UCLouvain
Institut de recherche en mathématique et physique
Centre de Cosmologie, Physique des Particules et Phénoménologie

Electroweak interaction

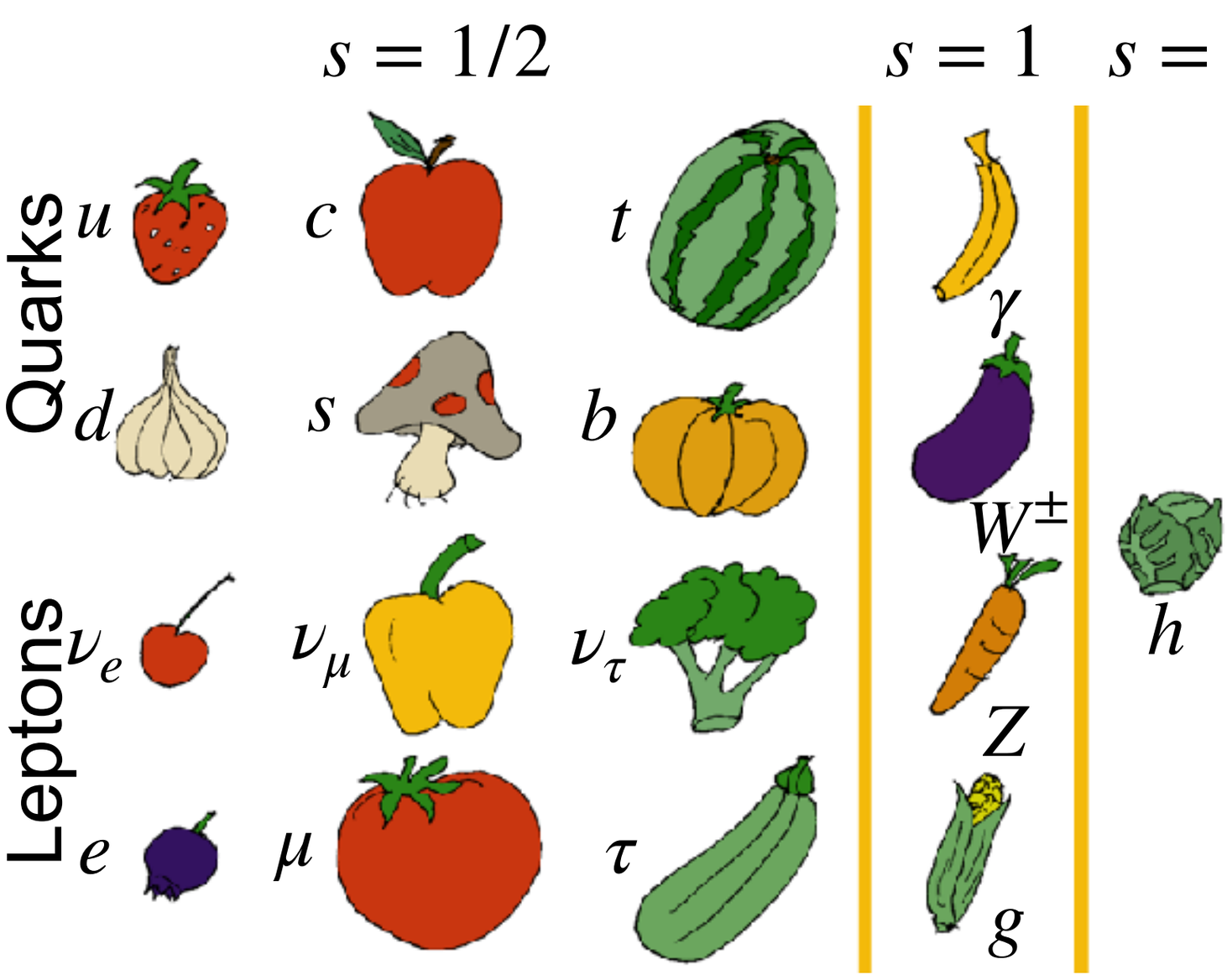
Celine Degrande

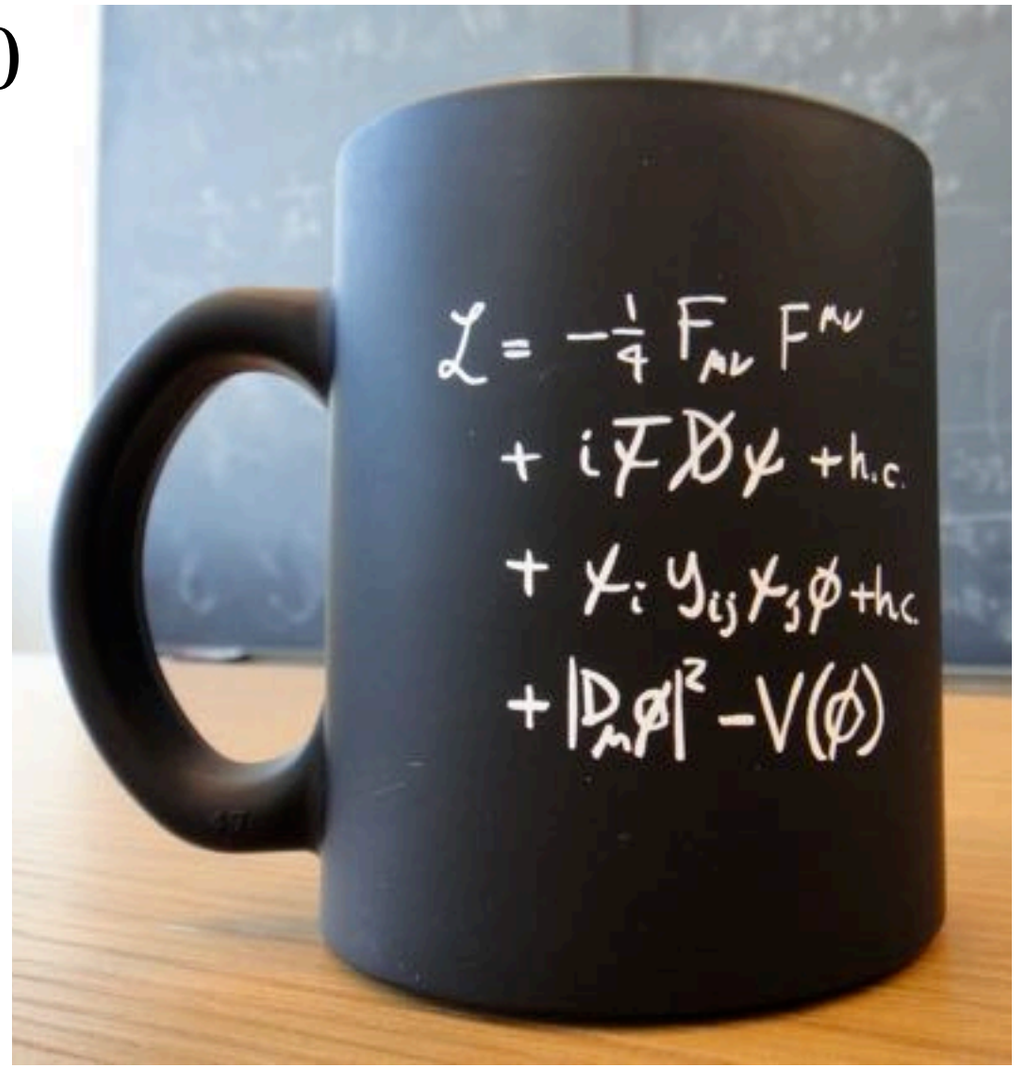
Plan

- NP introduction
- EFT introduction
- SMEFT for multiboson
- Which observables?
- PDF and EFT
- global fit

NP introduction

What do we know about the elementary particles?





$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

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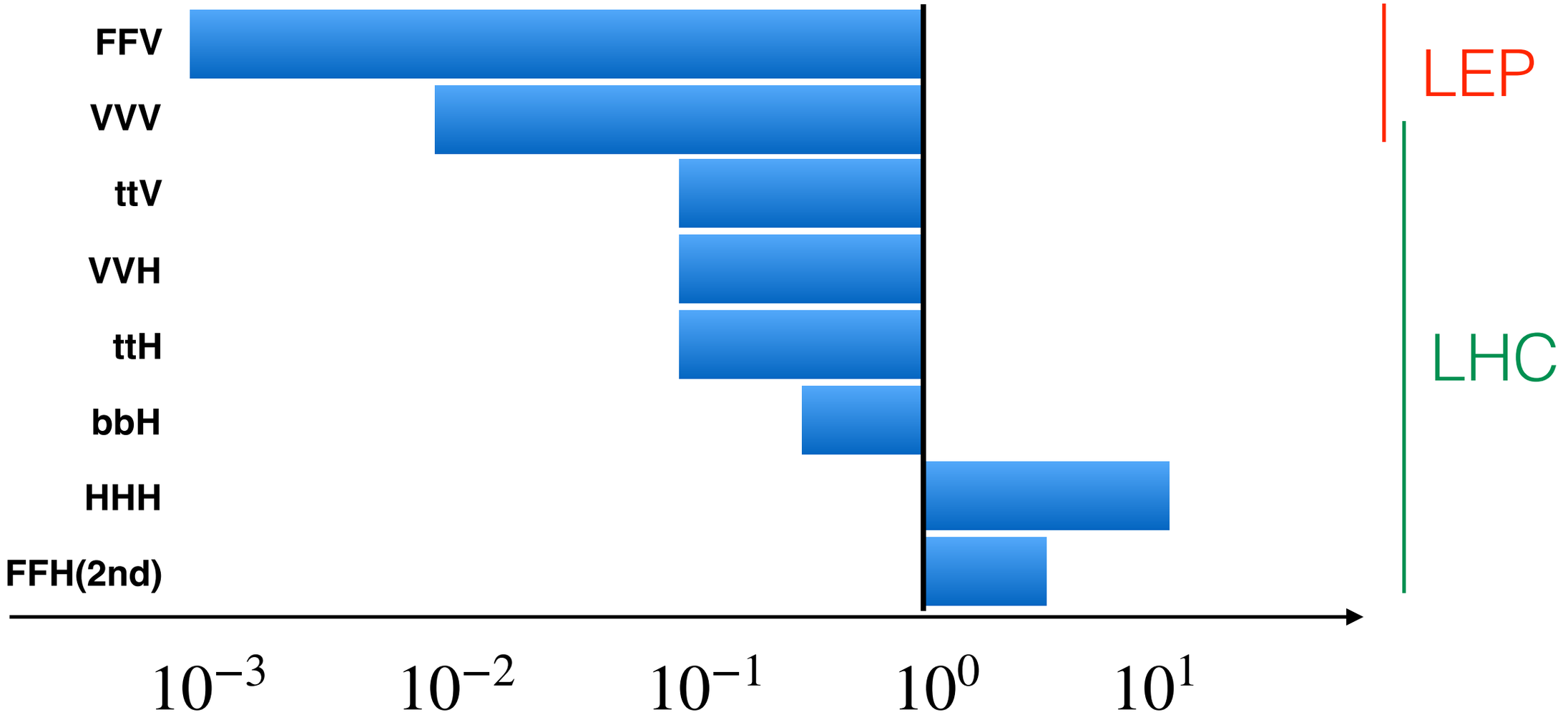
How well do we know the SM?



Testing mass relation (M_W), flavour universality, conservation law

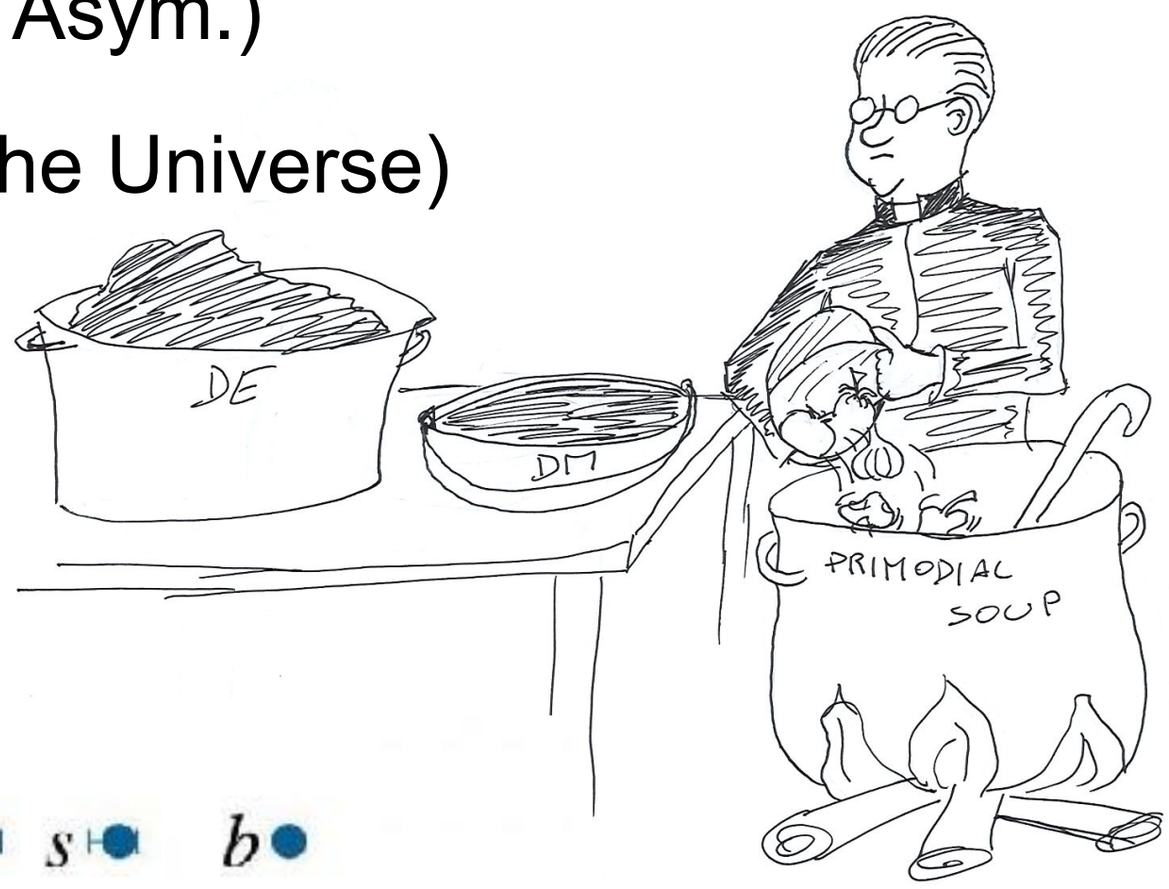
What is the future of the SM?

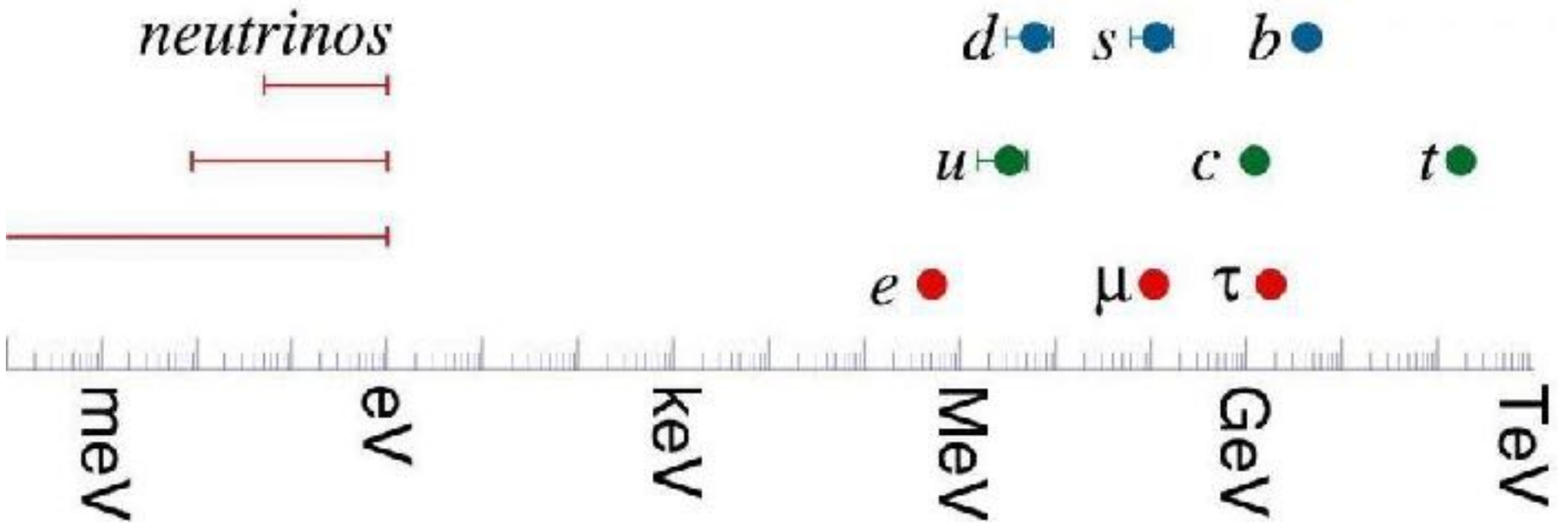
What is the future of the SM?

I don’t know

Why does the higgs matters?

- Only source of CPV (Baryon Asym.)
- Phase transition (History of the Universe)
- 2/3 portals towards DM, ν,…
- Understanding flavour





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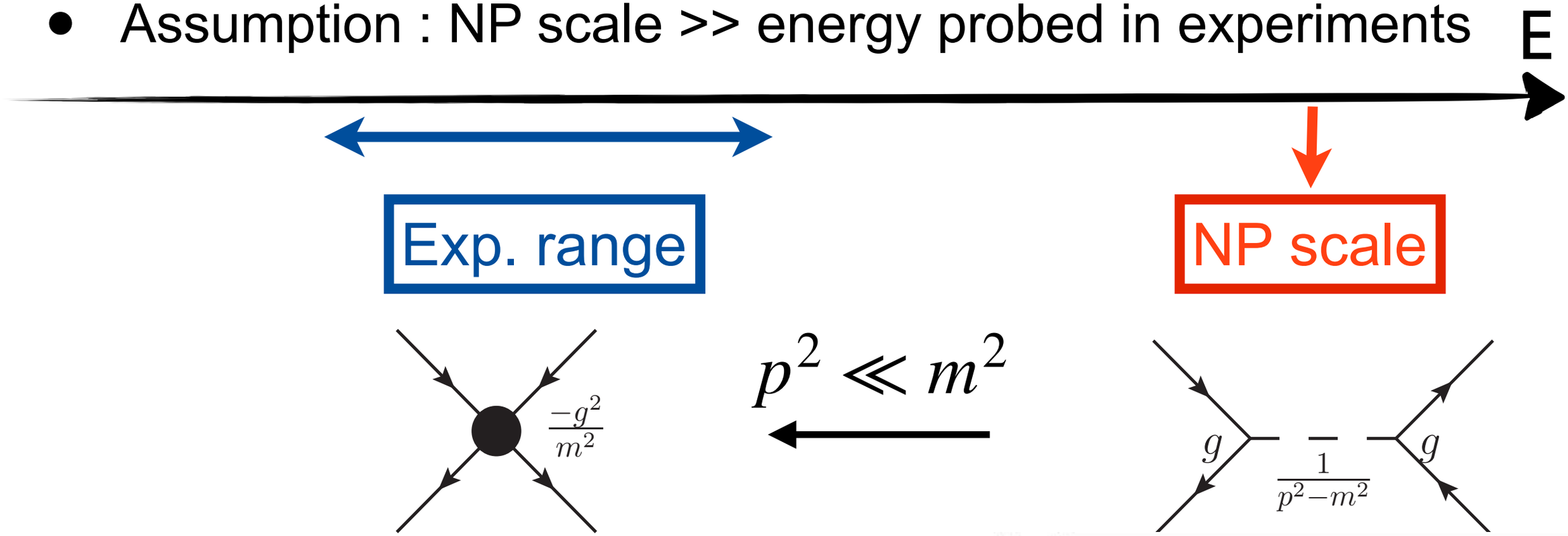
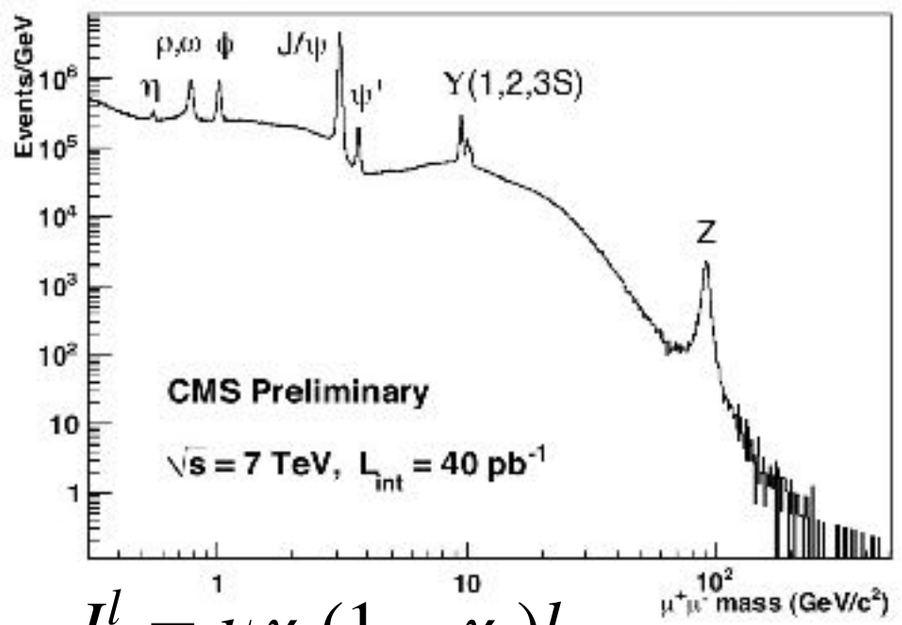
EFT introduction

Indirect detection of NP

- Assumption : NP scale >> energy probed in experiments



One assumption : $p^2 \ll m^2$



Ex : Fermi theory $-\frac{G_F}{Sqrt[2]} J^\mu J_\mu, \quad J_\mu = J_\mu^l + J_\mu^h, \quad J_\mu^l = \nu_l \gamma_\mu (1-\gamma_5) l$

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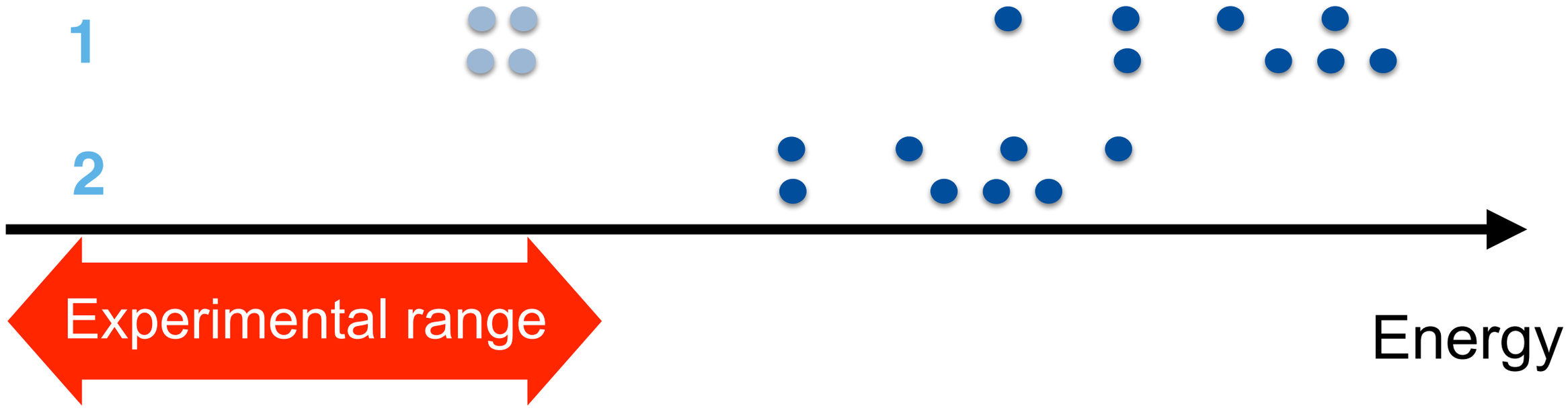
Bottom-up approach



- Simple extensions of the SM : cover classes of models
  - one/a few new particles/fields (1) : 2HDM, spin-2
  - new interactions between SM particles (2) : Effective Field Theories
- Complementary : (1) new particles / (2) new interactions
- Motivate/improve new searches/measurements

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Indirect detection of new physics

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Indirect detection of new physics

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Expansion of the Lagrangian

$$L^{NP} = -\frac{1}{4}V^{\mu\nu}V_{\mu\nu} + M^2 V^{\mu}V_{\mu} + \sum_i g_i V_{\mu} J_i^{\mu} + h.c.$$

- if V is very heavy $$-\frac{1}{4}V^{\mu\nu}V_{\mu\nu} \sim 0$$

- and the EOM is $$V^{\mu} = -\frac{1}{M^2}\sum_i g_i J_i^{\mu} + h.c.$$

$$L_{EFT}^{NP} = -\frac{\left(\sum_i g_i J_i^{\mu}\right)\left(\sum_i g_i J_{\mu_i}\right)^{\dagger}}{M^2}$$

EFT

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$ ← SM fields & sym.

EFT

Parametrize any NP but an ∞ number of coefficients

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

← SM fields & sym.

Only one dim-5

- Assumption : $E_{exp} << \Lambda$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i} \frac{C_i}{\Lambda^2} \mathcal{O}_i^6$$

a finite number of coefficients =>Predictive!

- Model independent (i.e. parametrize a large class of models) : any HEAVY NP
- SM is the leading term : EFT for precision physics

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EFT

Parametrize any NP but an ∞ number of coefficients

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Only one dim-5

- Assumption : $E_{exp} << \Lambda$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i} \frac{C_i}{\Lambda^2} \mathcal{O}_i^6$$

measure only C_i/Λ^2

a finite number of coefficients =>Predictive!

- Model independent (i.e. parametrize a large class of models) : any HEAVY NP
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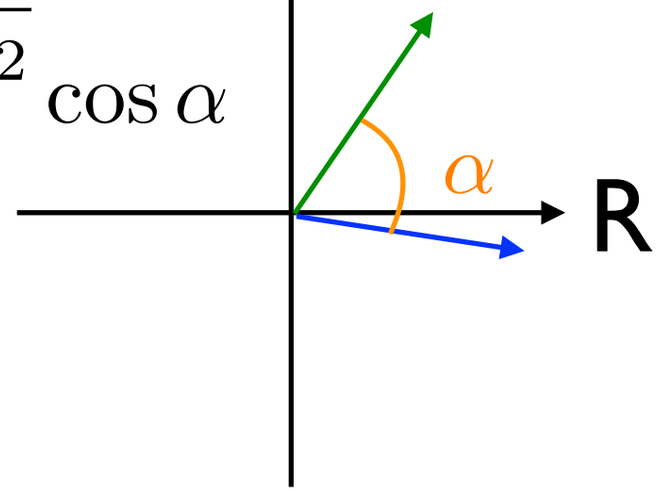
Interference

$$|M(x)|^2 = \underbrace{|M_{SM}(x)|^2}_{\Lambda^0} + \underbrace{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)}_{\Lambda^{-2}} + \underbrace{|M_{d6}(x)|^2 + \ldots}_{\mathcal{O}\left(\Lambda^{-4}\right)}$$

$$\Re\left(M_{SM}(x)M^*_{d6}(x)\right) = \sqrt{|M_{SM}(x)|^2 |M_{d6}(x)|^2}\cos\alpha$$



mom&spin

Not always positive

Can be suppressed

$$\sigma \propto \sum_x |M(x)|^2 \quad \textbf{if} \quad M_{SM}(x_1) = 1,\ M_{SM}(x_2) = 0 \quad M_{d6}(x_1) = 0,\ M_{d6}(x_2) = 1$$

$$\sigma_{int} = 0$$

Observable dependent

Interference

$$|M(x)|^2 = \underbrace{|M_{SM}(x)|^2}_{\Lambda^0} + \underbrace{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)}_{\Lambda^{-2}} + \underbrace{|M_{d6}(x)|^2 + \ldots}_{\mathcal{O}\left(\Lambda^{-4}\right)}$$

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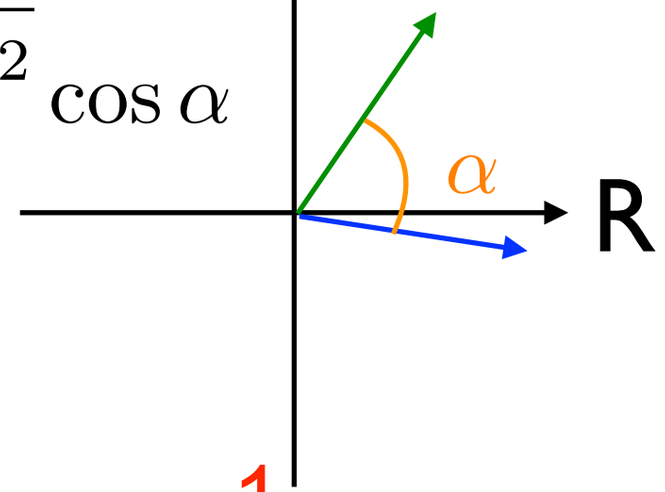

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Observable dependent

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mom&spin

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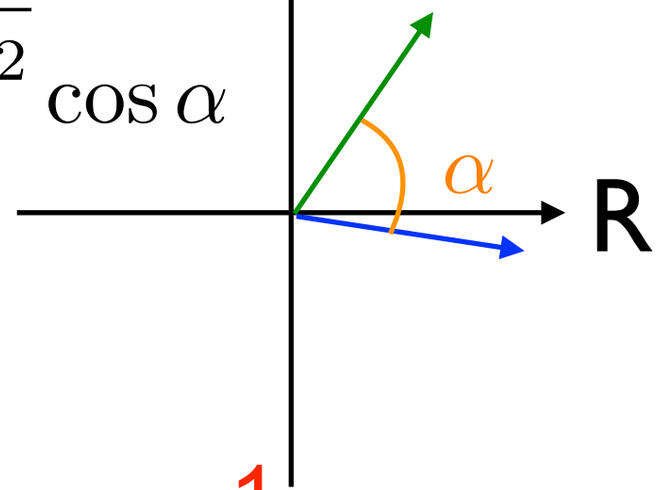

Can be suppressed

$$\sigma \propto \sum_x |M(x)|^2 \quad \text{if} \quad M_{SM}(x_1) = 1,\ M_{SM}(x_2) = \cancel{0}$$

$$M_{d6}(x_1) = \cancel{0},\ M_{d6}(x_2) = 1$$

$$\sigma_{int} = 0$$

Observable dependent

or $\alpha \approx \pi/2$ $\qquad M^2 \to M^2 - i\Gamma M \qquad \sigma_{int} \propto \Gamma$

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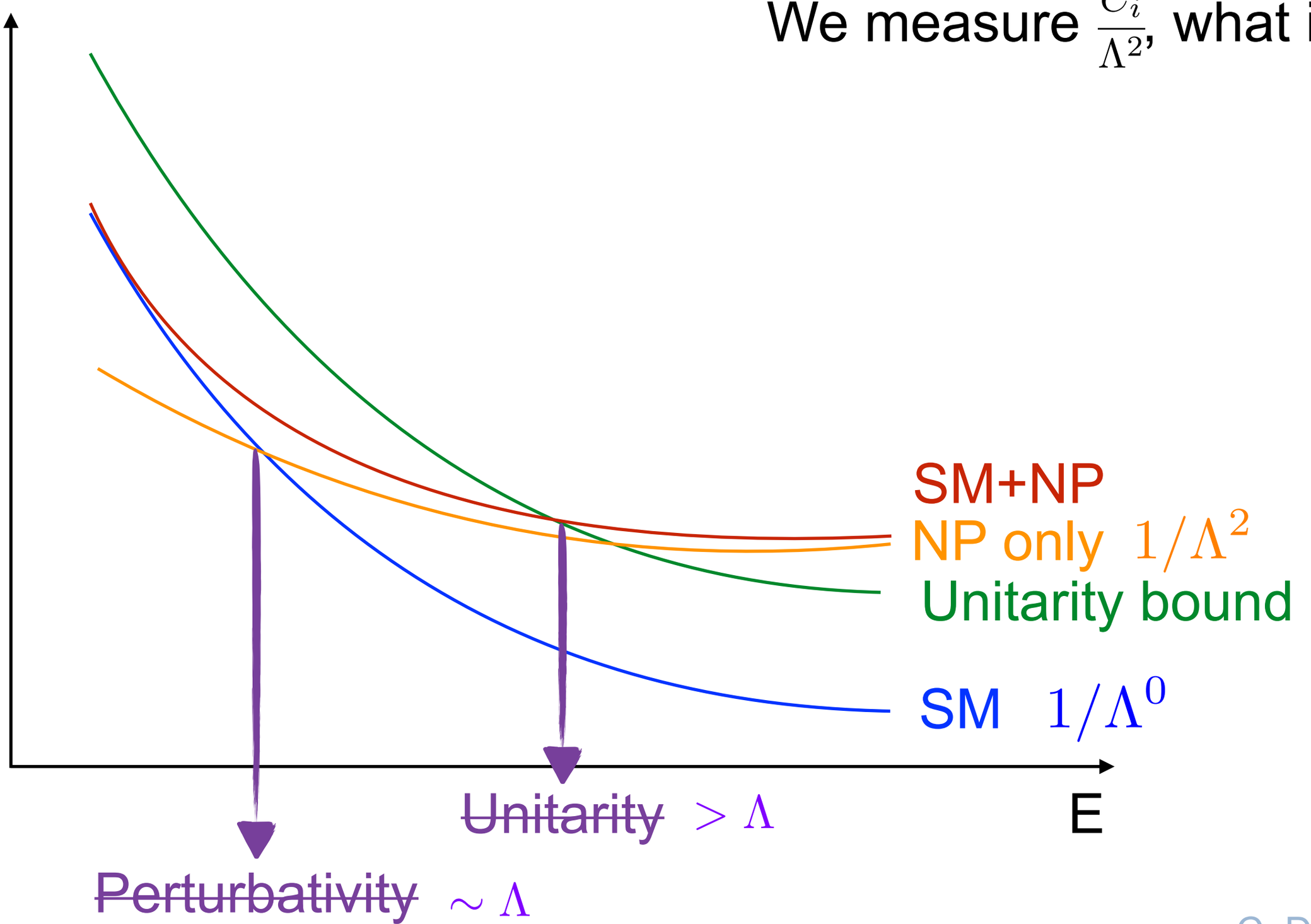
EFT & scales

We measure $\frac{C_i}{\Lambda^2}$, what is Λ?



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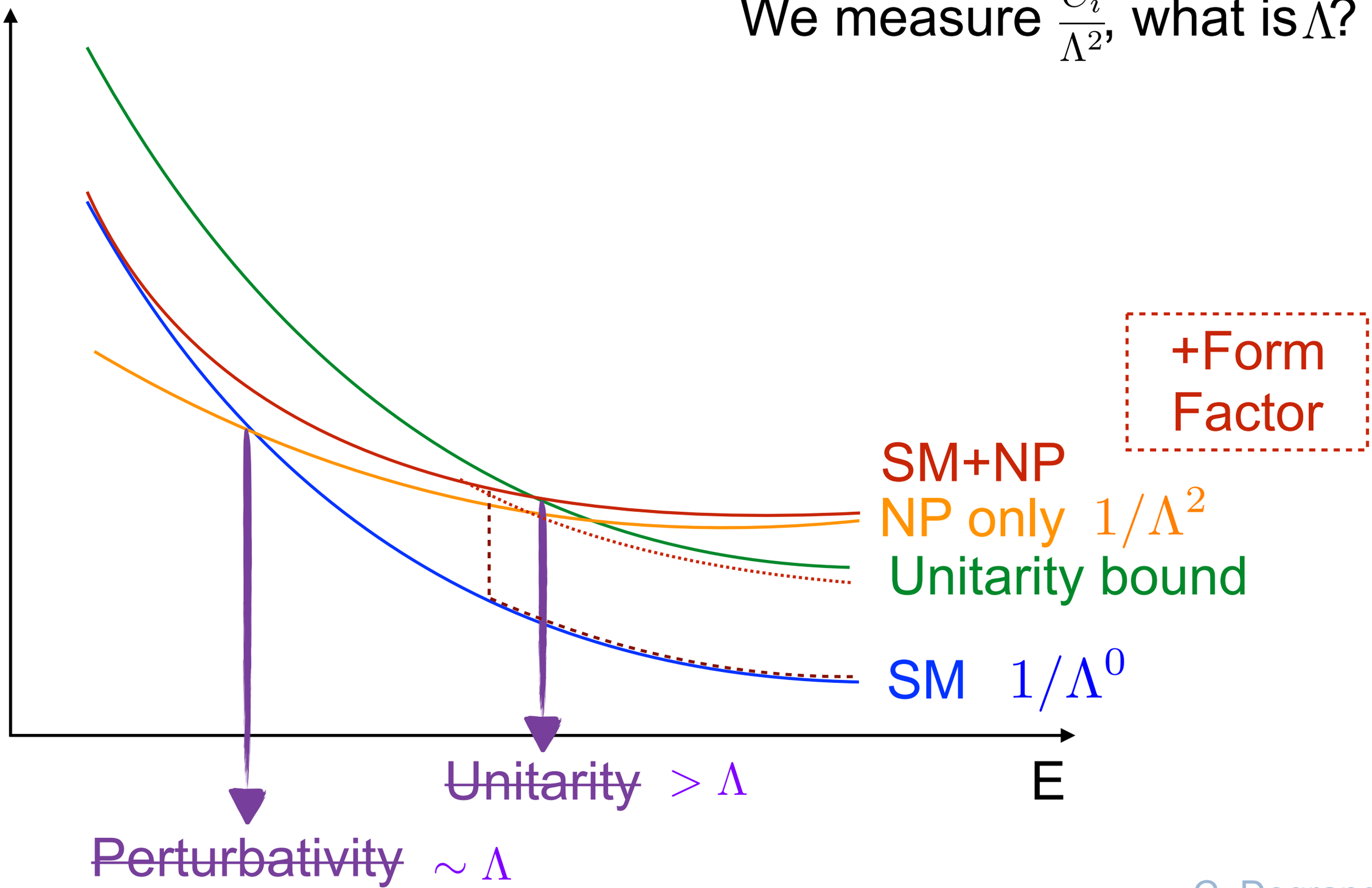

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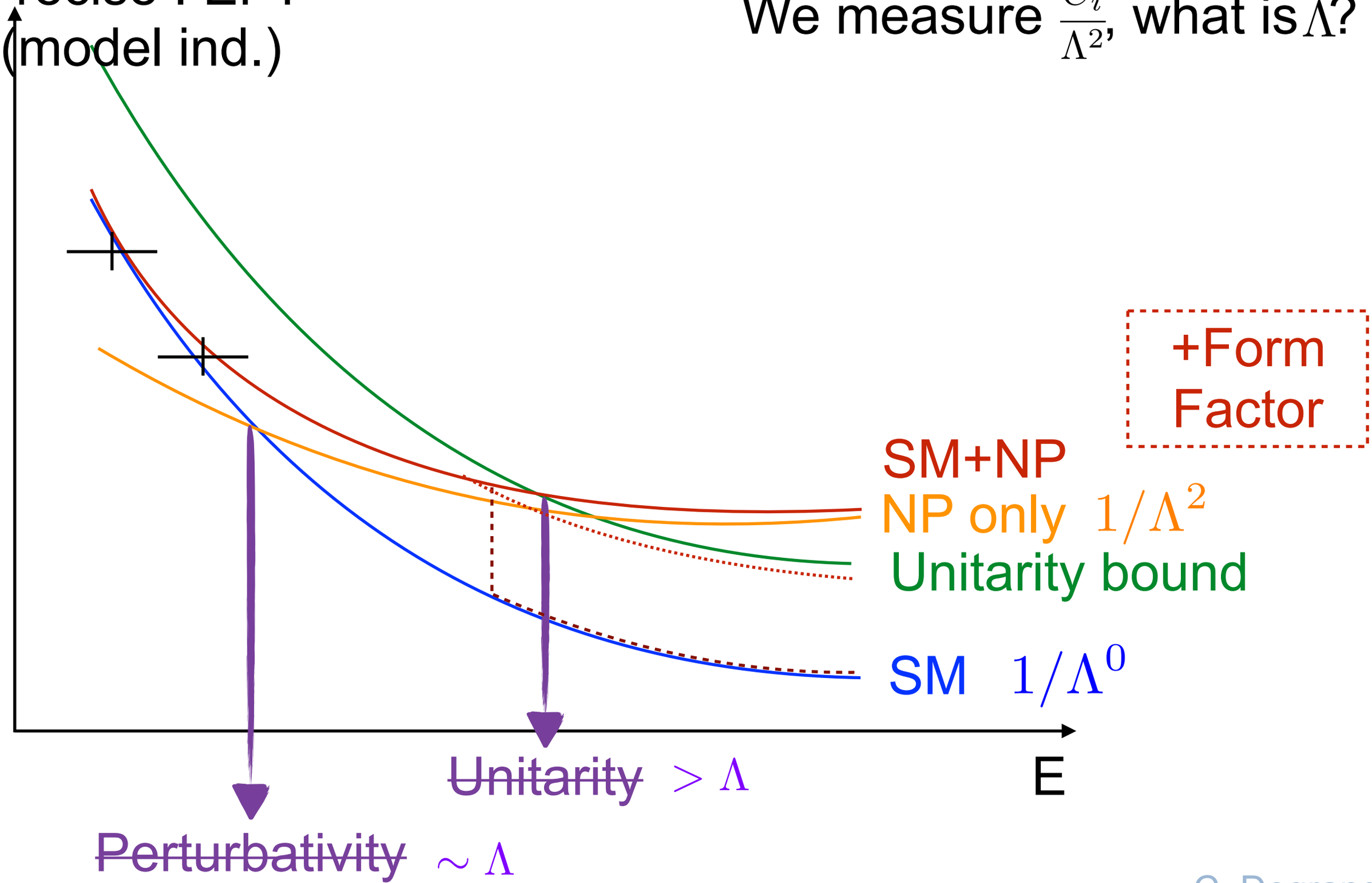
EFT & scales

Precise : EFT
(model ind.)

We measure $\frac{C_i}{\Lambda^2}$, what is Λ?



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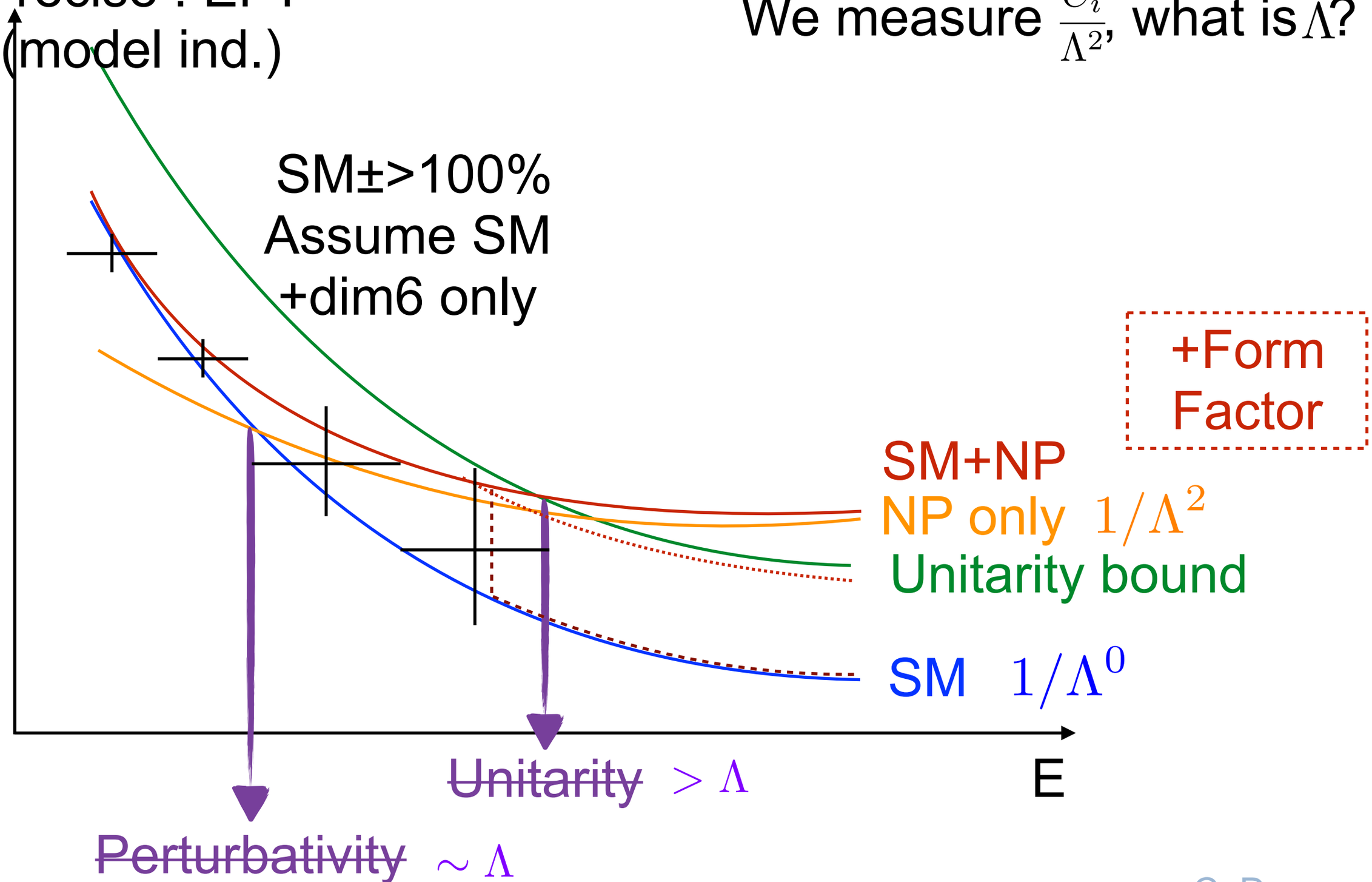

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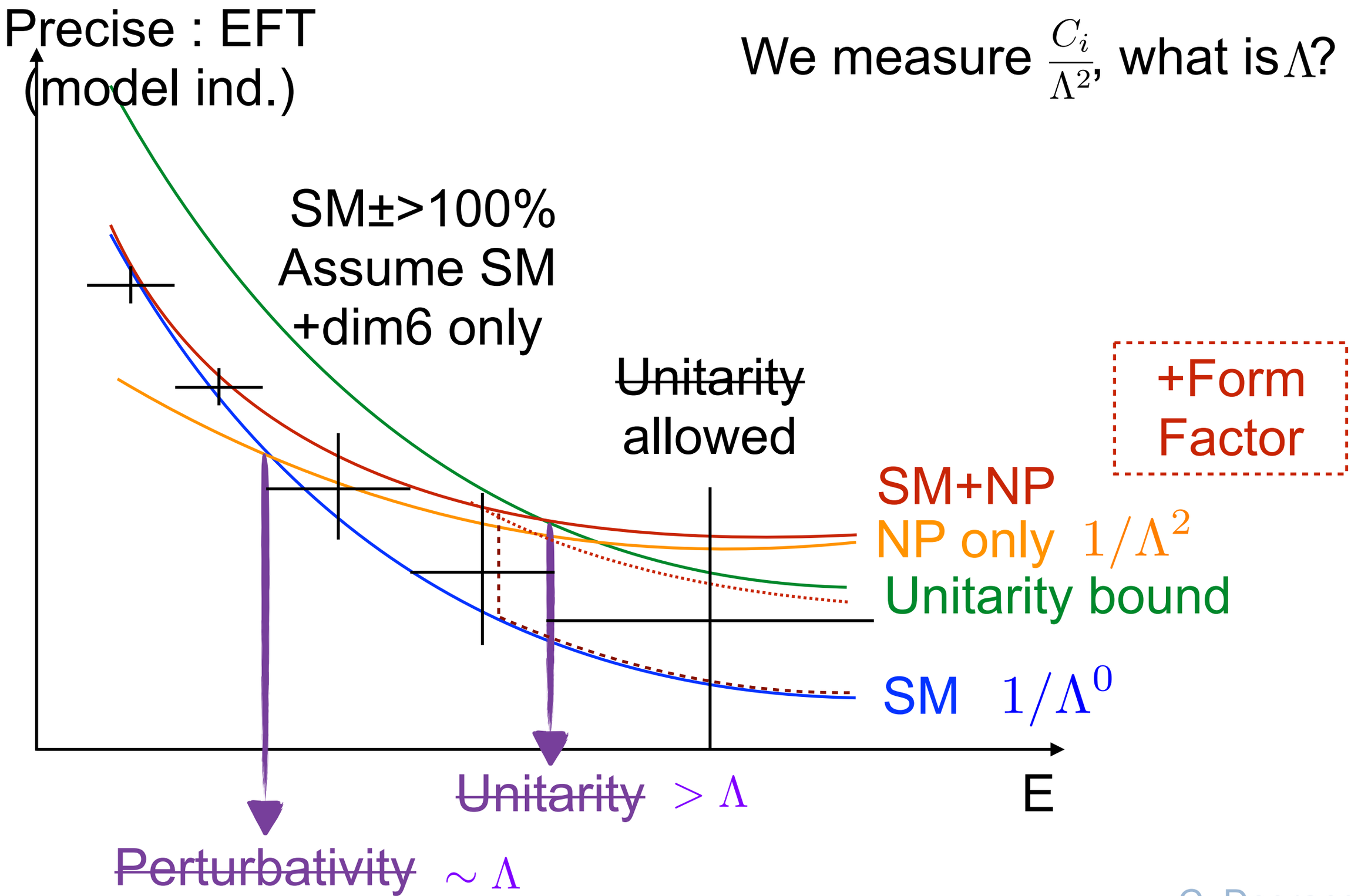
EFT & scales



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0/2F operators

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

Parameters redef.

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Fields&Parameters redefinition

0/2F operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
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Parameters redef.

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
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$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
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$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
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Fields&Parameters redefinition

Muon decay

4F operators

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Effects in and outside the resonance

C. Degrande

4F operators

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

Muon decay

$(\bar{L}R)(\bar{R}L)$ 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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Effects in and outside the resonance

Basis reduction

- EOM

$$
\begin{aligned}
(D^\mu D_\mu \varphi)^j &= m^2 \varphi^j - \lambda \left(\varphi^\dagger \varphi\right) \varphi^j - \bar{e}\, \Gamma_e^\dagger l^j + \varepsilon_{jk} \bar{q}^k\, \Gamma_u u - \bar{d}\, \Gamma_d^\dagger q^j, \\
(D^\rho G_{\rho\mu})^A &= -g_s \left(\bar{q} \gamma_\mu T^A q + \bar{u} \gamma_\mu T^A u + \bar{d} \gamma_\mu T^A d\right), \\
(D^\rho W_{\rho\mu})^I &= -\frac{g}{2} \left(\varphi^\dagger i \overleftrightarrow{D}{}^I_\mu \varphi + \bar{l} \gamma_\mu \tau^I l + \bar{q} \gamma_\mu \tau^I q\right), \\
\partial^\rho B_{\rho\mu} &= -g' Y_\varphi\, \varphi^\dagger i \overleftrightarrow{D}_\mu \varphi - g' \sum_{\psi \in \{l,e,q,u,d\}} Y_\psi\, \bar{\psi} \gamma_\mu \psi.
\end{aligned}
$$

$$
i\not{D} l = \Gamma_e e \varphi, \qquad i\not{D} e = \Gamma_e^\dagger \varphi^\dagger l, \qquad i\not{D} q = \Gamma_u u \widetilde{\varphi} + \Gamma_d d \varphi, \qquad i\not{D} u = \Gamma_u^\dagger \widetilde{\varphi}^\dagger q, \qquad i\not{D} d = \Gamma_d^\dagger \varphi^\dagger q.
$$

- $[D_\mu, D_\nu] \sim X_{\mu\nu}$
- Integration by part
- Bianchi identities $D^\rho \widetilde{X}_{\rho\mu} = 0$
- Fierz (Dirac and gauge group)

(SM-like) Top decay

$$t \to bW \qquad \mathcal{O}_{\phi q}^{(3)} = i\left(\phi^\dagger \tau^i D_\mu \phi\right)\left(\bar{Q}\gamma^\mu \tau^i Q\right) + h.c.$$
$$\mathcal{O}_{tW} = \bar{Q}\sigma_{\mu\nu}\tau^i t\tilde{\phi}W_i^{\mu\nu}.$$

C. Zhang, S Willenbrock, PRD83, 034008

$$t \to bl\nu_l \qquad \mathcal{O}_{ql}^{(3)} = \left(\bar{Q}\gamma^\mu \tau^i Q\right)\left(\bar{l}\gamma_\mu \tau^i l\right)$$

J.A. Aguilar-Saavedra, NPB843, 683

+ one four-fermion operator for the hadronic decay

$$\frac{1}{2}\Sigma|M|^2 = \frac{V_{tb}^2 g^4 u(m_t^2-u)}{2(s-m_W^2)^2}\left(1+2\frac{C_{\phi q}^{(3)}v^2}{V_{tb}\Lambda^2}\right) + \frac{4\sqrt{2}\mathrm{Re}C_{tW}V_{tb}m_t m_W}{\Lambda^2}\frac{g^2 su}{(s-m_W^2)^2}$$
$$+\frac{4C_{ql}^{(3)}}{\Lambda^2}\frac{g^2 u(m_t^2-u)}{s-m_W^2} + \mathcal{O}\left(\Lambda^{-4}\right)$$

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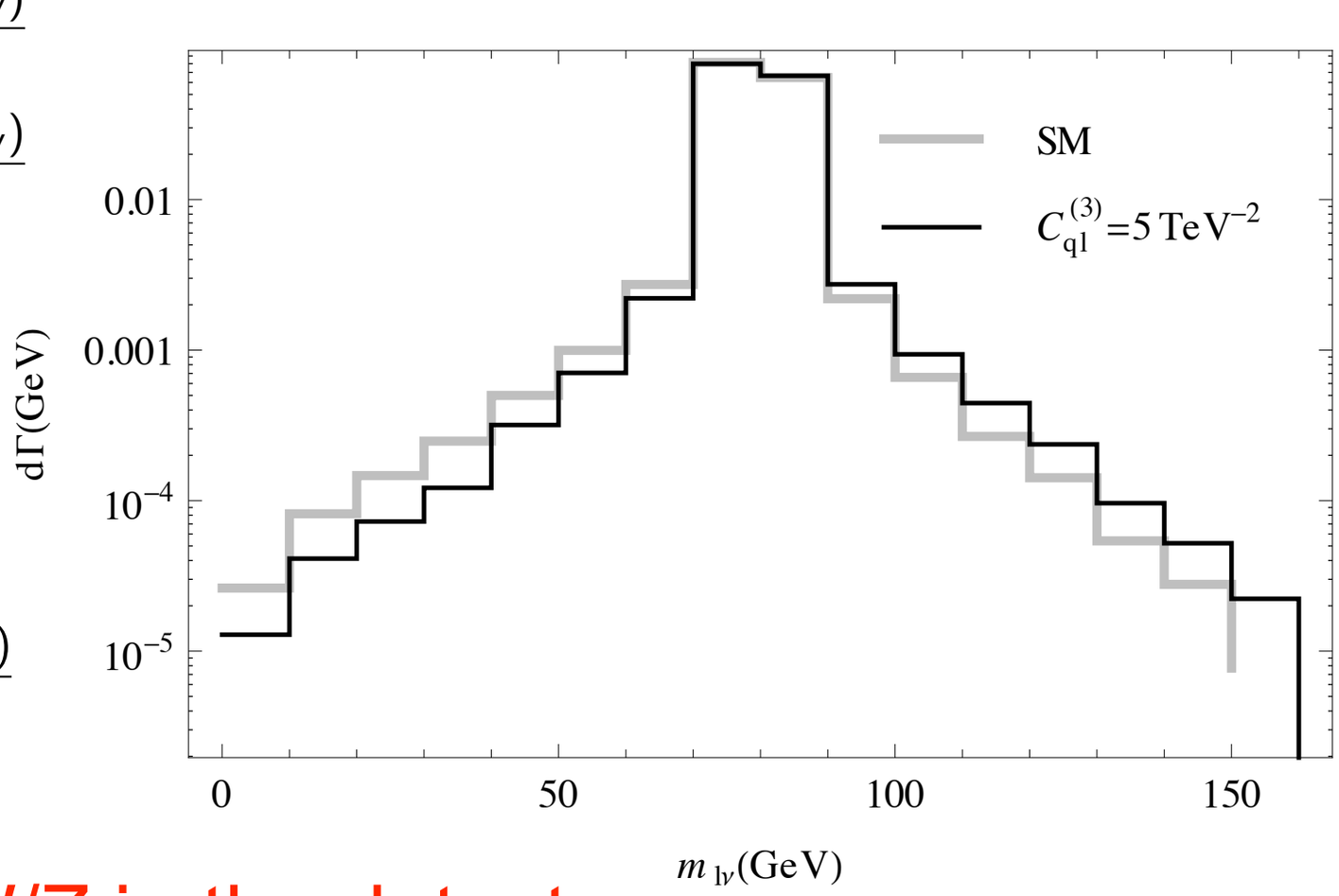
Width, W helicities and …

$$\frac{\Gamma\left(t \to be^{+}\nu_e\right)}{GeV} = 0.1541 + \left[0.019\frac{C_{\phi q}^{(3)}}{\Lambda^2} + 0.026\frac{C_{tW}}{\Lambda^2} + 0\frac{C_{ql}^{(3)}}{\Lambda^2}\right] \mathrm{TeV}^2$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{8}(1+\cos\theta)^2 F_R + \frac{3}{8}(1-\cos\theta)^2 F_L + \frac{3}{4}\sin^2\theta F_0$$

$$\begin{aligned} F_0 &= \frac{m_t^2}{m_t^2+2m_W^2} - \frac{4\sqrt{2}\mathrm{Re}C_{tW}v^2}{\Lambda^2 V_{tb}}\frac{m_t m_W(m_t^2-m_W^2)}{(m_t^2+2m_W^2)^2} \\ F_L &= \frac{2m_W^2}{m_t^2+2m_W^2} + \frac{4\sqrt{2}\mathrm{Re}C_{tW}v^2}{\Lambda^2 V_{tb}}\frac{m_t m_W(m_t^2-m_W^2)}{(m_t^2+2m_W^2)^2} \\ F_R &= 0 \end{aligned}$$

$$\frac{1}{2}\Sigma|M|^2 = \frac{V_{tb}^2 g^4 u(m_t^2-u)}{2(s-m_W^2)^2} + \frac{4C_{ql}^{(3)}}{\Lambda^2}\frac{g^2 u(m_t^2-u)}{s-m_W^2}$$



We never see the W/Z in the detector

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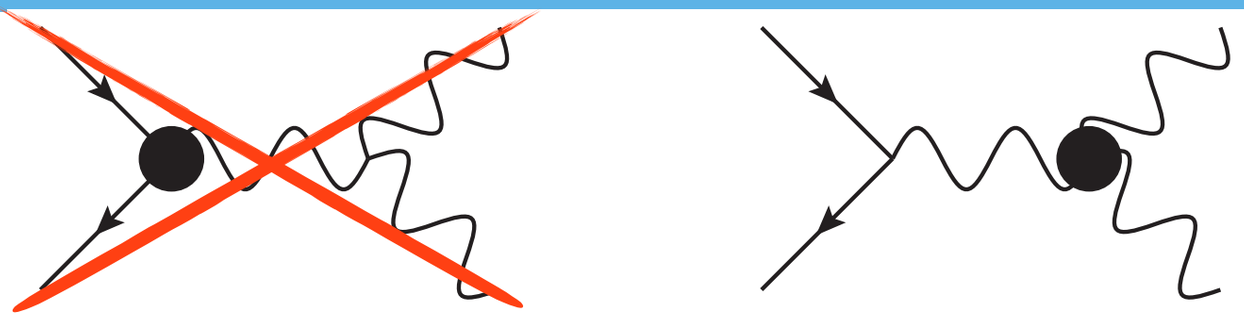
SMEFT for multiboson

WW(WZ/WA) production



CP even operators

$$\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] \\
\mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)
\end{aligned}$$

TGC's and weak boson masses are affected by different operators at the tree-level in this basis

CP odd operators

$$\begin{aligned}
\mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] \\
\mathcal{O}_{\tilde{W}} &= (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)
\end{aligned}$$

Only 5 operators!

EW operators

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

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

EW operators

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

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
~~$Q_{\varphi G}$~~	~~$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$~~	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
~~$Q_{\varphi\widetilde{G}}$~~	~~$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$~~	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}~~	~~$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\,G_{\mu\nu}^A$~~	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\,B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

EW operators

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

Pure H

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
~~$Q_{\varphi G}$~~	~~$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$~~	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p\gamma^\mu l_r)$
~~$Q_{\varphi\widetilde{G}}$~~	~~$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$~~	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	~~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}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	~~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}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

C. Degrande

EW operators

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

Pure H

EW bosons

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
~~$Q_{\varphi G}$~~	~~$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$~~	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p\gamma^\mu l_r)$
~~$Q_{\varphi\widetilde{G}}$~~	~~$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$~~	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	~~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}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi} W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	~~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}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

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EW operators

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

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
~~$Q_{\varphi G}$~~	~~$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$~~	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
~~$Q_{\varphi\widetilde{G}}$~~	~~$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$~~	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	~~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}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi} W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	~~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}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

EW bosons

Pure H

FFB(B)(B)

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4F operators

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Effects in and outside the resonance

C. Degrande

4F operators

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

Muon decay

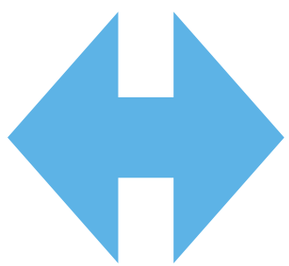
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Effects in and outside the resonance

Basis of TGC

$$Q_{\varphi WB} \left| \quad \varphi^\dagger \tau^I \varphi \, W^I_{\mu\nu} B^{\mu\nu} \right.$$

$$Q_{\varphi D} \left| \quad \left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right) \right.$$



$$\begin{aligned} \mathcal{O}_W &= (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \\ \mathcal{O}_B &= (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) \end{aligned}$$

+ other 0F/2F operators of the basis + dim8

2pt functions modification

3+ vertices

WW production

$$\begin{aligned}\mathcal{L} =& ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho\right.\\ &+ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma\\ &\left.+\tilde{\kappa}_V W^+_\mu W^-_\nu\tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu\tilde{V}^\mu_\rho\right),\end{aligned}$$

$$g_{WWZ} = -e\cot\theta_W \qquad g_{WW\gamma} = -e$$

EM gauge invariance implies : $g_1^\gamma = 1 \quad g_4^\gamma = g_5^\gamma = 0$

WW production

$$\begin{aligned}\mathcal{L} =& ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho\right.\\ &+ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma\\ &\left.+\tilde{\kappa}_V W^+_\mu W^-_\nu\tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu\tilde{V}^\mu_\rho\right),\end{aligned}$$

$$g_{WWZ} = -e\cot\theta_W \qquad g_{WW\gamma} = -e$$

EM gauge invariance implies : $g_1^\gamma = 1 \quad g_4^\gamma = g_5^\gamma = 0$

11(5+6) parameters

WW production

$$\mathcal{L} = ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho\right.$$
$$+ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V [illegible]\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma$$
$$\left.+\tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W[illegible]_\rho\right),$$

Why not adding derivatives

$$g_{WWZ} = -e\cot\theta_W \qquad g_{WW\gamma} = -e$$

EM gauge invariance implies : $g_1^\gamma = 1 \quad g_4^\gamma = g_5^\gamma = 0$

11(5+6) parameters

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WW production

$$\mathcal{L} = ig_{WWV}\left(g_1^V (W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho \right.$$
$$+ ig_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V \epsilon^{\mu\nu\rho\sigma}(W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma$$
$$\left. + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \right),$$

$$+ \frac{g_2^V}{M_W^2}\left(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu}\right)\partial^\rho\partial_\rho V^\nu$$

WW production

$$\mathcal{L} = ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho\right.$$
$$+ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma$$
$$\left.+\tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho\right),$$

$$+\frac{g_2^V}{M_W^2}\left(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu}\right)\partial^\rho\partial_\rho V^\nu$$

Dimension-six

$$\frac{1}{\left(\frac{s}{\Lambda^2}+1\right)^2} = \sum_{k=0}^{\infty}(k+1)\left(-\frac{s}{\Lambda^2}\right)^k$$

$$\sigma\left(pp \to WW\right) = \sigma_{SM} + g_1^V\left(1 + \frac{g_2^V}{g_1^V}\frac{s}{M_W^2}\right)\sigma_1$$

Form factors are higher dimension operators with arbitrarily fixed coefficients

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WW production

$$\mathcal{L} = ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho\right.$$
$$+ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma$$
$$\left.+\tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho\right),$$

$$+\frac{g_2^V}{M_W^2}\left(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu}\right)\partial^\rho\partial_\rho V^\nu$$

Dimension-six

$$\sigma(pp \to WW) = \sigma_{SM} + g_1^V\left(1 + \frac{g_2^V}{g_1^V}\frac{s}{M_W^2}\right)\sigma_1$$

$$\sigma(pp \to WV) = \sigma_{SM} + g_1^V\left(1 + \frac{g_2^V}{g_1^V}\frac{M_V^2}{M_W^2}\right)\sigma_1$$

EFT versus Anomalous

	EFT	AC
Lorentz	✔	✔
$SU(2)_L$	✔	✘
$U(1)_{EM}$	✔	(✔)
Scale suppression	✔	✘
# parameters	5	11+

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AC/EFT

$$\mathcal{L} = ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho + ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)\right.$$
$$\left. -ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho\right)$$

CP even Operators

$$\begin{aligned}\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^\mu_\rho]\\ \mathcal{O}_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)\\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

CP odd operators

$$\begin{aligned}\mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W^\mu_\rho]\\ \mathcal{O}_{\tilde{W}} &= (D_\mu\Phi)^\dagger\tilde{W}^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

$$\begin{aligned}g_1^Z &= 1 + c_W\frac{m_Z^2}{2\Lambda^2}\\ \kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2}\\ \kappa_Z &= 1 + (c_W - c_B\tan^2\theta_W)\frac{m_W^2}{2\Lambda^2}\\ \lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2m_W^2}{2\Lambda^2}\\ g_4^V &= g_5^V = 0\\ \tilde{\kappa}_\gamma &= c_{\tilde{W}}\frac{m_W^2}{2\Lambda^2}\\ \tilde{\kappa}_Z &= -c_{\tilde{W}}\tan^2\theta_W\frac{m_W^2}{2\Lambda^2}\\ \tilde{\lambda}_\gamma &= \tilde{\lambda}_Z = c_{\tilde{W}WW}\frac{3g^2m_W^2}{2\Lambda^2}\end{aligned}$$

Constants !

AC/EFT

$$\mathcal{L} = ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho + ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)\right.$$
$$\left. -ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho\right)$$

CP even Operators

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^\mu_\rho]$$
$$\mathcal{O}_W = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_B = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

CP odd operators

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W^\mu_\rho]$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)$$

$$g_1^Z = 1 + c_W\frac{m_Z^2}{2\Lambda^2} \qquad \Delta X = X - 1$$

$$\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W\Delta\kappa_\gamma$$

$$\kappa_Z = 1 + (c_W - c_B)\frac{m_W^2}{2\Lambda^2}$$

$$\lambda_\gamma = \lambda_Z = c_{WWW}\frac{3g^2m_W^2}{2\Lambda^2}$$

$$g_4^V = g_5^V = 0$$

$$\tilde{\kappa}_\gamma = \frac{m_W^2}{\Lambda^2}$$

$$0 = \tilde{\kappa}_Z + \tan^2\theta_W\tilde{\kappa}_\gamma$$

$$\tilde{\lambda}_\gamma = \tilde{\lambda}_Z = c_{\tilde{W}WW}\frac{3g^2}{2\Lambda^2}$$

Constants !

Which observables?

Invariant mass and polarisation

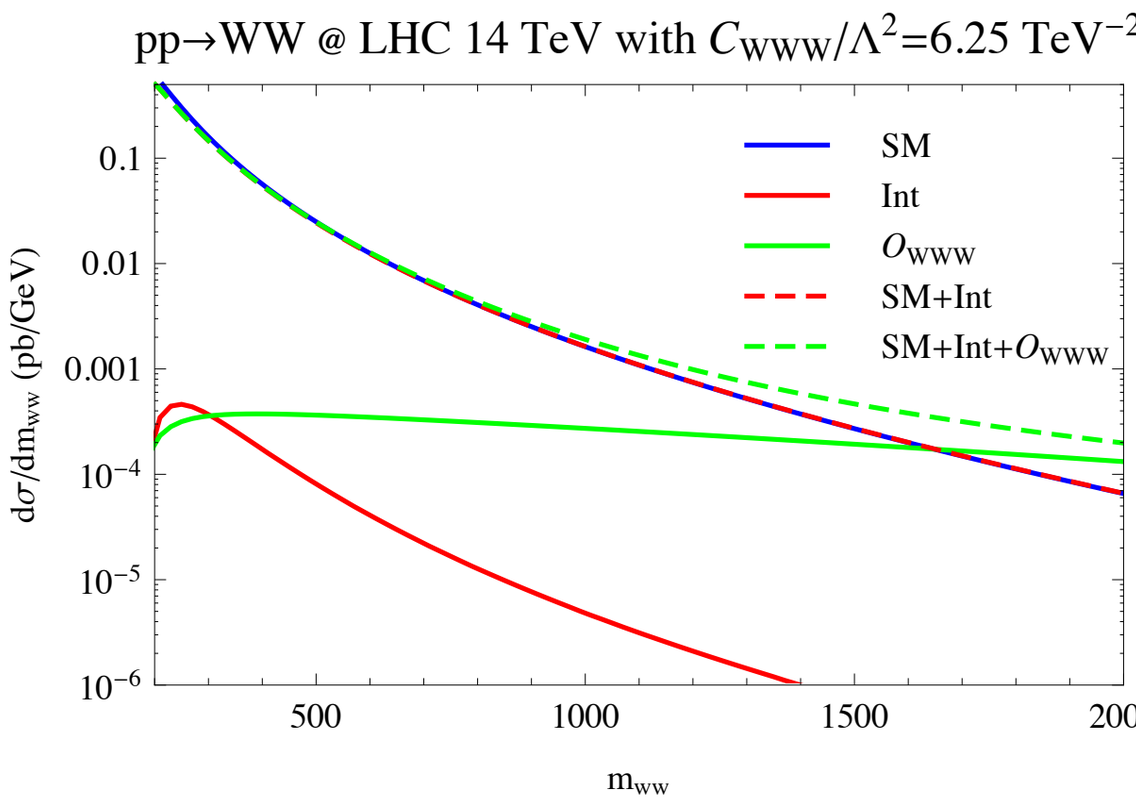
	O_{WWW}	O_W	O_B	SM
LL	0	$1\,(s)$	$1\,(s)$	$1/s$
LT	$1/s\,(1)$	$1/s\,(1)$	$1/s\,(1)$	$1/s^2$
TT	$1/s\,(s)$	$1/s^2\,(1/s)$	0	$1/s$
Sum	$1/s\,(s)$	$1\,(s)$	$1\,(s)$	$1/s$

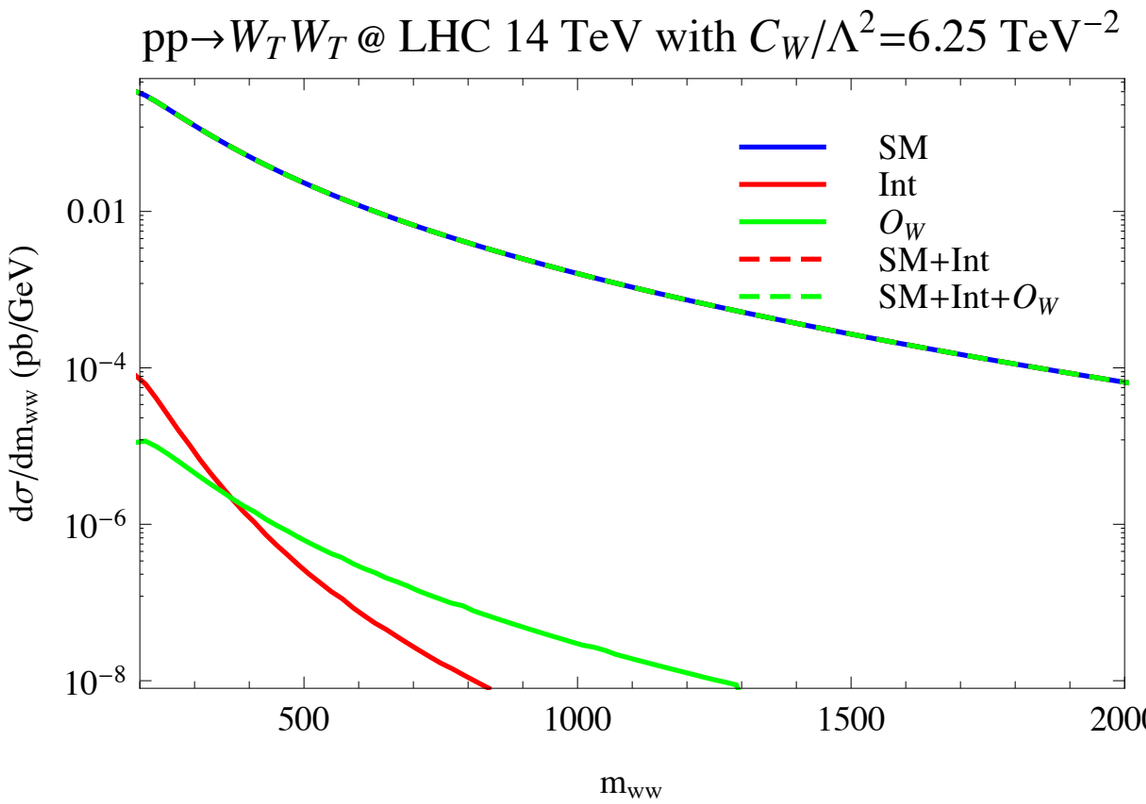
Helicity Selection Rules and Non-Interference for BSM Amplitudes,

A. Azatov, R. Contino, C. S. Machado and F. Riva,

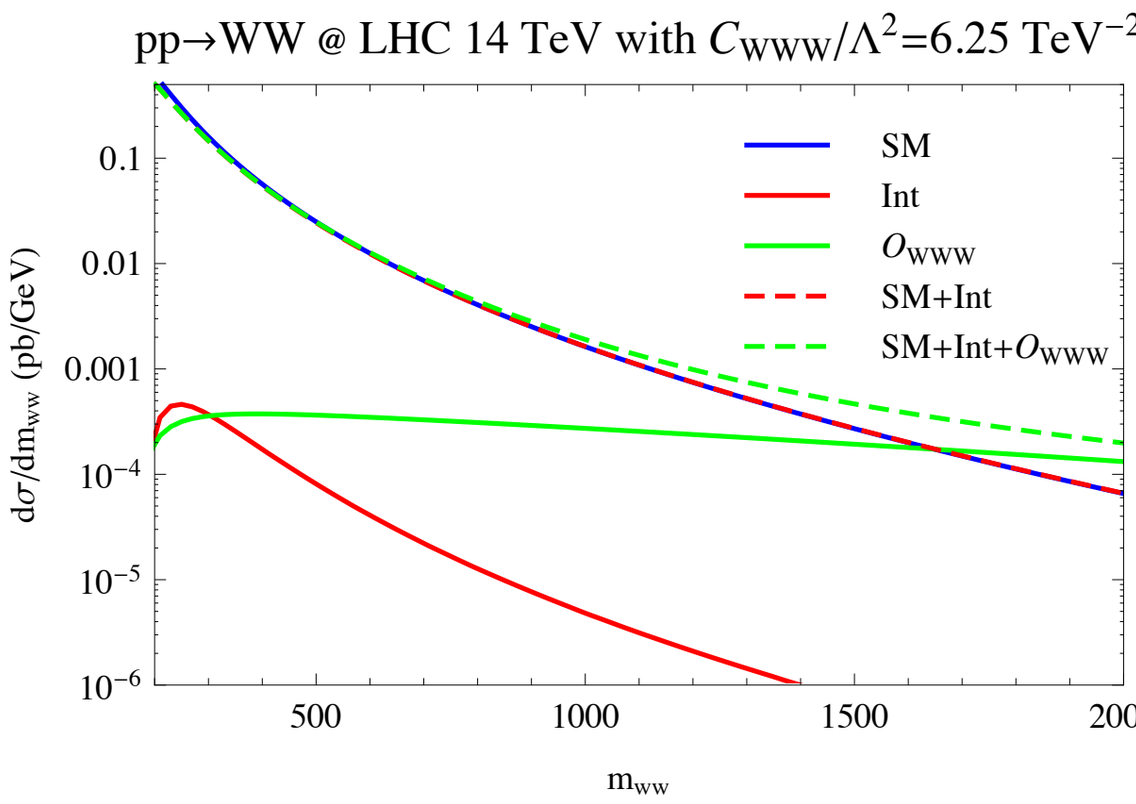
Phys.Rev. D95 (2017) no.6, 065014

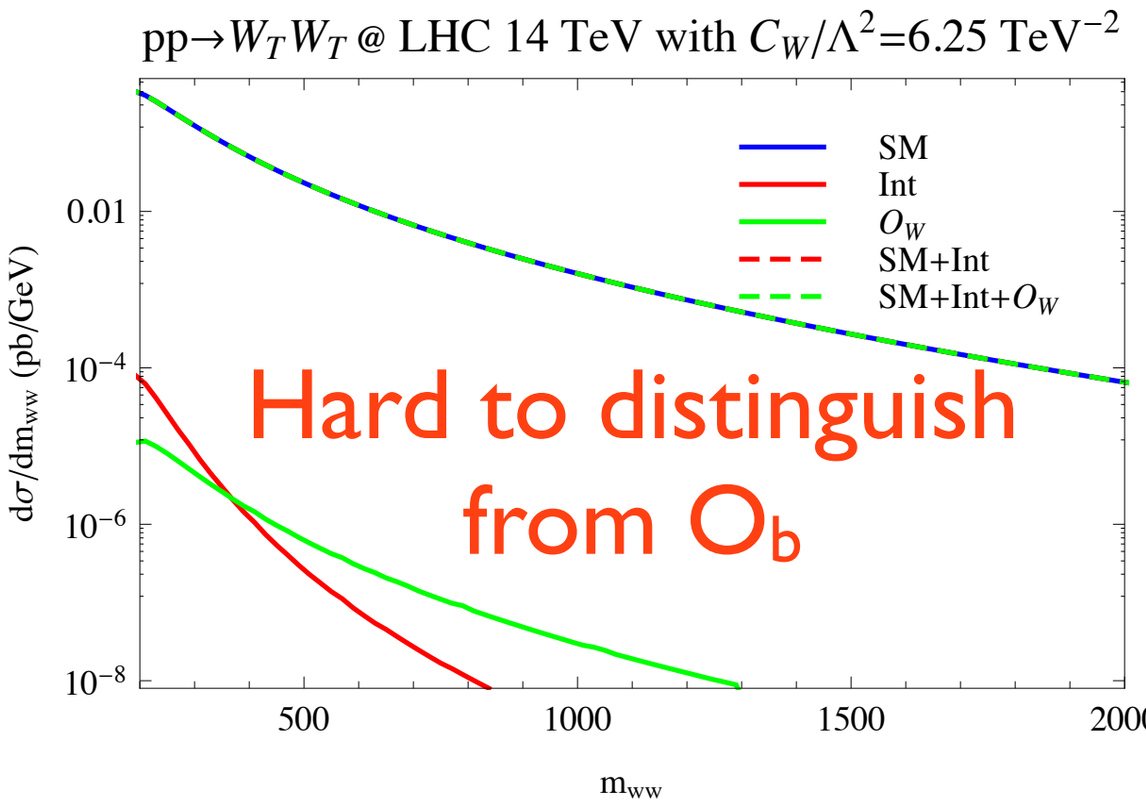
Tranverse polarizations



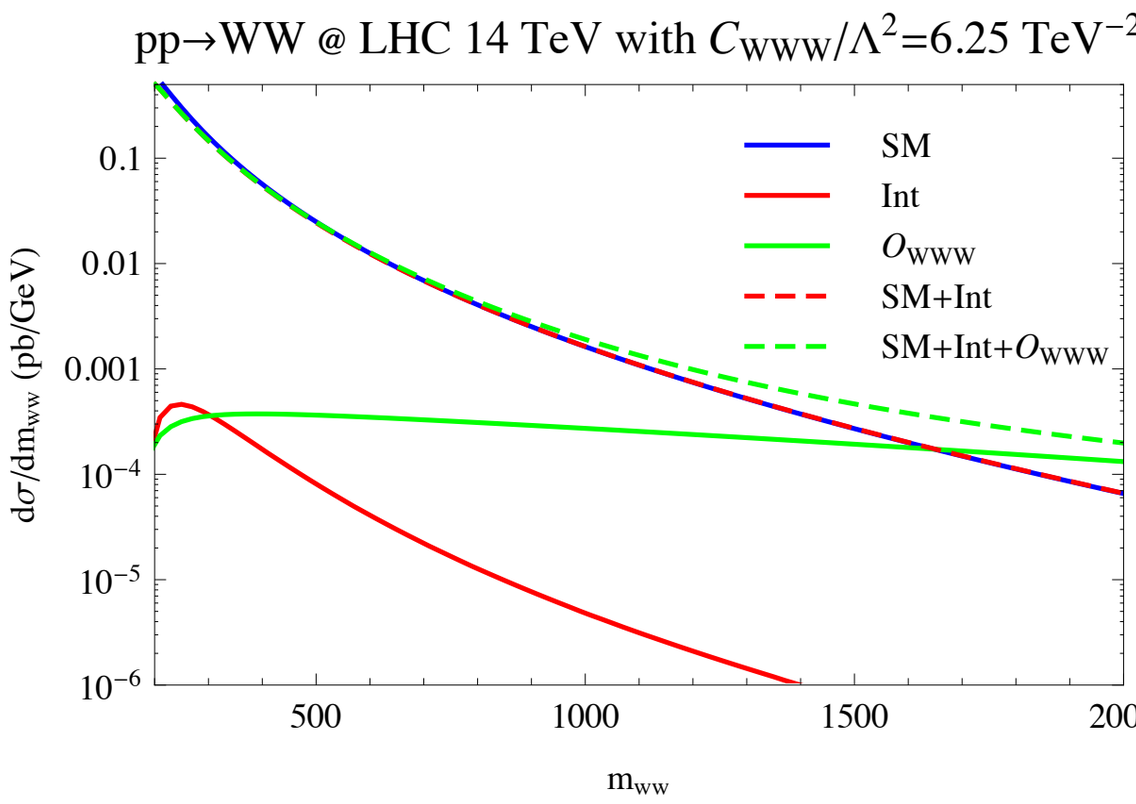


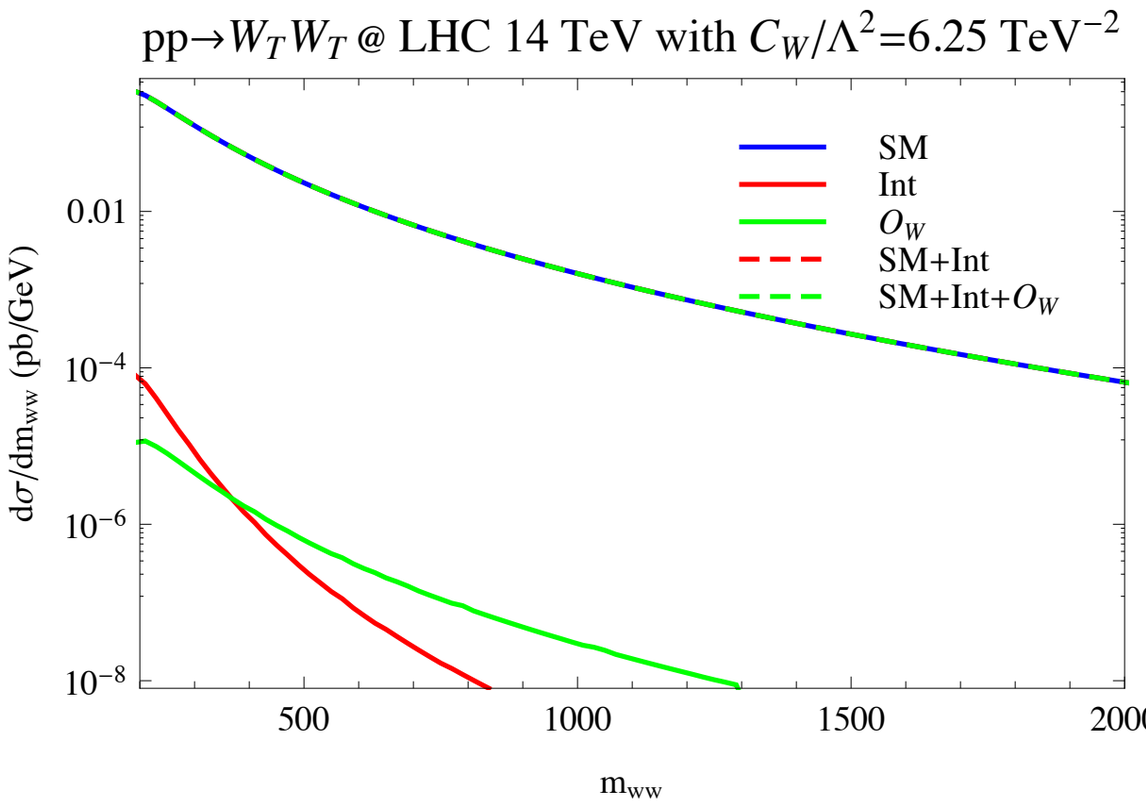
Tranverse polarizations





Tranverse polarizations



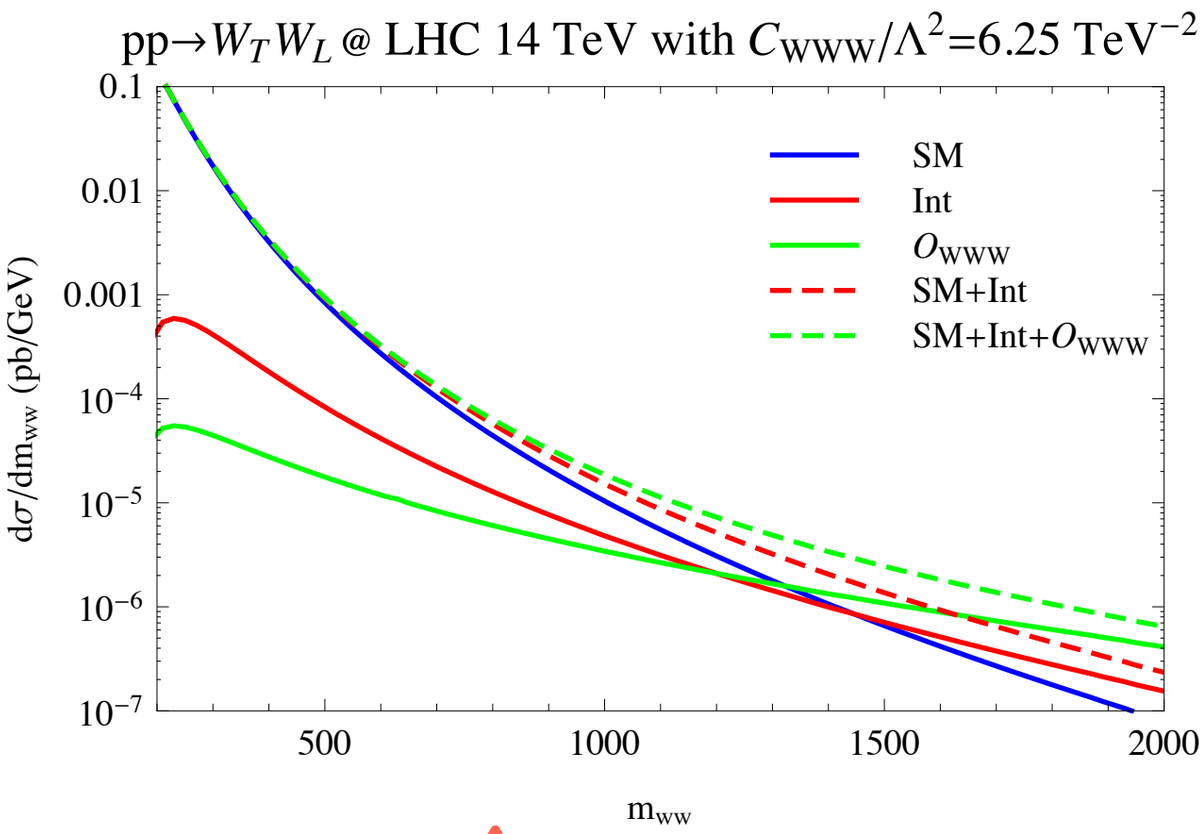


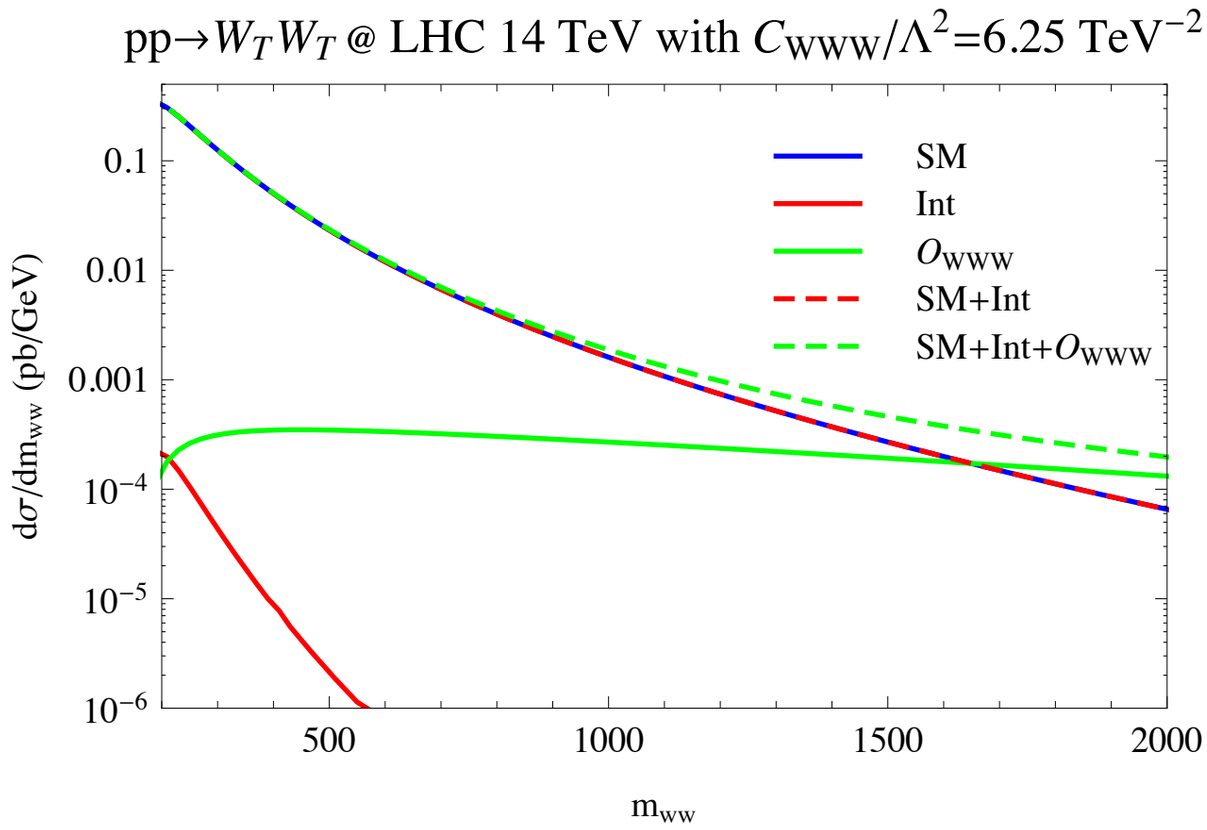
SM has a large contribution

Dim-6 operators have small contributions

→ Cut ?

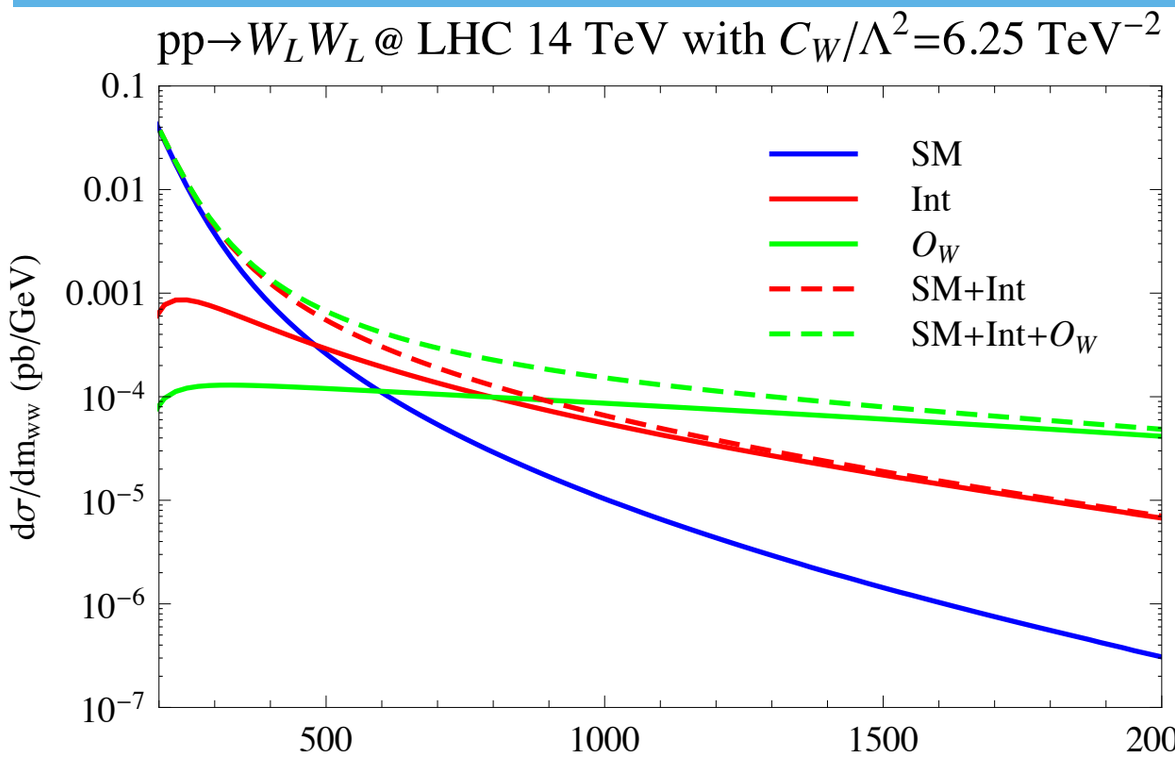
O_{WWW}

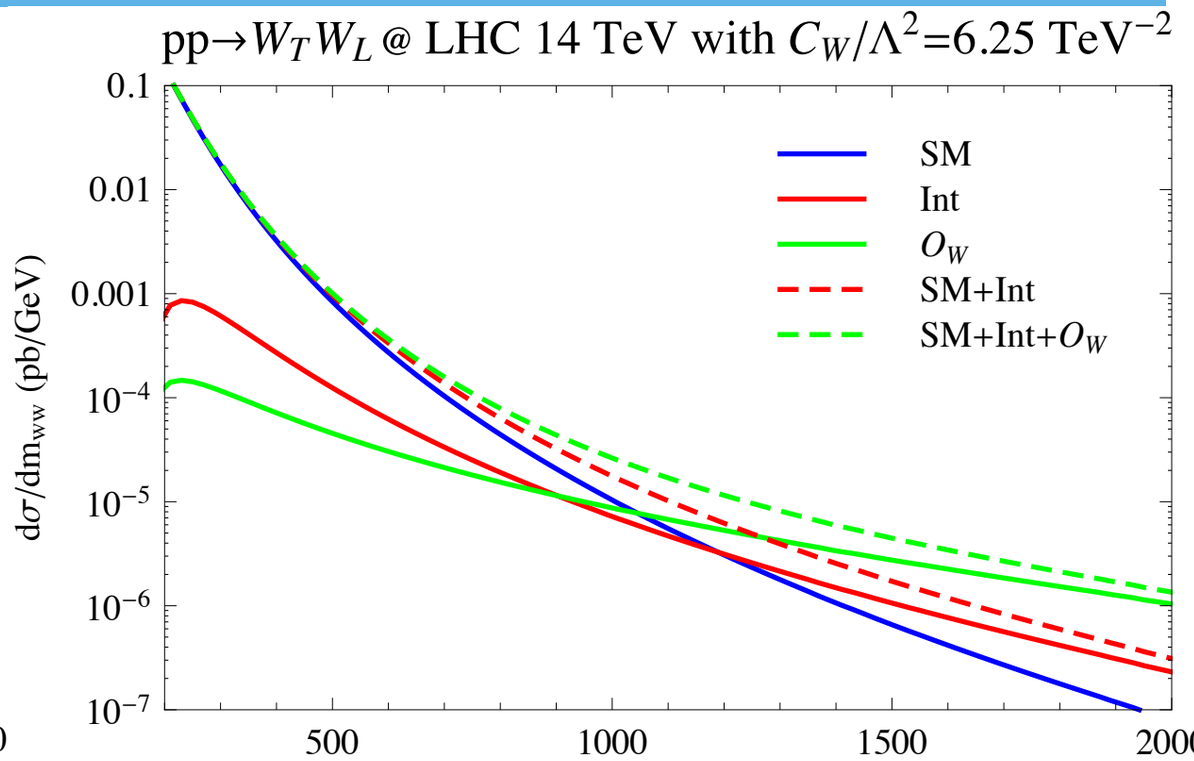




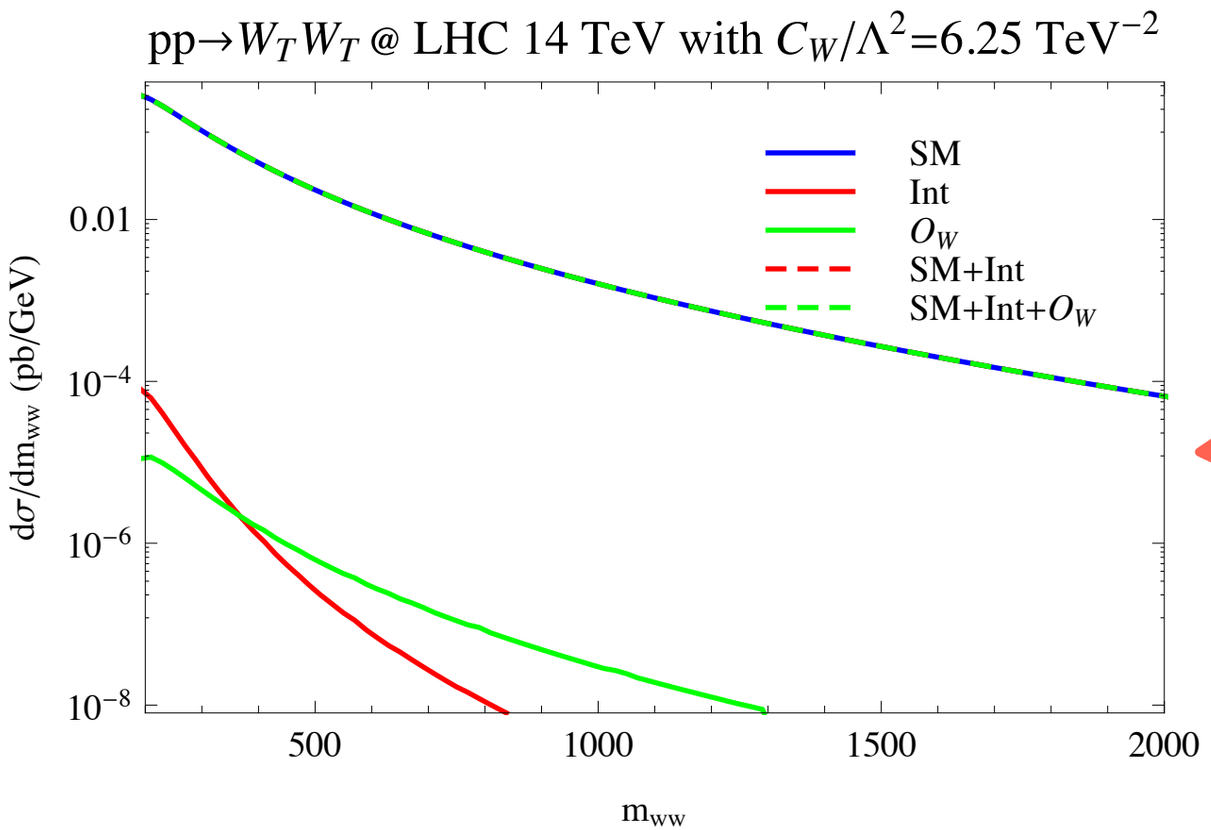
Largest for O_{WWW}

O_W





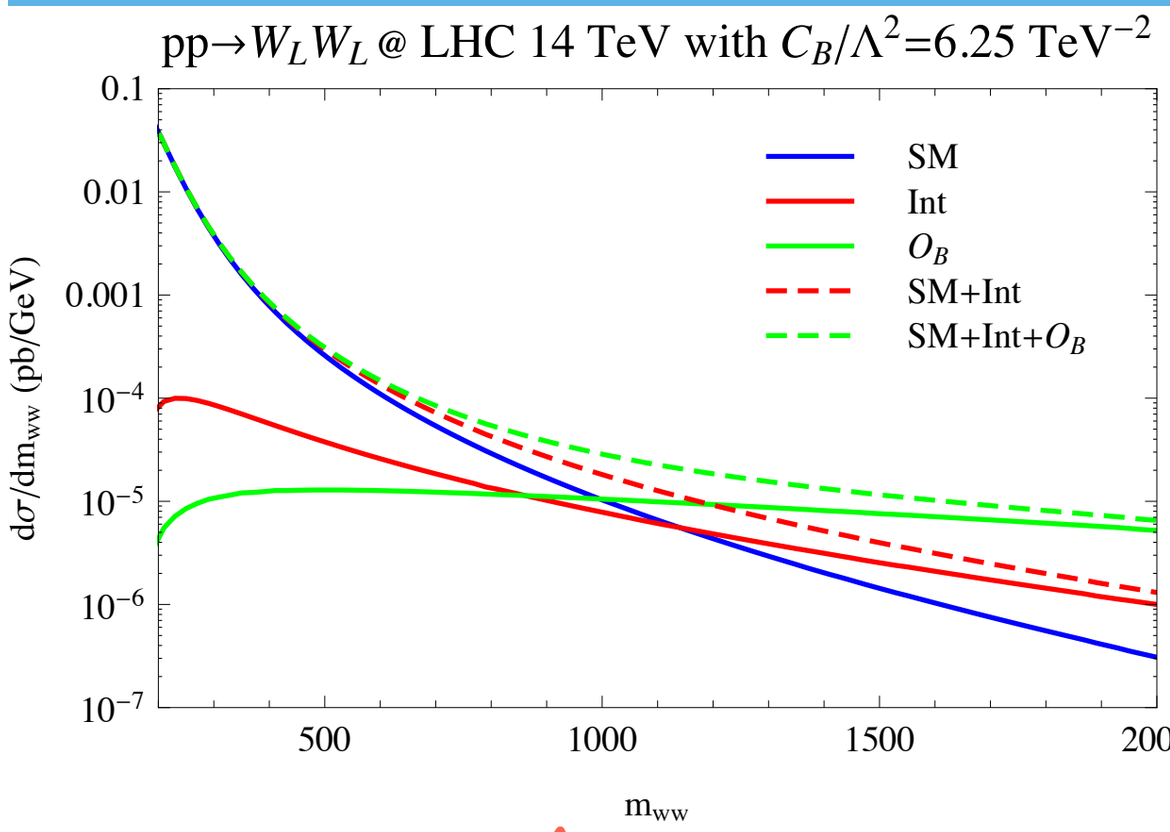
Largest for O_W
Smallest for SM

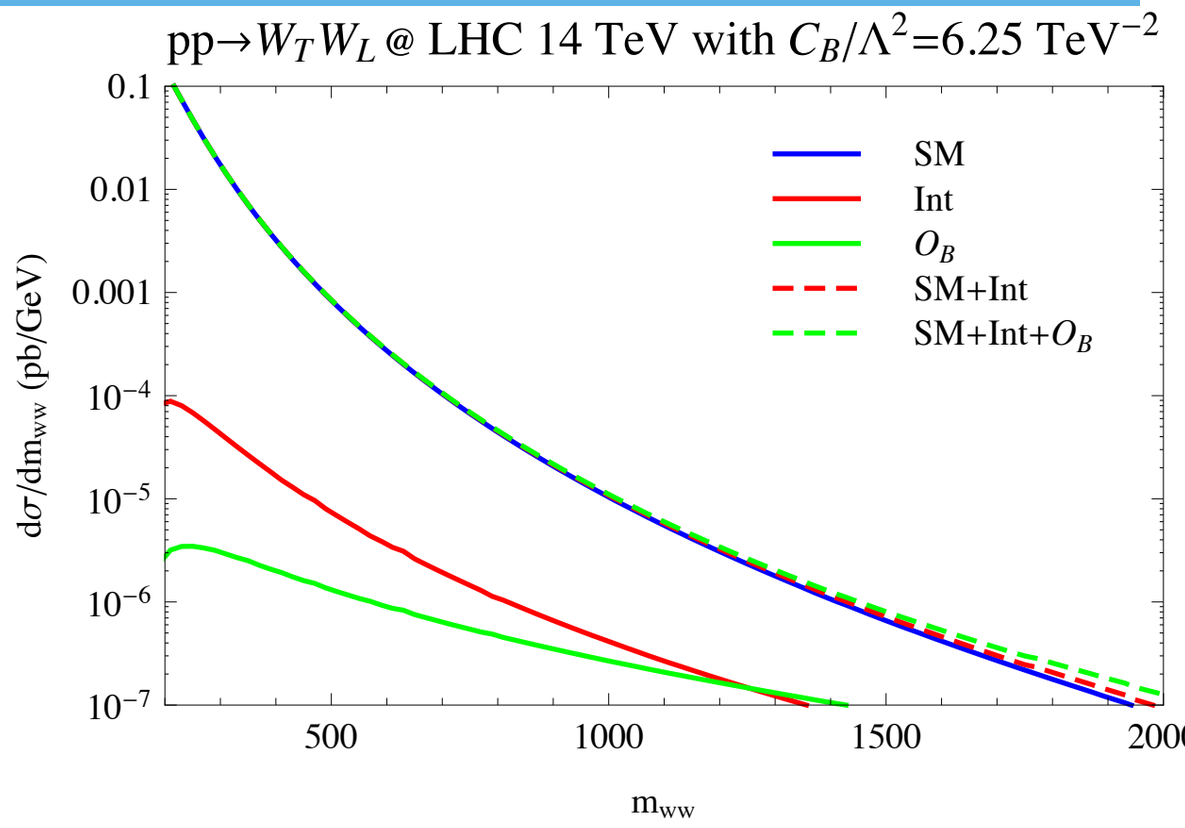


Smallest for O_W
Largest for SM

C. Degrande

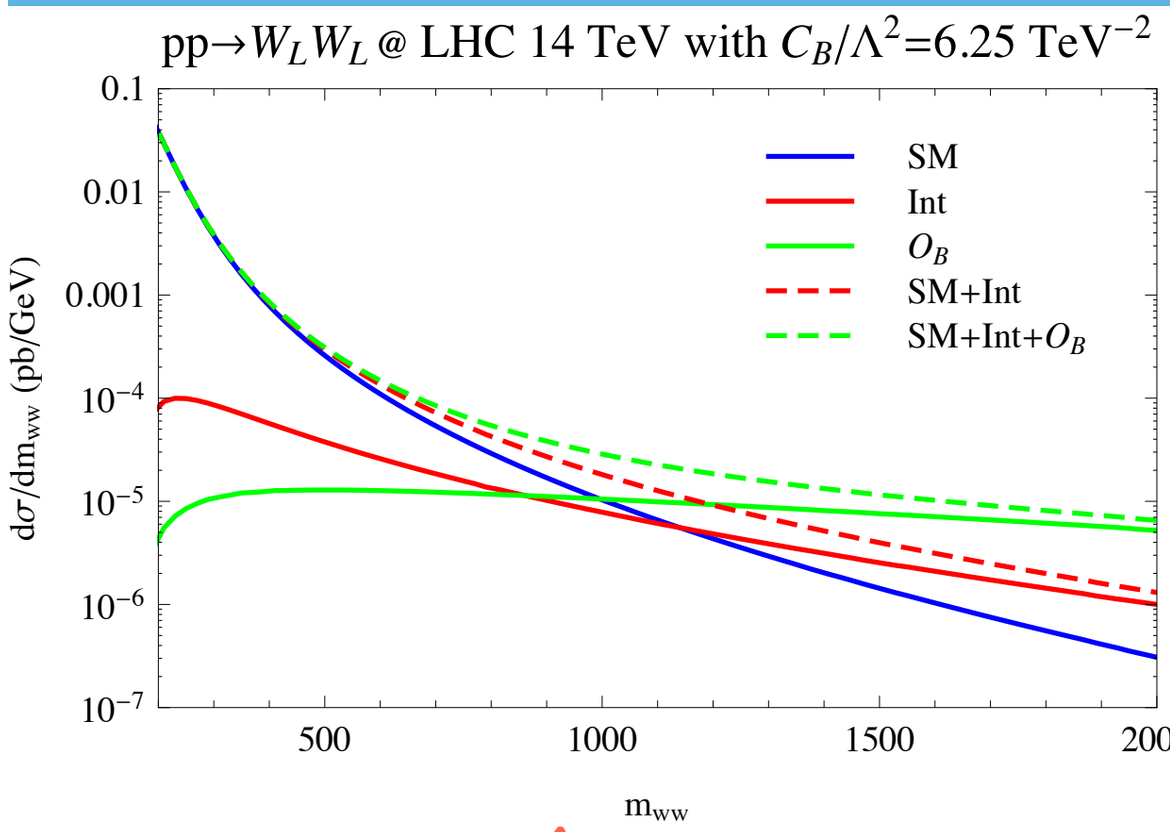
O_B

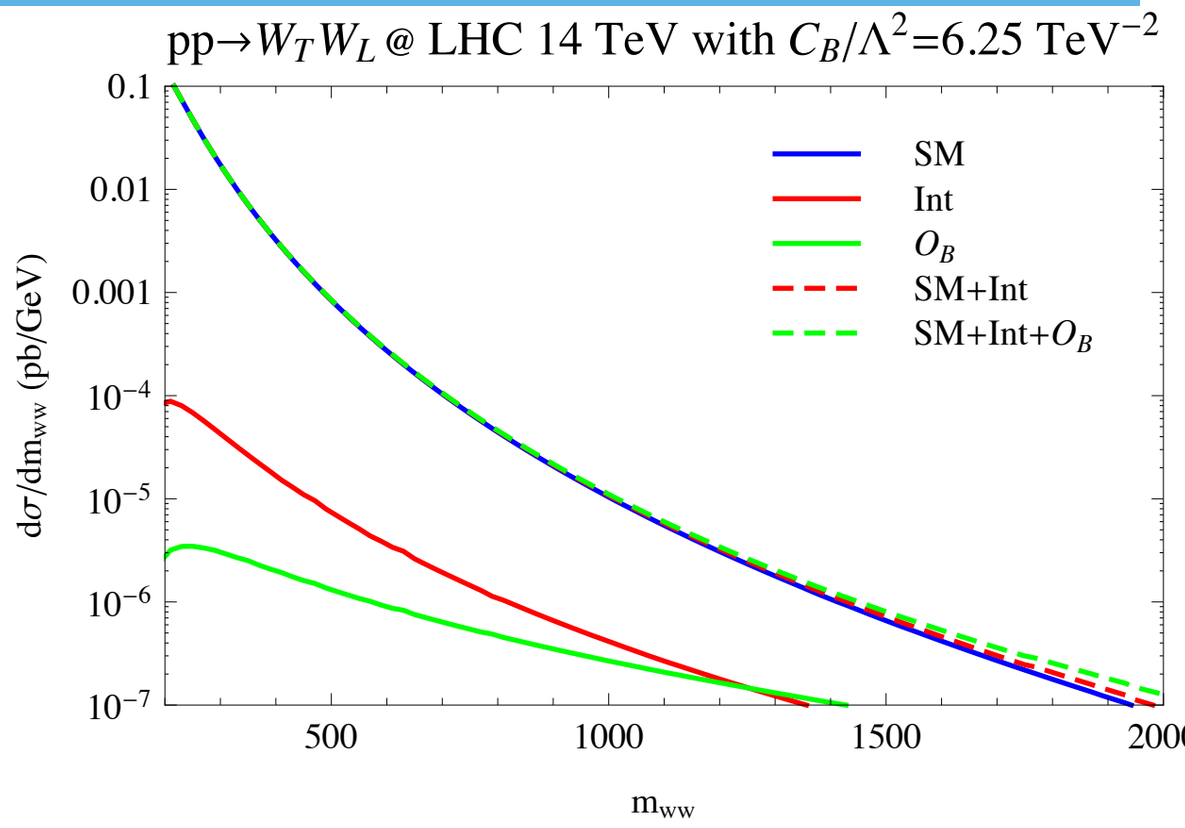




Largest for O_b
Smallest for SM

O_B



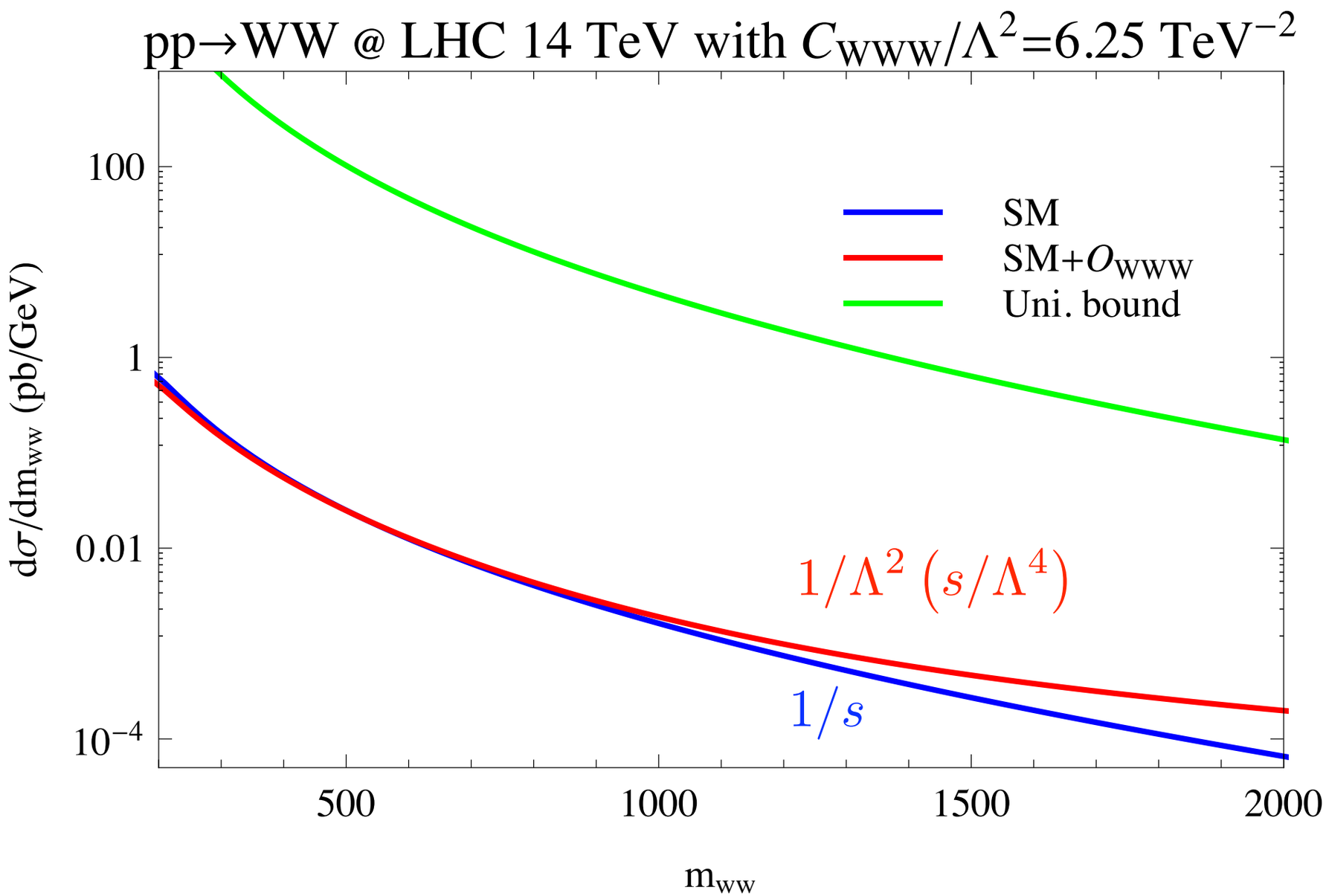


Largest for O_b
Smallest for SM

Similar to O_w with a smaller coefficient

C. Degrande

Unitarity bound

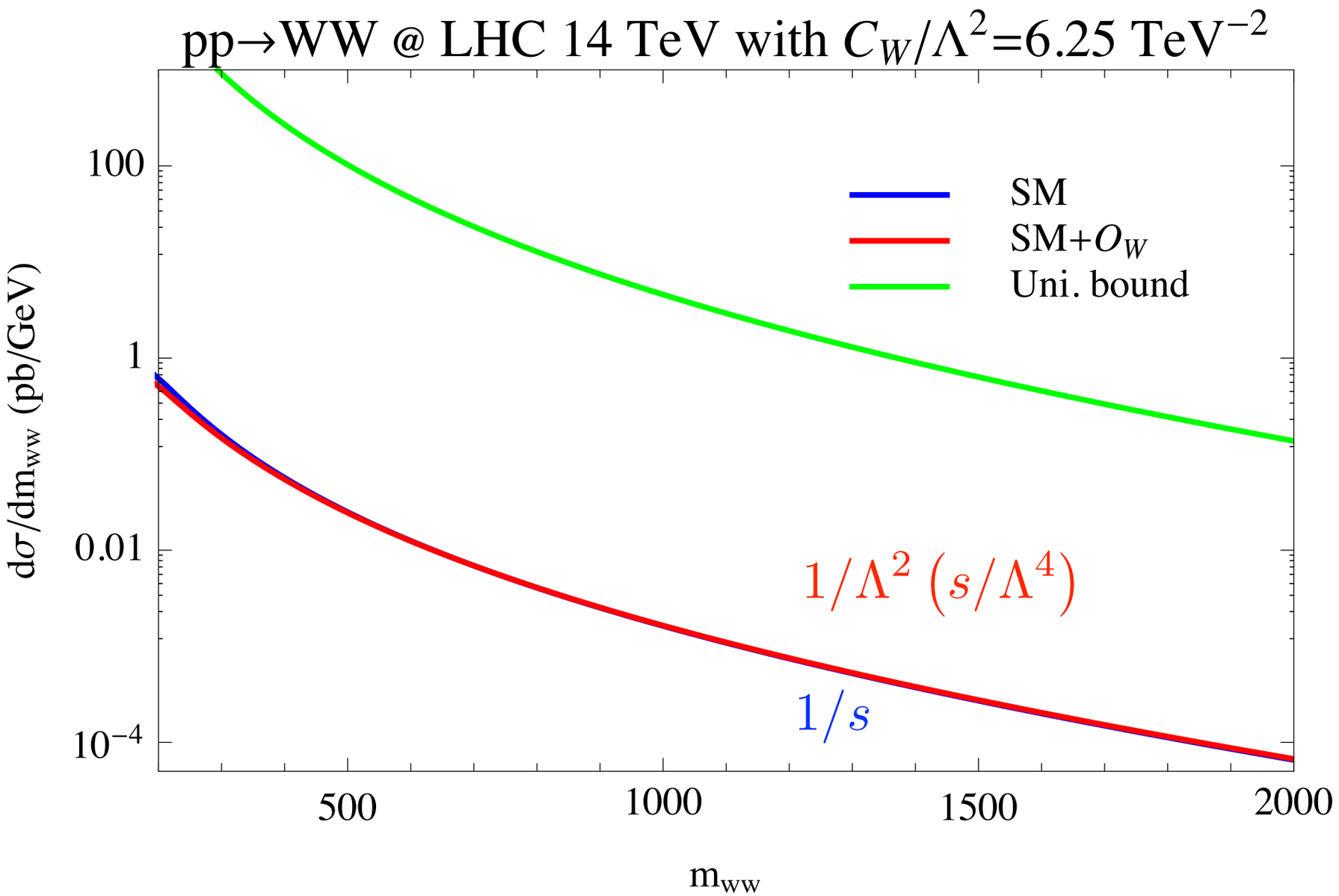


More than 2 orders of magnitude

Form factors are not needed!

C. Degrande

Unitarity bound



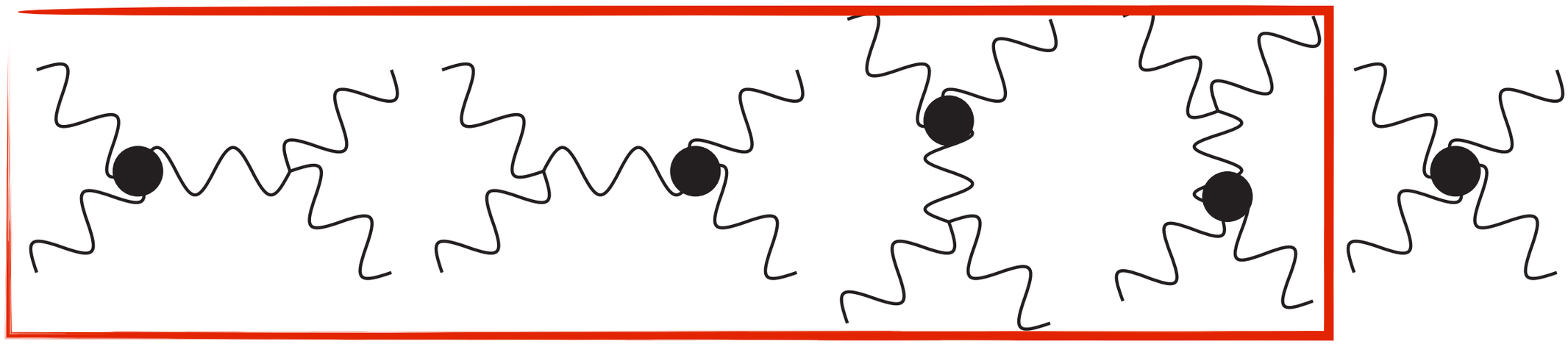
More than 2 orders of magnitude

Form factors are not needed!

C. Degrande

EFT for QGC

- Same operators than for TGC give WWWW, WWZA, WWAA, WWZZ vertices
- gauge invariance requires 3 and 4 legs vertices to be related



TGC's alone are not gauge invariant

EFT for QGC

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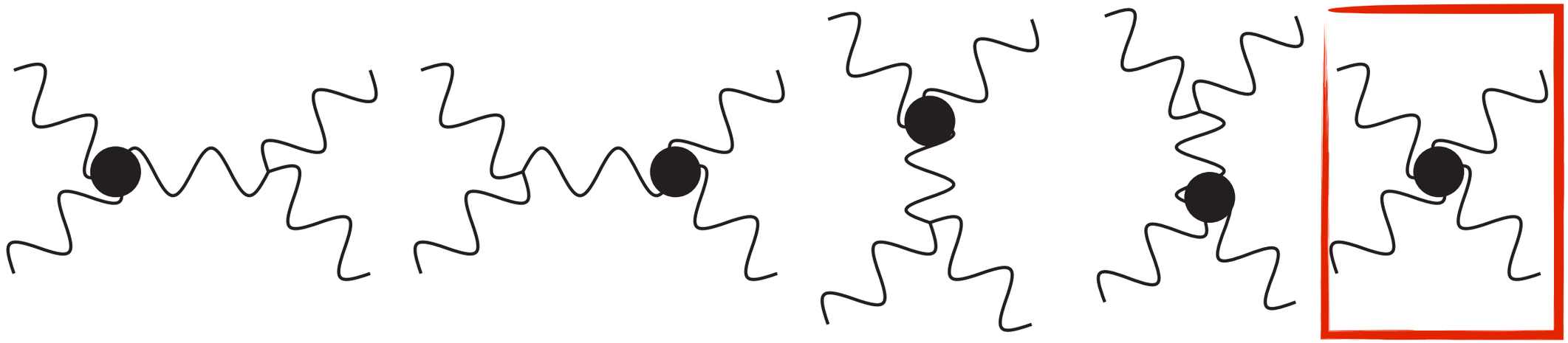

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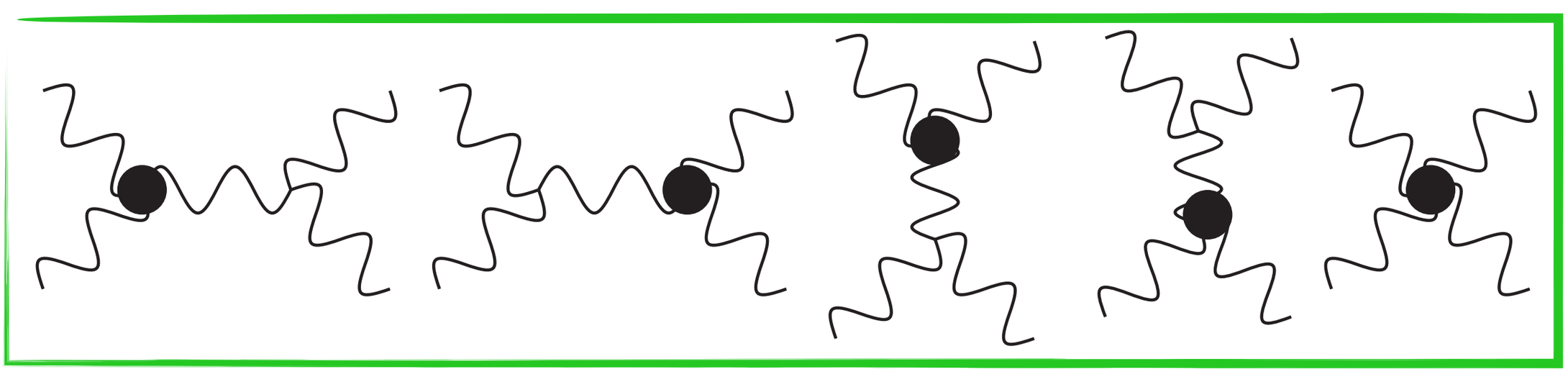


TGC's and QGC's from the dimension-six operators are gauge invariant

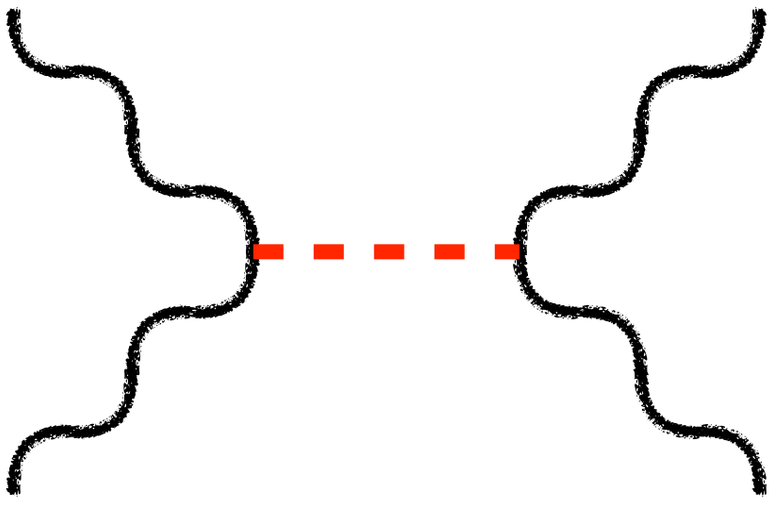
Extra dim6 for VBS or 3B

$$\mathcal{O}_{\Phi d} = \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right) \quad \rightarrow \quad h \rightarrow h(1 - \frac{c_{\Phi d}}{\Lambda^2} v^2)$$

$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger \Phi\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}] \quad \rightarrow \quad \mathcal{O}_{\Phi W} = \left(\Phi^\dagger \Phi - v^2\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}]$$

$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger \Phi\right) B^{\mu\nu} B_{\mu\nu} \quad \rightarrow \quad \mathcal{O}_{\Phi B} = \left(\Phi^\dagger \Phi - v^2\right) B^{\mu\nu} B_{\mu\nu}$$

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	X	X					X	X	X	X
$\mathcal{O}_{W}$	X	X	X	X	X		X	X	X	
$\mathcal{O}_{B}$	X	X		X	X					
$\mathcal{O}_{\Phi d}$			X	X						
$\mathcal{O}_{\Phi W}$			X	X	X	X				
$\mathcal{O}_{\Phi B}$				X	X	X				



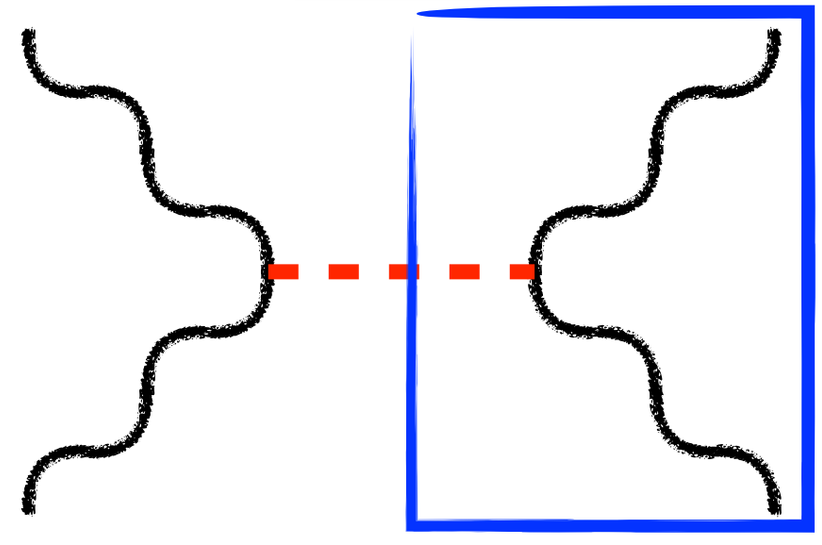
Extra dim6 for VBS or 3B

$$\mathcal{O}_{\Phi d} = \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right) \quad \rightarrow \quad h \rightarrow h(1 - \frac{c_{\Phi d}}{\Lambda^2} v^2)$$

$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger \Phi\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}] \quad \rightarrow \quad \mathcal{O}_{\Phi W} = \left(\Phi^\dagger \Phi - v^2\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}]$$

$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger \Phi\right) B^{\mu\nu} B_{\mu\nu} \quad \rightarrow \quad \mathcal{O}_{\Phi B} = \left(\Phi^\dagger \Phi - v^2\right) B^{\mu\nu} B_{\mu\nu}$$

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	X	X					X	X	X	X
$\mathcal{O}_{W}$	X	X	X	X	X		X	X	X	
$\mathcal{O}_{B}$	X	X		X	X					
$\mathcal{O}_{\Phi d}$			X	X						
$\mathcal{O}_{\Phi W}$			X	X	X	X				
$\mathcal{O}_{\Phi B}$				X	X	X				



Constraints from Higgs

C. Degrande

QGC from Dimension-eight

- pp>WW does not fixe completely pp>WWW, … only at leading order
- Ex: Some dimension-eight operators induce QGC but no TGC
- Some QGC are gauge invariant on their own

Dimension and errors

- Smaller effects or larger errors for higher dimension operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \sum \frac{d_i}{\Lambda^4}\mathcal{O}_i^8 + \mathcal{O}\left(\Lambda^{-6}\right)$$

1 10% 1% 0.1%

Dimension and errors

- Smaller effects or larger errors for higher dimension operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \sum \frac{d_i}{\Lambda^4}\mathcal{O}_i^8 + \mathcal{O}\left(\Lambda^{-6}\right)$$

1	10%	1%	0.1%
1	0%	10%	3%

Dimension and errors

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$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \sum \frac{d_i}{\Lambda^4}\mathcal{O}_i^8 + \mathcal{O}\left(\Lambda^{-6}\right)$$

1 10% 1% 0.1%

1 0% 10% 3%

- Extra assumptions if first order does not vanishes

Dimension and errors

- Smaller effects or larger errors for higher dimension operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \sum \frac{d_i}{\Lambda^4}\mathcal{O}_i^8 + \mathcal{O}\left(\Lambda^{-6}\right)$$

1 10% 1% 0.1%

1 0% 10% 3%

- Extra assumptions if first order does not vanishes

- More parameters/less guidance

Dimension and errors

- Smaller effects or larger errors for higher dimension operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \sum \frac{d_i}{\Lambda^4}\mathcal{O}_i^8 + \mathcal{O}\left(\Lambda^{-6}\right)$$

1 10% 1% 0.1%

1 0% 10% 3%

- Extra assumptions if first order does not vanishes
- More parameters/less guidance
- Can affect a new observable

C. Degrande

QGC from Dimension-eight

From O. Eboli

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right]$$
$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \ ,$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \ ,$$
$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \ ,$$
$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \ .$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \ ,$$
$$\mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \ ,$$
$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu} \ ,$$
$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu} \ ,$$
$$\mathcal{O}_{M,6} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right] \ ,$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right] \ ,$$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

C. Degrande

Top fit

Data

Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
$t\bar{t}$	`ATLAS_tt_8TeV_ljets`	**8 TeV**	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	5, 8, 7, 5	[92]
$t\bar{t}$	`CMS_tt_8TeV_ljets`	**8 TeV**	lepton+jets	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	10, 8, 7, 10	[93]
$t\bar{t}$	`CMS_tt2D_8TeV_dilep`	**8 TeV**	dileptons	$d^2\sigma/dy_t dp_t^T$, $d^2\sigma/dy_t dm_{t\bar{t}}$, $d^2\sigma/dp_{t\bar{t}}^T dm_{t\bar{t}}$, $d^2\sigma/dy_{t\bar{t}} dm_{t\bar{t}}$	16, 16, 16, 16	[94]
$t\bar{t}$	`CMS_tt_13TeV_ljets`	**13 TeV**	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	7, 9, 8, 6	[97]
$t\bar{t}$	`CMS_tt_13TeV_ljets2`	**13 TeV**	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	11, 12, 10, 10	[99]
$t\bar{t}$	`CMS_tt_13TeV_dilep`	**13 TeV**	dileptons	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	8, 6, 6, 8	[100]
$t\bar{t}$	`ATLAS_WhelF_8TeV`	**8 TeV**	W helicity fract	F_0, F_L, F_R	3	[95]
$t\bar{t}$	`CMS_WhelF_8TeV`	**8 TeV**	W helicity fract	F_0, F_L, F_R	3	[96]

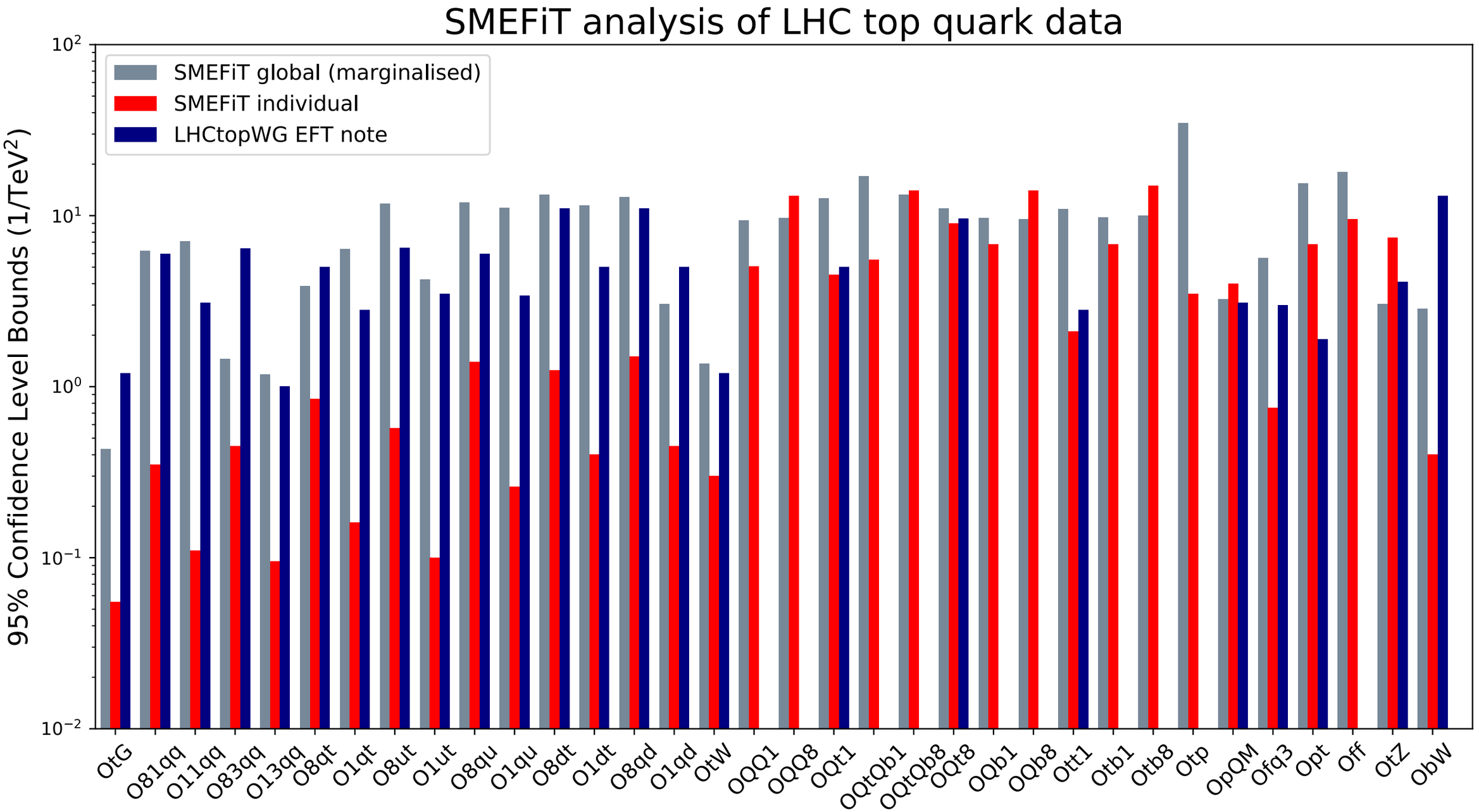
Only one distribution per measurement (correlation)

N.P. Hartland, F.Maltoni, E. R. Nocera, J. Rojo, E. Slade, E. Vryonidou and C.~Zhang,JHEP 1904 (2019) 100

Data

Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
$t\bar{t}b\bar{b}$	`CMS_ttbb_13TeV`	**13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[101]
$t\bar{t}t\bar{t}$	`CMS_tttt_13TeV`	**13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[102]
$t\bar{t}Z$	`CMS_ttZ_8_13TeV`	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	2	[103, 104]
$t\bar{t}Z$	`ATLAS_ttZ_8_13TeV`	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	2	[105, 106]
$t\bar{t}W$	`CMS_ttW_8_13TeV`	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	2	[103, 104]
$t\bar{t}W$	`ATLAS_ttW_8_13TeV`	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	2	[105, 106]
$t\bar{t}H$	`CMS_tth_13TeV`	**13 TeV**	signal strength	$\mu_{t\bar{t}H}$	1	[107]
$t\bar{t}H$	`ATLAS_tth_13TeV`	**13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}H)$	1	[108]

Global top Fit



Marg. less constrained than ind.

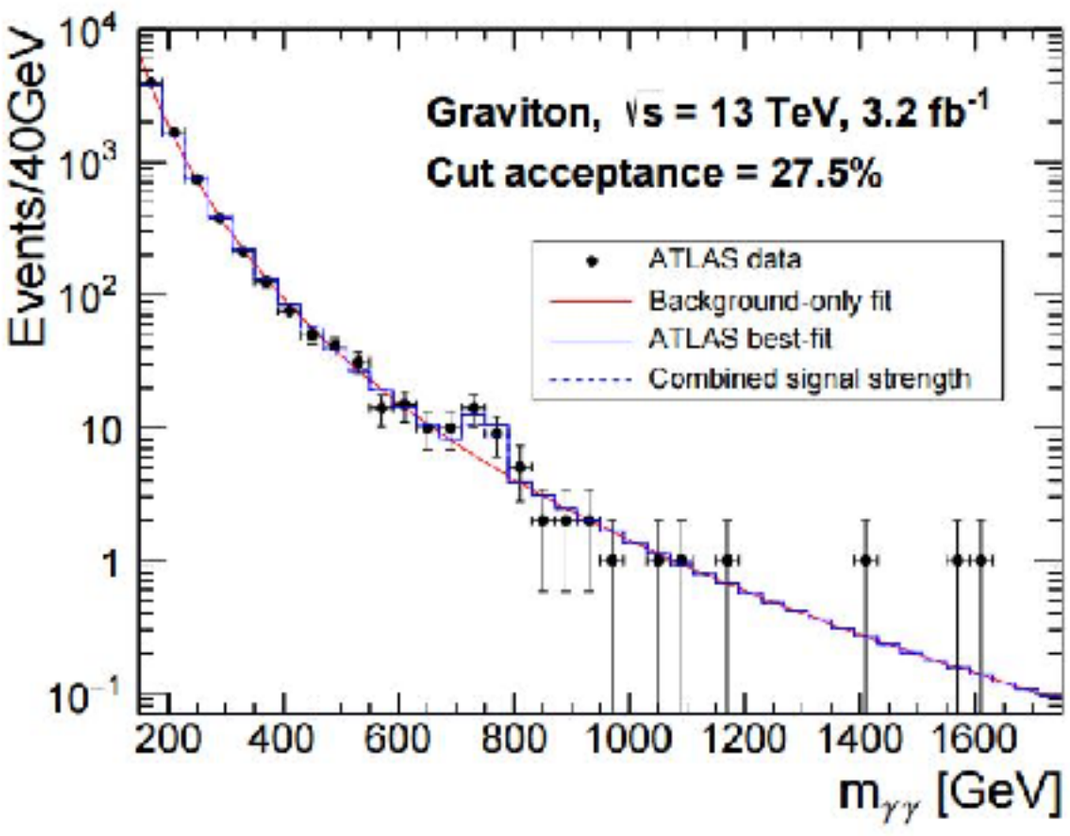
C. Degrande

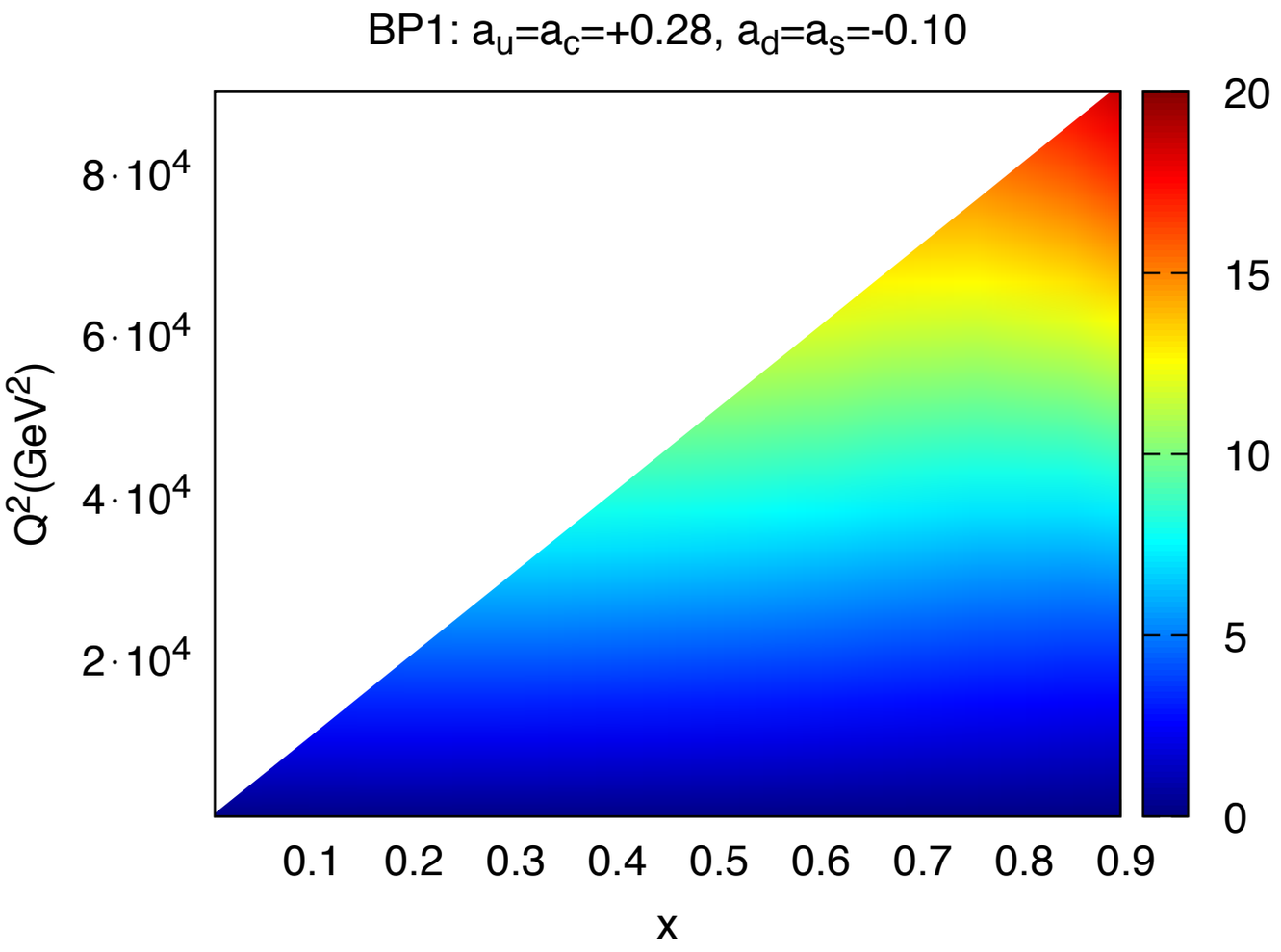
EFT and PDF

EFT and PDF

1905.05215 with S. Carrazza, S. Iranipour, J. Rojo and M. Ubiali

$$\mathcal{O}_{lq} = \left(\bar{l}_R \gamma^\mu l_R\right)\left(\bar{q}_R \gamma_\mu q_R\right) \;,\; q = u, d, s, c \,,$$





$$\Delta F_2^{\text{smeft}} \supset \frac{x}{12e^4}\left(4a_u e^2 \frac{Q^2}{\Lambda^2}(1 + 4K_Z s_W^4) + 3a_u^2 \frac{Q^4}{\Lambda^4}\right) \times \left(u(x,Q^2) + \bar{u}(x,Q^2)\right)$$

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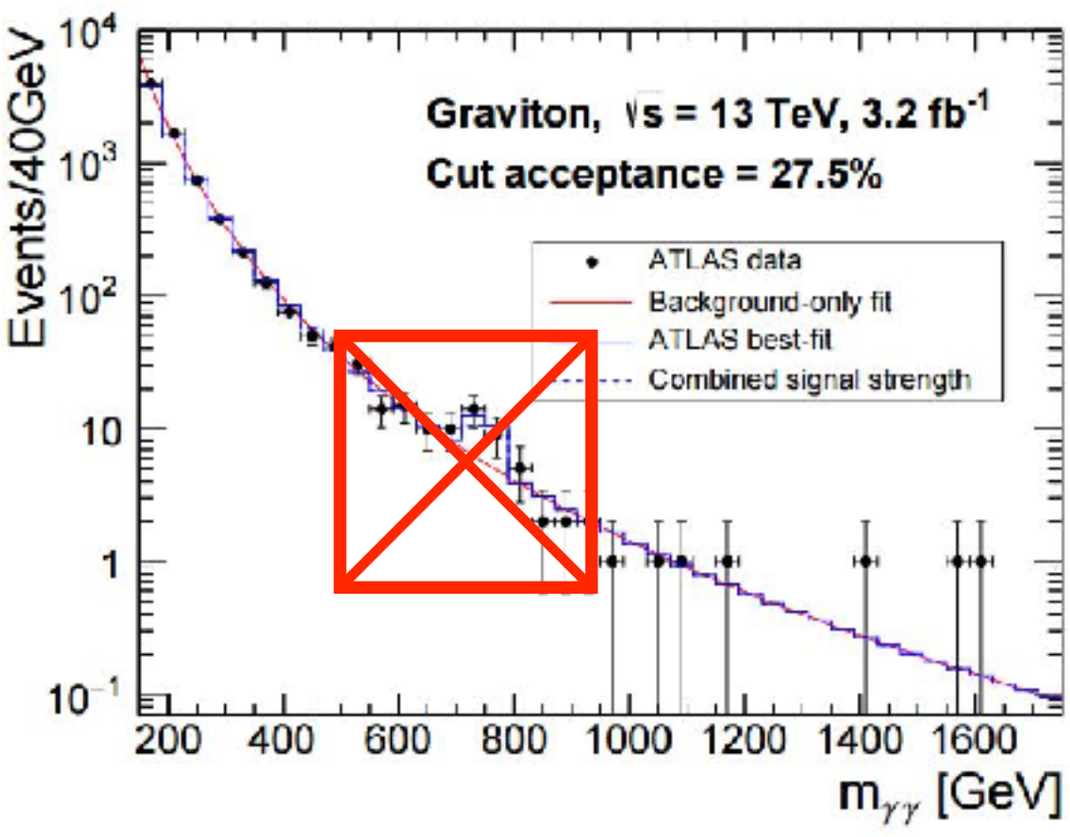

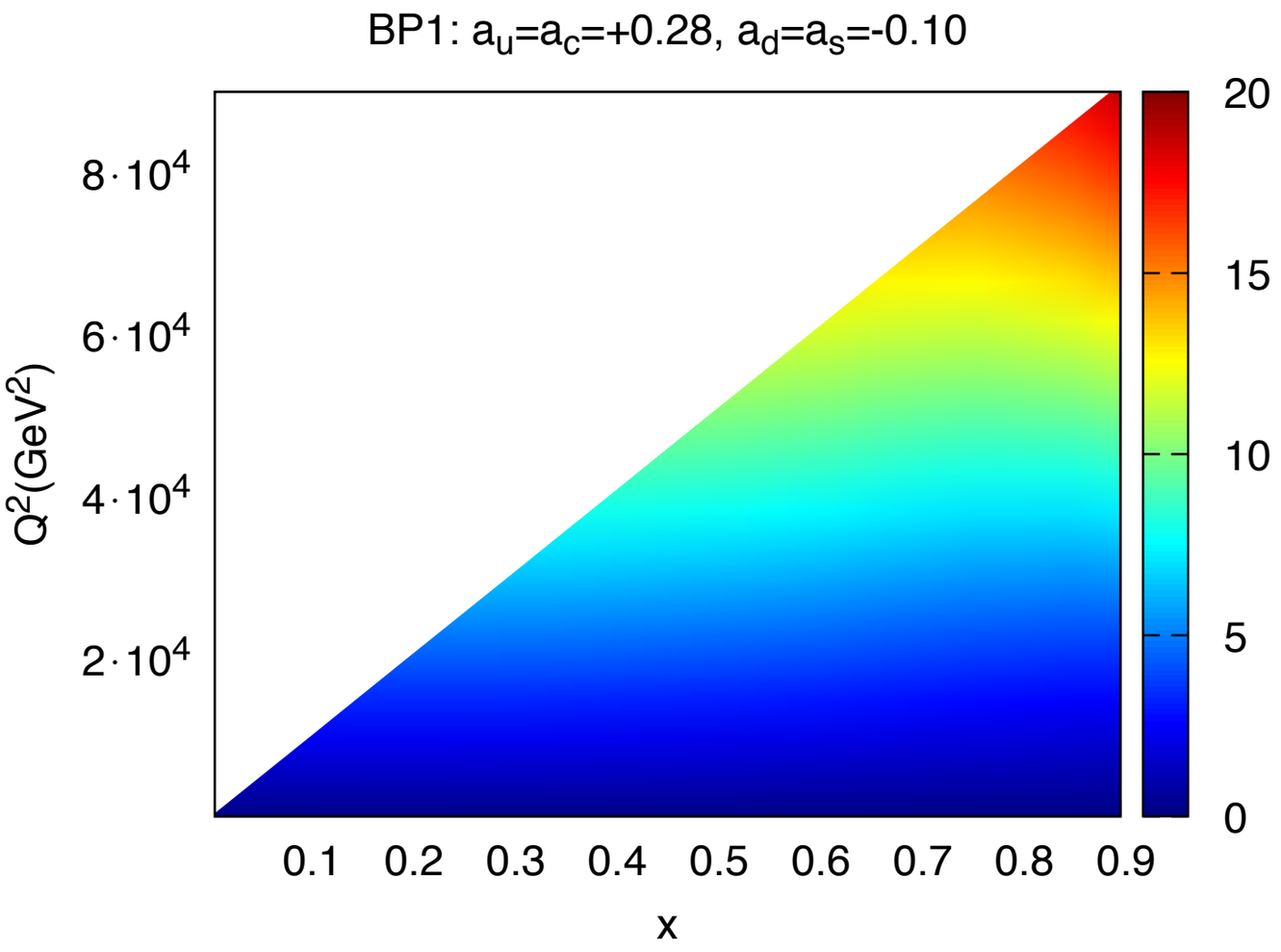

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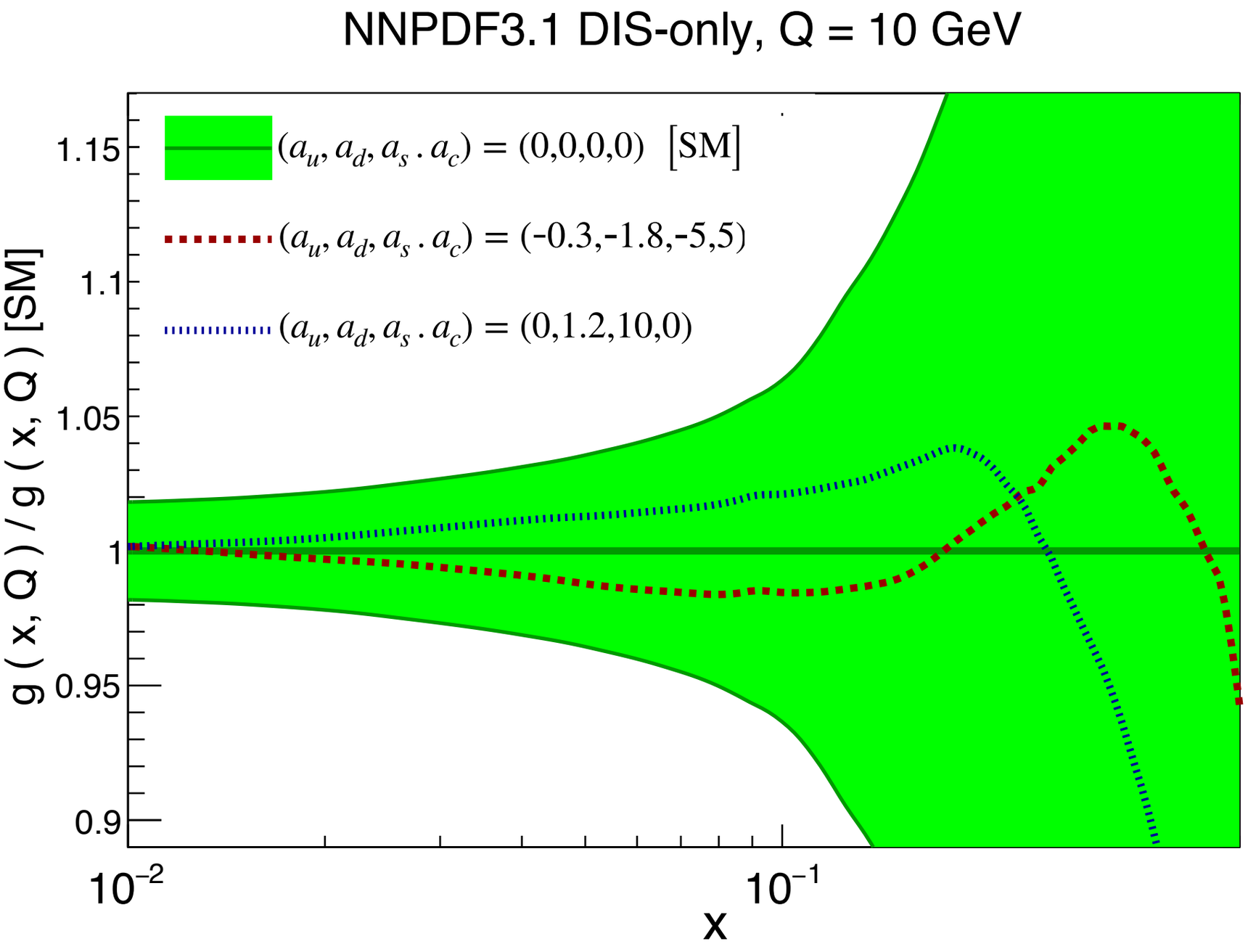
EFT and PDF



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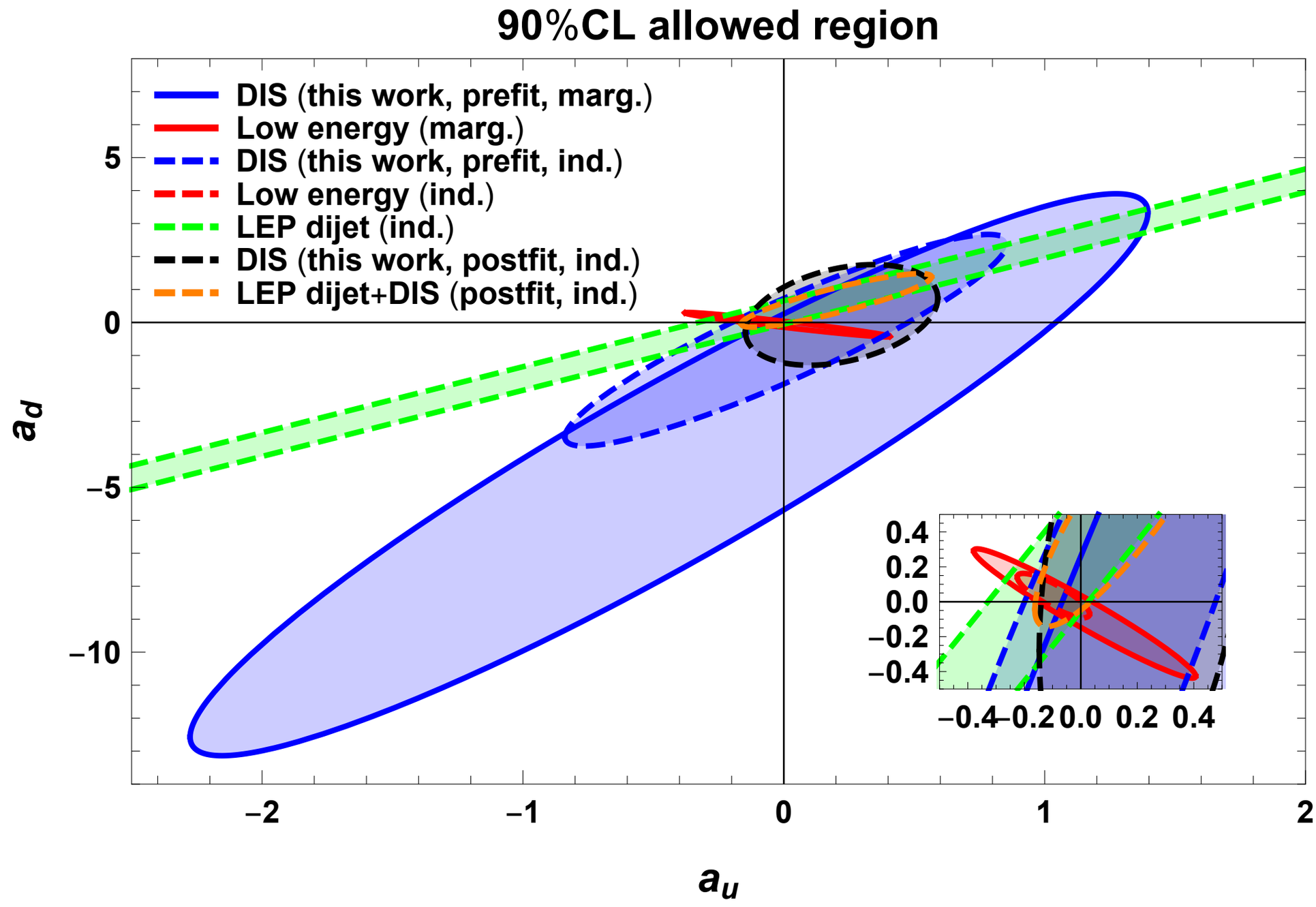
EFT and PDF



C. Degrande

Summary

Looking for new physics

C. Degrande

Summary

- EFT provide guidance (which observable)
- Check the validity of the single EFT assumption
- Int(SM,dim6) suppression: observables
- EFT is multi-channel/observable : correlation
- Global fit with a large number of parameters
- Distinguish PDF and EFT
- provide NLO for EFT

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Summary

Thank you

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