Composite Higgs Sketch

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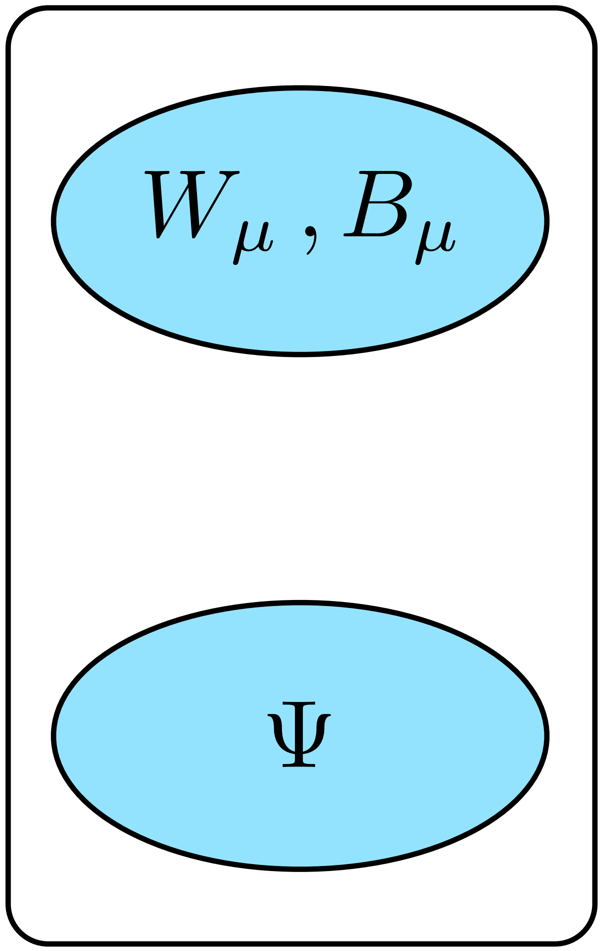
based on a work with
C. Csaki, J. Hubisz, J. Serra & J. Terning

CERN
TH Summer Institute, June 25th 2012

Composite Sketch

EWSB-sector

gauge-sect.



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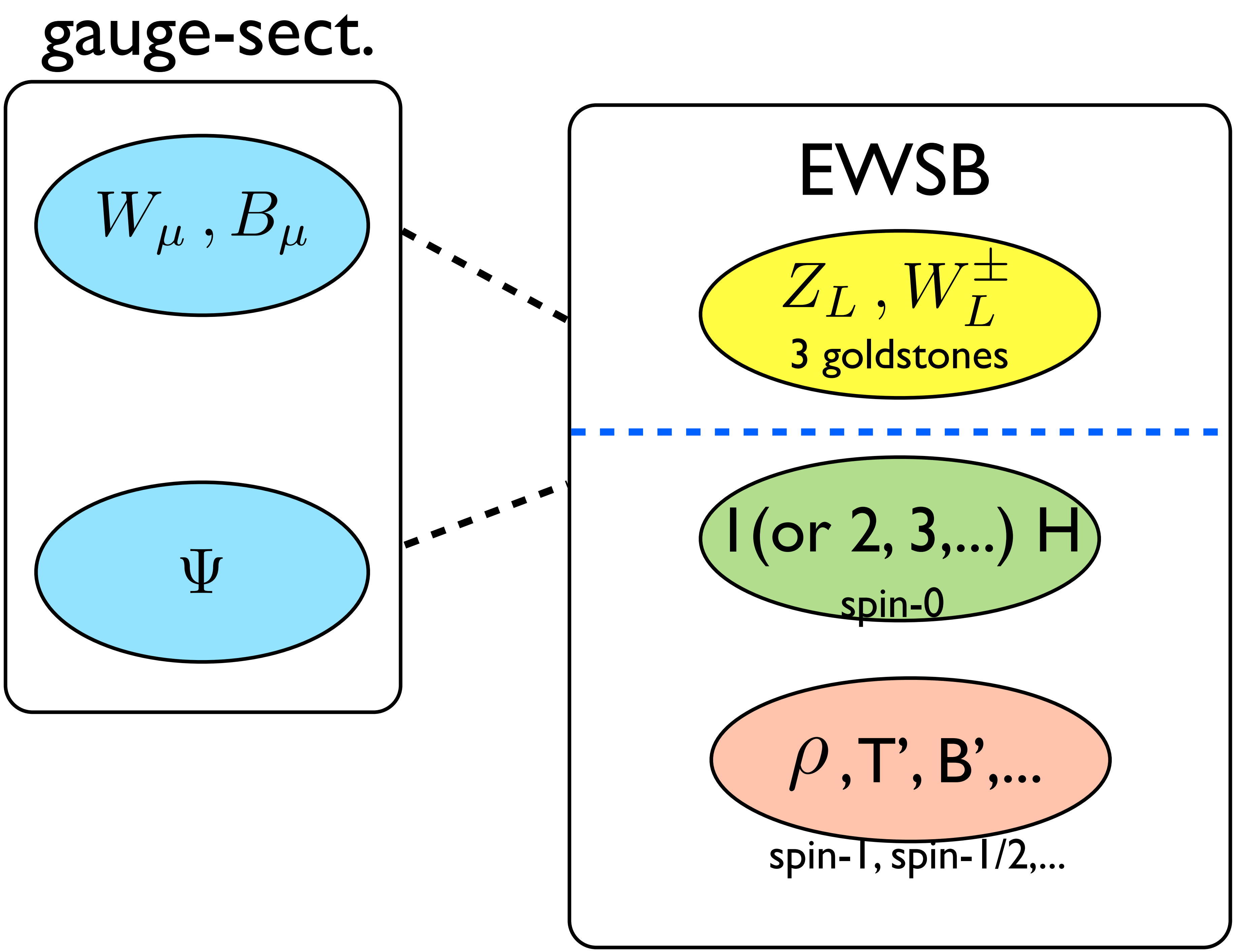
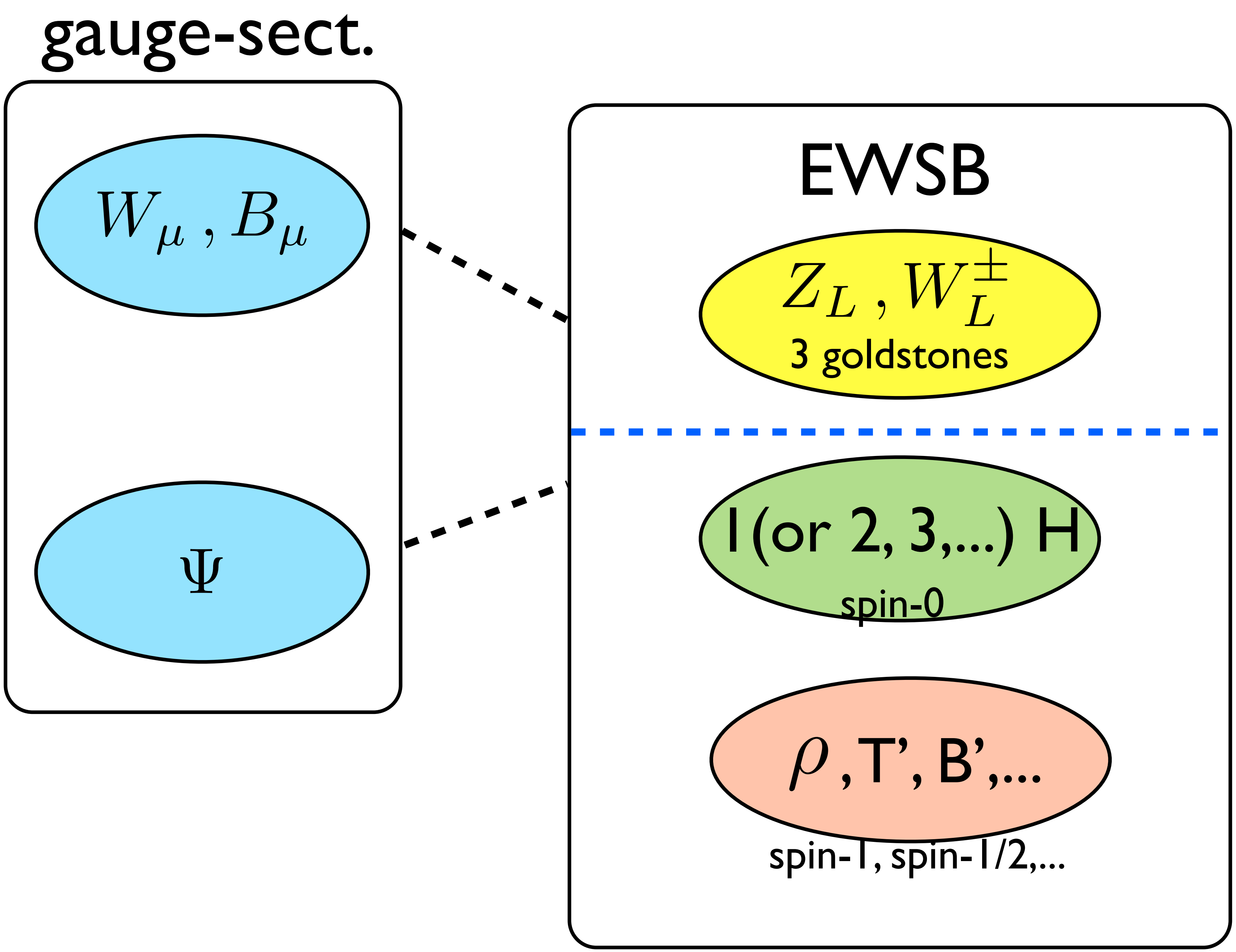

gauge-sect.
$W_\mu \, , B_\mu$
Ψ
EWSB
$Z_L \, , W_L^\pm$
3 goldstones
1 (or 2, 3,...) H
spin-0
ρ , T', B',...
spin-1, spin-1/2,...

EWSB-sector

$$\rho - 1 = 0.00\ldots$$



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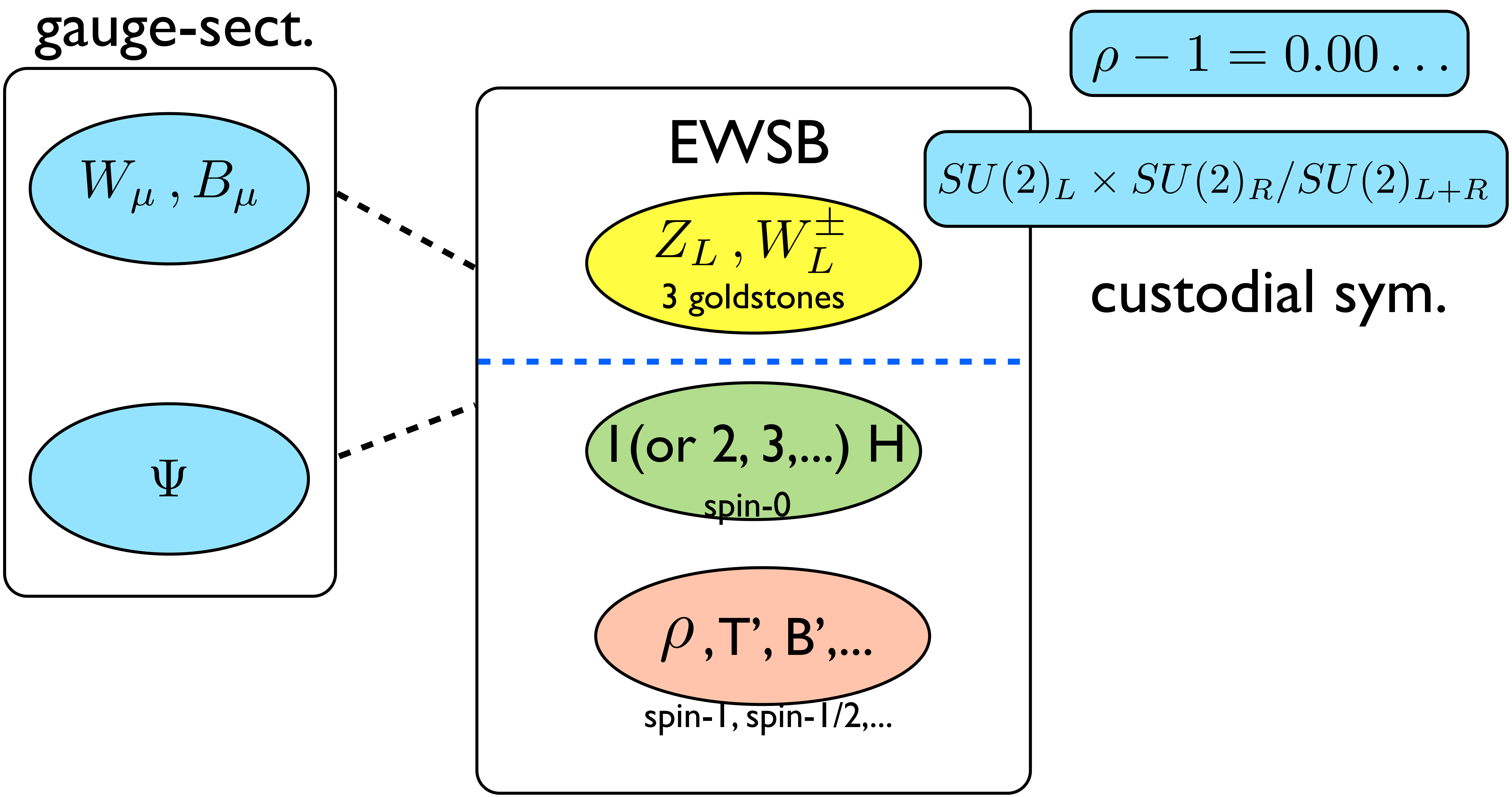
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$SU(2)_L \times SU(2)_R / SU(2)_{L+R}$
custodial sym.

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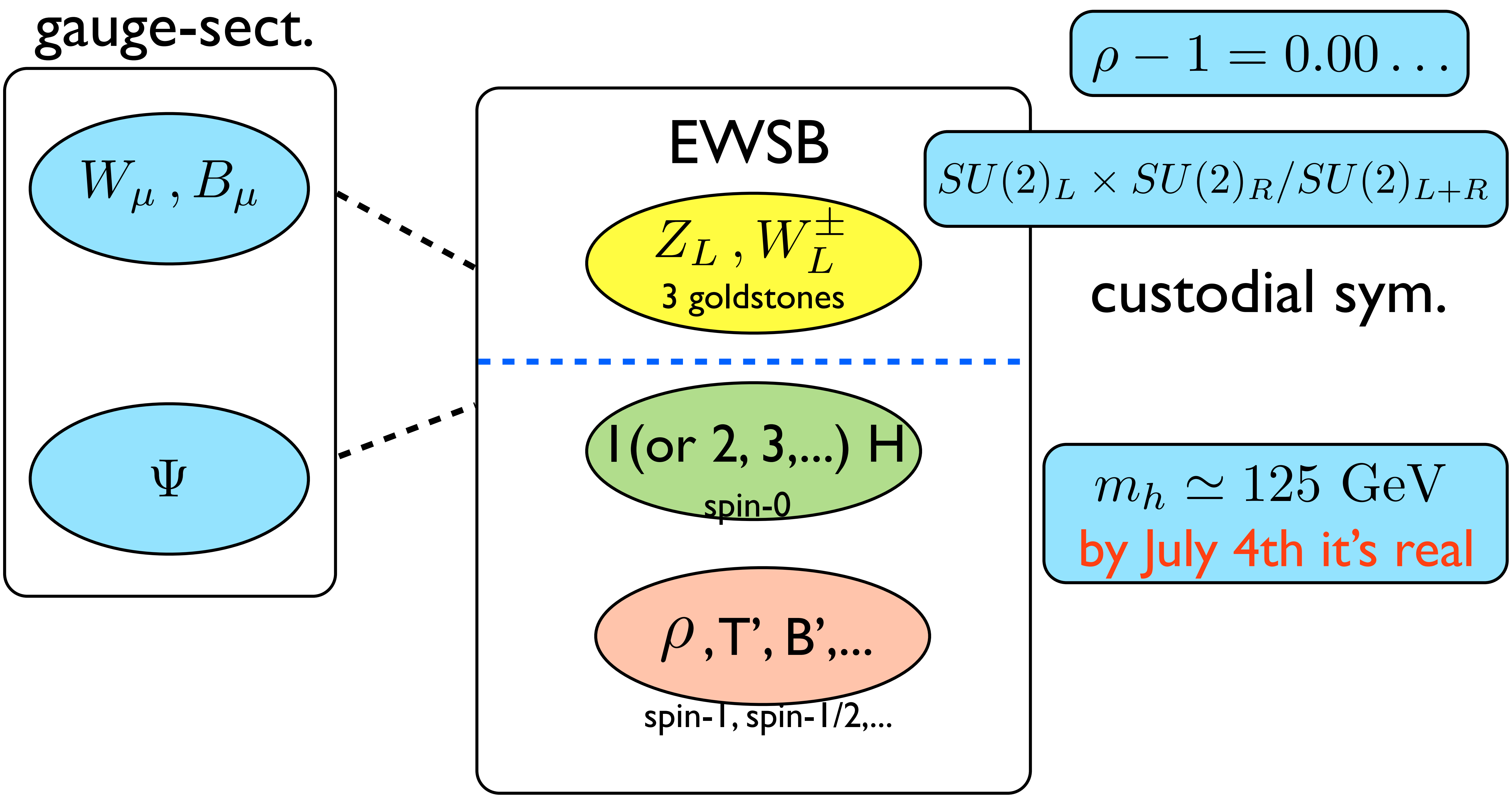
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$SU(2)_L \times SU(2)_R / SU(2)_{L+R}$
custodial sym.
$m_h \simeq 125 \text{ GeV}$
by July 4th it's real

EW-Chiral Lagrangian

expansion in derivatives

EW-Chiral Lagrangian

expansion in derivatives

$$\begin{aligned}\mathcal{L} =& \frac{v^2}{4}|D_\mu \Sigma|^2 \left(1 + 2a\frac{h}{v} + b^2\frac{h^2}{v^2} + \ldots\right) \\ & - \sum m_f \bar{f} f \left(1 + c_f \frac{h}{v} + \ldots\right) \\ & + \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{2v} m_h^2 h^3 + \ldots\end{aligned} \quad \Bigg] \; \mathcal{O}(p^2)$$

$$+ c_\gamma \frac{\alpha}{\pi v} h F_{\mu\nu}^2 + + c_g \frac{\alpha_s}{12\pi v} h G_{\mu\nu}^2 + \ldots \quad \Big] \; \mathcal{O}(p^4)$$

$$+ \ldots \quad \Big] \; \mathcal{O}(p^6)$$

EW-Chiral Lagrangian

expansion in derivatives

$$\mathcal{L} = \frac{v^2}{4}|D_\mu \Sigma|^2 \left(1 + 2a\frac{h}{v} + b^2\frac{h^2}{v^2} + \dots\right)$$

$$- \sum m_f \bar{f} f \left(1 + c_f \frac{h}{v} + \dots\right)$$

$$+ \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_3}{2v} m_h^2 h^3 + \dots$$

$\mathcal{O}(p^2)$

$$\boxed{m_h \simeq 125 \text{ GeV}}$$

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$$\boxed{m_h \simeq 125 \text{ GeV}}$$

$$a\ ,\ b\ ,\ c_f\ ,\ d_3\ ,\ c_g\ ,\ c_\gamma\ \ldots = ??$$

$$+ c_\gamma \frac{\alpha}{\pi v} h F_{\mu\nu}^2 + + c_g \frac{\alpha_s}{12\pi v} h G_{\mu\nu}^2 + \ldots \quad \Big] \quad \mathcal{O}(p^4)$$

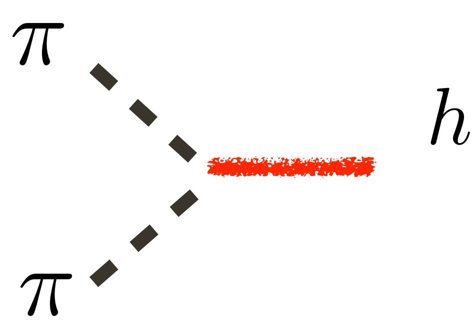
$$+ \ldots \quad \Big] \quad \mathcal{O}(p^6)$$

EW-Chiral Lagrangian

$$\mathcal{L}_{eff} = a\left(\frac{m_Z^2}{v}Z_\mu^2 + \frac{2m_W^2}{v}W_\mu^2\right)h + c_f\frac{m_f}{v}\bar{f}fh + c_\gamma\frac{\alpha}{\pi v}hF_{\mu\nu}^2 + c_g\frac{\alpha_s}{12\pi v}hG_{\mu\nu}^2$$

EW-Chiral Lagrangian

controls the hWW and hZZ vertex



$$= a\, g_{VVh}^{\mathrm{S}M}$$

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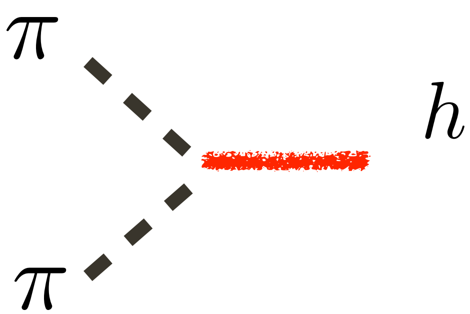

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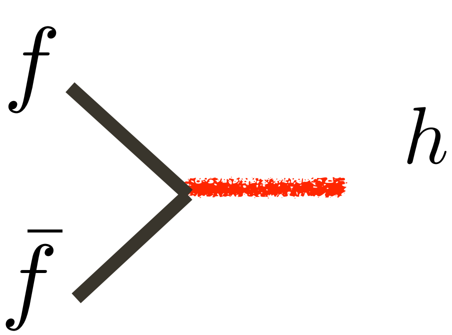
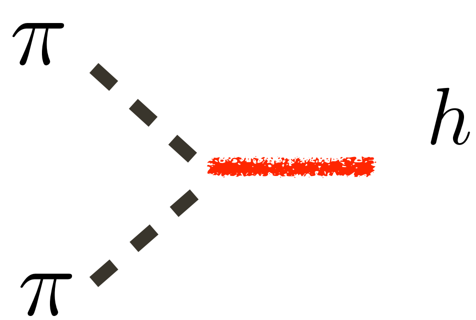
controls the $h\bar{f}f$ vertex



$$= c_f\, g^{\mathrm{SM}}_{\bar{f}fh}$$

EW-Chiral Lagrangian

controls the hWW and hZZ vertex



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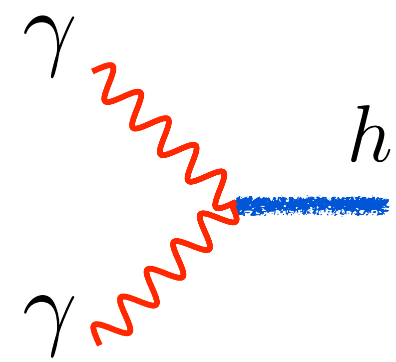
$\gamma\gamma$ decay



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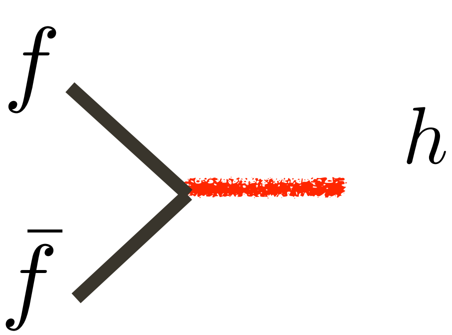

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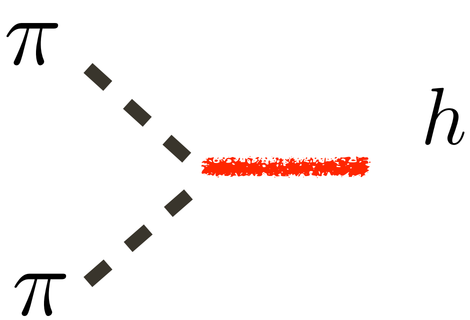

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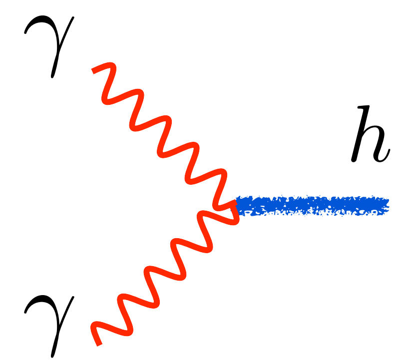

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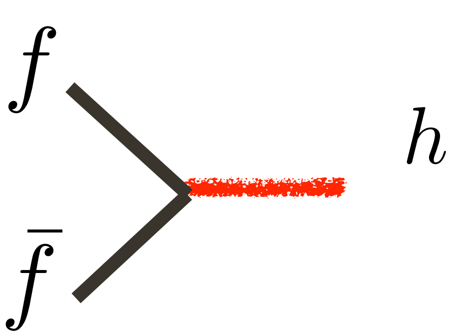
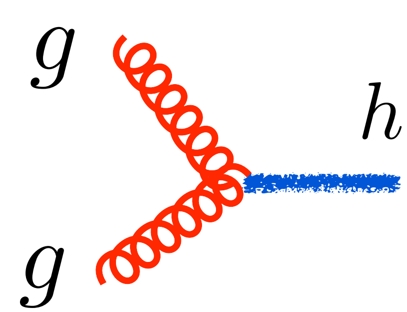


$$= c_f\, g^{SM}_{\bar{f}fh}$$

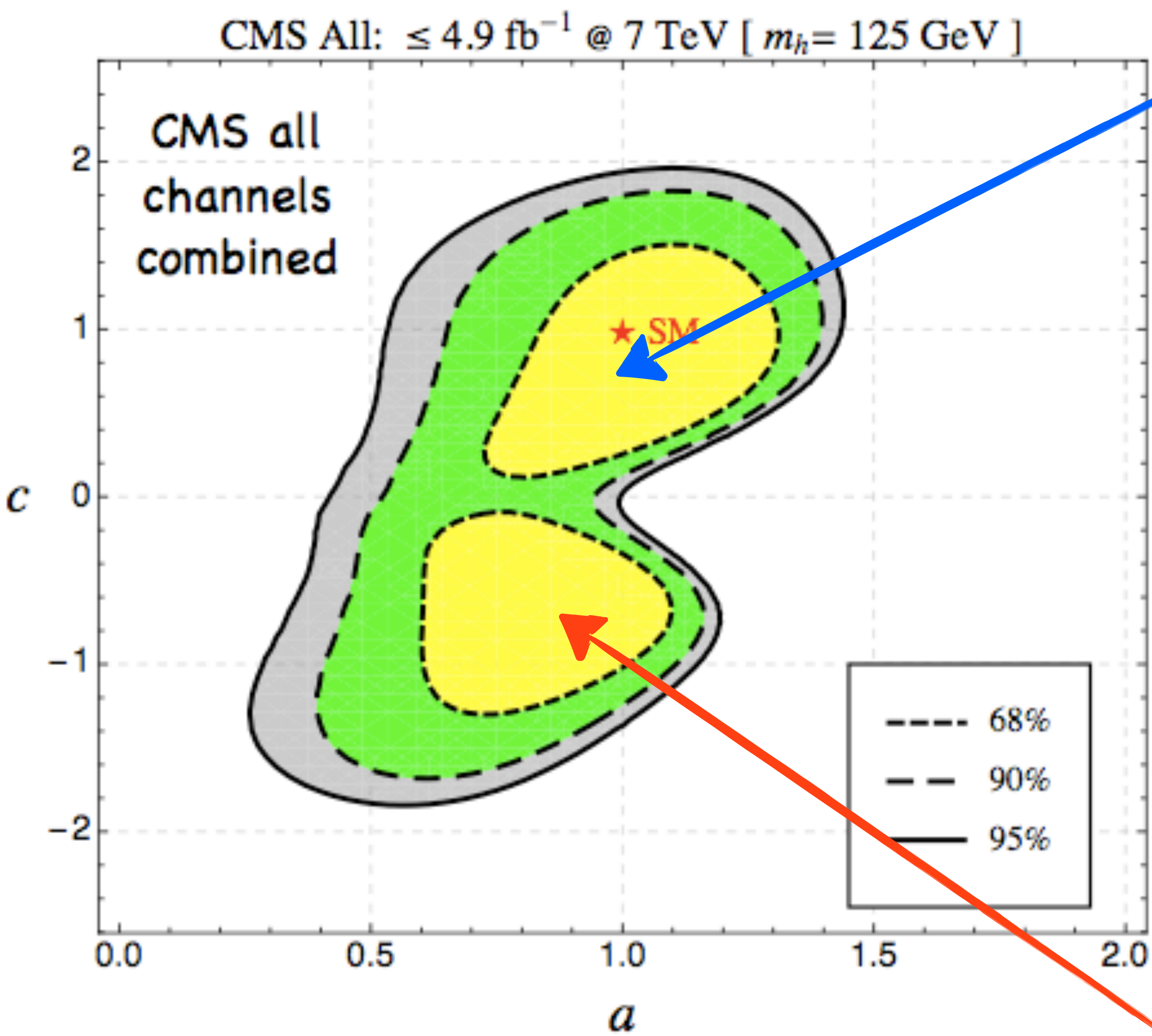
ggh and gluon fusion

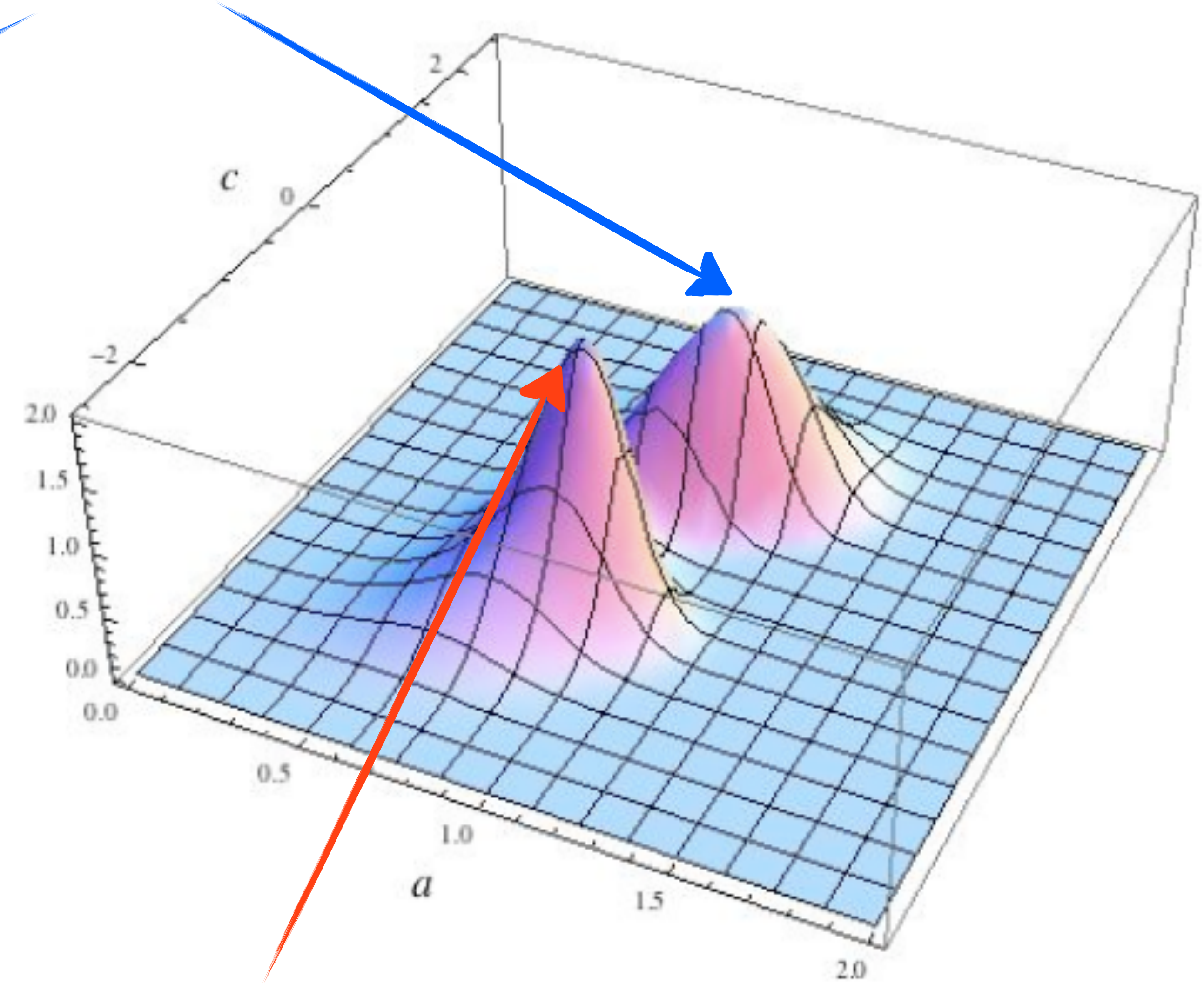


$$= c_g$$

fitting data

$a=1.0,\ c=0.75$





see e.g. Azatov, Contino, Galloway, [1202.3415]

$a=0.85,\ c=-0.6$

dysfermiofilia?

Where is new physics?

Where is new physics?

unitarity arguments!

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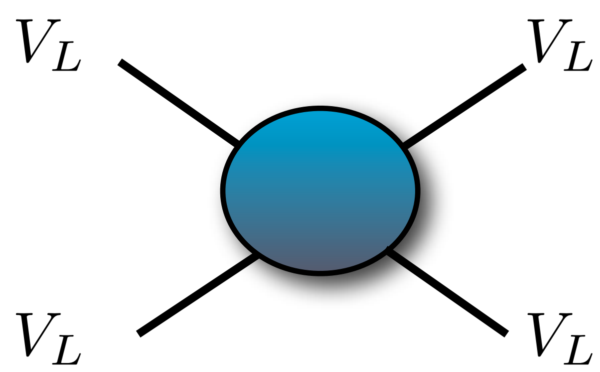
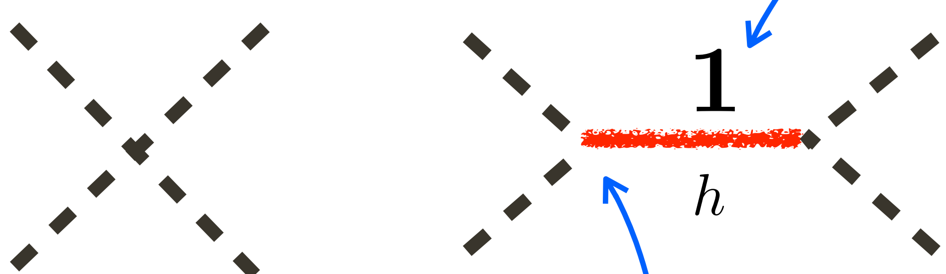


$$\mathbf{3} \times \mathbf{3} = \mathbf{1} + \mathbf{3} + \mathbf{5}$$



+ crossing

$$\mathcal{A} \sim (1 - a^2)\frac{s}{v^2}$$

$$|D_\mu \Sigma|^2 \left(1 + 2a\frac{h}{v} + \ldots\right)$$

$$\Lambda \approx \frac{4\pi v}{\sqrt{1-a^2}} \ll \Lambda_{SM} \sim \infty$$

Examples

- SM-Higgs $a^2 = 1$ $\Lambda = \infty$
- THDM $a_{h1}^2 + a_{h2}^2 = 1$ $\Lambda = \infty$
- pNGB $a^2 = 1 - \frac{v^2}{f^2}$ $\Lambda = 4\pi f$
- Dilaton $a^2 = \frac{v^2}{f^2}$ $\Lambda = \frac{4\pi v}{\sqrt{1 - v^2/f^2}}$

Resonances

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- add new resonances coupled to the Pi's
  (the first ones that go strong)

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Delay the onset of strong dynamics

Increase the cutoff

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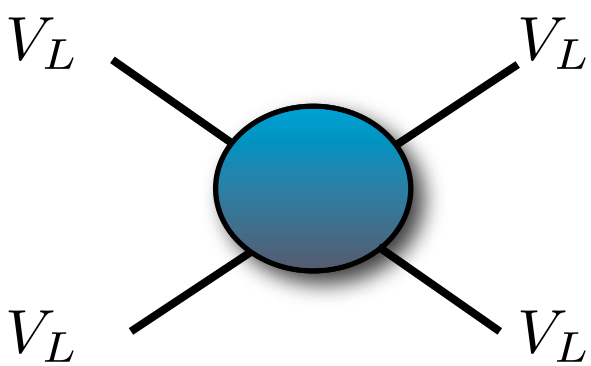
Delay the onset of strong dynamics

Increase the cutoff

familiar example: the SM Higgs

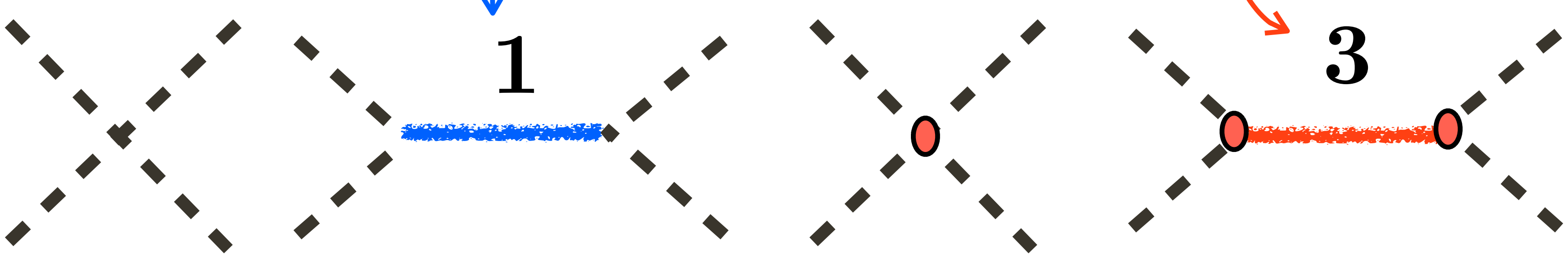
Higgsless $\Lambda \sim 4\pi v$ → Higgs $\Lambda = \infty$

UV-Moderators



$$\mathbf{3} \times \mathbf{3} = \mathbf{1} + \mathbf{3} + \mathbf{5}$$

$$\left(1 - a^2 - \frac{3}{4} a_\rho^2\right) \frac{s}{v^2}$$



+ crossing

$$-\frac{1}{4 g_\rho^2} \rho_{\mu\nu}^2 + a_\rho^2 \frac{v^2}{2} \left[\rho_\mu^2 + (\vec{\rho}_\mu \times \partial_\mu \vec{\pi}) \cdot \vec{\pi} + \frac{1}{2} (\vec{\pi} \times \partial_\mu \vec{\pi})^2 + \ldots \right]$$

Examples

- QCD (vmd) $a_\rho^2 \approx 2$ $\Lambda \sim m_\rho$
- Higgsless $\sum_N \frac{3}{4} a_{\rho_N}^2 = 1$ $\Lambda \gg 4\pi v$

  Csaki et al. hep-ph/0305237

$\Lambda_{NDA} \sim \Lambda_{unitary}$ $\sqrt{s} \lesssim 2m_\rho$

inelastic threshold

Adding a vector

one spin-1 below the cutoff (techni-rho, KK-W, ...)

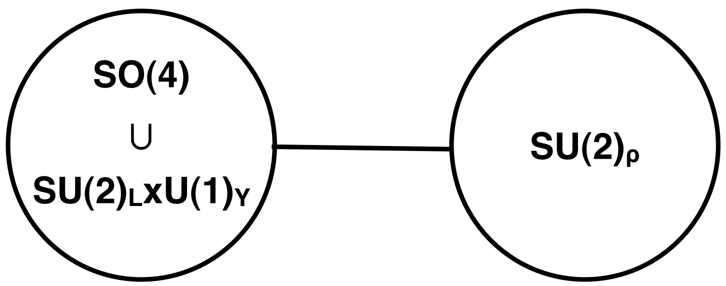
ρ_μ as gauge vector $\rho \longrightarrow h\rho h^\dagger - ih\partial_\mu h$

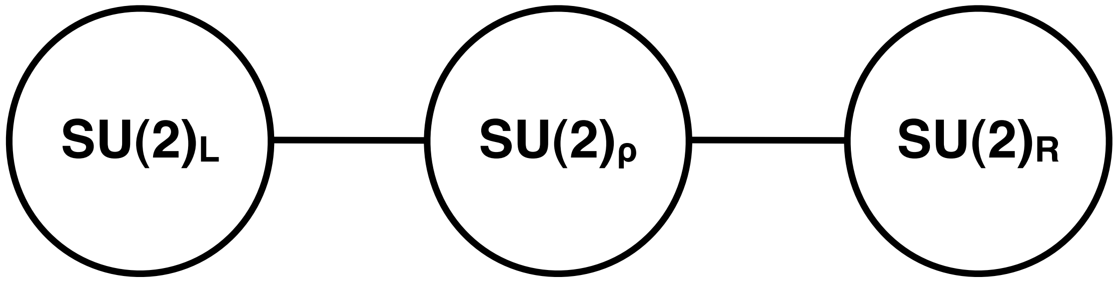
$h \in H \subset \mathrm{custodial}$

- UV-behavior $\rho_L \longrightarrow \partial\eta$
- no weird NDA $\mathcal{L} \not\ni \dfrac{\mathcal{O}}{m_\rho^\#}$
- perturbative limit $\Sigma = e^{i\pi} \longrightarrow e^{i\pi}(1 + \dfrac{h}{v})$
- easy (e.g. to implement on MC)

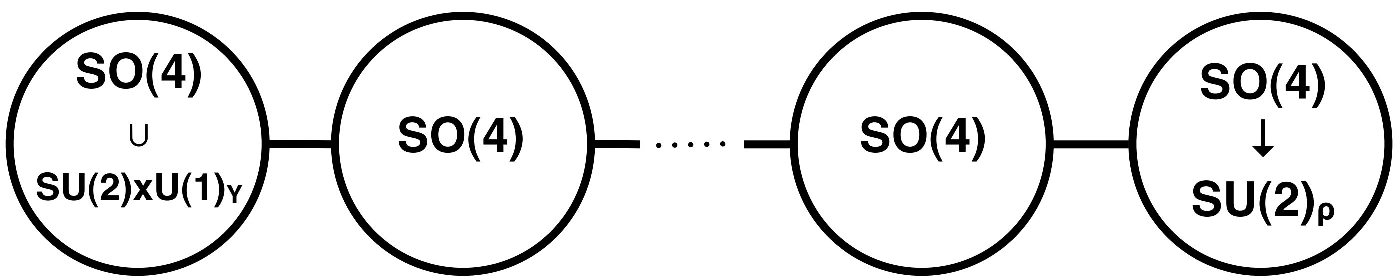
EXAMPLES

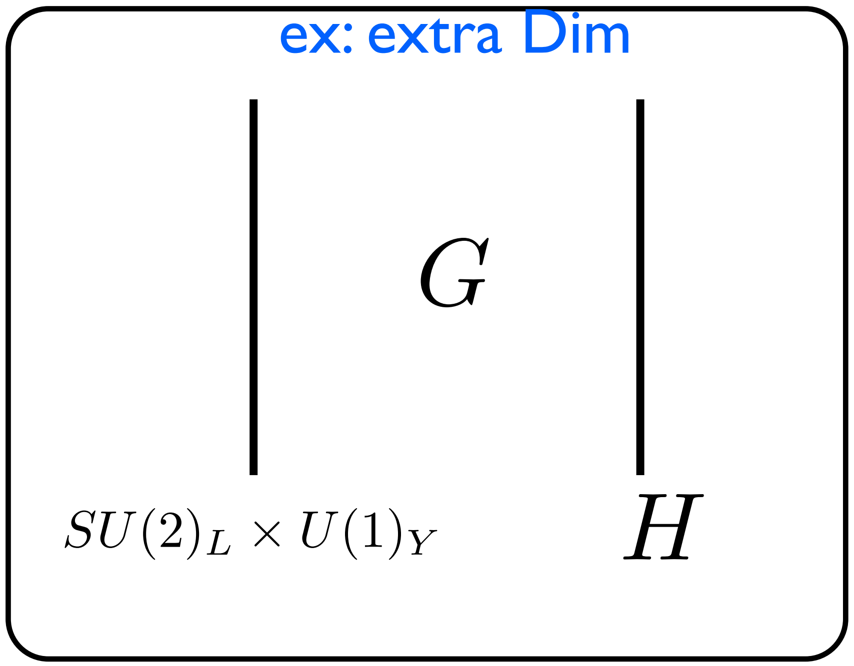
minimal mose



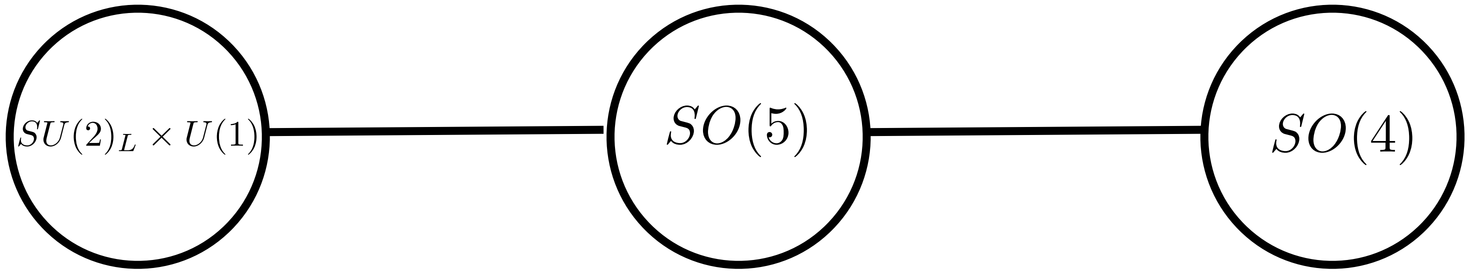


more sites

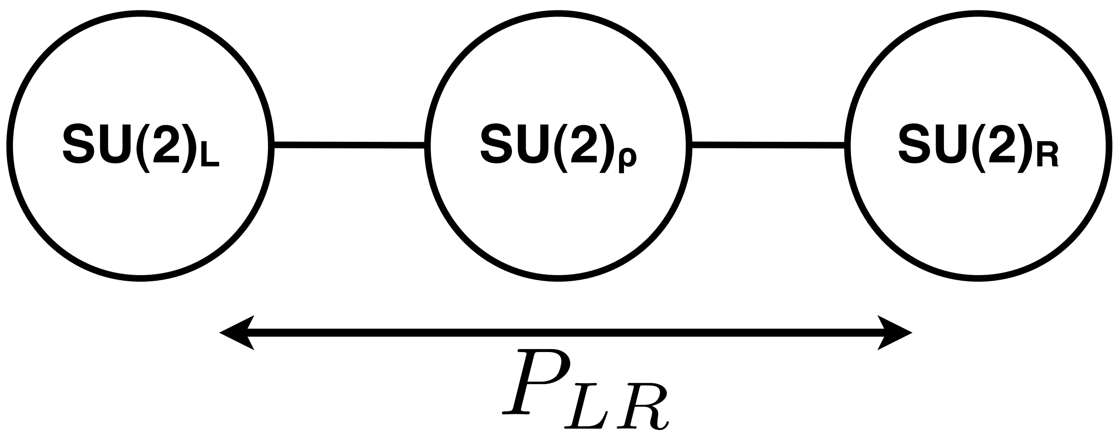




larger groups

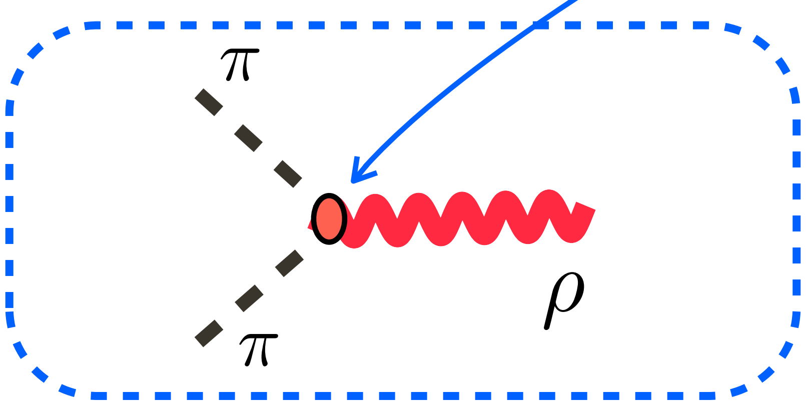


MINIMAL+Z2



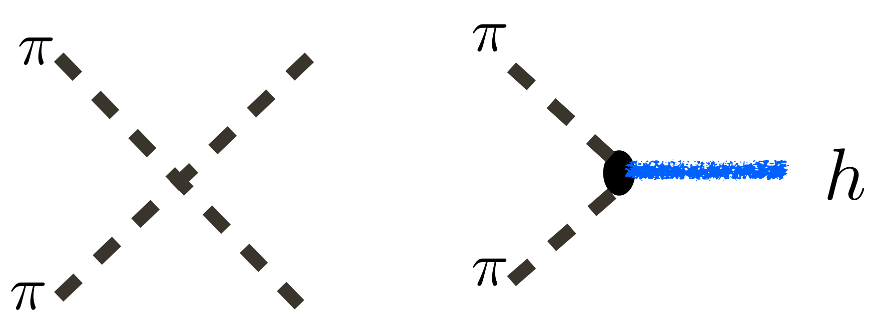
spin-1: couples to the conserved custodial current

$$g_\rho \rho^a_\mu J^a_{C\,\mu} = g_\rho a_\rho^2 \epsilon^{abc} \rho^a_\mu \partial_\mu \pi^b \pi^c + \ldots$$



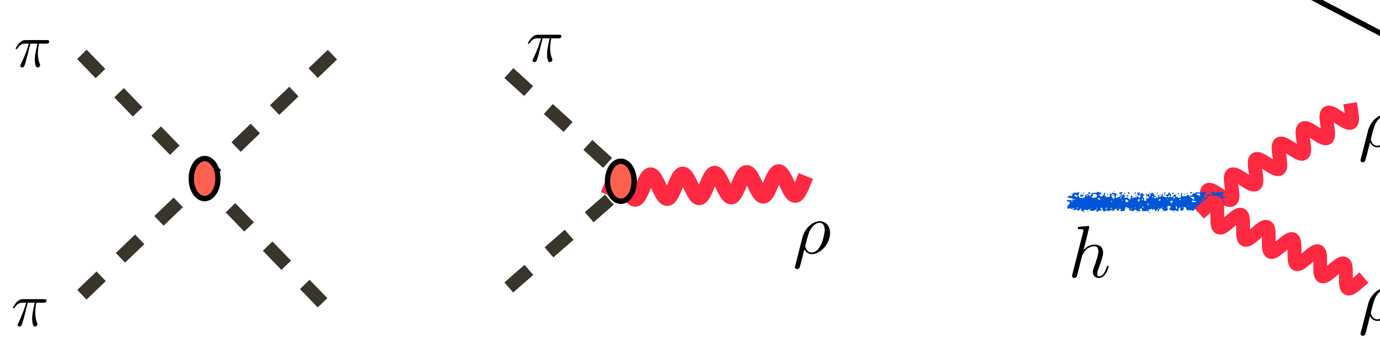
Higgs+vector

Higgs: $$|D_\mu\Sigma|^2\left(1+2a\frac{h}{v}+\dots\right)+c_t h\bar{t}t+\dots$$



spin-1: $$-\frac{1}{4g_\rho^2}\rho_{\mu\nu}^2+\frac{a_\rho^2 v^2}{2}\left(\rho_\mu^a+\dots\right)^2\left[1+2c_\rho\frac{h}{v}+\dots\right]$$

$$\vec{\pi}\times\partial_\mu\vec{\pi}+\dots$$



SUM RULES

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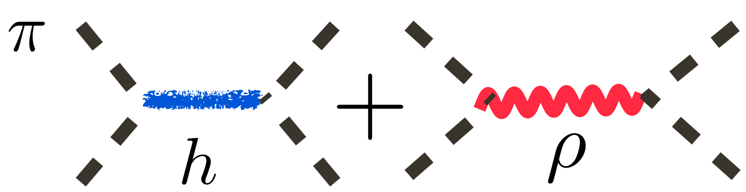
elastic sum-rule

$$\pi\pi \longrightarrow \pi\pi$$



$$a^2 + \frac{3}{4}a_\rho^2 = 1$$

$$A \sim (1 - a^2 - \frac{3}{4}a_\rho^2)\frac{s}{v^2}$$

SUM RULES

elastic sum-rule

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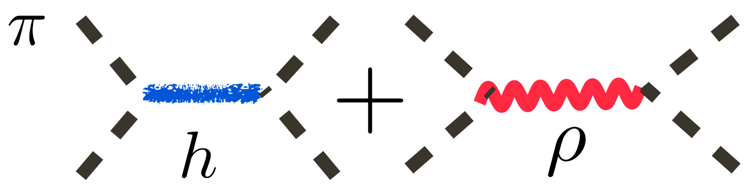

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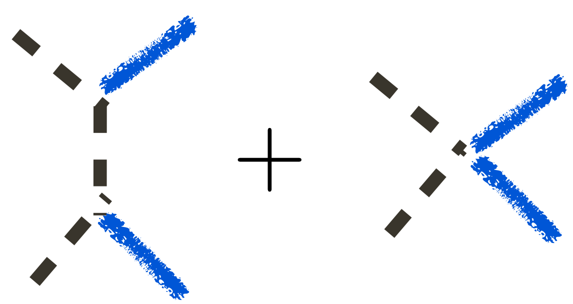
inelastic sum-rule

$$\pi\pi \longrightarrow hh$$



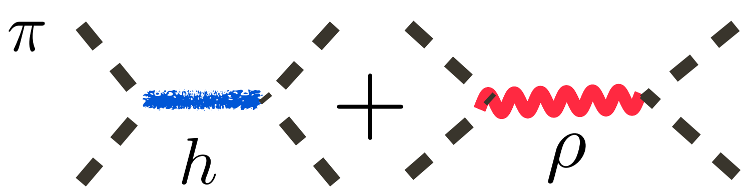
$$a^2 = b$$

$$\mathcal{A} \sim (a^2 - b) \frac{s}{v^2}$$

SUM RULES

elastic sum-rule

$$\pi\pi \to \pi\pi$$



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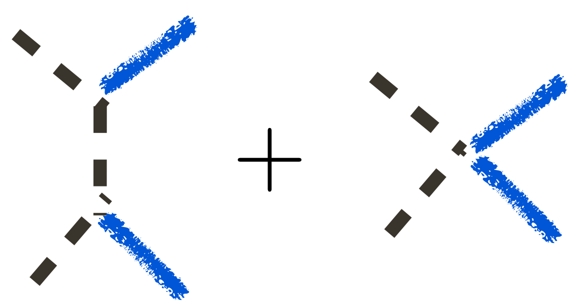

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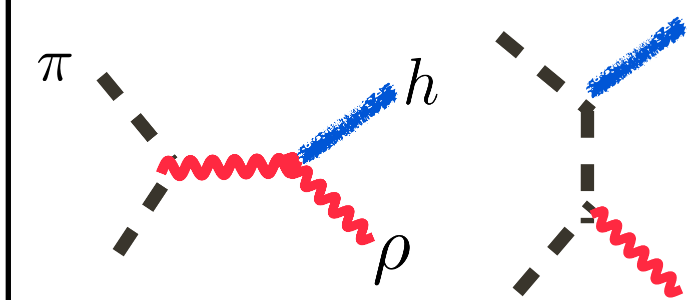
inelastic sum-rule

$$\pi\pi \to \rho_L h$$

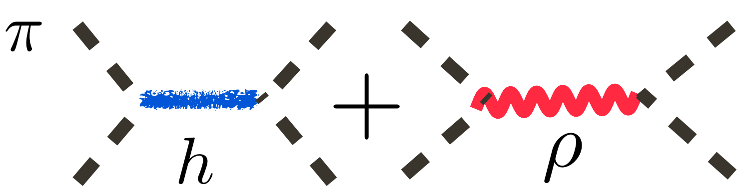


$$a = c_\rho$$

$$\mathcal{A} \sim i\frac{t-u}{2v^2}(a - c_\rho)a_\rho$$

SUM RULES

elastic sum-rule	inelastic sum-rule	inelastic sum-rule
$\pi\pi \to \pi\pi$	$\pi\pi \to hh$	$\pi\pi \to \rho_L h$



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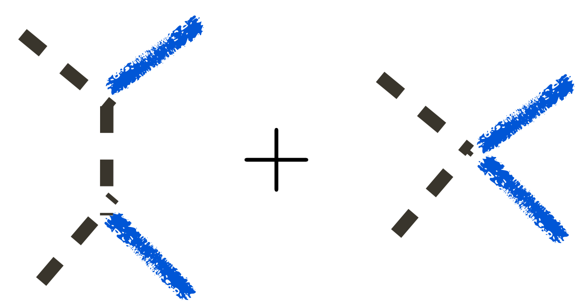

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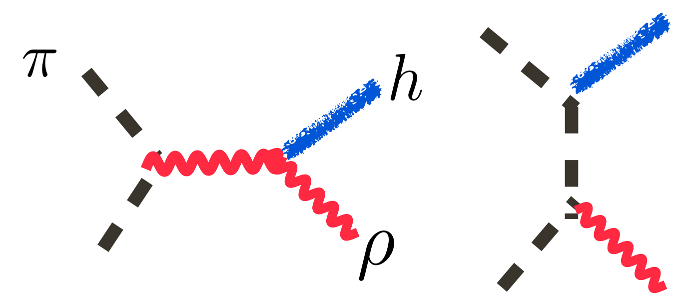

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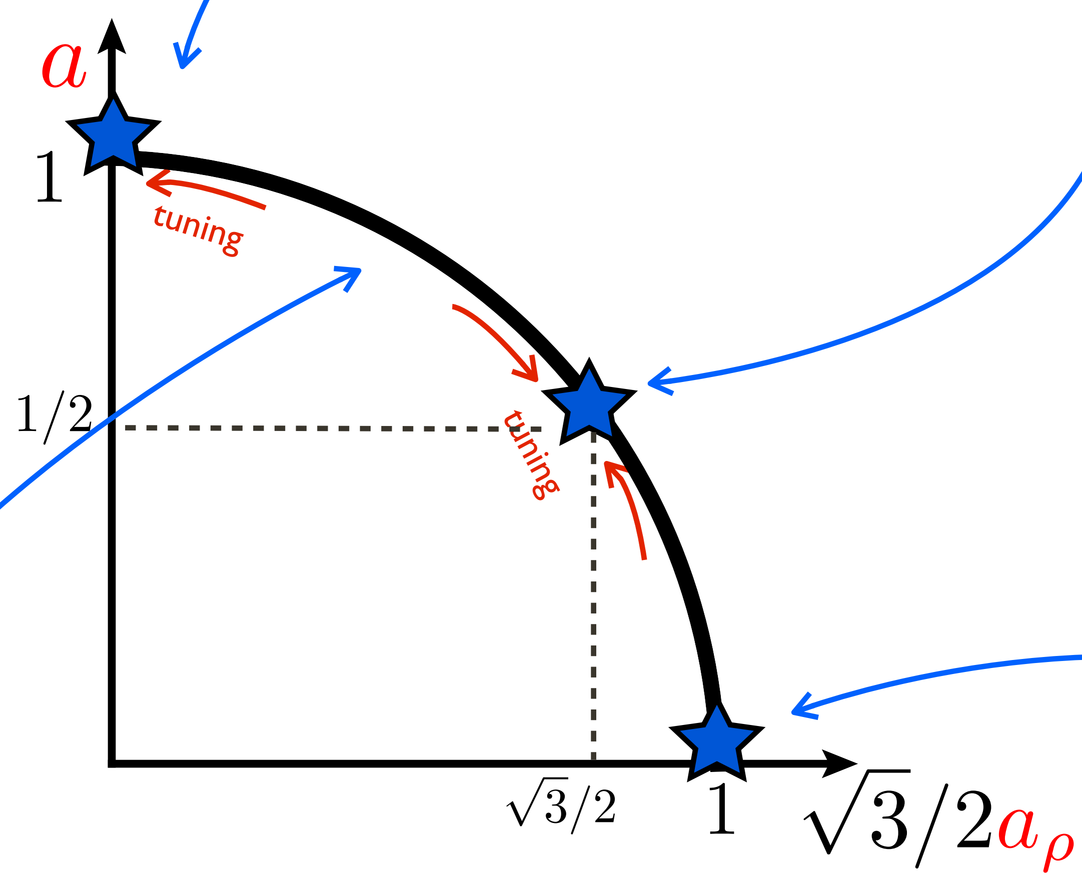
$\cancel{3}$+3 parameters

$\cancel{c_\rho}$ $\cancel{b}$ $\cancel{a_\rho}$ m_ρ a c_{top}

Models on a circle

$$\boxed{a^2 + \frac{3}{4} a_\rho^2 = 1}$$

sm-higgs
$\Lambda = \infty$



weak 3-site (see Carcamo, Torre 1005.3809)

$\Lambda \sim m_H \lesssim 2m_\rho$ Integrate-out H

$\Lambda \gg 2m_\rho$ Integrate-in H

parity-odd

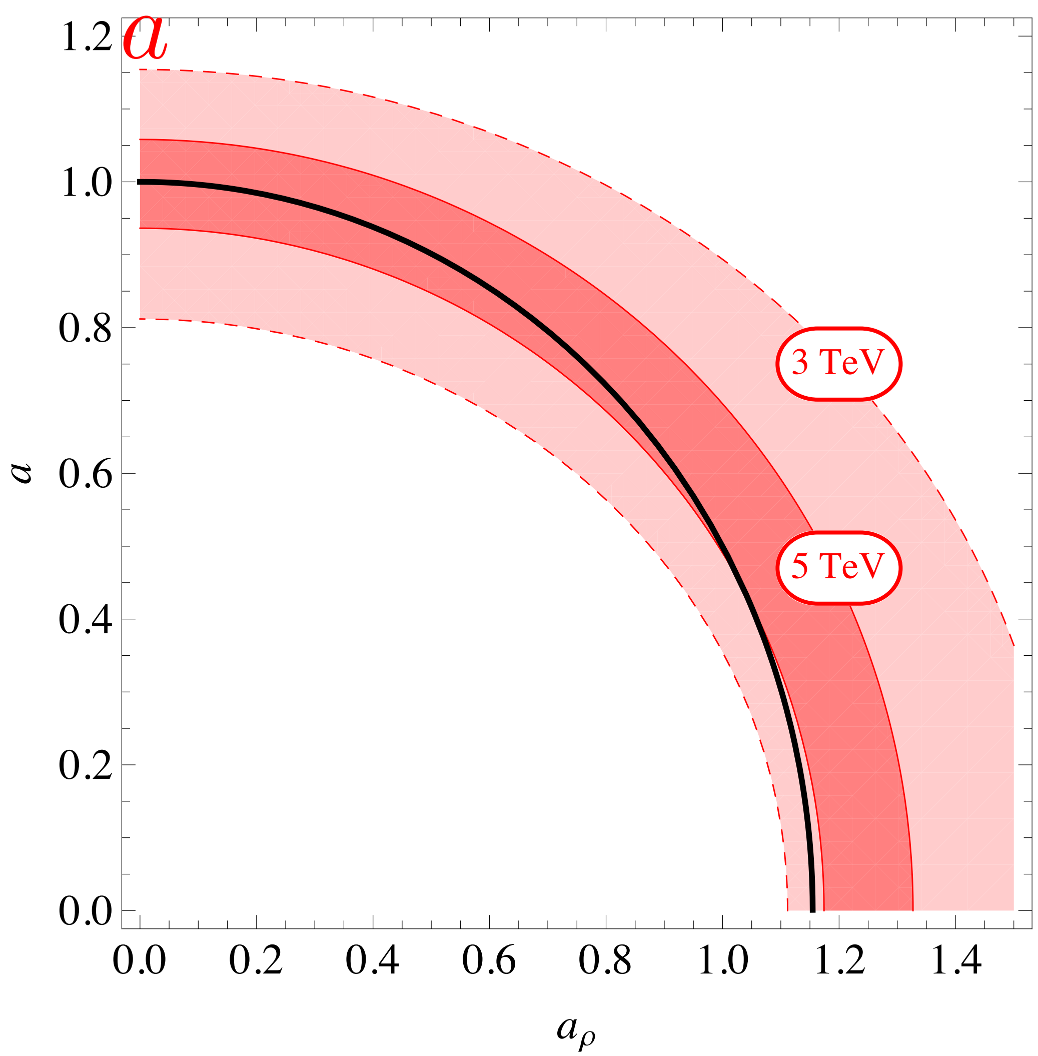
no change in
$\pi\pi \longrightarrow \pi\pi$

Higgsless XD
$\Lambda \sim 2m_\rho$

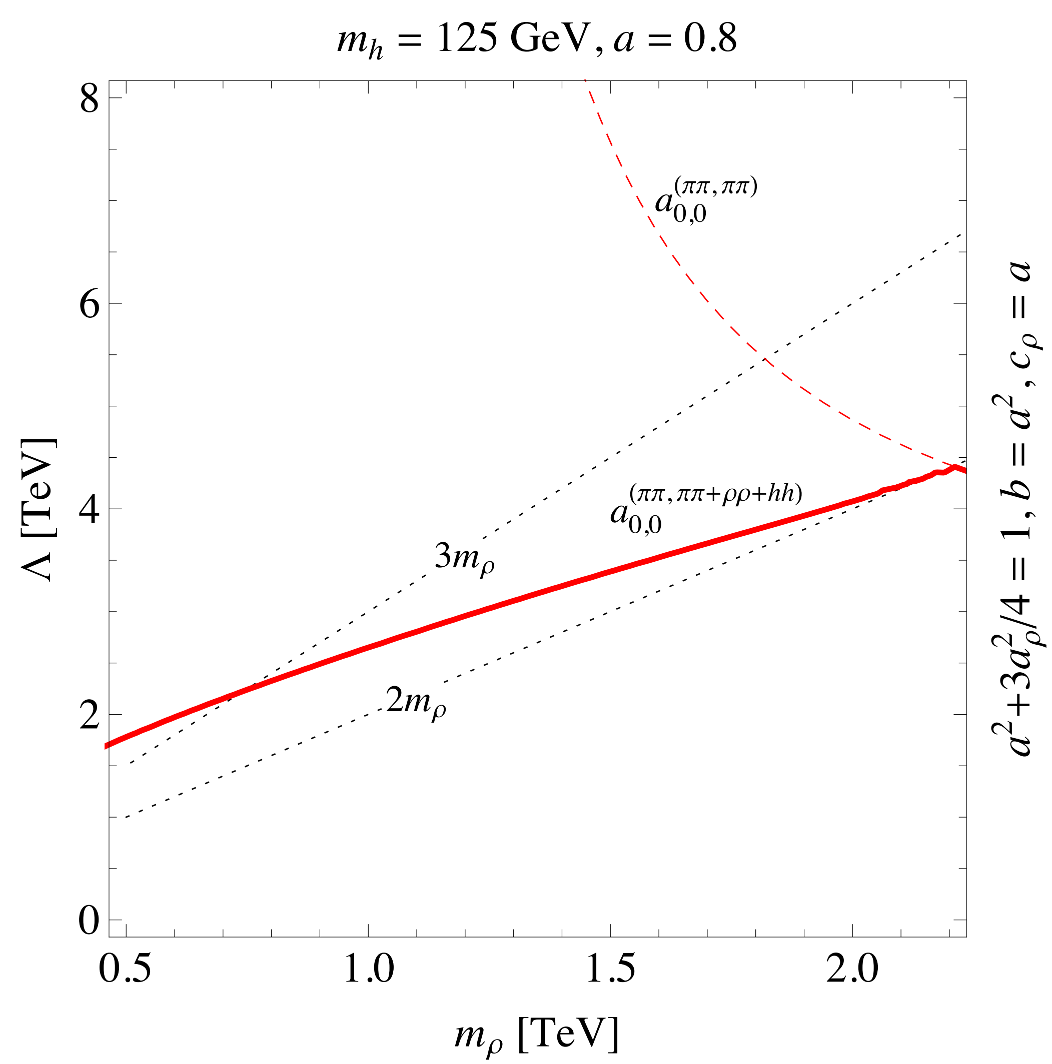
gaugephobic
see Cacciapaglia et al. hep-ph/0611358

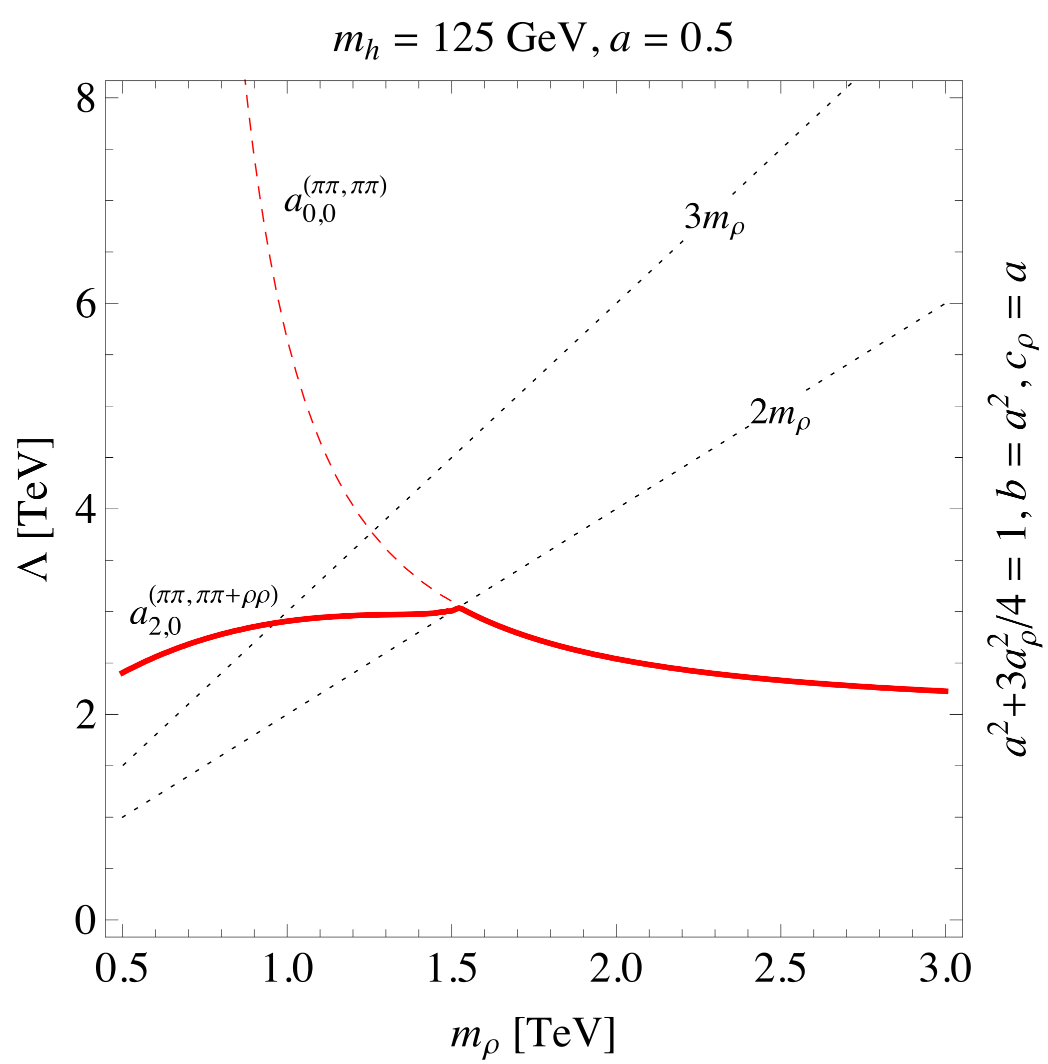
Models on a circle

$$\boxed{a^2 + \frac{3}{4}a_\rho^2 = 1}$$



INELASTIC CHANNELS





PARAMETER SPACE

predictive:

3 parameters and several decay and production modes

$$a \qquad c_t \qquad m_\rho$$

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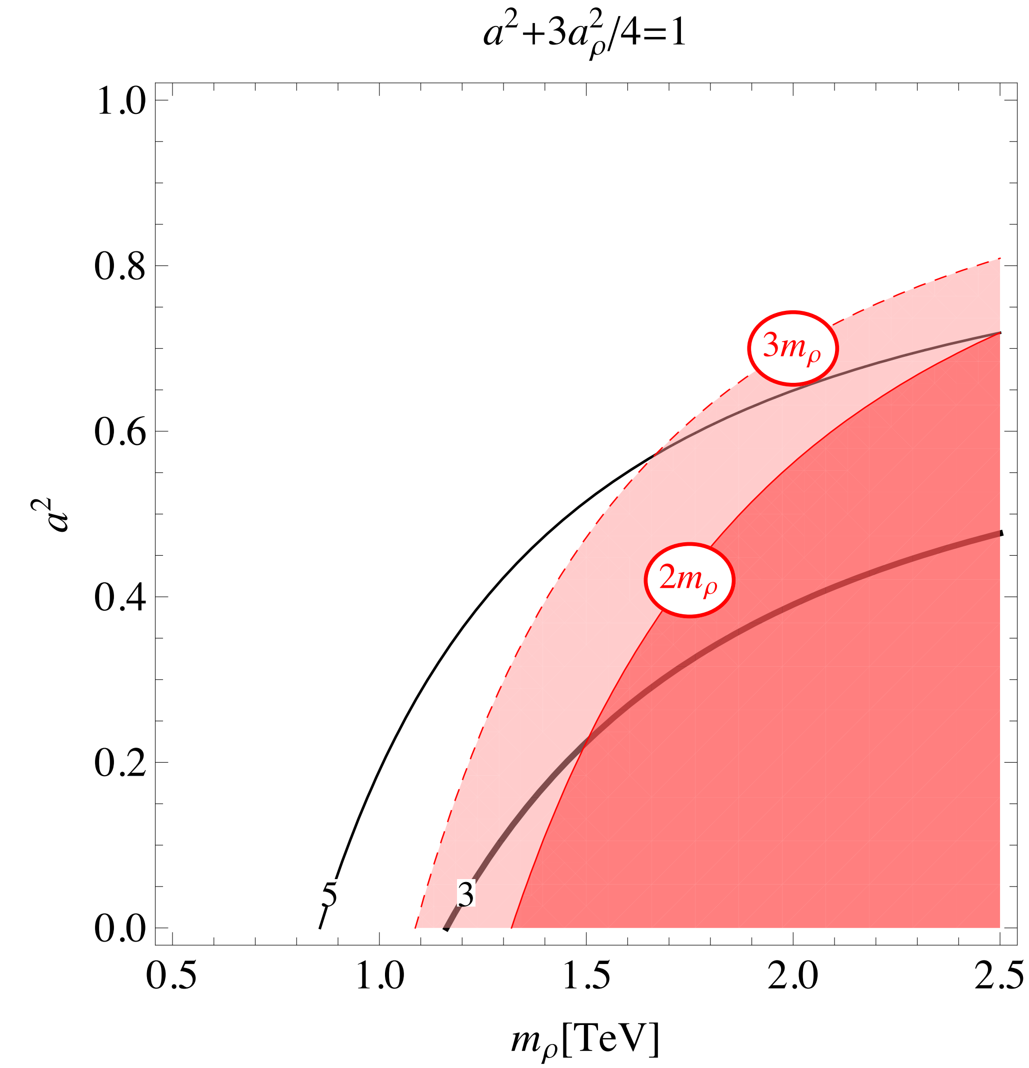

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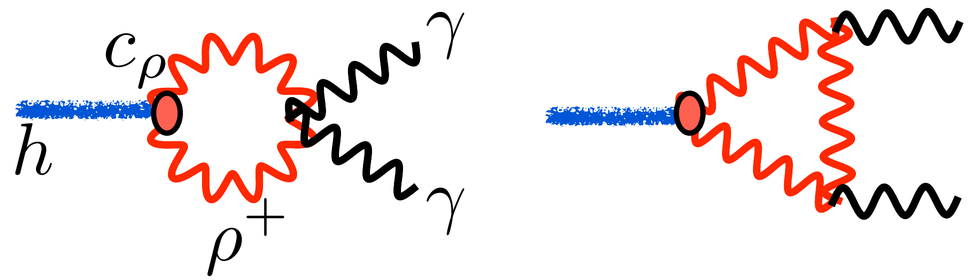
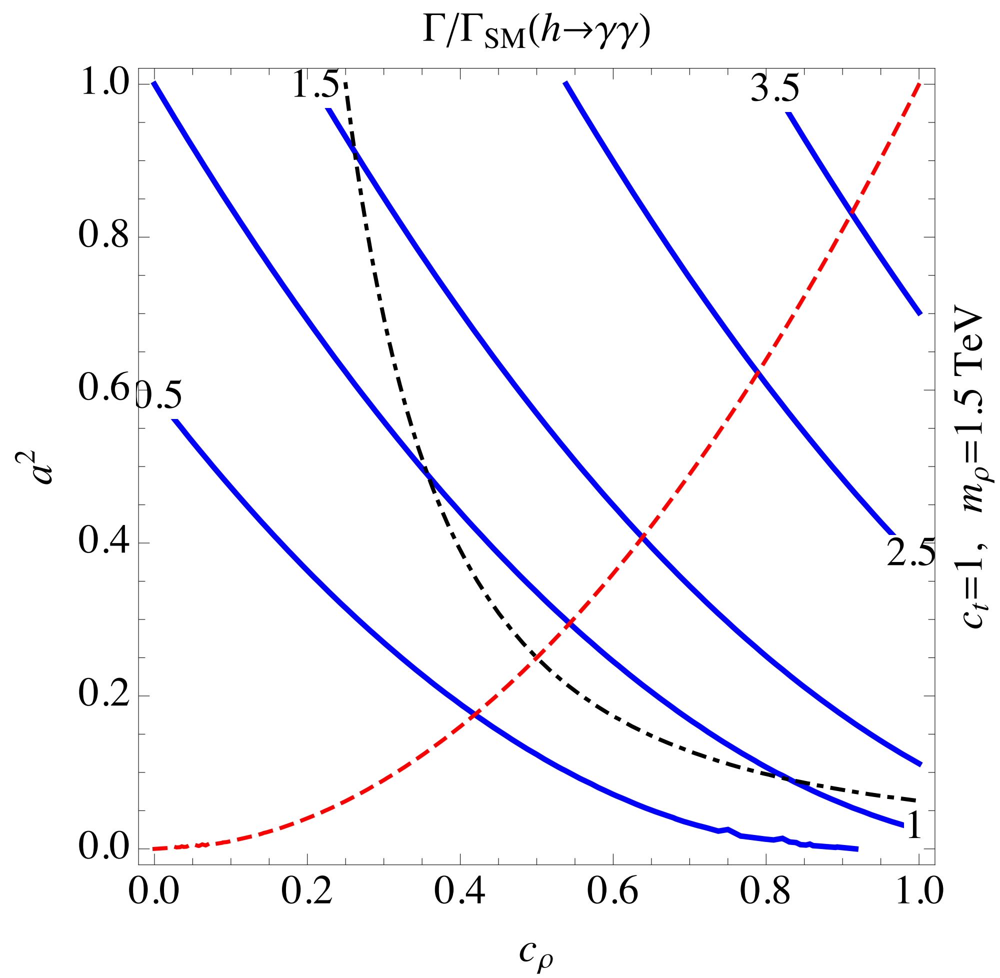
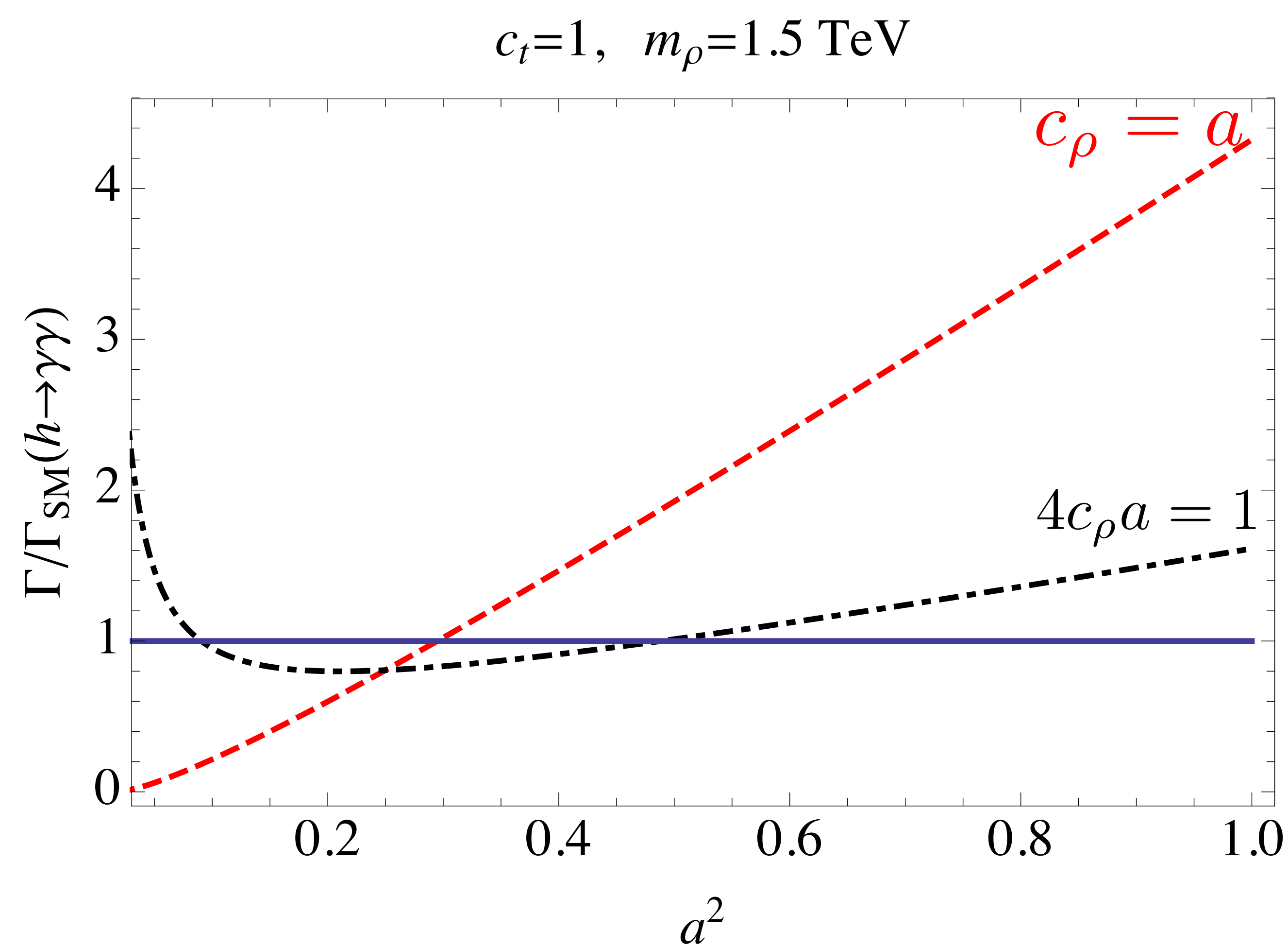
Higgs into gammas

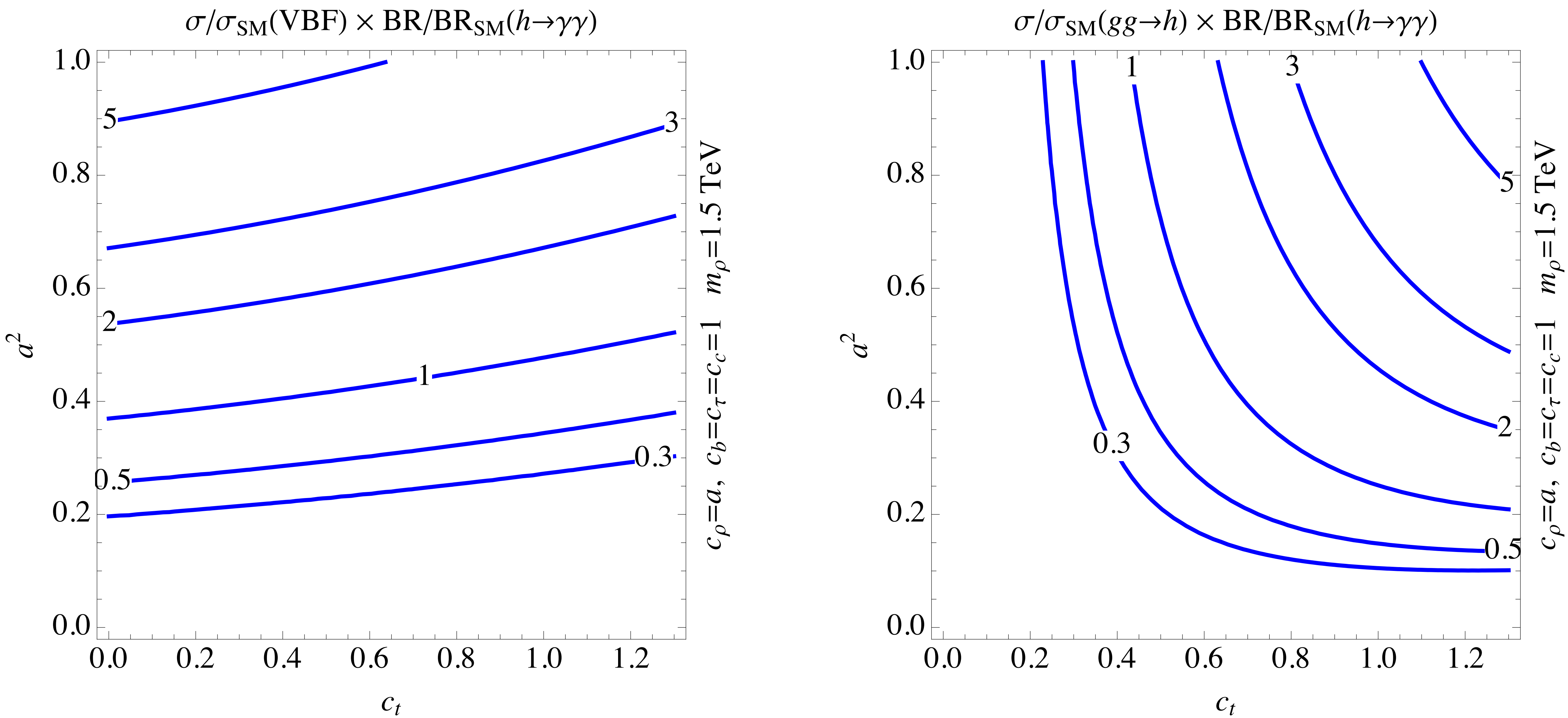






$$\frac{\Gamma}{\Gamma_{SM}}(h \to \gamma\gamma) \simeq \left[1 + \frac{9}{8}c_\rho + \frac{9}{7}(a-1) - \frac{2}{7}(c_t - 1)\right]^2$$

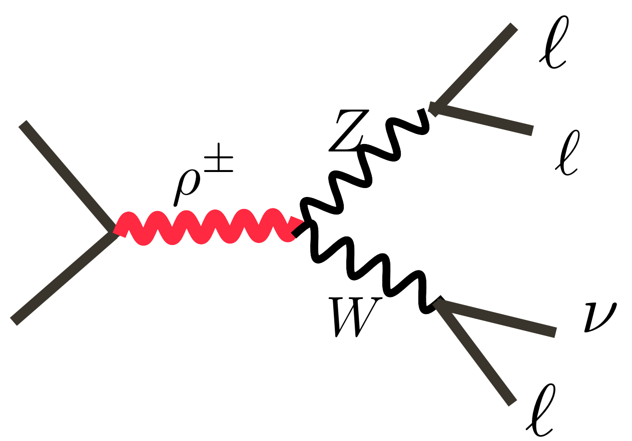
Boost into gammas

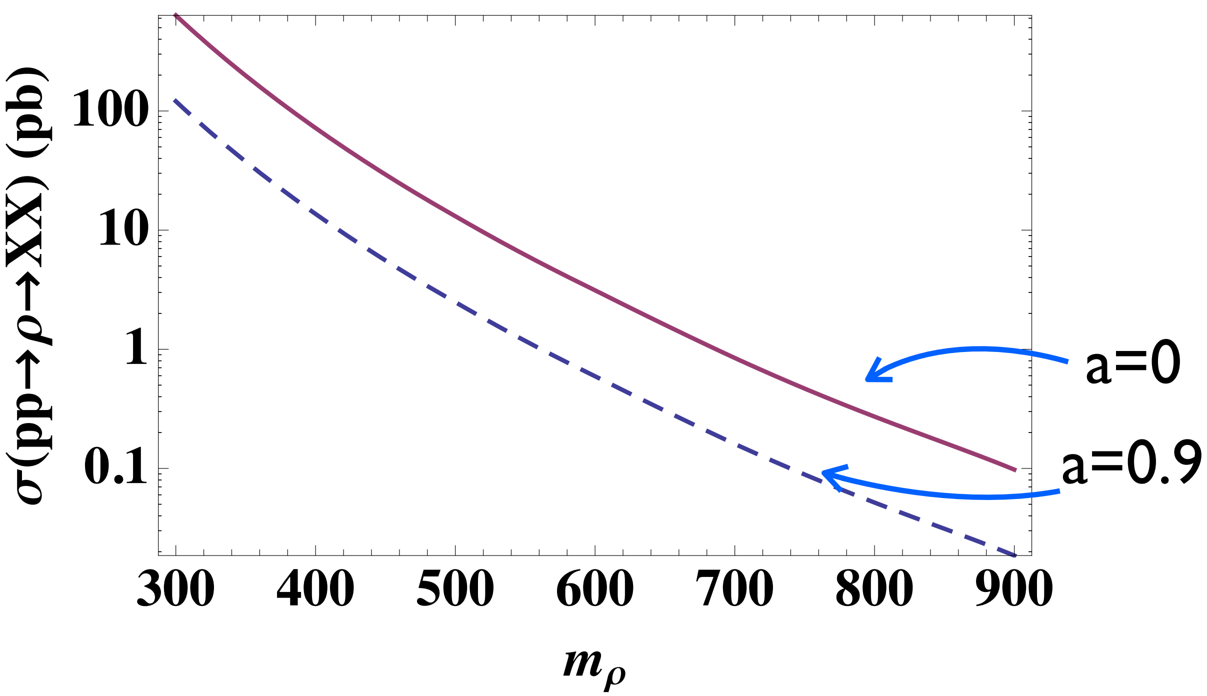


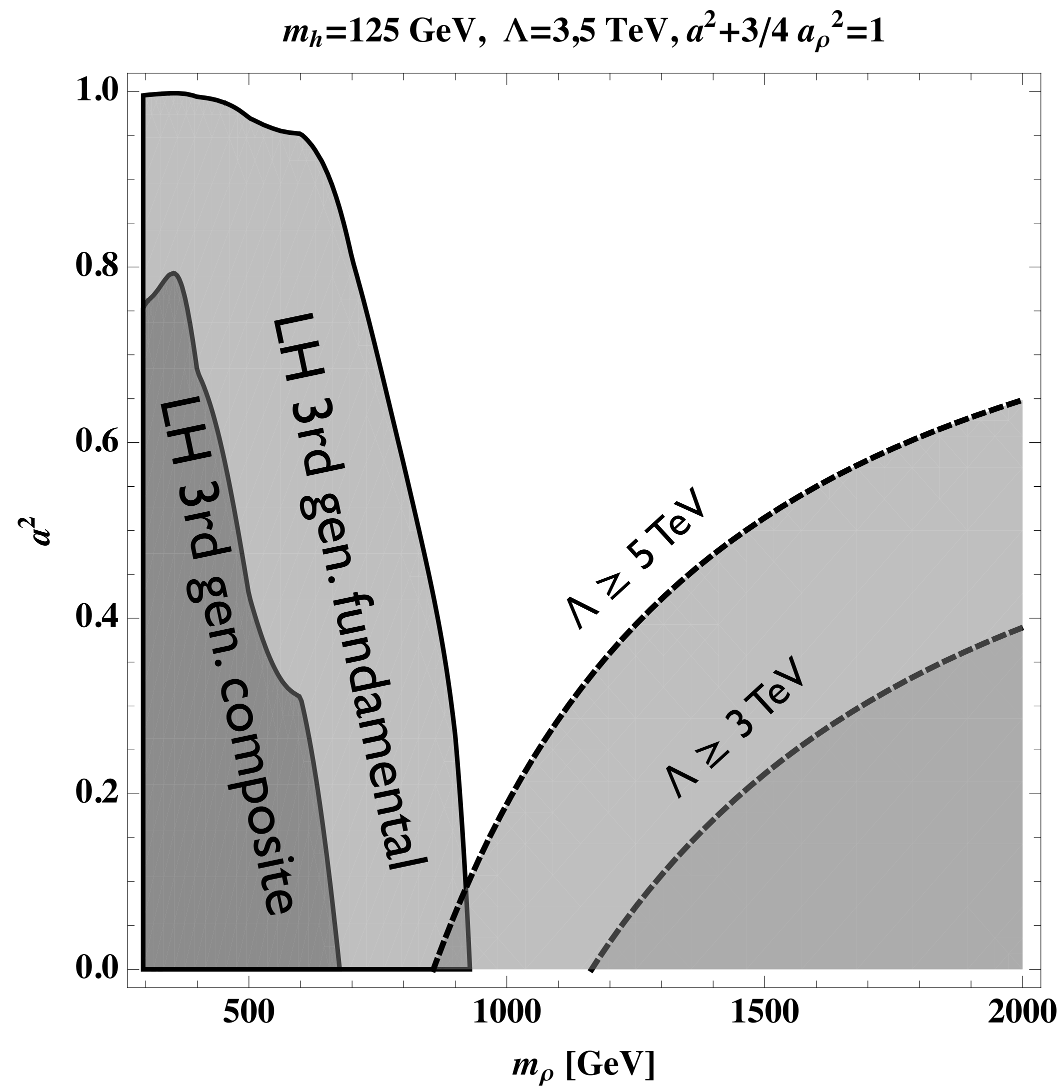
$$\frac{\mathrm{BR}}{\mathrm{BR_{SM}}}(h\to\gamma\gamma)\simeq\frac{\left[1+\frac{9}{8}c_\rho+\frac{9}{7}(a-1)-\frac{2}{7}(c_t-1)\right]^2}{c_b^2\mathrm{BR_{SM}}(h\to b\bar{b})+a^2\mathrm{BR_{SM}}(h\to VV^*)+\dots}$$

$$\frac{\sigma}{\sigma_{\mathrm{SM}}}(q\bar{q}\to hjj)\simeq a^2 \qquad \frac{\sigma}{\sigma_{\mathrm{SM}}}(gg\to h)\simeq c_t^2$$

Limits on rho+-



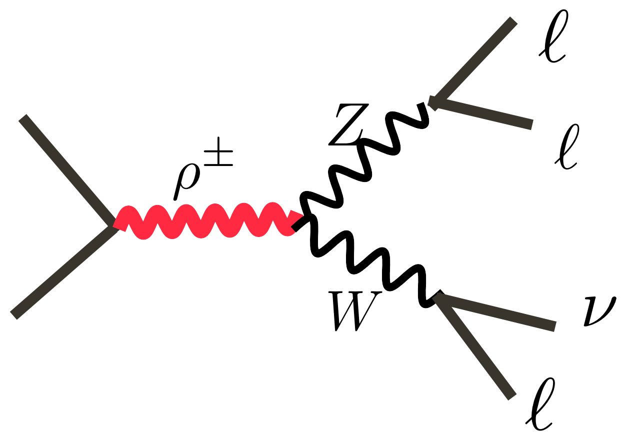


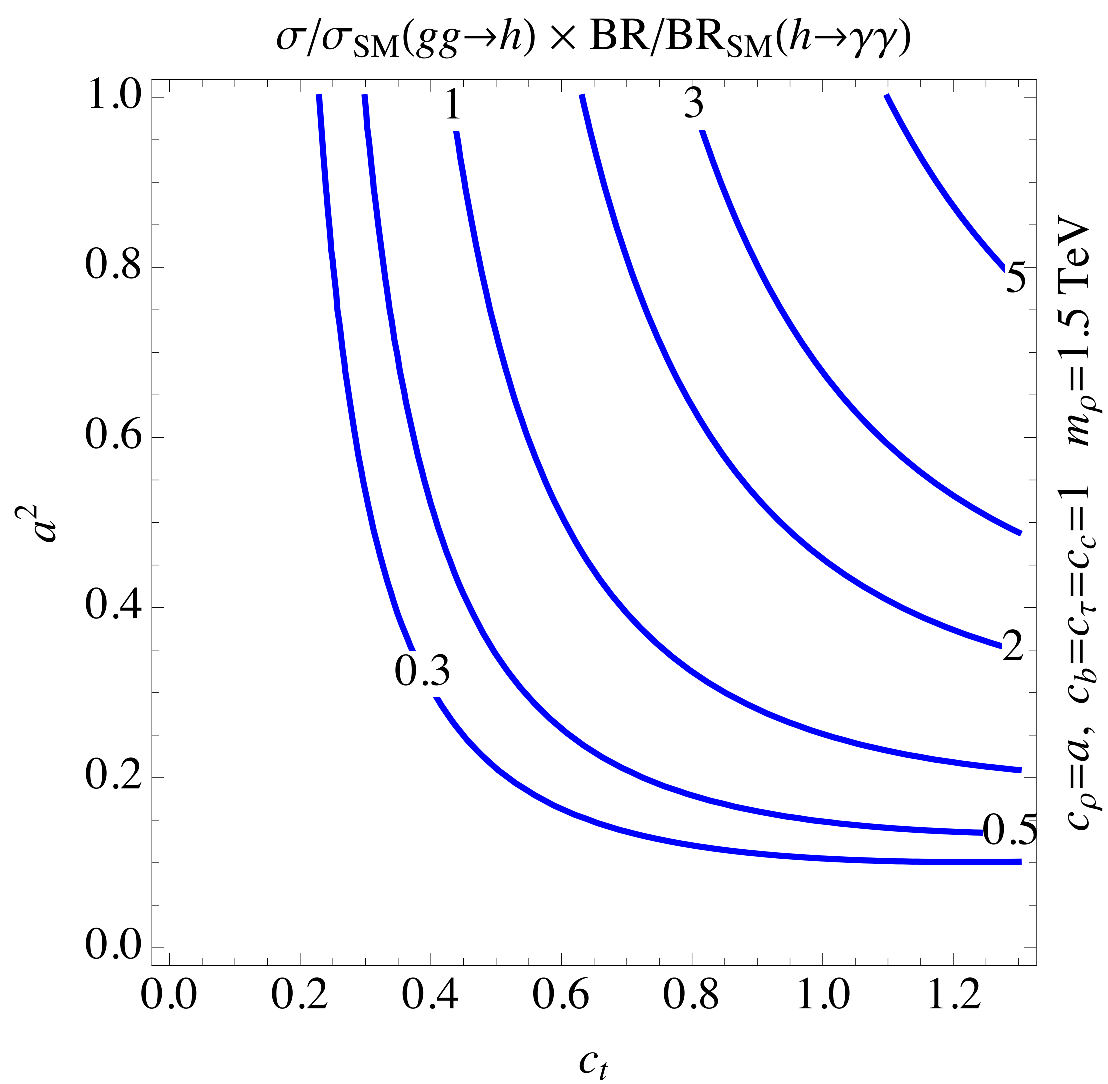


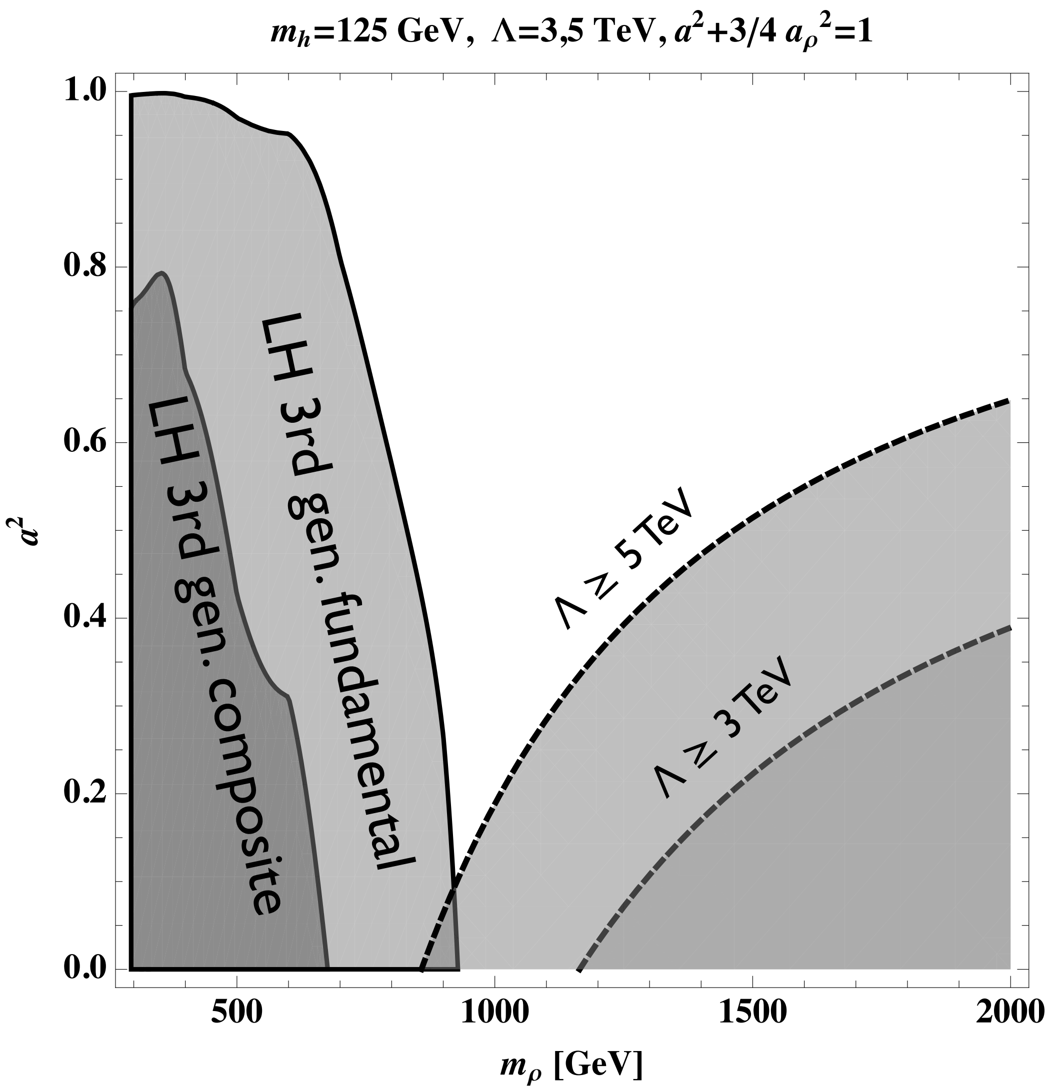
$$\Gamma_{min}/m_\rho \sim 0.04 \left(\frac{m_\rho}{1\ \mathrm{TeV}}\right)^2$$

$$\sigma \sim 50\ \mathrm{fb\ at\ 1\ TeV}$$

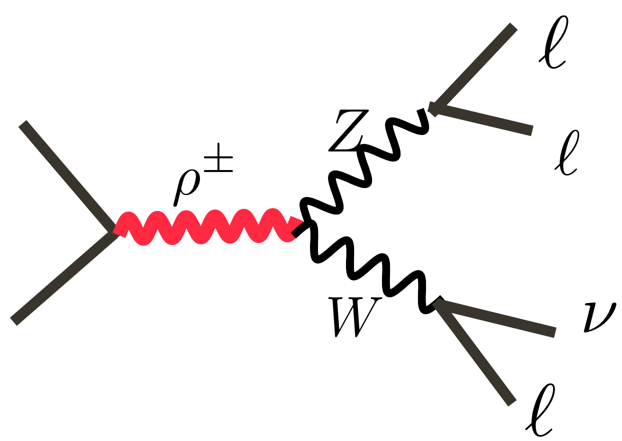
Limits on rho+-

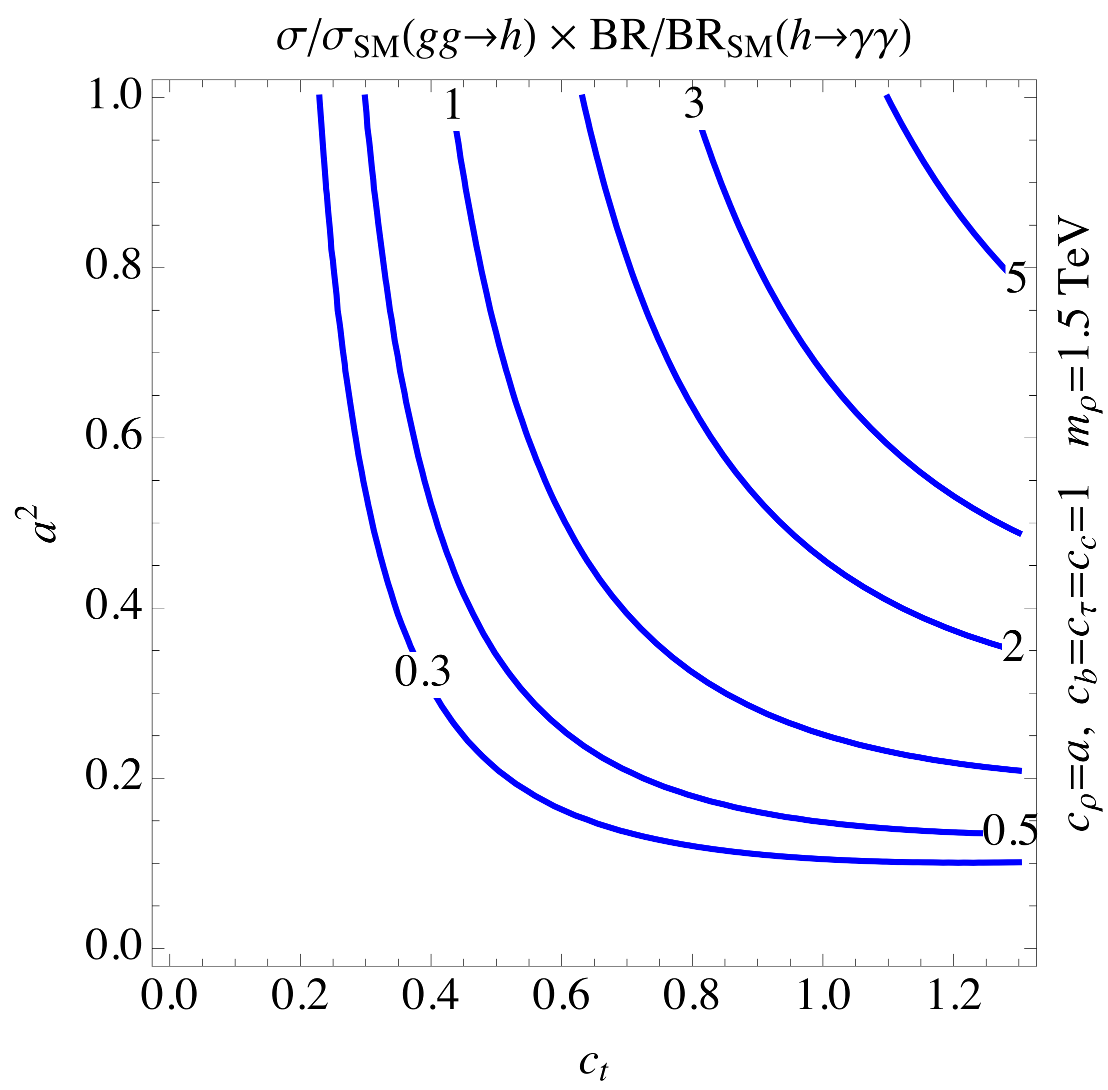


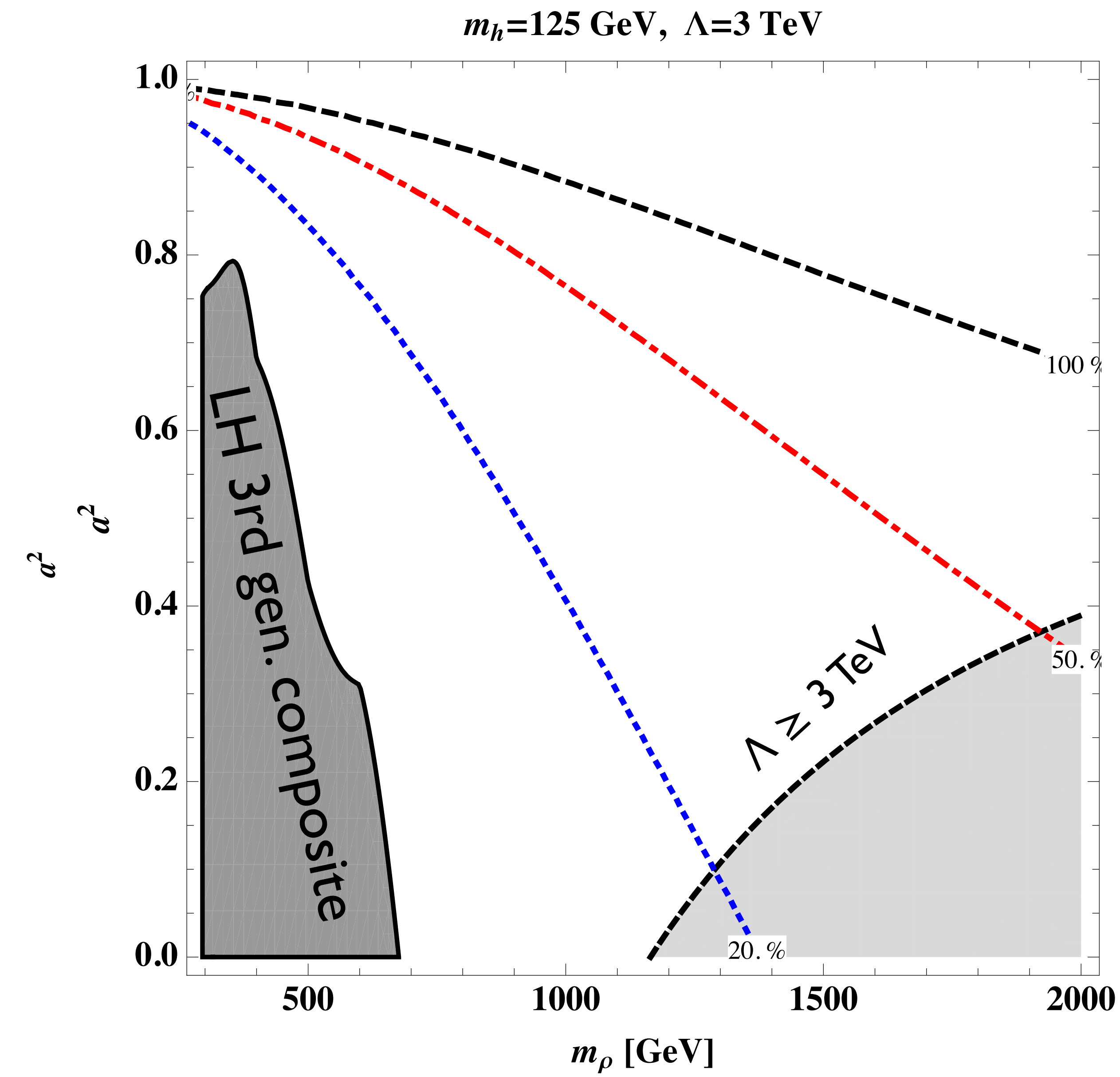




Limits on rho+-







conclusions

- non standard higgs couplings: new resonances below the cutoff

- Effective theory of Higgs + spin-1

- Elastic and inelastic unitarity sum rules reduce the parameters

- generic prediction for a single resonance below cutoff:
  smaller h->VV
  larger h->2 gammas

Thank you!