Composite Higgs Sketch

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Composite Sketch

Outline

- composite resonances in EWSB
- EFT for Higgs + spin-1 resonance
- sum rules and parameter space
- higgs rates: enhancement in gamma-gamma
- limits on vector resonances
- conclusions

Found the Higgs: what next?

e.g. what about the couplings?

strong dynamics $\Rightarrow$ O(1) change

Higgs effective lagrangian (w/ custodial sym.)

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

lower cut-off

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

Examples

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

Higgs + resonances

can we delay the onset of strong dynamics?

can we increase the cutoff?

- add new resonances coupled to the Pi's (the first that go strong)
- enforce perturbative unitarity up to higher scales

familiar example: the SM Higgs

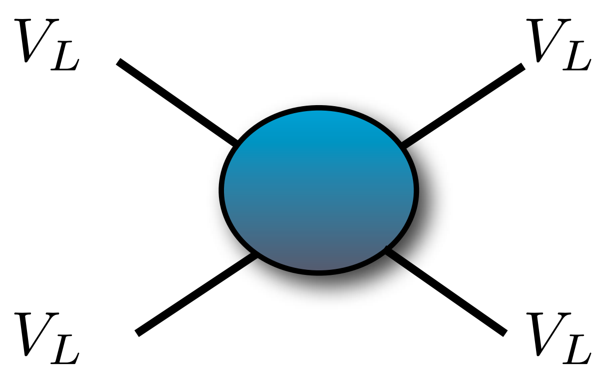
Higgsless: low cutoff

$$\Lambda \sim 4\pi v$$

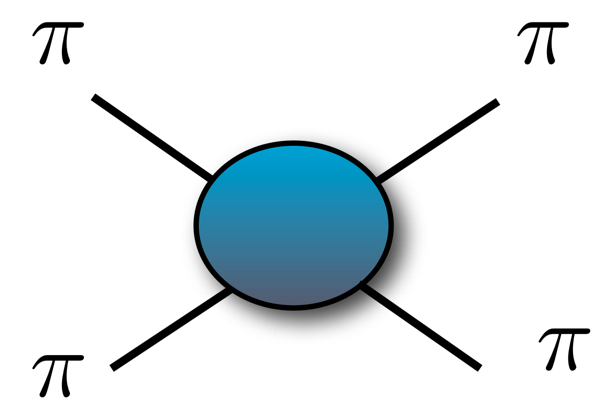
add the Higgs

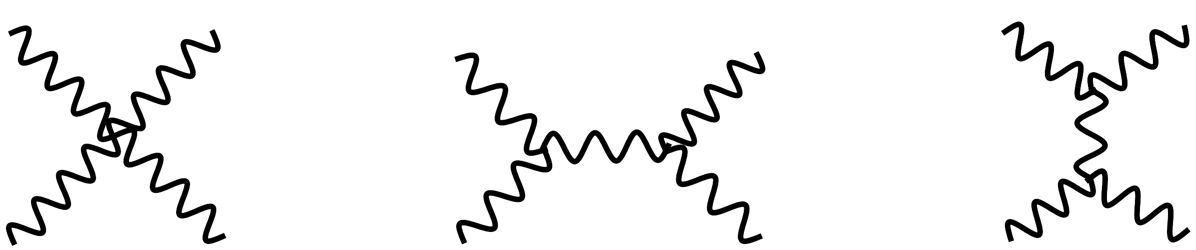
$$\Lambda = \infty$$

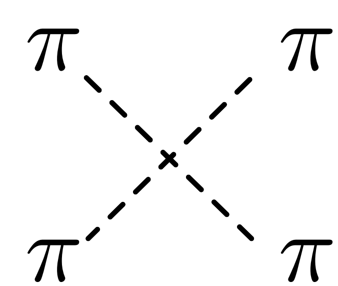
UV behavior and cutoff



$E \gg v$







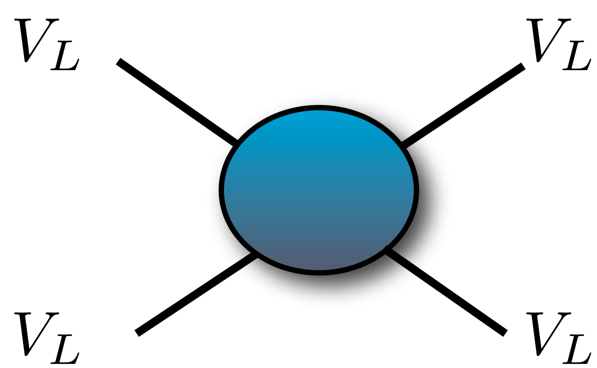
$$\sim \left(\frac{E}{v}\right)^2$$

$$\left(V_\mu + \partial_\mu \pi + \frac{1}{6}[[\pi, \partial_\mu \pi], \pi] + \ldots\right)^2 \longrightarrow \frac{1}{6}\left[(\vec{\pi}\partial_\mu\vec{\pi})^2 - \vec{\pi}^2(\partial_\mu\vec{\pi})^2\right]$$

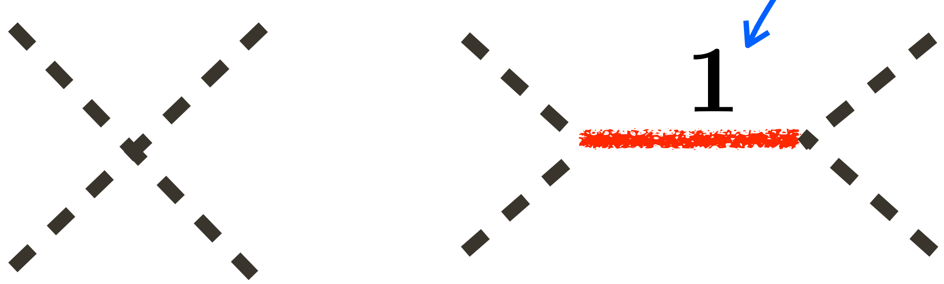
Equivalence theorem

$$\Lambda \sim 4\pi v$$

UV-Moderators I



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



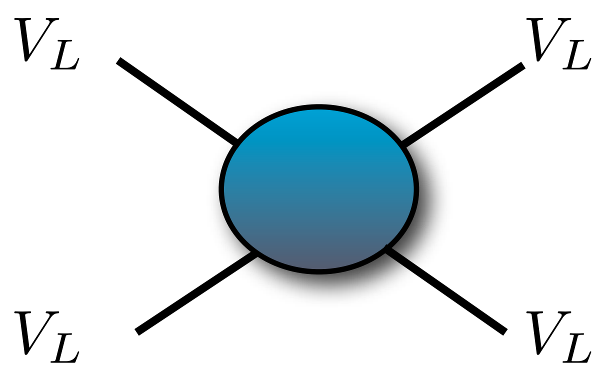
+ crossing

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

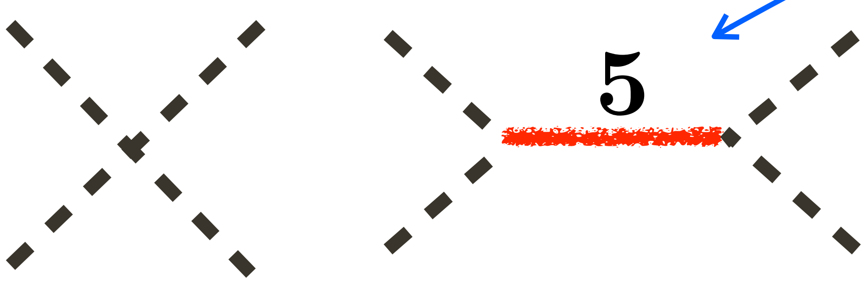
$$\boxed{|D_\mu \Sigma|^2 \left(1 + 2a\frac{h}{v} + b^2\frac{h^2}{v^2} + \dots\right)}$$

Contino et al.1002.1011 [hep-ph]

UV-Moderators II



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

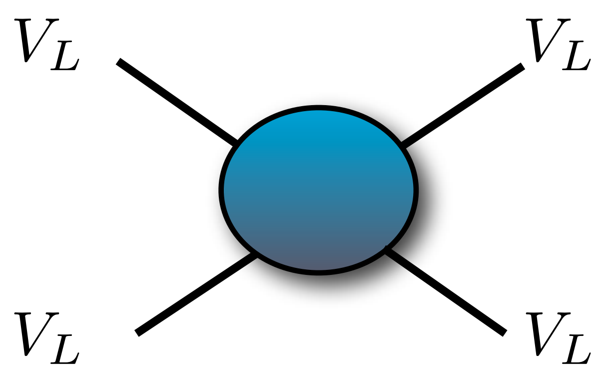


+ crossing

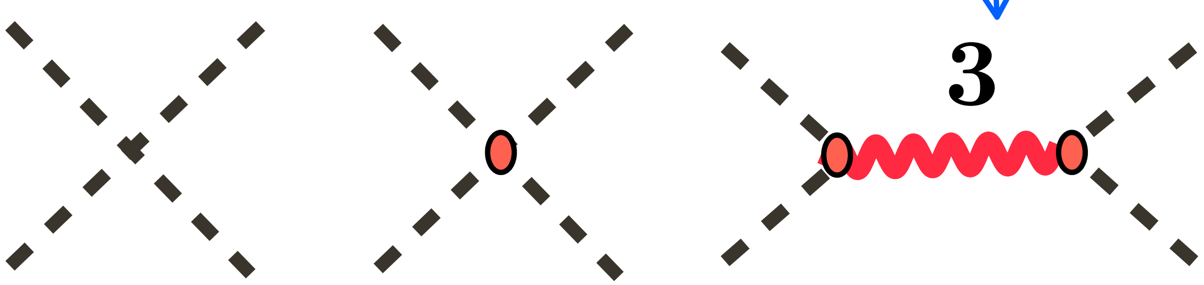
$$\left(1 + \frac{5}{6} a_Q^2\right) \frac{s}{v^2}$$

see e.g. 1202.1532 [hep-ph] and Falkowski's talk

UV-Moderators III



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



+ crossing

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

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

more later...

Examples

- QCD (vmd) $\quad a_\rho^2 \approx 2 \quad$ $\Lambda \sim m_\rho$

- Higgsless $\quad \sum_N \frac{3}{4} a_{\rho_N}^2 = 1 \quad$ $\Lambda \gg 4\pi v$

  Csaki et al. hep-ph/0305237

$$\Lambda_{NDA} \sim \Lambda_{unitary}$$

$$\sqrt{s} \lesssim 2m_\rho$$

inelastic threshold

Higgs + Spin-1

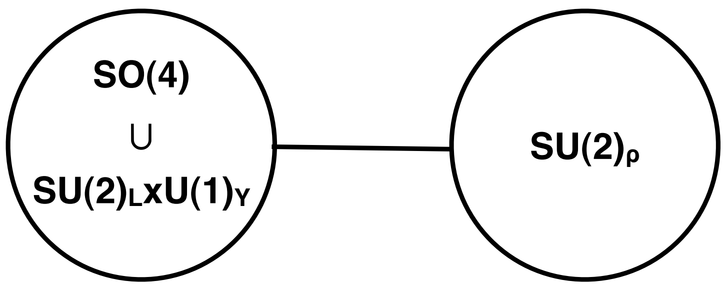
one spin-1 below the cutoff (techni-rho, KK-W, ...)

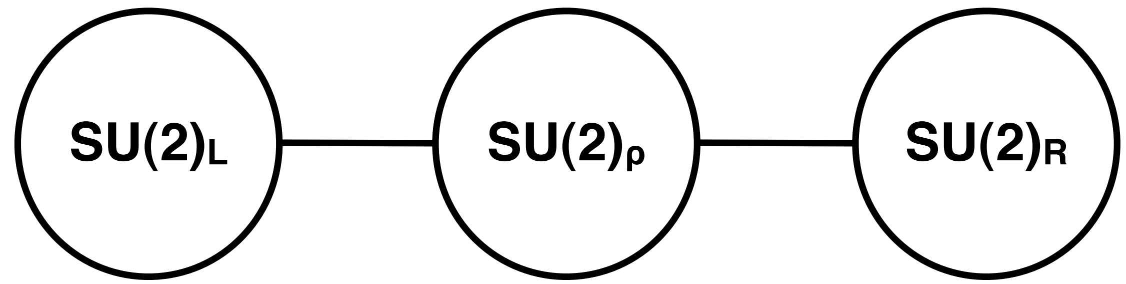
$\boxed{\rho_\mu \qquad \text{as gauge vector} \qquad \rho \longrightarrow h\rho h^\dagger - ih\partial_\mu h}$

- 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

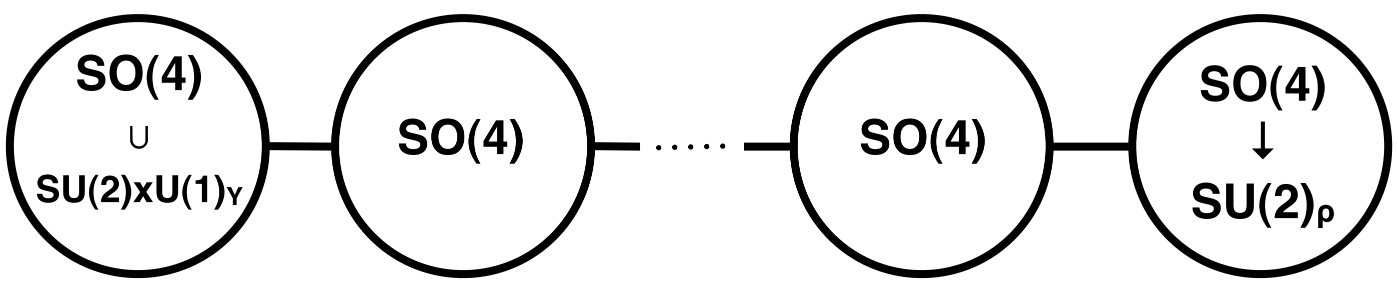
minimal setup

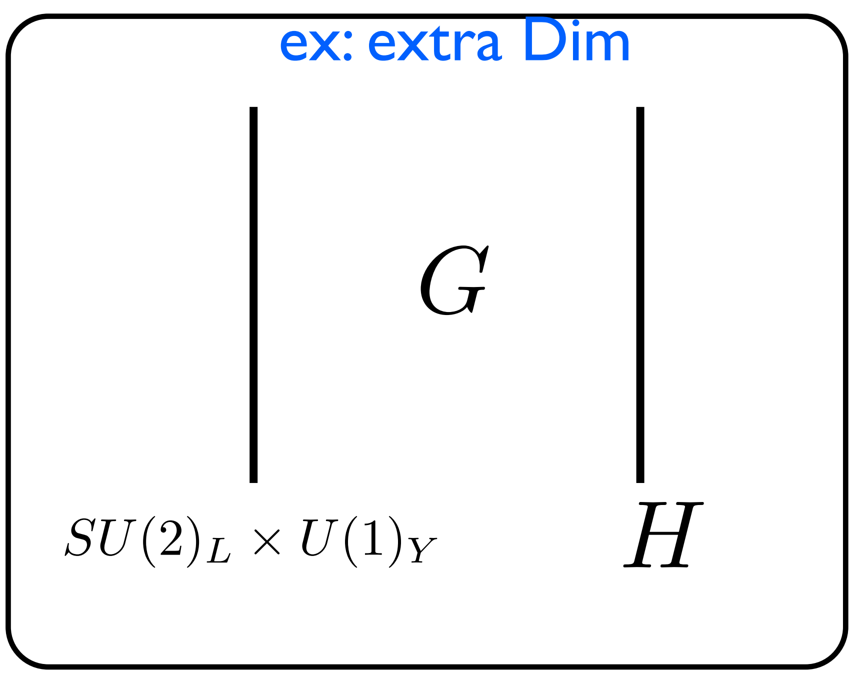




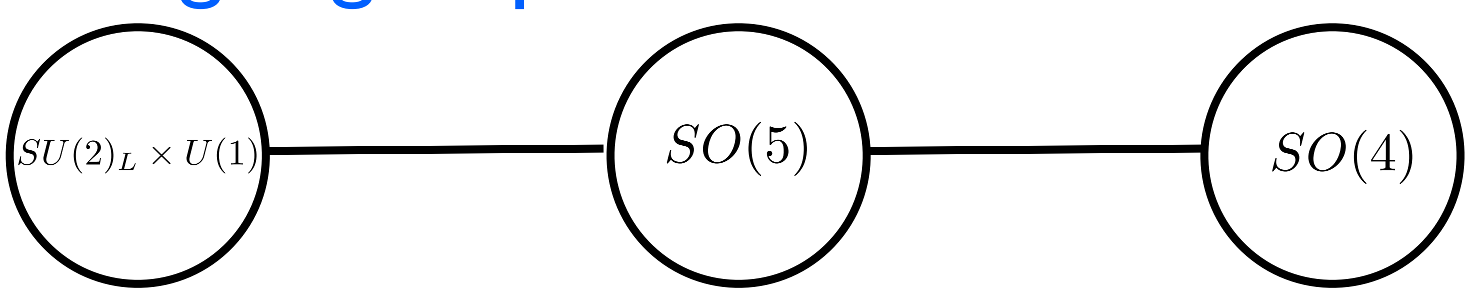
~BESS model [Casalbuoni et al. `85]

more sites

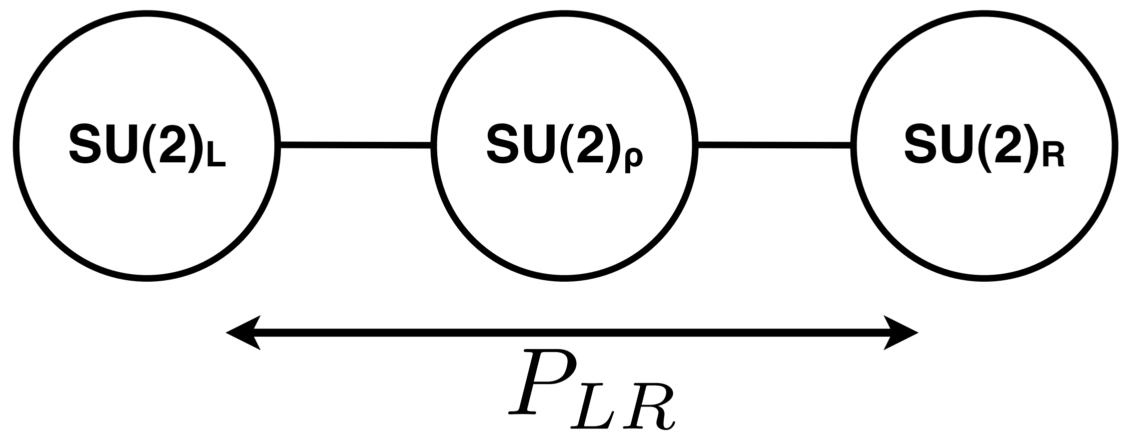




larger groups

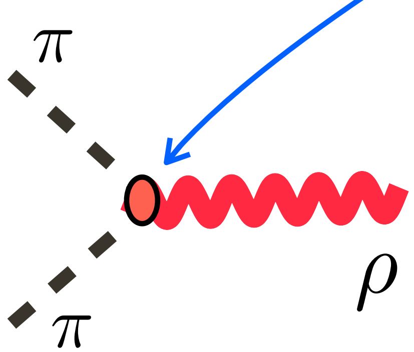


MINIMAL+Z2

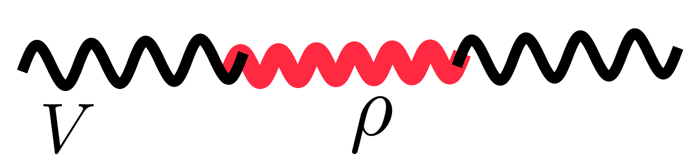


spin-1: couples to the conserved custodial current

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

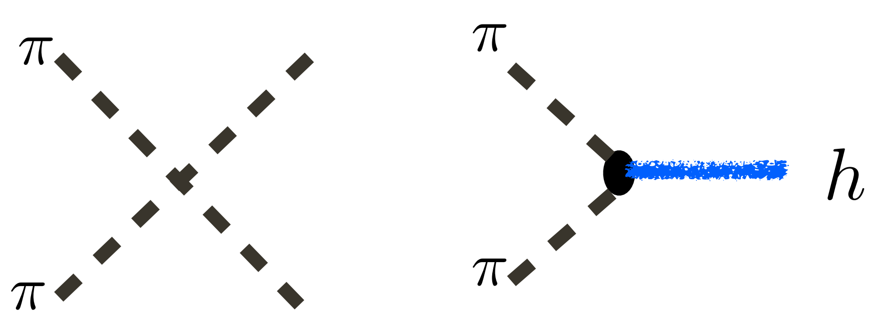


gauging=mixing



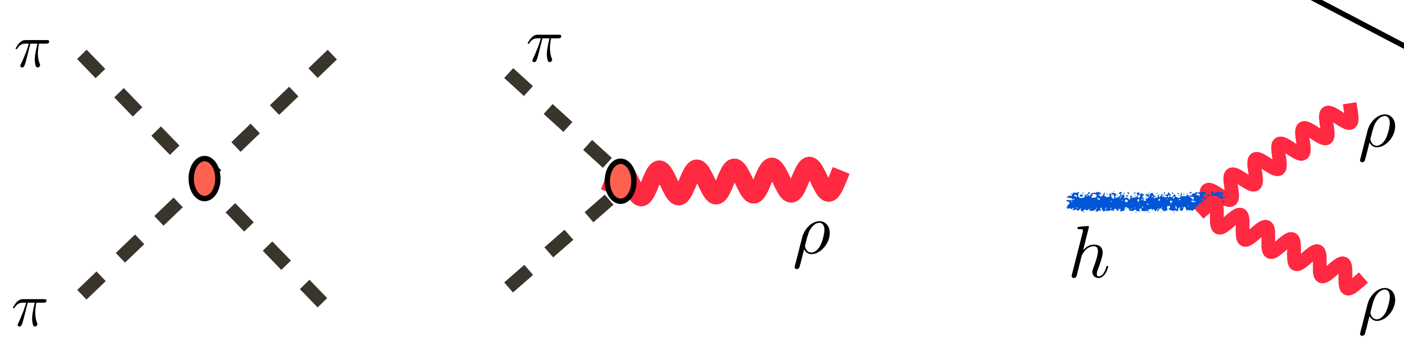
Higgs+vector

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



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

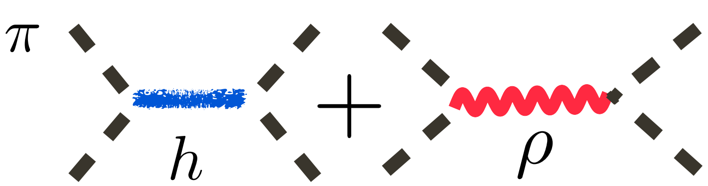
$$\vec{\pi} \times \partial_\mu \vec{\pi} + \ldots$$



SUM RULES

elastic sum-rule

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



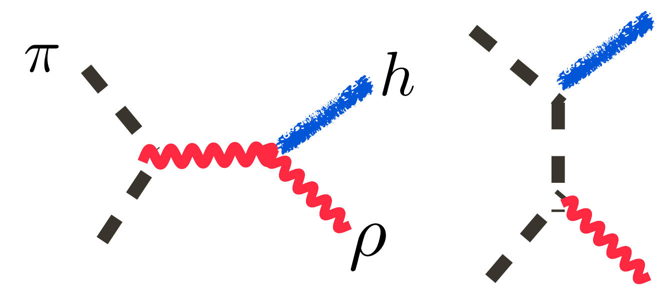
$$\pi\pi \to \pi\pi$$

$\cancel{2}$+3 parameters

$a \quad \cancel{a_\rho} \quad m_\rho \quad \cancel{c_\rho} \quad c_{top}$

inelastic sum-rule

$$a = c_\rho$$



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

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

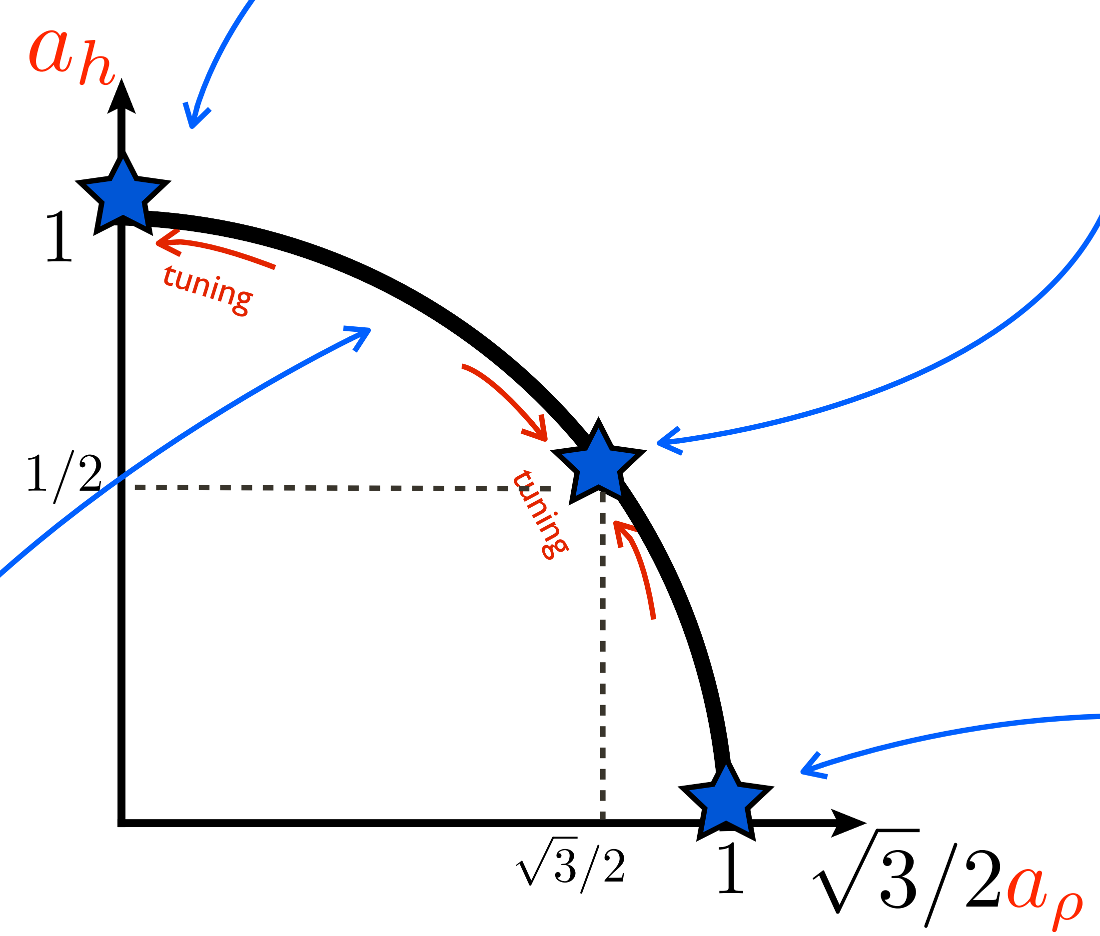
$$\mathcal{A}(\pi^a\pi^b \to \rho_L^c h) = i\epsilon^{abc}\frac{t-u}{2v^2}(a - c_\rho)a_\rho$$

Models on a circle

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

sm-higgs

$\Lambda = \infty$



(see Carcamo, Torre 1005.3809)

weak 3-site

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

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

parity-odd

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

Higgsless XD

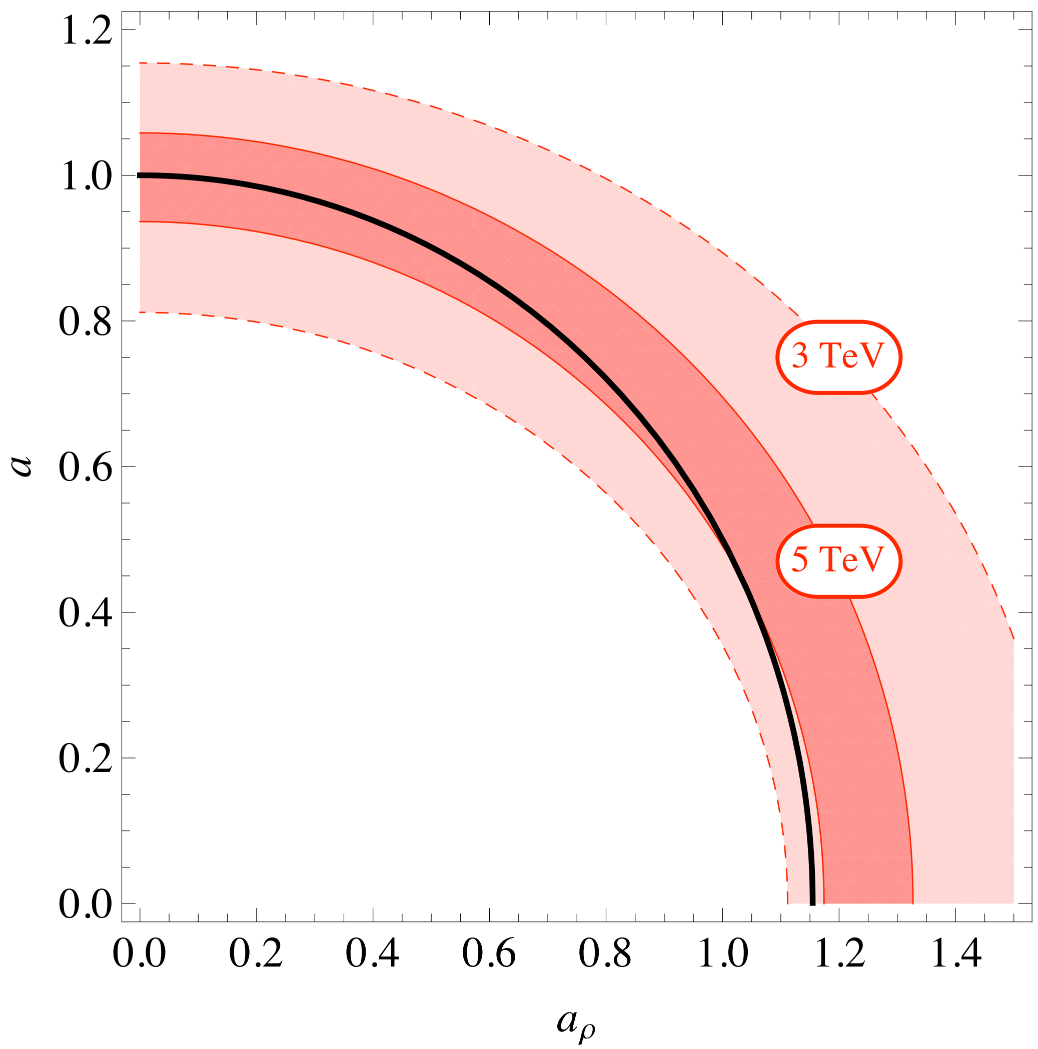
$\Lambda \sim 2m_\rho$

gaugephobic

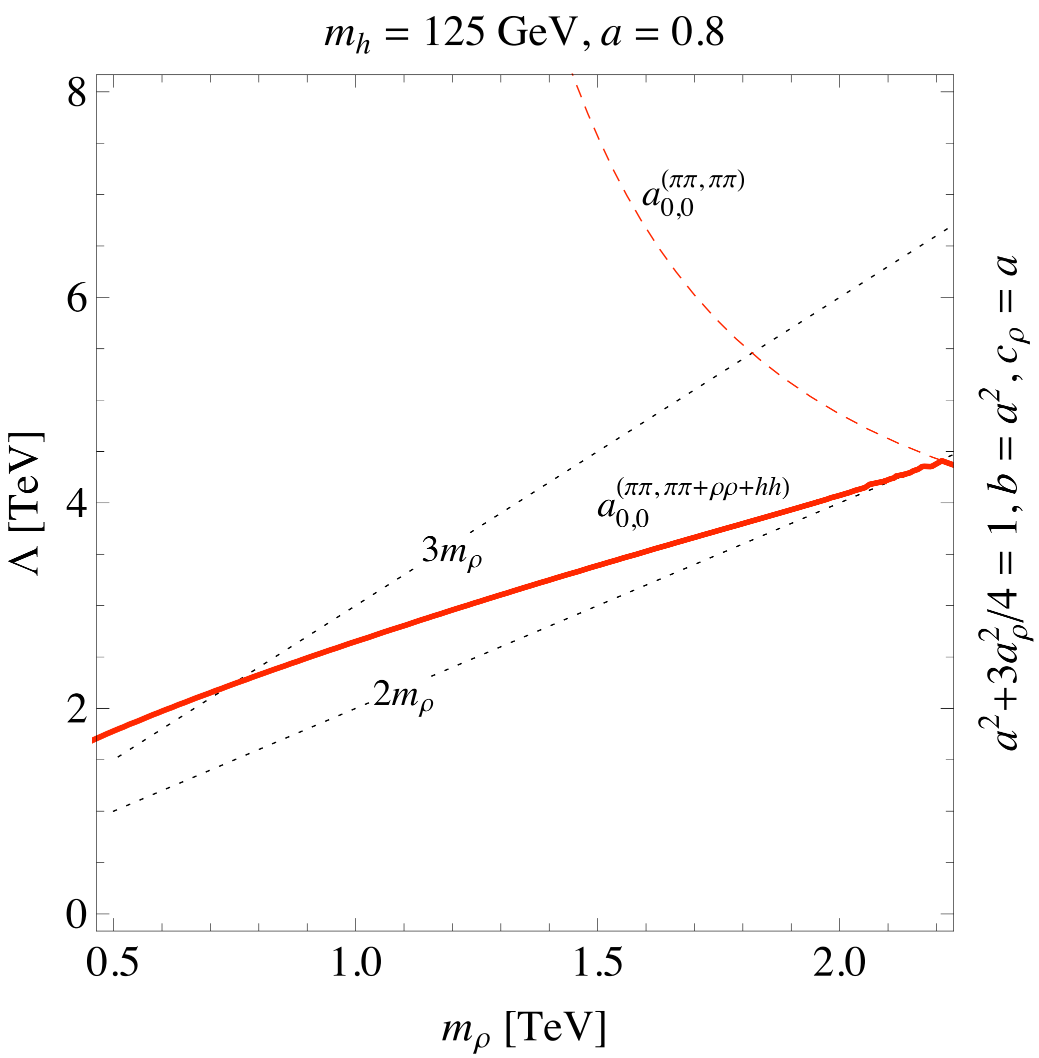
see Cacciapaglia et al. hep-ph/0611358

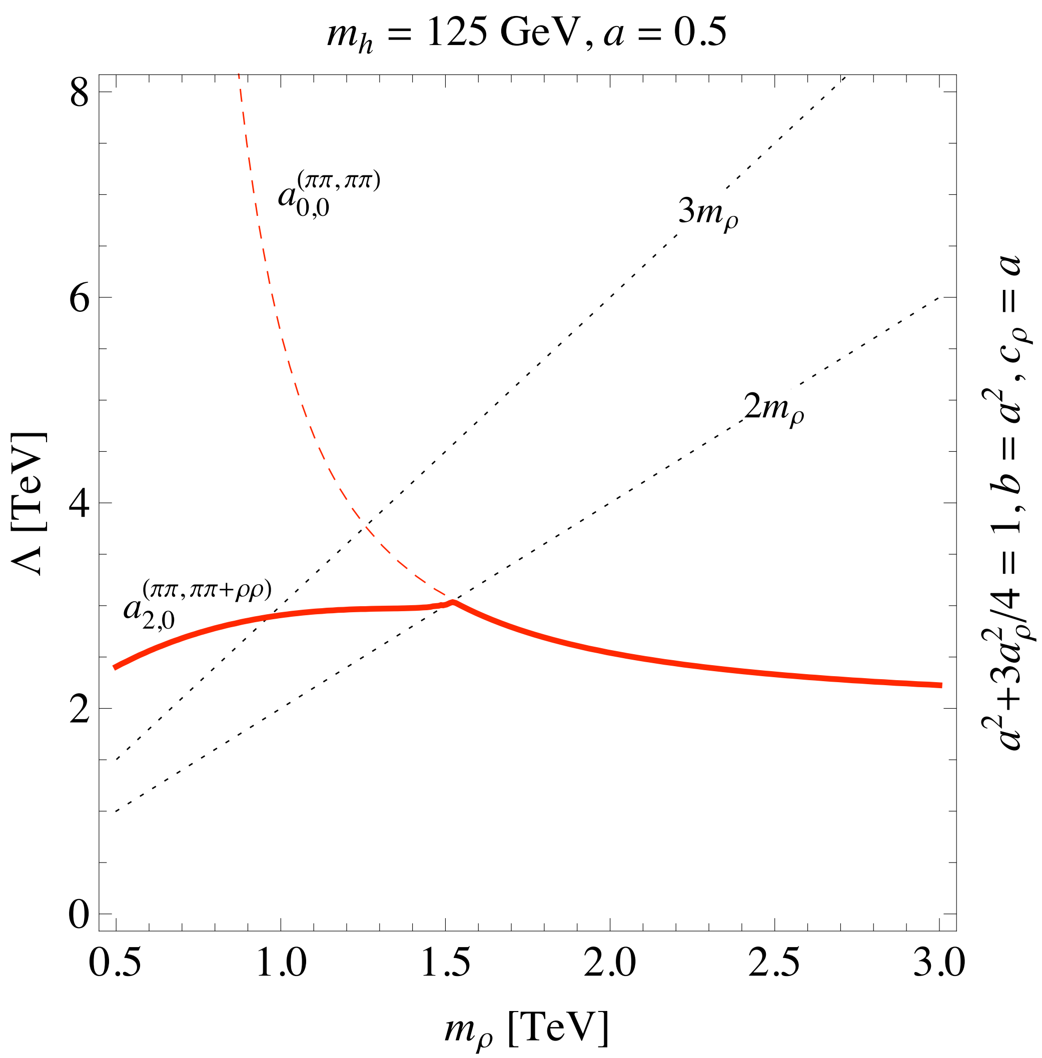
Models on a circle

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



INELASTIC CHANNELS





PARAMETER SPACE

predictive:
3 parameters and several decay and production modes

$a \qquad m_\rho \qquad c_t$

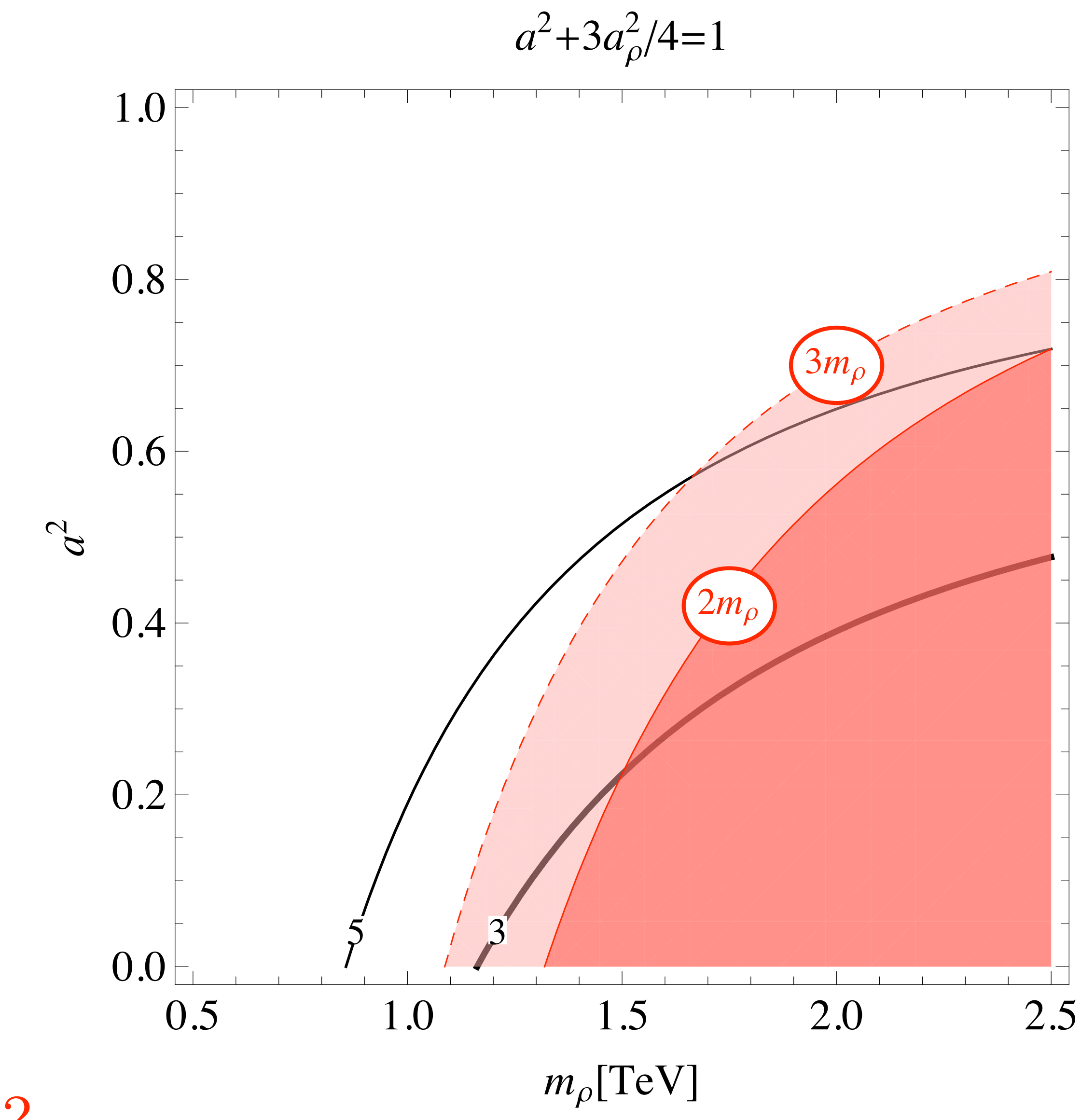
$$\frac{\Gamma}{\Gamma_{\mathrm{SM}}}(h \to VV^*) = a^2$$ decays

...

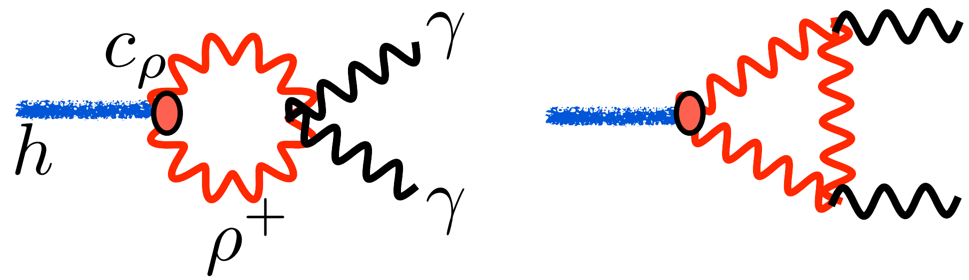
$$\frac{\sigma}{\sigma_{\mathrm{SM}}}(q\bar{q} \to hjj) = \frac{\sigma}{\sigma_{\mathrm{SM}}}(q\bar{q} \to hW) = a^2$$

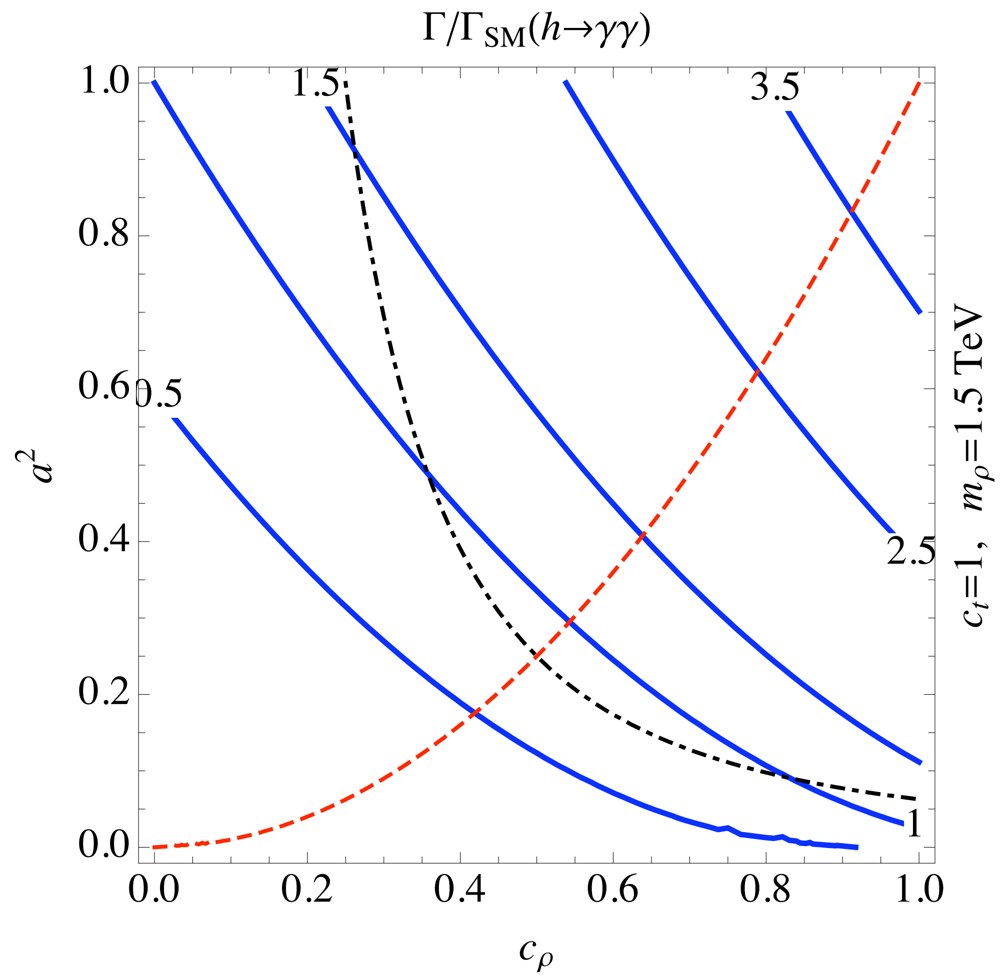
$$\frac{\sigma}{\sigma_{\mathrm{SM}}}(gg \to h) \simeq \frac{\sigma}{\sigma_{\mathrm{SM}}}(gg \to ht\bar{t}) = c_t^2$$

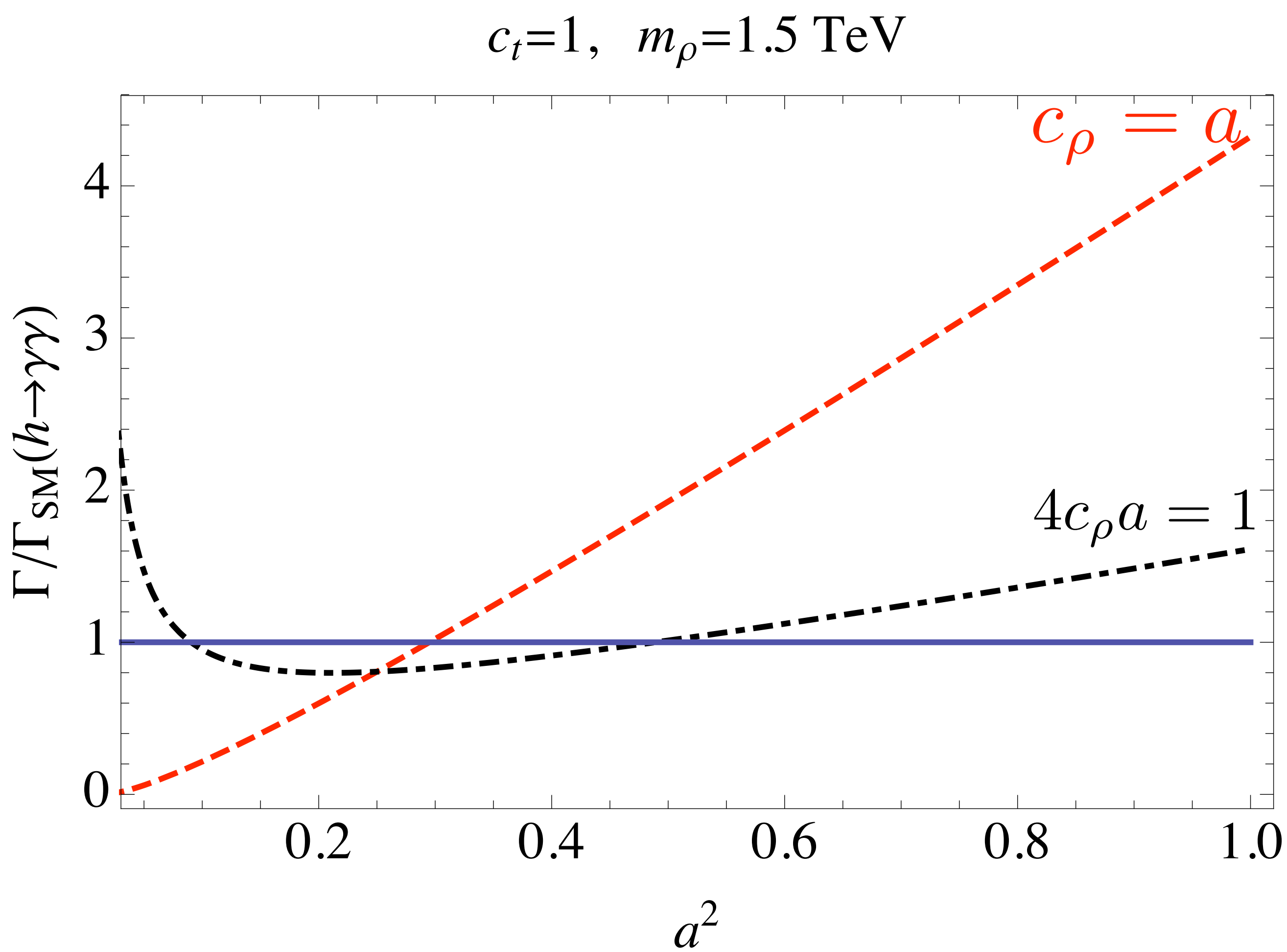
production



Higgs into gammas

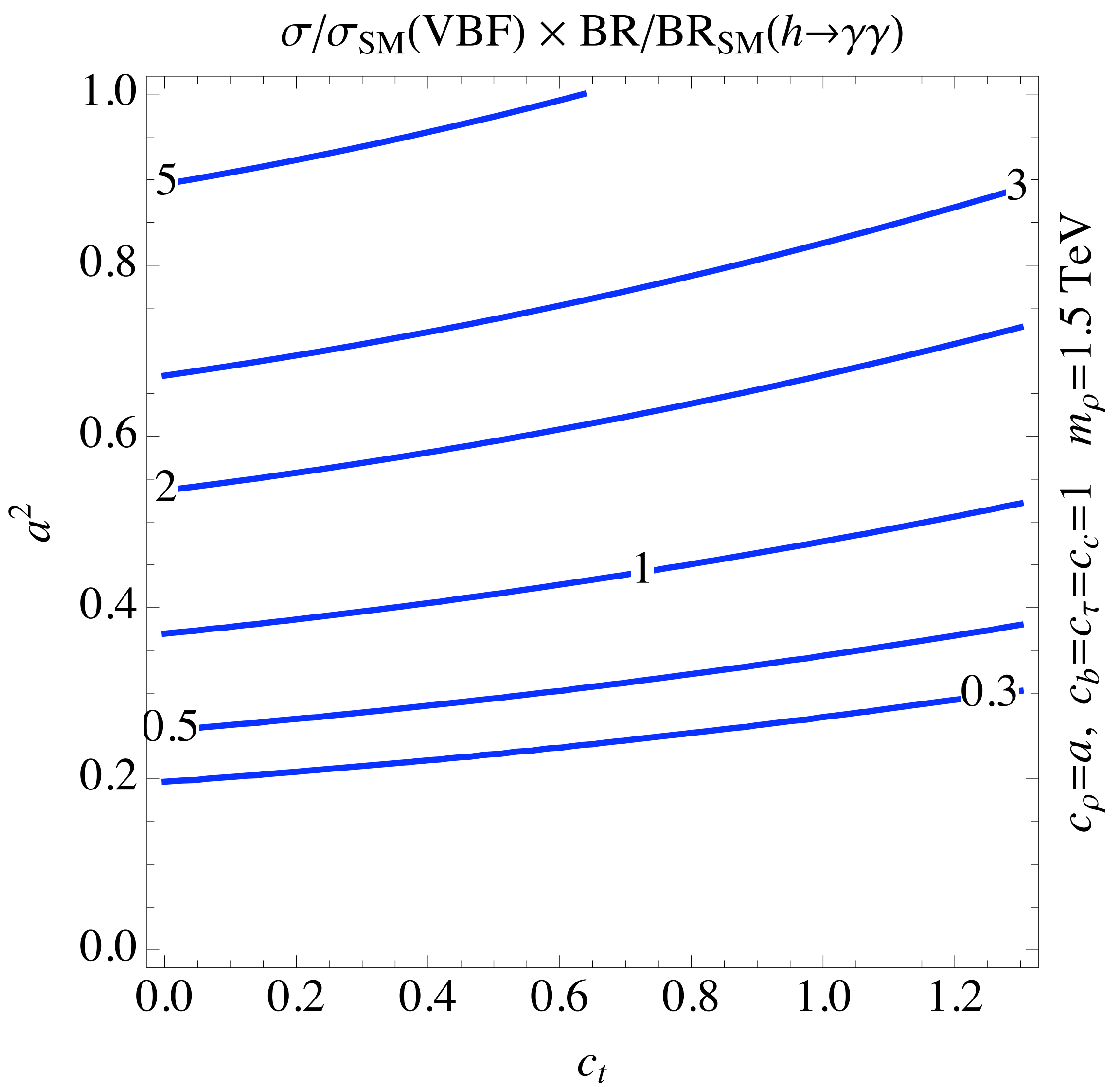


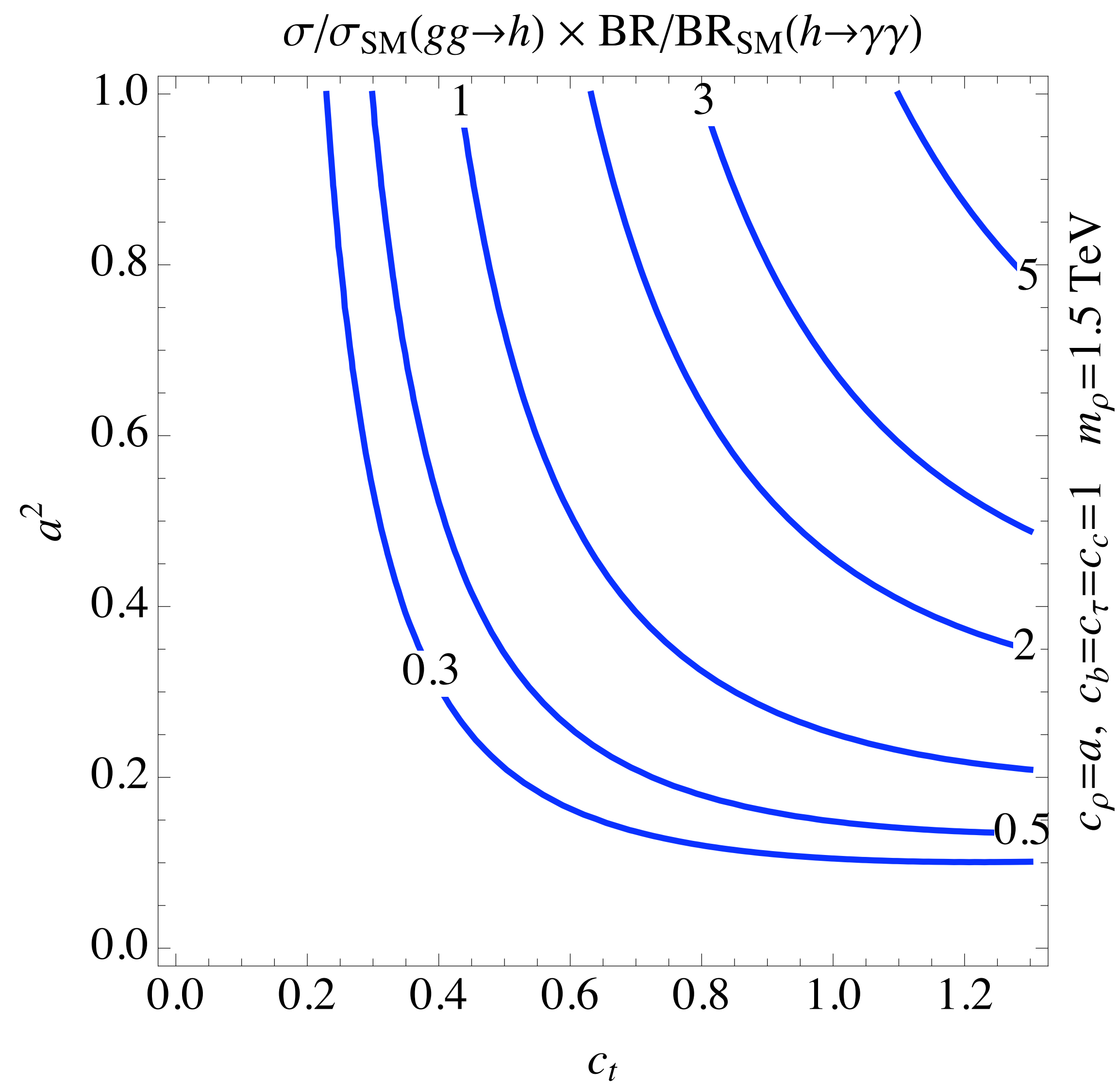




$$\frac{\Gamma}{\Gamma_{SM}}(h \to \gamma\gamma) \simeq \left[1 + \frac{9}{8}c_\rho + \frac{9}{7}(a-1) - \frac{2}{7}(c_t - 1)\right]^2$$

Boost into gammas

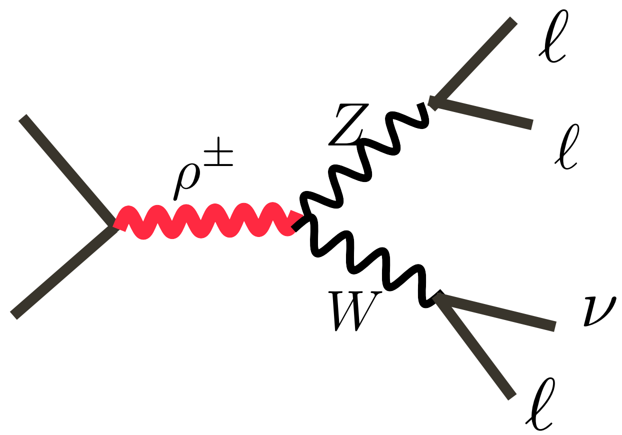


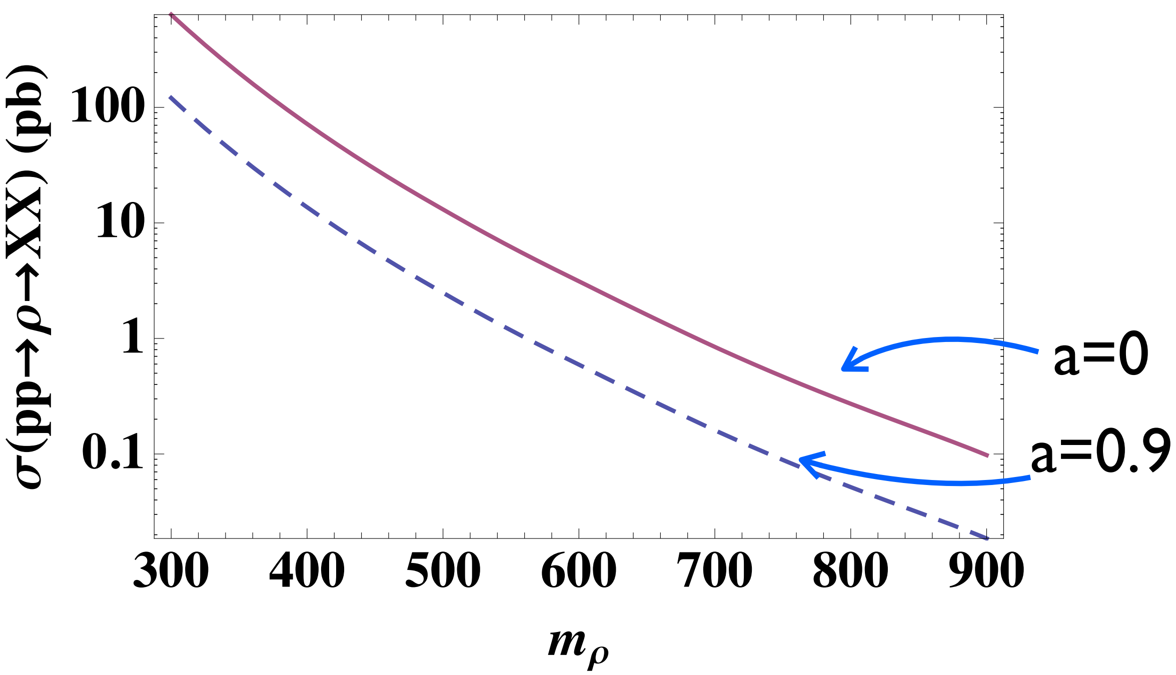


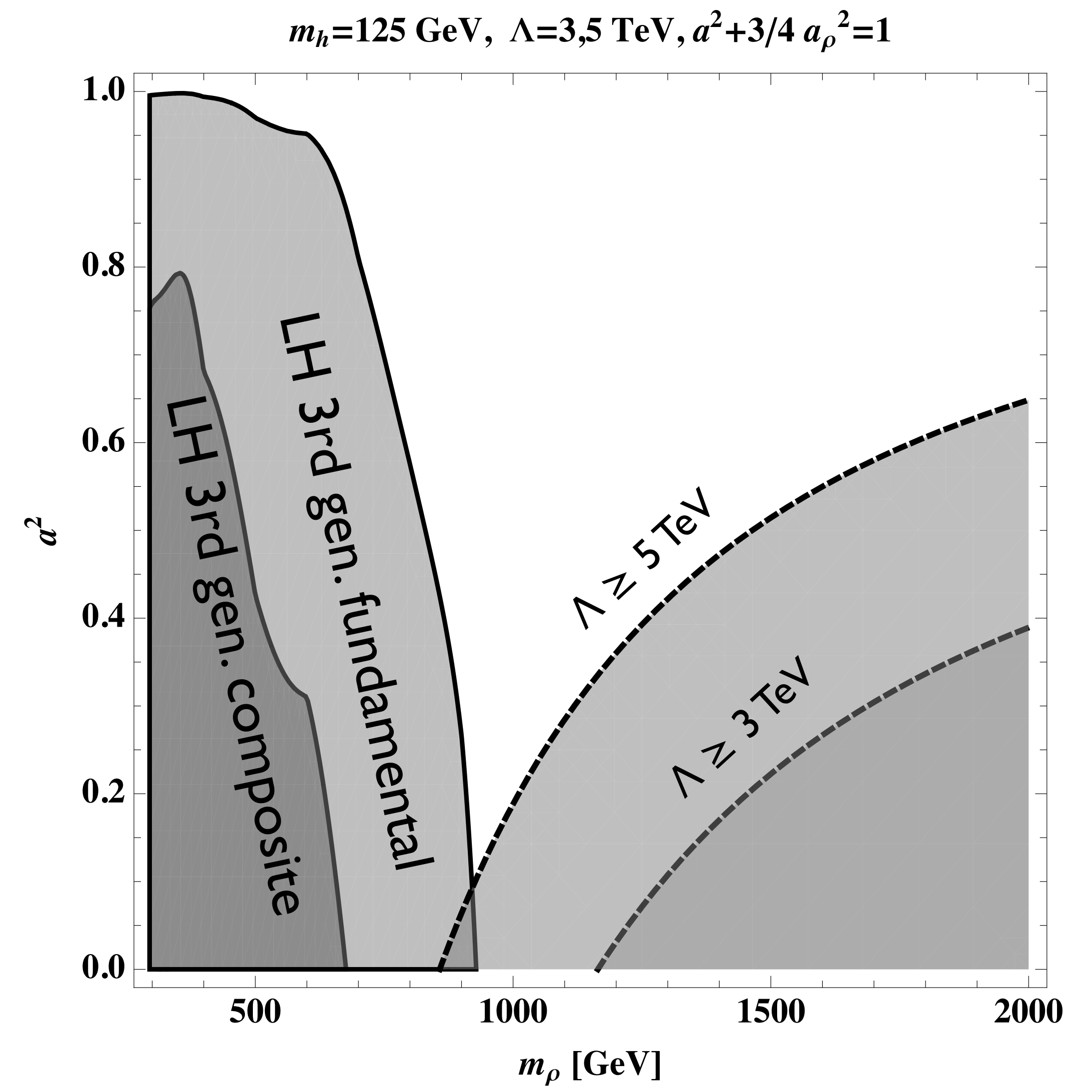
$$\frac{\mathrm{BR}}{\mathrm{BR}_{\mathrm{SM}}}(h \to \gamma\gamma) \simeq \frac{\left[1 + \frac{9}{8} c_\rho + \frac{9}{7}(a-1) - \frac{2}{7}(c_t - 1)\right]^2}{c_b^2 \mathrm{BR}_{\mathrm{SM}}(h \to b\bar{b}) + a^2 \mathrm{BR}_{\mathrm{SM}}(h \to VV^*) + \ldots}$$

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

Add Limits on rho+-



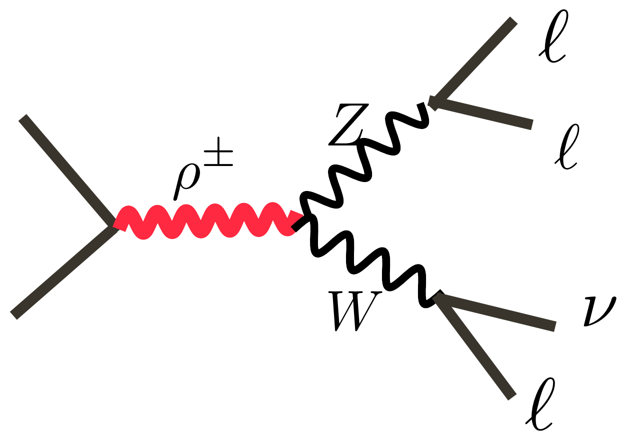


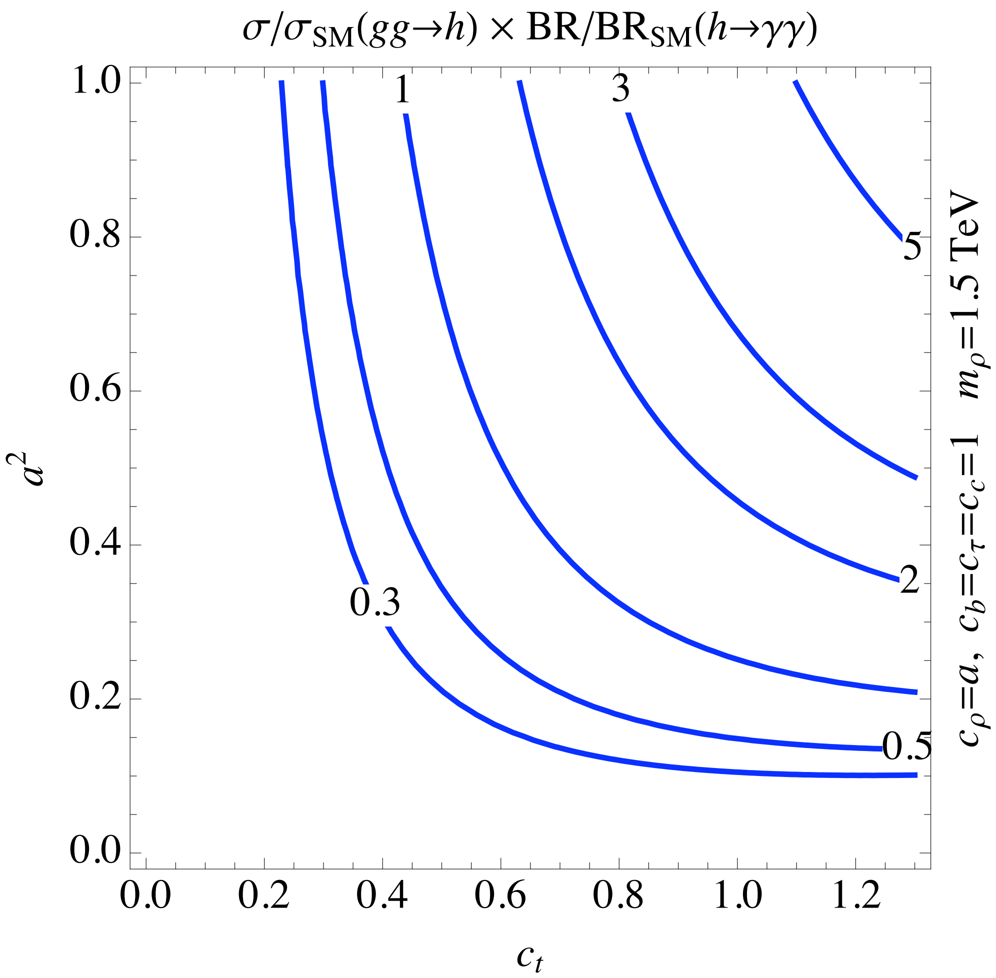


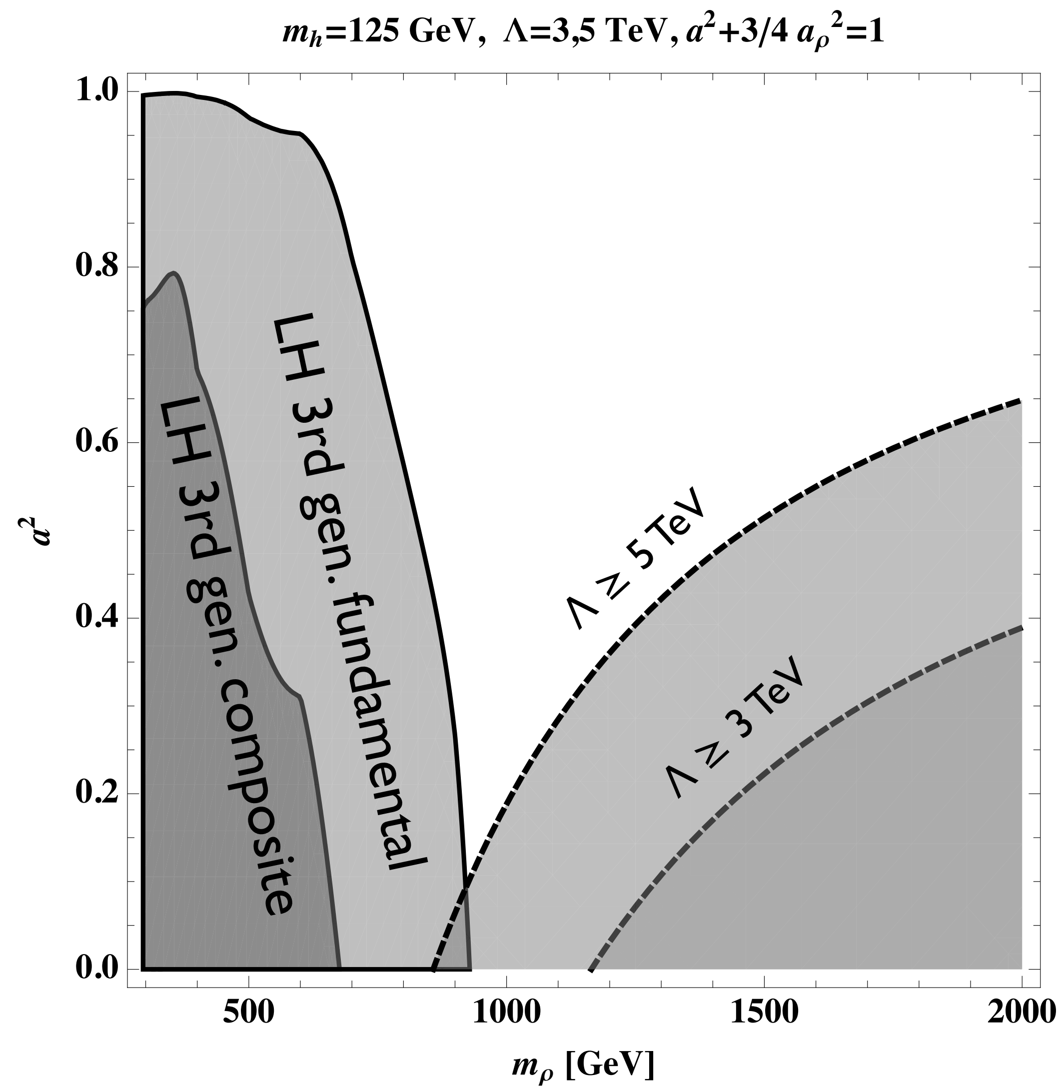
$$\Gamma_{min}/m_\rho \sim 0.04 \left(\frac{m_\rho}{1\ \mathrm{TeV}}\right)^2$$

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

ADD LIMITS ON RHO+-







conclusions

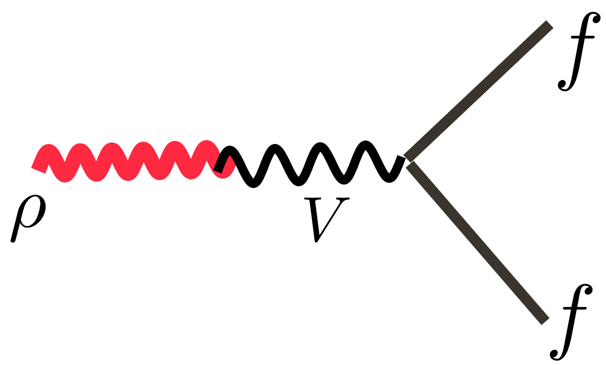
- non standard higgs couplings -> new resonances below the cutoff
- Effective theory of Higgs + spin-1
- Elastic and inelastic sum rules to reduce the parameters
- smaller h->VV but larger h->2 gammas (even x4 SM)
- CMS-bound on rho+- up to 900 GeV

Thank you!

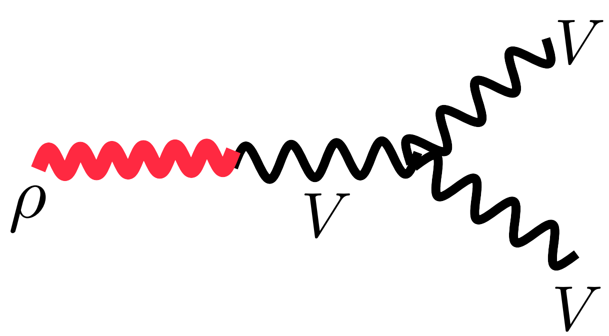
BACKUP SLIDES

COUPLING TO FERMIONS

COUPLING TO FERMIONS



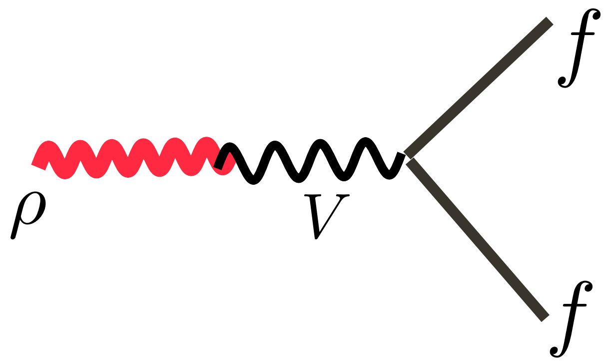
$$g_{\rho^\pm f f'} = g_{SM}\left(a_\rho \frac{m_W}{m_\rho}\right)$$



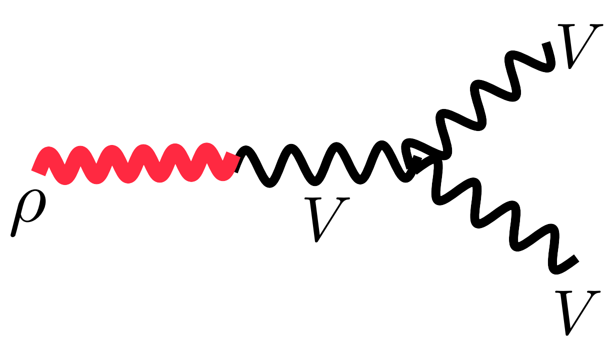
$$g_{\rho^\pm W^\mp Z} = g_{SM}\left(a_\rho \frac{m_Z}{m_\rho}\right)$$

model independent

COUPLING TO FERMIONS

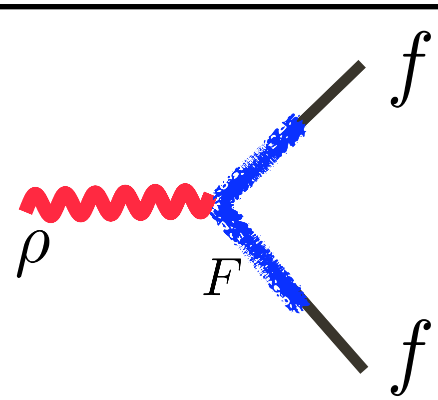


$$g_{\rho^\pm f f'} = g_{SM}\left(a_\rho \frac{m_W}{m_\rho}\right)$$



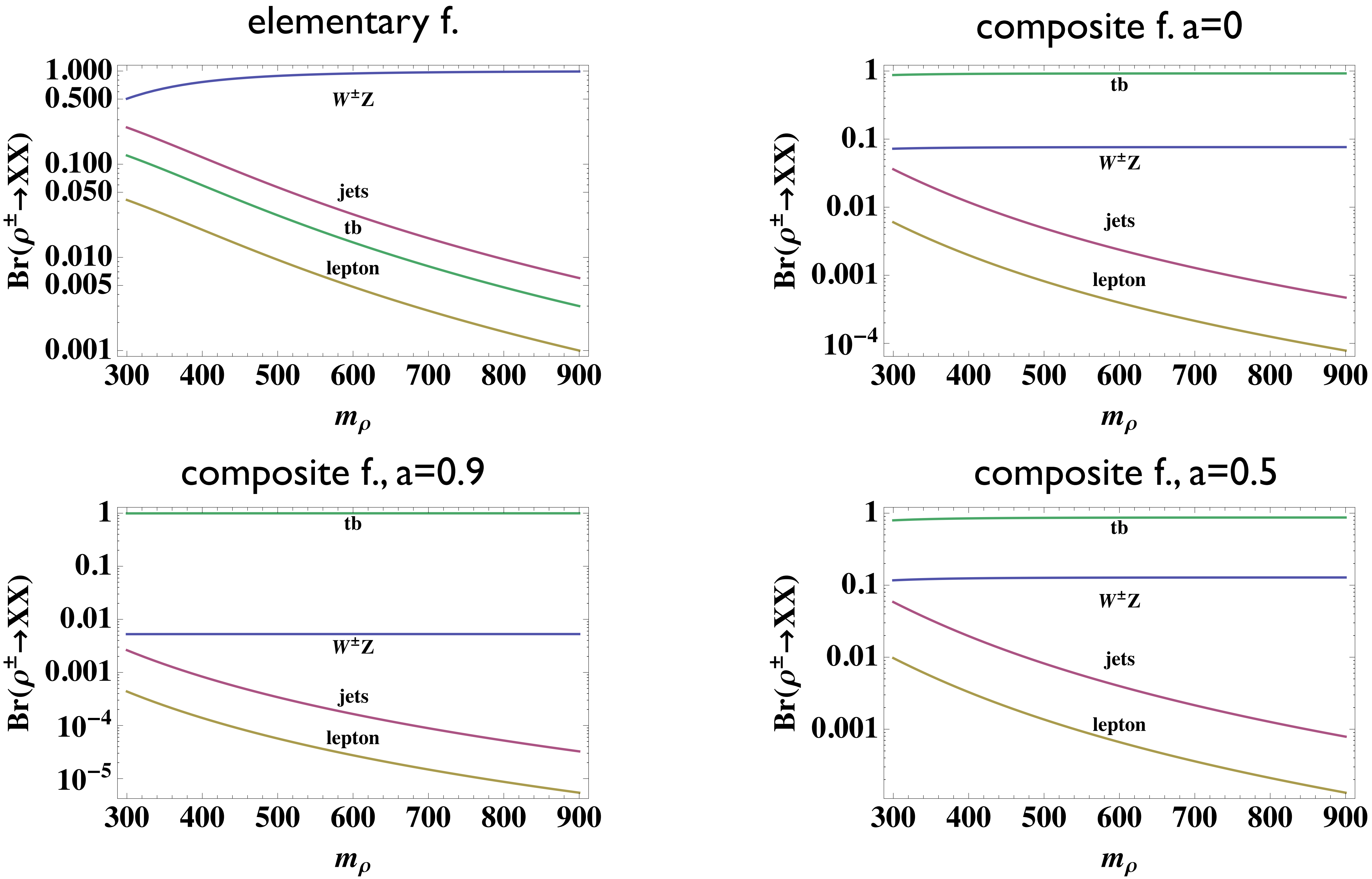
$$g_{\rho^\pm W^\mp Z} = g_{SM}\left(a_\rho \frac{m_Z}{m_\rho}\right)$$

model independent

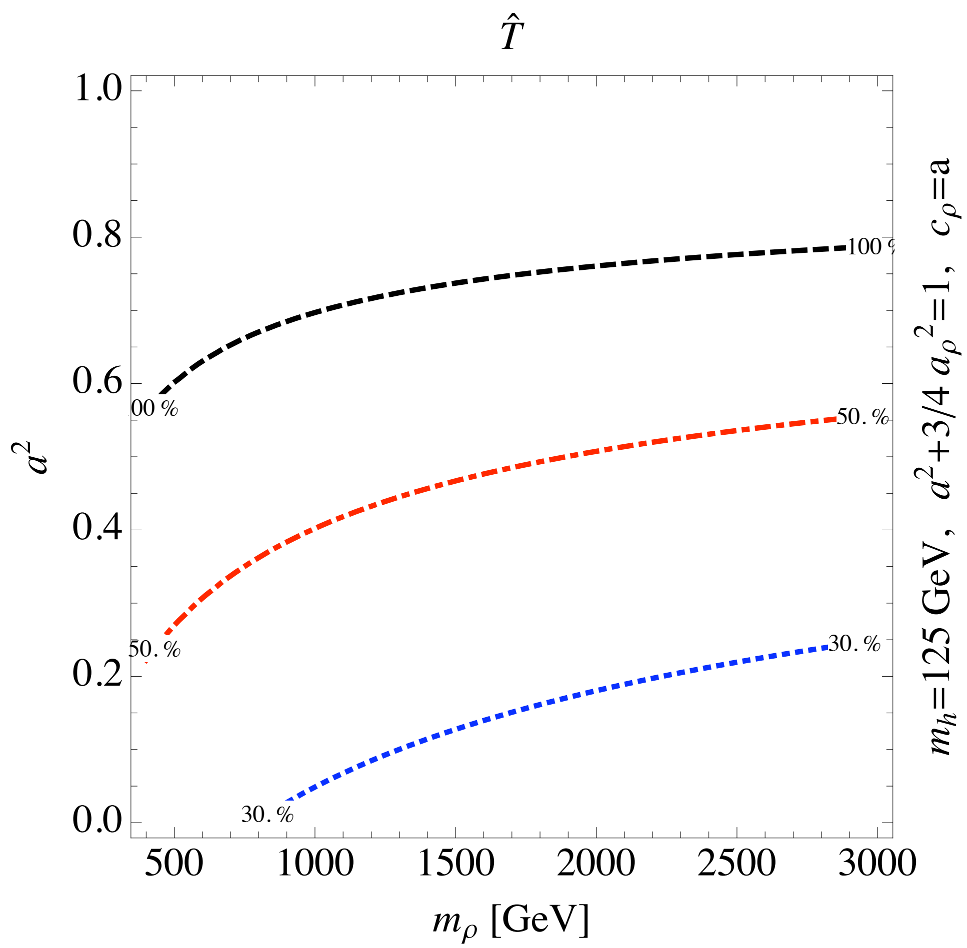


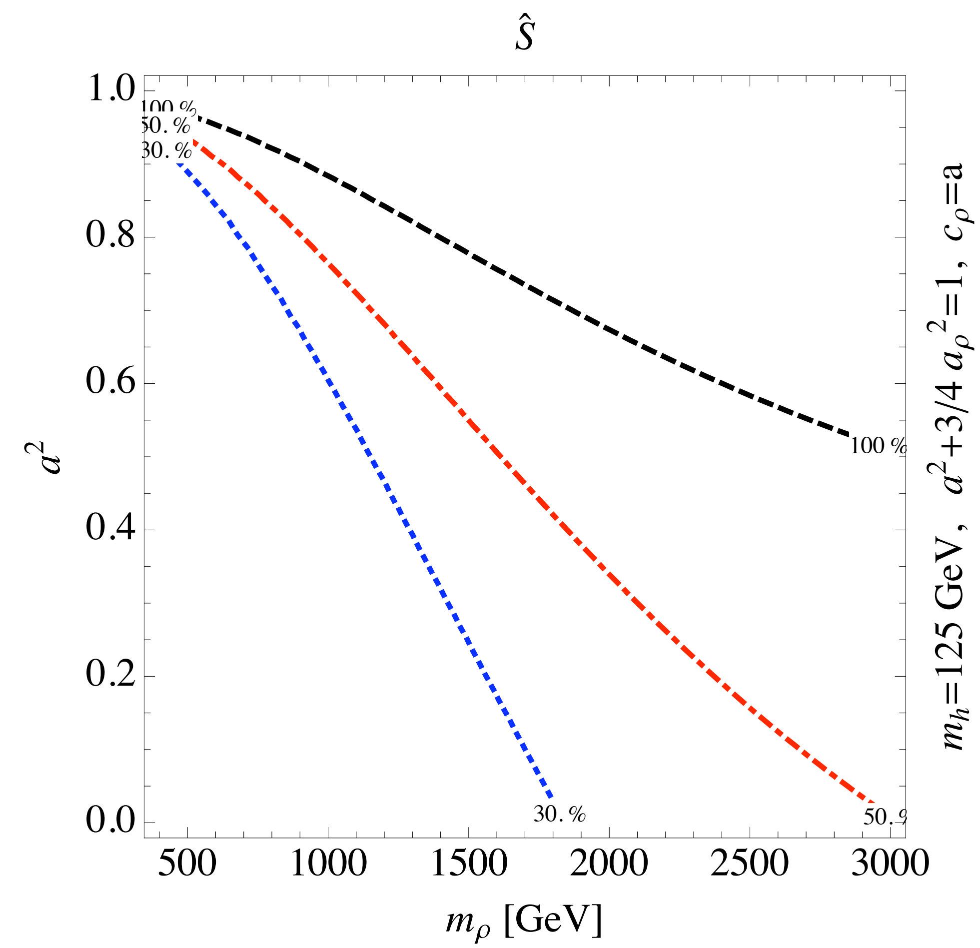
compositeness: model dependent

$$g_{\rho f f}^{comp} \sim g_\rho \sin\theta^2$$


elementary f.
composite f. a=0
composite f., a=0.9
composite f., a=0.5
Br(ρ±→XX)
mρ
W±Z
jets
tb
lepton
1.000
0.500
0.100
0.050
0.010
0.005
0.001
1
0.1
0.01
0.001
10−4
10−5
300
400
500
600
700
800
900

S and T

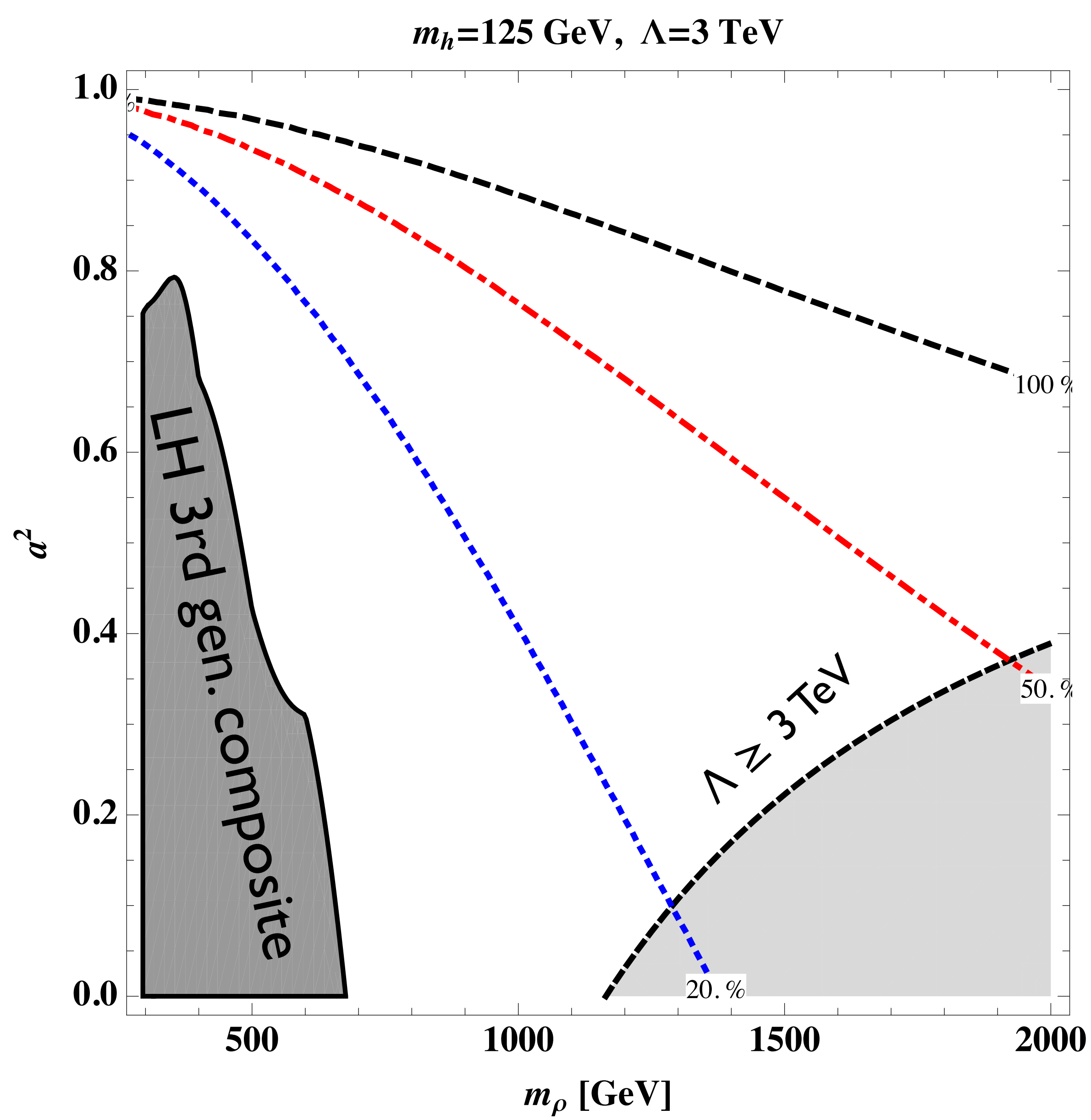




cancellations?
(axial vectors...)

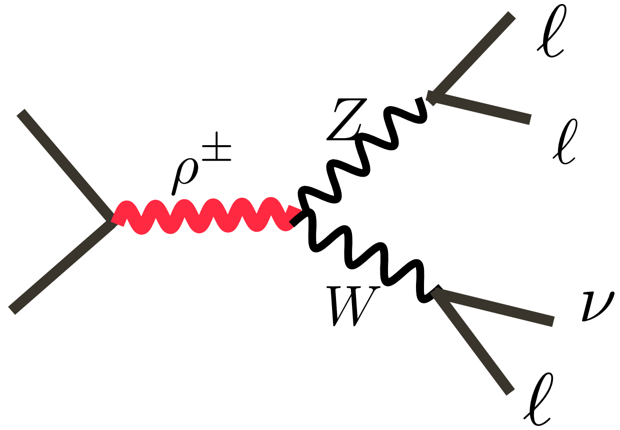
tree-level
contribution

S-parameter



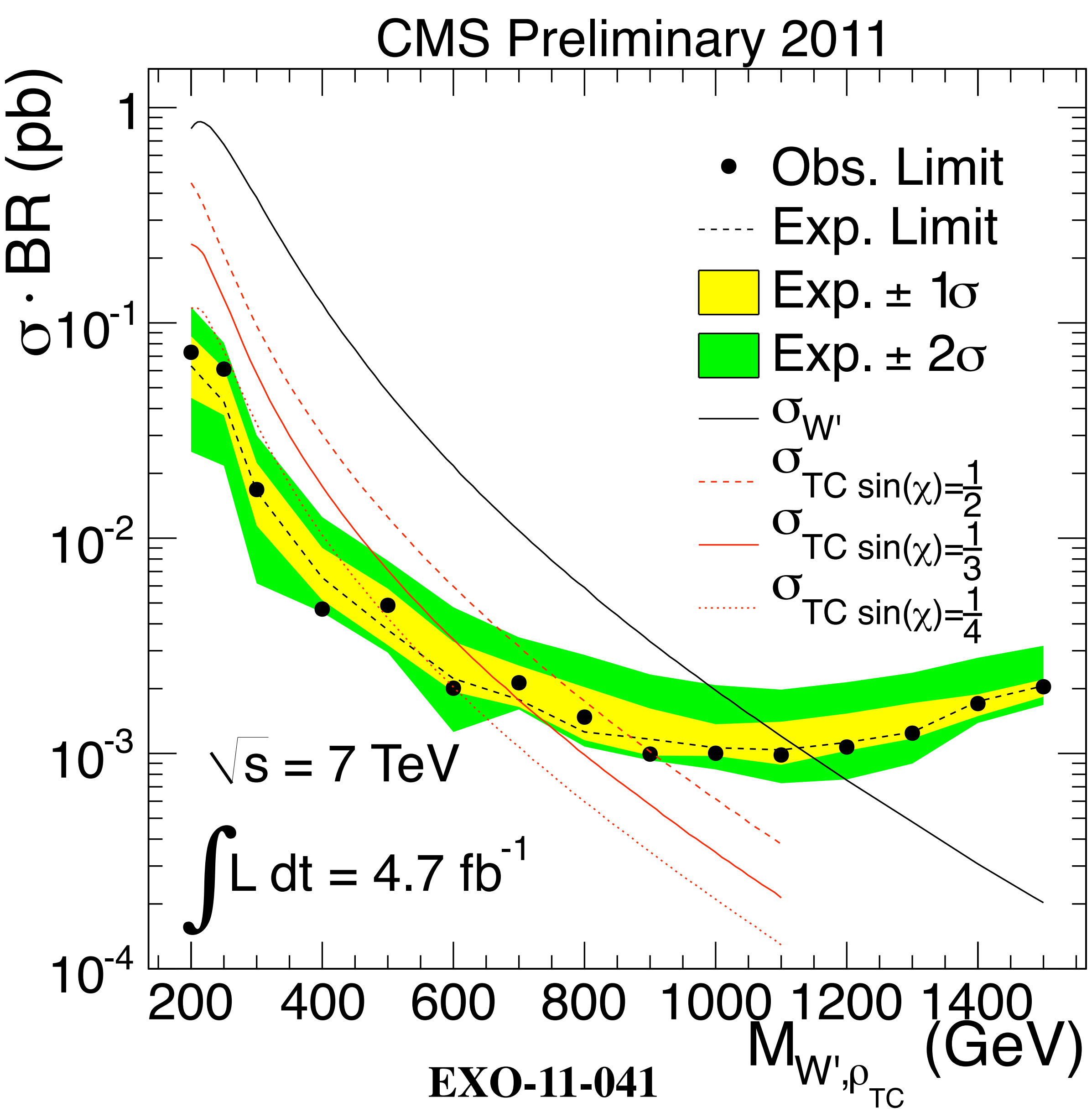
m_h=125 GeV, Λ=3 TeV
1.0
0.8
0.6
0.4
0.2
0.0
500
1000
1500
2000
m_ρ [GeV]
a^2
100 %
50. %
20. %
Λ ≥ 3 TeV
LH 3rd gen. composite

Limits on rho+-

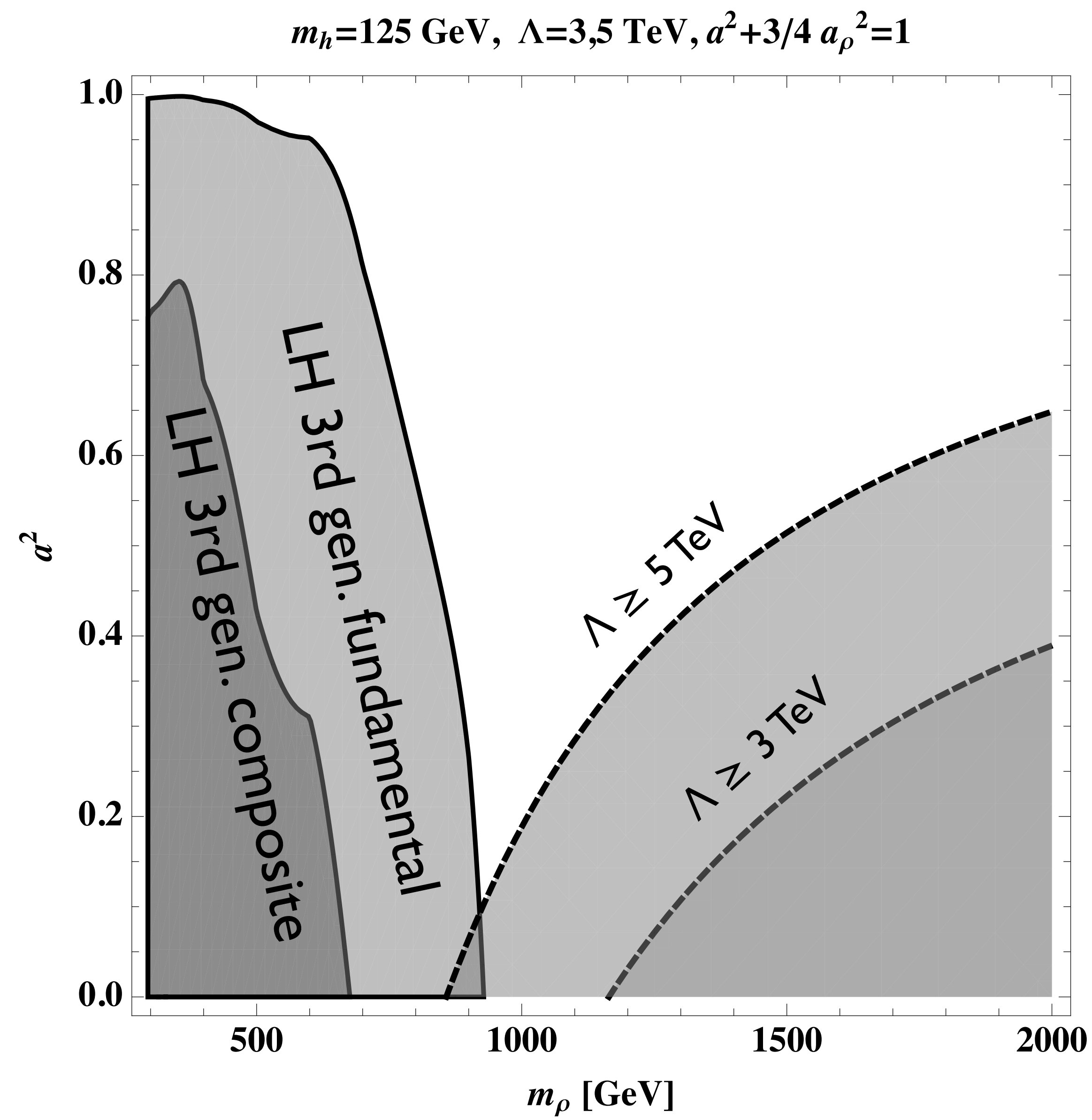


$$\Gamma_{min}/m_\rho \sim 0.04 \left(\frac{m_\rho}{1\ \mathrm{TeV}}\right)^2$$

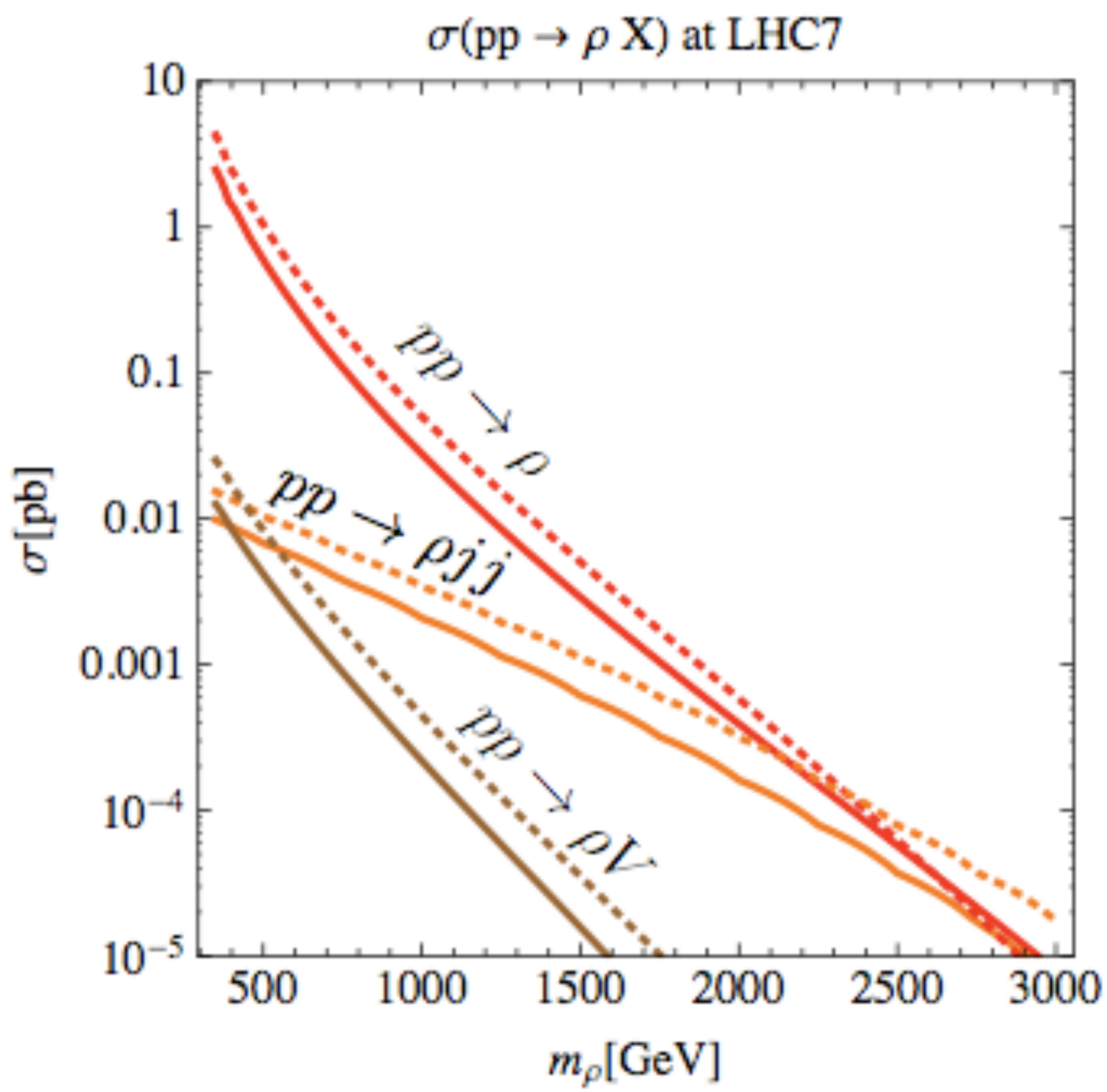
$$\sigma \sim 50\ \mathrm{fb\ at\ 1\ TeV}$$



EXO-11-041

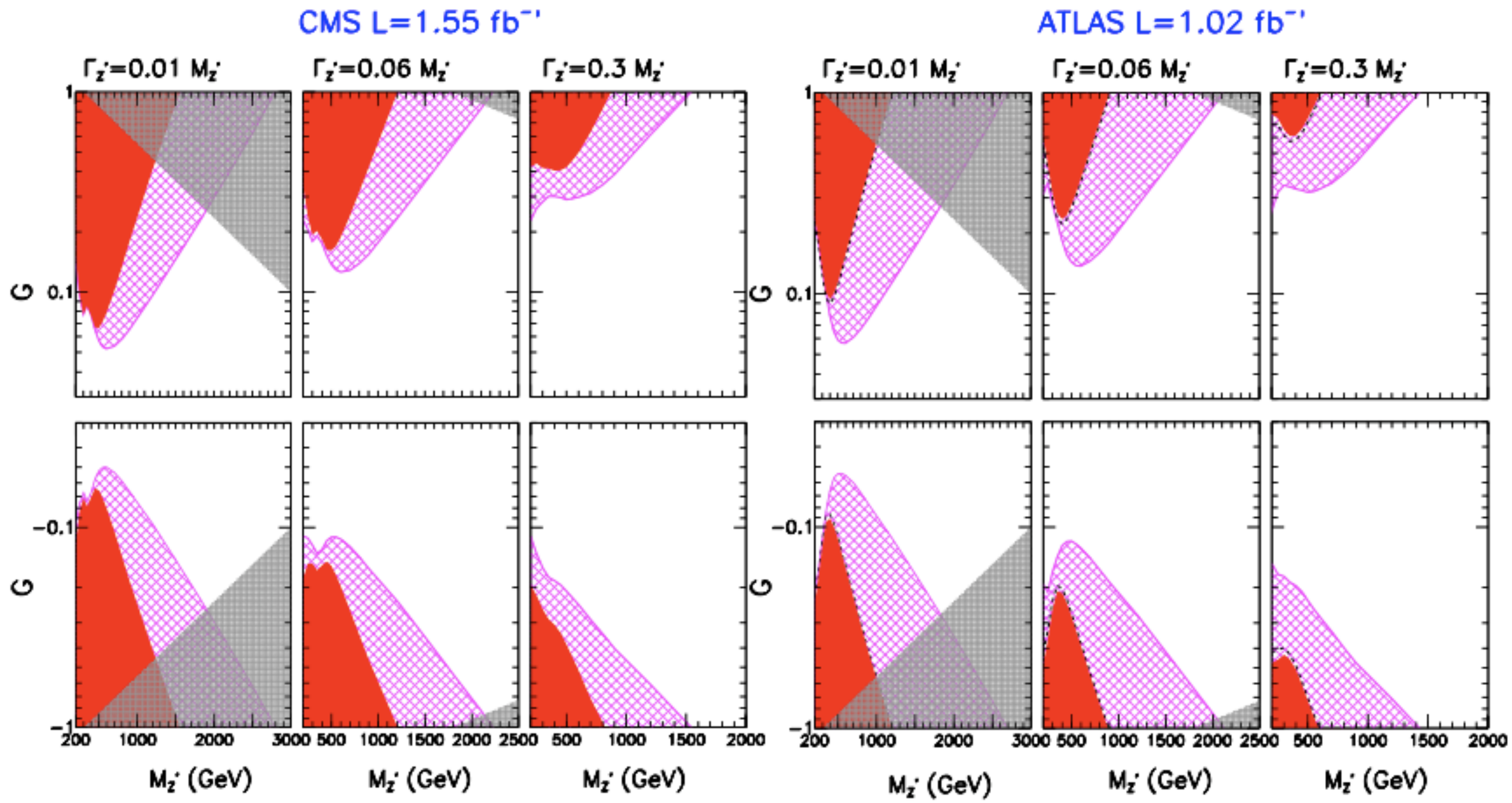


resonance production



Falkowski et al. 1108.1183 [hep-ph]

limits on rho->WW from h->WW

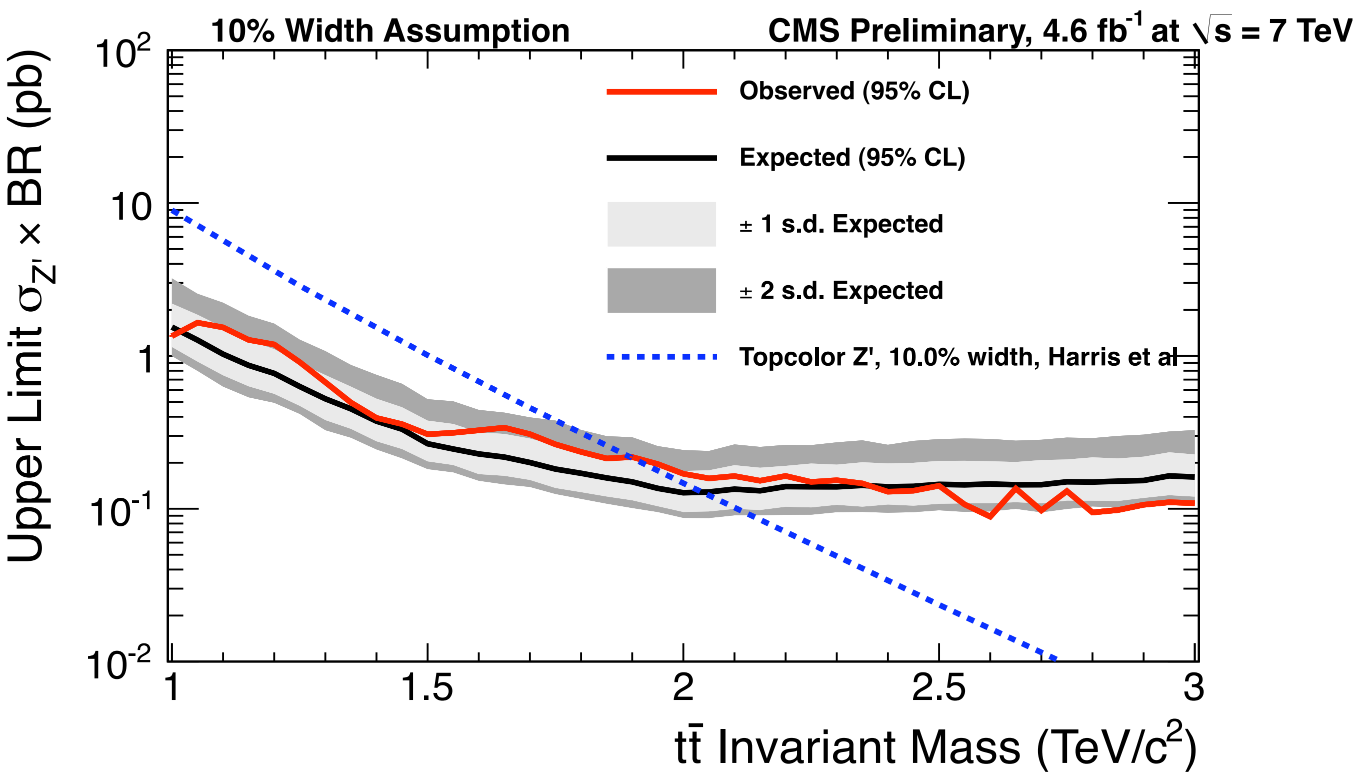


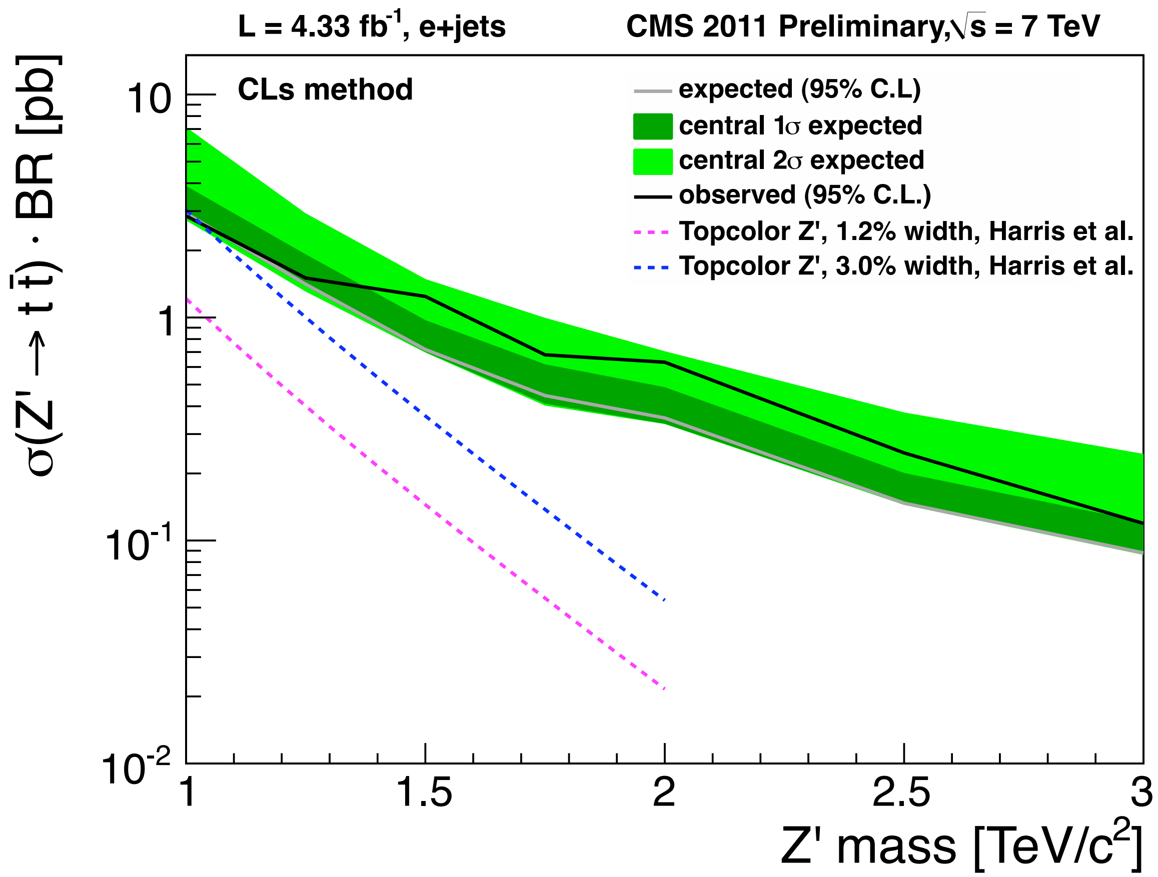
$$G = \left(\frac{g_{Z'q\bar{q}}}{g_{Zq\bar{q}}}\right)\left(\frac{g_{Z'WW}}{g_{Z'WW\,max}}\right)$$

Eboli et al. 1112.0316 [hep-ph]

rho in DY; h in gluon and VB Fusion
h->WW optimal for SM couplings

rho->top pairs





composite top=large BR(rho->tt)

$\sigma \sim 50$ fb at 1 TeV

limits~0.1-1 pb up to 3 TeV

More on the Inelastic