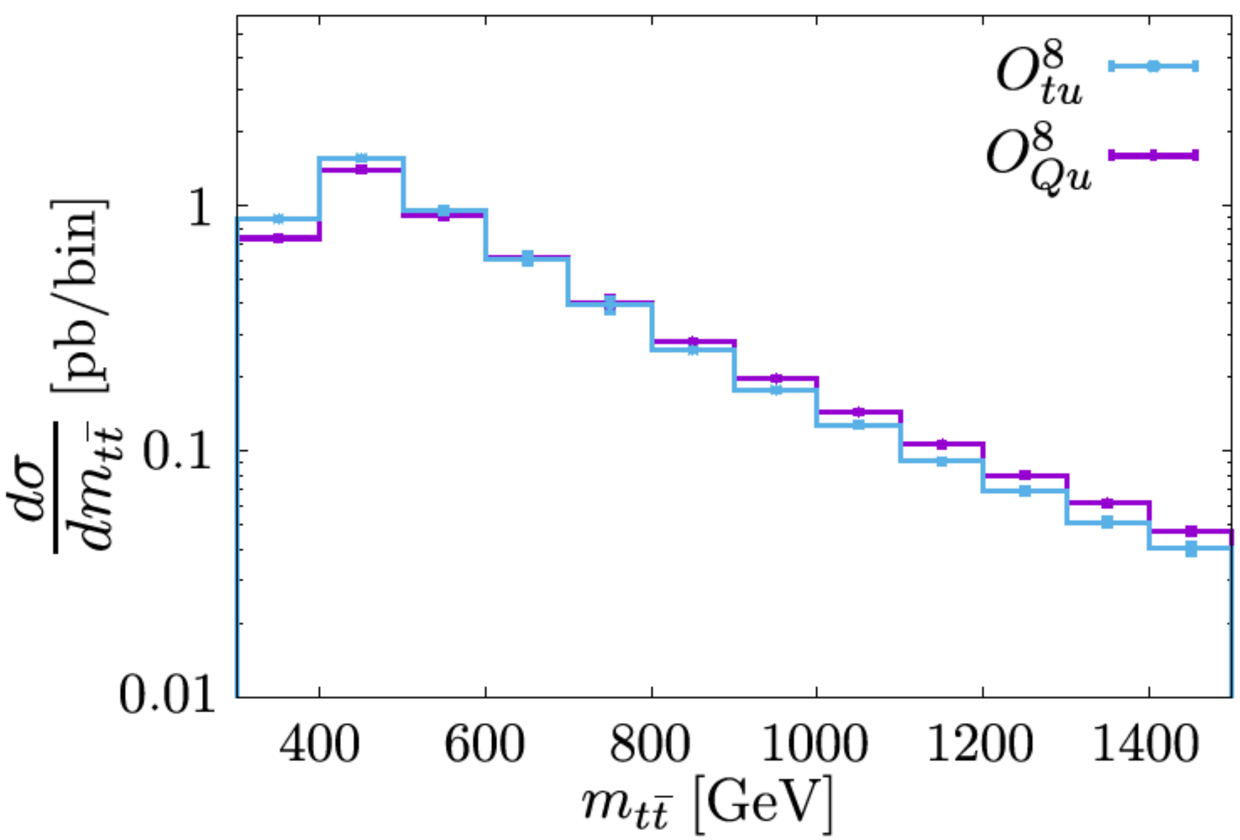
tHj ↓

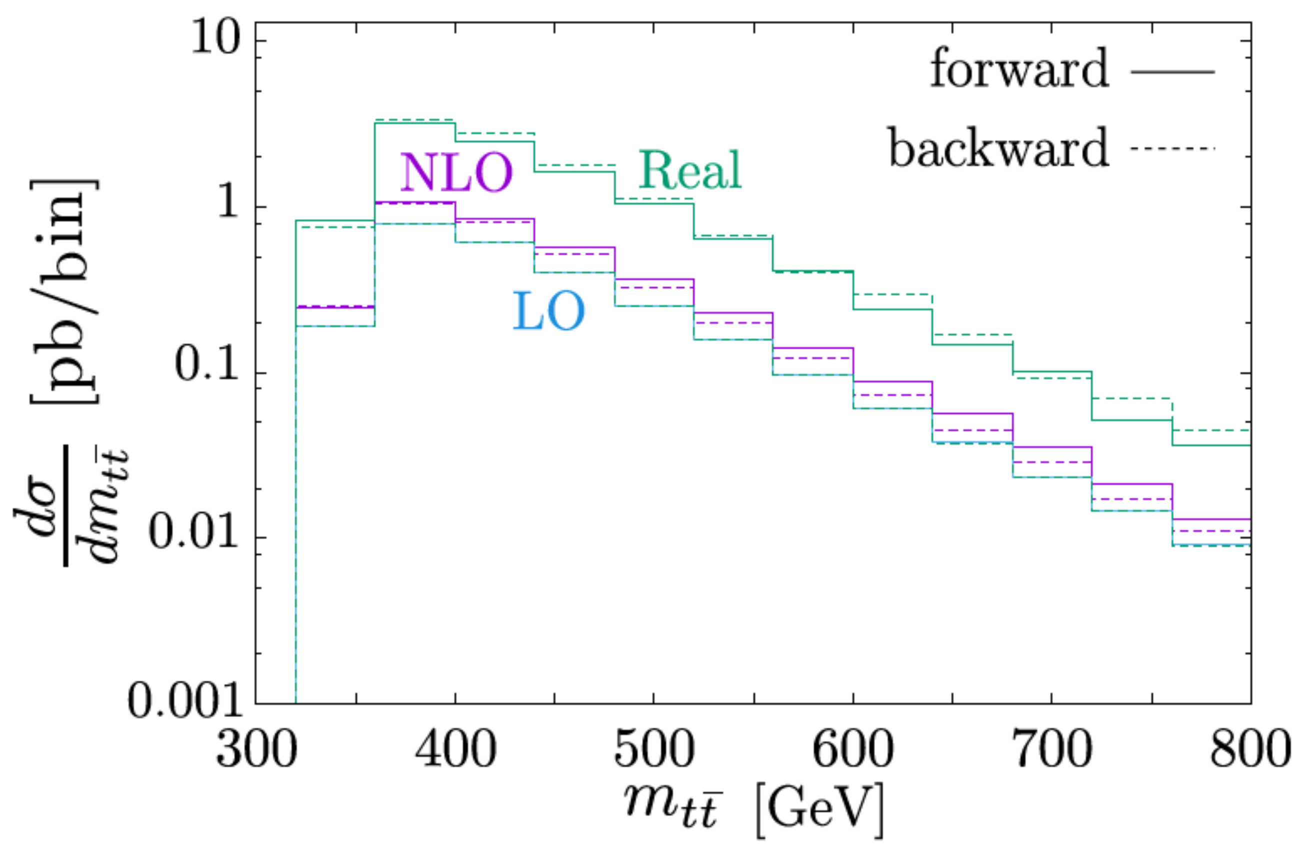
σ [fb]	LO	NLO	K-factor
σ_{SM}	$57.56(4)^{+11.2\%}_{-7.4\%} \pm 10.2\%$	$75.87(4)^{+2.2\%}_{-6.4\%} \pm 1.2\%$	1.32
$\sigma_{\varphi W}$	$8.12(2)^{+13.1\%}_{-9.3\%} \pm 9.3\%$	$7.76(2)^{+7.0\%}_{-6.3\%} \pm 1.0\%$	0.96
$\sigma_{\varphi W,\varphi W}$	$5.212(7)^{+10.6\%}_{-6.8\%} \pm 10.2\%$	$6.263(7)^{+2.6\%}_{-7.8\%} \pm 1.3\%$	1.20
$\sigma_{t\varphi}$	$-1.203(6)^{+12.0\%}_{-15.6\%} \pm 8.9\%$	$-0.246(6)^{+144.5[31.4]\%}_{-157.8[19.0]\%} \pm 2.1\%$	0.20
$\sigma_{t\varphi,t\varphi}$	$0.6682(9)^{+12.7\%}_{-8.9\%} \pm 9.6\%$	$0.7306(8)^{+4.6[0.6]\%}_{-7.3[0.2]\%} \pm 1.0\%$	1.09
σ_{tW}	$19.38(6)^{+13.0\%}_{-9.3\%} \pm 9.4\%$	$22.18(6)^{+3.8[0.4]\%}_{-6.8[0.9]\%} \pm 1.0\%$	1.14
$\sigma_{tW,tW}$	$46.40(8)^{+9.3\%}_{-5.5\%} \pm 11.1\%$	$71.24(8)^{+7.4[1.5]\%}_{-14.0[6.9]\%} \pm 1.9\%$	1.54
$\sigma_{\varphi Q^{(3)}}$	$-3.03(3)^{+0.0\%}_{-2.2\%} \pm 15.4\%$	$-10.04(4)^{+11.1\%}_{-8.9\%} \pm 1.8\%$	3.31
$\sigma_{\varphi Q^{(3)},\varphi Q^{(3)}}$	$11.23(2)^{+9.4\%}_{-5.6\%} \pm 11.2\%$	$15.28(2)^{+5.0\%}_{-10.9\%} \pm 1.8\%$	1.36
$\sigma_{\varphi tb}$	0	0	–
$\sigma_{\varphi tb,\varphi tb}$	$2.752(4)^{+9.4\%}_{-5.5\%} \pm 11.3\%$	$3.768(4)^{+5.0\%}_{-10.9\%} \pm 1.8\%$	1.54
σ_{HW}	$-3.526(4)^{+5.6\%}_{-9.5\%} \pm 10.9\%$	$-5.27(1)^{+6.5\%}_{-2.9\%} \pm 1.5\%$	1.50
$\sigma_{HW,HW}$	$0.9356(4)^{+7.9\%}_{-4.0\%} \pm 12.3\%$	$1.058(1)^{+4.8\%}_{-11.9\%} \pm 2.3\%$	1.13
σ_{tG}	$-0.418(5)^{+12.3\%}_{-9.8\%} \pm 1.1\%$		–
$\sigma_{tG,tG}$	$1.413(1)^{+21.3\%}_{-30.6\%} \pm 2.5\%$		–
$\sigma_{Qq^{(3,1)}}$	$-22.50(5)^{+8.0\%}_{-11.8\%} \pm 9.7\%$	$-20.10(5)^{+13.8\%}_{-13.3\%} \pm 1.1\%$	0.89
$\sigma_{Qq^{(3,1)},Qq^{(3,1)}}$	$69.78(3)^{+8.0\%}_{-4.1\%} \pm 12.1\%$	$62.20(3)^{+11.5\%}_{-15.9\%} \pm 2.3\%$	0.89
$\sigma_{Qq^{(3,8)}}$	–	$0.25(3)^{+25.4\%}_{-27.1\%} \pm 4.7\%$	–
$\sigma_{Qq^{(3,8)},Qq^{(3,8)}}$	$15.53(2)^{+8.0\%}_{-4.1\%} \pm 12.1\%$	$14.07(2)^{+11.0\%}_{-15.7\%} \pm 2.1\%$	0.91

Breaking degeneracies: tt+jet

[Brivio et al.; JHEP 2002 (2020) 131]

Many four-fermion operators enter in ttbar production.





$$\frac{d\sigma(u\bar{u} \to t\bar{t})}{d\cos\theta_t} \propto \left(1 + 2\beta_{t\bar{t}}\cos\theta_t + 4\bar{m}^2 + \beta^2_{t\bar{t}}\cos^2\theta_t\right) C^8_{tu} \longrightarrow \text{forward}$$

$$+ \left(1 - 2\beta_{t\bar{t}}\cos\theta_t + 4\bar{m}^2 + \beta^2_{t\bar{t}}\cos^2\theta_t\right) C^8_{Qu} \longrightarrow \text{backward}$$

Plan for today's lecture

- SMEFT essentials
- The SMEFT precision frontier
- Example: Fitting in the Top (with Higgs/EW) sector
- Bringing the lesson home

Plan for today's lecture

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SMEFT global fit

- Measurements:
  - Total as well as differential, unfolded and/or fiducial, including uncertainties and correlations.
  - Reference SMEFT interpretations done by the experimental collaboration for best sensitivity targets.

- Theoretical predictions:
  - SM at the best possible accuracy
  - SMEFT at least at NLO in QCD

- Fitting:
  - Robust and scalable fitting technology
  - Combination with low/energy, flavour and LEP measurements

An application: A global top fit@NLO

Theory

(N)NLO QCD+ NLO EW for SM
NLO QCD for SMEFT
State-of-the-art PDFs without top data

Data

Top pair production and single top (differential)
Associated production with W,Z,H
W helicity fractions
Parton-level

Global SMEFT fit of the top-quark sector

Based on NNPDF
Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

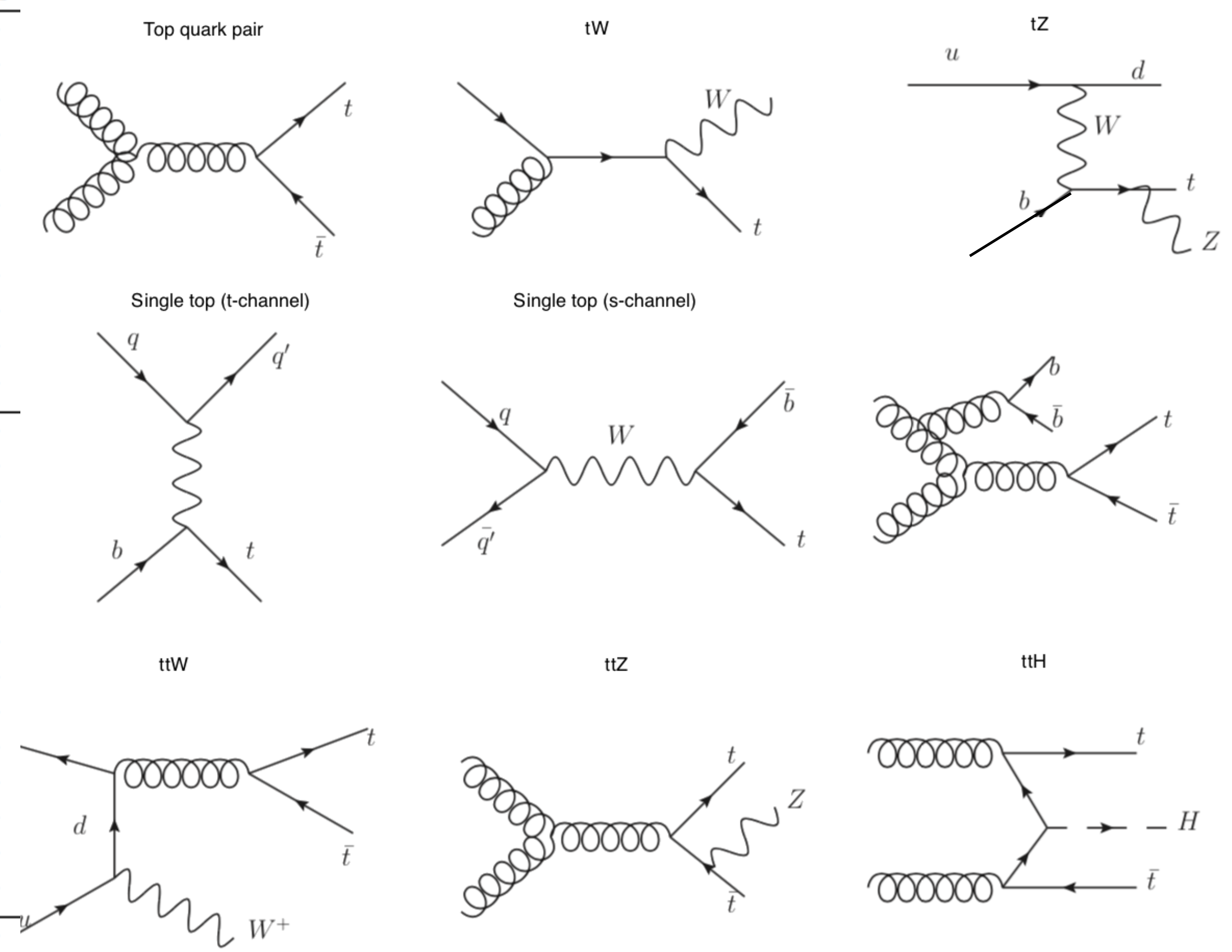
Methodology

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added
Plan to extend to Higgs, gauge sector etc

Output

An application: A global top fit@NLO

Class	Notation	Degree of Freedom	Operator Definition	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
				$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
$QQQQ$	OQQ1	c^{1}_{QQ}	$2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$								✓	✓
	OQQ8	c^{8}_{QQ}	$8C^{3(3333)}_{qq}$								✓	✓
	OQt1	c^{1}_{Qt}	$C^{1(3333)}_{qu}$								✓	✓
	OQt8	c^{8}_{Qt}	$C^{8(3333)}_{qu}$								✓	✓
	OQb1	c^{1}_{Qb}	$C^{1(3333)}_{qd}$									✓
	OQb8	c^{8}_{Qb}	$C^{8(3333)}_{qd}$									✓
	Ott1	c^{1}_{tt}	$C^{(3333)}_{uu}$								✓	
	Otb1	c^{1}_{tb}	$C^{1(3333)}_{ud}$									✓
	Otb8	c^{8}_{tb}	$C^{8(3333)}_{ud}$									✓
	OQtQb1	c^{1}_{QtQb}	$C^{1(3333)}_{quqd}$									✓
	OQtQb8	c^{8}_{QtQb}	$C^{8(3333)}_{quqd}$									✓
$QQqq$	O81qq	$c^{1,8}_{Qq}$	$C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$	✓				✓	✓	✓	✓	✓
	O11qq	$c^{1,1}_{Qq}$	$C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$	(✓)				(✓)	(✓)	(✓)	✓	✓
	O83qq	$c^{3,8}_{Qq}$	$C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$	✓	(✓)		(✓)	✓	✓	✓	✓	✓
	O13qq	$c^{3,1}_{Qq}$	$C^{3(ii33)}_{qq} + \frac{1}{6}(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq})$	(✓)	✓		✓	(✓)	(✓)	(✓)	✓	✓
	O8qt	c^{8}_{tq}	$C^{8(ii33)}_{qu}$	✓				✓	✓	✓	✓	✓
	O1qt	c^{1}_{tq}	$C^{1(ii33)}_{qu}$	(✓)				(✓)	(✓)	(✓)	✓	✓
	O8ut	c^{8}_{tu}	$2C^{(i33i)}_{uu}$	✓					✓	✓	✓	✓
	O1ut	c^{1}_{tu}	$C^{(ii33)}_{uu} + \frac{1}{3}C^{(i33i)}_{uu}$	(✓)					(✓)	(✓)	✓	✓
	O8qu	c^{8}_{Qu}	$C^{8(33ii)}_{qu}$	✓					✓	✓	✓	✓
	O1qu	c^{1}_{Qu}	$C^{1(33ii)}_{qu}$	(✓)					(✓)	(✓)	✓	✓
	O8dt	c^{8}_{td}	$C^{8(33ii)}_{ud}$	✓					✓	✓	✓	✓
	O1dt	c^{1}_{td}	$C^{1(33ii)}_{ud}$	(✓)					(✓)	(✓)	✓	✓
	O8qd	c^{8}_{Qd}	$C^{8(33ii)}_{qd}$	✓					✓	✓	✓	✓
	O1qd	c^{1}_{Qd}	$C^{1(33ii)}_{qd}$	(✓)					(✓)	(✓)	✓	✓
$QQ+V,G,\varphi$	OtG	c_{tG}	$\mathrm{Re}\{C^{(33)}_{uG}\}$	✓		✓		✓	✓	✓	✓	✓
	OtW	c_{tW}	$\mathrm{Re}\{C^{(33)}_{uW}\}$		✓	✓	✓					
	ObW	c_{bW}	$\mathrm{Re}\{C^{(33)}_{dW}\}$		(✓)	(✓)	(✓)					
	OtZ	c_{tZ}	$\mathrm{Re}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$				✓		✓			
	Off	$c_{\varphi tb}$	$\mathrm{Re}\{C^{(33)}_{\varphi ud}\}$		(✓)	(✓)	(✓)					
	Ofq3	$c^{3}_{\varphi Q}$	$C^{3(33)}_{\varphi q}$		✓	✓	✓					
	OpQM	$c^{-}_{\varphi Q}$	$C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$				✓		✓			
	Opt	$c_{\varphi t}$	$C^{(33)}_{\varphi u}$				✓		✓			
	Otp	$c_{t\varphi}$	$\mathrm{Re}\{C^{(33)}_{u\varphi}\}$							✓		



Rich phenomenology

34 d.o.f. CP-conserving

[Hartland, FM, Nocera, Rojo, Slade, Vryonidou and Zhang, 2019]

Observables and theory predictions

Data

Top-pair production
W-helicities

4 tops, ttbb, top-pair associated production

Single top
t-channel, s-channel, tW, tZ

One distribution from each dataset, to avoid double counting

Dataset	$\chi^2/n_{\rm dat}$ (prior)	$\chi^2/n_{\rm dat}$ (fit)	$n_{\rm dat}$
ATLAS_tt_8TeV_ljets [$m_{t\bar{t}}$]	1.51	1.25	7
CMS_tt_8TeV_ljets [$y_{t\bar{t}}$]	1.17	1.17	10
CMS_tt2D_8TeV_dilep [$(m_{t\bar{t}}, y_t)$]	1.38	1.38	16
CMS_tt_13TeV_ljets2 [$m_{t\bar{t}}$]	1.09	1.28	8
CMS_tt_13TeV_dilep [$m_{t\bar{t}}$]	1.34	1.42	6
CMS_tt_13TeV_ljets_2016 [$m_{t\bar{t}}$]	1.87	1.87	10
ATLAS_WhelF_8TeV	1.98	0.27	3
CMS_WhelF_8TeV	0.31	1.18	3
CMS_ttbb_13TeV	5.00	1.29	1
CMS_tttt_13TeV	0.05	0.02	1
ATLAS_tth_13TeV	1.61	0.55	1
CMS_tth_13TeV	0.34	0.01	1
ATLAS_ttZ_8TeV	1.32	5.29	1
ATLAS_ttZ_13TeV	0.01	1.06	1
CMS_ttZ_8TeV	0.04	0.06	1
CMS_ttZ_13TeV	0.90	0.67	1
ATLAS_ttW_8TeV	1.34	0.27	1
ATLAS_ttW_13TeV	0.82	0.65	1
CMS_ttW_8TeV	1.54	0.54	1
CMS_ttW_13TeV	0.03	0.09	1
CMS_t_tch_8TeV_dif	0.11	0.32	6
ATLAS_t_tch_8TeV [y_t]	0.91	0.43	4
ATLAS_t_tch_8TeV [$y_{\bar{t}}$]	0.39	0.45	4
ATLAS_t_sch_8TeV	0.08	1.92	1
ATLAS_t_tch_13TeV	0.02	0.09	2
CMS_t_tch_13TeV_dif [y_t]	0.46	0.49	4
CMS_t_sch_8TeV	1.26	0.76	1
ATLAS_tW_inc_8TeV	0.02	0.06	1
CMS_tW_inc_8TeV	0.00	0.07	1
ATLAS_tW_inc_13TeV	0.52	0.82	1
CMS_tW_inc_13TeV	4.29	1.68	1
ATLAS_tZ_inc_13TeV	0.00	0.00	1
CMS_tZ_inc_13TeV	0.66	0.34	1
Total	**1.11**	**1.06**	**103**

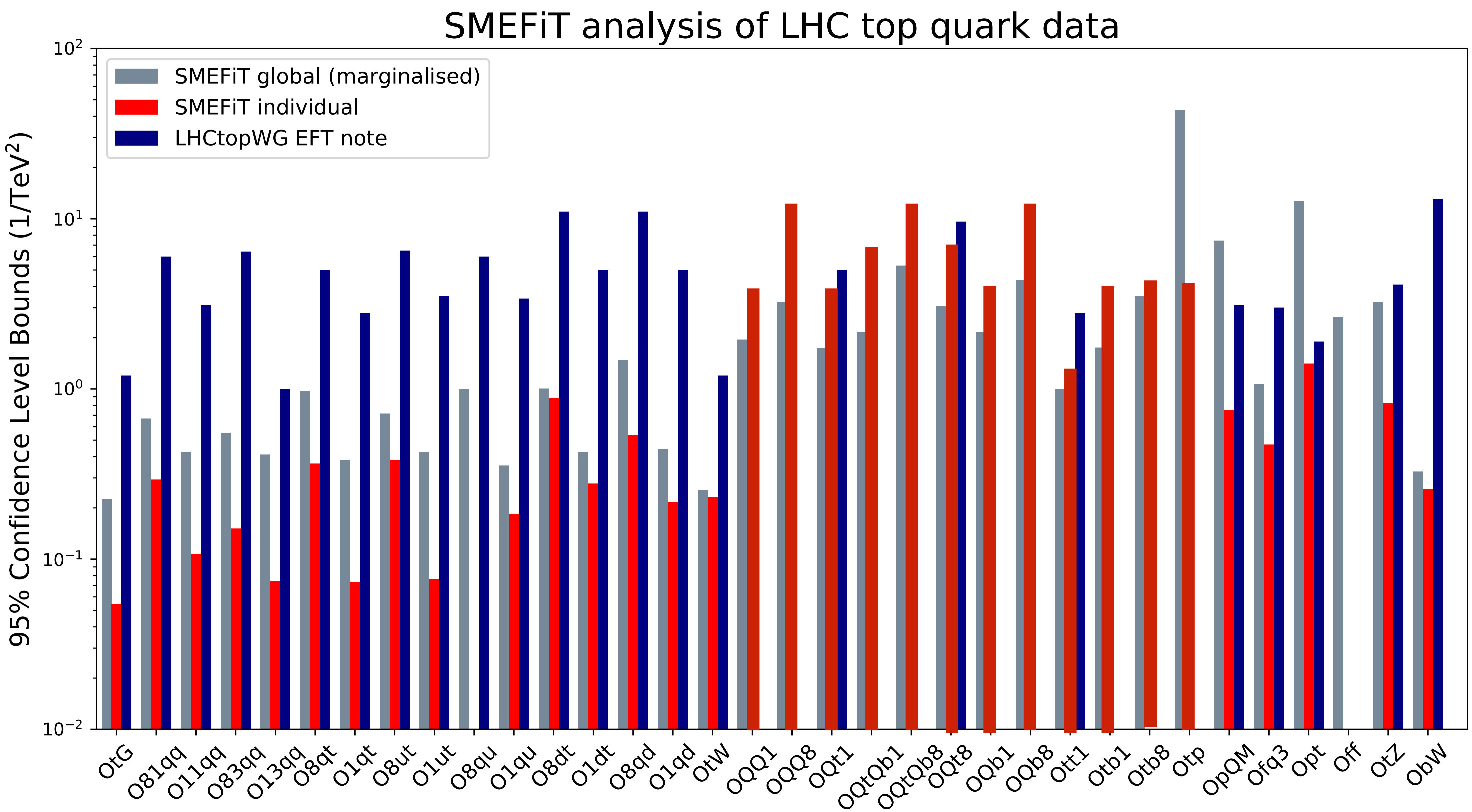
Theoretical predictions

Process	SM	SMEFT
$t\bar{t}$	NNLO QCD	NLO QCD
single-t (t-ch)	NNLO QCD	NLO QCD
single-t (s-ch)	NLO QCD	NLO QCD
tW	NLO QCD	NLO QCD
tZ	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}W(Z)$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}h$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}t\bar{t}$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}b\bar{b}$	NLO QCD	LO QCD + NLO SM K-factors

Baseline fit includes:

- Best available SM predictions
- NLO EFT predictions
- $O(1/\Lambda^4)$ terms

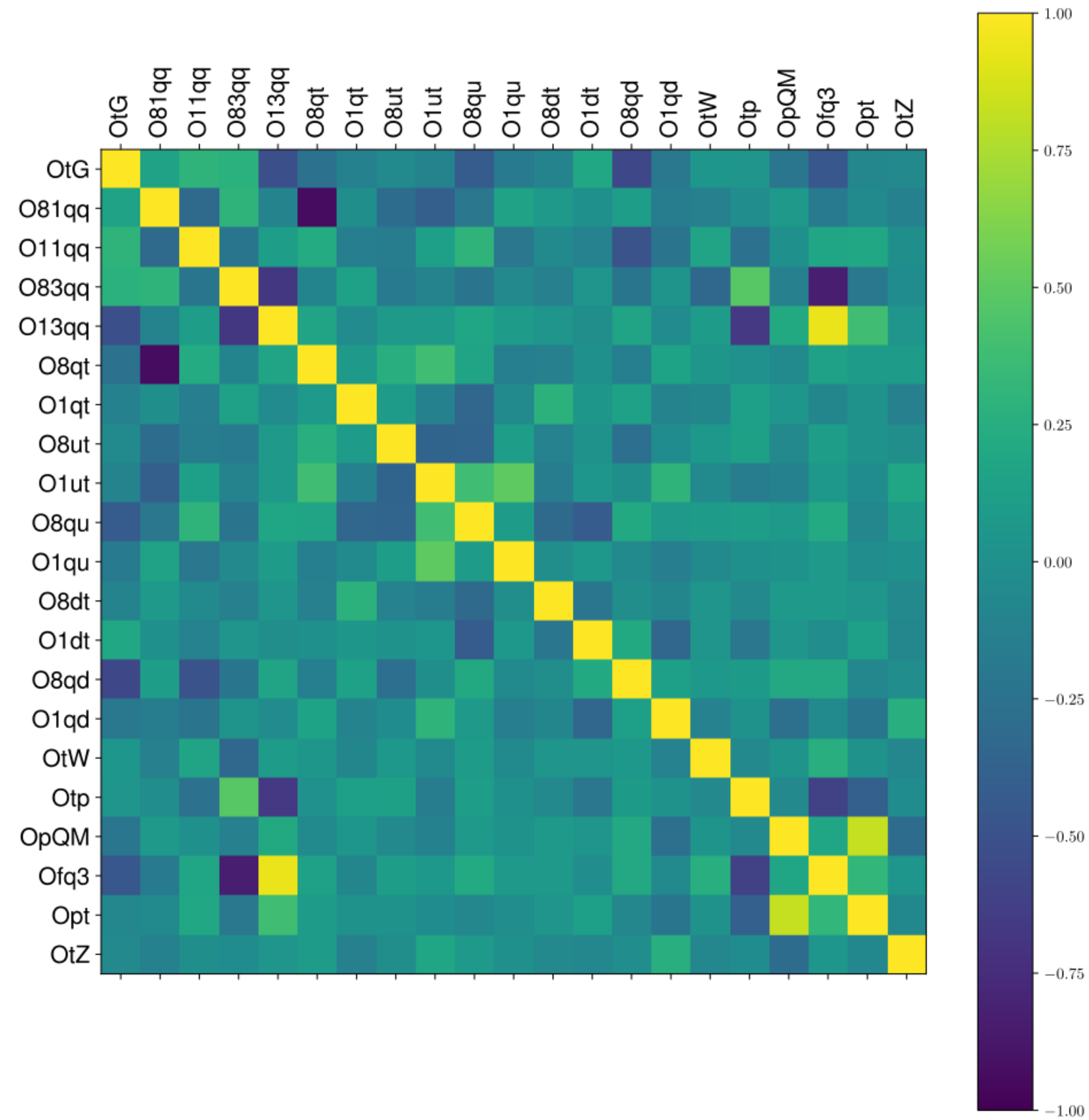
Results



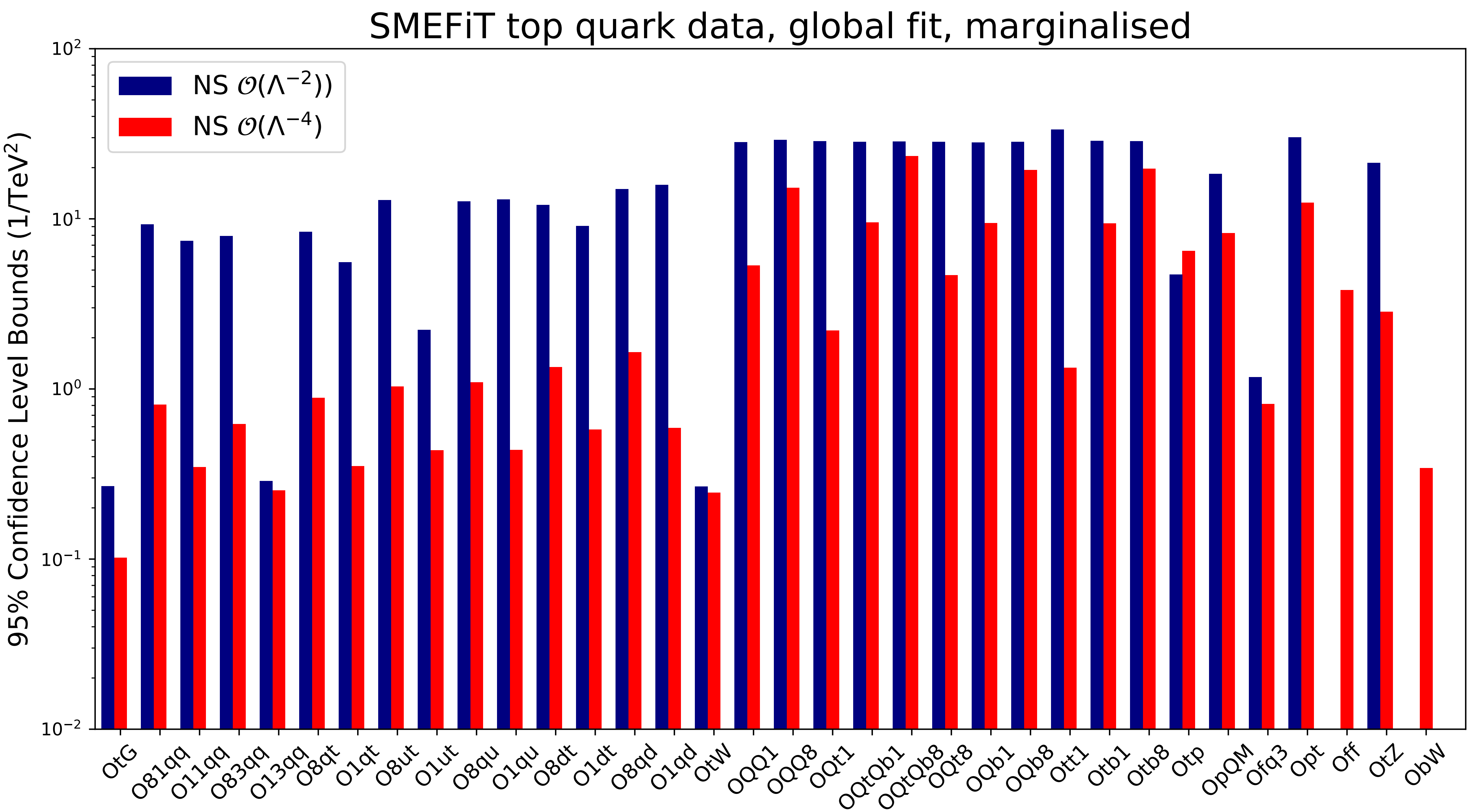
N. Hartland et. al. JHEP 1904 (2019) 100, updated

Results

- Correlations of fit parameters via color map
- Not all parameters completely independent!



Linear vs quadratic



Top-philic scenario

- Same flavour symmetries as baseline scenario (MFV : $U(2)_q \times U(2)_u \times U(2)_d$)
- Assumes new physics couples more strongly to 3rd-generation LH doublet and RH up-type singlet (+ bosons)

$$c_{t\varphi}^{[I]}, \quad c_{\varphi Q}^{-}, \quad c_{\varphi Q}^{3}, \quad c_{\varphi t}, \quad c_{tW}^{[I]}, \quad c_{tZ}^{[I]}, \quad c_{tG}^{[I]},$$

$$c_{\varphi tb}^{[I]} \text{ and } c_{bW}^{[I]} \quad \text{appear proportional to } y_b$$

$$c_{QQ}^{1}, \quad c_{QQ}^{8}, \quad c_{Qt}^{1}, \quad c_{Qt}^{8}, \quad c_{tt}^{1},$$

$$c_{QDW} = c_{Qq}^{3,1} = c_{Ql}^{3(\ell)},$$

$$c_{QDB} = 6c_{Qq}^{1,1} = \frac{3}{2}c_{Qu}^{1} = -3c_{Qd}^{1} = -3c_{Qb}^{1} = -2c_{Ql}^{1(\ell)} = -c_{Qe}^{(\ell)},$$

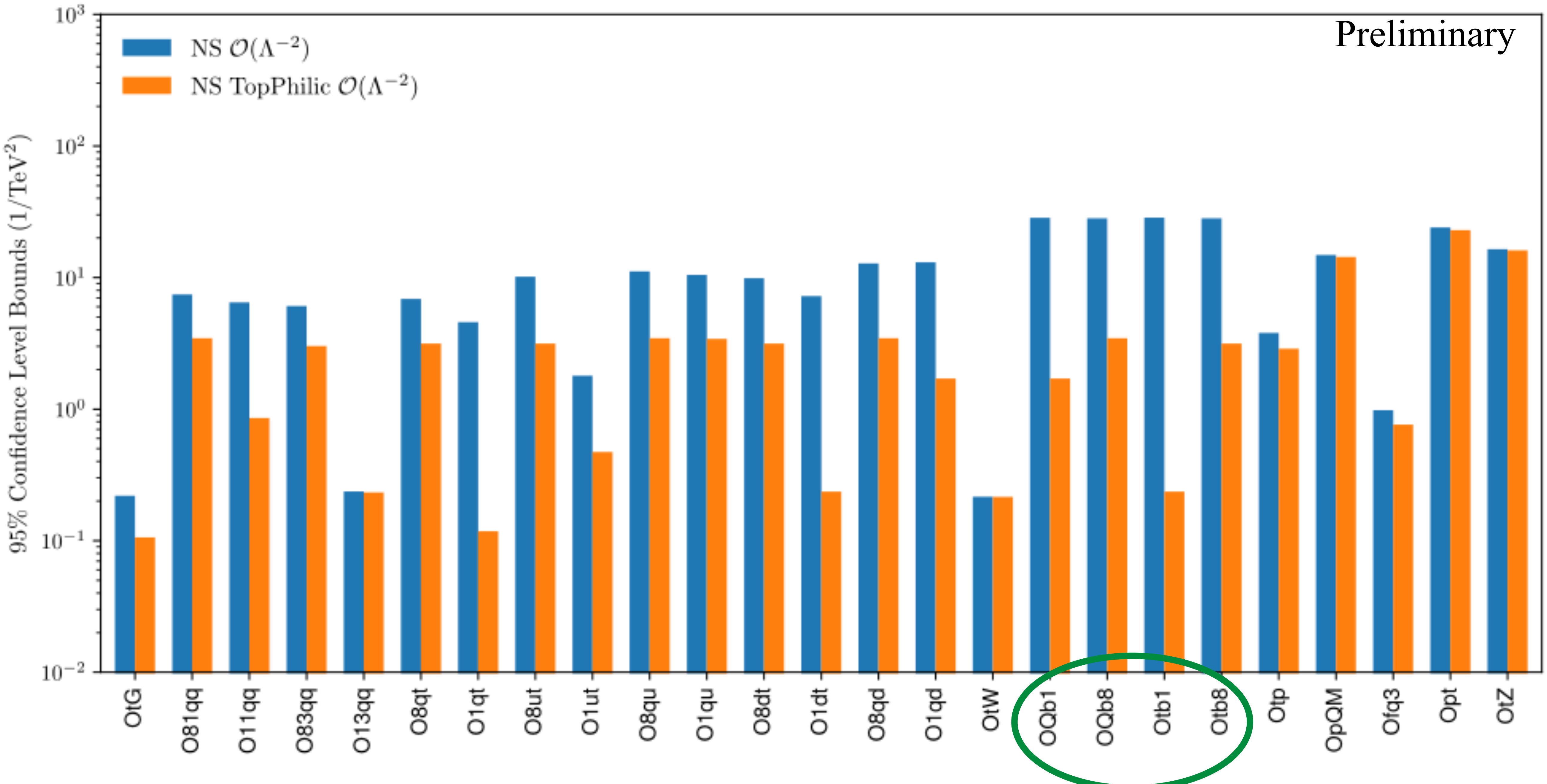
$$c_{tDB} = 6c_{tq}^{1} = \frac{3}{2}c_{tu}^{1} = -3c_{td}^{1} = -3c_{tb}^{1} = -2c_{tl}^{(\ell)} = -c_{te}^{(\ell)},$$

$$c_{QDG} = c_{Qq}^{1,8} = c_{Qu}^{8} = c_{Qd}^{8} = c_{Qb}^{8},$$

$$c_{tDG} = c_{tq}^{8} = c_{tu}^{8} = c_{td}^{8} = c_{tb}^{8}.$$

- 34 parameter basis reduced to 19 free parameters

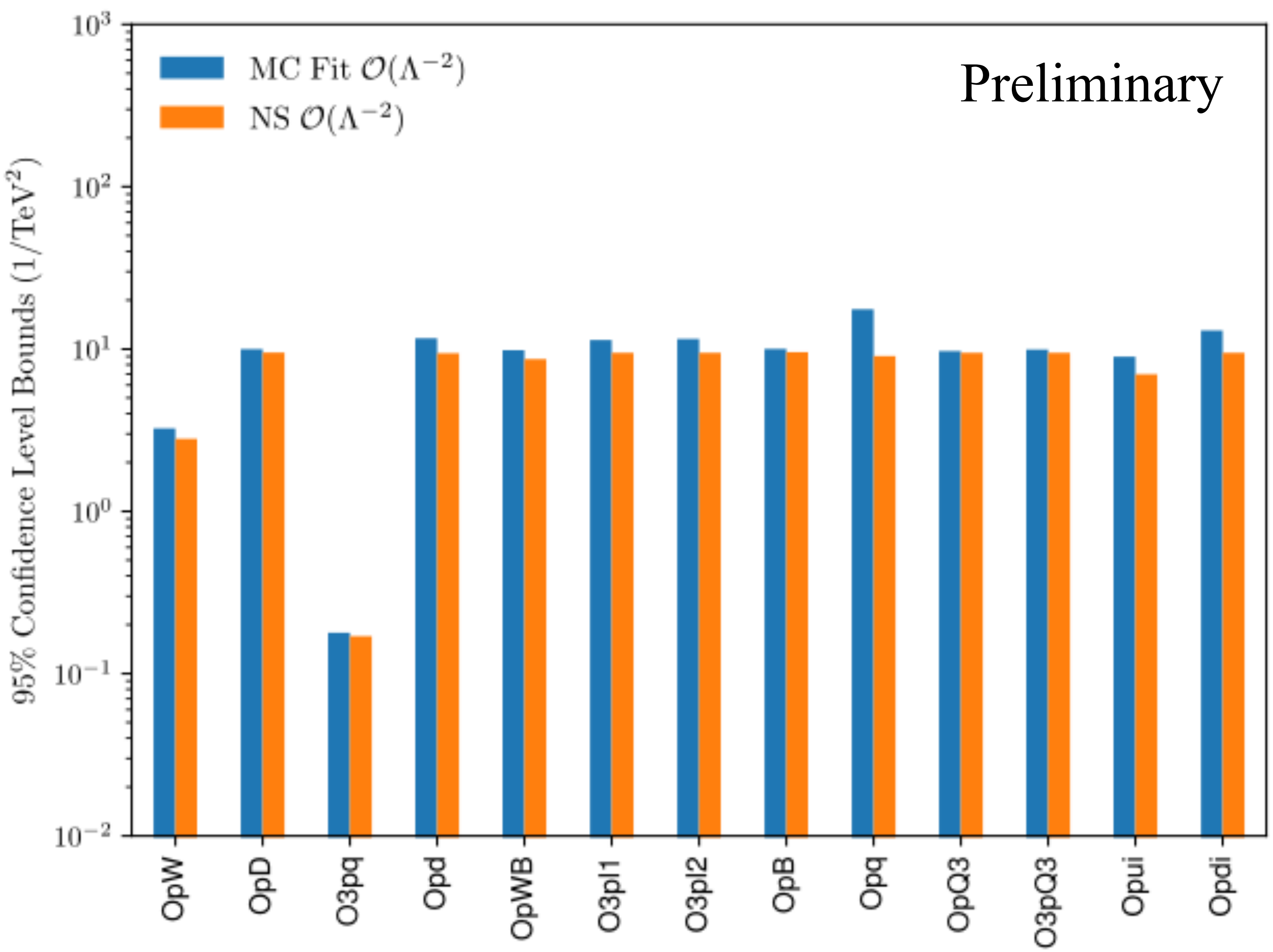
Top-philic scenario



- Significantly stronger constraints with top-philic scenario

Adding the Higgs data

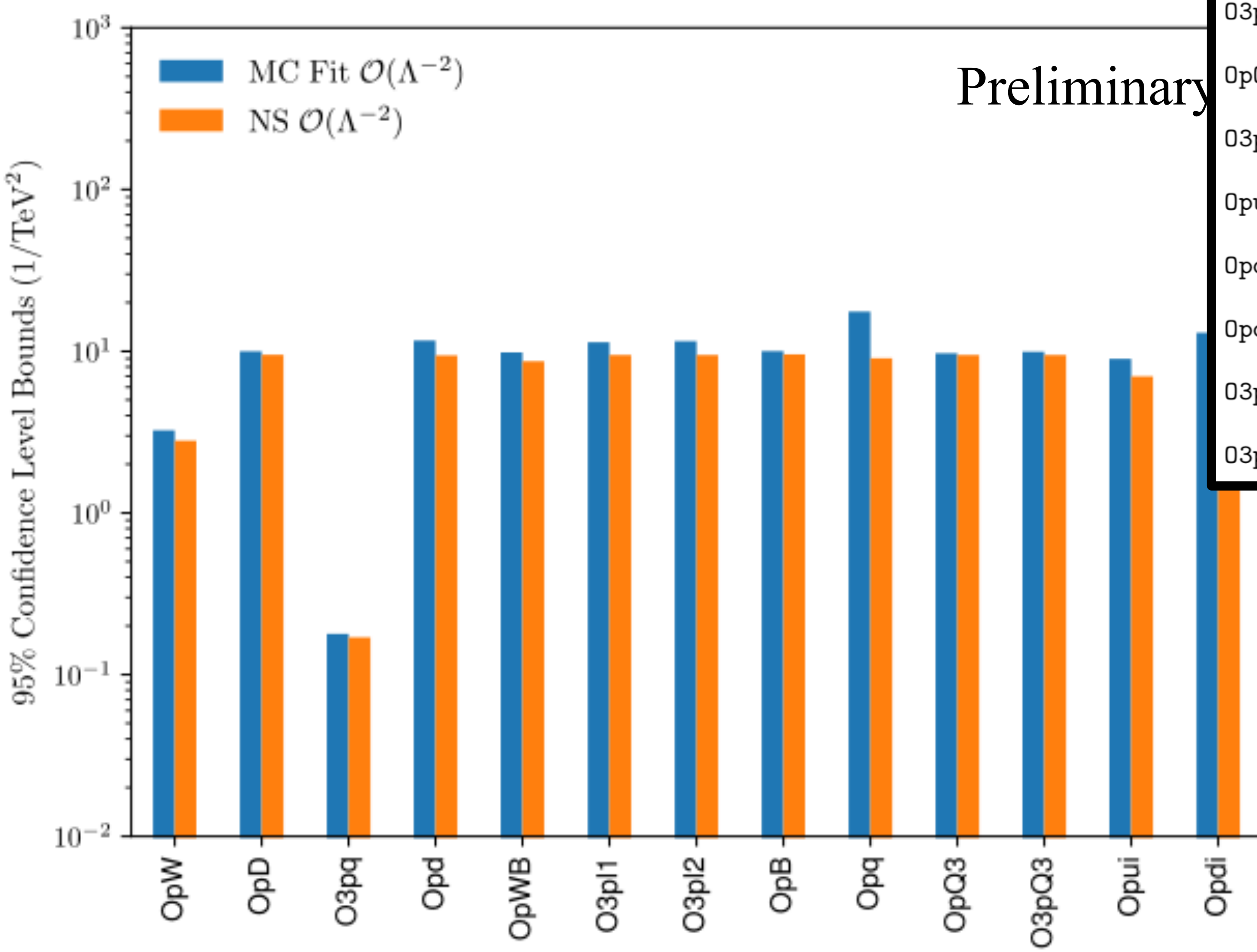
- Analysis of VH production data from ATLAS at 13 TeV
- Single dataset of 5 points
- Same SM prediction as ATLAS analysis



- No interference with top sector
- Total error dominated by statistical uncertainties – reflects in resulting coefficient bounds

Adding the Higgs data

- Analysis of VH production data from ATLAS at 13 TeV
- Single dataset of 5 points
- Same SM prediction as ATLAS analysis

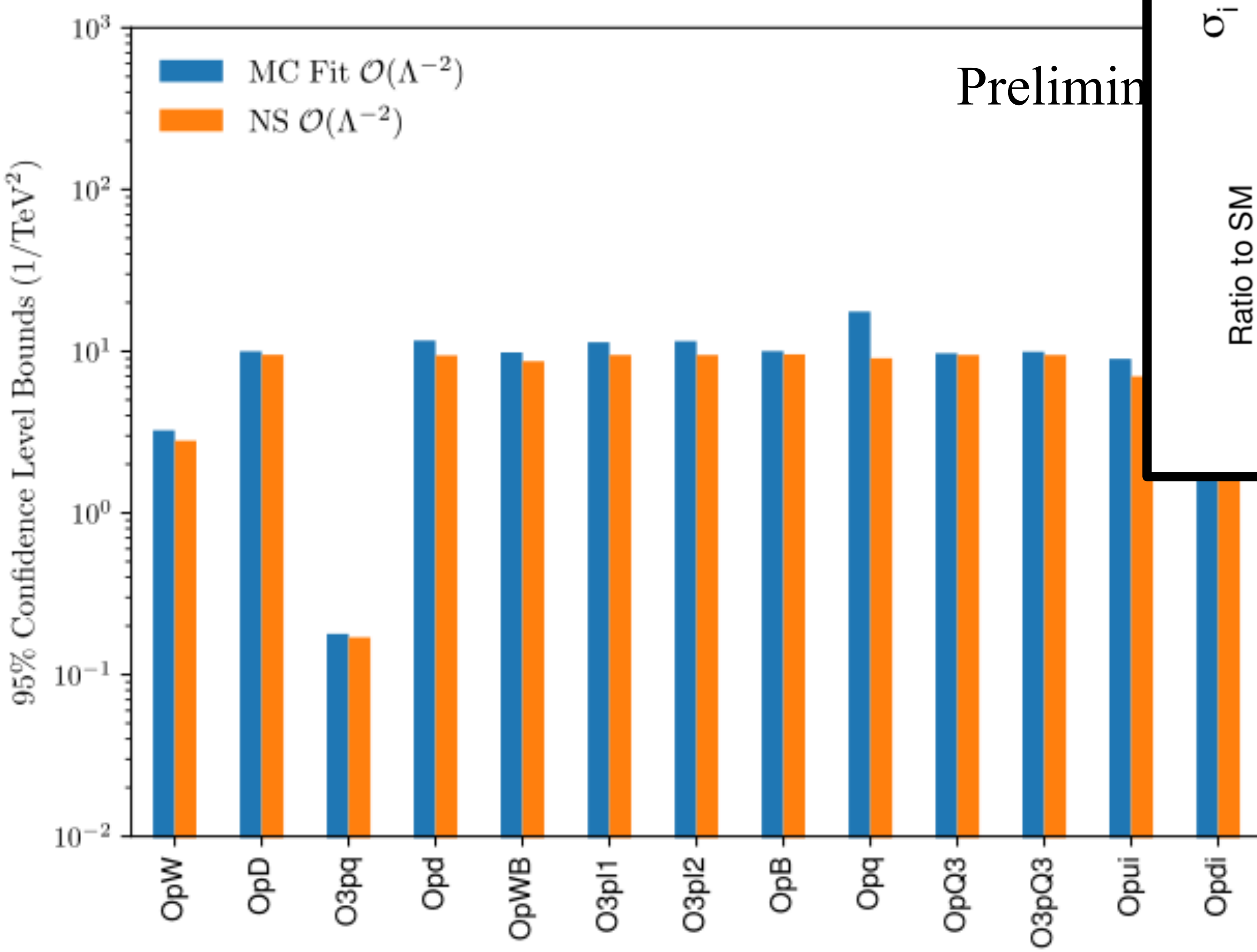


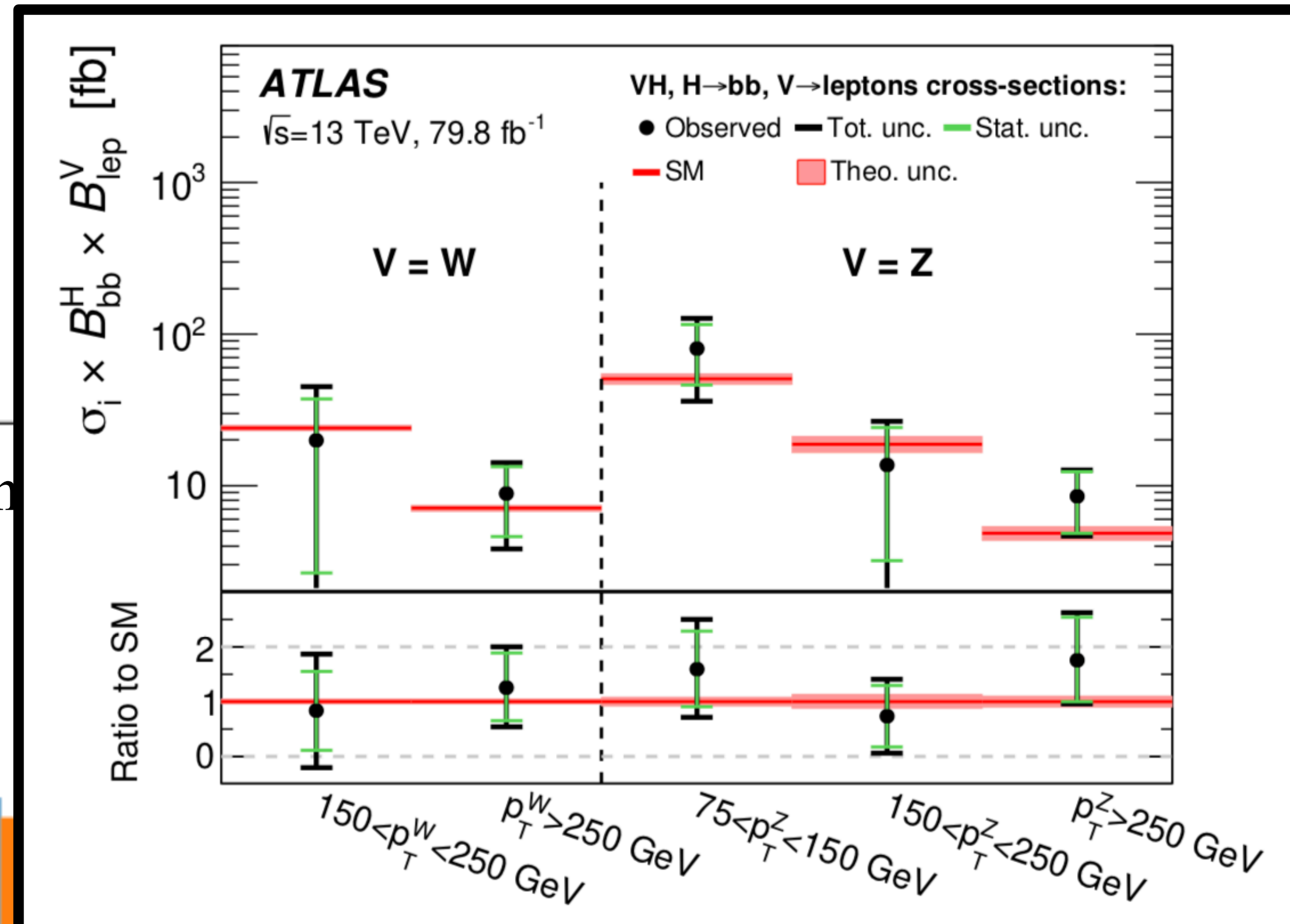
Operator	Wilson Coefficient	Degree of Freedom	Operator Definition
OpW	cpW	$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$
OpB	cpB	$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$
OpWB	cpWB	$\mathcal{O}_{\varphi WB}$	$\left(\varphi^\dagger \tau_I \varphi\right) B^{\mu\nu} W^I_{\mu\nu}$
OpD	cpDC	$\mathcal{O}_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\dagger \left(\varphi^\dagger D_\mu \varphi\right)$
Opq	cpqi	$\mathcal{O}^{(1)}_{\varphi q_i}$	$\sum_{j=1,2} i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{q}_j \gamma^\mu q_j\right)$
O3pq	c3pqi	$\mathcal{O}^{(3)}_{\varphi q_i}$	$\sum_{j=1,2} i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi\right)\left(\bar{q}_j \gamma^\mu \tau^I q_j\right)$
OpQ3	cpQ3	$\mathcal{O}^{(1)}_{\varphi Q}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\,\gamma^\mu Q\right)$
O3pQ3	c3pQ3	$\mathcal{O}^{(3)}_{\varphi Q}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi\right)\left(\bar{Q}\,\gamma^\mu \tau^I Q\right)$
Opui	cpu	$\mathcal{O}_{\varphi u_i}$	$\sum_{j=1,2} i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{u}_j \gamma^\mu u_j\right)$
Opdi	cpd	$\mathcal{O}_{\varphi d_i}$	$\sum_{j=1,2(,3)} i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{d}_j \gamma^\mu d_j\right)$
Opd	cdp	$\mathcal{O}_{\varphi d}$	$\partial_\mu\left(\varphi^\dagger\varphi\right)\partial^\mu\left(\varphi^\dagger\varphi\right)$
O3pl1	c3pl1	$\mathcal{O}^{(3)}_{\varphi l_1}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi\right)\left(\bar{l}_1 \gamma^\mu \tau^I l_1\right)$
O3pl2	c3pl2	$\mathcal{O}^{(3)}_{\varphi l_2}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi\right)\left(\bar{l}_2 \gamma^\mu \tau^I l_2\right)$

- No interference with top sector
- Total error dominated by statistical uncertainties – reflects in resulting coefficient bounds

Adding the Higgs data

- Analysis of VH production data from ATLAS at 13 TeV
- Single dataset of 5 points
- Same SM prediction as ATLAS analysis





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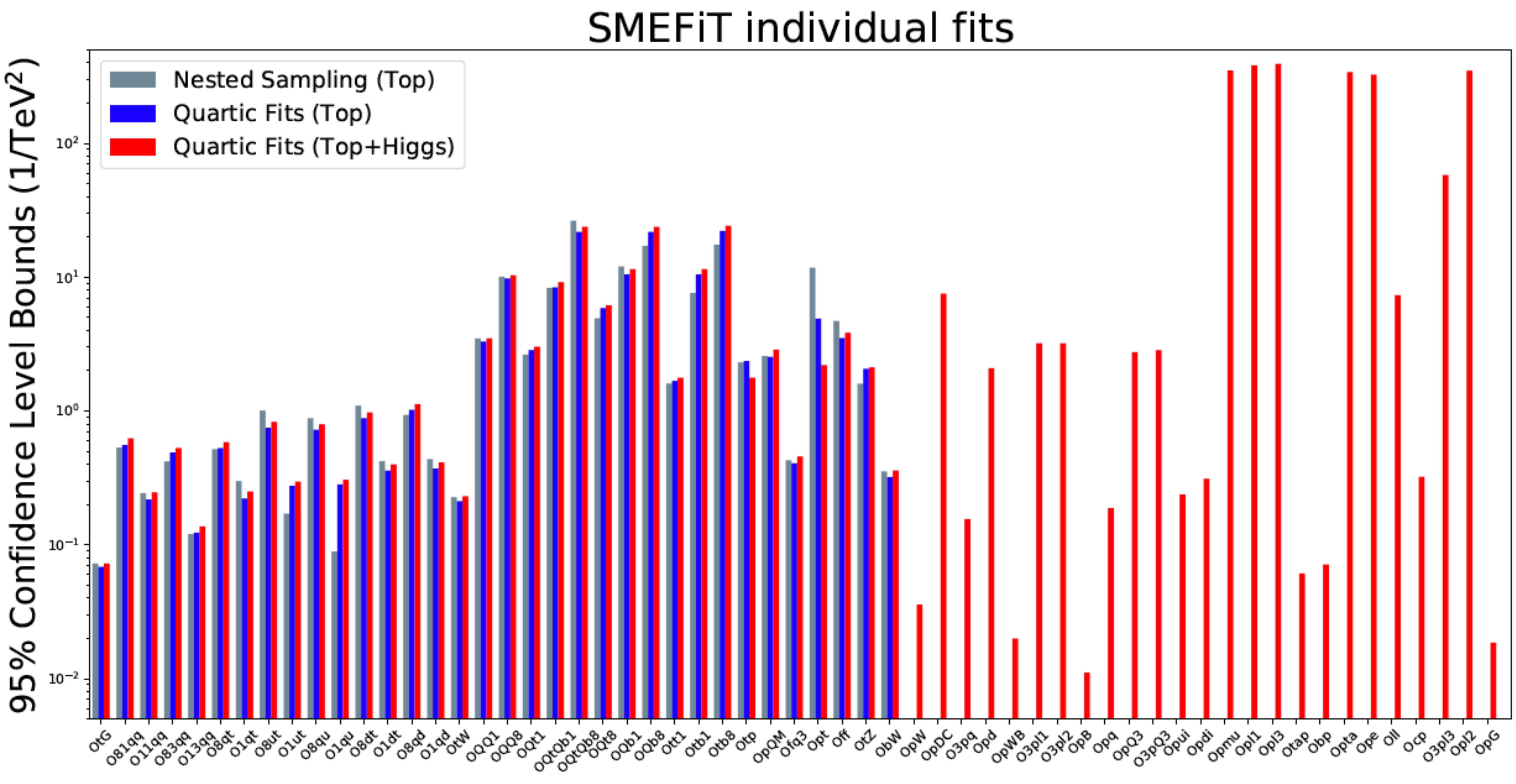
Towards a global top/H/EW fit…



Plan for today's lecture

- SMEFT essentials
- The SMEFT precision frontier
- Example: Fitting in the Top (with Higgs/EW) sector
- Bringing the lesson home

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TRUE or FALSE?

10 questions you always wanted to know about the SMEFT and never dared to ask

[Contino et al. , 1604.06444] [Aguilar-Saavedra ,1802.07237] [Many discussions…]

Λ is the scale of New Physics

1

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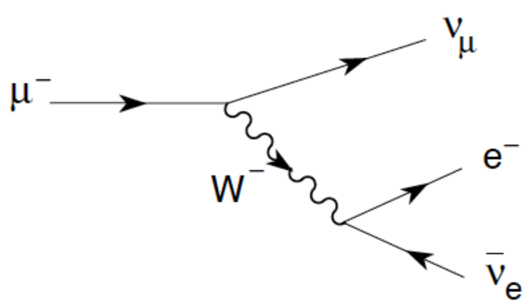
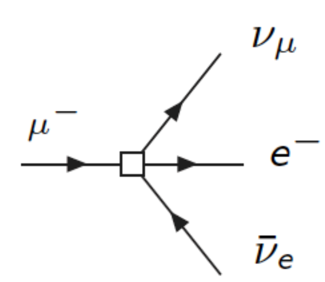
Consider the case of the Fermi theory of the muon decay:



$$\mathbf{g^2}\,\frac{-g_{\mu\nu}+\frac{q_\mu q_\nu}{M_W^2}}{q^2-M_W^2}\xrightarrow{q^2\ll M_W^2}\frac{g_{\mu\nu}}{M_W^2}\,\mathbf{g^2}$$



$$\frac{G_F}{\sqrt{2}}\;\psi\,\psi\,\psi\,\psi$$

From the measured value of the Fermi constant G_F

$$\frac{G_F}{\sqrt{2}}=\left(\frac{g}{2\sqrt{2}}\right)^2\frac{1}{m_W^2}=\frac{1}{2v^2}$$

So (4 pi) v is the upper bound on the scale of New Physics. If the theory is weakly interacting the first massive state will have mass of the order g v << v. If the theory is strongly interacting, g ~4 pi, (4 pi) v will coincide with the scale of NP.

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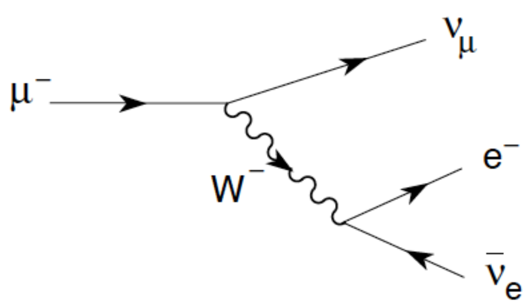

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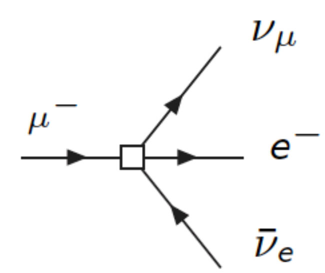

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1

Note: Reinstating dimensions

$$\mathcal{L}_i^{\mathrm{dim}=6} = \frac{g^{n_i-4}}{\Lambda^2}\mathcal{O}_i$$

$$\mathrm{loop-factor} = \frac{g^2\hbar}{(4\pi)^2}$$

$$M = g\Lambda = \mathrm{GeV}$$

$$[G_{\mu\nu}] = \sqrt{\hbar}\ \mathrm{GeV}^2$$

$$[\phi] = [v] = [\Lambda] = \sqrt{\hbar}\ \mathrm{GeV}$$

$$[A_\mu] = \sqrt{\hbar}\ \mathrm{GeV}$$

$$[\psi] = \sqrt{\hbar}\ \mathrm{GeV}^{3/2}$$

$$[g] = [\sqrt{\lambda}] = 1/\sqrt{\hbar}$$

$$\mathcal{L} = \frac{g^2}{\Lambda^2}\phi^6 = \frac{g^4}{M^2}\phi^6$$

$$\mathcal{L} = \frac{g}{\Lambda^2}\phi\phi Q\phi u = \frac{g^3}{M^2}\phi\phi Q\phi u$$

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The aim of an EFT is to reproduce the IR behaviour of (a possibly) wide set of UV theories. However, it always relies on (generic) assumptions on the UV dynamics. The SMEFT@dim6, for examples, assumes:

1. The upper bound on the scale of new physics is Λ.
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Associating a “natural" normalisation to (class of) operators implies a UV bias, either some scaling rules and/or already an interpretation in mind. This is certainly legitimate, yet not necessary at the data analysis stage, if maximal flexibility/generality is desired.

At the SMEFT@dim6 one can work leaving the normalisation arbitrary (i.e. fixing the simplest convention) and just using data to constrain the coefficients. At the end only relations between observables as implied by the model are physically meaningful. And these do not depend on the normalisation.

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The usefulness of the up to $1/\Lambda^2$ approximation will depend:

1. On the assumptions (explicit and implicit) on the UV model.

2. On the specific observables/interactions which might not be sensitive to dim=6 effects. For example a ZZZ vertex appears only at dim=8:

$$ie\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,q_3) = \frac{-e(q_3^2-m_V^2)}{M_Z^2}\left[f_4^V\left(q_3^\alpha g^{\mu\beta}+q_3^\beta g^{\mu\alpha}\right) - f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right],$$

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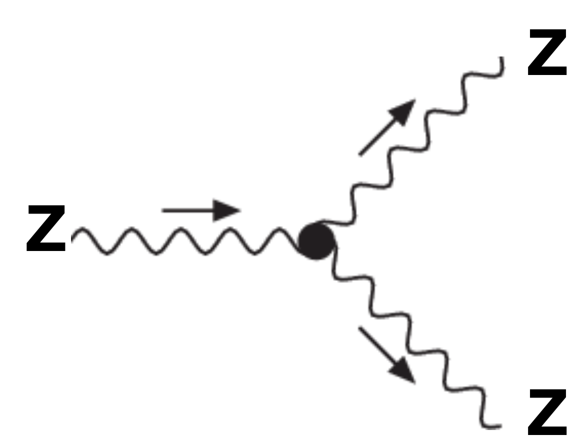

[Degrande, 1308.6323]

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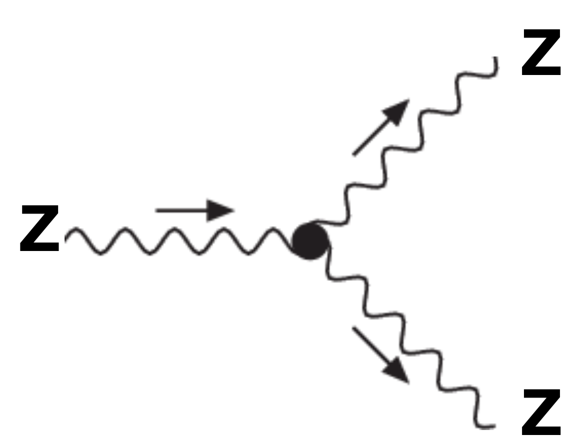

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A necessary condition for the EFT to be consistent is the E<Λ. However, predictions depend on c_i/Λ^2 .

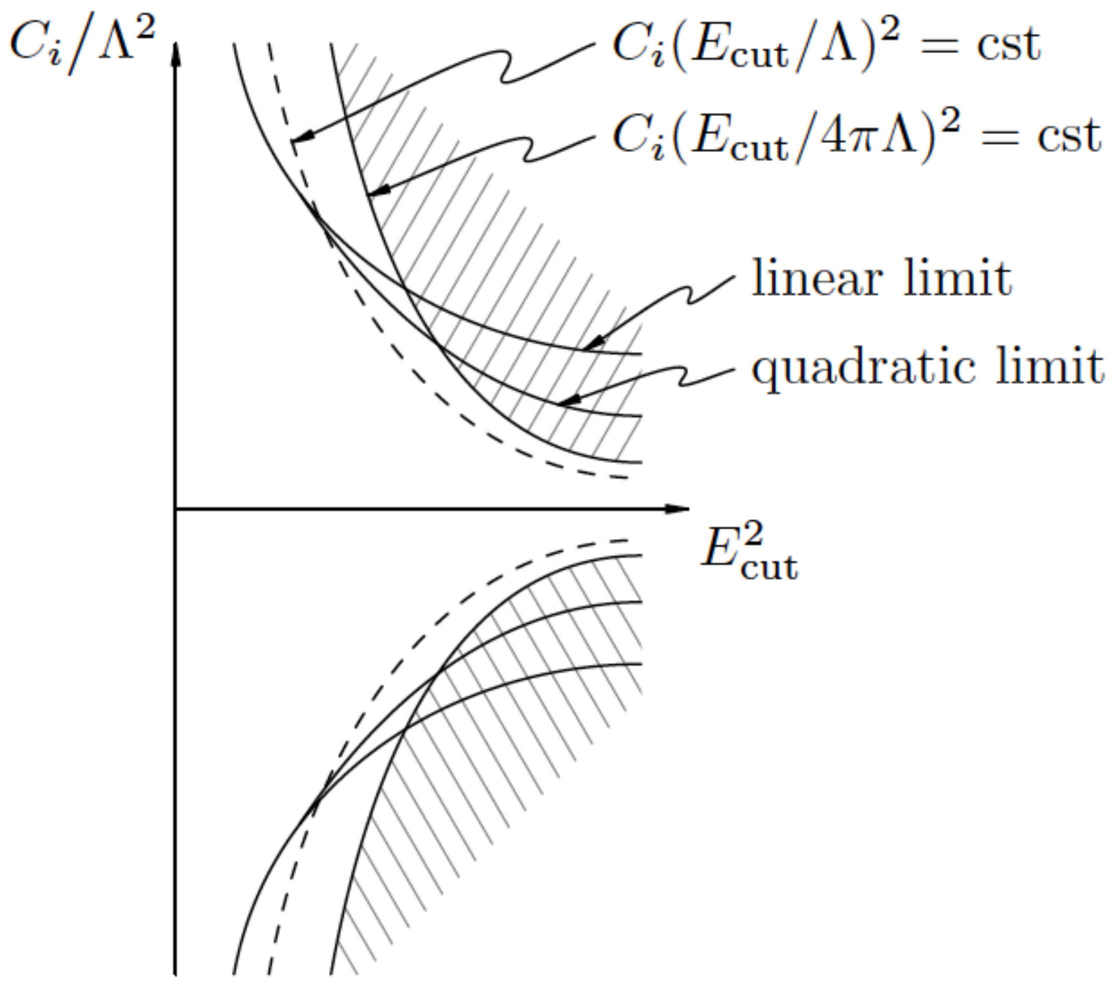

Figure 1: Illustration of the limit set on an EFT parameter as function of a cut on the characteristic energy scale of the process considered (see item 6). Qualitatively, one expects the limits to be progressively degraded as E_{cut} is pushed towards lower and lower values. At high cut values, beyond the energy directly accessible in the process considered, a plateau should be reached. The regions excluded when the dimension-six EFT is truncated to linear and quadratic orders are delimited by solid lines (see item 5c). The hatched regions indicate where the dimension-six EFT loses perturbativity (see item 7). In practice, curves will not be symmetric with respect to $C_i/\Lambda^2 = 0$.

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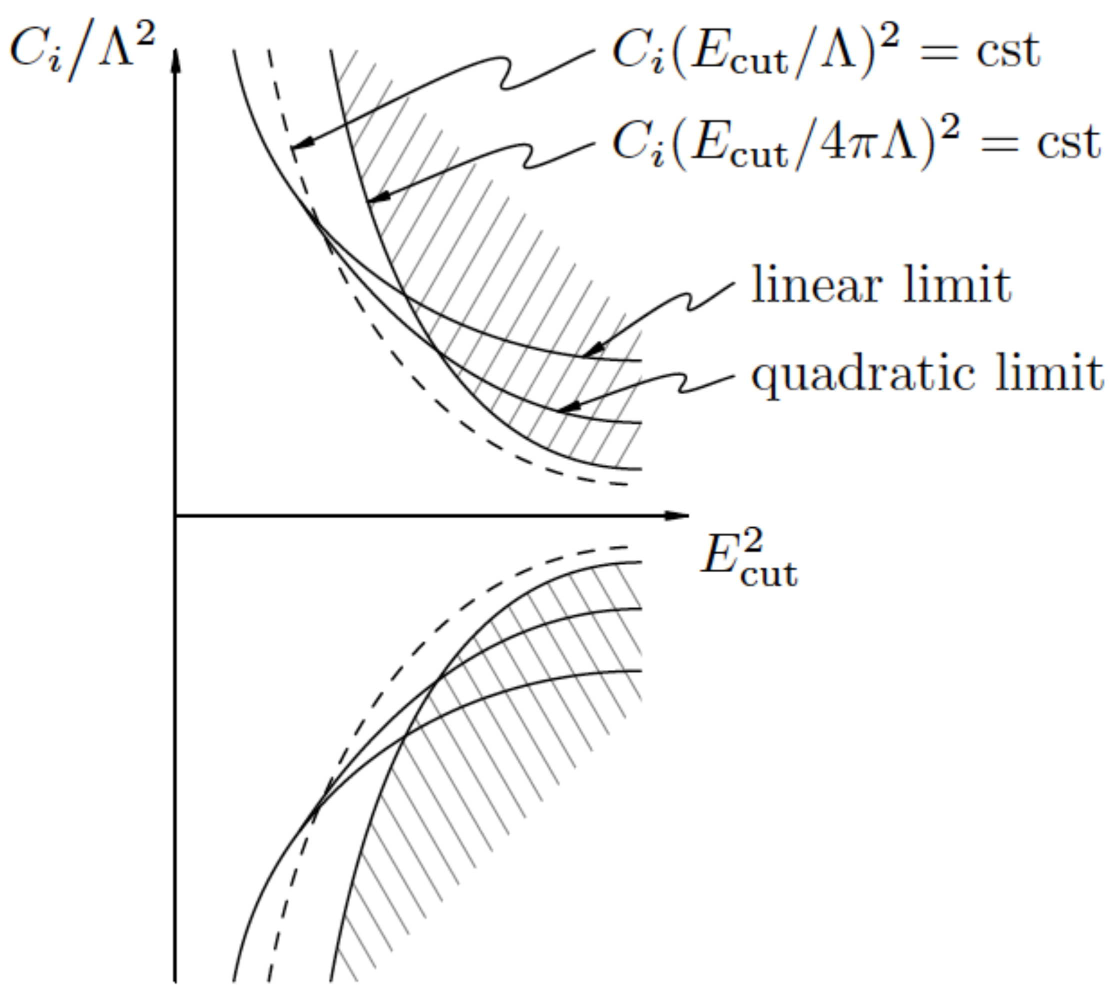

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Squared terms are not uniquely defined and should not be employed in pheno analyses

At the amplitude level:

$$A = A_{\rm SM} + \sum_i \tilde{c}_i^6 A_i^6 + \sum_k \tilde{c}_k^8 A_k^8 + \ldots$$

At $1/\Lambda^2$ level, the dim=6 term is uniquely defined. One can change the basis, perform field redifinitions, use the EOM, yet the full blue sum remains the same, generating however, corrections of order $1/\Lambda^4$, feeding into the red term . This means that

$$|A|^2 = |A_{\rm SM} + \sum_i \tilde{c}_i^6 A_i^6|^2$$

$$= |A_{\rm SM}|^2 + 2\sum_i \tilde{c}_i^6 \,\mathrm{Re}\left[A_{\rm SM}^* A_i^6\right] + \sum_{ij} \tilde{c}_i^6 \tilde{c}_j^{6*} A_i^{6*} A_j^6$$

is parametrisation invariant. The last term is order $1/\Lambda^4$, yet uniquely defined.

7

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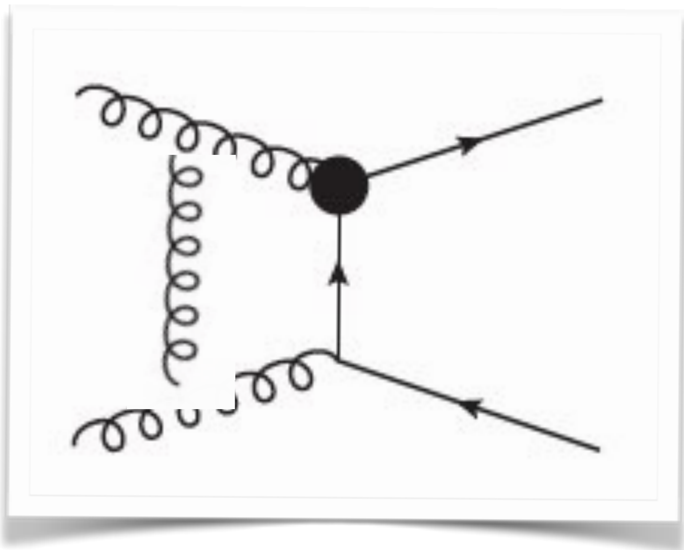
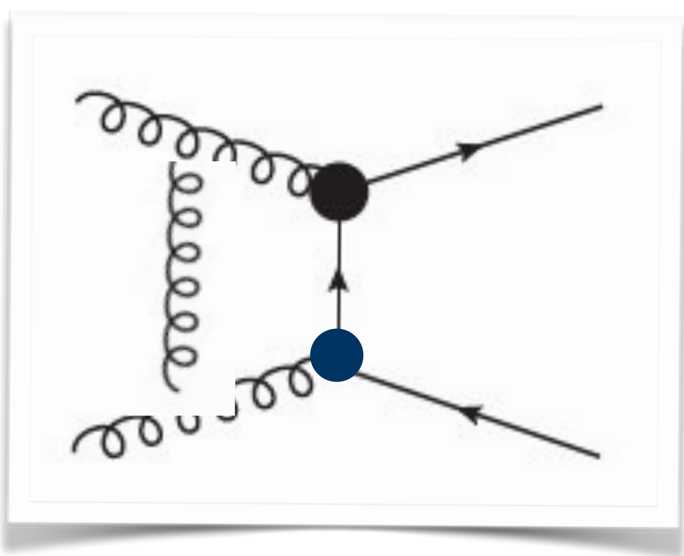


This amplitude will need max dim=6 operators for renormalisation



This amplitude will generically need dim=8 operators for renormalisation

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In many cases the squared term should be included and in any case can be included:

1) If the interference term is highly suppressed because of symmetries (such as absence of FCNC at the tree-level in the SM) or selection rules (helicity selection for VV productions, i.e. the GGG operator in gg→gg), the squared term is always the dominant contribution.

2) There are UV models, for which the squared terms are foreseen to be the dominant $1/\Lambda^4$ contributions:

$$C_i^2 \frac{E^4}{\Lambda^4} > C_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

EFT condition satisfied but $O(1/\Lambda^4)$ large for large operator coefficients

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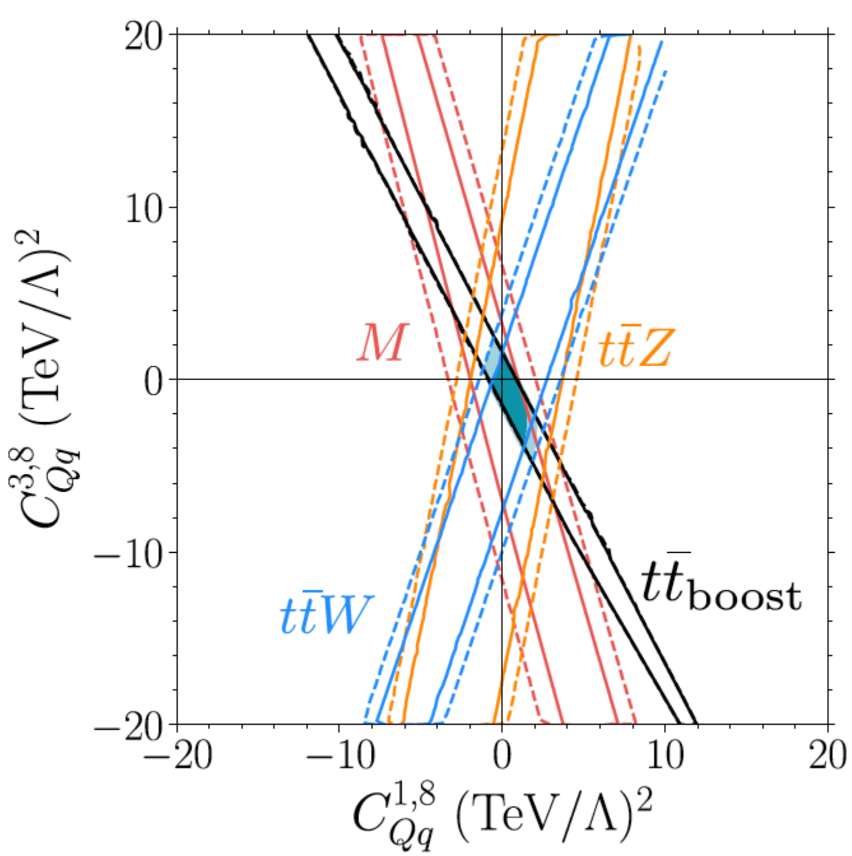
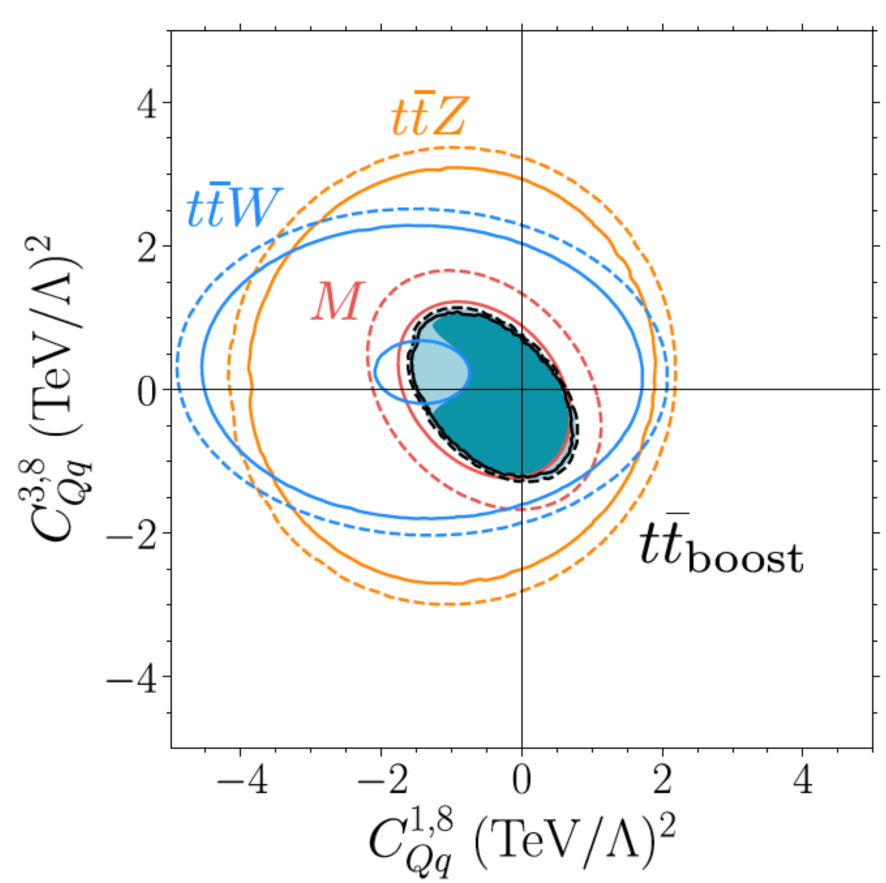
At the fitting level the squared can have an important effect, as there are no flat directions in the fit with the squares:

[Brivio et al. , 1910.03606]





In general without knowing the effect of the squares one is left in the dark about meaning/reliabilty of the fit.

Provide constraints using i) linear and ii) linear+squared terms

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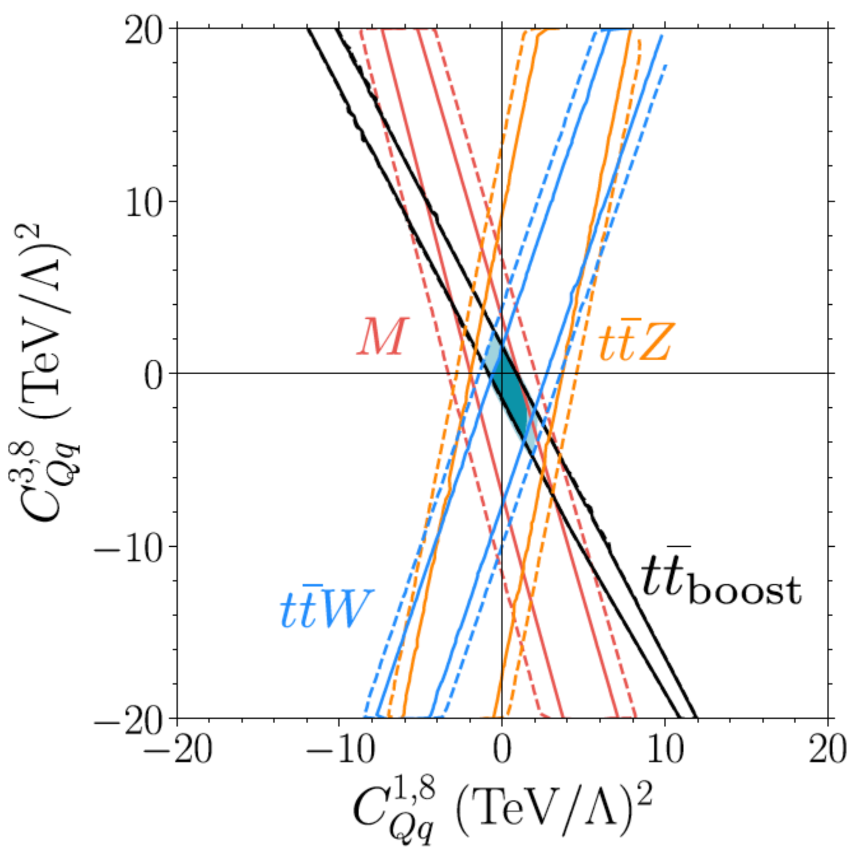

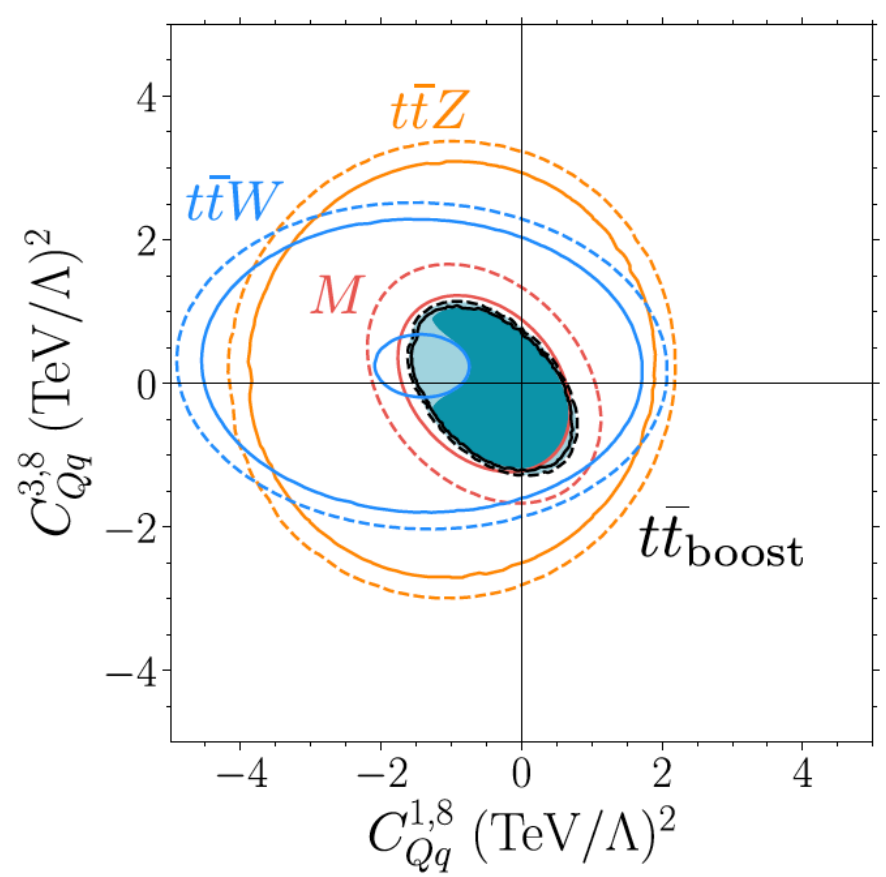

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If a light resonance is found, the EFT approach is of no use

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There are at least two cases where this will not be the case:

1. The new resonance is quite heavy with respect to the collider energy and no other states are found ⇒ it could be the first of particle of a new heavy sector. EFT can include it and search for indirect effects of other states/phenomena.

2. The new resonance is light and very weakly interacting (like an axion) so that it does not impact collider phenomenology.

$v = 246\,\text{GeV}$, $f_a \sim 2 \times 10^{12}\,\text{GeV}$, $v/f_a \sim 10^{-10}$, $m_a \sim 2\mu\text{eV}$. Need

$$-\frac{g^2}{2M_W^2} + \frac{1}{f_a^2}\frac{q^2}{q^2 - m_a^2} = -\frac{2}{v^2}\left[1 + \frac{v^2}{2f_a^2}\frac{q^2/m_a^2}{q^2/m_a^2 - 1}\right]$$

$$\left|\frac{q^2}{m_a^2} - 1\right| \sim \frac{v^2}{f_a^2} \sim 10^{-20} \implies \Delta q \sim 10^{-25}\,\text{GeV}$$

Ex. by Manohar

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It is true that the SMEFT approach is global in nature. This is due to RGE, reparametrisation invariance, and so on. However, individual constraints and constraints on subsets are extremely useful. For example:

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2. Using pairs or triplets to understand the correlations and the flat directions and how to break them.

3. Technically, it might be complicated to include all operators in an analysis. However, having previous knowledge about where the sensitivity of an operator comes from, bounds from other processes/experiments, RGE information and, if desired, also UV model dependent information, one can establish a hierarchy and make maximal use of experimental information.

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Understanding and quantifying the higher order effects in the SMEFT is needed because of many reasons:

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2. NLO brings more accurate central values (k-factors) and reduction of the uncertainties (which can be gauged with the scale dependence, including EFT.

3. NLO QCD effects are important at the LHC, due to the nature of the collision. Not only rates can be greatly affected but also distributions.

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A quote

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Sun Tzu, The Art of War

A special thanks to

Ken Mimasu and Eleni Vryonidou

for providing material and insights for this lecture

General SMEFT Strategy

Courtesy of Ken Mimasu

General SMEFT Strategy

Basis

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General SMEFT Strategy

Basis

Warsaw, SILH, HISZ, Higgs Basis

Courtesy of Ken Mimasu

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Warsaw, SILH, HISZ, Higgs Basis

Flavor assumptions

Universal, diagonal, 3rd gen, general?

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Warsaw, SILH, HISZ, Higgs Basis

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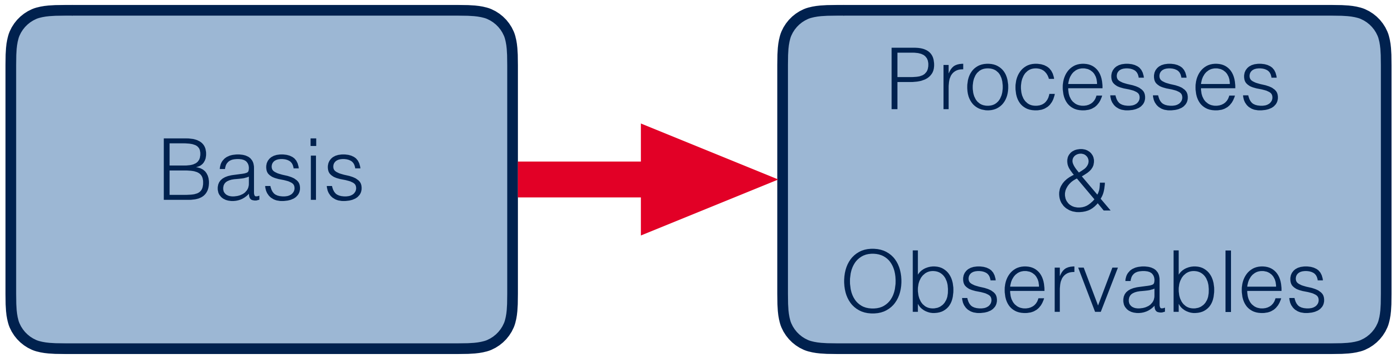
Universal, diagonal, 3rd gen, general?

Symmetries

CP, Baryon/Lepton number?

Courtesy of Ken Mimasu

General SMEFT Strategy



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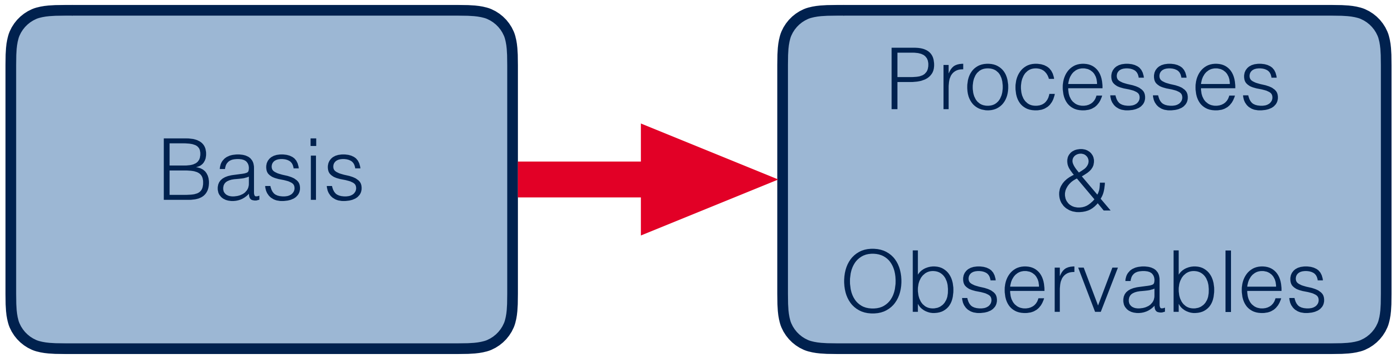

$$\sigma_{\text{tot.}}\,, \qquad \mu = \frac{\sigma}{\sigma_{\text{SM}}}$$

Courtesy of Ken Mimasu

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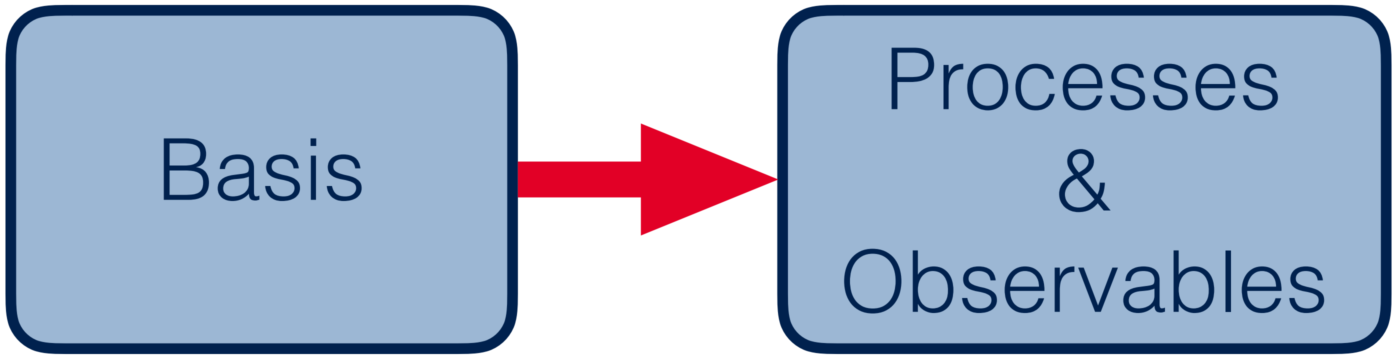


$$\sigma_{\text{tot.}}\,, \qquad \mu = \frac{\sigma}{\sigma_{\text{SM}}}$$

Differential

Courtesy of Ken Mimasu

General SMEFT Strategy

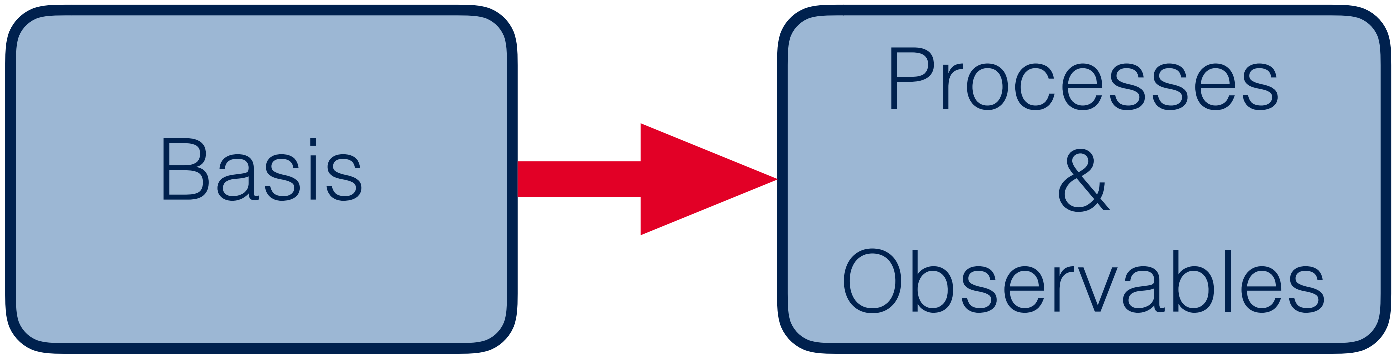
Basis → Processes & Observables

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

Differential $\displaystyle \frac{d\sigma}{dM_{\text{XX}}}$

Courtesy of Ken Mimasu

General SMEFT Strategy



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Differential $\quad \dfrac{d\sigma}{dM_{\text{XX}}} \quad$ *energy, angular*

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High-level

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High-level *optimal observables*

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NN-output

Courtesy of Ken Mimasu

General SMEFT Strategy

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General SMEFT Strategy

Determine dependence on
Wilson coefficients

Courtesy of Ken Mimasu

General SMEFT Strategy

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

Courtesy of Ken Mimasu

General SMEFT Strategy

Basis → Processes & Observables → Sensitivity

Determine dependence on Wilson coefficients

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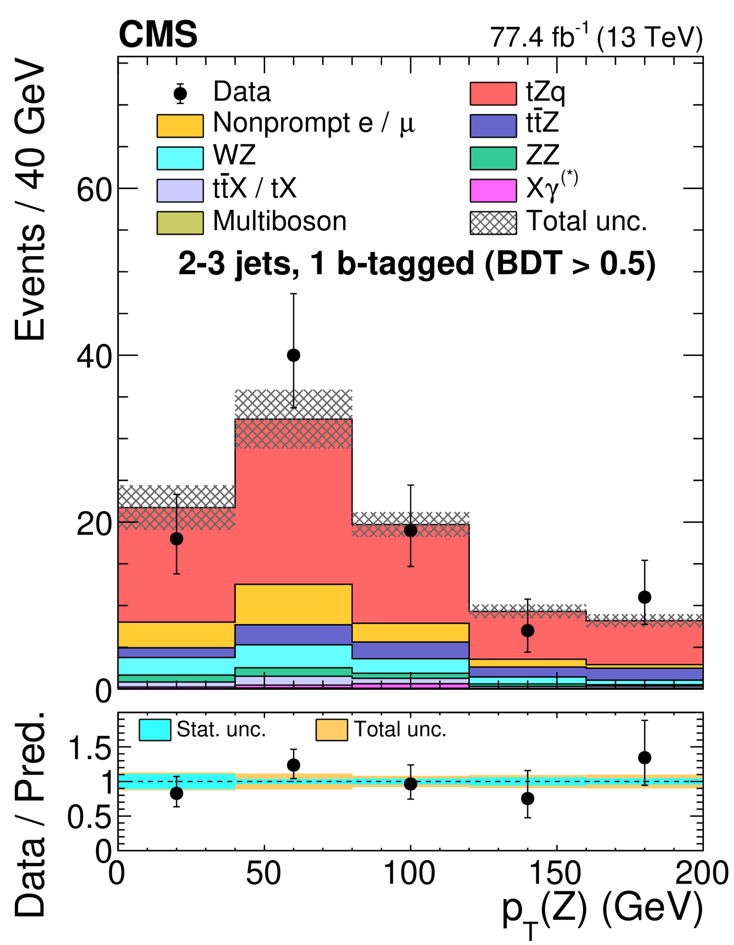
Precise Monte Carlo tools

Courtesy of Ken Mimasu

General SMEFT Strategy

Basis → Processes & Observables → Sensitivity → Measurement

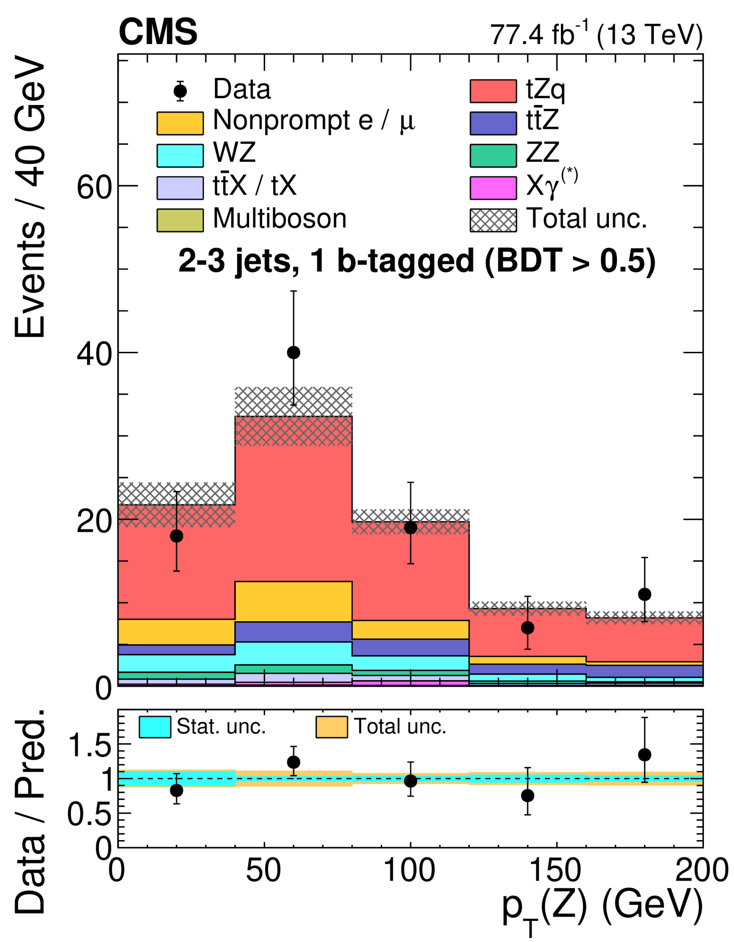


[CMS: PRL 122 (2019) 132003]

Courtesy of Ken Mimasu

General SMEFT Strategy

Basis → Processes & Observables → Sensitivity → Measurement



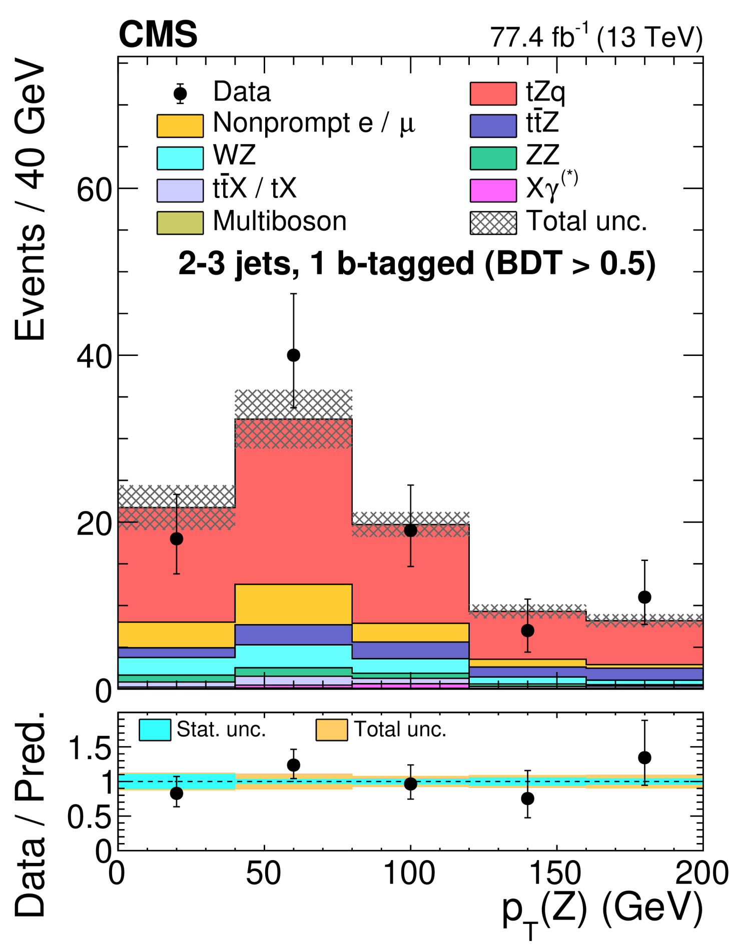
Fiducial volume

Not sensitive to deviations outside acceptance (model dependent)

Courtesy of Ken Mimasu [CMS, PRL 122 (2019) 132003]

General SMEFT Strategy

Basis → Processes & Observables → Sensitivity → Measurement



Fiducial volume

Not sensitive to deviations outside acceptance (model dependent)

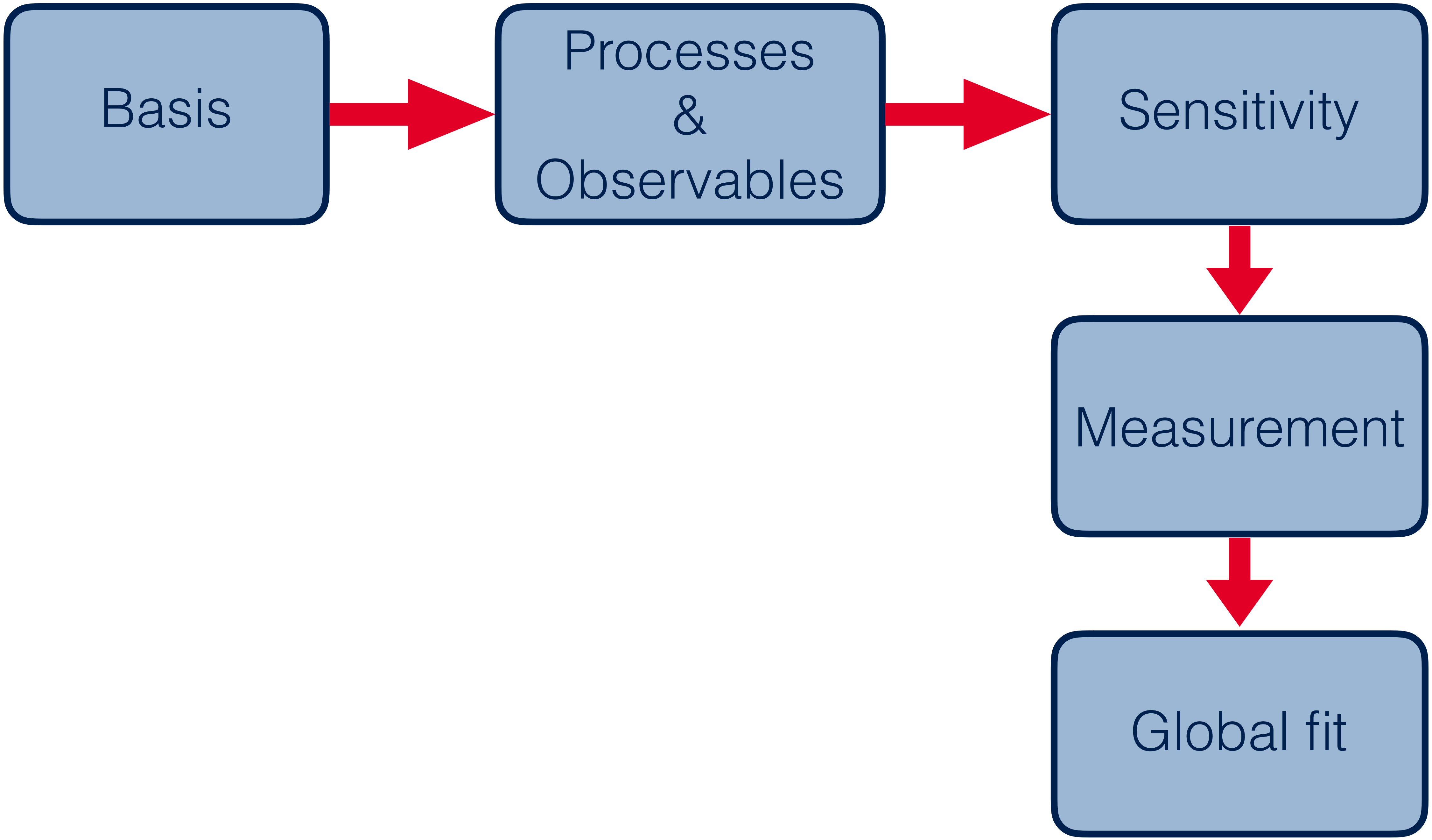
Extract limits

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

Courtesy of Ken Mimasu

[CMS, PRL 122 (2019) 132003]

General SMEFT Strategy



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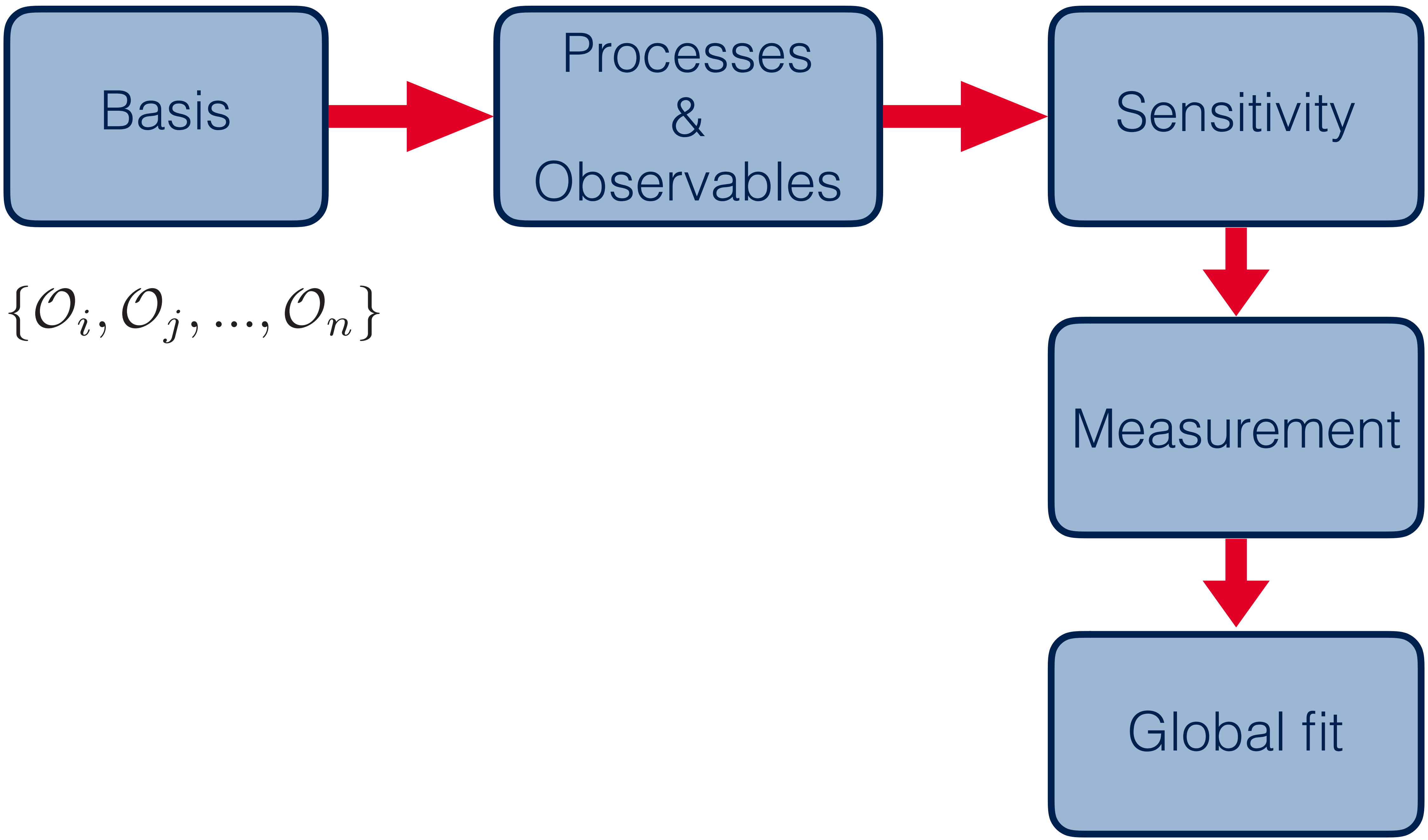
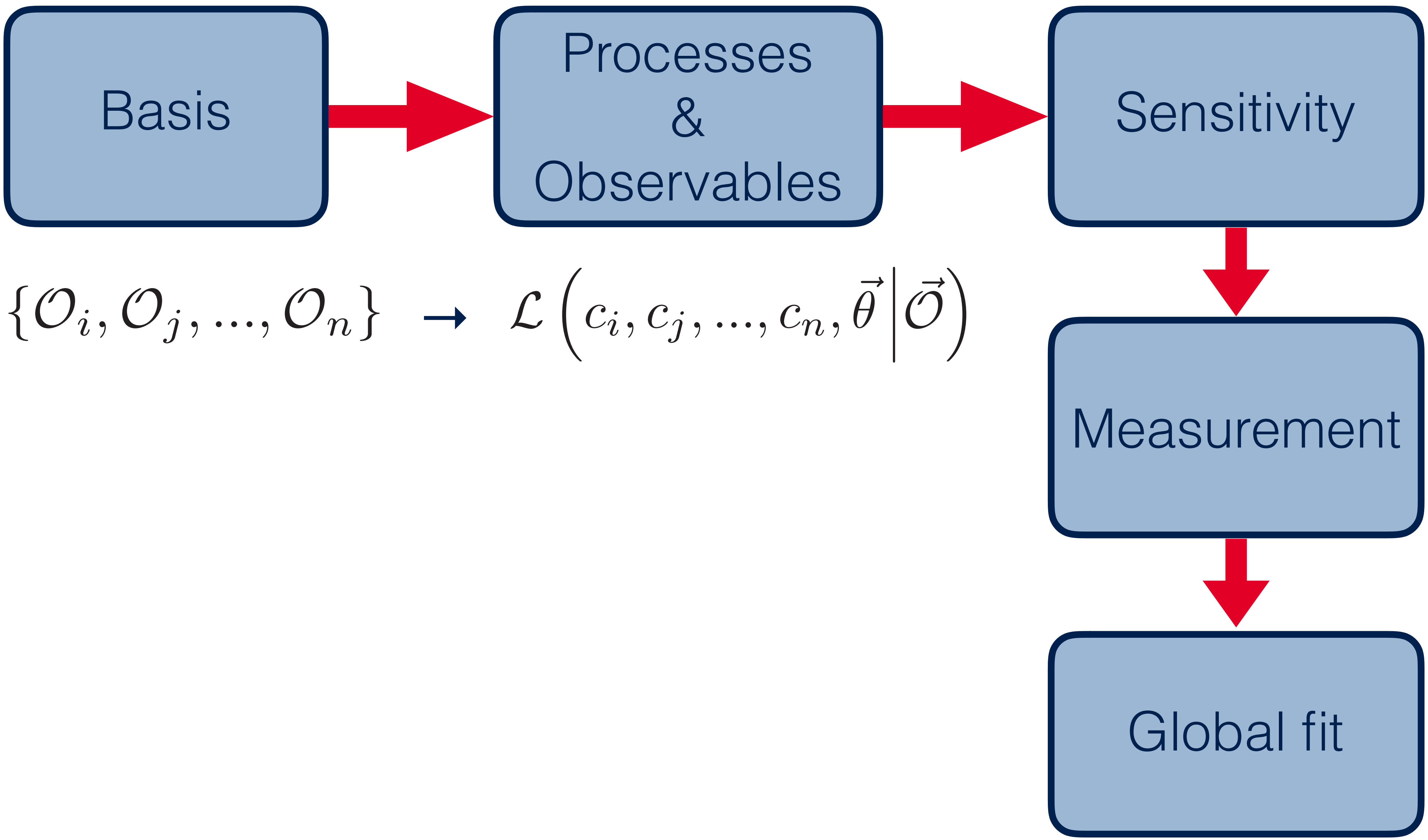
General SMEFT Strategy



$$\{\mathcal{O}_i, \mathcal{O}_j, \ldots, \mathcal{O}_n\}$$

Courtesy of Ken Mimasu

General SMEFT Strategy



$$\{\mathcal{O}_i, \mathcal{O}_j, \ldots, \mathcal{O}_n\} \;\rightarrow\; \mathcal{L}\left(c_i, c_j, \ldots, c_n, \vec{\theta} \,\middle|\, \vec{\mathcal{O}}\right)$$

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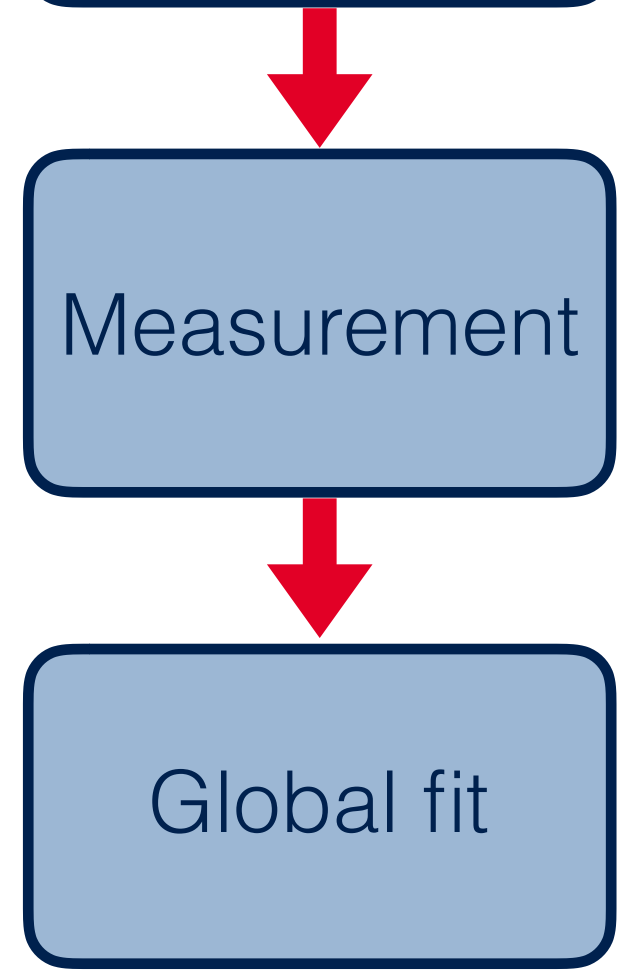

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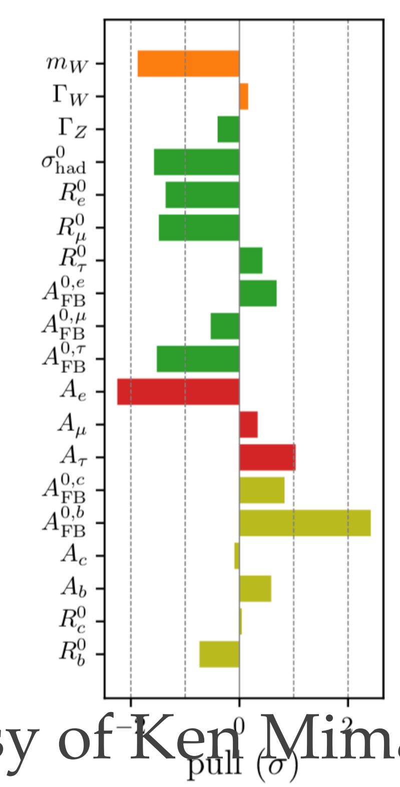
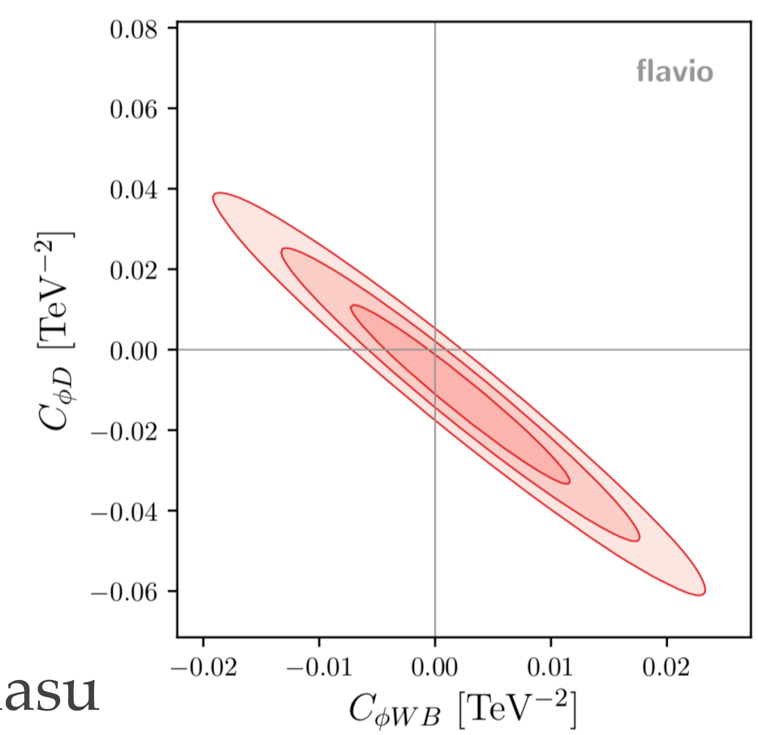




Courtesy of Ken Mimasu

General SMEFT Strategy

Basis → Processes & Observables → Sensitivity

↓

Measurement

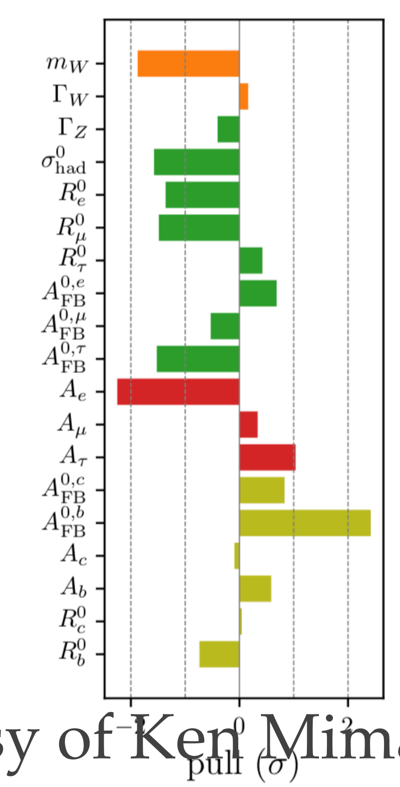
↓

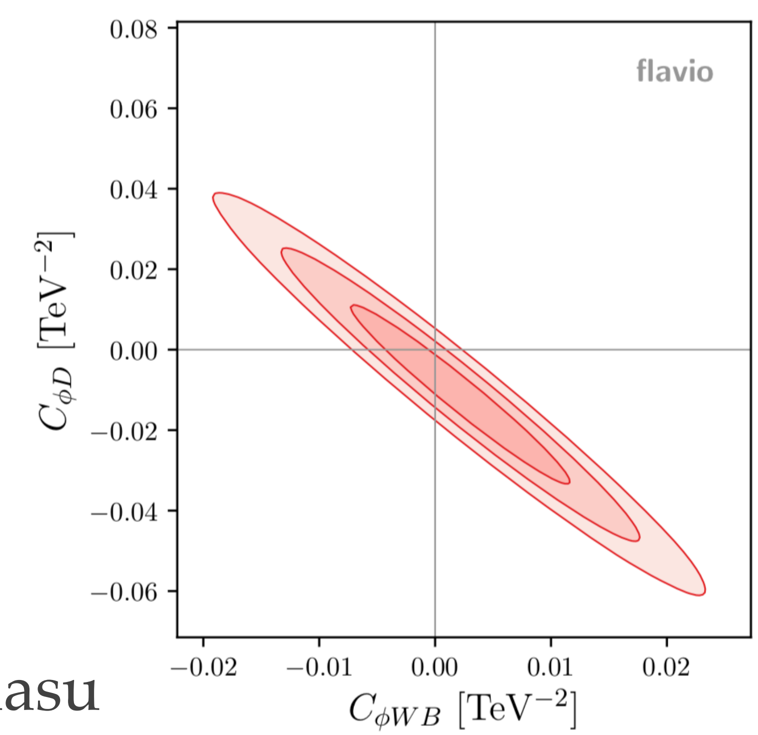
Global fit

$$\{\mathcal{O}_i, \mathcal{O}_j, ..., \mathcal{O}_n\} \rightarrow \mathcal{L}\left(c_i, c_j, ..., c_n, \vec{\theta}\,\middle|\,\vec{\mathcal{O}}\right)$$

[Aebischer et al.; arXiv:1810.07698]

Observations/ Limits





Courtesy of Ken Mimasu

General SMEFT Strategy

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

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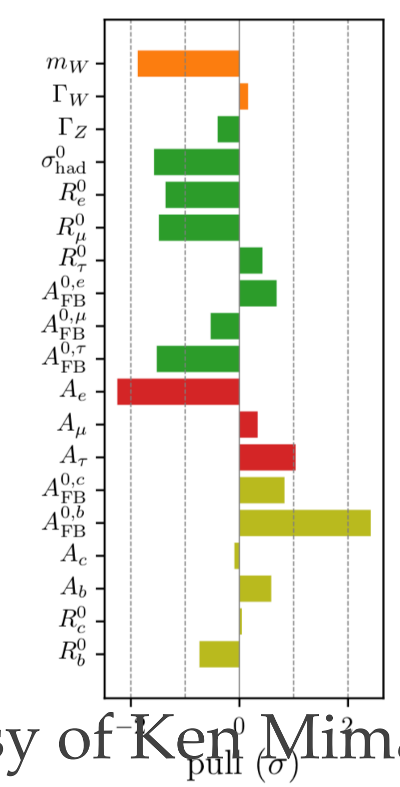
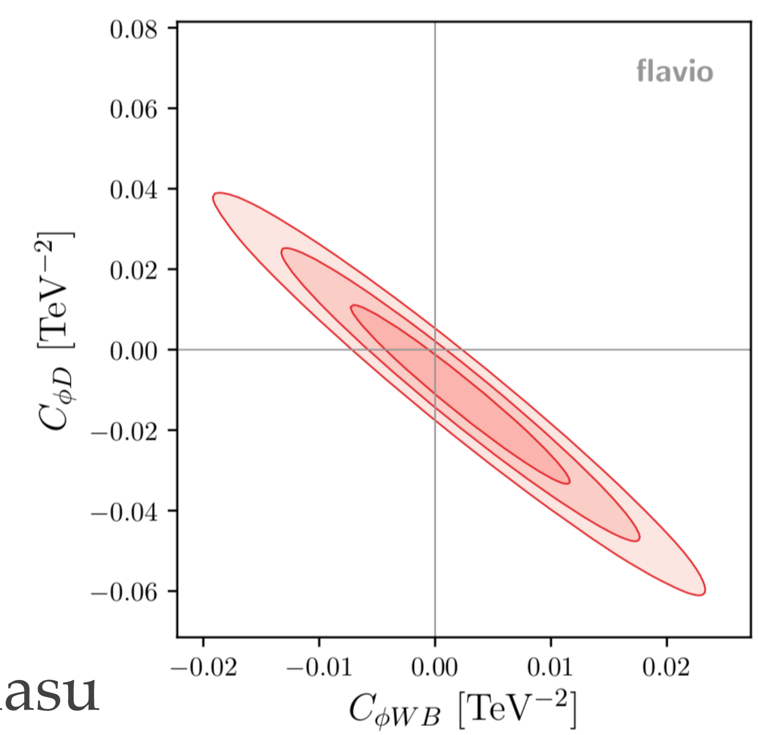
Observations/
Limits

Individual
Marginalised
Pulls,…





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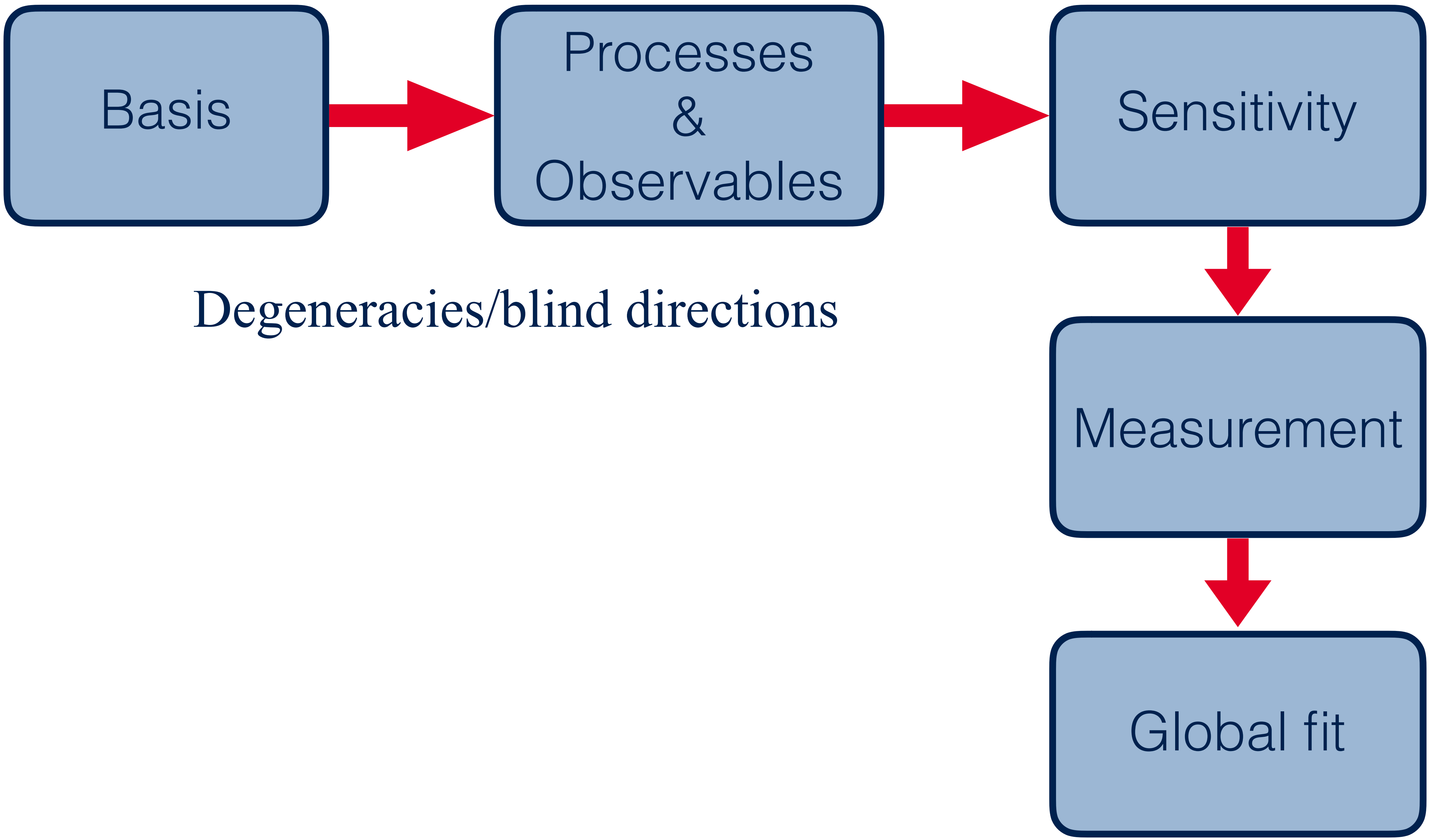

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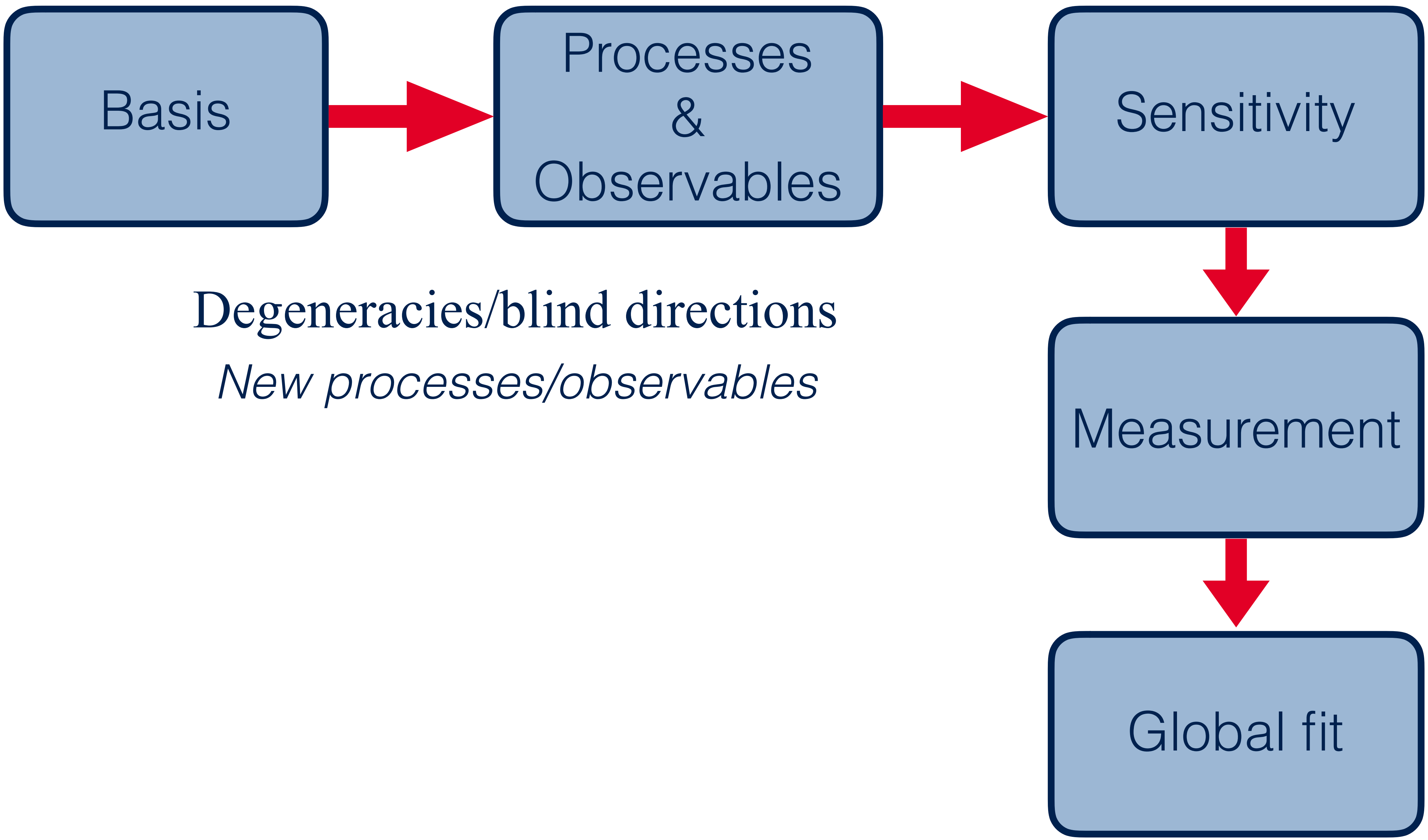

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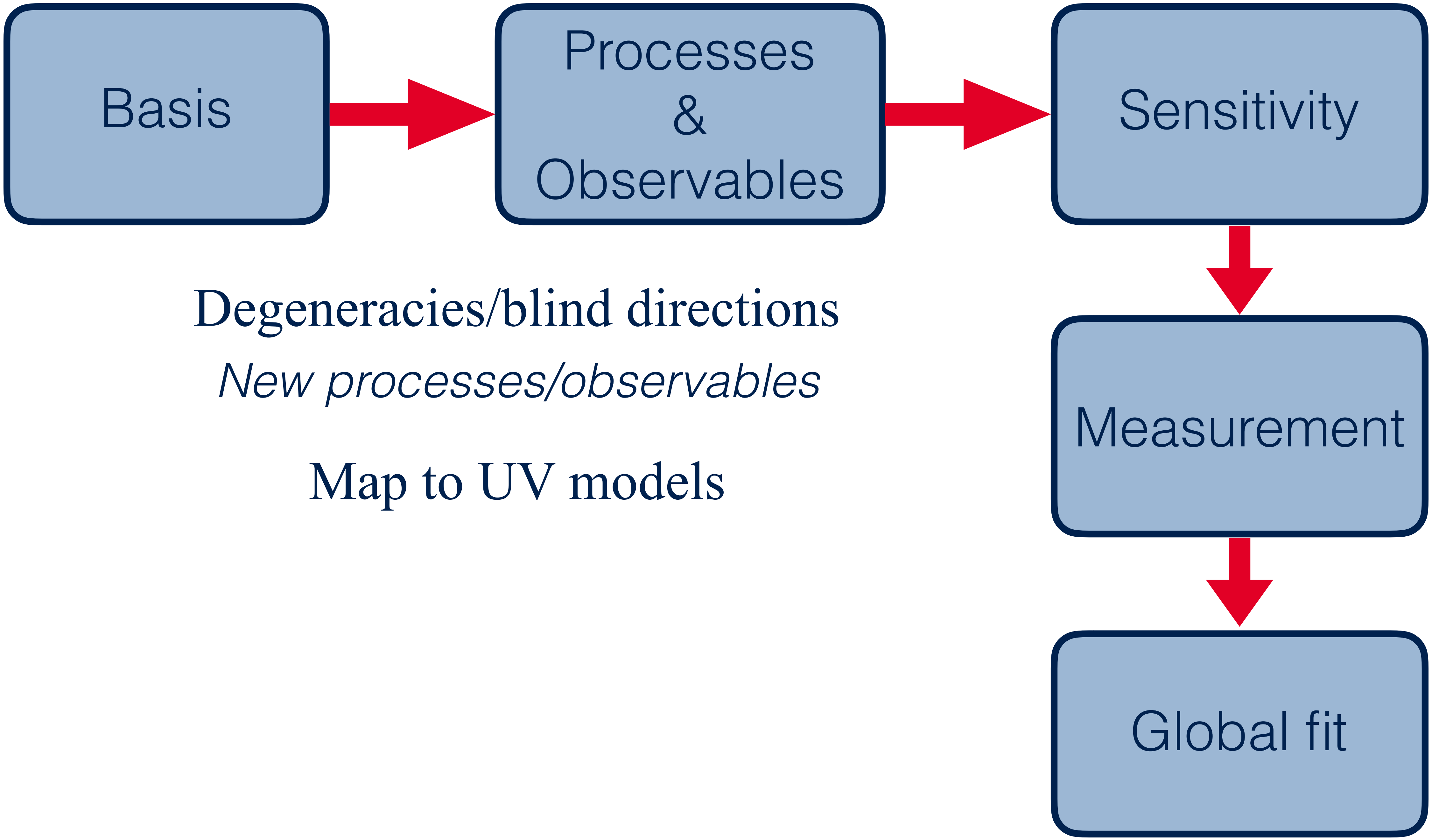

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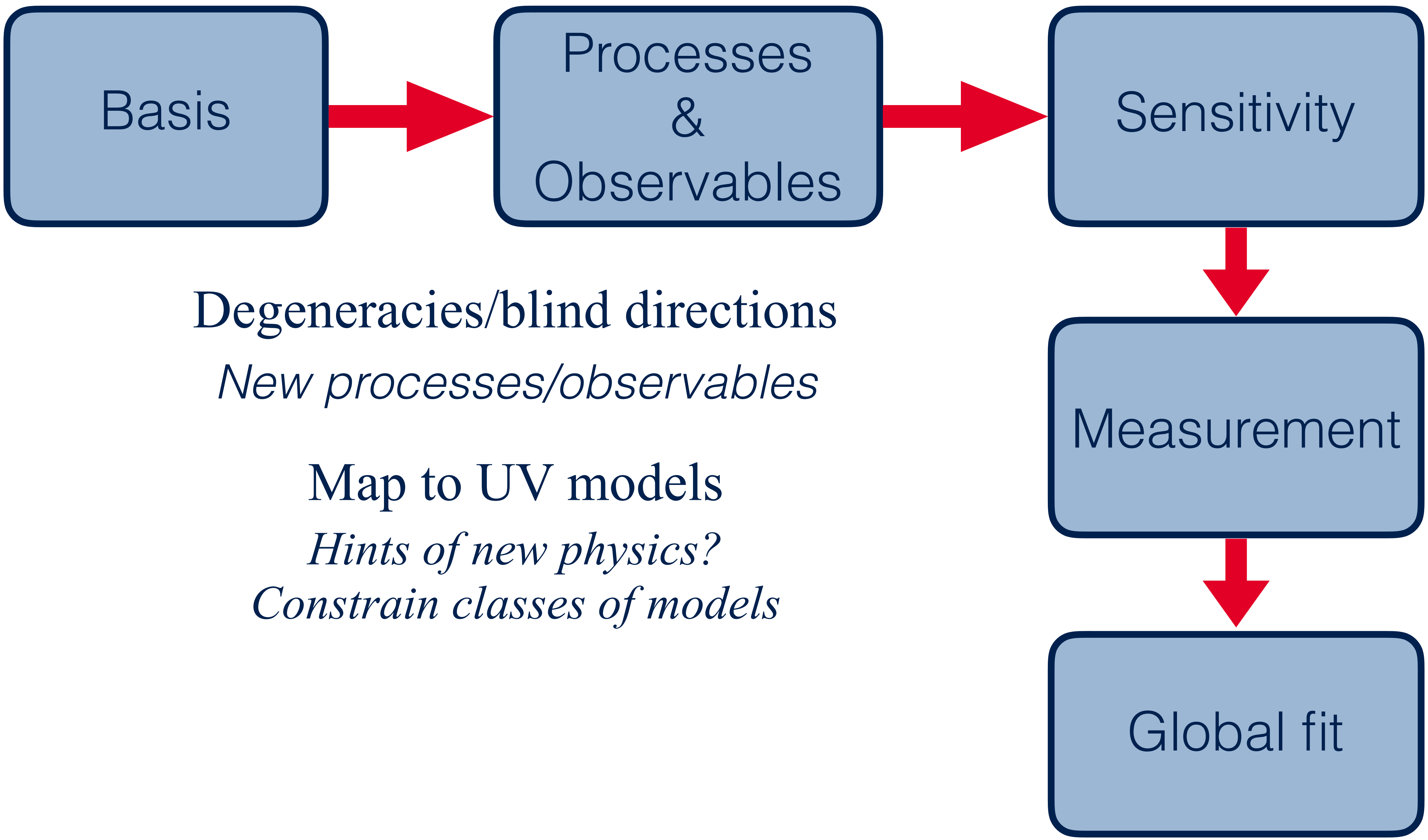

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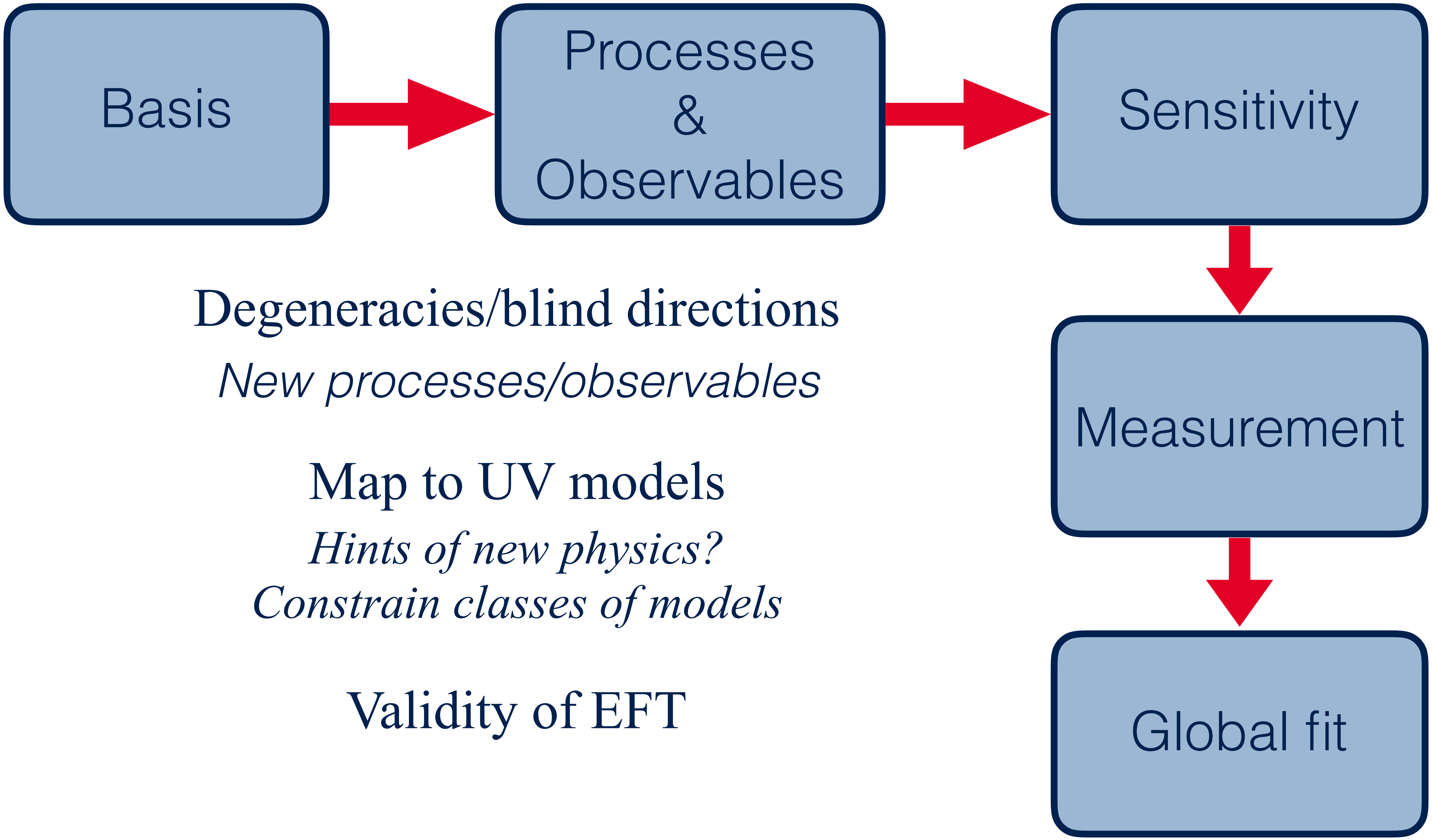

Degeneracies/blind directions

New processes/observables

Map to UV models

Hints of new physics?

Constrain classes of models

Validity of EFT

Courtesy of Ken Mimasu

General SMEFT Strategy

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

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Validity of EFT

A posteriori*: depends on sensitivity*
Intrinsically model dependent

Courtesy of Ken Mimasu

Statistical tools

Statistical tools

- Global interpretation is the holy grail of SMEFT analysis
  - ‘individual’ constraints (setting other c’s to 0) are instructive but not robust
  - Cancellations (blind directions) among different operators
  - A priori don’t know which operators will be generated by new physics
  - Operators run & mix under RGE → **c=0 is scale dependent**
  - Symmetries are the safe way to restrict your parameter space

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- Need flexible, open source tools to pool knowledge & effort

Rosetta

[Falkowski et al.; EPJ C75 (2015) no.12, 583]
https://rosetta.hepforge.org

- Basis translation tool for SMEFT
- Underlines basis independence
  - No one basis is the 'best', all physically equivalent
  - Some may be more practical for a given study (Higgs, EWPO,…)
- Command line interface with SLHA input/output
  - User-defined basis implementations & translations (pure python)
  - Warsaw, SILH, Higgs Basis, HISZ, HiggsPO,…
- Provides interfaces to third party codes
  - Developed in specific bases → increase user base & validation
- Linked to anomalous couplings model: BSMCharacterisation
  - FeynRules/UFO for LO event generation

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

Rosetta

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https://rosetta.hepforge.org

```
usage: rosetta [-h] [-s] [-v] [--force] INTERFACE ...

Main Rosetta command-line executable.

Global options:
  -h, --help          show this help message and exit
  -s, --silent        Suppress all warnings and take default answers to all
                      questions
  -v, --verbose       Activate verbose setting for program output
  --force             Take default answers to all questions

Arguments:
  INTERFACE
    translate         Translate an SLHA input card from one basis to another
    signalstrengths
                      Standalone SignalStrengths interface
    lilith            Standalone Lilith interface
    defaultcard       Generate an SLHA parameter card for an implemented basis
    ewpo              EWPO interface
    ehdecay           Standalone eHDECAY interface
    dihiggs           Double Higgs production at the LHC
```

```
bin/rosetta translate --flavor=universal -o my_output.dat my_input.dat
```

Smelli

[Aebischer et al.; EPJ C79 (2019) no.6, 509]
https://smelli.github.io

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- Wrapper around flavio tool

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[Straub; arXiv:1810:08132]
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  - Initially developed for flavour physics observables
  - EFT predictions for flavour, EWPO, LFV decays, lepton MDM, neutron EDM

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  - Running SMEFT coefficients down to EW scale
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[Celis et a.; EPJ C77 (2017) no.6, 405]
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Specifically for interfacing SMEFT tools

Code	Import	Export
DsixTools	✓	✓
EOS	✓	
flavio	✓	✓
FlavorKit		✓
FormFlavor	✓	✓
wilson	✓	✓
SMEFT Feynman Rules	✓	✓
SMEFTsim	✓	
smelli	✓	✓
SPheno		✓
wcxf-python	✓	✓

WCxf

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Specifically for interfacing SMEFT tools

- yaml, json formats for basis definition
- Rosetta-inspired translation functionality
- Predefined Warsaw, WET

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EFT file

```
eft: SMEFT
sectors:
  dB=dL=0:
  dB=dL=1:
  dL=2:
```

WC file

```
eft: SMEFT
basis: Warsaw
scale: 1e16
values:
    Gtilde: 3.1e-6
    uphi11:
      Re: 0
      Im: 0.0001
```

```
name: Warsaw
eft: SMEFT
sectors:
  dB=dL=0:
    G:
      real: true
    Gtilde:
      real: true
    W:
      real: true
    [...]
    uphi_11:
    uphi_12:
    uphi_13:
    [...]
```

Basis file

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Flavorful Higgs & EWPO

[Falkowski & Straub; arXiv:1911:07866, Falkowski & Riva; JHEP 1502 (2015) 039], Efrati et al.; JHEP 1507 (2015) 018]

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- **Flavour general** description → 31 parameters

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- **Flavour general** description → 31 parameters

Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}\gamma^\mu l)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}u\widetilde{\varphi})$
$Q_{\varphi G}$	$\varphi^\dagger\varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}\tau^I\gamma^\mu l)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}d\varphi)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi B_{\mu\nu}B^{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}\gamma^\mu e)$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}e\varphi)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}\gamma^\mu q)$	Q_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}\tau^I\gamma^\mu q)$		
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}\gamma^\mu u)$		
$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$				
$\mathcal{O}_W$	$\varepsilon_{IJK}\,W_{\mu\nu}^I\,W^{J,\nu\rho}\,W^{K,\mu}_{\rho}$				

Flavorful Higgs & EWPO

[Falkowski & Straub; arXiv:1911:07866, Falkowski & Riva; JHEP 1502 (2015) 039], Efrati et al.; JHEP 1507 (2015) 018]

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Higgs, EWPO & diboson

Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}\gamma^\mu l)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q} u \widetilde{\varphi})$
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}\tau^I \gamma^\mu l)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q} d \varphi)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l} e \varphi)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$	Q_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}\tau^I \gamma^\mu q)$		
$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$		
$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$				
$\mathcal{O}_W$	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W^{K,\mu}_{\rho}$				

Flavorful Higgs & EWPO

[Falkowski & Straub; arXiv:1911:07866, Falkowski & Riva; JHEP 1502 (2015) 039], Efrati et al.; JHEP 1507 (2015) 018]

- **Flavour general** description → 31 parameters

Constrained by multijet

Higgs, EWPO & diboson

$\cancel{Q_G}$	$\cancel{f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}\gamma^\mu l)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q} u \widetilde{\varphi})$
$Q_{\varphi G}$	$\varphi^\dagger \varphi G^A_{\mu\nu} G^{A\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}\tau^I \gamma^\mu l)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q} d \varphi)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l} e \varphi)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W^I_{\mu\nu} W^{I\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$	Q_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W^I_{\mu\nu} B^{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}\tau^I \gamma^\mu q)$		
$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$		
$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$				
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Flavorful Higgs & EWPO

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Higgs, EWPO & diboson

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$Q_{\varphi G}$	$\varphi^\dagger\varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}\tau^I\gamma^\mu l)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}d\varphi)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi B_{\mu\nu}B^{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}\gamma^\mu e)$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}e\varphi)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}\gamma^\mu q)$	Q_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}\tau^I\gamma^\mu q)$		
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}\gamma^\mu u)$		
$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$				
$\mathcal{O}_W$	$\varepsilon_{IJK}W_{\mu\nu}^I W^{J,\nu\rho}W^{K,\mu}_\rho$				

Independent f_i,f_j entries

Flavorful Higgs & EWPO

[Falkowski & Straub; arXiv:1911:07866, Falkowski & Riva; JHEP 1502 (2015) 039], Efrati et al.; JHEP 1507 (2015) 018]

- **Flavour general** description → 31 parameters

$\cancel{Q_G}$	$\cancel{f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}\gamma^\mu l)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q} u \widetilde{\varphi})$
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}\tau^I \gamma^\mu l)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q} d \varphi)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l} e \varphi)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$	Q_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}\tau^I \gamma^\mu q)$		
$Q_{\varphi \Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$		
$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$				
$\mathcal{O}_W$	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W^{K,\mu}_{\rho}$				

Constrained by multijet

Higgs, EWPO & diboson

Independent f_i, f_j entries

3rd gen. only

Flavorful Higgs & EWPO

[Falkowski & Straub; arXiv:1911:07866, Falkowski & Riva; JHEP 1502 (2015) 039], Efrati et al.; JHEP 1507 (2015) 018]

- **Flavour general** description → 31 parameters

Constrained by multijet

Higgs, EWPO & diboson

$\cancel{Q_G}$	$\cancel{f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}\gamma^\mu l)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}u\widetilde{\varphi})$
$Q_{\varphi G}$	$\varphi^\dagger\varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}\tau^I\gamma^\mu l)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}d\varphi)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi B_{\mu\nu}B^{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}e\varphi)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$	Q_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}\tau^I\gamma^\mu q)$		
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$		
$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$				
$\mathcal{O}_W$	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W_\rho^{K,\mu}$				

Independent f_i,f_j entries

3rd gen. only

1st,2nd gen.

Flavorful Higgs & EWPO

[Falkowski & Straub; arXiv:1911:07866, Falkowski & Riva; JHEP 1502 (2015) 039], Efrati et al.; JHEP 1507 (2015) 018]

- **Flavour general** description → 31 parameters

Constrained by multijet

Higgs, EWPO & diboson

$\cancel{Q_G}$	$\cancel{f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}\gamma^\mu l)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}u\widetilde{\varphi})$
$Q_{\varphi G}$	$\varphi^\dagger\varphi G^A_{\mu\nu} G^{A\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}\tau^I\gamma^\mu l)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}d\varphi)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}e\varphi)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi W^I_{\mu\nu} W^{I\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$	Q_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi W^I_{\mu\nu} B^{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}\tau^I\gamma^\mu q)$		
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$		
$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$				
$\mathcal{O}_W$	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_\rho$				

3rd gen. only

1st,2nd gen.

Independent f_i,f_j entries

Input data:
- Z, W pole observables
- LEP 2 total and differential WW
- Run 1 & 2 Higgs signal strengths

Results

Results

$$
\begin{aligned}
\delta g_L^{W\ell} &= c_{\varphi l}^{(3)} + f(1/2,0) - f(-1/2,-1), \\
\delta g_L^{Z\ell} &= -\frac{1}{2}c_{\varphi l}^{(3)} - \frac{1}{2}c_{\varphi l}^{(1)} + f(-1/2,-1), \\
\delta g_R^{Z\ell} &= -\frac{1}{2}c_{\varphi e}^{(1)} + f(0,-1), \\
\delta g_L^{Zu} &= \frac{1}{2}c_{\varphi q}^{(3)} - \frac{1}{2}c_{\varphi q}^{(1)} + f(1/2,2/3), \\
\delta g_L^{Zd} &= -\frac{1}{2}c_{\varphi q}^{(3)} - \frac{1}{2}c_{\varphi q}^{(1)} + f(-1/2,-1/3), \\
\delta g_R^{Zu} &= -\frac{1}{2}c_{\varphi u} + f(0,2/3), \\
\delta g_R^{Zd} &= -\frac{1}{2}c_{\varphi d} + f(0,-1/3), \\
\delta c_z &= c_{\varphi\Box} - \frac{1}{4}c_{\varphi D} - \frac{3}{2}\Delta_{G_F}, \\
c_{z\Box} &= \frac{1}{2g_L^2}\left(c_{\varphi D} + 2\Delta_{G_F}\right), \\
c_{gg} &= \frac{4}{g_s^2}c_{\varphi G}, \\
c_{\gamma\gamma} &= 4\left(\frac{1}{g_L^2}c_{\varphi W} + \frac{1}{g_Y^2}c_{\varphi B} - \frac{1}{g_L g_Y}c_{\varphi WB}\right), \\
c_{zz} &= 4\left(\frac{g_L^2 c_{\varphi W} + g_Y^2 c_{\varphi B} + g_L g_Y c_{\varphi WB}}{(g_L^2+g_Y^2)^2}\right), \\
c_{z\gamma} &= 4\left(\frac{c_{\varphi W} - c_{\varphi B} - \frac{g_L^2-g_Y^2}{2g_L g_Y}c_{\varphi WB}}{g_L^2+g_Y^2}\right).
\end{aligned}
$$

$$
f(T^3,Q) \equiv \left\{ -Q\frac{g_L g_Y}{g_L^2-g_Y^2}c_{\varphi WB} - \mathbf{1}\left(\frac{1}{4}c_{HD} + \frac{1}{2}\Delta_{G_F}\right)\left(T^3 + Q\frac{g_Y^2}{g_L^2-g_Y^2}\right)\right\}\mathbf{1},
$$

Results

$$\delta g_L^{W\ell} = c_{\varphi l}^{(3)} + f(1/2, 0) - f(-1/2, -1),$$

$$\delta g_L^{Z\ell} = -\frac{1}{2}c_{\varphi l}^{(3)} - \frac{1}{2}c_{\varphi l}^{(1)} + f(-1/2, -1),$$

$$\delta g_R^{Z\ell} = -\frac{1}{2}c_{\varphi e}^{(1)} + f(0, -1),$$

$$\delta g_L^{Zu} = \frac{1}{2}c_{\varphi q}^{(3)} - \frac{1}{2}c_{\varphi q}^{(1)} + f(1/2, 2/3),$$

$$\delta g_L^{Zd} = -\frac{1}{2}c_{\varphi q}^{(3)} - \frac{1}{2}c_{\varphi q}^{(1)} + f(-1/2, -1/3),$$

$$\delta g_R^{Zu} = -\frac{1}{2}c_{\varphi u} + f(0, 2/3),$$

$$\delta g_R^{Zd} = -\frac{1}{2}c_{\varphi d} + f(0, -1/3),$$

$$\delta c_z = c_{\varphi\Box} - \frac{1}{4}c_{\varphi D} - \frac{3}{2}\Delta_{G_F},$$

$$c_{z\Box} = \frac{1}{2g_L^2}\left(c_{\varphi D} + 2\Delta_{G_F}\right),$$

$$c_{gg} = \frac{4}{g_s^2}c_{\varphi G},$$

$$c_{\gamma\gamma} = 4\left(\frac{1}{g_L^2}c_{\varphi W} + \frac{1}{g_Y^2}c_{\varphi B} - \frac{1}{g_L g_Y}c_{\varphi WB}\right),$$

$$c_{zz} = 4\left(\frac{g_L^2 c_{\varphi W} + g_Y^2 c_{\varphi B} + g_L g_Y c_{\varphi WB}}{(g_L^2 + g_Y^2)^2}\right),$$

$$c_{z\gamma} = 4\left(\frac{c_{\varphi W} - c_{\varphi B} - \frac{g_L^2 - g_Y^2}{2 g_L g_Y}c_{\varphi WB}}{g_L^2 + g_Y^2}\right).$$

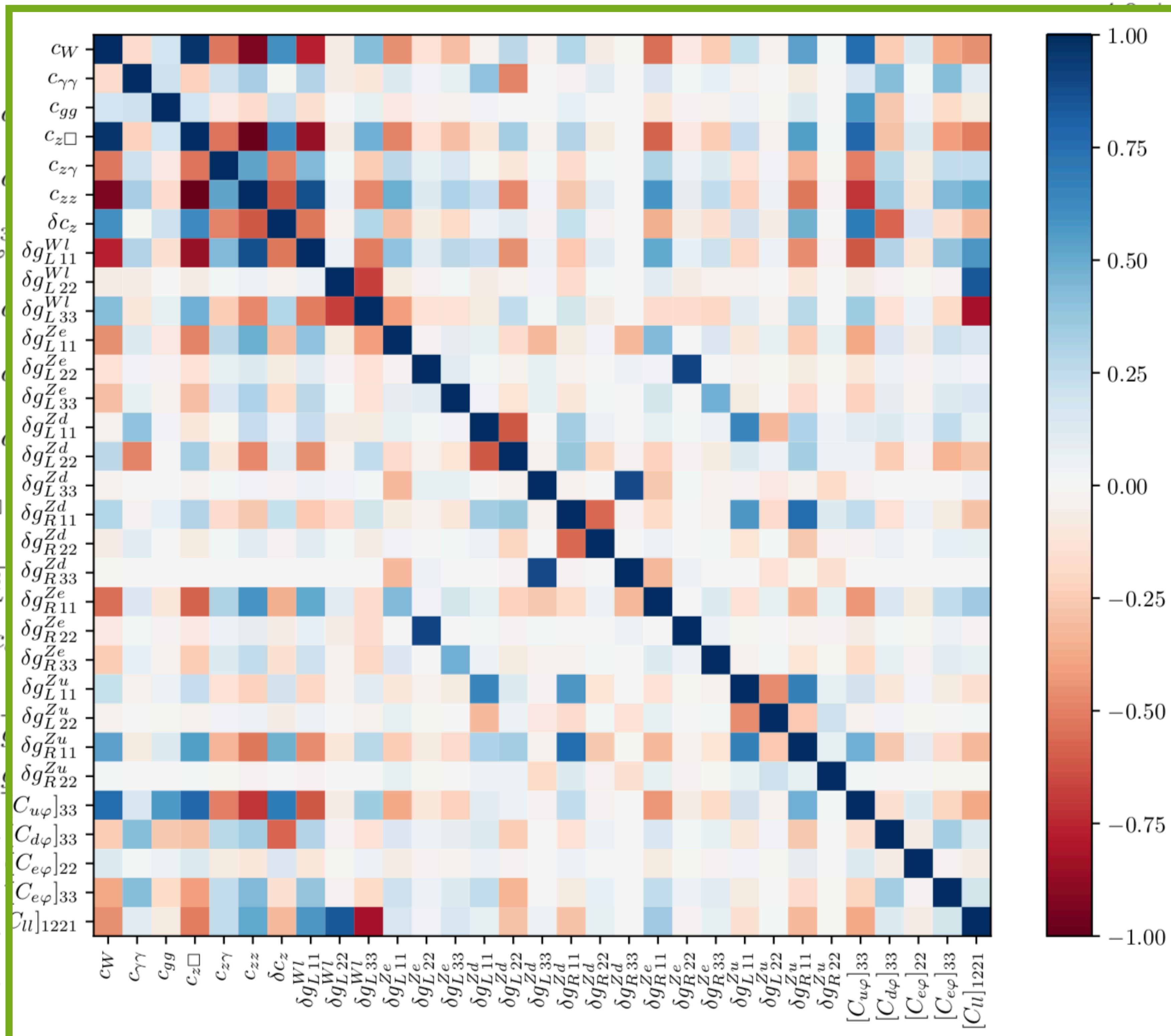
$$f(T^3, Q) \equiv \left\{ -Q\frac{g_L g_Y}{g_L^2 - g_Y^2}c_{\varphi WB} - \mathbf{1}\left(\frac{1}{4}c_{HD} + \frac{1}{2}\Delta_{G_F}\right)\left(T^3 + Q\frac{g_Y^2}{g_L^2 - g_Y^2}\right)\right\}\mathbf{1},$$

Coeff.	central	unc.	pull $[\sigma]$
C_W	0.19	$\pm$ 1.9	0.1
$c_{\gamma\gamma}$	-0.056	$\pm$ 0.11	0.5
c_{gg}	-0.017	$\pm$ 0.014	1.2
$c_{z\Box}$	4.9	$\pm$ 6.2	0.8
$c_{z\gamma}$	-0.6	$\pm$ 0.63	1.0
c_{zz}	-12.0	$\pm$ 16.0	0.8
δc_z	0.49	$\pm$ 1.5	0.3
$\delta g_{L\,11}^{Wl}$	-0.09	$\pm$ 0.053	1.7
$\delta g_{L\,22}^{Wl}$	-0.24	$\pm$ 0.083	2.9
$\delta g_{L\,33}^{Wl}$	0.26	$\pm$ 0.1	2.6
$\delta g_{L\,11}^{Ze}$	-0.0074	$\pm$ 0.0052	1.4
$\delta g_{L\,22}^{Ze}$	-0.0014	$\pm$ 0.018	0.1
$\delta g_{L\,33}^{Ze}$	-0.0054	$\pm$ 0.01	0.5
$\delta g_{L\,11}^{Zd}$	-0.17	$\pm$ 0.66	0.3
$\delta g_{L\,22}^{Zd}$	0.43	$\pm$ 0.57	0.8
$\delta g_{L\,33}^{Zd}$	0.052	$\pm$ 0.027	1.9
$\delta g_{R\,11}^{Zd}$	1.5	$\pm$ 1.0	1.4
$\delta g_{R\,22}^{Zd}$	0.27	$\pm$ 0.73	0.4
$\delta g_{R\,33}^{Zd}$	0.33	$\pm$ 0.11	3.1
$\delta g_{R\,11}^{Ze}$	-0.0086	$\pm$ 0.0056	1.5
$\delta g_{R\,22}^{Ze}$	-0.0018	$\pm$ 0.021	0.1
$\delta g_{R\,33}^{Ze}$	0.0084	$\pm$ 0.01	0.8
$\delta g_{L\,11}^{Zu}$	0.14	$\pm$ 0.5	0.3
$\delta g_{L\,22}^{Zu}$	-0.027	$\pm$ 0.072	0.4
$\delta g_{R\,11}^{Zu}$	1.3	$\pm$ 0.85	1.5
$\delta g_{R\,22}^{Zu}$	-0.056	$\pm$ 0.084	0.7
$[C_{u\varphi}]_{33}$	-0.18	$\pm$ 2.7	0.1
$[C_{d\varphi}]_{33}$	0.016	$\pm$ 0.049	0.3
$[C_{e\varphi}]_{22}$	0.004	$\pm$ 0.0054	0.8
$[C_{e\varphi}]_{33}$	-0.0018	$\pm$ 0.019	0.1
$[C_{ll}]_{1221}$	-0.68	$\pm$ 0.2	3.3

Results

Coeff.	central	unc.	pull [σ]
C_W	0.19 $\pm$	1.9	0.1
$c_{\gamma\gamma}$	-0.056 $\pm$	0.11	0.5
c_{gg}	-0.017 $\pm$	0.014	1.2
		6.2	0.8
		0.63	1.0
		16.0	0.8
		1.5	0.3
		0.053	1.7
		0.083	2.9
		0.1	2.6
		0.0052	1.4
		0.018	0.1
		0.01	0.5
		0.66	0.3
		0.57	0.8
		0.027	1.9
		1.0	1.4
		0.73	0.4
		0.11	3.1
		0.0056	1.5
		0.021	0.1
		0.01	0.8
		0.5	0.3
		0.072	0.4
		0.85	1.5
		0.084	0.7
		2.7	0.1
		0.049	0.3
		0.0054	0.8
		0.019	0.1
		0.2	3.3

$$\delta g_L^{W\ell} = c_{\varphi l}^{(3)}$$
$$\delta g_L^{Z\ell} = -\frac{1}{2}c$$
$$\delta g_R^{Z\ell} = -\frac{1}{2}c$$
$$\delta g_L^{Zu} = \frac{1}{2}c_{\varphi}^{(3}$$
$$\delta g_L^{Zd} = -\frac{1}{2}c$$
$$\delta g_R^{Zu} = -\frac{1}{2}c$$
$$\delta g_R^{Zd} = -\frac{1}{2}c$$
$$\delta c_z = c_{\varphi\Box}$$
$$c_{z\Box} = \frac{1}{2g_L^2}$$
$$c_{gg} = \frac{4}{g_s^2}c$$
$$c_{\gamma\gamma} = 4\left(\right.$$
$$c_{zz} = 4\left(\right.$$
$$c_{z\gamma} = 4\left(\right.$$
$$f(T^3, Q) \equiv \left\{ - \right.$$



Results

Coeff.	central	unc.	pull [σ]
C_W	$0.19 \pm$	1.9	0.1
$c_{\gamma\gamma}$	$-0.056 \pm$	0.11	0.5
c_{gg}	$-0.017 \pm$	0.014	1.2
		6.2	0.8
		0.63	1.0
		16.0	0.8
		1.5	0.3
		0.053	1.7
		0.083	2.9
		0.1	2.6
		0.0052	1.4
		0.018	0.1
		0.01	0.5
		0.66	0.3
		0.57	0.8
		0.027	1.9
		1.0	1.4
		0.73	0.4
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		0.049	0.3
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$$\delta g_L^{W\ell} = c_{\varphi l}^{(3)}$$
$$\delta g_L^{Z\ell} = -\frac{1}{2} c \ldots$$
$$\delta g_R^{Z\ell} = -\frac{1}{2} c \ldots$$
$$\delta g_L^{Zu} = \frac{1}{2} c_{\varphi}^{(3} \ldots$$
$$\delta g_L^{Zd} = -\frac{1}{2} \ldots$$
$$\delta g_R^{Zu} = -\frac{1}{2} \ldots$$
$$\delta g_R^{Zd} = -\frac{1}{2} \ldots$$
$$\delta c_z = c_{\varphi\Box} \ldots$$
$$c_{z\Box} = \frac{1}{2g_L^2} \ldots$$
$$c_{gg} = \frac{4}{g_s^2} c \ldots$$
$$c_{\gamma\gamma} = 4 \left(\ldots \right.$$
$$c_{zz} = 4 \left(\ldots \right.$$
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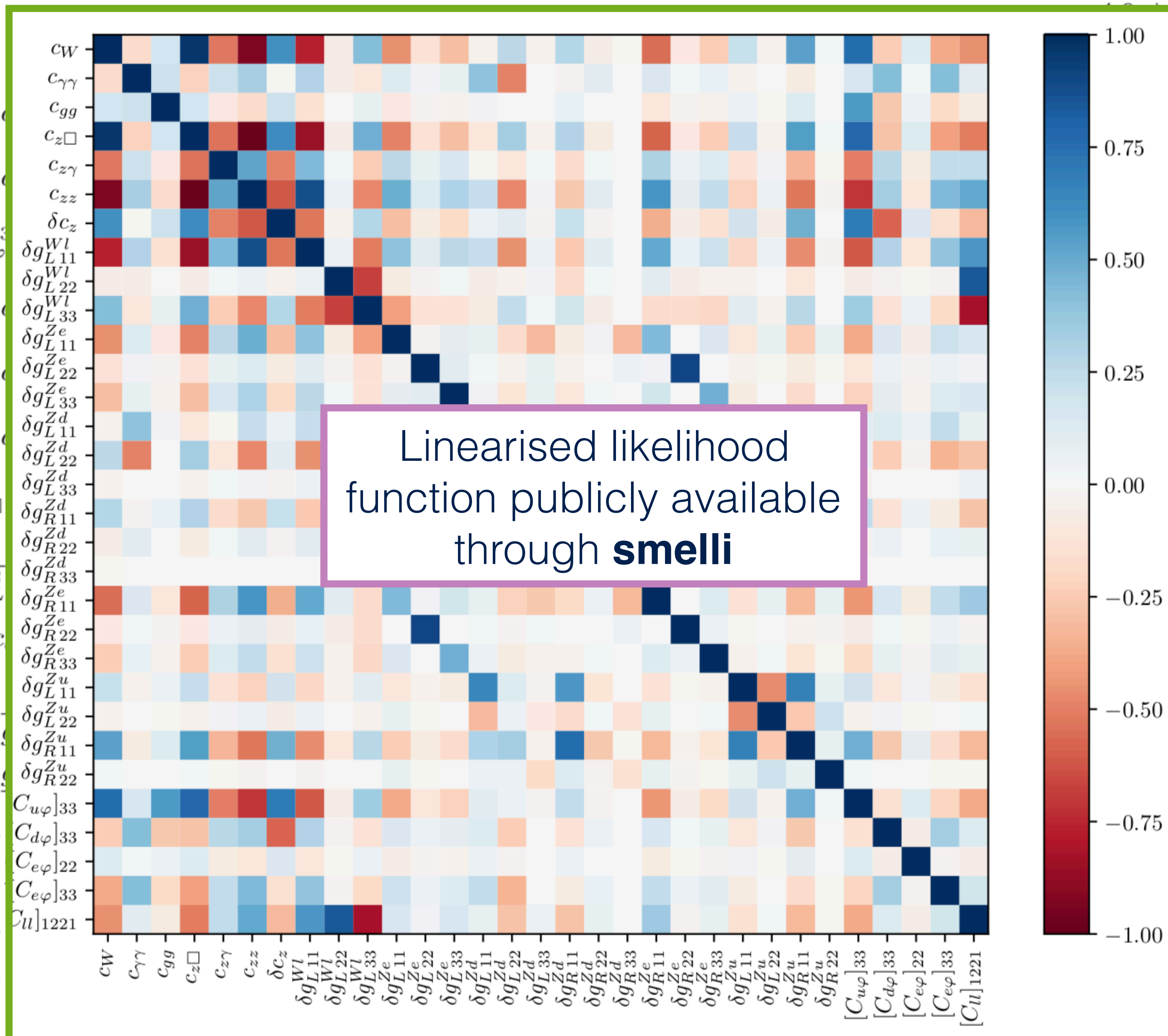

Linearised likelihood function publicly available through **smelli**

HEPfit

[de Blas et al.; arXiv: 1910.14012]
http://hepfit.roma1.infn.it

HEPfit

[de Blas et al.; arXiv: 1910.14012]
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- Standard model & extensions (specifically SMEFT)

HEPfit

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- Standard model & extensions (specifically SMEFT)

Bayesian statistical framework

HEPfit

[de Blas et al.; arXiv: 1910.14012]
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- Standard model & extensions (specifically SMEFT)

Bayesian statistical framework

- Markov-Chain Monte Carlo (MCMC) via Bayesian Analysis Toolkit

[Caldwell et al.; Comp. Phys. Comm. 180 (2009) 2197]

HEPfit

[de Blas et al.; arXiv: 1910.14012]
http://hepfit.roma1.infn.it

- Standard model & extensions (specifically SMEFT)

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Posterior distribution

$$P(\vec{\mathbf{x}}|D) = \frac{P(D|\vec{\mathbf{x}})P_0(\vec{\mathbf{x}})}{\int P(D|\vec{\mathbf{x}})P_0(\vec{\mathbf{x}})d\vec{\mathbf{x}}}$$

Likelihood, Prior & Bayesian evidence

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Likelihood, Prior &
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Observables

- Higgs signal strengths (LHC & Future lepton colliders incl. polarisation)
- EW precision data in (m_Z, α, G_F) scheme
- Flavour observables
- BSM model-specific (incl. theoretical constraints)

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