Effective theory approach for electroweak boson interactions

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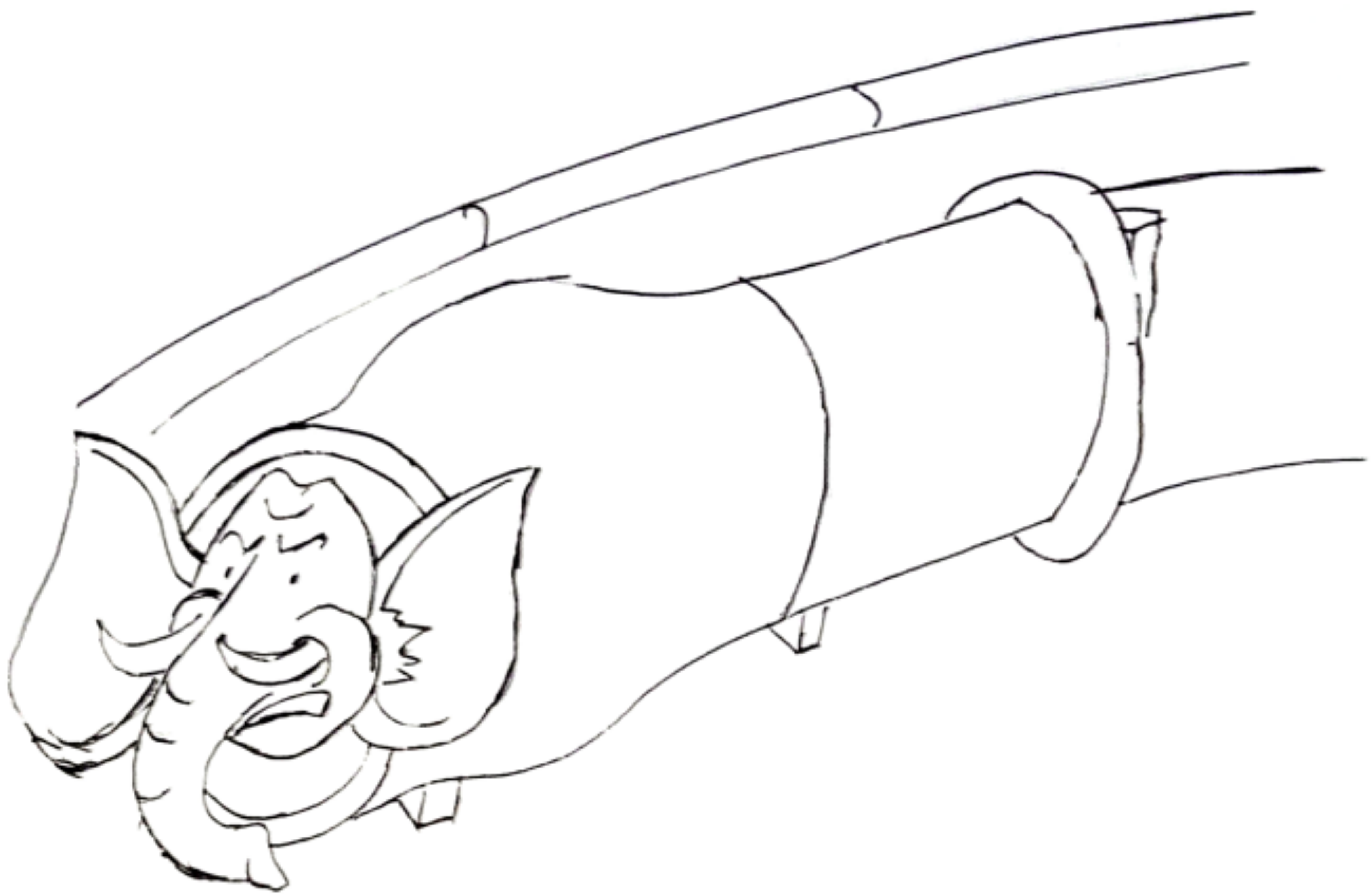
KITP, May 2016

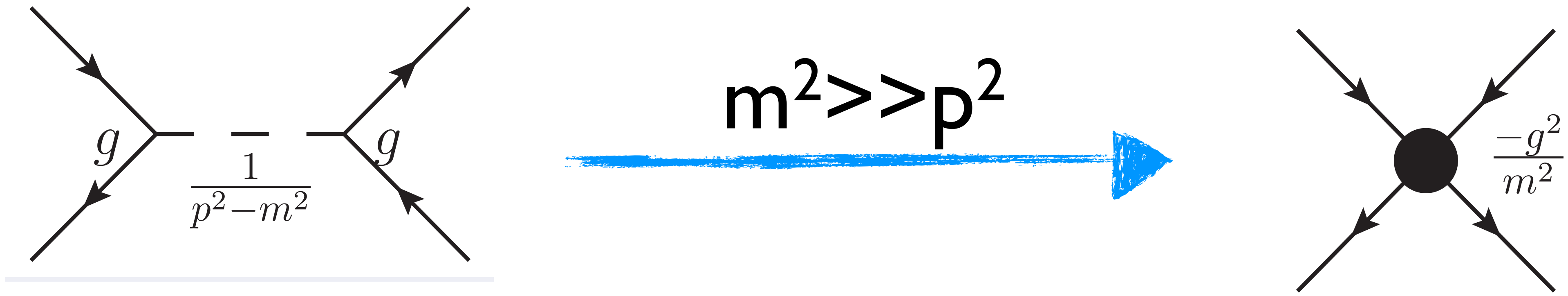
Plan

- Introduction to EFT
- EFT for EW bosons
- Implementation in MC tools
- Concluding remarks

What if the new physics is heavy?



What if the new physics is heavy?



direct detection of new d.o.f as resonance, …

Indirect detection of new d.o.f as new/modified interaction between SM fields

Fermi theory : $M_W >> m_b$

Easier full theory

Use EFT without knowing the full theory

Low energy at the LHC : $\Lambda^2 << p^2$

Effective Field Theory

Parametrize any NP but an ∞ number of coefficients

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

- 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

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EFT : Example

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

Should not be included, be small
Error estimate

- SM is $\mathcal{O}\left(\Lambda^0\right)$, NP is $\mathcal{O}\left(\Lambda^{-2}\right)$:
  - Precision Physics : small effects
  - Quantisation of NP constraints
- Hadron vs lepton collider
  - Energy range (Assumption, sensitivity)
  - Precision (Th, Exp)

Safety tool : Unitarity

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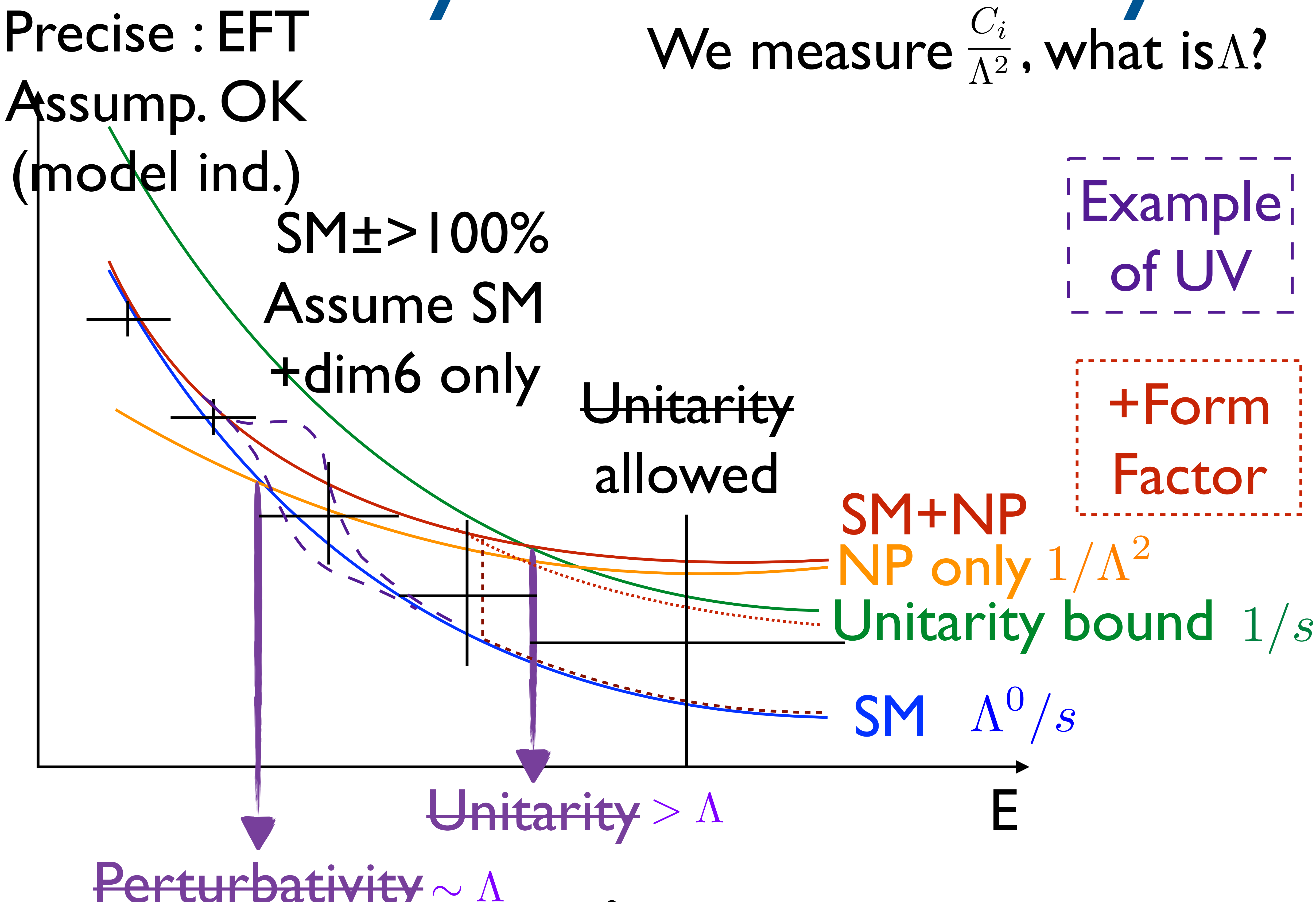
Unitarity/Perturbativity

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



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EW operators (CP even)

W. Buchmuller, D. Wyler
NPB268 (1986) 621-653
B. Grzadkowski *et al*
JHEP**1010(2010)** 085

$$\mathcal{O}_h = \left(H^\dagger H\right)^3$$

$$\mathcal{O}_{\partial h} = \partial_\mu \left(H^\dagger H\right) \partial^\mu \left(H^\dagger H\right)$$

$$\mathcal{O}_{HB} = \left(H^\dagger H\right) B^{\mu\nu} B_{\mu\nu}$$

$$\mathcal{O}_{HW} = \left(H^\dagger H\right) \langle W^{\mu\nu} W_{\mu\nu} \rangle$$

$$\mathcal{O}_{WWW} = \langle W^{\mu\nu} W_{\nu\rho} W^{\rho}_{\mu} \rangle$$

$$\mathcal{O}_W = (D_\mu H)^\dagger W^{\mu\nu} D_\nu H$$

$$\mathcal{O}_B = (D_\mu H)^\dagger B^{\mu\nu} D_\nu H$$

↔

$$\mathcal{O}_{Dh} = \left(H^\dagger D_\mu H\right)^\dagger \left(H^\dagger D^\mu H\right)$$

$$\mathcal{O}_{HBW} = \left(H^\dagger B^{\mu\nu} W_{\mu\nu} H\right)$$

* No fermions, no gluons

Example : basis translation

More operators than measurable operators

Rosetta, A Falkowski *et al* EPJC75 (2015) no.12, 583

$$\mathcal{O}_W = (D_\mu H)^\dagger W^{\mu\nu} D_\nu H$$

Integration by part

$$= -(D_\nu D_\mu H)^\dagger W^{\mu\nu} H - (D_\mu H)^\dagger D_\nu W^{\mu\nu} H$$

$$D_\nu D_\mu \to [D_\nu, D_\mu] = c_1 W_{\mu\nu} + c_2 B_{\mu\nu}$$

$$D^\mu W^I_{\nu\mu} \quad = \quad ig\left(H^\dagger \sigma^I D_\nu H - D_\nu H^\dagger \sigma^I H\right)$$

$$= a_1 \mathcal{O}_{HW} + a_2 \mathcal{O}_{HBW} + a_3 \mathcal{O}_{DH} + a_4 \mathcal{O}_{\partial H}$$

Basis choice

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

$\mathcal{O}_{\partial h} = \partial_\mu (H^\dagger H)\, \partial^\mu (H^\dagger H)$

$\mathcal{O}_{HB} = (H^\dagger H)\, B^{\mu\nu} B_{\mu\nu}$

$\mathcal{O}_{HW} = (H^\dagger H)\, \langle W^{\mu\nu} W_{\mu\nu} \rangle$

$\mathcal{O}_{WWW} = \langle W^{\mu\nu} W_{\nu\rho} W^\rho_\mu \rangle$

$\mathcal{O}_W = (D_\mu H)^\dagger W^{\mu\nu} D_\nu H$

$\mathcal{O}_B = (D_\mu H)^\dagger B^{\mu\nu} D_\nu H$

aTGC aHC

to avoid redefinition :

$$(H^\dagger H) \to \left(H^\dagger H - \frac{v^2}{2}\right)$$

$$h \to h\left(1 - \frac{c_{\partial h}}{\Lambda^2} v^2\right)$$

$\mathcal{O}_{Dh} = (H^\dagger D_\mu H)^\dagger (H^\dagger D^\mu H)$

$\mathcal{O}_{HBW} = (H^\dagger B^{\mu\nu} W_{\mu\nu} H)$

Redefinition of the A/Z, EW vector boson masses

!no redefinition of SM input!

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Anomalous couplings

K. Hagiwara *et al.* PLB283 (1992) 353-359, PRD48 (1993) 2182-22[illegible]

$$\mathcal{L} = i g_{WWV} \Big(g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \kappa_V W \ldots [illegible] \ldots + \frac{\lambda_V}{M_W^2} W^{\nu +}_{\mu} W^{-\rho}_{\nu} V^{\mu}_{\rho}$$

$$+ i g_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - i g_5^V \ldots [illegible] \ldots \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu) V_\sigma$$

$$+ \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W \ldots [illegible] \ldots {}_\rho \Big),$$

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

Anomalous couplings

$$\mathcal{L} = i g_{WWV} \Big(g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho$$
$$+ i g_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - i g_5^V \epsilon^{\mu\nu\rho\sigma} (W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu) V_\sigma$$
$$+ \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \Big),$$

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

Dimension-six

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

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

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

Form factors are higher dimension operators with arbitrarily fixed coefficients

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Anomalous coupling

$$\mathcal{L} = ig_{WWV}\Big(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho + ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)$$

$$-ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma + \tilde\kappa_V W^+_\mu W^-_\nu \tilde V^{\mu\nu} + \frac{\tilde\lambda_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde V^\mu_\rho\Big)$$

CP even Operators

$$\mathcal{O}_{WWW} = \langle W^{\mu\nu}W_{\nu\rho}W^\rho_\mu\rangle$$

$$\mathcal{O}_W = (D_\mu H)^\dagger W^{\mu\nu} D_\nu H$$

$$\mathcal{O}_B = (D_\mu H)^\dagger B^{\mu\nu} D_\nu H$$

CP odd operators

$$\mathcal{O}_{\tilde W WW} = \left\langle \tilde W^{\mu\nu}W_{\nu\rho}W^\rho_\mu\right\rangle$$

$$\mathcal{O}_{\tilde W} = (D_\mu H)^\dagger \tilde W^{\mu\nu}(D_\nu H)$$

$$g_1^Z = 1 + c_W\frac{m_Z^2}{2\Lambda^2}$$

$\Delta X = X - 1$

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

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

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

$$0 = \tilde\kappa_Z + \tan^2\theta_W\tilde\kappa_\gamma$$

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

Constants !

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EFT/AC

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

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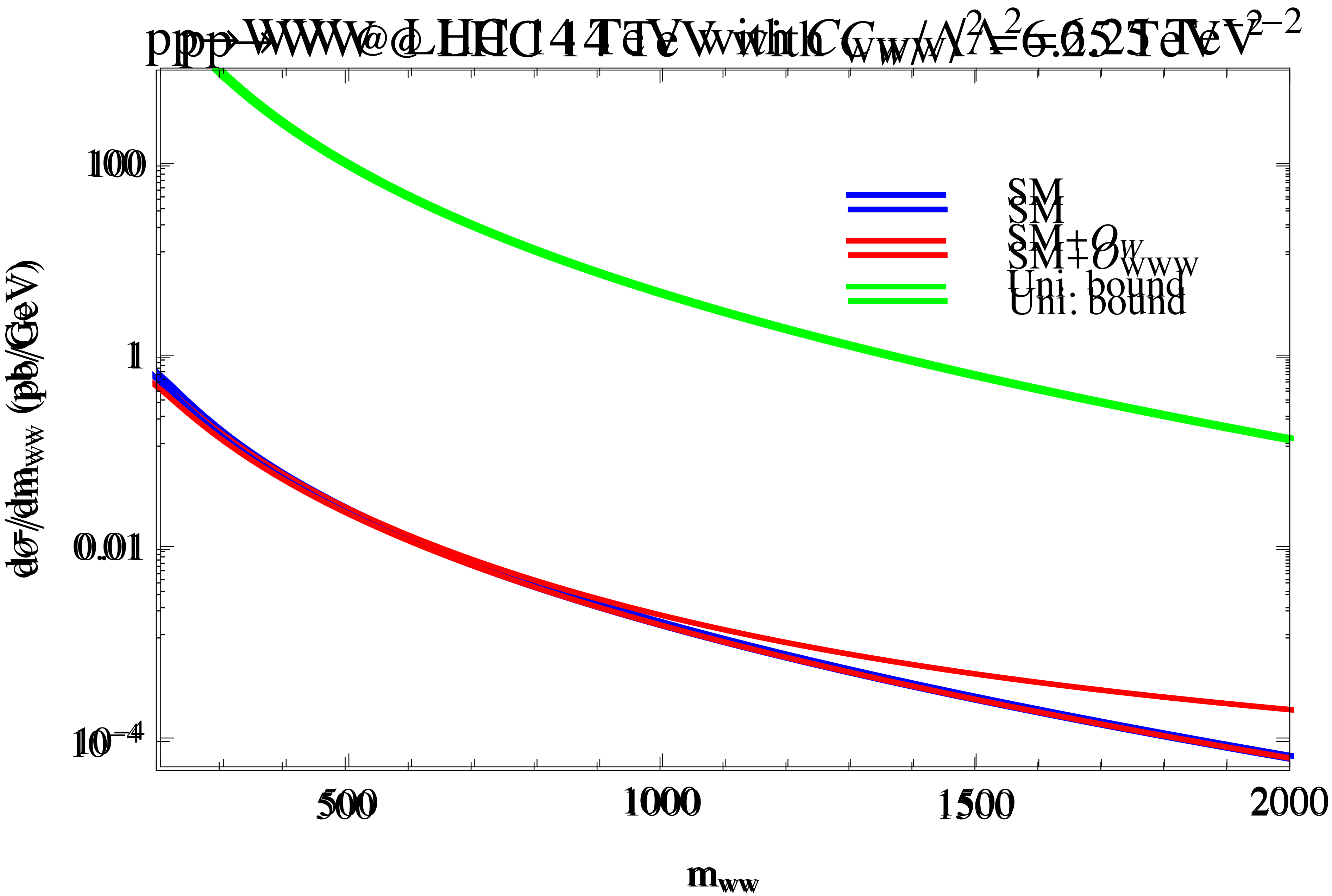
Unitarity

CD *et al.* AP 335 (2013) 21-32



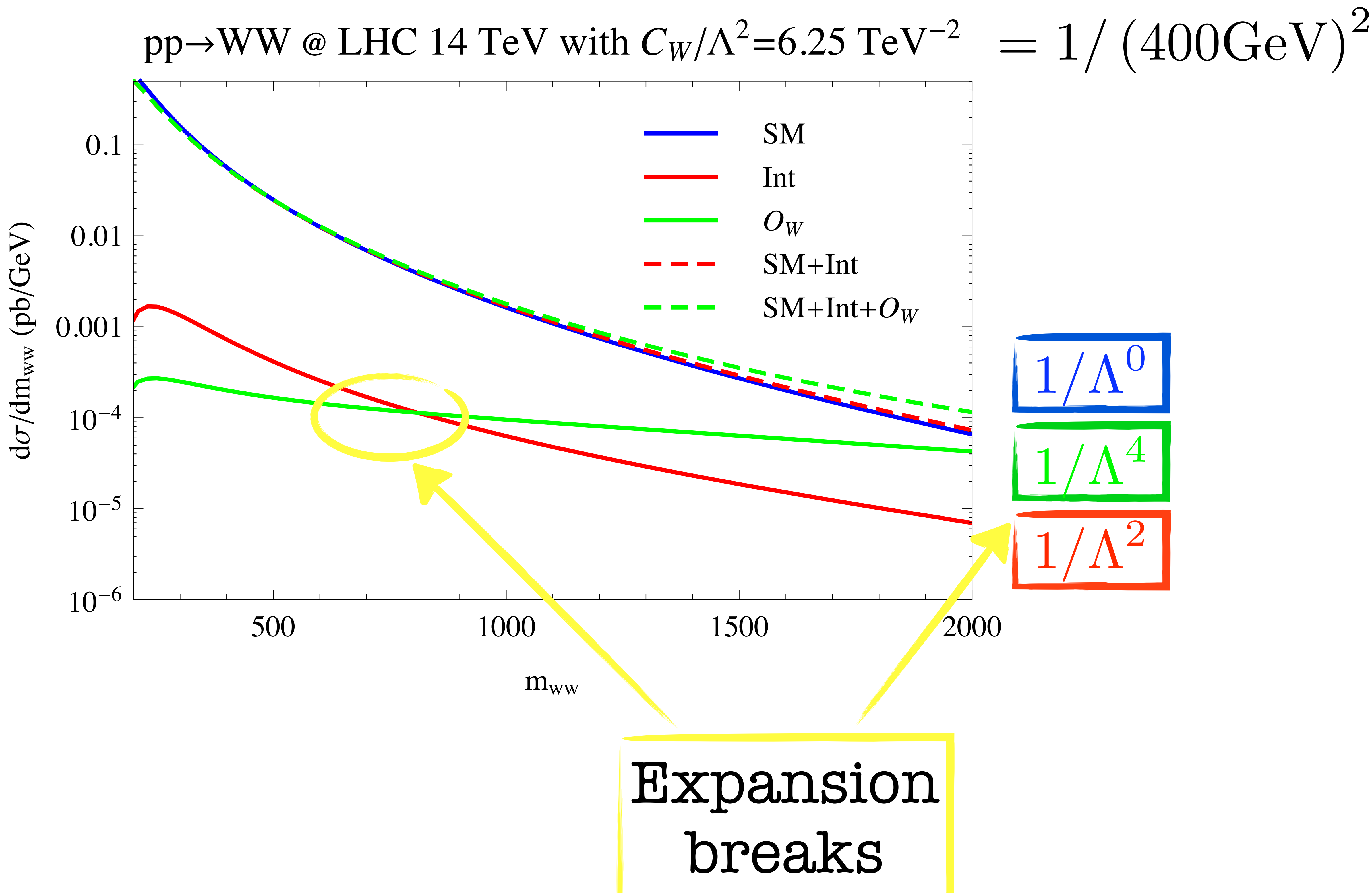
More than 2 orders of magnitude

Form factors are not needed!

LEP @ 68%

$$c_{WWW}/\Lambda^2 \in [-11.9, -1, 94]$$
$$c_W/\Lambda^2 \in [-8.48, 1.44]$$

Perturbativity



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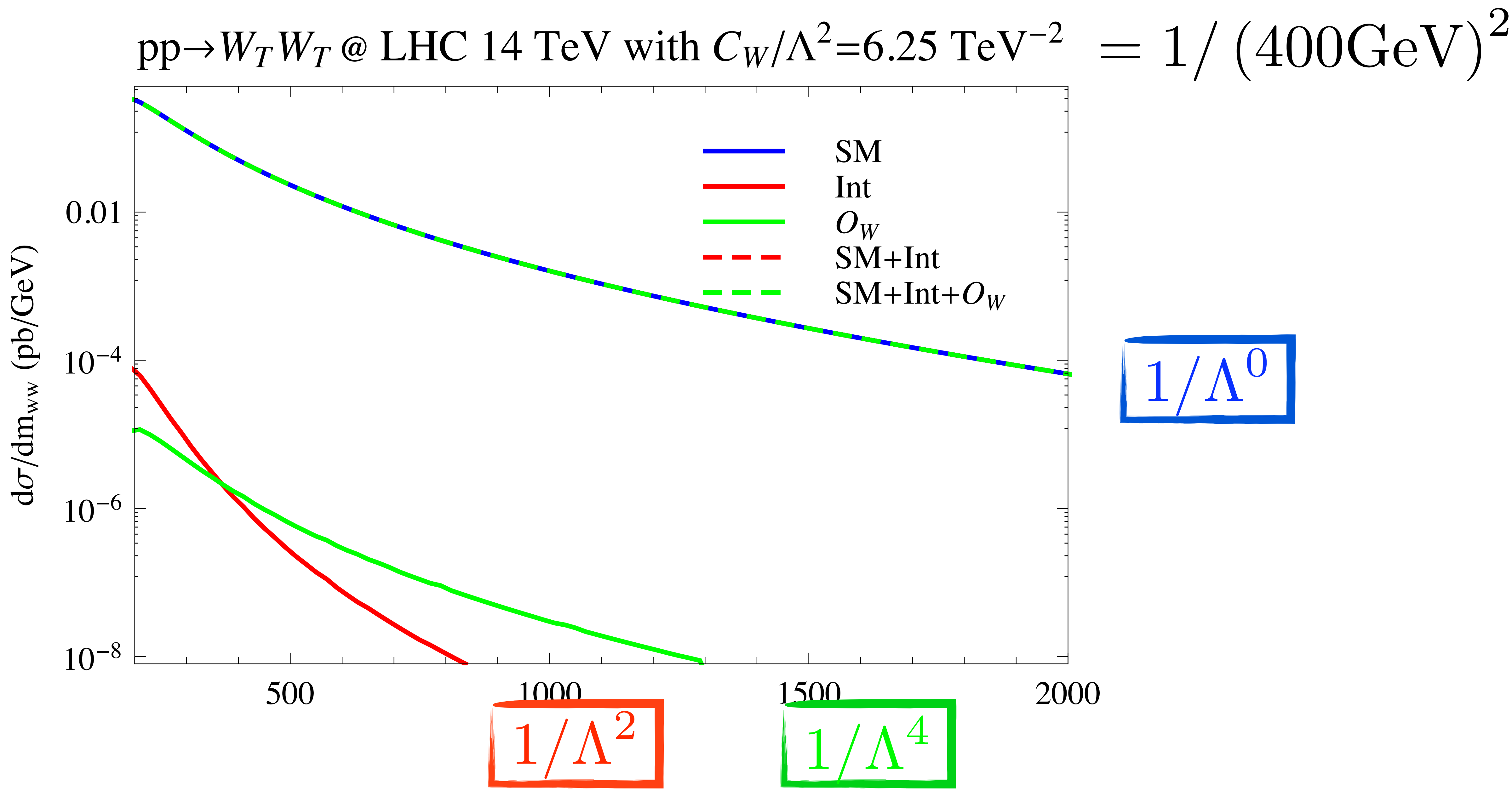
Expansion and errors



NP is suppressed : Bad estimate of the scale

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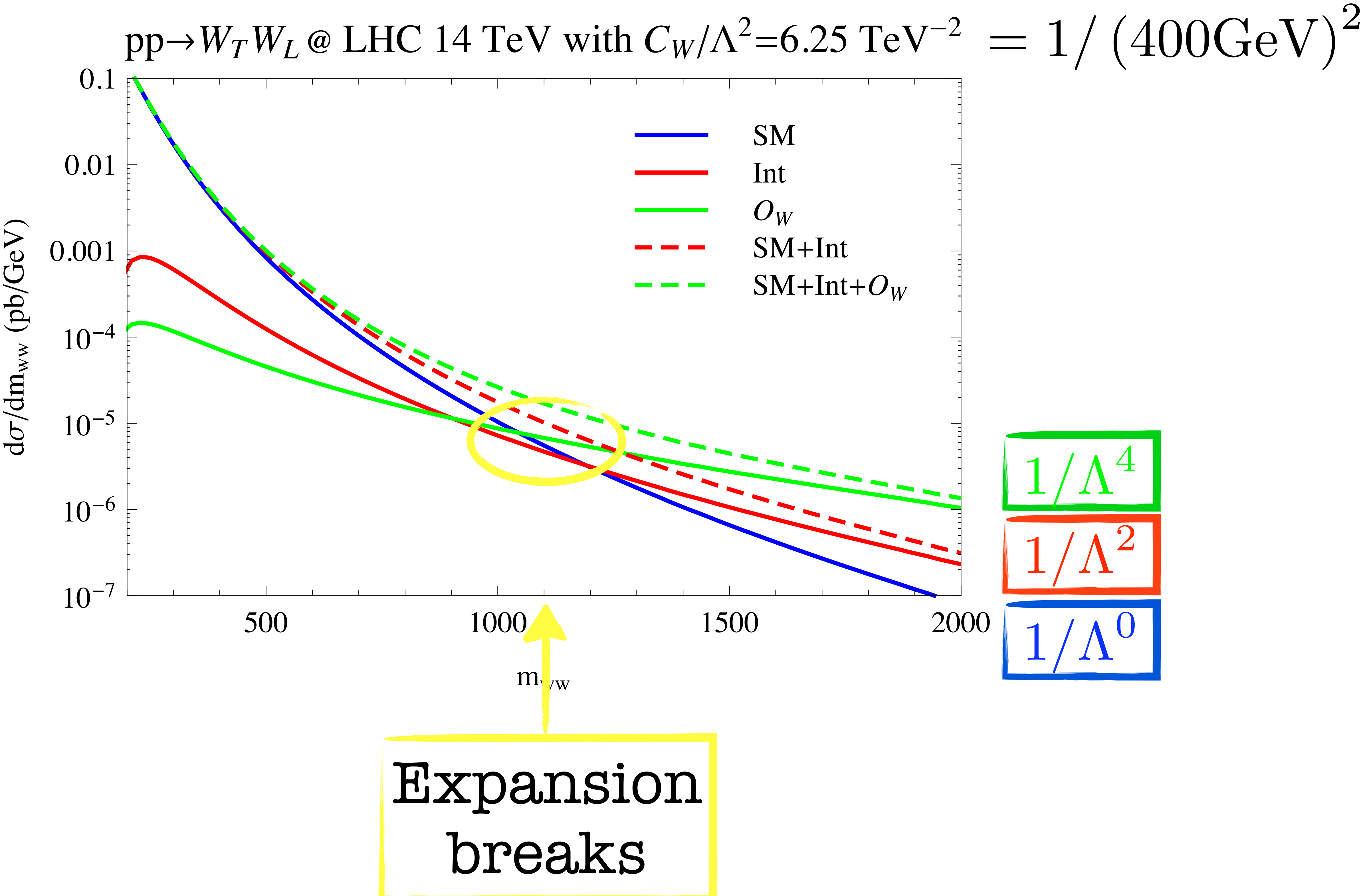
Expansion and errors



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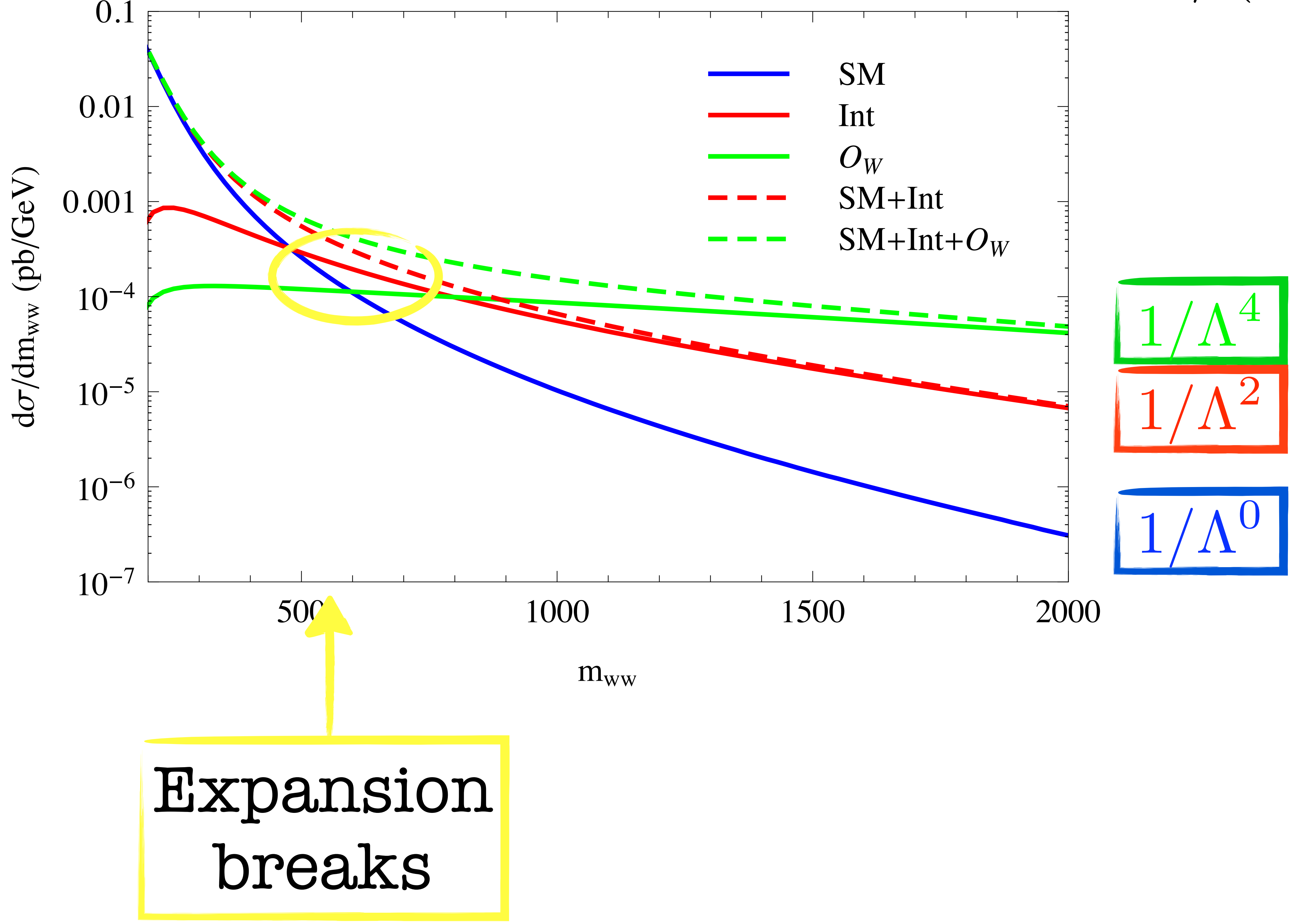
Expansion and errors

pp$\rightarrow W_L W_L$ @ LHC 14 TeV with C_W/Λ^2=6.25 TeV^{-2} $= 1/\left(400\text{GeV}\right)^2$



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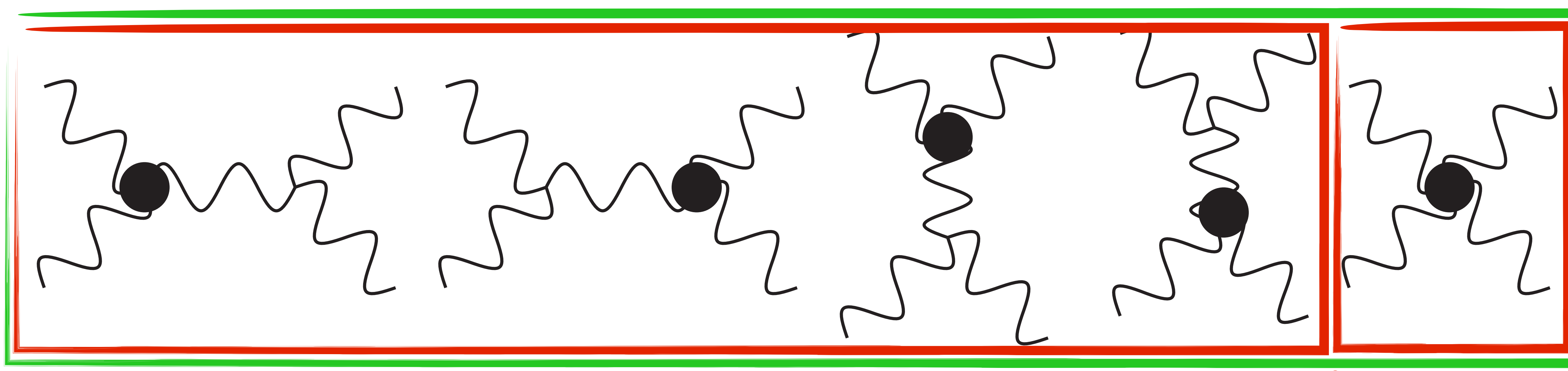
QGC from EFT

- 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

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

QGC's alone are not gauge invariant

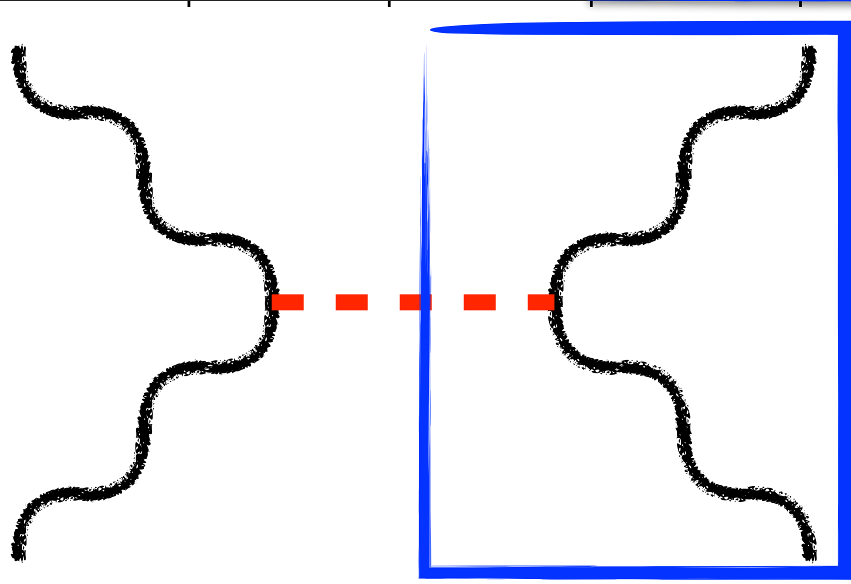
VBS/Triple prod.

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

$$\left.\begin{aligned}\mathcal{O}_{HB} &= \left(H^\dagger H\right) B^{\mu\nu} B_{\mu\nu} \\ \mathcal{O}_{HW} &= \left(H^\dagger H\right) \langle W^{\mu\nu} W_{\mu\nu} \rangle\end{aligned}\right\} \longrightarrow \left\{\begin{aligned}\mathcal{O}_{HB} &= \left(H^\dagger H - v^2\right) B^{\mu\nu} B_{\mu\nu} \\ \mathcal{O}_{HW} &= \left(H^\dagger H - v^2\right) \langle W^{\mu\nu} W_{\mu\nu} \rangle\end{aligned}\right.$$

	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					
$\mathcal{O}_{\partial h}$			X	X						
$\mathcal{O}_{HW}$			X	X	X	X				
$\mathcal{O}_{HB}$				X	X	X				

No new operators
small effects



Constraints from Higgs

Combination

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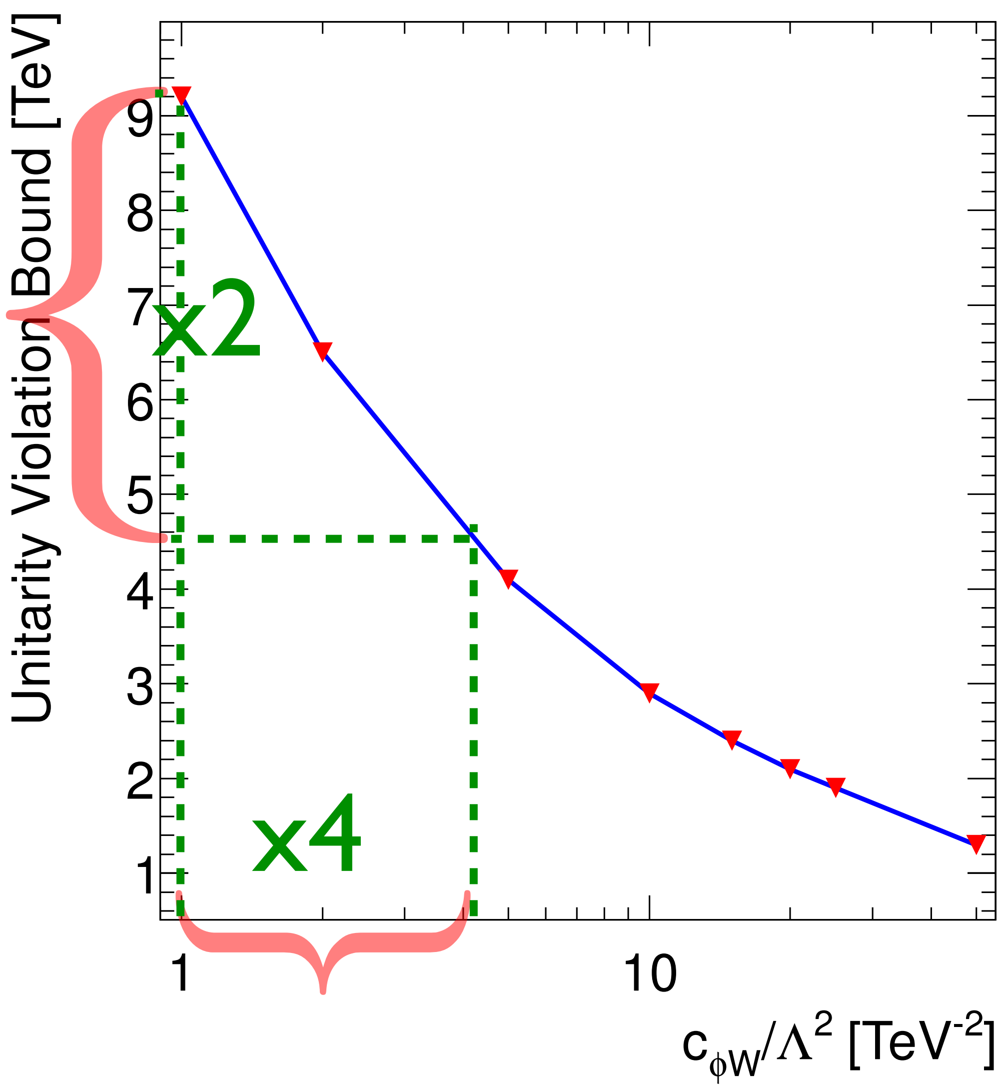
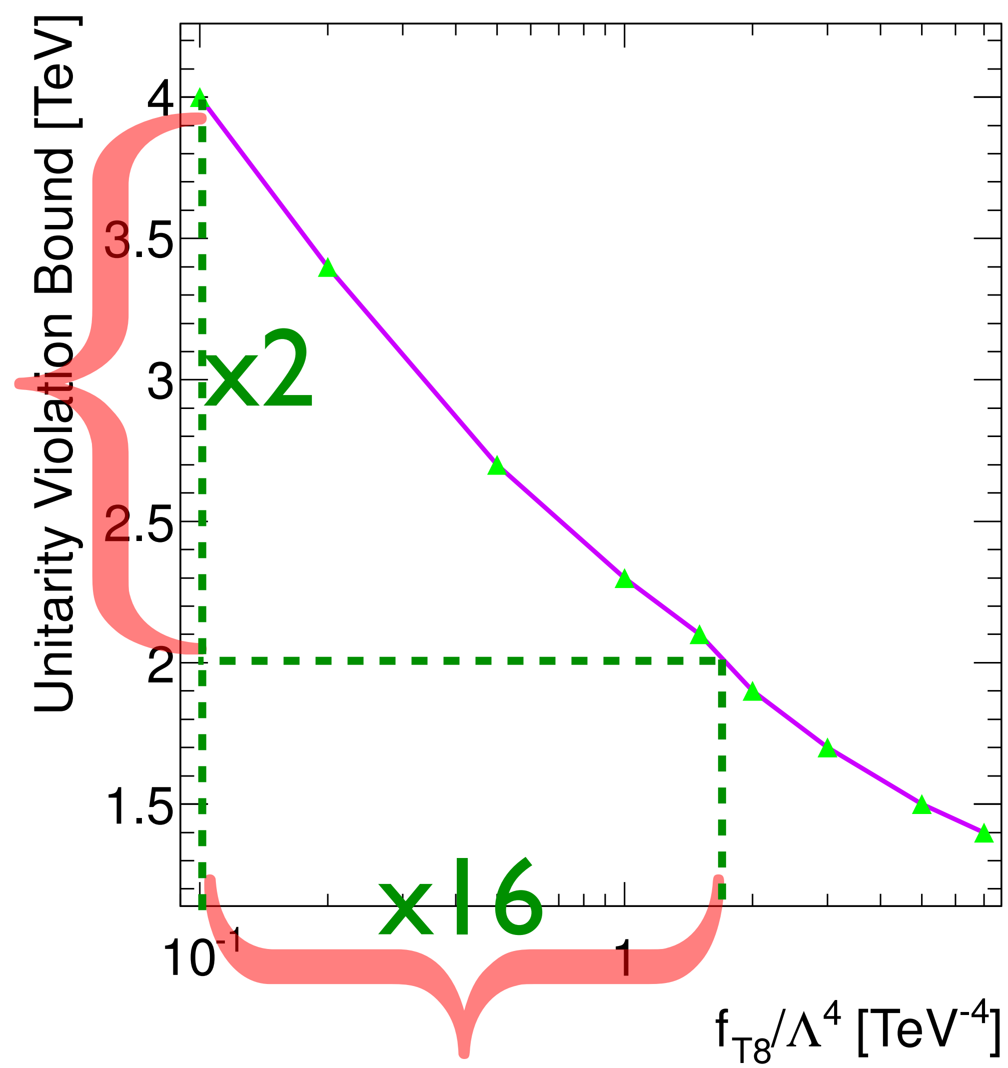
VBS/Triple prod.

- Go to dim-8 operators
  - dim-8 effects are smaller than dim-6 if EFT is valid
  - Lot of operators (~20 QGC without TCG)
  - EFT are worse for dim-8





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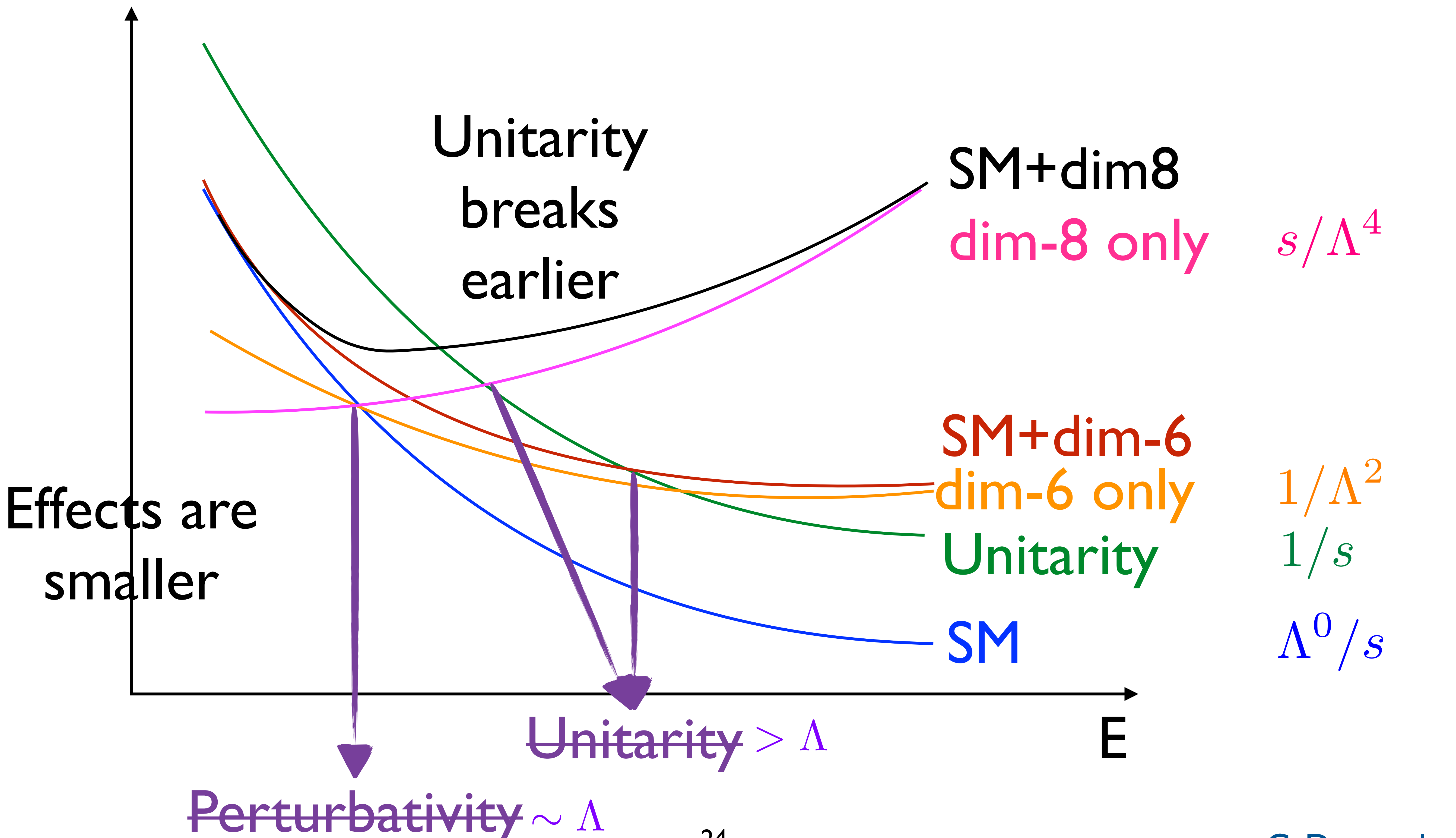
Unitarity/Perturbativity



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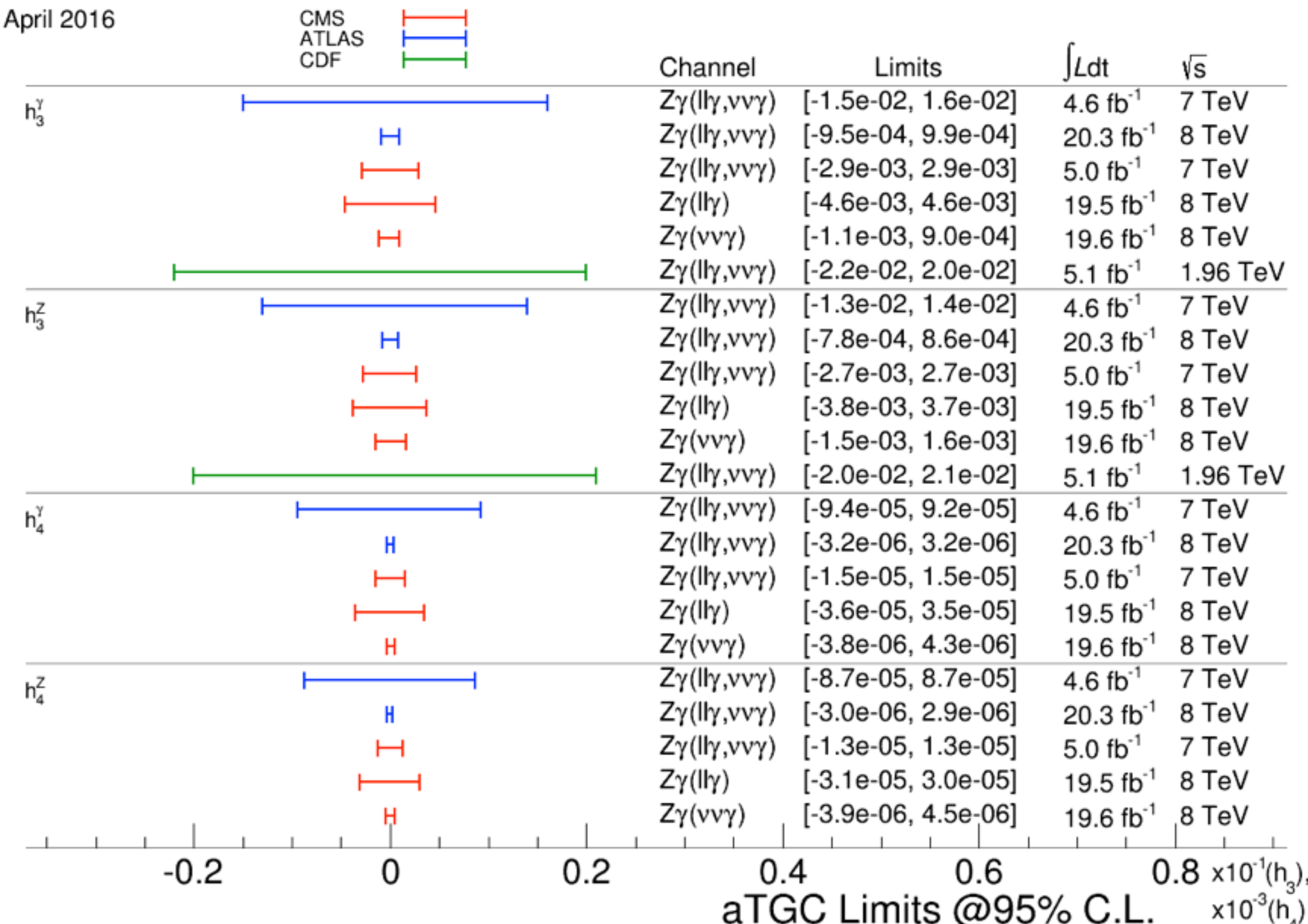
nTGC



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nTGC

$$\mathcal{L}^{nTGC} = \mathcal{L}_{SM} + 0 + \sum_i \frac{C_i}{\Lambda^4} \mathcal{O}_i^8$$

No dim-6 operators

Smaller effects

1 CP-even operator

$$\mathcal{O}_{\widetilde{B}W} = i\, H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H$$

Only AZZ

3 CP-odd operators

$$\begin{aligned} \mathcal{O}_{BW} &= i\, H^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H \\ \mathcal{O}_{WW} &= i\, H^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H \\ \mathcal{O}_{BB} &= i\, H^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\} H \end{aligned}$$

On-shell or attached to massless fermion

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nTGC

On-shell

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

$$ie\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,q_3) = \frac{-e(q_3^2-m_V^2)}{M_Z^2}\left\{h_1^V(q_2^\mu g^{\alpha\beta}-q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{M_Z^2}q_3^\alpha[(q_3q_2)g^{\mu\beta}-q_2^\mu q_3^\beta] - h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{M_Z^2}q_3^\alpha\epsilon^{\mu\beta\rho\sigma}q_{3\rho}q_{2\sigma}\right\}$$

$$f_5^\gamma = \frac{v^2M_Z^2}{4c_ws_w}\frac{C_{\tilde{B}W}}{\Lambda^4} \qquad f_5^Z = 0$$

$$h_3^Z = \frac{v^2M_Z^2}{4c_ws_w}\frac{C_{\tilde{B}W}}{\Lambda^4} \qquad h_4^Z = 0$$

$$h_3^\gamma = 0$$

$$h_4^\gamma = 0$$

$$-1.3\text{TeV}^{-4} < \frac{C_{\tilde{B}W}}{\Lambda^4} < 1.44\text{TeV}^{-4}$$

CP-odd see CD, JHEP 1402 (2014) 101

EFT in MC tools

- Automated MC tools (any process)
  - Madgraph5_aMC@NLO
  - Sherpa

Model from FeynRules ←

- Dedicated MC tools (process by process)
  - VBFNLO
  - MCFM
  - POWHEG Box
- Disclaimer : my apologies if anything is missing

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POWHEG Box

Anomalous Triple gauge boson couplings

$$\mathcal{L} = i g_{WWV} \left(g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho \right.$$
$$+ i g_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - i g_5^V \epsilon^{\mu\nu\rho\sigma} (W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu) V_\sigma$$
$$\left. + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \right),$$

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MCFM

- TGC : anomalous couplings
- Higgs

$$\begin{aligned}\mathcal{L}_{HAC} = & -\frac{1}{4}g^{(1)}_{hzz}Z_{\mu\nu}Z^{\mu\nu}h - g^{(2)}_{hzz}Z_{\nu}\partial_{\mu}Z^{\mu\nu}h + \frac{1}{2}g^{(3)}_{hzz}Z_{\mu}Z^{\mu}h - \frac{1}{4}\tilde{g}_{hzz}Z_{\mu\nu}\tilde{Z}^{\mu\nu}h \\ & -\frac{1}{2}g^{(1)}_{hww}W^{\mu\nu}W^{\dagger}_{\mu\nu}h - \left[g^{(2)}_{hww}W^{\nu}\partial^{\mu}W^{\dagger}_{\mu\nu}h + \text{h.c.}\right] + g^{(3)}_{hww}W_{\mu}W^{\dagger\mu}h - \frac{1}{2}\tilde{g}_{hww}W^{\mu\nu}\tilde{W}^{\dagger}_{\mu\nu}h \\ & -\frac{1}{2}g^{(1)}_{haz}Z_{\mu\nu}F^{\mu\nu}h - g^{(2)}_{haz}Z_{\nu}\partial_{\mu}F^{\mu\nu}h - \frac{1}{2}\tilde{g}_{haz}Z_{\mu\nu}\tilde{F}^{\mu\nu}h\end{aligned}$$

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VBFNLO

TGC : AC and Dimension-six operators

QGC as dimension-eight operators

Higgs - Vector - Vector vertex

$$T^{\mu\nu} = a_1(x,y)g^{\mu\nu} + a_2(x,y)[x\cdot y g^{\mu\nu} - y^\mu x^\nu] + a_3(x,y)\varepsilon^{\mu\nu\rho\sigma}x_\rho y_\sigma$$

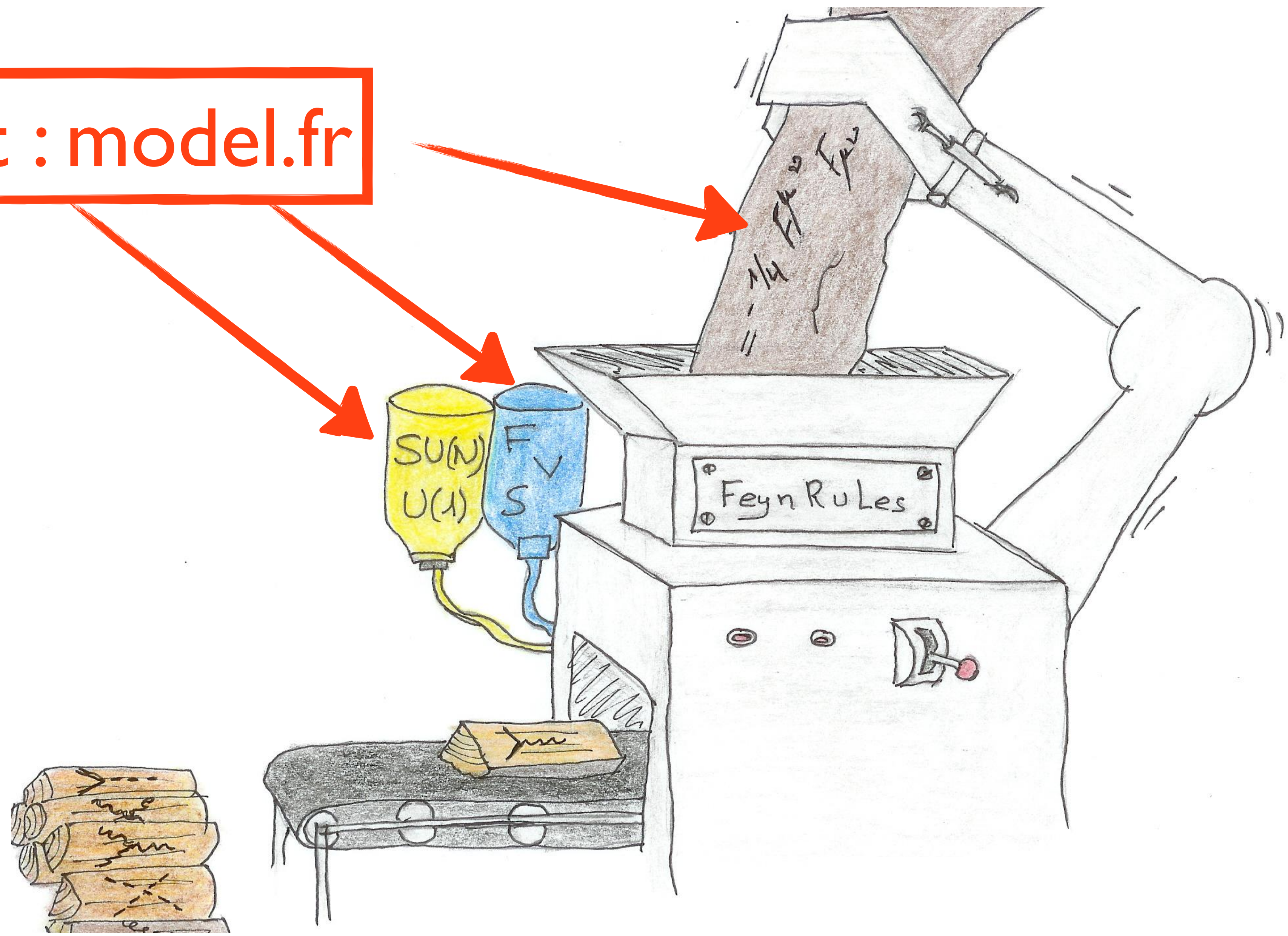
+ translation to other parametrisation

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W_-^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W_-^{\mu\nu}$$
$$+ \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}$$

and the dimension-six

FeynRules

Input : model.fr



Output : vertices

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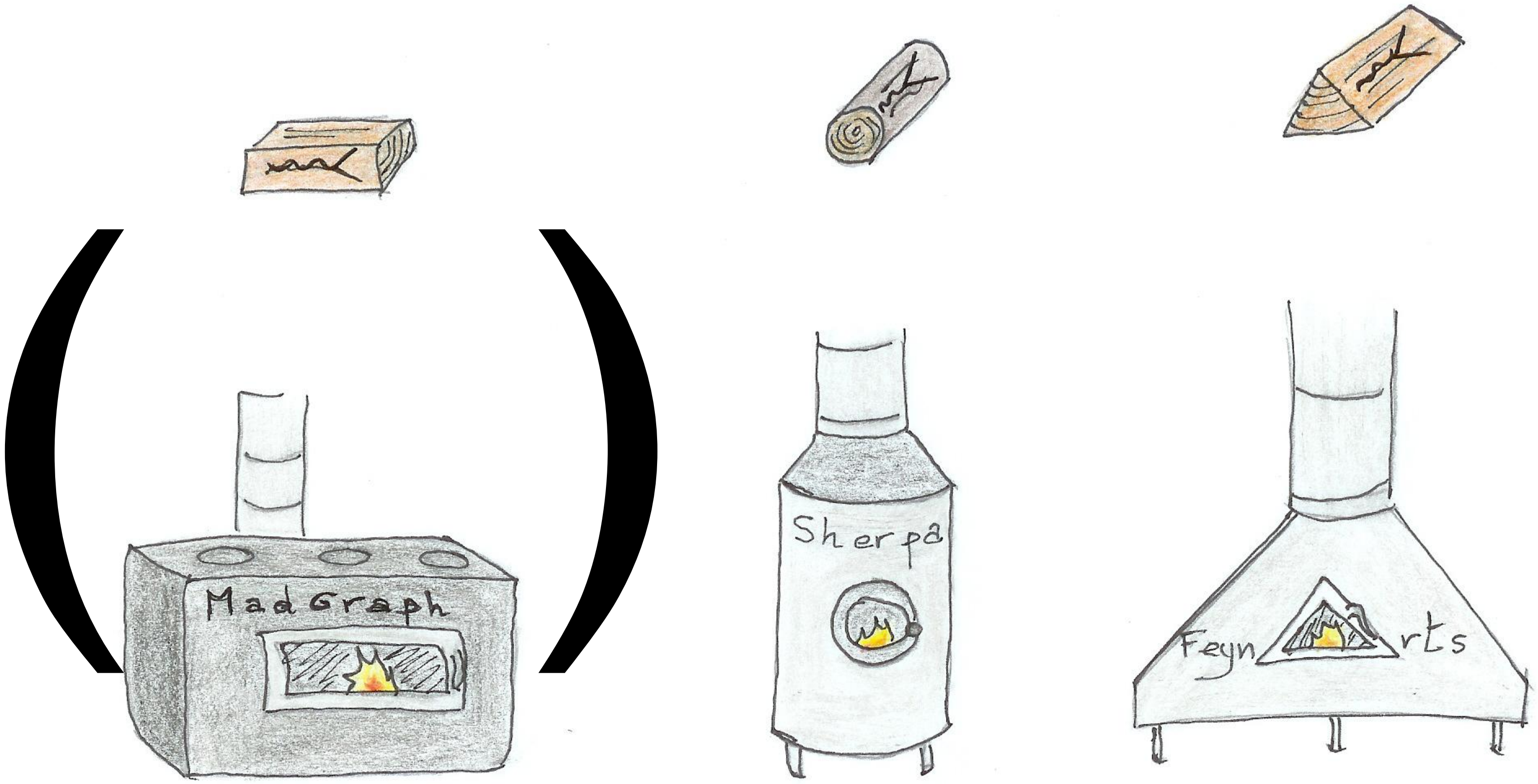
FeynRules outputs



FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

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FR model/UFO for EW

$$\mathcal{O}_h = \left(H^\dagger H\right)^3$$

$$\mathcal{O}_{\partial h} = \partial_\mu \left(H^\dagger H\right) \partial^\mu \left(H^\dagger H\right)$$

$$\mathcal{O}_{HB} = \left(H^\dagger H\right) B^{\mu\nu} B_{\mu\nu}$$

$$\mathcal{O}_{HW} = \left(H^\dagger H\right) \langle W^{\mu\nu} W_{\mu\nu} \rangle$$

$$\mathcal{O}_{WWW} = \langle W^{\mu\nu} W_{\nu\rho} W^{\rho}_{\mu} \rangle$$

$$\mathcal{O}_W = \left(D_\mu H\right)^\dagger W^{\mu\nu} D_\nu H$$

$$\mathcal{O}_B = \left(D_\mu H\right)^\dagger B^{\mu\nu} D_\nu H$$

Full UFO model :

All the vertices (up to 6 ext)

Any process

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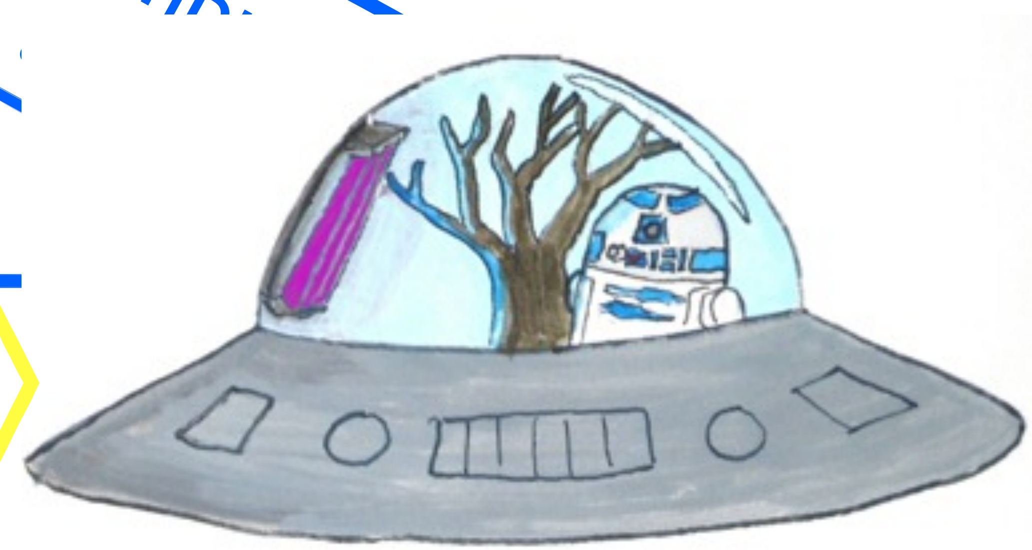
Ingredients

- Madgraph5_aMC@NLO : automated NLO+PS for the SM
- Required ingredients :
  - Tree-level vertices
  - R2 vertices
  - UV counterterms vertices
- Result : UFO at NLO

New, comp
NLOCT



Done for renomalizable models (<=dim4)

done for EFT - 4F

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Loop computation

$$\mathcal{A}^{1-loop} = \sum_i d_i \text{ Box}_i + \sum_i c_i \text{ Triangle}_i + \sum_i b_i \text{ Bubble}_i + \sum_i a_i \text{ Tadpole}_i + R$$

- Box, Triangle, Bubble and Tadpole are known scalar integrals
- Loop computation = find the coefficients
  - Unitarity
  - Multiple cuts
  - Tensor reduction (OPP)

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R_2

$$\bar{A}(\bar{q}) = \frac{1}{(2\pi)^4} \int d^d \bar{q} \frac{\bar{N}(\bar{q})}{\bar{D}_0 \bar{D}_1 \ldots \bar{D}_{m-1}}, \qquad \bar{D}_i = (\bar{q} + p_i)^2 - m_i^2$$

$$\bar{N}(\bar{q}) = N(q) + \tilde{N}(\tilde{q}, q, \epsilon)$$

d 4 ε

$$R_2 \equiv \lim_{\epsilon \to 0} \frac{1}{(2\pi)^4} \int d^d \bar{q} \frac{\tilde{N}(\tilde{q}, q, \epsilon)}{\bar{D}_0 \bar{D}_1 \ldots \bar{D}_{m-1}}$$

Finite set of vertices that can be computed once for each model

Needed by Madgraph5_aMC@NLO (tool-dep.)

C. Degrande

R_1

Due to the ε dimensional parts of the denominators

Like for the 4 dimensional part but with a different set of integrals

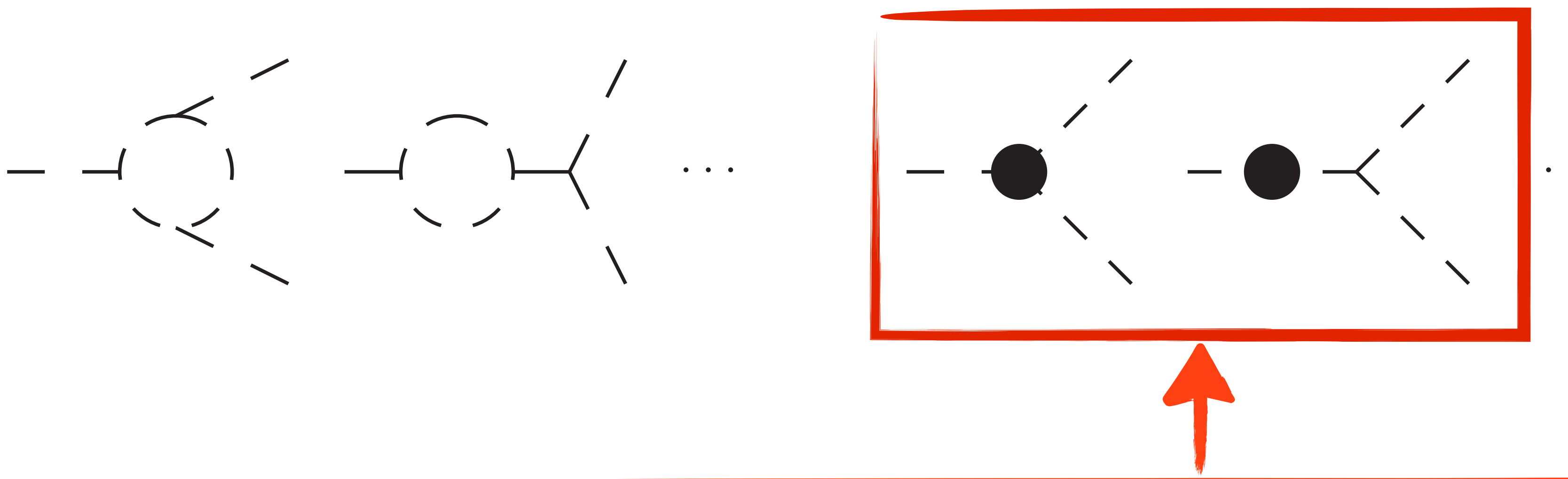
$$\begin{aligned}
\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_i\bar{D}_j} &= -\frac{i\pi^2}{2}\left[m_i^2+m_j^2-\frac{(p_i-p_j)^2}{3}\right]+\mathcal{O}(\epsilon)\,,\\
\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_i\bar{D}_j\bar{D}_k} &= -\frac{i\pi^2}{2}+\mathcal{O}(\epsilon)\,,\\
\int d^n\bar{q}\frac{\tilde{q}^4}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_l} &= -\frac{i\pi^2}{6}+\mathcal{O}(\epsilon)\,.
\end{aligned}$$

Only $R = R_1+R_2$ is gauge invariant ⇨ Check

C. Degrande

UV

$$\bar{A}(\bar{q}) = \frac{1}{(2\pi)^4} \int d^d\bar{q} \frac{\bar{N}(\bar{q})}{\bar{D}_0 \bar{D}_1 \ldots \bar{D}_{m-1}} = K \frac{1}{\epsilon} + \mathcal{O}\left(\epsilon^0\right)$$



$$= 0\frac{1}{\epsilon} + \mathcal{O}\left(\epsilon^0\right)$$

Relations fixed by the Lagrangian (finite part)

Finite set of vertices that can be computed once for each model

C. Degrande

EFT@NLO

- EFT are renormalizable order by order

Need EFT not ano. vertices !

$\bar{Q}_L H \sigma^{\mu\nu} G_{\mu\nu} t_R$

$H^\dagger H G_{\mu\nu} G^{\mu\nu}$

- mixing of operators
- full set to basis
- Higher powers of the loop momentum in the vertices and in the numerators of the integrals

C. Degrande

EW boson interations at NLO in QCD

No QCD corrections to EW gauge boson interactions

Recipe = SM with NLO QCD (i.e. tree-level vertices, R2 and UV) + LO(tree-level only) EW dim6

EW gauge boson interations at NLO in QED

- FR/MG5_aMC are starting NLO in QED for the SM and renomalizable (dim<=4) BSM
- All the issues of NLO for EFT
- $\alpha_{EW} = 0.01$

Concluding remarks

- EFT : probe/constrain heavy new physics
- EFT for EW : few operators ⇒combination (VV,H,VVV,VBS, …)
- LHC challenges (Validity, precision)
- Available in MC
- NLO in QCD for EW gauge boson interactions : Done (Trivial)