Standard Model Effective Field Theory

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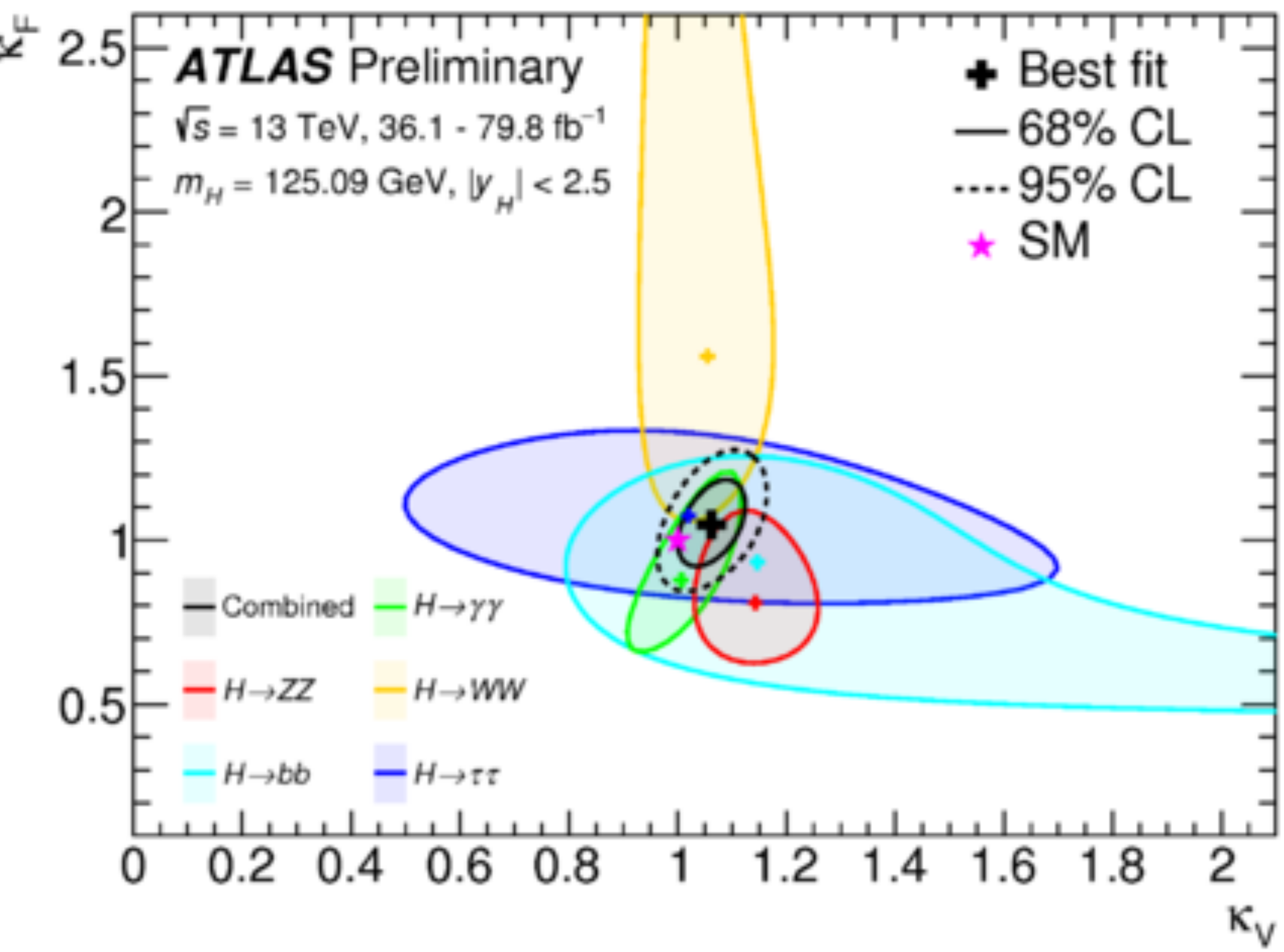
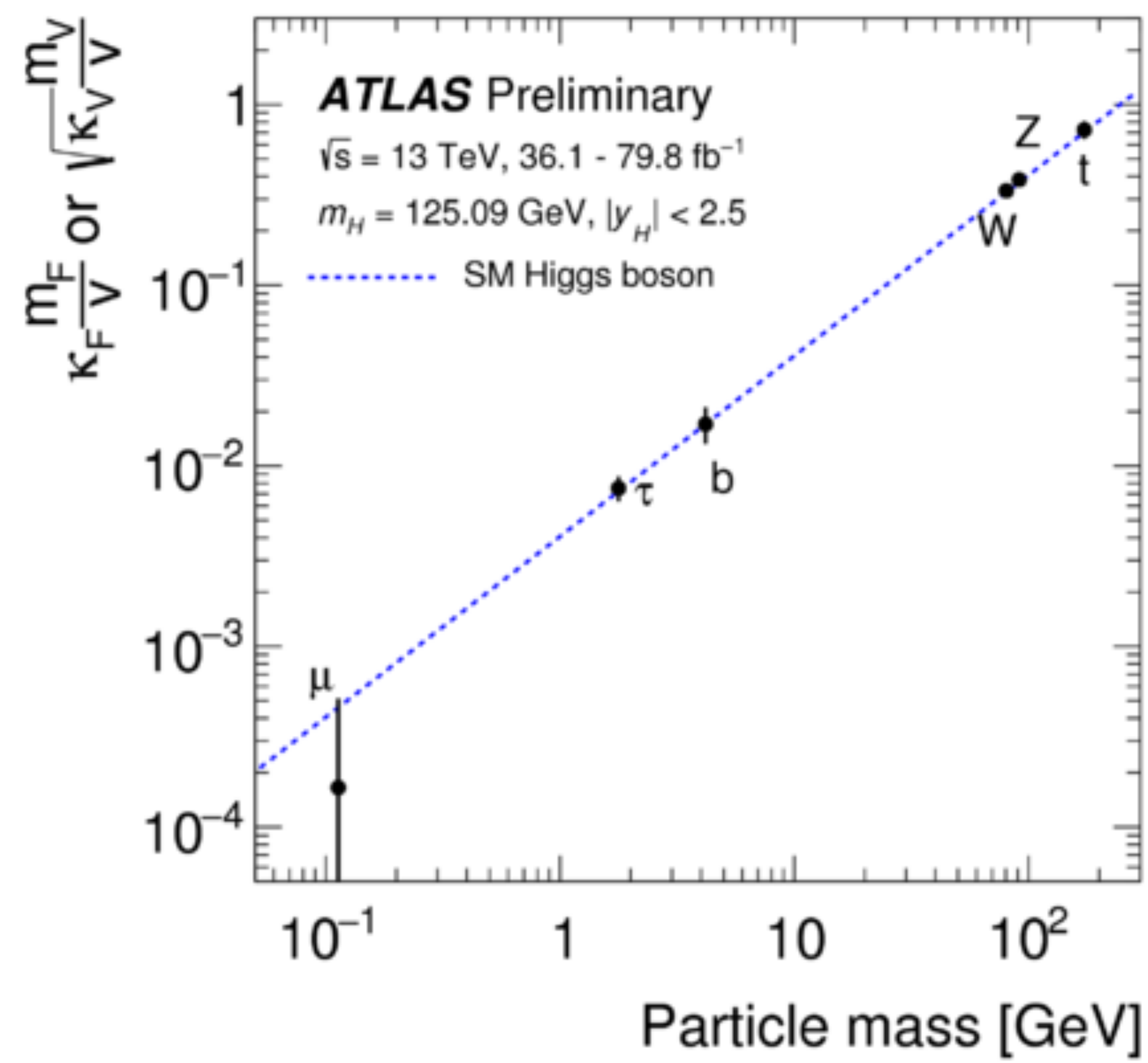
CERN TH

1st Worshop on HET and Gender
CERN
28/9/18

LHC: the story so far

Higgs couplings

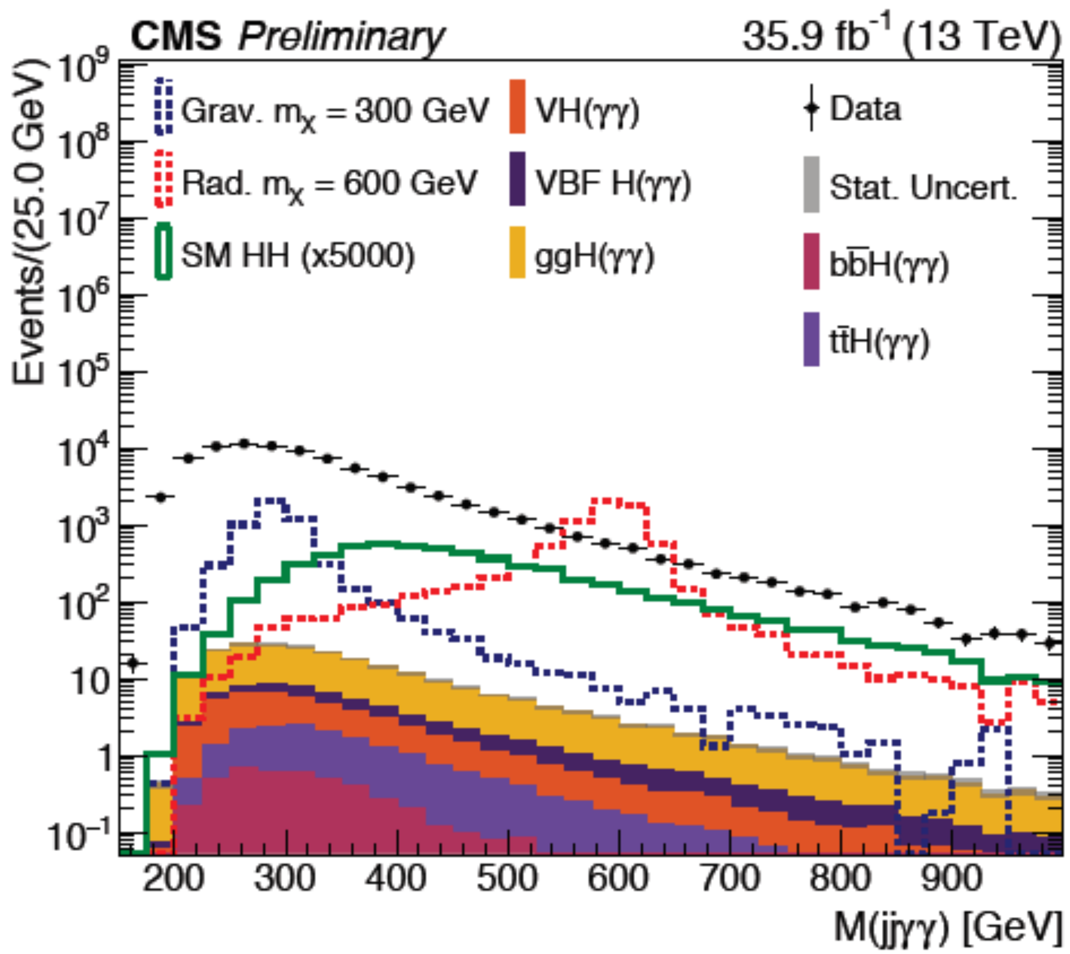




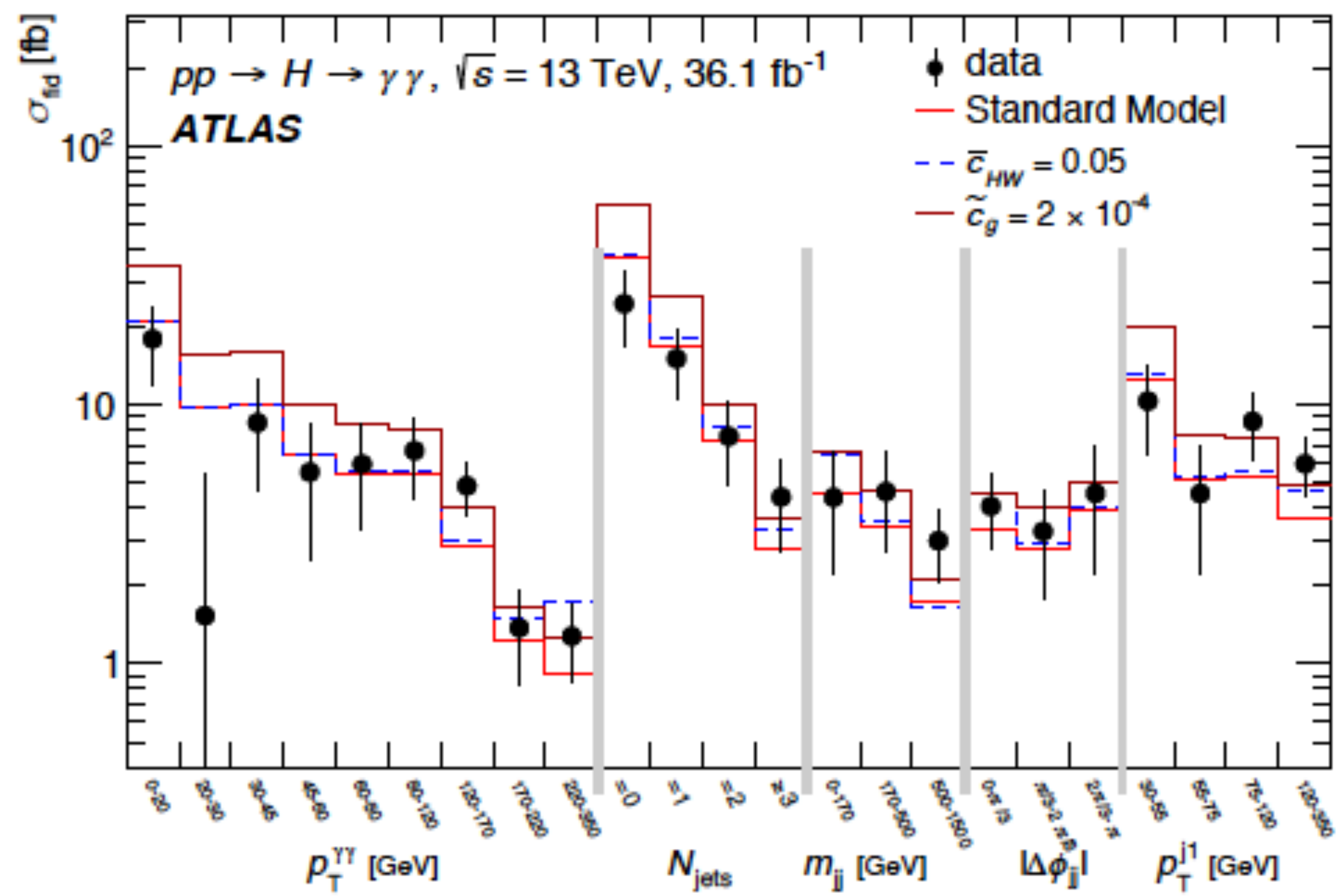
Good agreement with the SM predictions

How to look for new physics?

Model-dependent	Model-Independent
SUSY,1HSM,2HDM…	anomalous couplings, EFT
New particles	New Interactions



Resonance peaks



Deviations in tails

How to look for new physics?

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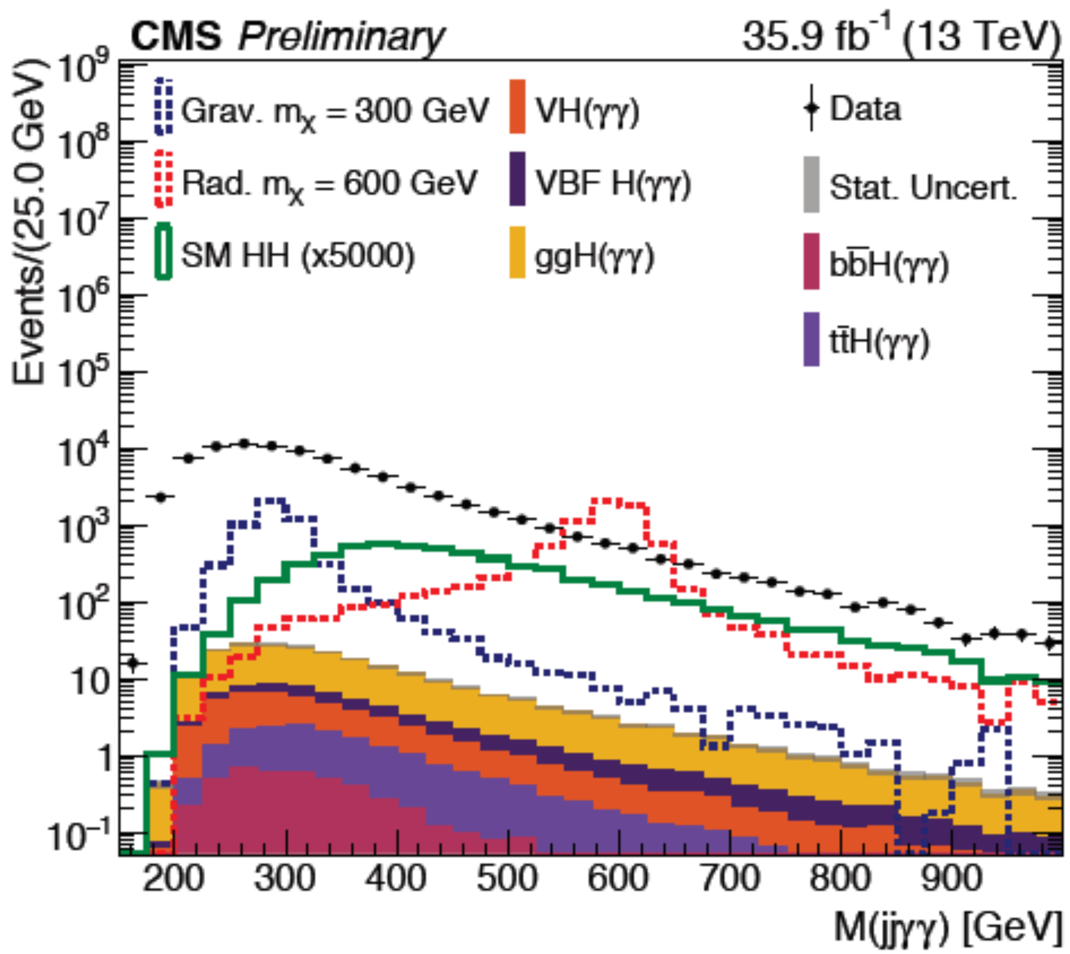
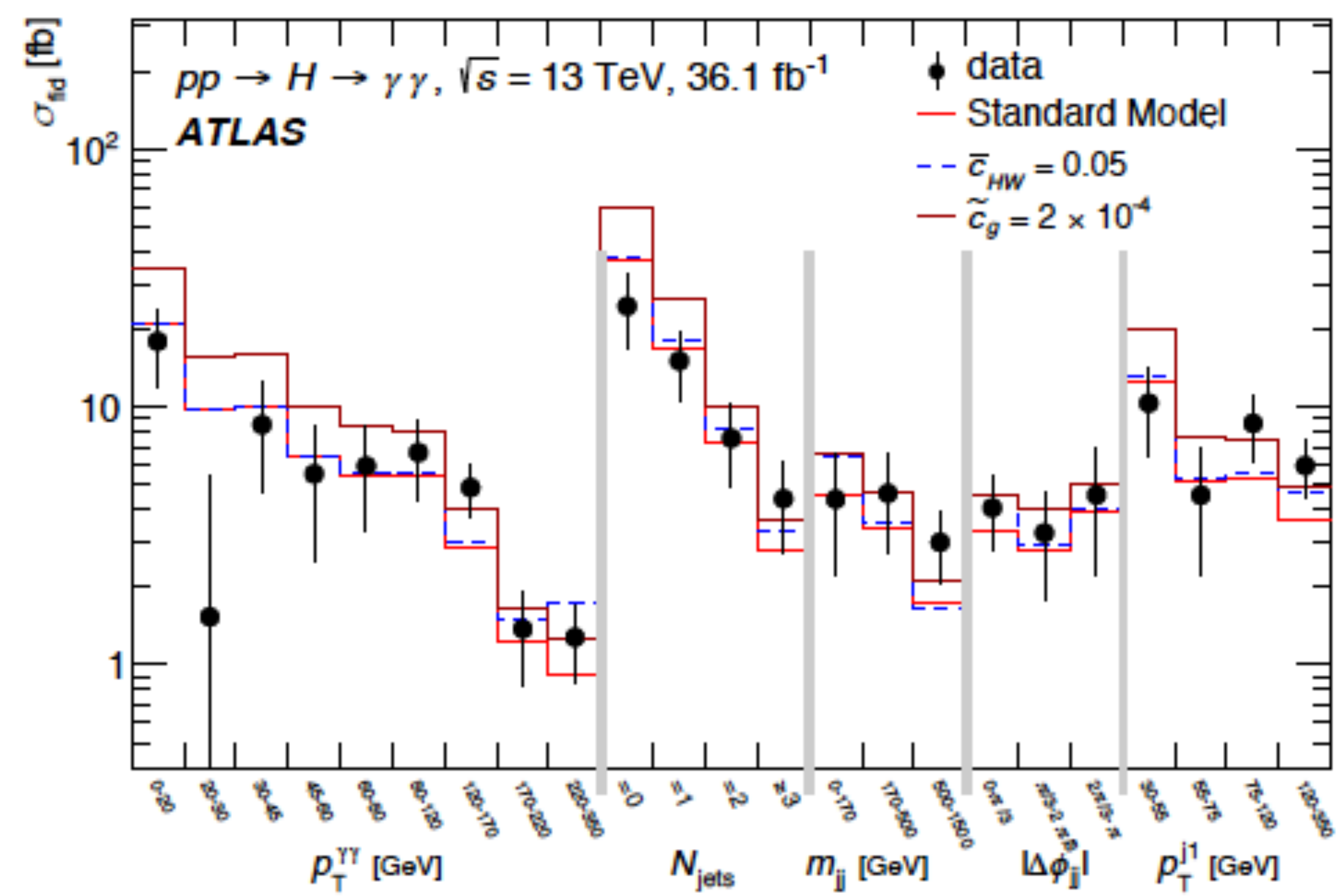
New particles	**New Interactions**





Resonance peaks

Deviations in tails

Plethora of measurements and searches

How to look for new physics?

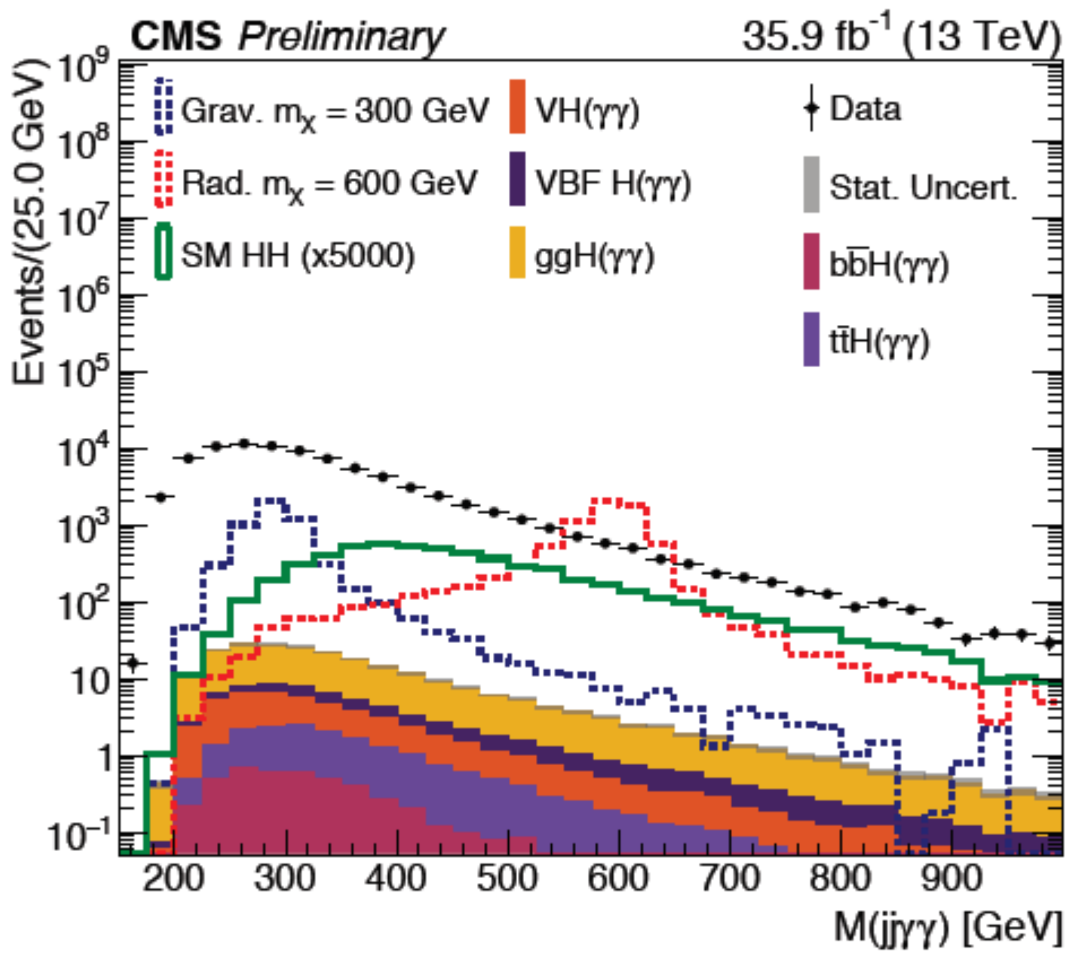
Model-dependent | **Model-Independent**

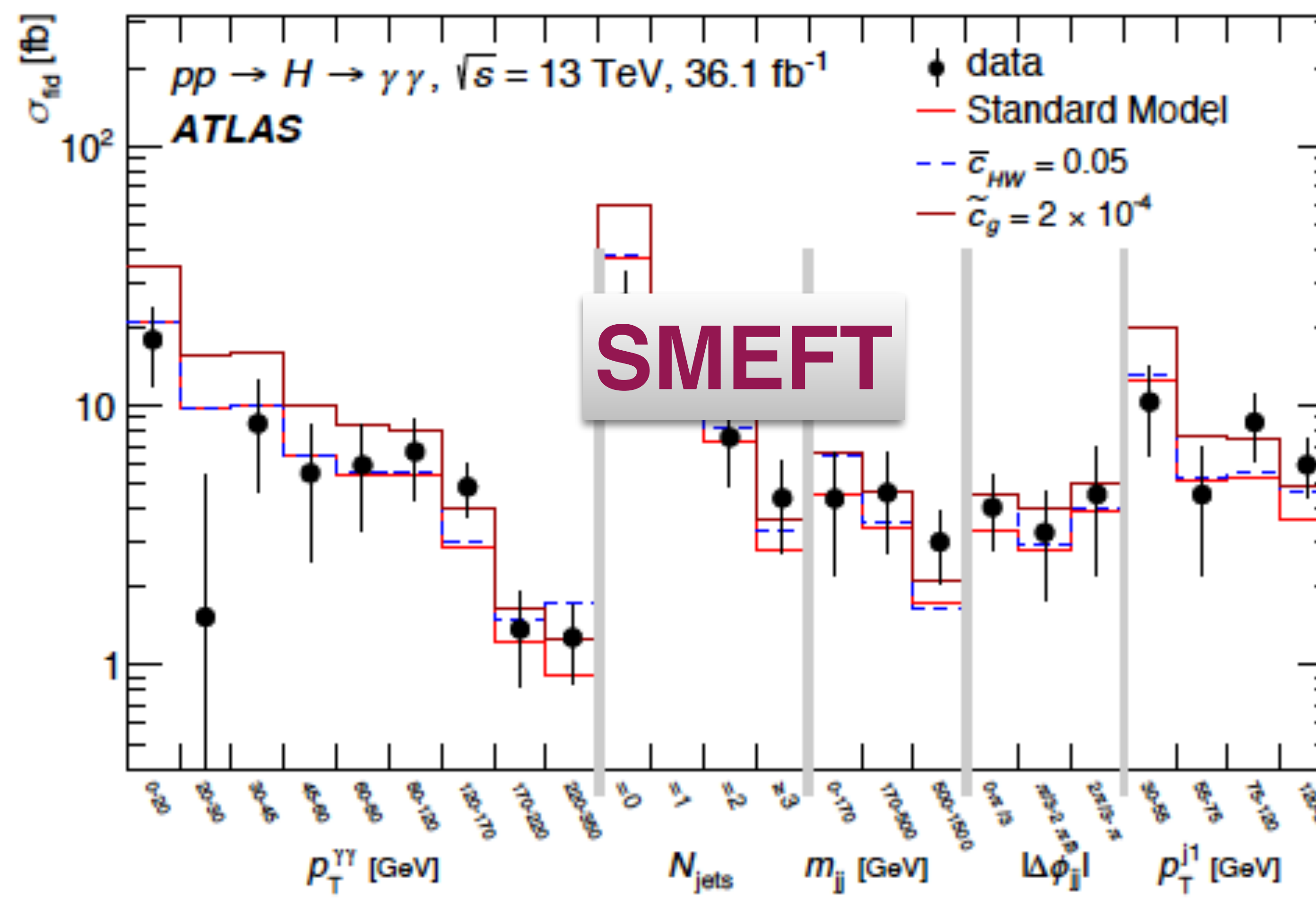
SUSY,1HSM,2HDM…

anomalous couplings, EFT

New particles

New Interactions





SMEFT

Resonance peaks

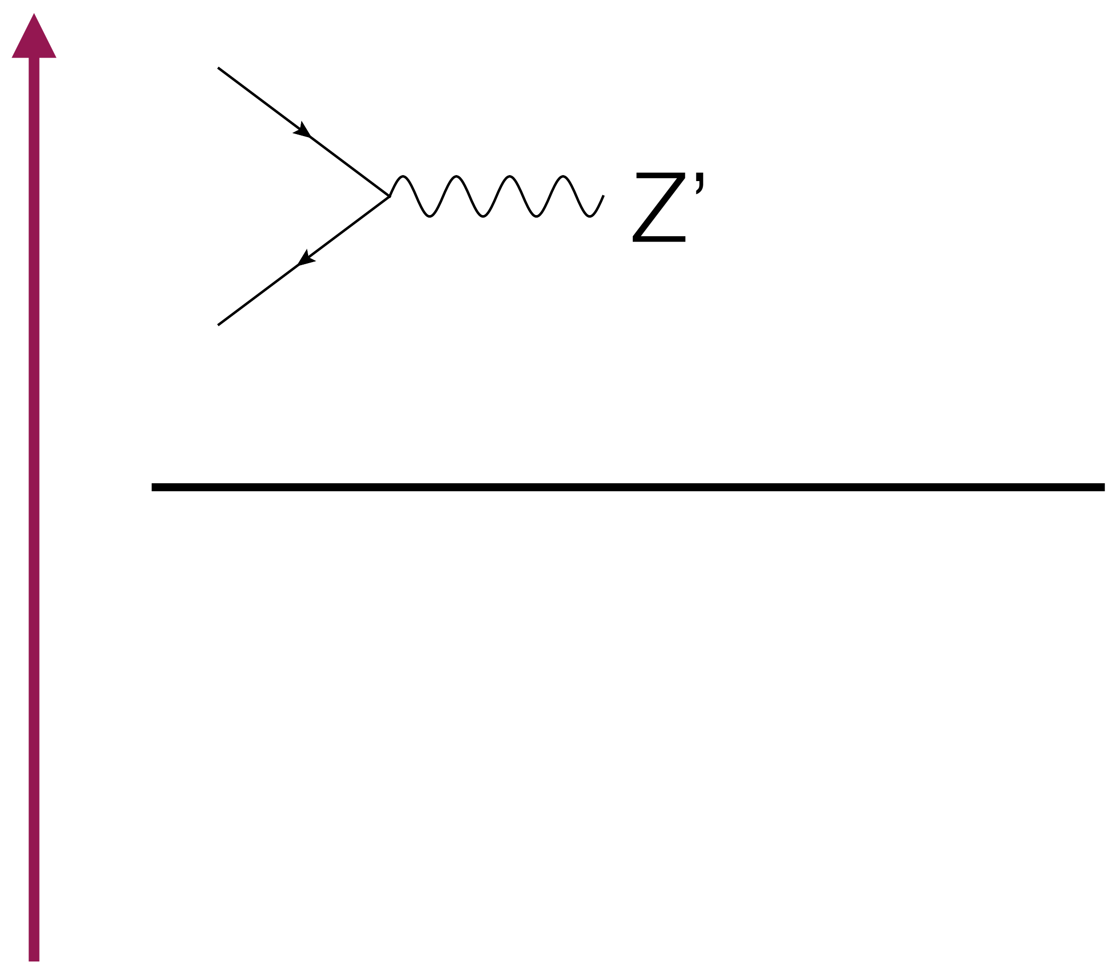
Deviations in tails

Plethora of measurements and searches

SMEFT: What is it all about?

Energy

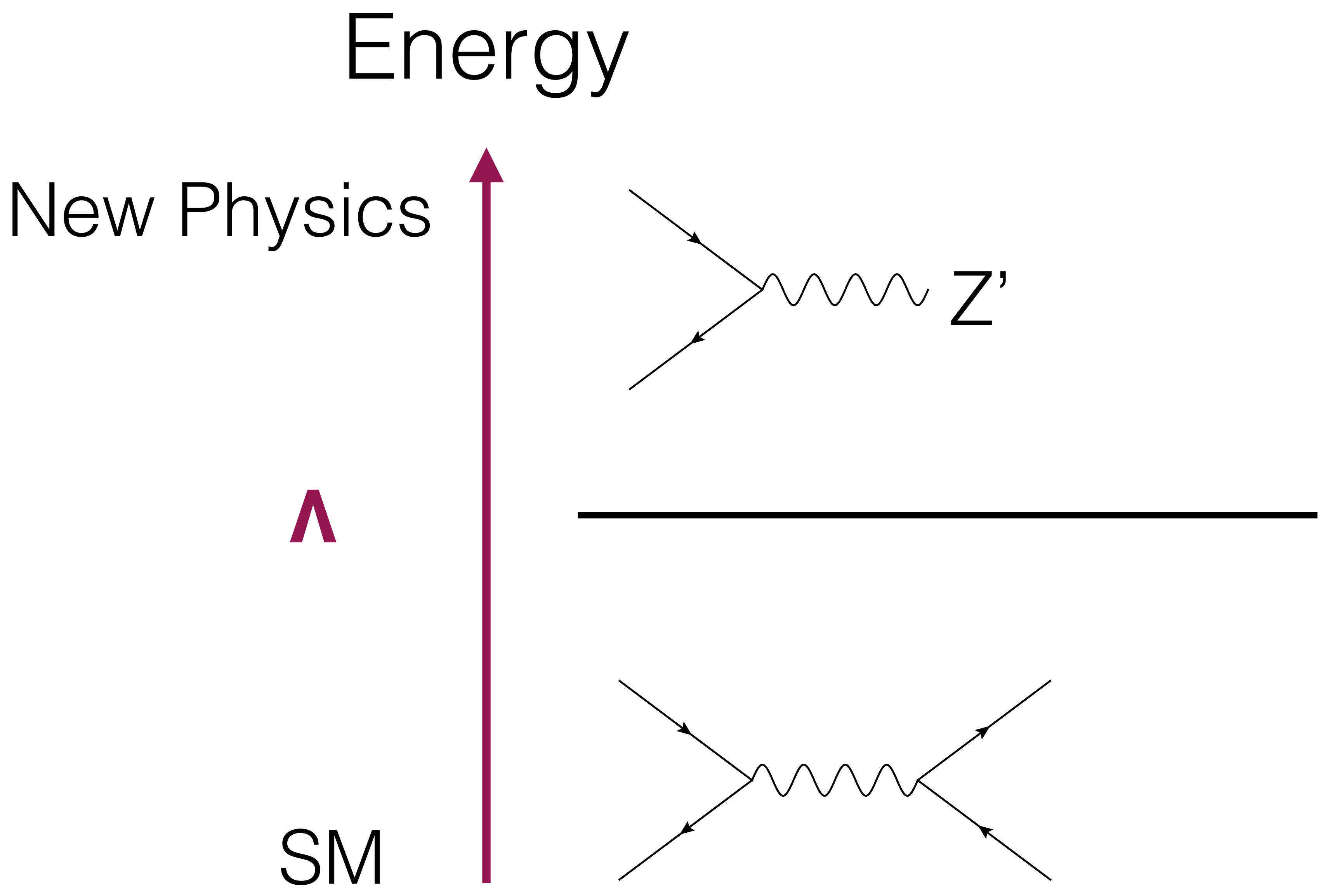
New Physics



Λ

SM

SMEFT: What is it all about?



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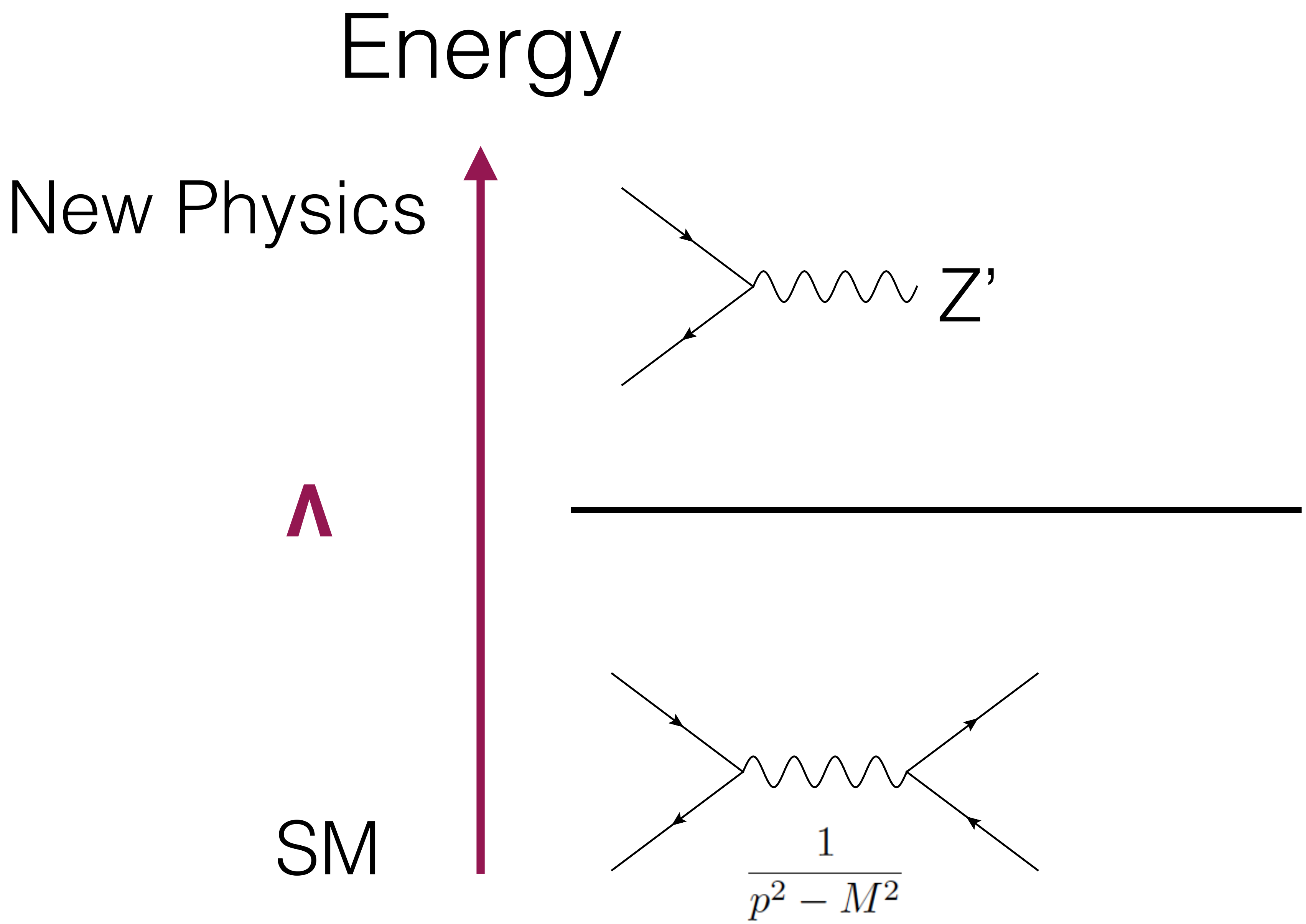
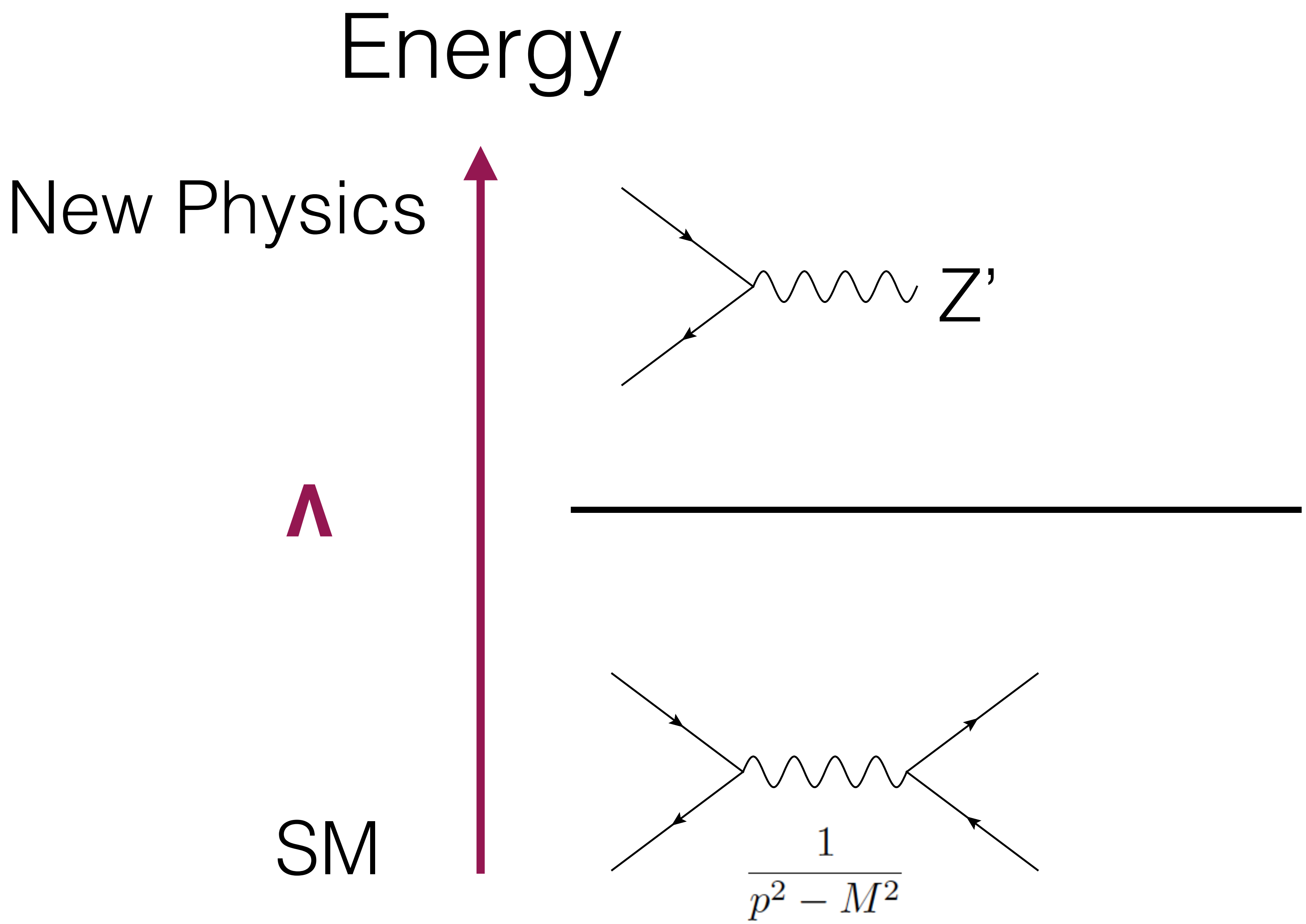
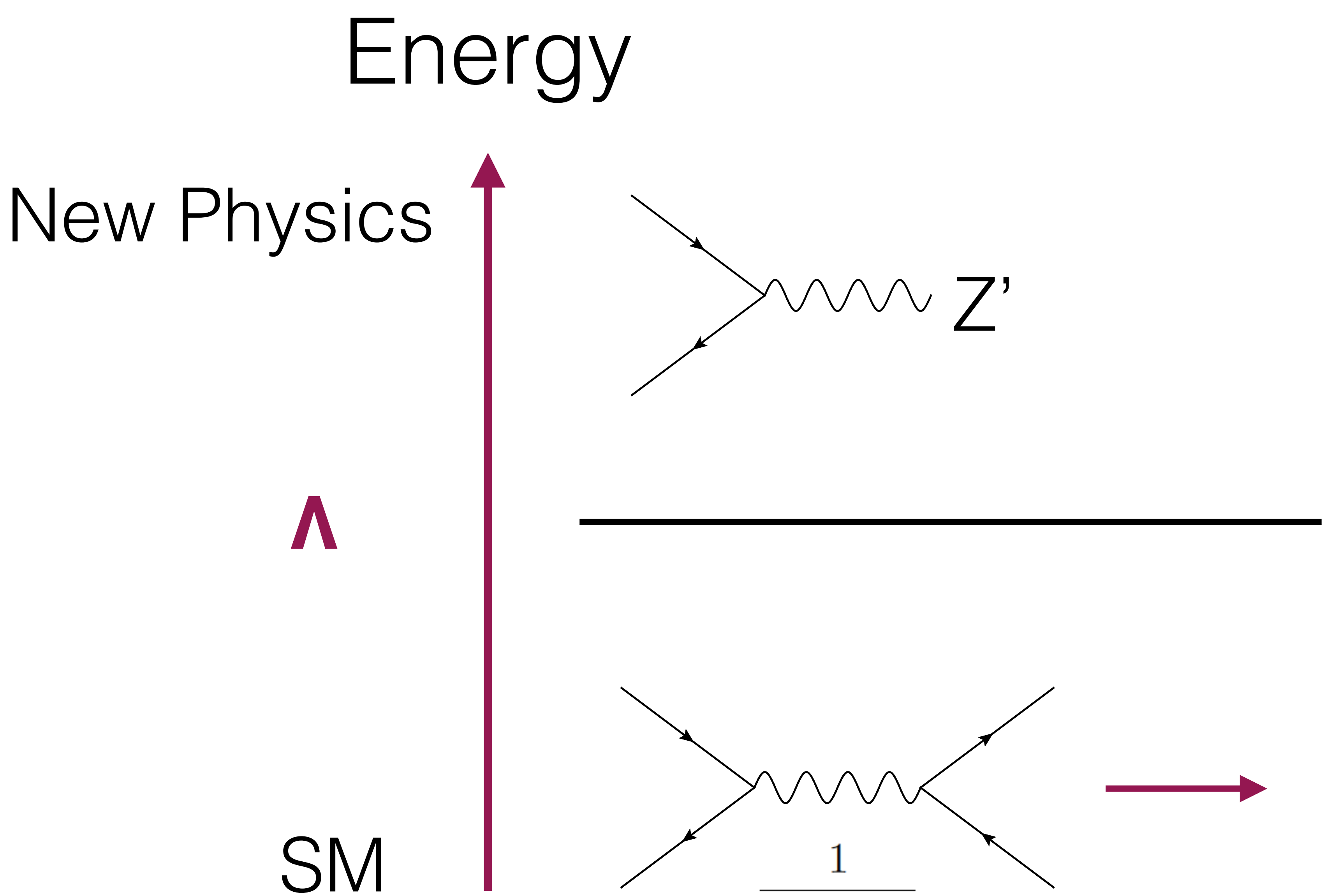


SMEFT: What is it all about?



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

SMEFT: What is it all about?



$$\frac{1}{p^2 - M^2}$$

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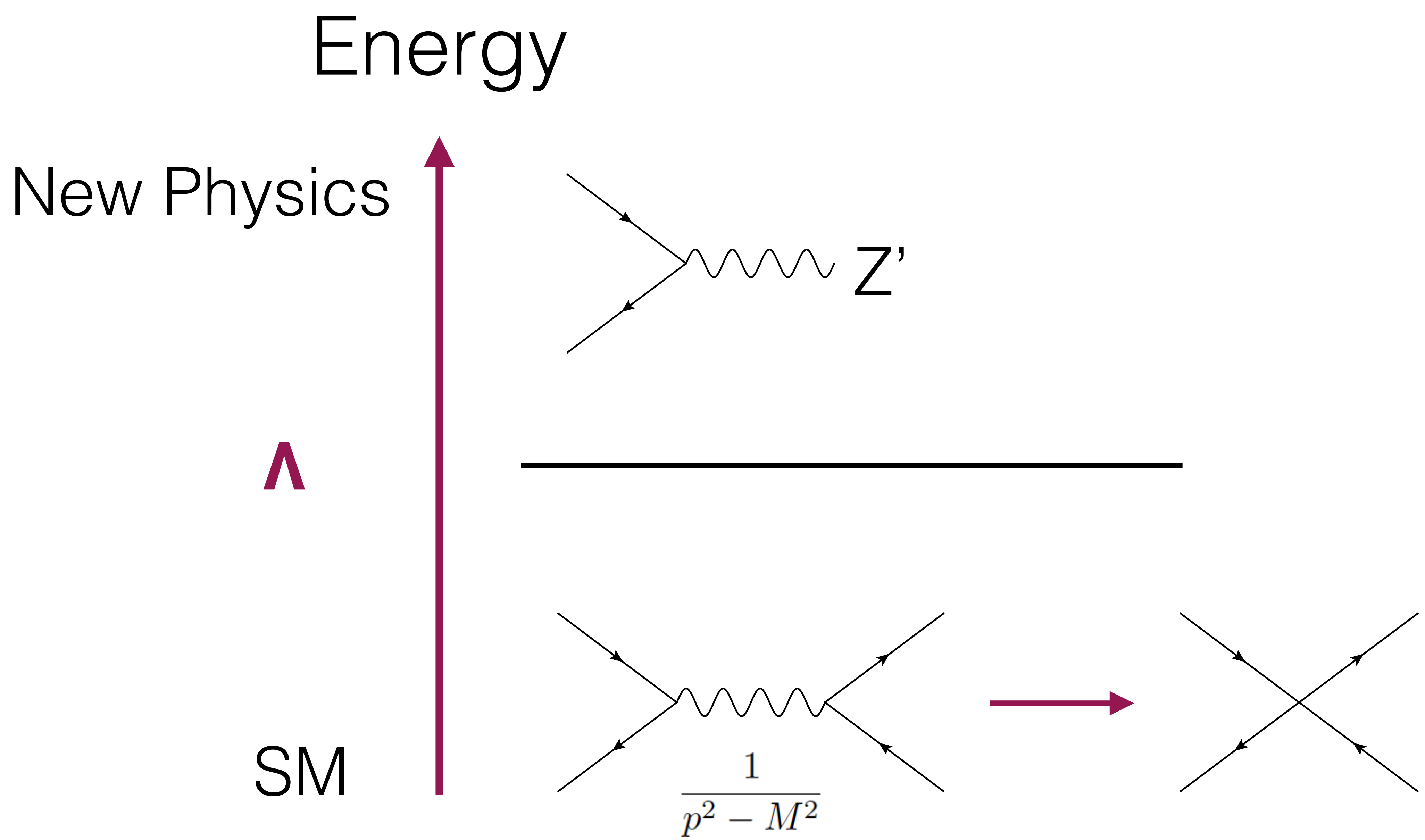

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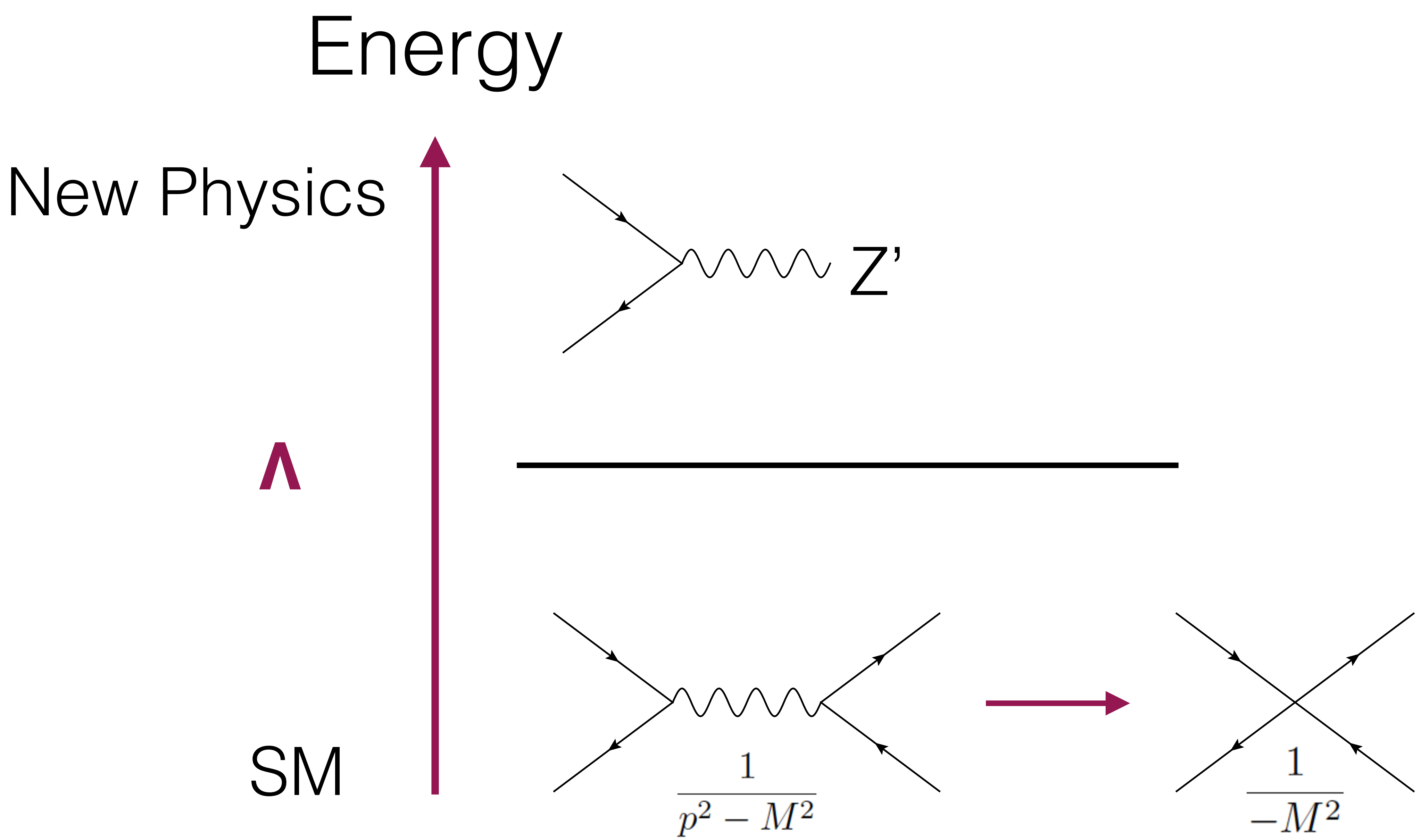

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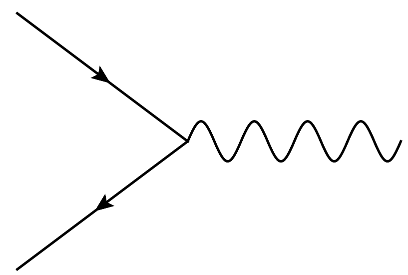
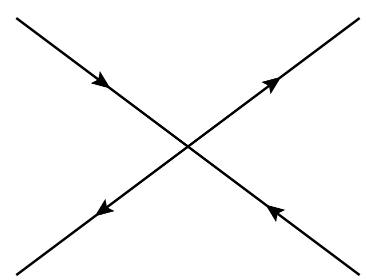


$$\mathcal{L}_{NP}(\varphi, Z')$$

Λ~M

SM



$$\frac{1}{-M^2}$$

$$\mathcal{L}_{SM}(\varphi) + \mathcal{L}_{Dim6}(\varphi) + \cdots$$

$$\mathcal{L}_{Dim6}(\varphi) = \frac{C}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

SMEFT

- BSM? New Interactions of SM particles

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

- 59(3045) operators at dim-6: 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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

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

SMEFT

- BSM? ➡ New Interactions of SM particles

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

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$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	[illegible]	[illegible]	[illegible]
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	[illegible]	[illegible]	[illegible]
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		[illegible]		[illegible]	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	[illegible]	[illegible]	[illegible]
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger \varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	[illegible]	[illegible]	[illegible]
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger \varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger \varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
[illegible]	[illegible]	[illegible]	[illegible]	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
[illegible]	[illegible]	[illegible]	[illegible]	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
[illegible]	[illegible]	[illegible]	[illegible]	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
[illegible]	[illegible]	[illegible]	[illegible]	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
[illegible]	[illegible]	[illegible]	[illegible]	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
[illegible]	[illegible]	[illegible]	[illegible]	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
[illegible]	[illegible]	[illegible]	[illegible]	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

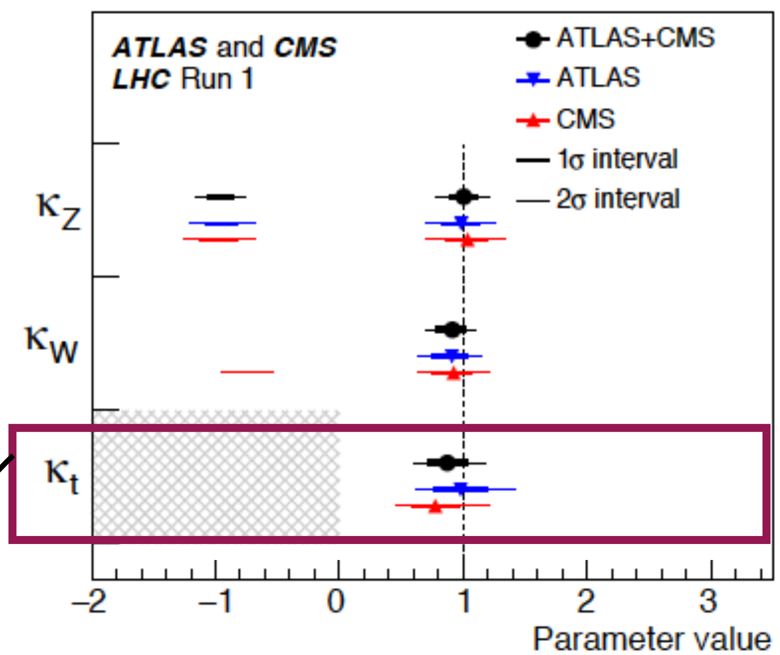
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(d_p^\alpha)^T C u_r^\beta\right] \left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	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}	$\varepsilon^{\alpha\beta\gamma} \left[(d_p^\alpha)^T C u_r^\beta\right] \left[(u_s^\gamma)^T C e_t\right]$

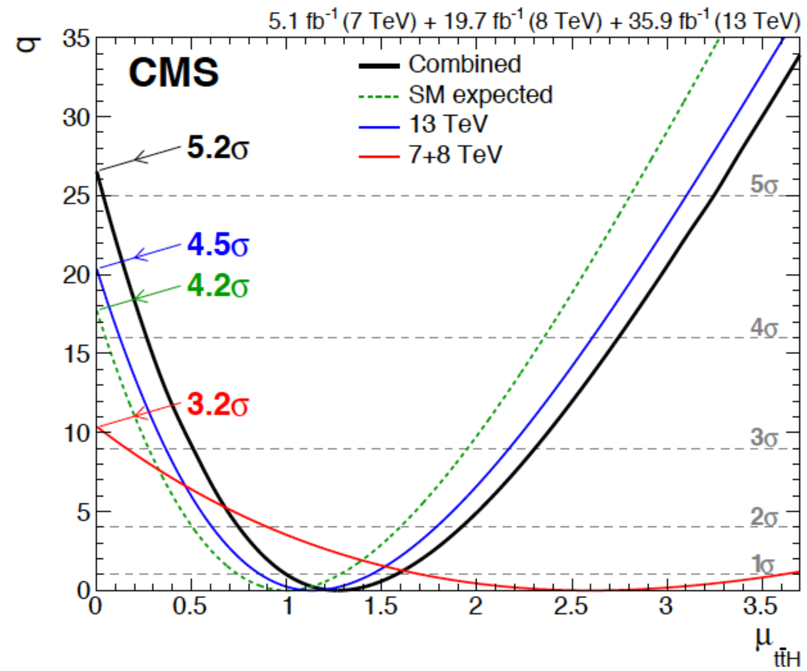
A model independent framework for parametrising deviations from the SM in the absence of light states

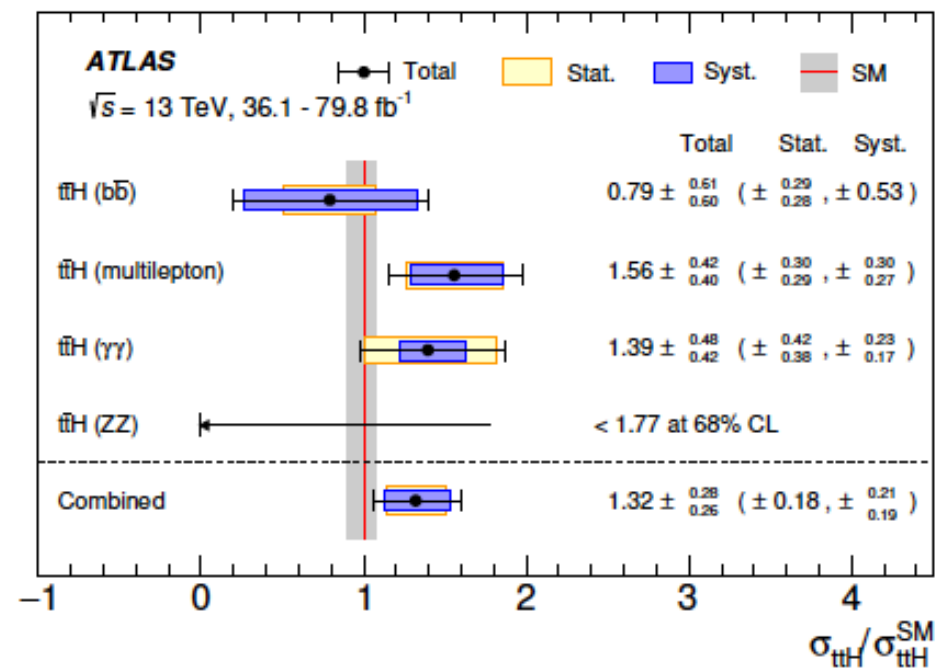
Outline

I. SMEFT for top and Higgs
II. Precision in the SMEFT
III. SMEFT and the Higgs self-coupling

Example 1) Top-Higgs interaction



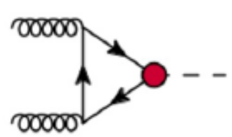




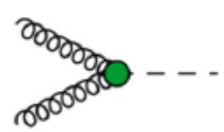
~20% accuracy

First observation of ttH

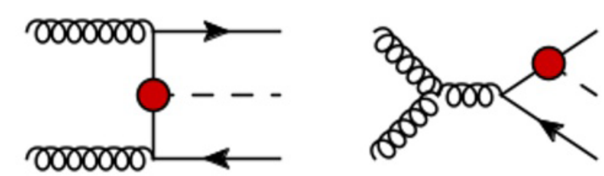
H



or

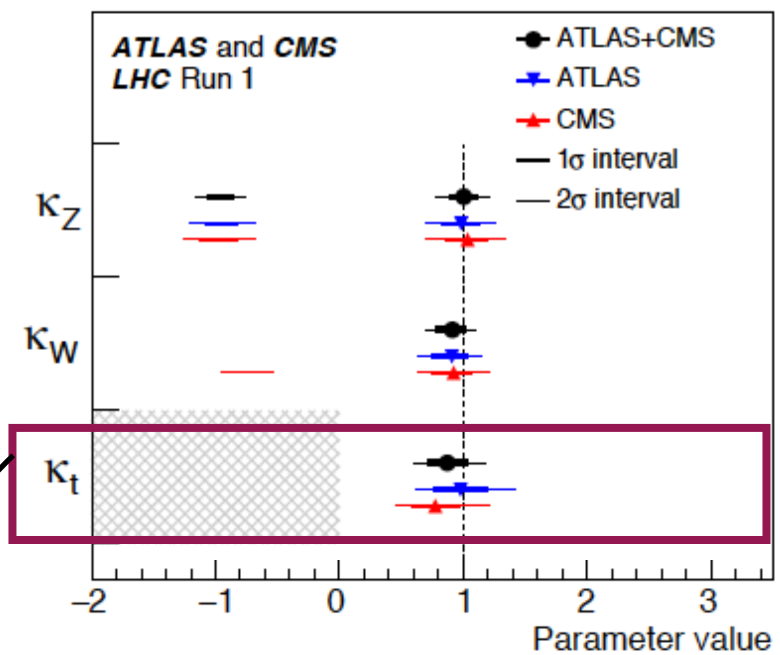


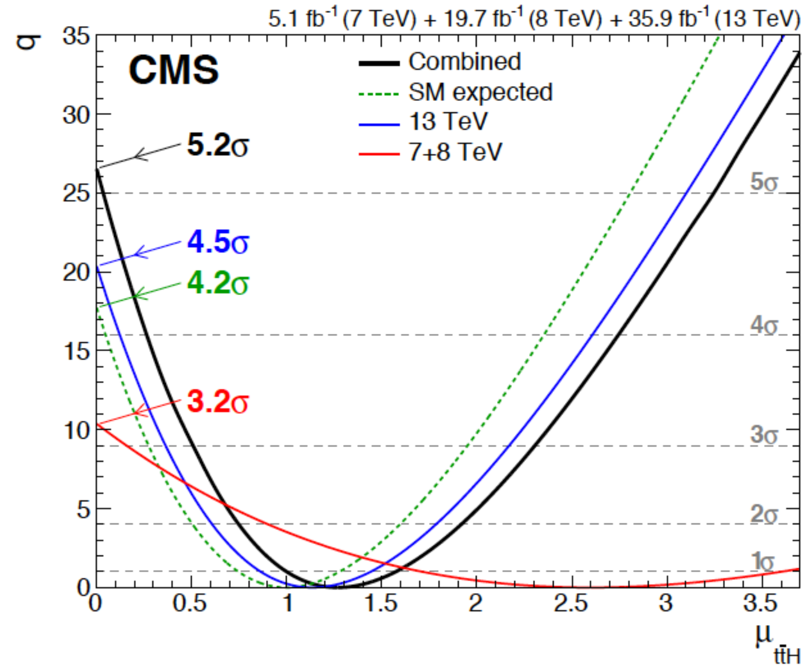
ttH

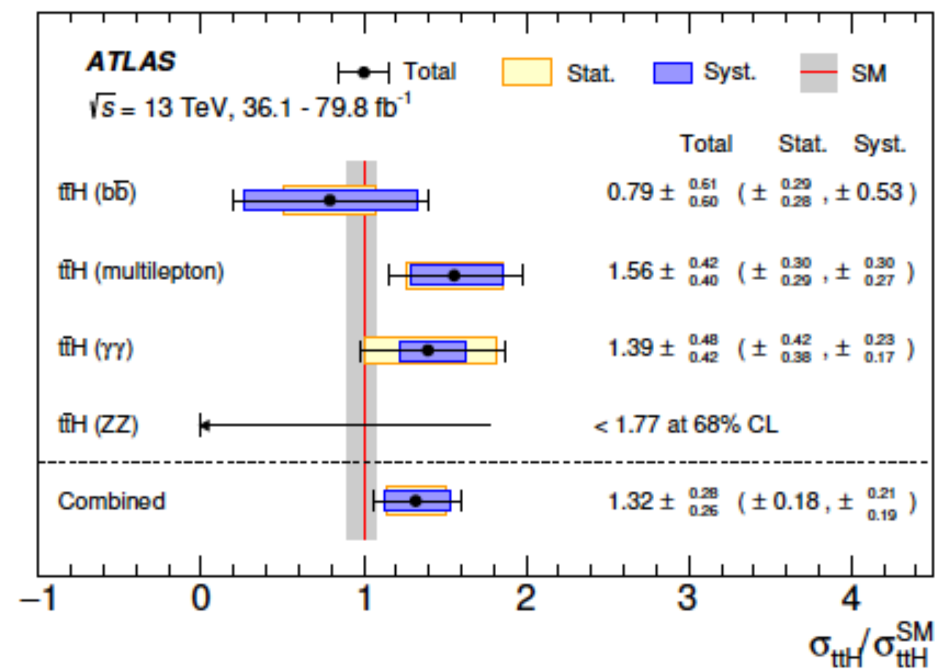


Heavy particles
in the loops?

Example 1) Top-Higgs interaction



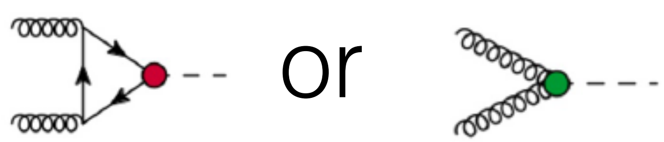




~20% accuracy

First observation of ttH

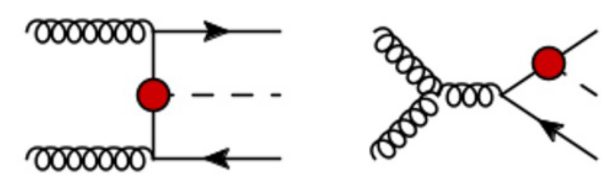
H



or

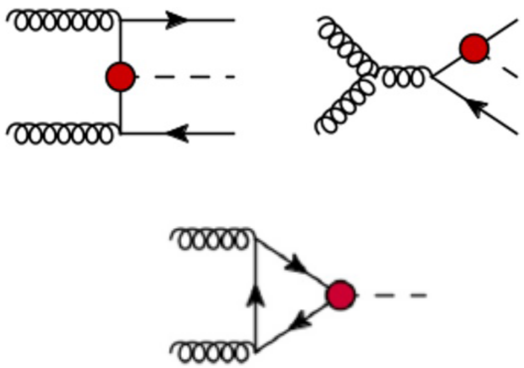
Heavy particles in the loops?

ttH

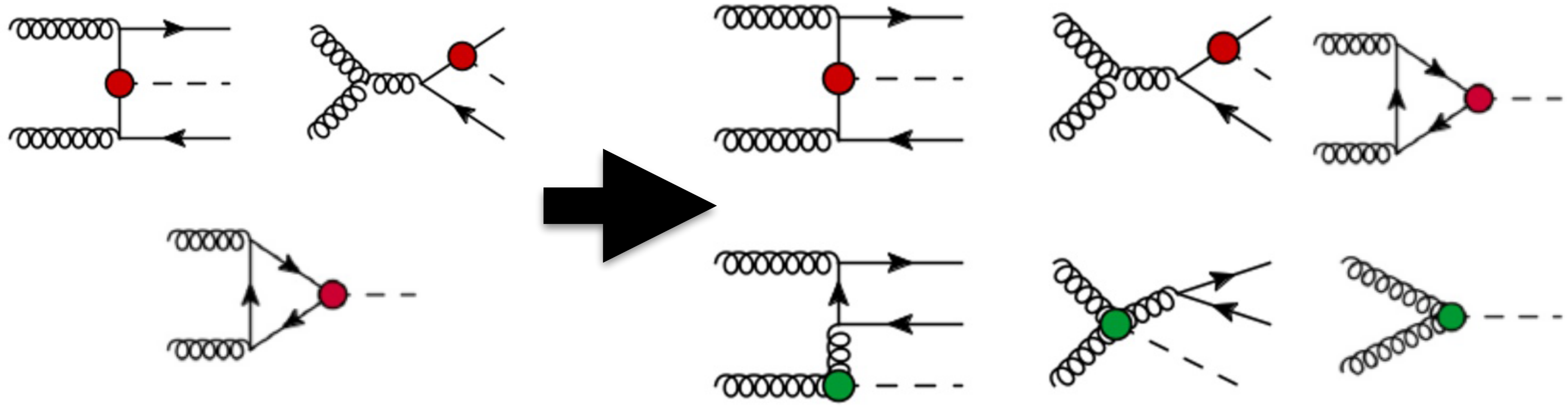


Direct evidence of the coupling of the top to the Higgs

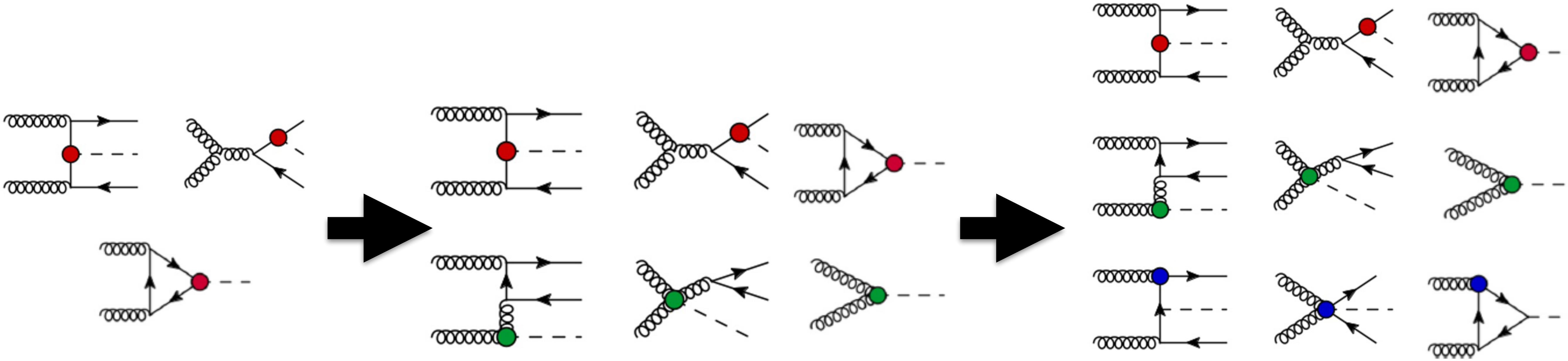
SMEFT for top & Higgs



SMEFT for top & Higgs



SMEFT for top & Higgs



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

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$
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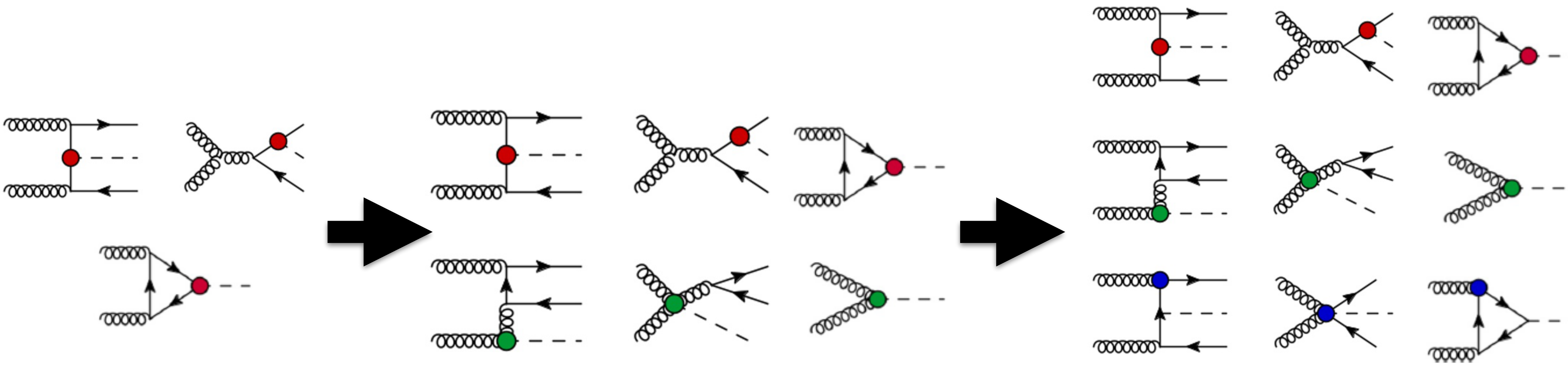
SMEFT for top & Higgs



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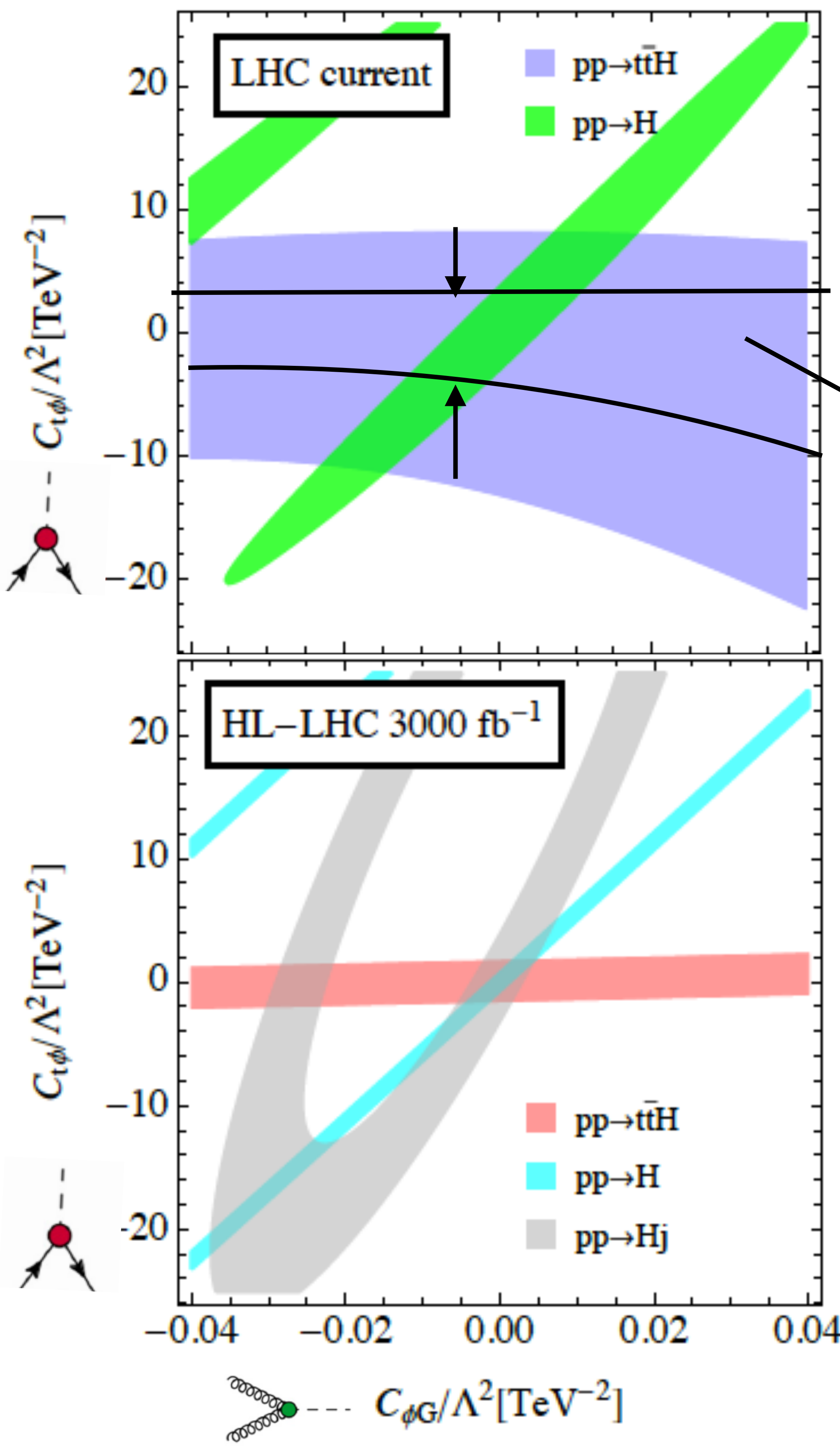
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

How can we constrain these operators?

Probing the top-Higgs interaction



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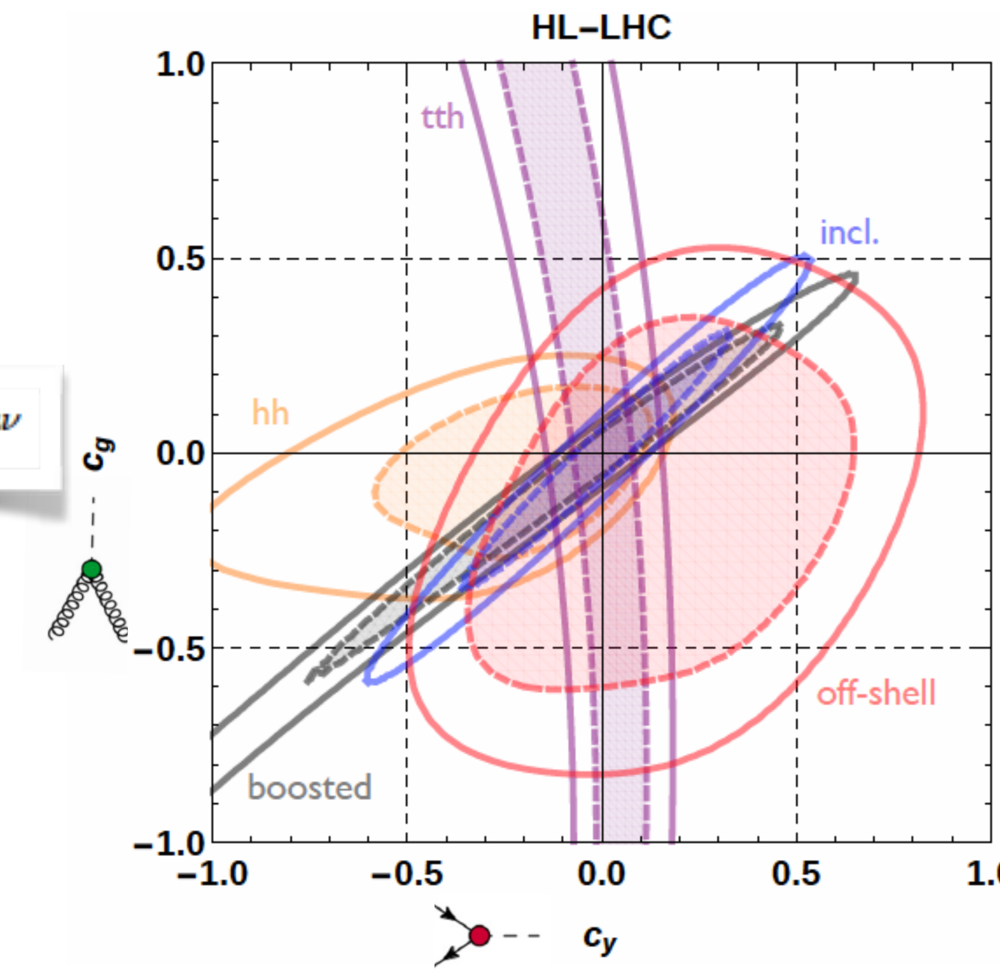
Run I LHC

Maltoni, EV, Zhang
arXiv:1607.05330

14TeV projection
3000 fb^{-1}

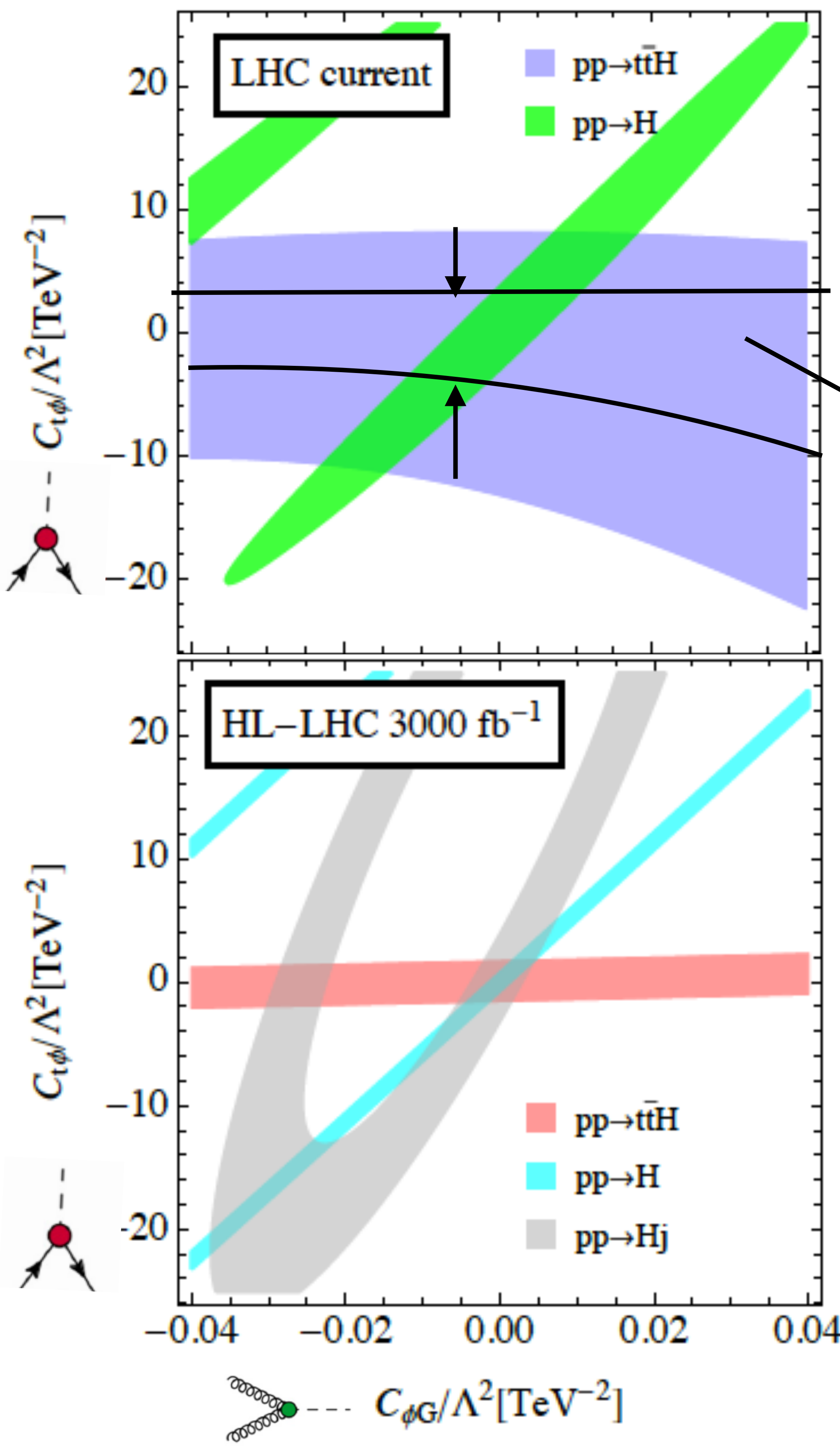


Azatov et al arXiv:1608.00977

Combination:

- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs

Probing the top-Higgs interaction



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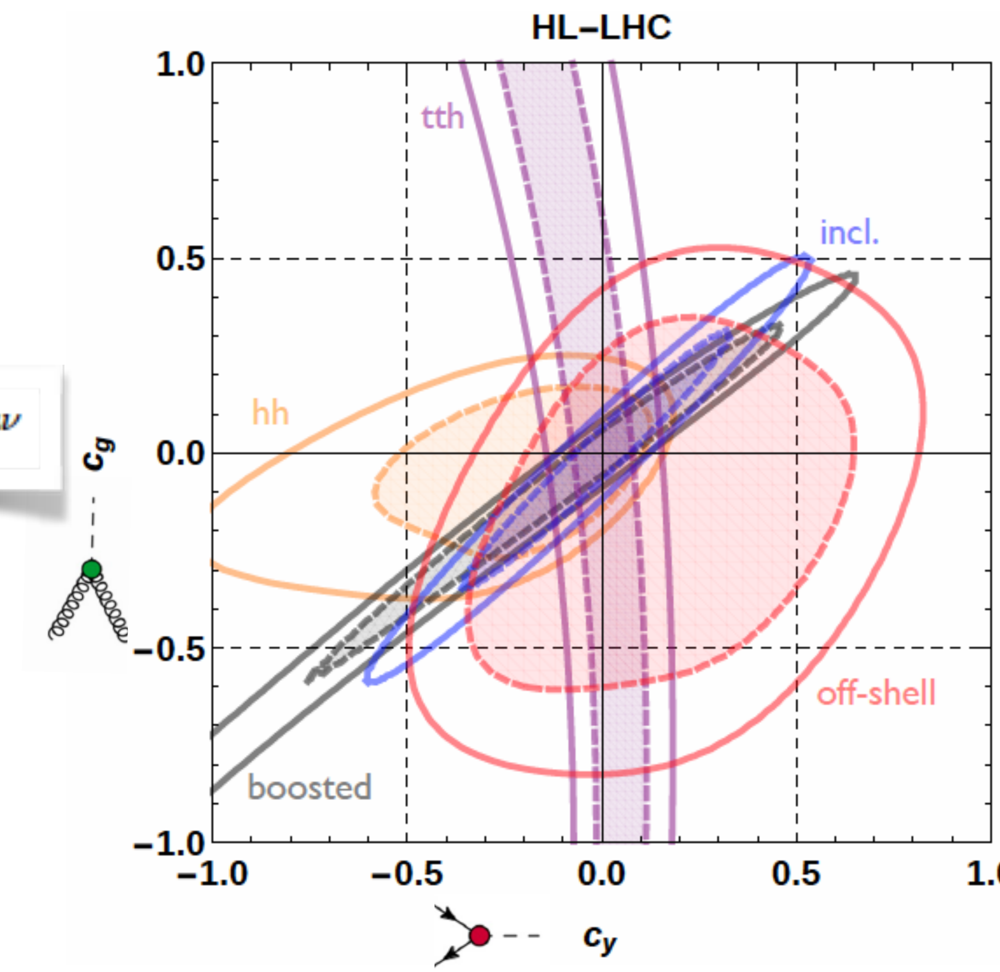
impact of recent ttH observation

Run I LHC

Maltoni, EV, Zhang arXiv:1607.05330

14TeV projection 3000 fb^{-1}



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Combination:

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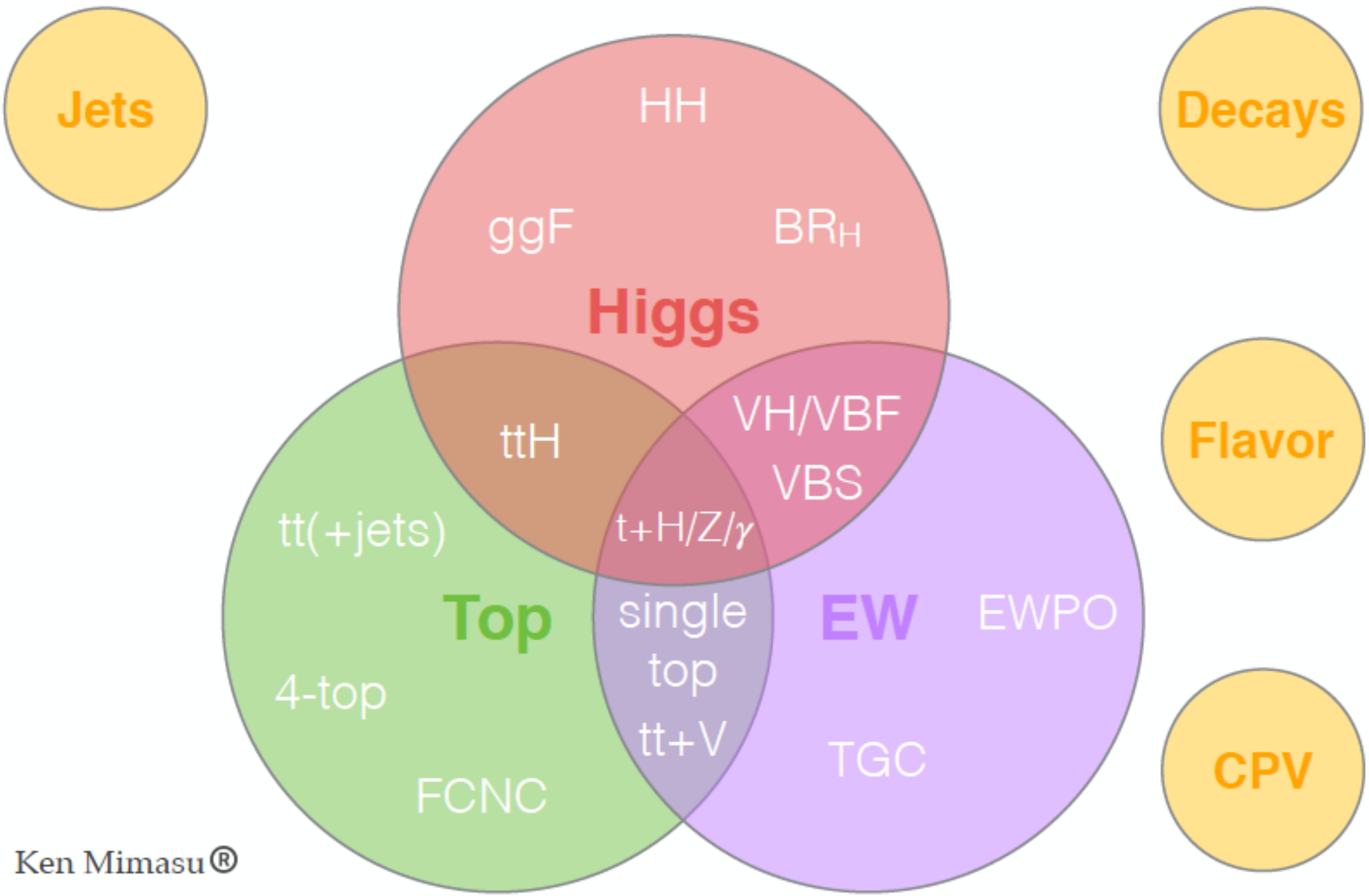
The Global EFT picture



SMEFT in the top-Higgs sector

Processes:

Process	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$
$t \to bW \to bl^+\nu$	N		L	L			
$pp \to tj$	N		L	L			
$pp \to tW$	L		L	L			
$pp \to t\bar{t}$	L						
$pp \to t\bar{t}j$	L						
$pp \to t\bar{t}\gamma$	L	L	L				
$pp \to t\bar{t}Z$	L	L	L	L	L	L	
$pp \to t\bar{t}W$	L						
$pp \to t\gamma j$	N	L	L	L			
$pp \to tZj$	N	L	L	L	L	L	
$pp \to t\bar{t}t\bar{t}$	L						
$pp \to t\bar{t}H$	L						L
$pp \to tHj$	N		L	L			L
$gg \to H$	L						L
$gg \to Hj$	L						L
$gg \to HH$	L						L
$gg \to HZ$	L			L	L	L	L

Top operators:

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

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

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

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

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

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

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

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

Need for a Global approach

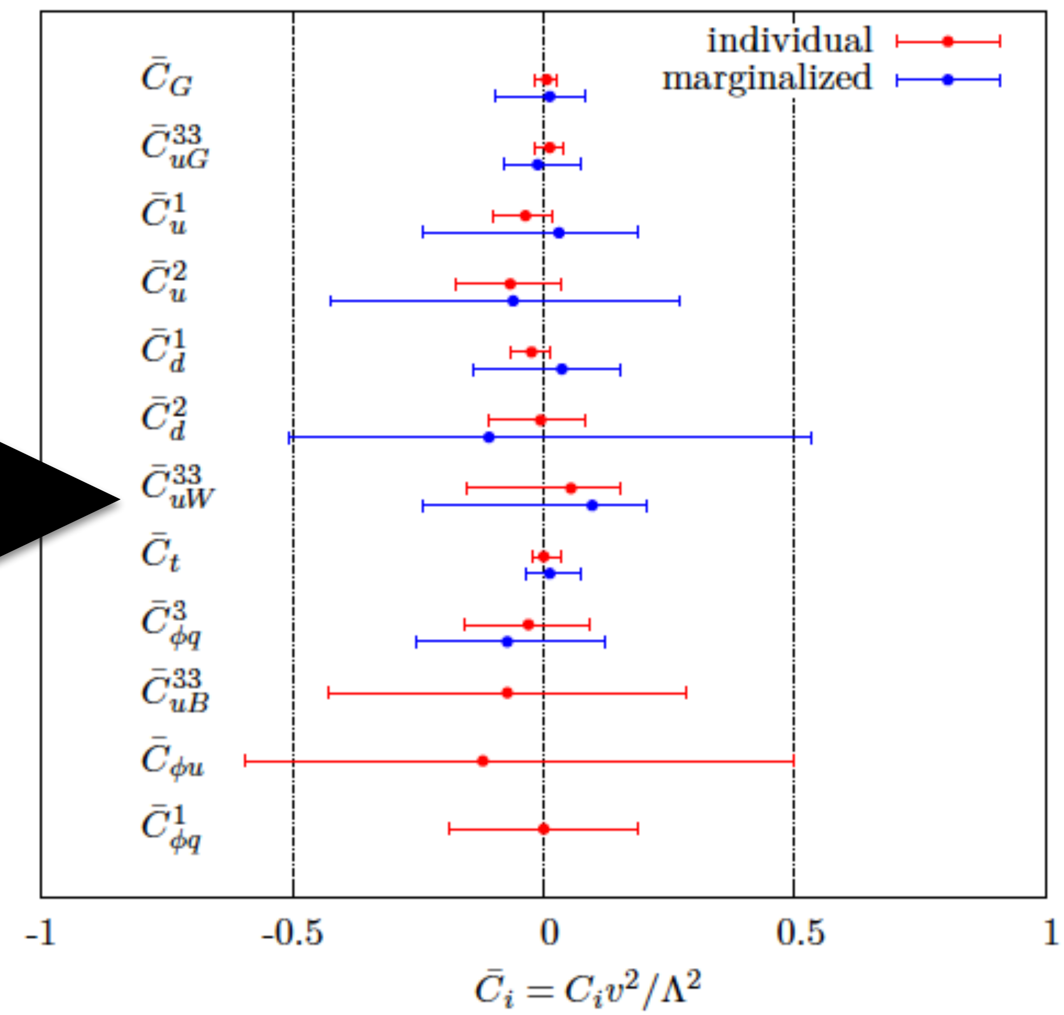
Global EFT fits in the top sector

First work towards global fits:

Buckley et al arxiv:1506.08845 and 1512.03360

(N)NLO SM + LO EFT

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production							
Total cross-sections:				Differential cross-sections:			
ATLAS	7	lepton+jets	1406.5375	ATLAS	7	$p_T(t), M_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	1407.0371
ATLAS	7	dilepton	1202.4892	CDF	1.96	$M_{t\bar{t}}$	0903.2850
ATLAS	7	lepton+tau	1205.3067	CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
ATLAS	7	lepton w/o b jets	1201.1889	CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
ATLAS	7	lepton w/ b jets	1406.5375	DØ	1.96	$M_{t\bar{t}}, p_T(t), \lvert y_t\rvert$	1401.5785
ATLAS	7	tau+jets	1211.7205				
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573	Charge asymmetries:			
ATLAS	8	dilepton	1202.4892	ATLAS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	all hadronic	1302.0508	CMS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CMS	7	dilepton	1208.2761	CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
CMS	7	lepton+jets	1212.6682	DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
CMS	7	lepton+tau	1203.6810				
CMS	7	tau+jets	1301.5755	Top widths:			
CMS	8	dilepton	1312.7582	DØ	1.96	Γ_{top}	1308.4050
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	Γ_{top}	1201.4156
Single top production				*W*-boson helicity fractions:			
ATLAS	7	t-channel (differential)	1406.7844	ATLAS	7		1205.2484
CDF	1.96	s-channel (total)	1402.0484	CDF	1.96		1211.4523
CMS	7	t-channel (total)	1406.7844	CMS	7		1308.3879
CMS	8	t-channel (total)	1406.7844	DØ	1.96		1011.6549
DØ	1.96	s-channel (total)	0907.4259				
DØ	1.96	t-channel (total)	1105.2788				
Associated production				*Run II data*			
ATLAS	7	$t\bar{t}\gamma$	1502.00586	CMS	13	$t\bar{t}$ (dilepton)	1510.05302
ATLAS	8	$t\bar{t}Z$	1509.05276				
CMS	8	$t\bar{t}Z$	1406.7830				

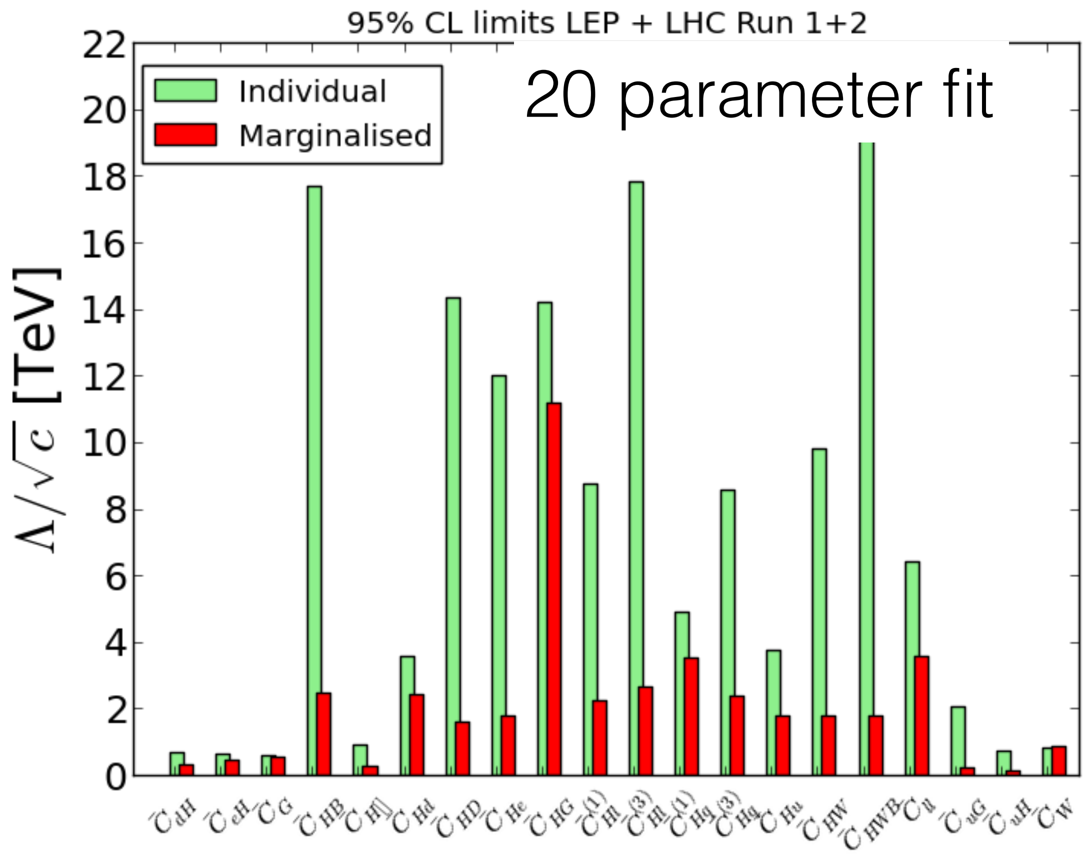


Tevatron and LHC data

Cross-sections and distributions

Limits

Towards more global fits



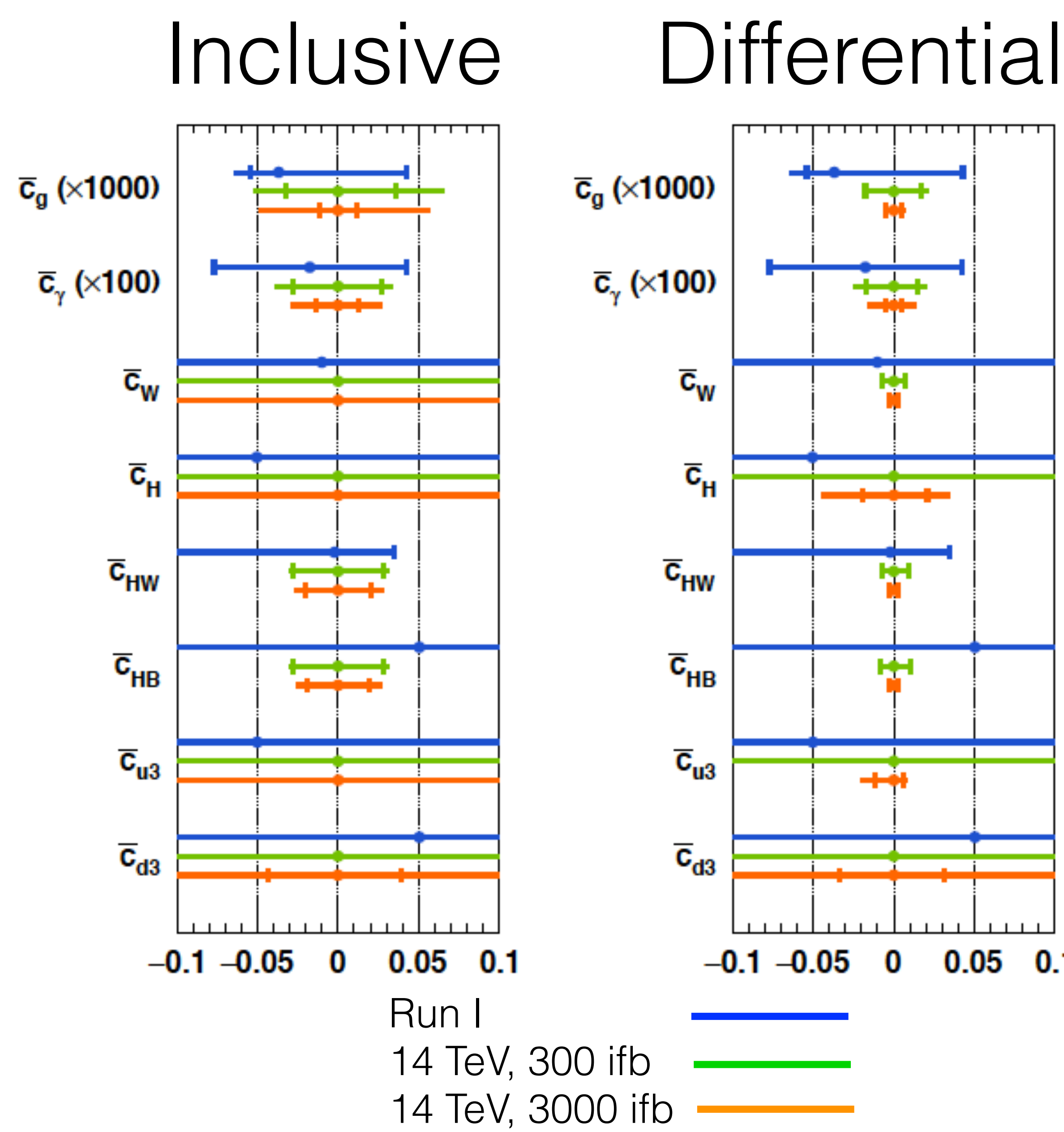
A Global fit: LEP and LHC Run I and II

$$\begin{aligned}\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset\ & \frac{\bar C_{Hl}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l\tau^I\gamma^\mu l) + \frac{\bar C_{Hl}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l\gamma^\mu l) + \frac{\bar C_{ll}}{v^2}(\bar l\gamma_\mu l)(\bar l\gamma^\mu l)\\ & + \frac{\bar C_{HD}}{v^2}\left|H^\dagger D_\mu H\right|^2 + \frac{\bar C_{HWB}}{v^2}H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}\\ & + \frac{\bar C_{He}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e\gamma^\mu e) + \frac{\bar C_{Hu}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u\gamma^\mu u) + \frac{\bar C_{Hd}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d\gamma^\mu d)\\ & + \frac{\bar C_{Hq}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q\tau^I\gamma^\mu q) + \frac{\bar C_{Hq}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q\gamma^\mu q) + \frac{\bar C_W}{v^2}\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset\ & \frac{\bar C_{eH}}{v^2}y_e(H^\dagger H)(\bar l e H) + \frac{\bar C_{dH}}{v^2}y_d(H^\dagger H)(\bar q d H) + \frac{\bar C_{uH}}{v^2}y_u(H^\dagger H)(\bar q u\widetilde H)\\ & + \frac{\bar C_G}{v^2}f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho + \frac{\bar C_{H\Box}}{v^2}(H^\dagger H)\Box(H^\dagger H) + \frac{\bar C_{uG}}{v^2}y_u(\bar q\sigma^{\mu\nu}T^A u)\widetilde H\, G^A_{\mu\nu}\\ & + \frac{\bar C_{HW}}{v^2}H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu} + \frac{\bar C_{HB}}{v^2}H^\dagger H\, B_{\mu\nu}B^{\mu\nu} + \frac{\bar C_{HG}}{v^2}H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}\,.\end{aligned}$$

Ellis et al arXiv:1803.03252

The future of global fits



Using differential information will be crucial

Englert, Kogler, Spannowsky arXiv:1511.05170

EFT: some considerations

- Theory uncertainties:
  - SM: factorisation and renormalisation scale, PDF uncertainties
  - EFT: as in SM but also EFT scale c(μ), running and mixing
  - EFT expansion: dimension-8 operators see Hays et al arXiv:1808.00442
- Validity of the EFT expansion: **E<Λ**, report limits as a function of the max scale probed: Contino et al arXiv:1604.06444
- $1/\Lambda^2$ vs $1/\Lambda^4$ contributions
  - $1/\Lambda^2$ suppressed due to helicity: Azatov et al arXiv:1607.05236
  - $1/\Lambda^4$ can be large for loosely constrained operator coefficients/strongly coupled theories

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

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

- Range of Wilson coefficients:
  - The theory: perturbativity, unitarity, linear or non-linear EFT, UV completion

Outline

I. SMEFT for top and Higgs
II. Precision in the SMEFT
III. SMEFT and the Higgs self-coupling

What's next?

Use SMEFT to parametrise and look for deviations from SM predictions

What's next?

Use SMEFT to parametrise and look for deviations from SM predictions → Use as many experimental measurements as possible Cross-sections+differential distributions

What's next?

Use SMEFT to parametrise and look for deviations from SM predictions

→

Use as many experimental measurements as possible Cross-sections+differential distributions

↓

Use the best SM predictions QCD/EW corrections

What's next?

Use SMEFT to parametrise and look for deviations from SM predictions

Use as many experimental measurements as possible Cross-sections+differential distributions

Use the best SM predictions QCD/EW corrections

Need for precision also in SMEFT

What's next?

Use SMEFT to parametrise and look for deviations from SM predictions

Use as many experimental measurements as possible
Cross-sections+differential distributions

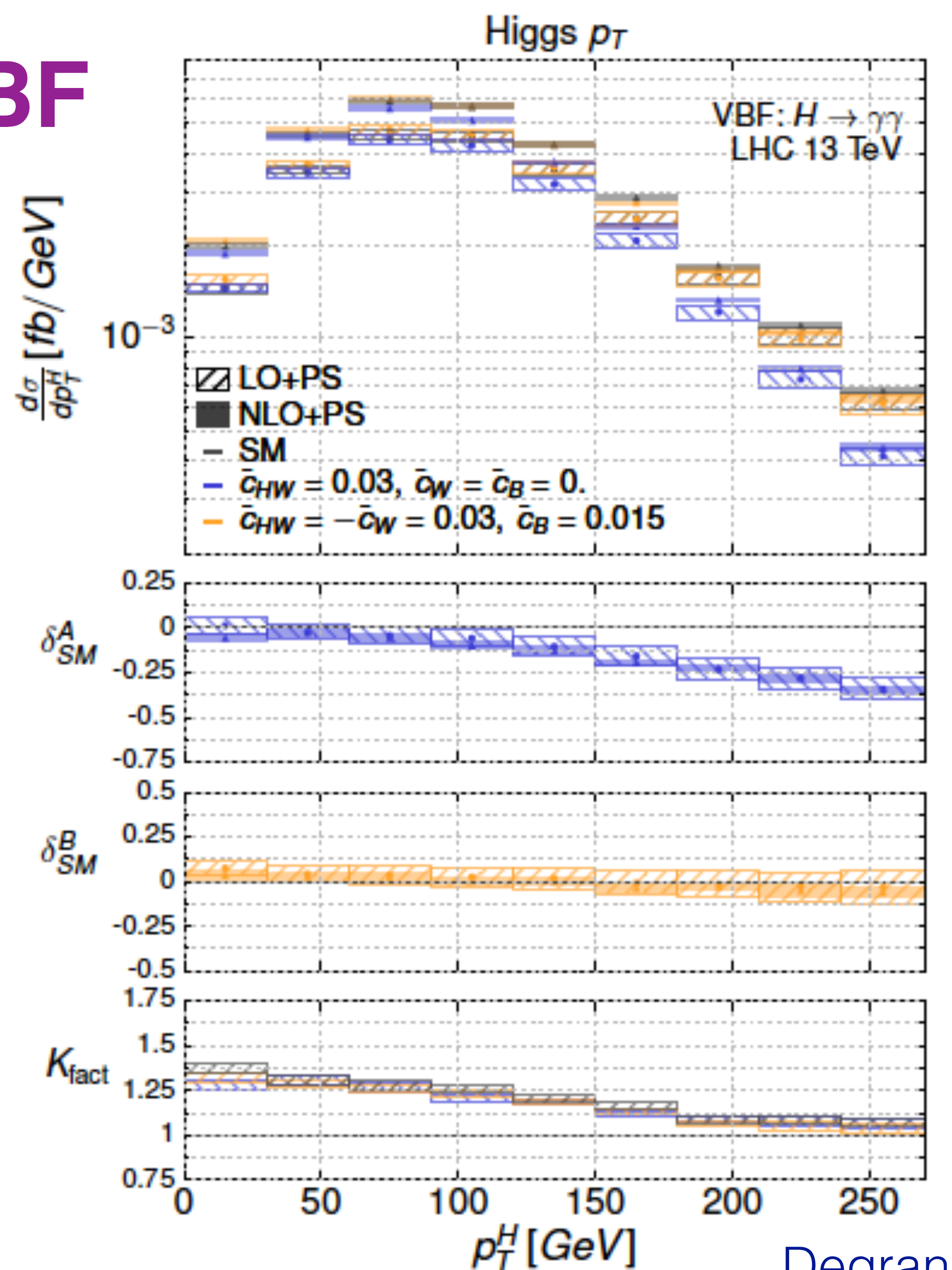
Use the best SM predictions
QCD/EW corrections

Need for precision also in SMEFT

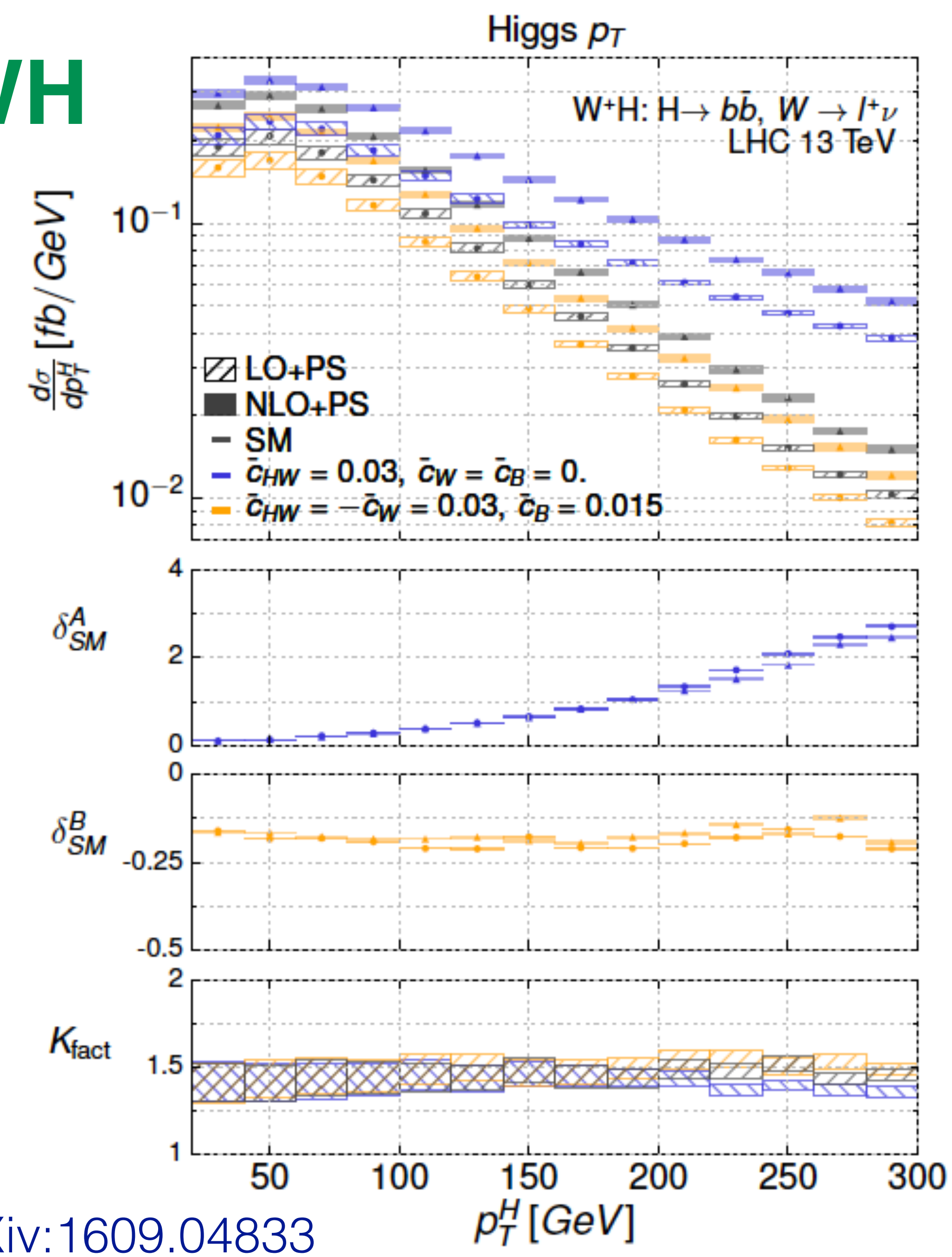
Need for precision calculations
Automated tools for the EFT

Precision calculations in the EFT: NLO QCD

VBF



WH



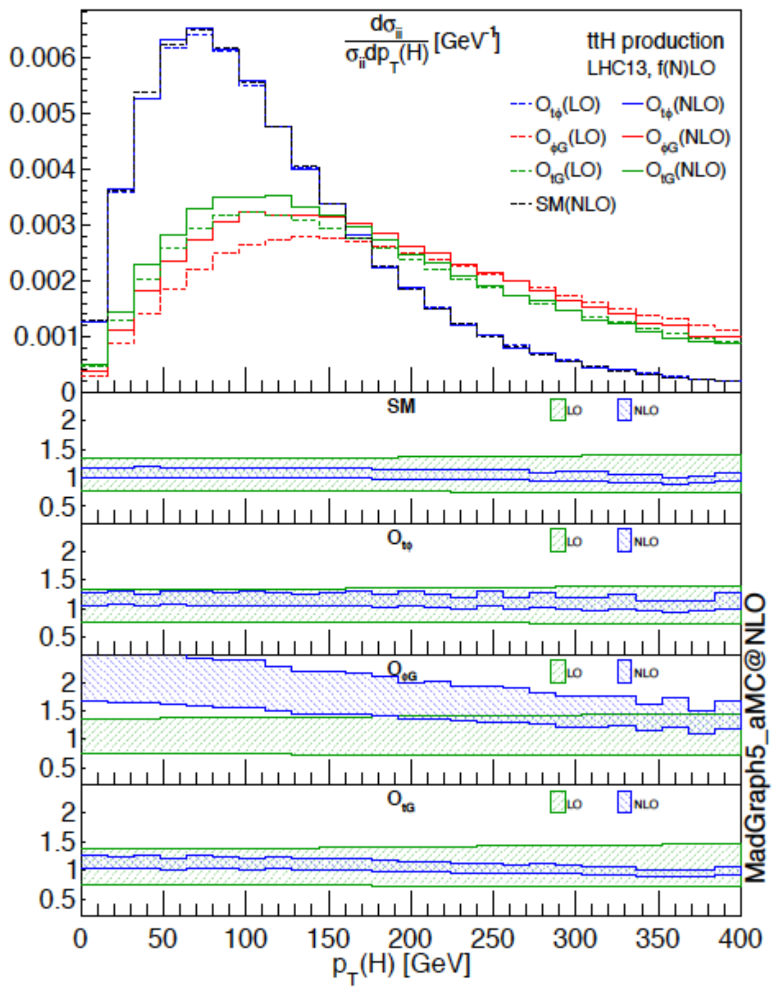
Degrande et al: arXiv:1609.04833

$$\mathcal{L} = + \frac{ig'}{2\Lambda^2}\bar{c}_B\,[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi]\,\partial_\nu B^{\mu\nu} + \frac{ig}{2\Lambda^2}\bar{c}_W\,[\Phi^\dagger T_{2k} \overleftrightarrow{D}_\mu \Phi]\,D_\nu W^{k,\mu\nu} + \frac{ig}{\Lambda^2}\bar{c}_{HW}\,[D_\mu \Phi^\dagger T_{2k} D_\nu \Phi]\,W^{k,\mu\nu}$$

Use of differential information will be crucial

Precision calculations in the EFT: NLO QCD

ttH



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

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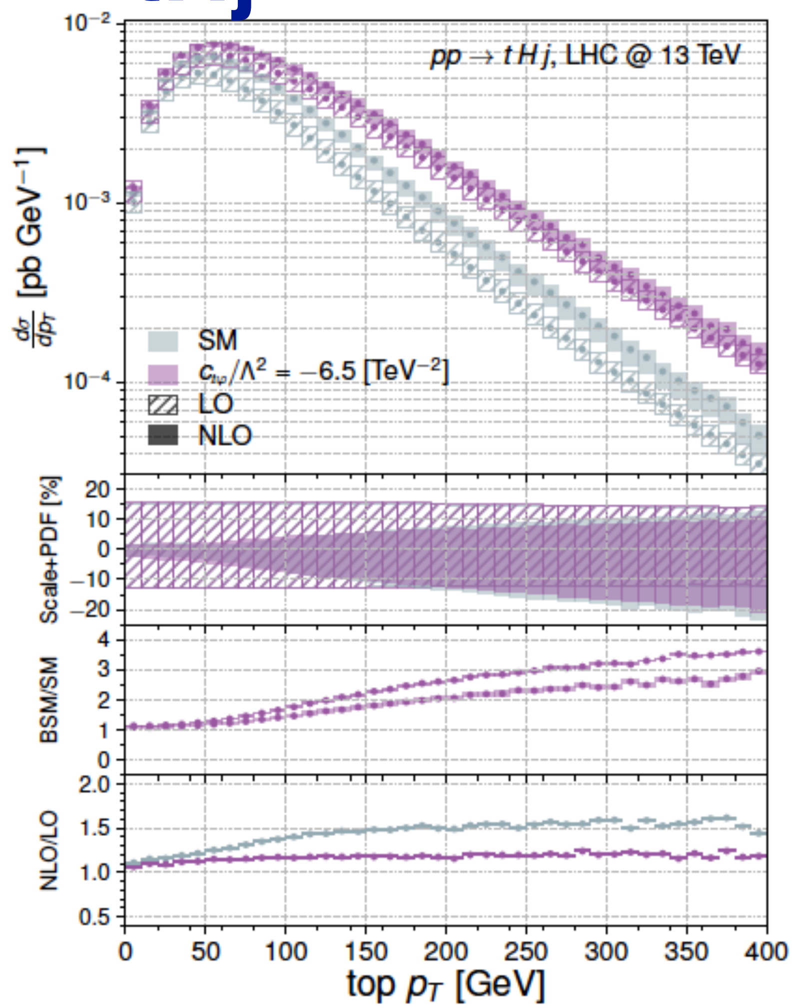
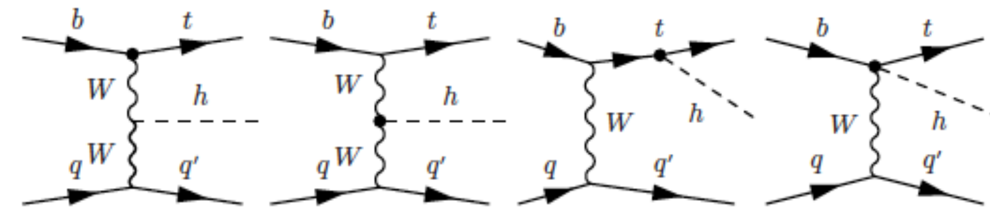
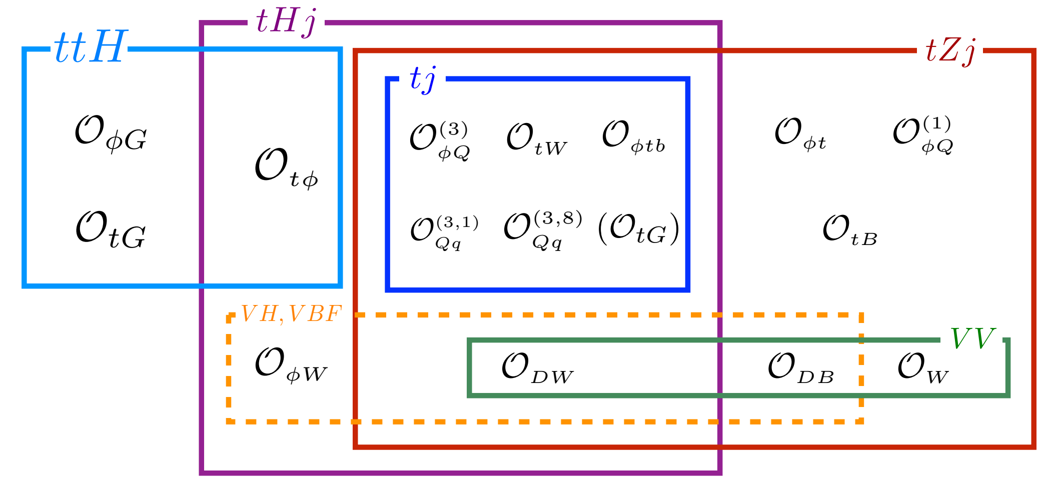
Maltoni, EV, Zhang arXiv:1607.05330

tHj







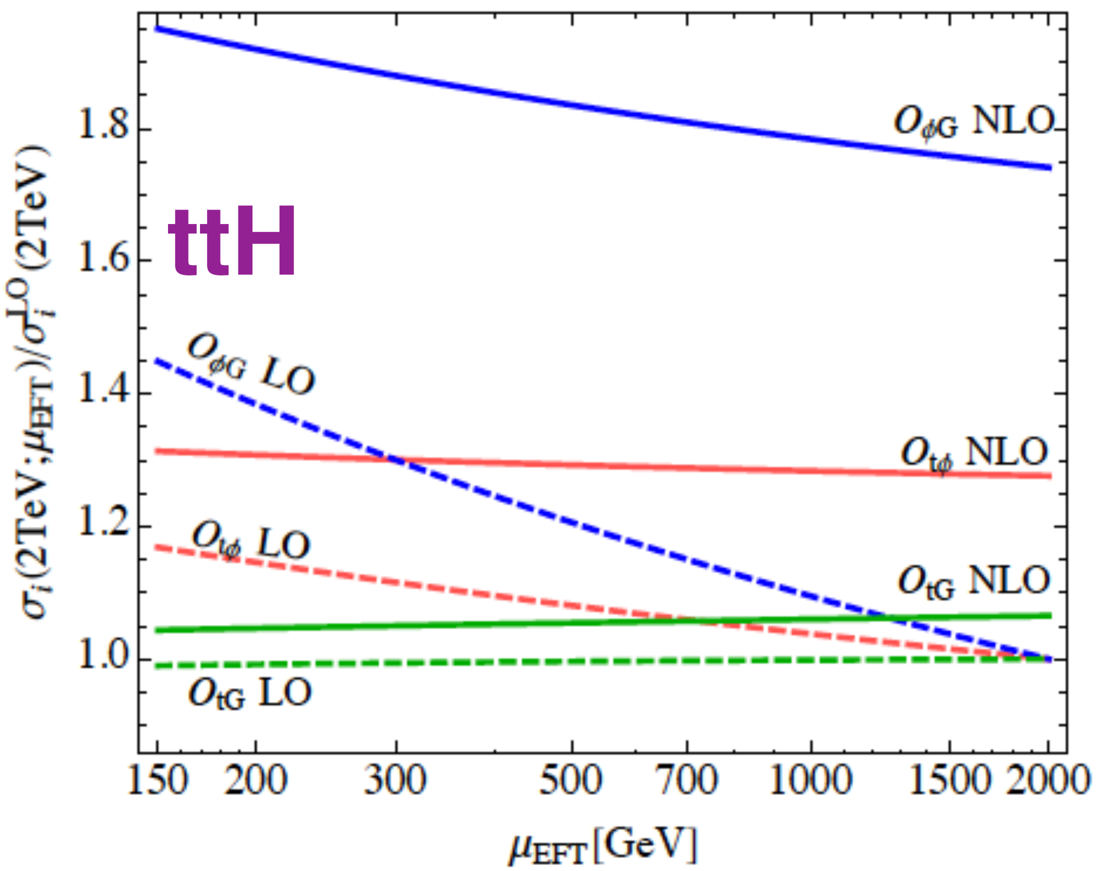
The global EFT picture

Degrande, Maltoni, Mimasu, EV, Zhang arXiv:1804.07773

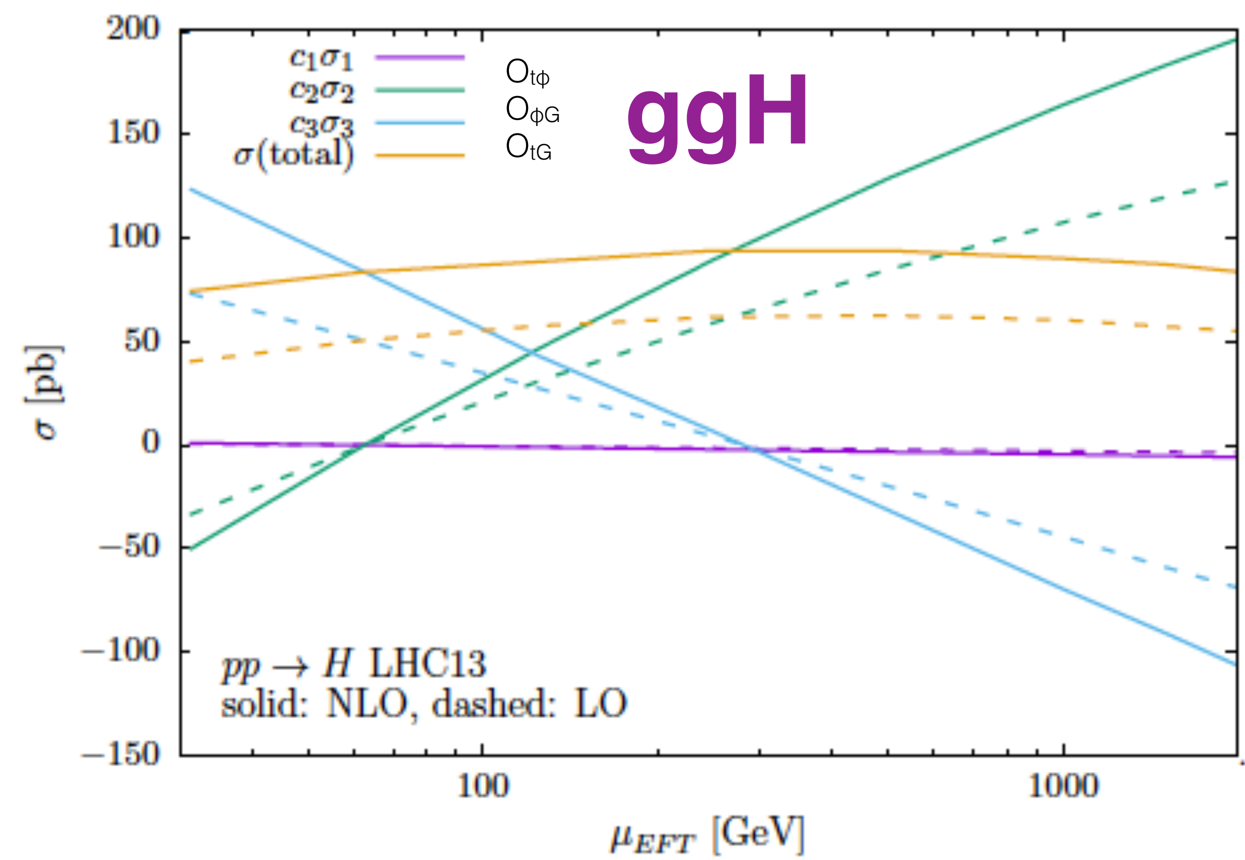
- Rare processes: important HL-LHC
- Higher-order corrections for the EFT have become available for a range of processes
- Full automation underway

Towards theoretical uncertainties in the EFT

Operators run and mix with the scale:



Maltoni, EV, Zhang arXiv:1607.05330

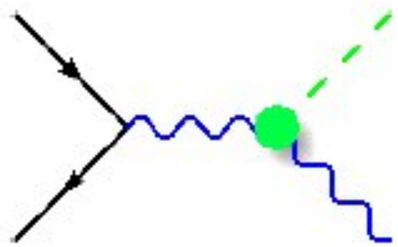
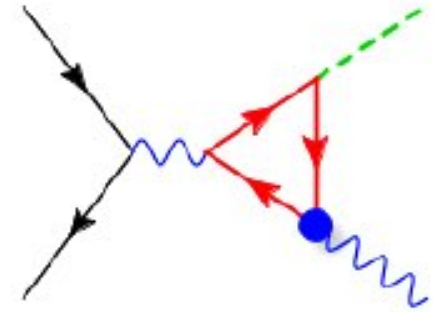


Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

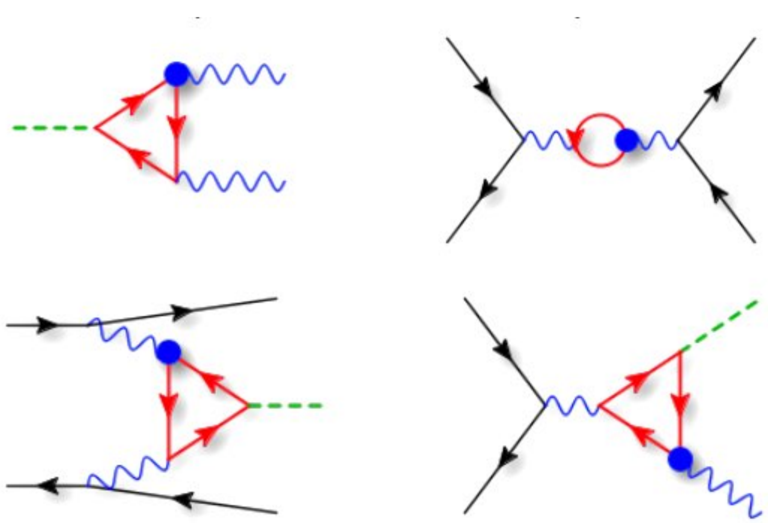
RG corrections not a good approximation to the NLO result, underestimate the NLO corrections

Milder EFT scale dependence at NLO, when running and mixing effects also taken into account

Towards weak loops in the EFT

Are we measuring  or  ?

NLO EW in SMEFT may not be small: $\mathcal{O}(\alpha_{EW}/\pi \cdot C_t/C_H)$ **instead of** $\mathcal{O}(\alpha_{EW}/\pi)$



+

$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\,(\varphi^\dagger\varphi) + h.c.,$$
$$O_{\varphi Q}^{(3)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{Q}\gamma^\mu\tau^I Q),$$
$$O_{\varphi tb} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{t}\gamma^\mu b) + h.c.,$$
$$O_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\,\tilde{\varphi}B_{\mu\nu} + h.c.,$$
$$O_{\varphi t} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t),$$
$$O_{\varphi Q}^{(1)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q),$$
$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c.,$$

+

Current constraints

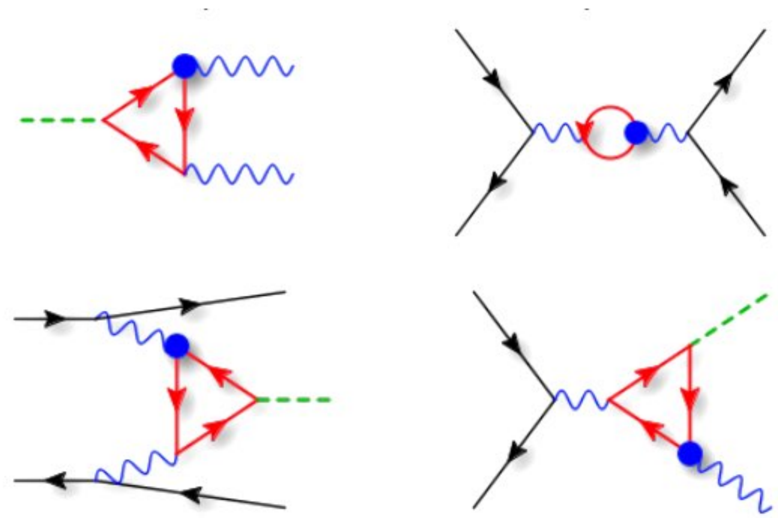
Operator	Top Fitter	RHCC	$\sigma_{t\bar{t}H}$ [28]
$C_{\varphi tb}$		[-5.28,5.28]	
$C_{\varphi Q}^{(3)}$	[-2.59,1.50]		
$C_{\varphi Q}^{(1)}$	[-3.10,3.10]		
$C_{\varphi t}$	[-9.78,8.18]		
C_{tW}	[-2.49,2.49]		
C_{tB}	[-7.09,4.68]		
$C_{t\varphi}$			[-6.5,1.3]

Uncertainties on Higgs measurements at the LHC:

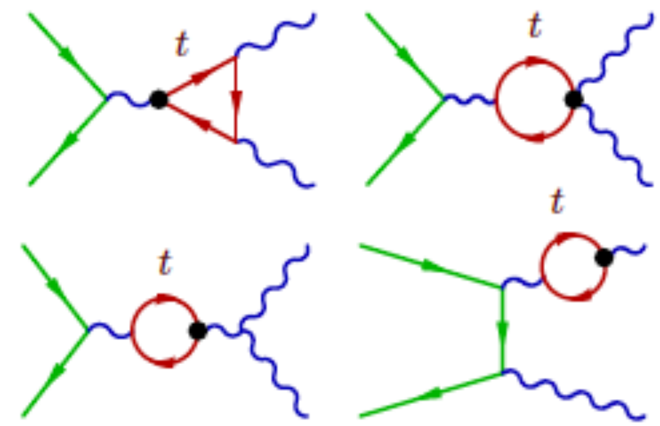
	$\gamma\gamma$	γZ	bb	WW*	ZZ*	$\tau\tau$	$\mu\mu$
gg	(-100%,1980%)	(-88%,200%)	(-40%,48%)	(-40%,47%)	(-40%,46%)	(-40%,48%)	(-40%,48%)
VBF	(-100%,1880%)	(-88%,170%)	(-6.1%,5.3%)	(-6.8%,6.7%)	(-8.8%,9.2%)	(-6.2%,5.9%)	(-6.2%,5.9%)
WH	(-100%,1880%)	(-88%,170%)	(-5.5%,4.2%)	(-6.1%,5.6%)	(-7.8%,7.9%)	(-5.8%,5.1%)	(-5.8%,5.1%)
ZH	(-100%,1880%)	(-87%,170%)	(-6.5%,5.9%)	(-7.1%,7.1%)	(-9.4%,9.9%)	(-6.8%,6.7%)	(-6.8%,6.7%)

Towards weak loops in the EFT

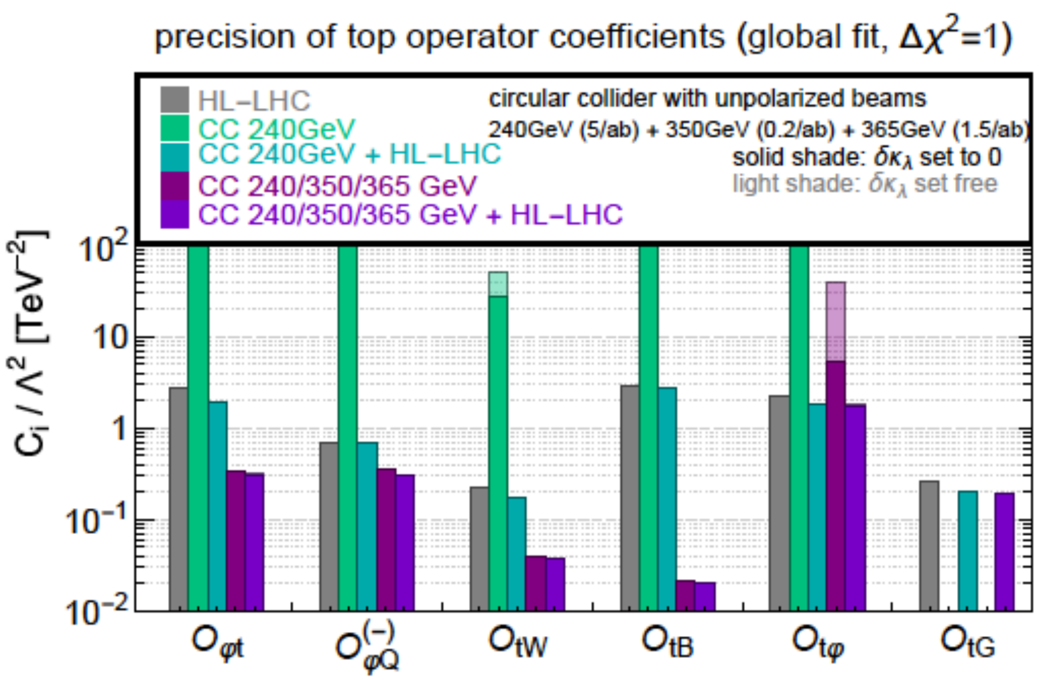
Circular Electron Positron Collider & HL-LHC: Top + Higgs Global Fit

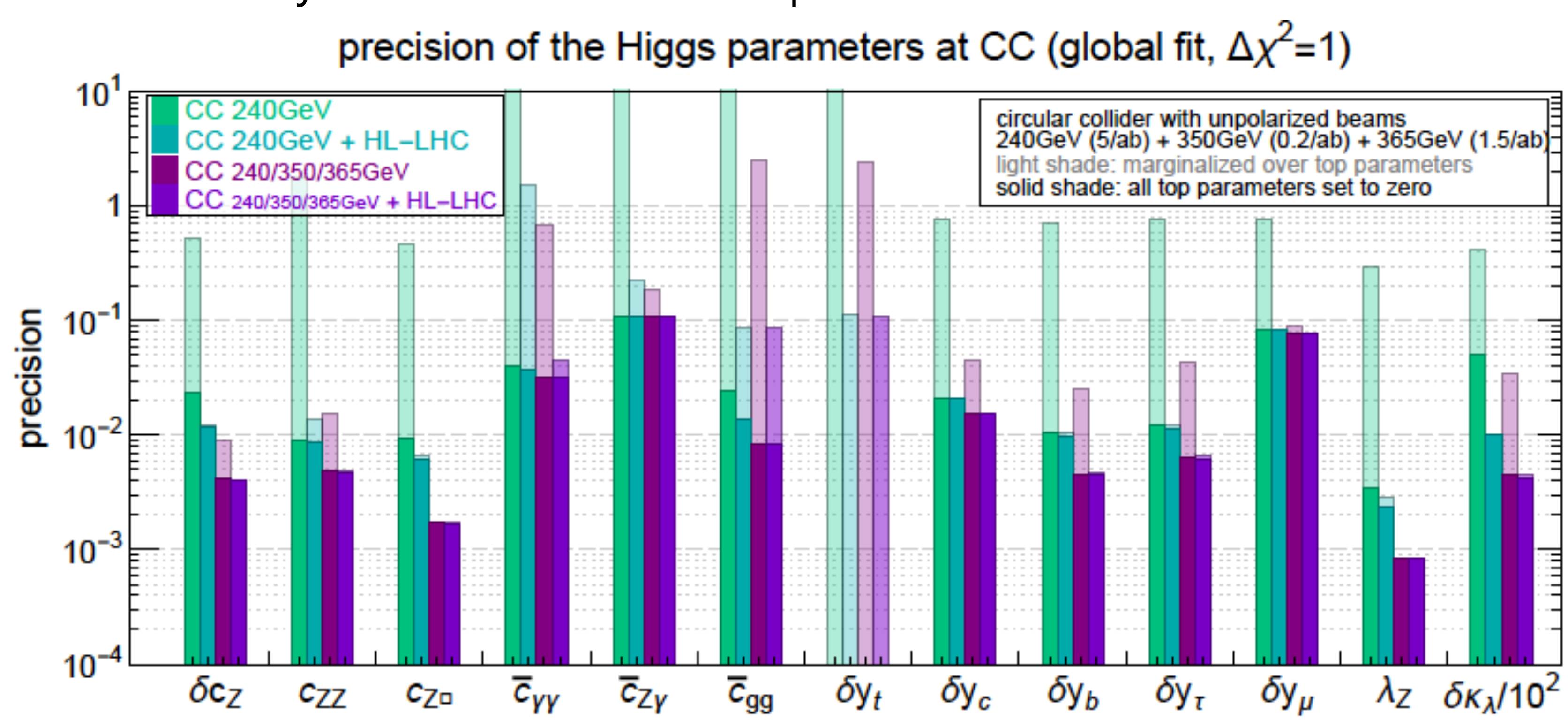


Higgs production and decay



WW production





Durieux, Gu, EV, Zhang arXiv:1809.03520

Outline

I. SMEFT for top and Higgs
II. Precision in the SMEFT
III. SMEFT and the Higgs self-coupling

The Higgs potential

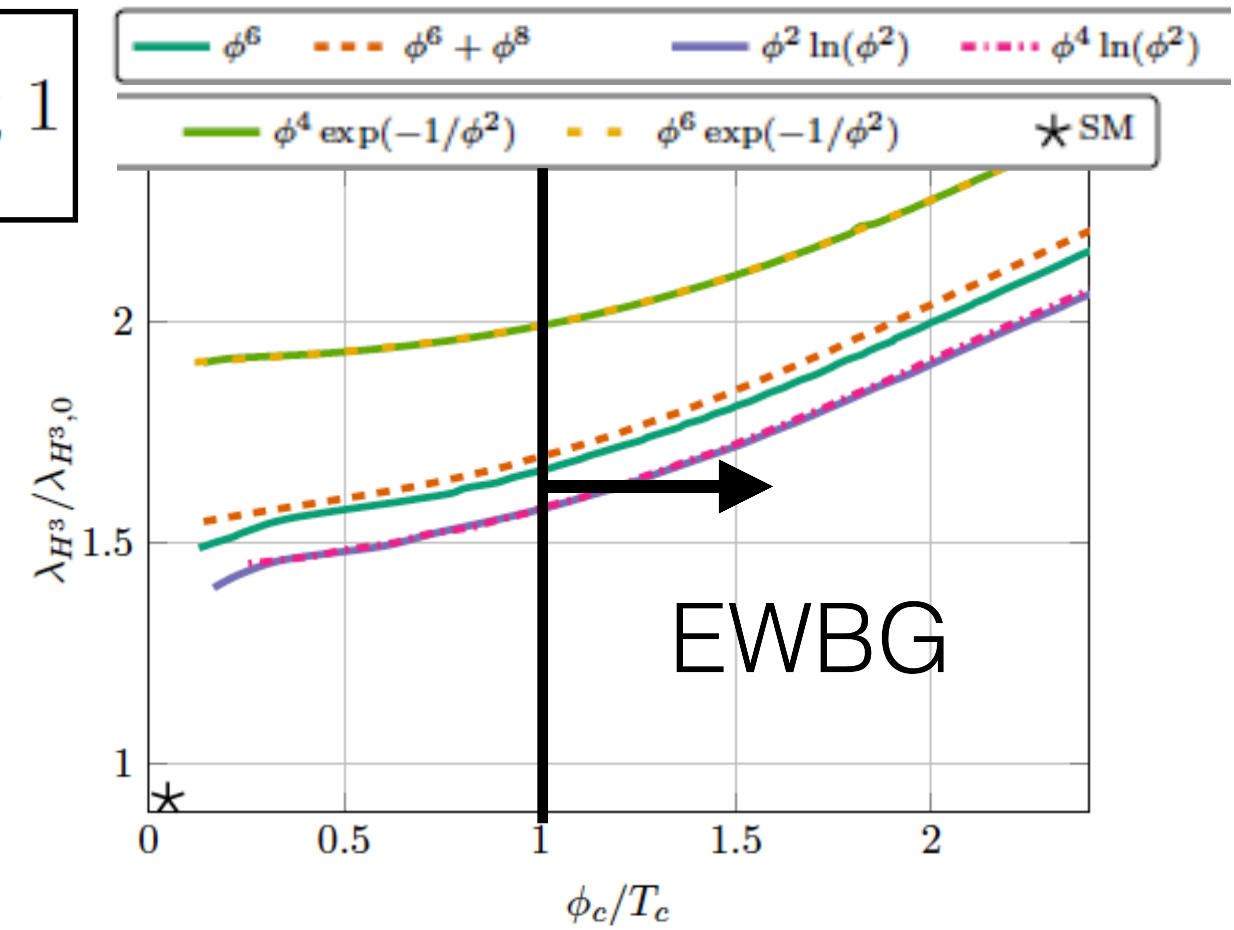
Higgs potential: $$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

Fixed values in the SM: $$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

Measuring λ_{HHH} and λ_{HHHH} tests the SM

What can measuring λ_{HHH} tell us?

Electroweak baryogenesis requires a first order strong EWPT → $$\frac{\phi_c}{T_c} \gtrsim 1$$



Reichert et al: arXiv:1711.00019

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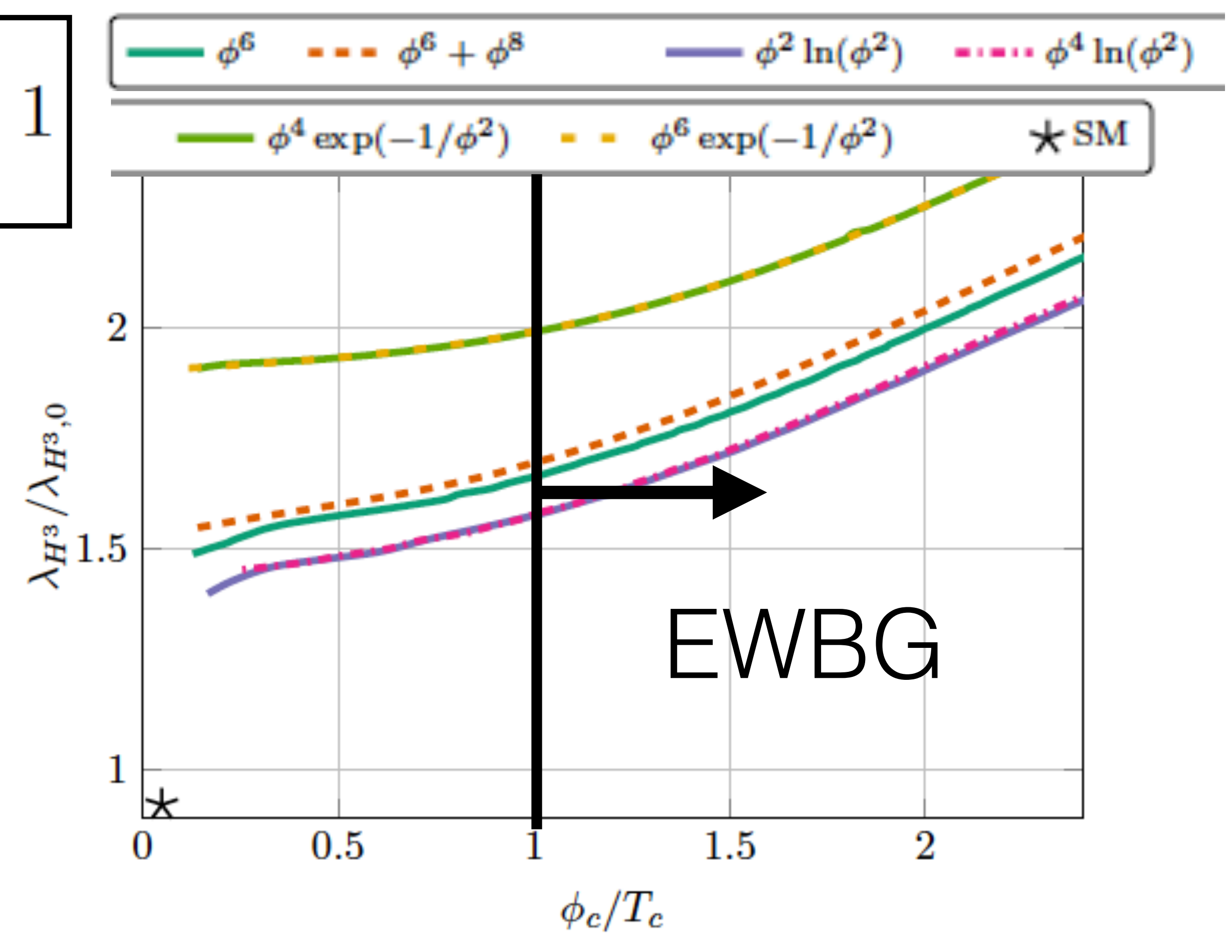
$$\lambda_{H^3}/\lambda_{H^3,SM} < 1.5 : \phi_c/T_c < 1$$

EW baryogenesis is disfavoured

$$\lambda_{H^3}/\lambda_{H^3,SM} > 2 : \phi_c/T_c > 1$$

EW baryogenesis is favoured



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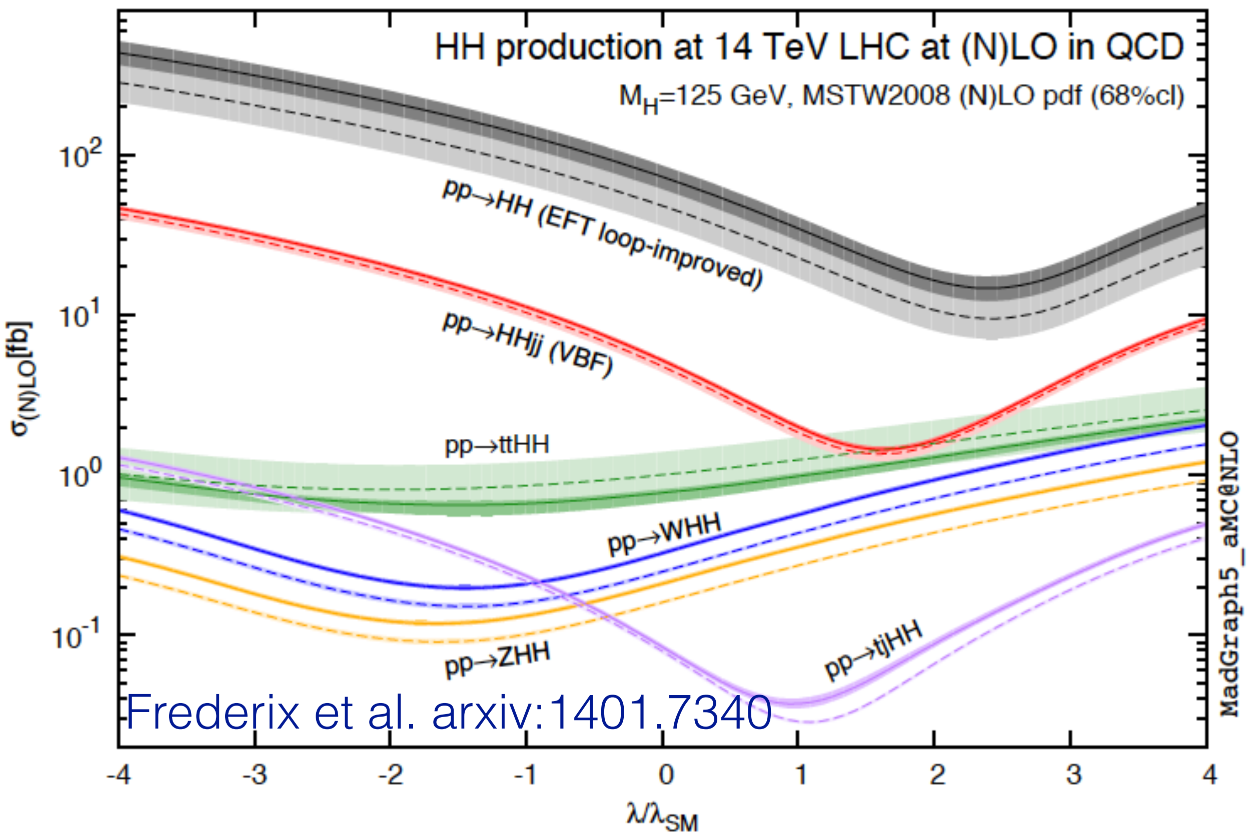
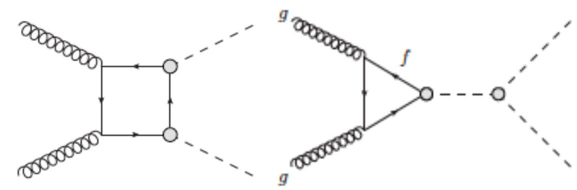
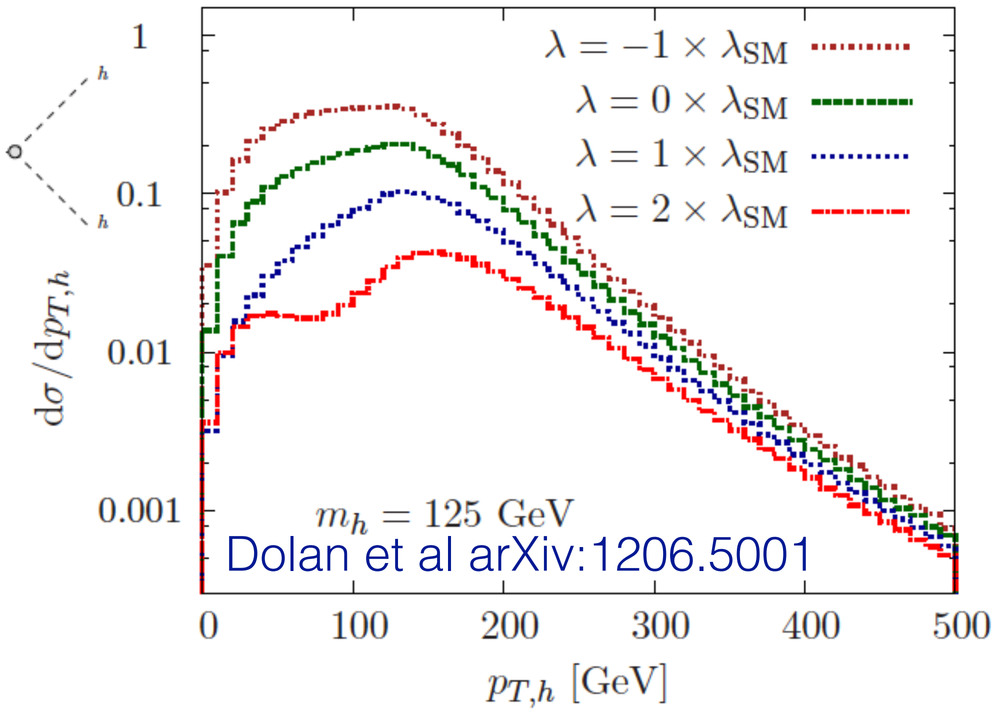
How to extract λ_{HHH}: 1) HH







SM cross sections

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
$\sigma(HH)$[fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$

Grazzini et al arXiv:1803.02463

Current combination limits:

CMS: $\sigma/\sigma_{SM} < 22$

ATLAS: $\sigma/\sigma_{SM} < 7$

Projections for HL-LHC:

$bbbb$ $0.2 < \lambda/\lambda_{SM} < 7.0$ (stat)

ATL-PHYS-PUB -2016-024

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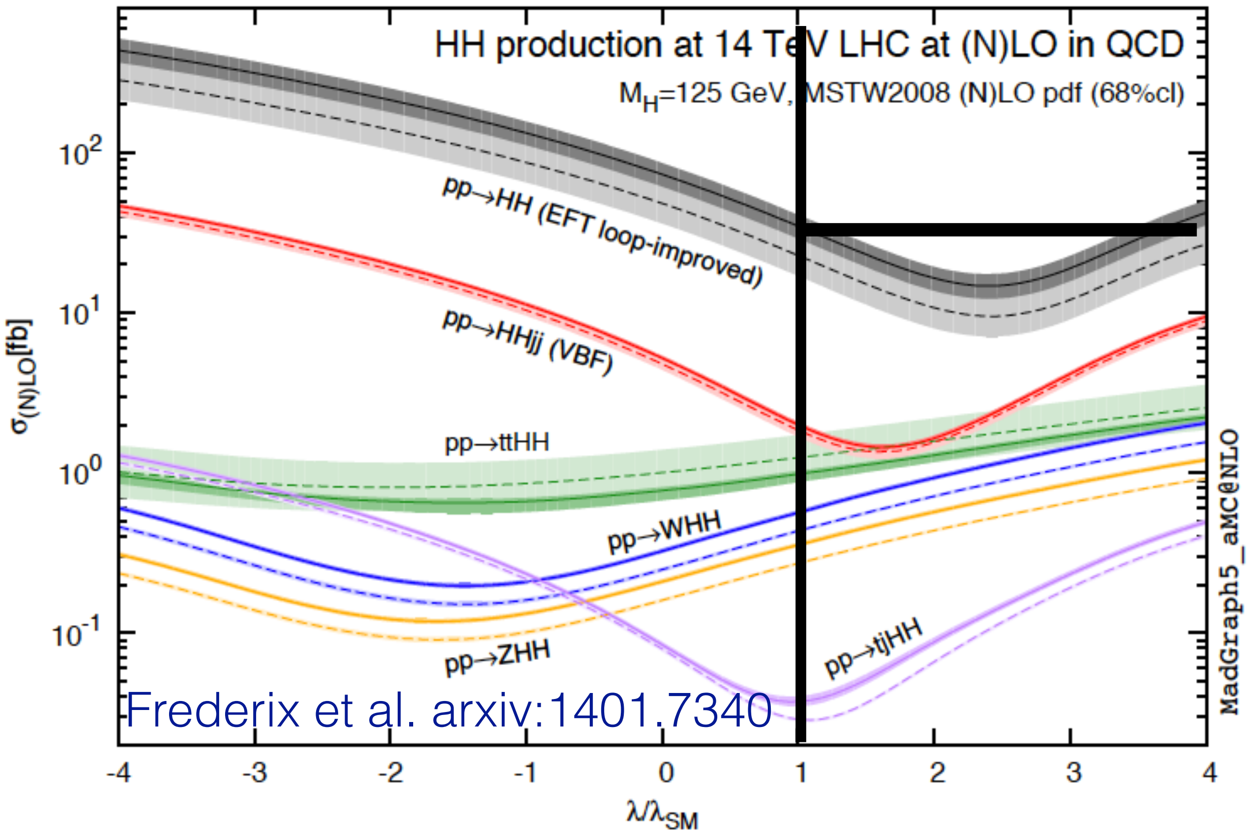

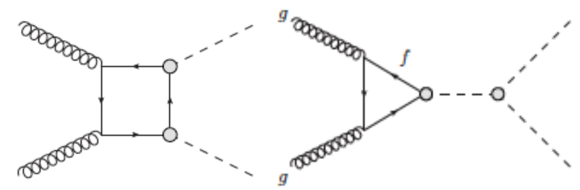

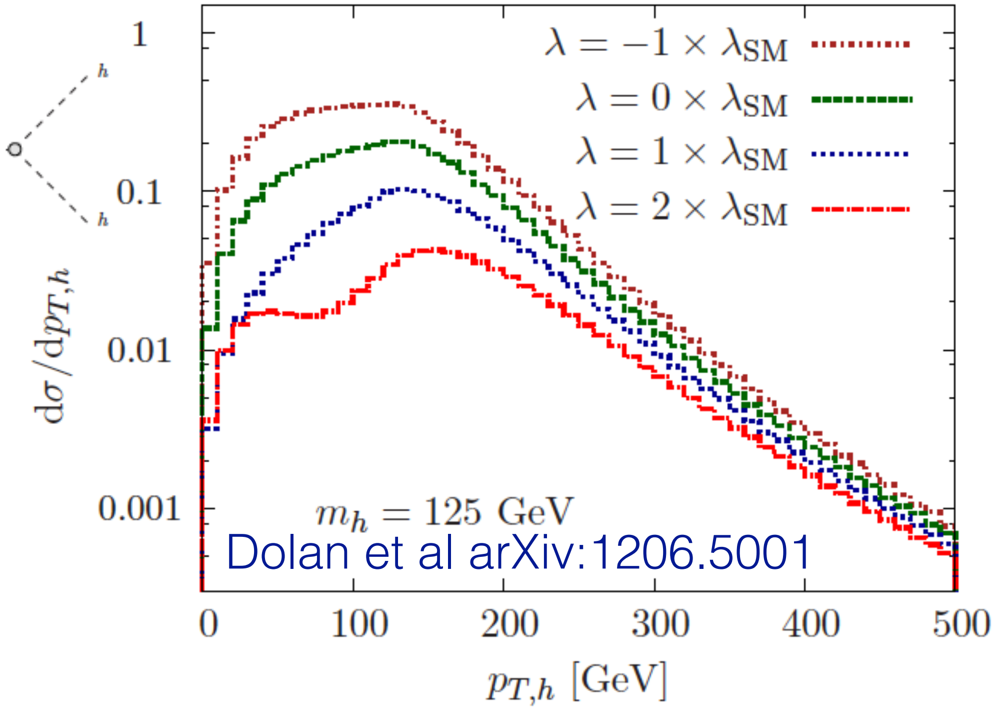

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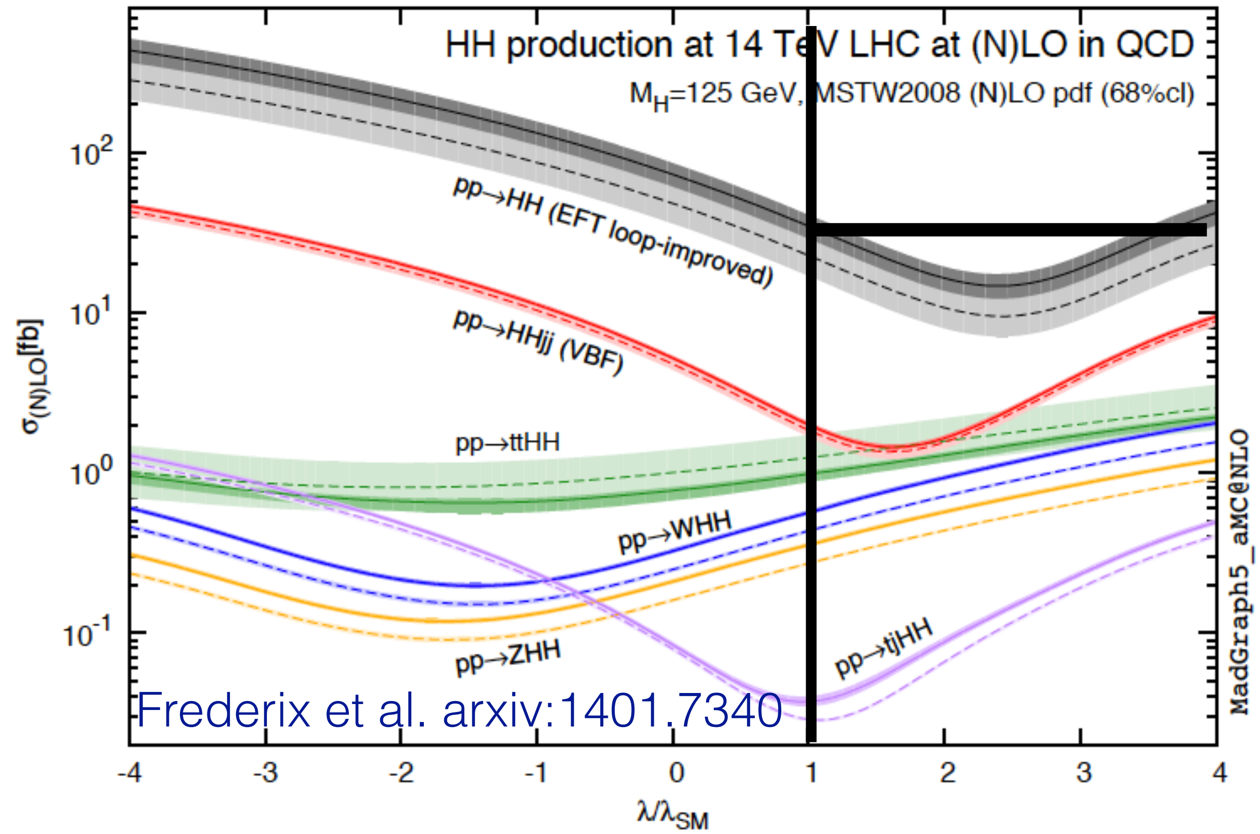

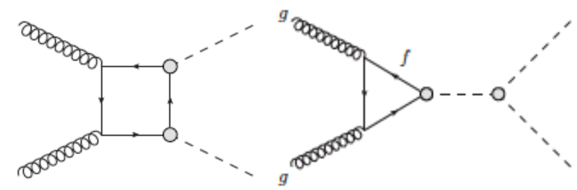

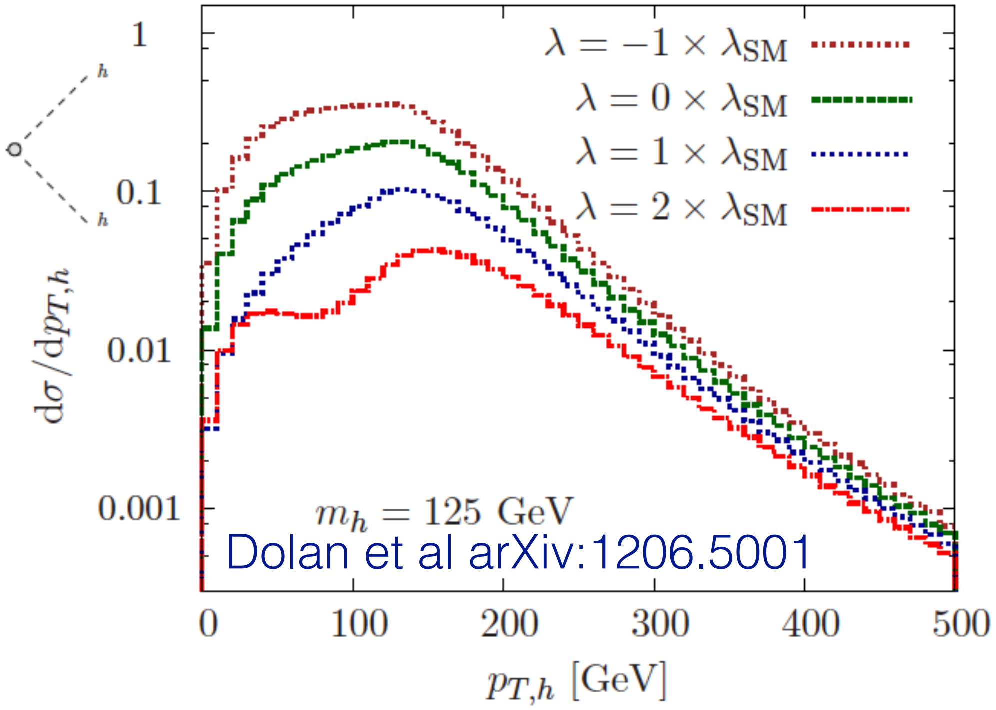

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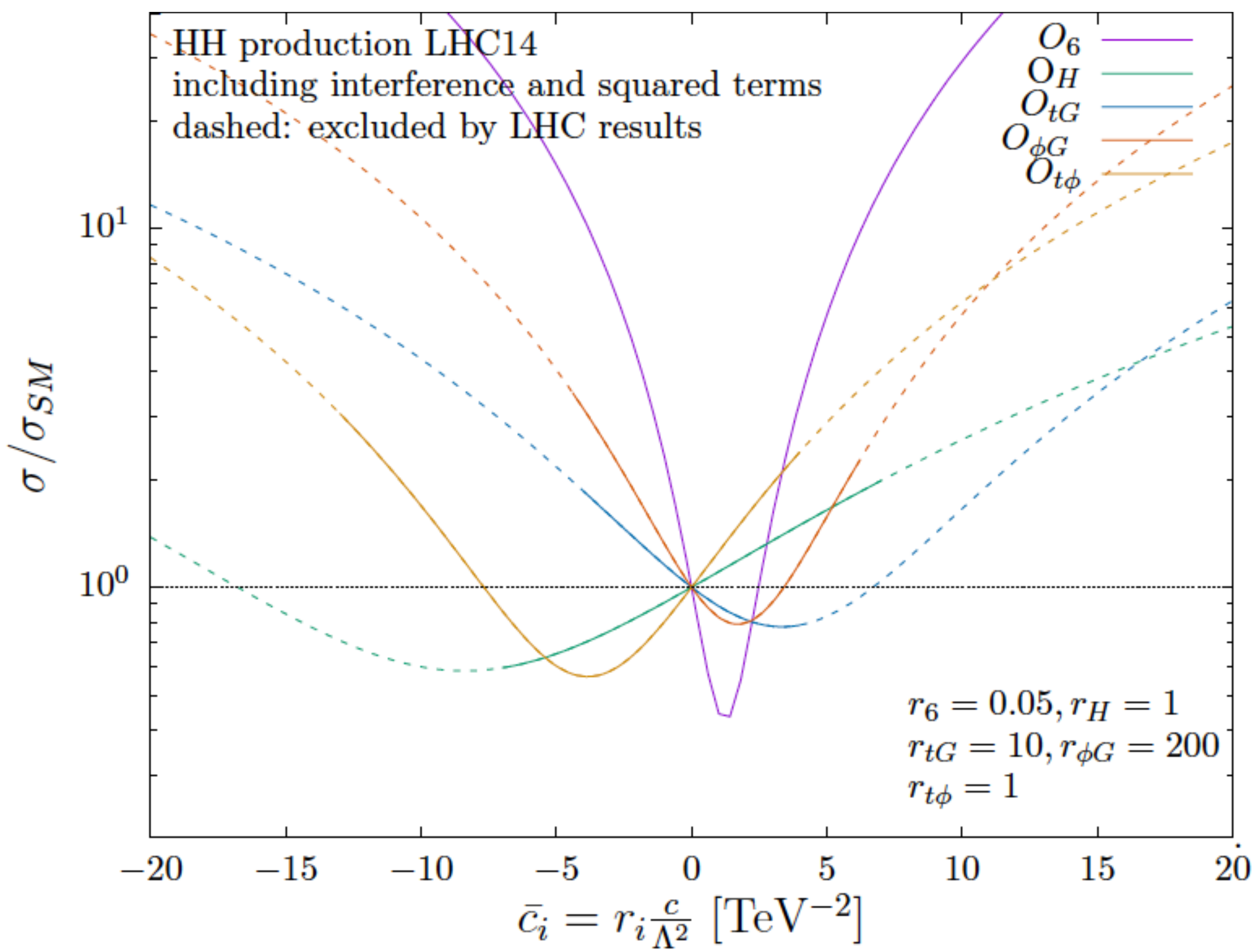
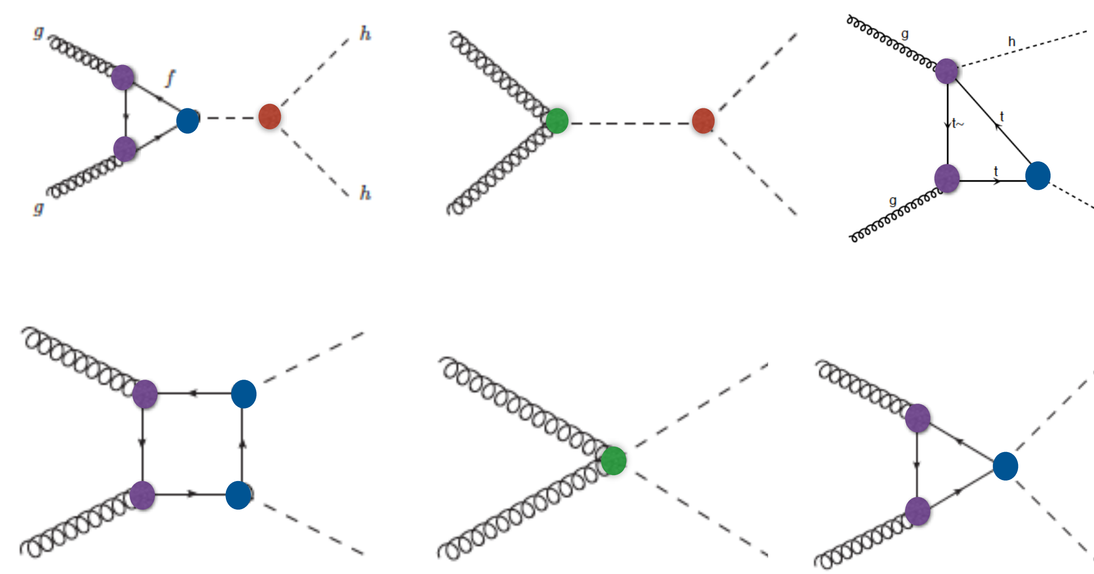
A challenge even for the HL-LHC

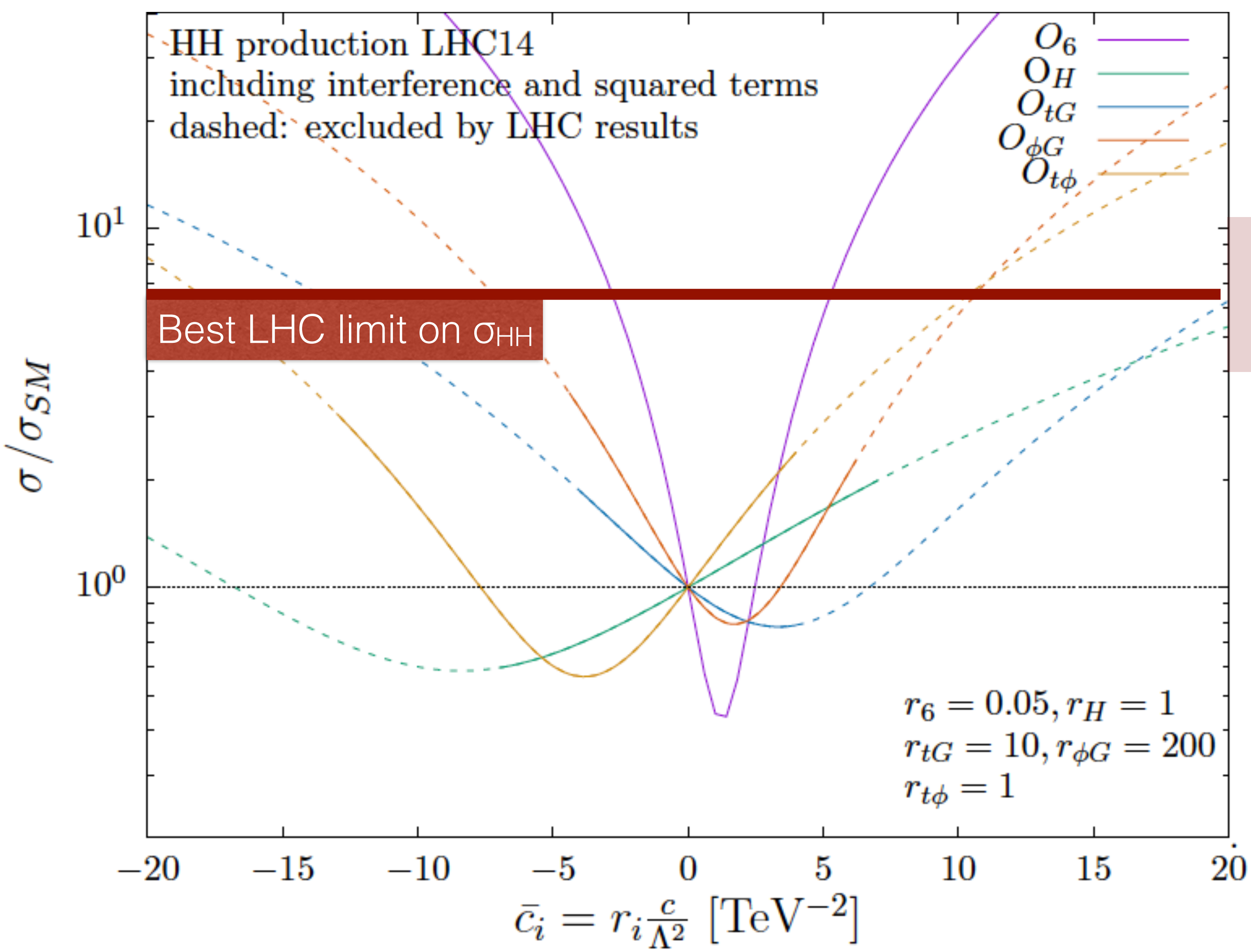
HH in the EFT





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

HH in the EFT



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

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

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

$$O_6 = -\lambda(\phi^\dagger\phi)^3$$

$$O_H = \frac{1}{2}(\partial_\mu(\phi^\dagger\phi))^2$$

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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

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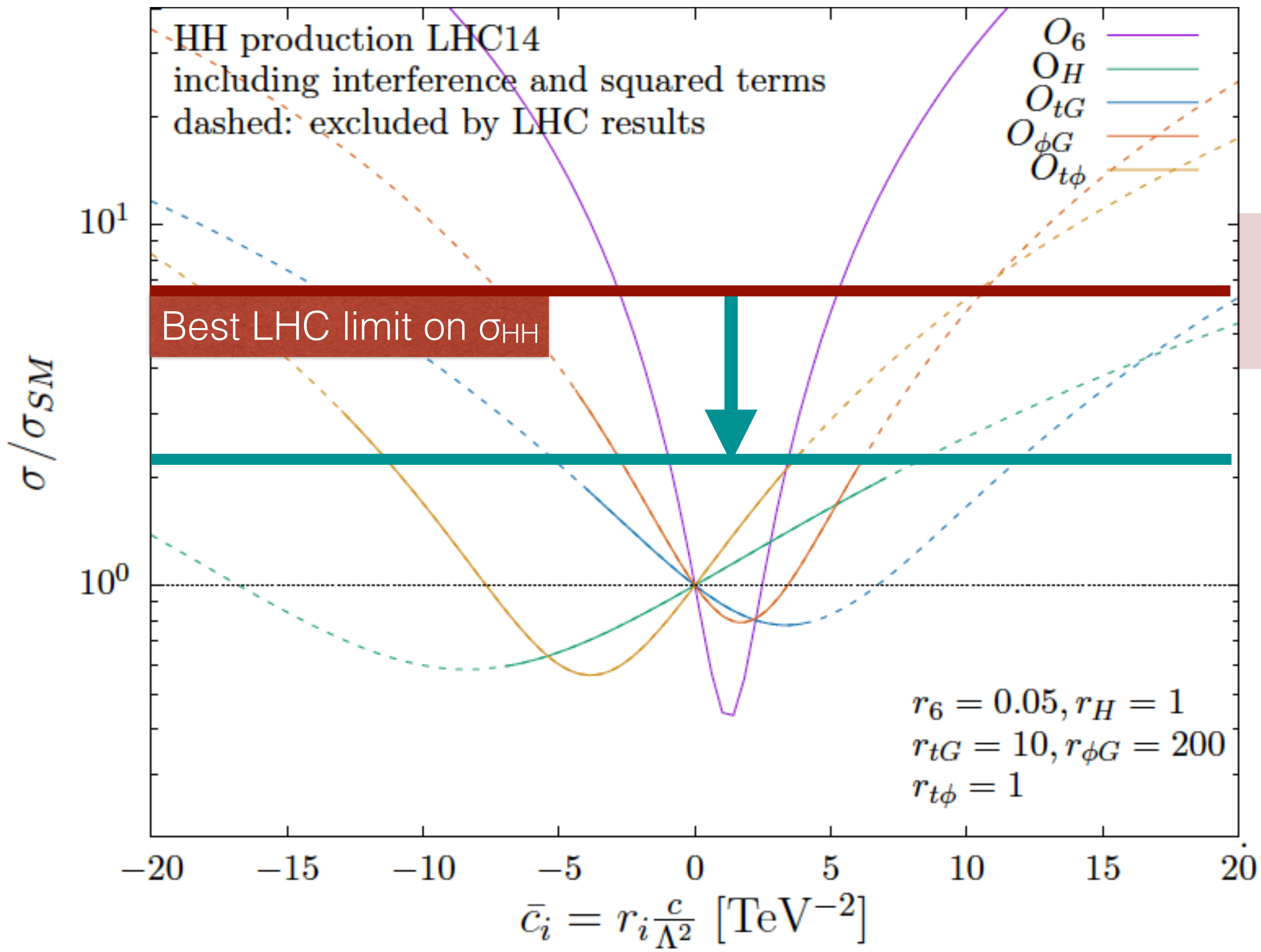

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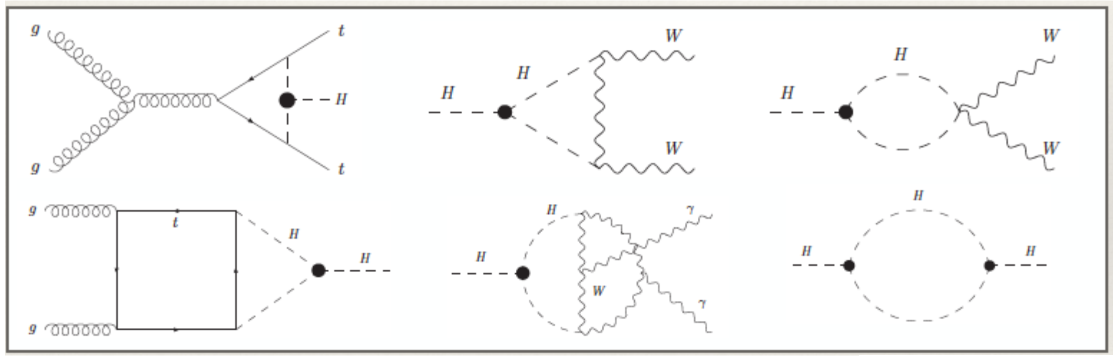
Given the current constraints on σ(HH), σ(H) and the fresh ttH measurement, the Higgs self-coupling can be currently constrained “ignoring” other couplings

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

How to extract λ_{HHH}: 2) Indirectly



Higgs observables: production and decay at NLO (EW)

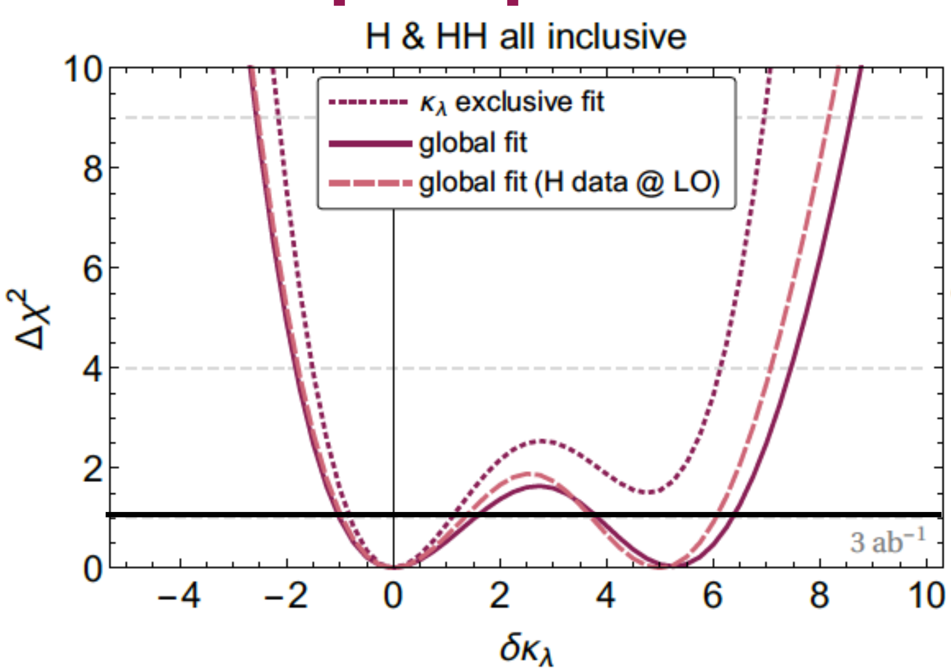
Run I single Higgs results: $\kappa_\lambda^{2\sigma} = [-9.4, 17.0]$

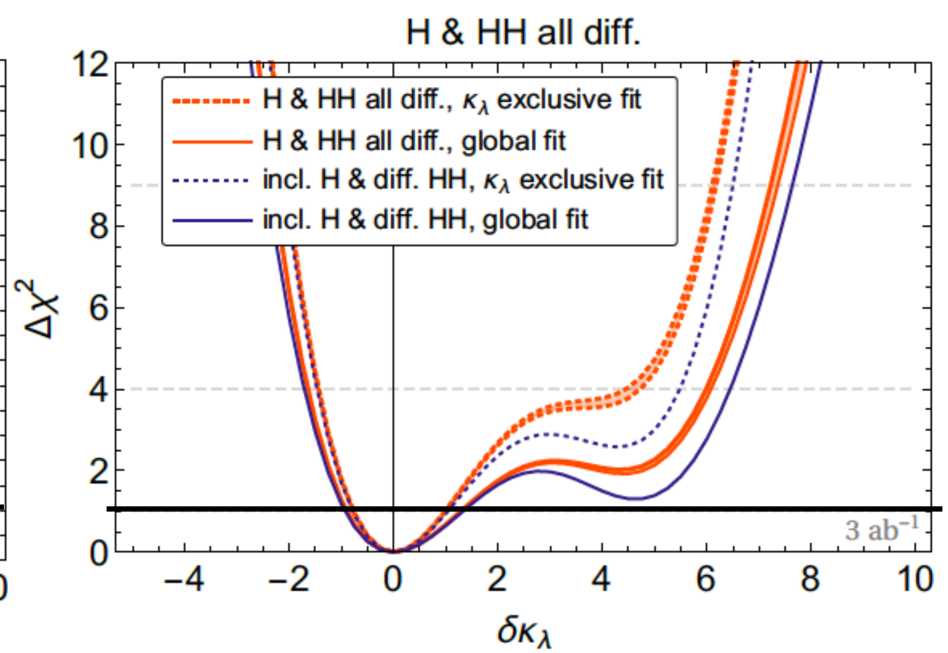
Degrassi et al. arXiv:1607.04251

c.f. HH: $\kappa_\lambda^{2\sigma} = [-8.82, 15.04]$

See also: Gorbahn, Haisch 1607.03773, Bizon et al 1610.05771, Maltoni et al 1709.08649

Future prospects:

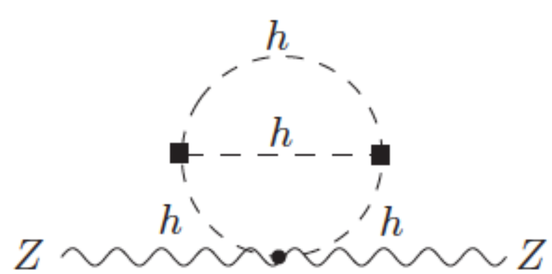


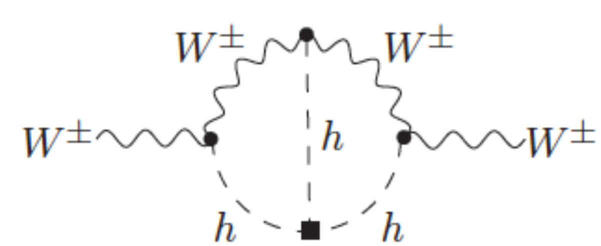


- Synergy between H and HH production
- Differential distributions crucial to break degeneracies at HL-LHC

Di Vita et al. arXiv:1704.01953

EWPO:





$\kappa_\lambda \in [-11.1, 14.6]$

Degrassi et al 1702.01737
Kribs et al 1702.07678

Summary

LHC Higgs measurements are exploring Higgs and top couplings, with no clear sign of deviation from the SM predictions, **yet.**

The SMEFT provides a pathway to new physics by probing scales above the direct collider energy reach.

LHC measurements should be interpreted in the SMEFT framework in a global way.

Predictions in the SMEFT can be systematically improved and promoted to NLO in QCD and EW

Thanks for your attention