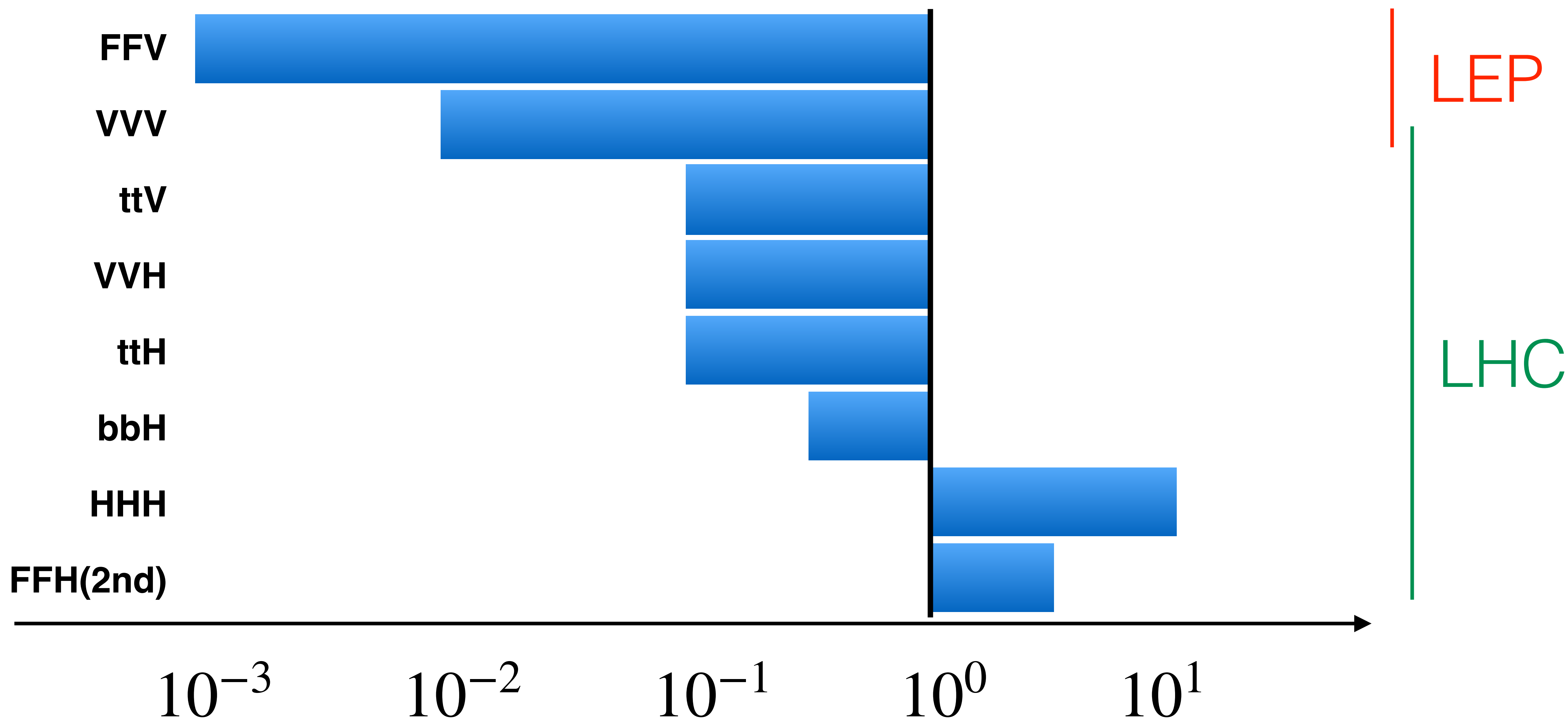
Effective field theory

Precision: LEP vs LHC

How well do we know the SM?



LHC<LEP: QCD perturbative (α_S) and non-pert. (PDF,hadronisation), backgrounds, …

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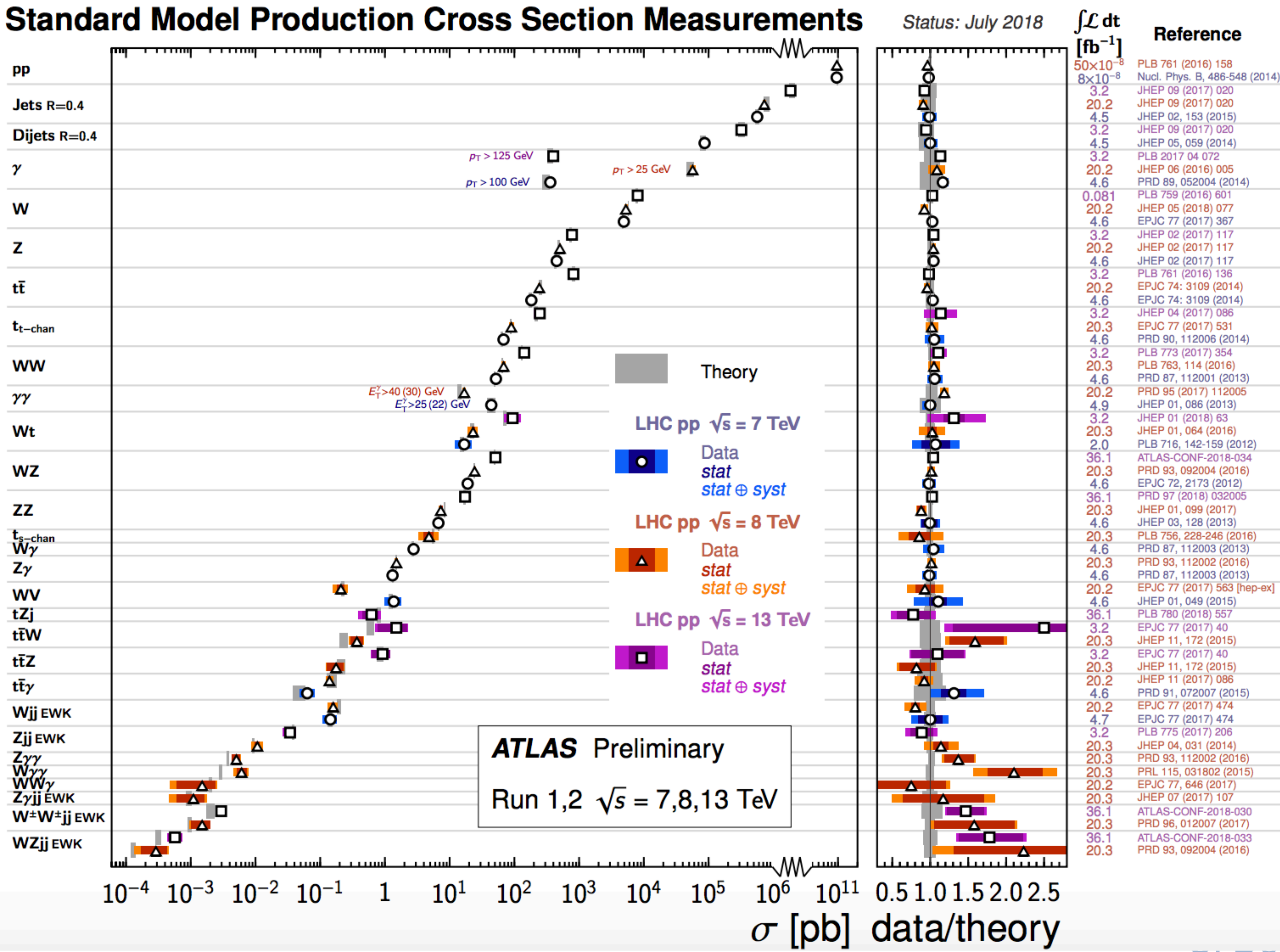
Precision era at the LHC

Multiplicity, power of α_{EW}, masses



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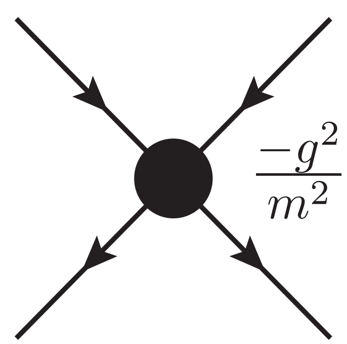
Indirect detection of NP

- Assumption : NP scale >> energies probed in experiments

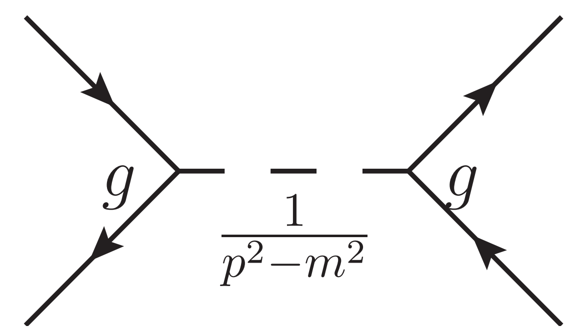
E

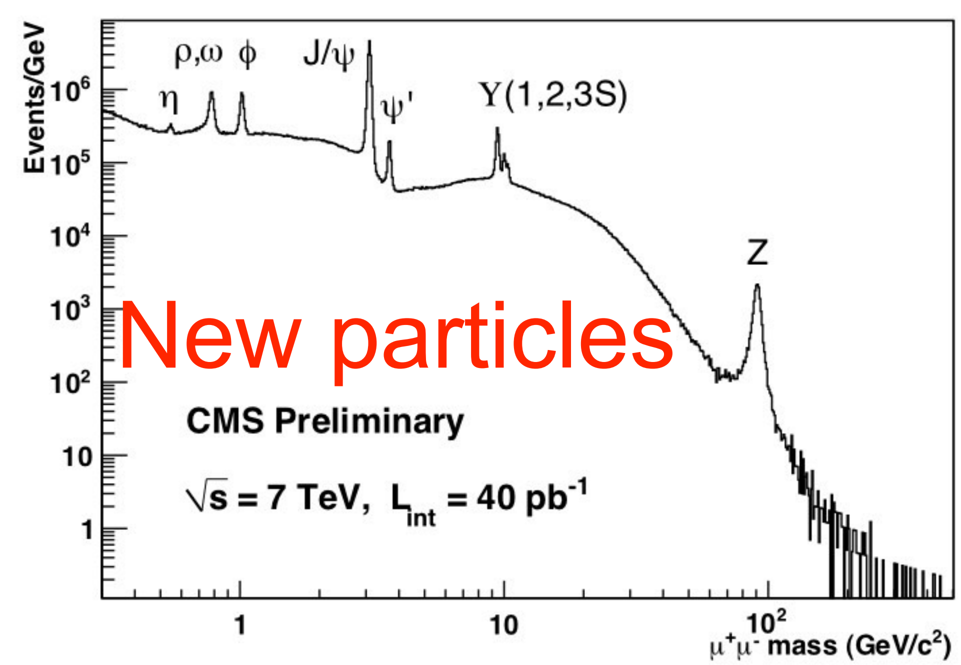
Exp. range

NP scale



$$p^2 \ll m^2$$





New particles

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

New/modified interactions between SM particles

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EFT

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

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.

- 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
- higher the exp. precision => smaller EFT error

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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.

- 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
- SM is the leading term : EFT for precision physics
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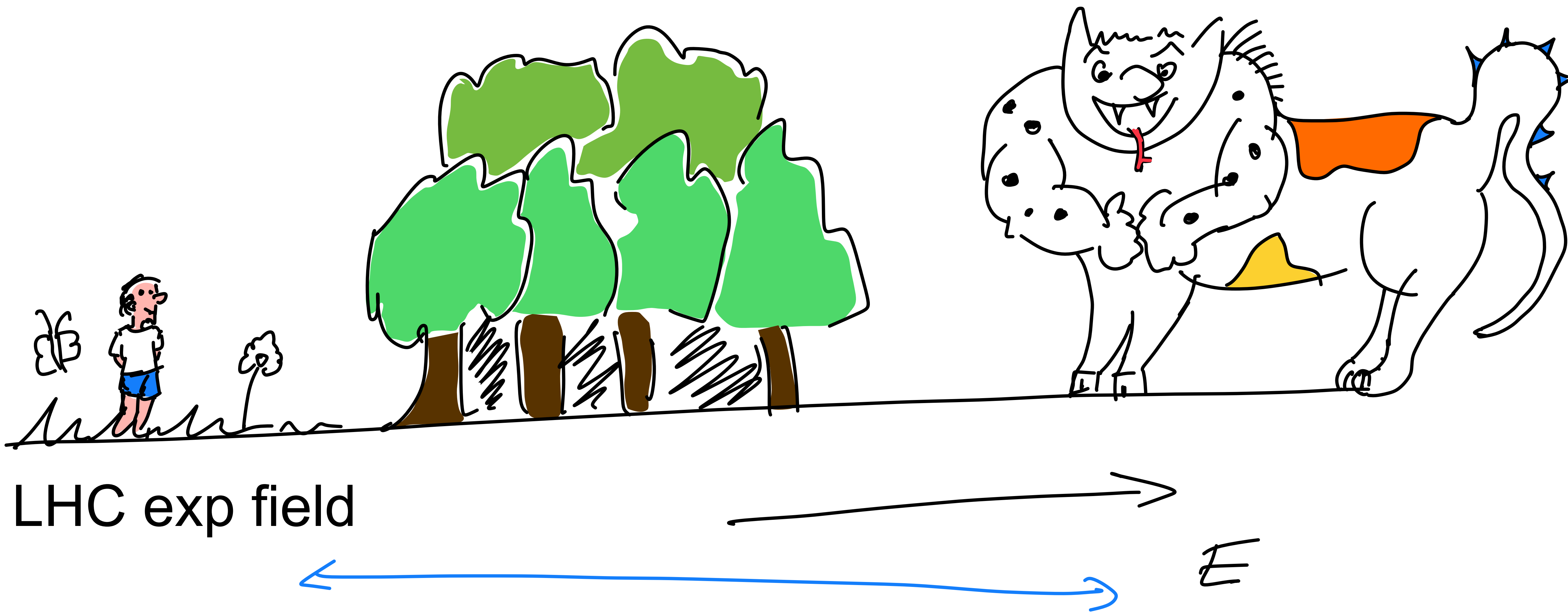
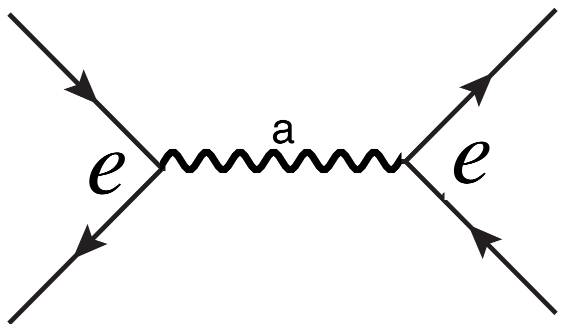
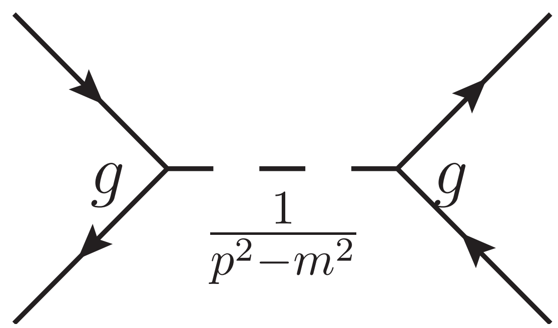
One hypothesis



Validity: How far?

How big of a gap?





$$\frac{e^2}{p^2} + \ldots \frac{g^2}{m^2} + \mathcal{O}\left(\frac{p^2}{m^4}\right)$$

$$\frac{e^2}{p^2}\left(1 + \ldots g^2\frac{p^2}{m^2} + \mathcal{O}\left(\frac{p^4}{m^4}\right)\right)$$

$$\boxed{p^2/m^2 \sim 0.1}$$

Weakly $\quad g^2 \lesssim 1$

p^2/m^2

dim

$$g^2\frac{p^2}{m^2} \quad < \quad g^2\frac{p^4}{m^4}$$

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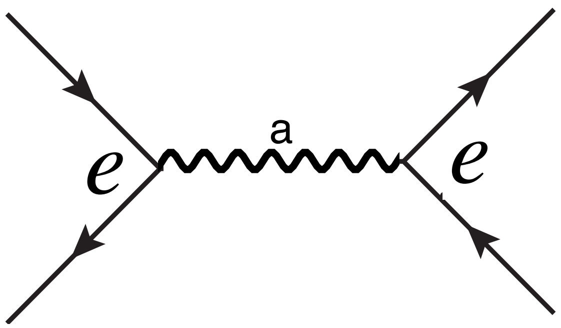
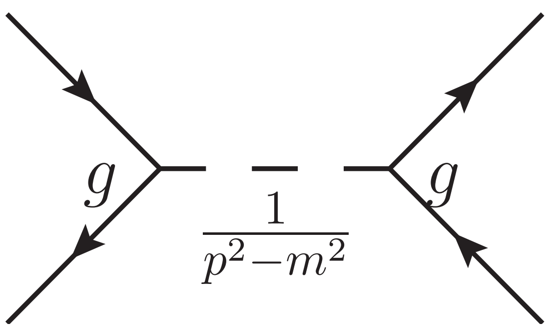
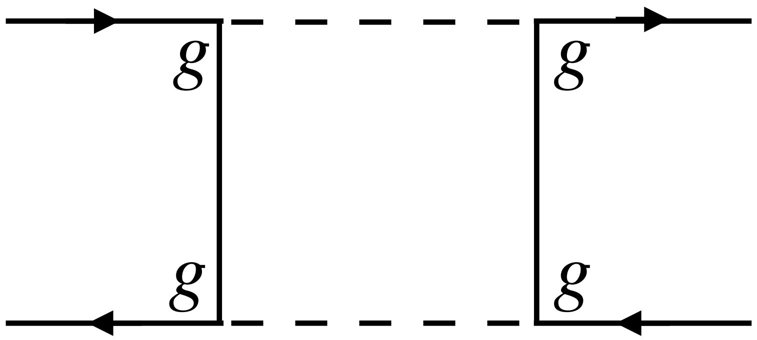
How big of a gap?







$$\frac{e^2}{p^2} + \ldots \frac{g^2}{m^2} + \mathcal{O}\left(\frac{p^2}{m^4}\right)$$

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p^2/m^2

dim

$$g^2\frac{p^2}{m^2} \quad < \quad g^2\frac{p^4}{m^4}$$

$$g^4\frac{p^2}{m^2} \quad < \quad g^4\frac{p^4}{m^4}$$

g^2

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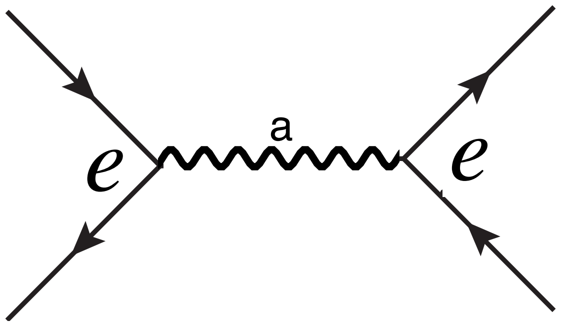
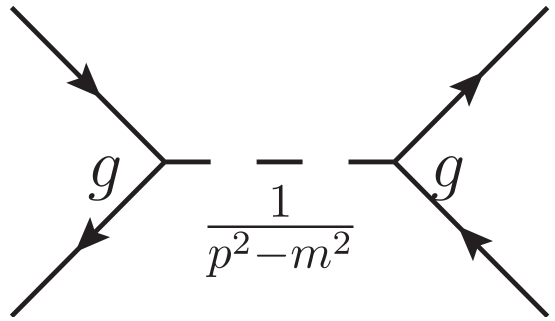
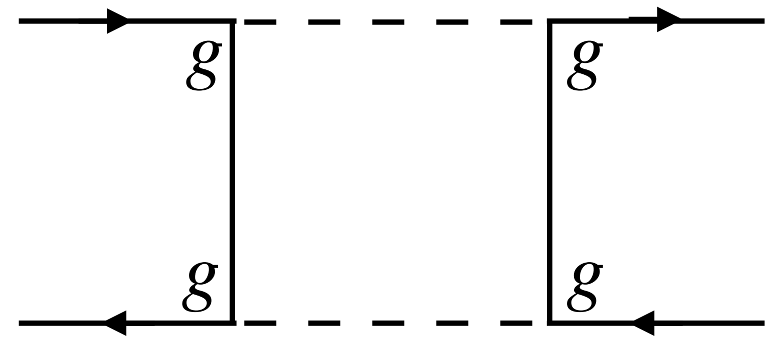
How big of a gap?







$$\frac{e^2}{p^2} + \ldots \frac{g^2}{m^2} + \mathcal{O}\left(\frac{p^2}{m^4}\right)$$

$$\frac{e^2}{p^2}\left(1 + \ldots g^2\frac{p^2}{m^2} + \mathcal{O}\left(\frac{p^4}{m^4}\right)\right)$$

$$\boxed{p^2/m^2 \sim 0.1}$$

Weakly $g^2 \lesssim 1$

Strongly $g^2 \sim 10$

p^2/m^2

dim

$$g^2\frac{p^2}{m^2} \quad < \quad g^2\frac{p^4}{m^4}$$

$$\approx$$

$$g^4\frac{p^2}{m^2} \quad < \quad g^4\frac{p^4}{m^4}$$

g^2

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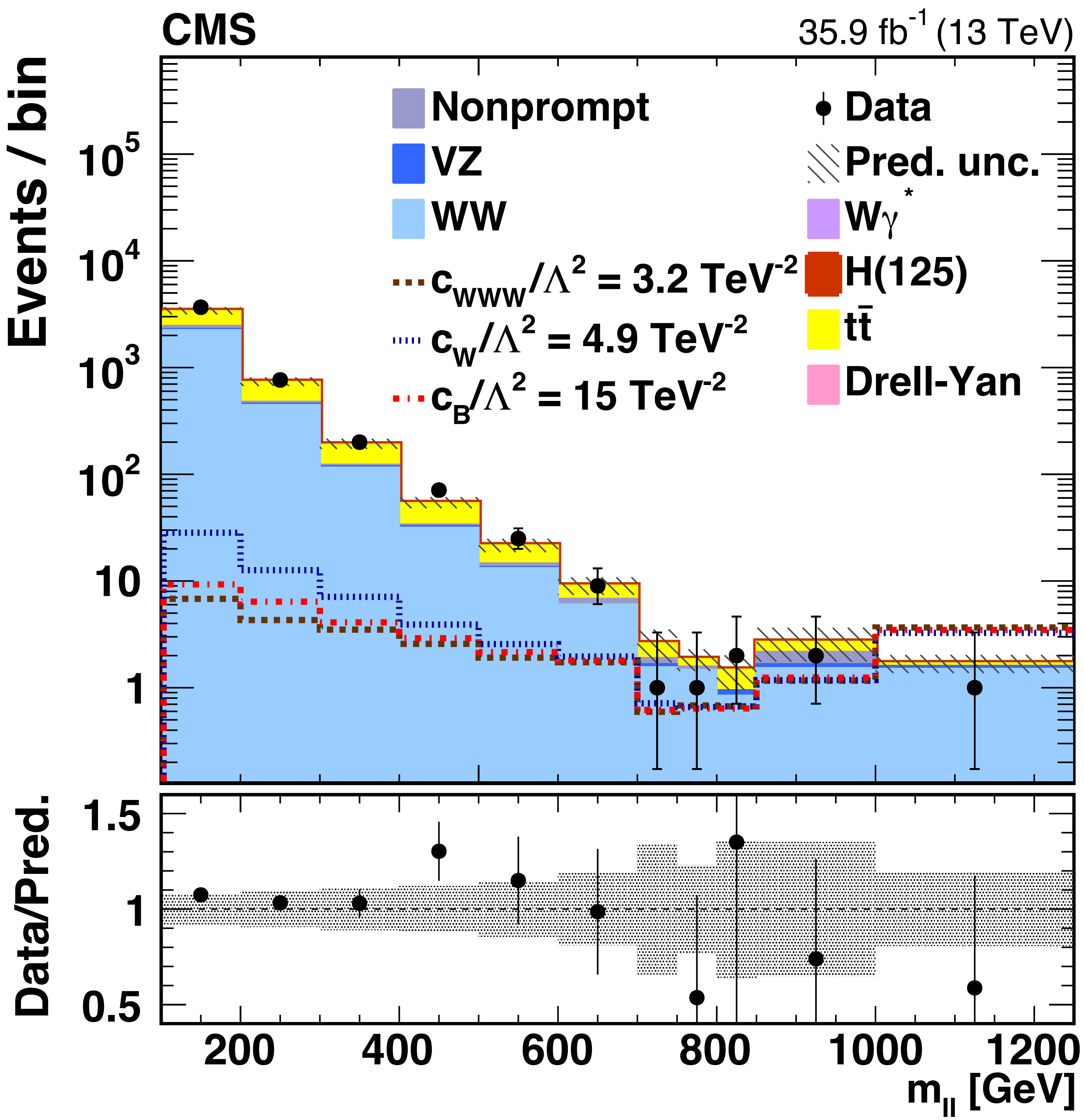
High energy tails



2009.00119

Cross-sections and precision plummet at high energy

EFT/SM is larger at H.E. but so are the EFT errors

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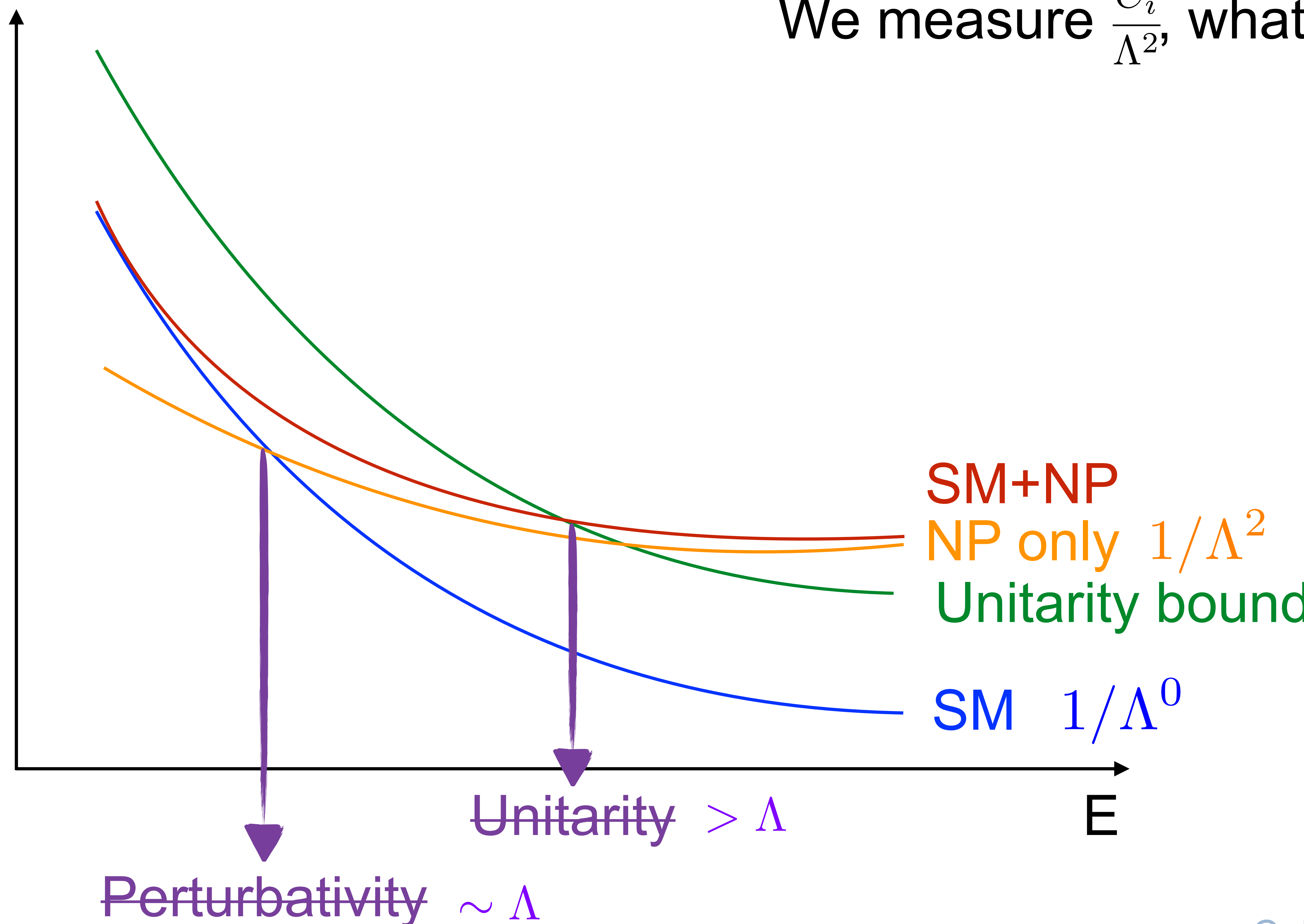
EFT & scales

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



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EFT & scales

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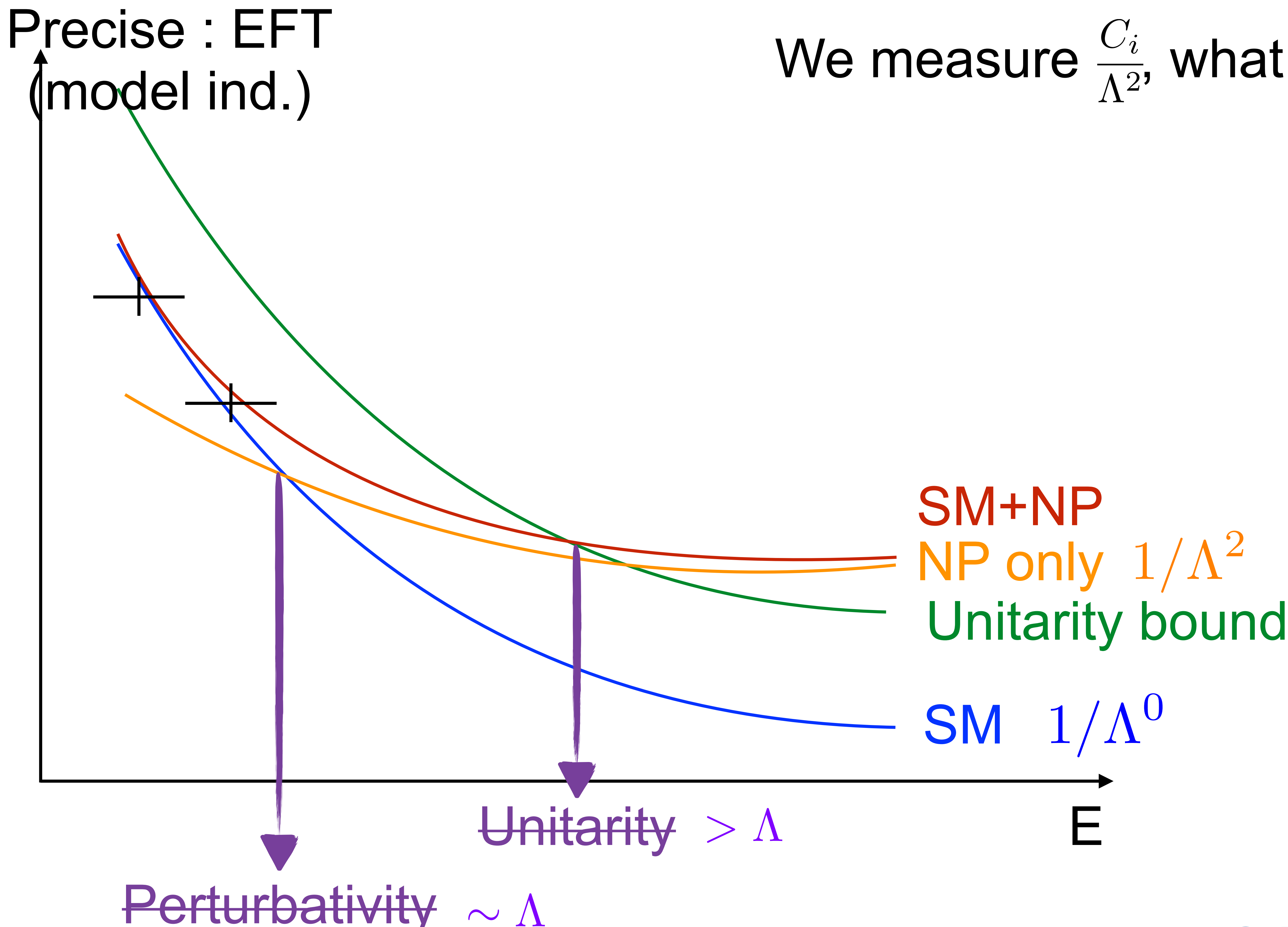

C. Degrande

EFT & scales

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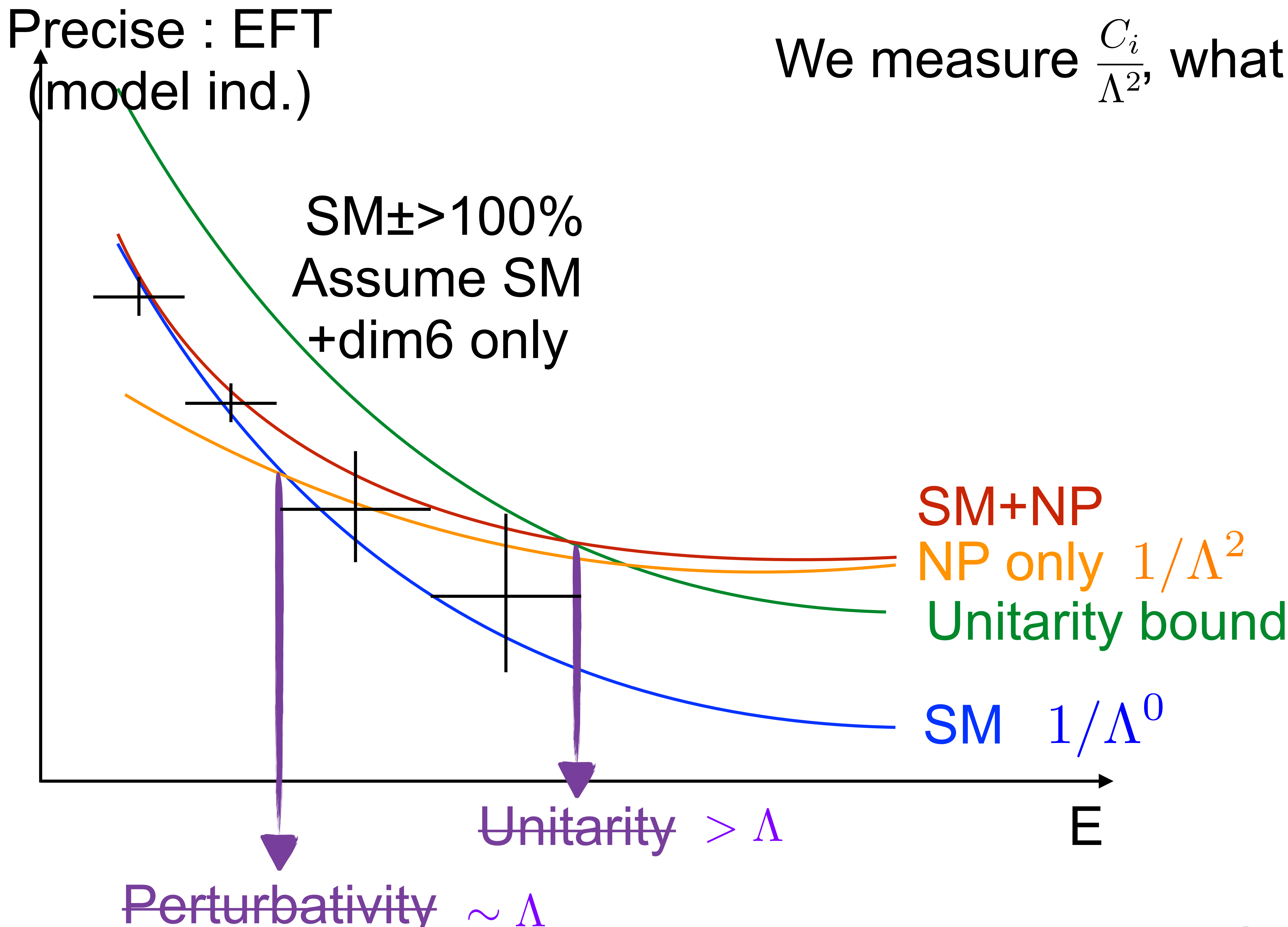

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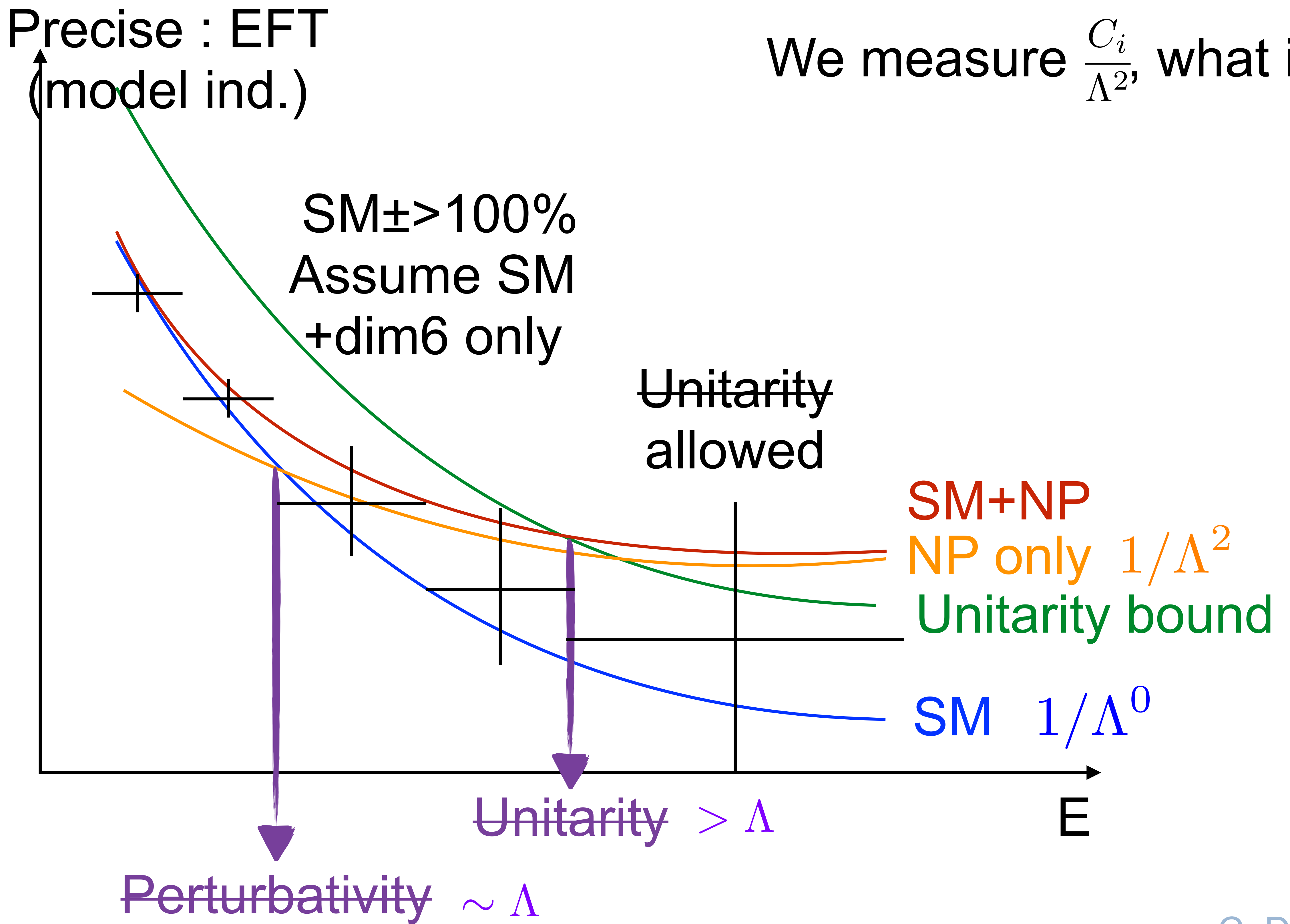

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EFT & scales

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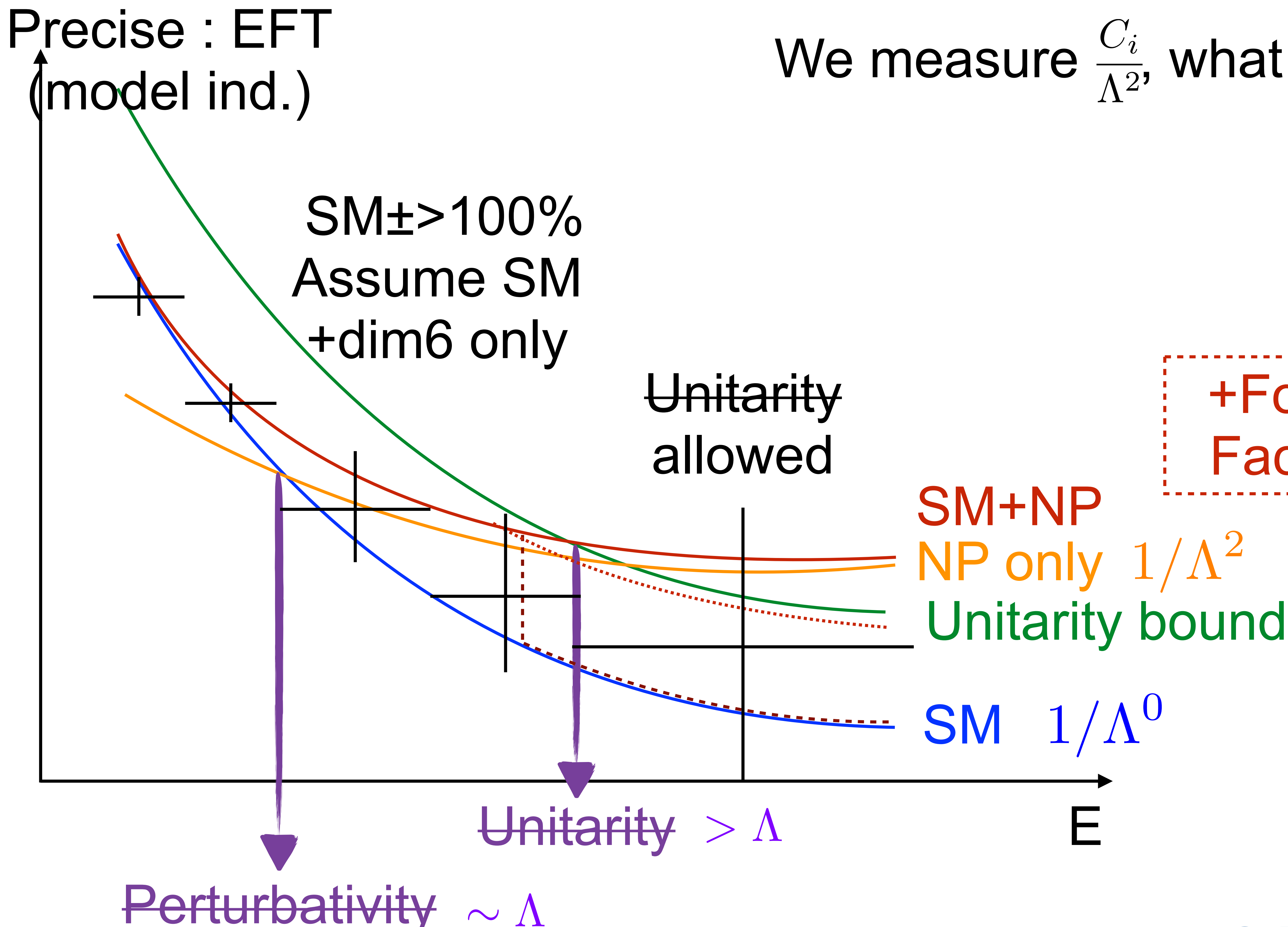

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0/2F operators

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

New interactions + param/field redefinitions

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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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

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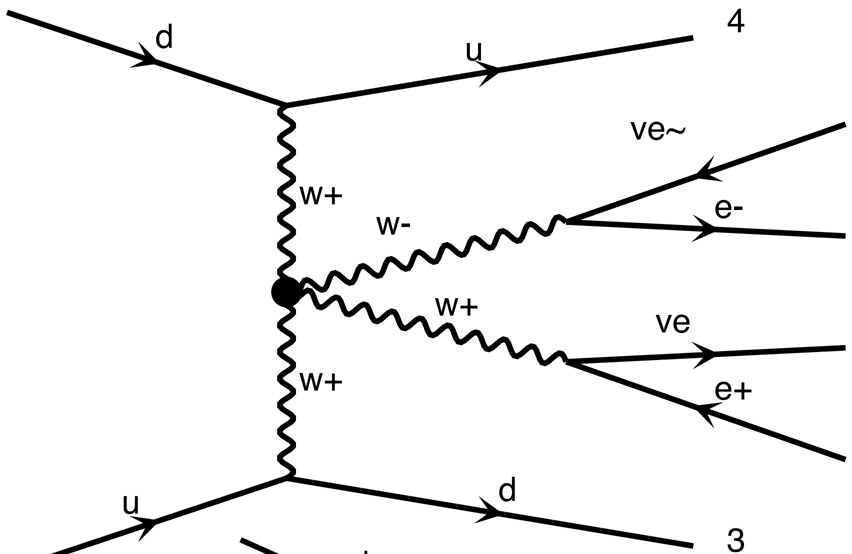
VBS

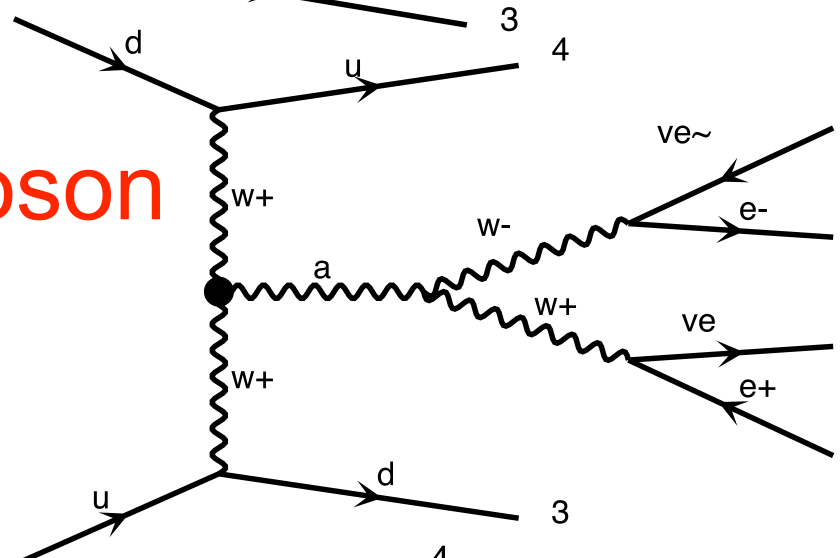
Operators → ↓ Processes	Q_{HD}	$Q_{H\Box}$	Q_{HWB}	$Q_{Hq}^{(1)}$	$Q_{Hq}^{(3)}$	Q_{HW}	Q_{W}	$Q_{Hl}^{(1)}$	$Q_{Hl}^{(3)}$	$Q_{ll}^{(1)}$	$Q_{qq}^{(3)}$	$Q_{qq}^{(3,1)}$	$Q_{qq}^{(1,1)}$	$Q_{qq}^{(1)}$	Q_{ll}
WW	✓		✓	✓	✓		✓	(✓)	✓	✓					
SSWW+2j EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
OSWW+2j EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
WZ+2j EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZZ+2j EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZV+2j EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
OSWW+2j QCD	✓		✓	✓	✓		✓	✓	✓	✓					
WZ+2j QCD	✓		✓	✓	✓		✓	✓	✓	✓					(✓)
ZZ+2j QCD	✓		✓	✓	✓			✓	✓	✓					(✓)
ZV+2j QCD	✓		✓	✓	✓		✓	✓	✓	✓					

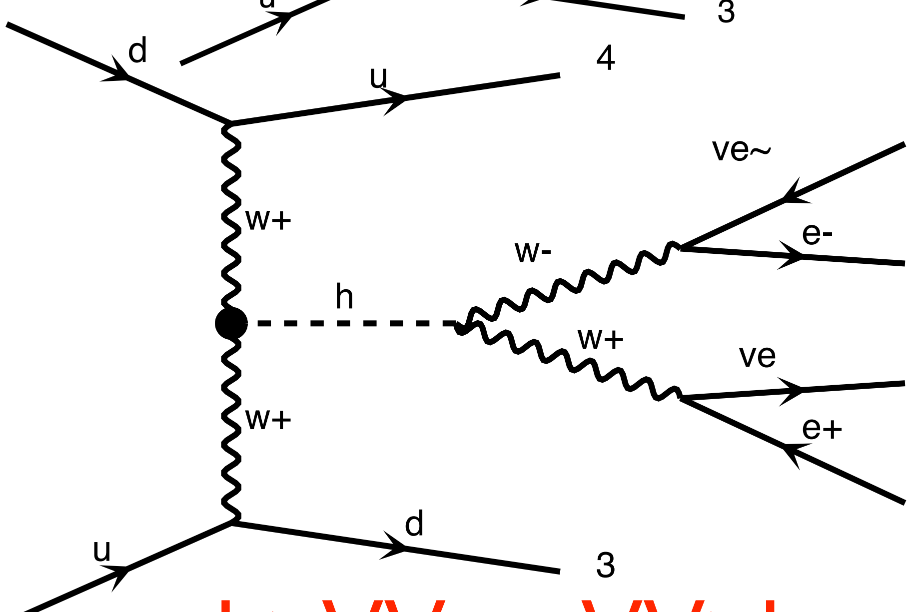
Bellan et al., 2108.03199

VBS

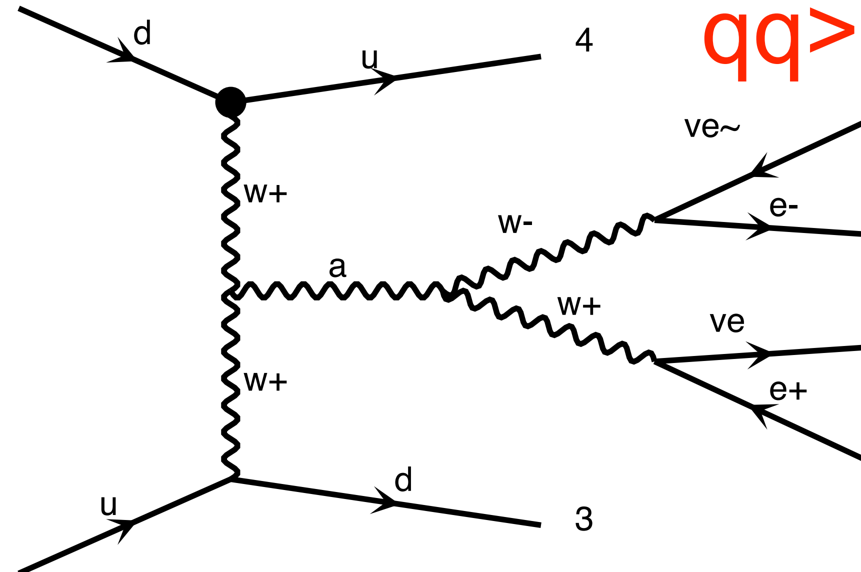


Diboson

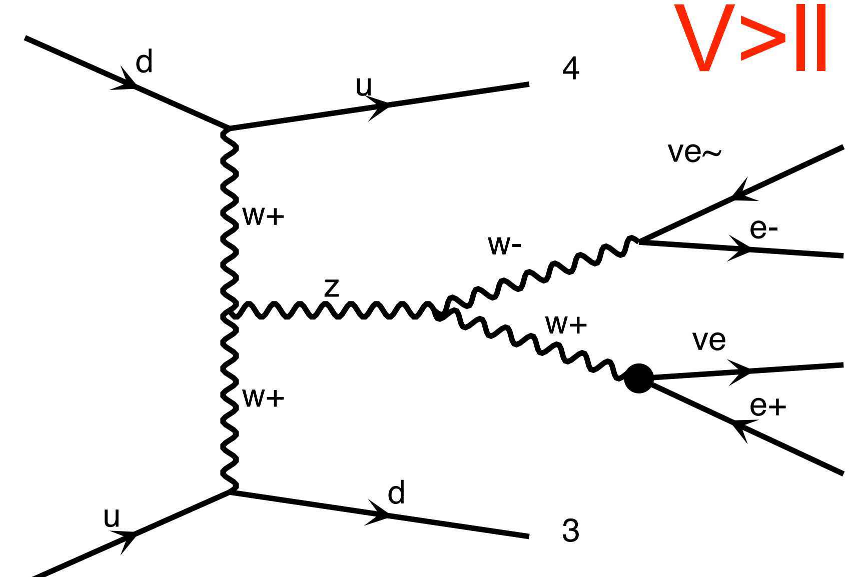




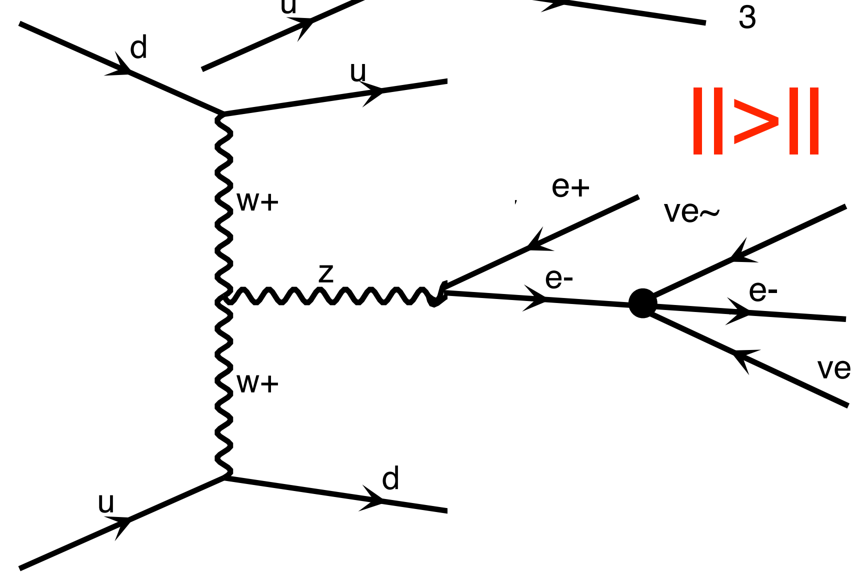
h>VV or VV>h



qq>V or V>qq



V>ll or ll>V



ll>ll

qq>qq

+ with 4q

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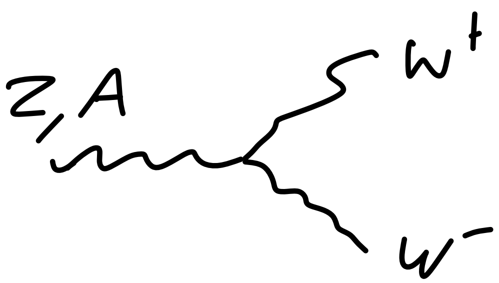
Pure gauge

$$Q_W \quad \Big| \; \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

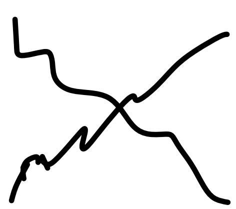


$\propto p^3$

TGC

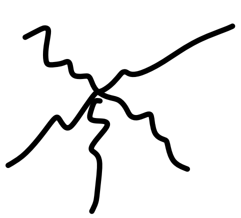
Together by gauge inv

QGC

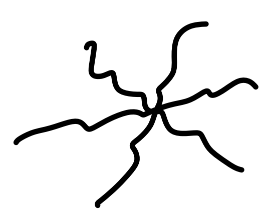


WWWW, WWZZ, WWZA, WWAA

$\propto p^2$



$\propto p$



$\propto p^0$

similar for Gluon

and ~~CP~~

diboson, VBF, VBS, multiboson

n-jets $n \geq 2$ in principle

No neutral TGC (ZZA, ZAA)

Higgs operators

Potential/self-coupling modification

$$\frac{c_\varphi}{\Lambda^2}\left(\frac{h+v}{\sqrt{2}}\right)^6 + \mu^2\left(\frac{h+v}{\sqrt{2}}\right)^2 - \lambda\left(\frac{h+v}{\sqrt{2}}\right)^4$$

$\hookrightarrow hv\left(\mu^2 - \lambda v^2 + \frac{3}{2}\frac{c_\varphi}{\Lambda^2}v^4\right) + h^2\ldots$

$+h^3\ldots \quad + h^4\ldots$

$\hookrightarrow$ ---x modification of $v-\mu^2-\lambda$ relation

Q_φ	$(\varphi^\dagger\varphi)^3$
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$

or $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3 \longrightarrow$ only  $\neq$ SM but only one free parameter

$n\,h$ with $n \geq 2$

Field redefinition

$\ni h\Box h \overset{\text{by part}}{=} \partial_\mu h\,\partial^\mu h \qquad h \to h\left(1 + \frac{c_{\varphi\Box}v^2}{\Lambda^2}\right)$

change all the SM Higgs coupling

$FFh \longrightarrow y_F\left(1 + \frac{c_{\varphi D}v^2}{\Lambda^2}\right), \ldots$ by the same amount

h prod & decay

Mass redefinition

$$+\frac{c_{\varphi D}}{\Lambda^2}\frac{v^4}{16}\left(-g_2 W_3^\mu + g_1 B^\mu\right)^2$$

External parameter dependent

any weak process, $nhZZ$, nhZ, nh $(1 \leq n \leq n)$

C. Degrande

Higgs-Fermion

$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$

break the mass-coupling relation

$$\ni \left(v^3 \, \bar{u}_L u_R \to m_u = y_u v + \frac{c_{u\varphi}}{\Lambda^2} v^3 \right.$$
$$\left. + \, 3 h v^2 \bar{u}_L u_R + \dots \right)$$

mass & coupling have $\neq$ contributions

OR $$\underbrace{\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)}_{\left(hv + \frac{h^2}{2}\right)} \underbrace{\left(\bar{q} \, u \, \tilde{\varphi}\right)}_{\left(\bar{u}_L u_R \left(\frac{h+v}{\sqrt{2}}\right)\right)}$$

h prod & decay

only change , no mass redefinition

! one operator for each fermion unless FLAVOUR assumption

multi Higgs

More Higgs and gauge

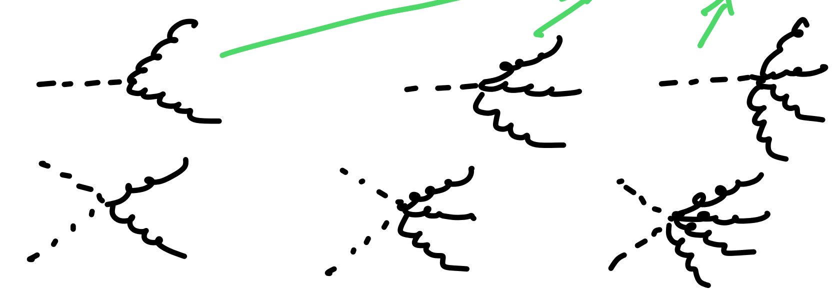
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{\varphi \widetilde{G}}$	$\varphi^\dagger \varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{\varphi \widetilde{W}}$	$\varphi^\dagger \varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi \widetilde{B}}$	$\varphi^\dagger \varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi \widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$\longrightarrow \ni \frac{v^2}{2} G^A_{\mu\nu} G^{\mu\nu}_A$

Modification of the kinetic term

Field redefinition or

$(\varphi^+\varphi - v^2/2) \to$ only



$\propto v$

$\propto p^2$ $\quad \propto p$ $\quad \propto p^0$

Not allowed: A-Z mixing

$\frac{c_{\varphi WB}}{\Lambda^2} \frac{v^2}{4} W^3_{\mu\nu} B^{\mu\nu} \to$ kinetic mixing

$\downarrow$

mass mixing

depend on which external parameters are chosen

$h \to VV$, hV $\quad V = Z, W, \gamma, g$

$VV \to h$, VBS ...

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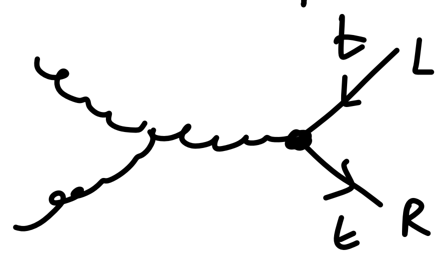
Dipoles

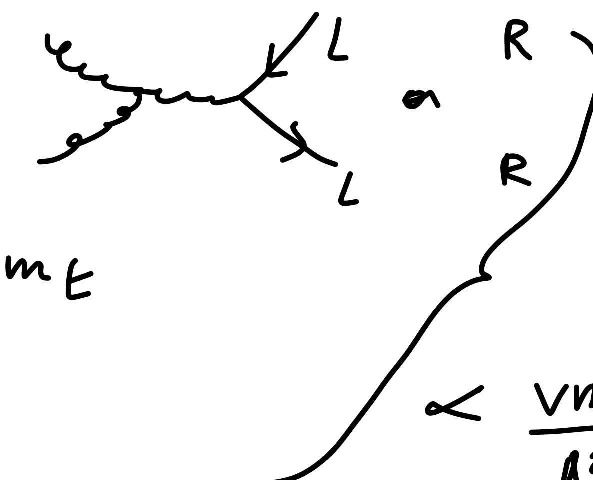
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$

like EDM or MDM

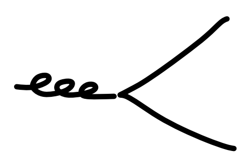
$\downarrow$ $\cancel{CP}$ $\quad$ $\downarrow$ CP

L – R operators

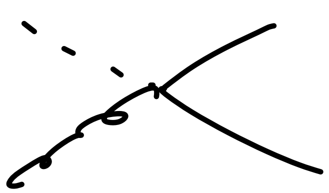




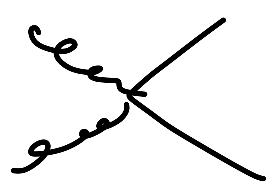
$\propto \frac{v m}{\Lambda^2}$



$\propto v\, p$



$\propto p$



$\propto v$

same for other gauge bosons (W, Z, γ)

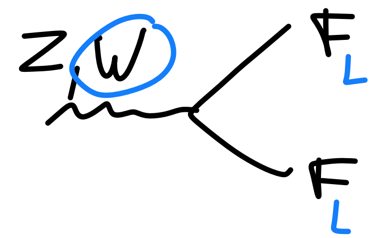
$t\bar{t}h$, single top, ...

C. Degrande

Higgs, gauge and fermion

$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$\rightarrow Z\, F_R\, F_R$

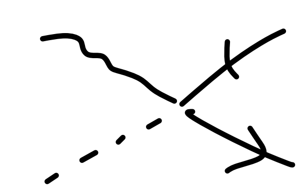


like SM (γ^μ)

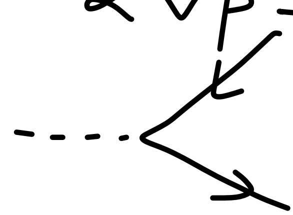
V prod & decay

No $\gamma F F$ with γ^μ because of $U(1)_{EM}$

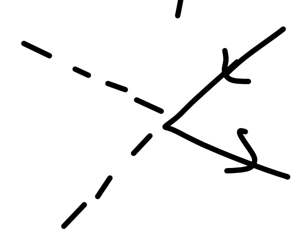
\+ $\propto v$

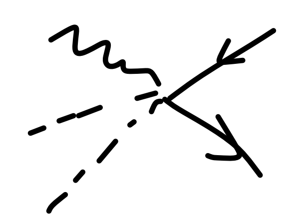


$\propto v p \rightarrow \propto m_F$



$\propto p$





hV

h decay

di Higgs

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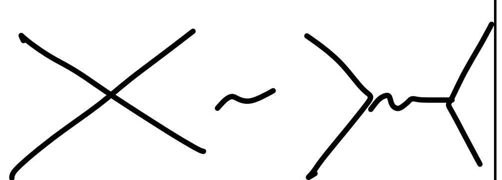
4F

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

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

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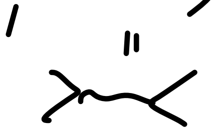
Comments

more legs → more operators

more loop ↗

Weak bosons (Z, W, h) are never observed (+decay, 4F)



SM parameter relation → fit of c_i & SM param

SMEFT is almost everywhere → including in background!

↳ PDF are extracted from data assuming SM

Flavour!

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(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

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

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Width, W helicities and …

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

$$\left.\begin{aligned} \frac{\Gamma_t}{GeV} &= \Gamma_{SM} + \left[0.17\frac{C_{\phi q}^{(3)}}{\Lambda^2} + 0.23\frac{C_{tW}}{\Lambda^2}\right]\mathrm{TeV}^2 \\ \Gamma^{meas} &= 1.42^{+0.19}_{-0.15}\ \mathrm{GeV} \\ \Gamma_{SM}^{**} &= 1.33\,\mathrm{GeV} \end{aligned}\right\} \frac{C_{\phi q}^{(3)}}{\Lambda^2} + 1.35\frac{C_{tW}}{\Lambda^2} = 4^{+2.8}_{-2.5}\mathrm{TeV}^{-2}$$

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

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

$$\frac{C_{\phi q}^{(3)}}{\Lambda^2} = 1.1^{+2.3}_{-2.1}\mathrm{TeV}^{-2}$$

$$\left.\begin{aligned} F_0^{SM*} &= 0.687 \pm 5 \\ F_0^{meas**} &= 0.66 \pm 5 \end{aligned}\right\} \frac{C_{tW}}{\Lambda^2} = 0.44 \pm 0.9\mathrm{TeV}^{-2}$$

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4F and Validity

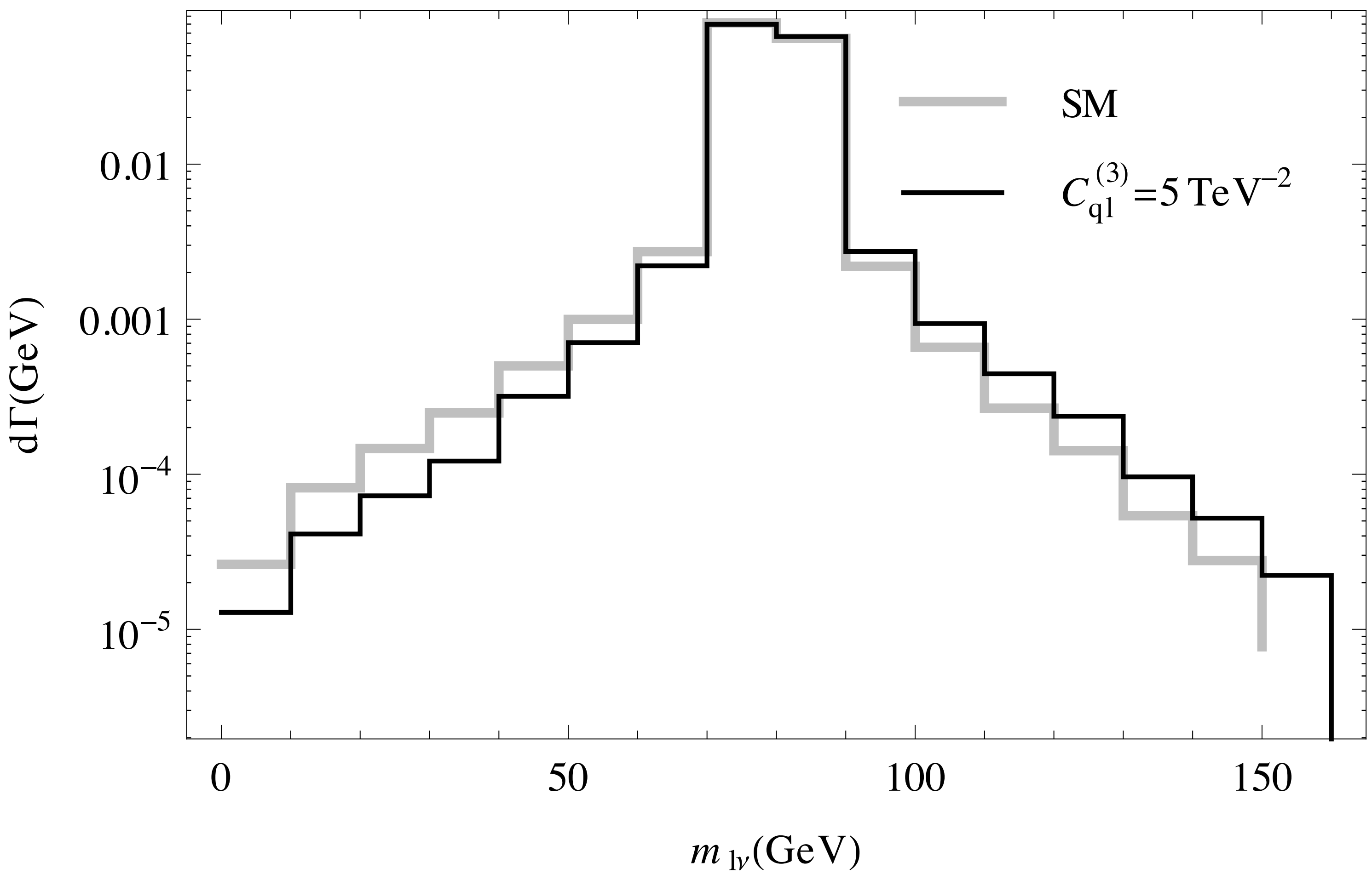
$$\frac{1}{2}\Sigma|M|^2 = \frac{V_{tb}^2 g^4 u(m_t^2-u)}{2(s-m_W^2)^2} + \frac{4C_{ql}^{(3)}}{\Lambda^2}\frac{g^2 u(m_t^2-u)}{s-m_W^2}$$

$$\frac{c}{\Lambda^2} \sim \frac{1}{(1\,\mathrm{TeV})^2}$$

$$s = m_t^2$$

$$\frac{m_t^2}{(1\,\mathrm{TeV})^2} \sim (0.2)^2 = 4\%$$

$$\left(\frac{m_t^2}{(0.5\,\mathrm{TeV})^2}\right) \sim (0.4)^2 = 16\%$$



Exp error ~ 10%

Almost pure shape effect

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SMEFT and interference

Errors : higher power of $1/\Lambda$

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

- Contains :
  - 1 dim6 insertion squared
  - interference with 2 dim6 insertions
  - interference with 1 dim8 insertion
  - … at $1/\Lambda^{-6}$
- Error (estimate)

usually not included

Dimension 8 basis: Li et al., 2005.00008

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Errors : higher power of $1/\Lambda$

$$|M(x)|^2 = \boxed{|M_{SM}(x)|^2} + \boxed{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)} + \boxed{|M_{d6}(x)|^2 + \ldots}$$

Λ^0 $\quad$ Λ^{-2} $\quad$ $\mathcal{O}\left(\Lambda^{-4}\right)$

$\mathcal{O}(1)$ $\quad$ $\mathcal{O}(0.1)$ $\xleftrightarrow{10\%}$ $\mathcal{O}(0.01)$

$\mathcal{O}(1)$ $\quad$ $\mathcal{O}(0.5)$ $\xleftrightarrow{50\%}$ $\mathcal{O}(0.25)$

- Contains :
  - 1 dim6 insertion squared
  - interference with 2 dim6 insertions
  - interference with 1 dim8 insertion
  - … at $1/\Lambda^{-6}$
- Error (estimate)

usually not included

Dimension 8 basis: Li et al., 2005.00008

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interference suppression

Azatov et al., Helicity Selection Rules and Non-Interference for BSM Amplitudes, 1607.05236

A_4	$\|h(A_4^{\mathrm{SM}})\|$	$\|h(A_4^{\mathrm{BSM}})\|$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

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interference suppression

Azatov et al., Helicity Selection Rules and Non-Interference for BSM Amplitudes, 1607.05236

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

$$|M(x)|^2 = \underbrace{\boxed{|M_{SM}(x)|^2}}_{\Lambda^0} + \underbrace{\boxed{2\Re\left(M_{SM}(x)M_{d6}^*(x)\right)}}_{\Lambda^{-2}} + \underbrace{\boxed{|M_{d6}(x)|^2 + \ldots}}_{\Lambda^{-4}} + \mathcal{O}(\Lambda^{-6})$$

$\mathcal{O}(1)$ ~0 $\mathcal{O}(0.1)$ 30% $\mathcal{O}(0.03)$

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interference suppression

Azatov et al., Helicity Selection Rules and Non-Interference for BSM Amplitudes, 1607.05236

A_4	$\lvert h(A_4^{\mathrm{SM}})\rvert$	$\lvert h(A_4^{\mathrm{BSM}})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2

$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

$$|M(x)|^2 = \underbrace{\boxed{|M_{SM}(x)|^2}}_{\Lambda^0} + \underbrace{\boxed{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)}}_{\Lambda^{-2}} + \underbrace{\boxed{|M_{d6}(x)|^2 + \ldots}}_{\Lambda^{-4}} + \mathcal{O}(\Lambda^{-6})$$

$\mathcal{O}(1)$ ~0 $\mathcal{O}(0.1)$ 30% $\mathcal{O}(0.03)$

Assuming ~0

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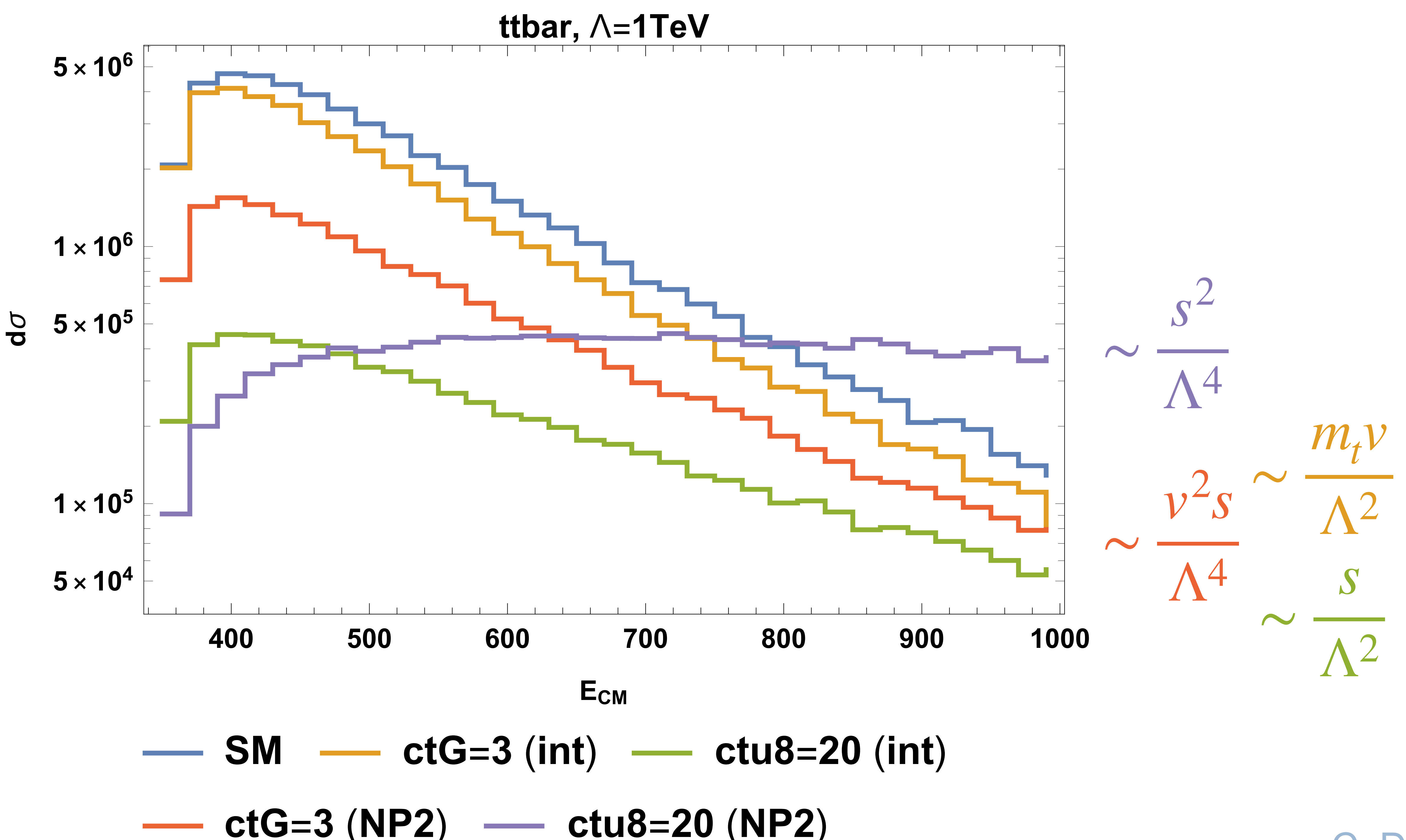
top pair production

4F interfere only with qq



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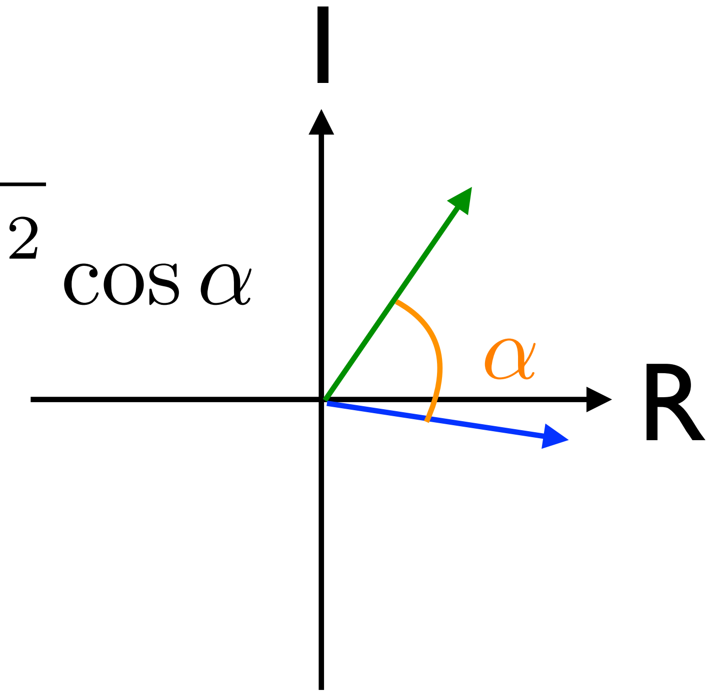
Interference

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

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

mom&spin

Not always positive



Can be suppressed

$$\sigma \propto \sum_x |M(x)|^2 \quad \textbf{if} \quad \begin{array}{l} M_{SM}(x_1) = 1,\ M_{SM}(x_2) = 0 \\ M_{d6}(x_1) = 0,\ M_{d6}(x_2) = 1 \end{array} \qquad \sigma_{int} = 0$$

Observable dependent

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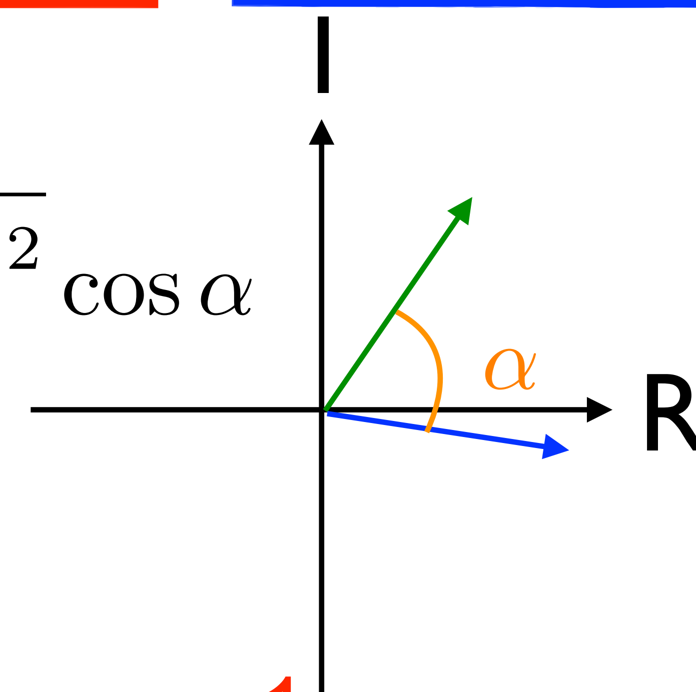
Interference

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

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



mom&spin

Not always positive

Can be suppressed

$$\sigma \propto \sum_x |M(x)|^2 \quad \text{if} \quad \begin{array}{l} M_{SM}(x_1) = 1,\ M_{SM}(x_2) = \overset{1}{\cancel{0}} \\ M_{d6}(x_1) = \underset{-1}{\cancel{0}},\ M_{d6}(x_2) = 1 \end{array}$$

$$\sigma_{int} = 0$$

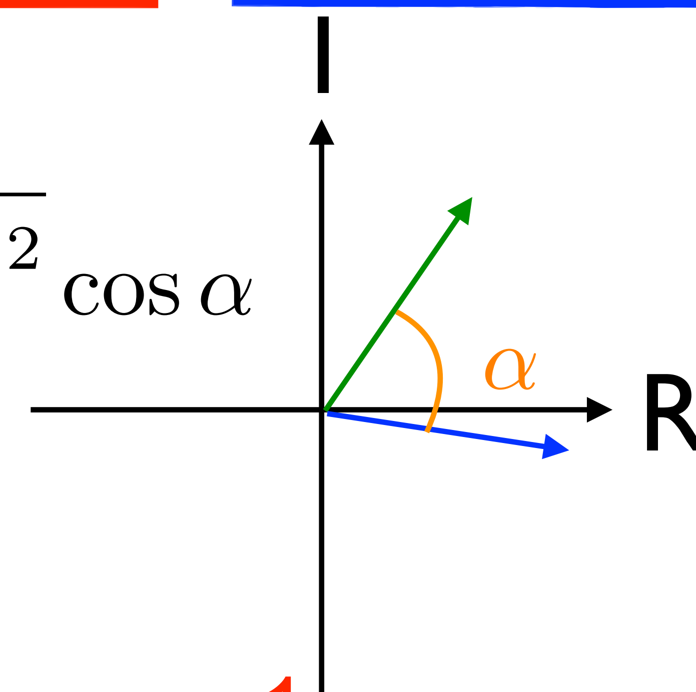
Observable dependent

C. Degrande

Interference

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

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



mom&spin

Not always positive

Can be suppressed

1

$$\sigma \propto \sum_x |M(x)|^2 \quad \text{if} \quad \begin{array}{l} M_{SM}(x_1) = 1,\ M_{SM}(x_2) = \cancel{0} \\ M_{d6}(x_1) = \cancel{0},\ M_{d6}(x_2) = 1 \end{array} \qquad \sigma_{int} = 0$$

-1

Observable dependent

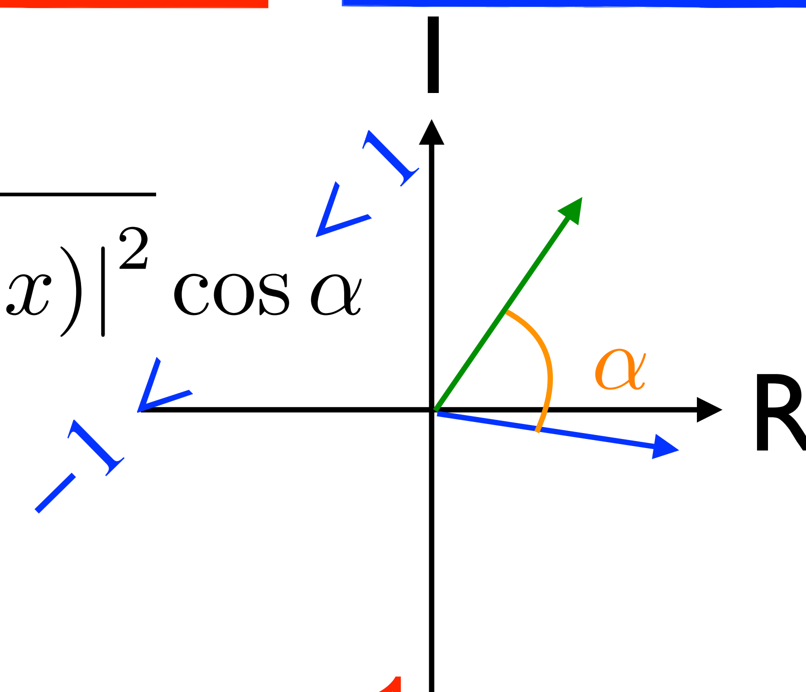
or $\alpha \approx \pi/2$ $\quad M^2 \to M^2 - i\Gamma M \quad \sigma_{int} \propto \Gamma$

C. Degrande

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

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

$$M_{d6}(x_1) = \cancel{0}\ {-1},\ M_{d6}(x_2) = 1 \qquad \sigma_{int} = 0$$

Observable dependent

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

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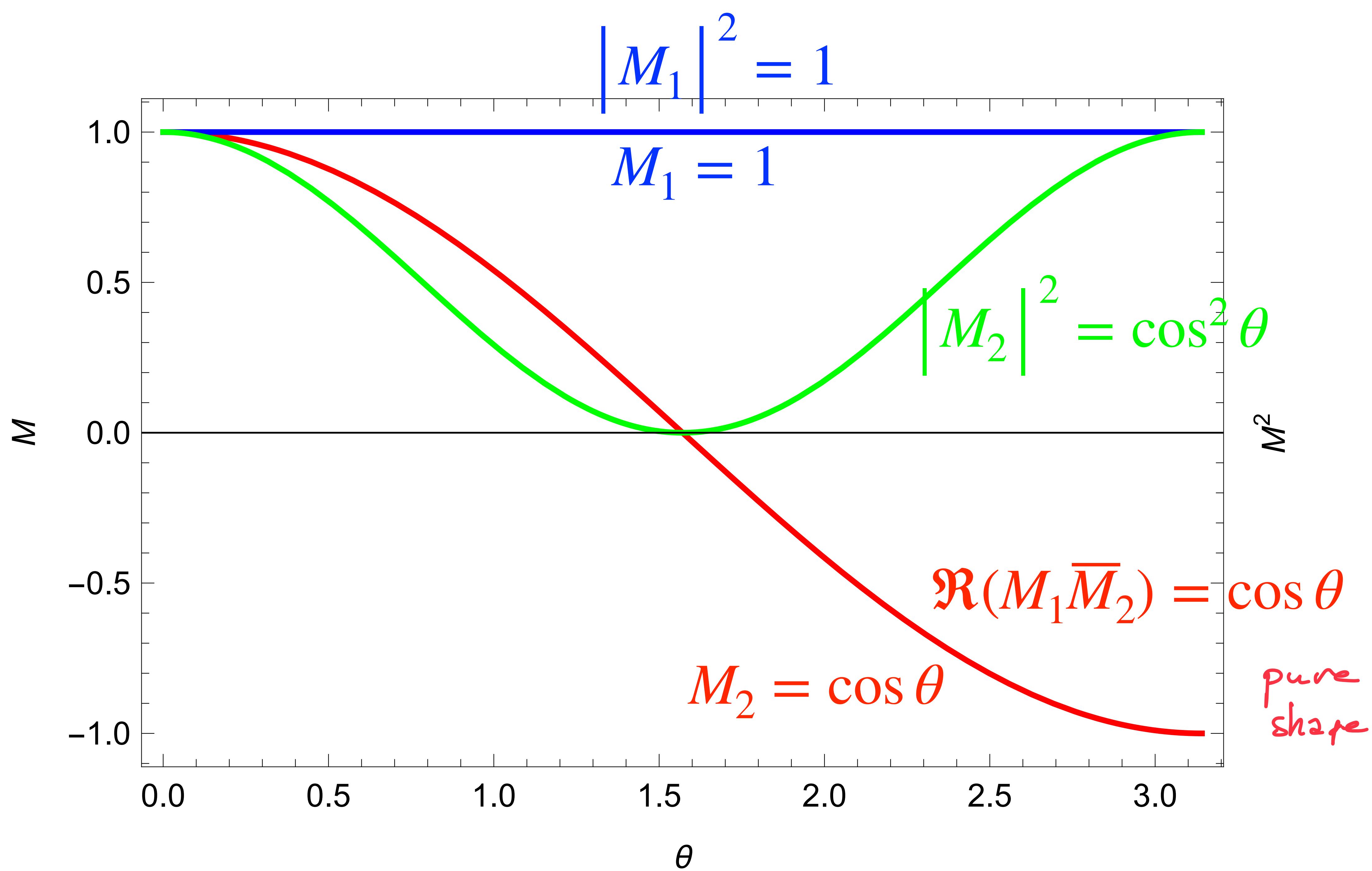
Interference suppression from phase space



$$\sigma_{int} = \int_0^\pi 2\Re(M_1\overline{M}_2)d\theta = \int_0^\pi 2\cos\theta d\theta = 0$$

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Interference revival: Formalism

C.D., M. Maltoni 2012.06595

$$\sigma^{|int|} \equiv \int d\Phi \left| \frac{d\sigma_{int}}{d\Phi} \right| \quad >> \sigma_{int}$$

=Phase space Suppression

$$\sigma^{|meas|} \equiv \int d\Phi_{meas} \left| \sum_{\{um\}} \frac{d\sigma}{d\Phi} \right|$$

$$= \lim_{N\to\infty} \sum_{i=1}^{N} w_i * \text{sign}\left(\sum_{um} ME(\vec{p}_i, um) \right)$$

Experimentally accessible?

neutrino momenta, helicities, jet flavours, initial parton direction,…

Fully: $\frac{d\sigma_{int}}{d\theta}(pp \to Z\gamma) \propto \cos\theta$

Not at all: $\sigma_{int}(\mu_L) = -\sigma_{int}(\mu_R)$

Interference revival : 1st example

$$O_G = g_s f_{abc}\, G_\nu^{a,\mu} G_\rho^{b,\nu} G_\mu^{c,\rho}$$

Interference vanishes in dijet

$$\frac{C_G}{\Lambda^2} < (0.031\ \mathrm{TeV})^{-2}$$ from dijet at $\mathcal{O}\left(1/\Lambda^4\right)$

R. Goldouzian, M. D. Hildreth, Phys. Lett. B **811**, 135889 (2020), arXiv:2001.02736

Triple gluon operator

add mass or more legs $\frac{c_G}{\Lambda^2} = 1\text{TeV}^{-2}$

	$p_T > 50$ GeV		$p_T > 200$ GeV		$p_T > 1000$ GeV	
proc.	σ [pb]	w>0	σ [pb]	w>0	σ [pb]	w>0
$t\bar{t}$	1.384	85%	1.384	85%	1.384	85%
$t\bar{t}j$	$5.20\cdot10^{-1}$	62%	$1.13\cdot10^{-1}$	60%	$1.37\cdot10^{-3}$	62%
jjj	$2.98\cdot10^{1}$	52%	$5.90\cdot10^{-1}$	52%	$4.91\cdot10^{-4}$	61%
$jjjj$	$-2.89\cdot10^{1}$	45%	$-2.50\cdot10^{-1}$	44%	$-4.12\cdot10^{-6}$	39%

Large SM x-sect
& int. cancellation

Part of the phase space with
positive interference

C. Degrande

Triple gluon operator

Close to Schwartz bound

much smaller than

	SM	$\mathcal{O}(1/\Lambda^2)$				$\mathcal{O}(1/\Lambda^4)$
$p_{T,min}$ [GeV]	σ [pb]	σ [pb]	wgt>0	$\sigma^{\lvert meas \rvert}$ [pb]	$\sigma^{\lvert int \rvert}$ [pb]	σ [pb]
50	$9.70 \cdot 10^{5}$	4.08	50.4%	$7.83 \cdot 10^{2}$	$1.05 \cdot 10^{3}$	$3.93 \cdot 10^{1}$
200	$8.96 \cdot 10^{2}$	$2.92 \cdot 10^{-1}$	51.4%	$3.5 \cdot 10^{1}$	$5.02 \cdot 10^{1}$	2.73
500	3.10	$1.69 \cdot 10^{-2}$	54.0%	$6.04 \cdot 10^{-1}$	$8.96 \cdot 10^{-1}$	$1.48 \cdot 10^{-1}$
1000	$9.08 \cdot 10^{-3}$	$4.56 \cdot 10^{-4}$	60.1%	$1.46 \cdot 10^{-3}$	$2.29 \cdot 10^{-3}$	$3.05 \cdot 10^{-3}$

Mostly accessible

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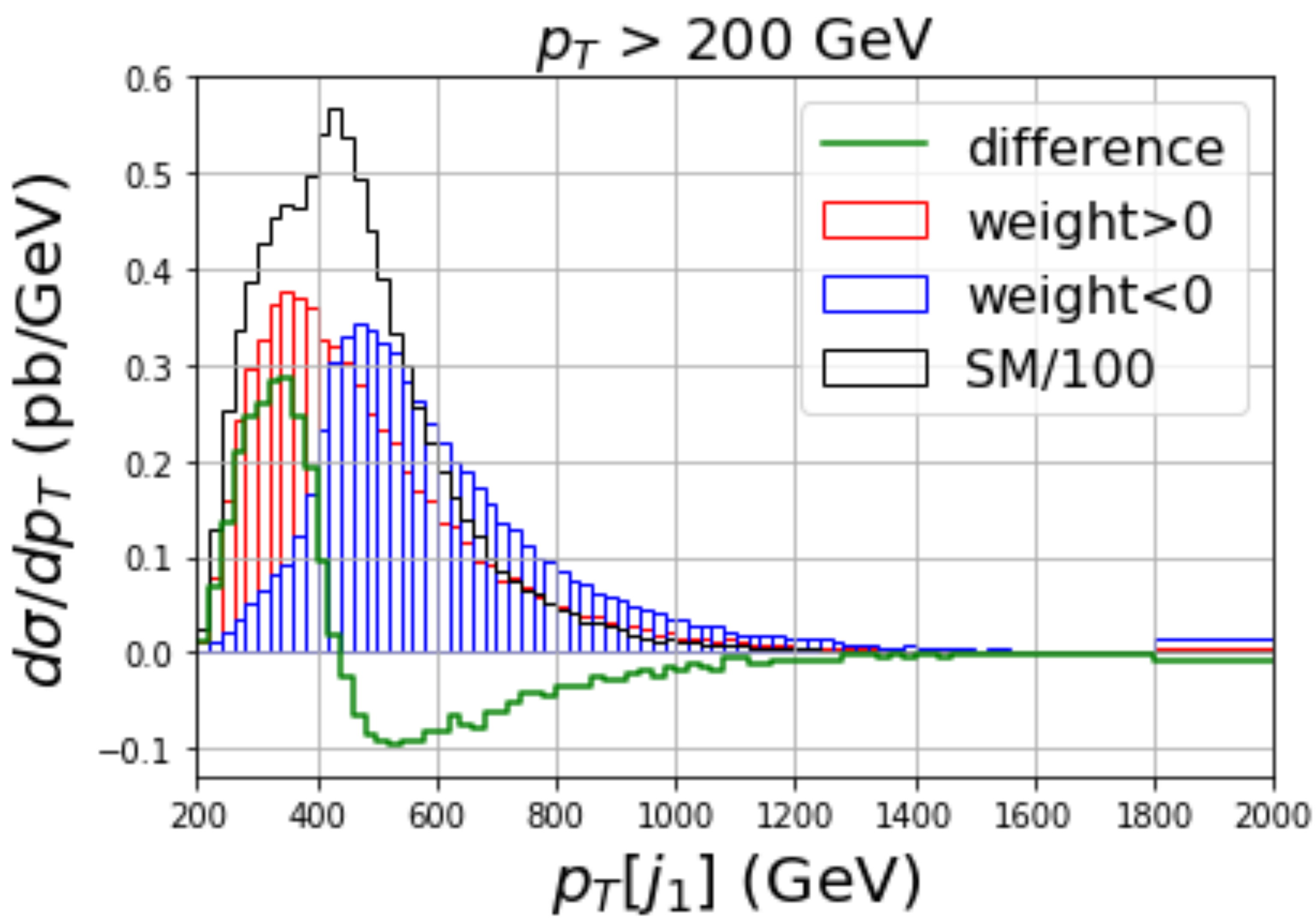
Transverse momentum

Efficiency of an observable to revive: $\frac{O}{\sigma^{|meas|}}$



~40% efficiency

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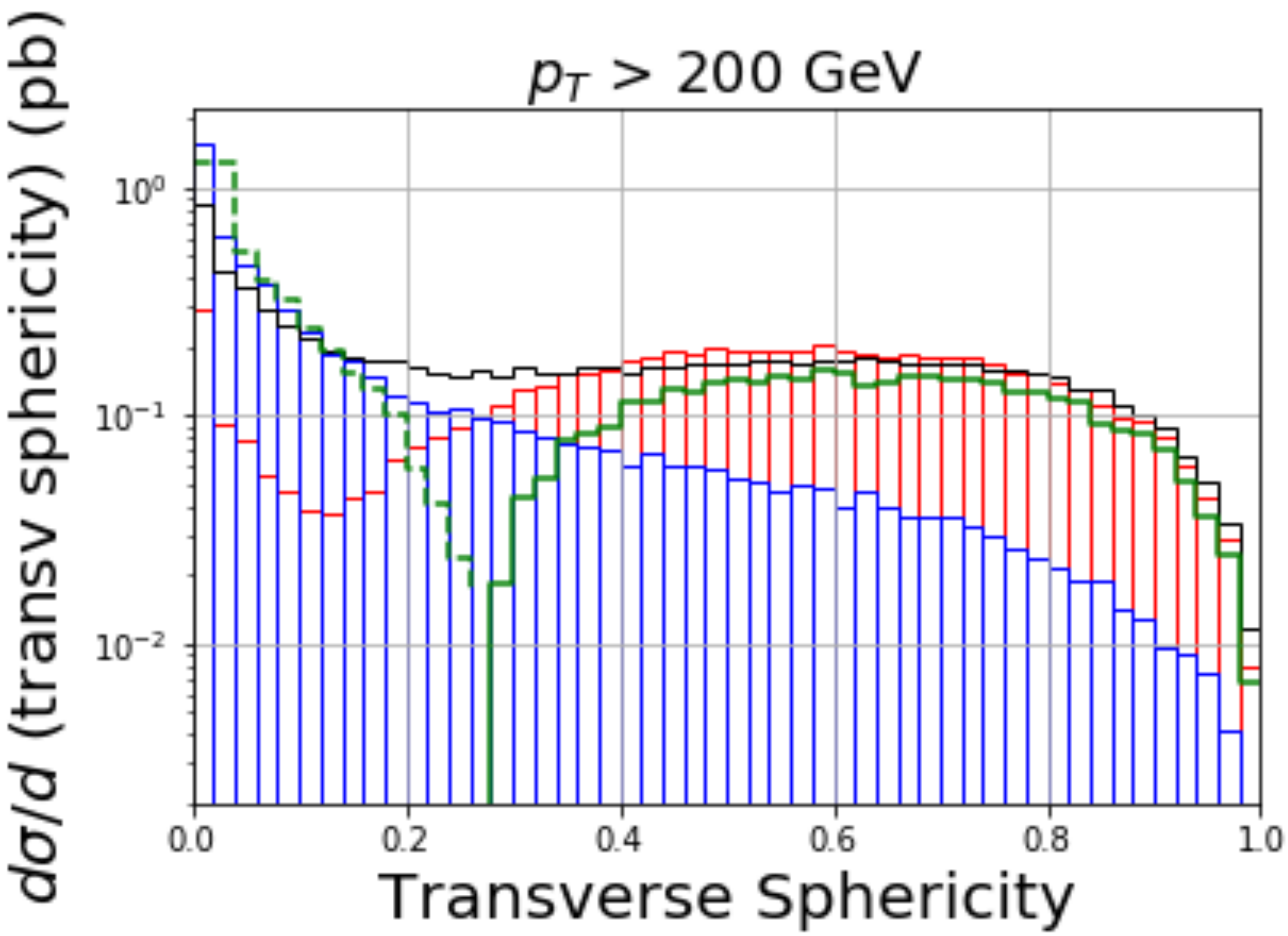
Transverse sphericity

$$M_{xy} = \sum_{i=1}^{N_{jets}} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 \end{pmatrix}, \; Sph_T = \frac{2\lambda_2}{\lambda_2 + \lambda_1}$$



~80% efficiency

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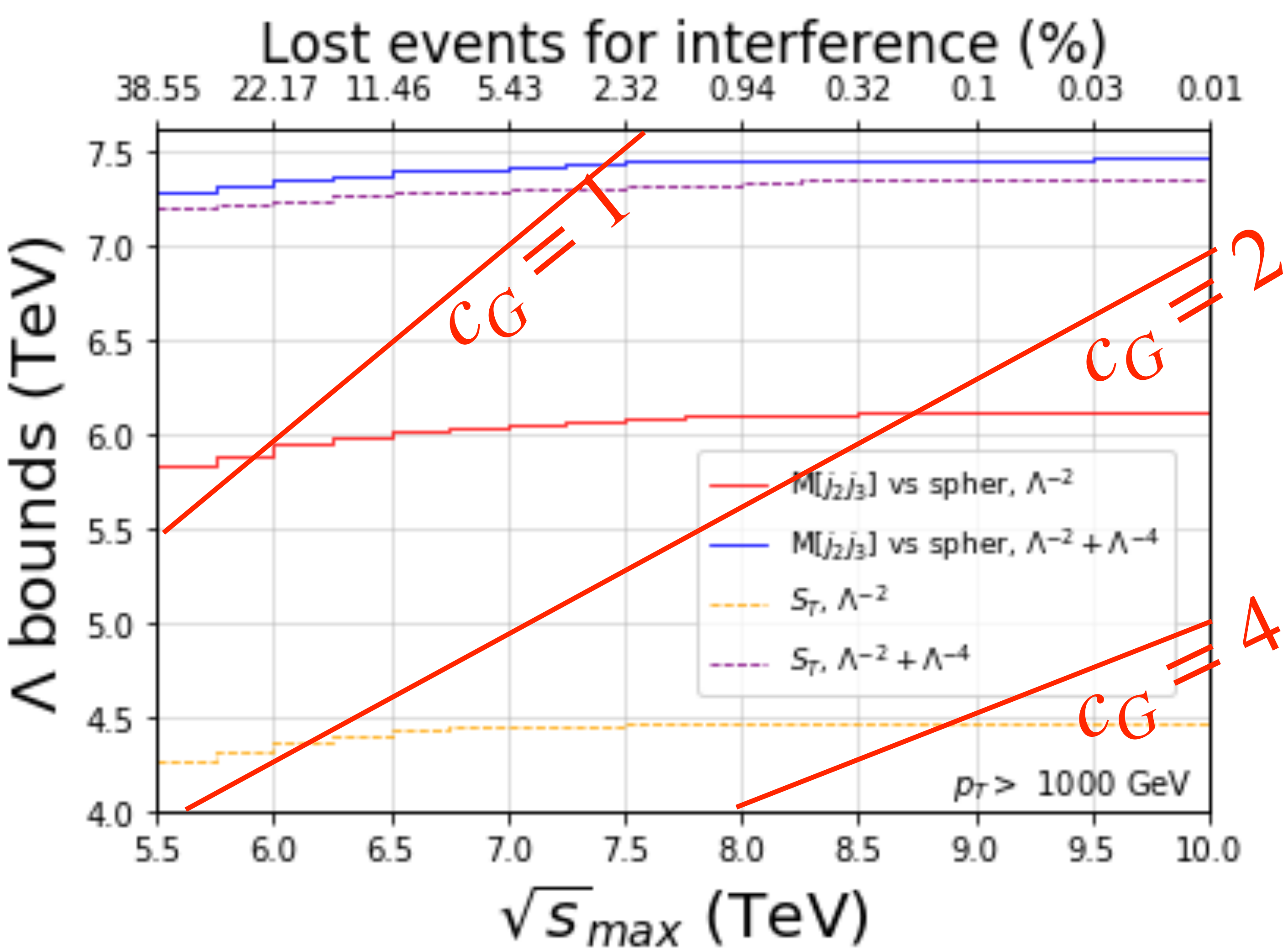
Better sensitivity

$p_{T,min}$ [GeV]	Distribution	Sph_T cut	Bins	Upper bound on C_G	Lower bound on C_G
50	$p_T[j_3]$ vs Sph_T	0.23	34	$2.5\cdot10^{-1}$ $(1.1\cdot10^{-1})$	$-2.5\cdot10^{-1}$ $(-1.2\cdot10^{-1})$
200	S_T vs Sph_T	0.27	34	$7.5\cdot10^{-2}$ $(2.3\cdot10^{-2})$	$-7.5\cdot10^{-2}$ $(-2.4\cdot10^{-2})$
500	$M[j_2j_3]$ vs Sph_T	0.31	21	$5.5\cdot10^{-2}$ $(5.3\cdot10^{-2})$	$-5.5\cdot10^{-2}$ $(-3.5\cdot10^{-2})$
1000	$M[j_2j_3]$ vs Sph_T	0.35	7	$2.6\cdot10^{-2}$ $(1.9\cdot10^{-2})$	$-2.6\cdot10^{-2}$ $(-1.8\cdot10^{-2})$

Λ^{-2} Λ^{-4}



Bounds dominated by the interference

EFT validity & error:

(3TeV/6TeV)^2~0.25

C. Degrande

Better sensitivity

$p_{T,min}$ [GeV]	Distribution	Sph_T cut	Bins	Upper bound on C_G	Lower bound on C_G
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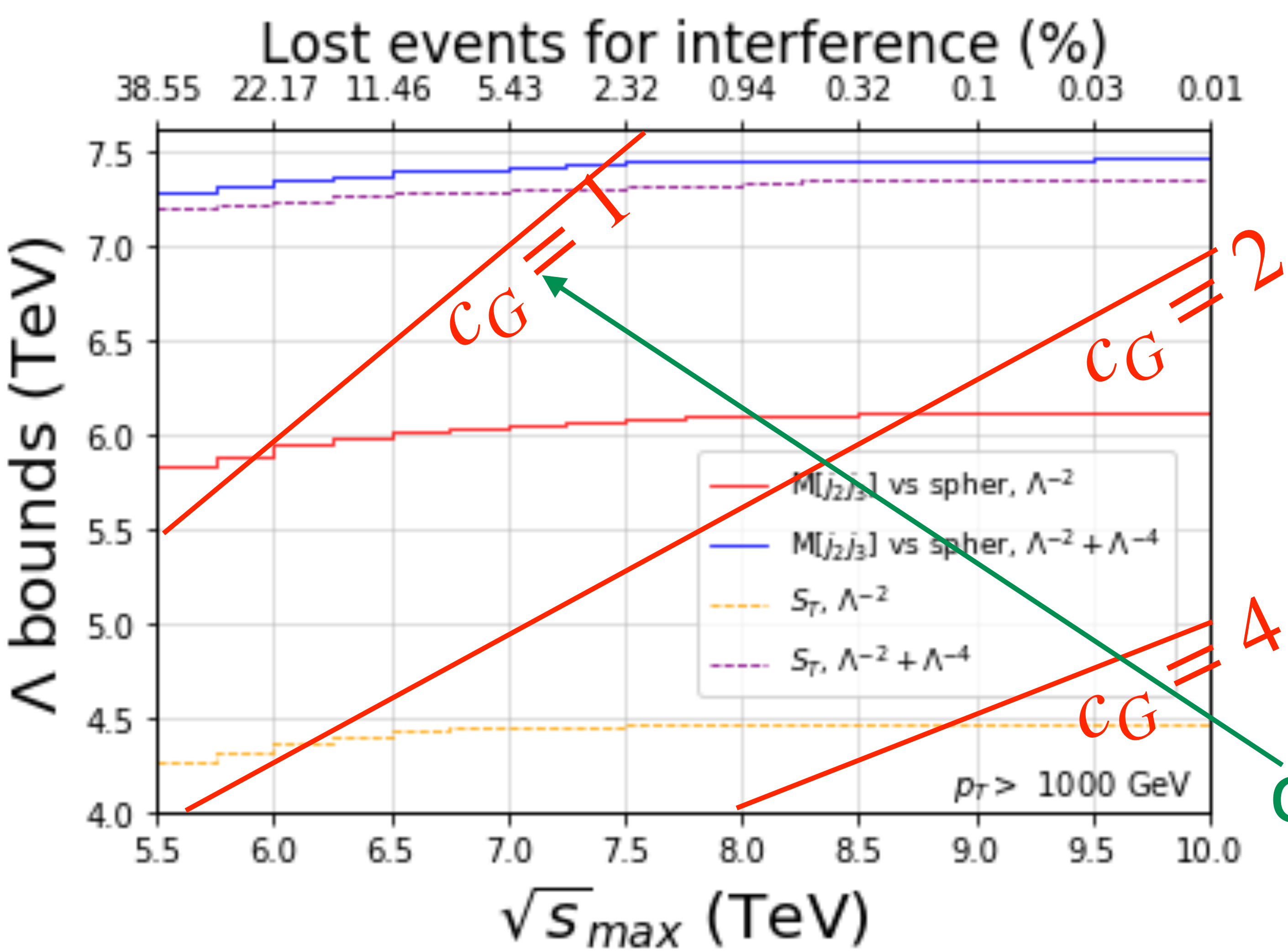
Λ^{-2} Λ^{-4}



Bounds dominated by the interference

EFT validity & error:

(3TeV/6TeV)^2~0.25

or $c_G = 2$ and $E^2/\Lambda^2 = 1/2$

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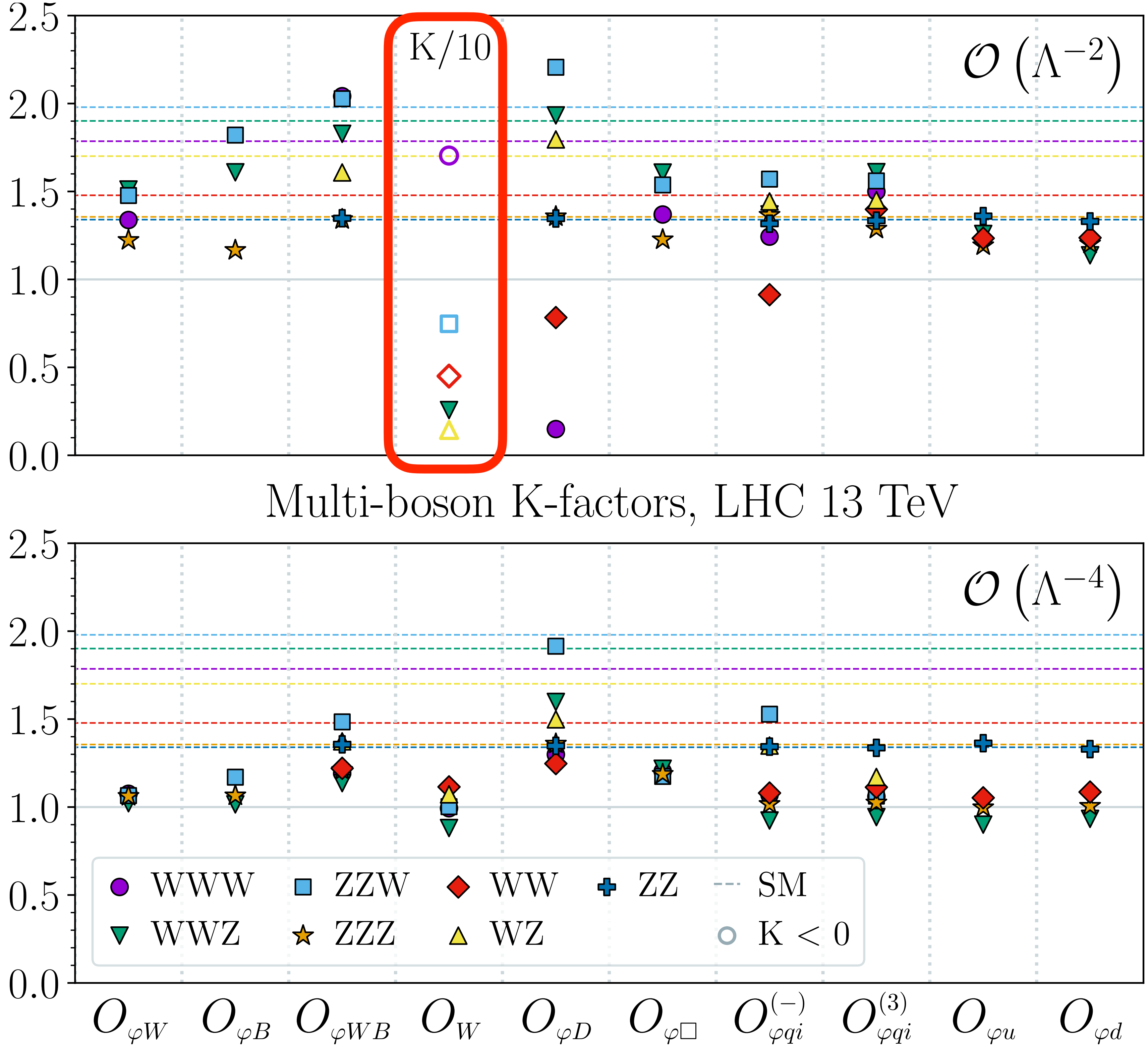
EW bosons production

Large negative K-factors

Converge?



SMEFT@NLO

2008.11743

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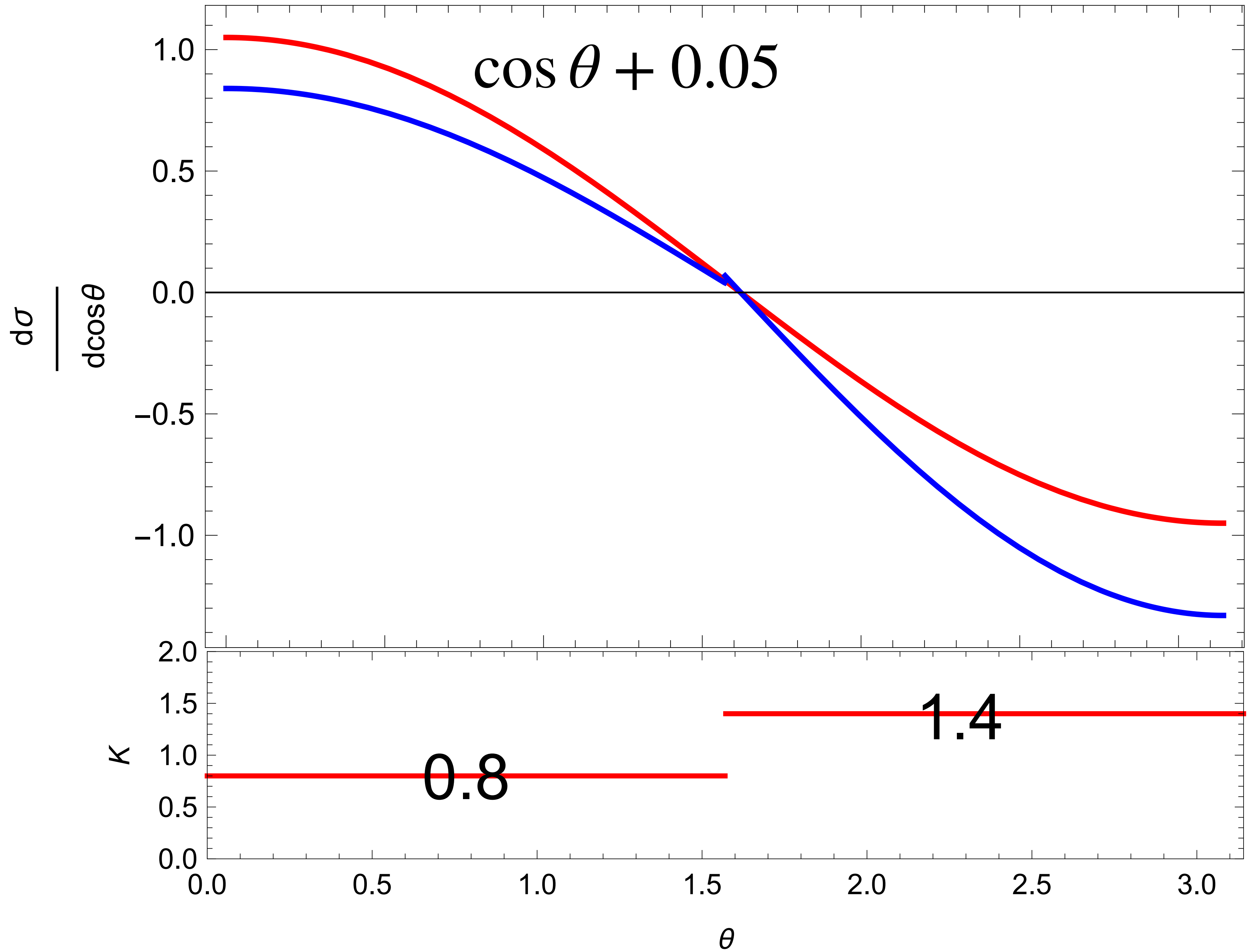
Large/small K-factor



$$\sigma_{int}^{LO} = 0.16$$

$$\sigma_{int}^{NLO} = -0.43$$

$$K_\sigma \approx -3$$

Uncertainty

σ is not the right variable to probe the interference

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Interference revival: toy example

$$A = d\sigma(\cos\theta > 0) - d\sigma(\cos\theta < 0)$$

$$A_{int}^{LO} = 2 \qquad\qquad >> \sigma_{int}^{LO} = 0.16$$

$$A_{int}^{NLO} = 2.15$$

$$K_A = 1.1$$

No/little cancellation
(Much) larger sensitivity
Less sensitive to corrections (smaller errors)

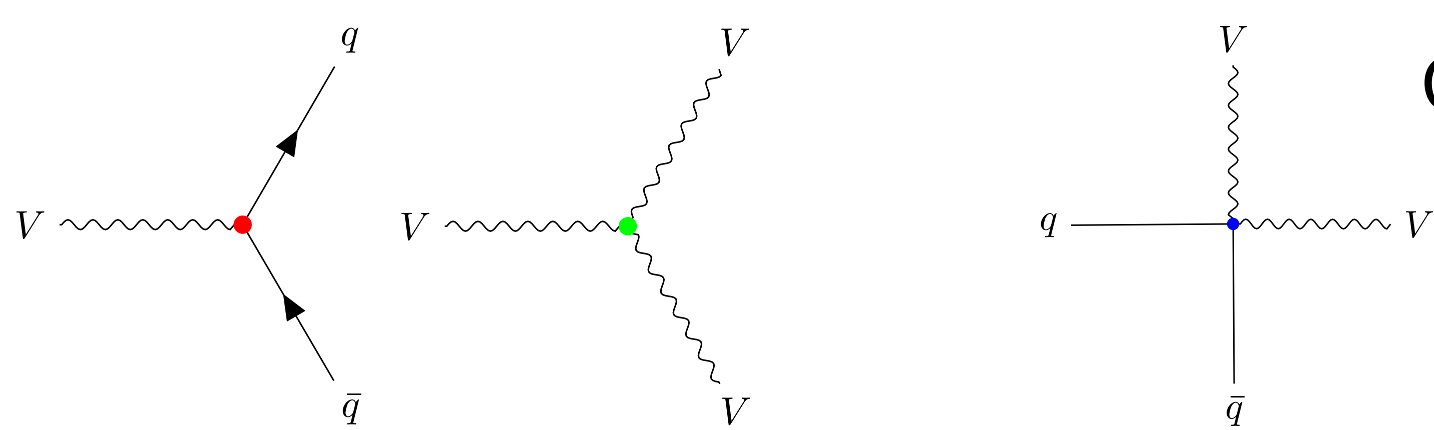
Dim-8

dim-8 operators

$$\mathcal{O}_1 = iB^{\mu}{}_{\nu}B^{\nu}{}_{\lambda}(\bar{d}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}d_{\mathrm{R}r}),$$
$$\mathcal{O}_2 = iB^{\mu}{}_{\nu}B^{\nu}{}_{\lambda}(\bar{u}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}u_{\mathrm{R}r}),$$
$$\mathcal{O}_3 = iB^{\mu}{}_{\nu}B^{\nu}{}_{\lambda}\left(\bar{q}_{\mathrm{L}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}r}\right),$$
$$\mathcal{O}_4 = iW^{I\mu}{}_{\lambda}B^{\nu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_5 = iW^{I\mu}{}_{\lambda}\tilde{B}^{\nu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_6 = iW^{I\nu}{}_{\lambda}B^{\mu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_7 = iW^{I\nu}{}_{\lambda}\tilde{B}^{\mu\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma_{\nu}\left(\tau^{I}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_8 = iW^{I\mu}{}_{\nu}W^{I\nu}{}_{\lambda}(\bar{d}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}d_{\mathrm{R}r}),$$
$$\mathcal{O}_9 = iW^{I\mu}{}_{\nu}W^{I\nu}{}_{\lambda}(\bar{u}_{\mathrm{R}p}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}u_{\mathrm{R}r}),$$

$$\mathcal{O}_{10} = iW^{I\mu}{}_{\nu}W^{I\nu}{}_{\lambda}\left(\bar{q}_{\mathrm{L}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}p}\right),$$
$$\mathcal{O}_{11} = i\epsilon^{IJK}W^{I\mu}{}_{\nu}W^{J\nu}{}_{\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma^{\lambda}\left(\tau^{K}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_{12} = i\epsilon^{IJK}\tilde{W}^{I\mu}{}_{\nu}W^{J\nu}{}_{\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma^{\lambda}\left(\tau^{K}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_{13} = i\epsilon^{IJK}W^{I\mu}{}_{\nu}\tilde{W}^{J\nu}{}_{\lambda}\left(\bar{q}^{i}_{\mathrm{L}p}\gamma^{\lambda}\left(\tau^{K}\right)_{i}{}^{j}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}rj}\right),$$
$$\mathcal{O}_{14} = i\left(\bar{u}_{\mathrm{R}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}u_{\mathrm{R}p}\right)\left(D_{\lambda}H^{\dagger}D^{\mu}H\right),$$
$$\mathcal{O}_{15} = i\left(\bar{d}_{\mathrm{R}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}d_{\mathrm{R}p}\right)\left(D_{\lambda}H^{\dagger}D^{\mu}H\right),$$
$$\mathcal{O}_{16} = i\left(\bar{q}_{\mathrm{L}r}\gamma^{\lambda}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}p}\right)\left(D_{\lambda}H^{\dagger}D^{\mu}H\right),$$
$$\mathcal{O}_{17} = i\left(\bar{q}_{\mathrm{L}p}\gamma^{\lambda}\tau^{K}\overleftrightarrow{D}_{\mu}q_{\mathrm{L}r}\right)\left(D_{\lambda}H^{\dagger}\tau^{K}D^{\mu}H\right),$$
$$\mathcal{O}_{18} = i(\bar{u}_{\mathrm{R}p}\gamma^{\mu}\overleftrightarrow{D}^{\nu}d_{\mathrm{R}r})\epsilon^{ij}(D^{\mu}H_iD^{\nu}H_j),$$

CD,H.-L. Li, 2303.10493



(a) dim-6 vertex corrections

(b) dim-8 contact corrections

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Interference behaviour

Operator	$2\,\mathrm{Re}(\mathcal{A}^{\mathrm{SM}}\mathcal{A}^{\mathrm{NP}*})$	$2\int d\Omega\,\mathrm{Re}(\mathcal{A}^{\mathrm{SM}}\mathcal{A}^{\mathrm{NP}*})$
$\mathcal{O}_8$	$d\bar{d}:\ b_8 S + c_8$	0
$\mathcal{O}_9$	$\bar{u}u:\ b_9 S + c_9$	0
$\mathcal{O}_{10}$	$u\bar{u}/d\bar{d}:\ a_{10}\cdot S^2 + b_{10}\cdot S + c_{10}$	$u\bar{u}/d\bar{d}:\ \bar{a}_{10}\cdot S^2 + \bar{b}_{10}\cdot S + \bar{c}_{10}$
$\mathcal{O}_{11}$	0	0
$\mathcal{O}_{12}$	$u\bar{u}:\ a^u_{12}S^2 + b^u_{12}S + c^u_{12}$	$u\bar{u}:\ \bar{a}^u_{12}S^2 + \bar{b}^u_{12}S + \bar{c}^u_{12} + \overline{D}^u_{12}\log S$
	$d\bar{d}:\ a^d_{12}S^2 + b^d_{12}S + c^d_{12}$	$d\bar{d}:\ \bar{a}^d_{12}S^2 + \bar{b}^d_{12}S + \bar{c}^d_{12} + \overline{D}^d_{12}\log S$
$\mathcal{O}_{13}$	$u\bar{u}:\ a^u_{13}S^2 + b^u_{13}S + c^u_{13}$	$u\bar{u}:\ \bar{a}^u_{13}S^2 + \bar{b}^u_{13}S + \bar{c}^u_{13} + \overline{D}^u_{13}\log S$
	$d\bar{d}:\ a^d_{13}S^2 + b^d_{13}S + c^d_{13}$	$d\bar{d}:\ \bar{a}^d_{13}S^2 + \bar{b}^d_{13}S + \bar{c}^d_{13} + \overline{D}^d_{13}\log S$
$\mathcal{O}_{14}$	$u\bar{u}:\ a_{14}S^2 + b_{14}S + c_{14}$	0
$\mathcal{O}_{15}$	$d\bar{d}:\ a_{15}S^2 + b_{15}S + c_{15}$	0
$\mathcal{O}_{16}$	$u\bar{u}:\ a^u_{16}S^2 + b^u_{16}S + c^u_{16}$	$u\bar{u}:\ \bar{b}^u_{16}S + \bar{c}^u_{16} + \overline{D}^u_{16}\log S$
	$d\bar{d}:\ a^d_{16}S^2 + b^d_{16}S + c^d_{16}$	$d\bar{d}:\ \bar{b}^d_{16}S + \bar{c}^d_{16} + \overline{D}^d_{16}\log S$
$\mathcal{O}_{17}$	$u\bar{u}:\ a^u_{17}S^2 + b^u_{17}S + c^u_{17}$	$u\bar{u}:\ \bar{b}^u_{17}S + \bar{c}^u_{17} + \overline{D}^u_{17}\log S$
	$d\bar{d}:\ a^d_{17}S^2 + b^d_{17}S + c^d_{17}$	$d\bar{d}:\ \bar{b}^d_{17}S + \bar{c}^d_{17} + \overline{D}^d_{17}\log S$

CPV

Asymmetric

Table 2: Scaling of $q\bar{q}\to WW$ interference amplitude after summing and averaging over spins and helicities.

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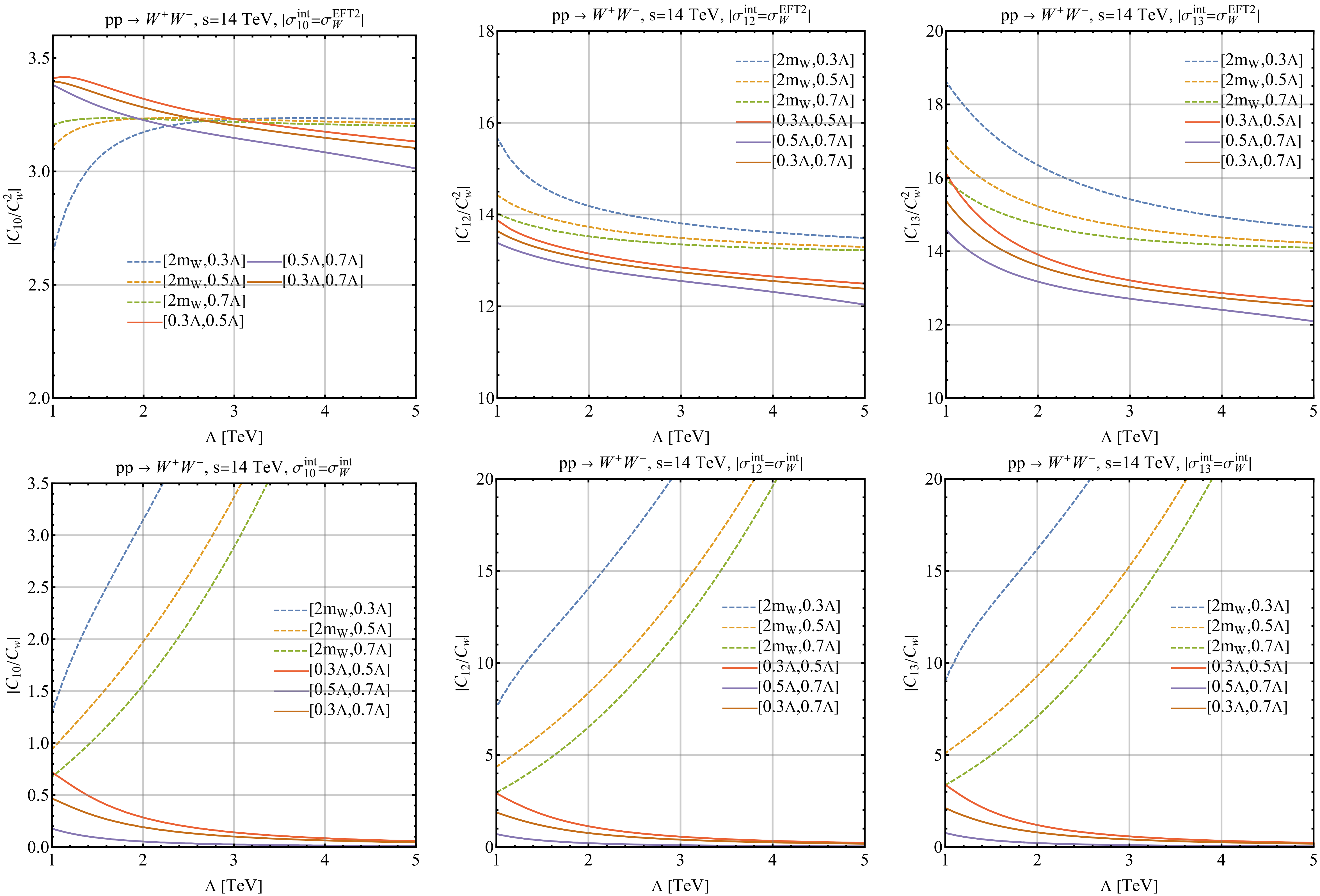
Comparison to dim6



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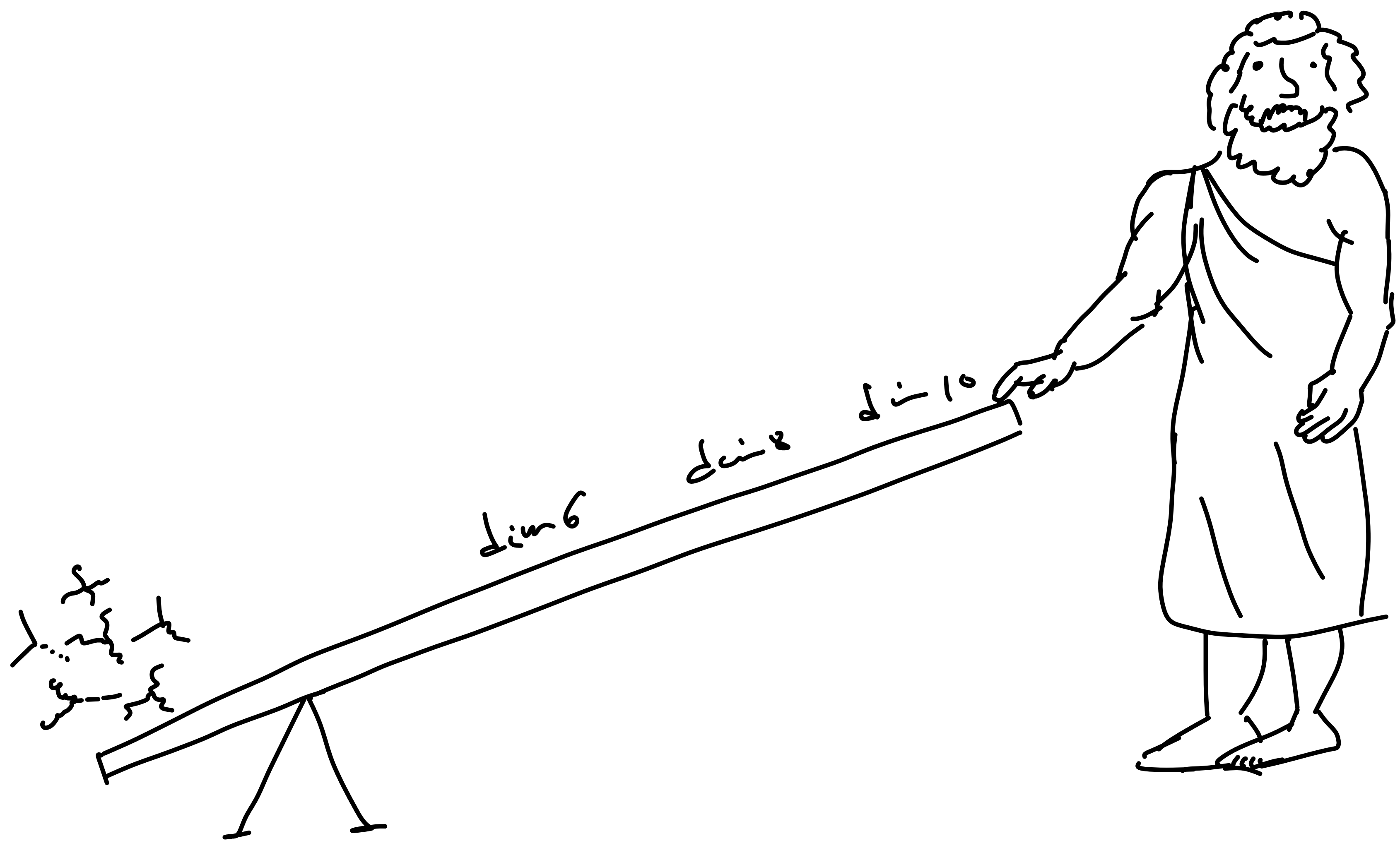
Many more possibilities

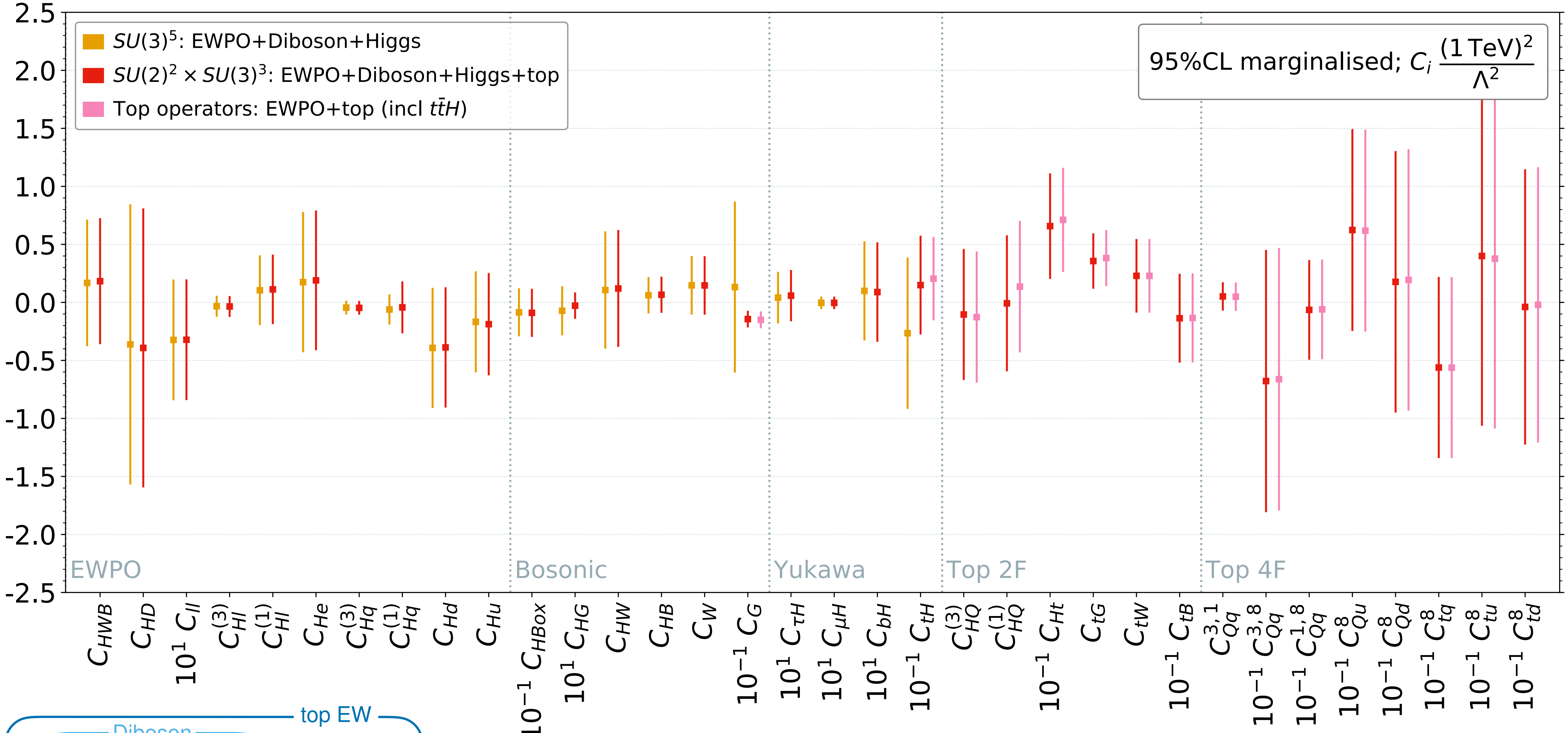
$ZZZ\,,\ ZZ\gamma\,,\ Z\gamma\gamma \subset \text{dim } 8$

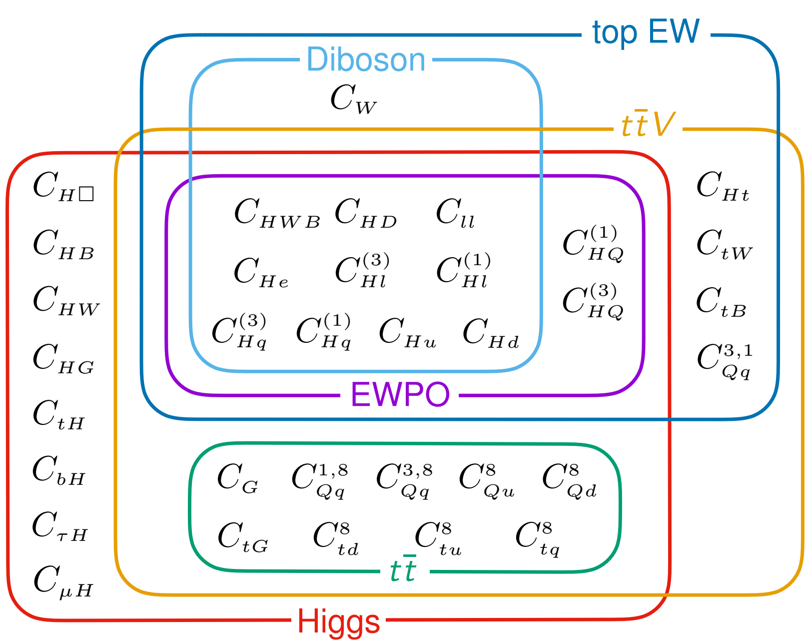
“Give me a lever long enough and a fulcrum on which to place it, and I shall move the world”



Further comments

Top, Higgs and EW fit





Ellis et al.,2012.02779
SMEFiT, 2105.00006
Almeida et al, 2108.04828

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Comments

- ME/ML trained vs Observable

validity

EFT error

↓

TH interpretation

[H.E. cuts]

- Efficient observables
  - more sensitive
  - smaller errors
- More differential measurements

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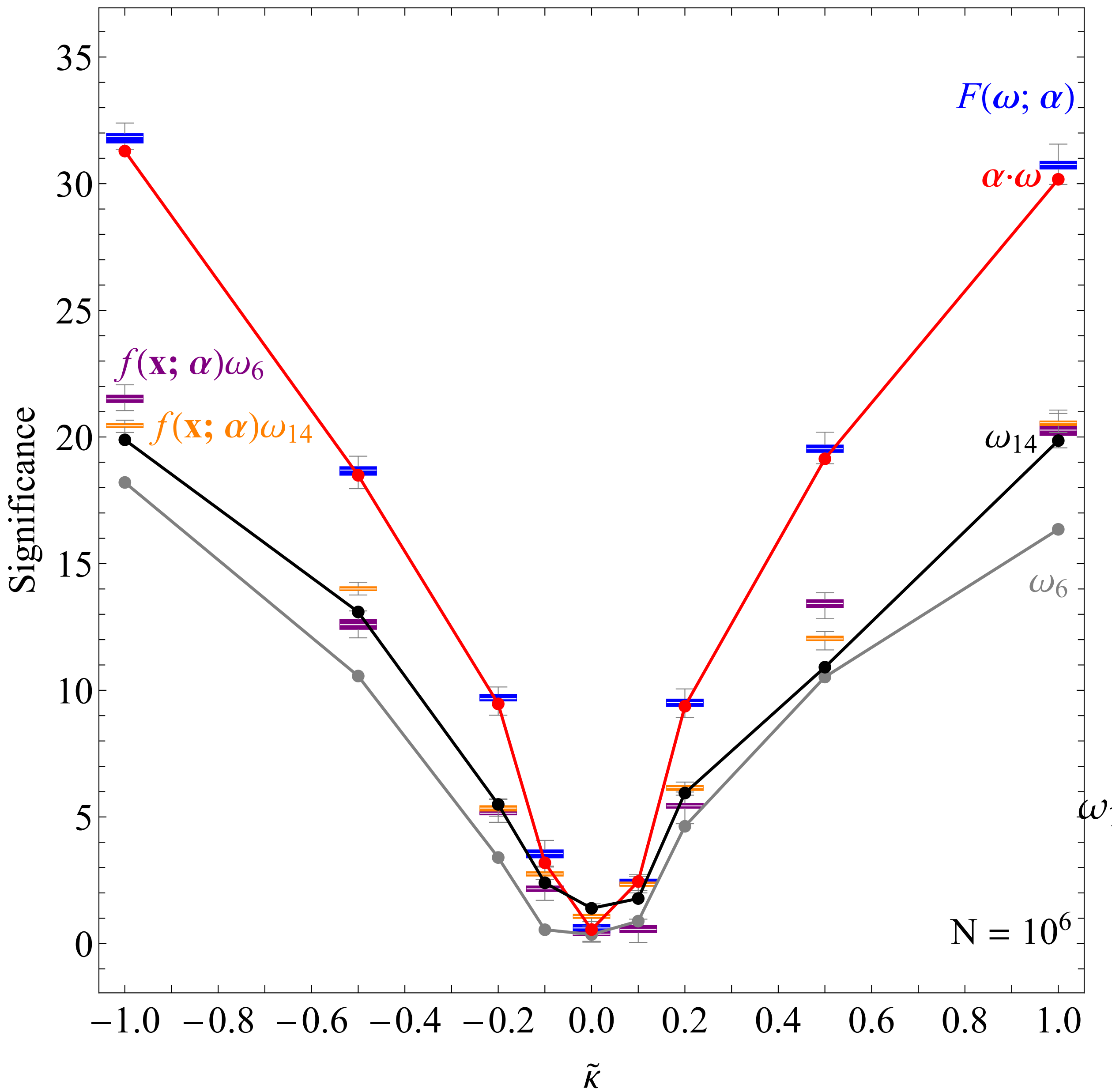
Observables vs ML trained on model

Faroughy, Bortolato, Kamenik, Kosnik Smolkovic,
Symmetry 13 (2021) no.7, 1129



Neural network

Linear combination

$$\omega_6 \sim [(\boldsymbol{p}_{\ell^-}\times\boldsymbol{p}_{\ell^+})\cdot(\boldsymbol{p}_b+\boldsymbol{p}_{\bar{b}})][(\boldsymbol{p}_{\ell^-}-\boldsymbol{p}_{\ell^+})\cdot(\boldsymbol{p}_b+\boldsymbol{p}_{\bar{b}})]$$

$$\omega_{14} \sim [(\boldsymbol{p}_{\ell^-}\times\boldsymbol{p}_{\ell^+})\cdot(\boldsymbol{p}_b-\boldsymbol{p}_{\bar{b}})][(\boldsymbol{p}_b-\boldsymbol{p}_{\bar{b}})\cdot(\boldsymbol{p}_{\ell^-}-\boldsymbol{p}_{\ell^+})]$$

Exercises

$pp \to Z$ in the SMEFTatNLO model
which operators?
what is the size of the contribution

$pp \to \ell^+ \ell^-$ idem

$pp \to t\bar{t}$

$pp \to jj \to$ check no G_G interference

find a process affected by $G_{\varphi D}$ without one of its new vertex