HIGGS COMPOSITENESS: CURRENT STATUS (AND FUTURE STRATEGIES)

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SUSY 2013 - ICTP, Trieste 26-31 August, 2013

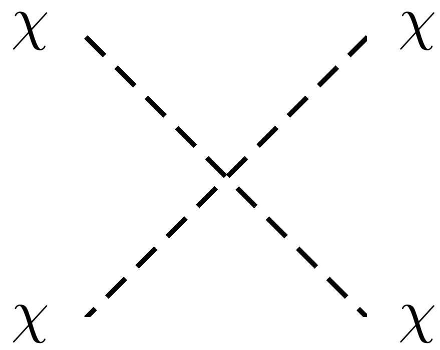
Outline

- 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

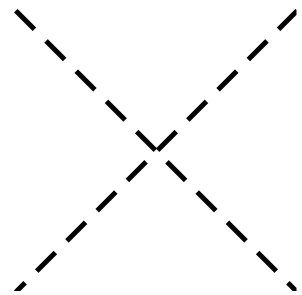
Strong vs Weak EWSB

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



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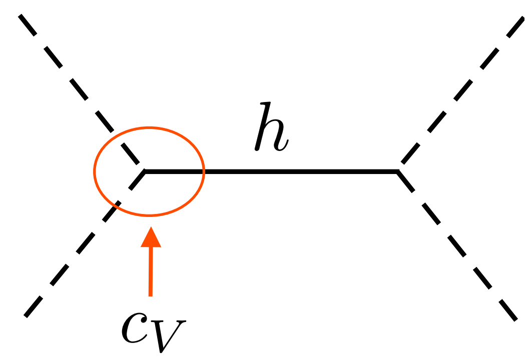
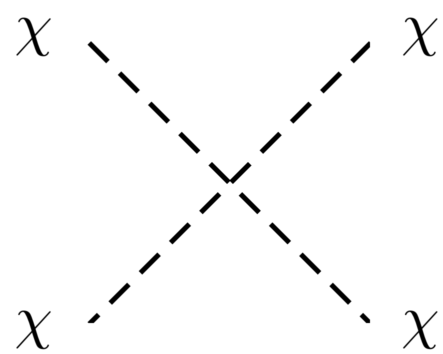


$$A \sim \frac{E^2}{v^2}(1 - c_V^2) - c_V^2\,\frac{m_h^2}{v^2}\,\frac{s}{s - m_h^2}$$

In the {SM-H}



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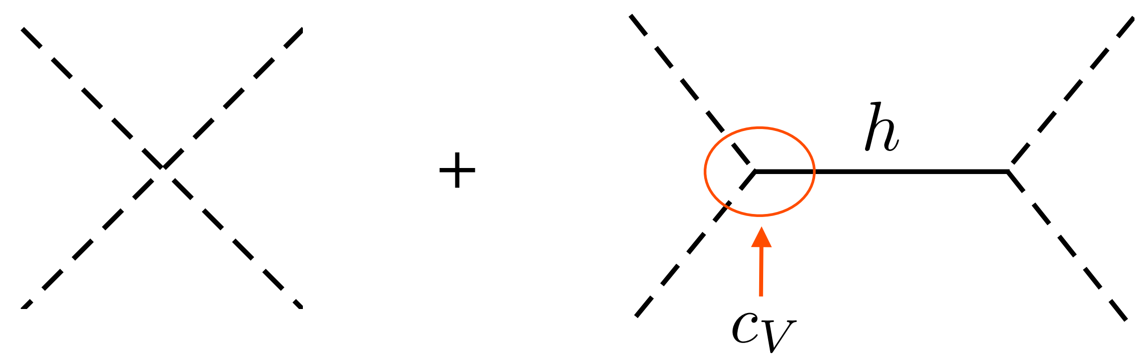
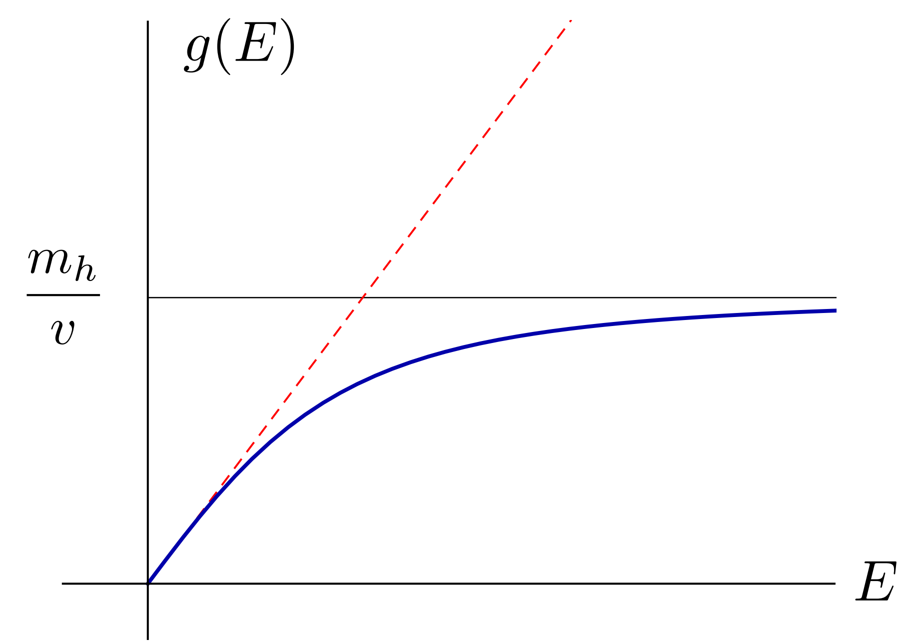


$$A \sim \underbrace{\frac{E^2}{v^2}(1 - c_V^2)}_{=\,0} - c_V^2 \, \frac{m_h^2}{v^2} \, \frac{s}{s - m_h^2}$$

Elementary Higgs: $\boxed{c_V = 1}$

weak



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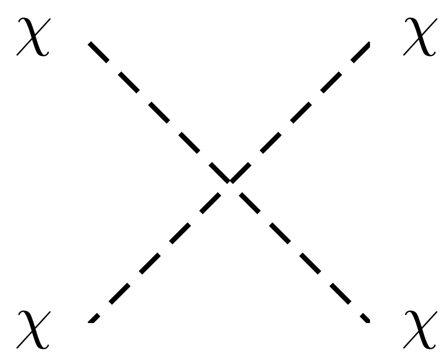

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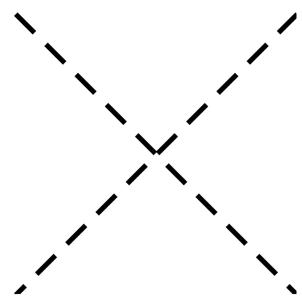
In the {SM-H} + H_i



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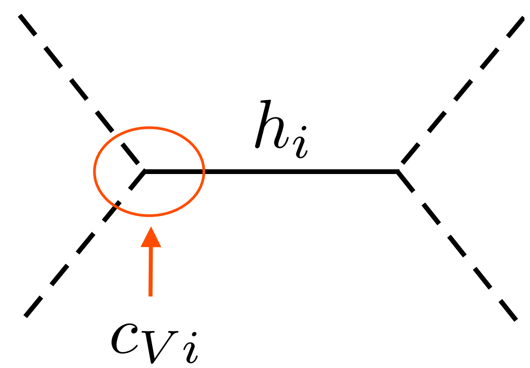
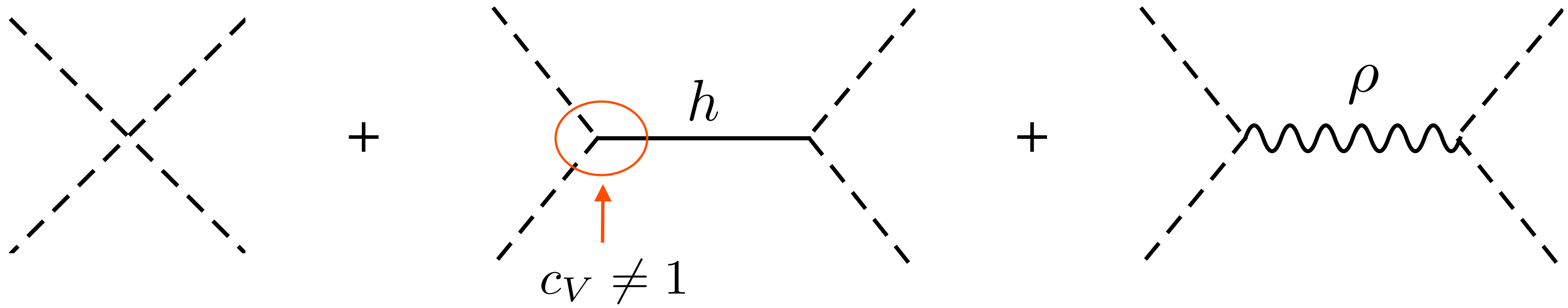


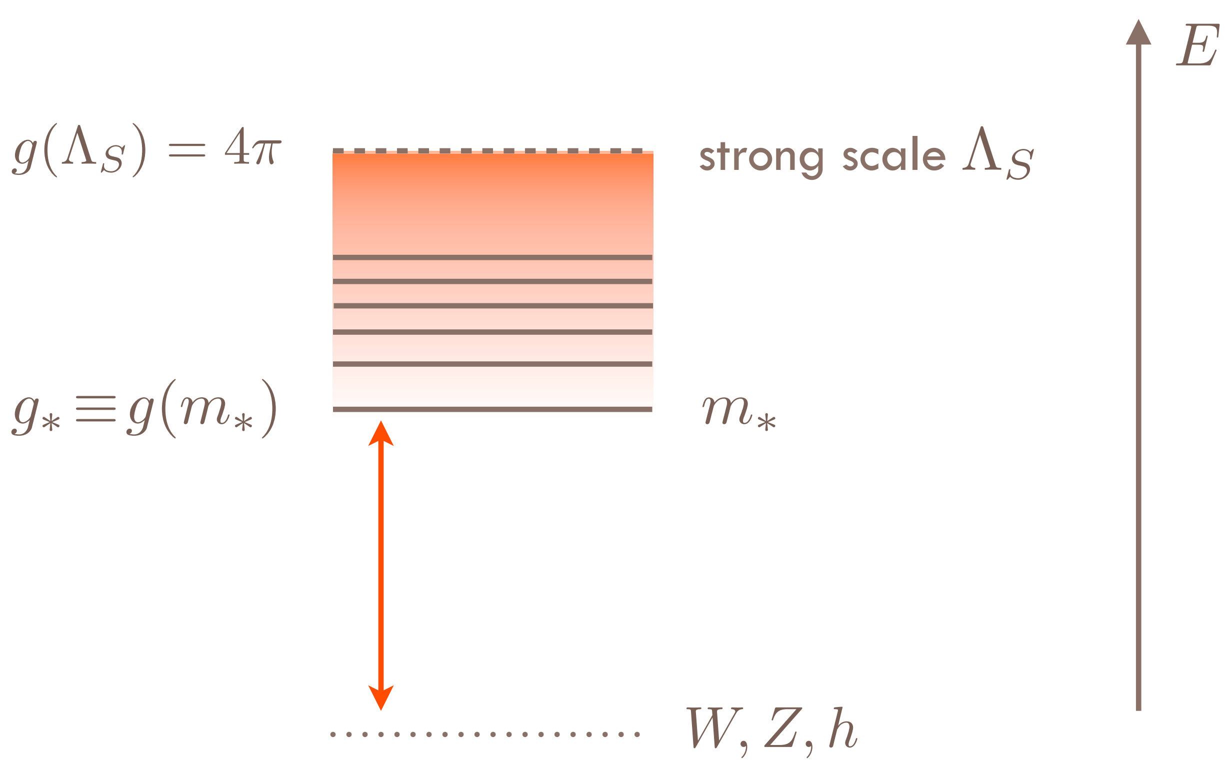
$$A \sim \frac{E^2}{v^2}\underbrace{\left(1-\sum_i c_{Vi}^2\right)}_{=0} + \dots$$

Elementary Higgses:
(more than one)

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

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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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: $c_V = 1 - c_H \left(\dfrac{v}{f} \right)^2 + \dots$

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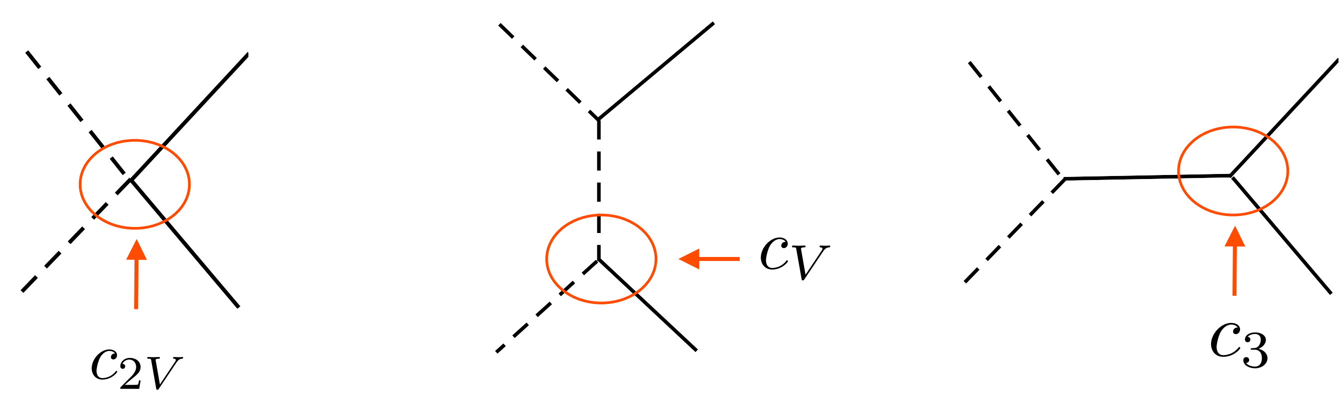
2. Scatterings involving the Higgs also grow with energy

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



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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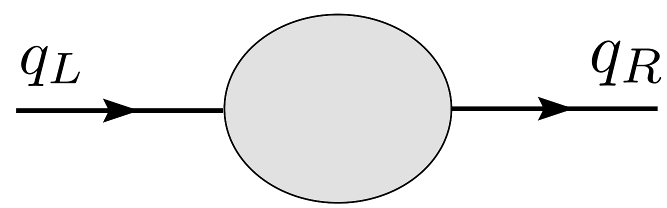
Quark masses need two such couplings



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

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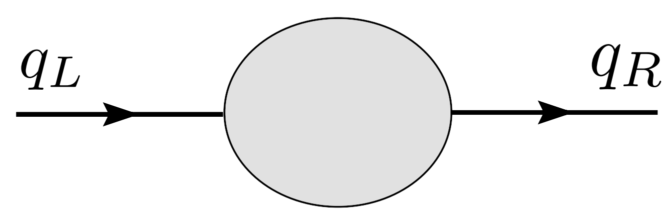

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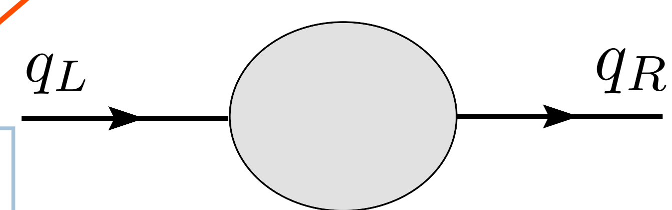
break explicitly the Goldstone symmetry



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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

$$\boxed{\begin{aligned}|\mathrm{SM}\rangle &= \cos\varphi\,|\psi\rangle + \sin\varphi\,|\chi\rangle\\ |\mathrm{heavy}\rangle &= -\sin\varphi\,|\psi\rangle + \cos\varphi\,|\chi\rangle\end{aligned}}$$

Higgs mass

Can a 125GeV Higgs be composite ?

Structure of the Higgs Potential

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

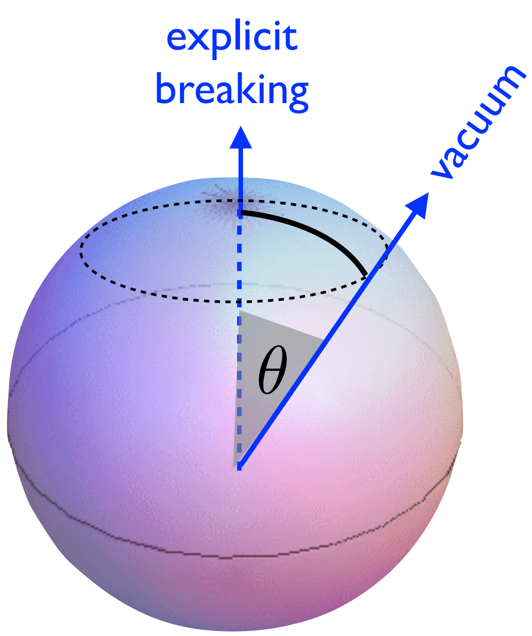
$$h \equiv \sqrt{H^\dagger H}$$

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

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

$\sin^4(x)$

$\vdots$



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explicit breaking of Goldstone symmetry (spurion couplings)

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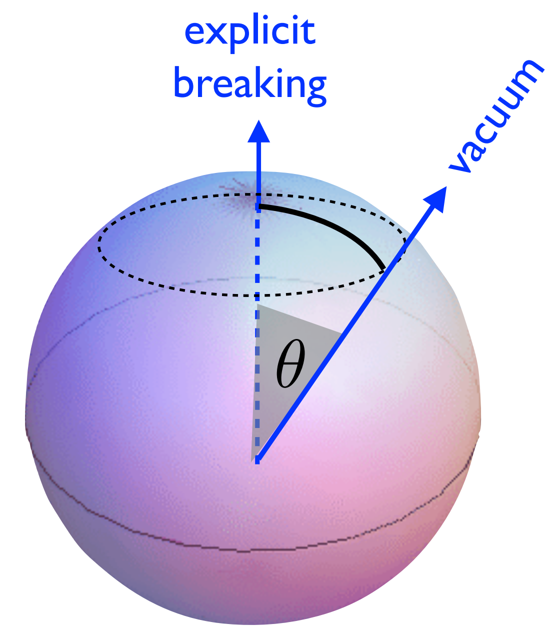

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Potential is FINITE - loop integral fully saturated at the compositeness scale

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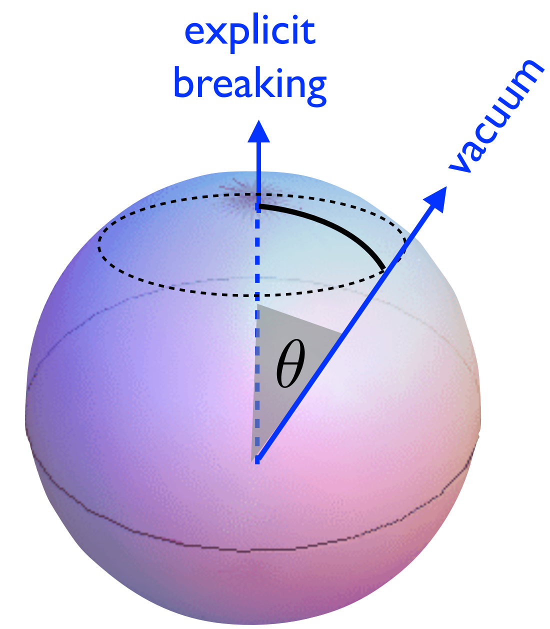

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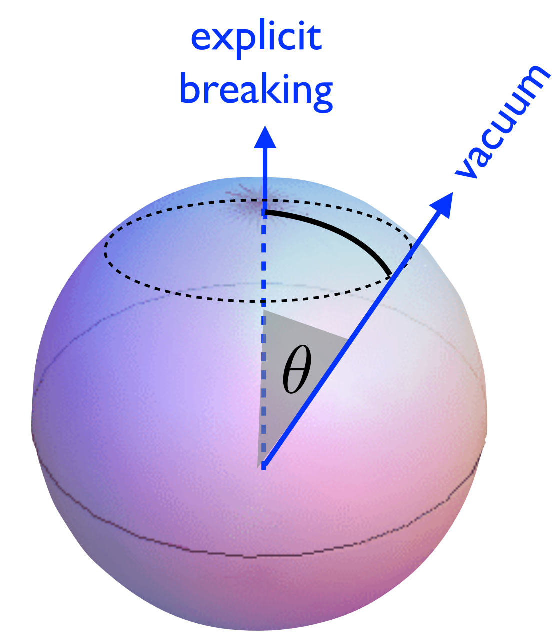

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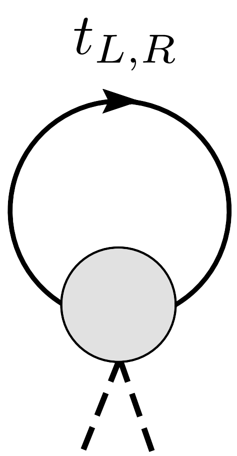
- To get EWSB ($0 < x \ll \pi$) at least <u>two</u> SO(4) structures are needed plus some tuning

$$\frac{SO(5)}{SO(4)} = S^4$$

vacuum manifold is the 4-sphere

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

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



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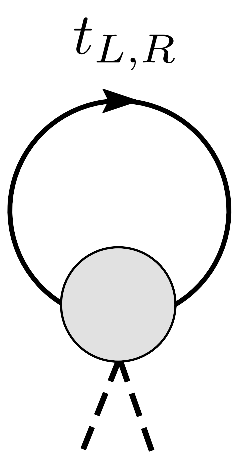

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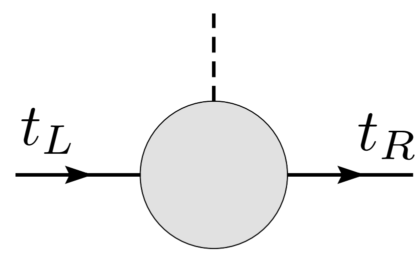

$$y_t \sim \frac{\lambda_L \lambda_R}{g_*}$$

⬇ assuming $\lambda_L \simeq \lambda_R$

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

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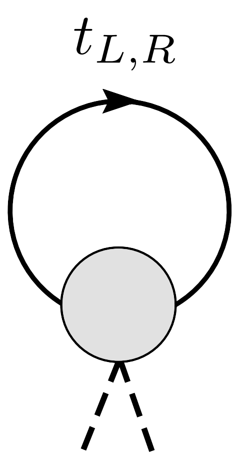

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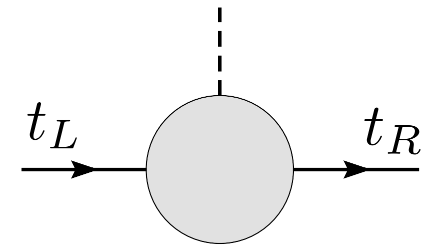

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Higgs tends to be too heavy
(unless $g_* \sim 1$)

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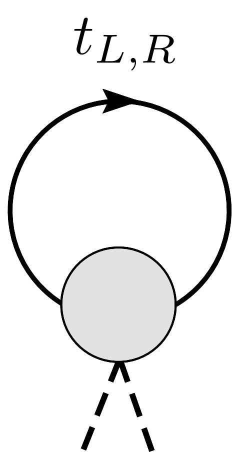

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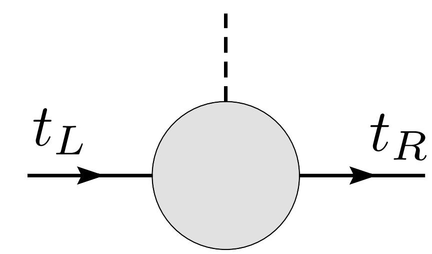

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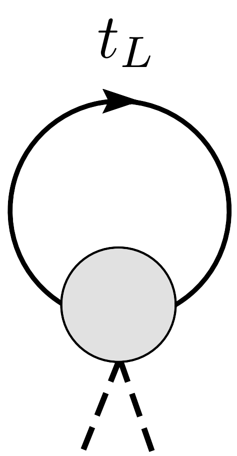
see however arXiv:1211.7290 for SUSY completion with extra spurion suppression

Talk by A. Parolini

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



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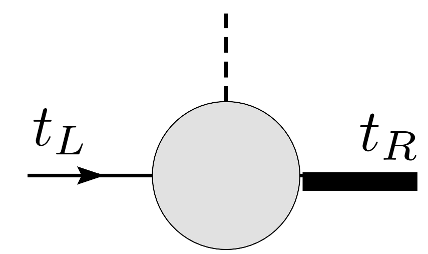

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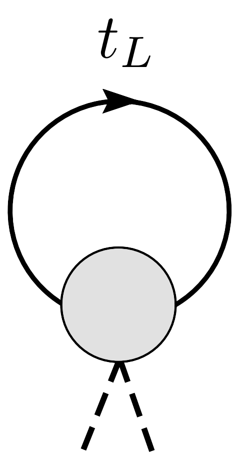

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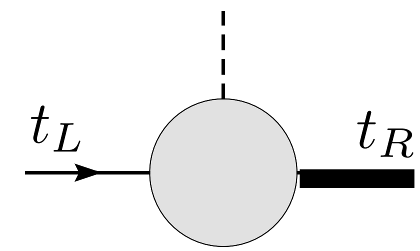

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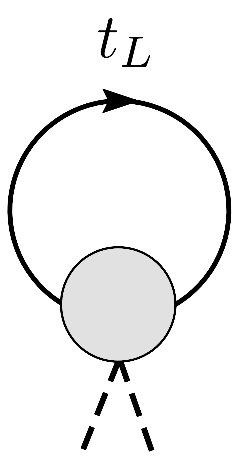
m_H=125GeV implies
top partners are naturally

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

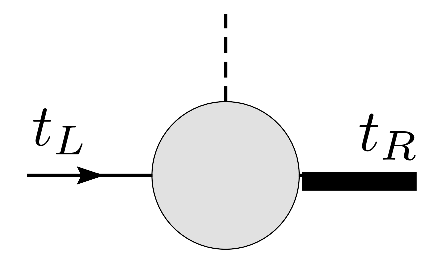
Matsedonskyi, Panico, Wulzer JHEP 1301 (2013) 164
Redi, Tesi JHEP 1210 (2012) 166
Marzocca, Serone, Shu JHEP 1208 (2012) 013
Pomarol, Riva JHEP 1208 (2012) 135
Panico, Redi, Tesi, Wulzer JHEP 1303 (2013) 051
De Simone et al. JHEP 1304 (2013) 004

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



$$V(h) \simeq \frac{m_*^4}{g_*^2}\frac{N_c}{8\pi^2}\lambda_L^2\, A\left(\frac{h}{f}\right)$$

$$m_h^2 \sim \frac{N_c}{4\pi^2}\frac{m_*^2}{f^2}\lambda_L^2\, v^2$$



$$y_t \sim \lambda_L$$

$$\lambda_L \simeq y_t$$

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

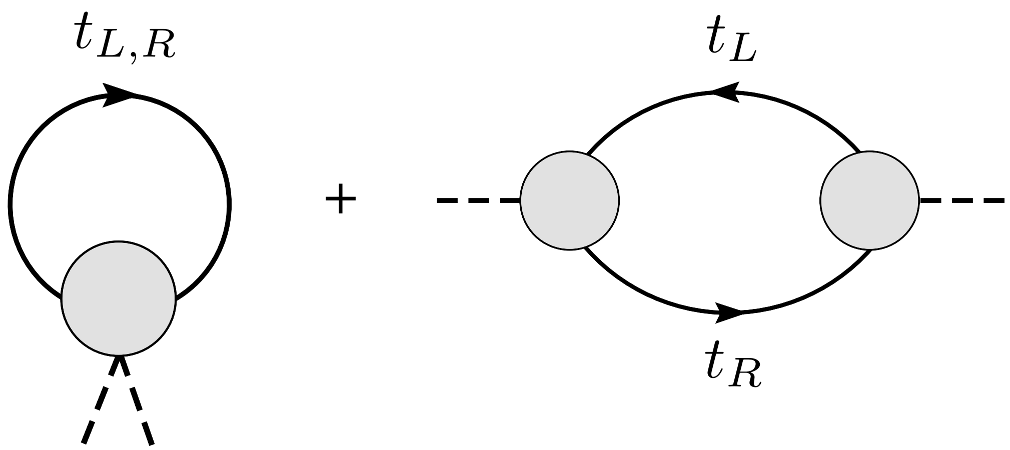
m_H=125GeV implies
top partners are naturally

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

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

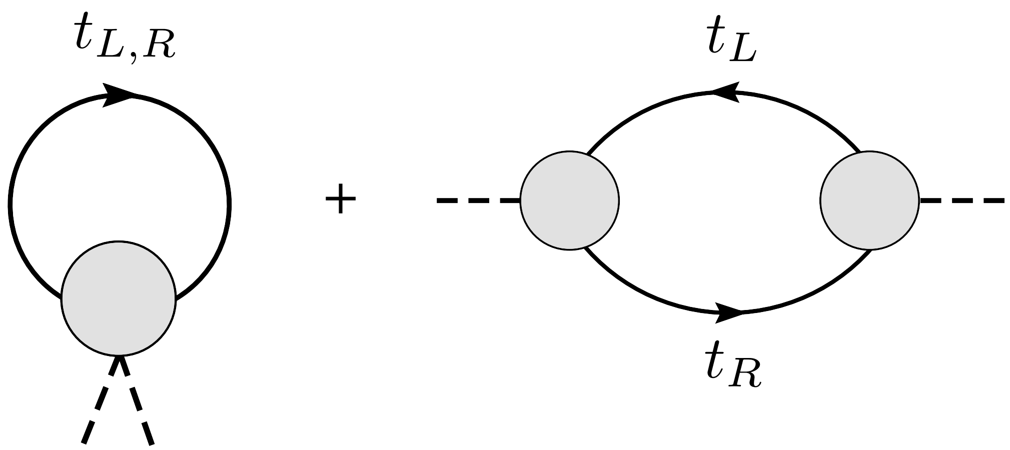
Matsedonskyi, Panico, Wulzer JHEP 1301 (2013) 164
Redi, Tesi JHEP 1210 (2012) 166
Marzocca, Serone, Shu JHEP 1208 (2012) 013
Pomarol, Riva JHEP 1208 (2012) 135
Panico, Redi, Tesi, Wulzer JHEP 1303 (2013) 051
De Simone et al. JHEP 1304 (2013) 004

- 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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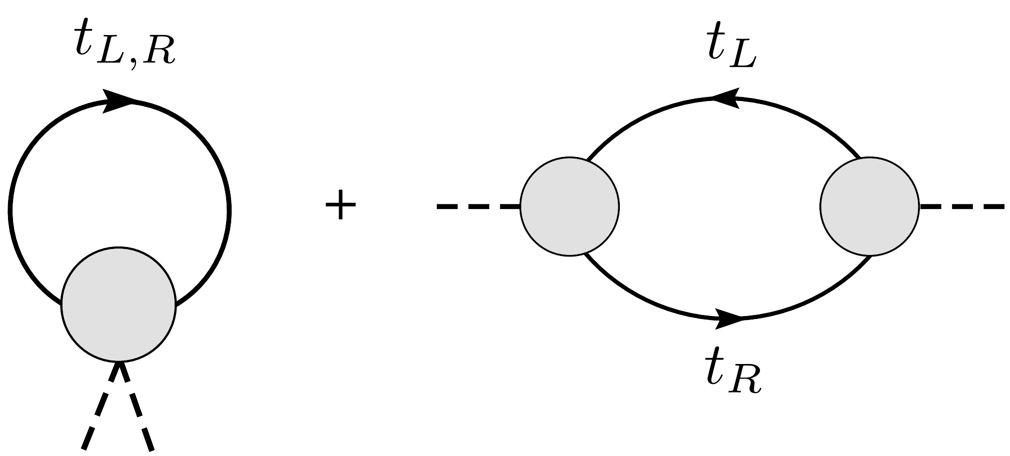

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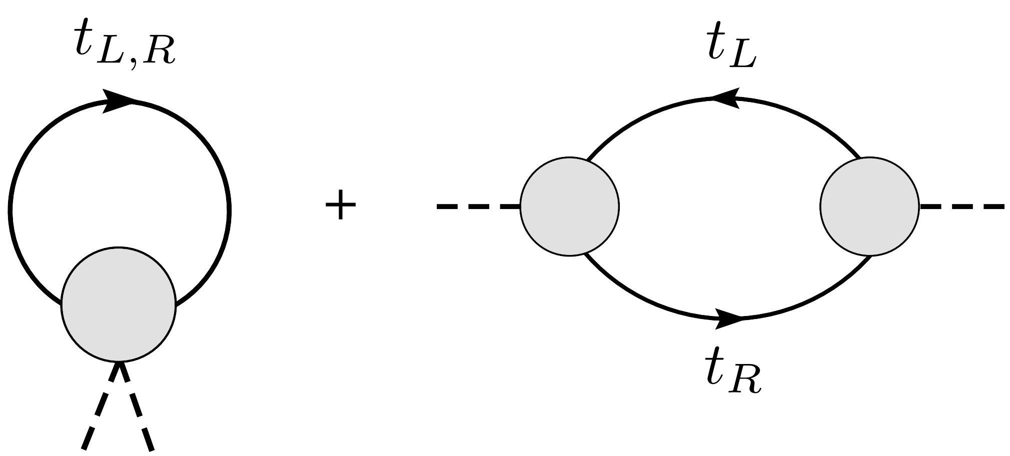

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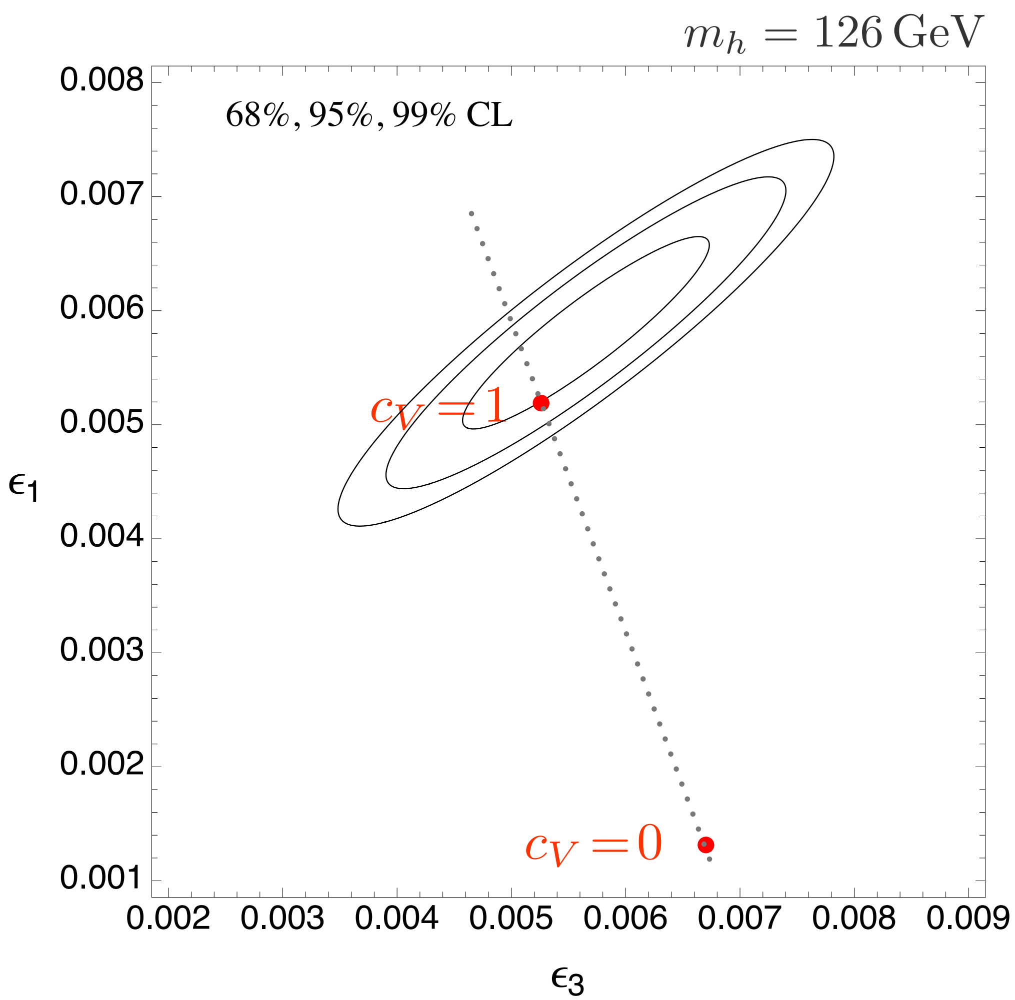
$$FT \sim \frac{v^2}{f^2} \times \frac{\lambda^2}{g_*^2} \simeq \left(\frac{525\,\mathrm{GeV}}{m_*}\right)^2 \times \frac{y_t}{g_*}$$

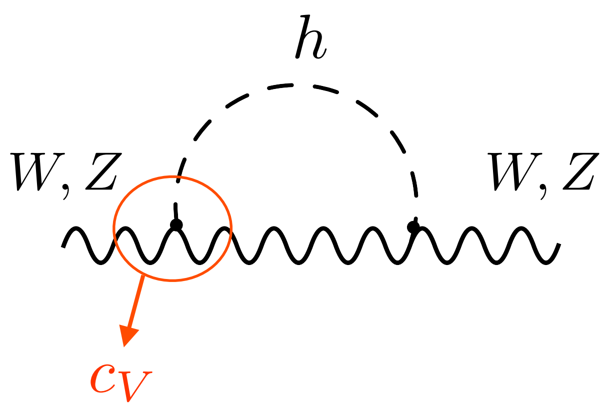
m_H automatically lighter but larger tuning to get EWSB

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

EW Precision Tests

Constraints on c_V from EW Precision Tests





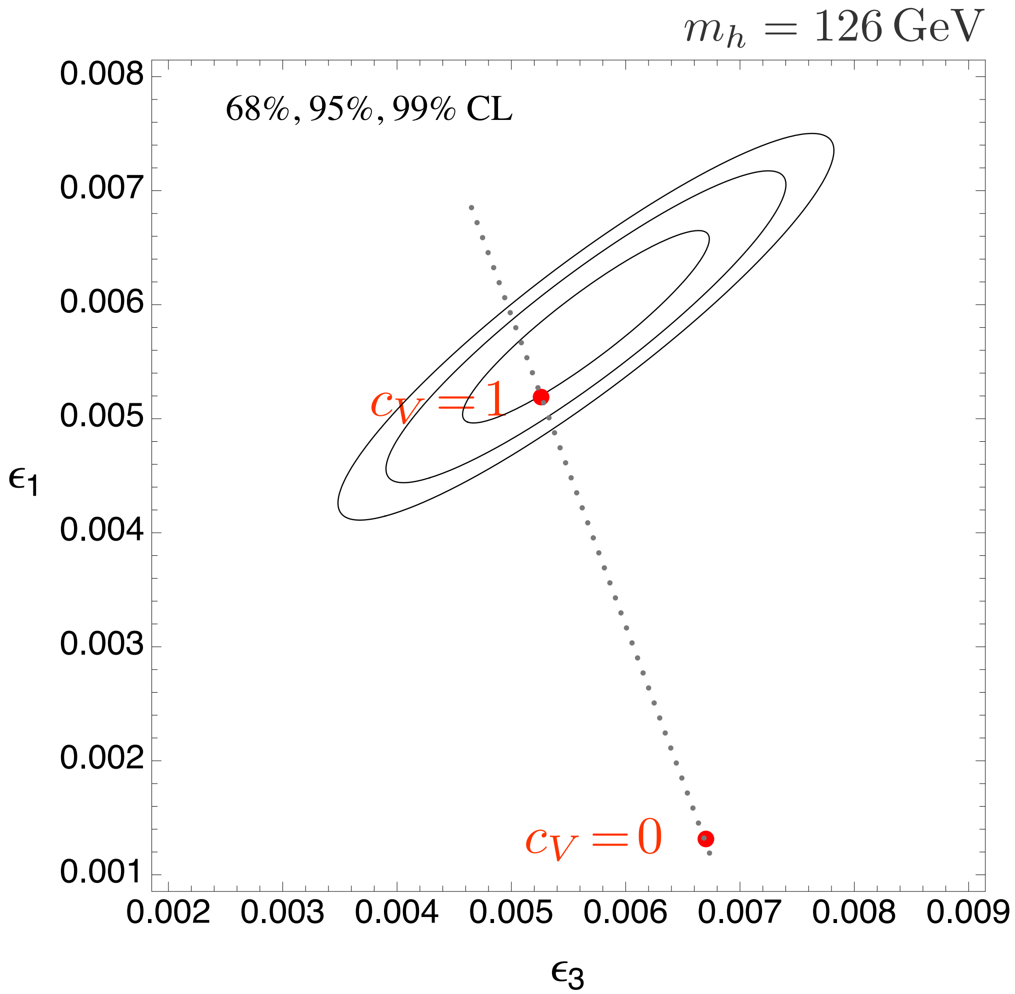
fit from: GFitter coll. Eur. Phys. J. C 72 (2012) 2205

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

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

Barbieri et al. PRD 76 (2007) 115008

Constraints on c_V from EW Precision Tests



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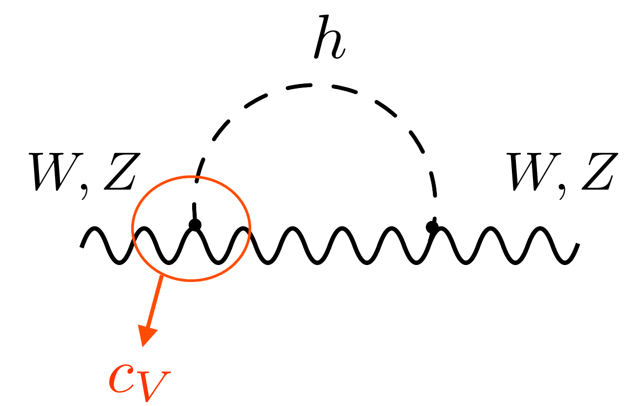
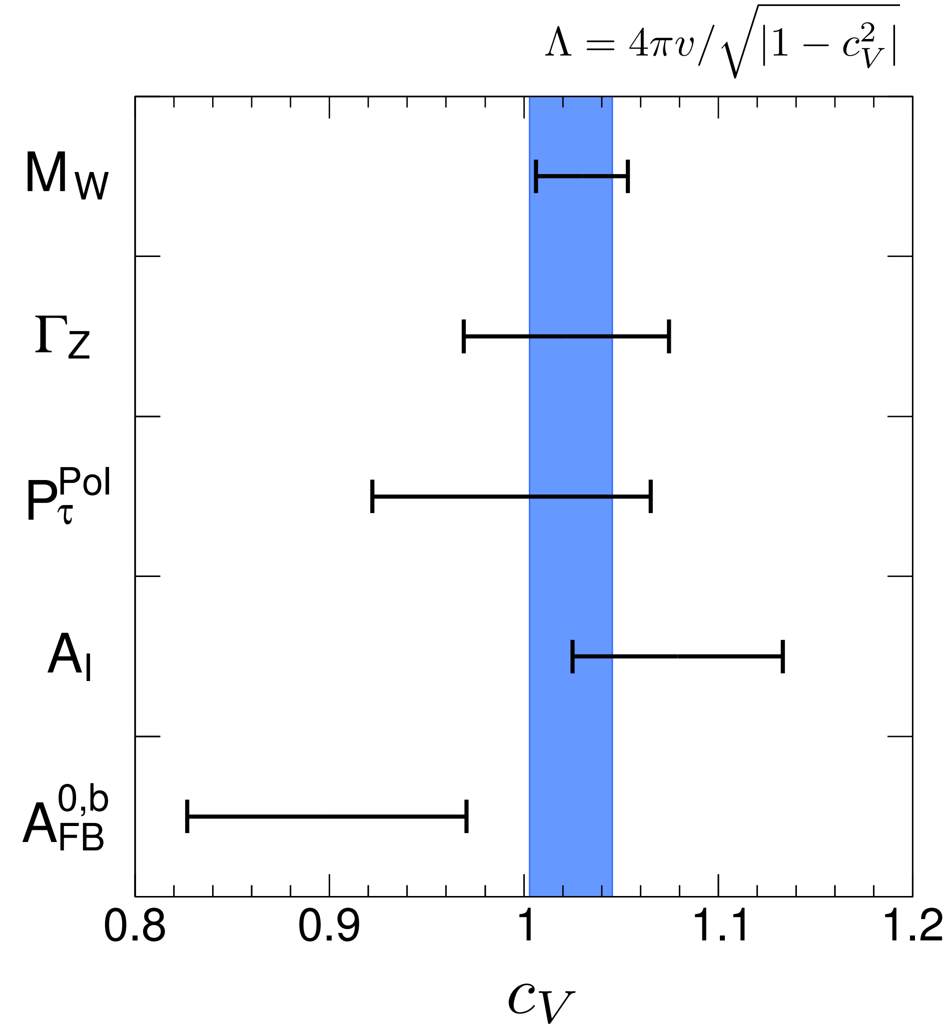
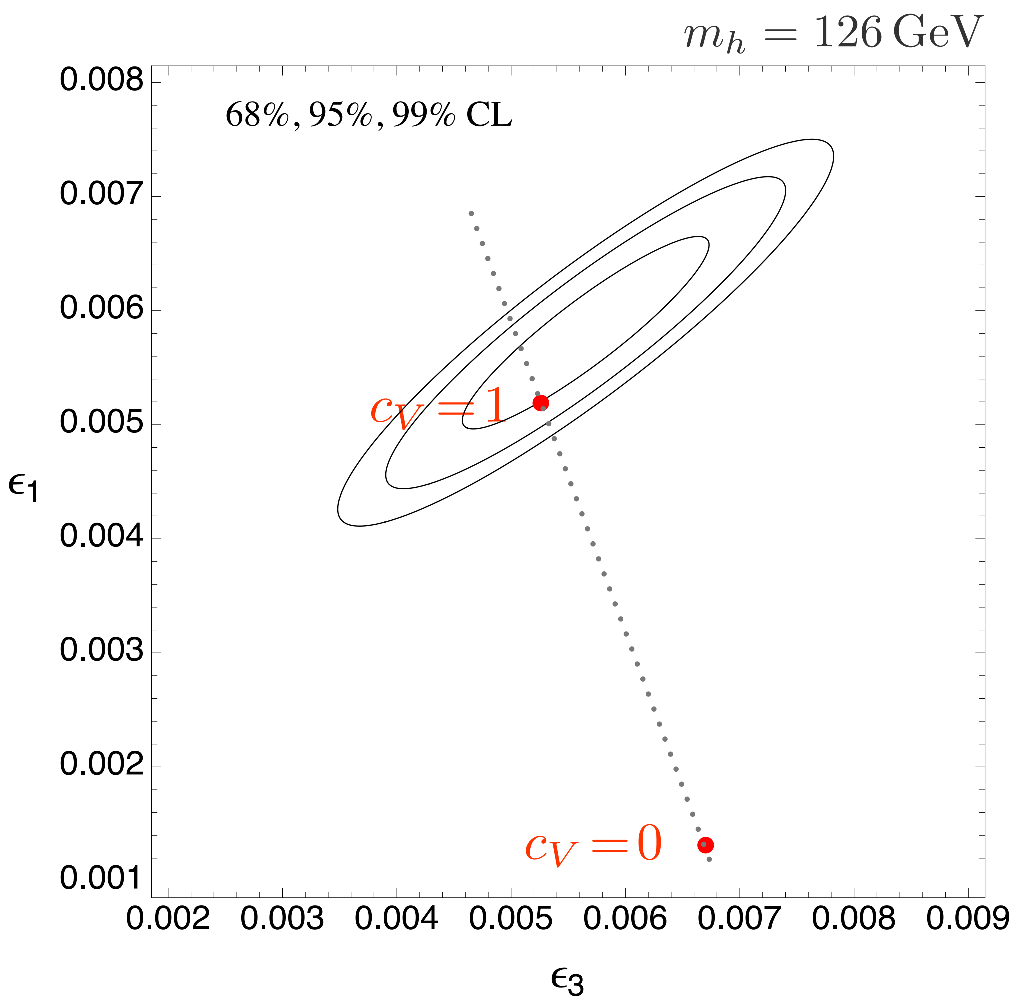




Ciuchini, Franco, Silvestrini, Mishima, arXiv:1306.4644

Barbieri et al. PRD 76 (2007) 115008

Constraints on c_V from EW Precision Tests



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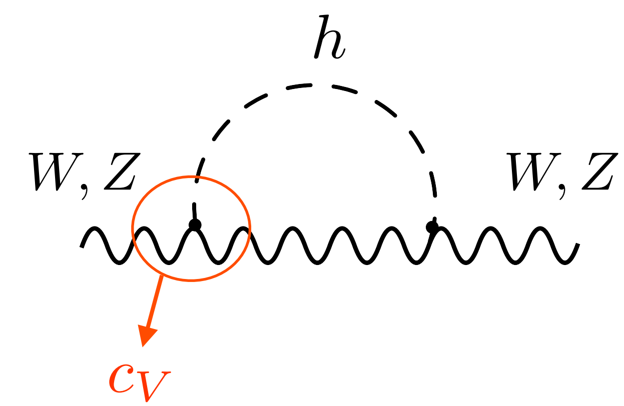

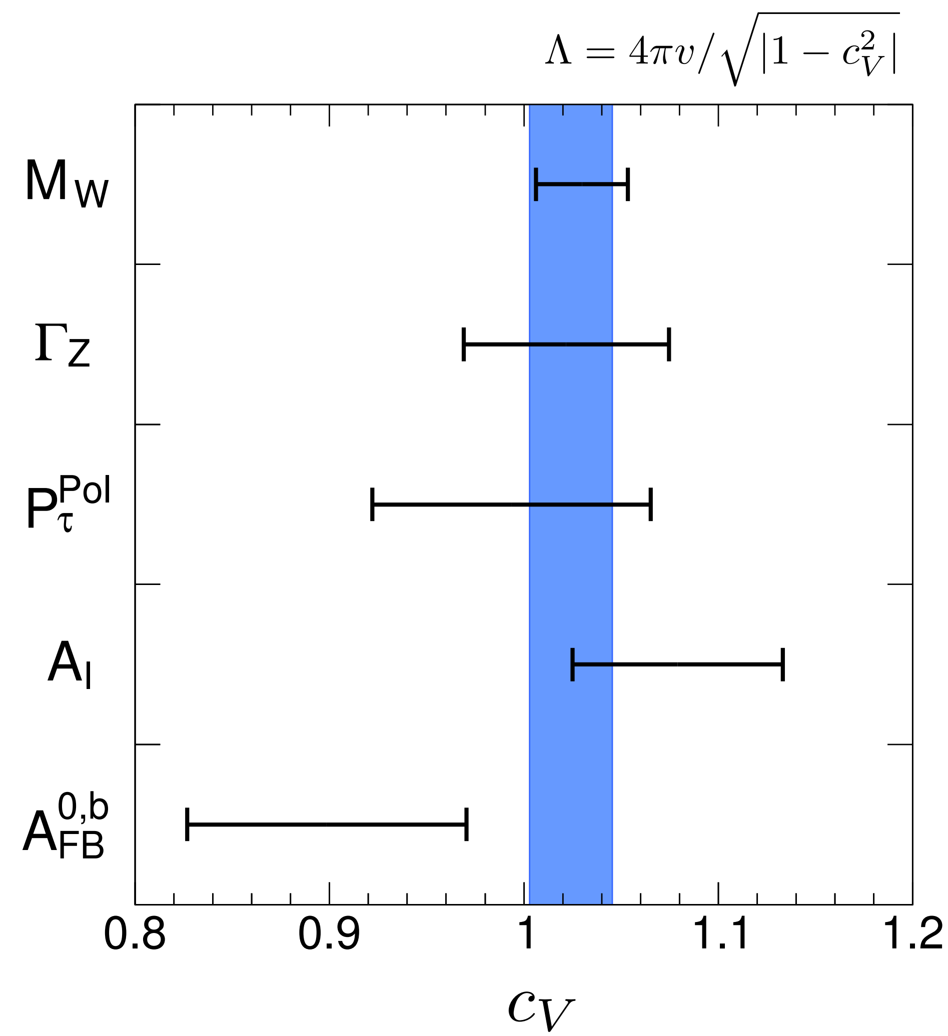

Ciuchini, Franco, Silvestrini, Mishima, arXiv:1306.4644

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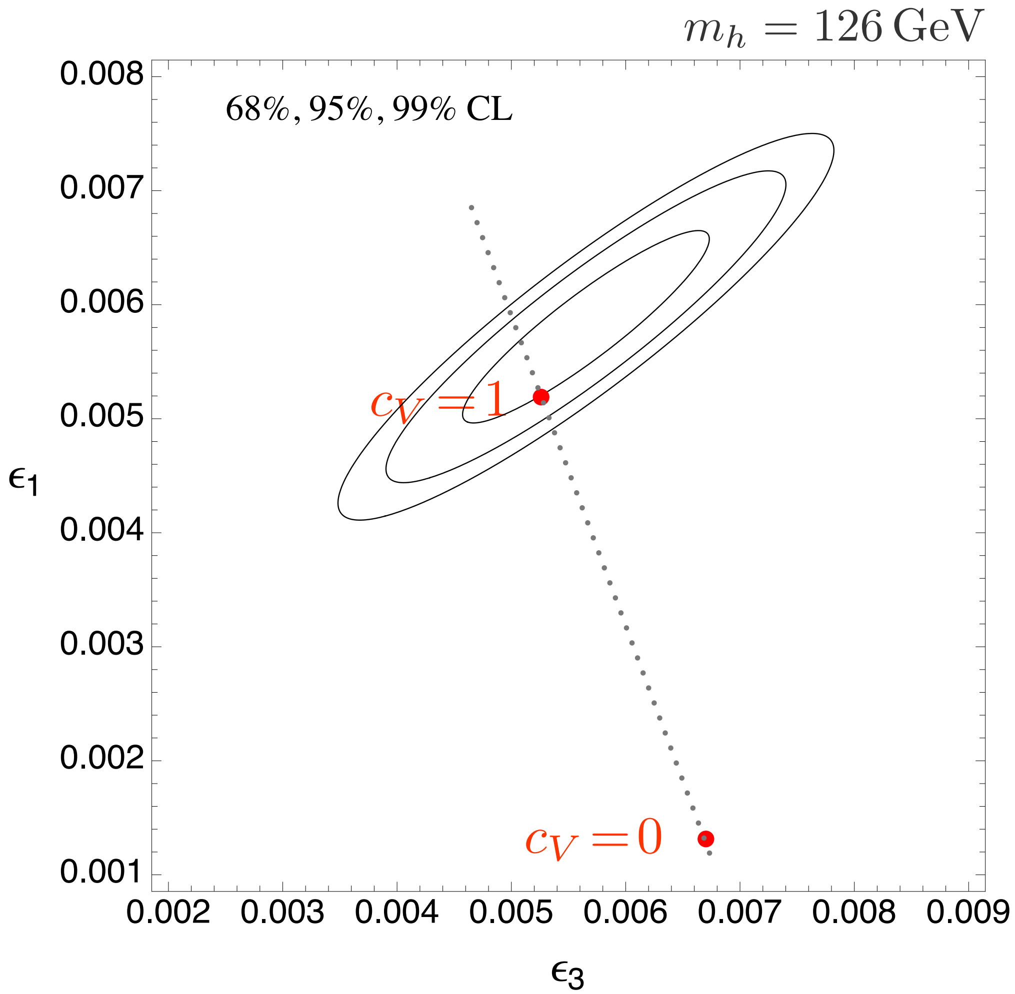
Barbieri et al. PRD 76 (2007) 115008

➡ **See talk by S. Mishima on Thursday**

Constraints on c_V from EW Precision Tests



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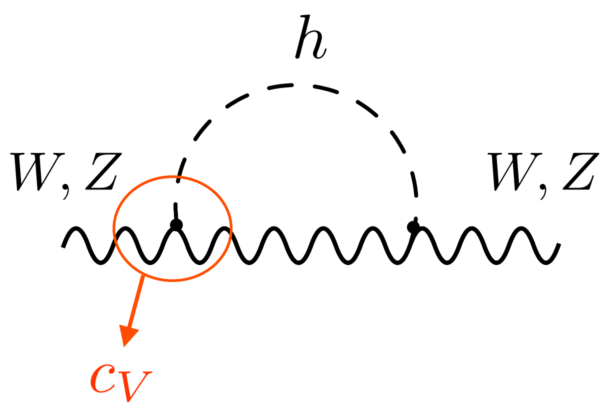
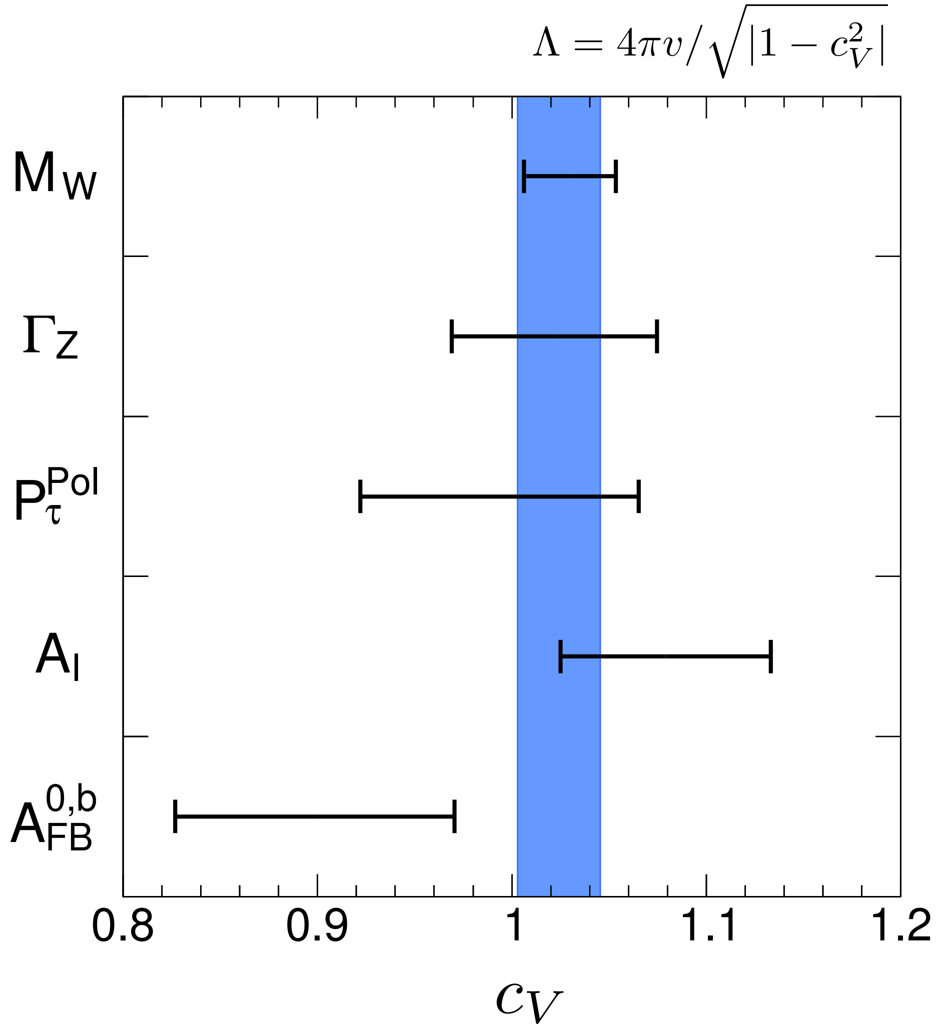




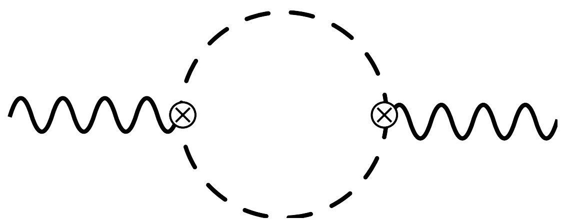
Ciuchini, Franco, Silvestrini, Mishima, arXiv:1306.4644

Precision on c_V at the level of ~5% !

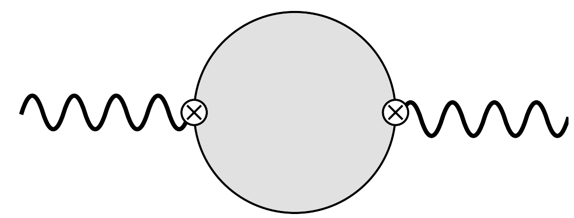
➡ Contribution from resonances REQUIRED to relax the bound

➡ **See talk by S. Mishima on Thursday**

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



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



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

S parameter

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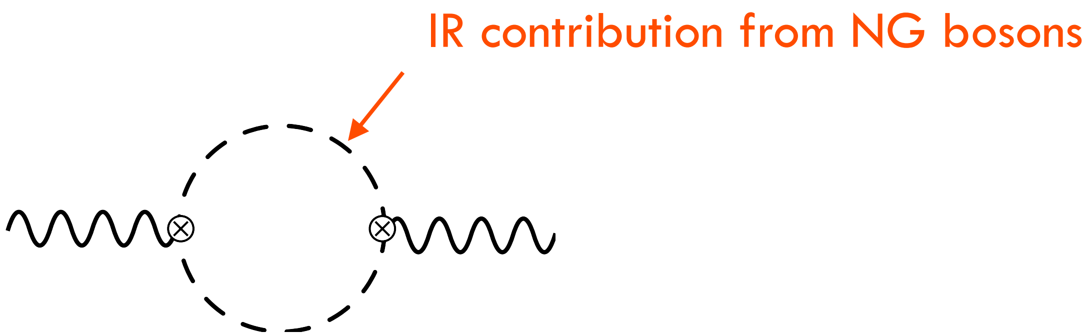

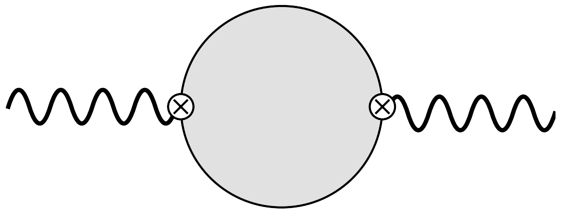

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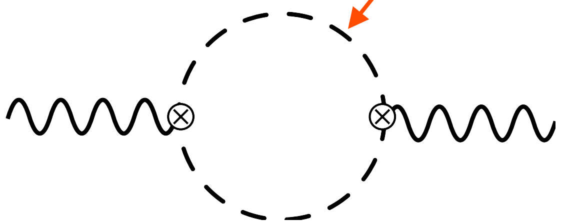
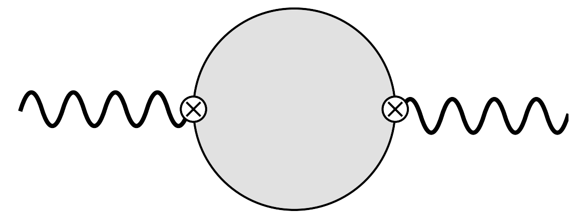
S parameter $\hat{S} = \hat{S}_{IR} + \hat{S}_{UV}$

IR contribution from NG bosons





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tree-level (rho)

S parameter

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

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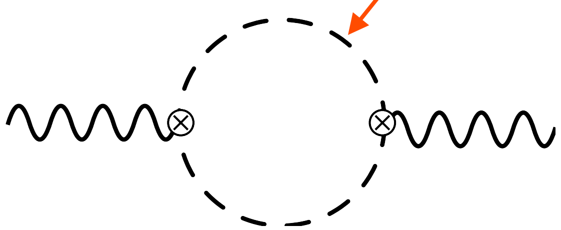

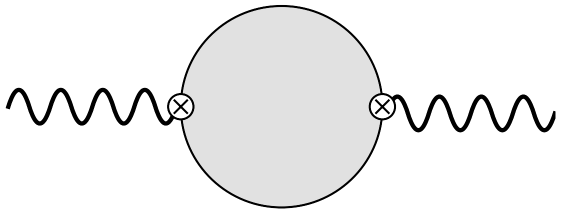

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tree-level (rho)

1-loop (fermions)

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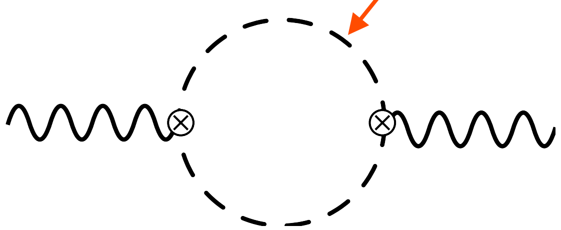

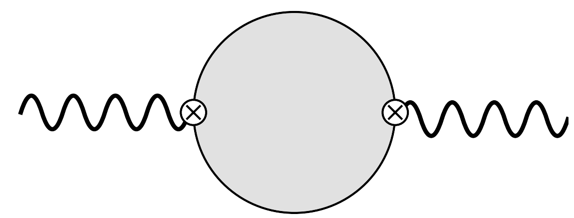

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tree-level (rho)

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, arXiv:1306.4655

Azatov, RC , Di Iura, Galloway, arXiv:1308.2676

fermion contribution can be *negative*

Best seen using a dispertion relation:

Orgogozo and Rychkov, JHEP 1306 (2013) 014

$$\boxed{\hat{S}_{UV} = \frac{g^2}{4}\sin^2\theta \int \frac{ds}{s}\left[\rho_{LL}(s) + \rho_{RR}(s) - 2\rho_{BB}(s)\right]}$$

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

$$\rho(s) = \frac{1}{\pi}\mathrm{Im}(\Pi(s))$$

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

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

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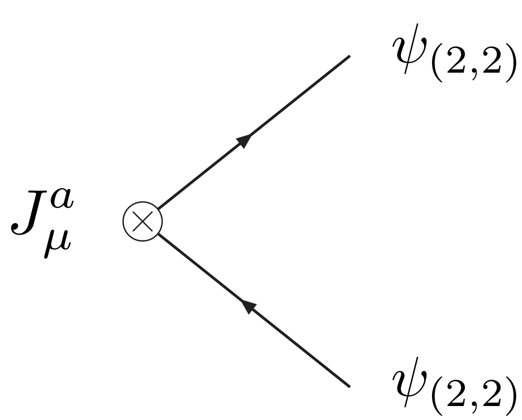
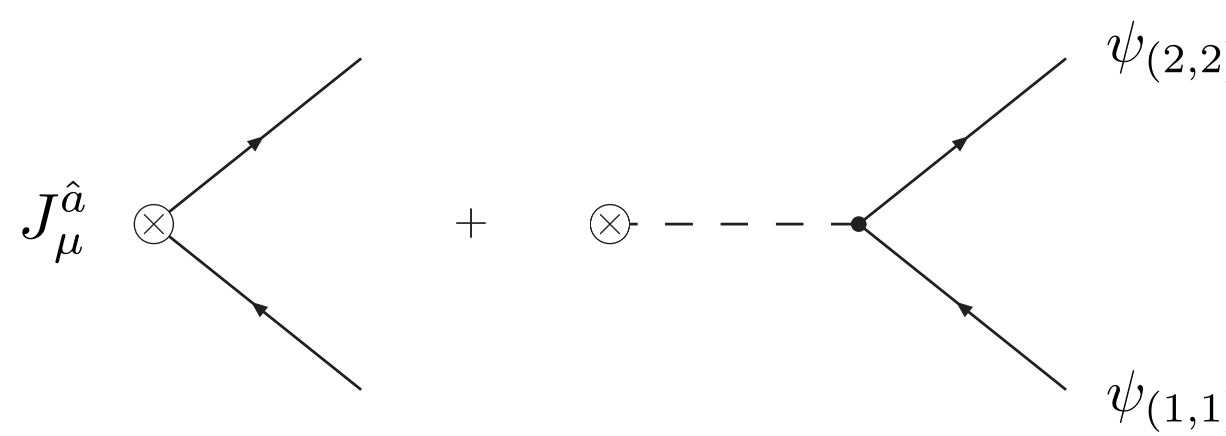
Example: [Azatov, RC , Di Iura, Galloway, arXiv:1308.2676]

$$\psi_5 = (1,1) + (2,2)$$

$$\mathcal{L} = \bar{\psi}_1\big(i\not{D} - m_1\big)\,\psi_1 + \bar{\psi}_4\big(i\not{\nabla} - m_4\big)\,\psi_4 - \zeta\,\bar{\psi}_4\gamma^\mu d_\mu\,\psi_1 + h.c.$$



$\rho_{LL,RR}$



ρ_{BB}

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Orgogozo and Rychkov, JHEP 1306 (2013) 014

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$$\not{A} + i\frac{\pi\not{\partial}\pi}{f^2} + \ldots$$

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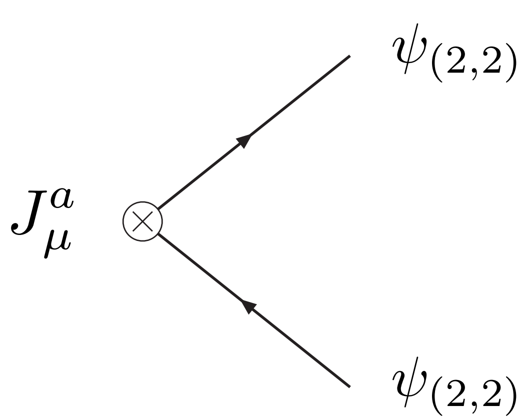

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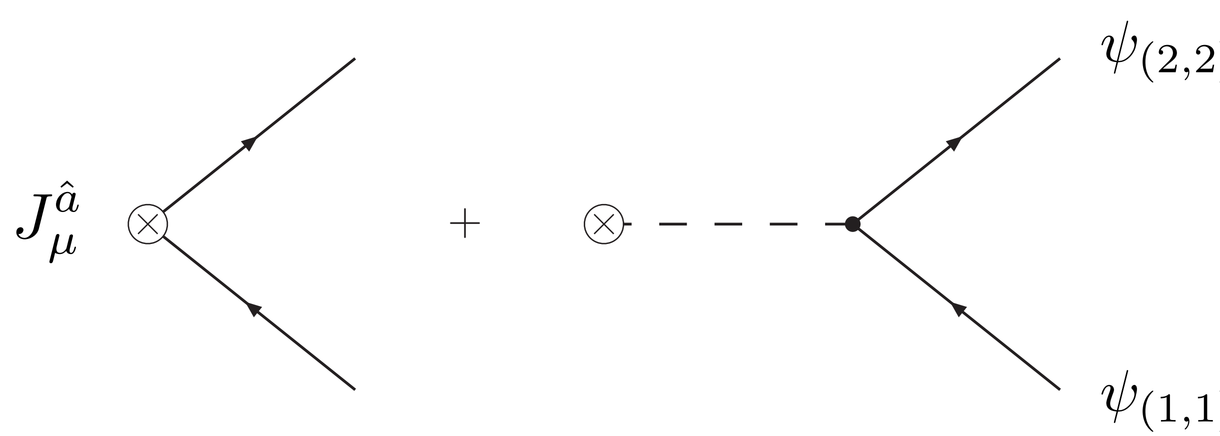

ρ_{BB}

➡ fermion contribution can be *negative*

Best seen using a dispertion relation:

Orgogozo and Rychkov, JHEP 1306 (2013) 014

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

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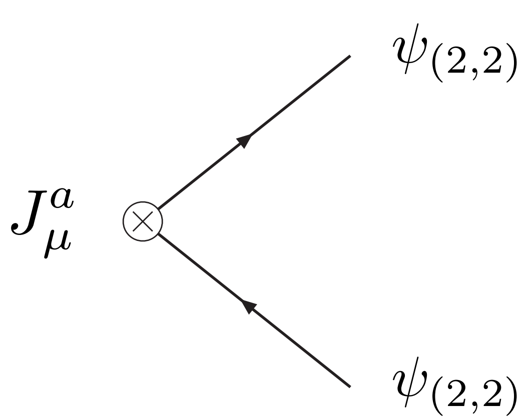
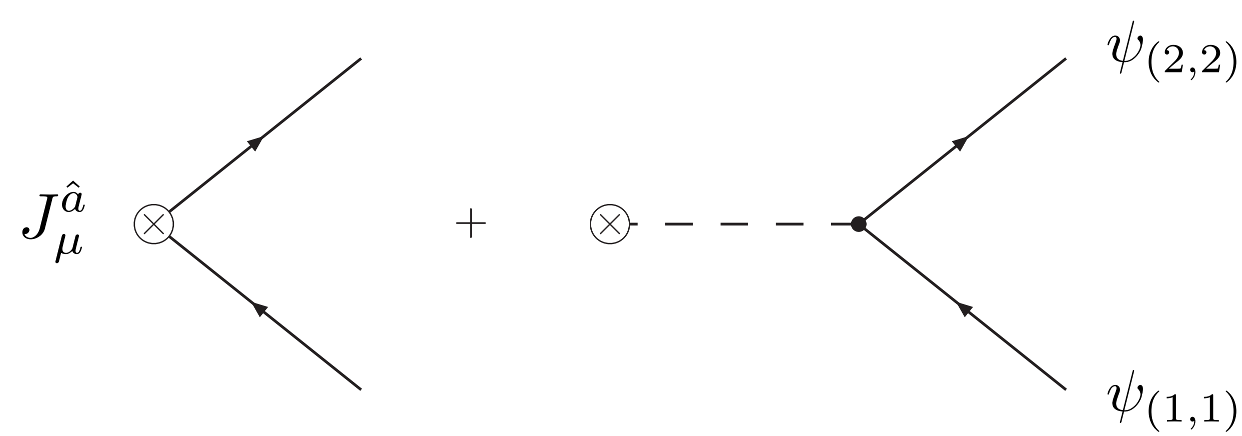


$\rho_{LL,RR}$



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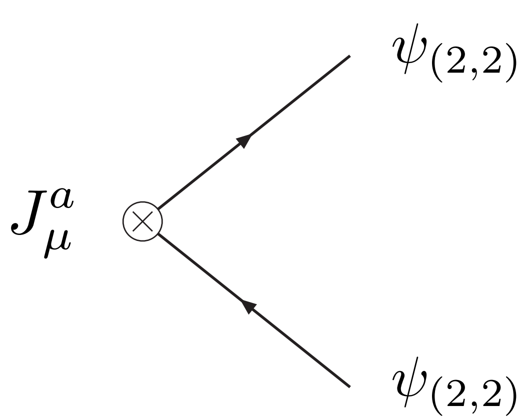
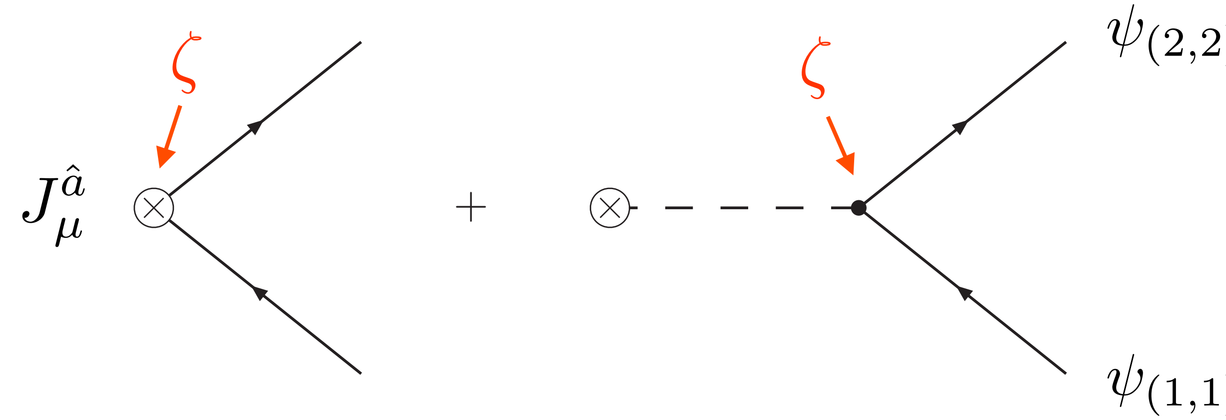
$$\mathcal{L} = \bar{\psi}_1\left(i\not{D} - m_1\right)\psi_1 + \bar{\psi}_4\left(i\not{\nabla} - m_4\right)\psi_4 - \zeta\,\bar{\psi}_4\gamma^\mu d_\mu \psi_1 + h.c.$$



$\rho_{LL,RR}$



ρ_{BB}

fermion contribution can be *negative*

Best seen using a dispertion relation:

Orgogozo and Rychkov, JHEP 1306 (2013) 014

$$\boxed{\hat{S}_{UV} = \frac{g^2}{4}\sin^2\theta \int \frac{ds}{s}\left[\rho_{LL}(s) + \rho_{RR}(s) - 2\rho_{BB}(s)\right]}$$

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

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

$$\rho(s) = \frac{1}{\pi}\mathrm{Im}(\Pi(s))$$

Example: [Azatov, RC , Di Iura, Galloway, arXiv:1308.2676]

$$\psi_5 = (1,1) + (2,2)$$

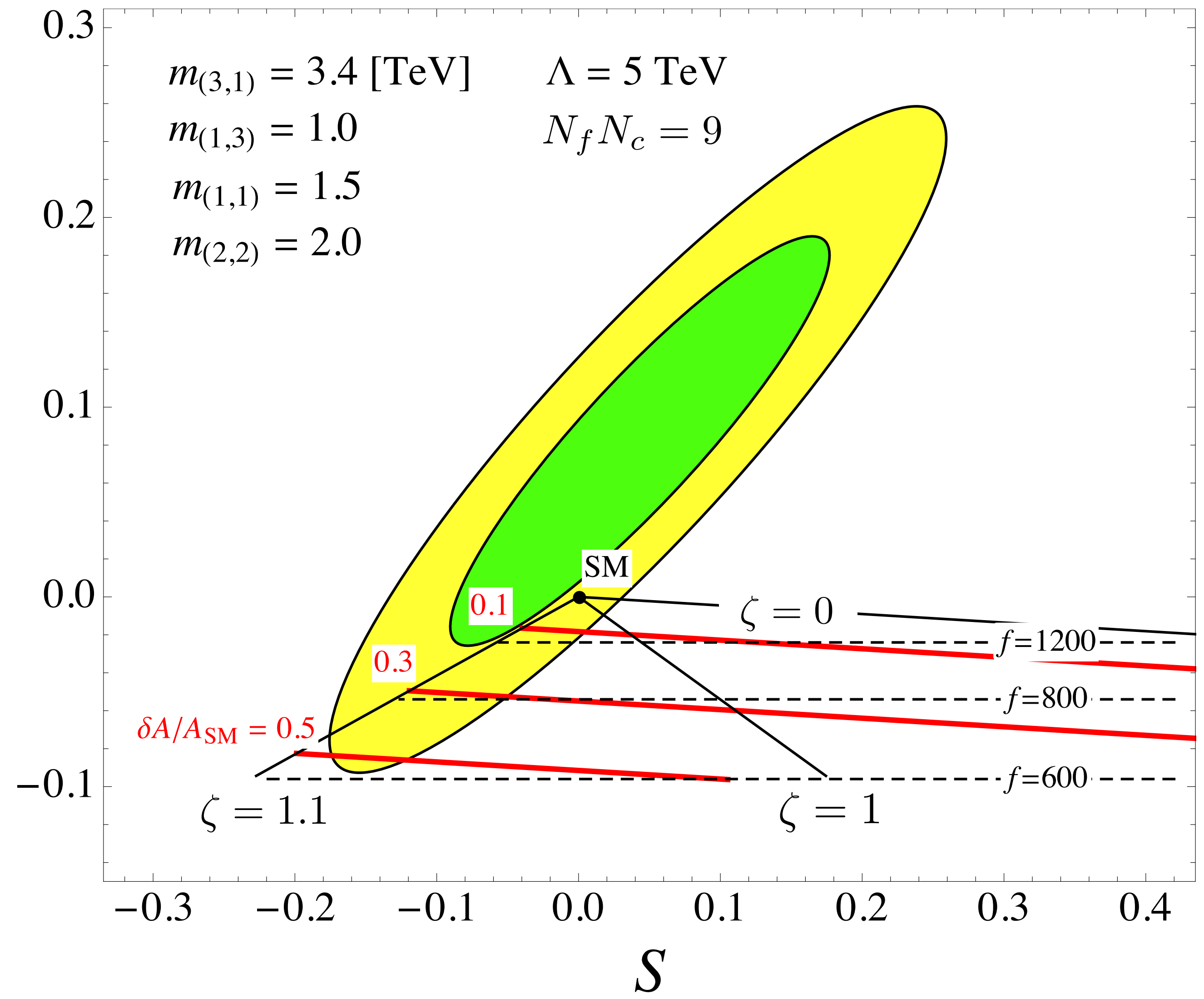
$$\mathcal{L} = \bar{\psi}_1\left(i\not{D} - m_1\right)\psi_1 + \bar{\psi}_4\left(i\underbrace{\not\nabla}_{\not{A} + i\frac{\pi\not\partial\pi}{f^2} + \dots} - m_4\right)\psi_4 - \zeta\,\bar{\psi}_4\gamma^\mu \underbrace{d_\mu}_{\frac{\partial_\mu\pi}{f} + \dots}\psi_1 + h.c.$$

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

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 arXiv:1308.2676

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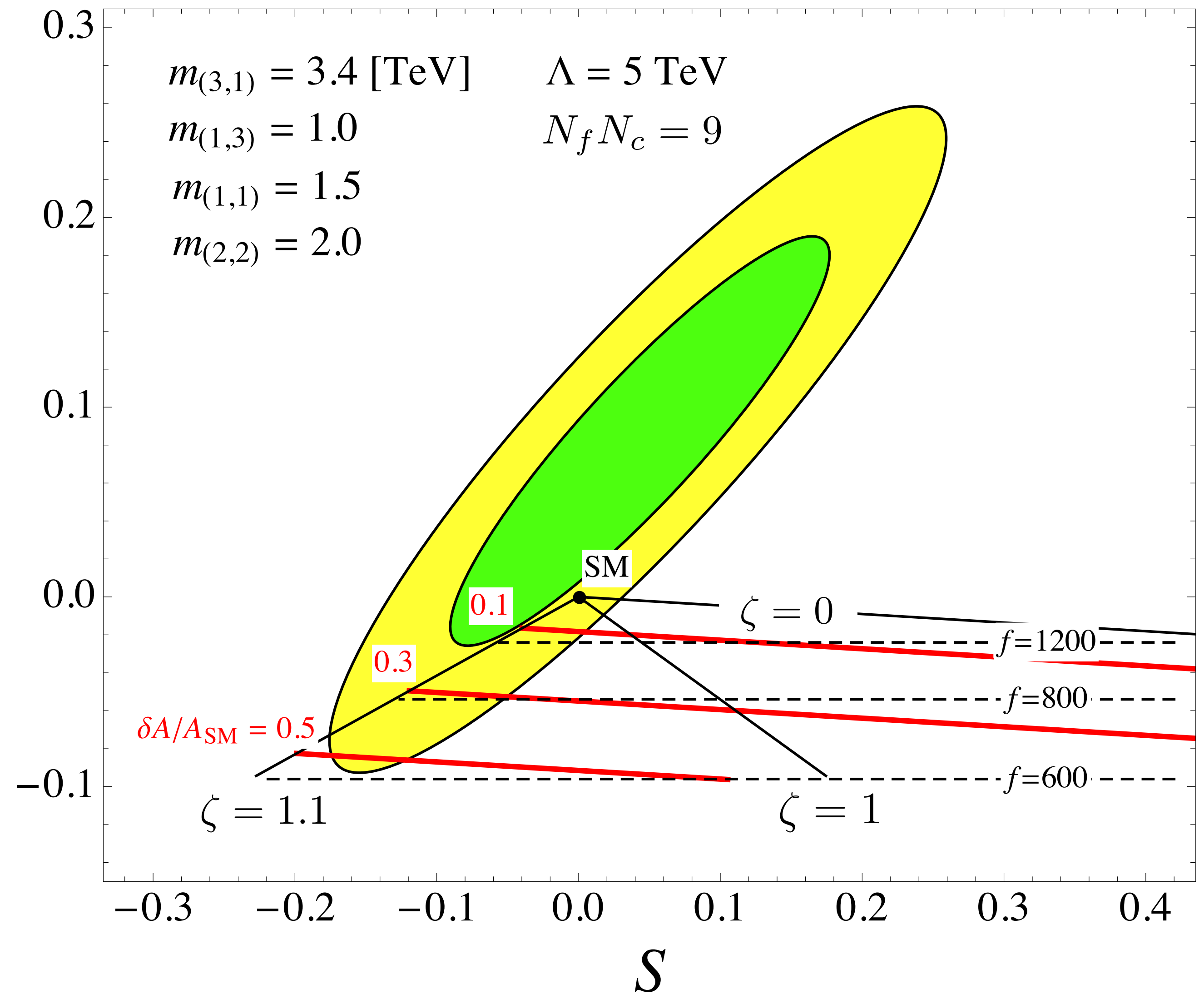

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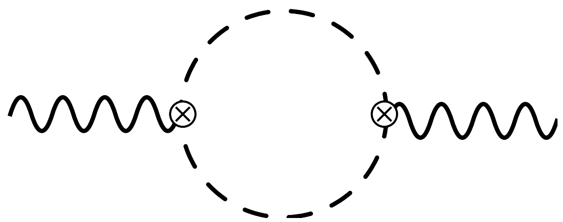
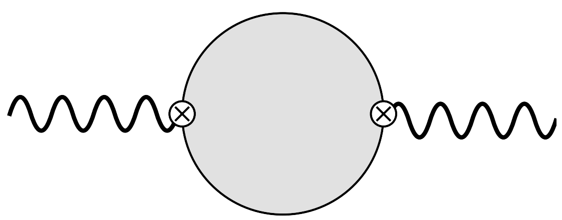
Ex: for $f = 800\,\mathrm{GeV}$ $g_\rho = 3$

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

tuning ~10% required to go back into the exp. 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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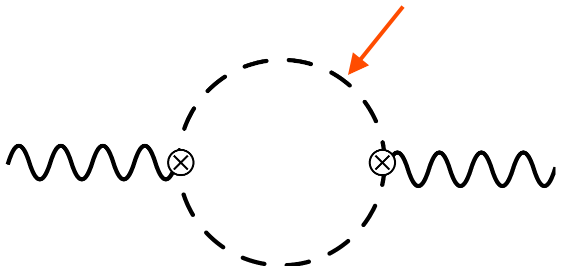
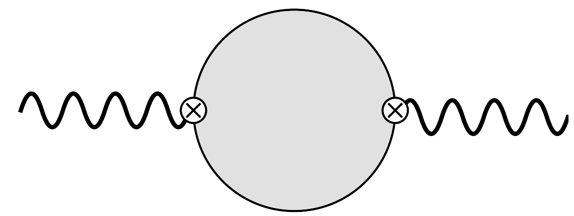
IR contribution from NG bosons





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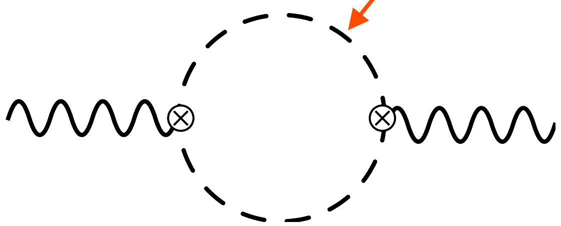

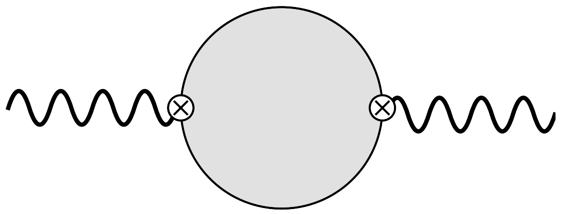

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1-loop (rho)

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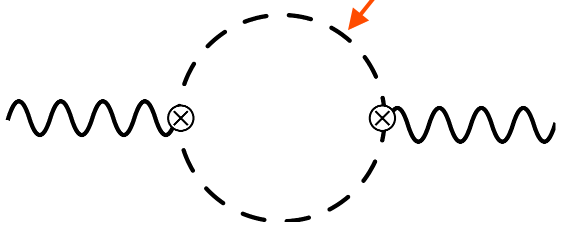

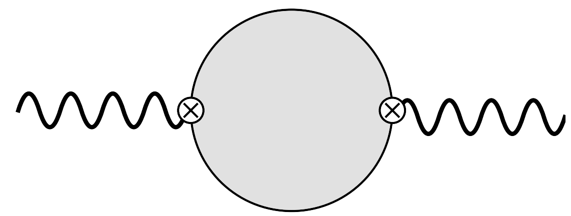

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1-loop (rho) 1-loop (fermions)

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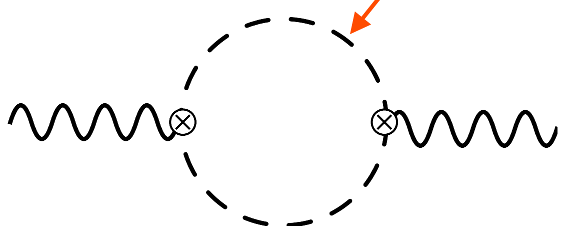

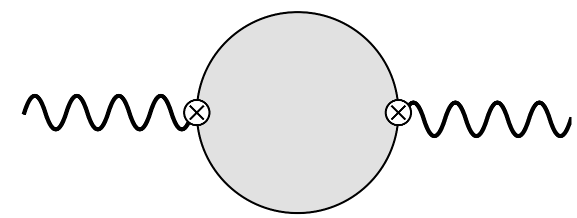

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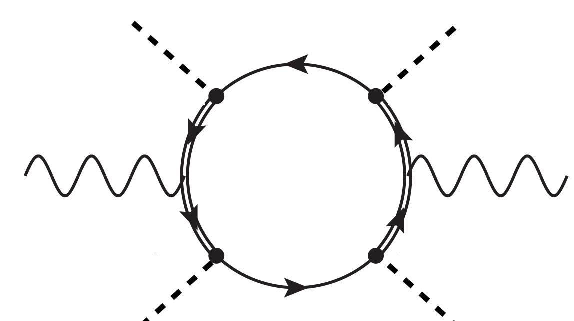
1-loop (rho)   1-loop (fermions)

- 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)

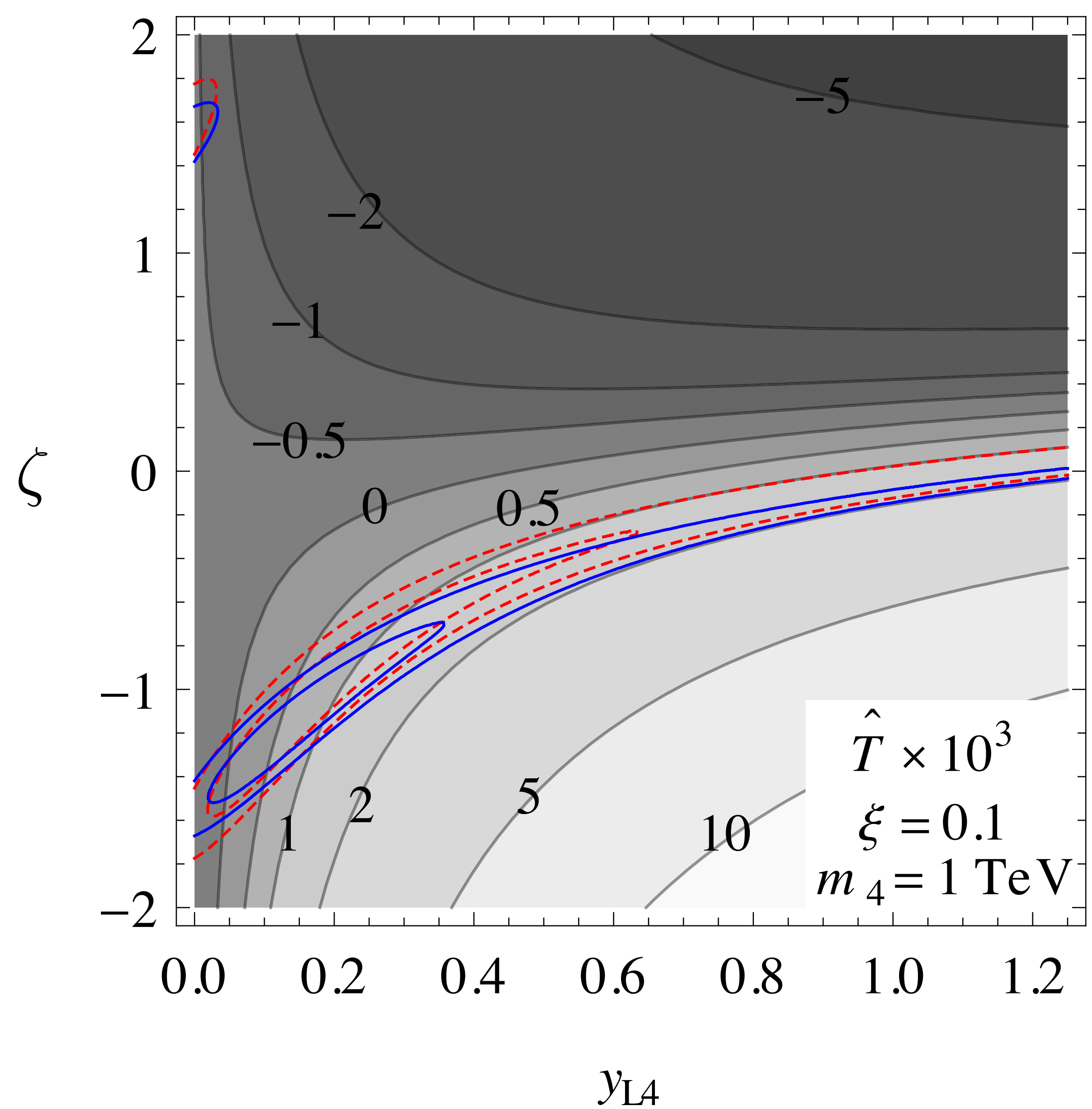


$\Delta\hat{T} > 0$ possible though not fully generic

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 arXiv:1306.4655

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 arXiv:1306.4655

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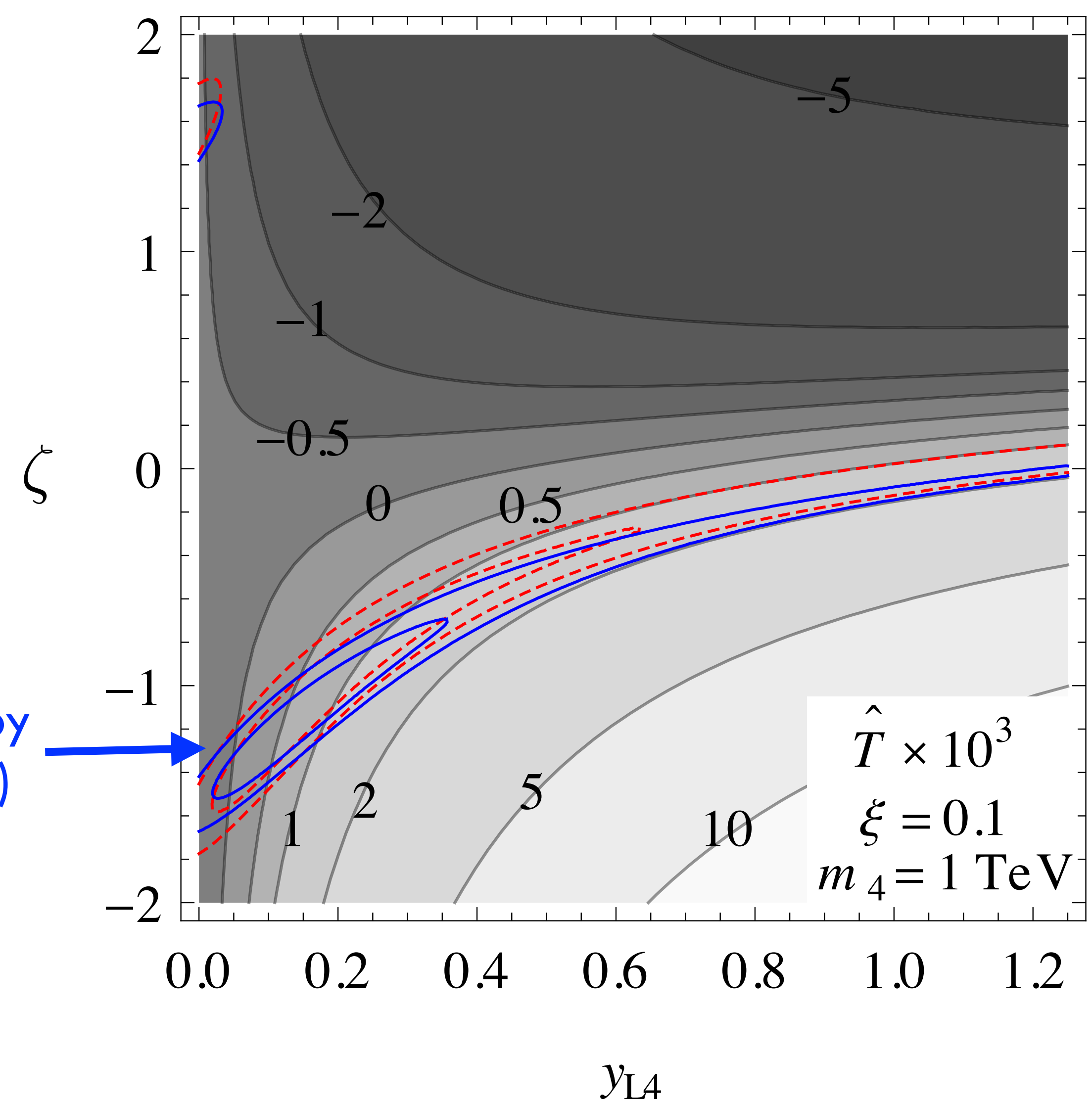
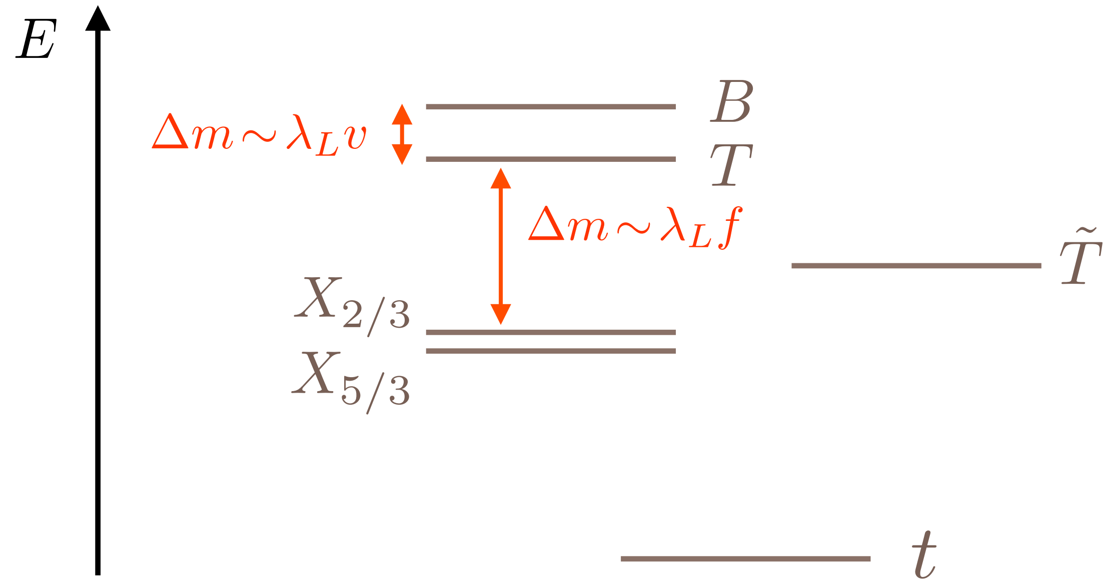
blue region allowed by EWPT at 68% (95%)



Grojean, Matsedonskyi, Panico arXiv:1306.4655

Searches of top partners

- Typical spectrum of top partners



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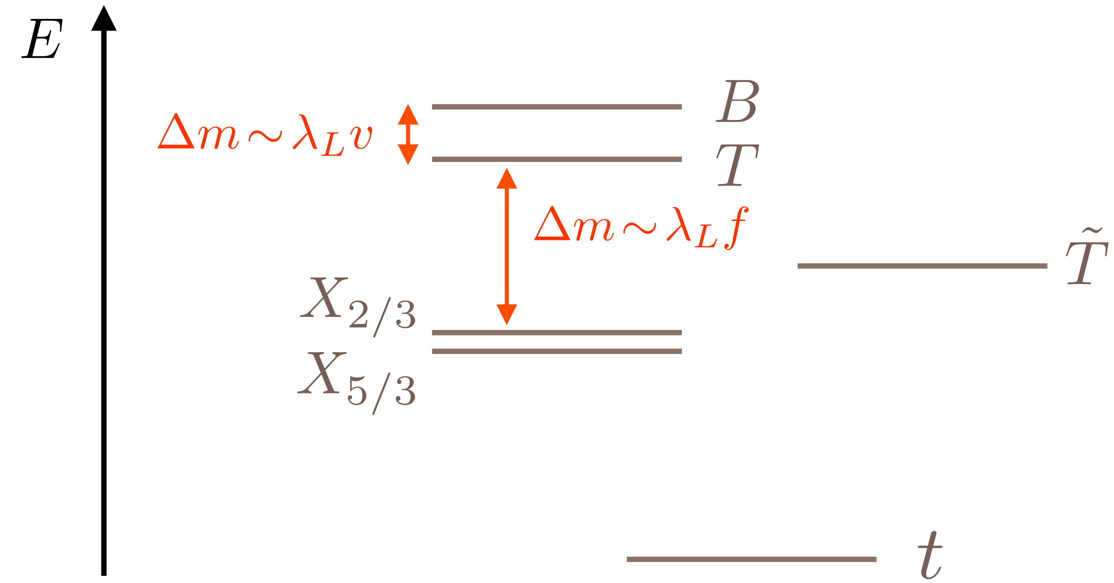
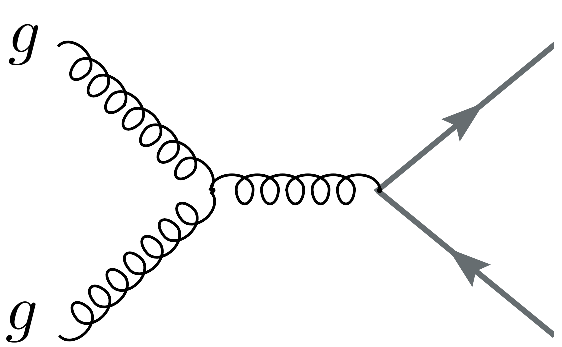
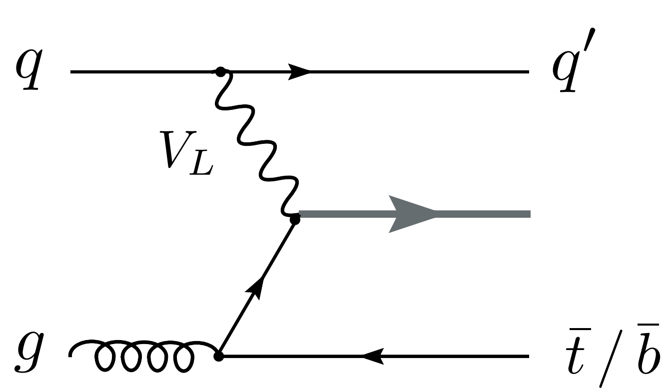


- Two main production modes:

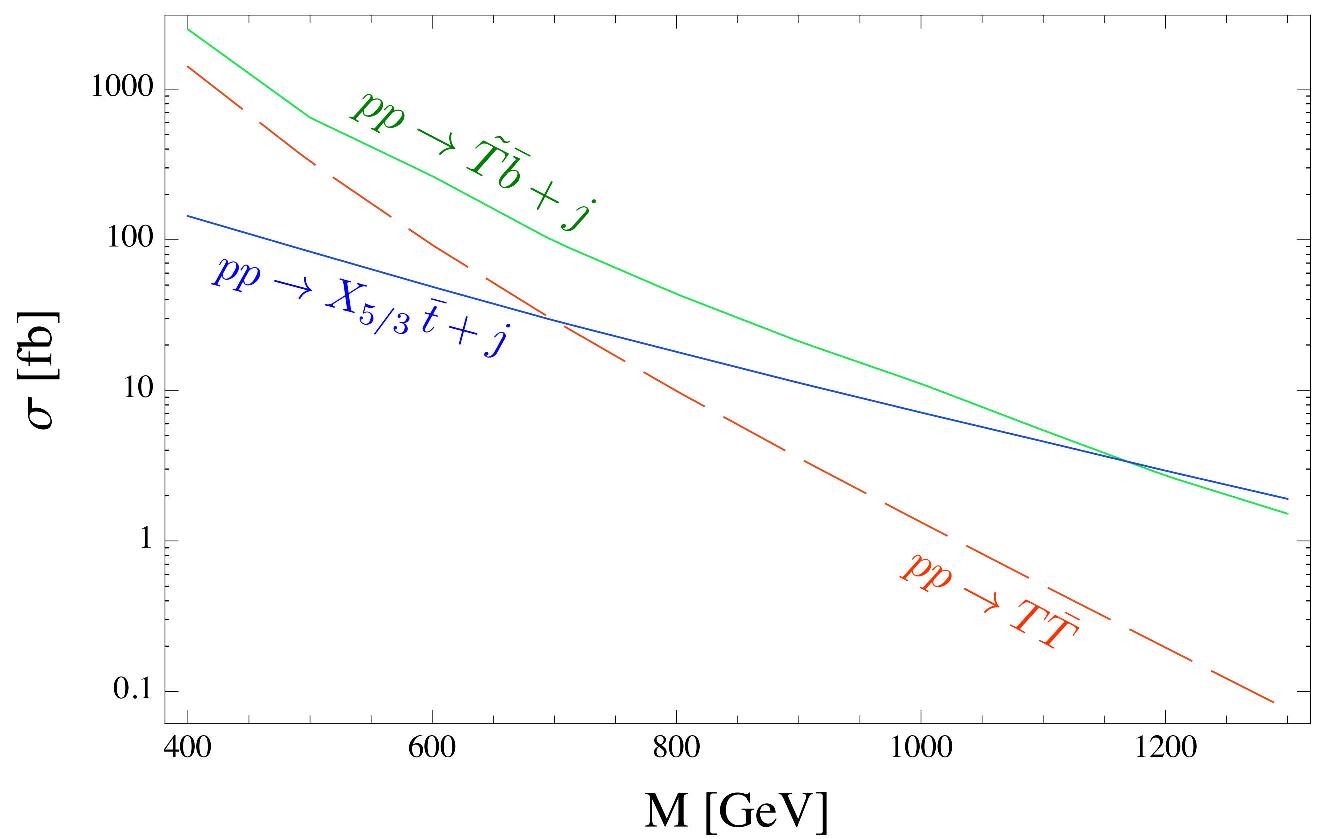


pair production



EW single production

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



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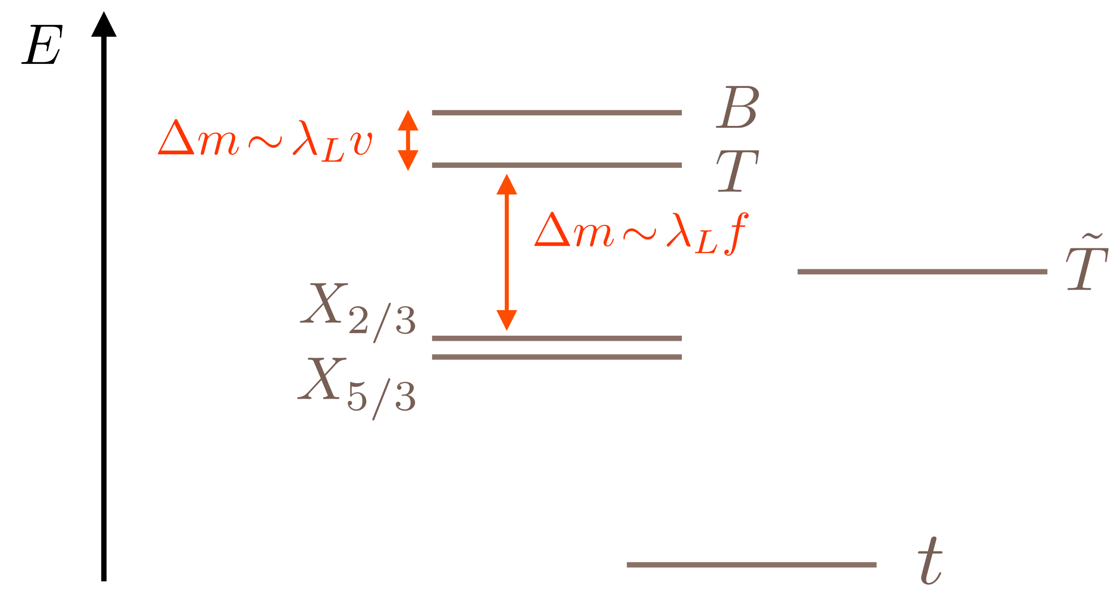

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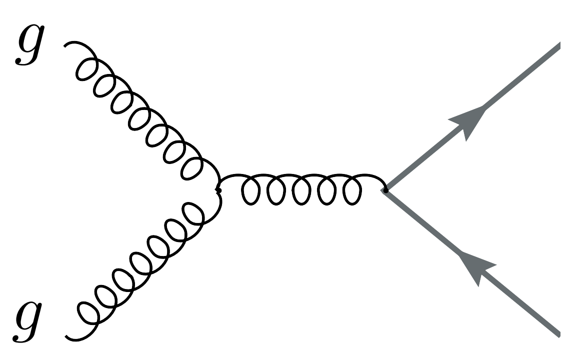
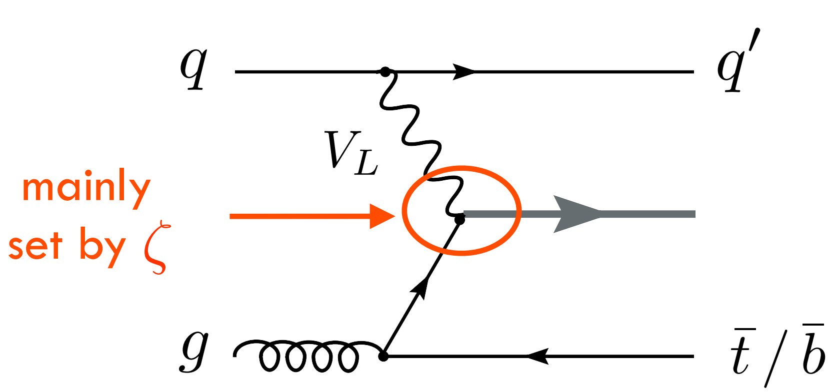


pair production



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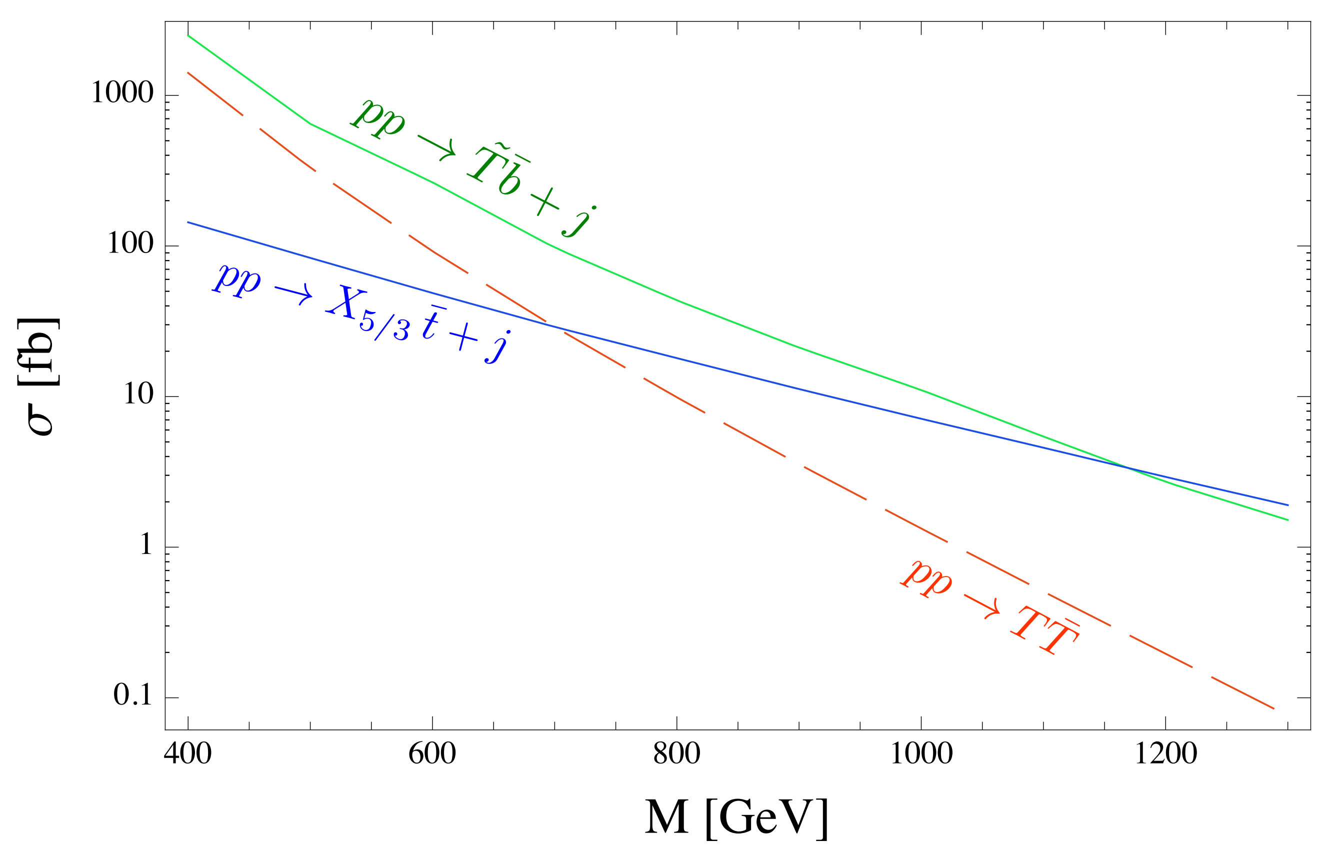
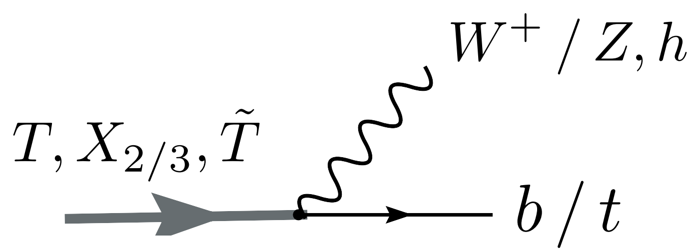
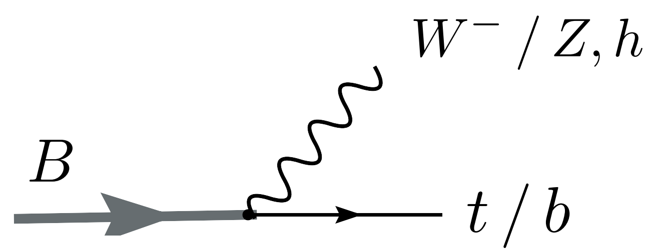
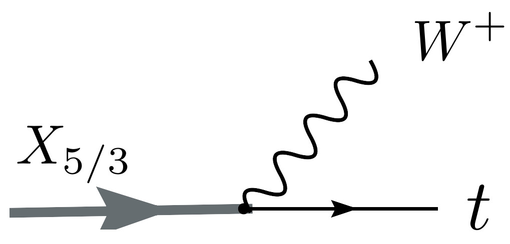


- Two-body decay modes:







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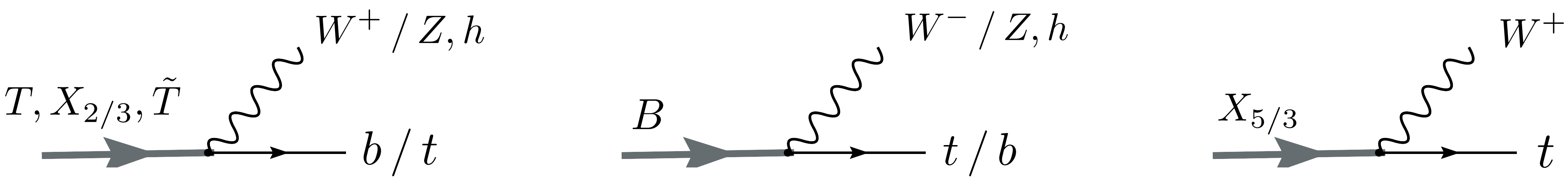
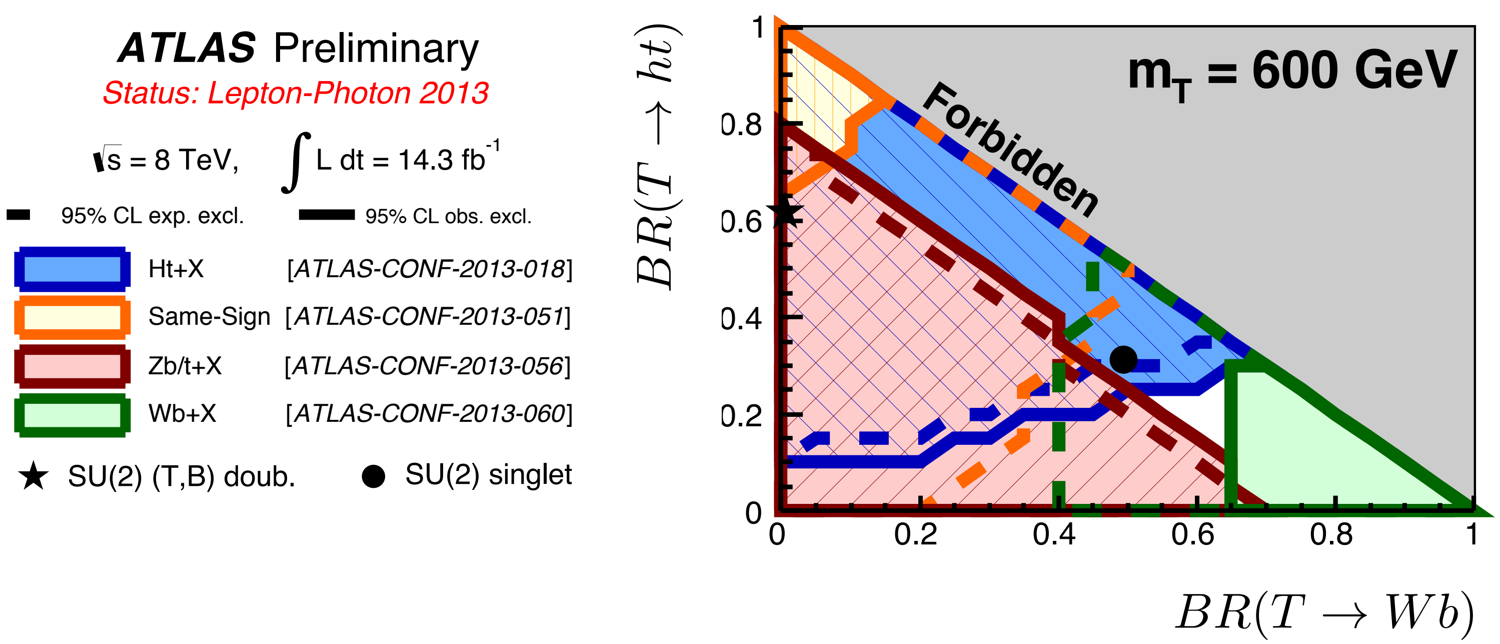
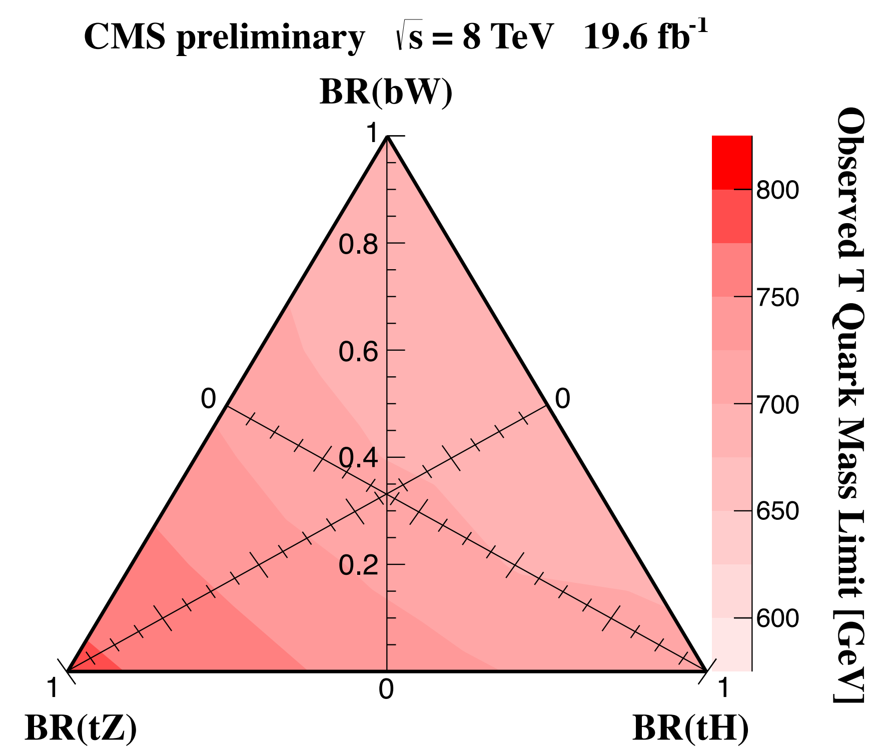


- Current experimental status in a nutshell

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





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

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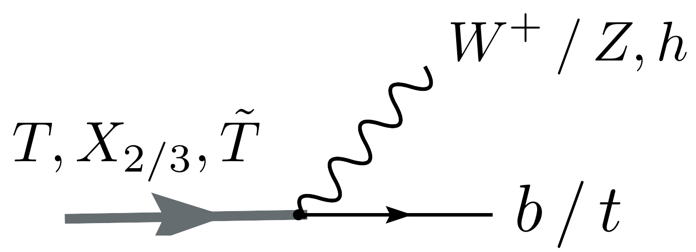

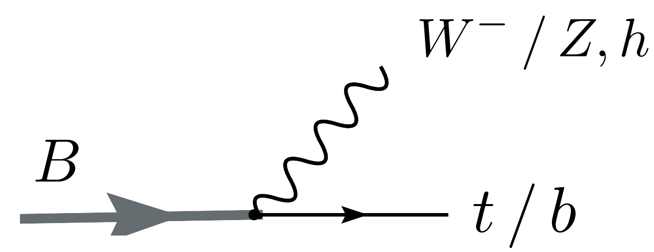

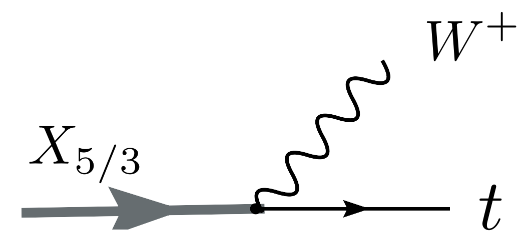

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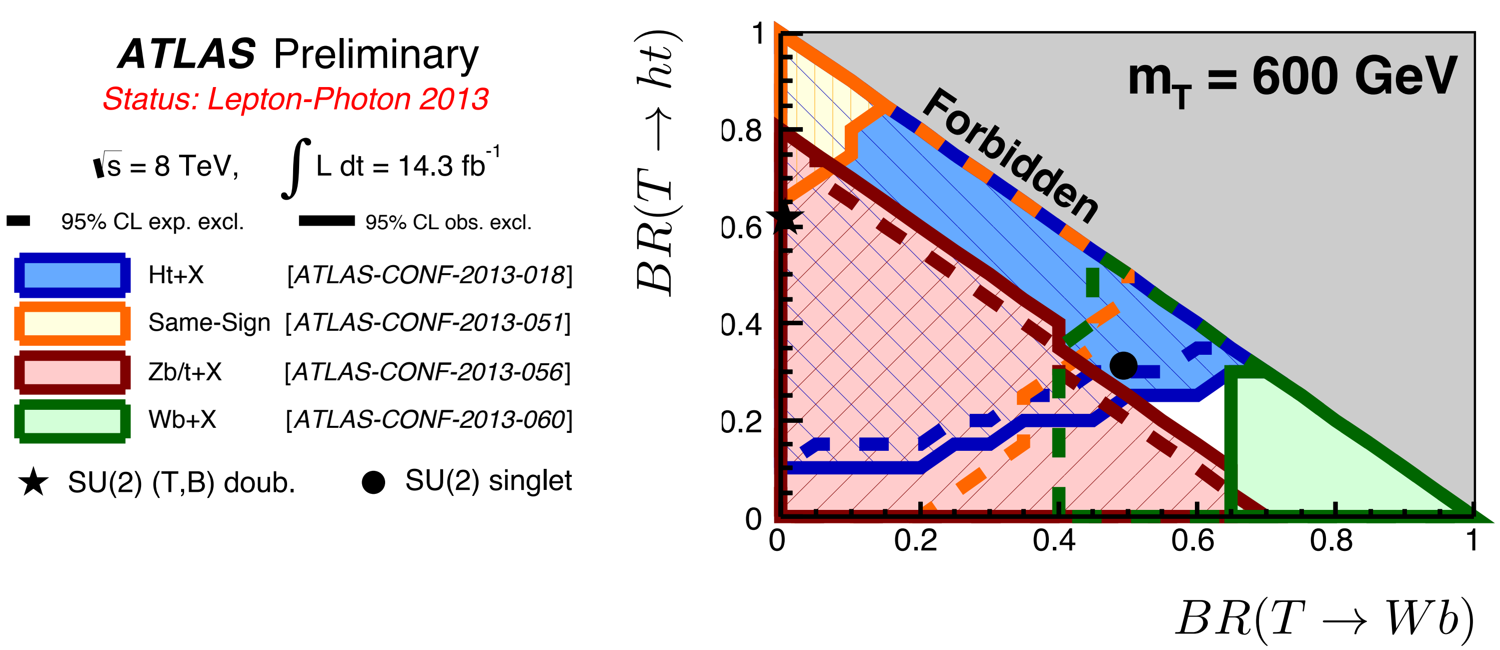
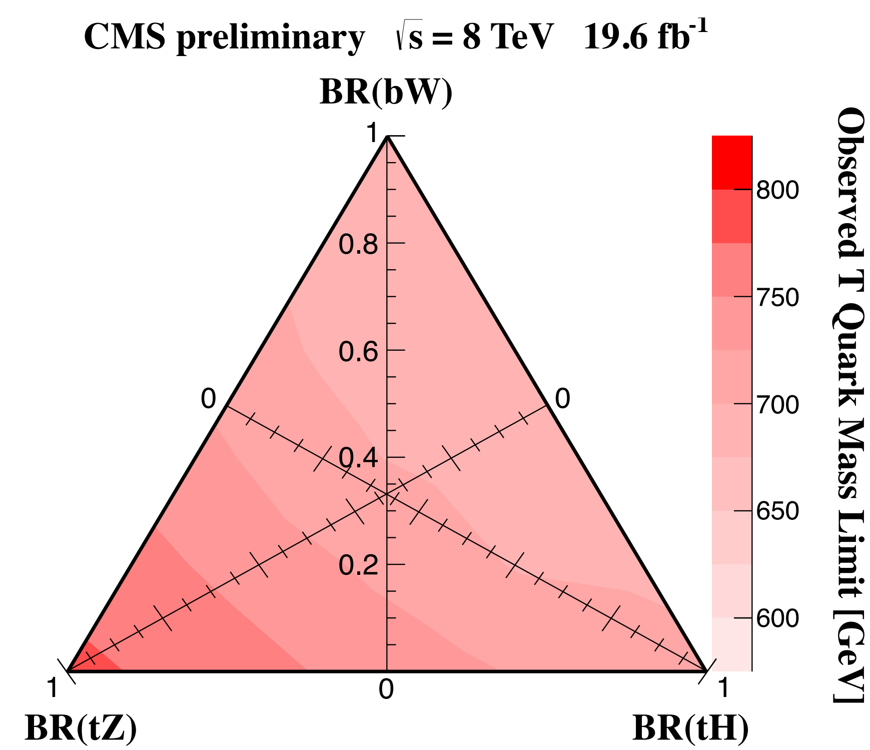
Limits in the 700-800 GeV range





CMS B2G-12-015
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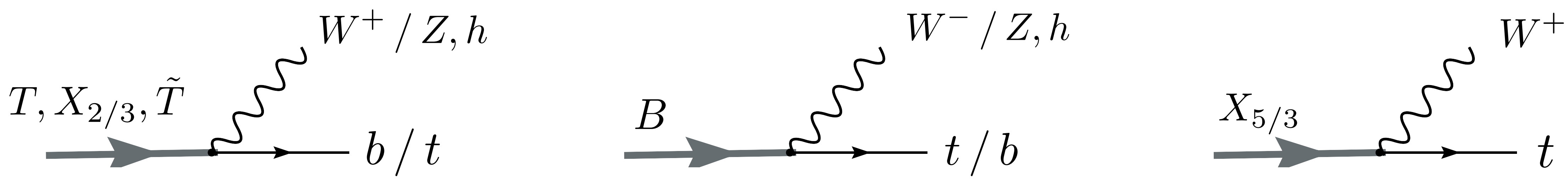

➡ **See talks by I.Vorobiev and R.Groeber on Friday**

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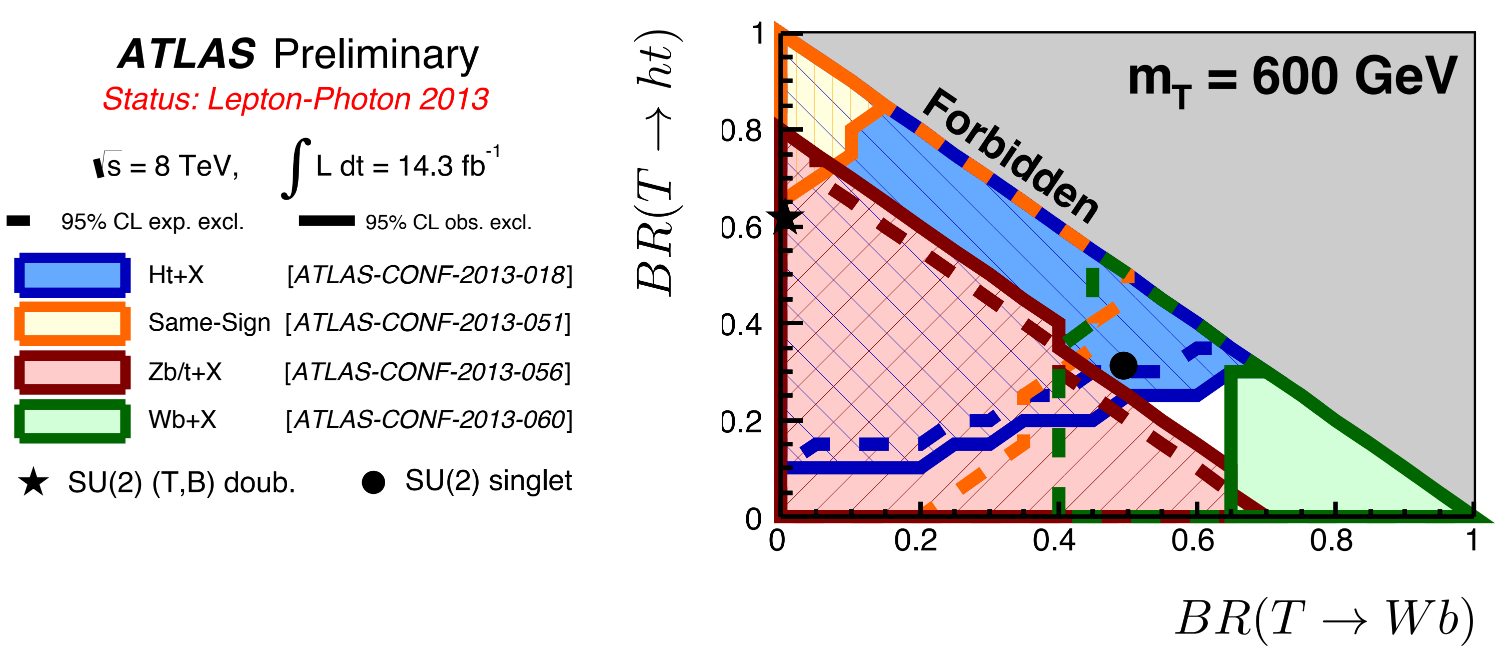
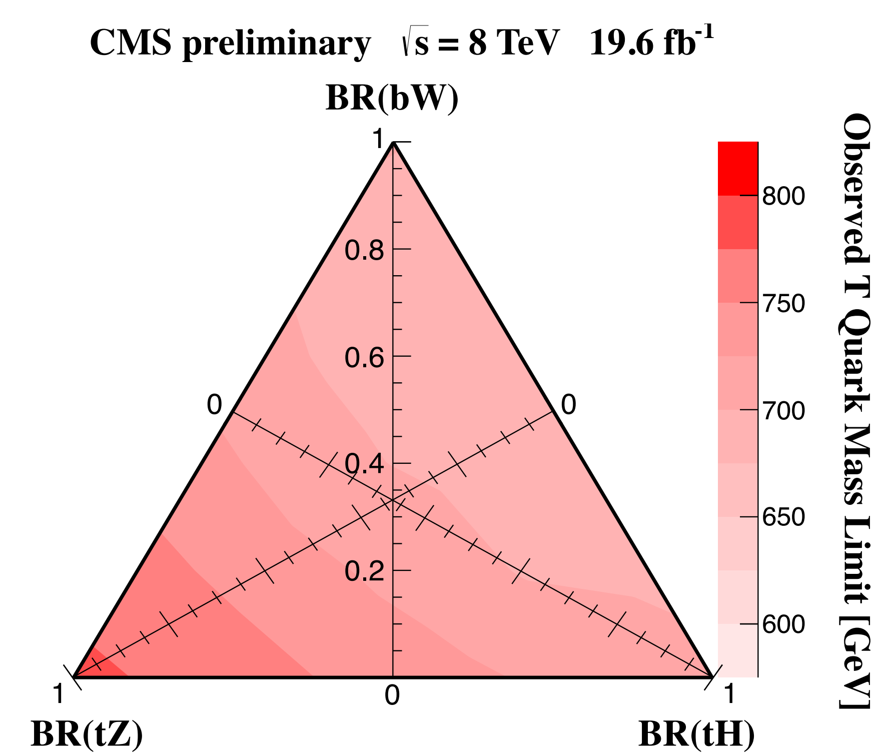
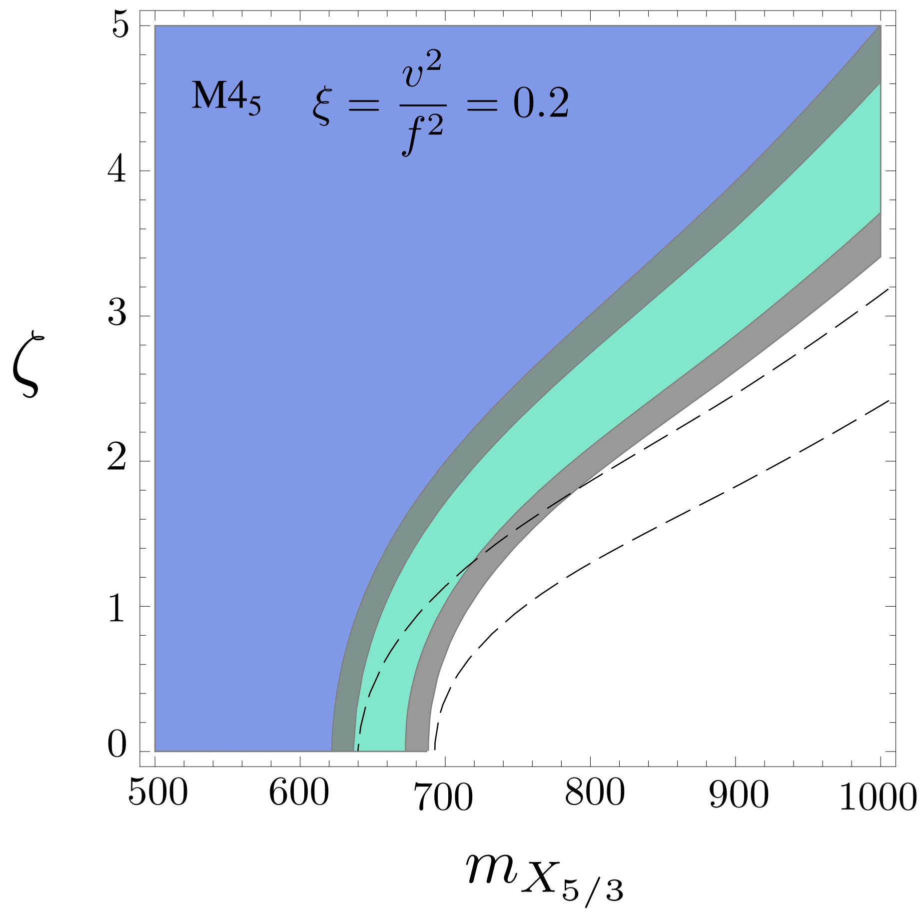




CMS B2G-12-015
CMS B2G-12-012

- 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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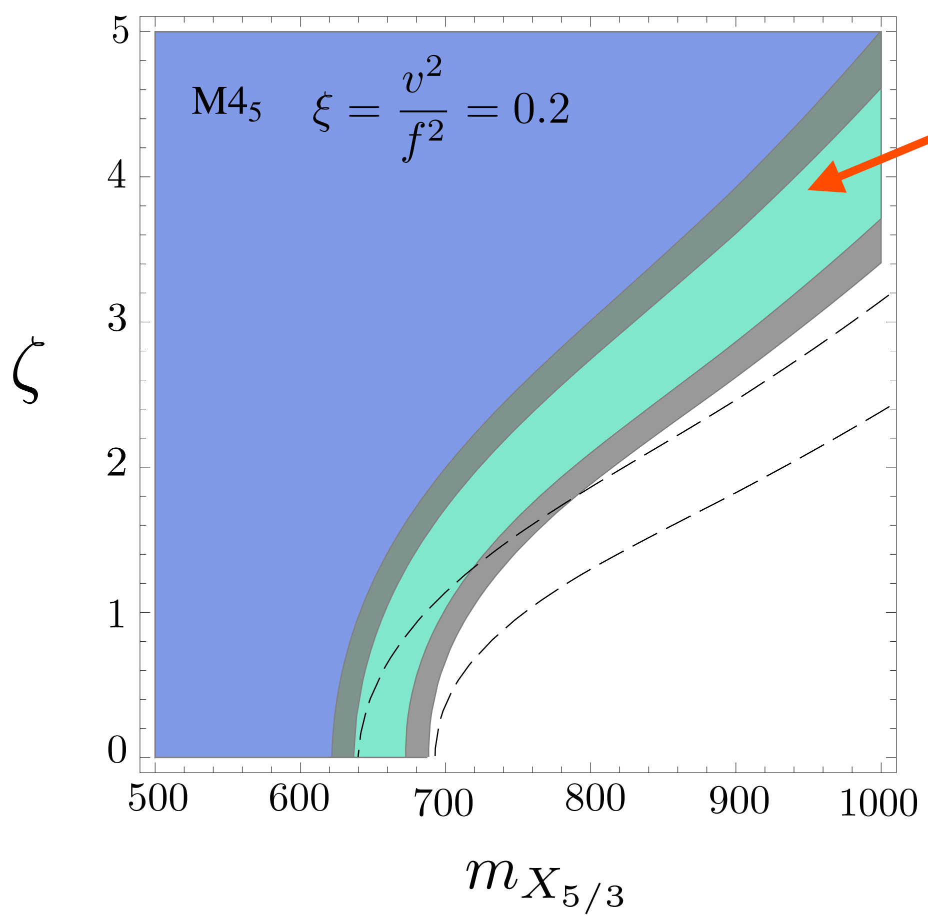

Effect of single production is NOT negligible

Stronger sensitivity from optimizing exp. analyses to include single production

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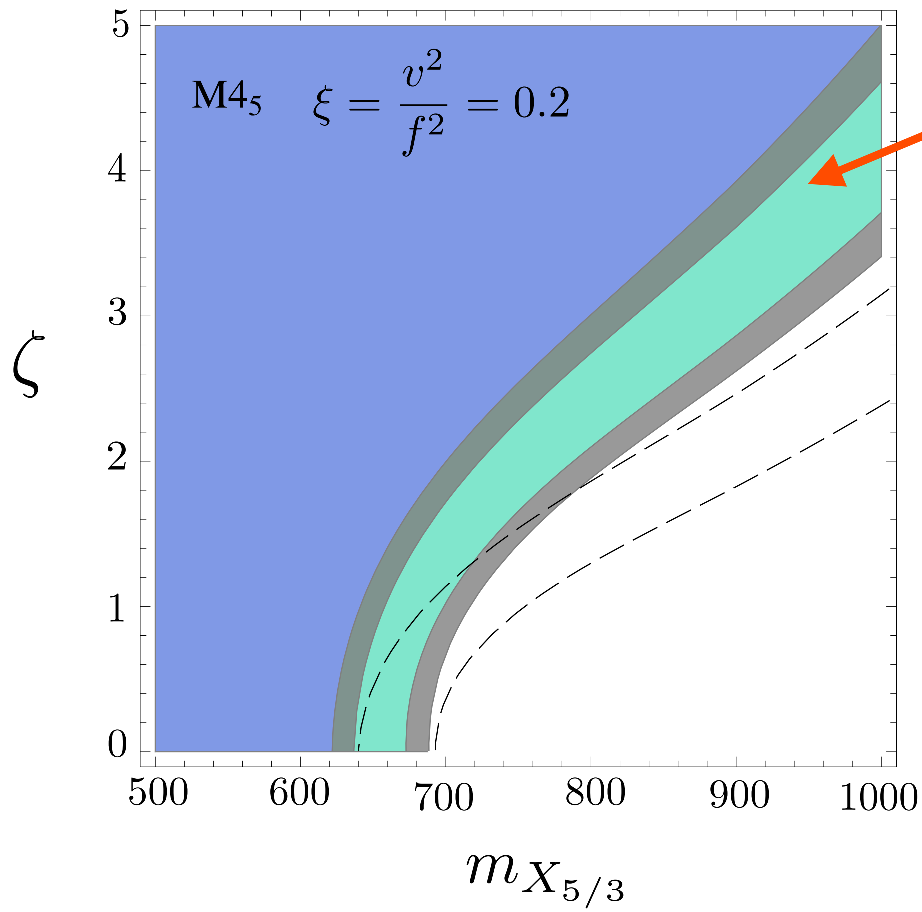

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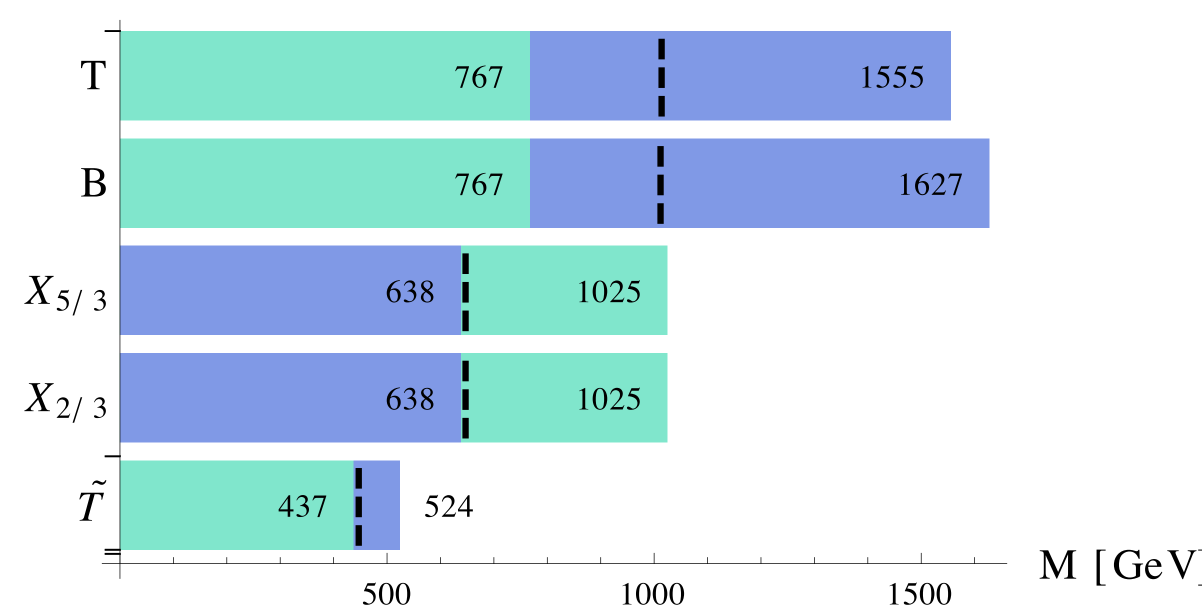
Multiplicity of states, connection among masses and inclusion of single production amplify limits on individual particles

limits for $\xi = 0.1, \ \zeta = 1, \ y_{L4} = 1$



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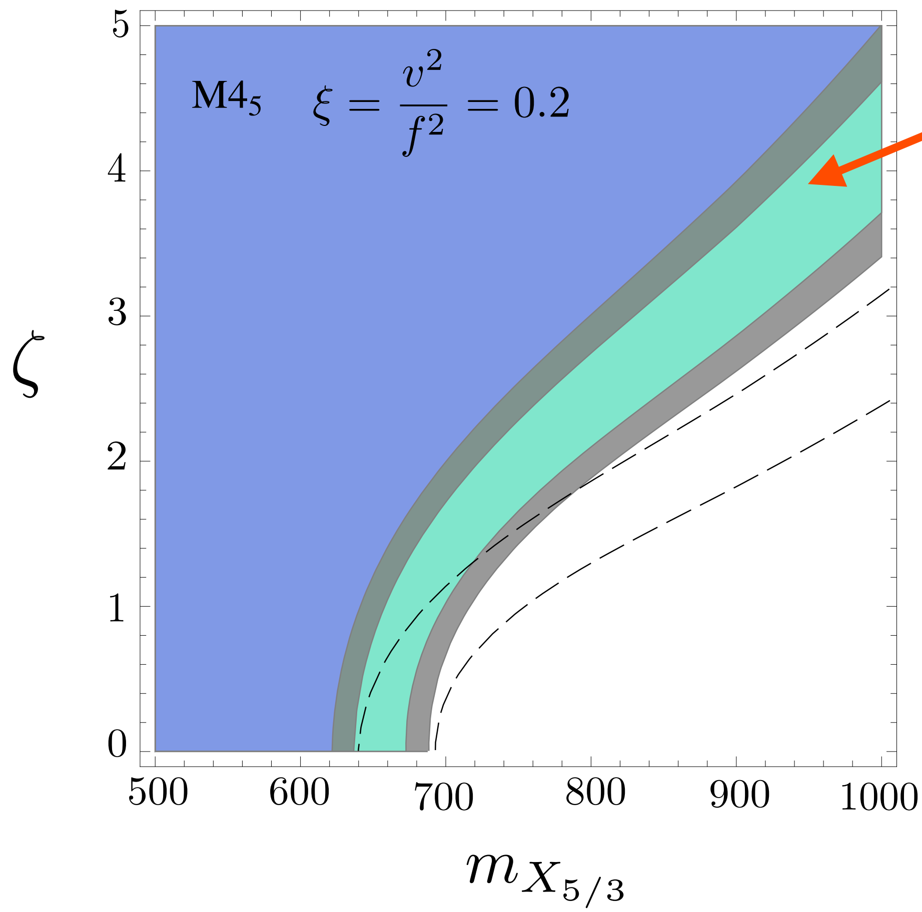

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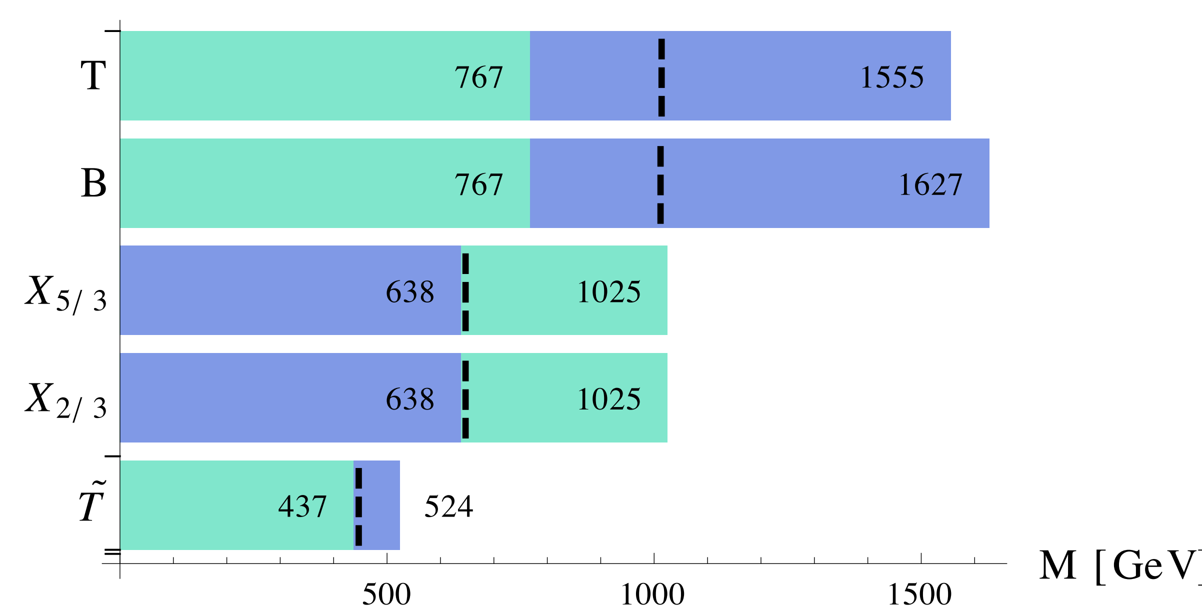
- - - - limits for $\xi = 0.1, \ \zeta = 1, \ y_{L4} = 1$



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

1 TeV masses typically excluded

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

Higgs couplings

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

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

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

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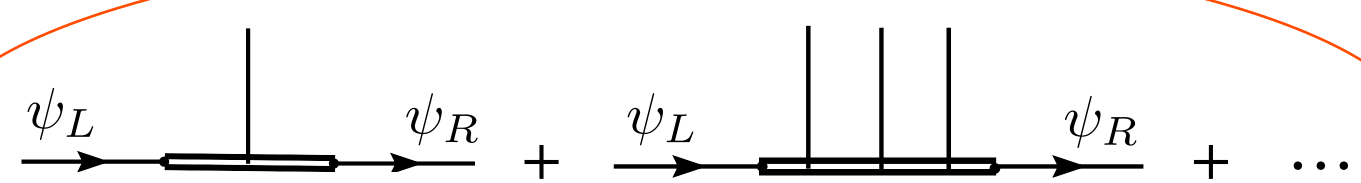

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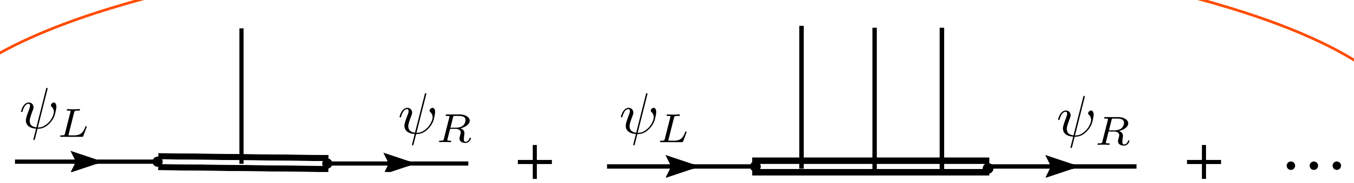

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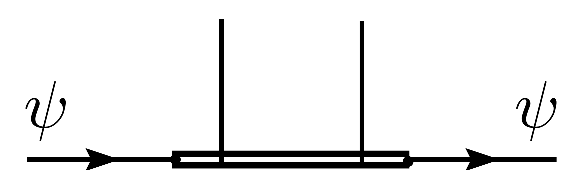
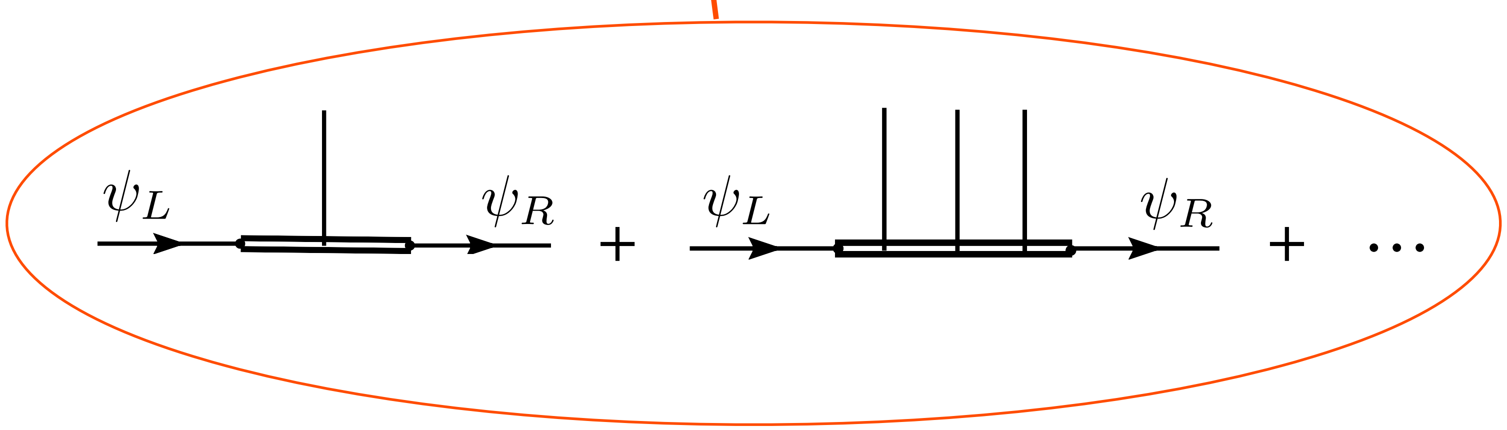
from wave-function renormalization





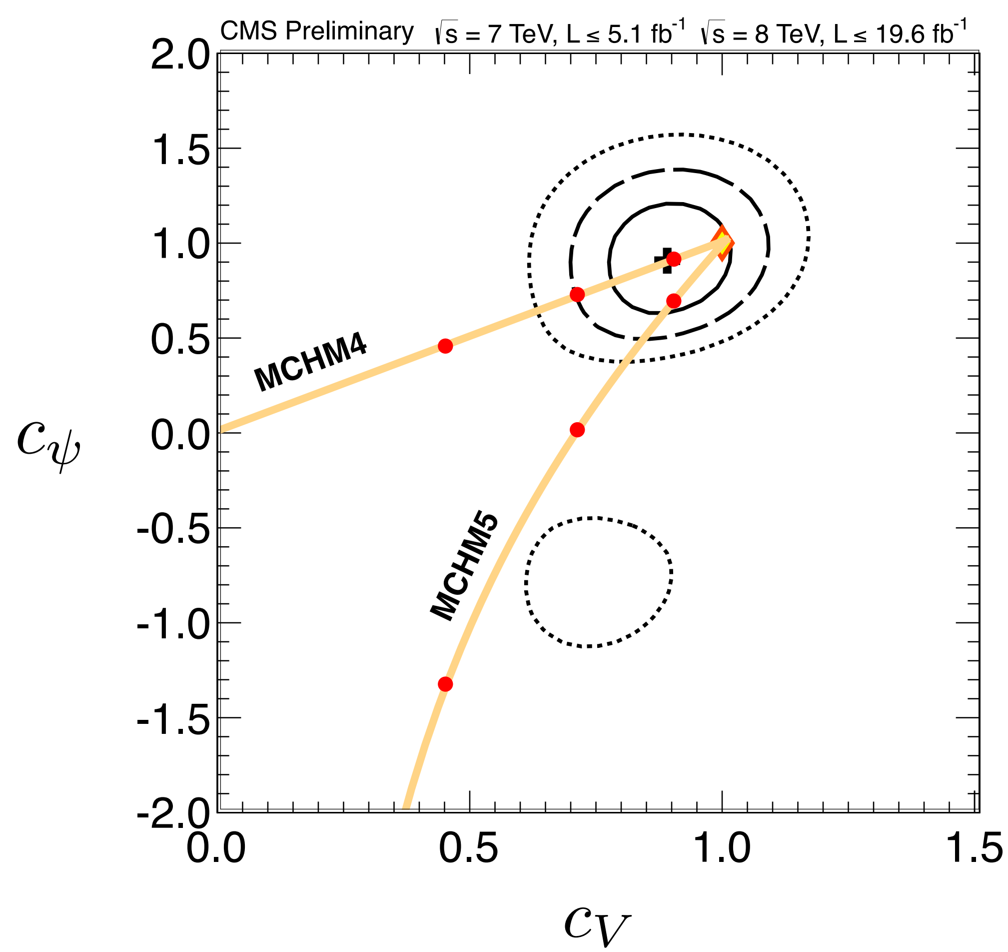
$$\boxed{\xi \equiv \frac{v^2}{f^2}}$$

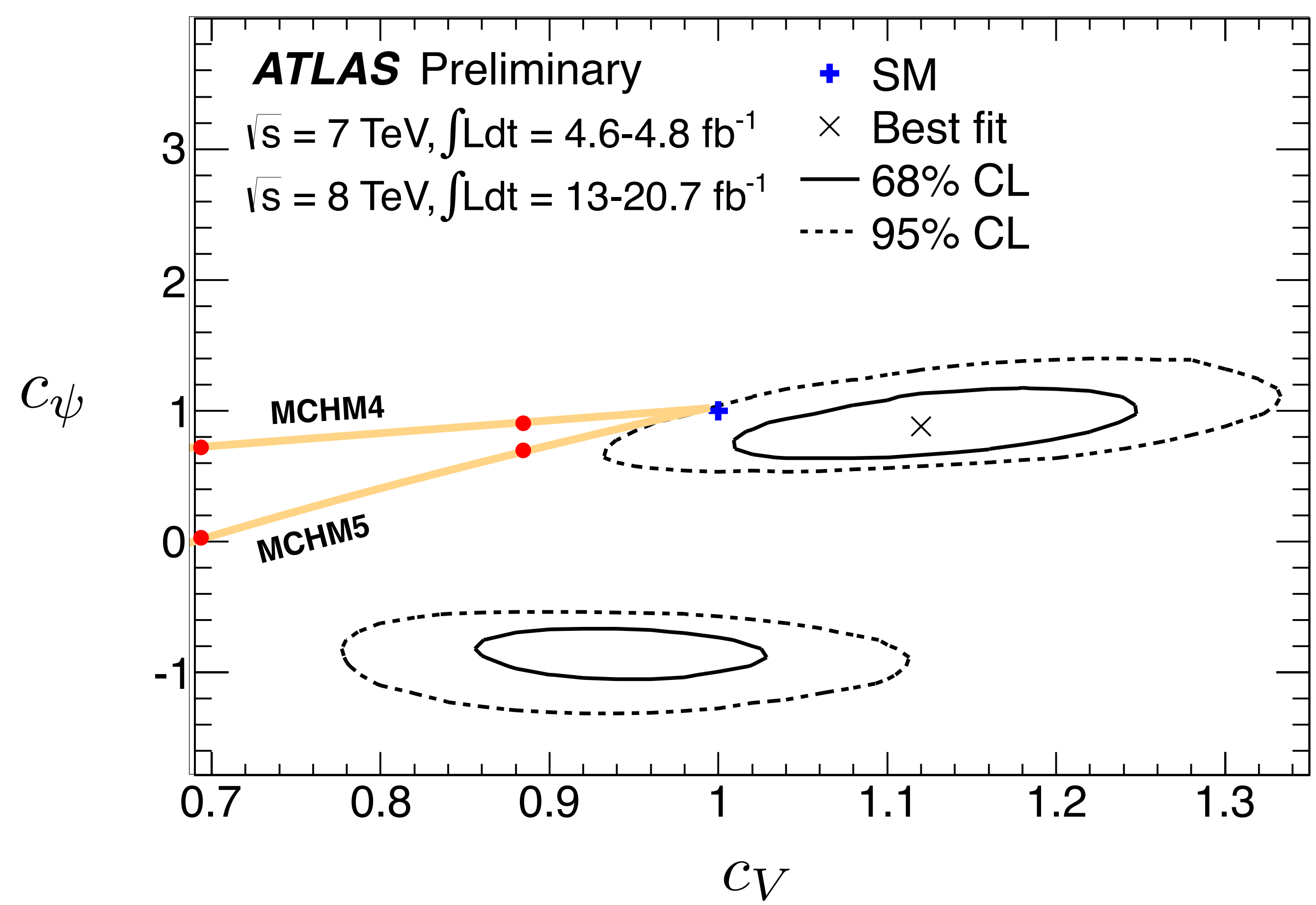
MCHM4: $c_V = c_\psi = \sqrt{1-\xi}$

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

MCHM5: $c_V = \sqrt{1-\xi} \qquad c_\psi = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

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





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

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

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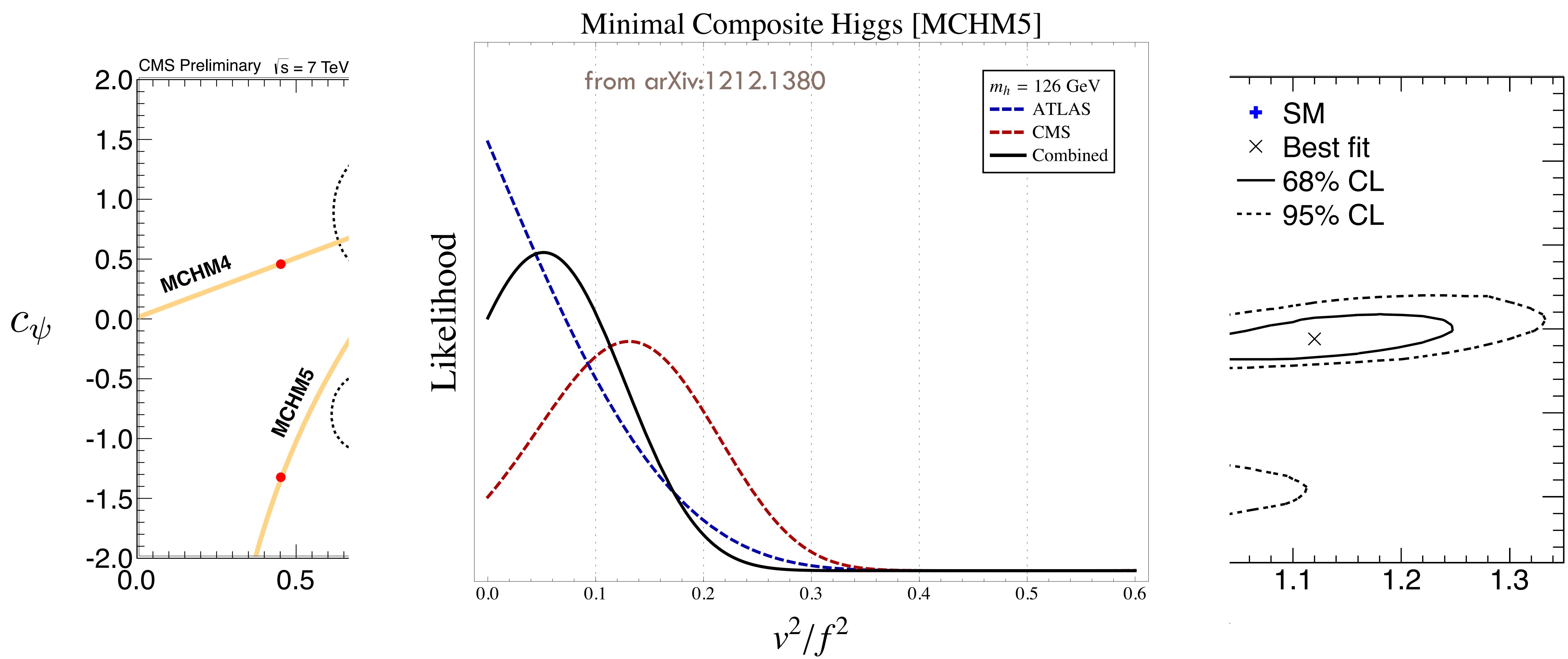

$\xi = (v/f)^2 < 0.22$ **at 95%** ➡ $m_{\rm new} \gtrsim 1.6\ \text{TeV}\left(\frac{g_*}{3}\right)$

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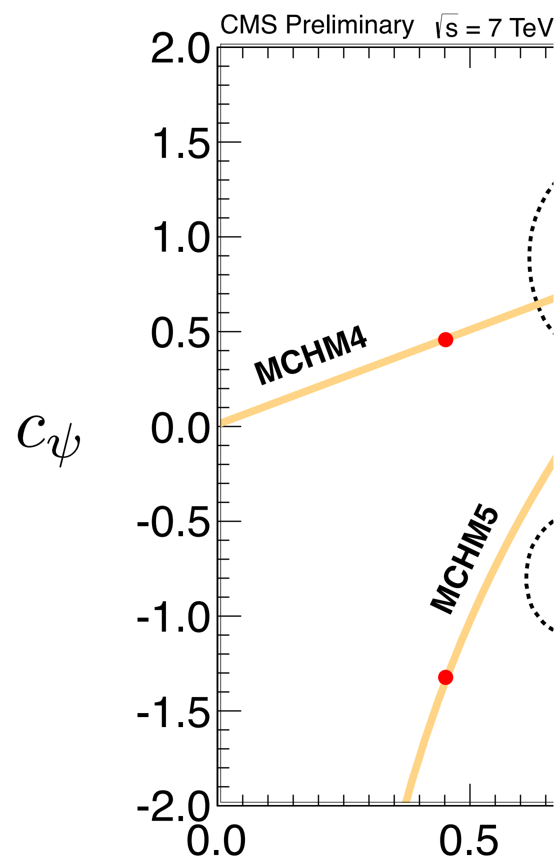
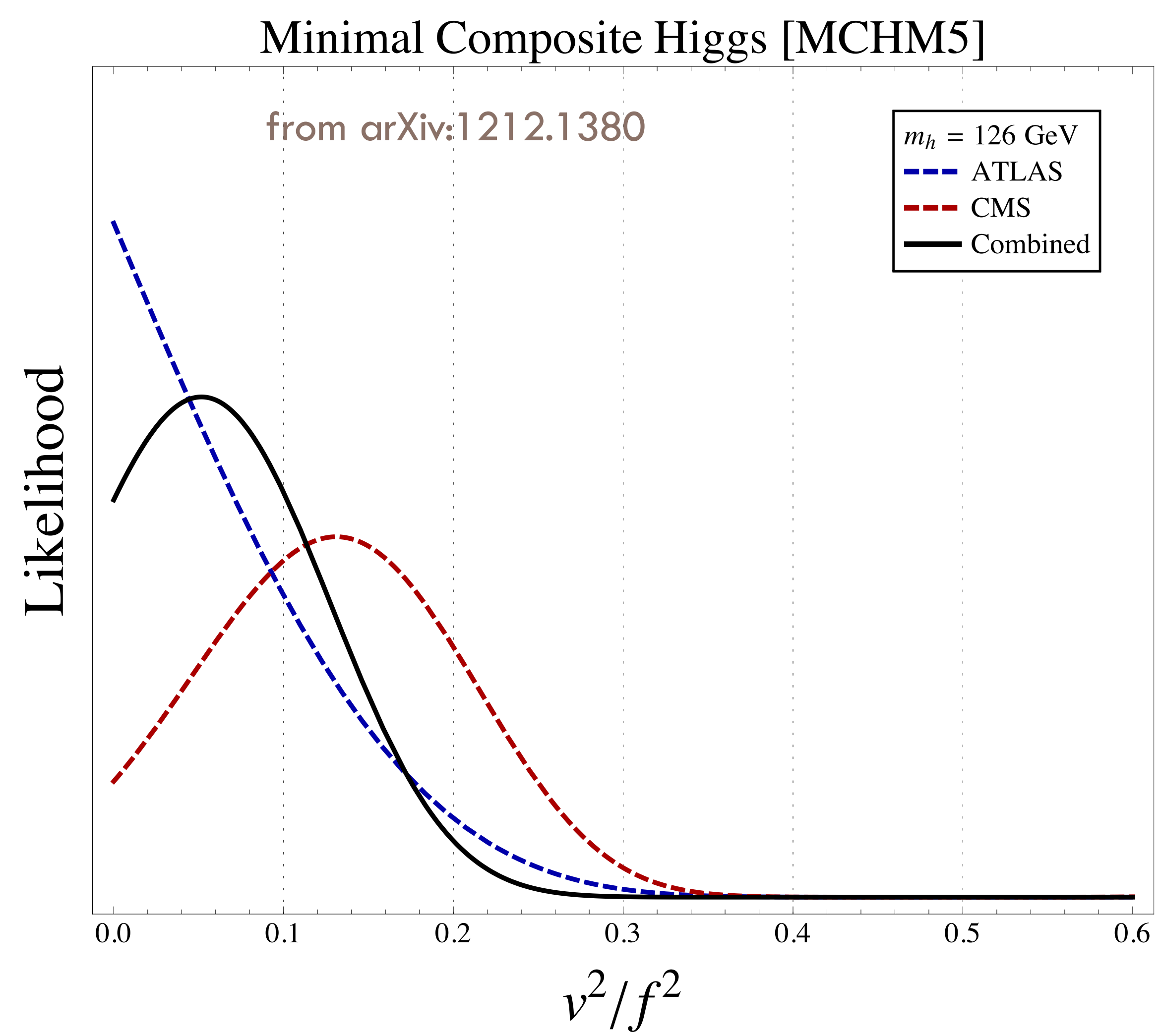
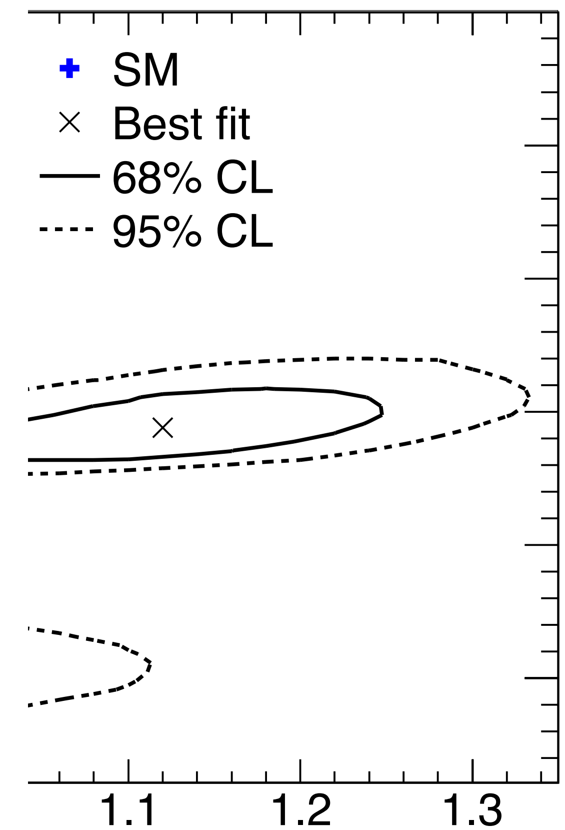


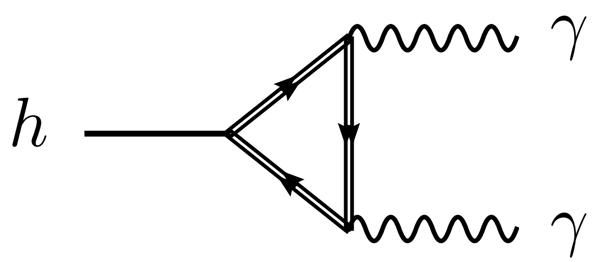




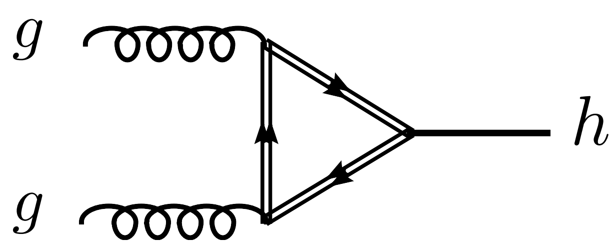
$\xi = (v/f)^2 < 0.22$ at 95% ⇒ $m_{\rm new} \gtrsim 1.6\,\mathrm{TeV}\left(\frac{g_*}{3}\right)$

Sensitivity comparable to direct searches

- Modifications to loop-level couplings *ggh*, $\gamma\gamma h$ suppressed due to the Goldstone symmetry



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



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Effective operators violate the Higgs shift symmetry:

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

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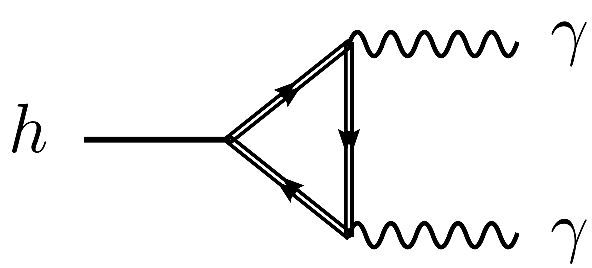

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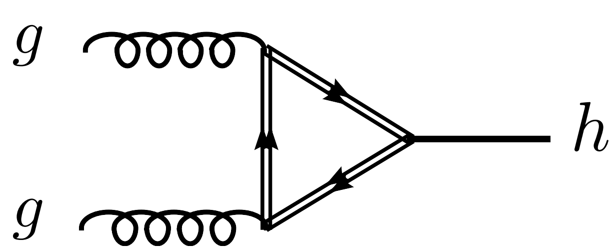

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$$\boxed{\frac{\delta\Gamma}{\Gamma_{SM}} = 1 + O\left(\frac{v^2}{f^2}\right) + O\left(\frac{g_*^2 v^2}{m_*^2} \times \frac{\lambda^2}{g_*^2}\right)}$$

'long-distance'
SM loops with modified couplings

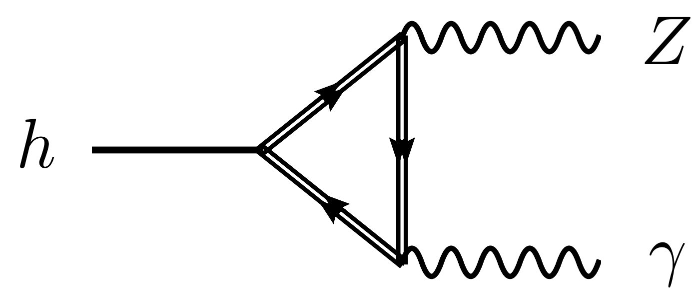
'short-distance'
loops of top partners

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

Azatov, RC , Di Iura, Galloway, arXiv:1308.2676

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

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



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1. Invariant under Higgs shift symmetry
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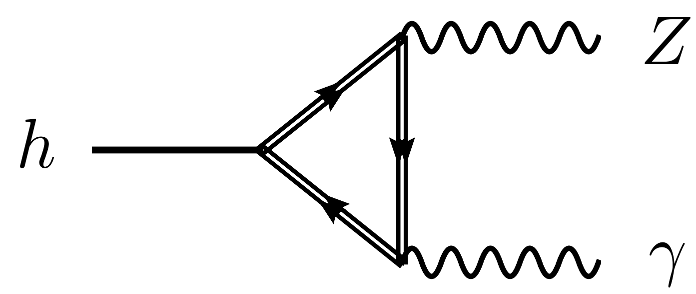

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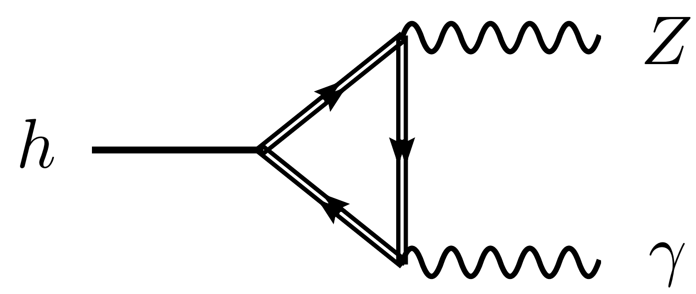

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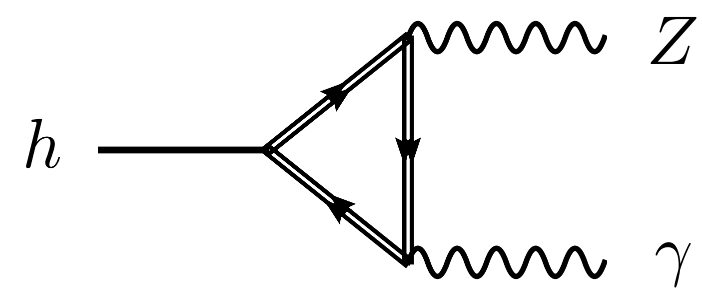

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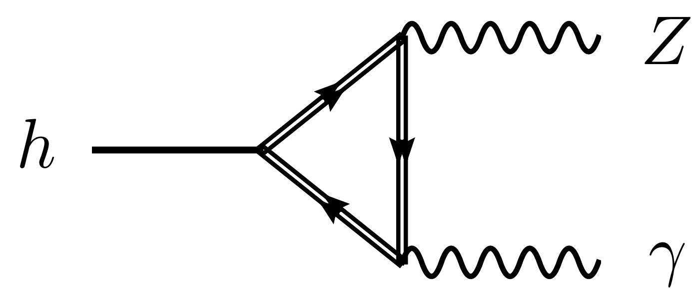

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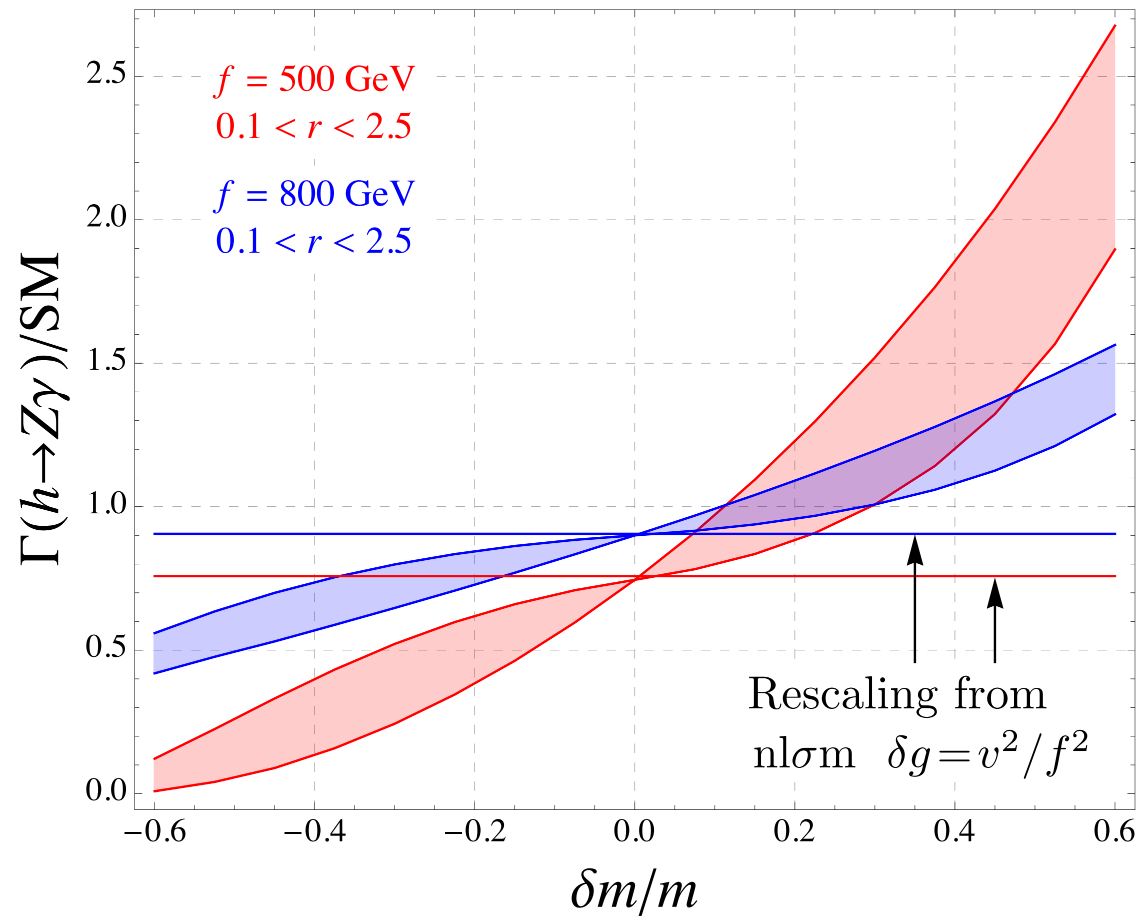

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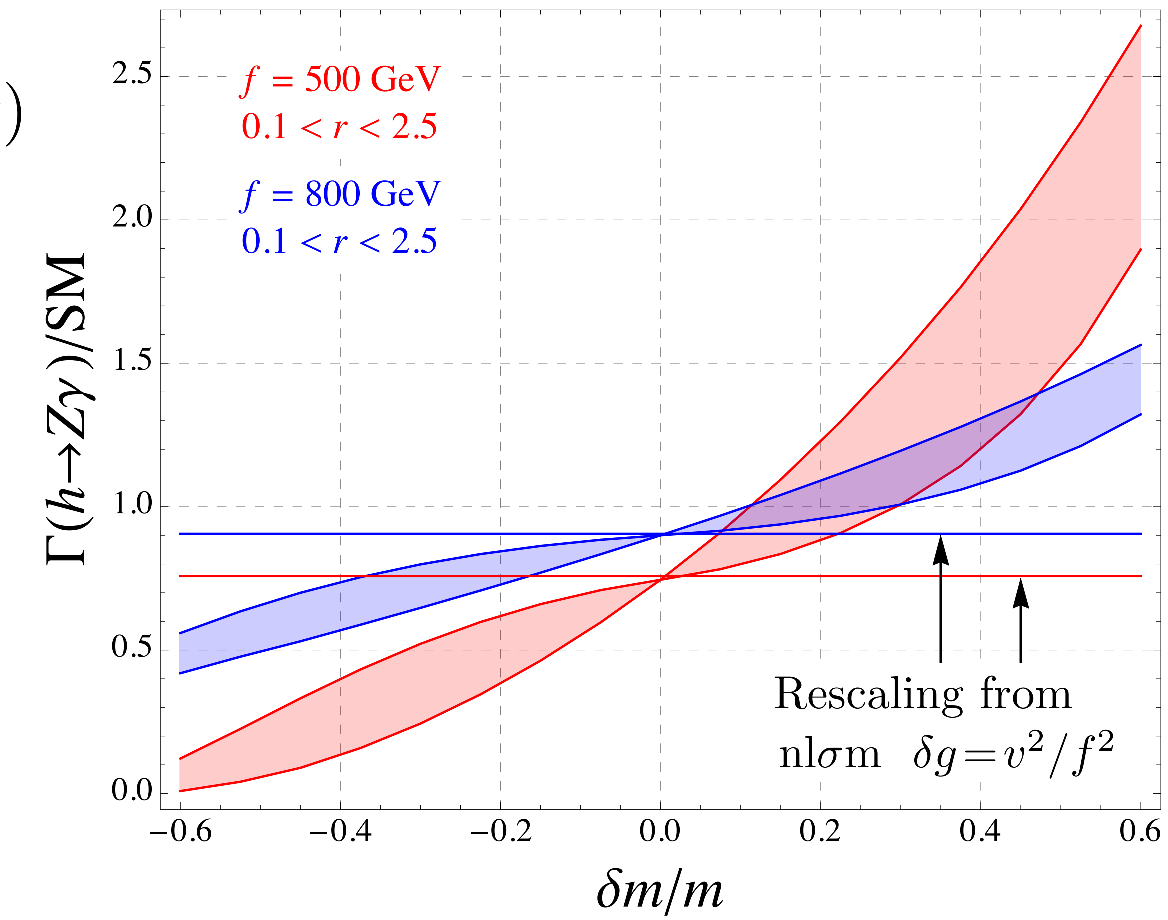

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See talk by A. Azatov on Friday

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- Higgs mass term (FT)

Finite in CH $$m_H^2 \sim \frac{3\lambda^2}{8\pi^2} m_*^2$$

Log divergent in SUSY $$m_{H_u}^2 \sim \frac{3y_t^2}{4\pi^2}\, m_{\tilde{t}}^2 \,\log \frac{\Lambda^2}{m_{\tilde{t}}^2}$$

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- Higgs quartic coupling

CH: tends to be too *large* $$\lambda_4 \sim \frac{3}{8\pi^2}\, g_*^3 y_t$$

SUSY: tends to be too *small* $$\lambda_4 \simeq \frac{g^2+g'^2}{4} + \frac{3y_t^4}{8\pi^2}\, \log\frac{m_{\tilde{t}}^2}{m_t^2}$$

Summary: CH vs SUSY

- Bounds on "top partners" from direct searches

SUSY: stops $\gtrsim 700\,\mathrm{GeV}$

CH: heavy tops/bottoms $\gtrsim 1\,\mathrm{TeV}$

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- Largest effects in Higgs sector expected in:

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

  CH: tree-level couplings; $h \to Z\gamma$ rate; double Higgs production ($gg \to hh$)