

SMEFT as a probe of New Physics at the LHC

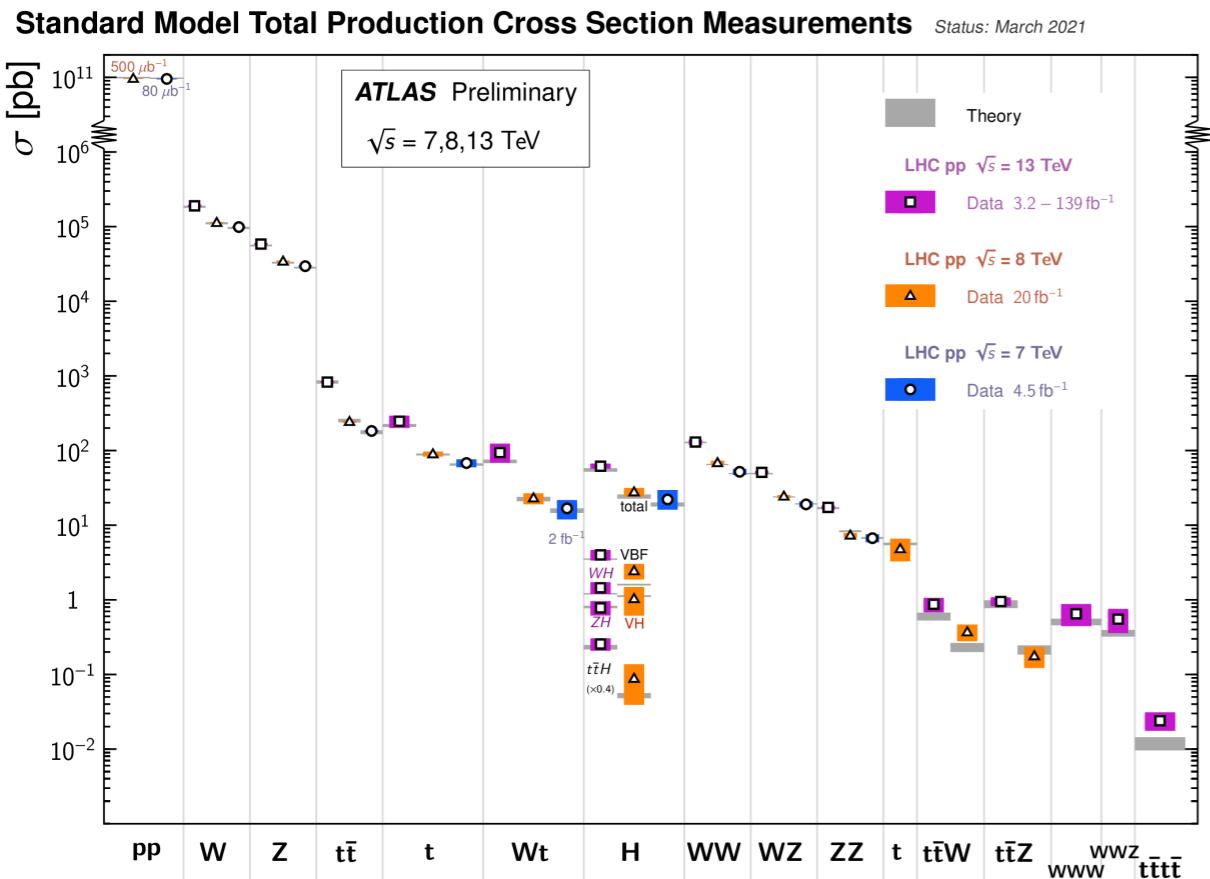
Eleni Vryonidou
University of Manchester



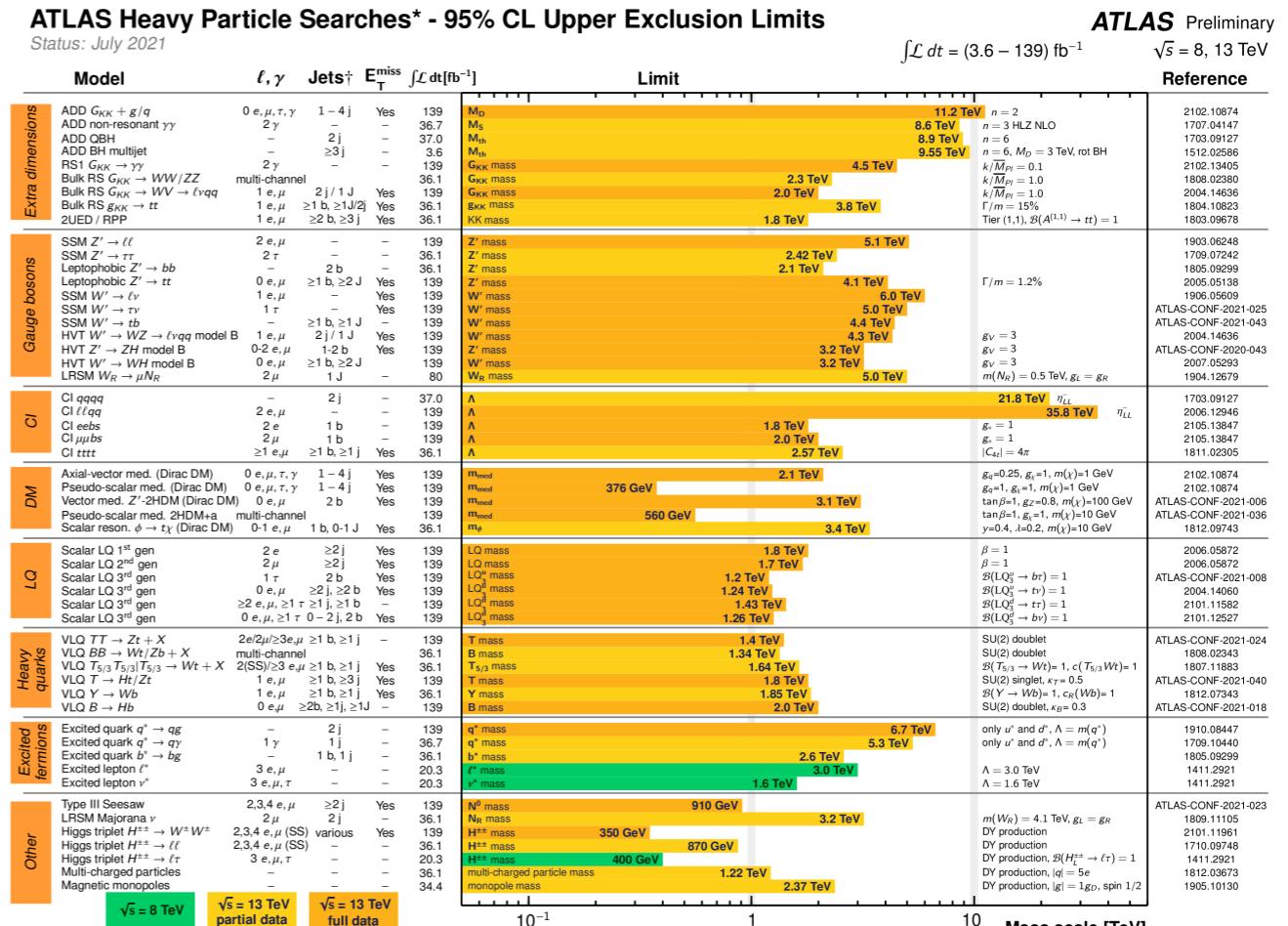
Xmas Theoretical Physics Workshop @Athens
22/12/22

LHC: the story so far

Rediscovering the SM



Searching for the unknown



Good agreement with the SM predictions
No sign of new light particles

What can New Physics be?

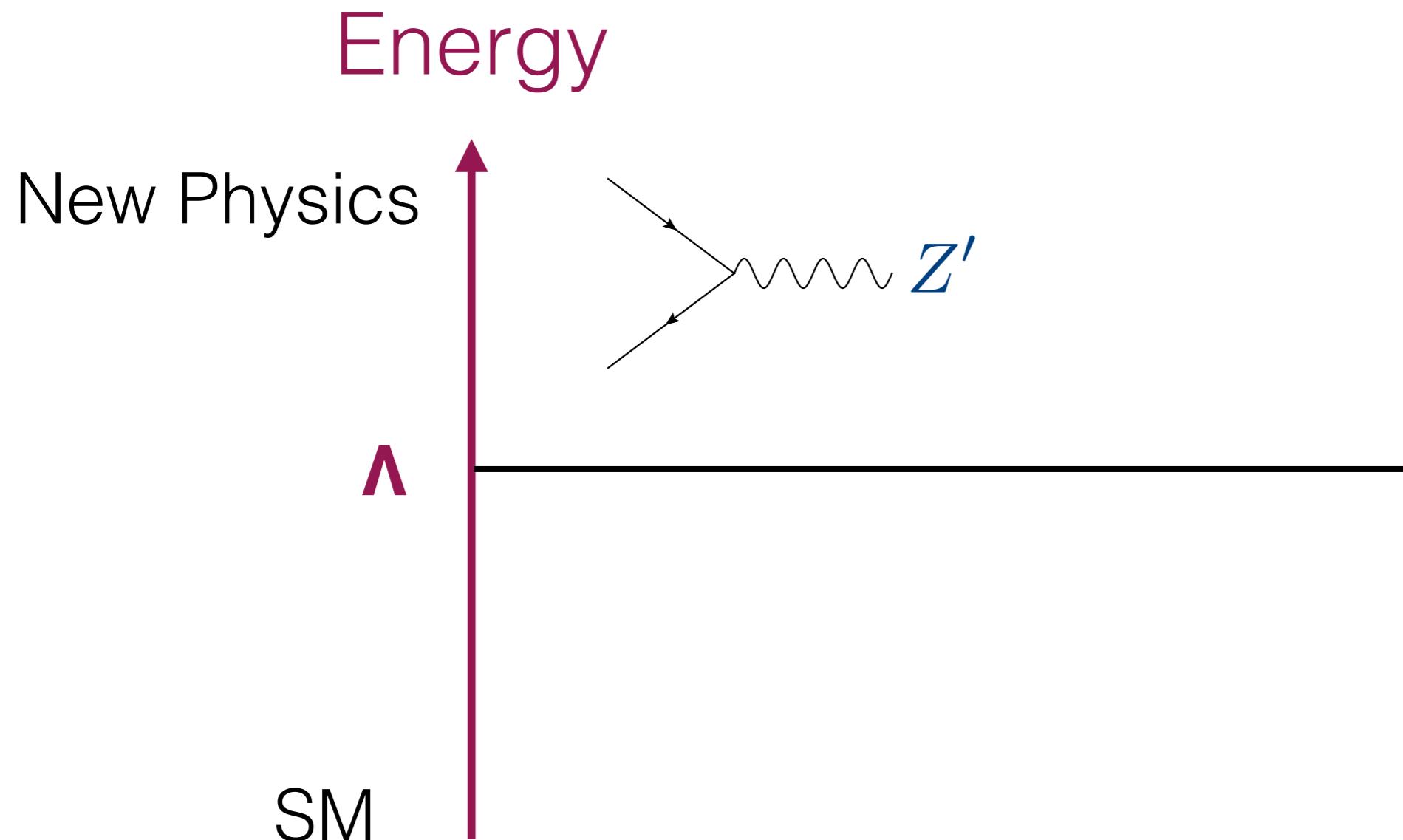
Possibilities and how to deal with them:

Weakly coupled: Small rates means that more Luminosity can help

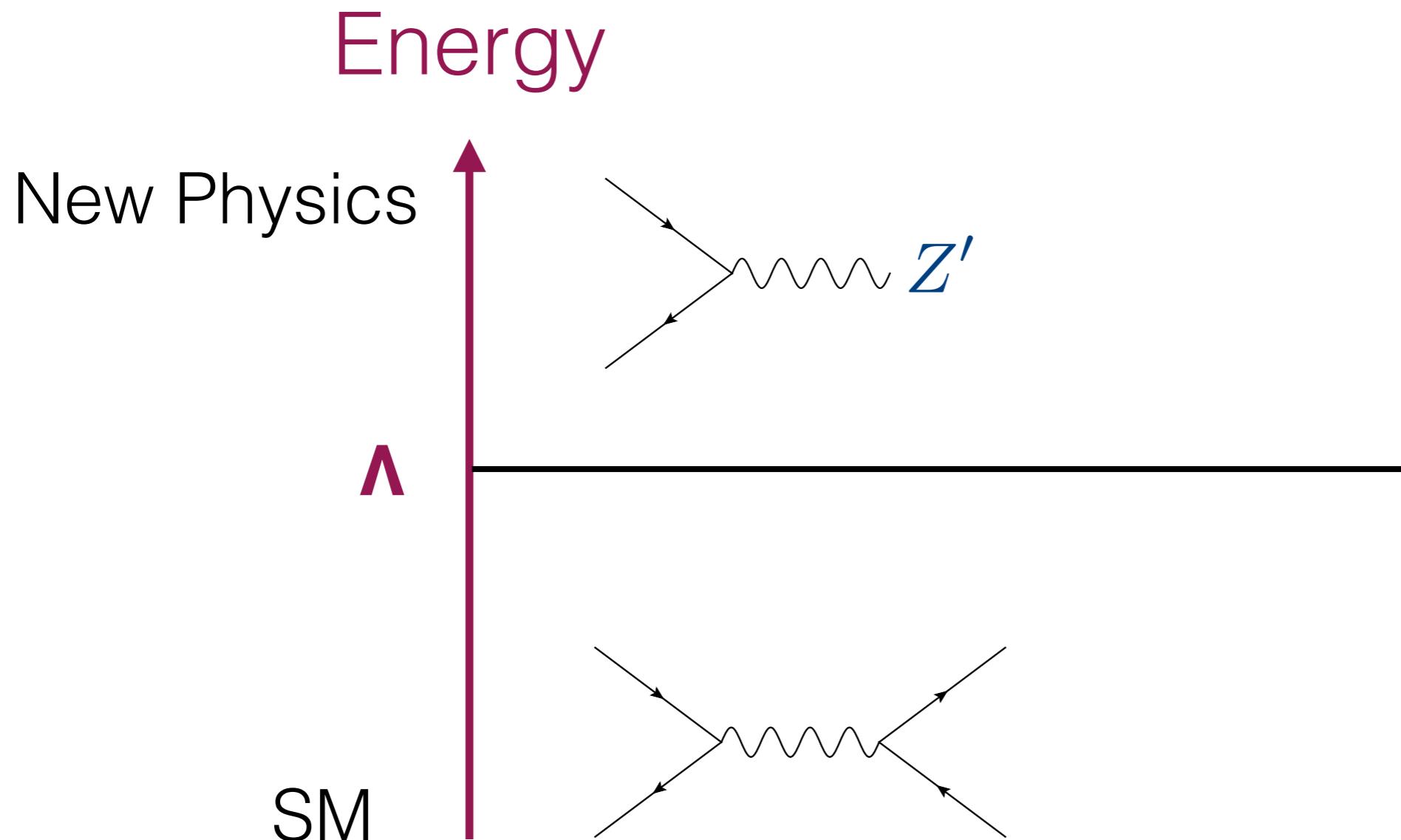
Exotic: Need new ways to search for it, going beyond standard searches or even beyond high-energy colliders

Heavy: Not enough energy to produce it
Need indirect searches → **SMEFT opens new directions**

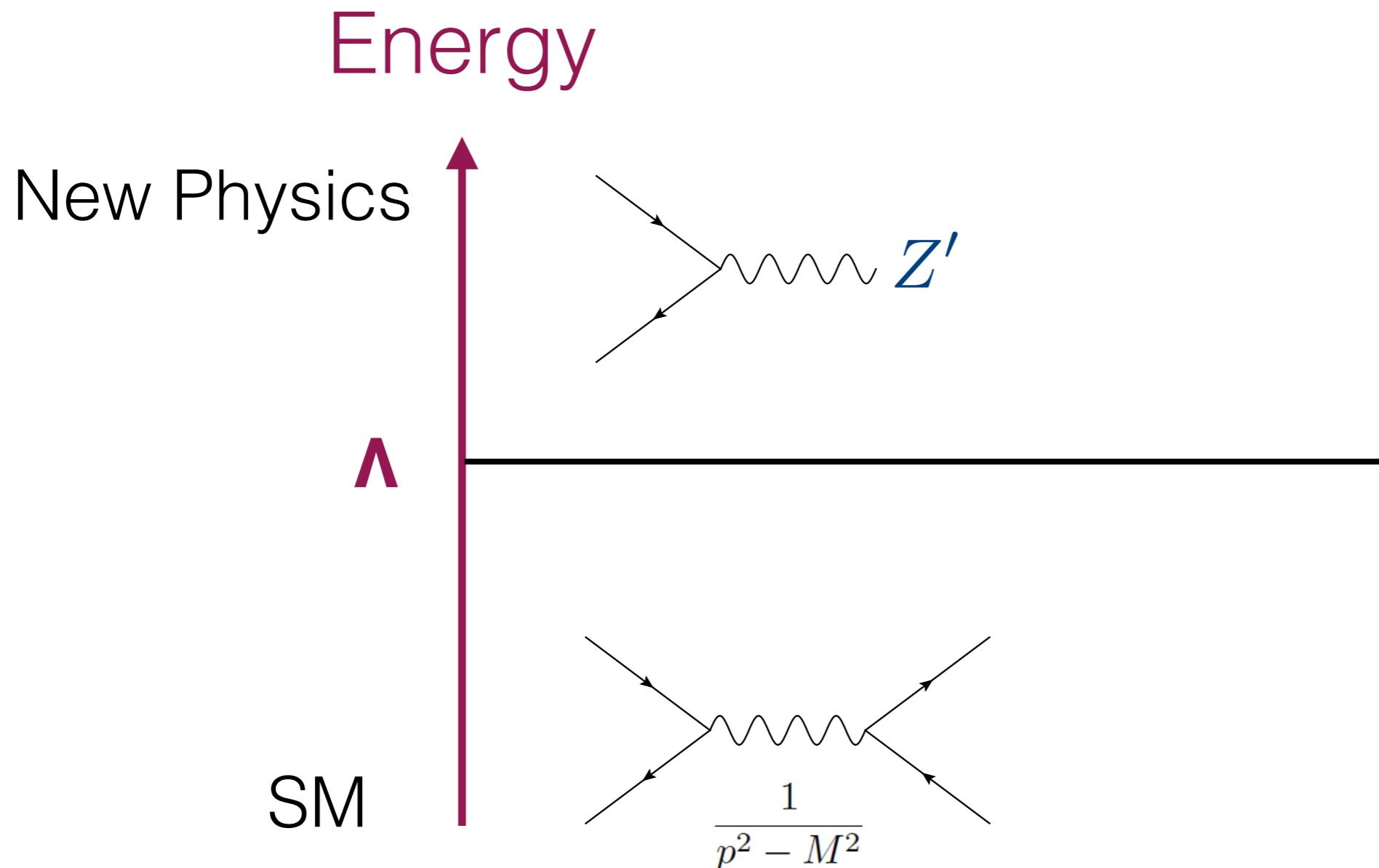
SMEFT: What is it all about?



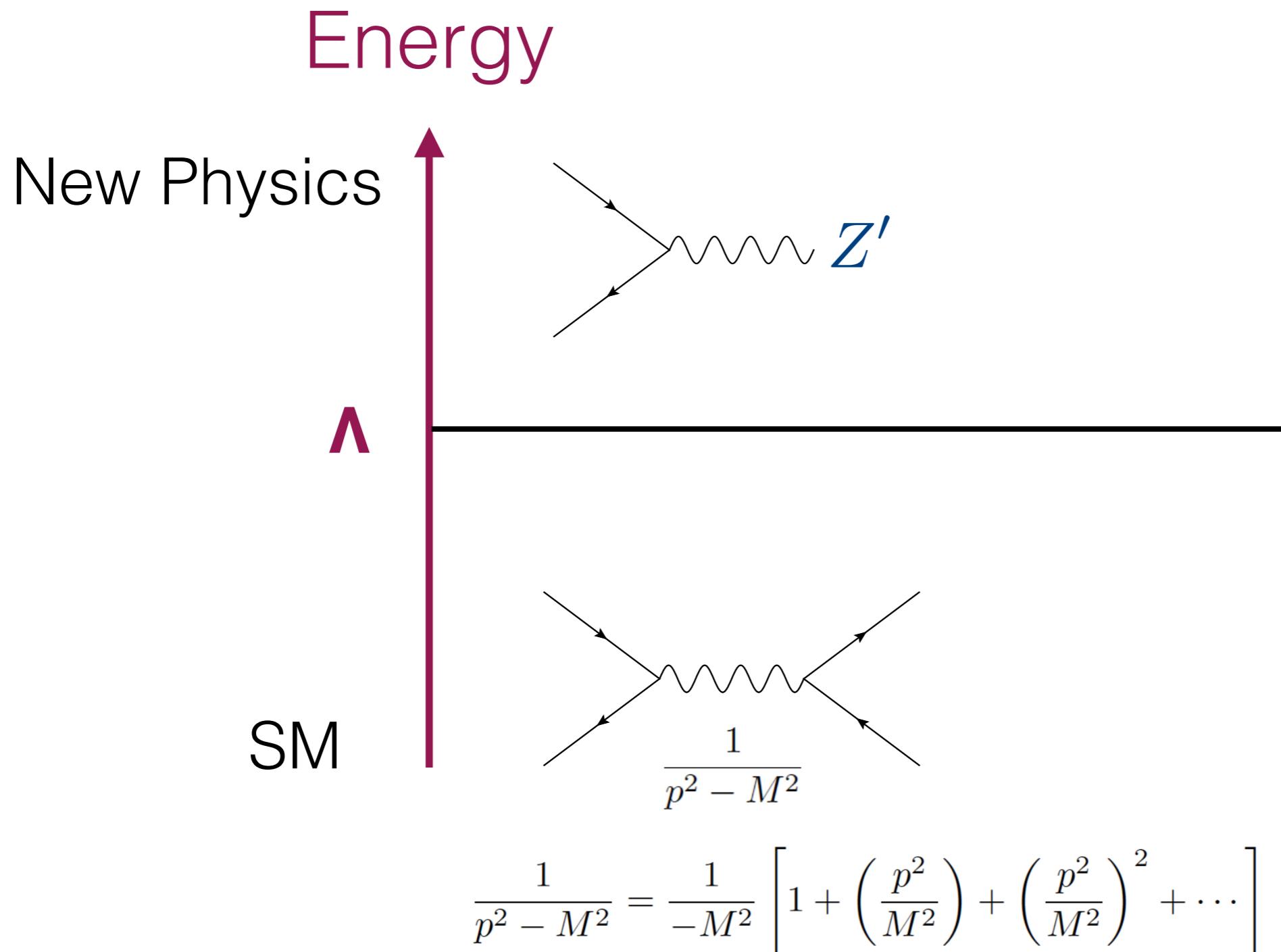
SMEFT: What is it all about?



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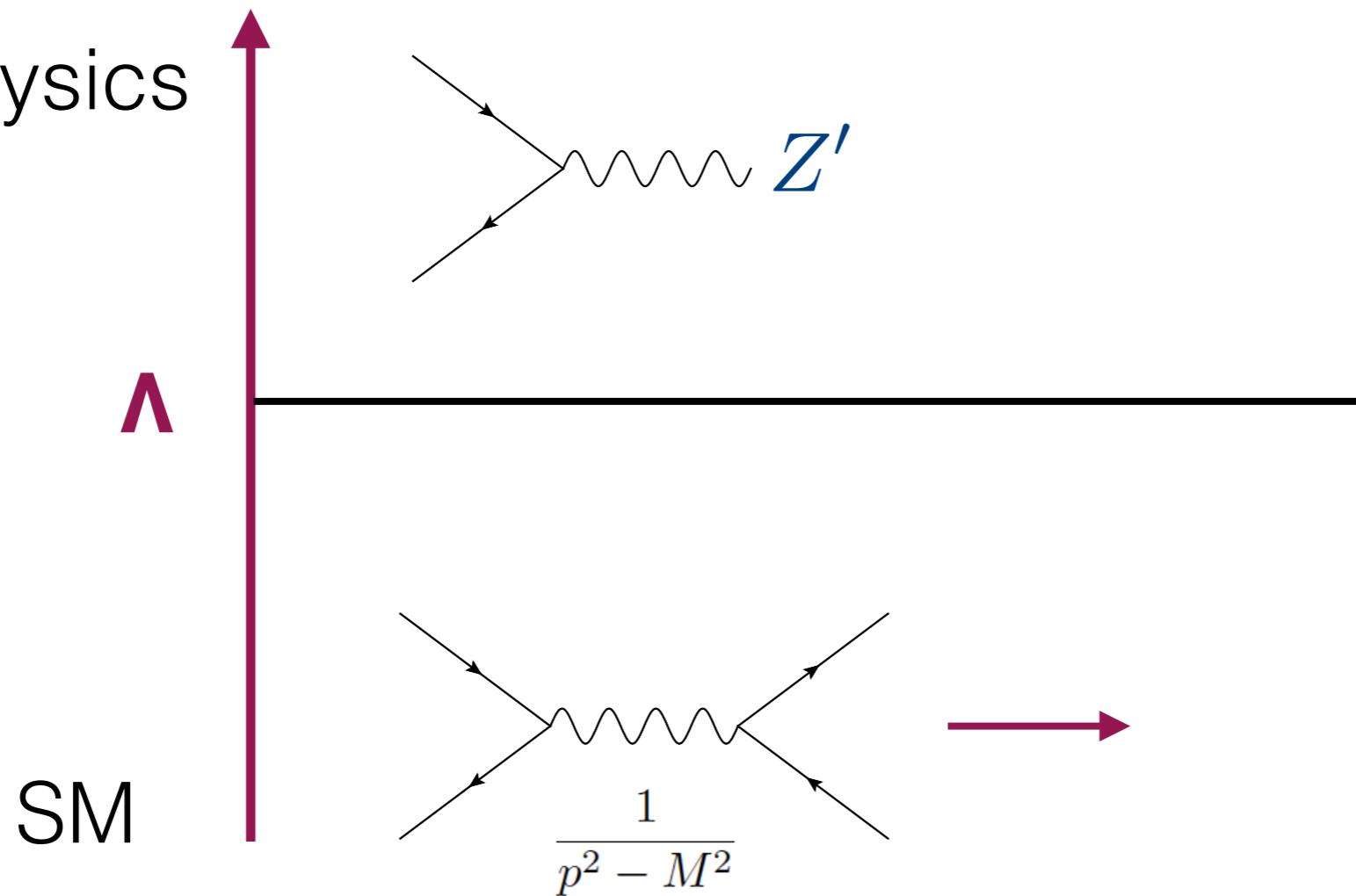


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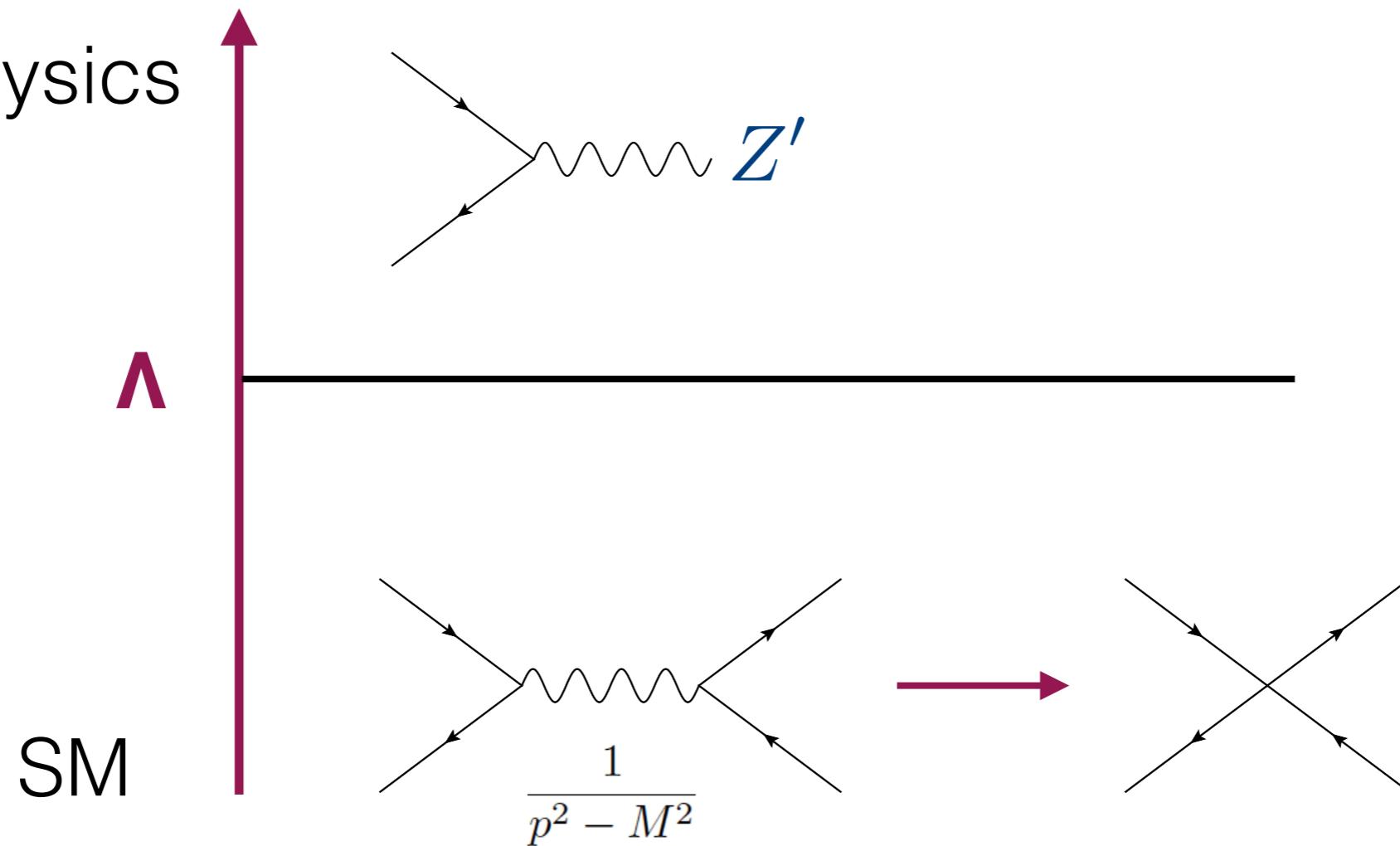
Energy
New Physics



$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2} \left[1 + \left(\frac{p^2}{M^2} \right) + \left(\frac{p^2}{M^2} \right)^2 + \dots \right]$$

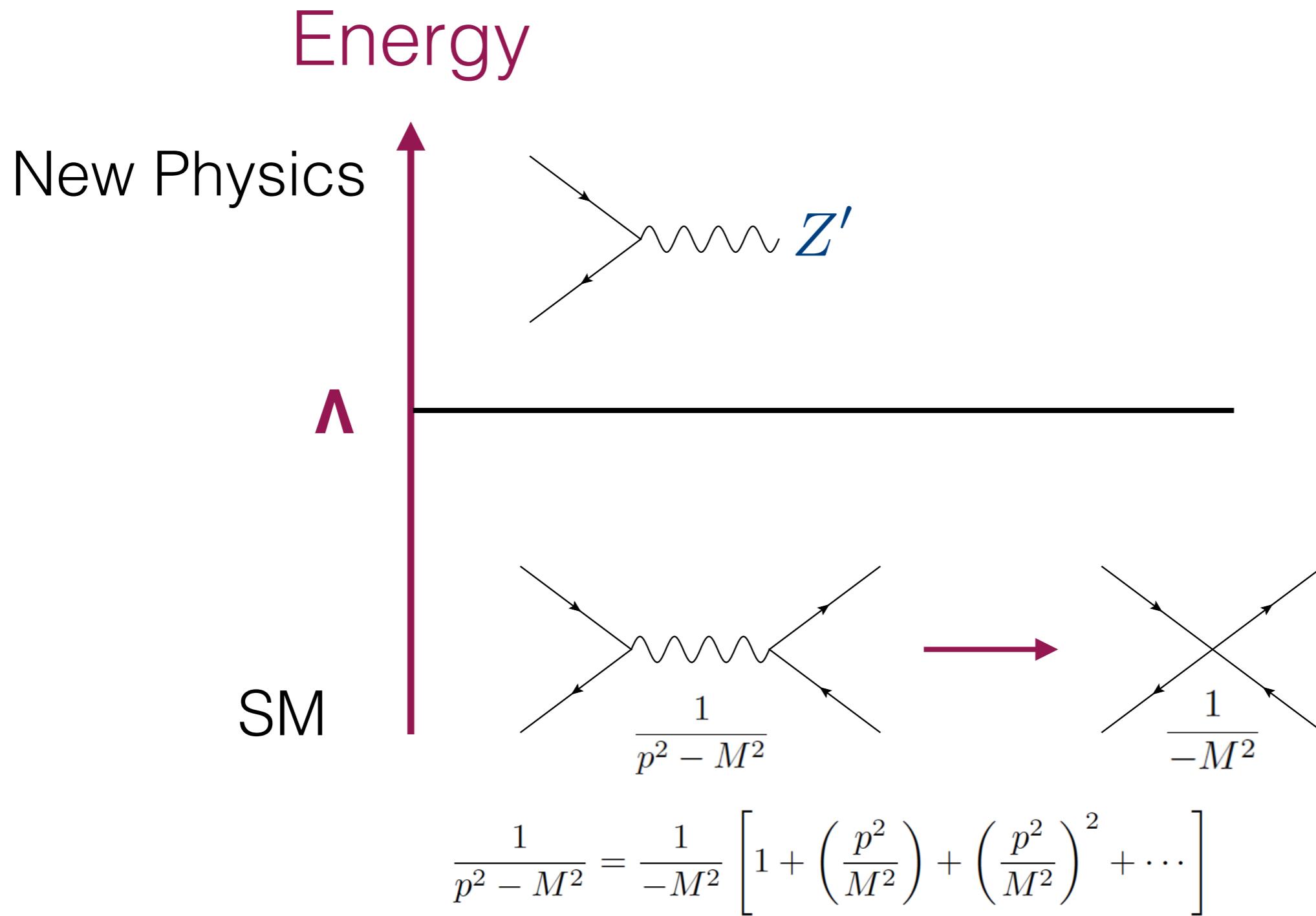
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Energy
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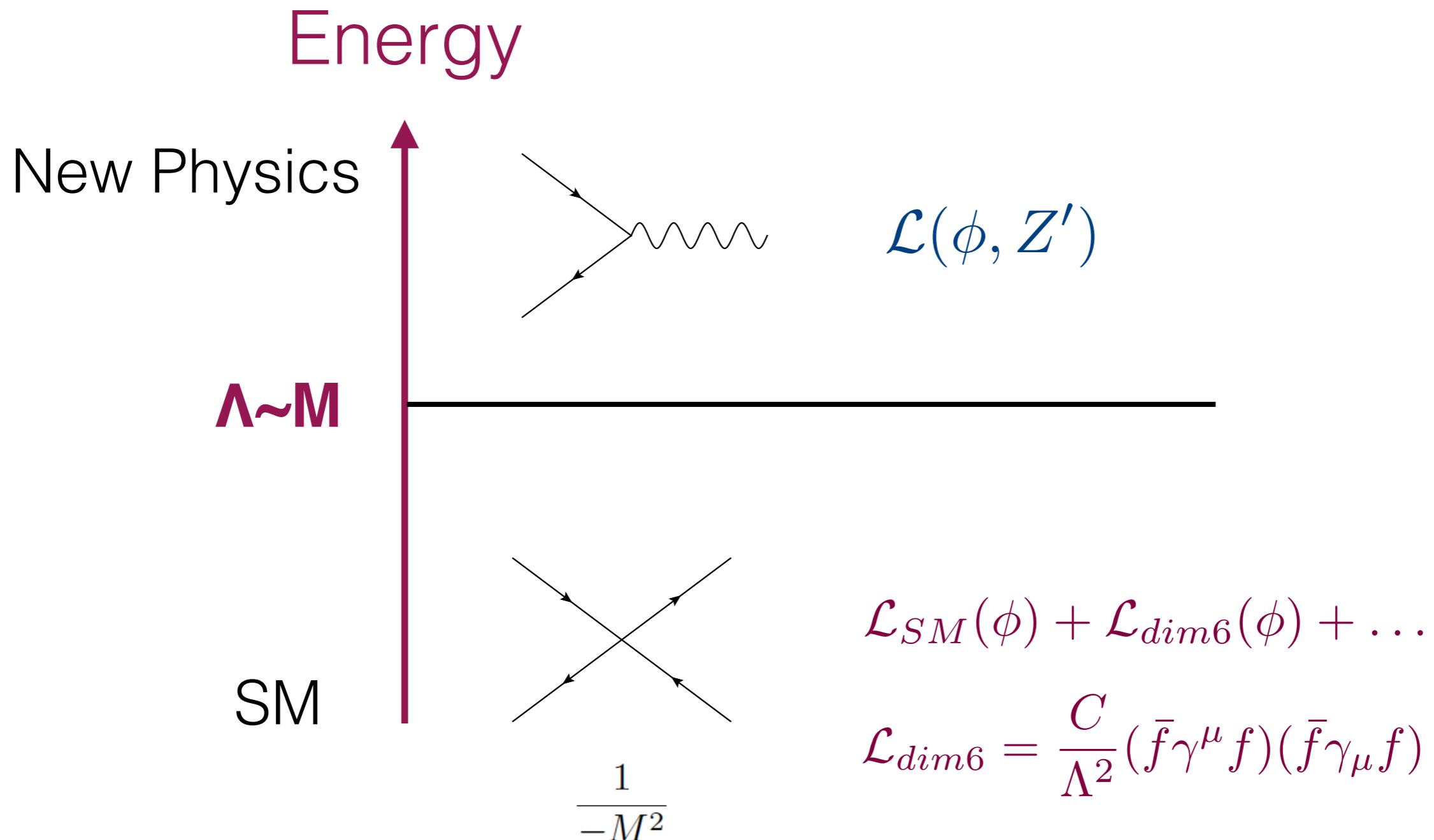


$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2} \left[1 + \left(\frac{p^2}{M^2} \right) + \left(\frac{p^2}{M^2} \right)^2 + \dots \right]$$

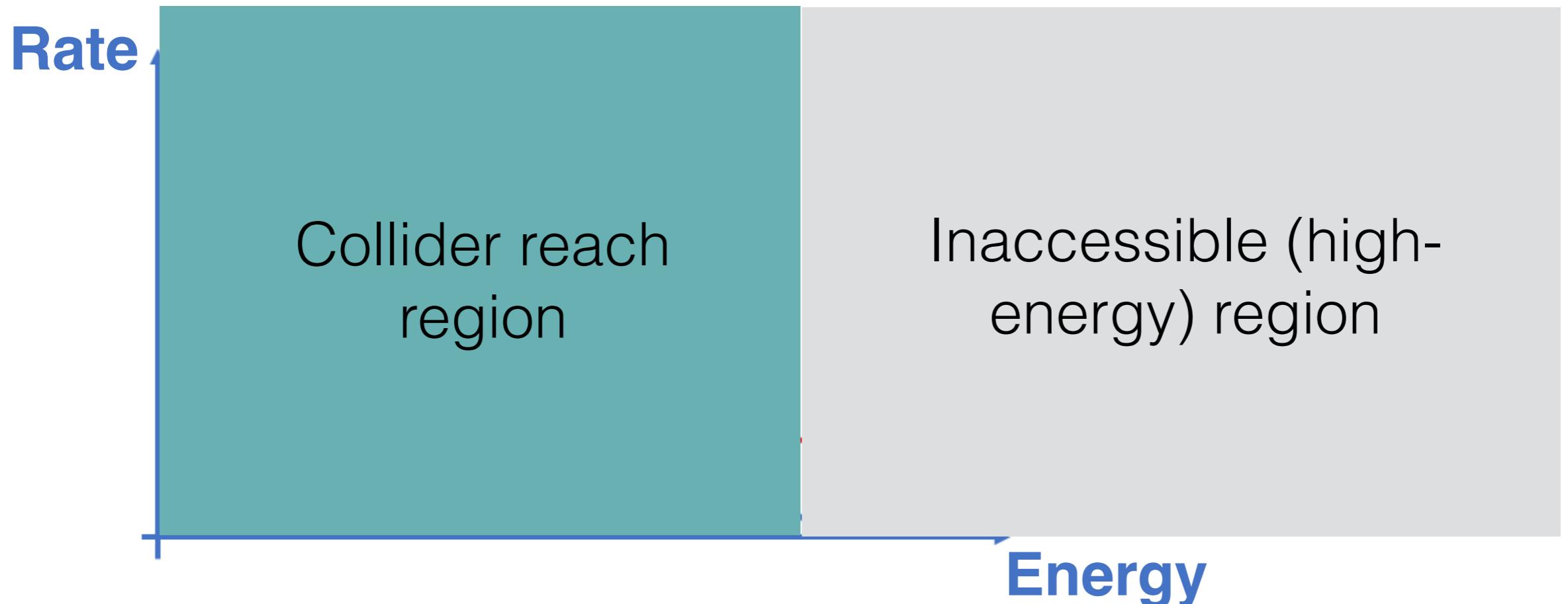
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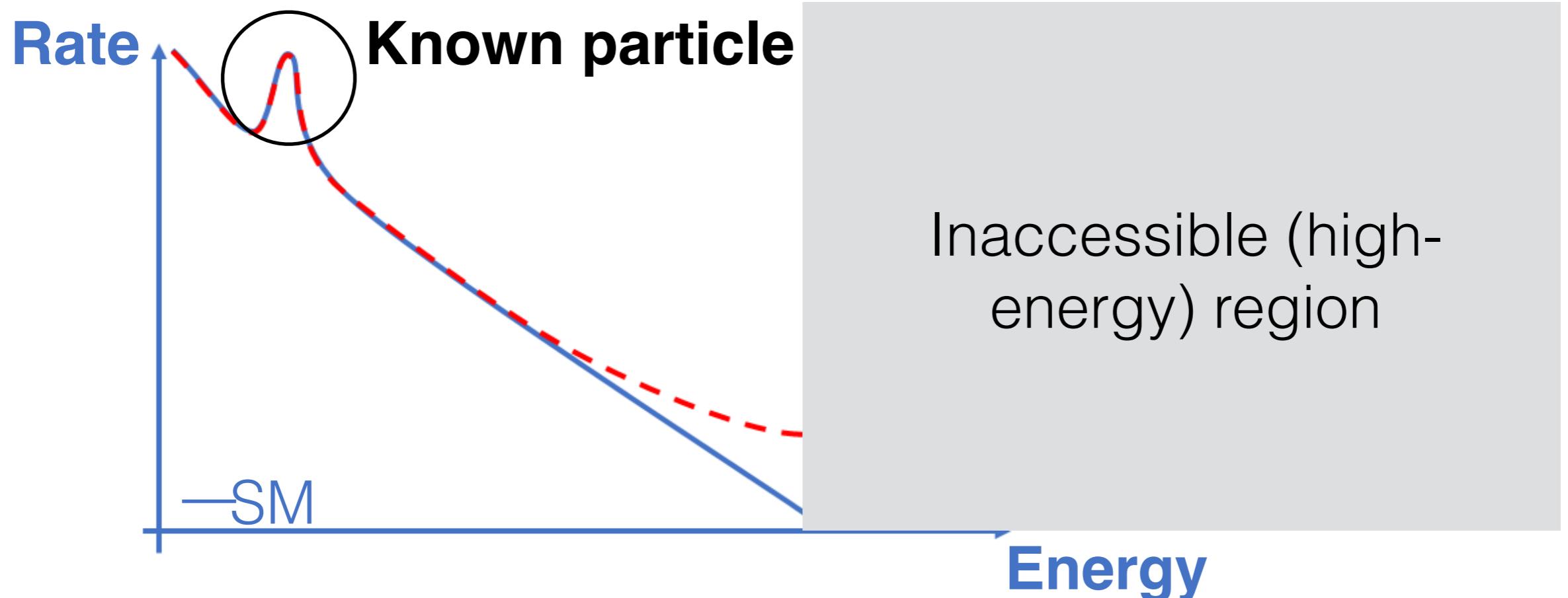


How to find new physics with EFT?



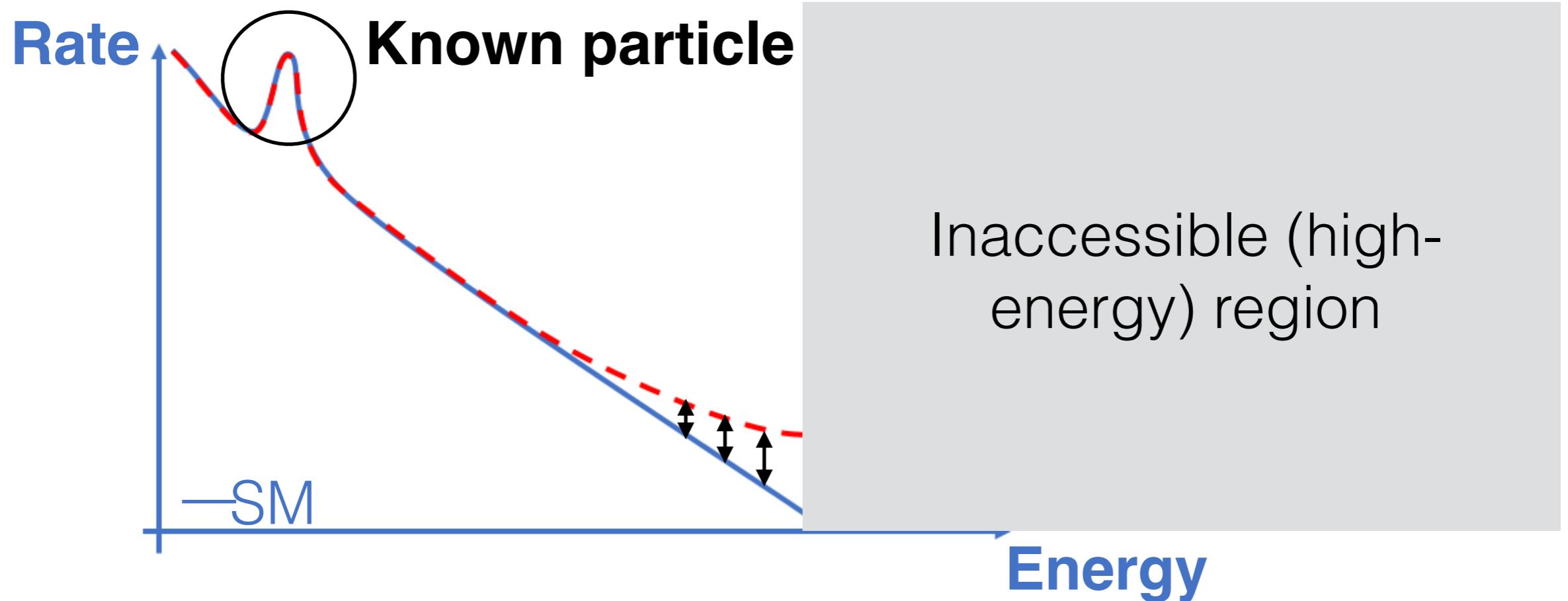
Effective Field Theory (EFT): The way to probe New Physics beyond the direct collider energy reach

How to find new physics with EFT?



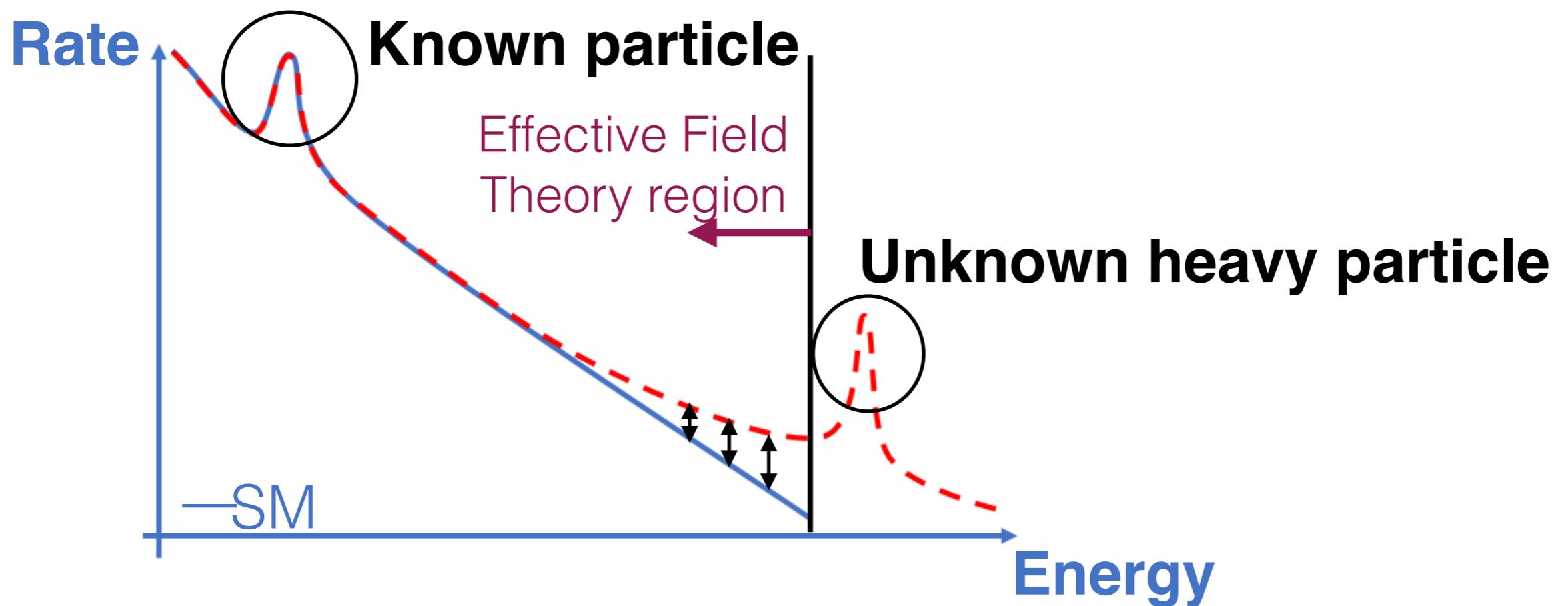
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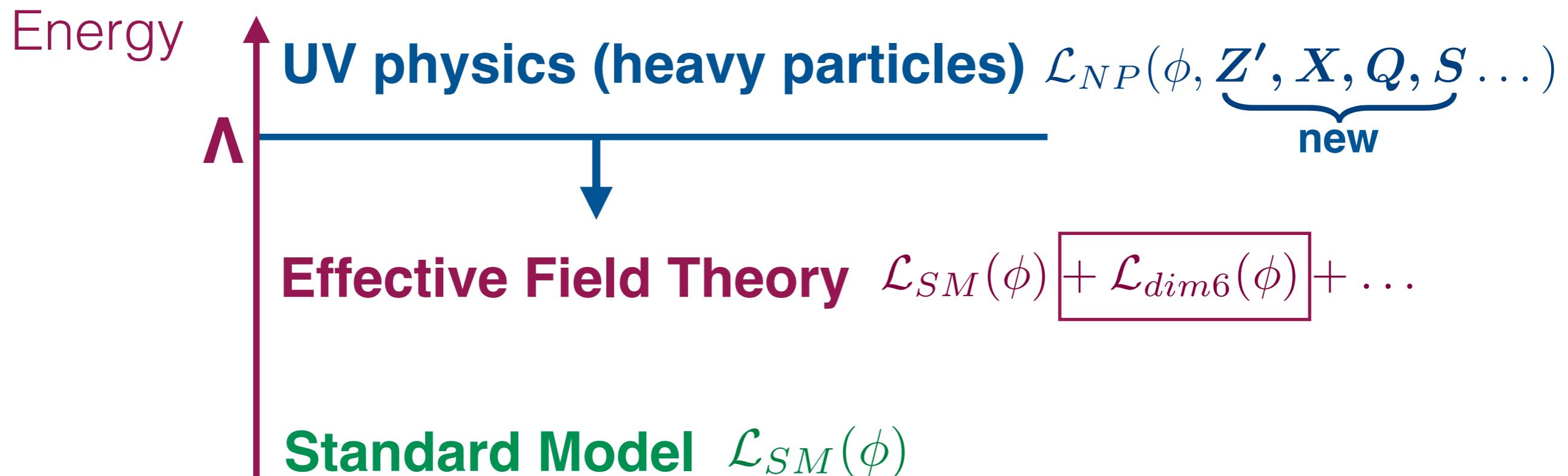
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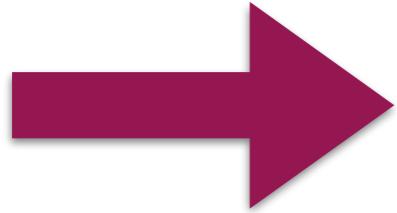
Effective Field Theory (EFT): The way to probe New Physics beyond the direct collider energy reach

Effective Field Theory



Effective Field Theory reveals high energy physics through precise measurements at low energy.

SMEFT basics



New Interactions of SM particles

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

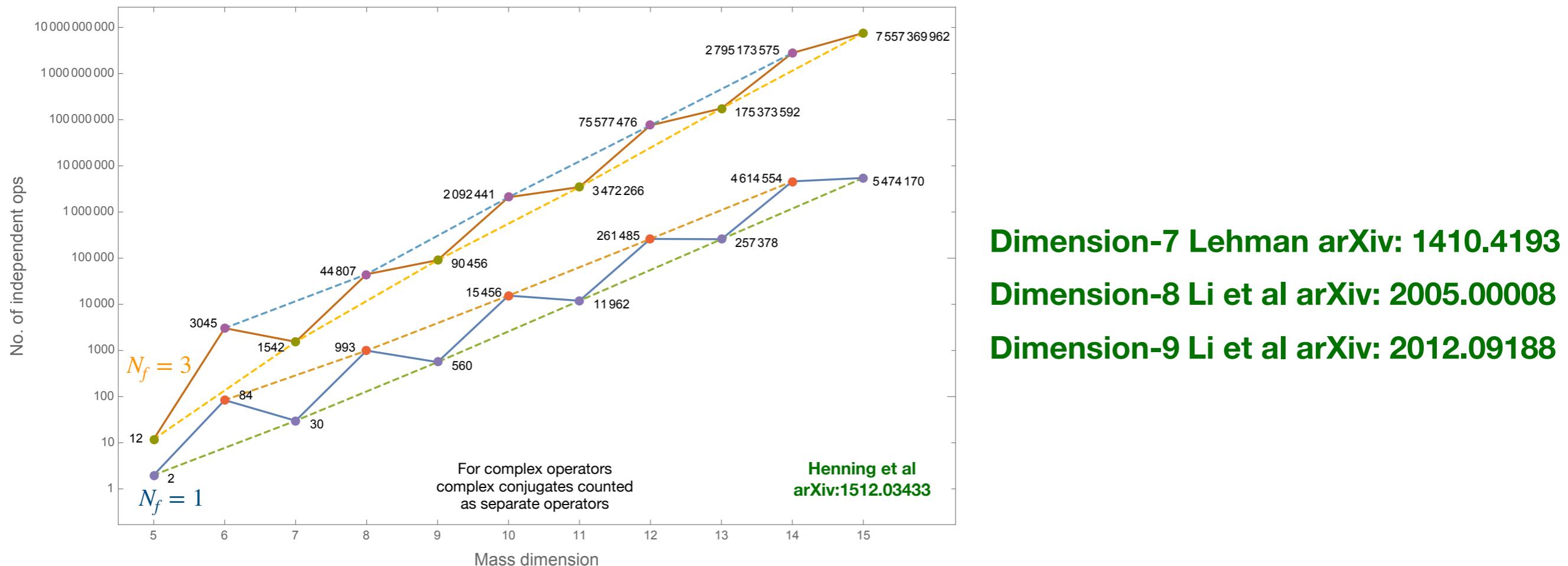
dim-6: 59 operators

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653
Grzadkowski et al arXiv:1008.4884

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	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\square}$	$(\varphi^\dagger \varphi) \square (\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^*$ $(\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
X ² φ^2		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(d_p^\alpha)^T C u_r^\beta] [(q_s^\gamma)^T C l_t^k]$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(q_p^\alpha)^T C q_r^{\beta k}] [(u_s^\gamma)^T C e_t]$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \varepsilon_{mn} [(q_p^\alpha)^T C q_r^{\beta k}] [(q_s^\gamma)^T C l_t^n]$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^\alpha)^T C q_r^{\beta k}] [(q_s^\gamma)^T C l_t^n]$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$		

SMEFT@higher dimensions



Code to generate a basis (non-redundant set) at arbitrary dimension in SMEFT:

Li et al arXiv:2201.04639

Let's take a tour of SMEFT

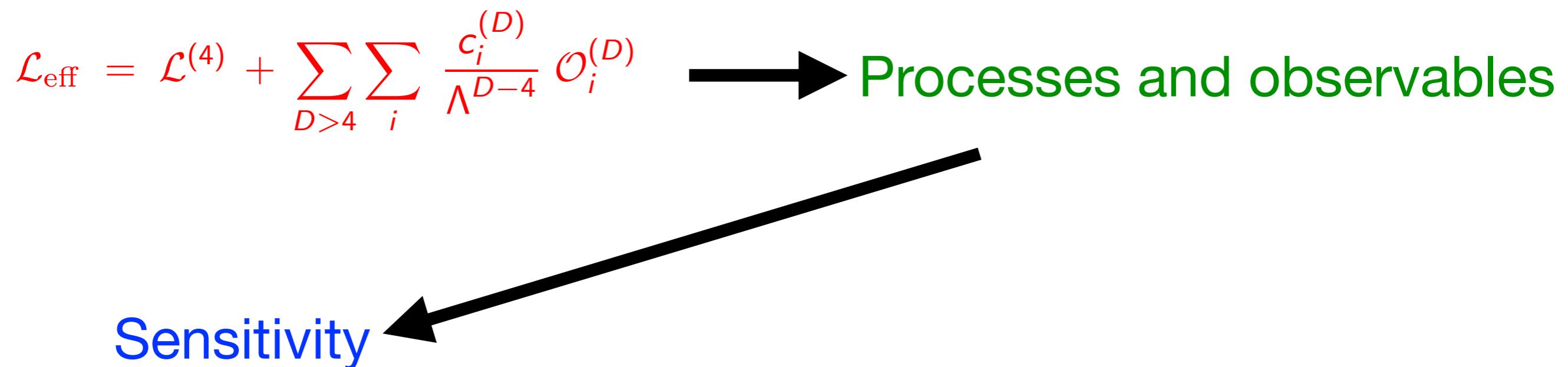
$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

Let's take a tour of SMEFT

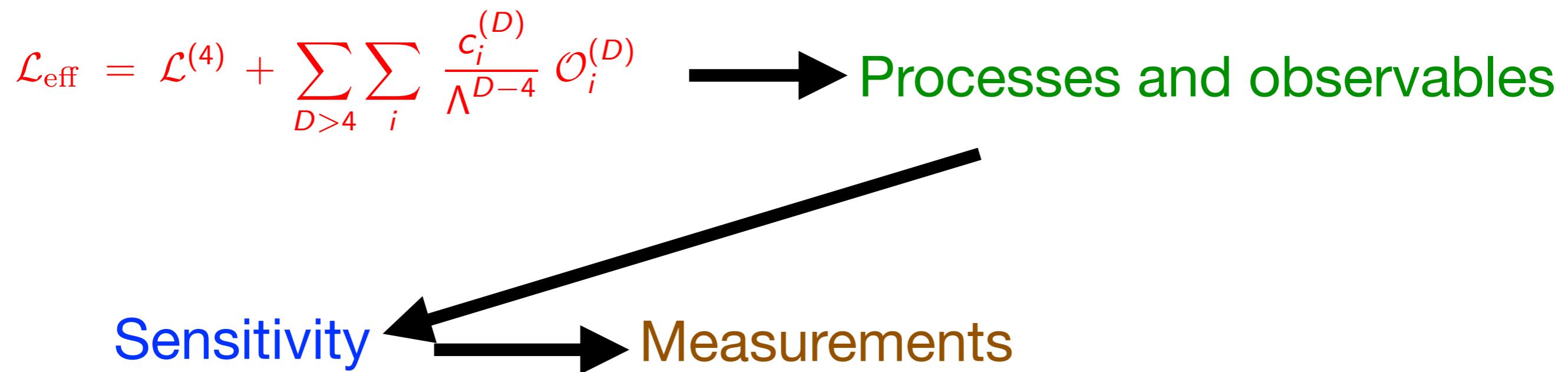
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Processes and observables

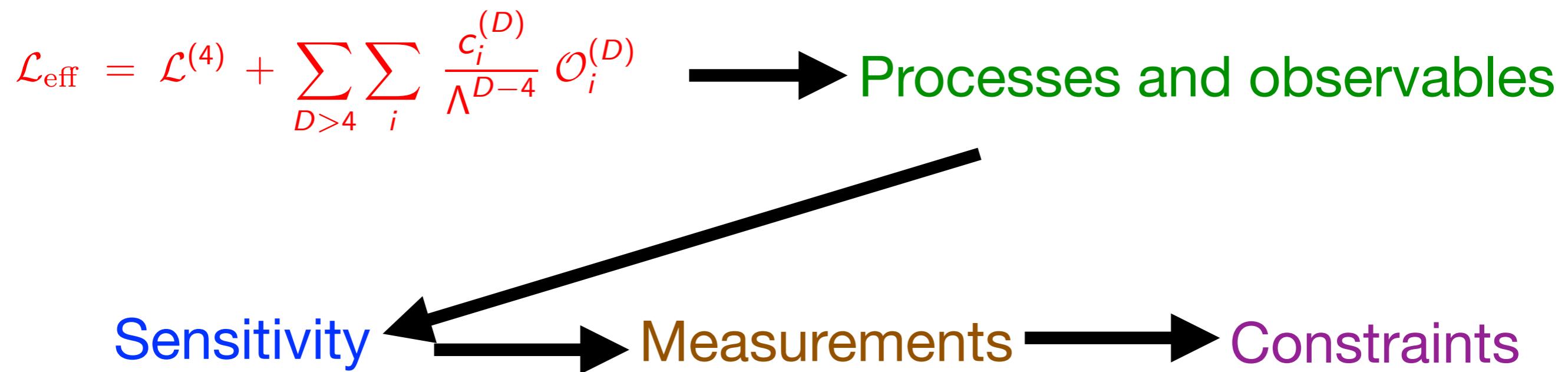
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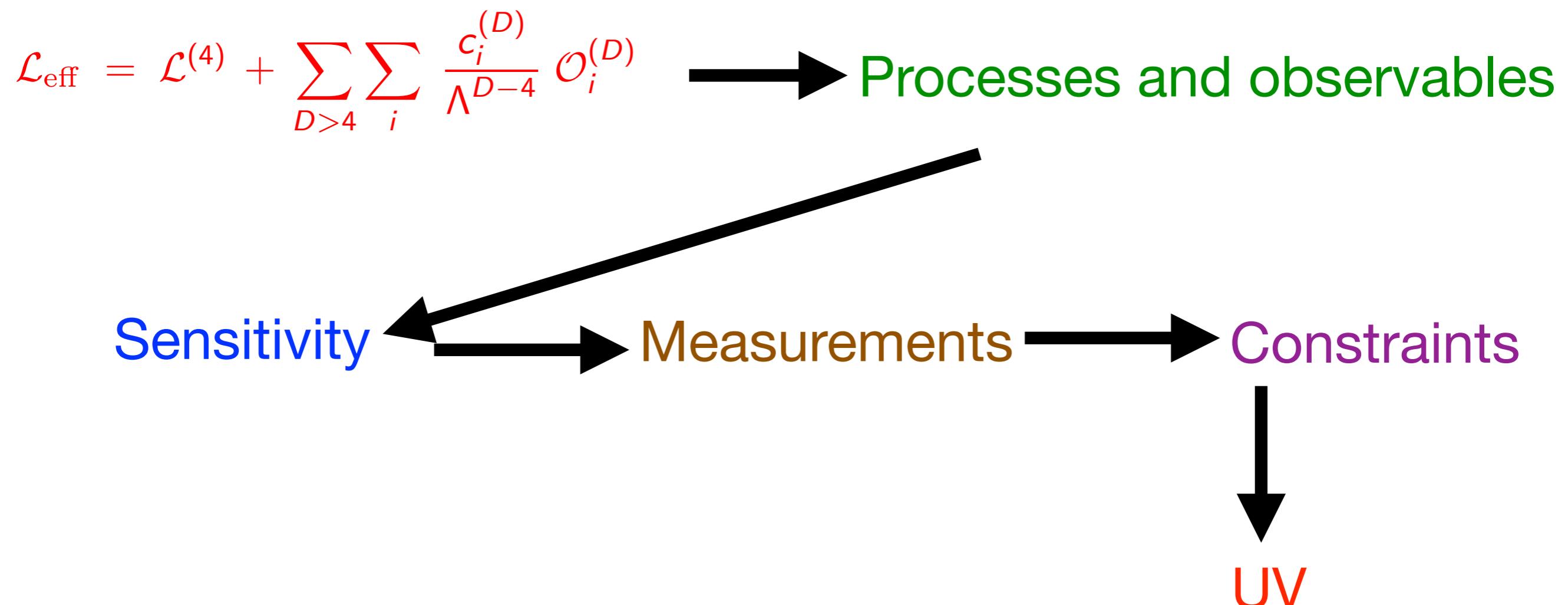
Let's take a tour of SMEFT



Let's take a tour of SMEFT



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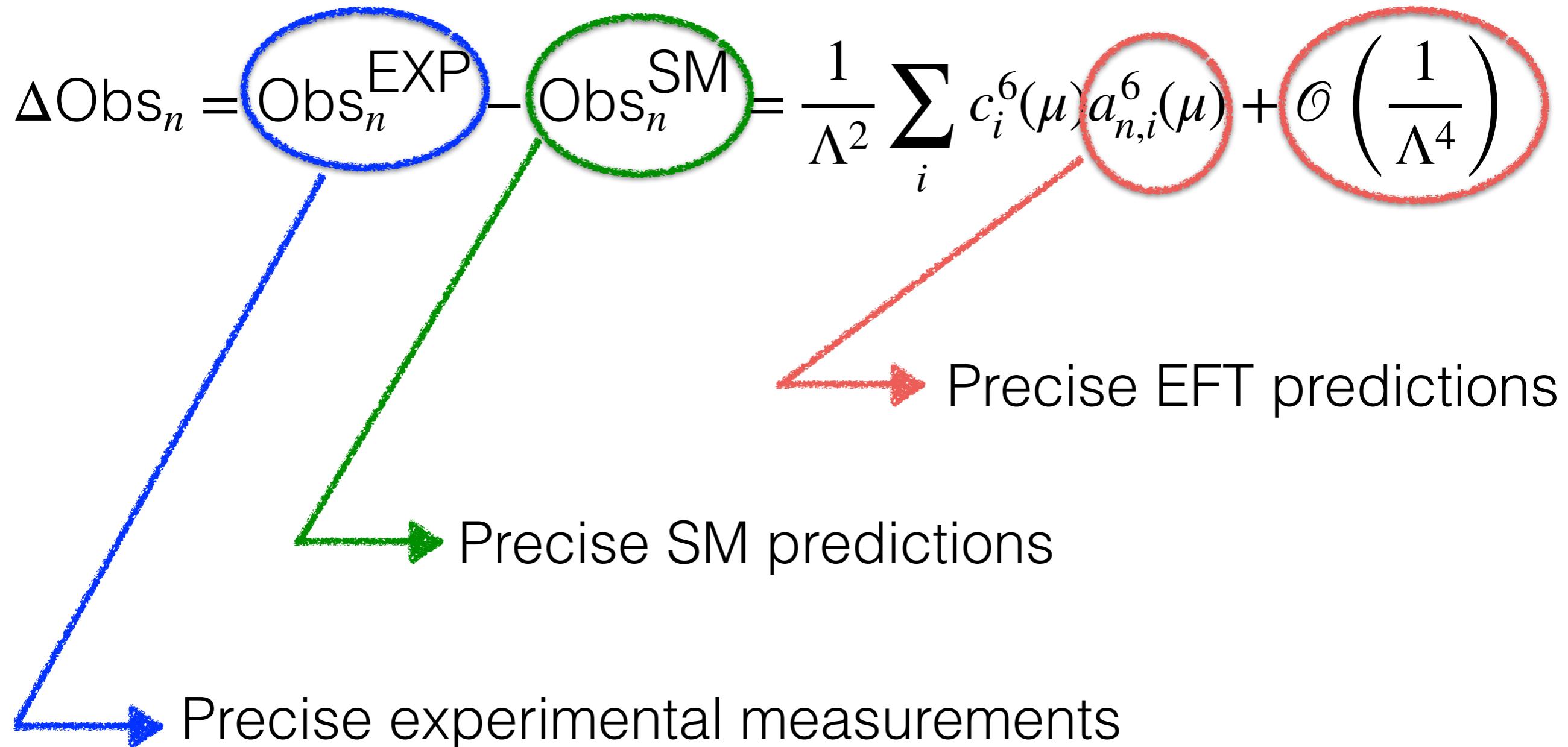
$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

→ Processes and observables



Huge effort to improve each one of these steps!

EFT pathway to New Physics



SMEFT@dim6

59 operators in flavour universal scenario

2499 if fully general

SMEFT@dim6

59 operators in flavour universal scenario

2499 if fully general 

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Is there any hope?

- Not all operators enter in all observables
- Many observables available
- We can make “reasonable” assumptions

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no B,L violation
Flavour (universality, MFV)

CP conservation

<100 operators for the LHC

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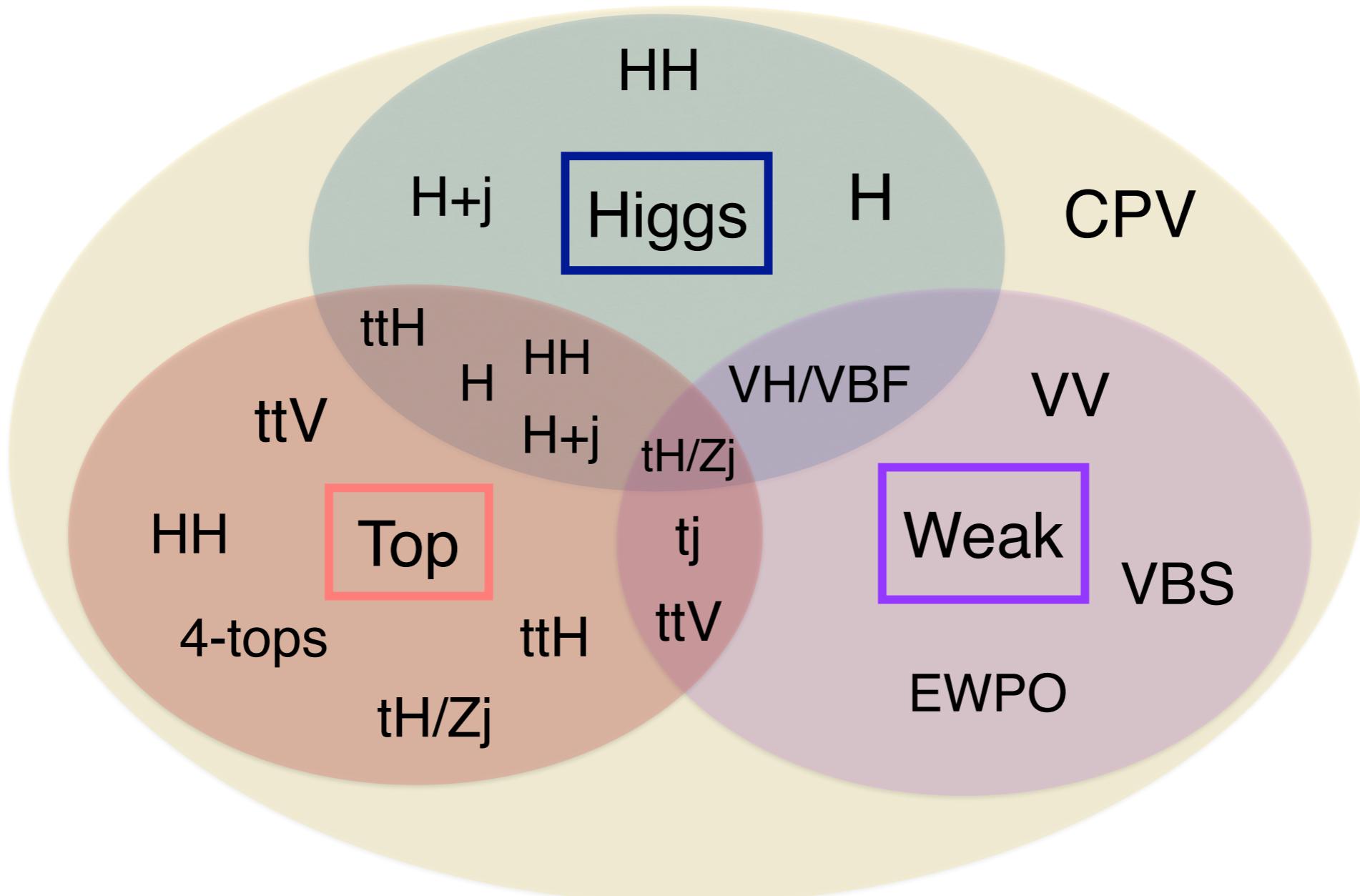
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<100 operators for the LHC



Global nature of EFT



Adapted from K. Mimasu

Examples of operators

Dimension-6 operators of the SMEFT:

Class	Example	Interaction	Impact
	$X^3 : \epsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W_{\rho}^{K,\mu}$		
	$H^6 : (\varphi^\dagger \varphi)^3$		
	$\psi^2 H^3 : (\varphi^\dagger \varphi) (\bar{q}_i u_j \tilde{\varphi})$		
	$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi) (\bar{q}_i \gamma^\mu q_j)$		
	$X^2 H^2 : (\varphi^\dagger \varphi) G_{\mu\nu}^a G_a^{\mu\nu}$		
	$H^4 D^2 : (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D^\mu \varphi)$		
	$\psi^2 X H : (\bar{q}_i \sigma^{\mu\nu} u_j \tilde{\varphi}) B_{\mu\nu}$		
	$\psi^4 : (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l)$		

Examples of operators

Dimension-6 operators of the SMEFT:

Class	Example	Interaction	Impact
X^3	$\epsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W_{\rho}^{K,\mu}$	gauge boson self-coupling	diboson
H^6	$(\varphi^\dagger \varphi)^3$	Higgs potential, self-coupling	di-Higgs
$\psi^2 H^3$	$(\varphi^\dagger \varphi) (\bar{q}_i u_j \tilde{\varphi})$	Higgs-fermion (Yukawa)	$t\bar{t}H, H \rightarrow b\bar{b}$
$\psi^2 H^2 D$	$(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j)$	gauge-fermion (Z, W)	Z, W production
$X^2 H^2$	$(\varphi^\dagger \varphi) G_{\mu\nu}^a G_a^{\mu\nu}$	gauge-Higgs	$ggH, H \rightarrow VV$
$H^4 D^2$	$(\varphi^\dagger D^\mu \varphi)^*(\varphi^\dagger D^\mu \varphi)$	Higgs- Z	m_Z (LEP)
$\psi^2 X H$	$(\bar{q}_i \sigma^{\mu\nu} u_j \tilde{\varphi}) B_{\mu\nu}$	dipole	$ffV, ffVH$
ψ^4	$(\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l)$	four fermion	ffff scattering

Aspects of EFT predictions

- * Higher Orders in $1/\Lambda^4$
 - * squared dim-6 contributions
 - * double insertions of dim-6
 - * dim-8 contributions
- * Higher Orders in QCD and EW
 - * EFT is a QFT, renormalisable order-by order in $1/\Lambda^2$
$$\mathcal{O}(\alpha_s, \alpha_{ew}) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_{ew}}{\Lambda^2}\right)$$

Application: Top quark and SMEFT

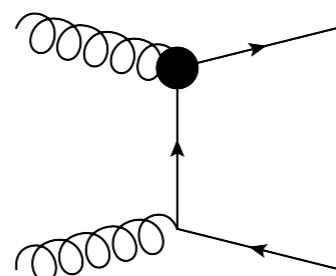
Why study the top quark ?

1. Heaviest known particle: Strong coupling to the Higgs
2. Portal to new physics: e.g. EWSB, composite Higgs
3. LHC is a top factory: precise access to top properties through a lot of production channels

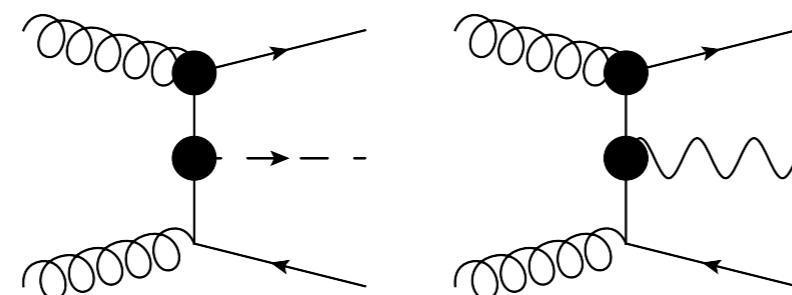
Tops at the LHC

Rich phenomenology:

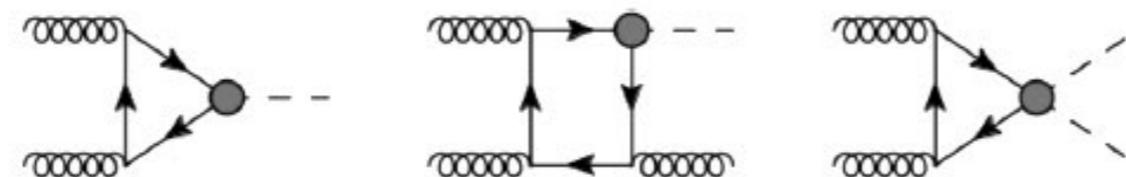
pair production



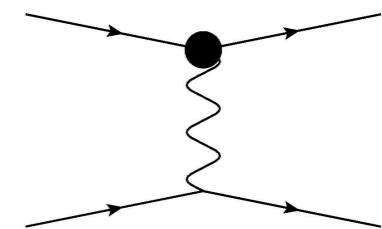
associated production



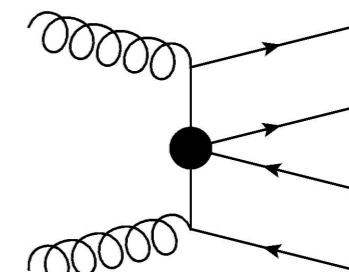
top loops



single



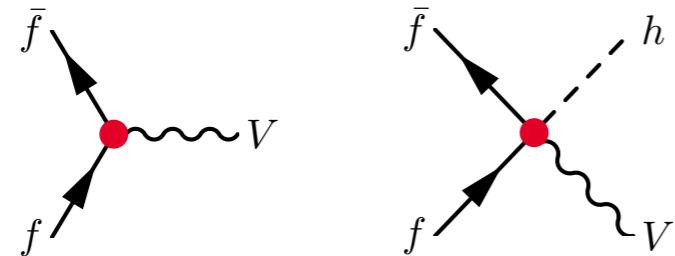
4 tops



connection to Higgs physics

Operator map

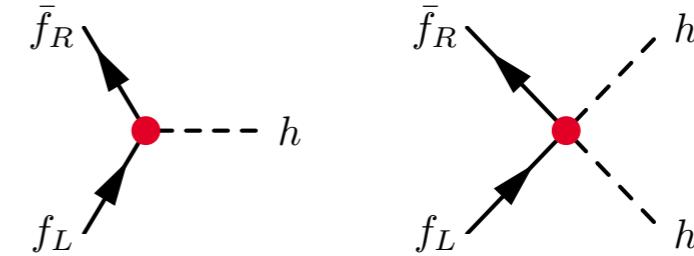
currents $i(\phi^\dagger \overleftrightarrow{D}^\mu \phi)(\bar{Q}\gamma^\mu Q)$



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

$C_{\phi f}$

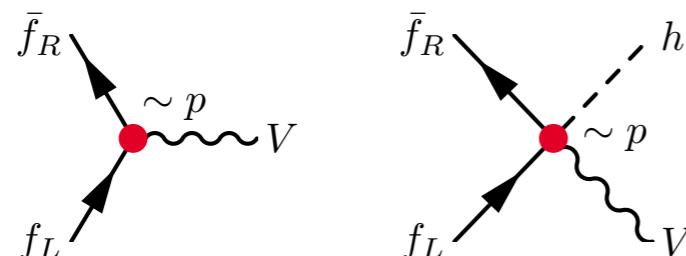
Yukawa $(\bar{q} t \tilde{\phi})(\phi^\dagger \phi)$



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

$C_{t\phi}$

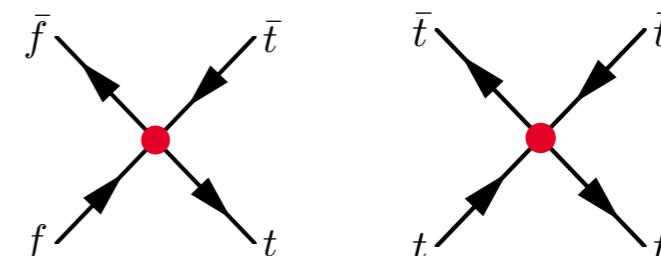
dipole $(\bar{q} \sigma_{\mu\nu} t \tilde{\phi})V^{\mu\nu}$



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

C_{tV}

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



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

C_{ft}

From K. Mimasu

How to look for top operators?

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

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

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

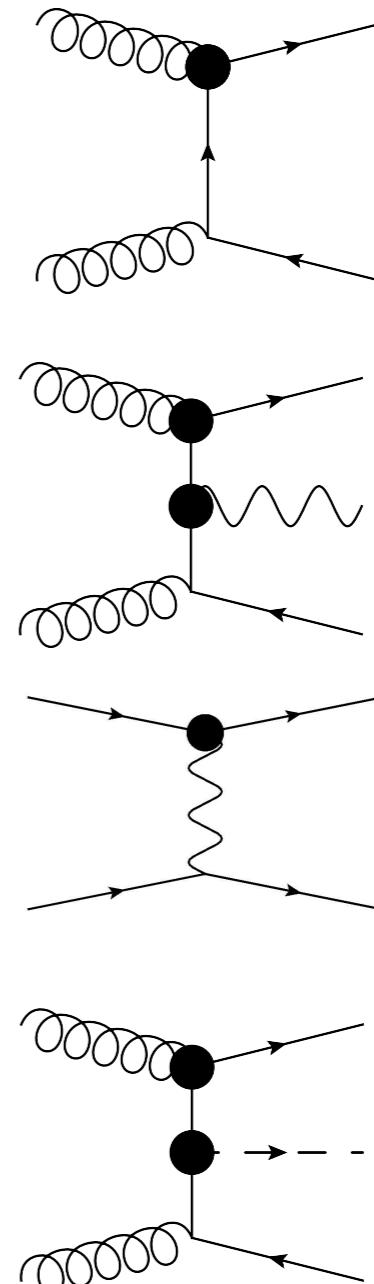
$$O_{tW} = y_t g_w (\bar{Q} \sigma^{\mu\nu} \tau^I t) \tilde{\varphi} W_{\mu\nu}^I$$

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

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

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

see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)



How to look for top operators?

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

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

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

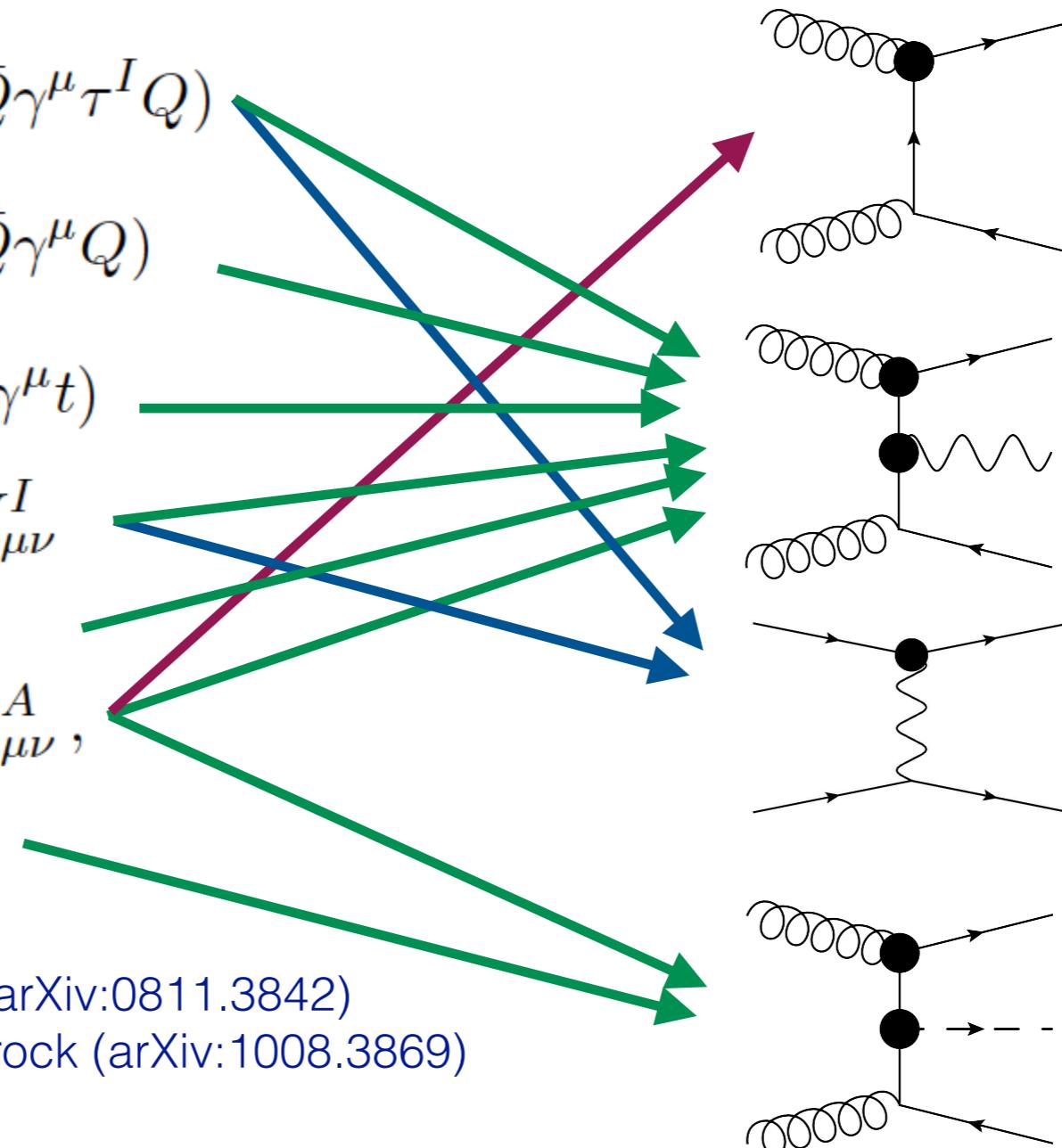
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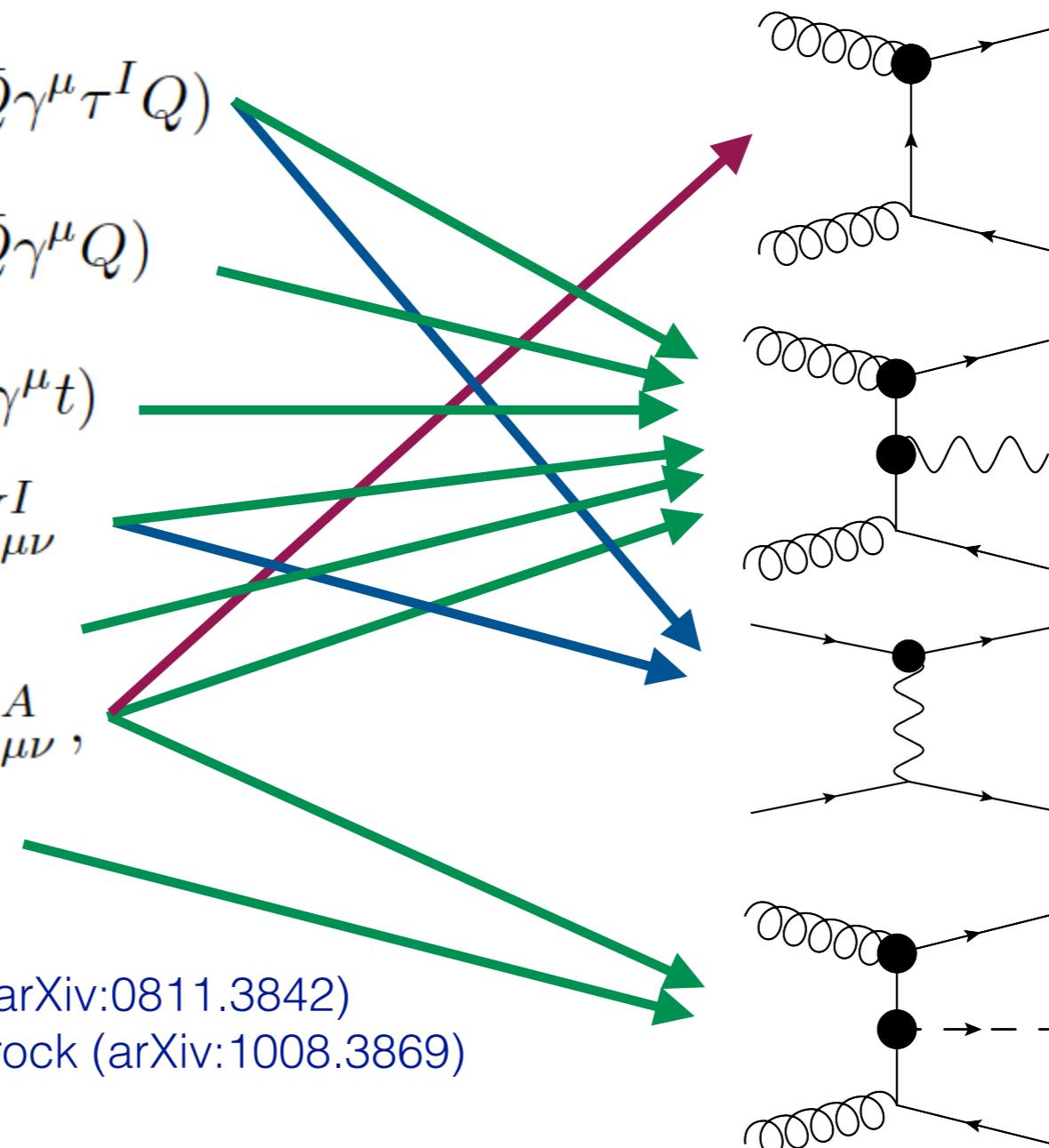
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see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)



Operators entering various processes: Global approach needed

EFT in top pair production

4-fermion operators

$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$$

$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i \gamma^\mu T^A \tau^I q_i)$$

$$O_{tu}^8 = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i \gamma^\mu T^A u_i)$$

$$O_{td}^8 = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i \gamma_\mu T^A d_i)$$

$$O_{Qu}^8 = (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i \gamma_\mu T^A u_i)$$

$$O_{Qd}^8 = (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i \gamma_\mu T^A d_i)$$

$$O_{tq}^8 = (\bar{q}_i \gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$$

$$O_{Qq}^{1,1} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i \gamma^\mu q_i)$$

$$O_{Qq}^{3,1} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i \gamma^\mu \tau^I q_i)$$

$$O_{tu}^1 = (\bar{t}\gamma_\mu t)(\bar{u}_i \gamma^\mu u_i)$$

$$O_{td}^1 = (\bar{t}\gamma^\mu t)(\bar{d}_i \gamma_\mu d_i) ;$$

$$O_{Qu}^1 = (\bar{Q}\gamma^\mu Q)(\bar{u}_i \gamma_\mu u_i)$$

$$O_{Qd}^1 = (\bar{Q}\gamma^\mu Q)(\bar{d}_i \gamma_\mu d_i)$$

$$O_{tq}^1 = (\bar{q}_i \gamma^\mu q_i)(\bar{t}\gamma_\mu t) ;$$

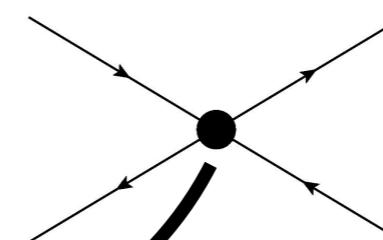
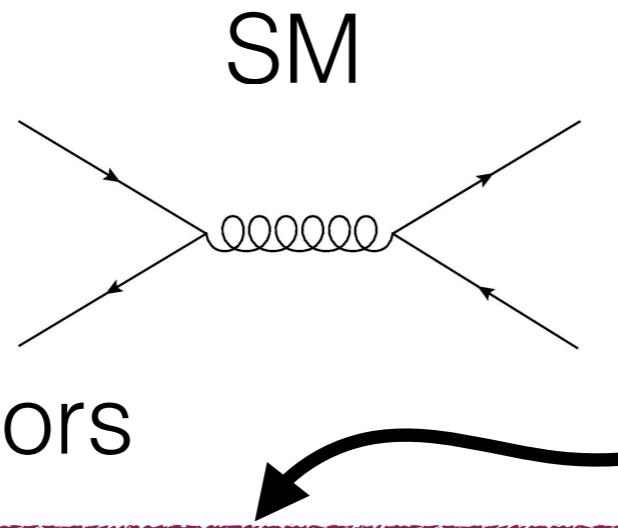
Octets

Singlets

Different chiralities and colour structures

EFT

Cross-section



c_t	$\mathcal{O}(\Lambda^{-2})$	
	LO	NLO
c_{tu}^8	$4.27^{+11\%}_{-9\%}$	$4.06^{+1\%}_{-3\%}$
c_{td}^8	$2.79^{+11\%}_{-9\%}$	$2.77^{+1\%}_{-3\%}$
c_{tq}^8	$6.99^{+11\%}_{-9\%}$	$6.67^{+1\%}_{-3\%}$
c_{Qu}^8	$4.26^{+11\%}_{-9\%}$	$3.93^{+1\%}_{-4\%}$
c_{Qd}^8	$2.79^{+11\%}_{-9\%}$	$2.93^{+0\%}_{-1\%}$
$c_{Qq}^{8,1}$	$6.99^{+11\%}_{-9\%}$	$6.82^{+1\%}_{-3\%}$
$c_{Qq}^{8,3}$	$1.50^{+10\%}_{-9\%}$	$1.32^{+1\%}_{-3\%}$

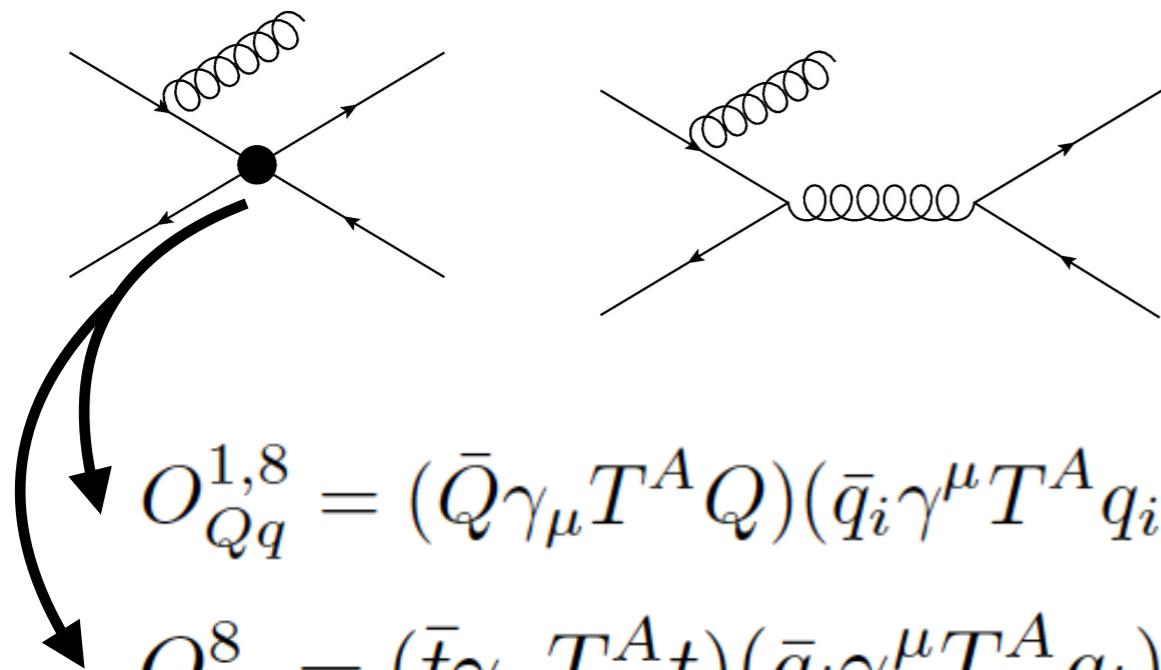
c_{tu}^1	$[0.67^{+1\%}_{-1\%}]$	$-0.078(7)^{+31\%}_{-23\%}$	$[0.41^{+13\%}_{-17\%}]$
c_{td}^1	$[-0.21^{+1\%}_{-2\%}]$	$-0.306^{+30\%}_{-22\%}$	$[-0.15^{+10\%}_{-13\%}]$
c_{tq}^1	$[0.39^{+0\%}_{-1\%}]$	$-0.47^{+24\%}_{-18\%}$	$[0.50^{+3\%}_{-2\%}]$
c_{Qu}^1	$[0.33^{+0\%}_{-0\%}]$	$-0.359^{+23\%}_{-17\%}$	$[0.57^{+6\%}_{-5\%}]$
c_{Qd}^1	$[-0.11^{+0\%}_{-1\%}]$	$0.023(6)^{+114\%}_{-75\%}$	$[-0.19^{+6\%}_{-5\%}]$
$c_{Qq}^{1,1}$	$[0.57^{+0\%}_{-1\%}]$	$-0.24^{+30\%}_{-22\%}$	$[0.39^{+9\%}_{-12\%}]$
$c_{Qq}^{1,3}$	$[1.92^{+1\%}_{-1\%}]$	$0.088(7)^{+28\%}_{-20\%}$	$[1.05^{+17\%}_{-22\%}]$

Interesting interference patterns

Degrade, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

New observables in $t\bar{t}$

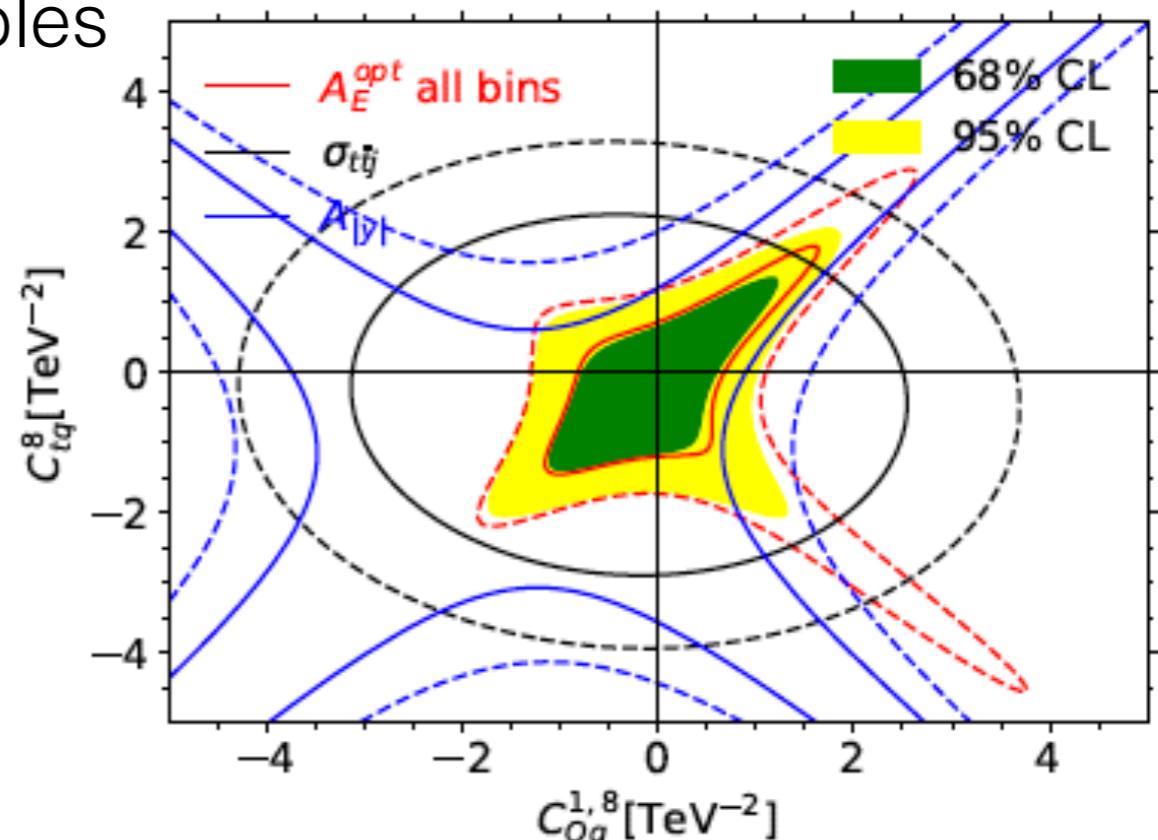
LHC can probe more sensitive observables



Different top chiralities

An asymmetry observable

$$A_E(\theta_j) = \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}$$



Basan, Berta, Masetti, EV, Westhoff arXiv:2001.07225

Optimised sensitivity
Broken degeneracies

How to compute these results?

Computing tools for SMEFT: SMEFT@NLO

Automated one-loop computations in the SMEFT

Céline Degrande,^{1,*} Gauthier Durieux,^{2,†} Fabio Maltoni,^{1,3,‡}
Ken Mimasu,^{1,§} Eleni Vryonidou,^{4,¶} and Cen Zhang^{5,6,**}

We present the automation of one-loop computations in the standard-model effective field theory at dimension six. Our implementation, dubbed SMEFT@NLO, contains ultraviolet and rational counterterms for bosonic, two- and four-fermion operators. It presently allows for fully differential predictions, possibly matched to parton shower, up to one-loop accuracy in QCD. We illustrate the potential of the implementation with novel loop-induced and next-to-leading order computations relevant for top-quark, electroweak, and Higgs-boson phenomenology at the LHC and future colliders.

Standard Model Effective Theory at One-Loop in QCD

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

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

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

Current implementation

UFO model: [SMEFTatNLO_v1.0.tar.gz](#)

- 2020/08/24 - v1.0: Official release including notably four-quark operators at NLO.

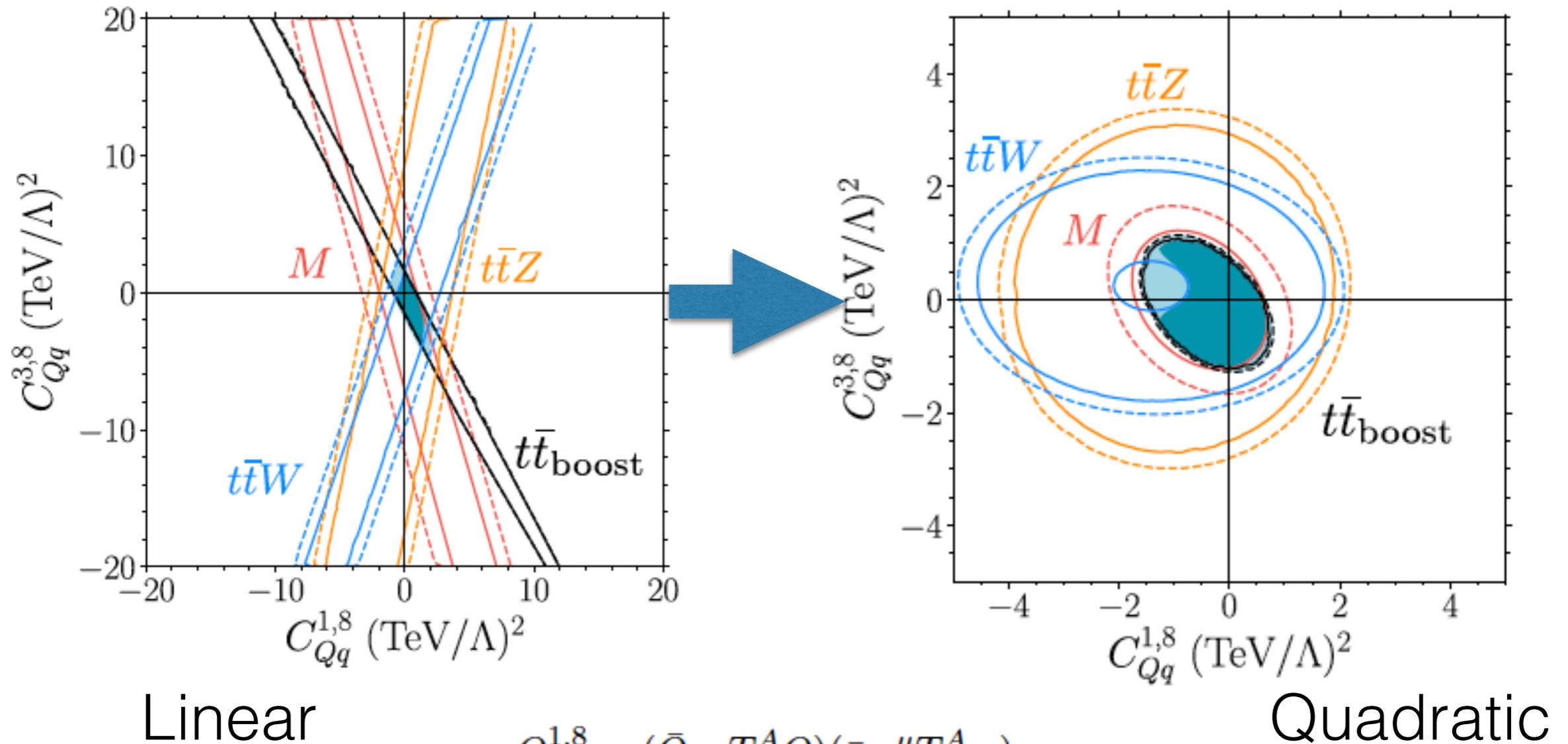
Support

Please direct any questions to smeftatnlo-dev@cern.ch.

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

Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

Probing top operators



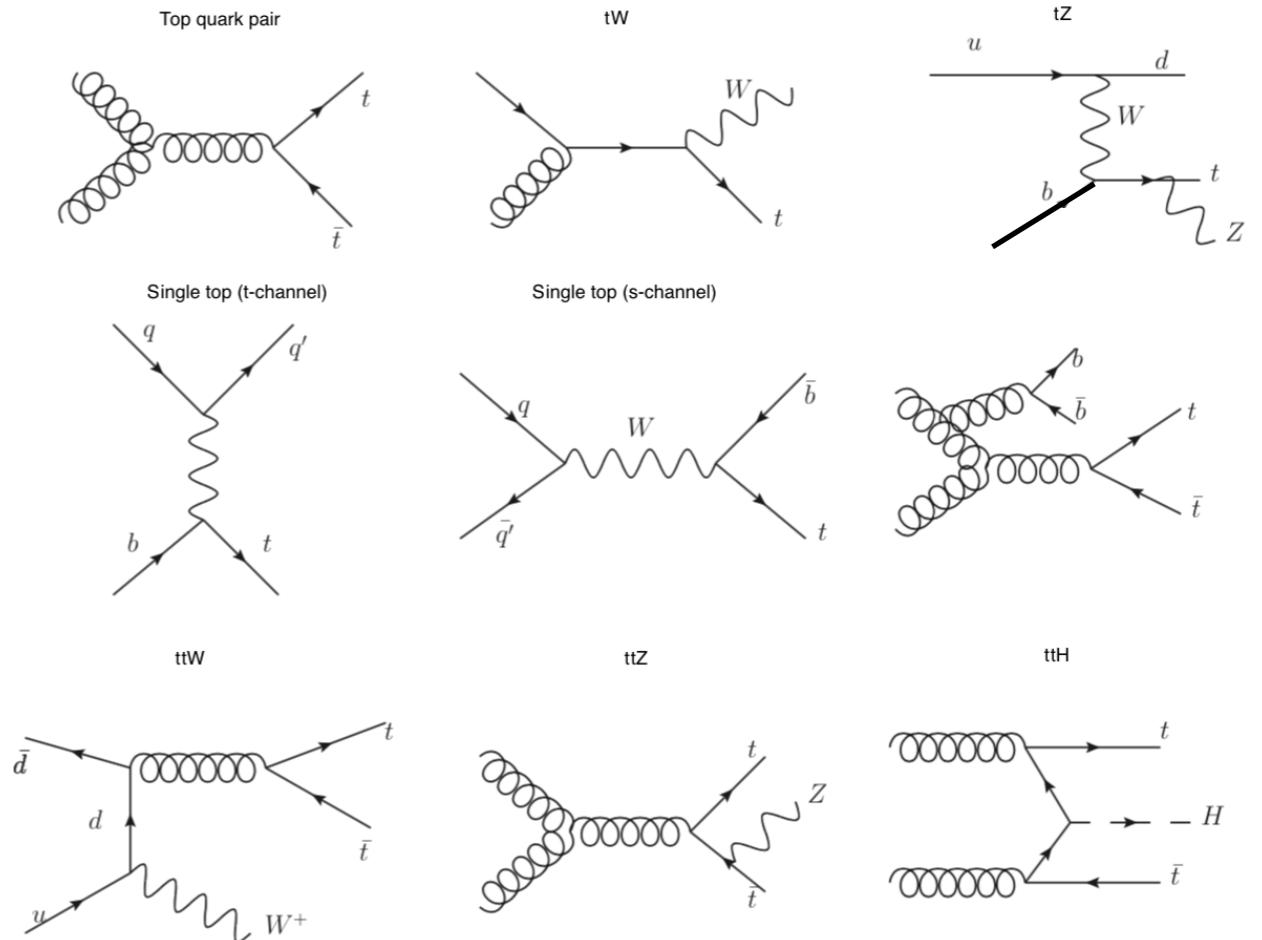
$$O_{Qq}^{1,8} = (\bar{Q} \gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$$

$$O_{Qq}^{3,8} = (\bar{Q} \gamma_\mu T^A \tau^I Q)(\bar{q}_i \gamma^\mu T^A \tau^I q_i)$$

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

A global top fit

Class	Notation	Degree of Freedom	Operator Definition
QQQQ	0QQ1	c_{QQ}^1	$2C_{qq}^{1(3333)} - \frac{2}{3}C_{qq}^{3(3333)}$
	0QQ8	c_{QQ}^8	$8C_{qq}^{9(3333)}$
	0Qt1	c_{Qt}^1	$C_{qu}^{1(3333)}$
	0Qt8	c_{Qt}^8	$C_{qu}^{8(3333)}$
	0Qb1	c_{Qb}^1	$C_{qd}^{1(3333)}$
	0Qb8	c_{Qb}^8	$C_{qd}^{8(3333)}$
	0tt1	c_{tt}^1	$C_{uu}^{1(3333)}$
	0tb1	c_{tb}^1	$C_{ud}^{1(3333)}$
	0tb8	c_{tb}^8	$C_{ud}^{8(3333)}$
	0QtQb1	c_{QtQb}^1	$C_{quqd}^{1(3333)}$
	0QtQb8	c_{QtQb}^8	$C_{quqd}^{8(3333)}$
QQqq	081qq	$c_{Qq}^{1,8}$	$C_{qq}^{1(4334)} + 3C_{qq}^{3(4334)}$
	011qq	$c_{Qq}^{1,1}$	$C_{qq}^{1(4334)} + \frac{1}{6}C_{qq}^{1(4334)} + \frac{1}{2}C_{qq}^{3(4334)}$
	083qq	$c_{Qq}^{3,8}$	$C_{qq}^{1(4334)} - C_{qq}^{3(4334)}$
	013qq	$c_{Qq}^{3,1}$	$C_{qq}^{3(4334)} + \frac{1}{6}(C_{qq}^{1(4334)} - C_{qq}^{3(4334)})$
	08qt	c_{tq}^8	$C_{qu}^{8(4334)}$
	01qt	c_{tq}^1	$C_{qu}^{1(4334)}$
	08ut	c_{tu}^8	$2C_{uu}^{(4334)}$
	01ut	c_{tu}^1	$C_{uu}^{(4334)} + \frac{1}{3}C_{uu}^{(4334)}$
	08qu	c_{Qu}^8	$C_{qu}^{8(3344)}$
	01qu	c_{Qu}^1	$C_{qu}^{1(3344)}$
	08dt	$c_{d\bar{d}}^8$	$C_{ud}^{8(3344)}$
	01dt	$c_{d\bar{d}}^1$	$C_{ud}^{1(3344)}$
	08qd	c_{Qd}^8	$C_{qd}^{8(3344)}$
	01qd	c_{Qd}^1	$C_{qd}^{1(3344)}$
$QQ + V, G, \varphi$	0tG	c_{tG}	$\text{Re}\{C_{uG}^{(33)}\}$
	0tW	c_{tW}	$\text{Re}\{C_{uW}^{(33)}\}$
	0bW	c_{bW}	$\text{Re}\{C_{dW}^{(33)}\}$
	0tZ	c_{tZ}	$\text{Re}\{-s_W C_{uB}^{(33)} + c_W C_{uW}^{(33)}\}$
	0ff	$c_{\varphi tb}$	$\text{Re}\{C_{\varphi ud}^{(33)}\}$
	0fq3	$c_{\varphi Q}^3$	$C_{\varphi q}^{3(33)}$
	0pQM	$c_{\varphi Q}^-$	$C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}$
	0pt	$c_{\varphi t}$	$C_{\varphi u}^{(33)}$
	0tp	$c_{t\varphi}$	$\text{Re}\{C_{u\varphi}^{(33)}\}$



Rich phenomenology

List of operators

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

Global fit Setup

Theory

Accurate predictions for the SM and the EFT

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

Global SMEFT fit
of the top-quark sector

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

Constraints on New Physics scale
Fit results can be used to bound specific UV complete models

Methodology

Output

Top observables

Data

Top-pair production
W-helicities,
asymmetry

Dataset	\sqrt{s}, \mathcal{L}	Info	Observables	n_{dat}	Ref
ATLAS_tt_8TeV_1jets	8 TeV, 20.3 fb $^{-1}$	lepton+jets	$d\sigma/dm_{t\bar{t}}$	7	[46]
CMS_tt_8TeV_1jets	8 TeV, 20.3 fb $^{-1}$	lepton+jets	$1/\sigma d\sigma/dy_{t\bar{t}}$	10	[47]
CMS_tt2D_8TeV_dilep	8 TeV, 20.3 fb $^{-1}$	dileptons	$1/\sigma d^2\sigma/dy_{t\bar{t}} dm_{t\bar{t}}$	16	[48]
ATLAS_tt_8TeV_dilep (*)	8 TeV, 20.3 fb $^{-1}$	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[54]
CMS_tt_13TeV_1jets_2015	13 TeV, 2.3 fb $^{-1}$	lepton+jets	$d\sigma/dm_{t\bar{t}}$	8	[51]
CMS_tt_13TeV_dilep_2015	13 TeV, 2.1 fb $^{-1}$	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[53]
CMS_tt_13TeV_1jets_2016	13 TeV, 35.8 fb $^{-1}$	lepton+jets	$d\sigma/dm_{t\bar{t}}$	10	[52]
CMS_tt_13TeV_dilep_2016 (*)	13 TeV, 35.8 fb $^{-1}$	dileptons	$d\sigma/dm_{t\bar{t}}$	7	[56]
ATLAS_tt_13TeV_1jets_2016 (*)	13 TeV, 35.8 fb $^{-1}$	lepton+jets	$d\sigma/dm_{t\bar{t}}$	9	[55]
ATLAS_WheLF_8TeV	8 TeV, 20.3 fb $^{-1}$	W hel. fract	F_0, F_L, F_R	3	[49]
CMS_WheLF_8TeV	8 TeV, 20.3 fb $^{-1}$	W hel. fract	F_0, F_L, F_R	3	[50]
ATLAS_CMS_tt_AC_8TeV (*)	8 TeV, 20.3 fb $^{-1}$	charge asymmetry	A_C	6	[57]
ATLAS_tt_AC_13TeV (*)	8 TeV, 20.3 fb $^{-1}$	charge asymmetry	A_C	5	[58]

4 tops, ttbb, top-
pair associated
production

Dataset	\sqrt{s}, \mathcal{L}	Info	Observables	N_{dat}	Ref
CMS_ttbb_13TeV	13 TeV, 2.3 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}bb)$	1	[70]
CMS_ttbb_13TeV_2016 (*)	13 TeV, 35.9 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}bb)$	1	[79]
ATLAS_ttbb_13TeV_2016 (*)	13 TeV, 35.9 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}bb)$	1	[78]
CMS_tttt_13TeV	13 TeV, 35.9 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}t\bar{t})$	1	[71]
CMS_tttt_13TeV_run2 (*)	13 TeV, 137 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}t\bar{t})$	1	[76]
ATLAS_tttt_13TeV_run2 (*)	13 TeV, 137 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}t\bar{t})$	1	[77]
CMS_ttZ_8TeV	8 TeV, 19.5 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}Z)$	1	[72]
CMS_ttZ_13TeV	13 TeV, 35.9 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}Z)$	1	[73]
CMS_ttZ_ptZ_13TeV (*)	13 TeV, 77.5 fb $^{-1}$	total xsec	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[81]
ATLAS_ttZ_8TeV	8 TeV, 20.3 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}Z)$	1	[74]
ATLAS_ttZ_13TeV	13 TeV, 3.2 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}Z)$	1	[75]
ATLAS_ttZ_13TeV_2016 (*)	13 TeV, 36 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}Z)$	1	[80]
CMS_ttW_8_TeV	8 TeV, 19.5 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}W)$	1	[72]
CMS_ttW_13TeV	13 TeV, 35.9 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}W)$	1	[73]
ATLAS_ttW_8TeV	8 TeV, 20.3 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}W)$	1	[74]
ATLAS_ttW_13TeV	13 TeV, 3.2 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}W)$	1	[75]
ATLAS_ttW_13TeV_2016 (*)	13 TeV, 36 fb $^{-1}$	total xsec	$\sigma_{\text{tot}}(t\bar{t}W)$	1	[80]

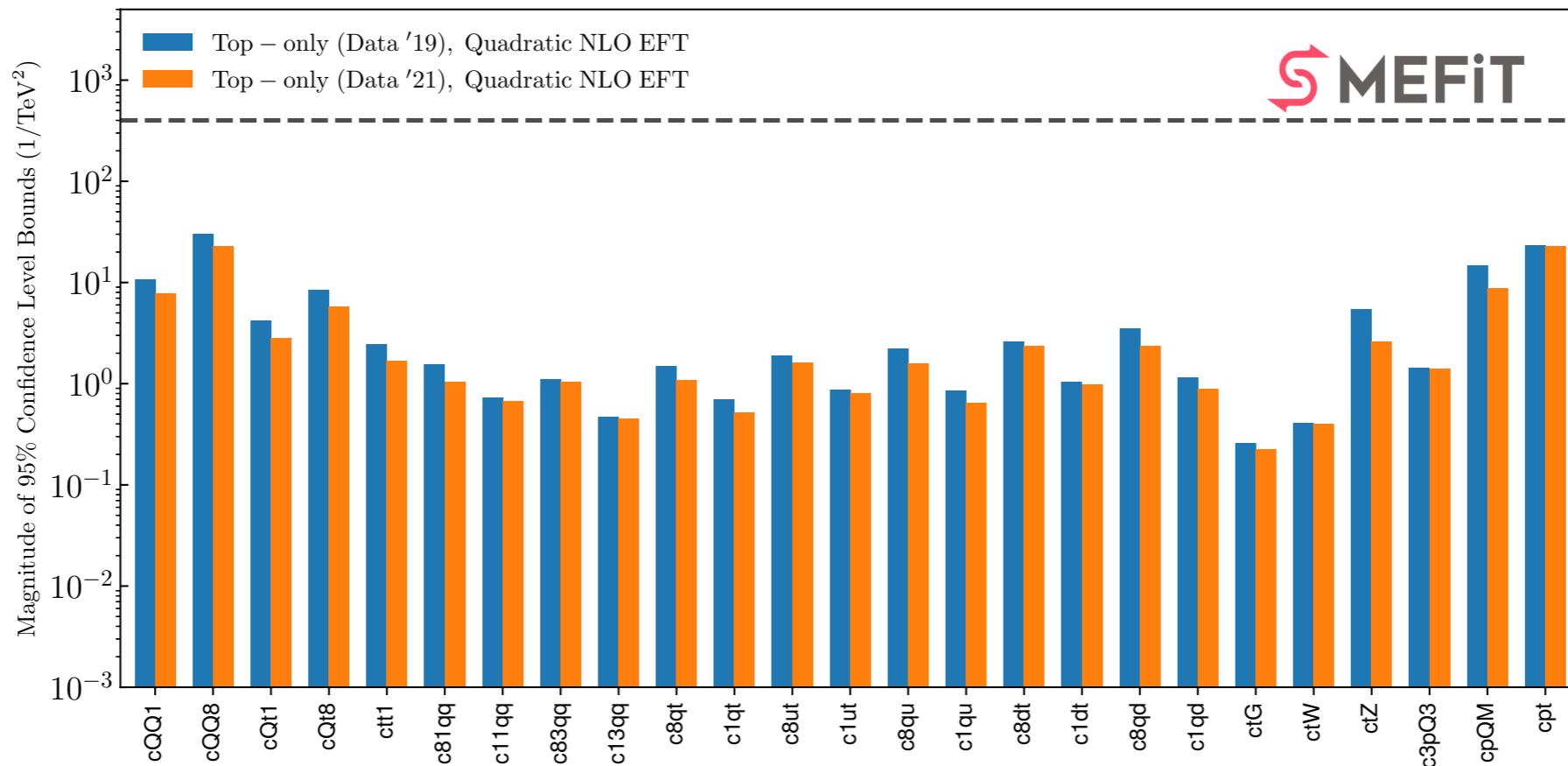
Dataset	\sqrt{s}, \mathcal{L}	Info	Observables	N_{dat}	Ref
CMS_t_tch_8TeV_inc	8 TeV, 19.7 fb $^{-1}$	t-channel	$\sigma_{\text{tot}}(t), \sigma_{\text{tot}}(\bar{t})$	2	[83]
ATLAS_t_tch_8TeV	8 TeV, 20.2 fb $^{-1}$	t-channel	$d\sigma(tq)/dy_t$	4	[85]
CMS_t_tch_8TeV_dif	8 TeV, 19.7 fb $^{-1}$	t-channel	$d\sigma/d y^{(t+\bar{t})} $	6	[84]
CMS_t_sch_8TeV	8 TeV, 19.7 fb $^{-1}$	s-channel	$\sigma_{\text{tot}}(t + \bar{t})$	1	[87]
ATLAS_t_sch_8TeV	8 TeV, 20.3 fb $^{-1}$	s-channel	$\sigma_{\text{tot}}(t + \bar{t})$	1	[86]
ATLAS_t_tch_13TeV	13 TeV, 3.2 fb $^{-1}$	t-channel	$\sigma_{\text{tot}}(t), \sigma_{\text{tot}}(\bar{t})$	2	[88]
CMS_t_tch_13TeV_inc	13 TeV, 2.2 fb $^{-1}$	t-channel	$\sigma_{\text{tot}}(t), \sigma_{\text{tot}}(\bar{t})$	2	[90]
CMS_t_tch_13TeV_dif	13 TeV, 2.3 fb $^{-1}$	t-channel	$d\sigma/d y^{(t+\bar{t})} $	4	[89]
CMS_t_tch_13TeV_2016 (*)	13 TeV, 35.9 fb $^{-1}$	t-channel	$d\sigma/d y^{(t)} $	5	[91]

Single top t-, s-channel

Dataset	\sqrt{s}, \mathcal{L}	Info	Observables	N_{dat}	Ref
ATLAS_tW_8TeV_inc	8 TeV, 20.2 fb $^{-1}$	inclusive (dilepton)	$\sigma_{\text{tot}}(tW)$	1	[95]
ATLAS_tW_inc_slep_8TeV (*)	8 TeV, 20.2 fb $^{-1}$	inclusive (single lepton)	$\sigma_{\text{tot}}(tW)$	1	[101]
CMS_tW_8TeV_inc	8 TeV, 19.7 fb $^{-1}$	inclusive	$\sigma_{\text{tot}}(tW)$	1	[96]
ATLAS_tW_inc_13TeV	13 TeV, 3.2 fb $^{-1}$	inclusive	$\sigma_{\text{tot}}(tW)$	1	[97]
CMS_tW_13TeV_inc	13 TeV, 35.9 fb $^{-1}$	inclusive	$\sigma_{\text{tot}}(tW)$	1	[98]
ATLAS_tZ_13TeV_inc	13 TeV, 36.1 fb $^{-1}$	inclusive	$\sigma_{\text{tot}}(tZq)$	1	[100]
ATLAS_tZ_13TeV_run2_inc (*)	13 TeV, 139.1 fb $^{-1}$	inclusive	$\sigma_{\text{fid}}(t\ell^+\ell^-q)$	1	[102]
CMS_tZ_13TeV_inc	13 TeV, 35.9 fb $^{-1}$	inclusive	$\sigma_{\text{fid}}(Wb^+\ell^-q)$	1	[99]
CMS_tZ_13TeV_2016_inc (*)	13 TeV, 77.4 fb $^{-1}$	inclusive	$\sigma_{\text{fid}}(t\ell^+\ell^-q)$	1	[103]

Category	Processes	n_{dat}
Top quark production	$t\bar{t}$ (inclusive)	94
	$t\bar{t}Z, t\bar{t}W$	14
	single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}, t\bar{t}b\bar{b}$	6
Total	150	

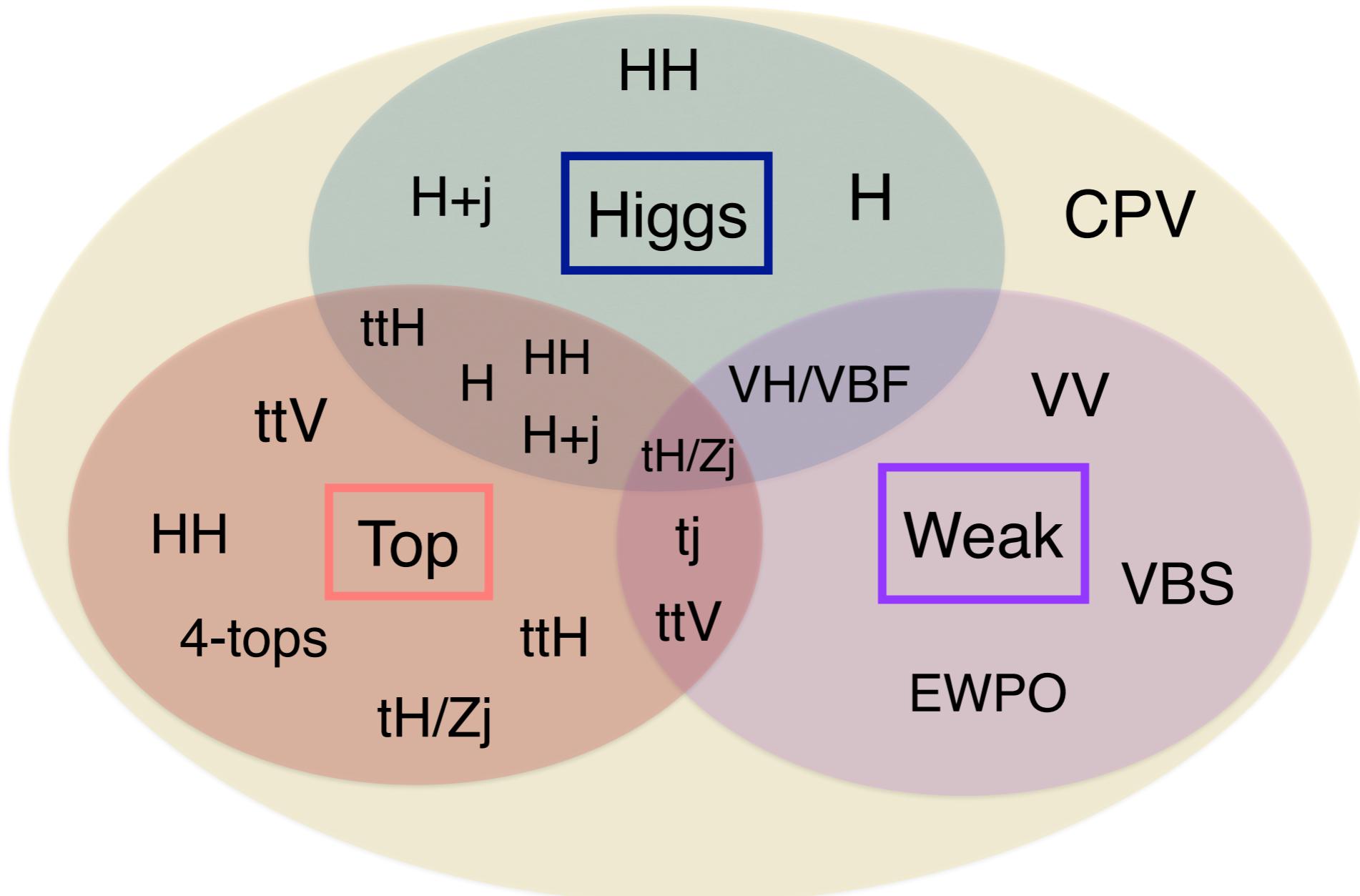
Global top fit results



Bounds vary between operators
ttZ ones and 4-heavy ones loosely constrained

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006
Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

Global nature of EFT



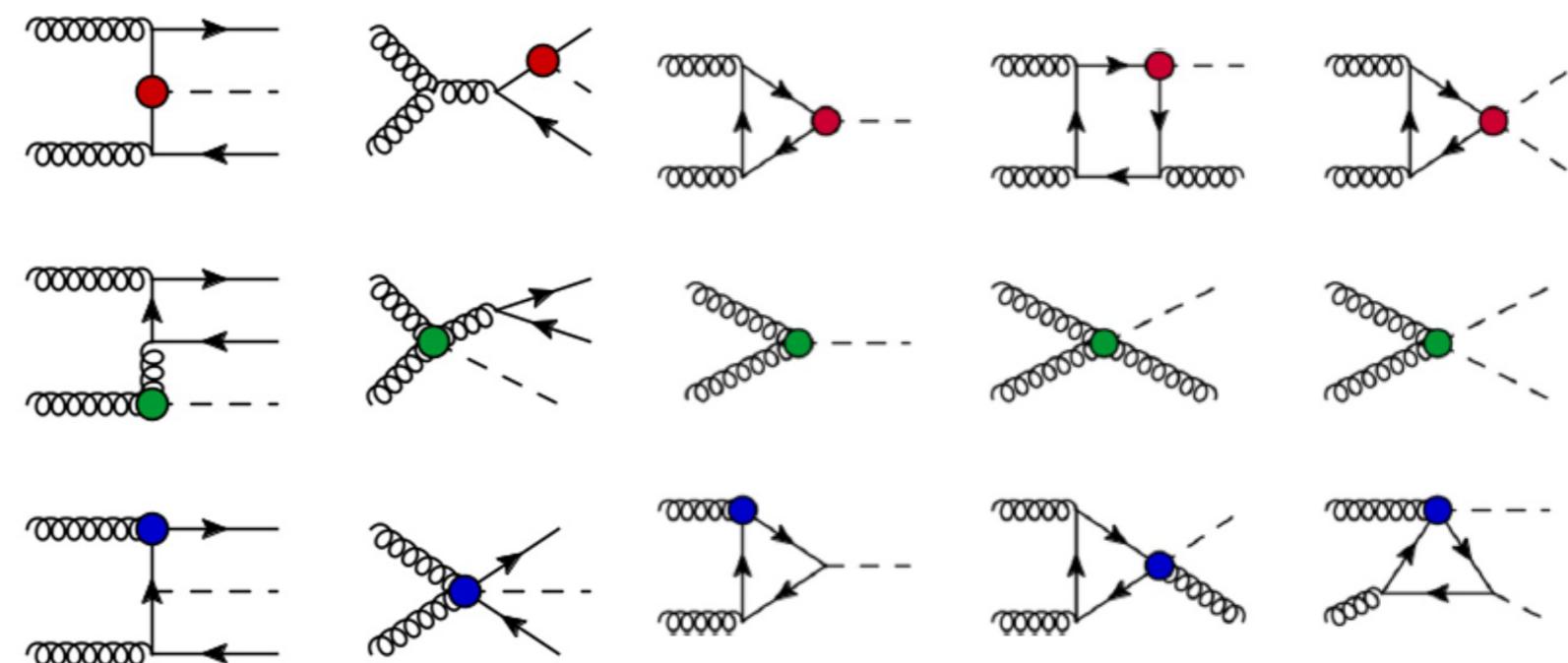
Adapted from K. Mimasu

The top-Higgs interface

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

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

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A$$



See also

Degrade et al. arXiv:1205.1065

Grojean et al. arXiv:1312.3317

Azatov et al arXiv:1608.00977

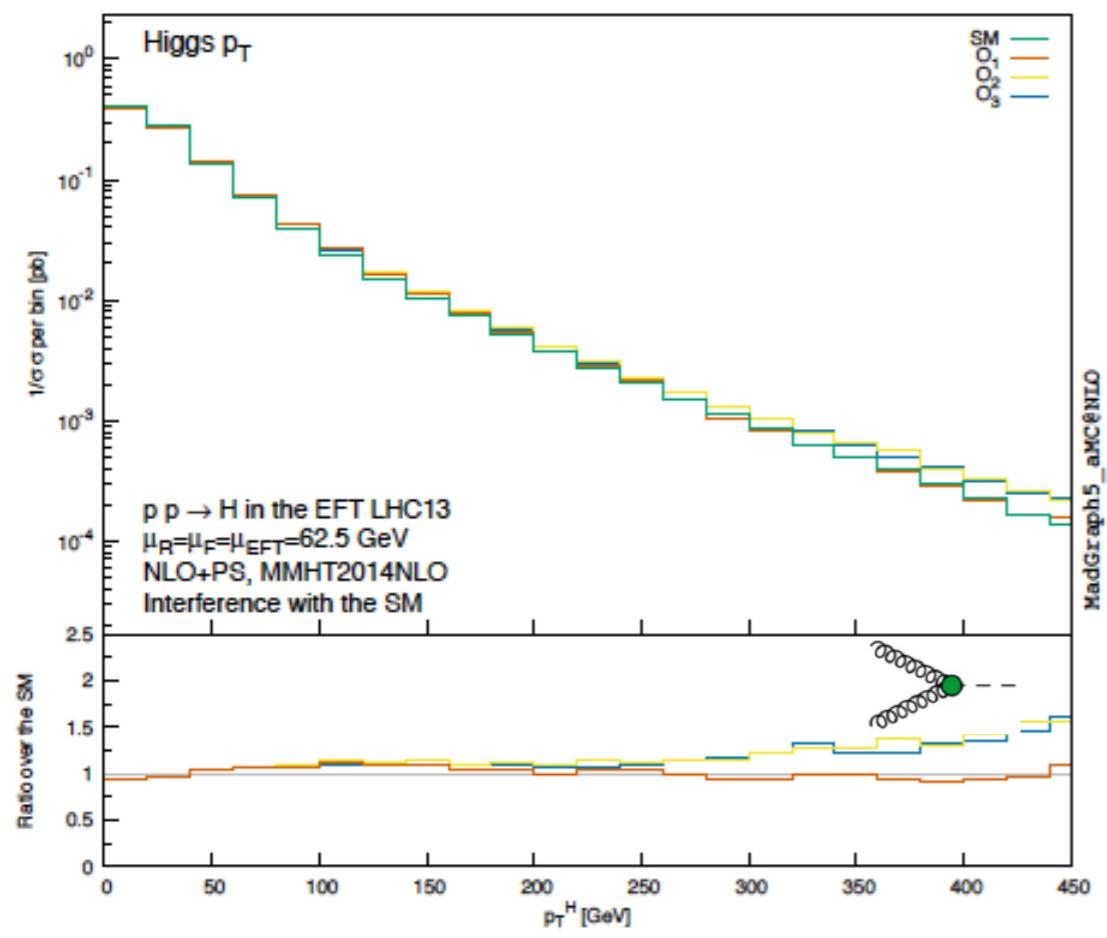
ttH

H, H+j, HH

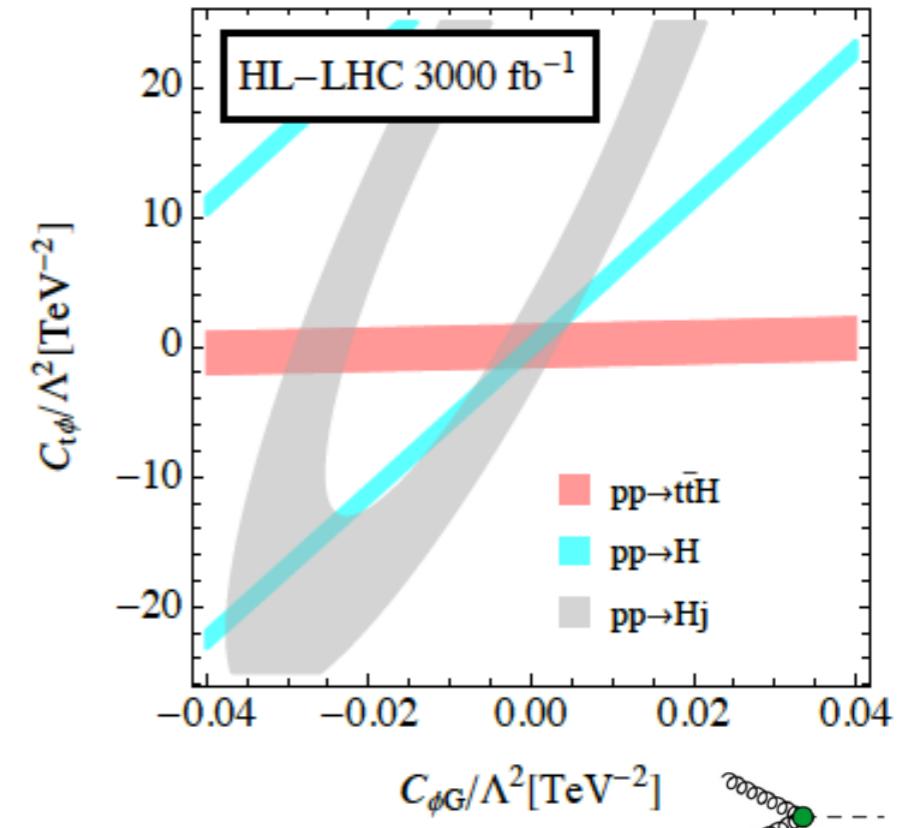
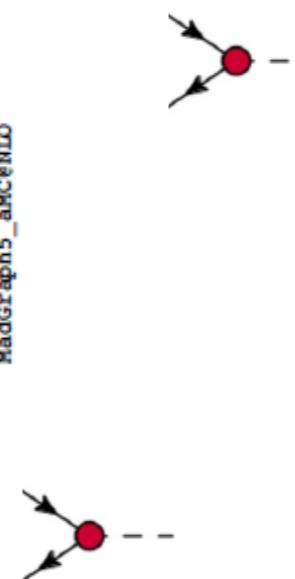
Use with 1) ttH and 2) H, H+j to break degeneracy between operators and extract maximal information on these operators

Maltoni, EV, Zhang: arXiv:1607.05330

SMEFT in Higgs production



Higgs p_T



14TeV projection
3000 fb $^{-1}$

Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

Grazzini et al 1612.00283

Extended top-Higgs interplay

Operators

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

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

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

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

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

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

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

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

Production process

gg → h

gg → hj

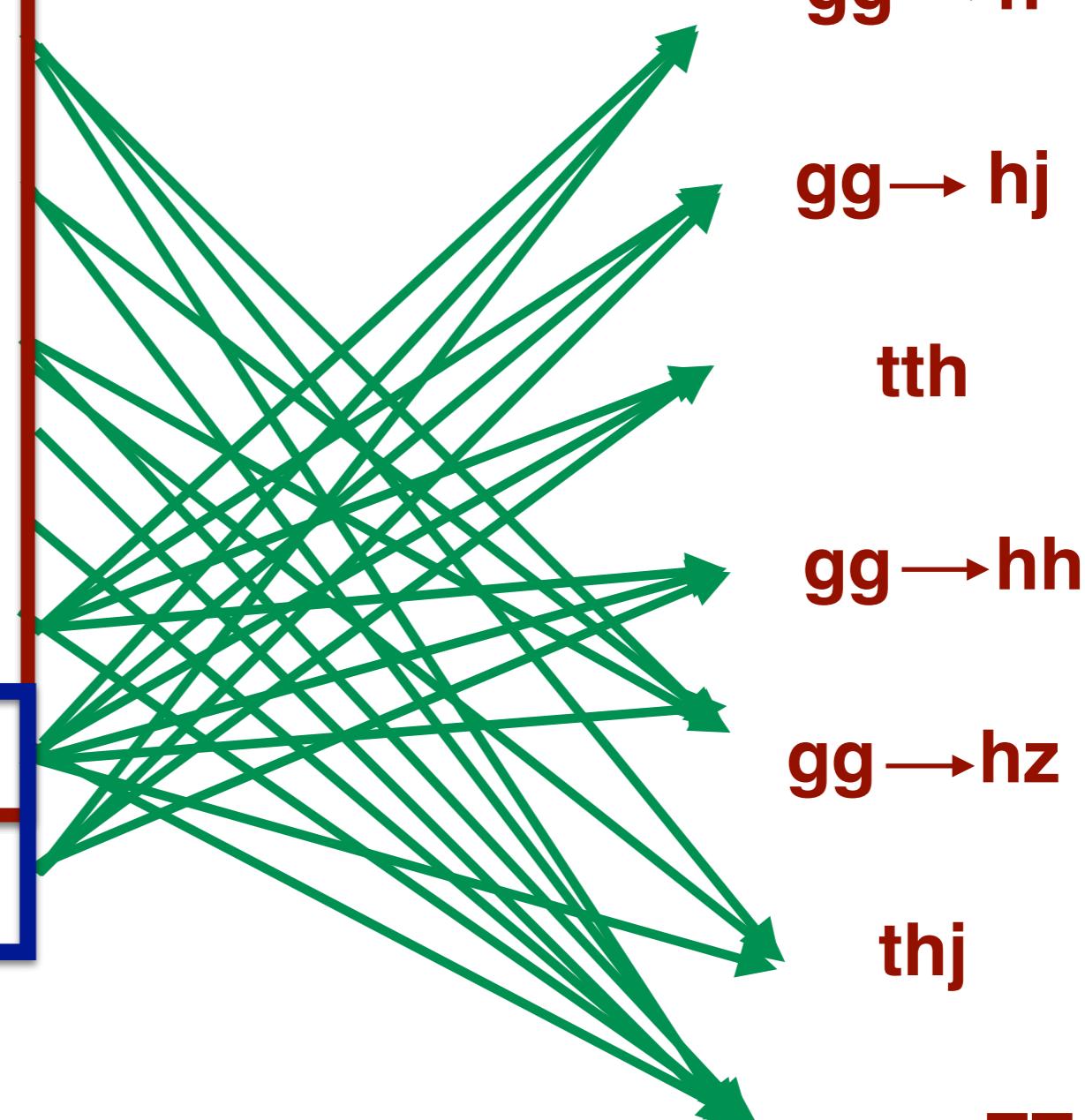
tth

gg → hh

gg → hz

thj

gg → ZZ



Top-Higgs are deeply connected

Exploring the interplay further

Top EW couplings

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

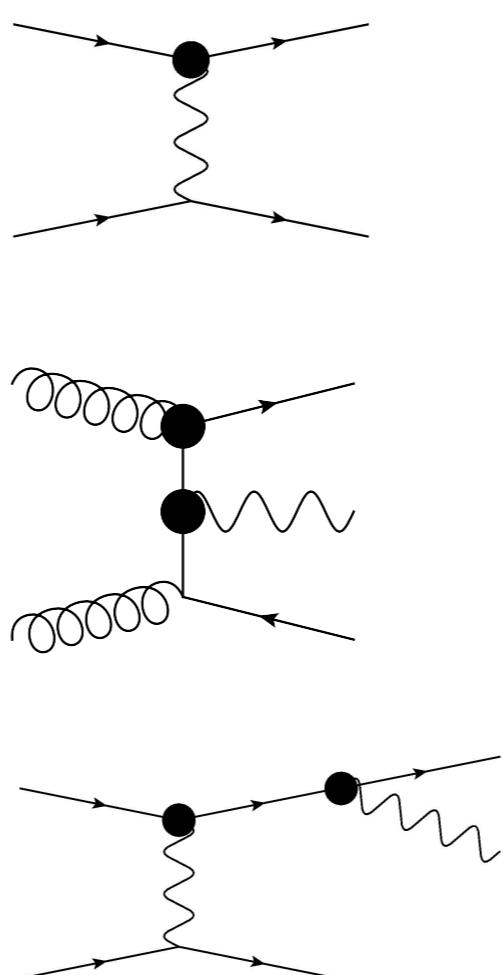
$$O_{\varphi Q}^{(1)} = i \frac{1}{2} y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi \right) (\bar{Q} \gamma^\mu Q)$$

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

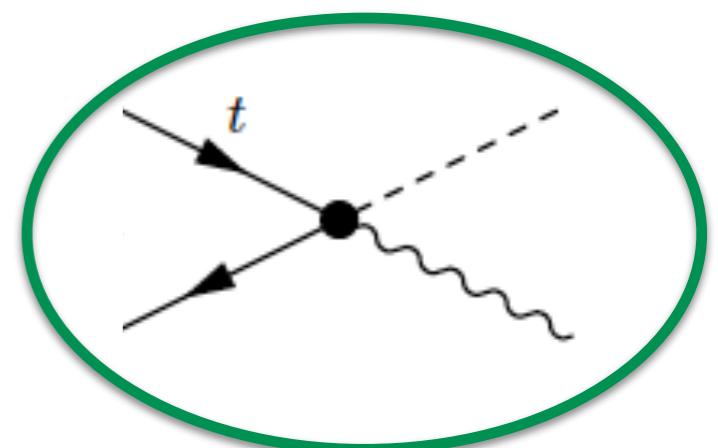
$$O_{tW} = y_t g_w (\bar{Q} \sigma^{\mu\nu} \tau^I t) \tilde{\varphi} W_{\mu\nu}^I$$

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

Typically searched for in



Also relevant for:



New Higgs interactions



**relevant for tHj, gg>HZ
gg>ZZ, H>Zγ**

Aren't these unconstrained from top fits?

A clear motivation for top+Higgs fits

Adding Higgs data to a global fit

New data

Run I & 2 signal strengths (CMS+ATLAS):
gluon fusion

VH

VBF

ttH

H decays

New predictions

NLO QCD for all production
Full decay width computation
Including corrections to V widths

New operators

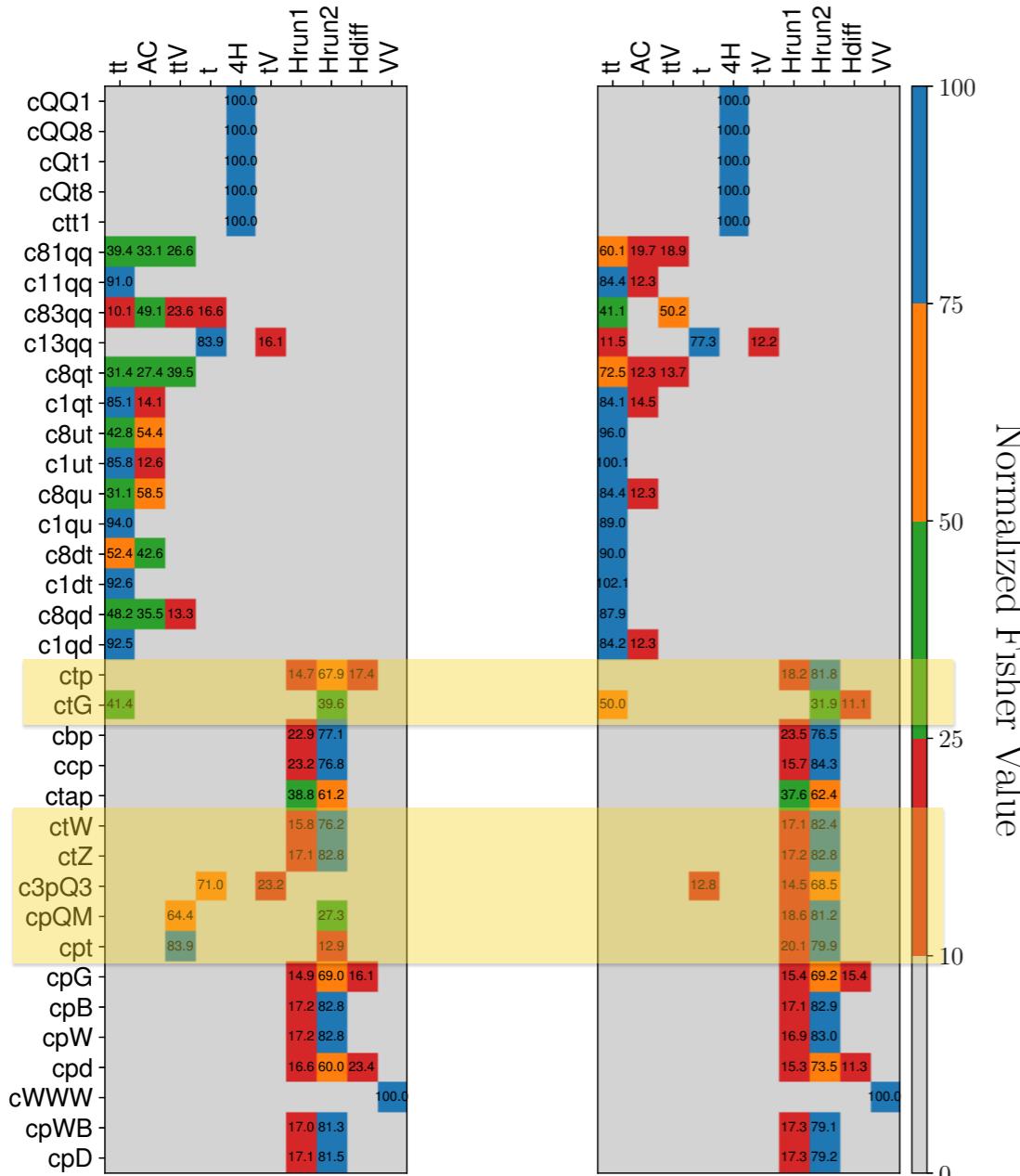
Bosonic					
$\mathcal{O}_{\phi G}$	0pG	$\left(\phi^\dagger \phi - \frac{v^2}{2}\right) G_A^{\mu\nu} G_{\mu\nu}^A$	$\mathcal{O}_{\phi B}$	0pB	$\left(\phi^\dagger \phi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$
$\mathcal{O}_{\phi W}$	0pW	$\left(\phi^\dagger \phi - \frac{v^2}{2}\right) W_I^{\mu\nu} W_{\mu\nu}^I$	$\mathcal{O}_{\phi WB}$	0pWB	$(\phi^\dagger \tau_I \phi) B^{\mu\nu} W_{\mu\nu}^I$
$\mathcal{O}_{\phi d}$	0pd	$\partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi)$	$\mathcal{O}_{\phi D}$	0pD	$(\phi^\dagger D^\mu \phi)^\dagger (\phi^\dagger D_\mu \phi)$

2 Fermions					
$\mathcal{O}_{t\varphi}$	0tp	$\left(\phi^\dagger \phi - \frac{v^2}{2}\right) \bar{Q} t \tilde{\phi} + \text{h.c.}$	\mathcal{O}_{tG}	0tG	$i g_s (\bar{Q} \tau^{\mu\nu} T_A t) \tilde{\phi} G_{\mu\nu}^A + \text{h.c.}$
$\mathcal{O}_{b\varphi}$	0bp	$\left(\phi^\dagger \phi - \frac{v^2}{2}\right) \bar{Q} b \phi + \text{h.c.}$	$\mathcal{O}_{c\varphi}$	0cp	$\left(\phi^\dagger \phi - \frac{v^2}{2}\right) \bar{Q} c \phi + \text{h.c.}$
$\mathcal{O}_{\tau\varphi}$	0tap	$\left(\phi^\dagger \phi - \frac{v^2}{2}\right) \bar{Q} \tau \tilde{\phi} + \text{h.c.}$	\mathcal{O}_{tW}	0tW	$i (\bar{Q} \tau^{\mu\nu} \tau_I t) \tilde{\phi} W_{\mu\nu}^I + \text{h.c.}$
\mathcal{O}_{tB}	-	$i (\bar{Q} \tau^{\mu\nu} t) \phi B_{\mu\nu} + \text{h.c.}$	\mathcal{O}_{tZ}	0tZ	$-\sin \theta_W \mathcal{O}_{tB} + \cos \theta_W \mathcal{O}_{tW}$
$\mathcal{O}_{\varphi l_1}^{(1)}$	0pl1	$i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{l}_1 \gamma^\mu l_1)$	$\mathcal{O}_{\varphi l_1}^{(3)}$	03pl1	$i (\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi) (\bar{l}_1 \gamma^\mu \tau^I l_1)$
$\mathcal{O}_{\varphi l_2}^{(1)}$	0pl2	$i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{l}_2 \gamma^\mu l_2)$	$\mathcal{O}_{\varphi l_2}^{(3)}$	03pl2	$i (\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi) (\bar{l}_2 \gamma^\mu \tau^I l_2)$
$\mathcal{O}_{\varphi l_3}^{(1)}$	0pl3	$i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{l}_3 \gamma^\mu l_3)$	$\mathcal{O}_{\varphi l_3}^{(3)}$	03pl3	$i (\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi) (\bar{l}_3 \gamma^\mu \tau^I l_3)$
$\mathcal{O}_{\varphi e}$	0pe	$i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{e} \gamma^\mu e)$	$\mathcal{O}_{\varphi \mu}$	0pmu	$i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{\mu} \gamma^\mu \mu)$
$\mathcal{O}_{\varphi \tau}$	0pta	$i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{\tau} \gamma^\mu \tau)$			
$\mathcal{O}_{\varphi q_i}^{(1)}$	-	$\sum_{i=1,2} i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{q}_i \gamma^\mu q_i)$	$\mathcal{O}_{\varphi q_i}^{(3)}$	03pq	$\sum_{i=1,2} i (\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi) (\bar{q}_i \gamma^\mu \tau^I q_i)$
$\mathcal{O}_{\varphi Q}^{(1)}$	-	$i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{Q} \gamma^\mu Q)$	$\mathcal{O}_{\varphi Q}^{(3)}$	03pQ3	$i (\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi) (\bar{Q} \gamma^\mu \tau^I Q)$
$\mathcal{O}_{\varphi q_i}^{(-)}$	0pqMi	$\mathcal{O}_{\varphi q_i}^{(1)} - \mathcal{O}_{\varphi q_i}^{(3)}$	$\mathcal{O}_{\varphi Q}^{(-)}$	0pQM	$\mathcal{O}_{\varphi Q}^{(1)} - \mathcal{O}_{\varphi Q}^{(3)}$
$\mathcal{O}_{\varphi u_i}$	0pui	$\sum_{i=1,2} i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{u}_i \gamma^\mu u_i)$	$\mathcal{O}_{\varphi d_i}$	0pdi	$\sum_{i=1,2} i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{d}_i \gamma^\mu d_i)$
$\mathcal{O}_{\phi t}$	0pt	$i (\phi^\dagger \overleftrightarrow{D}_\mu \phi) (\bar{t} \gamma^\mu t)$			
\mathcal{O}_u	011	$(l \gamma_\mu l)(l \gamma^\mu l)$			

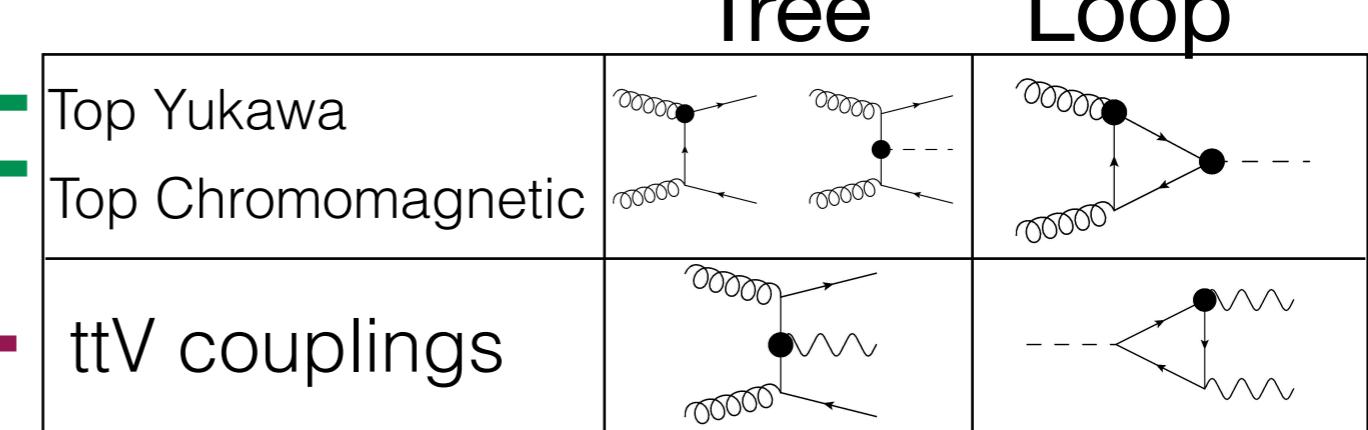
24 new d.o.f.s

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Where is most information from?



4F mostly top



Tree

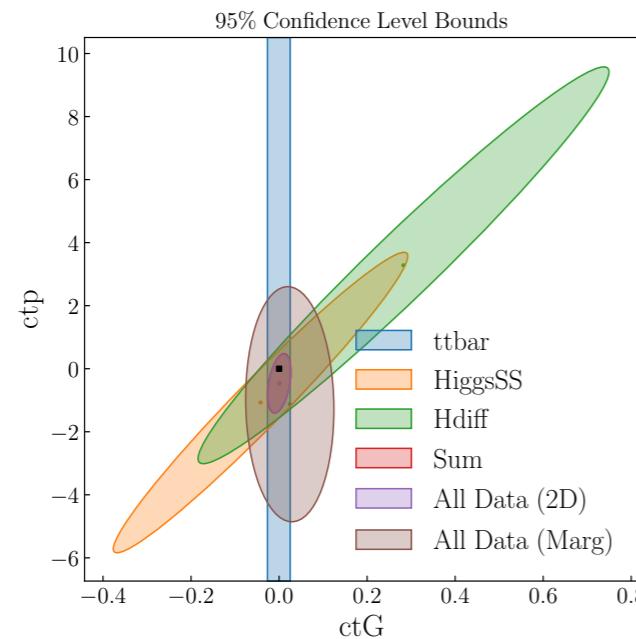
Loop

Fisher information table

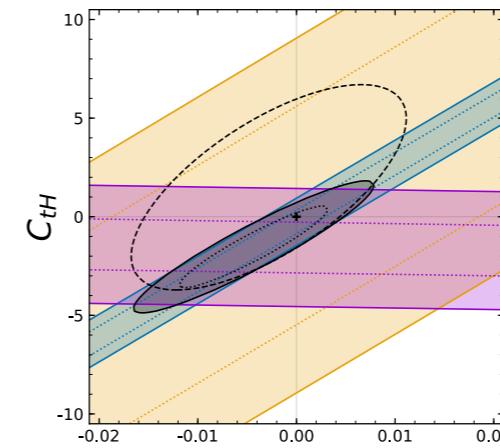
Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Higgs and top interplay

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



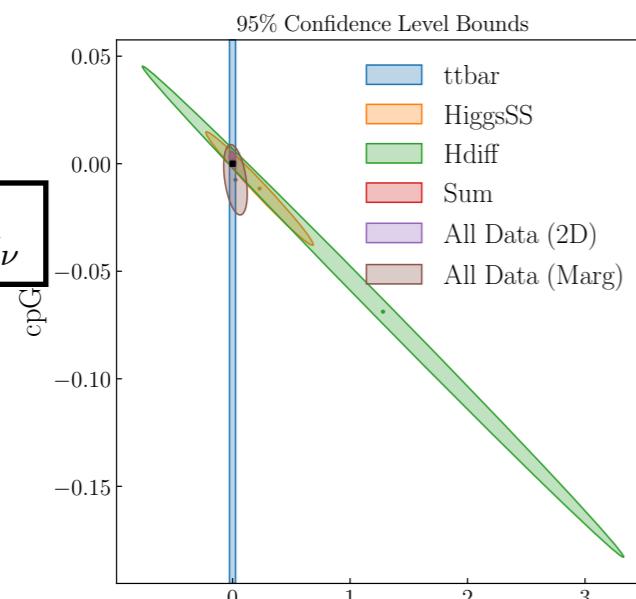
$$(\varphi^\dagger \varphi) \bar{Q} t \tilde{\varphi}$$



Individual 95% C. L.

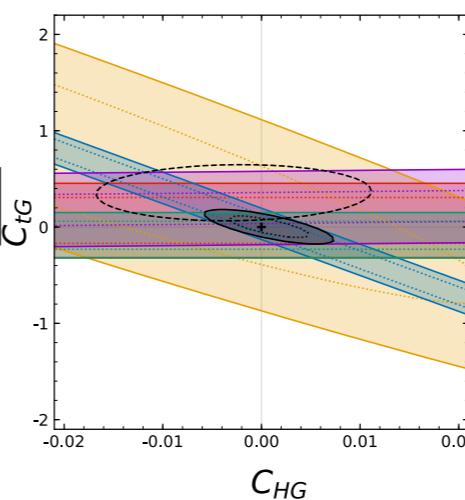
- ggF+0 jet STXS
- $t\bar{t}H$
- ggF+ ≥ 1 jet STXS
- $t\bar{t}$
- $t\bar{t}V$
- Combined
- Marginalised

$$(\varphi^\dagger \varphi) G_A^{\mu\nu} G_{\mu\nu}^A$$

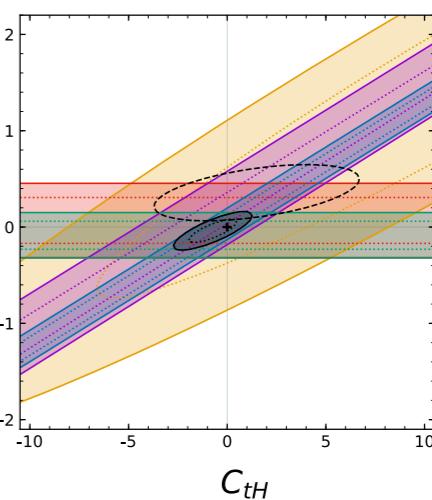


$$(\bar{Q} \tau^{\mu\nu} T_A t) \tilde{\varphi} G_{\mu\nu}^A$$

$$(\bar{Q} \tau^{\mu\nu} T_A t) \tilde{\varphi} G_{\mu\nu}^A$$



$$(\varphi^\dagger \varphi) G_A^{\mu\nu} G_{\mu\nu}^A$$



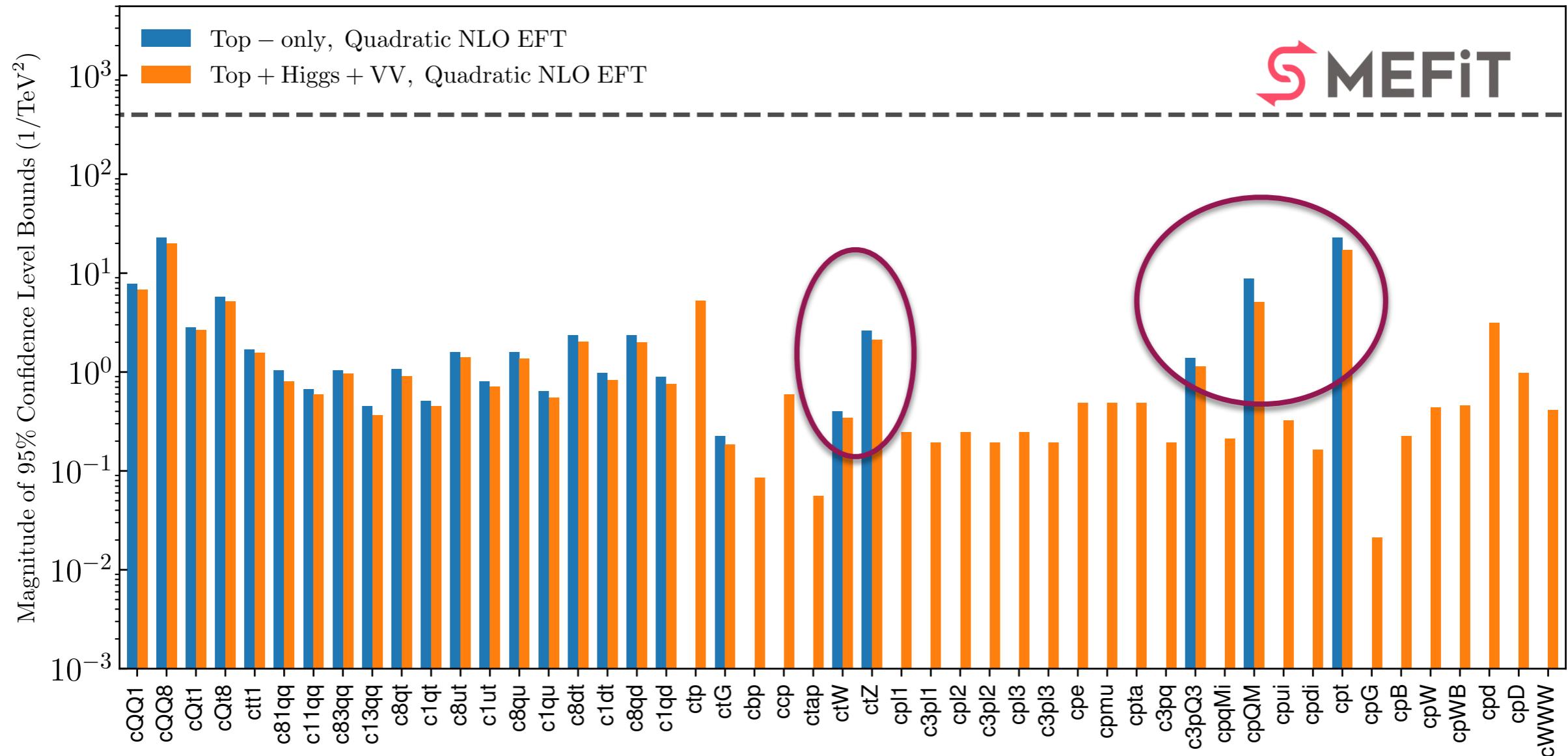
$$(\varphi^\dagger \varphi) \bar{Q} t \tilde{\varphi}$$

Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Top measurements break the degeneracy between Higgs operators

Global fit results



Higgs data improves certain top operator bounds

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

What do we learn from global fits?

Bounds on new physics scale vary from 0.1 TeV (unconstrained) to 10s of TeV.

Bounds depend on:

- the operator
- assumption of a strongly or weakly coupled theory
- individual or marginalised bounds (reality is somewhere in-between)
- linear or quadratic bounds

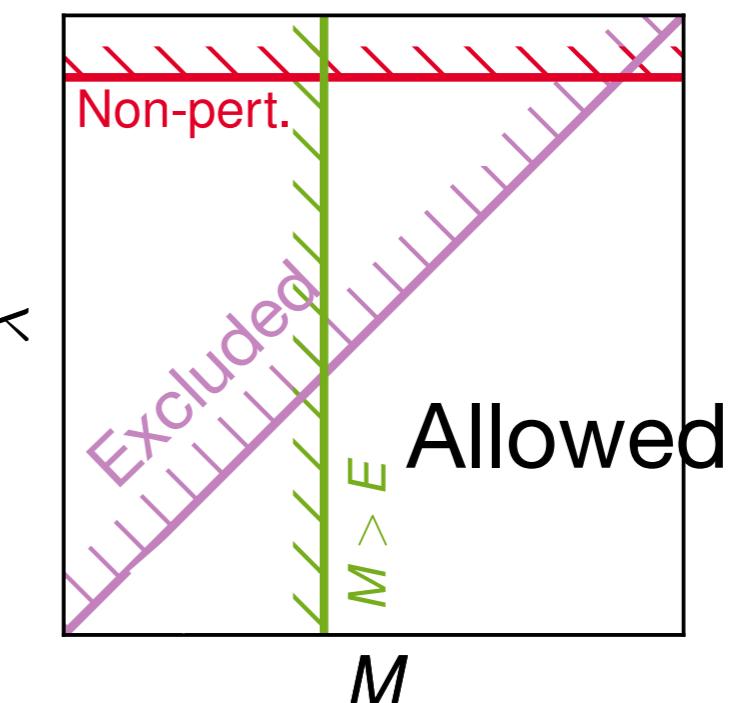
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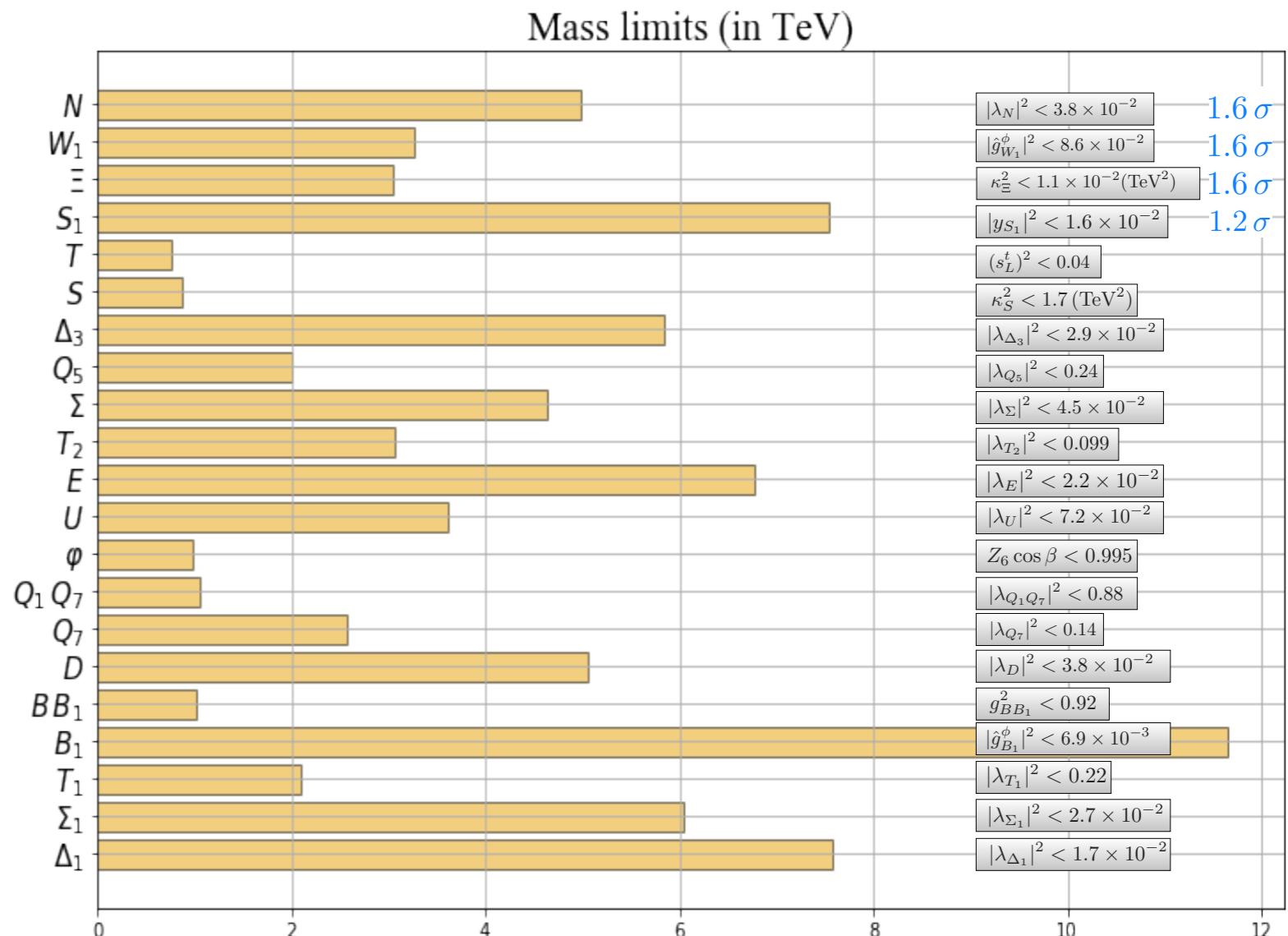
- the operator
- assumption of a strongly or weakly coupled theory
- individual or marginalised bounds (reality is somewhere in-between)
- linear or quadratic bounds

constraint: $\frac{c_i^6(\mu)}{\Lambda^2} = \frac{\lambda^2}{M^2} < X$



What can we learn from these fits?

- EFT bounds translate to constraints on parameters of UV models
- Simplest case: single-field extensions of the SM



Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

Outlook

- SMEFT is a consistent way to look for new interactions
- The LHC gives a lot of opportunities to explore top interactions through a lot of new top measurements
- First global fits results already available: important to combine as many processes as possible to extract maximal information
- Strong link between Higgs and top sectors
- Eventually global fit results give us a clear indication of the scale of potential new physics

Thank you for your attention