HIGGS COMPOSITENESS: CURRENT STATUS AND FUTURE STRATEGIES

Roberto Contino

CERN & EPFL Lausanne

CERN Theory Colloquium - 4 December, 2013

Outline

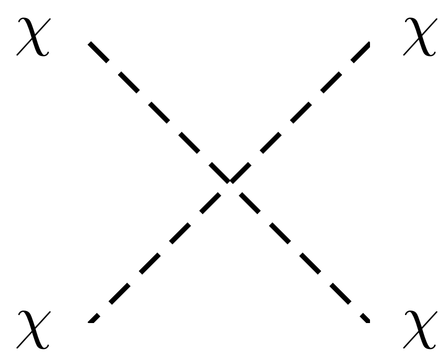
- Strong vs Weak EWSB
- Current Status of Higgs Compositeness:

  1. Higgs mass
  2. EW Precision Tests
  3. Impact of Searches for top partners
  4. Impact of data on Higgs couplings

- Future Strategies

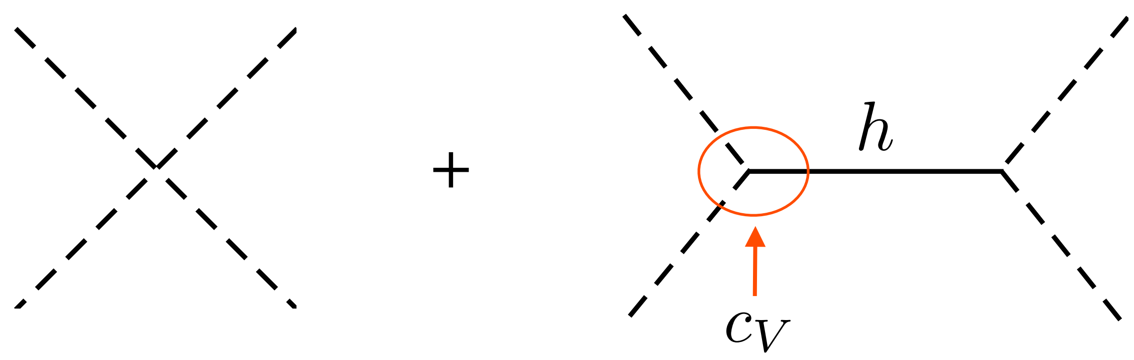
Strong vs Weak EWSB

In the {SM-H}



$$A(W_L W_L \to W_L W_L) = A(\chi\chi \to \chi\chi) \sim \frac{E^2}{v^2} \equiv g^2(E)$$

In the {SM-H} + H



$$A \sim \frac{E^2}{v^2}(1 - c_V^2) - c_V^2 \, \frac{m_h^2}{v^2} \, \frac{s}{s - m_h^2}$$

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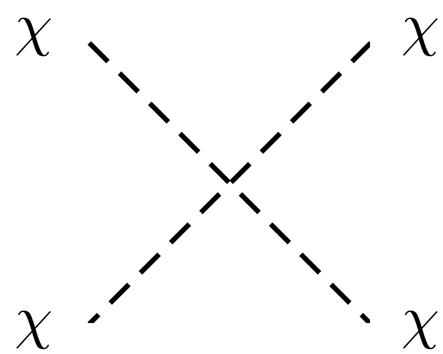

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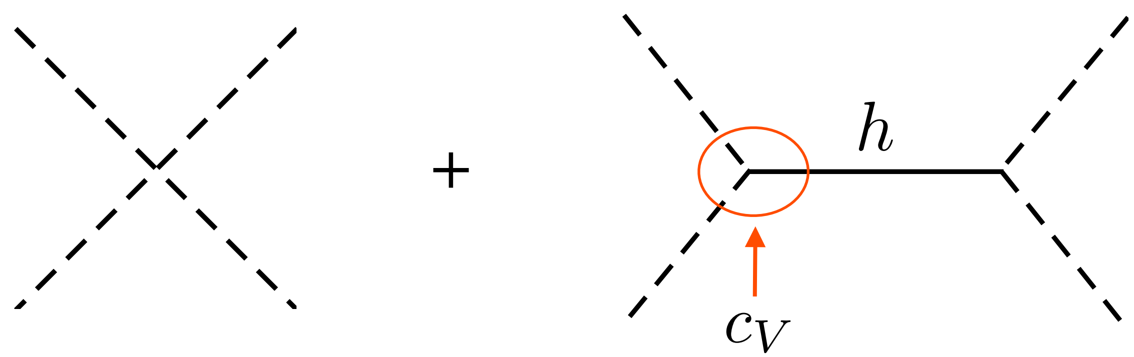

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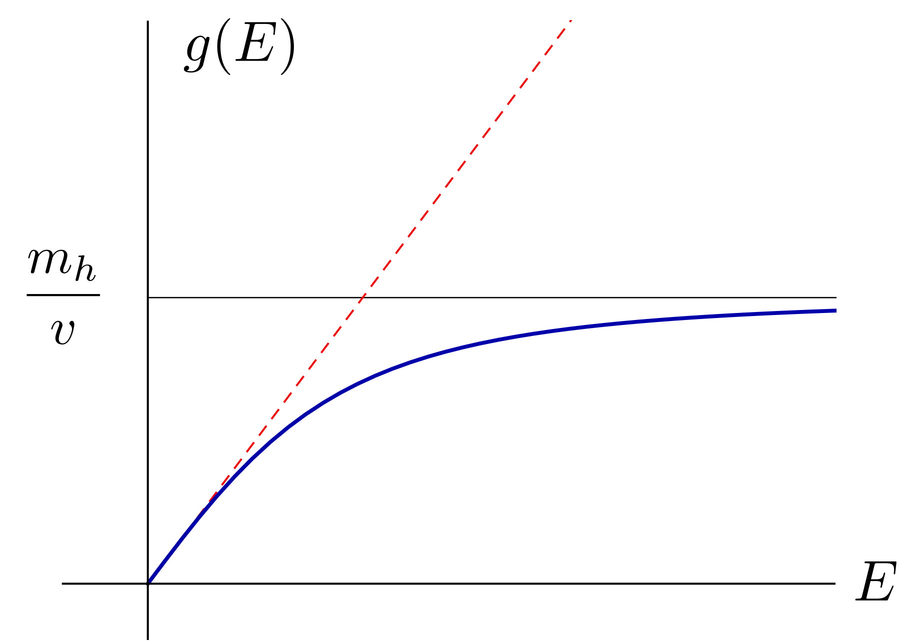
$= 0$

Elementary Higgs: $c_V = 1$

weak →



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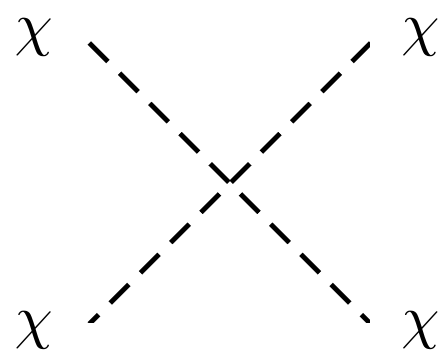

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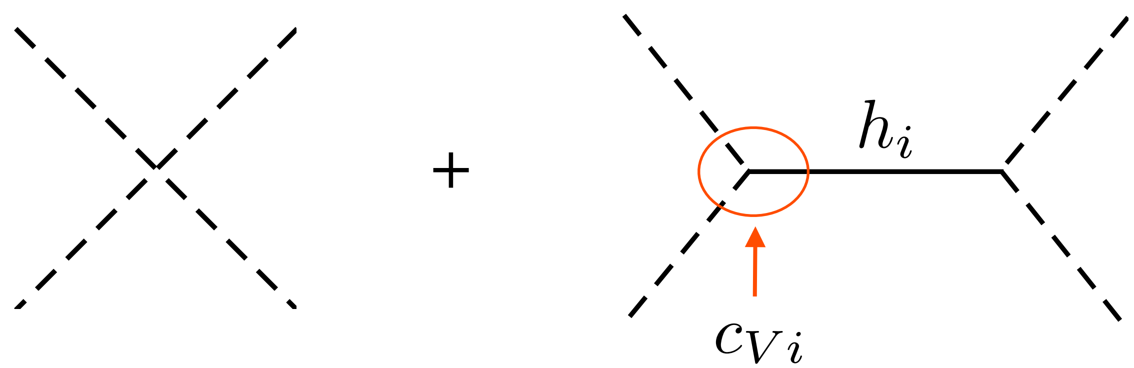
In the {SM-H} + H_i



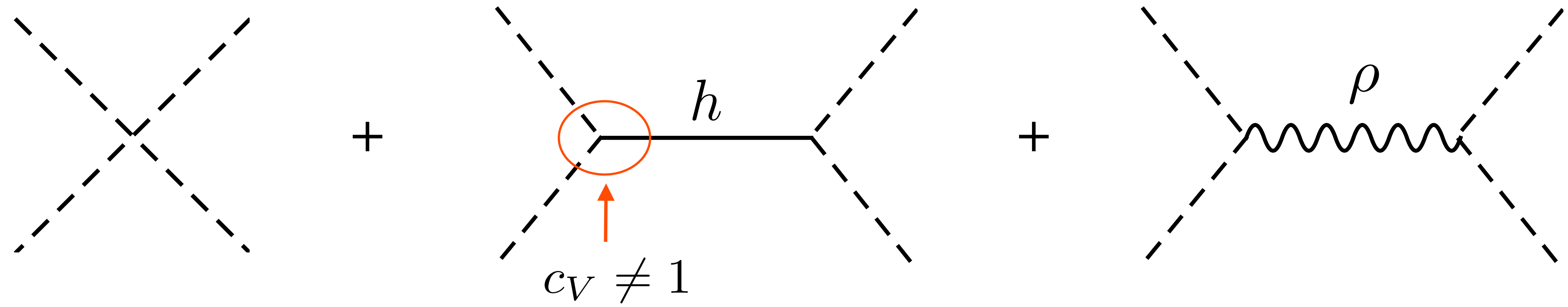
$$A \sim \frac{E^2}{v^2}\left(1 - \sum_i c_{Vi}^2\right) + \dots$$

$= 0$

Elementary Higgses:
(more than one)

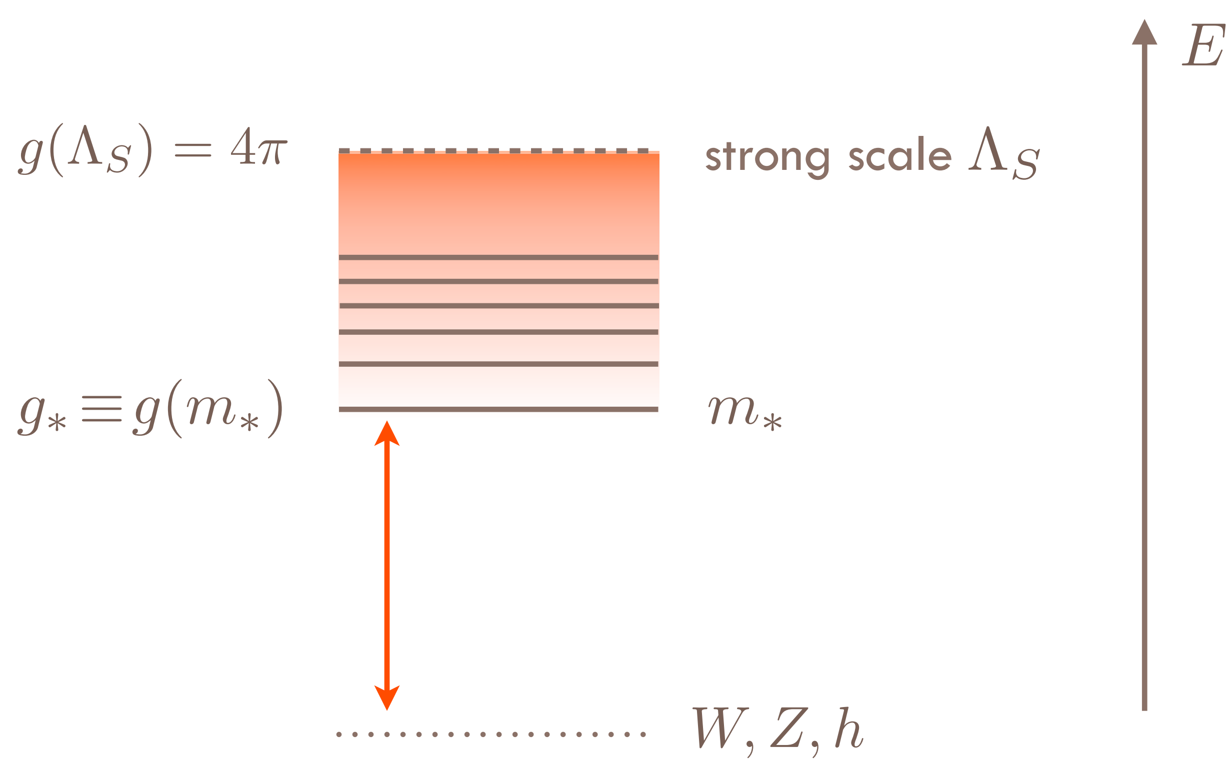
- $\delta c_{Vi} \sim O(1)$ possible
- sum rule: $\sum_i c_{Vi}^2 = 1$

Composite Higgs:



coupling strength grows with energy and saturates at $g_* \lesssim 4\pi$

Energy cartoon:



Analogy with $\pi\pi$ scattering in QCD: $h \leftrightarrow \sigma$

↓

Q: why light and narrow ?

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$\downarrow$

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A: the Higgs is itself a (pseudo) NG boson

Georgi & Kaplan, '80
Kaplan, Georgi, Dimopoulos

ex: $\frac{SO(5)}{SO(4)} \longrightarrow$ 4 NGBs transforming as a (2,2) of SO(4)~$SU(2)_L$x$SU(2)_R$

Agashe, RC, Pomarol NPB 719 (2005) 165

$$f^2 \left| \partial_\mu \, e^{i\pi/f} \right|^2 = (\partial\pi)^2 + \frac{(\pi\partial\pi)^2}{f^2} + \frac{\pi^2(\pi\partial\pi)^2}{f^4} + \dots$$

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Giudice et al. JHEP 0706 (2007) 045

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1. $O(v^2/f^2)$ shifts in tree-level Higgs couplings. Ex: $c_V = 1 - c_H \left(\frac{v}{f} \right)^2 + \dots$

Analogy with $\pi\pi$ scattering in QCD: $h \leftrightarrow \sigma$

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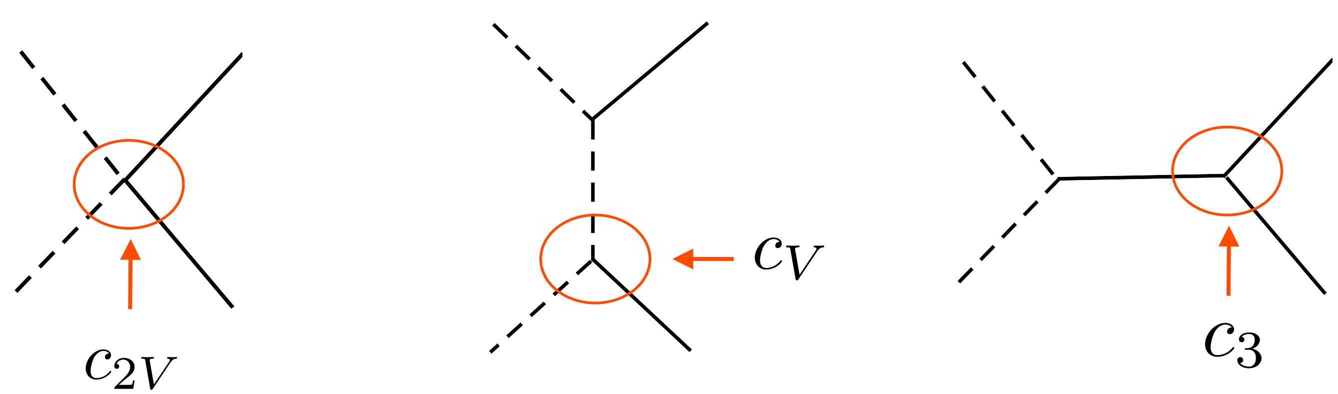
2. Scatterings involving the Higgs also grow with energy

$$A(WW \to hh) \sim \frac{s}{v^2} (c_V^2 - c_{2V})$$



Linear couplings

D.B. Kaplan NPB 365 (1991) 259
...
RS with bulk fermions

- Hypothesis: each SM fermion couples to a composite fermionic operator with the same $SU(3)_c x SU(2)_L x U(1)_Y$ quantum numbers

$$\mathcal{L} = \lambda_L \, \bar{q}_L O_R + \lambda_R \, \bar{u}_R O_L + h.c.$$

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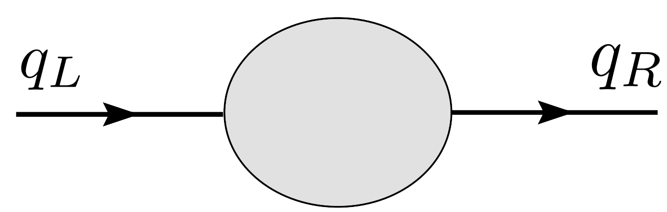
Quark masses need two such couplings



$$m_q \sim \frac{\lambda_L(\mu)\lambda_R(\mu)}{g_*} \, v \qquad \mu \sim m_*$$

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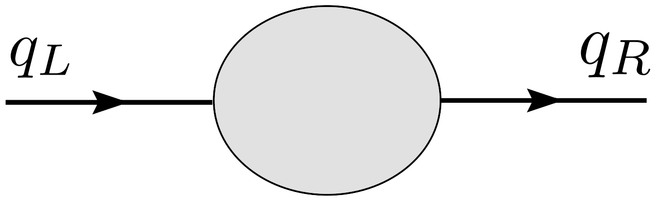

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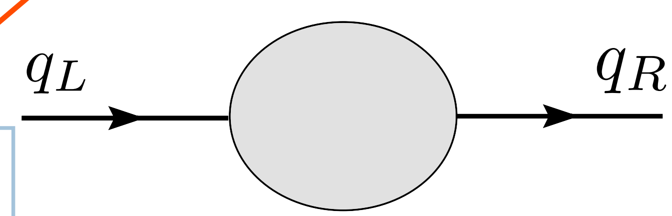
Quark masses need two such couplings

break explicitly the Goldstone symmetry



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- Fermionic operators can excite composite fermions at low energy:

$$\langle 0|O|\chi\rangle = \lambda\, f$$

same as for a conserved current:

$$\langle 0|J_\mu|\rho\rangle = \epsilon^r_\mu\, f_\rho\, m_\rho$$

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- Linear couplings imply mass mixings:

$$\mathcal{L} = \bar\psi\, i\partial\!\!\!/\, \psi + \bar\chi(\, i\nabla\!\!\!\!/ - m_*)\chi + \lambda f\, \bar\psi U(\pi)\chi + h.c.$$

rotating to mass eigenbasis:

$$\begin{pmatrix}\psi\\ \chi\end{pmatrix} \to \begin{pmatrix}\cos\varphi & \sin\varphi\\ \sin\varphi & \cos\varphi\end{pmatrix}\begin{pmatrix}\psi\\ \chi\end{pmatrix} \qquad \tan\varphi = \frac{\lambda\, f}{m_*}$$

φ parametrizes the degree of compositeness of the SM fermions

$$|\mathrm{SM}\rangle = \cos\varphi\,|\psi\rangle + \sin\varphi\,|\chi\rangle$$

$$|\mathrm{heavy}\rangle = -\sin\varphi\,|\psi\rangle + \cos\varphi\,|\chi\rangle$$

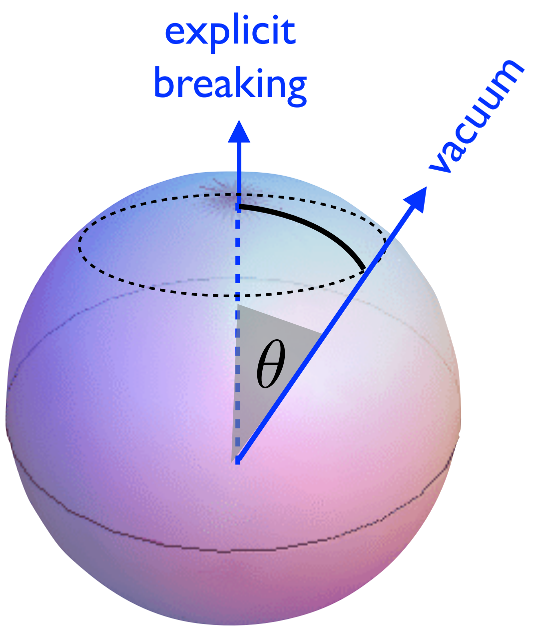
Higgs mass

Can a 125GeV Higgs be composite ?

Structure of the Higgs Potential

$$V(h) = \frac{m_*^4}{g_*^2}\frac{N_c}{8\pi^2}\left[\lambda^2 \sum_i A_i(h/f) + \lambda^4 \sum_i B_i(h/f) + \ldots\right]$$

$$h \equiv \sqrt{H^\dagger H}$$



$A_i(x), B_i(x)$ SO(4) structures

→ trigonometric functions: $\sin^2(x)$

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explicit breaking of Goldstone symmetry (spurion couplings)

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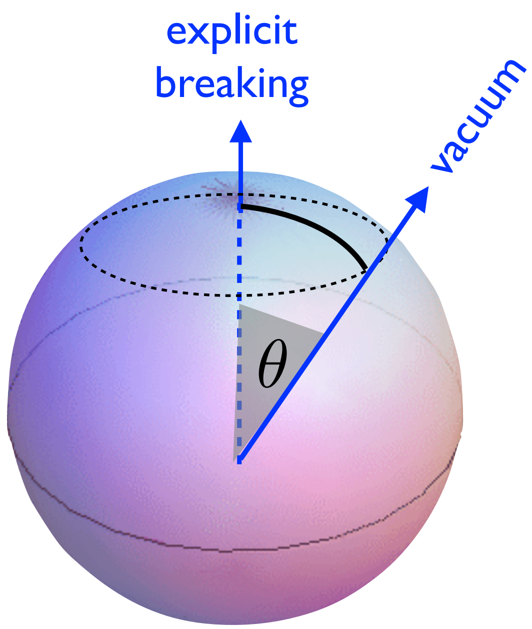

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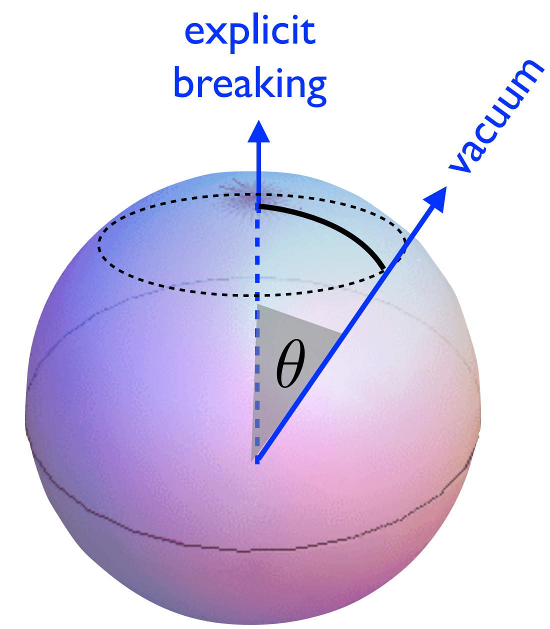

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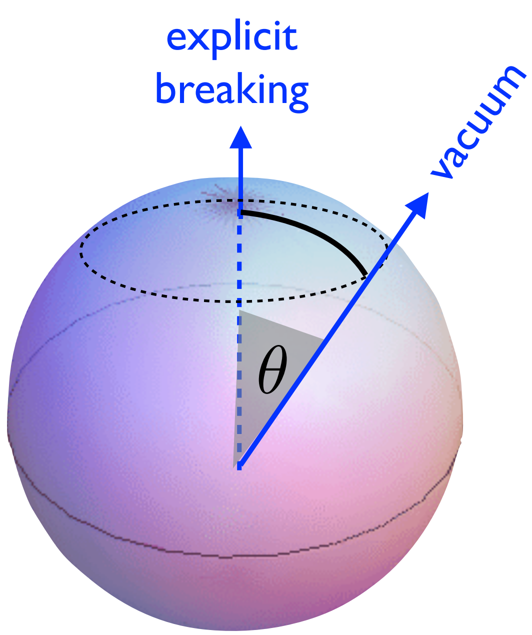

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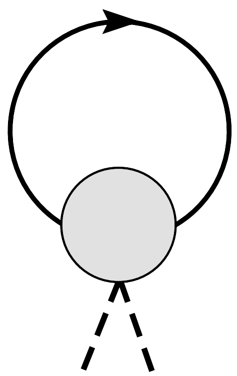
- To get EWSB ($0 < x \ll \pi$) at least <u>two</u> SO(4) structures are needed plus some tuning

$$\frac{SO(5)}{SO(4)} = S^4$$ vacuum manifold is the 4-sphere

$$FT = O\left(\frac{v^2}{f^2}\right)$$

- If EWSB is triggered at $O(\lambda^2)$



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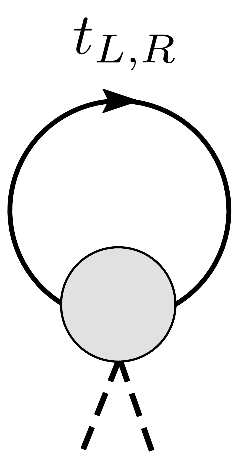

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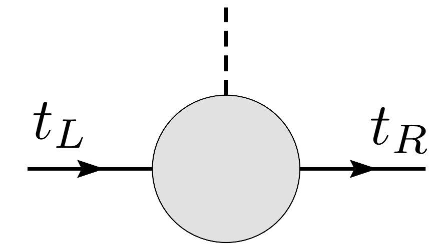

$$y_t \sim \frac{\lambda_L \lambda_R}{g_*}$$

assuming $\lambda_L \simeq \lambda_R$

$$m_h^2 \sim \frac{N_c}{4\pi^2} g_*^3 y_t \, v^2 = \left(330\,\mathrm{GeV} \times \left(\frac{g_*}{3}\right)^{3/2}\right)^2$$

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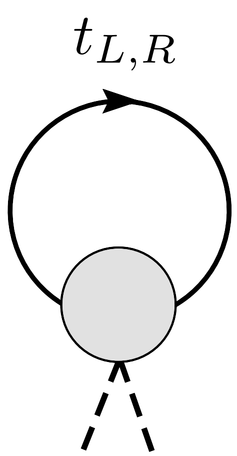

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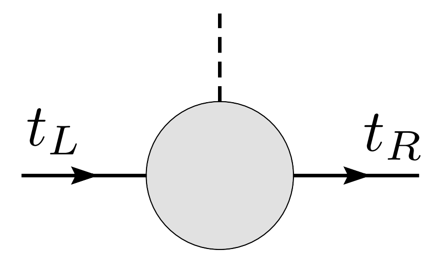

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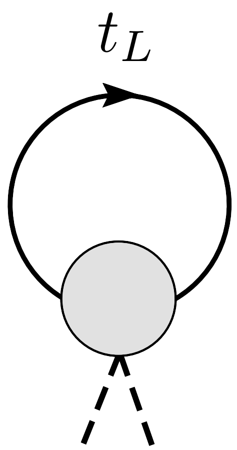
Higgs tends to be too heavy
(unless $g_* \sim 1$)

- If EWSB is triggered at $O(\lambda^2)$ + t_R fully composite



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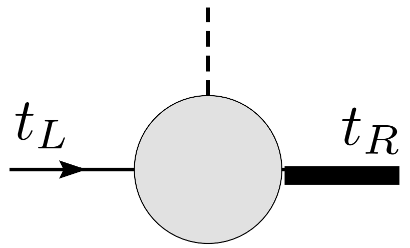

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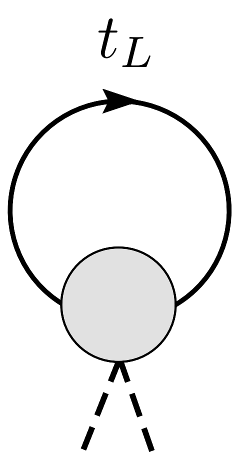

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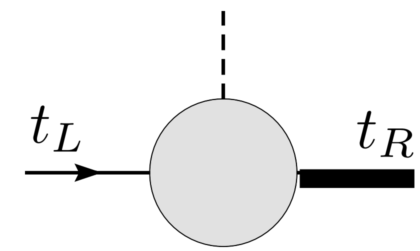

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m_H=125GeV implies that top partners are naturally

- not too strongly coupled, *hence*
- not too heavy

Matsedonskyi, Panico, Wulzer JHEP 1301 (2013) 164
Redi, Tesi JHEP 1210 (2012) 166
Marzocca, Serone, Shu JHEP 1208 (2012) 013
Pomarol, Riva JHEP 1208 (2012) 135
Panico, Redi, Tesi, Wulzer JHEP 1303 (2013) 051
De Simone et al. JHEP 1304 (2013) 004

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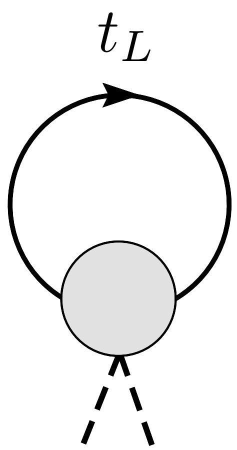

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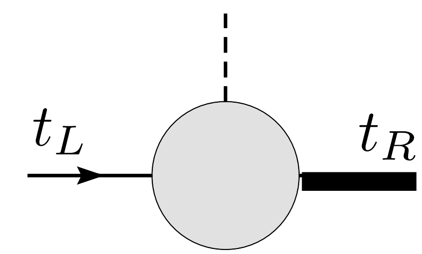

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$$FT \sim \frac{v^2}{f^2} \sim \frac{m_h^2}{m_*^2}\frac{4\pi^2}{N_c y_t^2} = \left(\frac{525\,\mathrm{GeV}}{m_*}\right)^2$$

Matsedonskyi, Panico, Wulzer JHEP 1301 (2013) 164
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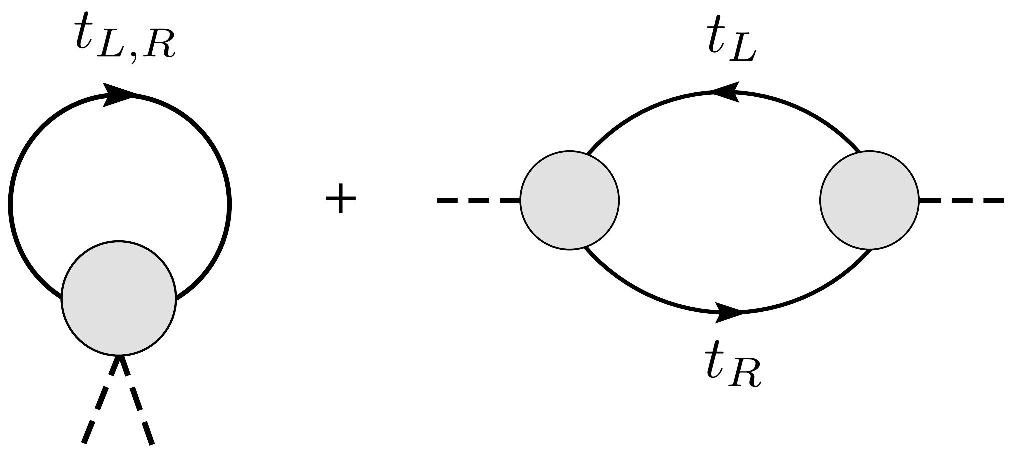
De Simone et al. JHEP 1304 (2013) 004

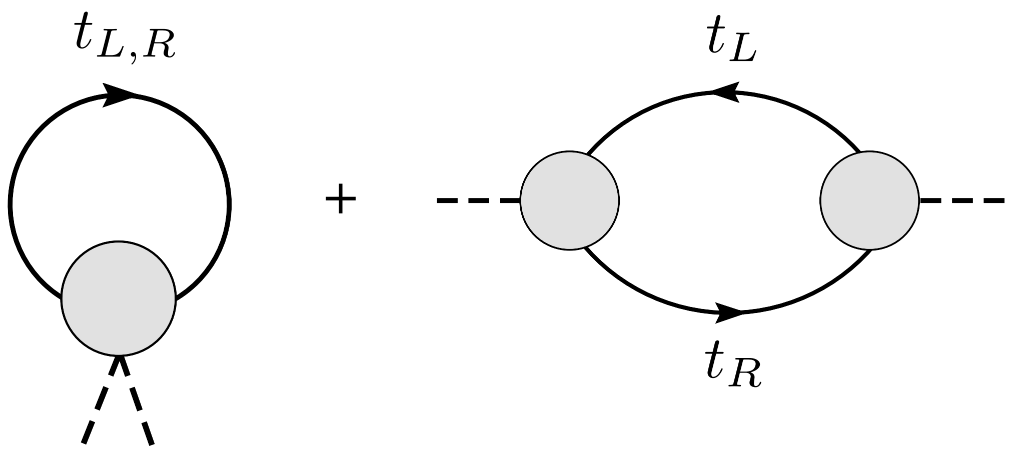
- If EWSB is triggered at $O(\lambda^4)$



$$V(h) \simeq \frac{m_*^4}{g_*^2}\,\frac{N_c}{8\pi^2}\left[\lambda_{L,R}^2\, A\left(\frac{h}{f}\right) + \frac{\lambda_L^2 \lambda_R^2}{g_*^2}\, B\left(\frac{h}{f}\right)\right]$$

- If EWSB is triggered at $O(\lambda^4)$

extra tuning required to suppress $O(\lambda^2)$ terms down to $O(\lambda^4)$



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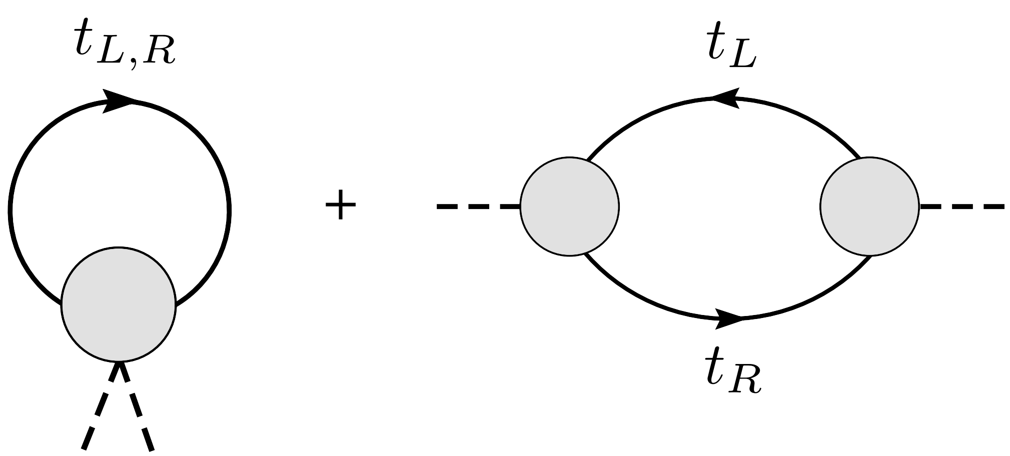

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$$V(h) \simeq \frac{m_*^4}{g_*^2}\frac{N_c}{8\pi^2}\left[\lambda_{L,R}^2\, A\left(\frac{h}{f}\right) + \frac{\lambda_L^2\lambda_R^2}{g_*^2}\, B\left(\frac{h}{f}\right)\right]$$

$$m_h^2 \sim \frac{N_c}{4\pi^2}\frac{m_*^2}{f^2}\frac{\lambda_L^2\lambda_R^2}{g_*^2}\, v^2 \sim \frac{N_c}{4\pi^2}\, g_*^2 y_t^2\, v^2 = \left(175\,\mathrm{GeV} \times \left(\frac{g_*}{3}\right)\right)^2$$

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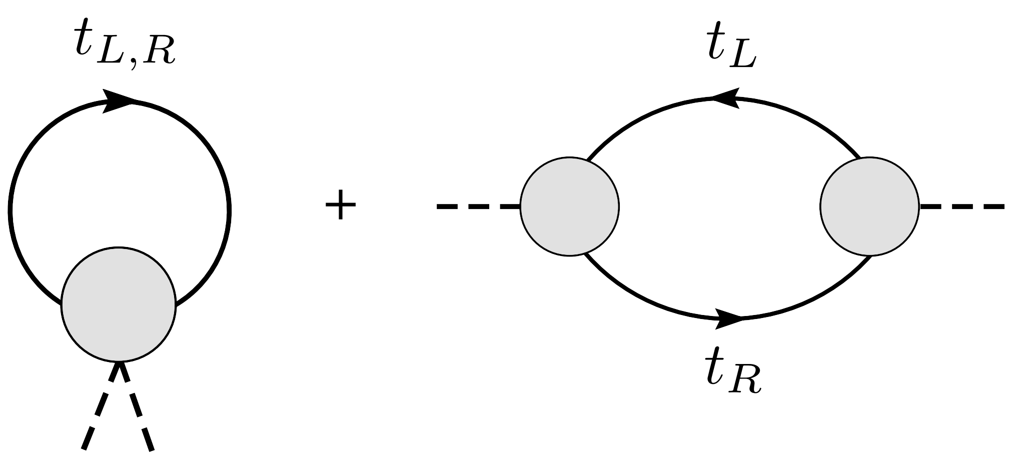

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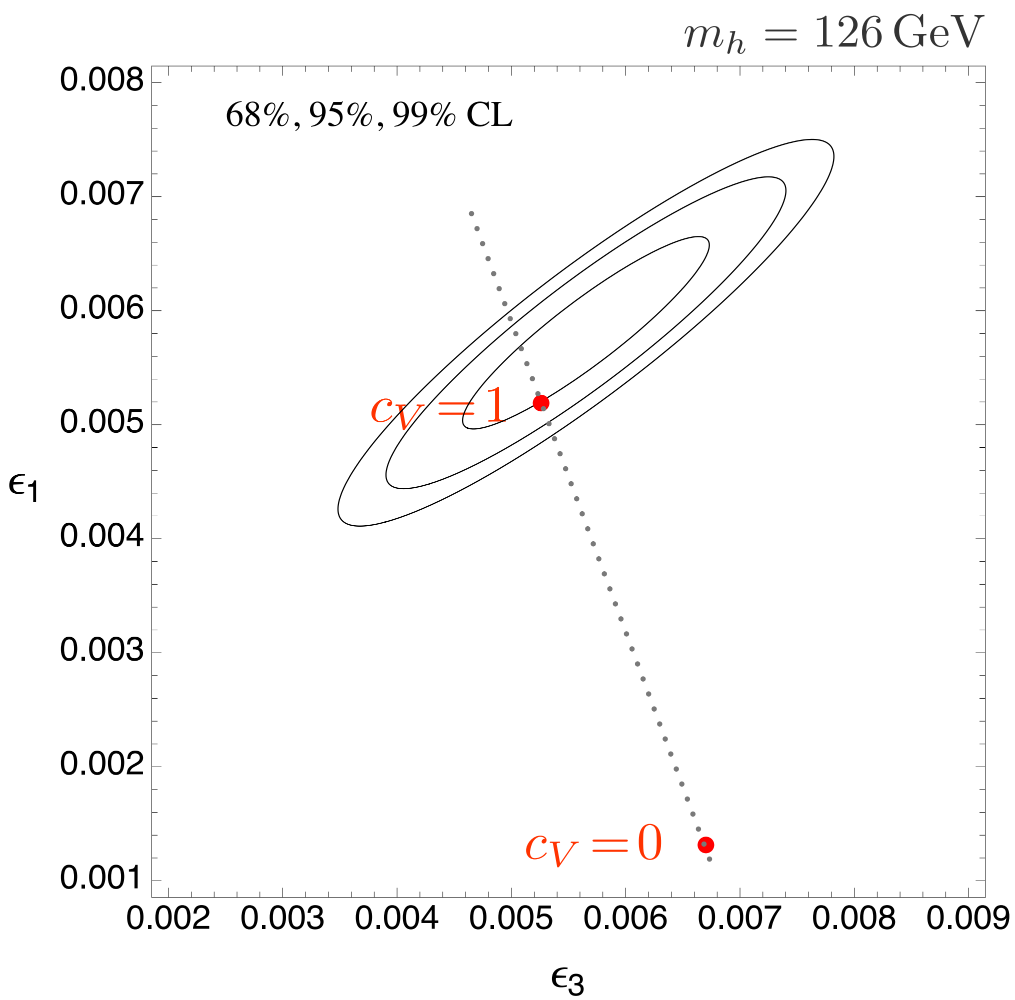
$$FT \sim \frac{v^2}{f^2} \times \frac{\lambda^2}{g_*^2} \simeq \left(\frac{525\,\mathrm{GeV}}{m_*}\right)^2 \times \frac{y_t}{g_*}$$

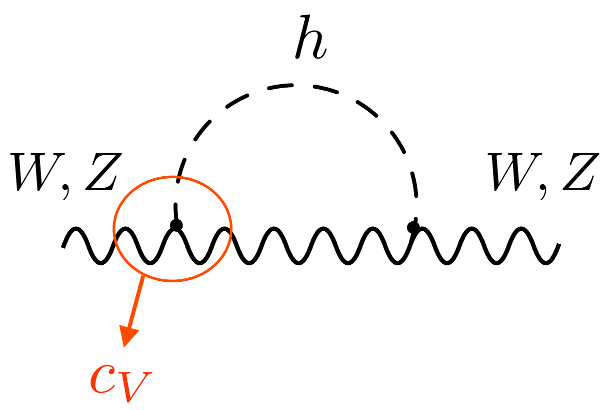
m_H automatically lighter but larger tuning to get EWSB

Panico, Redi, Tesi, Wulzer JHEP 1303 (2013) 051

EW Precision Tests

Constraints on c_V from EW Precision Tests





fit from: GFitter coll. Eur. Phys. J. C 72 (2012) 2205

$$\Delta\epsilon_1 = -\frac{3}{16\pi}\,\frac{\alpha_{em}}{\cos^2\theta_W}\,\log\frac{\Lambda^2}{m_Z^2}$$

$$\Delta\epsilon_3 = +\frac{1}{12\pi}\,\frac{\alpha_{em}}{4\sin^2\theta_W}\,\log\frac{\Lambda^2}{m_Z^2}$$

Barbieri et al. PRD 76 (2007) 115008

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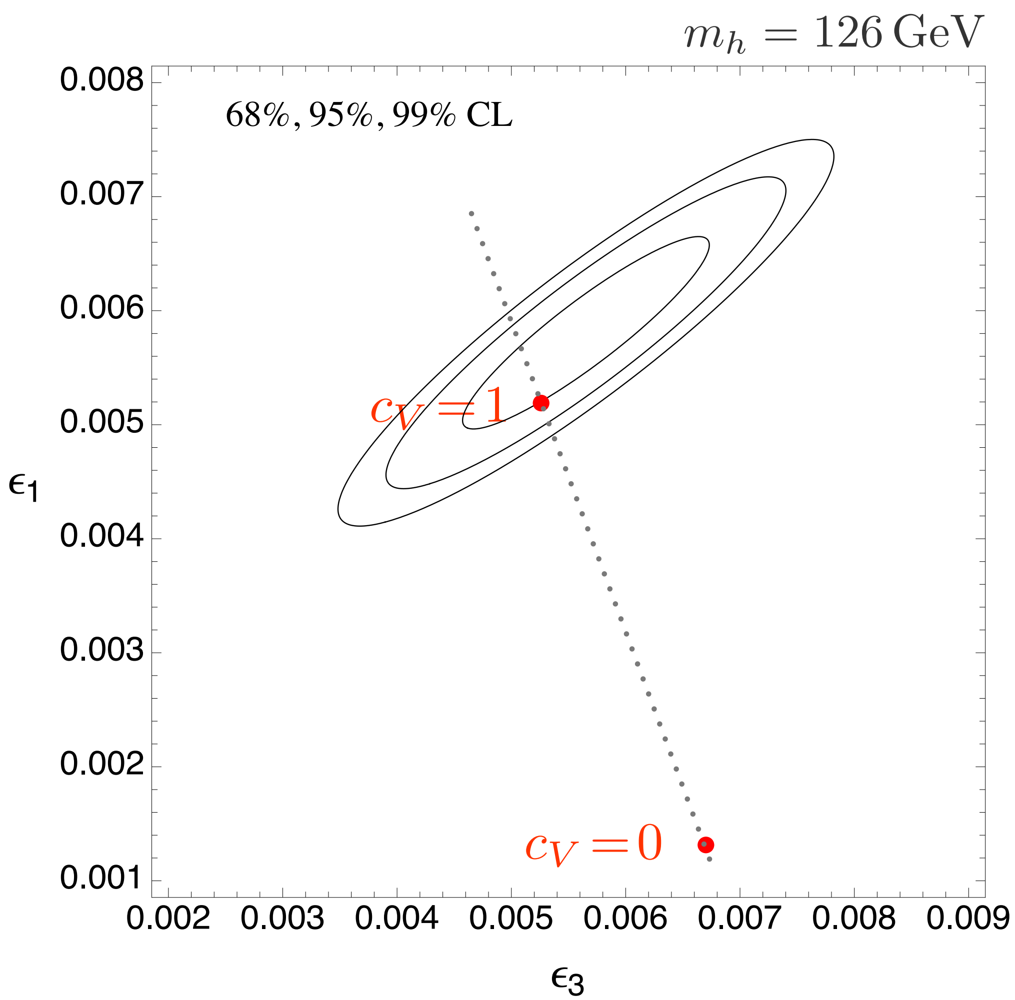

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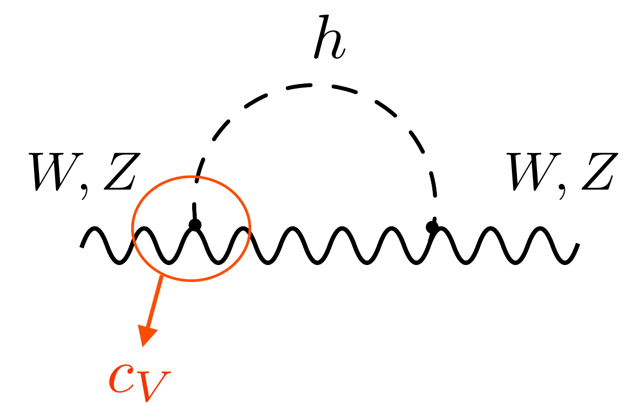

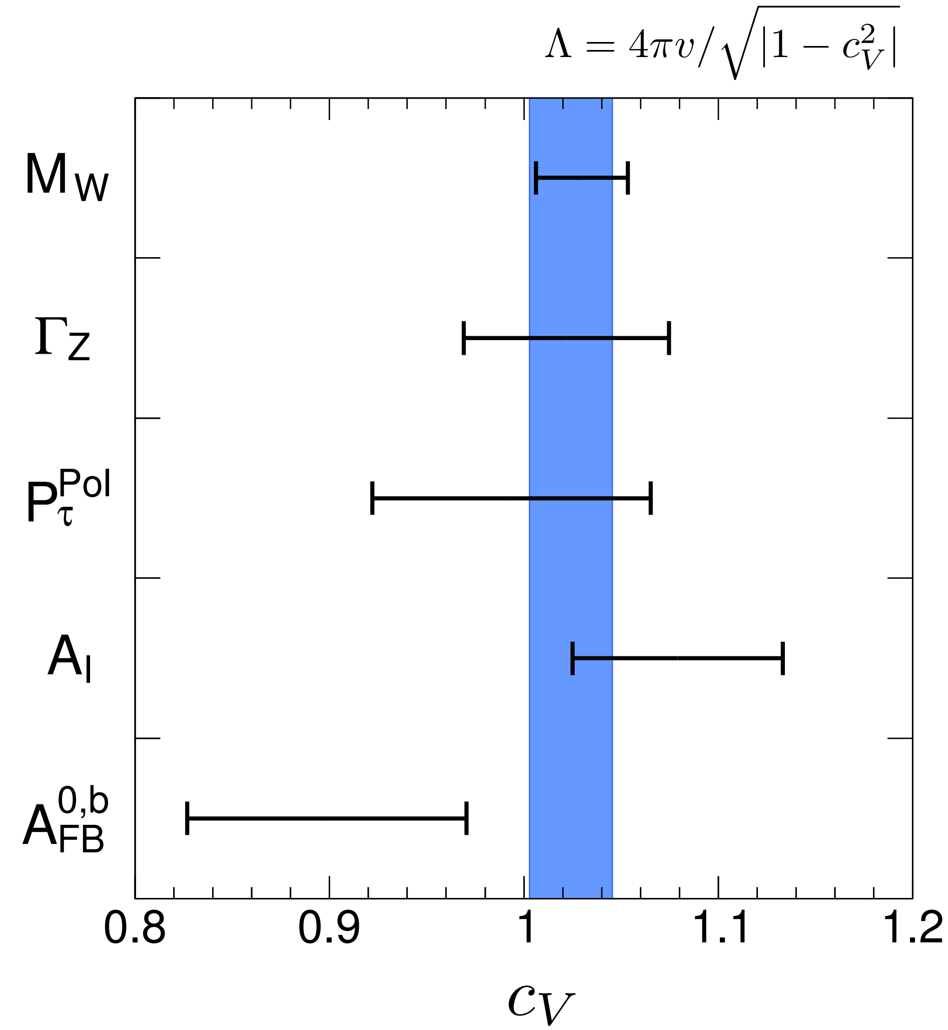

Ciuchini, Franco, Silvestrini, Mishima, arXiv:1306.4644

Barbieri et al. PRD 76 (2007) 115008

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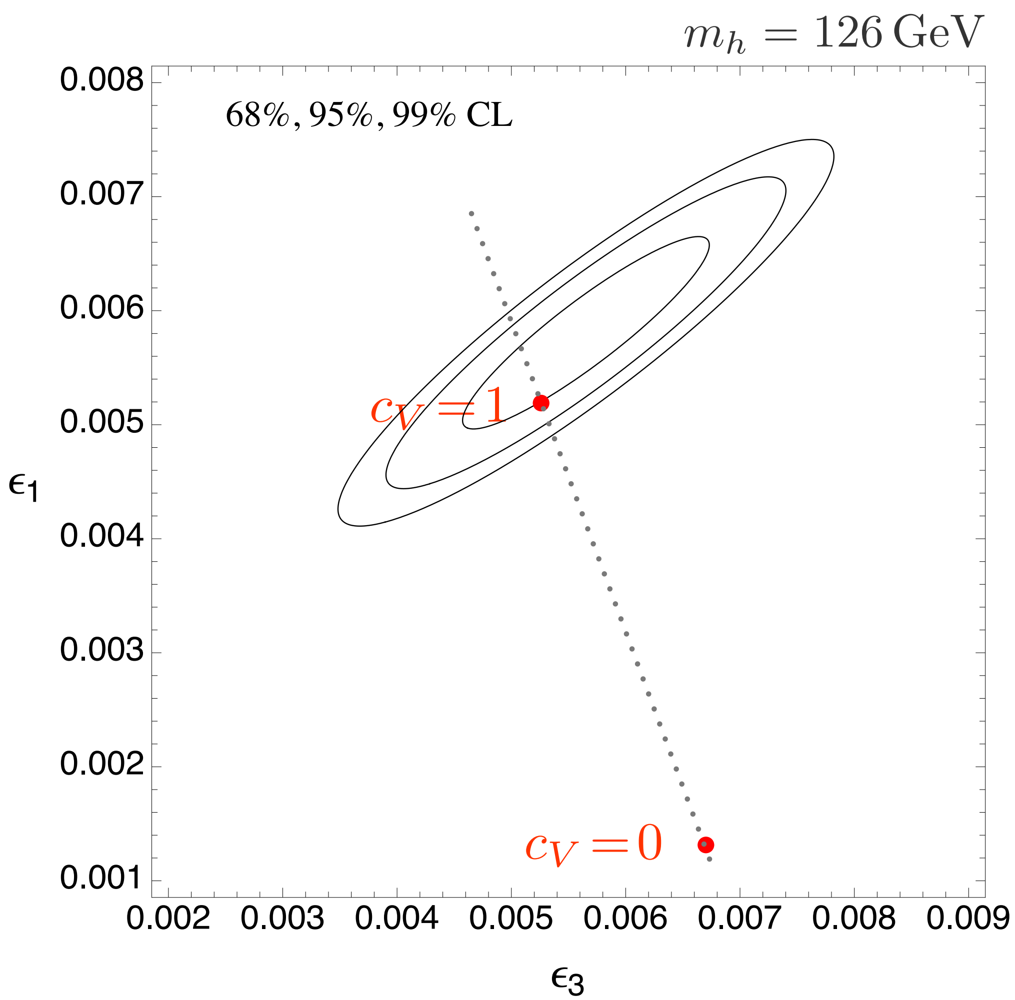
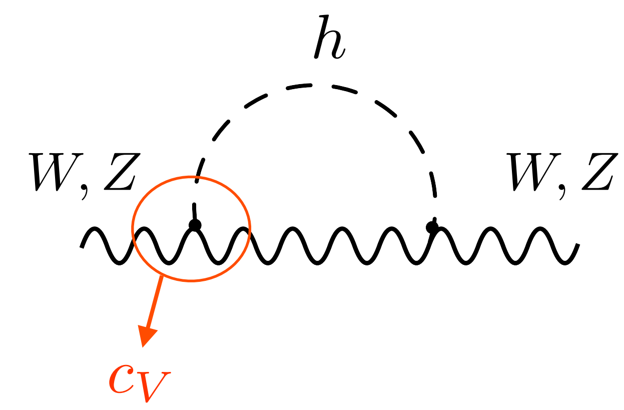
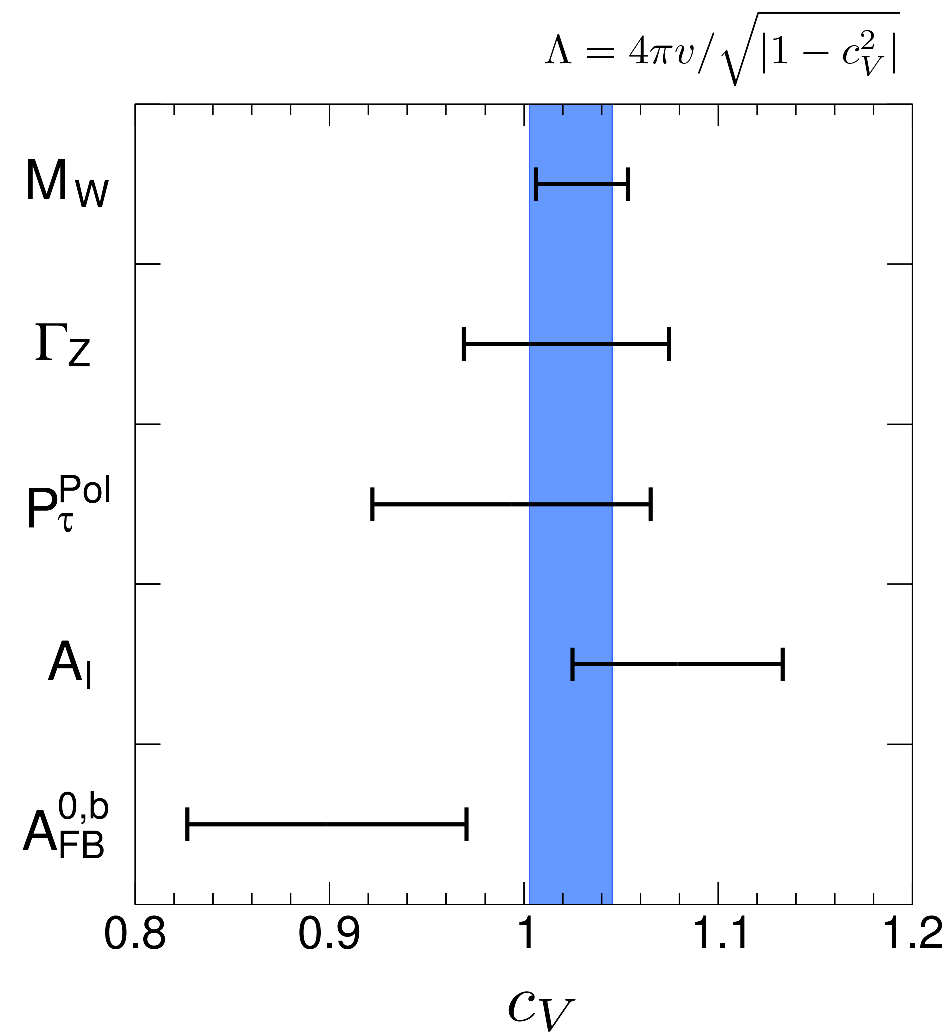


fit from: GFitter coll. Eur. Phys. J. C 72 (2012) 2205

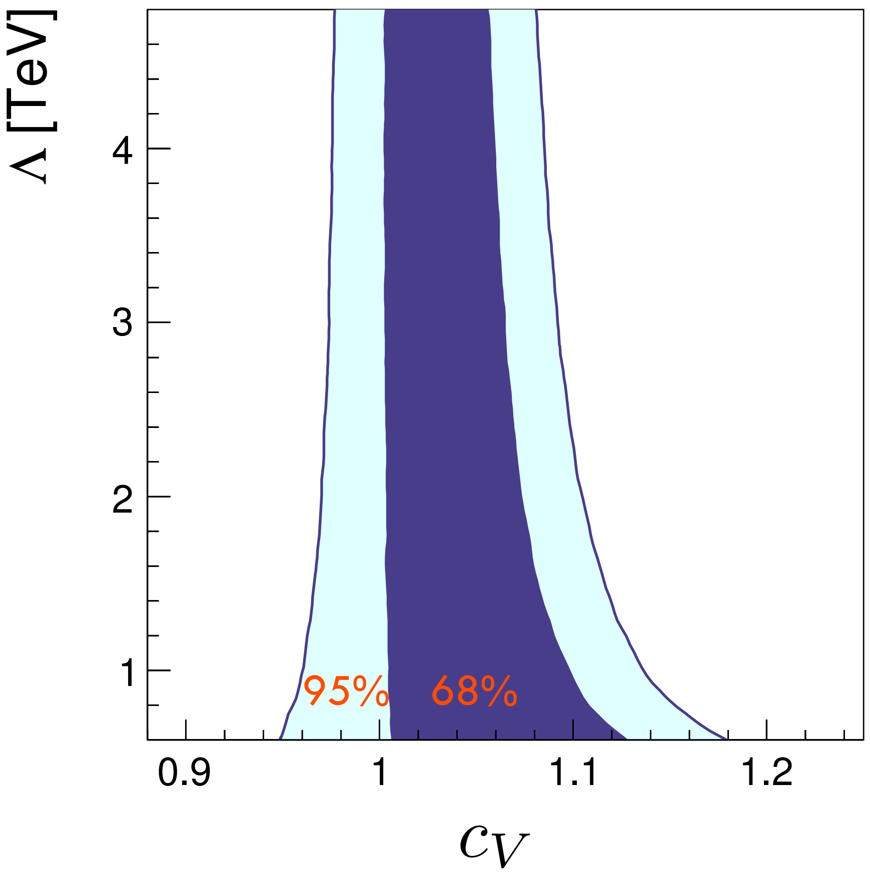
Precision on c_V at the level of ~5% !

Contribution from resonances REQUIRED to relax the bound





Ciuchini, Franco, Silvestrini, Mishima, arXiv:1306.4644



M. Ciuchini, E. Franco, L. Silvestrini, S. Mishima, arXiv:1306.4644

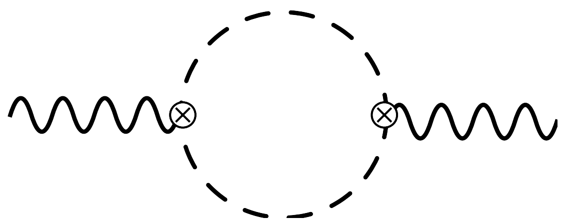
- Analyticity and crossing symmetry imply a sum rule on c_V

$$1 - c_V^2 = \frac{v^2}{6\pi} \int_0^\infty \frac{ds}{s} \left(2\,\sigma_{I=0}^{tot}(s) + 3\,\sigma_{I=1}^{tot}(s) - 5\,\sigma_{I=2}^{tot}(s)\right)$$

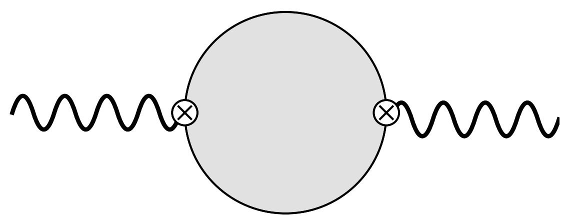
Falkowski, Rychkov, Urbano, JHEP 1204 (2012) 073
Low, Rattazzi, Vichi, JHEP 1004 (2010) 126

$c_V > 1$ possible only if I=2 ch. dominates $V_L V_L$ scattering
(requires: doubly-charged scalar resonance)

S parameter $\hat{S} = \hat{S}_{IR} + \hat{S}_{UV}$



$$\hat{S}_{IR} \sim \frac{v^2}{f^2}\,\frac{g^2}{16\pi^2}\log\left(\frac{\Lambda}{m_Z}\right)$$



$$\hat{S}_{UV} \sim g^2\frac{v^2}{f^2}\left[\frac{1}{g_*^2} + N_c N_F\frac{1}{16\pi^2}\log\left(\frac{\Lambda}{m_*}\right) + \ldots\right]$$

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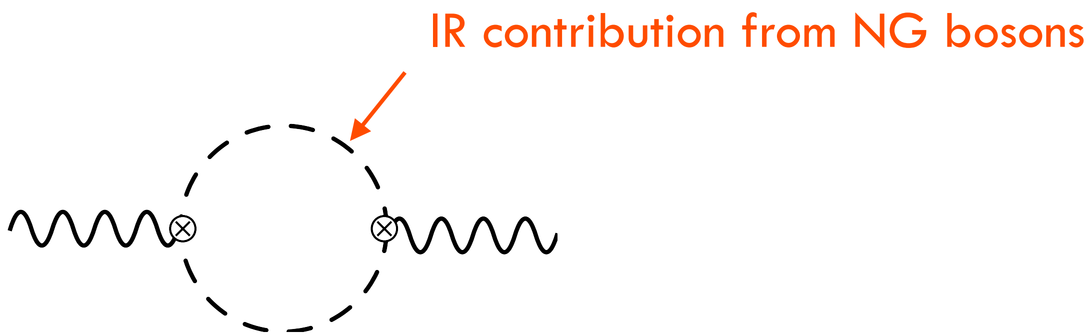

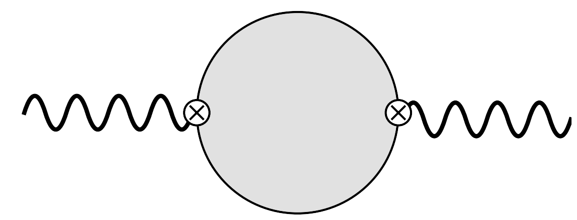

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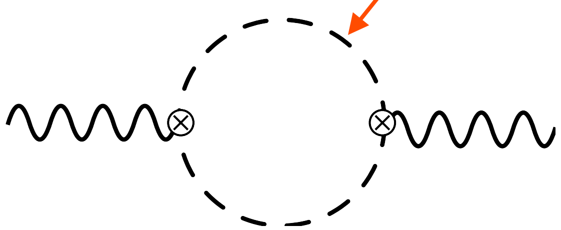
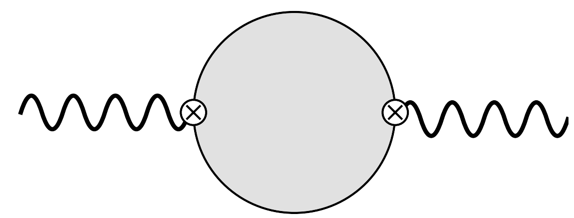
IR contribution from NG bosons





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tree-level (rho)

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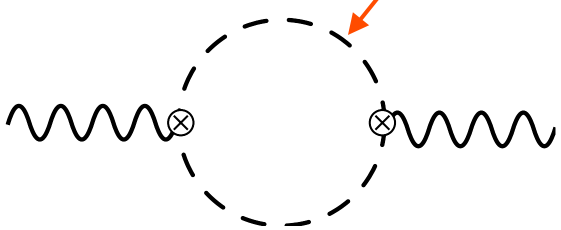

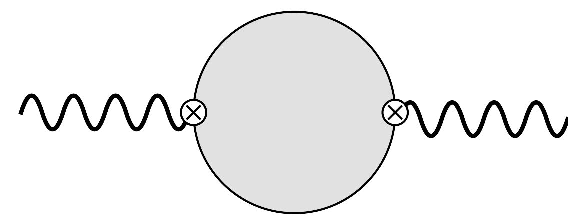

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1-loop (fermions)

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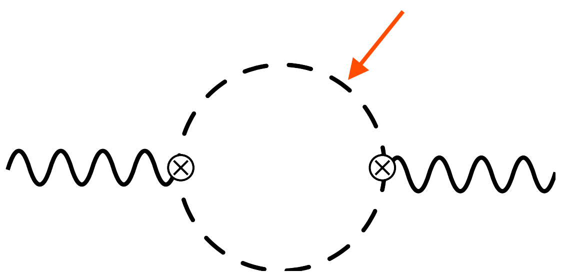

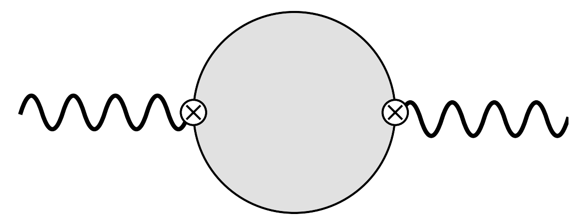

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tree-level (rho) $\qquad$ 1-loop (fermions)

➡ 1-loop contribution from fermions can be large (!)

Golden, Randall, NPB 361 (1991) 3

.....

Barbieri, Isidori, Pappadopulo, JHEP 0902 (2009) 029

Grojean, Matsedonskyi, Panico, JHEP 1310 (2013) 160

Azatov, RC, Di Iura, Galloway, PRD 88 (2013) 075019

fermion contribution can be *negative*

Best seen using a dispertion relation:

Orgogozo and Rychkov, JHEP 1306 (2013) 014

$$i \int d^4x\, e^{iq\cdot(x-y)} \langle 0|T(J_\mu(x)J_\nu(y))|0\rangle = (q^2\eta_{\mu\nu} - q_\mu q_\nu)\Pi(q^2)$$

$$\Pi(q^2) = \int ds\, \frac{\rho(s)}{q^2 - s + i\epsilon}$$

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negative contribution from spectral function of broken SO(5)/SO(4) currents

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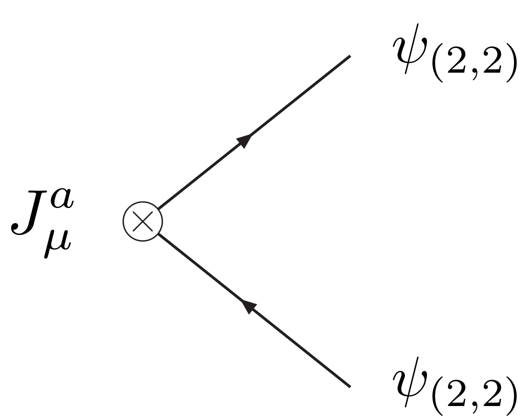
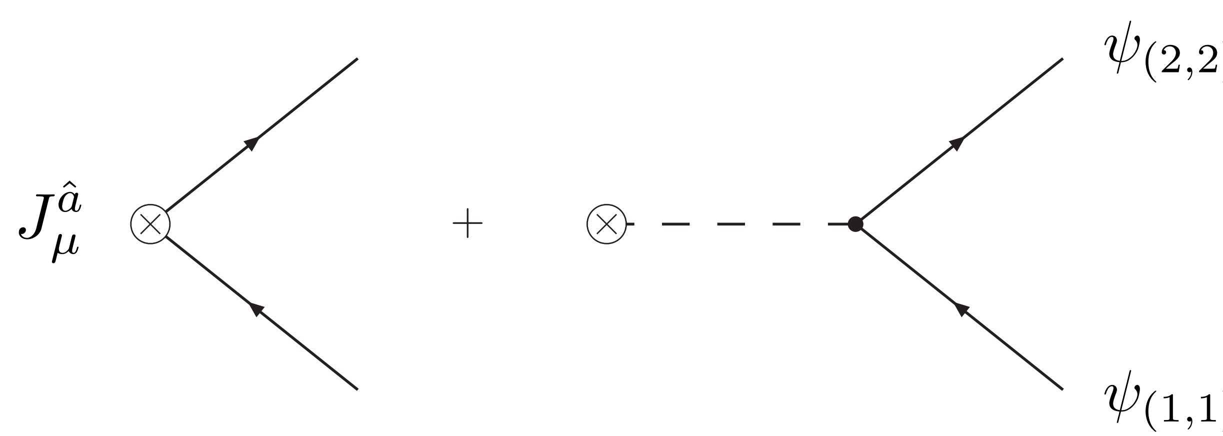
$$\psi_5 = (1,1) + (2,2) \qquad \mathcal{L} = \bar\psi_1\left(i\not{D} - m_1\right)\psi_1 + \bar\psi_4\left(i\not\nabla - m_4\right)\psi_4 - \zeta\,\bar\psi_4\gamma^\mu d_\mu\,\psi_1 + h.c.$$



$\rho_{LL,RR}$



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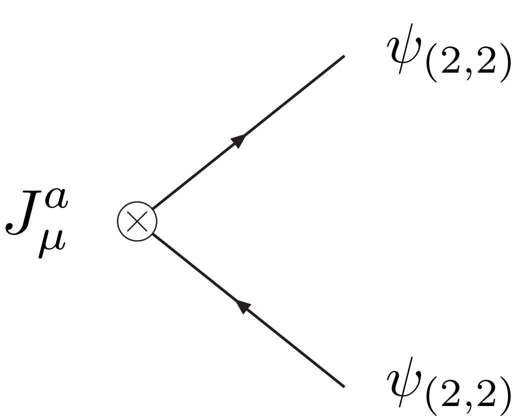
$$i\not{\nabla} \rightarrow \not{A}+i\frac{\pi\not{\partial}\pi}{f^2}+\dots$$



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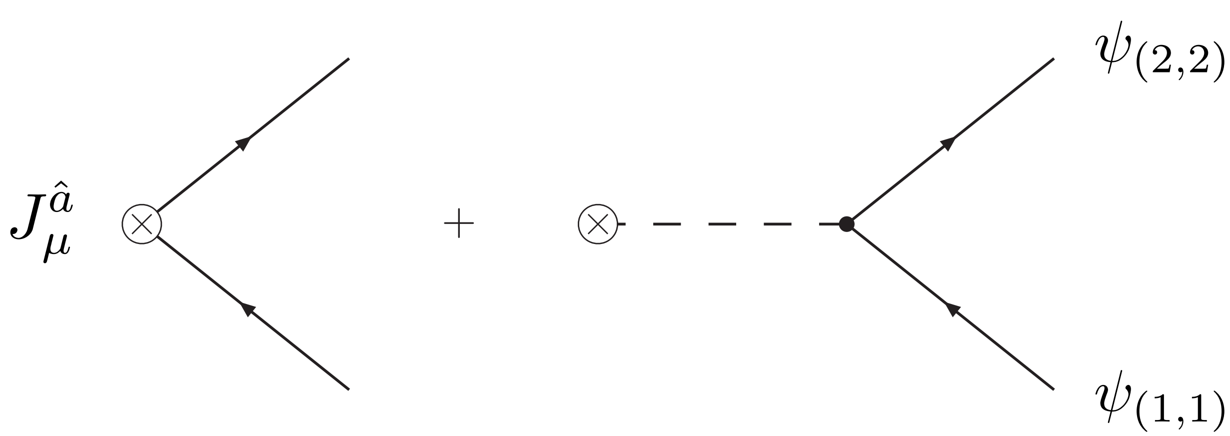

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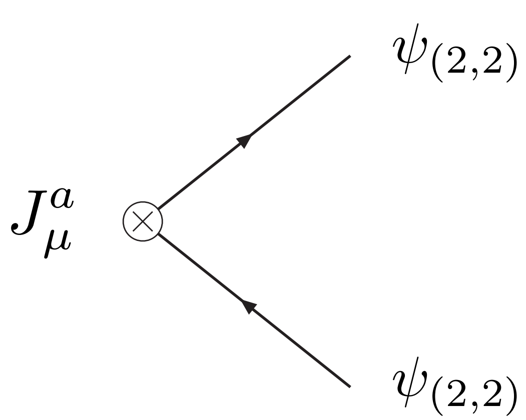

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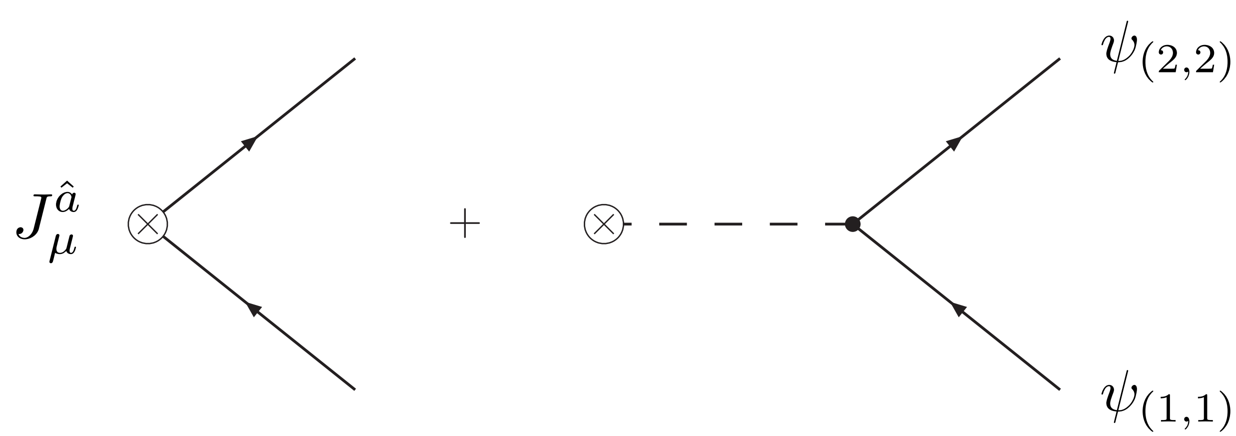

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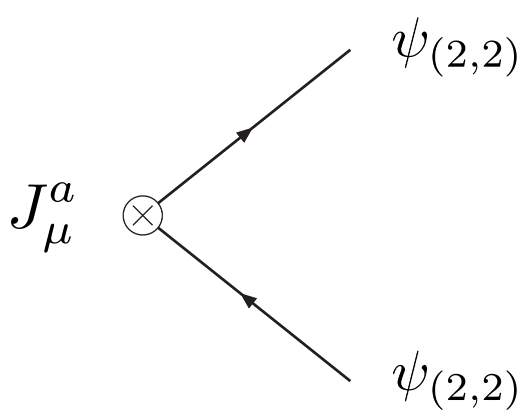

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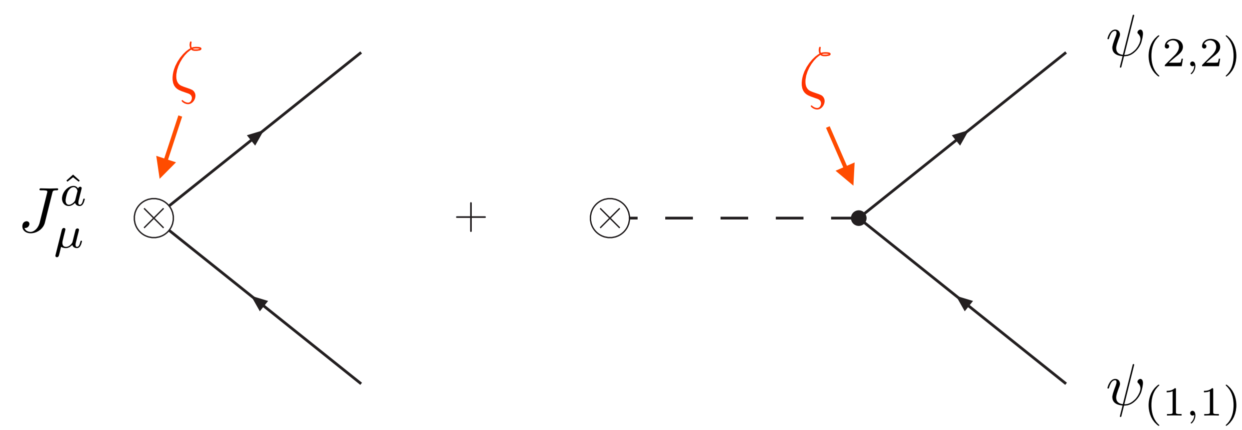

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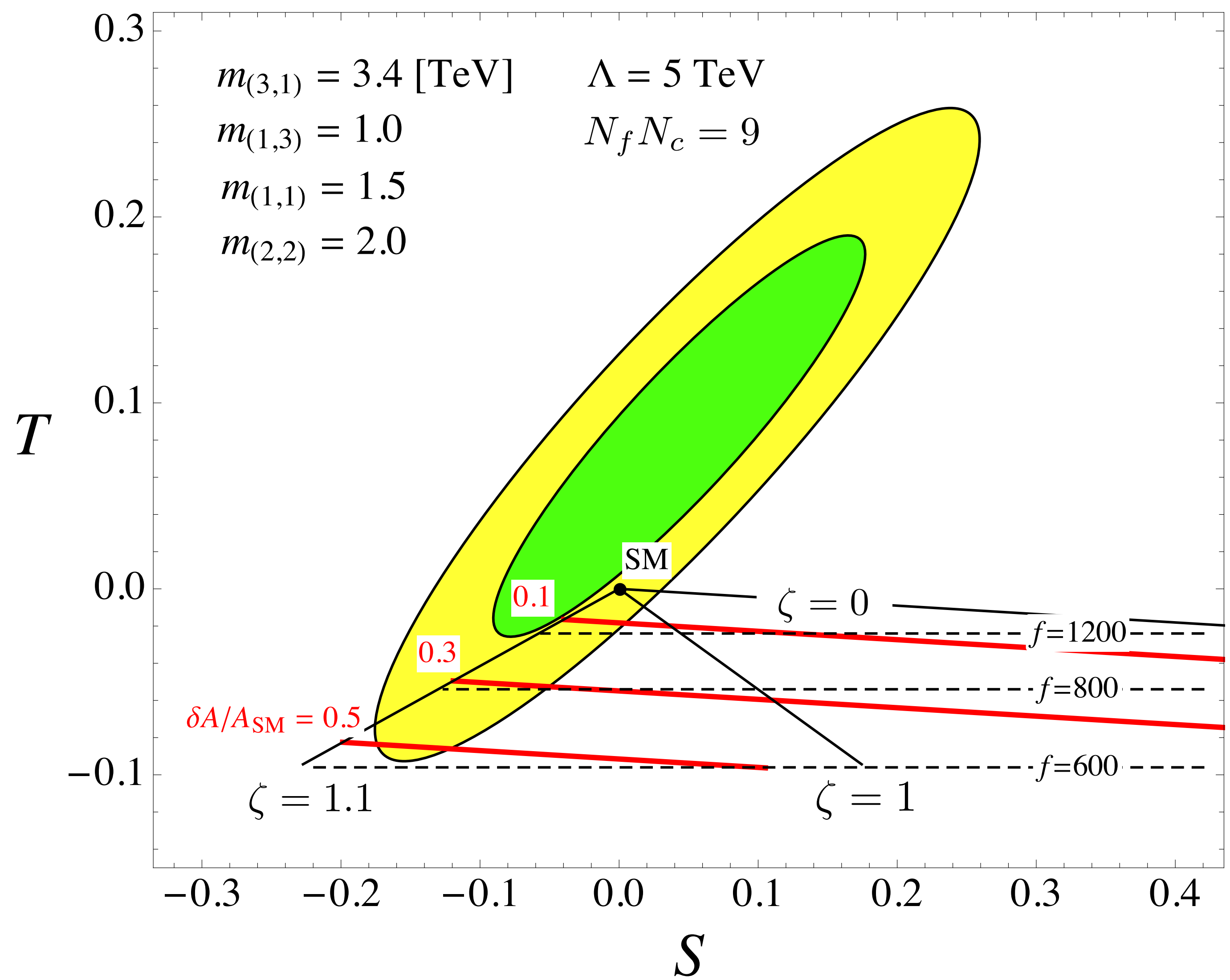
$$\hat{S}_{UV} = \frac{8}{3}\frac{m_W^2}{16\pi^2 f^2}N_c N_F\left(1 - |\zeta|^2\right)\log\left(\frac{\Lambda^2}{m_{(2,2)}^2}\right) + \text{finite terms}$$

from: Azatov, RC, Di Iura, Galloway PRD 88 (2013) 075019

SO(5)/SO(4) model:

$$\psi_5 = (1,1)_{2/3} + (2,2)_{2/3}$$

$$\psi_{10} = (2,2)_{-1/3} + (1,3)_{-1/3} + (3,1)_{-1/3}$$



from: Azatov, RC, Di Iura, Galloway PRD 88 (2013) 075019

SO(5)/SO(4) model:

$$\psi_5 = (1,1)_{2/3} + (2,2)_{2/3}$$

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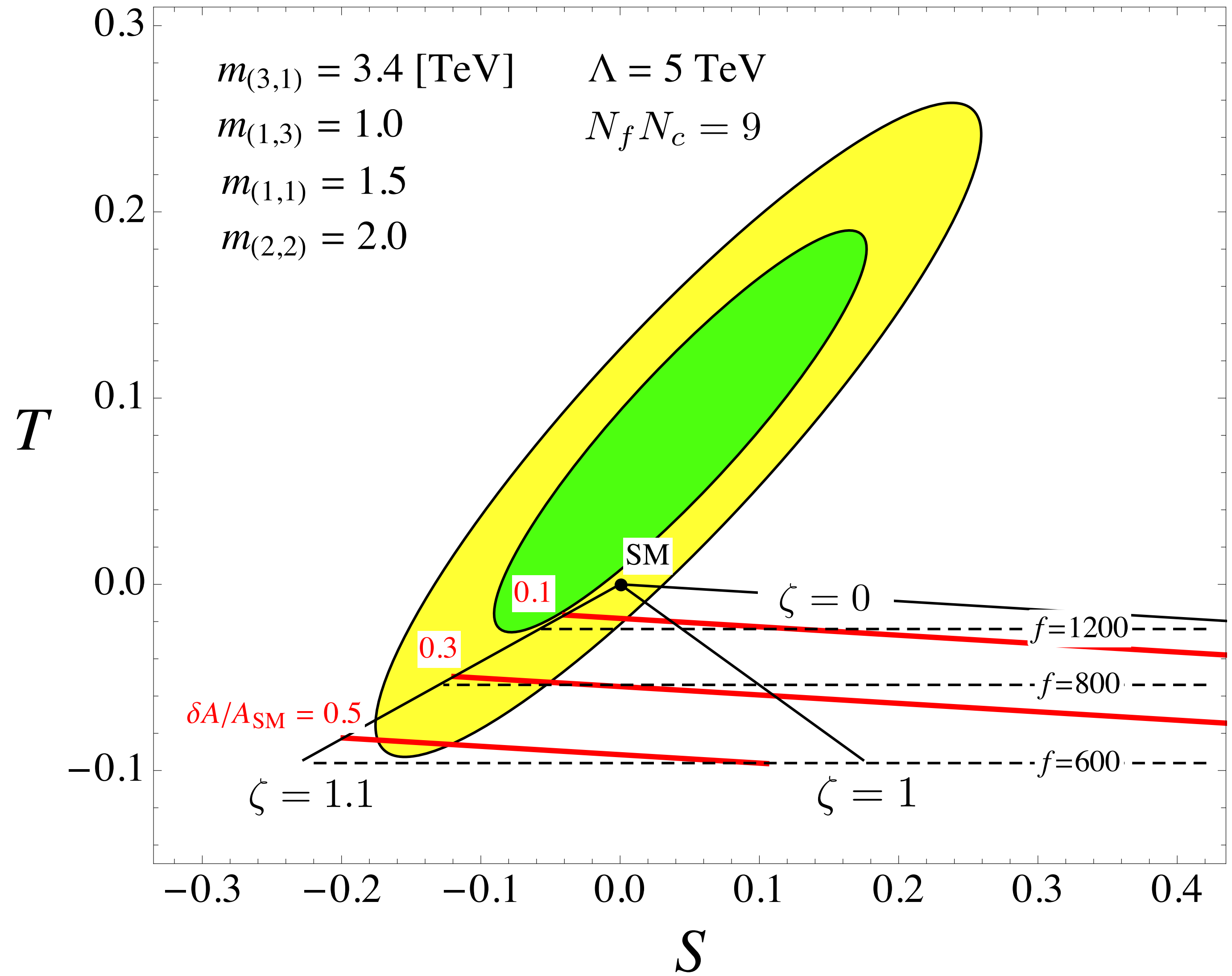
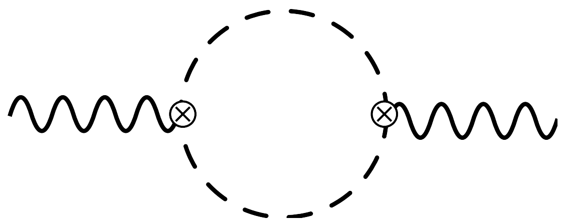


Ex: for $f = 800\,\mathrm{GeV}$ $g_\rho = 3$

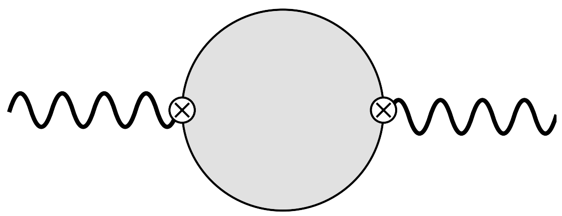
$\Delta S_\rho \simeq 0.13$ $\Delta S_\psi \simeq 0.8 \times (1 - |\zeta|^2)$ ➡ strong sensitivity on ζ

O(10%) tuning required to go back into the experimental ellipse

T parameter $\hat{T} = \hat{T}_{IR} + \hat{T}_{UV}$



$$\hat{T}_{IR} \sim -\frac{v^2}{f^2}\,\frac{g'^2}{16\pi^2}\log\left(\frac{\Lambda}{m_Z}\right)$$



$$\hat{T}_{UV} \sim \frac{v^2}{f^2}\left[\frac{g'^2}{16\pi^2}\log\left(\frac{\Lambda}{m_\rho}\right) + N_c\frac{\lambda_L^2}{16\pi^2}\,\frac{\lambda_L^2}{g_*^2} + \ldots\right]$$

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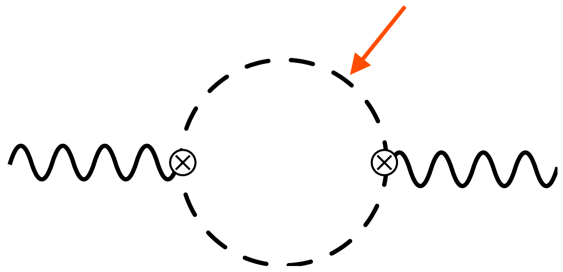
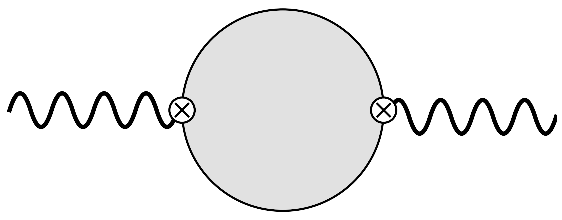
IR contribution from NG bosons





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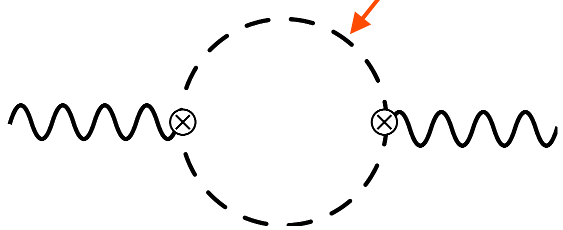

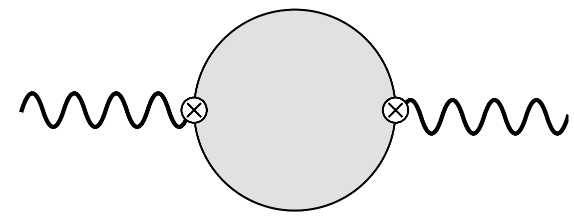

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1-loop (rho)

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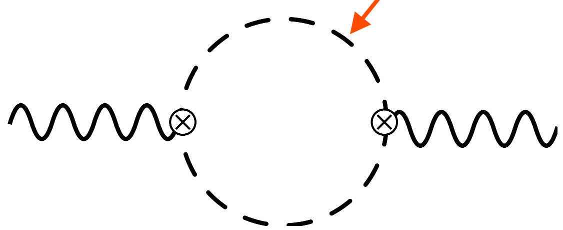

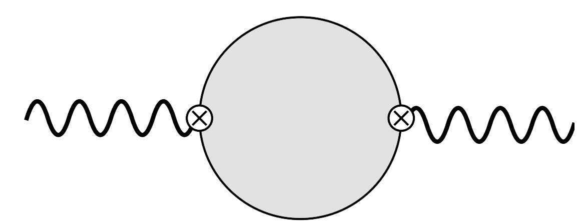

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1-loop (rho)

1-loop (fermions)

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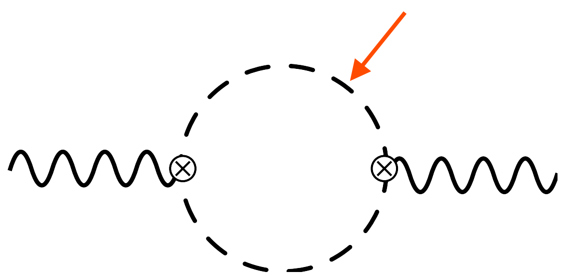

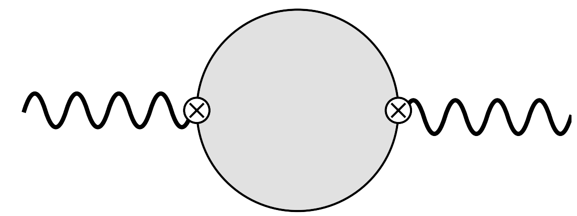

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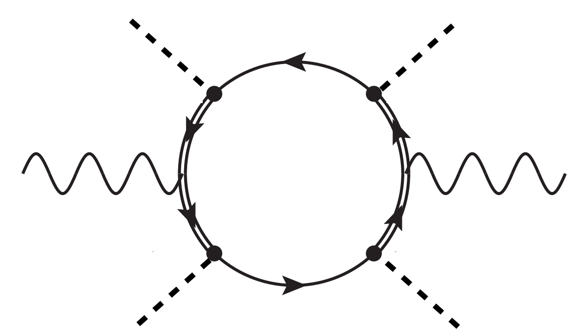
1-loop (rho) 1-loop (fermions)

- Custodial symmetry implies:

  1. No $\hat{T}$ at tree-level
  2. fermion correction is *finite* and starts at $O(\lambda_L^4)$ (only top partners contribute)

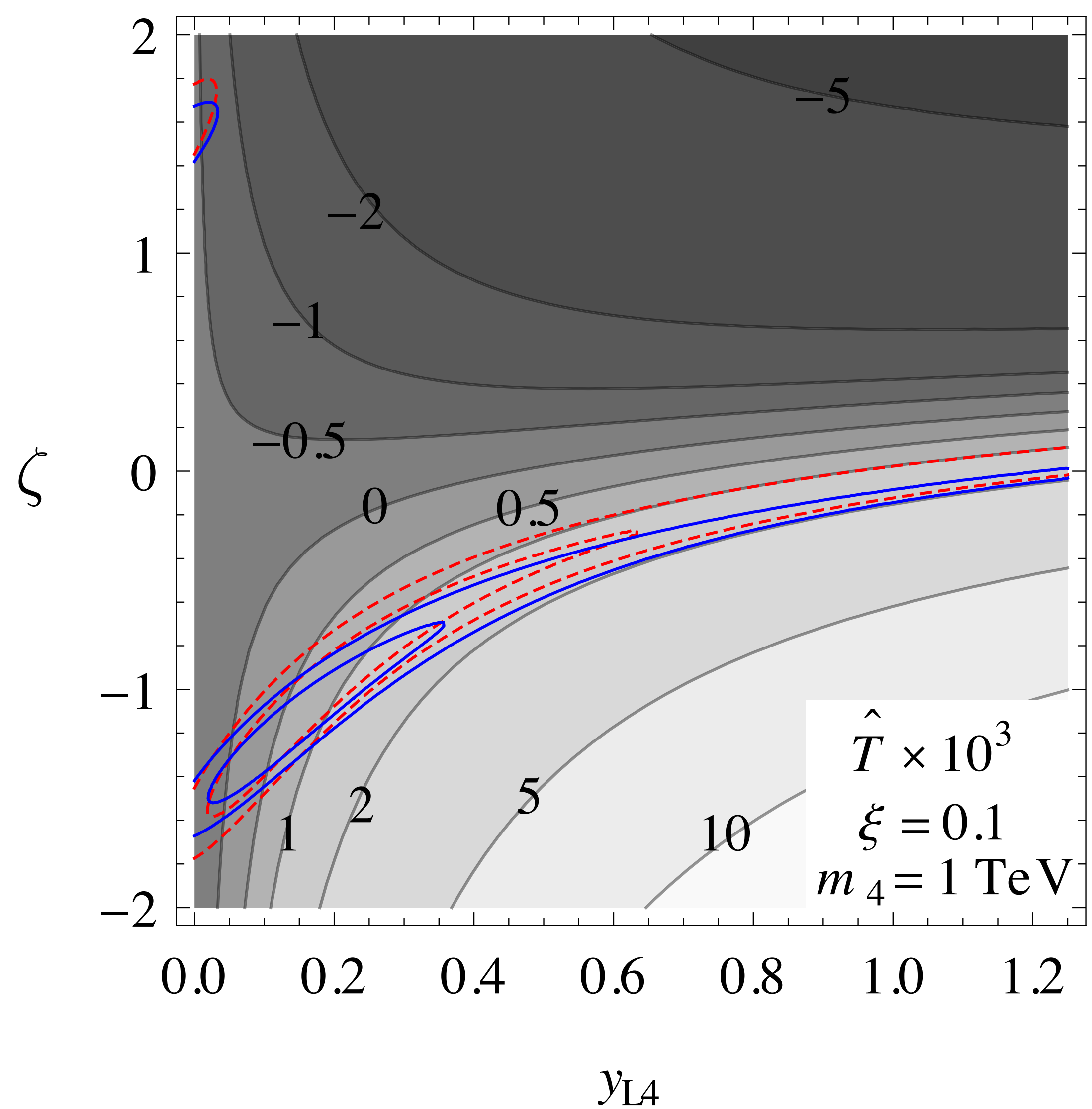


$\Delta\hat{T} > 0$ possible though not fully generic

Carena, et al. NPB 759 (2006) 202; PRD 76 (2007) 035006
Barbieri et al. PRD 76 (2007) 115008
Lodone JHEP 0812 (2008) 029
Pomarol, Serra, PRD 78 (2008) 074026
Gillioz PRD 80 (2009) 055003
⋮
Grojean, Matsedonskyi, Panico, JHEP 1310 (2013) 160

Example: model with $\psi_4 = (2,2)_{2/3}$ + t_R composite

$$\mathcal{L} = \bar{q}_L i \not{D}\, q_L + \bar{t}_R i \not{D}\, t_R + \bar{\psi}_4 (i \not{\nabla} - m_4)\psi_4$$
$$+ i\zeta\, \bar{\psi}_4^i \gamma^\mu d_\mu^i t_R + y_{Lt} f\, \bar{q}_L U(\pi) t_R + y_{L4} f\, \bar{q}_L U(\pi)\psi_4 + h.c.$$



Grojean, Matsedonskyi, Panico
JHEP 1310 (2013) 160

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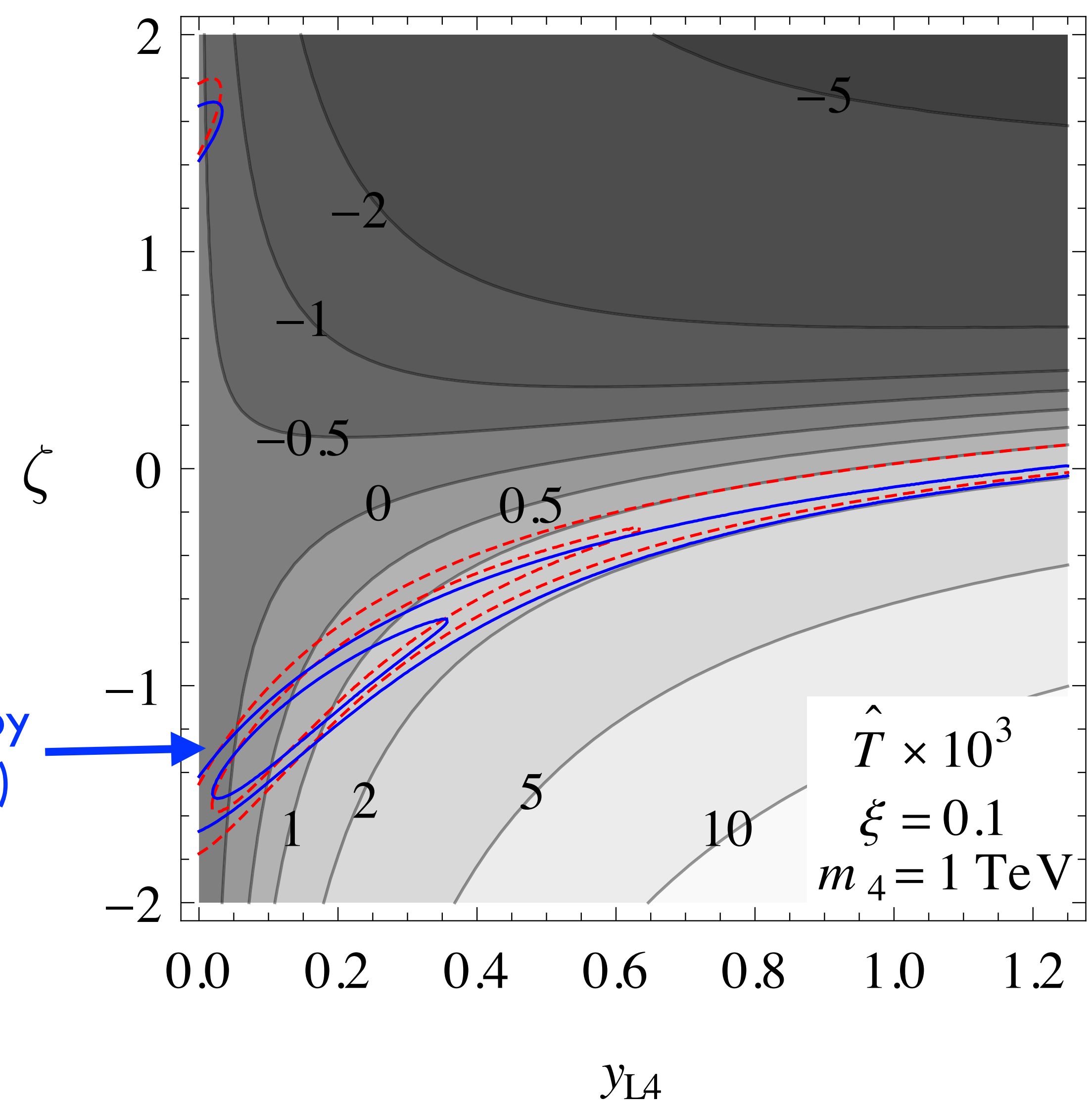
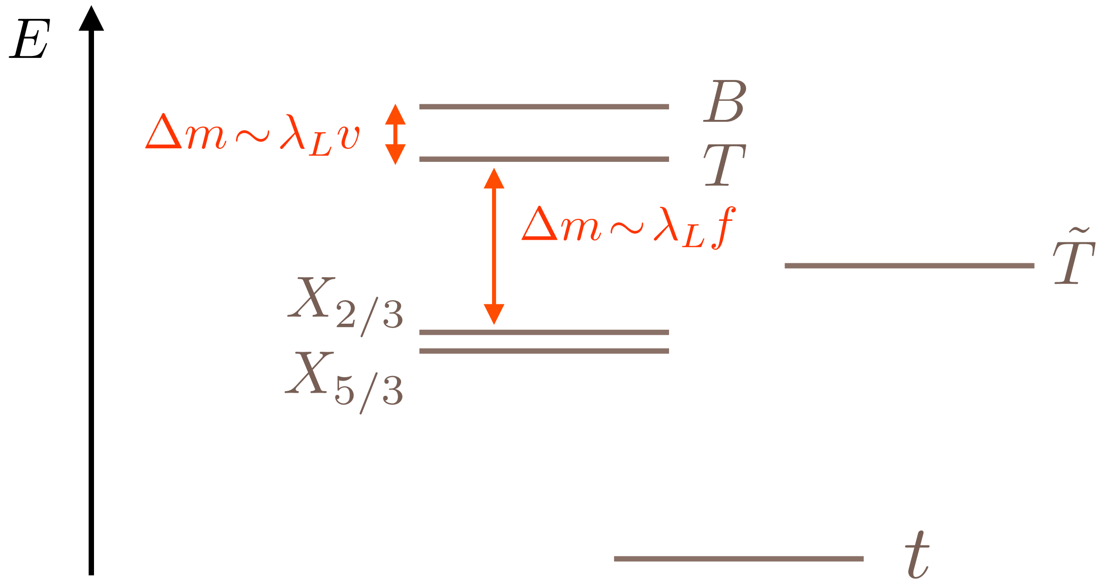
blue region allowed by EWPT at 68% (95%)



Grojean, Matsedonskyi, Panico
JHEP 1310 (2013) 160

Searches of top partners

- Typical spectrum of top partners



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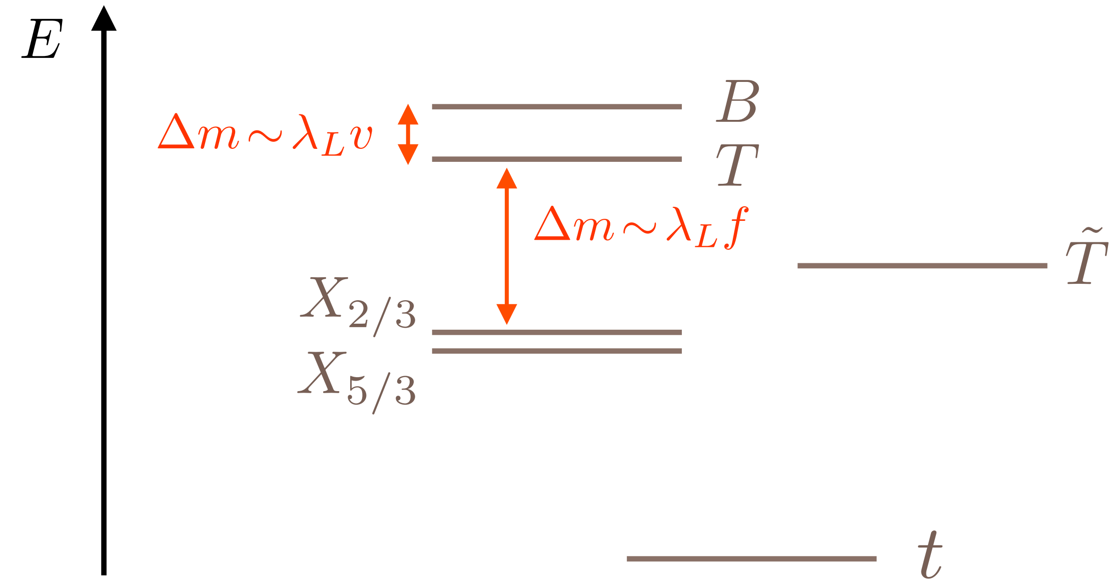
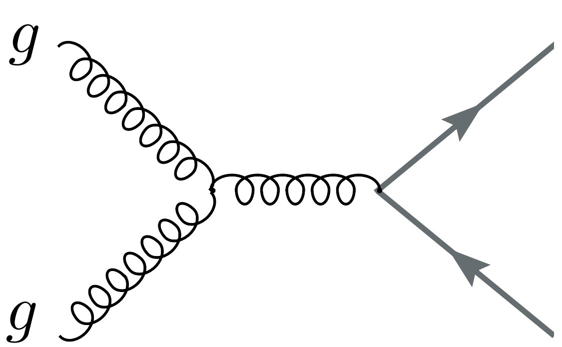
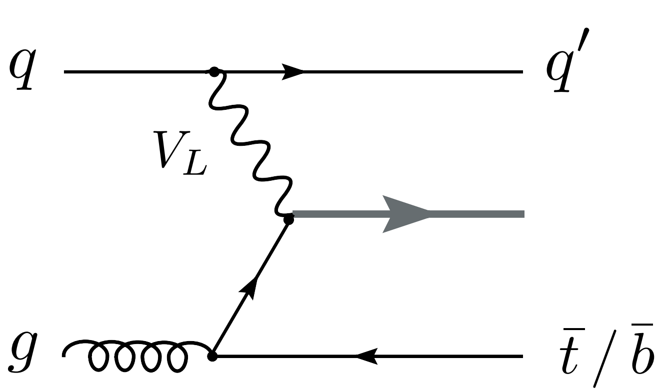


- Two main production modes:

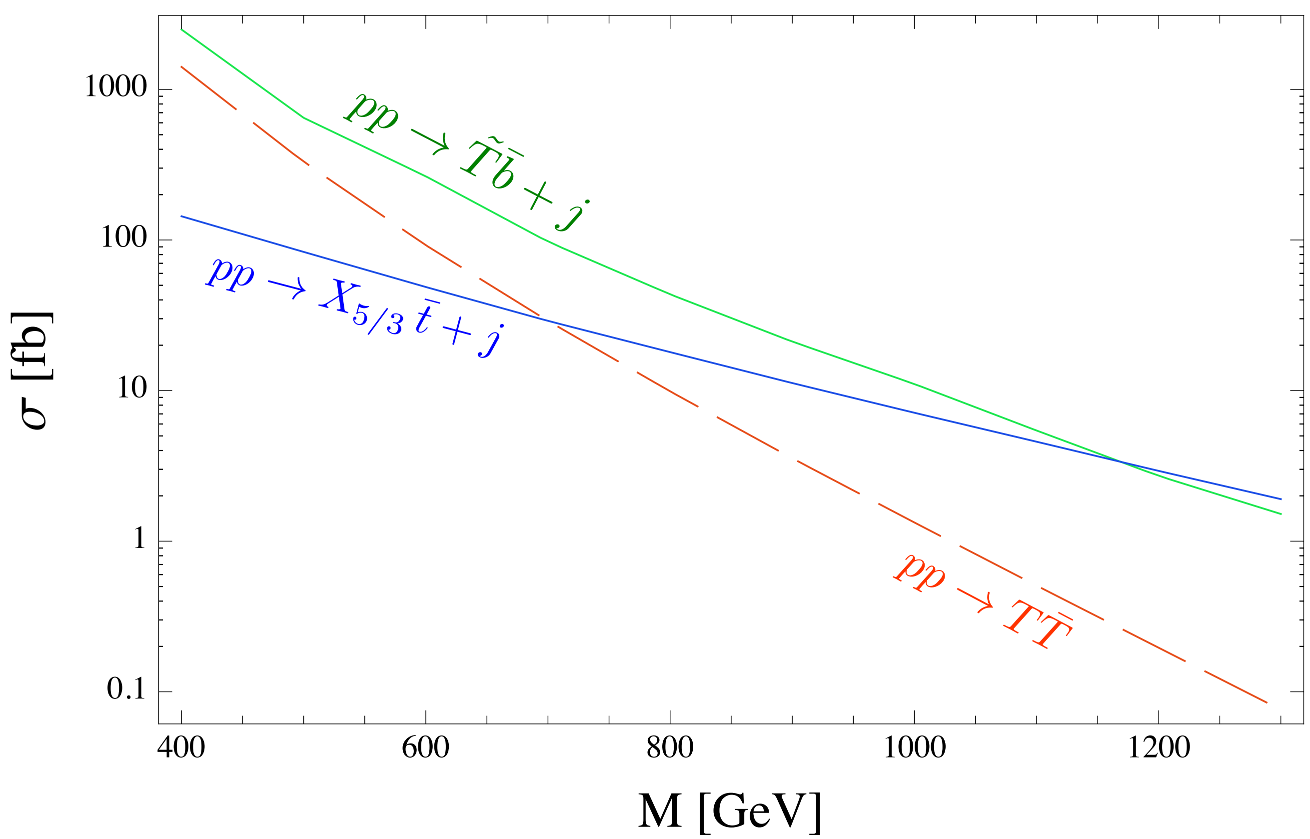


pair production



EW single production

from: De Simone, Matsedonskyi, Rattazzi, Wulzer
JHEP 1304 (2013) 004



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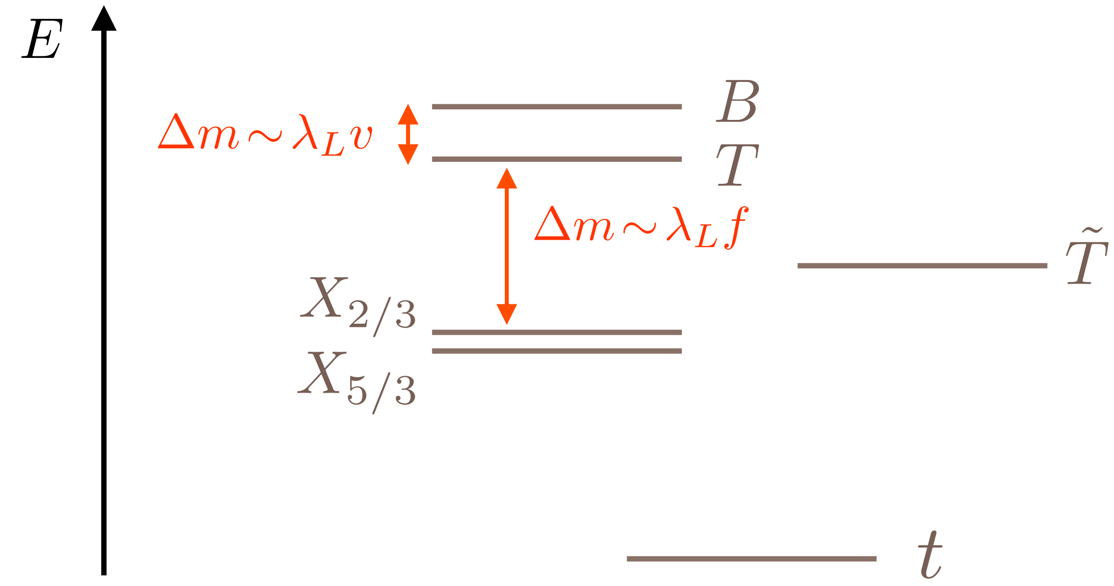

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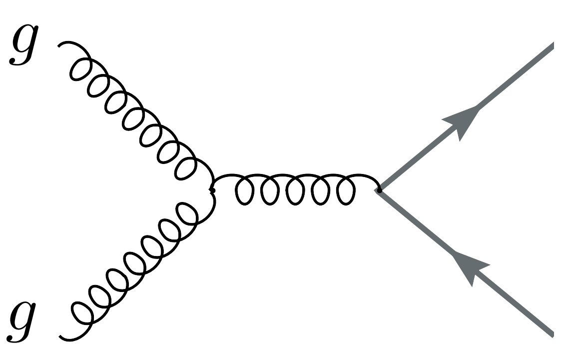
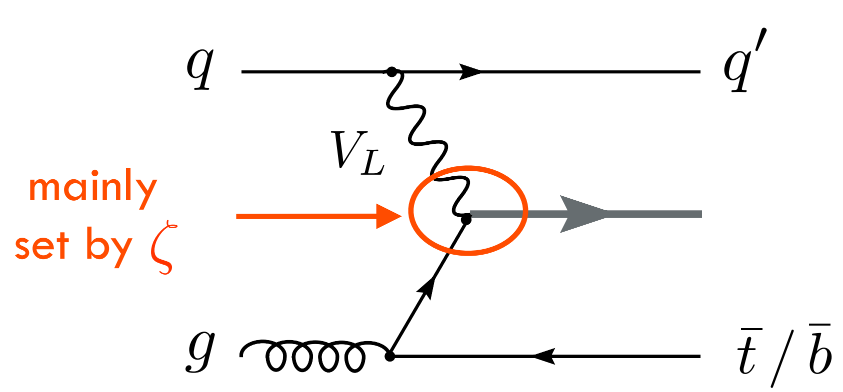


pair production



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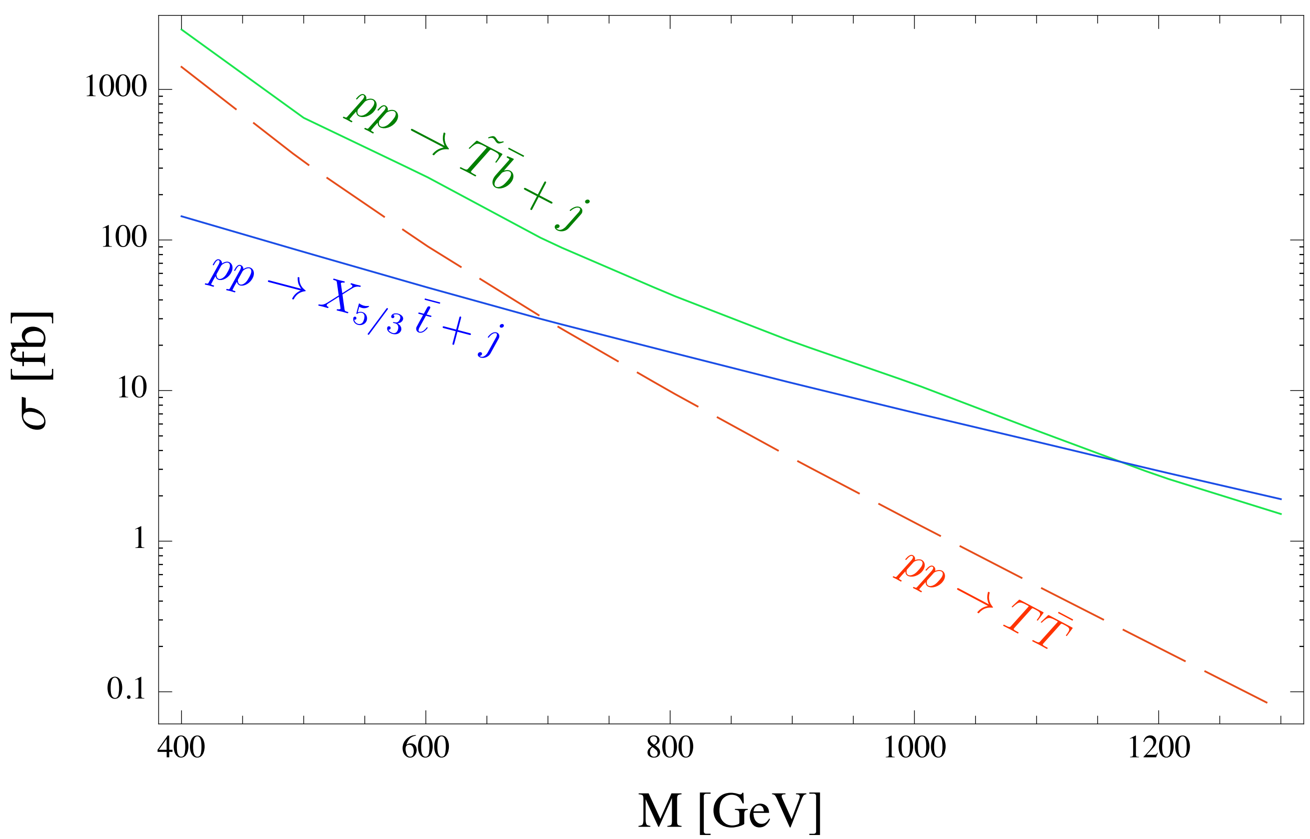
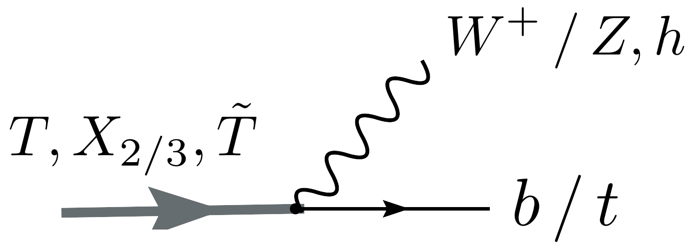
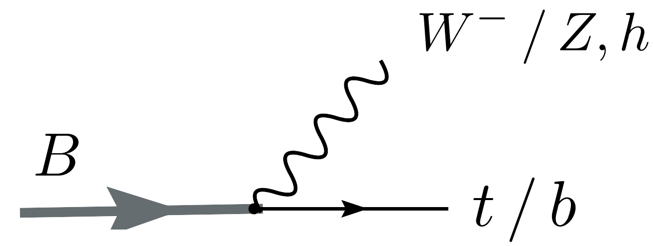
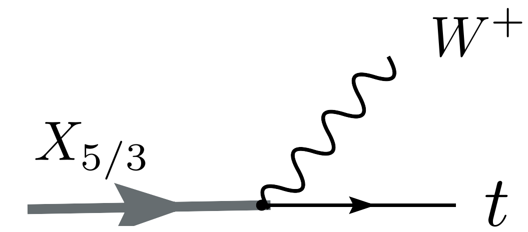


- Two-body decay modes:







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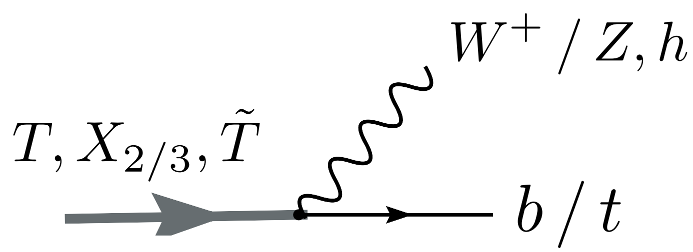
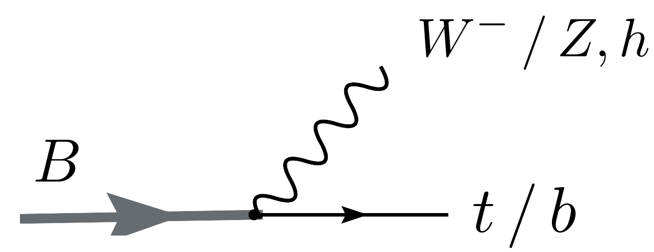
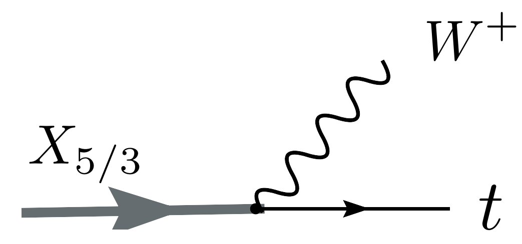
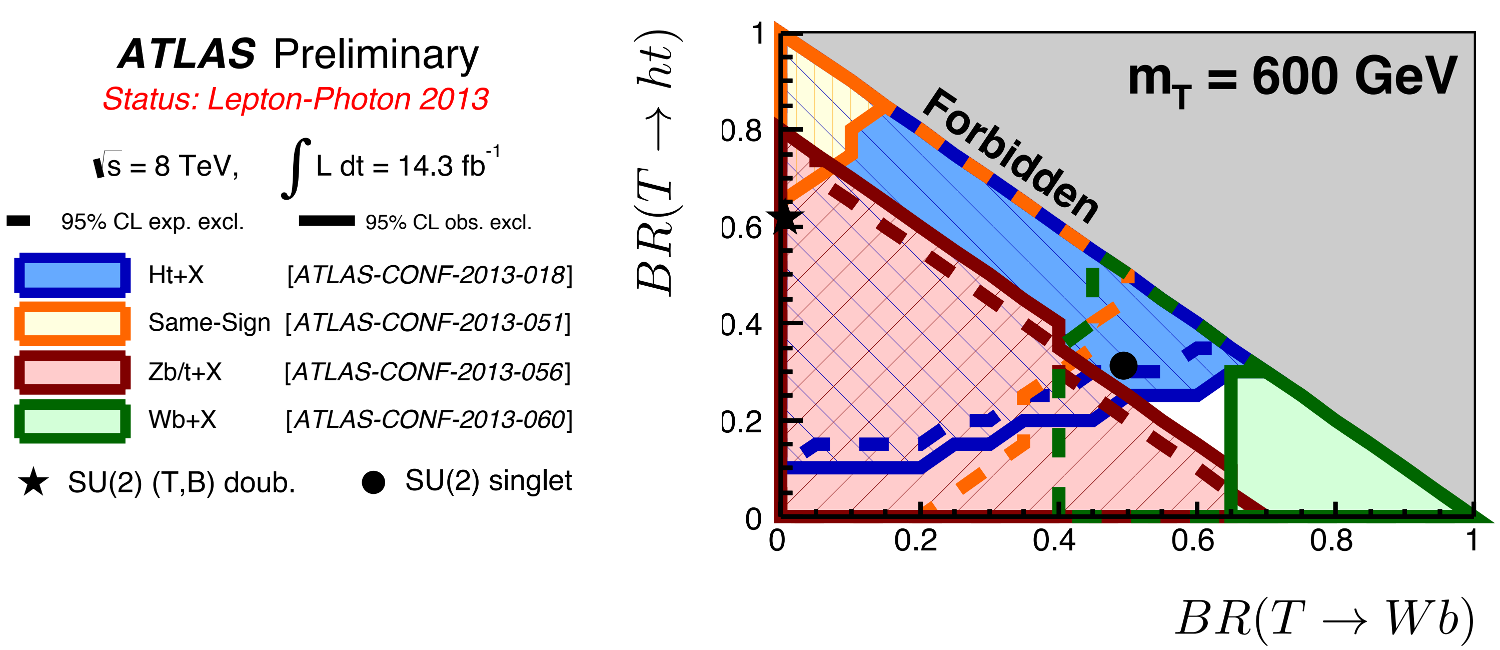


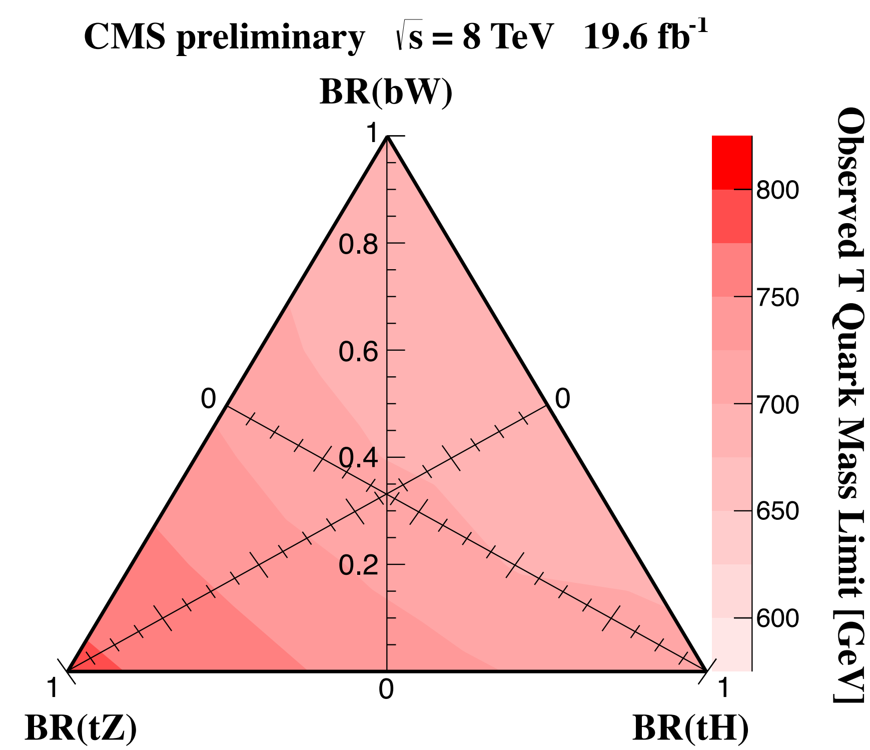




- Current experimental status in a nutshell

1. Almost all decays looked for
2. Analyses optimized on pair production





CMS B2G-12-015
CMS B2G-12-012

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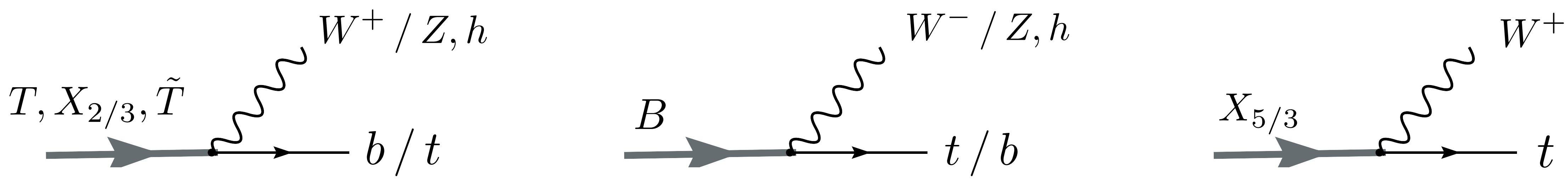

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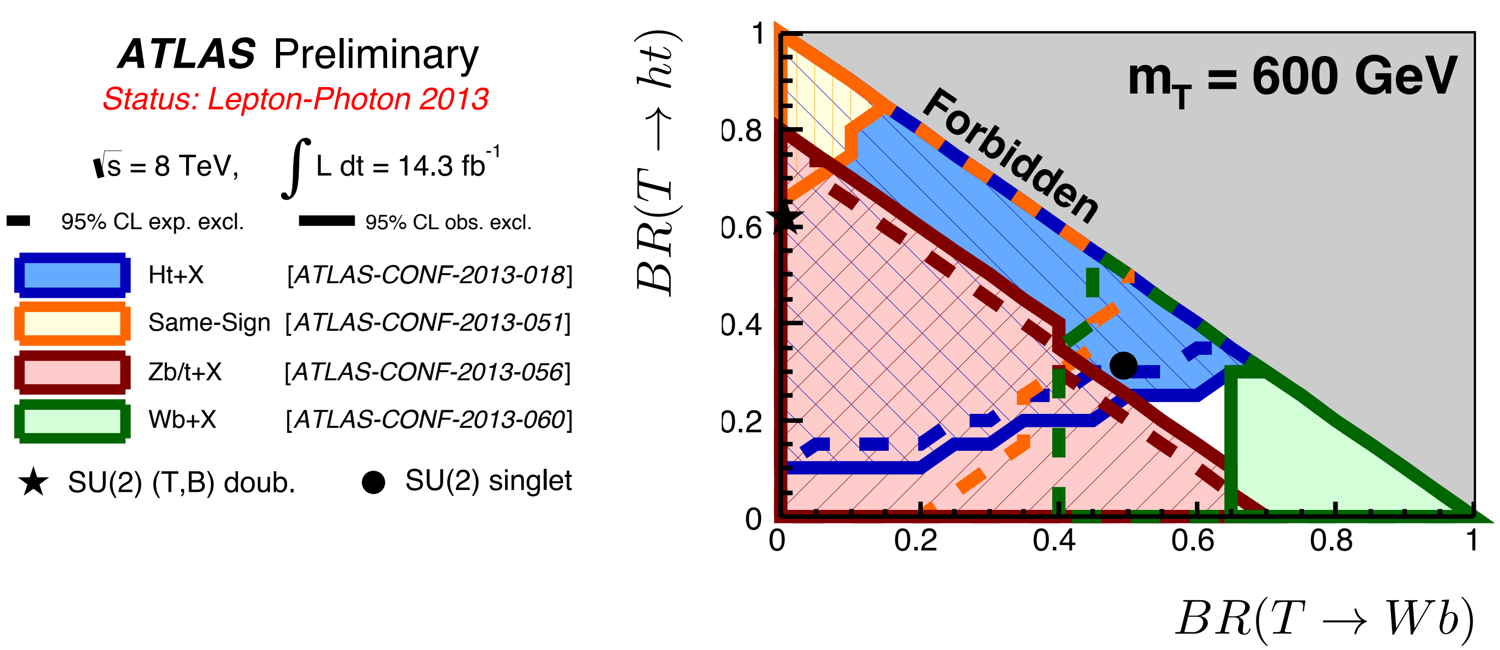
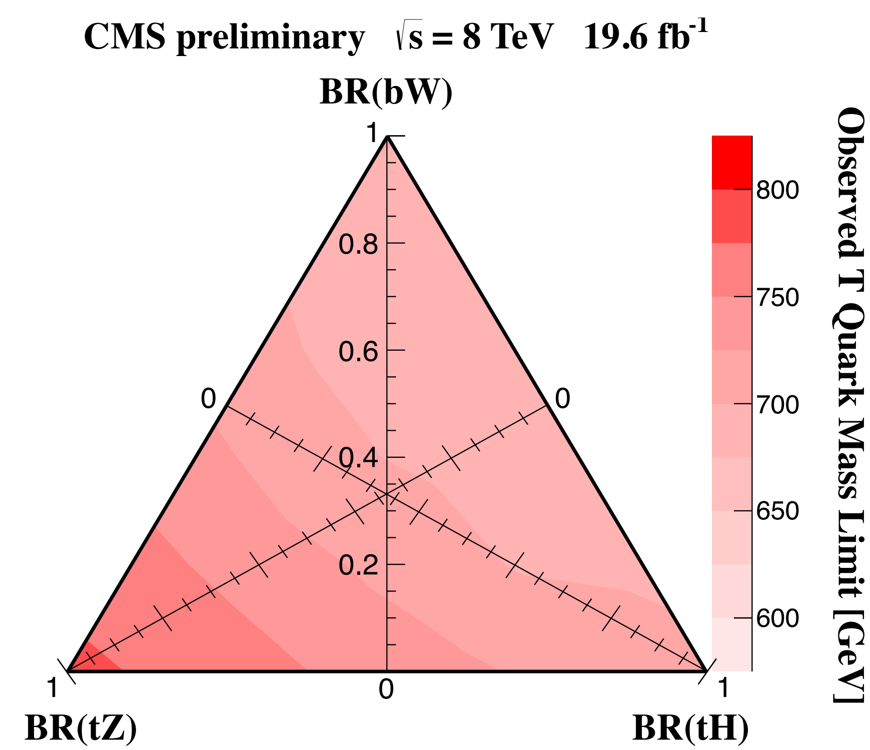
Limits in the 700-800 GeV range

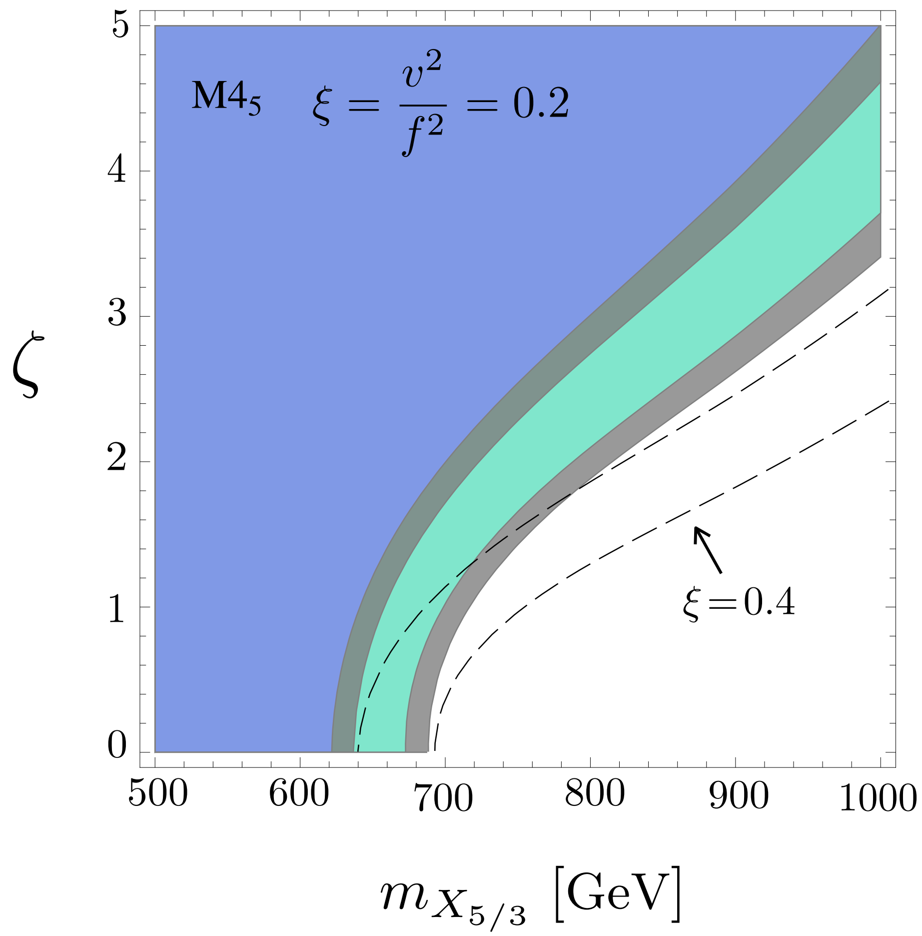




CMS B2G-12-015
CMS B2G-12-012

- Once recast on (simplified) theory space exp. bounds already exclude a big portion of the natural region

De Simone et al. JHEP 1304 (2013) 004



Blue region:

$y_{L4} = 3 \quad (m_B \gg m_{X_{5/3}})$

Green region:

$y_{L4} = 0.3 \quad (m_B \gtrsim m_{X_{5/3}})$

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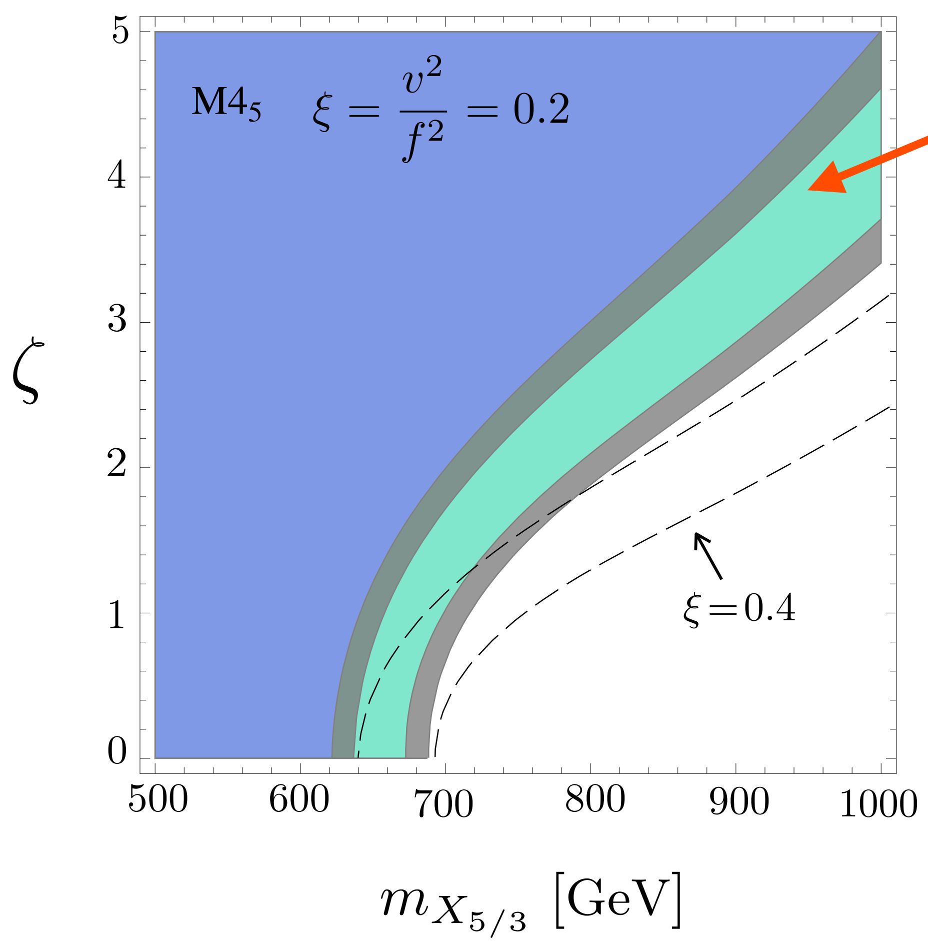

Effect of single production is NOT negligible

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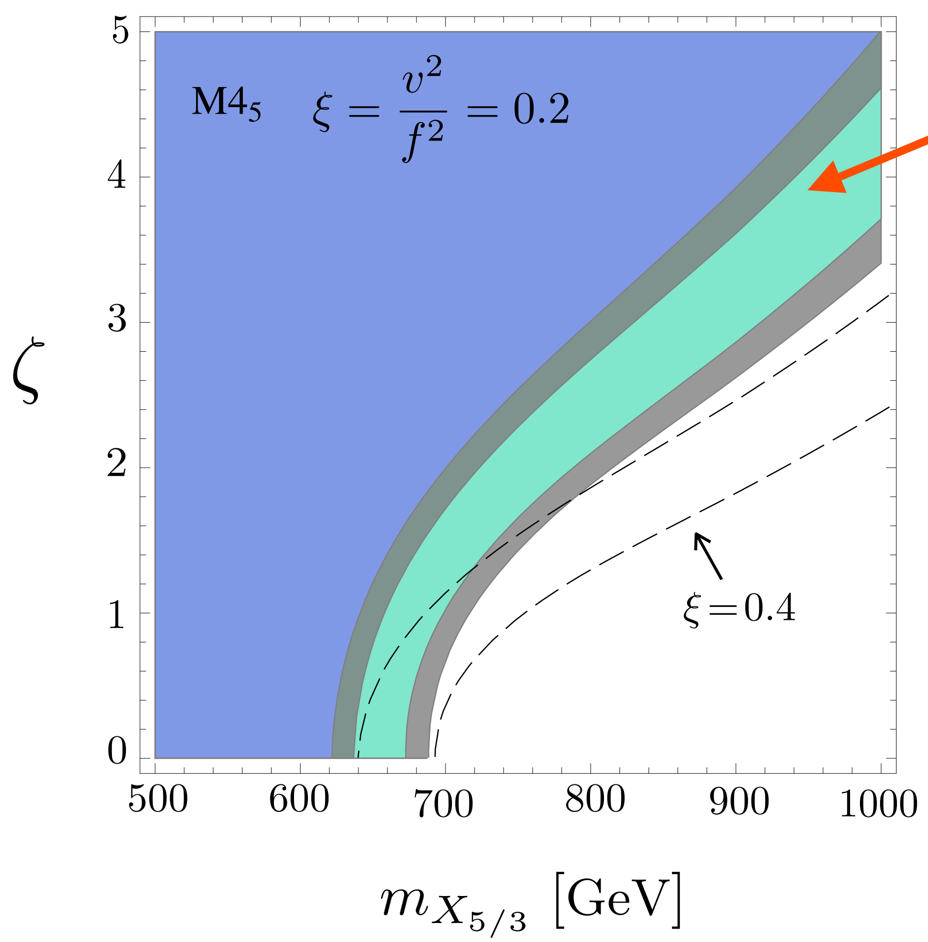

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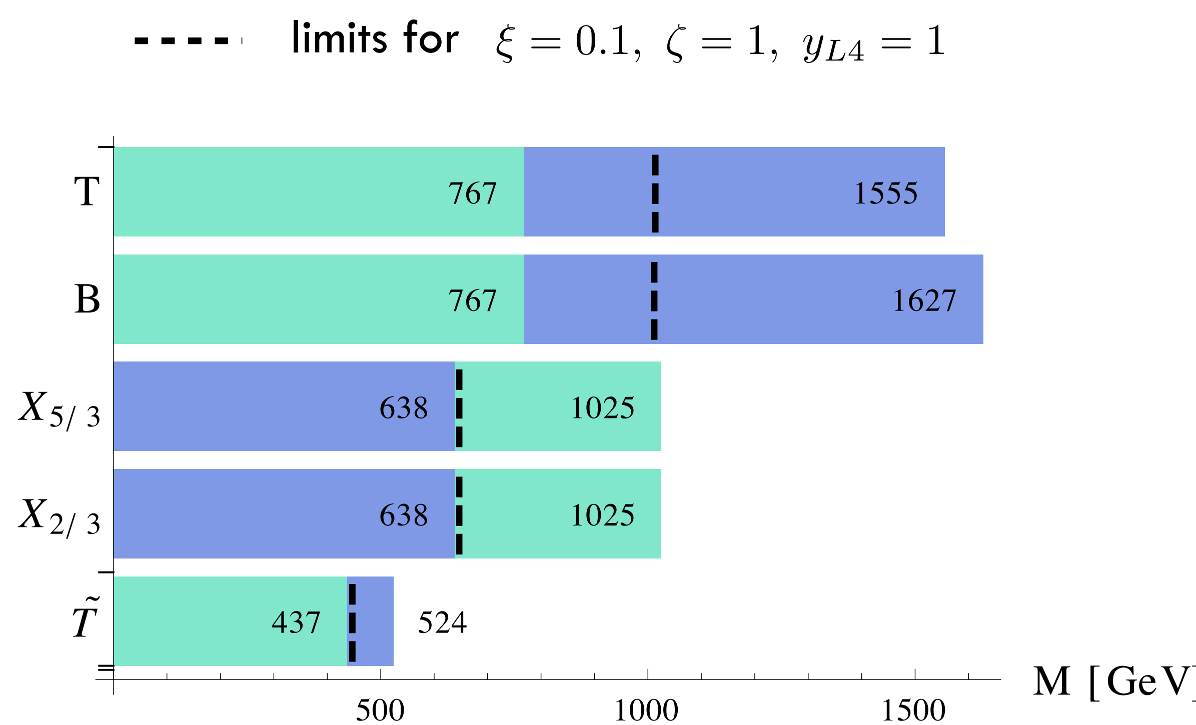

Multiplicity of states, connection among masses and inclusion of single production amplify limits on individual particles

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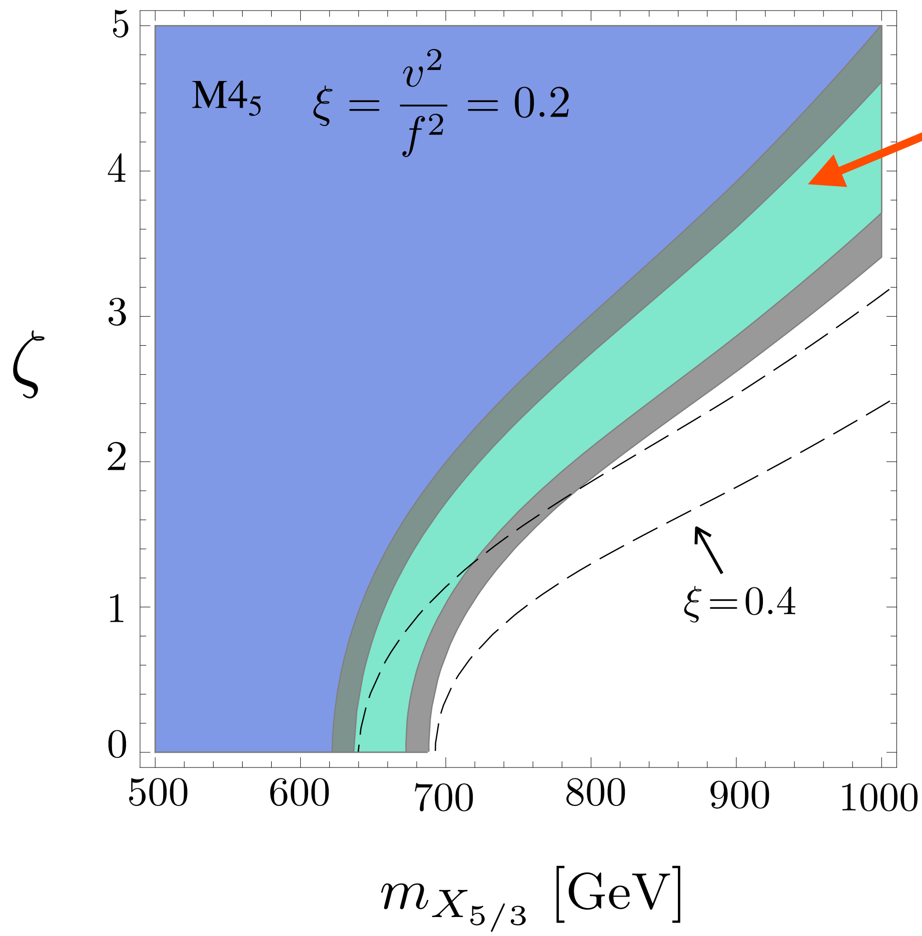
De Simone et al. JHEP 1304 (2013) 004



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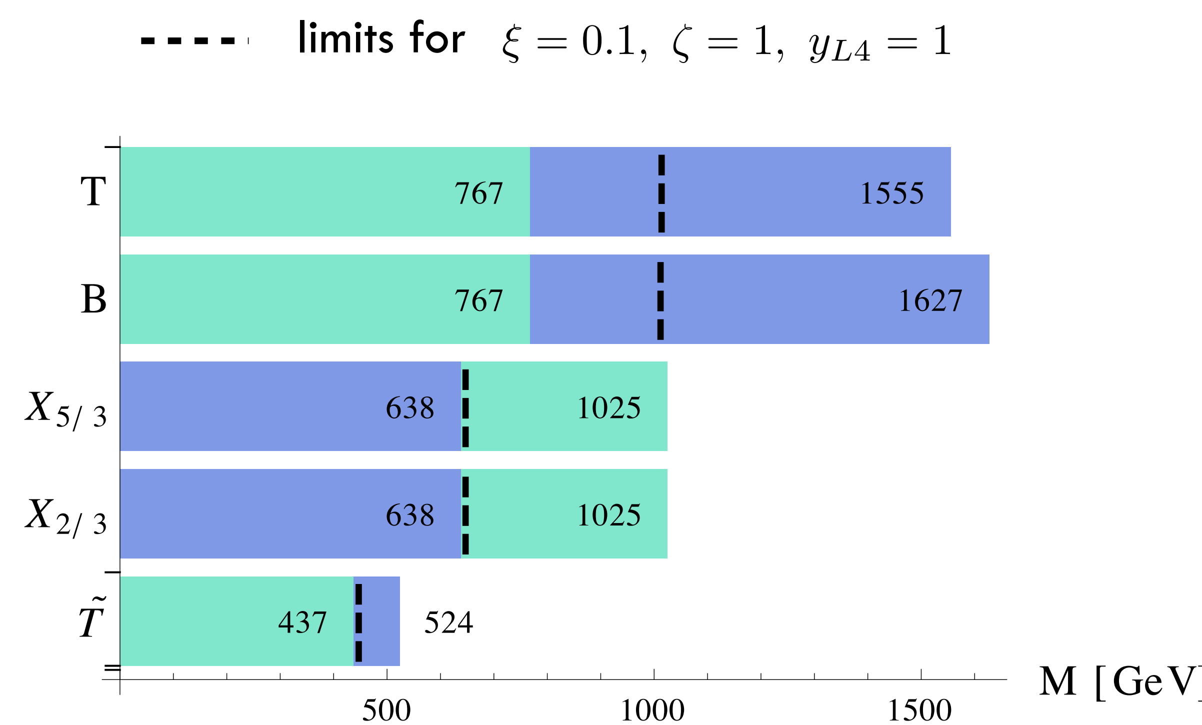


Multiplicity of states, connection among masses and inclusion of single production amplify limits on individual particles

1TeV masses typically excluded

LHC has already eaten up a big part of the natural region

Improving the limits still possible with current data

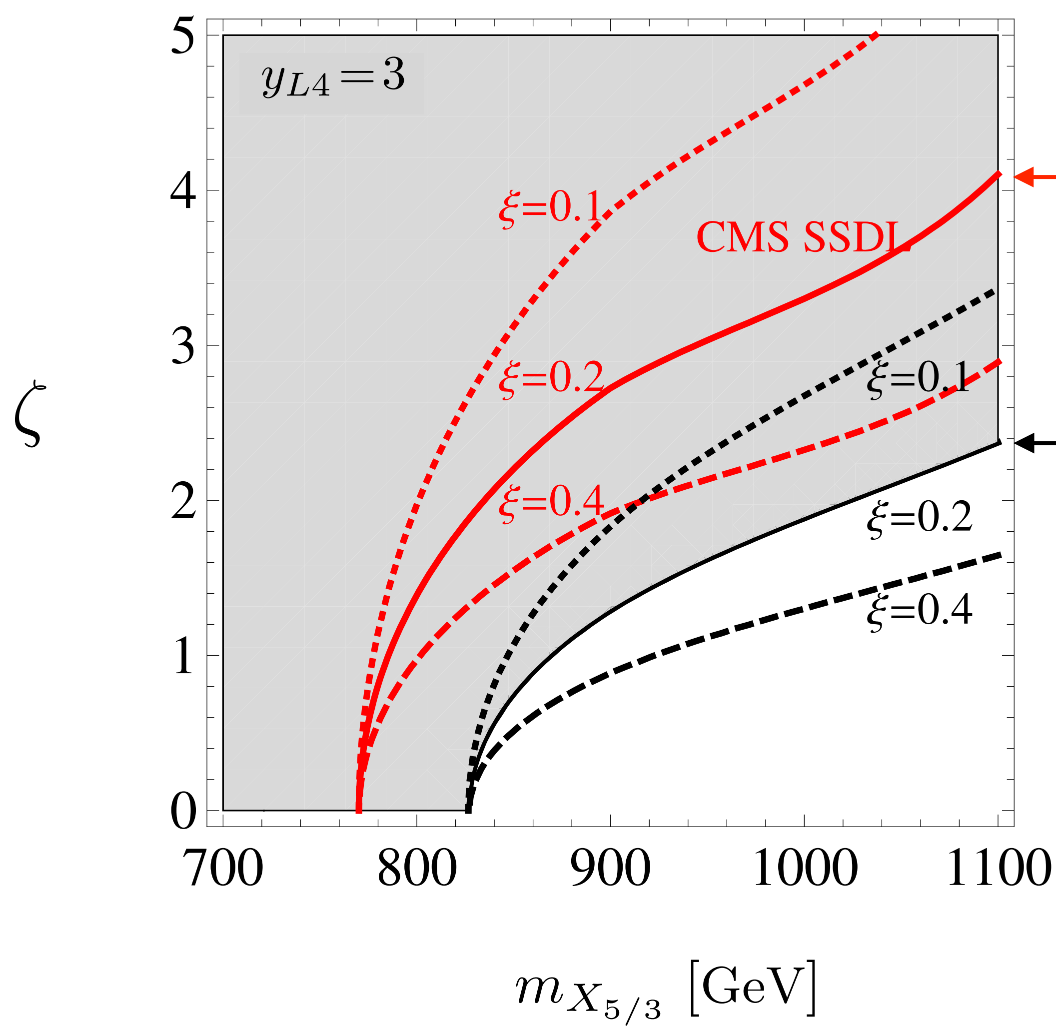
De Simone et al. JHEP 1304 (2013) 004

Azatov, Salvarezza, Son, Spannowsky arXiv:1308.6601

Ex: - optimize searches to include single production

- include single-lepton final states

- use boosted jet techniques



red = recast of SSDL analysis of CMS-PAS-B2G-12-012

black = improved analysis including 1L final states, from Azatov et al. arXiv:1308.6601

Higgs couplings

- LHC data currently set limits on modifications of the Higgs couplings at the 20-30% level

$$c_V = 1 + F\left(\frac{v^2}{f^2}\right) + O\left(\frac{v^2}{f^2}\,\frac{g_{\not G}^2}{g_*^2}\right)$$

$$c_\psi = 1 + F_\psi\left(\frac{v^2}{f^2}, \frac{m_i}{m_j}\right) + O\left(\frac{v^2}{f^2}\,\frac{\lambda^2}{g_*^2}\right)$$

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$O(v^2/f^2)$ from Higgs nlσm

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from heavy resonances

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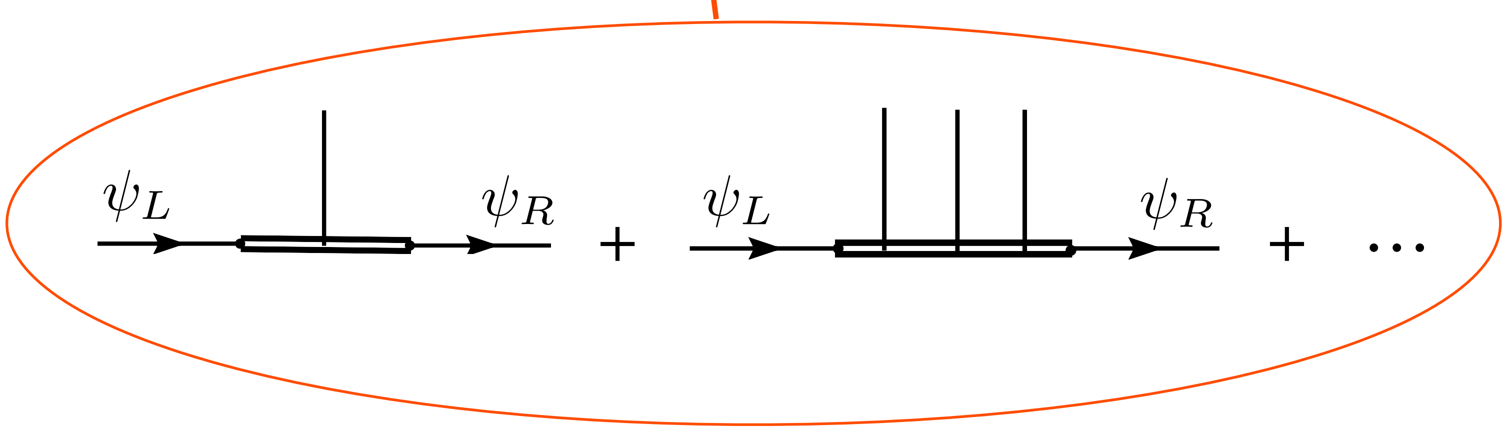

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$O(v^2/f^2)$ from Higgs nlσm

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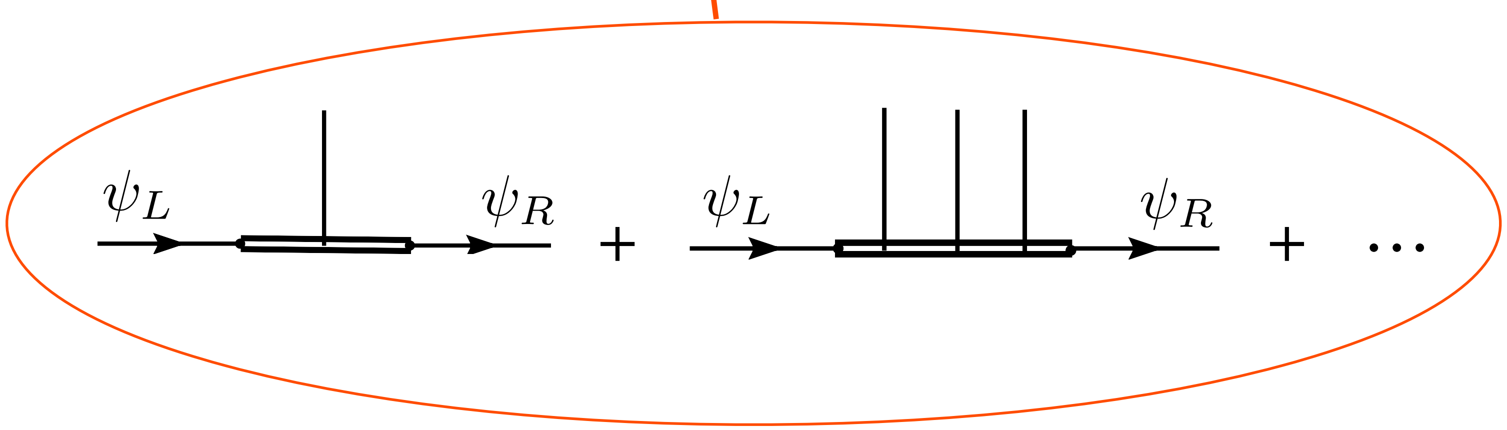
from heavy resonances

in the simplest models

$$c_\psi = 1 + F_\psi\left(\frac{v^2}{f^2}, \frac{m_i}{m_j}\right) + O\left(\frac{v^2}{f^2}\,\frac{\lambda^2}{g_*^2}\right)$$



- LHC data currently set limits on modifications of the Higgs couplings at the 20-30% level

$O(v^2/f^2)$ from Higgs nlσm

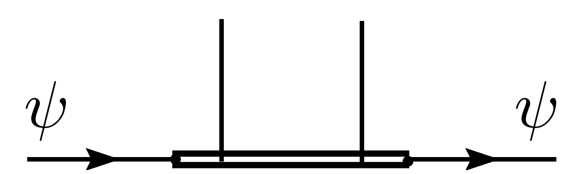
$$c_V = 1 + F\left(\frac{v^2}{f^2}\right) + O\left(\frac{v^2}{f^2}\,\frac{g_{\not G}^2}{g_*^2}\right)$$

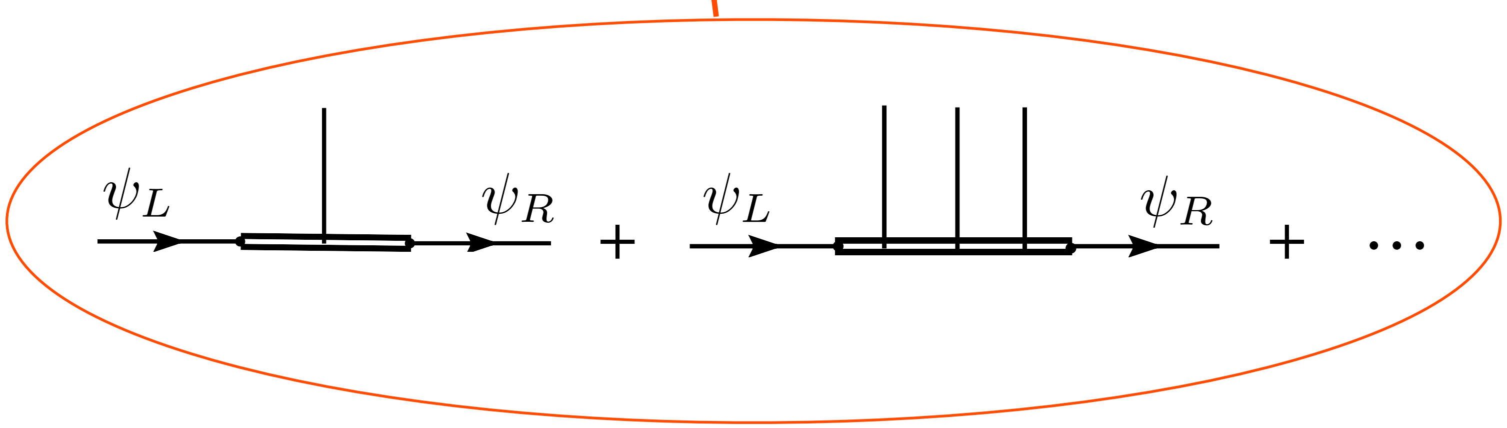
← from heavy resonances

in the simplest models

$$c_\psi = 1 + F_\psi\left(\frac{v^2}{f^2}, \cancel{\frac{m_i}{m_j}}\right) + O\left(\frac{v^2}{f^2}\,\frac{\lambda^2}{g_*^2}\right)$$

← from wave-function renormalization





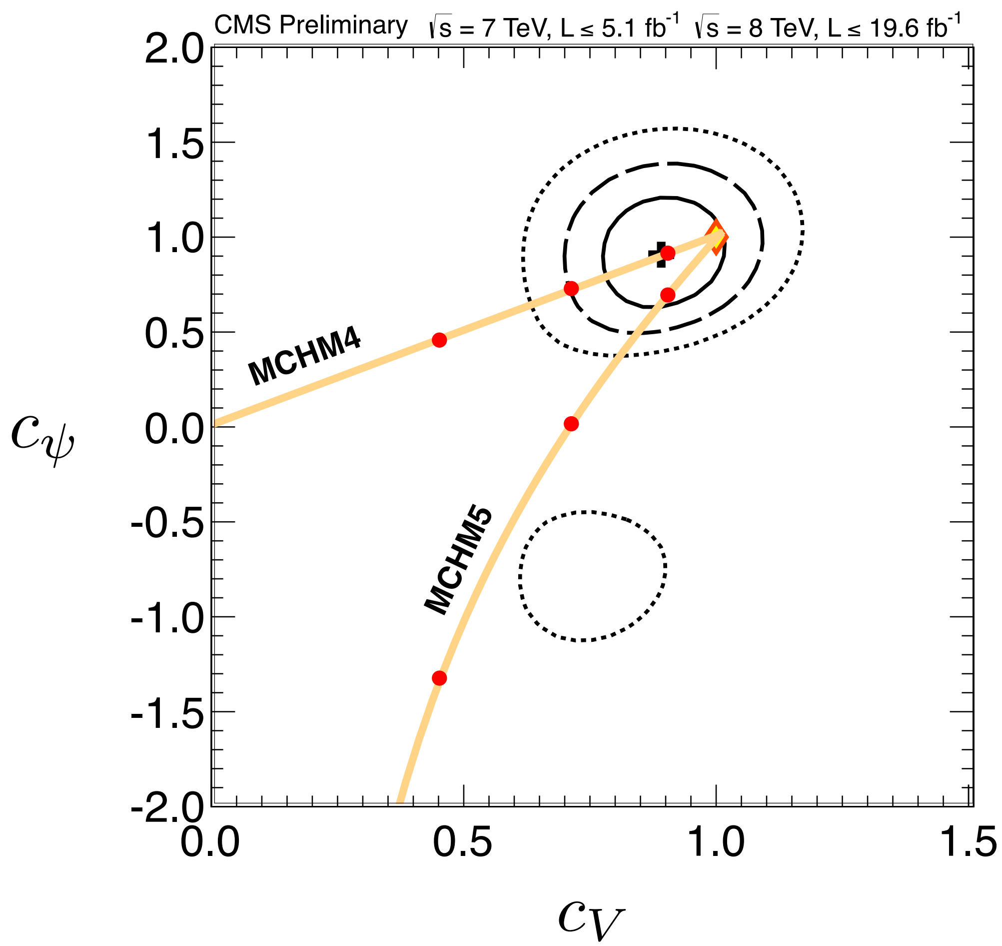
$$\xi \equiv \frac{v^2}{f^2}$$

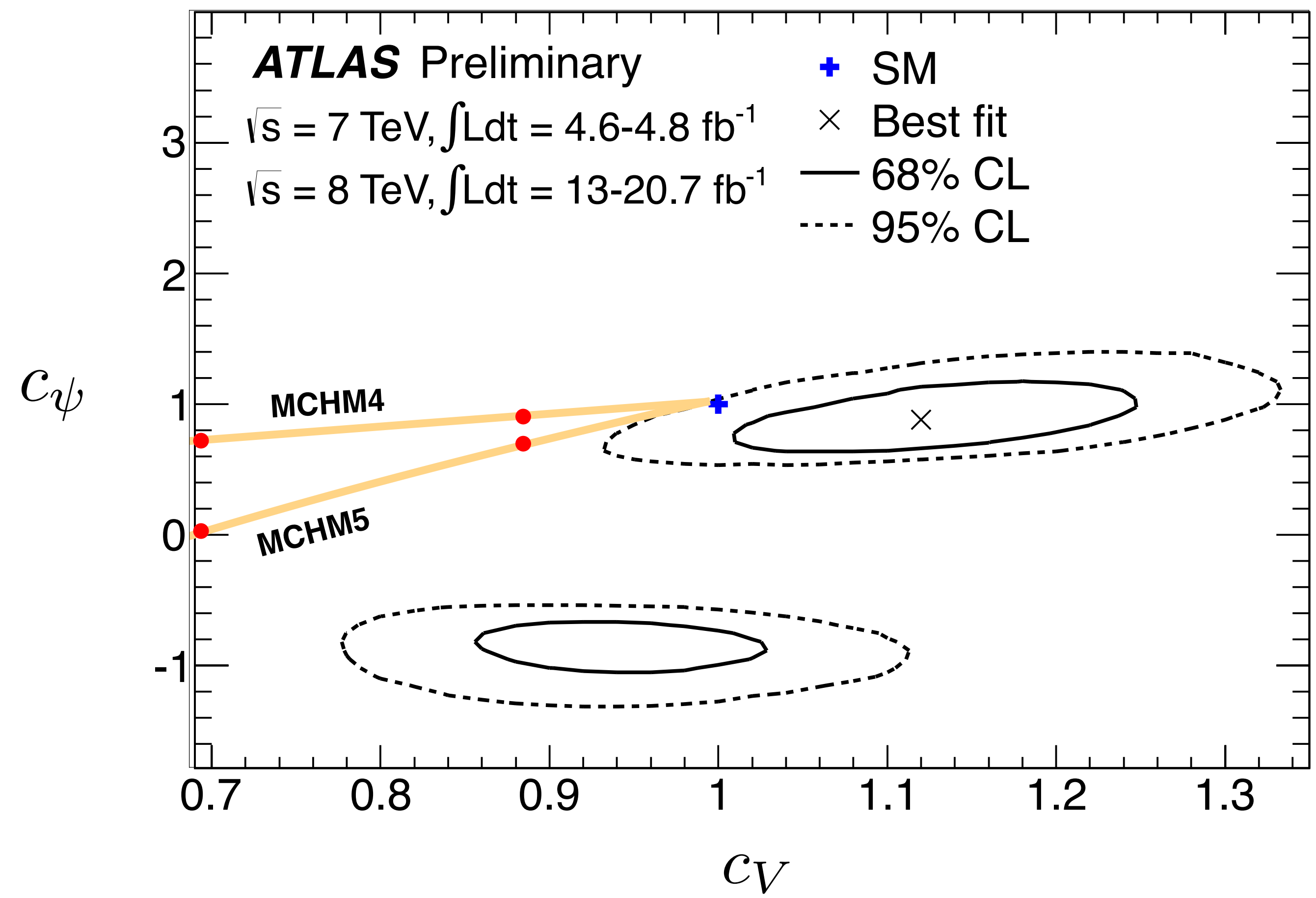
MCHM4: $c_V = c_\psi = \sqrt{1-\xi}$

Agashe, RC, Pomarol, NPB 719 (2005) 165

MCHM5: $c_V = \sqrt{1-\xi}$ $\quad c_\psi = \frac{1-2\xi}{\sqrt{1-\xi}}$

RC, DaRold, Pomarol, PRD 75 (2007) 055014
Carena, Ponton, Santiago, Wagner, PRD 76 (2007) 035006





Red points at $\xi \equiv (v/f)^2 = 0.2,\ 0.5,\ 0.8$

$$\xi \equiv \frac{v^2}{f^2}$$

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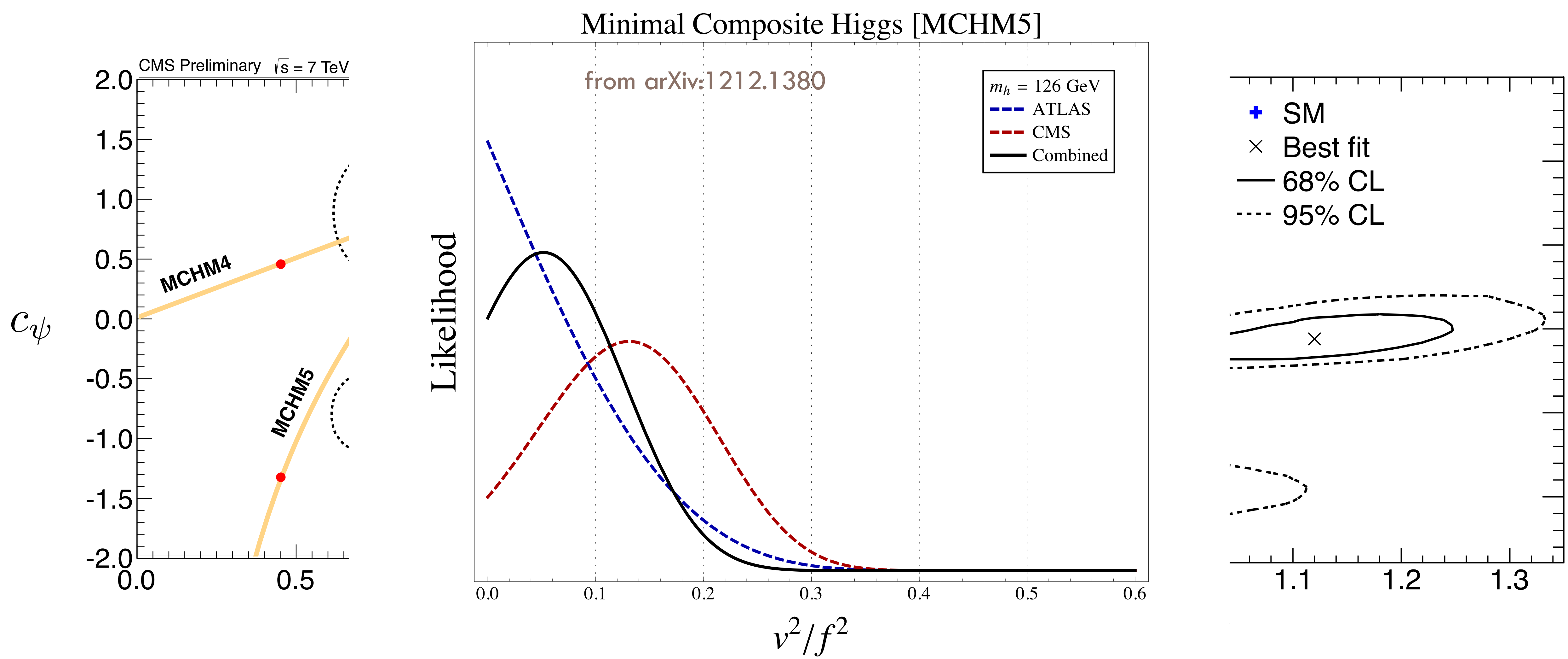

$\xi = (v/f)^2 < 0.22$ **at 95%** ➡ $m_{\rm new} \gtrsim 1.6\,\text{TeV}\left(\frac{g_*}{3}\right)$

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Agashe, RC, Pomarol, NPB 719 (2005) 165

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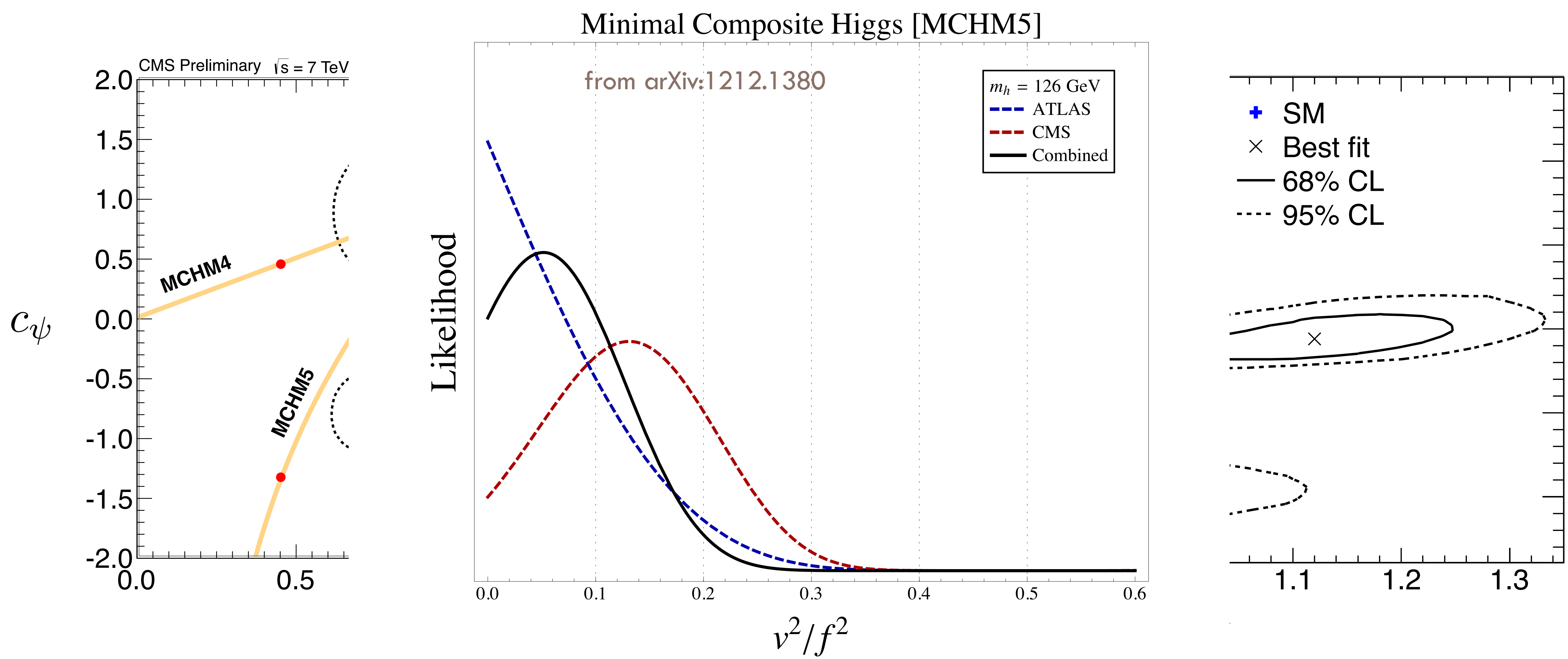

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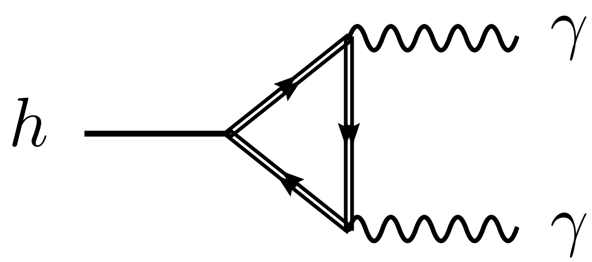
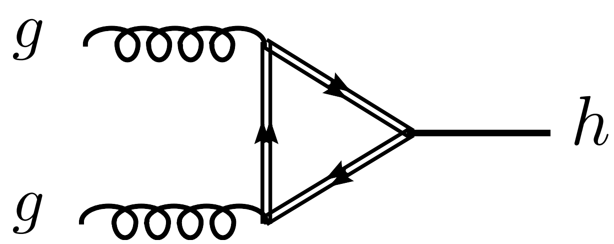
Sensitivity comparable to direct searches

- Modifications to loop-level couplings *ggh*, *γγh* suppressed due to the Goldstone symmetry



$$B_{\mu\nu}^2 H^\dagger H$$



$$G_{\mu\nu}^2 H^\dagger H$$

Effective operators violate the Higgs shift symmetry:

$$H^i \to H^i + \zeta^i$$

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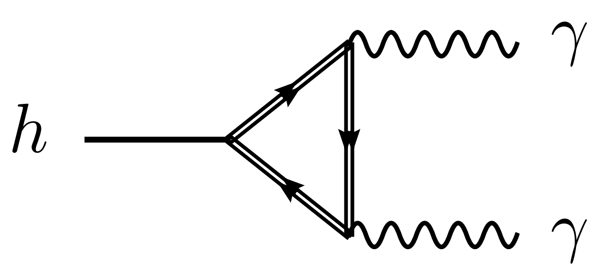

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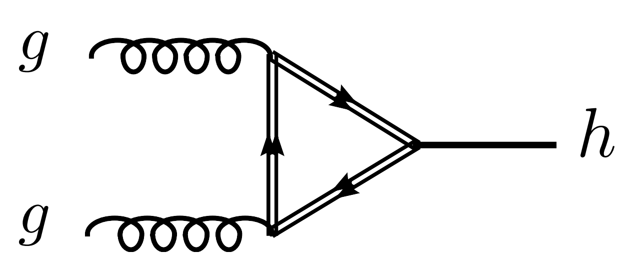

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Effective operators violate the Higgs shift symmetry:

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$$\frac{\delta\Gamma}{\Gamma_{SM}} = 1 + O\left(\frac{v^2}{f^2}\right) + O\left(\frac{g_*^2 v^2}{m_*^2} \times \frac{\lambda^2}{g_*^2}\right)$$

'long-distance'
SM loops with
modified couplings

'short-distance'
loops of top partners

Large modifications possible in $\Gamma(h \to Z\gamma)$

Azatov, RC, Di Iura, Galloway, PRD 88 (2013) 075019

$$\frac{\delta\Gamma(Z\gamma)}{\Gamma_{SM}(Z\gamma)} = O\left(\frac{v^2}{f^2}\right) + O\left(\frac{g_*^2 v^2}{m_*^2}\right)$$

Relevant operator is $O_{HW} - O_{HB}$

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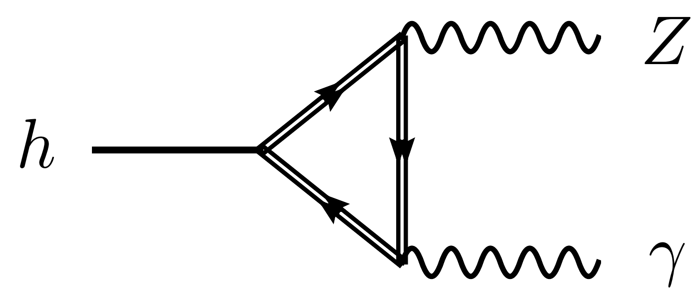

1. Invariant under Higgs shift symmetry
2. Odd under LR exchange

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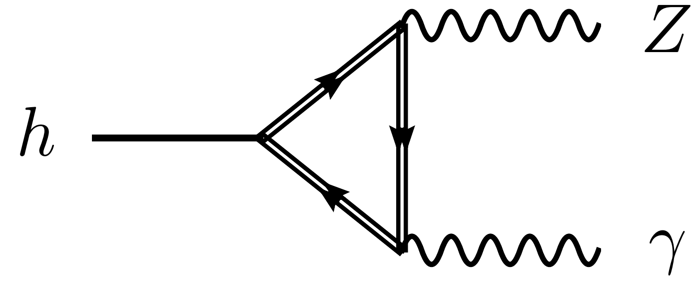

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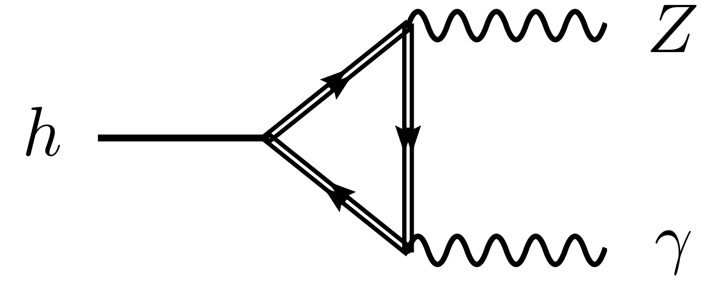

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$$A(h \to Z\gamma) = A_{SM} \times F(\xi) + \delta A$$

$$\frac{\delta A}{A_{SM}} \sim N_c N_F \left(\frac{g_*^2 v^2}{m_*^2}\right) \sim N_c N_F \frac{v^2}{f^2} \frac{\Delta m_*^2}{m_*^2}$$

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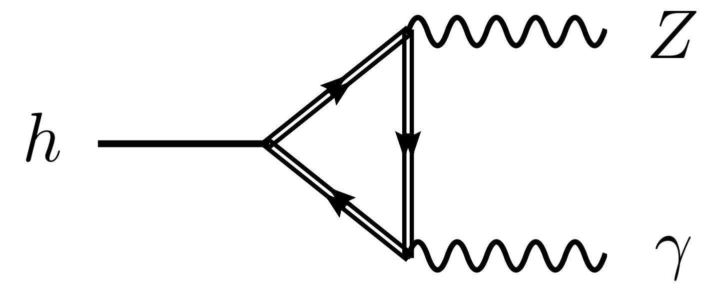

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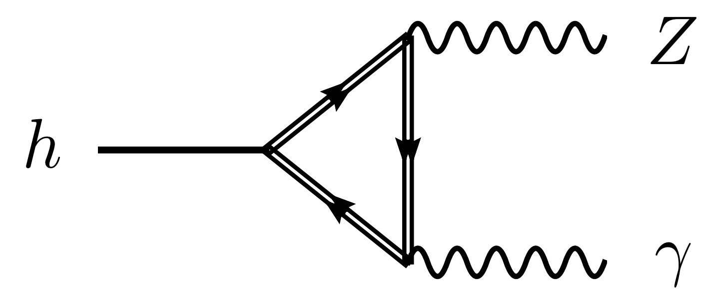

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$N_c N_F$: multiplicity of composite states

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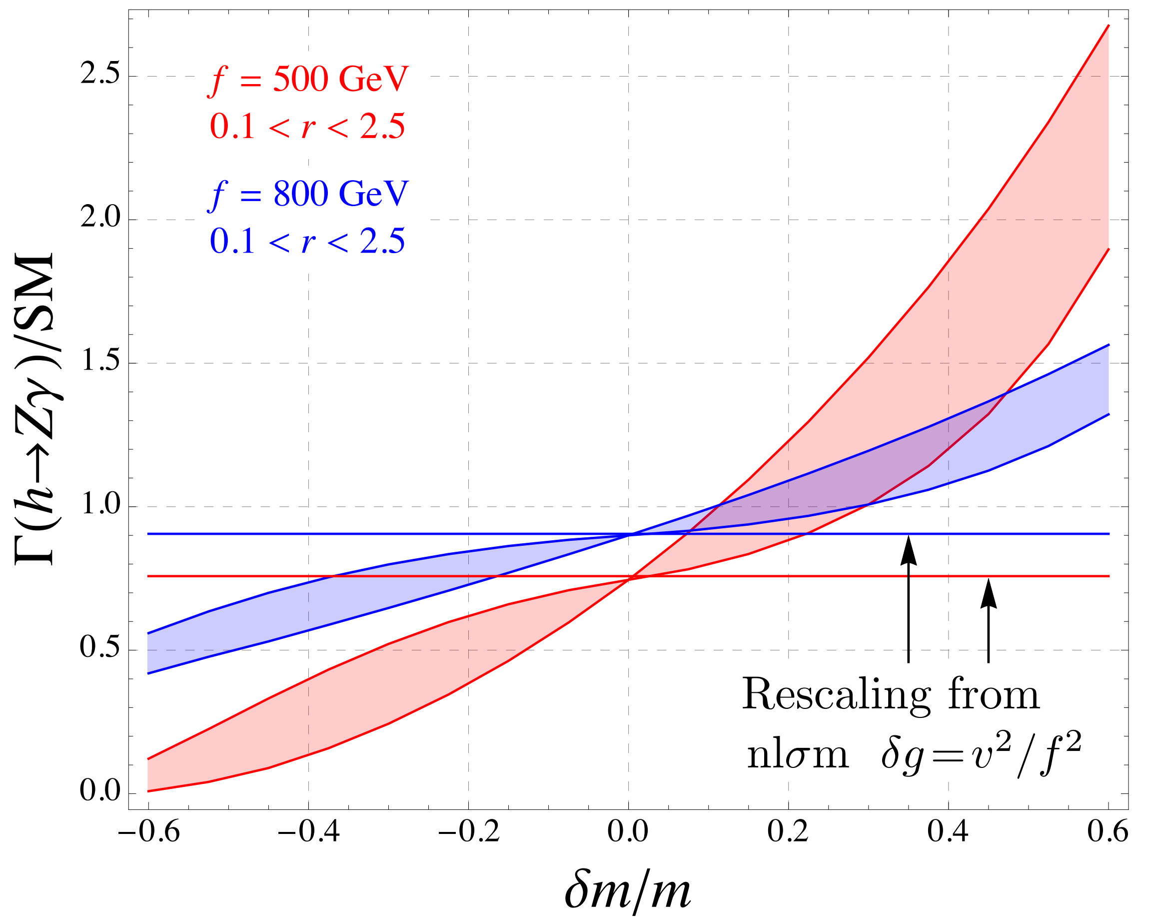

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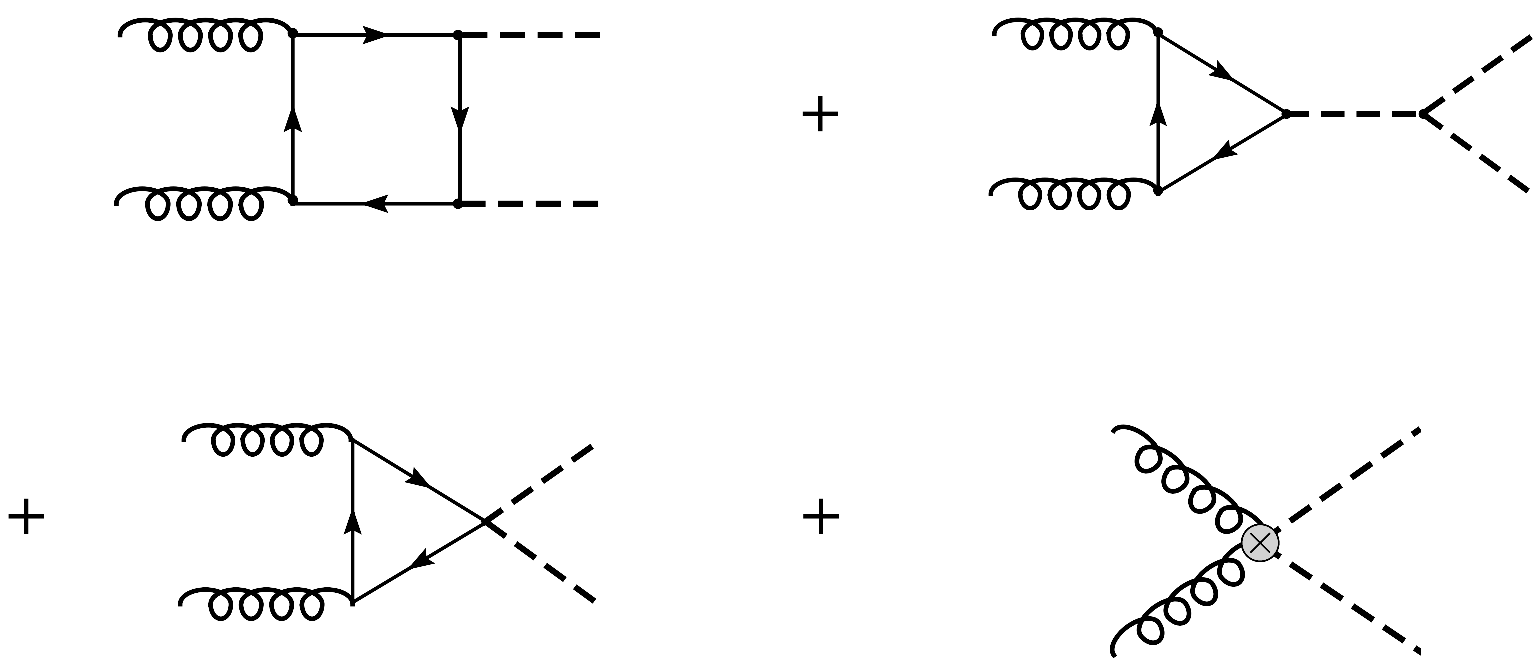
Future strategies

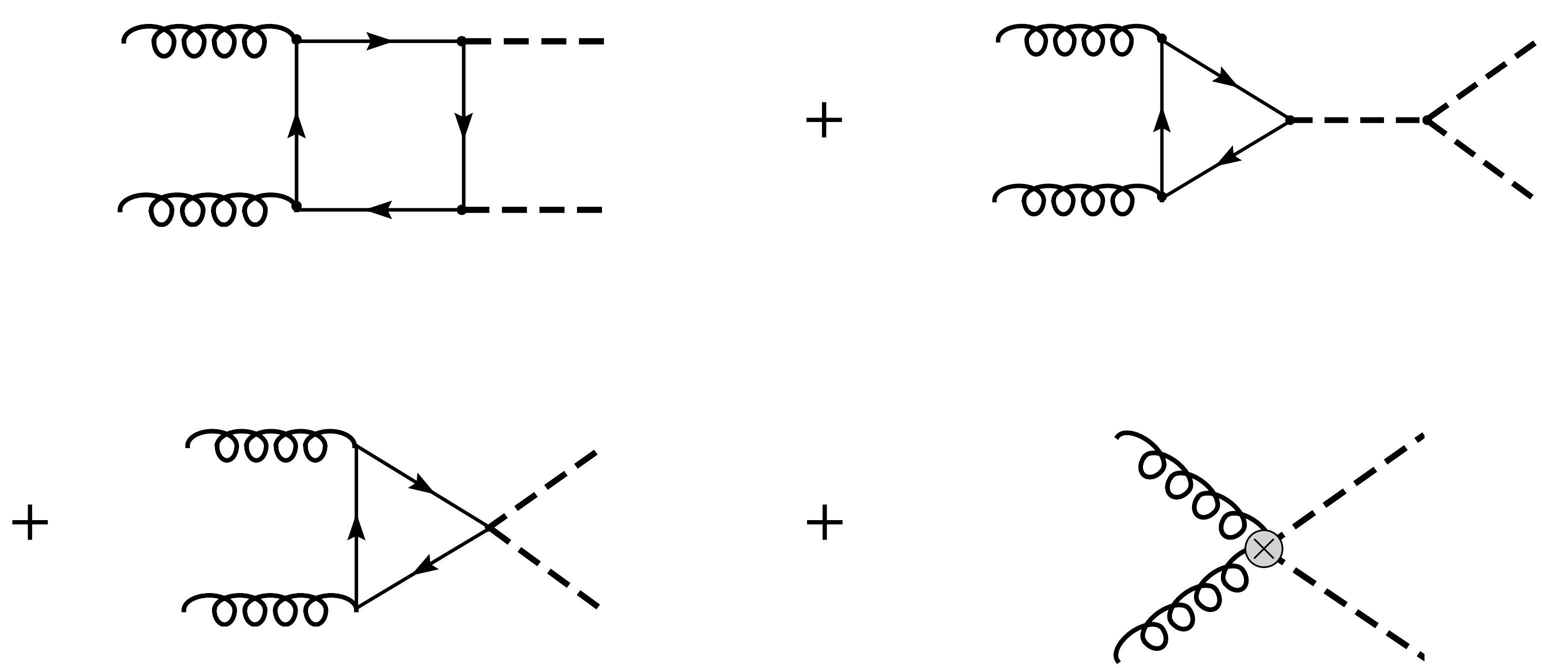
Double-Higgs production

Double Higgs Production via gluon fusion



Double Higgs Production via gluon fusion

$$\Delta\mathcal{L}^{(6)} = \frac{\bar{c}_H}{2v^2}[\partial_\mu(H^\dagger H)]^2 + \frac{\bar{c}_u}{v^2} y_u\, H^\dagger H\, \bar{q}_L H^c u_R - \frac{\bar{c}_6\lambda}{v^2}(H^\dagger H)^3$$



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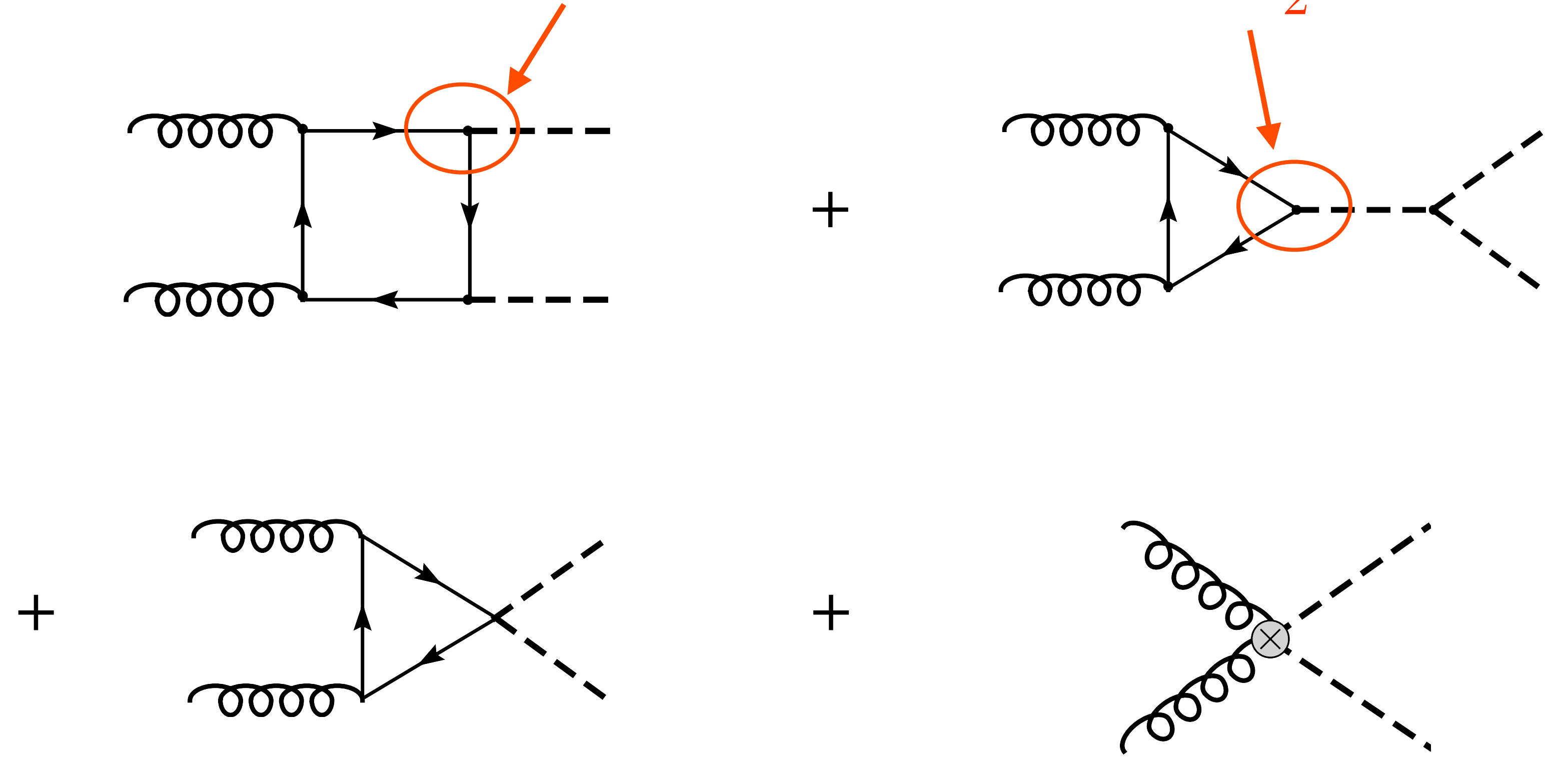
modified top Yukawa coupl. $c_t \simeq 1 - \frac{\bar{c}_H}{2} - \bar{c}_u$



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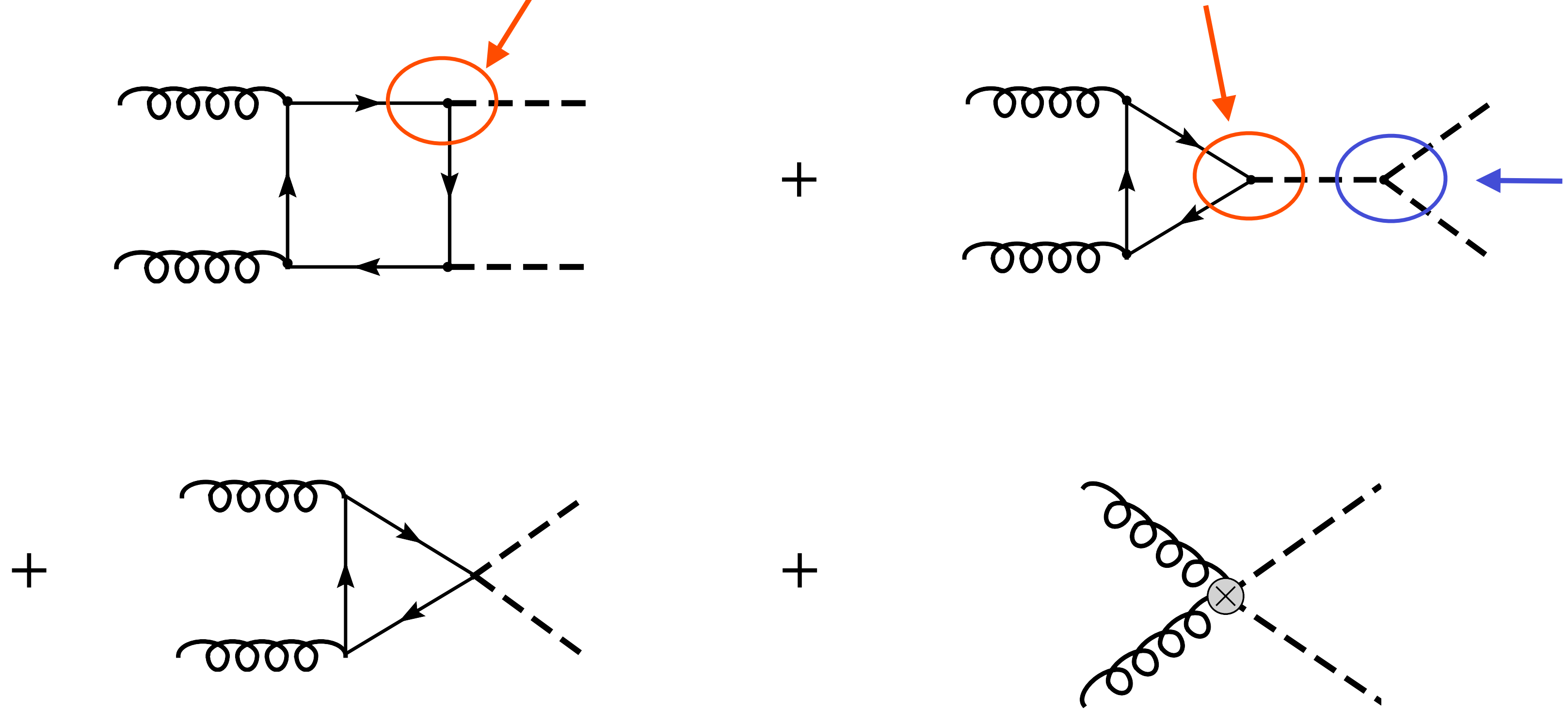
modified Higgs trilinear coupl.

$c_3 \simeq 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$



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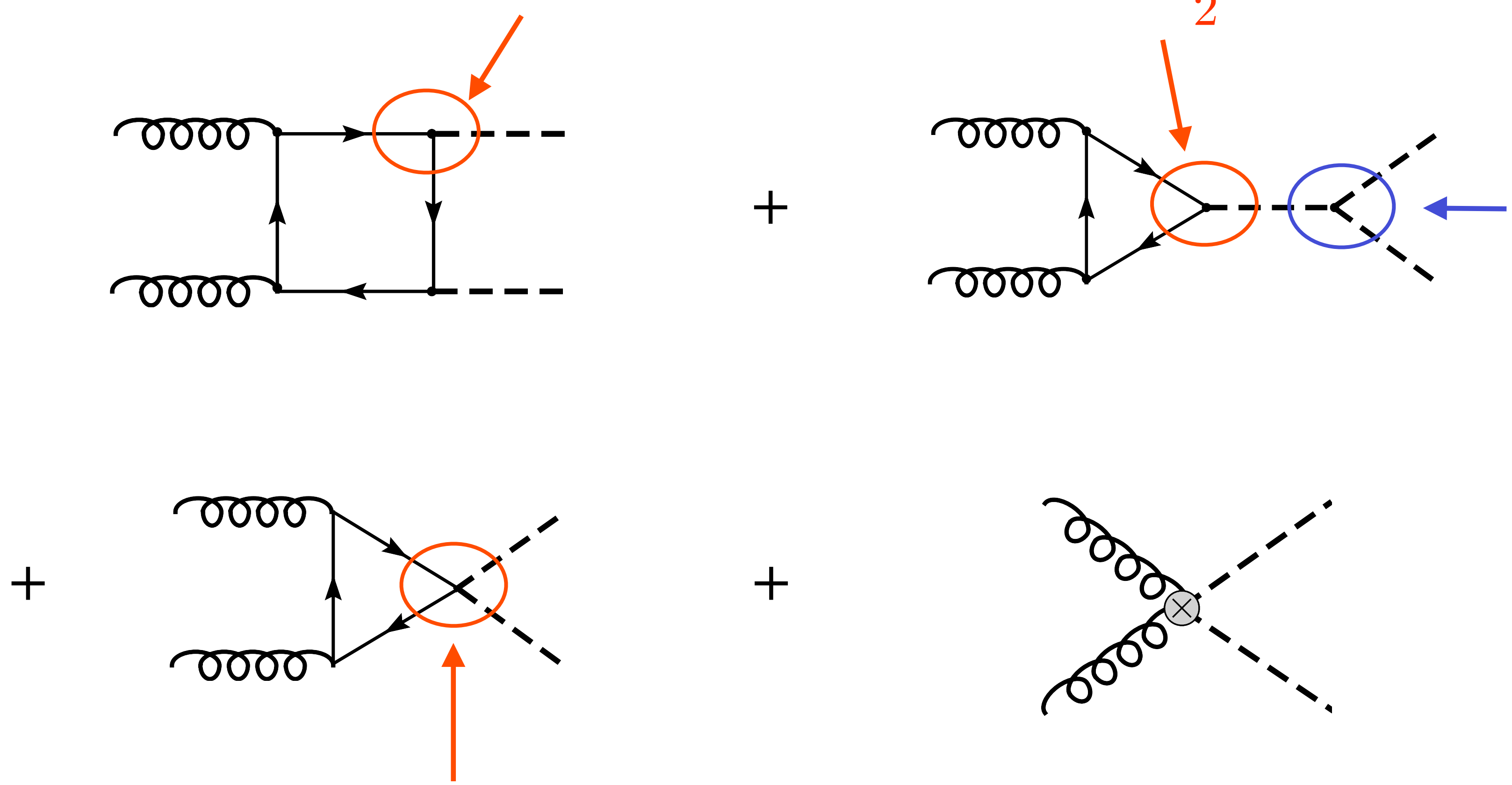

$c_{2t} \simeq -\frac{1}{2}(\bar{c}_H + 3\bar{c}_u)$

New tthh quartic vertex

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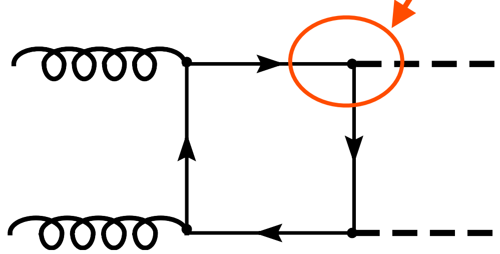

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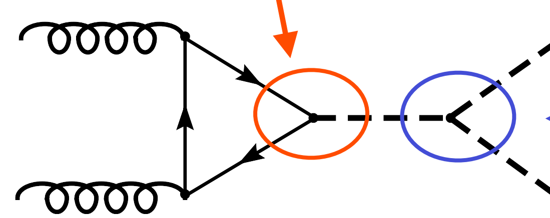

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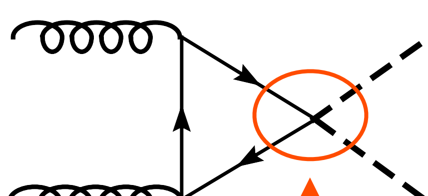

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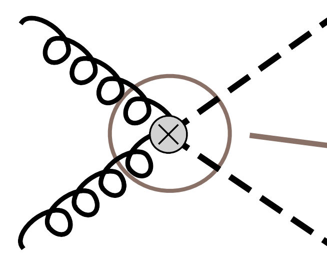
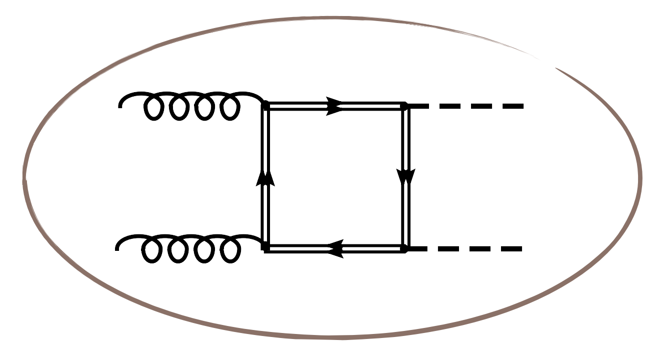


Contact vertex from heavy states



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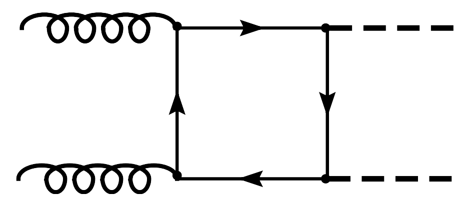
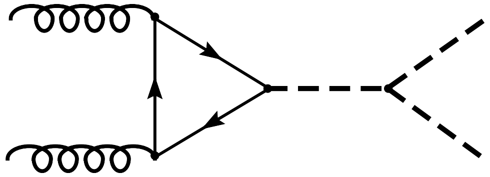
$G^2_{\mu\nu}\frac{H^\dagger H}{m_*^2}$

New tthh quartic vertex

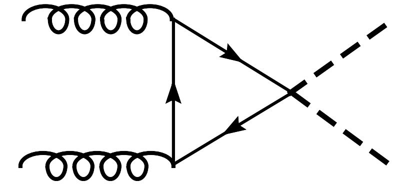
High-energy behavior



$\sim const.$



$\sim \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



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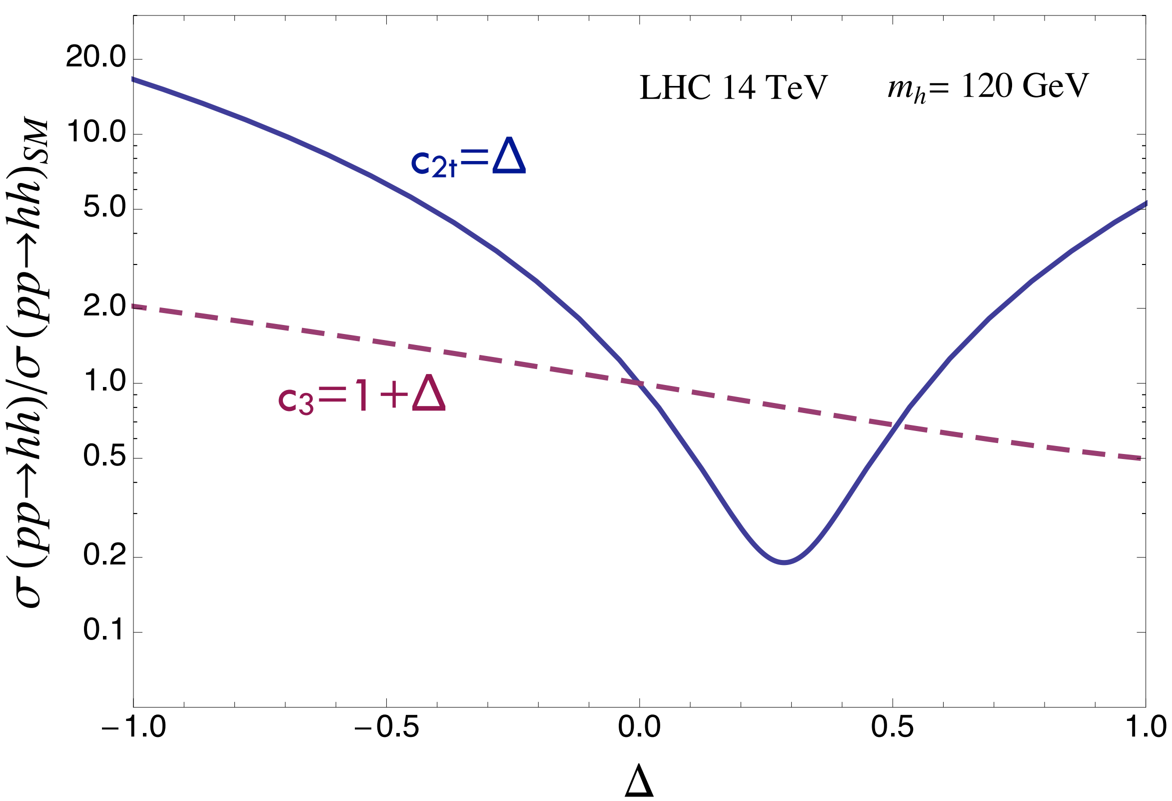


RC, Ghezzi, Moretti, Panico, Piccinini, Wulzer
JHEP 1208 (2012) 154

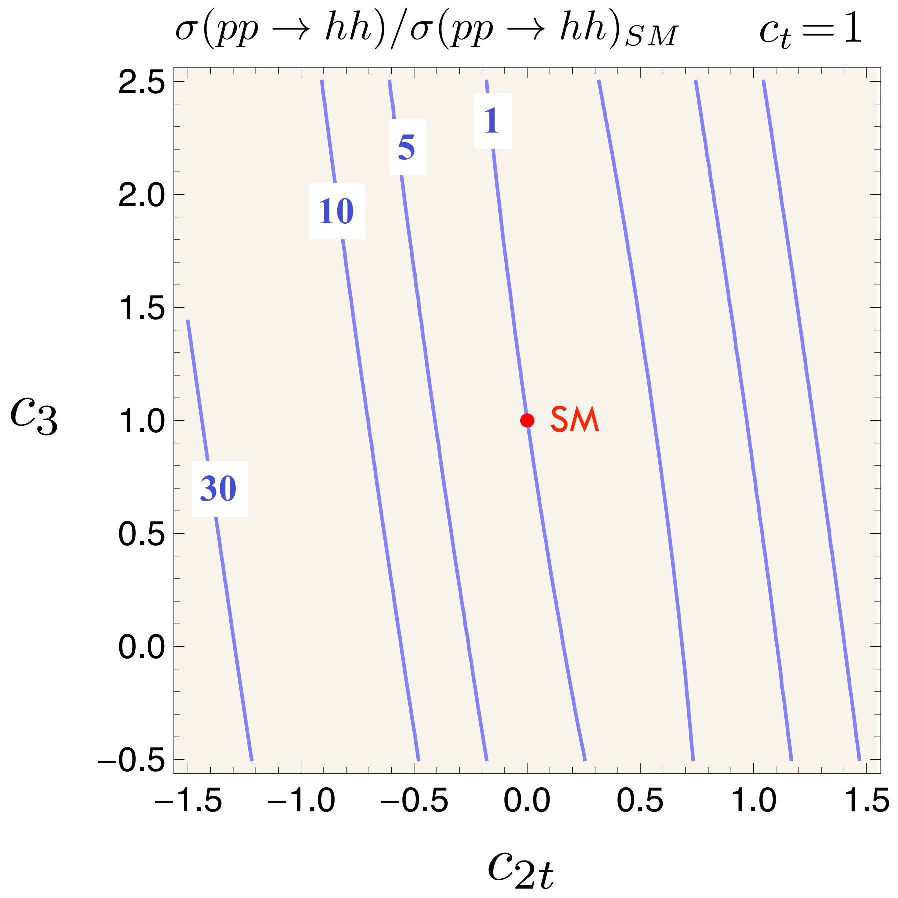
Suppression of SM triangle diagrams at high-energy implies:

much better sensitivity on c_{2t} than c_3

[First noticed by:
Dib, Rosenfeld, Zerwekh, JHEP 0605 (2006) 074
Grober and Muhlleitner, JHEP 1106 (2011) 020]

$$\sigma(pp \to hh + X)_{SM} = 28.7\,\text{fb}$$

(NLO $K = 2$ incl.)



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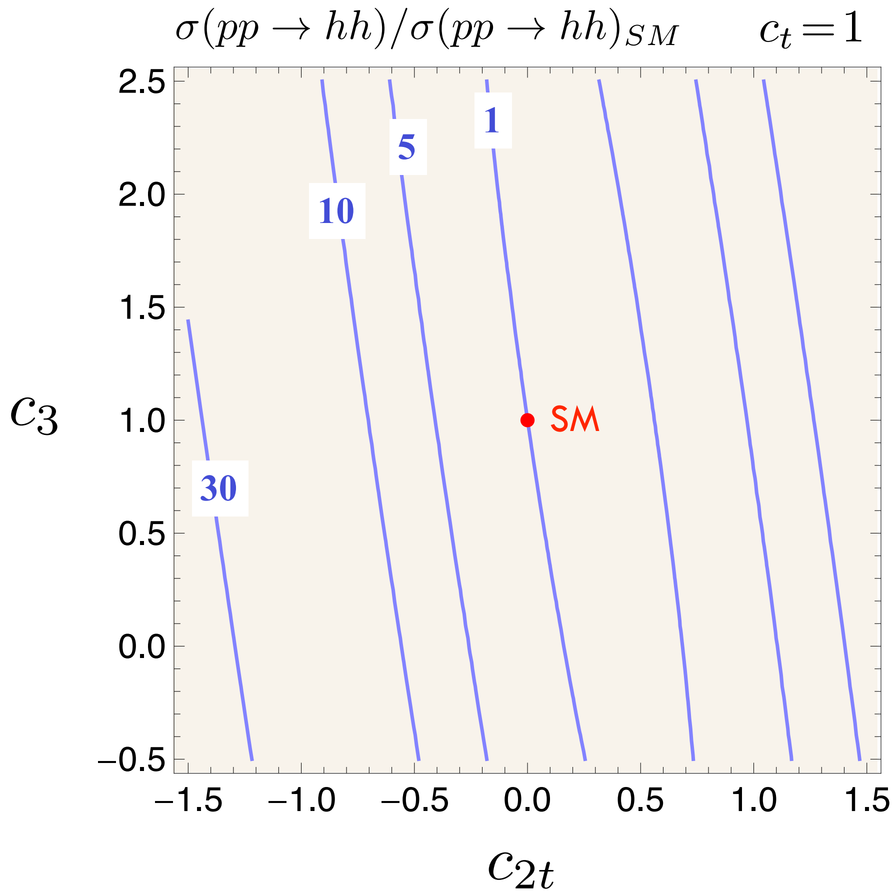

- $hh \to b\bar{b}\gamma\gamma$ seems the best channel

  Baur, Plehn, Rainwater, PRD 69 (2004) 053004
  ATLAS: ATL-PHYS-PUB-2012-004

- $hh \to b\bar{b}\tau\tau$ promising in the boosted regime

  Dolan, Englert, Spannowsky arXiv:1206.5001

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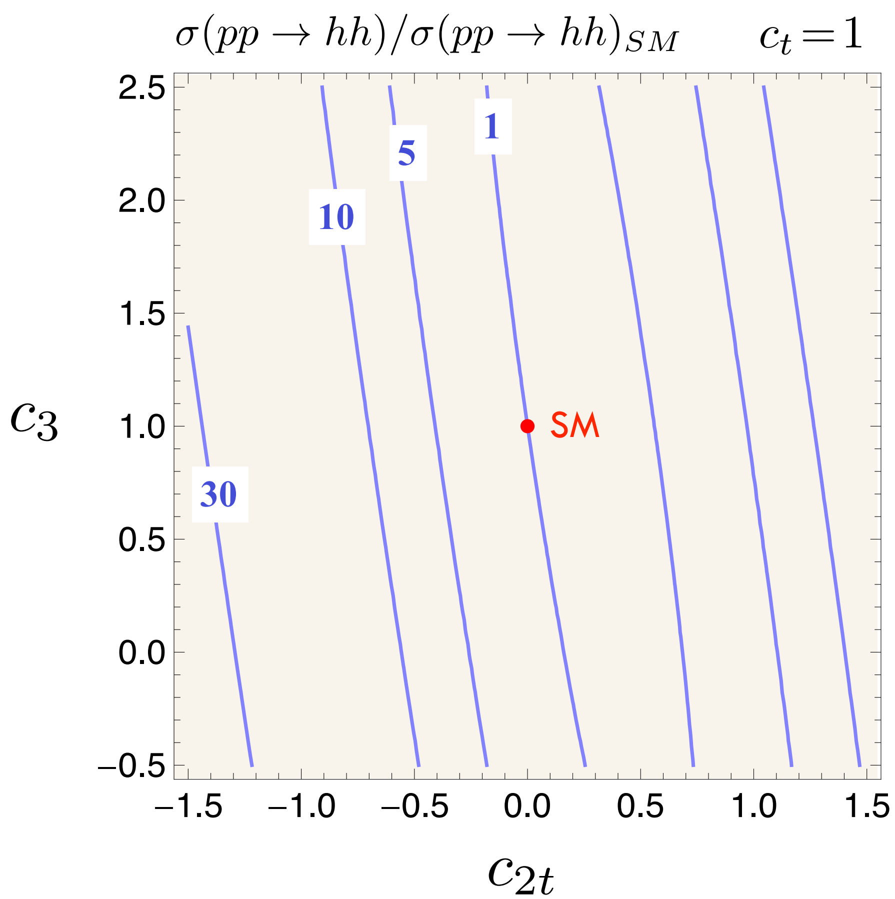

For example: in the MCHM5

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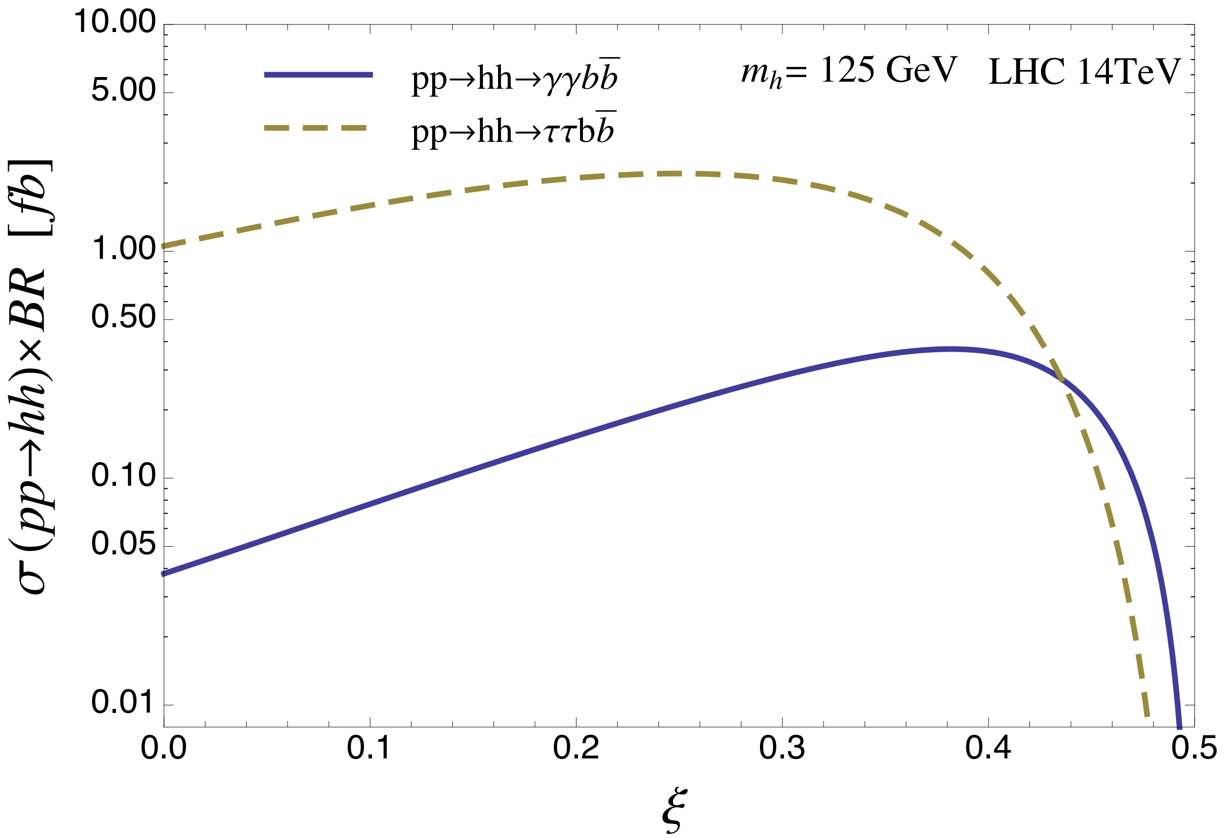

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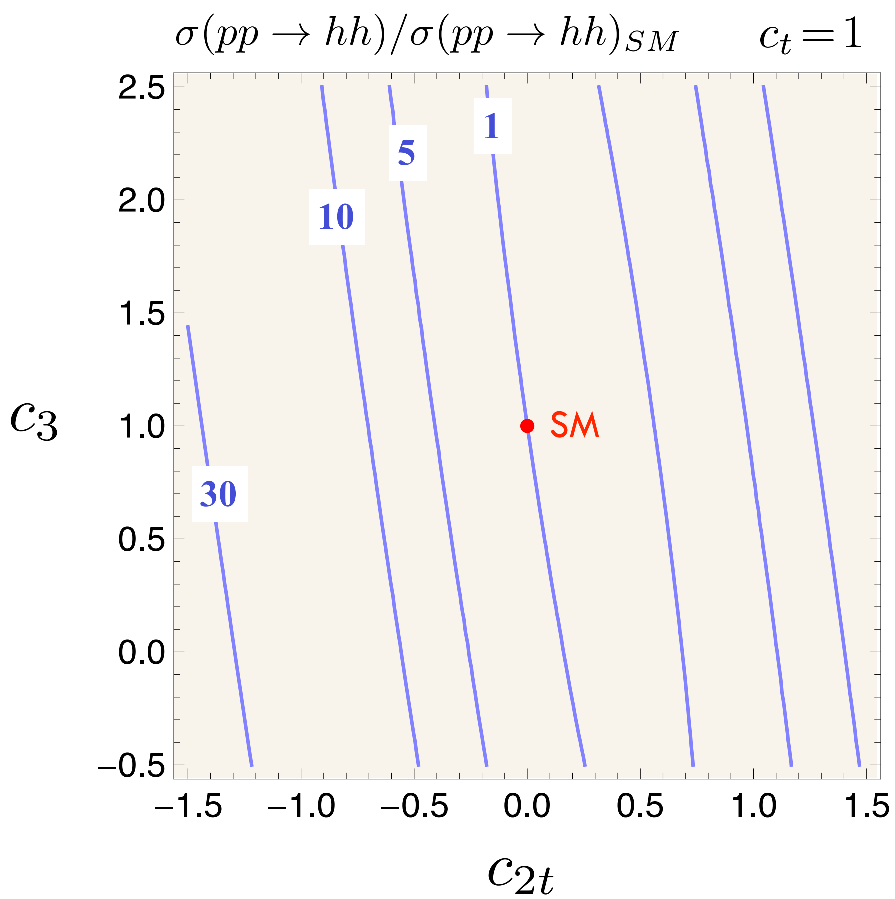

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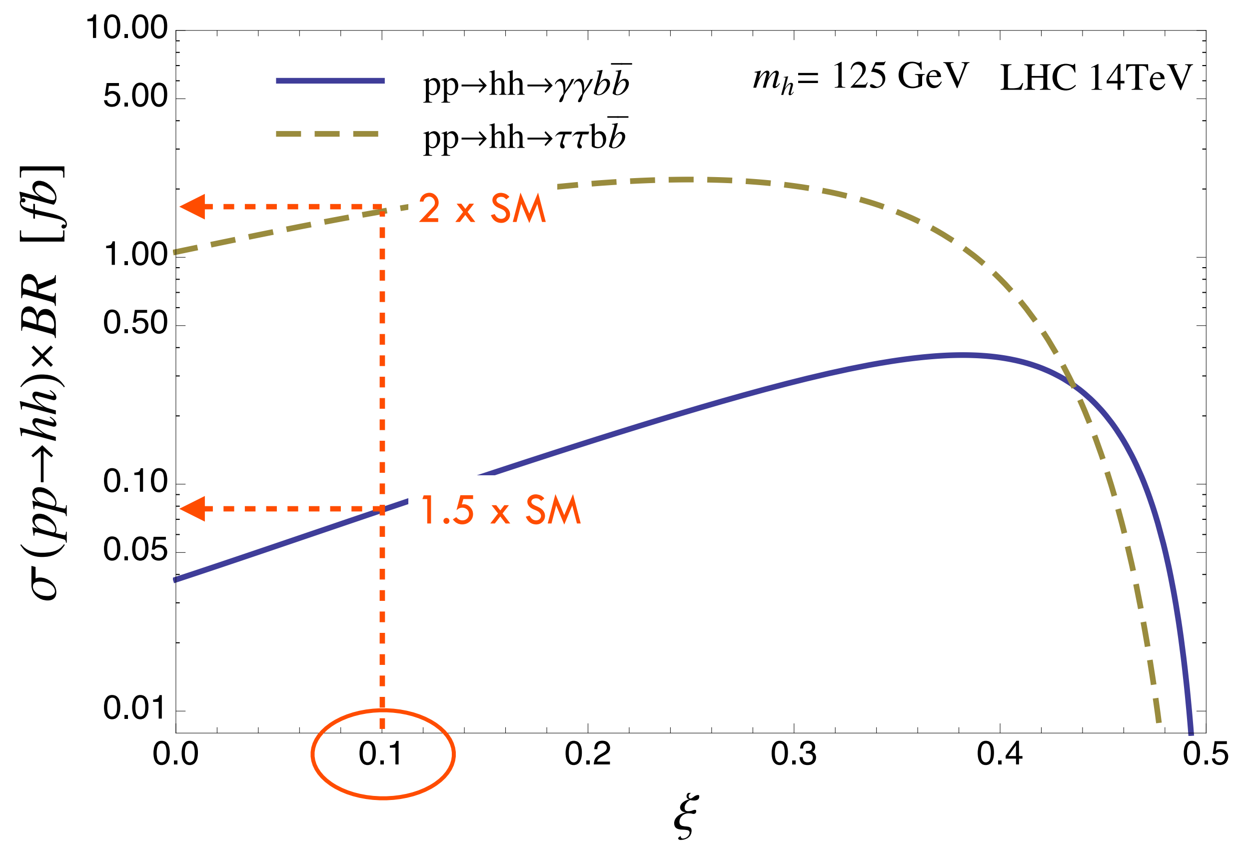
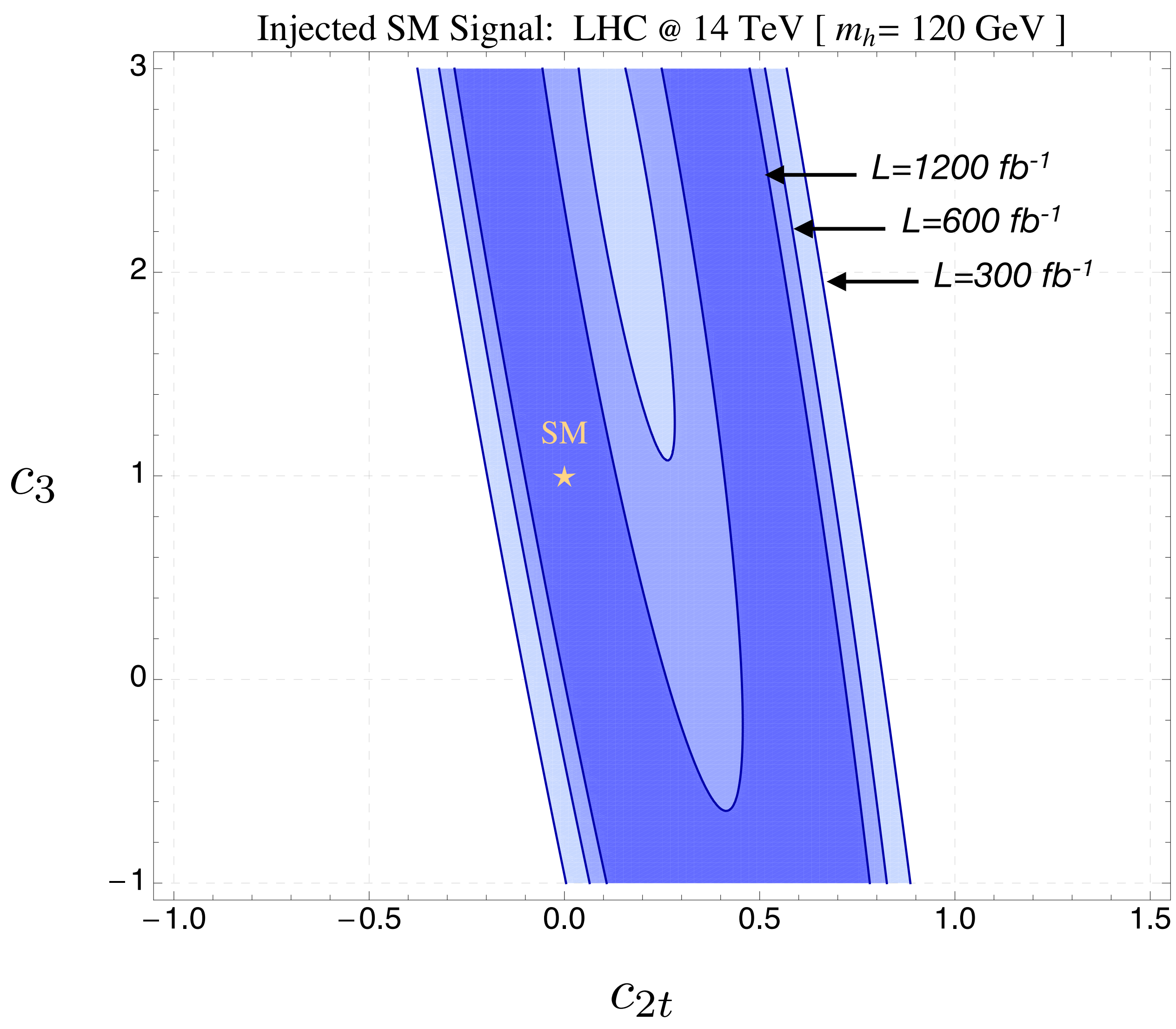
  Dolan, Englert, Spannowsky arXiv:1206.5001



Precision on couplings

Ex: Injected SM (c_t=c_3=1 c_{2t}=0)

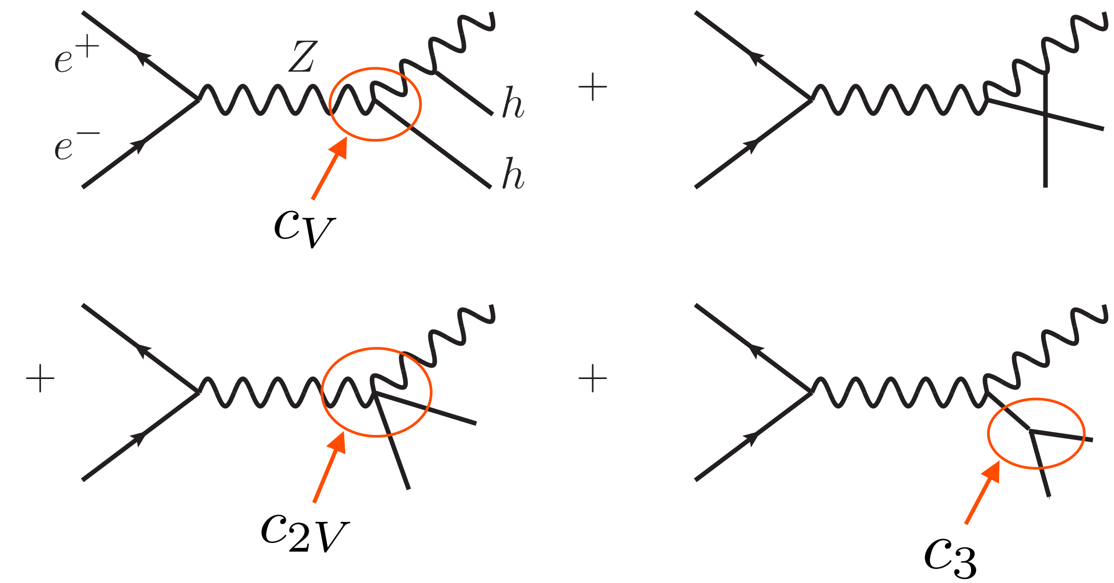


- curves at 68% prob.

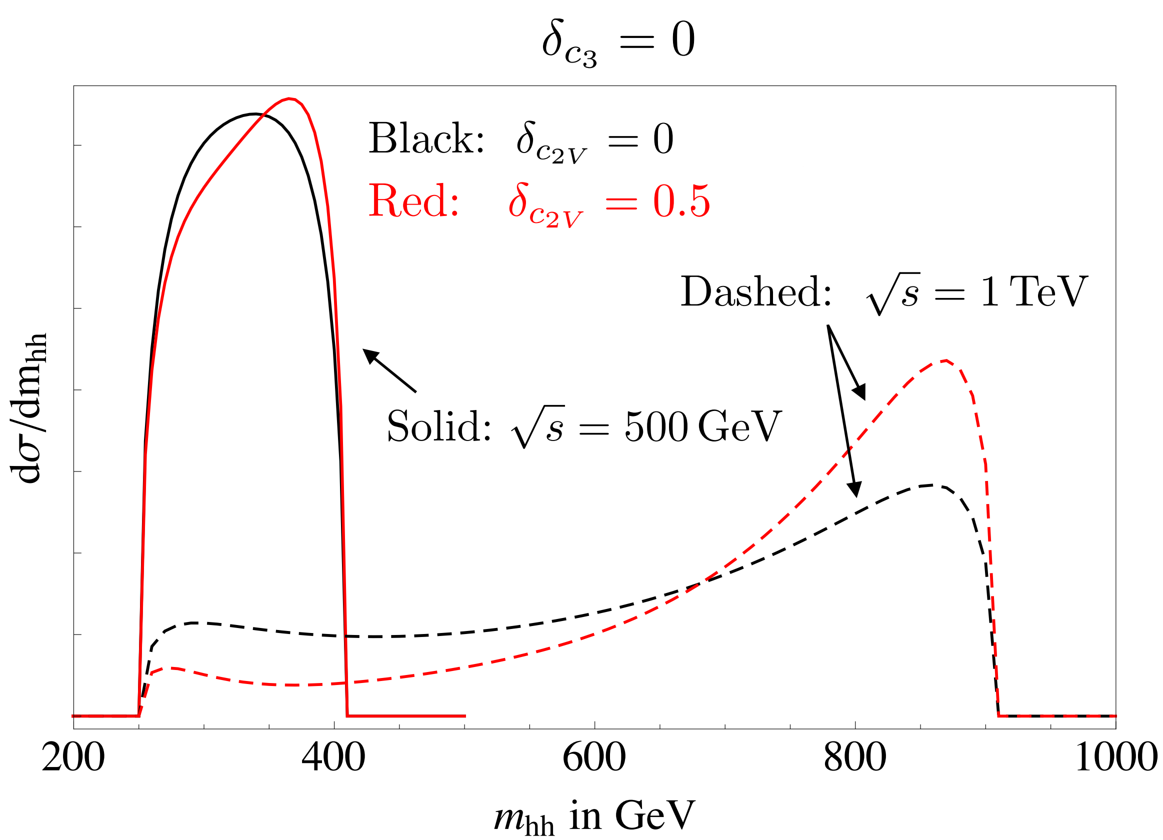
RC, Ghezzi, Moretti, Panico, Piccinini, Wulzer
JHEP 1208 (2012) 154

Double Higgs-strahlung at an e^+e^- linear collider with $\sqrt{s} = 500\,\text{GeV} - 1\,\text{TeV}$

[RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038]



$\sqrt{s}$	$\sigma_{SM}(e^+e^- \to hhZ)$
500 GeV	0.16 fb
1 TeV	0.12 fb



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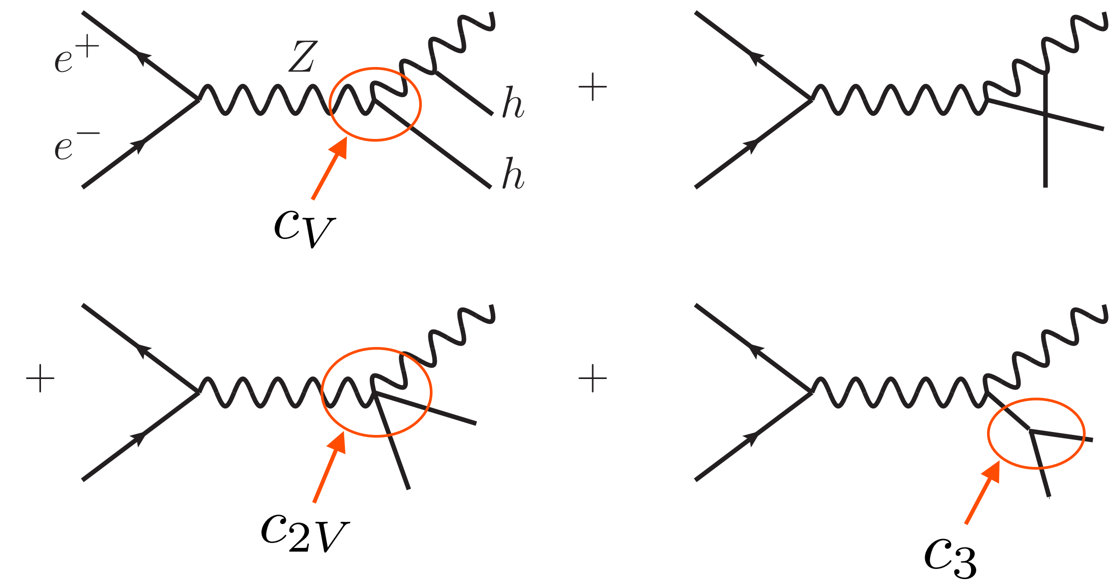

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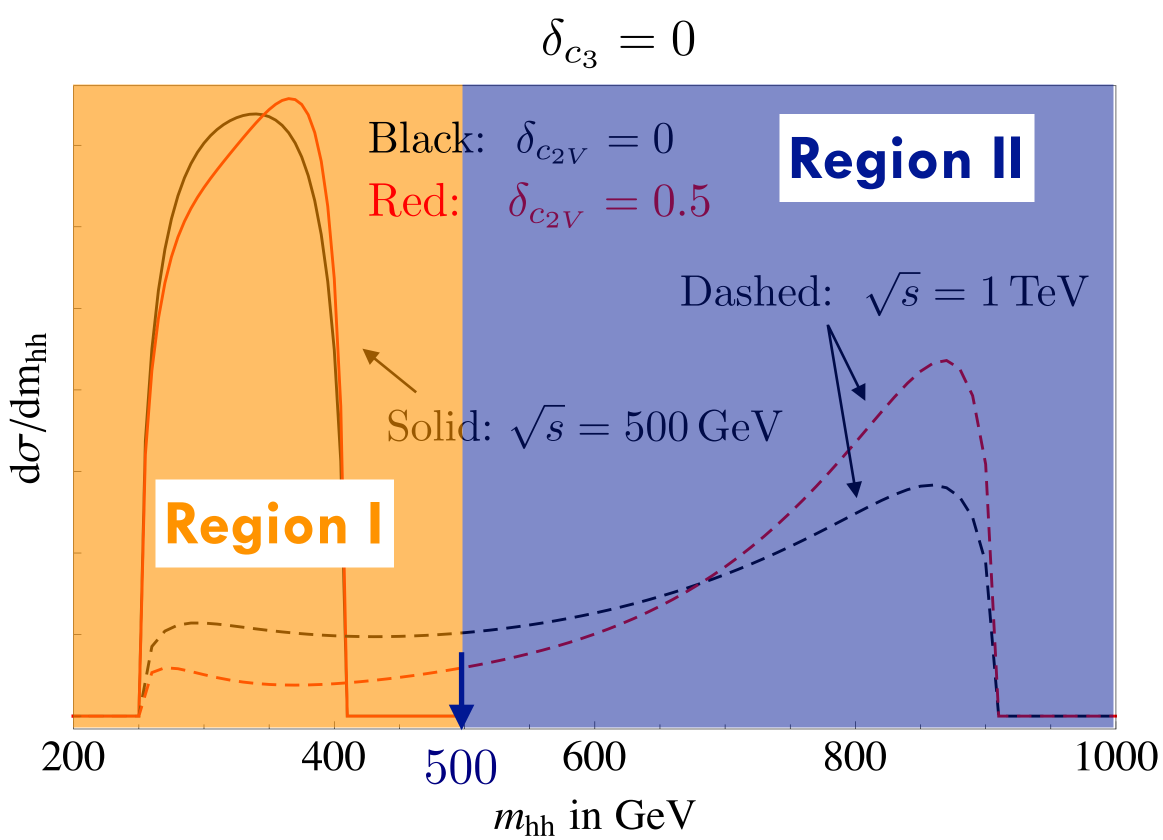

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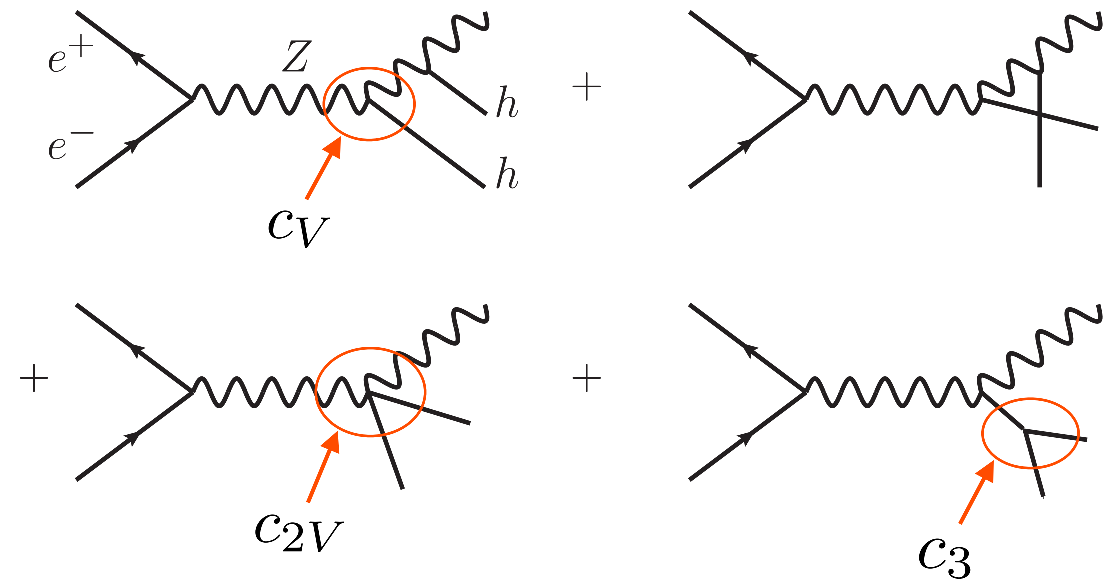

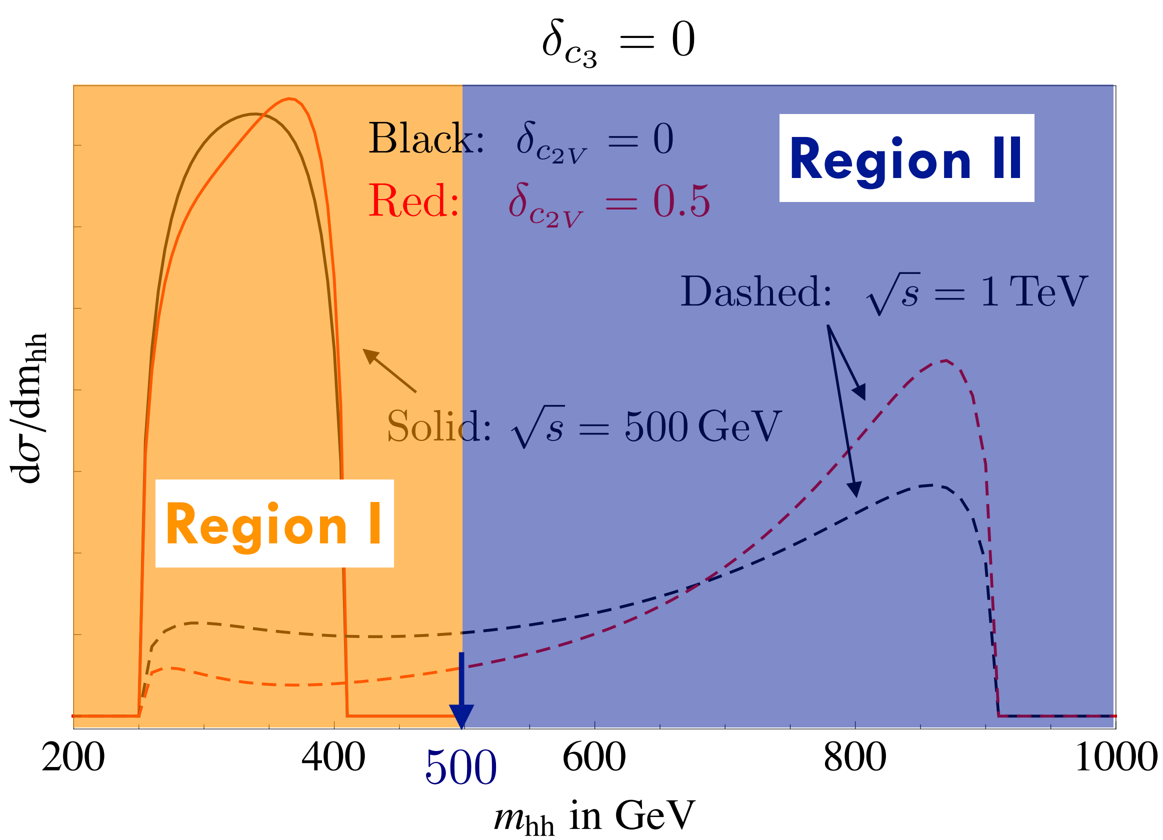

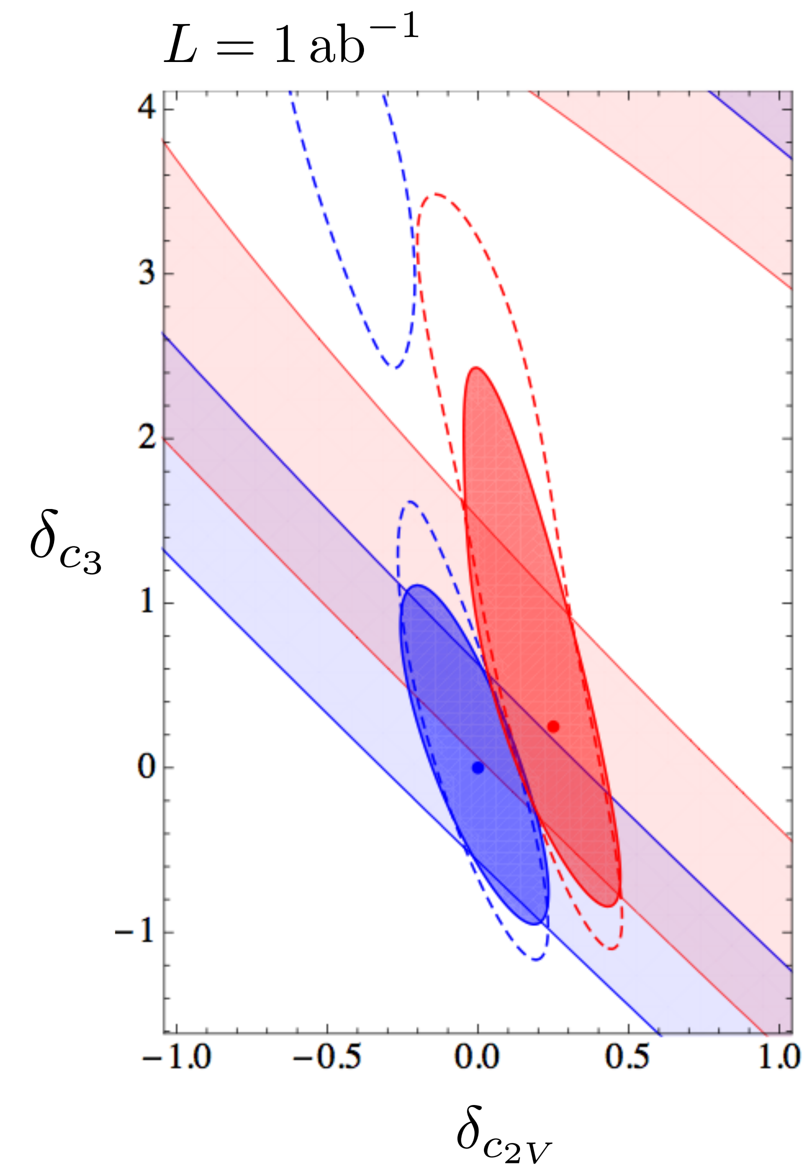

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[Assuming $c_V^2 (BR(b\bar{b})/BR(b\bar{b})_{SM}) = 1$]

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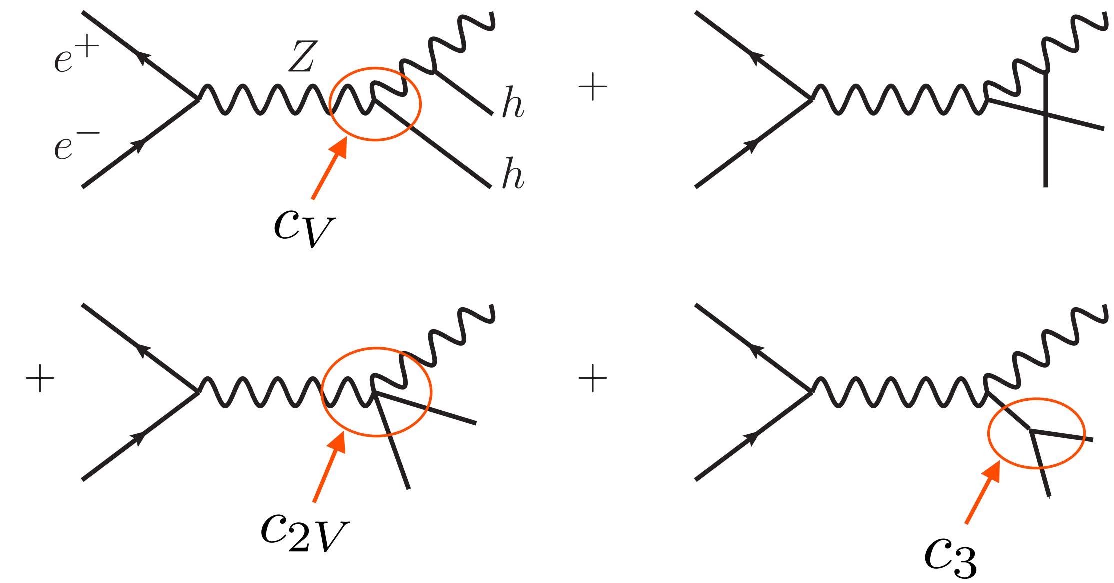

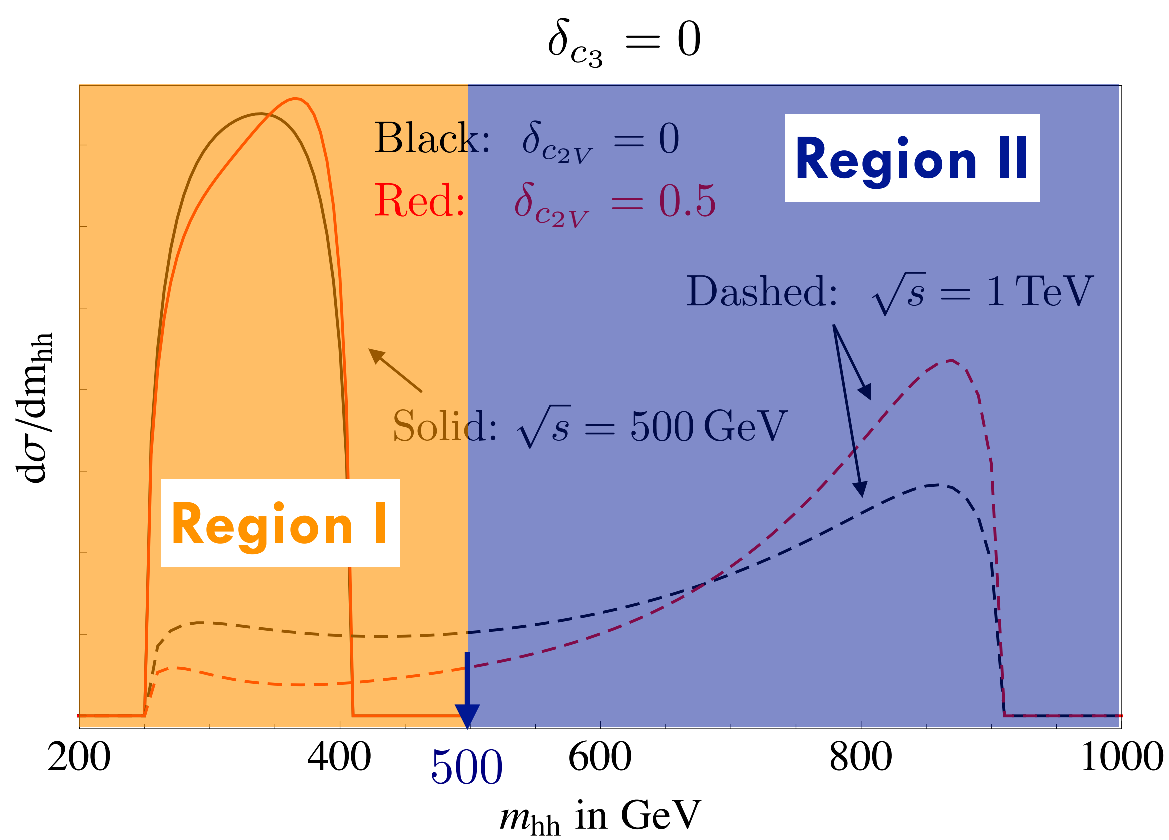

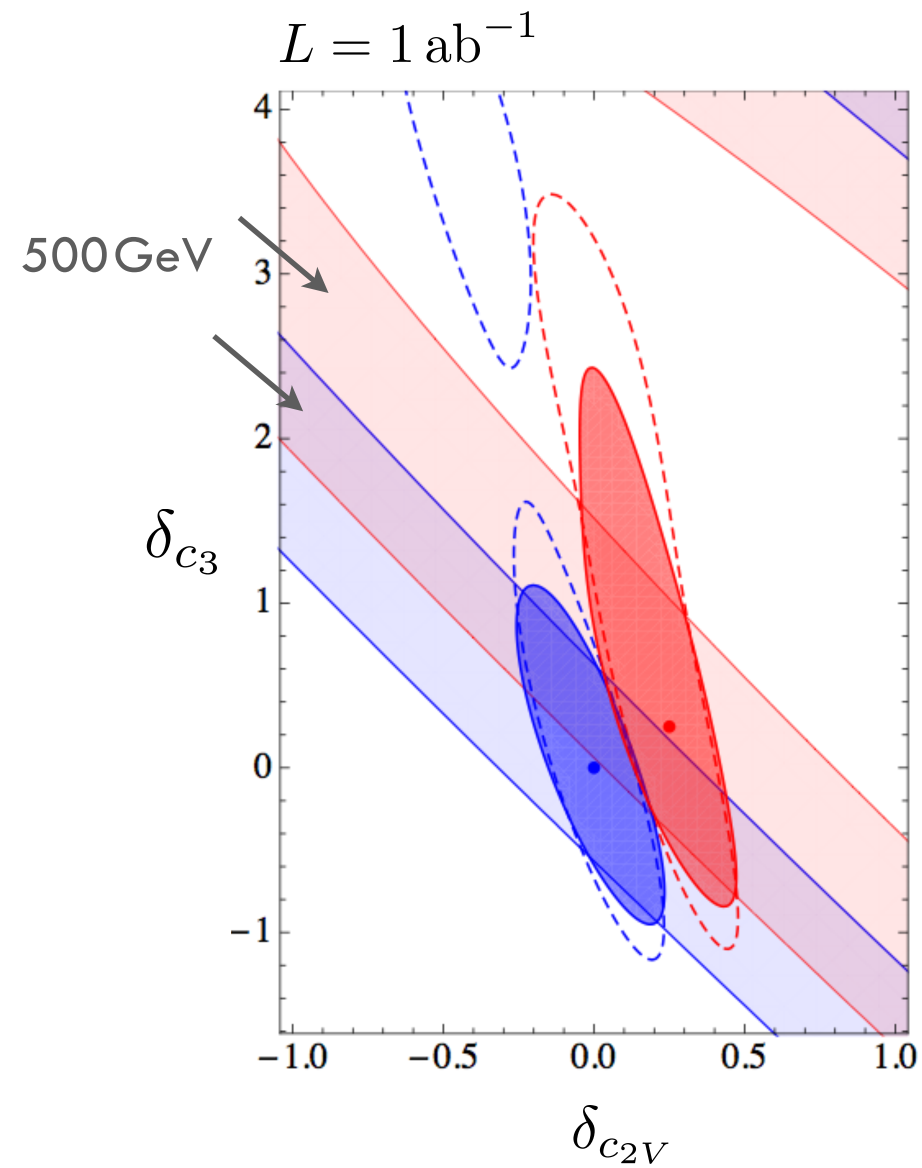

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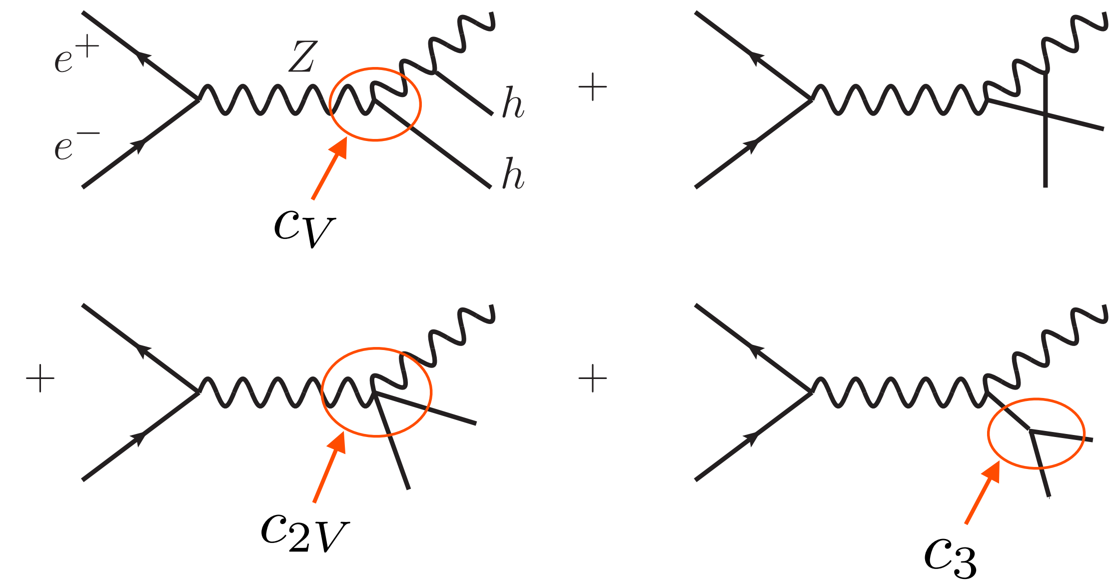
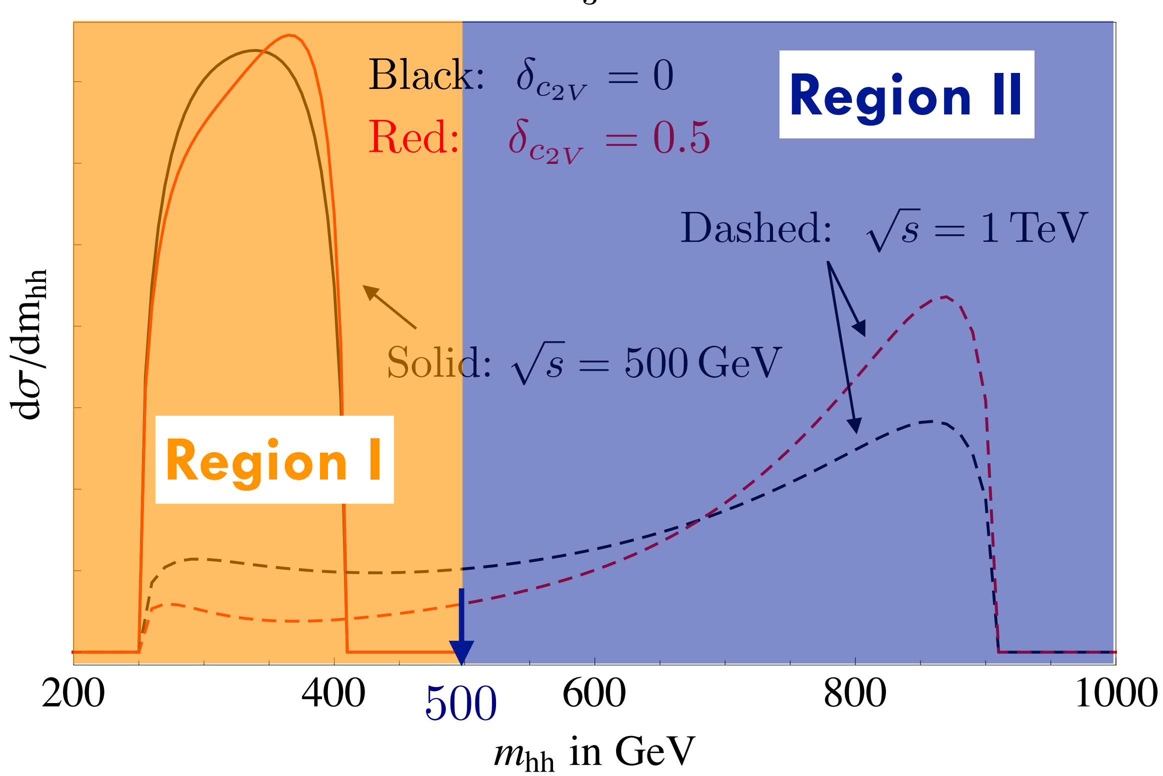
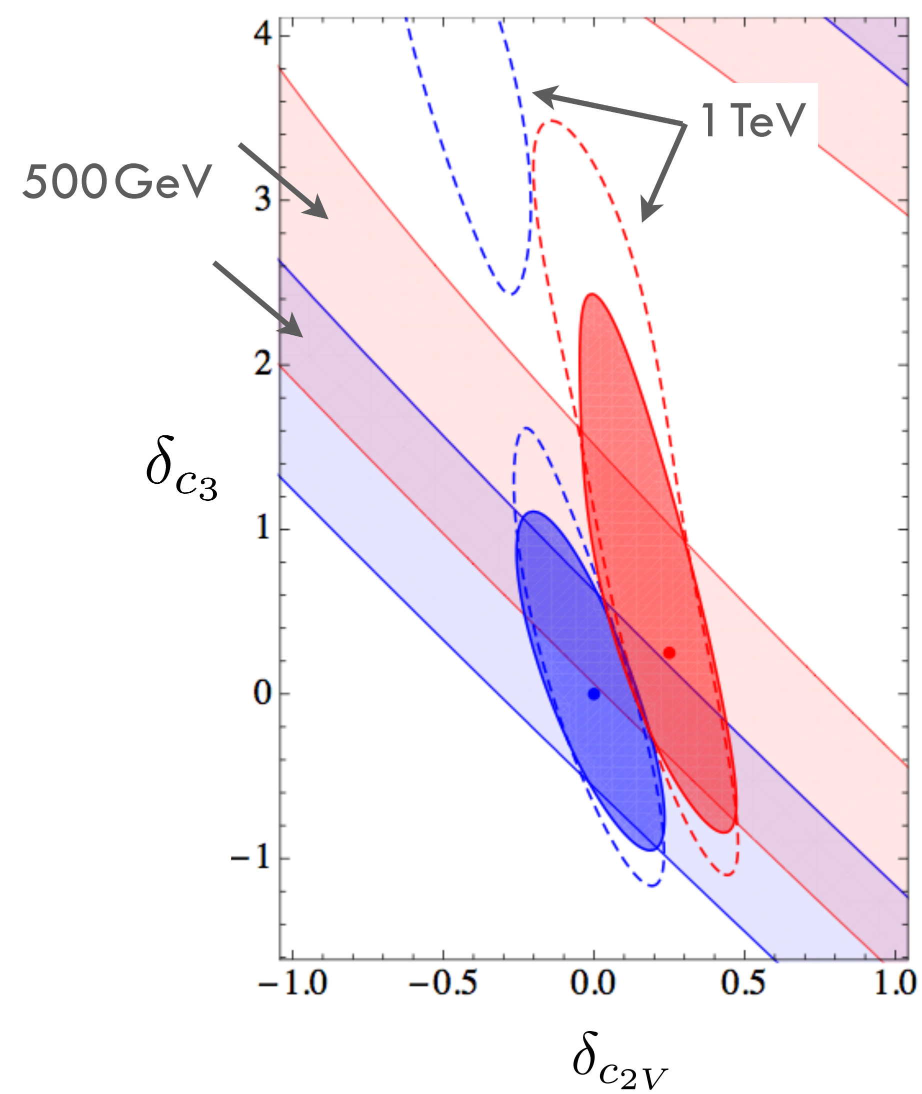


$\delta_{c_3} = 0$



$L = 1\,\mathrm{ab}^{-1}$



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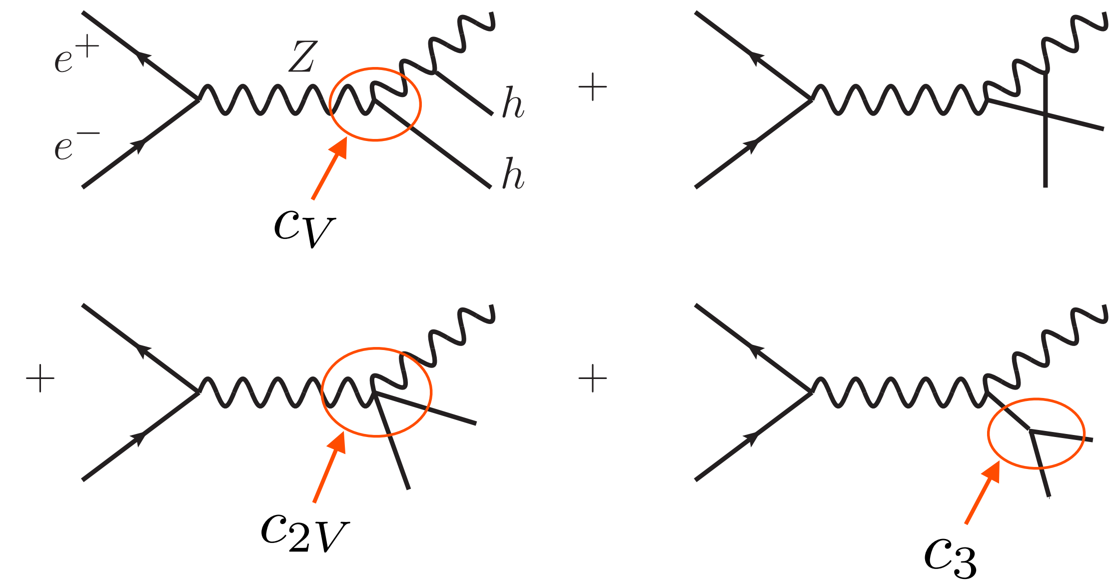

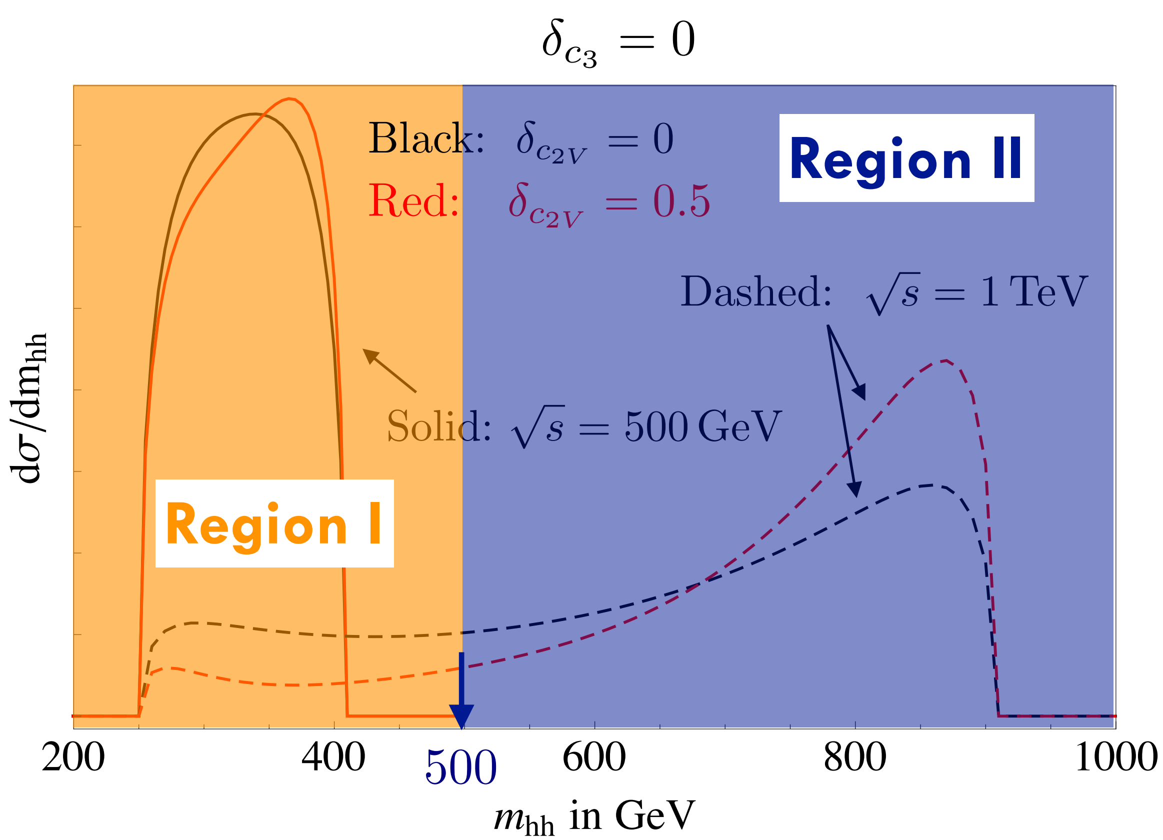

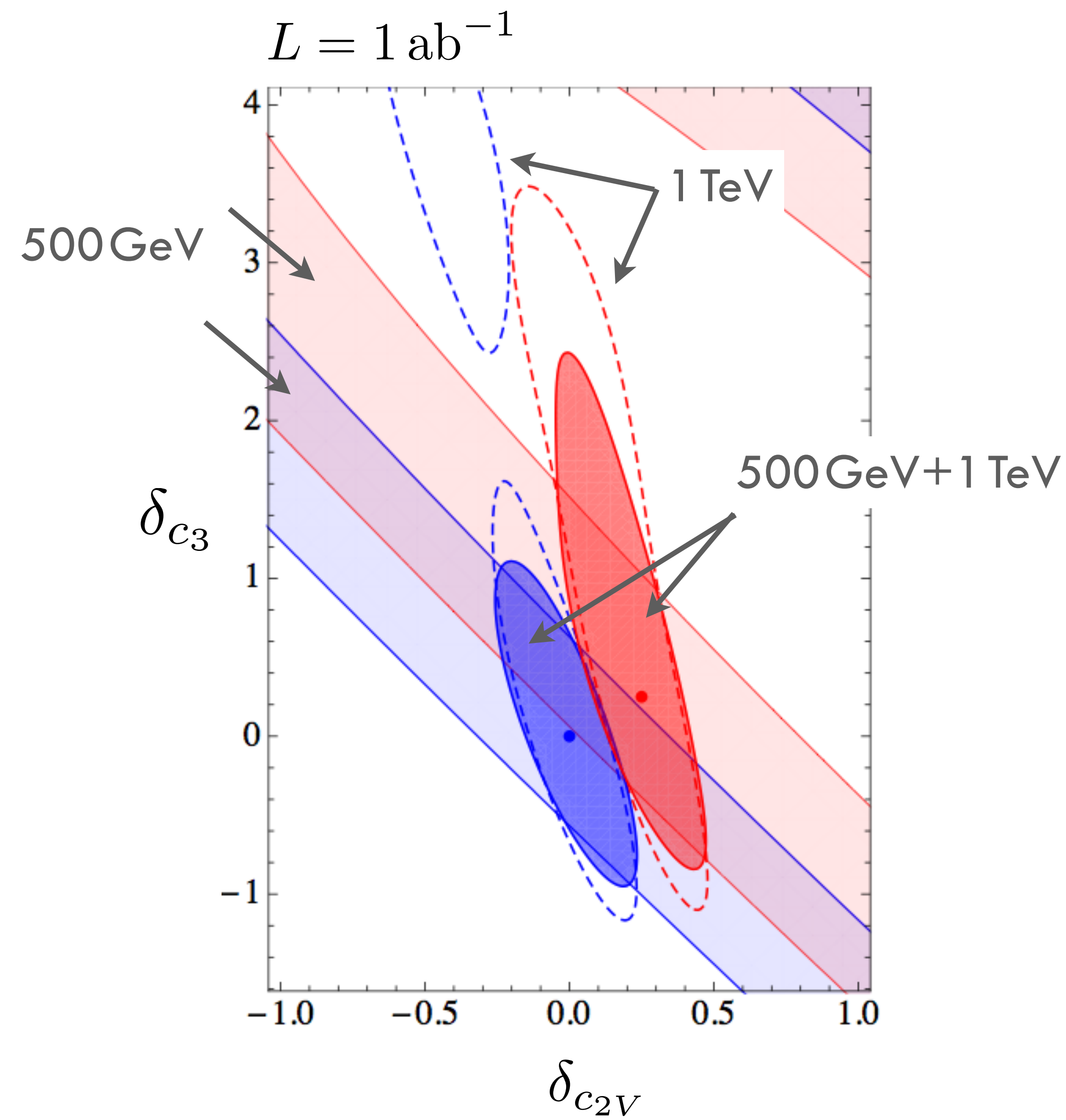

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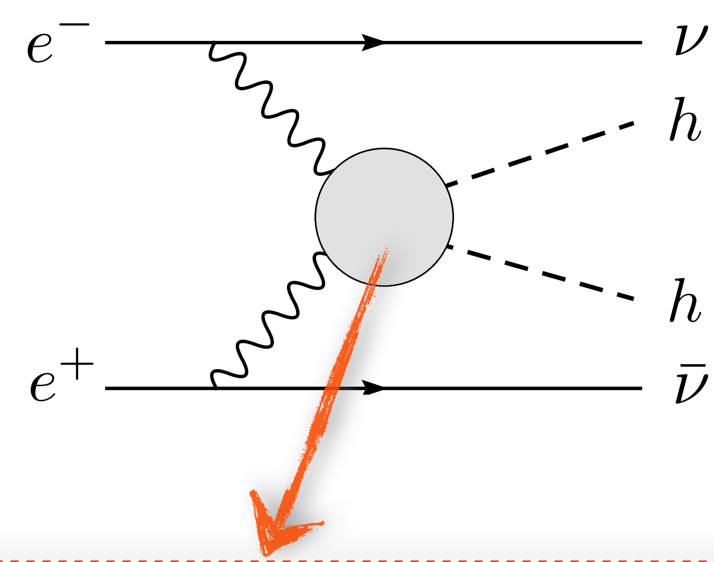
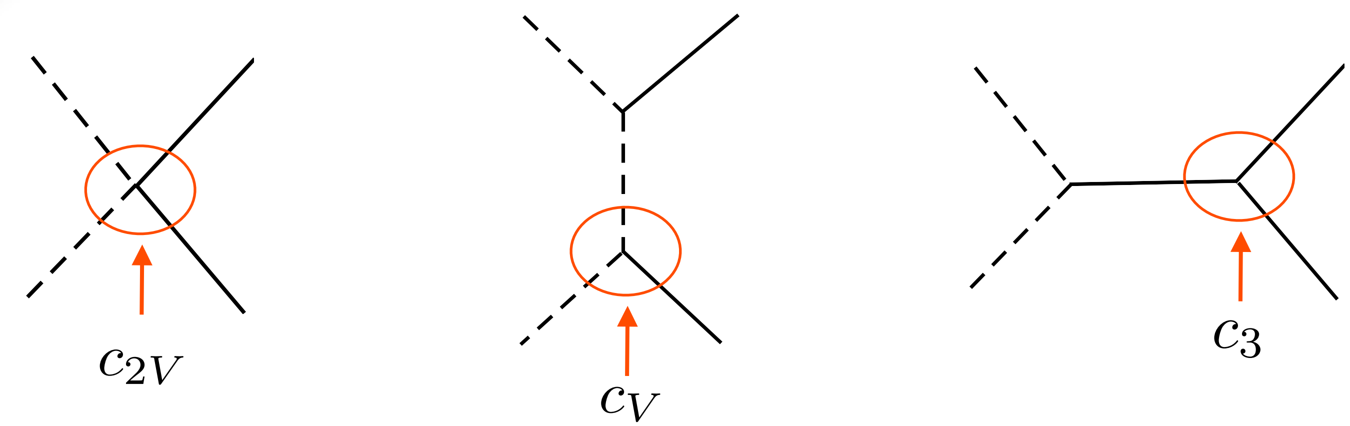
Double Higgs production via VBF at a 3TeV e$^+$e$^-$ linear collider (CLIC)

[RC, Grojean, Pappadopulo, Rattazzi, Thamm, arXiv:1309.7038]



$$\sigma_{SM}(e^+e^- \to hh\nu\bar\nu) = 0.83\,\text{fb}$$



$$A(WW \to hh) \sim \frac{s}{v^2}(c_V^2 - c_{2V})$$

dim 6: $$O_H = \frac{c_H}{2f^2}\partial_\mu |H|^2 \partial^\mu |H|^2$$

$$c_V = 1 - \frac{c_H}{2}\frac{v^2}{f^2} + \left(\frac{3c_H^2}{8} - \frac{c'_H}{4}\right)\frac{v^4}{f^4}$$

dim 8: $$O'_H = \frac{c'_H}{2f^4}|H|^2\partial_\mu |H|^2 \partial^\mu |H|^2$$

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[Higgs Effective Lagrangian (SILH basis)]

Ex: SO(5)/SO(4)

For a PNGB Higgs the whole series in H/f can be re-summed:

$$c_V = \sqrt{1-\xi}$$

$$c_{2V} = 1 - 2\xi$$

$$\xi = \frac{v^2}{f^2}$$

At dimension-6 level:

$$\Delta c_{2V} = 2\Delta c_V^2 \left(1 + O(\Delta c_V^2)\right)$$

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Expected precision with $L = 1\,\mathrm{ab}^{-1}$:
(SM injected)

5% on c_{2V}
30% on c_3

Much stronger sensitivity on c_{2V} than on c_3

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- Strength of EWSB dynamics (and its origin) can be inferred from:

  - single-Higgs data (Higgs couplings)

  - key scattering processes

for SUSY: coupling to bottom (c_b); $\gamma\gamma$ and gg rates; production of Heavy Higgses

for Comp. Higgs: tree-level couplings; $Z\gamma$ rate; double Higgs production