Scalar LeptoQuarks & Higgs Pair Production at the LHC

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based on:arXiv-1311.4445

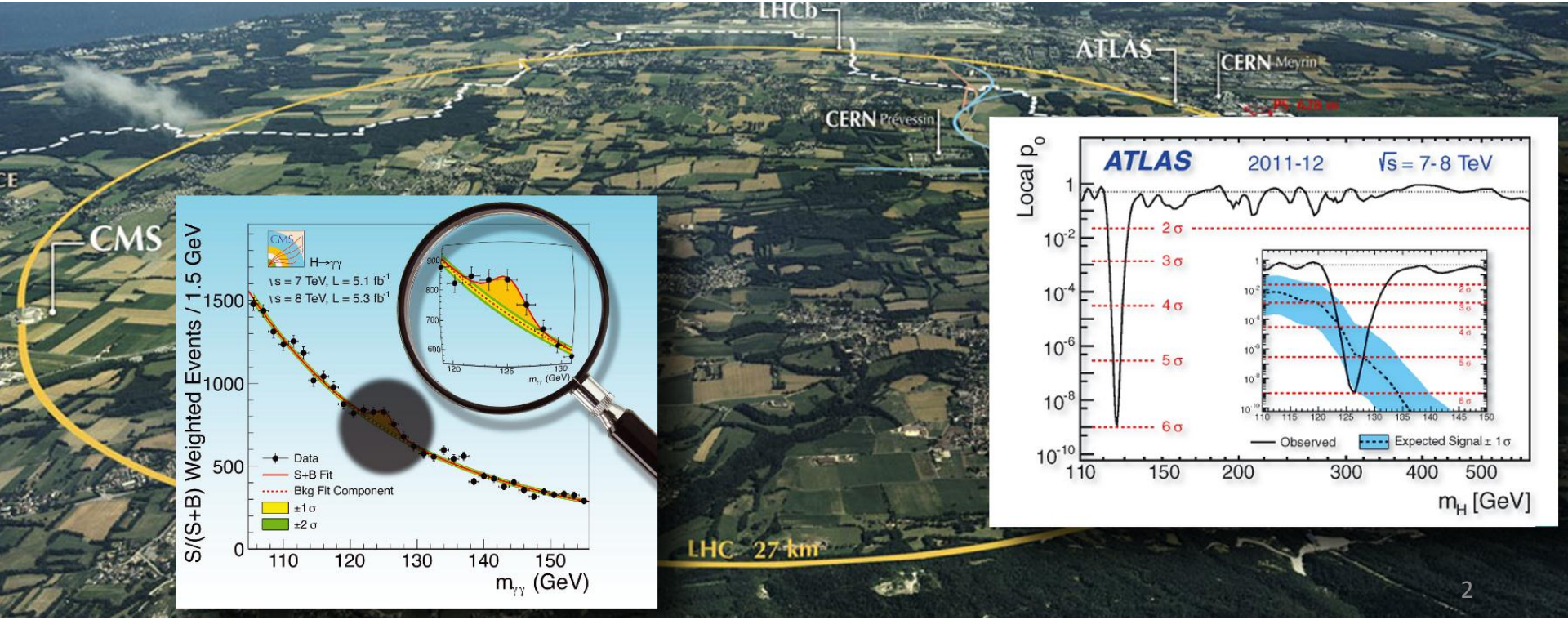
Overview

- Introduction & Motivation
- A model with Leptoquarks (LQ)
- Constraints
- Single & Pair Higgs productions at 8 TeV
- Conclusions

Introduction

The July 4 discovery brought a new era in Particle physics

G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716 (2012) 1
S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 716 (2012) 30



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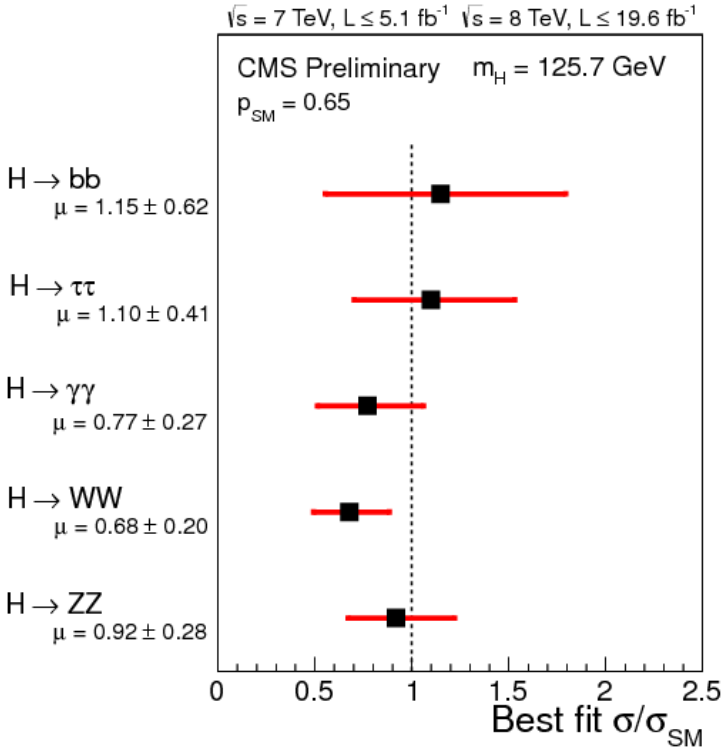

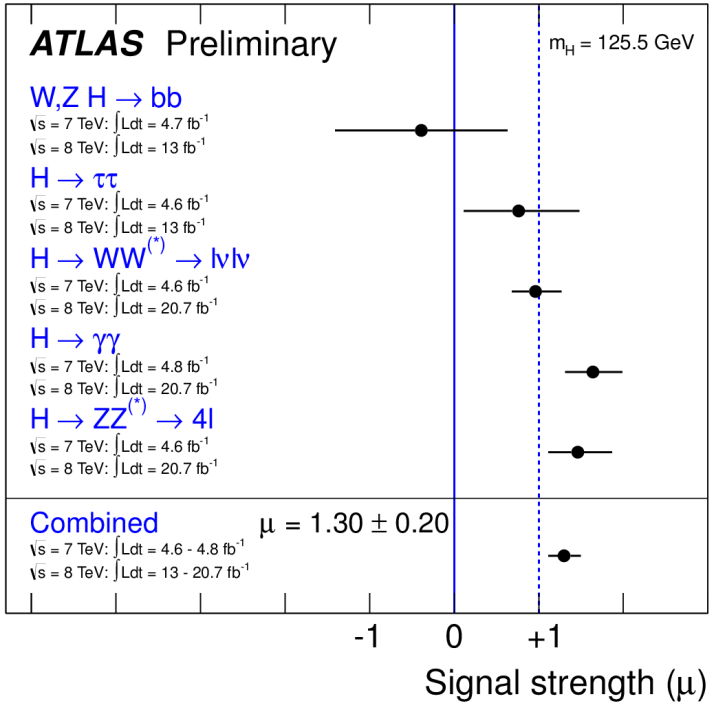

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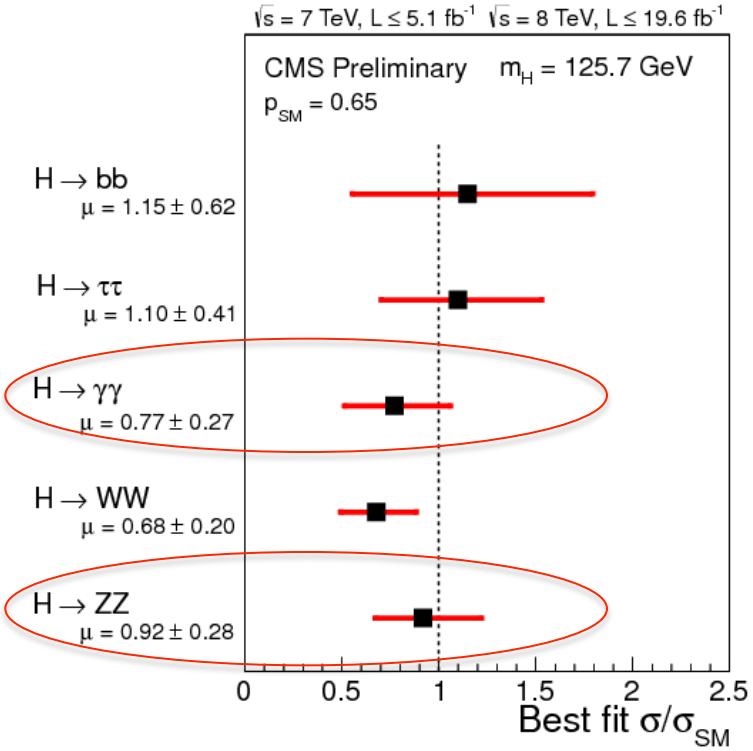

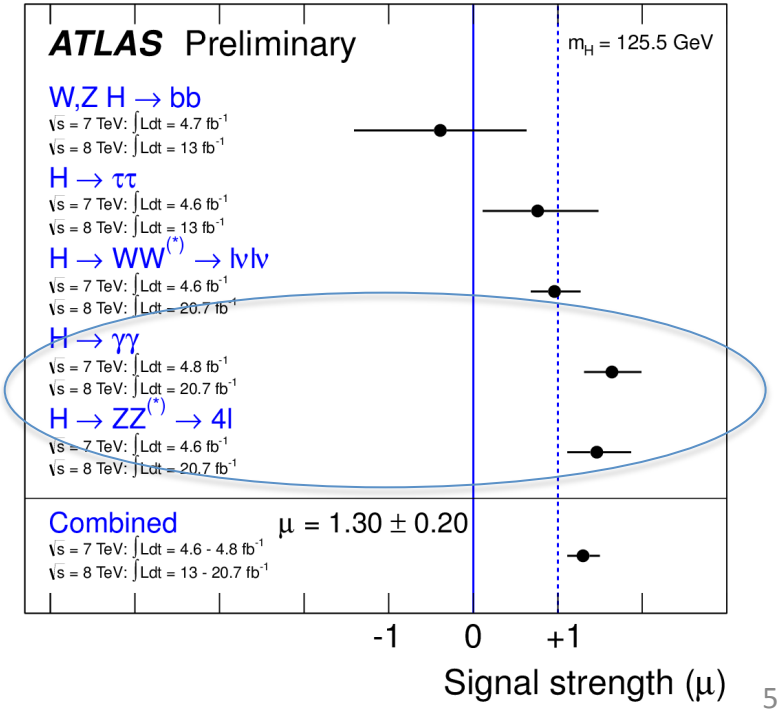

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Sensitive to new physics

✧ Many theories with Higgs portal coupling to new sector
✧ Among these models with colored new sector are easier to be seen at LHC

Models with colored particles

GUT remnants, LQs, Extra family, composite particles…many more

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Single vs multiple colored particles

To accommodate the Higgs results the contribution to the single Higgs production coupling(s) to Higgs should yield :

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e.g. G. Kribs & A. Martin, Phys.Rev. D86 (2012) 095023

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LQs for radiative neutrino masses where m_{LQ} <500GeV

e.g. K.S. Babu & J. Julio Nucl.Phys. B841 (2010) 130-156

The Model

SU(2) doublet and singlet color triplets

$$\Omega \equiv \begin{pmatrix} \omega^{2/3} \\ \omega^{-1/3} \end{pmatrix} \sim (3, 2, 1/6), \qquad \chi^{-1/3} \sim (3, 1, -1/3)$$

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The part of the Lagrangian for LQs

$$\begin{aligned} \mathcal{L} &= \left(Y_{ij}\Omega i\sigma_2 L_i d_j^c + F_{ij}\chi e_i^c u_j^c - \mu\Omega^\dagger H\chi + \text{h.c}\right) - m_\Omega^2|\Omega|^2 - m_\chi^2|\chi|^2 \\ &- \lambda_\omega|\Omega|^2|H|^2 - \lambda_\chi|\chi|^2|H|^2 - \kappa|\Omega^\dagger H|^2 \end{aligned}$$

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Mixing in -1/3 charged LQs

$$\begin{pmatrix} \omega^{-1/3} \\ \chi^{-1/3} \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

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Disclaimer: This is just an example. There are many models that can have similar same results

The masses and mixings

$$
\begin{aligned}
m_\omega^2 &= m_\Omega^2 + \frac{\lambda_\omega}{2} v^2, \\
m_{\chi_1,\chi_2}^2 &= \frac{1}{2}\left(m_\omega^2 + \frac{\kappa}{2} v^2 + m_\chi^2 + \frac{\lambda_\chi}{2} v^2 \mp \sqrt{m_\omega^2 + \frac{\kappa}{2} v^2 - m_\chi^2 - \frac{\lambda_\chi}{2} v^2 + 2\mu^2 v^2} \right), \\
\tan 2\vartheta &= \frac{2\sqrt{2}\mu v}{2m_\omega^2 + \kappa v^2 - 2m_\chi^2 - \lambda_\chi v^2},
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\end{aligned}
$$

The LQs & Higgs interaction

$$
\begin{aligned}
V_{\text{LQ-h}} &= \left\{ \left(\lambda_\omega c_\vartheta^2 + \kappa c_\vartheta^2 + \lambda_\chi s_\vartheta^2 \right) |\chi_1|^2 + \left(\lambda_\omega s_\vartheta^2 + \kappa s_\vartheta^2 + \lambda_\chi c_\vartheta^2 \right) |\chi_2|^2 \right. \\
&+ \left. \lambda_\omega |\omega|^2 + \left(\lambda_\omega + \kappa - \lambda_\chi \right) s_\vartheta c_\vartheta \left(\chi_1 \chi_2^* + \chi_2 \chi_1^* \right) \right\} \left(\frac{h^2}{2} + hv \right) \\
&+ \left\{ \mu \left(\left(|\chi_2|^2 - |\chi_1|^2 \right) c_\vartheta s_\vartheta + \chi_1^* \chi_2 c_\vartheta^2 - \chi_2^* \chi_1 s_\vartheta^2 \right) + \text{h.c} \right\} \frac{h}{\sqrt{2}},
\end{aligned}
$$

Status for LQ searches at the LHC experiments

$LQ \to eq$

@7TeV 5 fb^-1, 1st gen LQ m_{LQ}> 830 (640) GeV for BR=1(0.5)
CMS Collaboration Phys.Rev. D86 (2012) 052013

$LQ \to \mu q$

@8TeV 20 fb^-1, 2nd gen LQ m_{LQ}> 1070 (785) GeV for BR=1(0.5)
CMS PAS EXO-12-042

$LQ \to b\tau$

@7TeV 5fb^-1, 3d gen LQ m_{LQ}> 525 GeV for BR=1(0.6)
CMS Collaboration Phys.Rev.Lett. 110 (2013) 081801
@7TeV 5fb^-1, 3d gen LQ m_{LQ}> 534 GeV for BR=1
ATLAS Collaboration JHEP 1306 (2013) 033

$LQ \to b\nu_\tau$

@7TeV 5fb^-1, 3d gen LQ m_{LQ}> 450 (200) GeV for BR=1(0.6)
CMS Collaboration JHEP 1212 (2012) 055

$LQ \to t\tau$

No analysis from either of the 2 collaboration
There is a constraint from recent pp->ttH result

The mass spectrum

$$m_\omega > m_{\chi 2} > m_{\chi 1}$$

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To escape the direct search constraints assume:

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$$\Gamma_{\omega \to \chi W^*} >> \Gamma_{\omega \to \tau \bar{b}}$$
$$\Gamma_{\chi 2 \to t\tau} >> \Gamma_{\chi 2 \to \tau \bar{b}}$$
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The decay channels

$$\chi_i \to t\tau$$
$$\omega \to \chi_i W^*$$

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Events @ LHC

$$gg \to \omega\bar{\omega} \to \chi_i \bar{\chi}_j W^{+*} W^{-*}$$
$$gg \to \chi_i \bar{\chi}_i \to t\bar{t}\tau^+\tau^-$$

Higgs production X-section & diphoton rate

$$\sigma_{gg\to h} = \frac{G_F\alpha_s^2}{126\sqrt{2}\pi}\left|\frac{1}{2}A_{\frac{1}{2}}(x_t)+\sum_i C_i\frac{\lambda_i v^2}{4m_{s_i}^2}A_0(x_{s_i})\right|^2,$$

$$\Gamma_{\gamma\gamma} = \frac{G_F\alpha^2 m_h^3}{126\sqrt{2}\pi^3}\left|A_1(x_W)+\frac{4}{3}A_{\frac{1}{2}}(x_t)+\sum_i\frac{\lambda_i}{g_w}\frac{m_W^2}{m_{s_i}}d_iQ_i^2A_0(x_{s_i})\right|^2.$$

$$x_\phi = 4m_\phi^2/m_h^2 \text{ for } \phi = t, s_i, W$$

$$A_1(x) = -\left(2+3x+3x(2-x)f(x)\right),$$

$$A_{1/2} = 2x\left(1+(1-x)f(x)\right),$$

$$A_0 = -x\left(1-xf(x)\right),$$

$$f(x) = \begin{cases} \arcsin^2\left(1/\sqrt{x}\right), & \text{if } x\geq 1 \\ -\frac{1}{4}\left(\log\frac{1+\sqrt{1-x}}{1-\sqrt{1-x}}-i\pi\right)^2, & \text{if } x<1 \end{cases}$$

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Contributions from LQs

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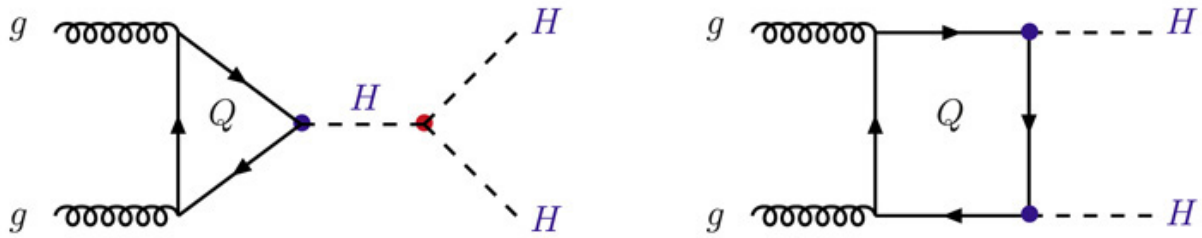
Higgs pair production mechanisms at LHC



$$\frac{d\hat{\sigma}_{gg\to hh}}{d\hat{t}} = \frac{G_F^2\alpha_s^2}{256(2\pi)^3}\left(\left|\frac{3m_h^2}{\hat{s}-m_h^2}F_{tri}+F_{box}\right|^2+|G_{box}|^2\right)$$

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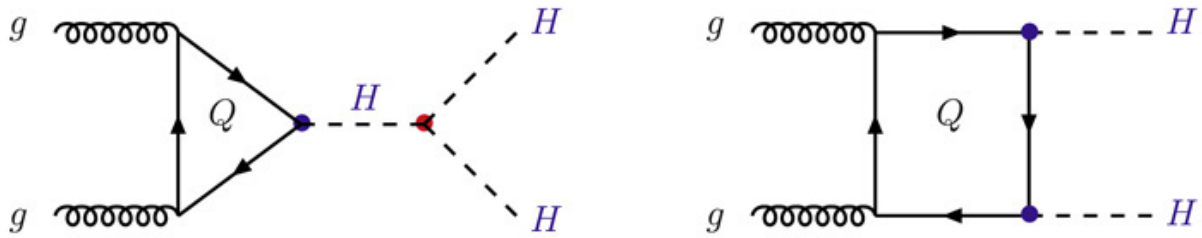

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E. W. N. Glover and J. J. van der Bij, Nucl. Phys. B 309, 282 (1988)

D. A. Dicus, C. Kao and S. S. D. Willenbrock, Phys. Lett. B 203, 457 (1988)

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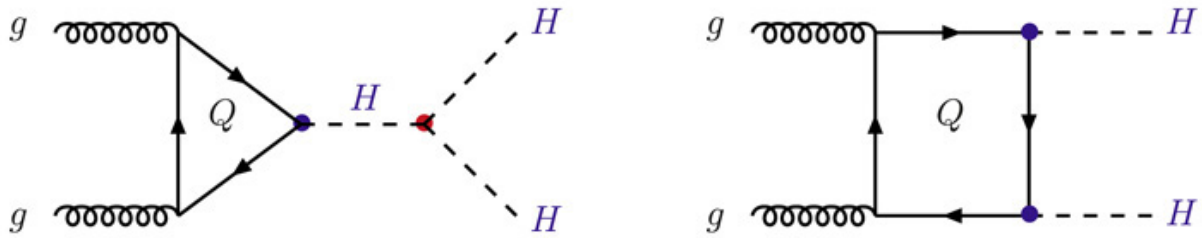

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QCD corrections

S. Dawson, S. Dittmaier, M. Spira, Phys.Rev. D58 (1998) 115012

T. Plehn, M. Spira, P.M. Zerwas, Nucl.Phys. B479 (1996) 46-64

Many recent works on NLO & NNLO…

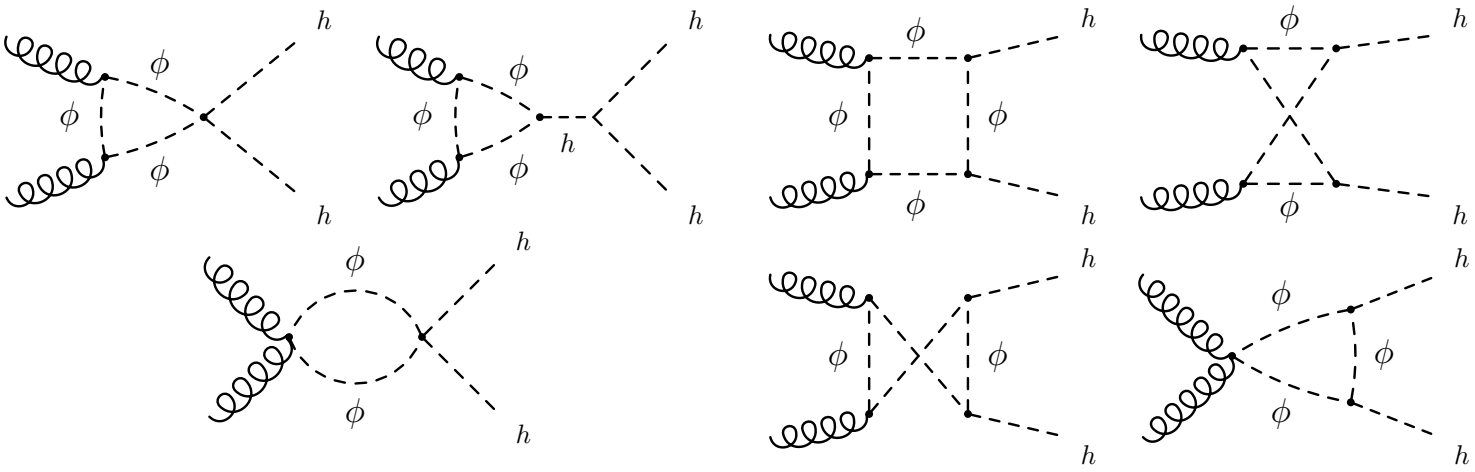
Amplitudes Higgs pair production in the SM

E. W. N. Glover and J. J. van der Bij, Nucl. Phys. B 309, 282 (1988)
T. Plehn, M. Spira and P. M. Zerwas, Nucl. Phys. B 479, 46 (1996)

$$
\begin{aligned}
F_{tri} &= \frac{2m_t^2}{s}\left(2+\left(4m_t^2-s\right)C_{AB}\right), \\
F_{box} &= \frac{2m_t^2}{s}\left(2+4m_t^2C_{AB}-\left(s+2m_h^2-8m_t^2\right)m_t^2\left(D_{ABC}+D_{BAC}+D_{ACB}\right)\right. \\
&+ \frac{m_h^2-4m_t^2}{s}\left(\left(t-m_h^2\right)\left(C_{AC}+C_{BD}\right)+\left(u-m_h^2\right)\left(C_{BC}+C_{AD}\right)\right. \\
&- \left.\left.\left(tu-m_h^4\right)D_{ACB}\right)\right) \\
G_{box} &= \frac{m_t^4}{s(tu-m_h^4)}\left(\frac{(t^2+m_h^4-8tm_t^2)}{m_t^2}(sC_{AB}+(t-m_h^2)(C_{AC}+C_{BD})-stD_{BAC})\right. \\
&+ \frac{(u^2+m_h^4-8um_t^2)}{m_t^2}(sC_{AB}+(u-m_h^2)(C_{BC}+C_{AD})-suD_{ABC}) \\
&- \frac{(t^2+u^2-2m_h^4)(t+u-8m_t^2)}{m_t^2}C_{CD} \\
&- \left.2(t+u-8m_t^2)(tu-m_h^4)\left(D_{ABC}+D_{BAC}+D_{ACB}\right)\right)
\end{aligned}
$$

Contributions from colored scalars

A. Belyaev et al, Phys. Rev. D 60, 075008 (1999) for MSSM
E. Asakawa et al, Phys. Rev. D 82, 115002 (2010) for LQ
G. D. Kribs and A. Martin, Phys. Rev. D 86, 095023 (2012) for Octet scalar



$$F^S_{tri} = -\frac{\lambda_S C_s v^2}{m_S^2}(2m_S^2 C_{AB} + 1),$$

$$F^S_{box} = -\frac{\lambda_S C_s v^2}{m_S^2}(2m_S^2 C_{AB} + 1) - \frac{2C_s(\lambda_S v^2)^2}{s}\left(m_S^2\left(D_{ABC} + D_{BAC} + D_{ACB}\right)\right.$$
$$\left. - \frac{t - m_h^2}{s}C_{AC} - \frac{u - m_h^2}{s}C_{BC} + \frac{ut - m_h^4}{2s}D_{ACB}\right),$$

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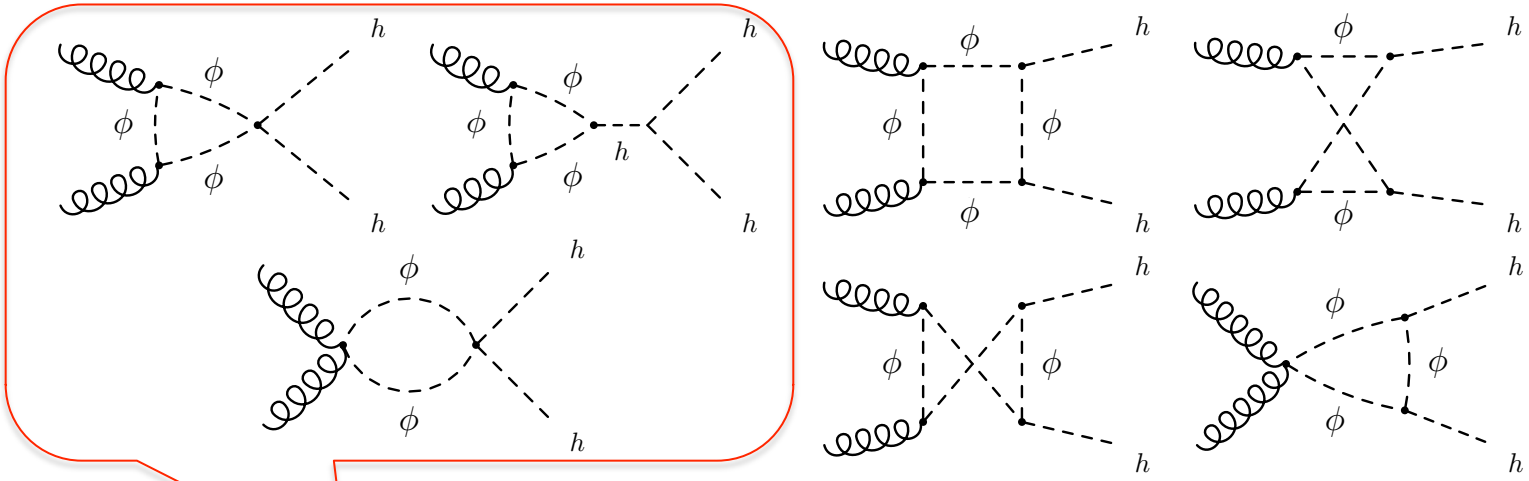

$$F^S_{tri} = -\frac{\lambda_S C_s v^2}{m_S^2}(2m_S^2 C_{AB} + 1),$$

$$F^S_{box} = -\frac{\lambda_S C_s v^2}{m_S^2}(2m_S^2 C_{AB} + 1) - \frac{2C_s(\lambda_S v^2)^2}{s}\left(m_S^2\left(D_{ABC} + D_{BAC} + D_{ACB}\right)\right.$$
$$\left. - \frac{t - m_h^2}{s}C_{AC} - \frac{u - m_h^2}{s}C_{BC} + \frac{ut - m_h^4}{2s}D_{ACB}\right),$$

Contributions from colored scalars

A. Belyaev et al, Phys. Rev. D 60, 075008 (1999) for MSSM
E. Asakawa et al, Phys. Rev. D 82, 115002 (2010) for LQ
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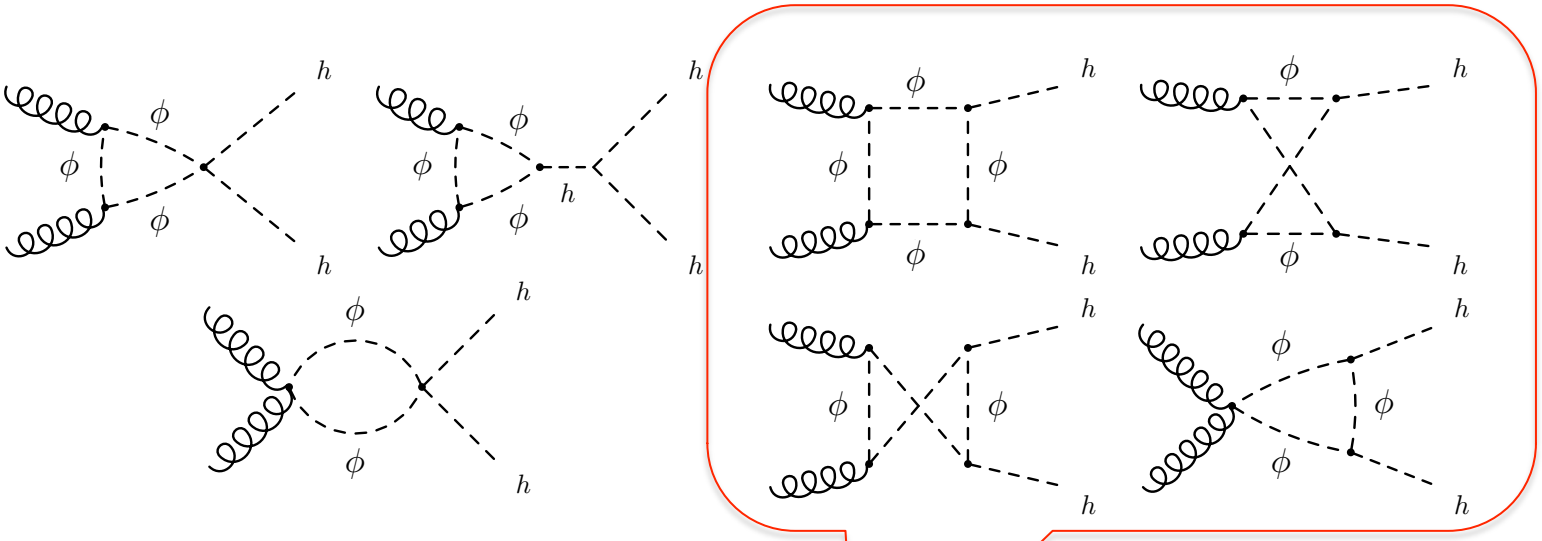

$$F_{tri}^{S} = -\frac{\lambda_S C_s v^2}{m_S^2}(2m_S^2 C_{AB} + 1),$$

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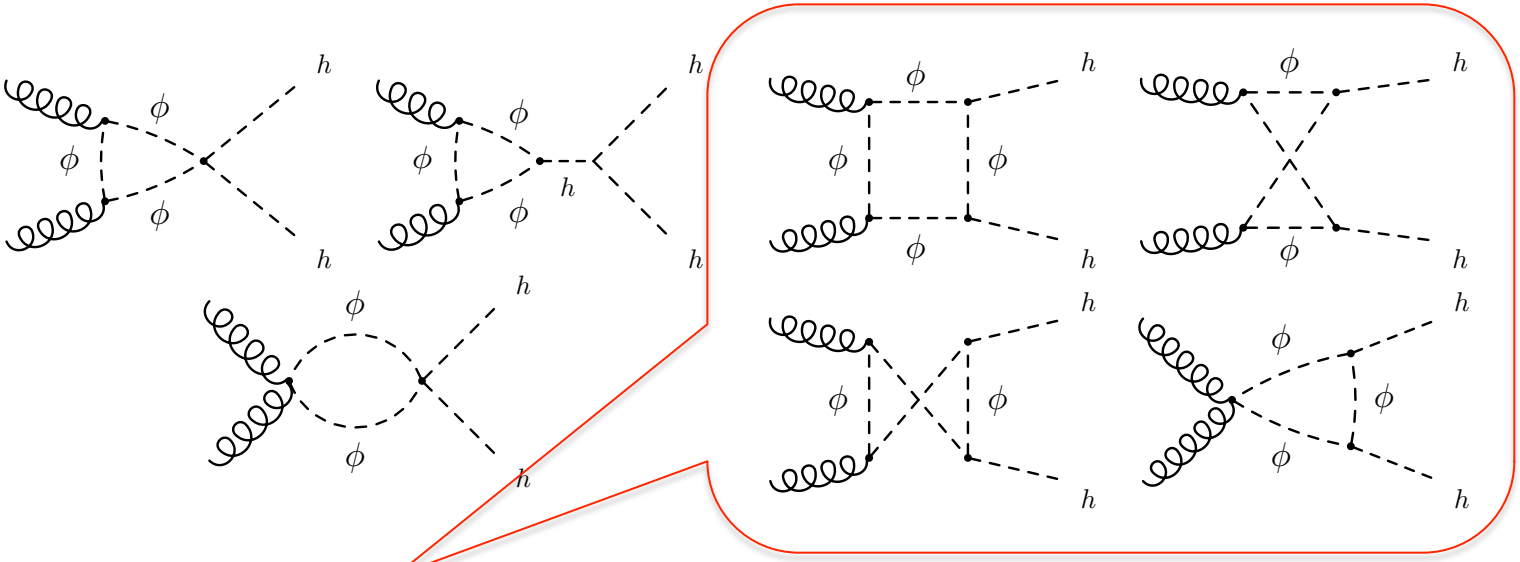

$$
\begin{aligned}
G^S_{box} &= -\frac{2C_s(\lambda_S v^2)^2}{s}(m_S^2\,(D_{ABC}+D_{BAC}+D_{ACB}) - C_{CD} \\
&+ \frac{1}{2(tu-m_h^4)}(st^2 D_{BAC} + su^2 D_{ABC} \\
&+ s(s-2m_h^2)C_{AB} + s(s-4m_h^2)C_{CD} \\
&- 2t(t-m_h^2)C_{AC} - 2u(u-m_h^2)C_{BC}))
\end{aligned}
$$

Estimate for Higgs pair prod. in the SM

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{12\pi}(\log H) G^a_{\mu\nu} G^{a\mu\nu} = \frac{\alpha_s}{12\pi}\left(\frac{h}{v} - \frac{h^2}{2v^2} + \cdots\right) G^a_{\mu\nu} G^{a\mu\nu}$$

$$F^t_{\rm eff} \simeq \frac{1}{3\pi}\left(-1 + \frac{3m_h^2}{\hat{s} - m_h^2}\right)$$

$$\sigma(gg \to hh) \sim O(10^{-3})\sigma(gg \to h)$$

- ✧ Distractive interference which makes the rate very small
- ✧ Very high luminosity required

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Prone to new physics contribution

Colored scalar:

$$F^S_{\rm eff} = \frac{\lambda^S C_s v^2}{24\pi m_S^2}\left(1 + \frac{3m_h^2}{\hat{s} - m_h^2} - \frac{\lambda^S v^2}{m_s^2}\right)$$

new physics contribution

Parameters

$$\lambda_\omega,\ \ \lambda_\chi,\ \sin\vartheta,\ \ m_{\chi_1},\ \ \Delta m \equiv m_\omega - m_{\chi_2},\ \ \ m_{\chi_2} - m_{\chi_1} = 10\ \mathrm{GeV}$$

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Small & large mass splitting

$$\Delta m = (10,\, 50)\ \mathrm{GeV}$$

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Small & large mass splitting

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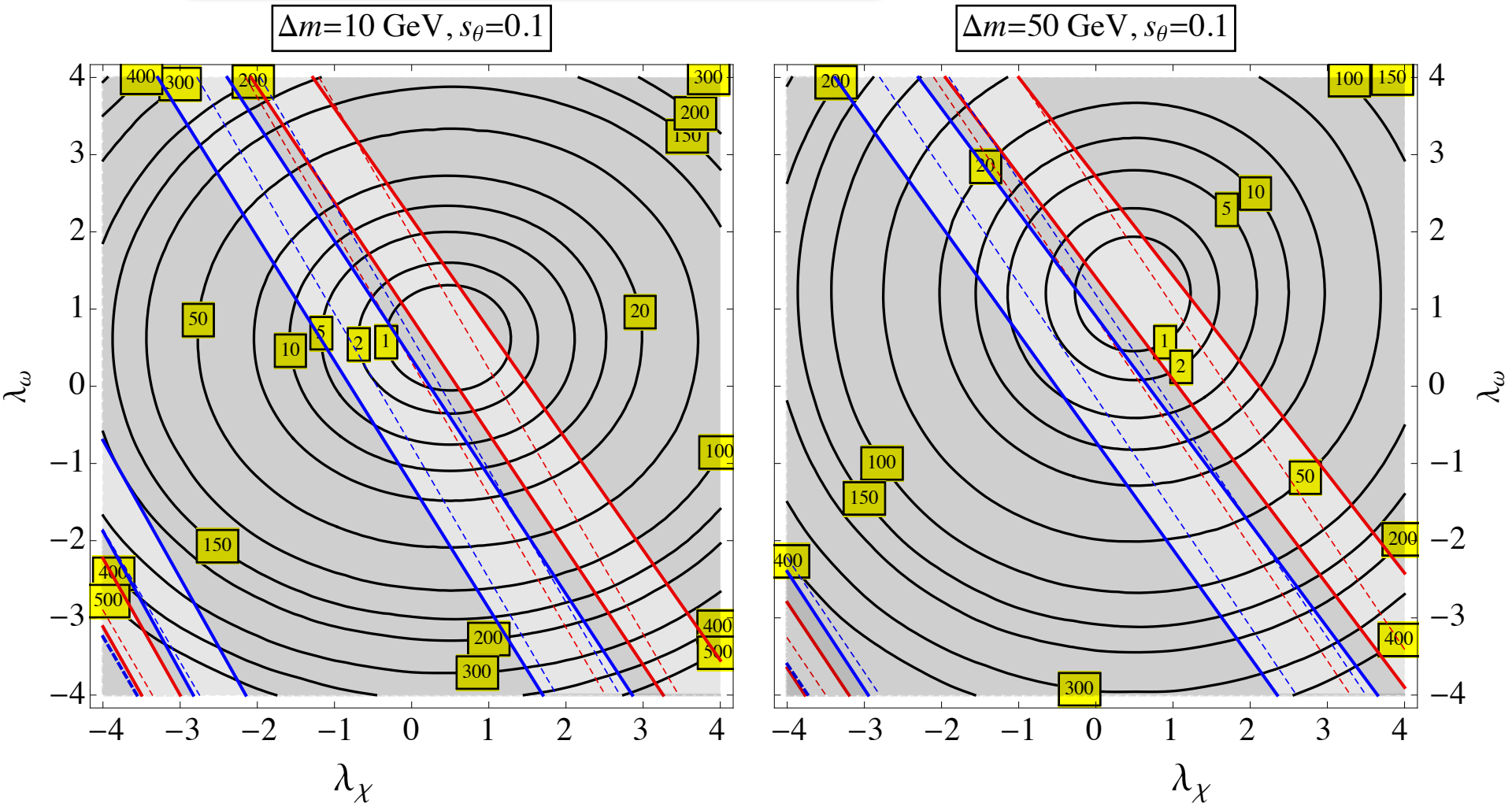
Procedures

- For $m_{\chi_1} = 200\ \text{GeV}$ scanning over $(\lambda_\omega,\ \lambda_\chi)$ is done to find regions allowed by Higgs production and decays
- Several set of $(\lambda_\omega,\ \lambda_\chi)$ pair values are chosen for the single and di Higgs production for higher m_{χ_1} values
- LQ contribution to di Higgs production is implemented in Madgraph 5. CTEQ6L1 pdf set used

Scan over portal couplings: Small mixing



The contours are the rate for Higgs pair production compared to the SM case

The enhancements are shown as labels. The lightest LQ mass is 200 GeV

The darker with blue(CMS) and ()ATLAS boundaries regions excluded by diphoton

The corresponding h->ZZ channel regions are drawn in dashed line

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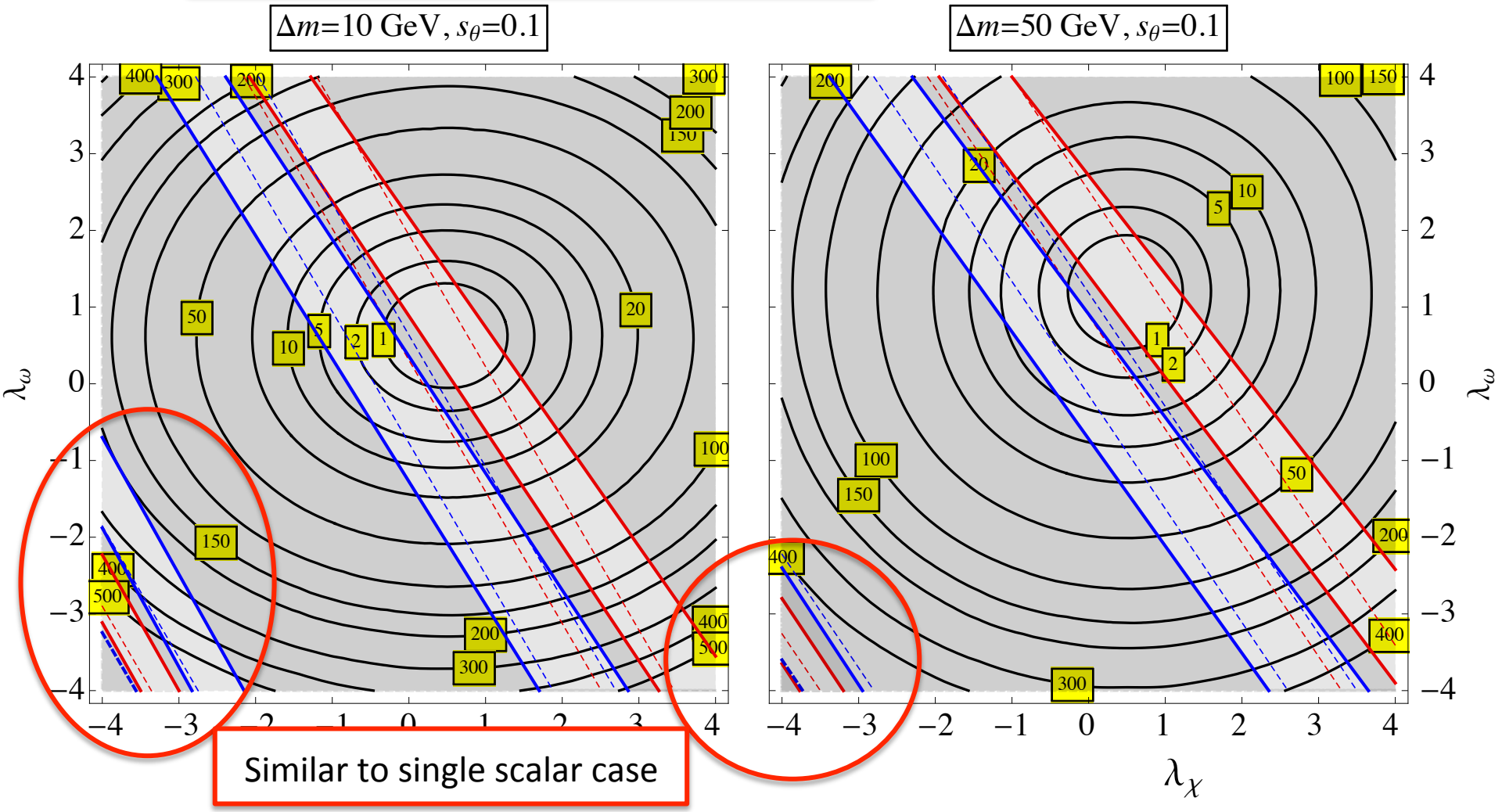

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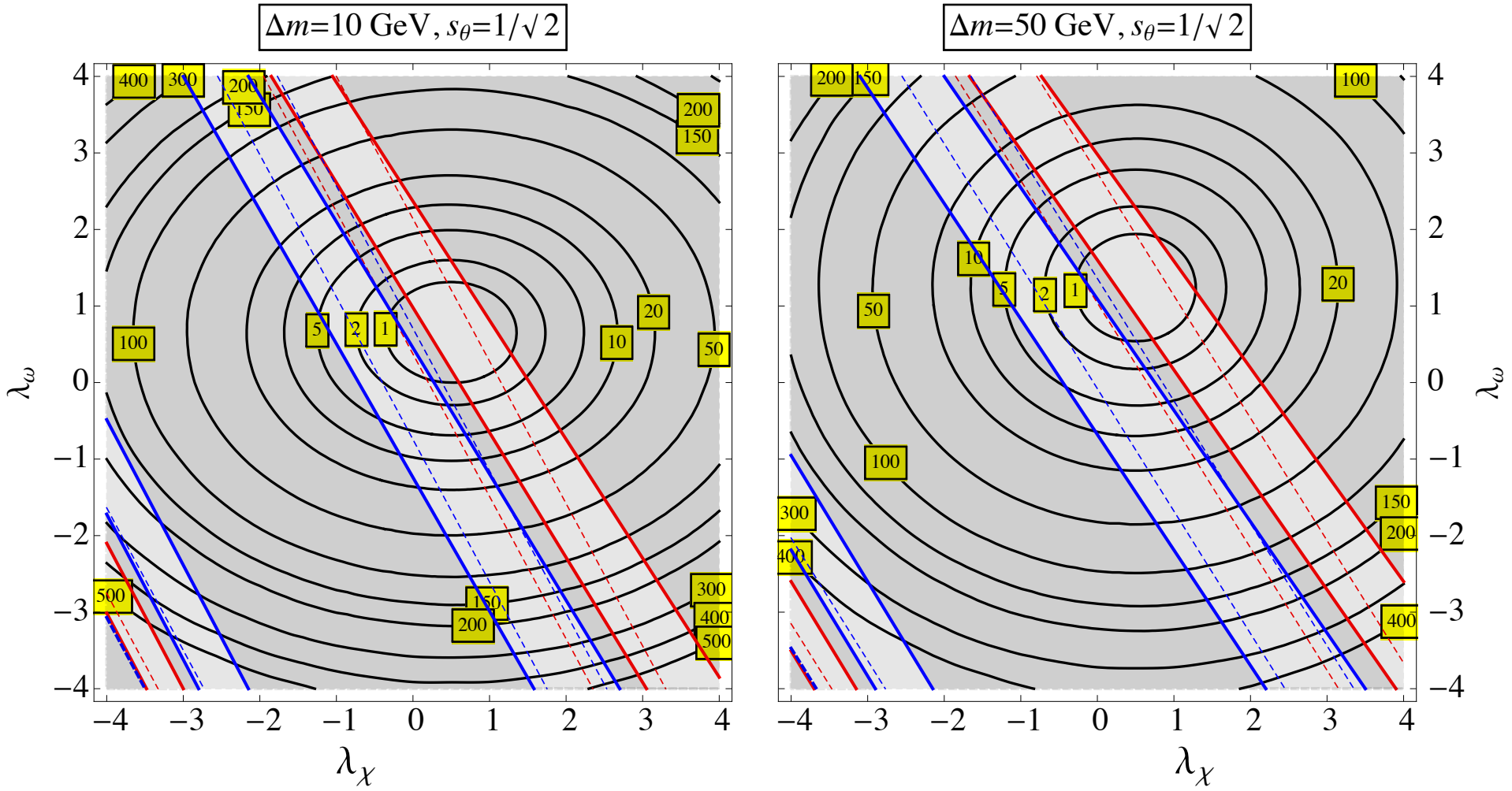

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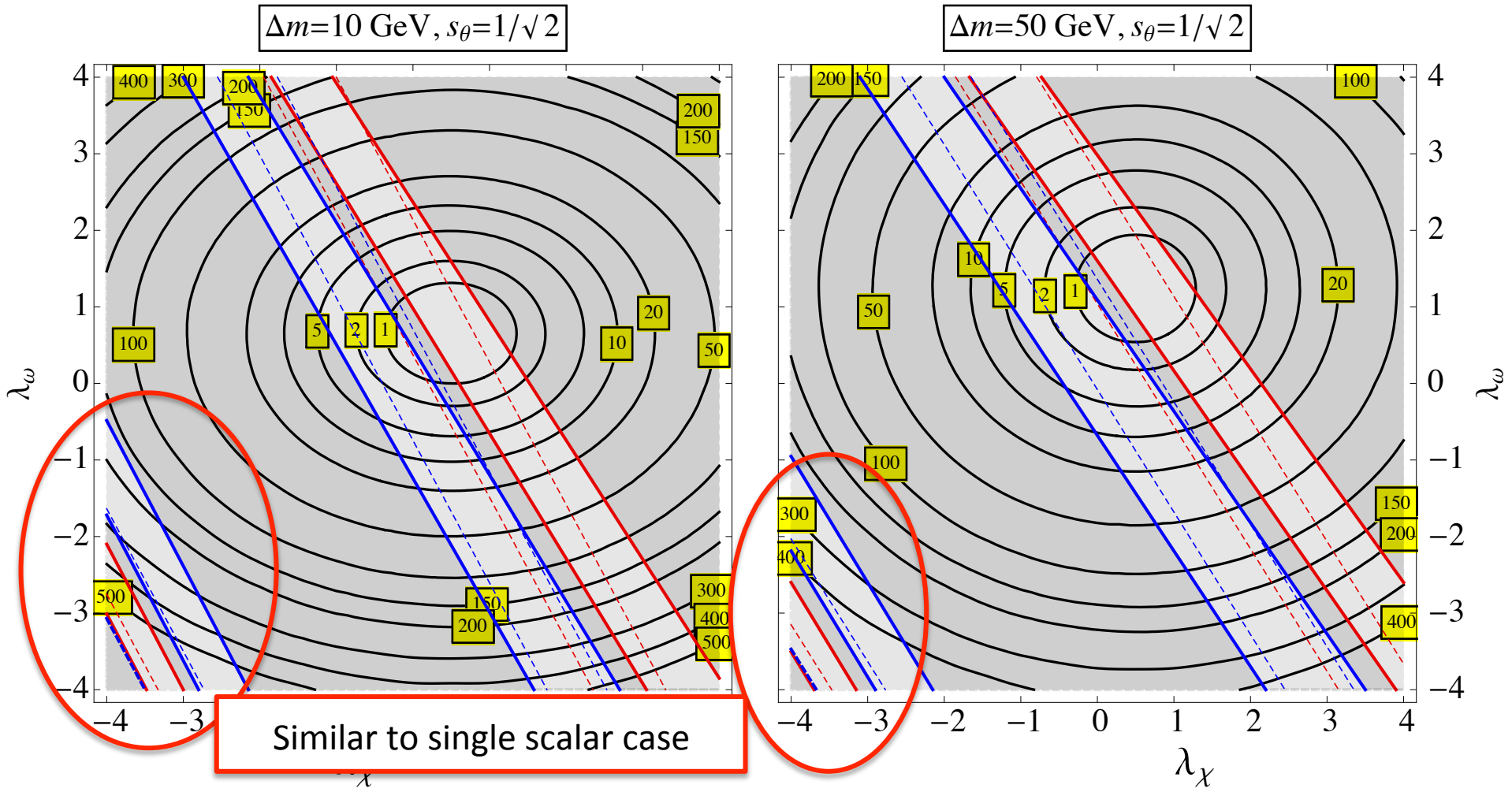

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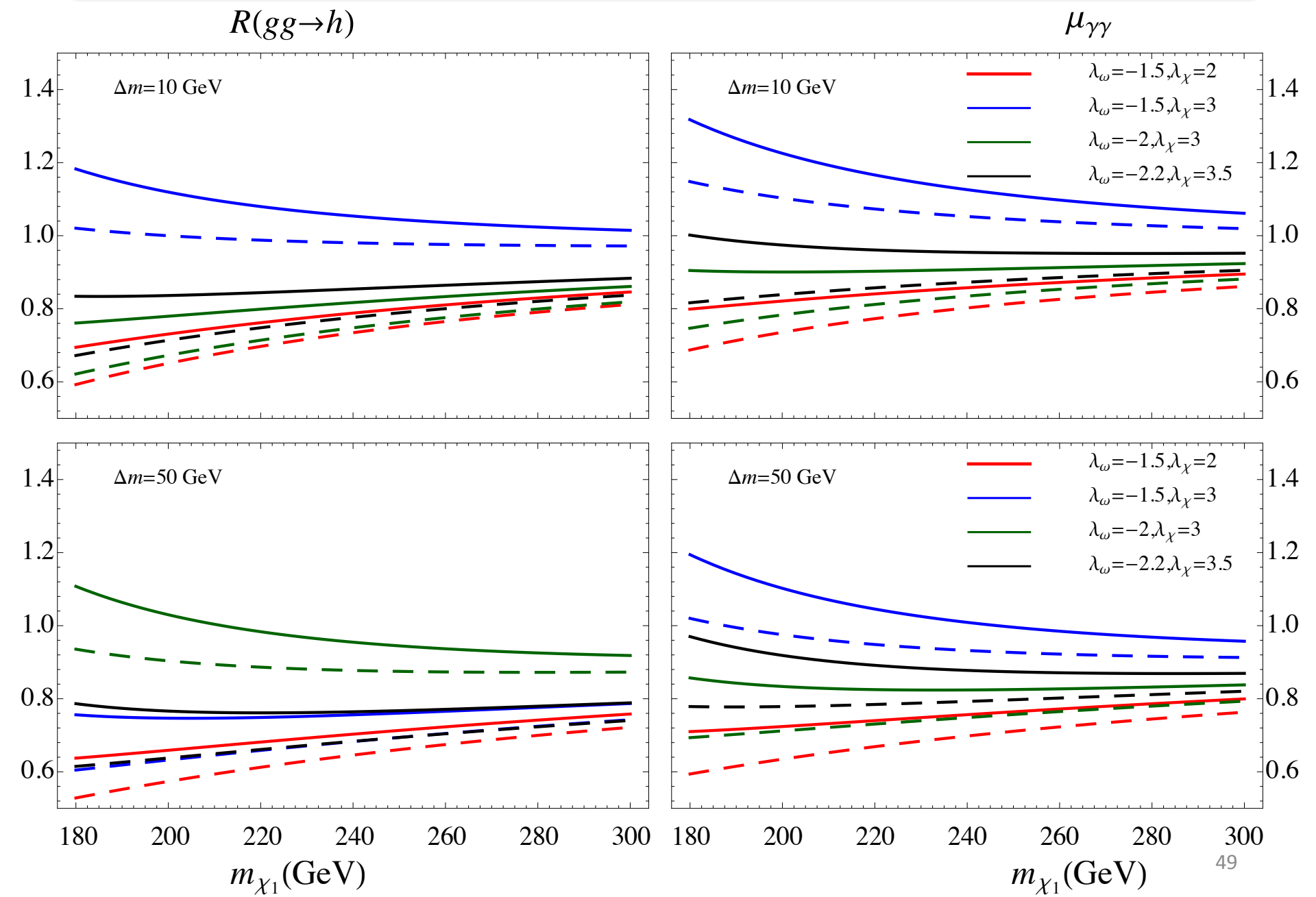
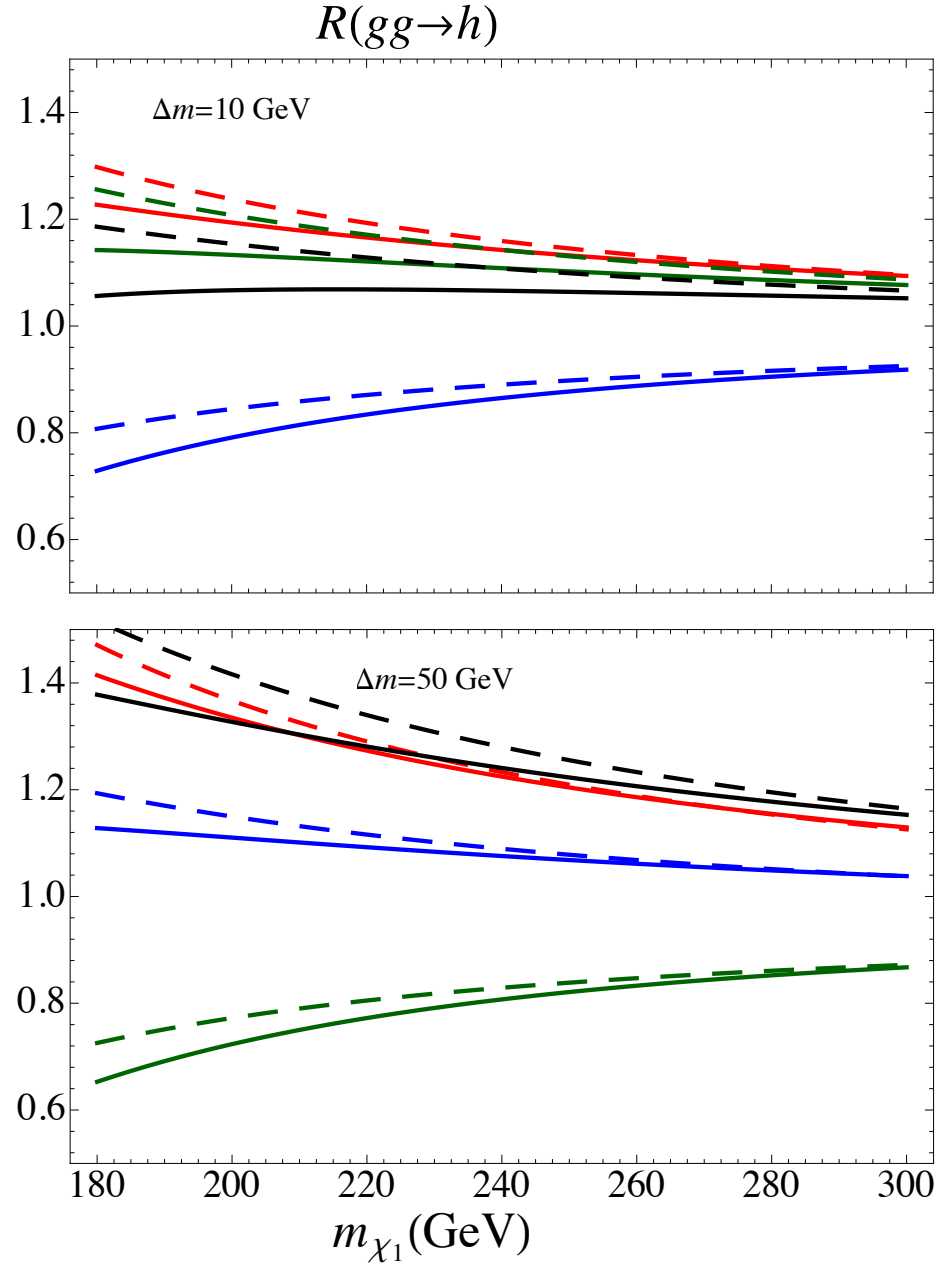
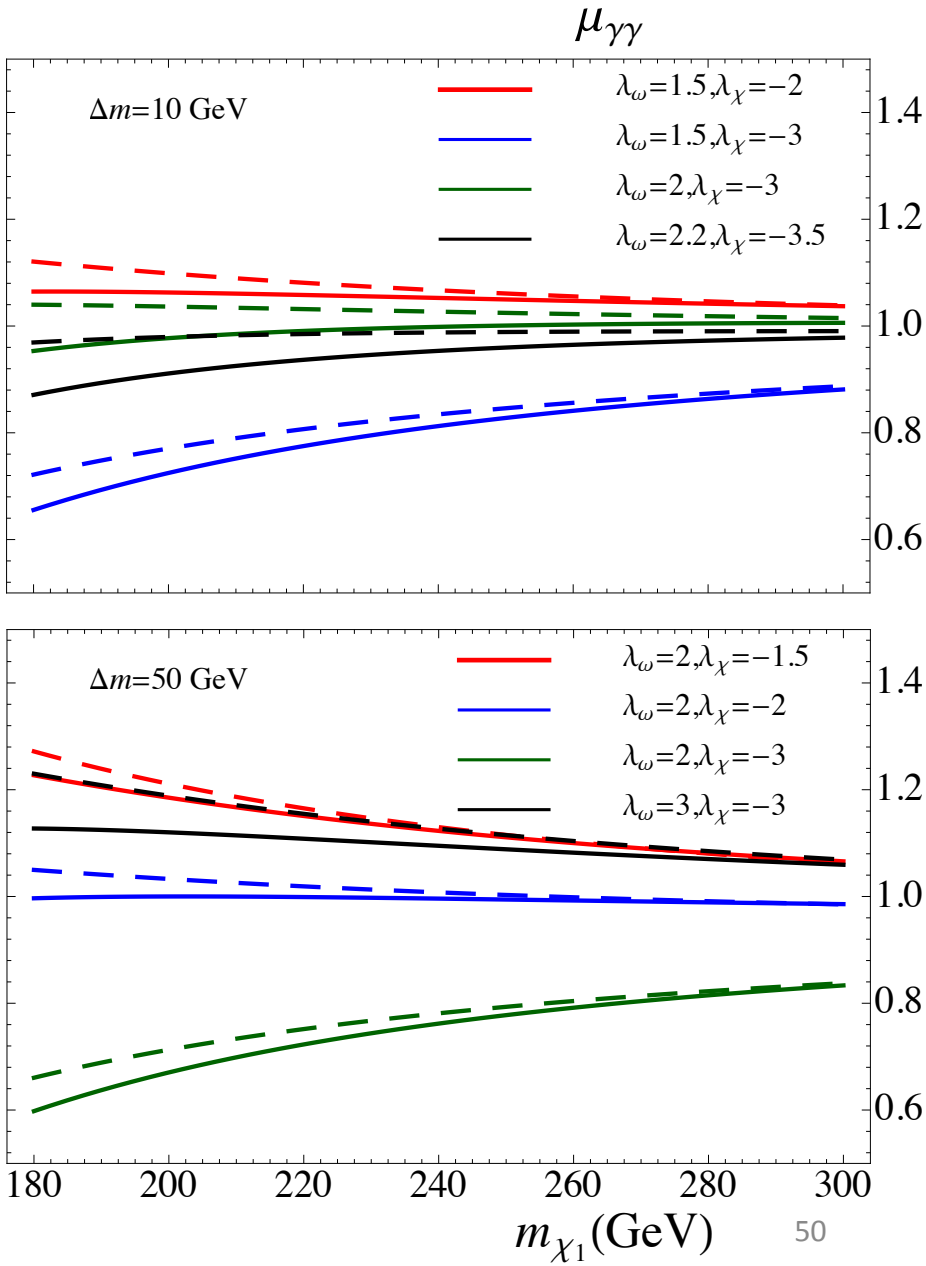
Higgs prod rate & diphoton significance at LHC: Small Mixing

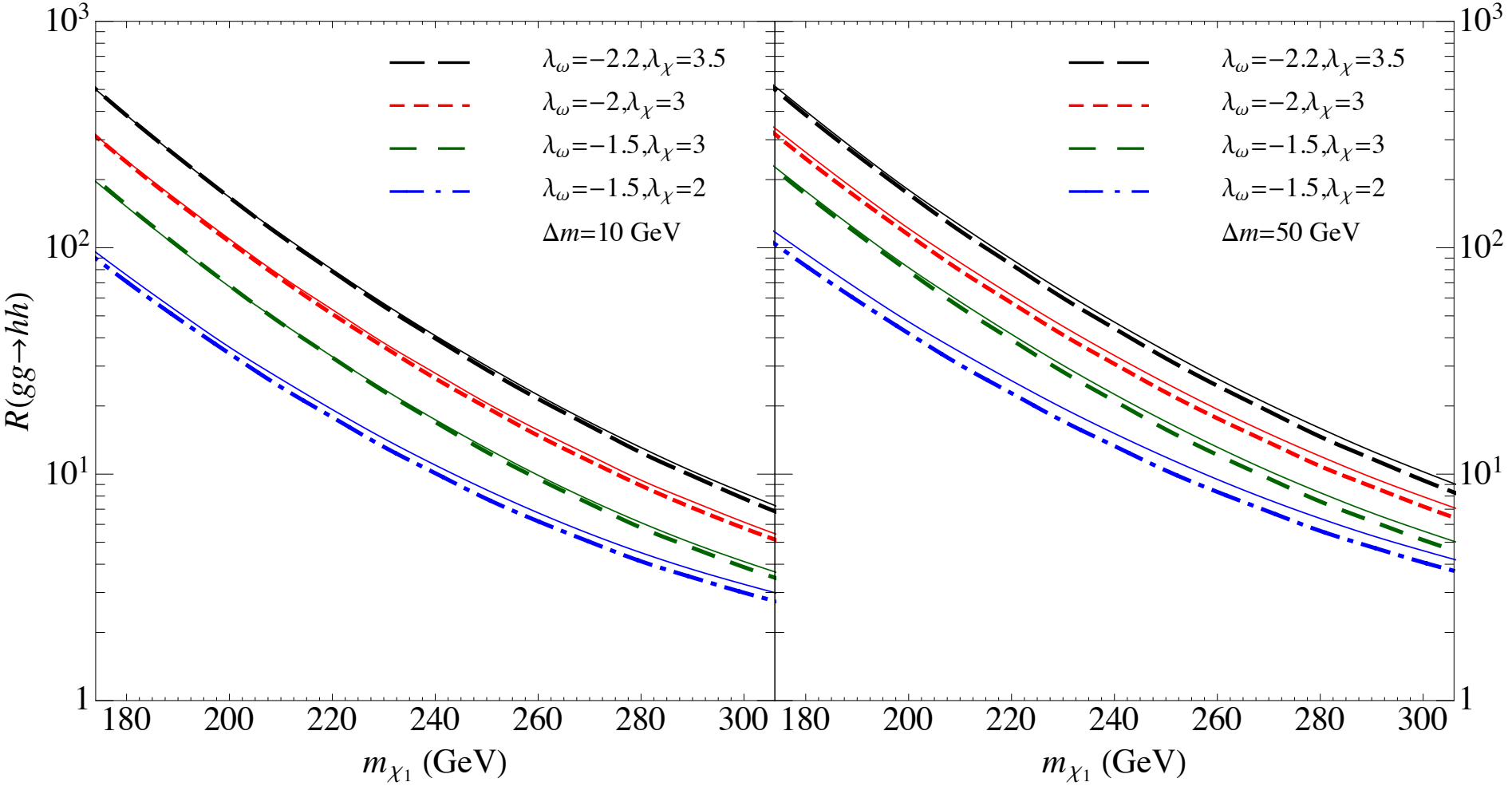


Higgs Pair production rate at LHC : Large mixing

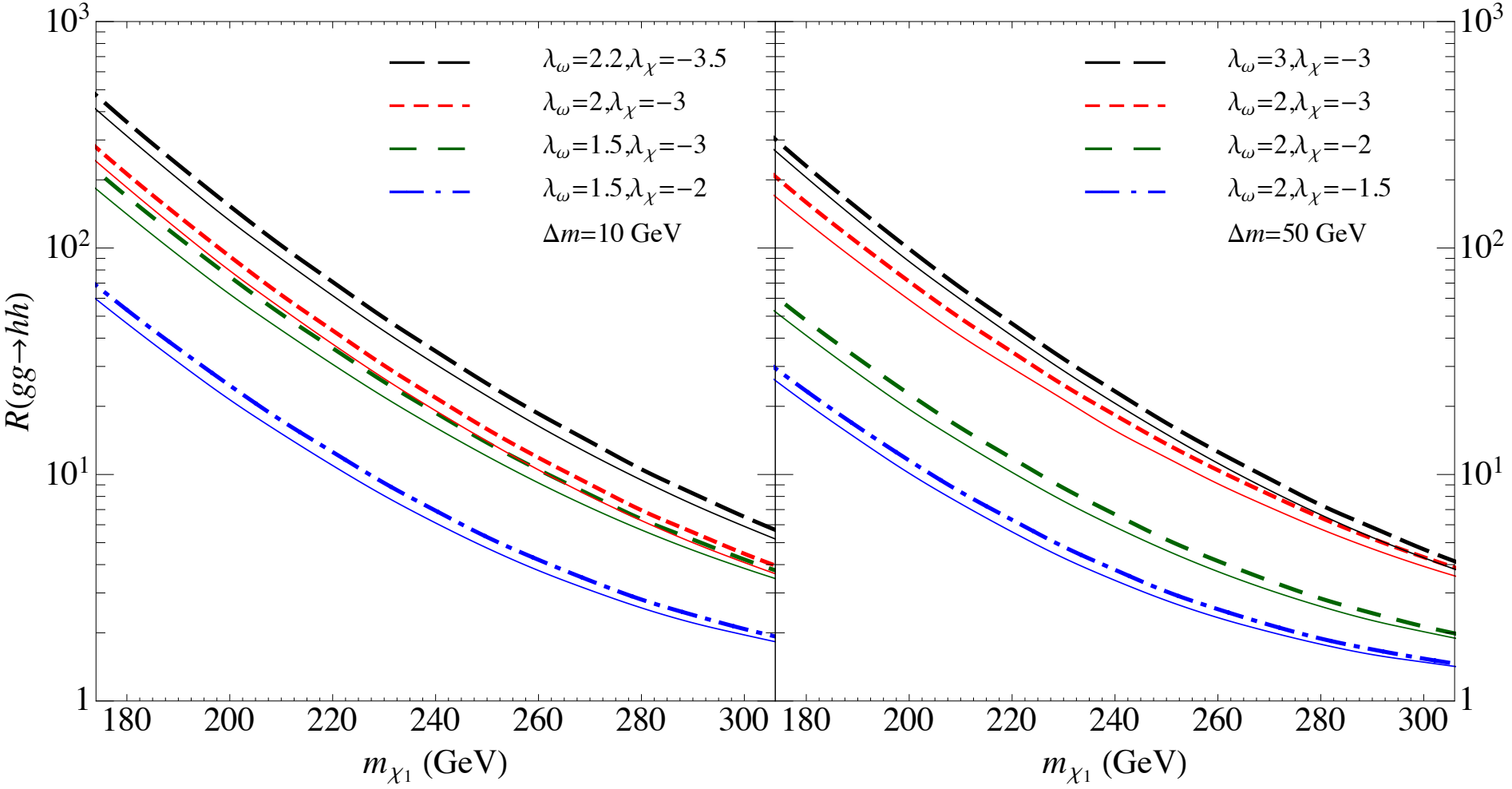




Higgs Pair production rate at LHC : Small mixing



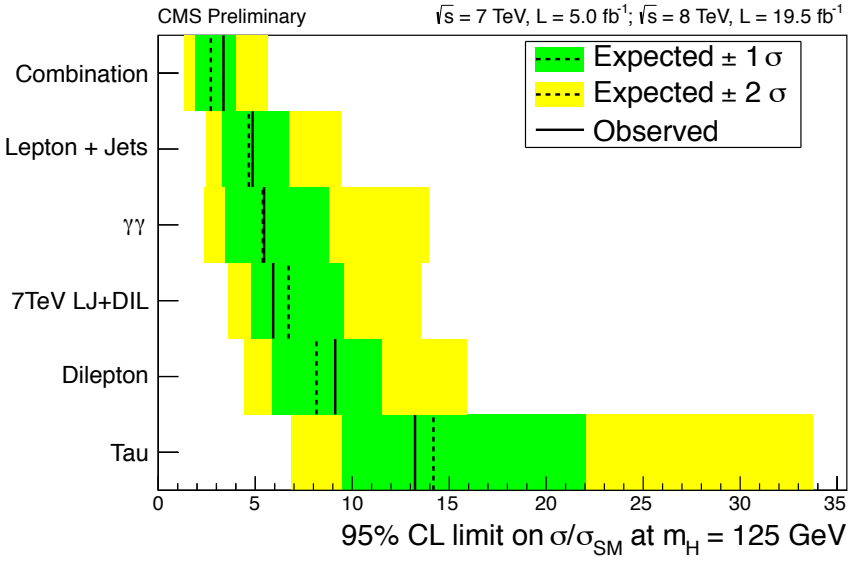
Higgs Pair production rate at LHC :Large mixing

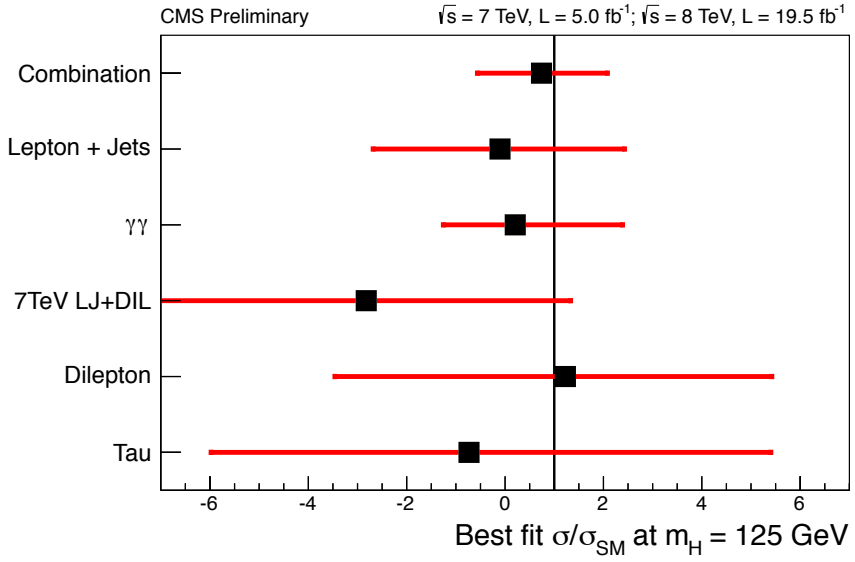


Higgs production in association with top pair

- Recent result on gg->ttH with H-> tau tau (hadronic) by CMS

CMS Collaboration CMS HIG 13-019





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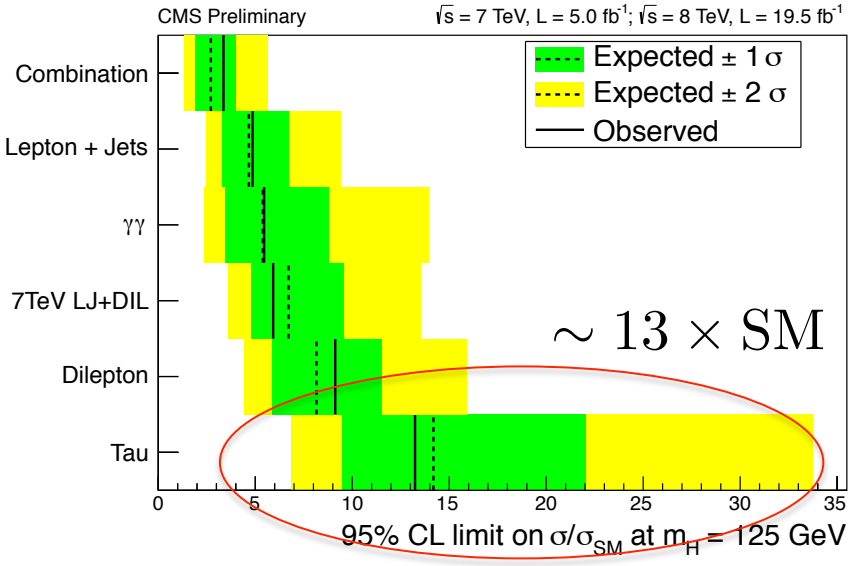

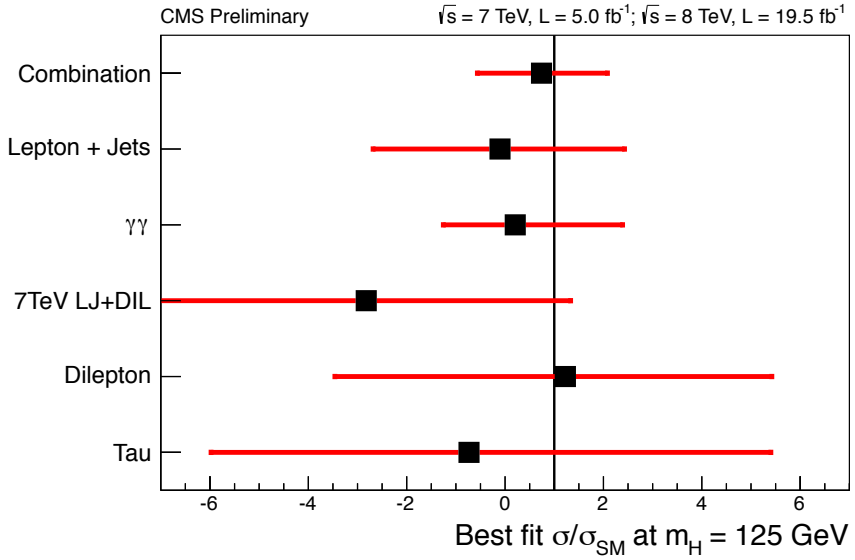

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CMS Collaboration CMS HIG 13-019

$$\sigma(pp \to t\bar{t}H) \sim 10^2 \text{fb}$$
$$BR(H \to \tau\tau) = 6.2\%$$

LQ pair production xsec~ 10(1)pb for m_{LQ}=180 (250) GeV

Some mass region may already be ruled out by the data

- ✧ But, for LQ-> t tau, tau may not be energetic enough to make the cut for low masses
- ✧ Detailed proper analysis is needed for full implication.
- ✧ It is nice these ideas are already facing experiment.

Conclusion

- The Higgs pair production is studied in the presence of LQs for LHC 8TeV run.
- As an example a radiative neutrino mass model is considered where at least two LQs are required & the masses are below 500 GeV.
- Single Higgs production constraint on the LQ-Higgs portal couplings have been studied by scanning over portal couplings.
- From this, several set of portal couplings are chosen which are consistent with the current data.
- Using these sets Higgs pair productions are calculated
- They have been found to be substantially enhanced even the single Higgs production receives moderate correction.
- Many other models with multiple colored particles can have similar results which are testable at the LHC
- This particular model already facing the LHC experiments

Thank you