Higgs Pair Production

First International HEP School & Conference in Western China

2018,Lanzhou, PRC

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Overview

- Introduction :
  - Experimental results

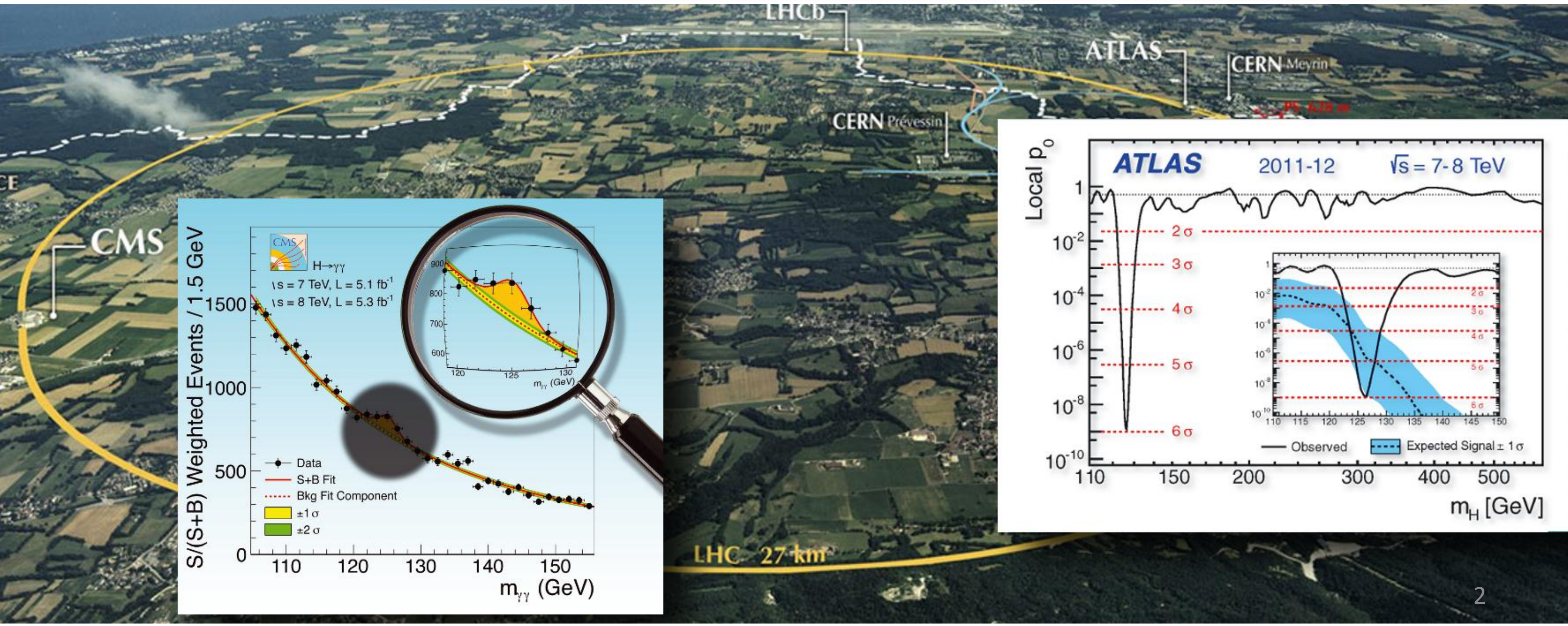
Higgs pair production in SM & beyond

- Single & Pair Higgs productions at the LHC
  - General Potential
  - Scalar and Vector Octets
- Conclusions

Introduction

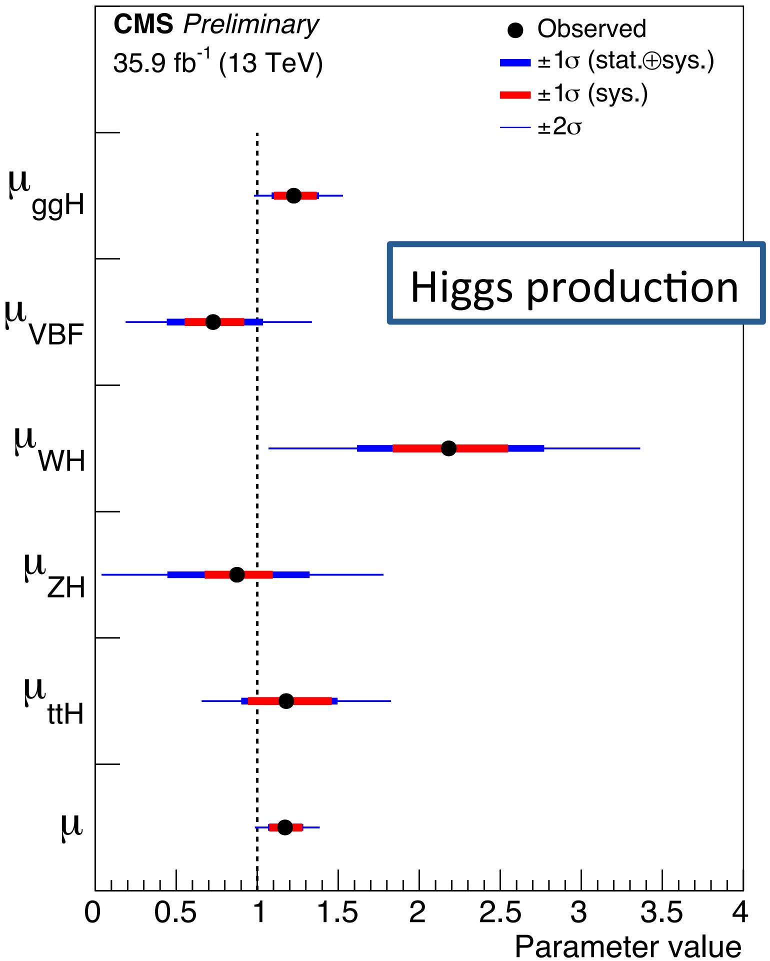
2012 discovery of a Higgs particle

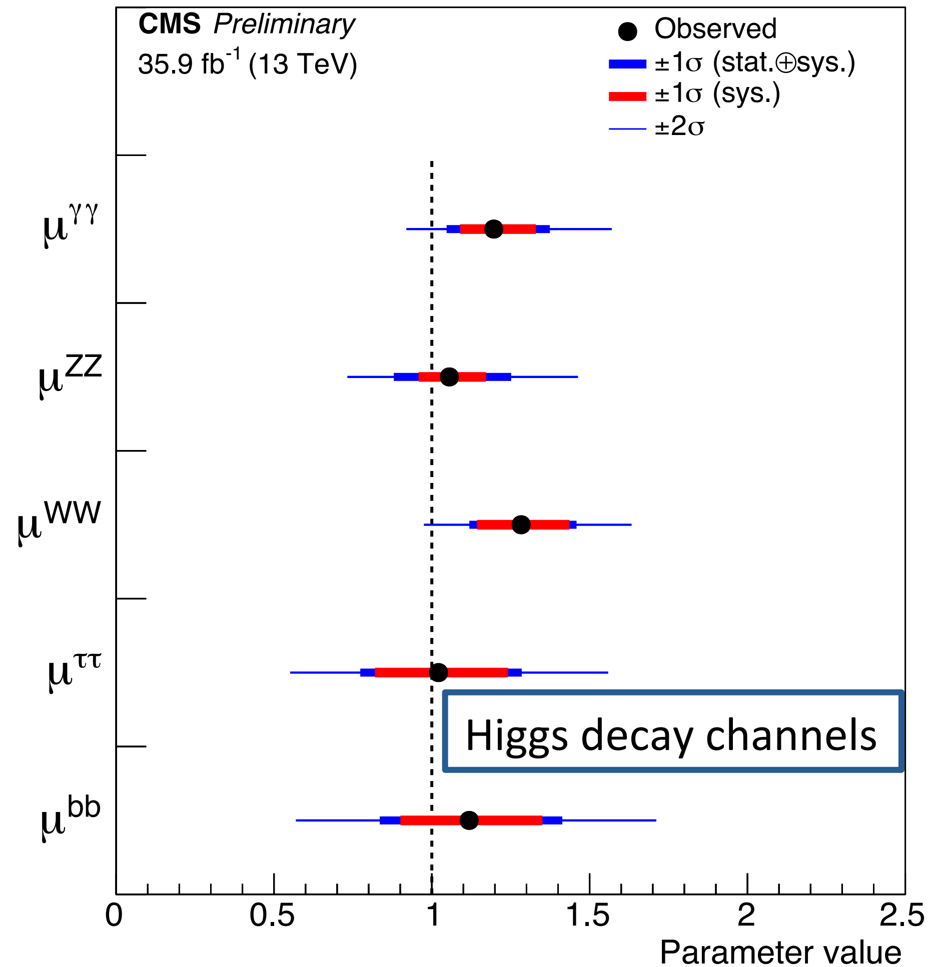
G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716 (2012) 1
S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 716 (2012) 30



As of 12.03.2018 : CMS-CONF-PAS-031

$$\mu_X \equiv \frac{\sigma(pp \to H)Br(H \to X)_{exp}}{\sigma(pp \to H)Br(H \to X)_{\rm SM}}$$





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What are the implications & questions ?

1. Scalar particle **h** for
   1. EW symmetry breaking(?)
2. Substantially couples to top quark
   1. Yukawa – New, 5th force of nature
      (**gg->h, h->ZZ* h->ττ**)
   2. Particle mass generation
3. Is it a probe to new physics at TeV scale
   1. via portal interactions?
   2. via scalar potential?

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3. Is it a probe to new physics at TeV scale
   1. via extended scalar potential?
   2. via portal interactions?

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General Extended Potential

Introduction

2012 discovery of a Higgs particle

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

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   1. via scalar potential?
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Color octet scalars & vectors

Models with modified Higgs interactions

Modified Higgs Potential

- Extension of the Higgs potential
  - Extra Higgses
  - Higher-Dim. terms in the Potential
  - General potential beyond renormalizibility

F. Boudjeama & E. Chopin Z. Phys. 73 (1996)
R. S. Chivukulla & V. Koulovasilopoulos PLB 309 (1993), PRD 50 (1994)
H.-J. He et al, PLB 554 (2003), PRD 67 (2003)
N. Haba e tal, PRD 89 (2014)

Recent works on Higgs pair

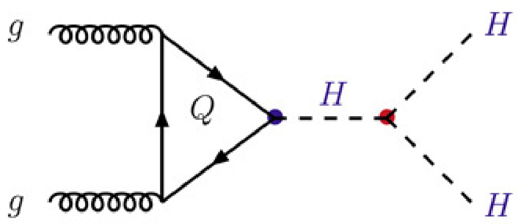
M. Carena PRD 97 (2018)
C.-W. Chiang etal, PRD 97 (2018)
Z. Kang, PLB 89 (2017)
G. Buchalla et al,arXiv:1806.05162….

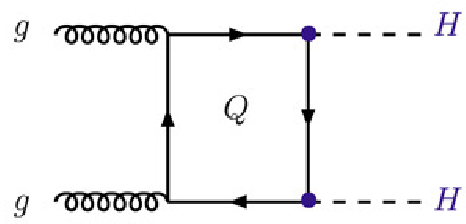
Higgs coupling to new particles

- Extra Higgses (doubly charged), singlets, dilaton, GUT remnants, colored particles: SUSY, LQs, Extra family, composite particles

A.V. Manohar, M.B. Wise PLB 786 (2006)
M. I. Gresham & M. B. Wise PRD 76 (2007)
D. Lopez-Val, J. Sola PRD 81 (2010)
R. Boughezal,
E.Asakawa etal, PRD 82 (2010)
B. A. Dobrescu etal, PLB 670 (2008)
G. Kribbs, A. Martin
J. Alwall etal PRD 86 (2012)

Higgs pair production via gluon fusion at LHC





- Distractive interference which makes the rate very small
  ~30-40fb at 14 TeV
- Very high luminosity required
- Sensitive to new physics

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

Higgs pair production in the SM

O. J. P. Eboli et al, Phys. Lett. B 197, 269 (1987).
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)
G.V. Jikia Nucl. Phys. B 412 (1994)
A. Djouadi, W. Kilian, P.M. Zerwas, EPJ C10 (1999) 45-49

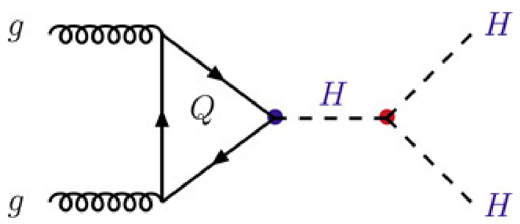
QCD corrections

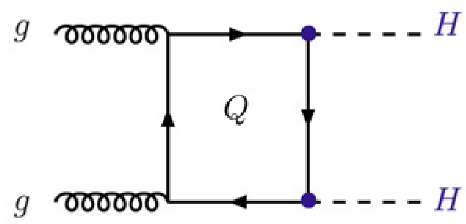
S. Dawson, S. Dittmaier, M. Spira, Phys.Rev. D58 (1998) 115012
T. Plehn, M. Spira, P.M. Zerwas, Nucl.Phys. B479 (1996) 46-64

Many recent works on NLO & NNLO…

D. de Florian et al, JHEP 1609 (2016), 1710 (2018)
M.Grazzini, JHEP 1805 (2018)……

Higgs pair production via gluon fusion at LHC





- ✧ Distractive interference which makes the rate very small
  ~30-40fb at 14 TeV
- ✧ Very high luminosity required
- ✧ Sensitive to new physics

Higgs pair production in the SM

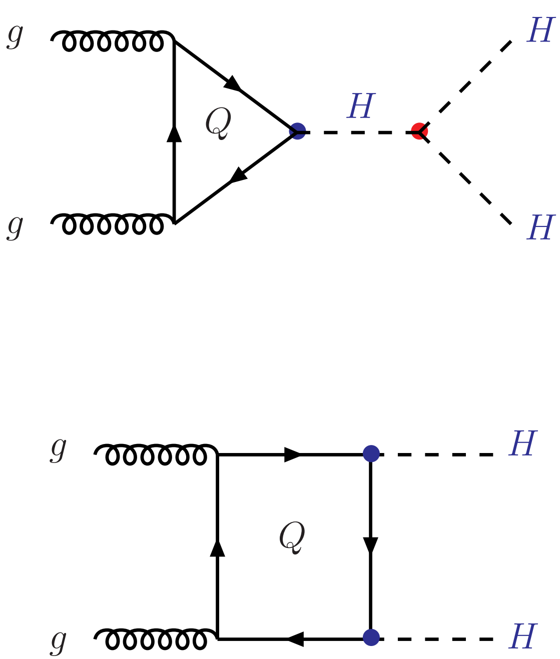
K. Hagiwara and H. Murayama, PRD 41 (1990)

$$\mathcal{L}_{eff} = \frac{\alpha_s}{12\pi} \log(h/v) G^{\mu\nu} G_{\mu\nu} \simeq \frac{\alpha_s}{12\pi} \left(\frac{h}{v} - \frac{h^2}{2v^2} + \ldots \right)$$

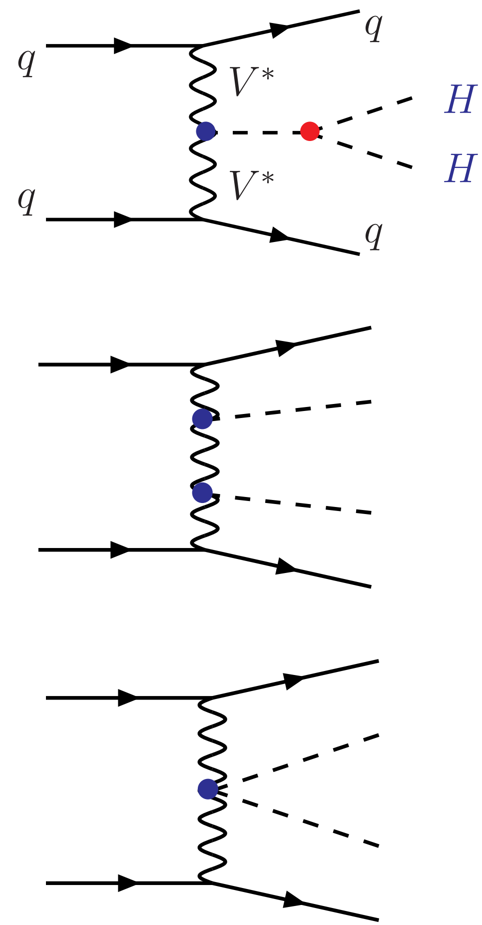
$$\mathcal{M}_{gg \to hh} = \frac{\alpha_s}{3\pi v^2} \left(1 - \frac{3m_h^2}{s - m_h^2} \right)$$

Higgs production mechanisms

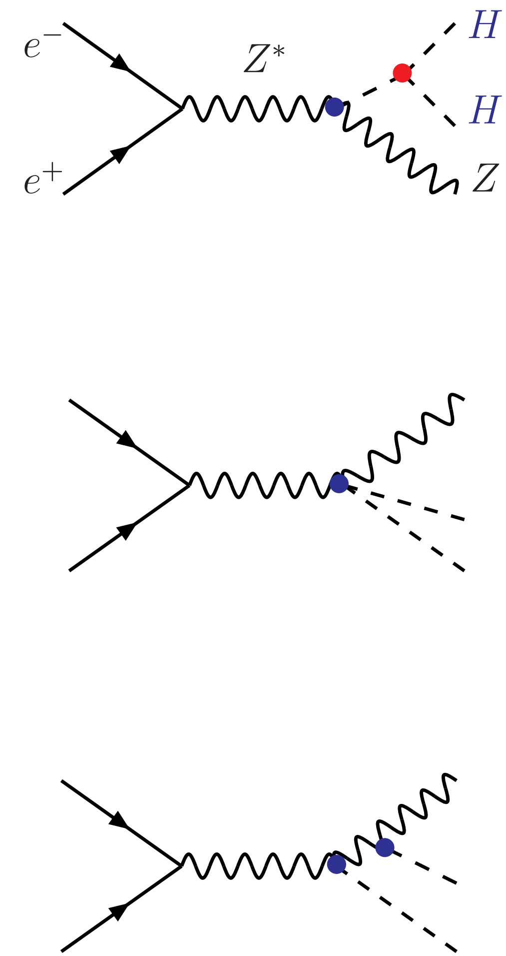
✧ gg-fusion



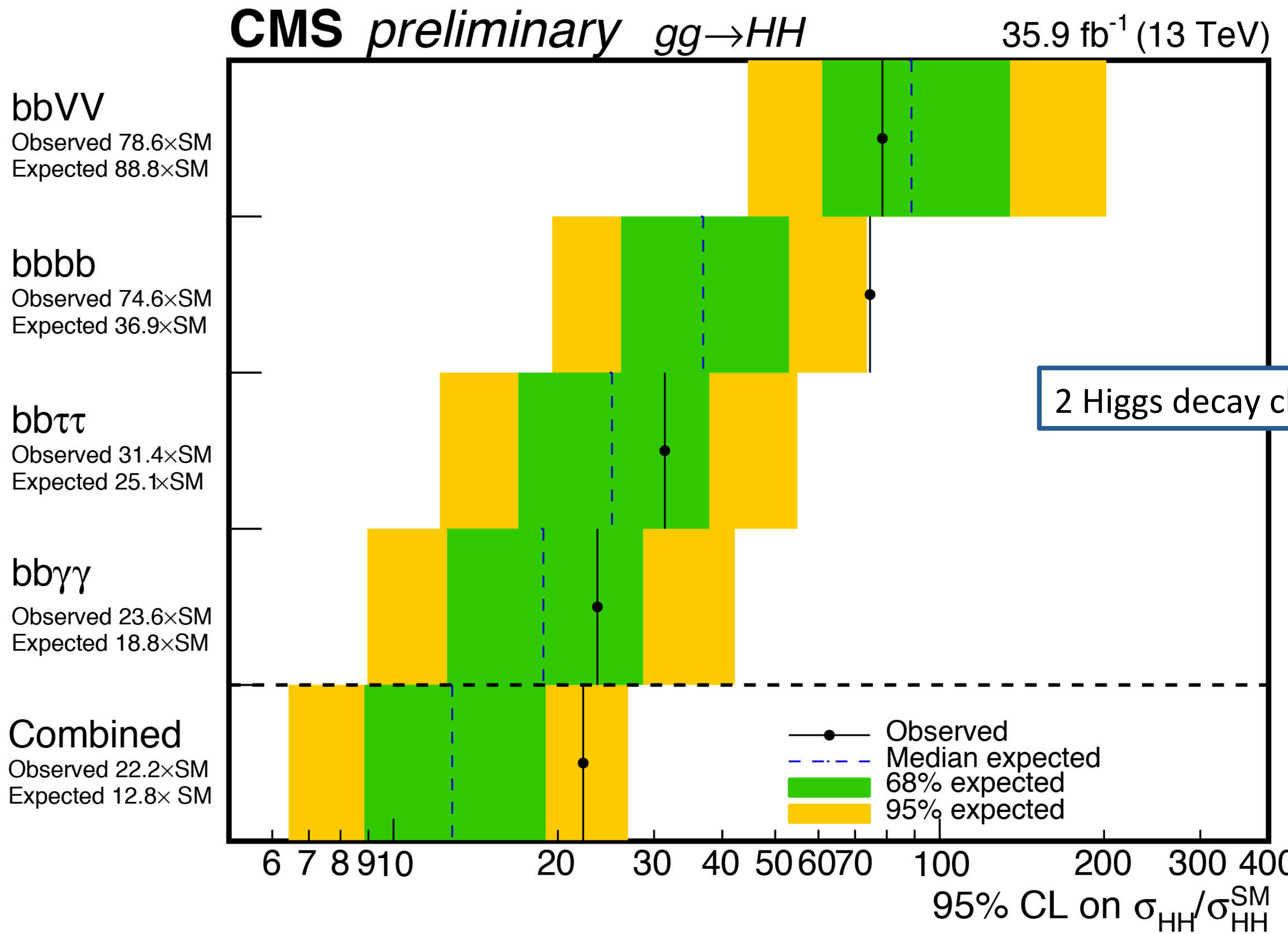
✧ VB-fusion



✧ Higgs-strahlung



ICHEP July 2018 : CMS on Higgs pair production



2 Higgs decay channels

General Potential for Higgs

Higgs potential as a general function of|H|^2=x

$$V = V(|H|^2) \qquad |H|^2 = \frac{v^2}{2} + vh + \frac{h^2}{2}$$

Expansion around minimum

$$V = V\left(\frac{v^2}{2}\right) + V'\left(\frac{v^2}{2}\right)\left(vh + \frac{h^2}{2}\right) + \frac{1}{2}V''\left(\frac{v^2}{2}\right)\left(vh + \frac{h^2}{2}\right)^2 + \frac{1}{6}V'''\left(\frac{v^2}{2}\right)\left(vh + \frac{h^2}{2}\right)^3 + \cdots.$$

The Minimum and the Higgs mass

$$V'(v^2/2) = 0$$

$$m_h^2 = v^2 V''\left(\frac{v^2}{2}\right)$$

Trilinear and Quartic interactions

$V''(v^2/2)$ -tree level

$V'''(v^2/2)$ -quantum correction

Example: Non-perturbative potential

N. Haba e tal, PRD 89 (2014) 015018

Simple example:

$$V = m_H^2 |H|^2 + \Lambda^{4-2a}(|H|^2)^a$$

⟹ Minimum:

$$m_H^2 + a\Lambda^{4-2a}x^{a-1} = 0$$

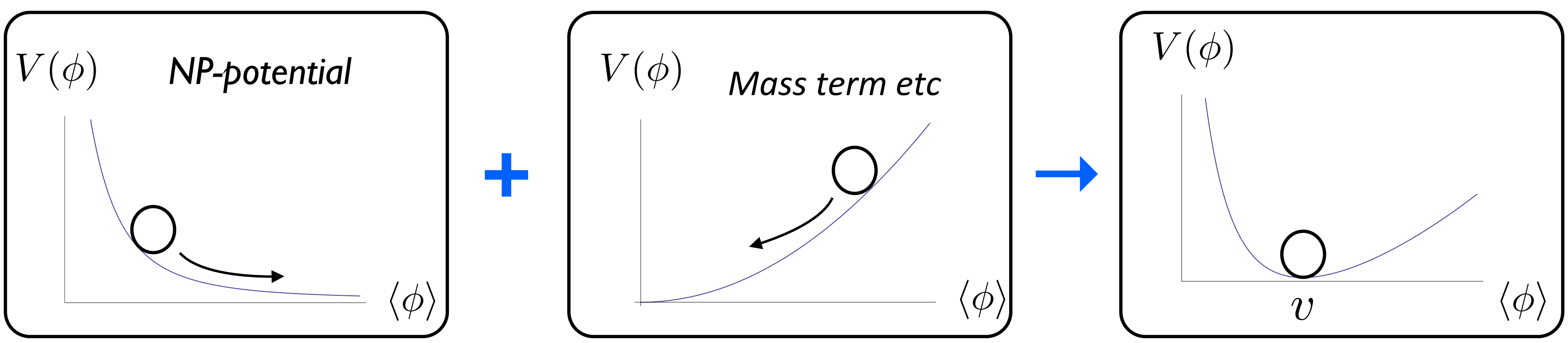
Higgs mass

$$m_h^2 = 2a(a-1)\Lambda^{4-2a}x^{a-1} = 2(1-a)m_H^2$$

$$C_h = \frac{2}{3}\frac{xV'''}{V''} = \frac{2}{3}(a-2)$$

$a < 0$ Non-perturbative runaway potential

$a \geq 2$ Renormalizable



Non-canonic kinetic term

Non canonical kinetic terms appear in several models with strong dynamics:

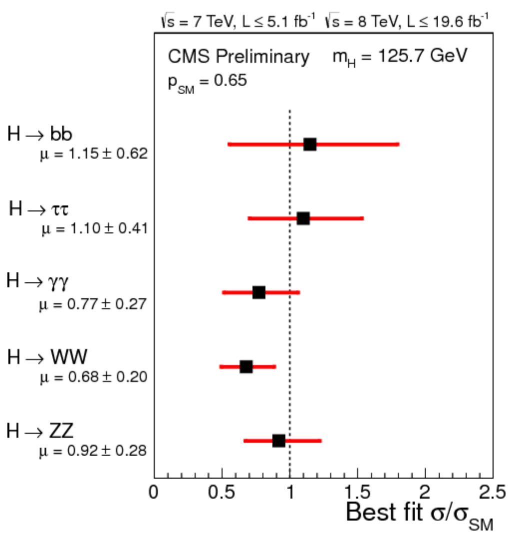
$$\mathcal{L}_{\rm kin} = F\left(\frac{2|H|^2}{v^2}\right) D_\mu H^\dagger D^\mu H \qquad F(1) = 1 \text{ for the SM.}$$

R. S. Chivukula and V. Koulovassilopoulos, Phys. Lett. B 309, 371 (1993); Phys. Rev. D 50, 3218 (1994).

$G(x) \equiv xF(x)$ and expand around $x = 1$

$$\Rightarrow (M_W^2 W^+ W^- + \frac{M_Z^2}{2} Z^2)\left(1 + G'(1)\frac{2h}{v} + (G'(1) + 2G''(1))\frac{h^2}{v^2} + \cdots\right)$$

$G'(1) = 1$, $G''(1) = 0$ in the SM.



✧ Not to conflict with data.

✧ General kinetic term

$$C_2 \equiv 2G''(1)$$

Example: Non-perturbative potential

I. Aflleck, M. Dine & N. Seiberg , PRL 51 (1983) 1026, NP B 241 (1984) 493

SUSY QCD:

$$SU(N) \times SU(N_f)_L \times SU(N_f)_R \times U(1)_B$$

$$Q : (\mathrm{N}, \mathrm{N_f}, 1), \quad \bar{Q} : (\bar{\mathrm{N}}, 1, \mathrm{N_f})$$

Instanton induced Superpotential

$$W_{np} = \frac{\Lambda_0^{3+\frac{2N_f}{N-N_f}}}{(\det \bar{Q}Q)^{\frac{1}{N-N_f}}}$$

N. Haba e tal, PRD 89 (2014) 015018 $N_f=2$

$$C_h = -\frac{5}{3} - \frac{4}{3}\kappa. \qquad \text{where } \kappa = 1/(N-2)$$

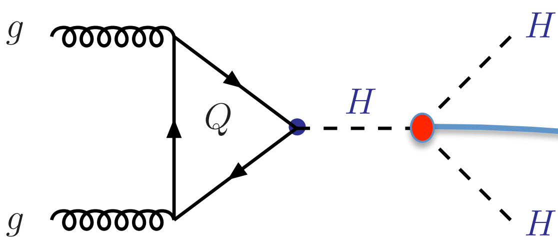
$$C_2^Z = 2$$

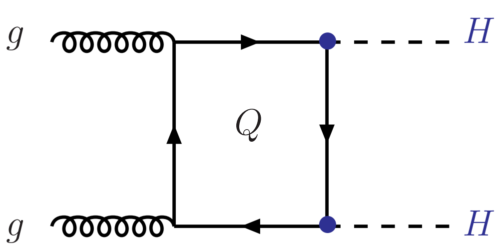
$$C_2^W = 8/9$$

2 Higgs case

Higgs pair production @LHC

✧ gg-fusion





✧ Effective operators & amplitudə:

$$\mathcal{L}_{\text{eff}} = \frac{\alpha_s}{12\pi}(\log H) G^a_{\mu\nu} G^{a\mu\nu}$$

$$= \frac{\alpha_s}{12\pi}\left(\frac{h}{v} - \frac{h^2}{2v^2} + \cdots\right) G^a_{\mu\nu} G^{a\mu\nu}$$

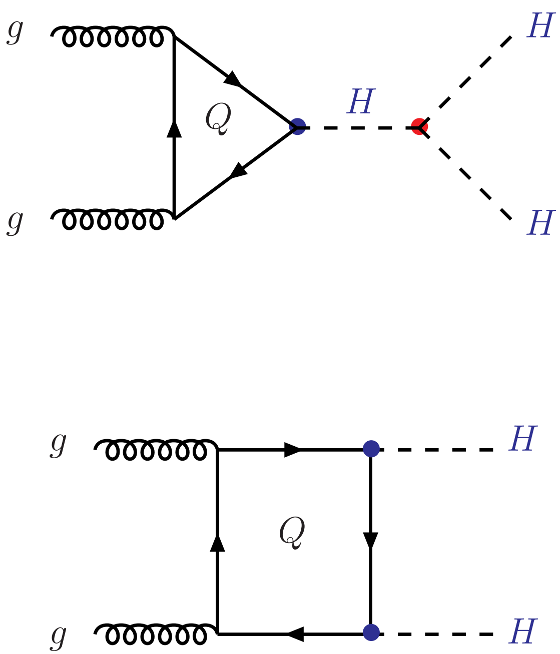
$$\mathcal{M} = \frac{\alpha_s}{3\pi v^2}\left(1 - \frac{3m_h^2(1 + C_h)}{\hat{s} - m_h^2}\right)$$

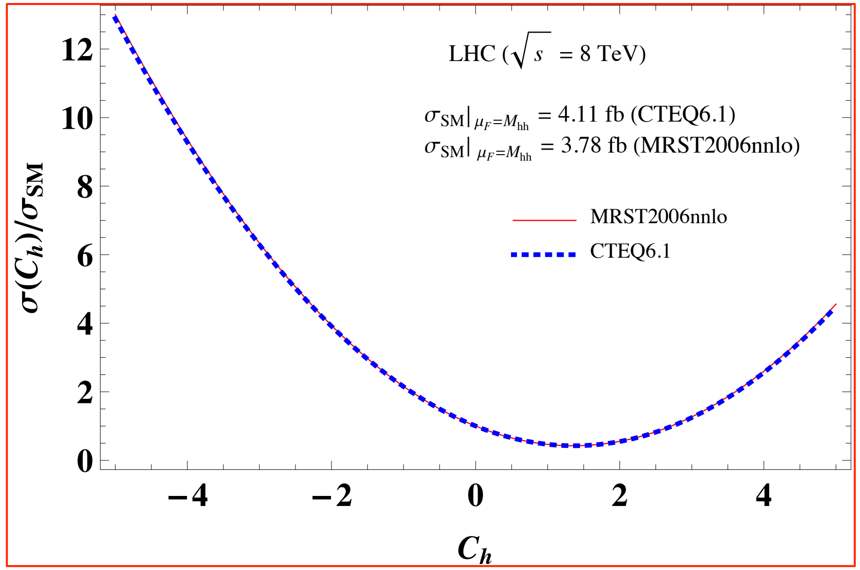
✧ Cancellation $\hat{s} = (4 + 3C_h) m_h^2$

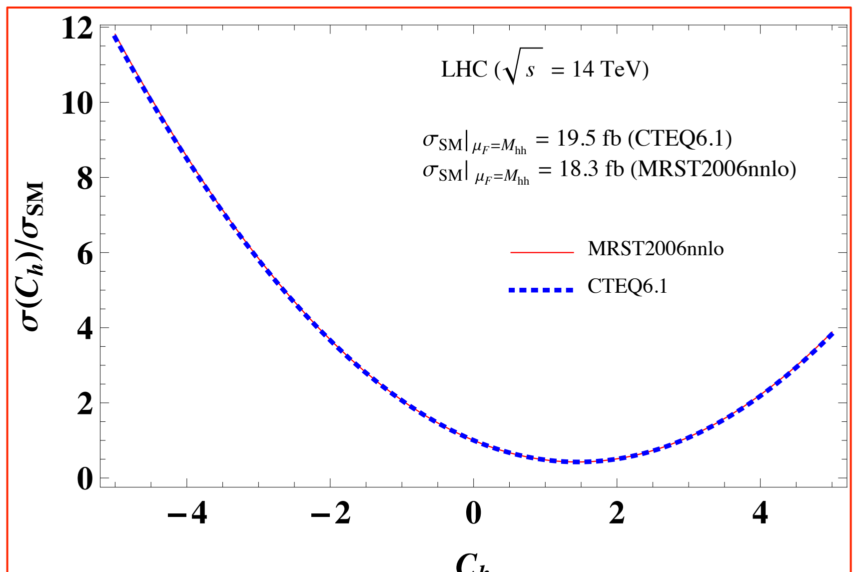
✧ Negative C_h -> increase

Higgs pair production @LHC

✧ gg-fusion

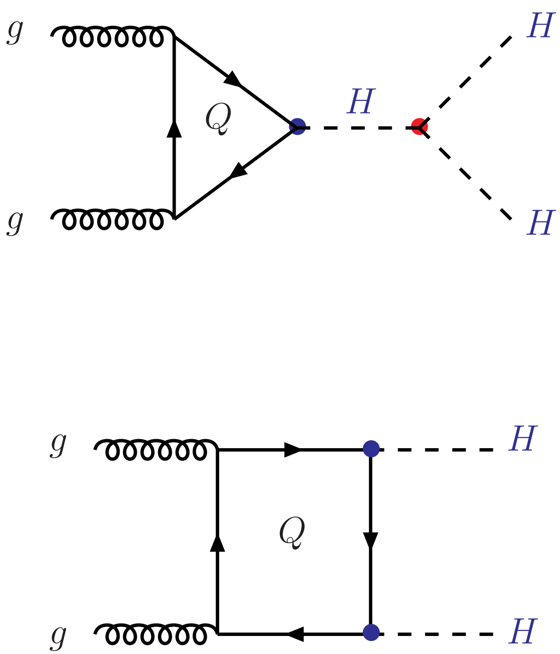






Higgs pair production @LHC

✧ gg-fusion



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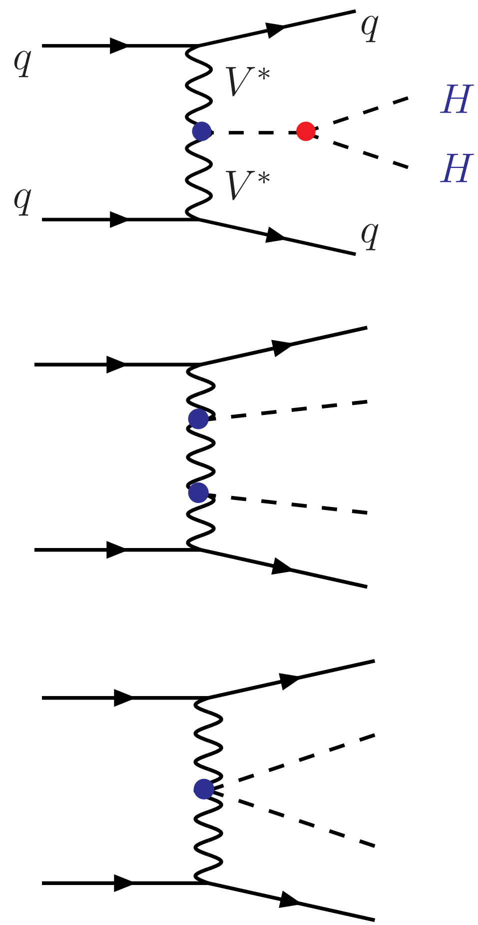
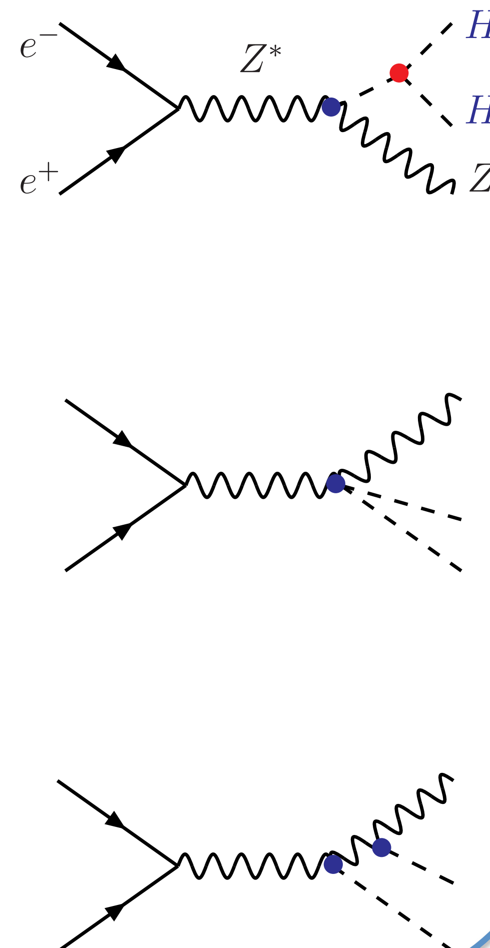
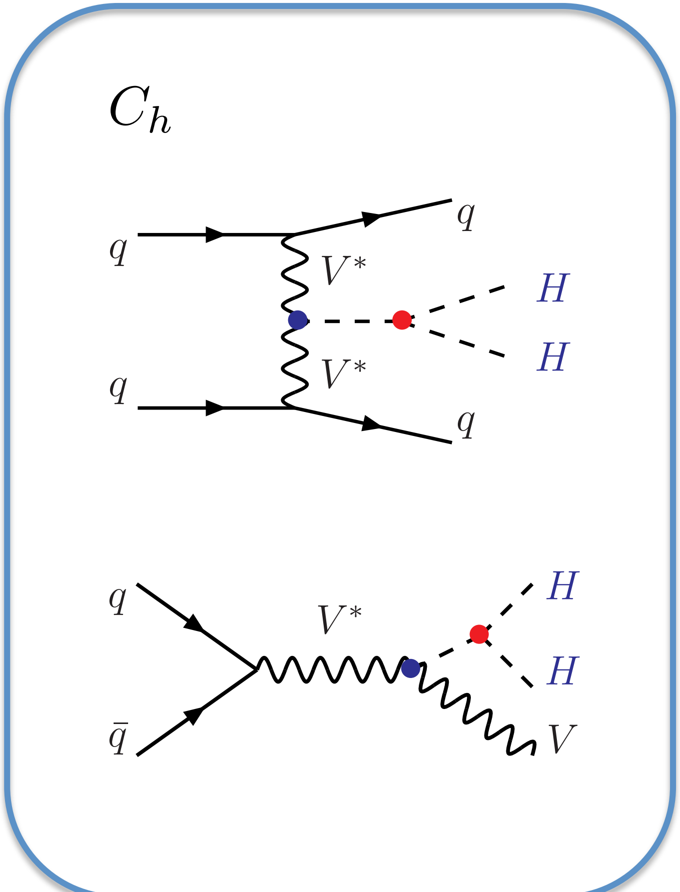


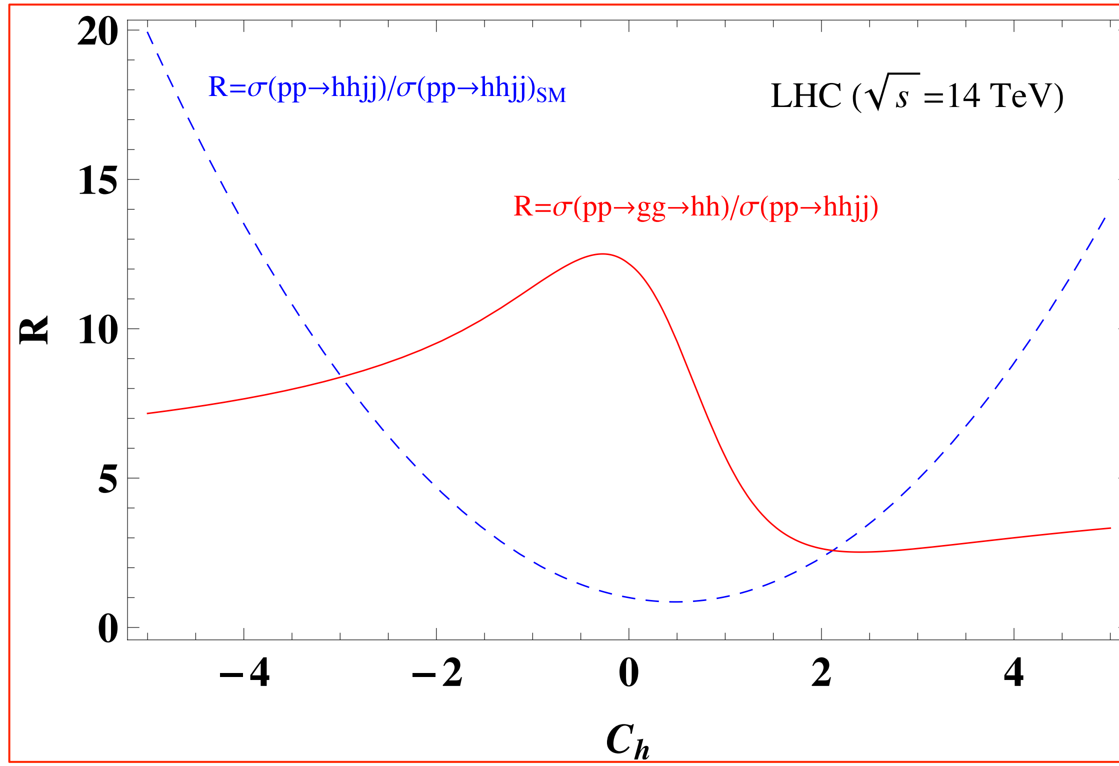
✧ Higgs-strahlung



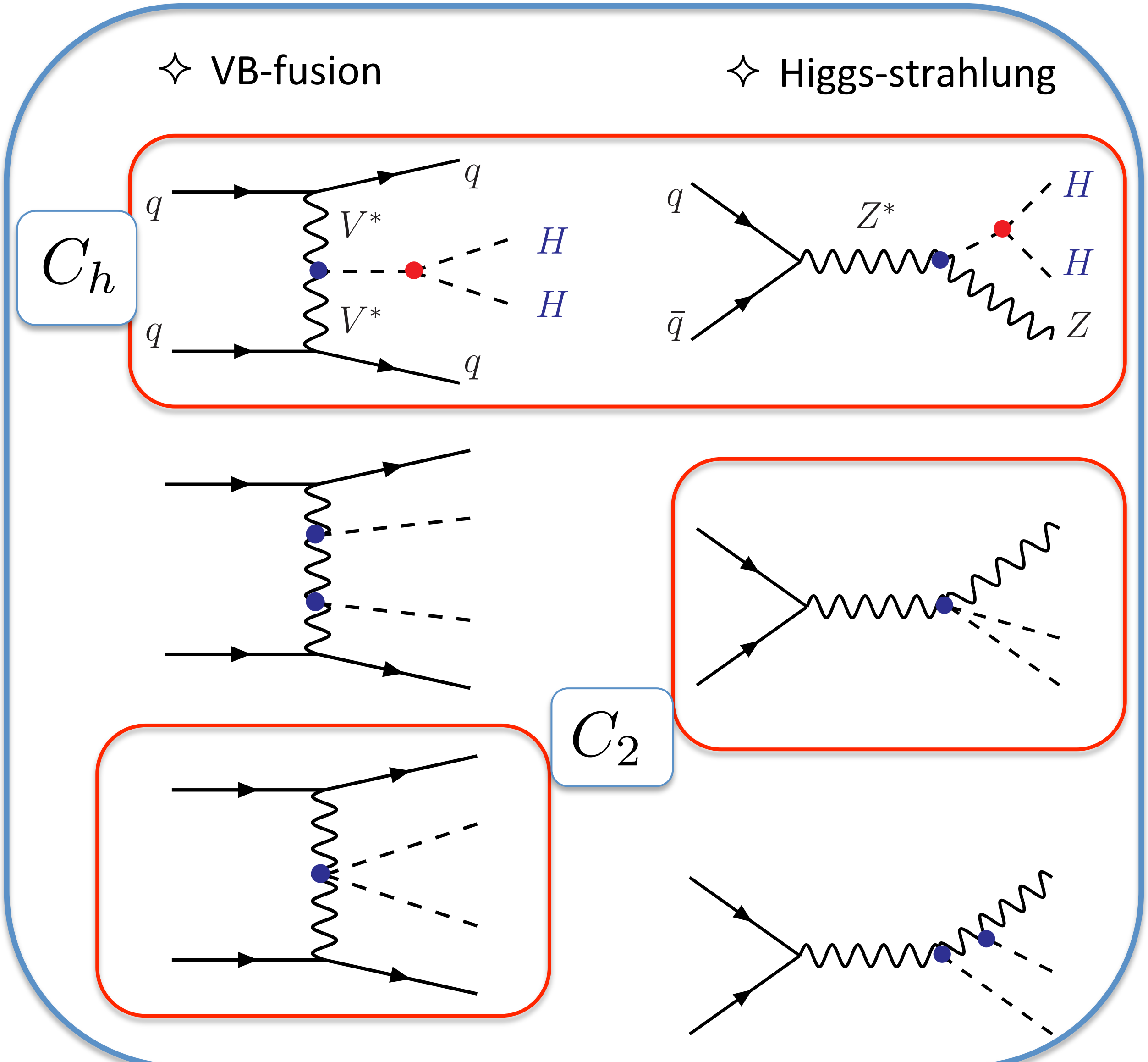
Higgs pair production @LHC



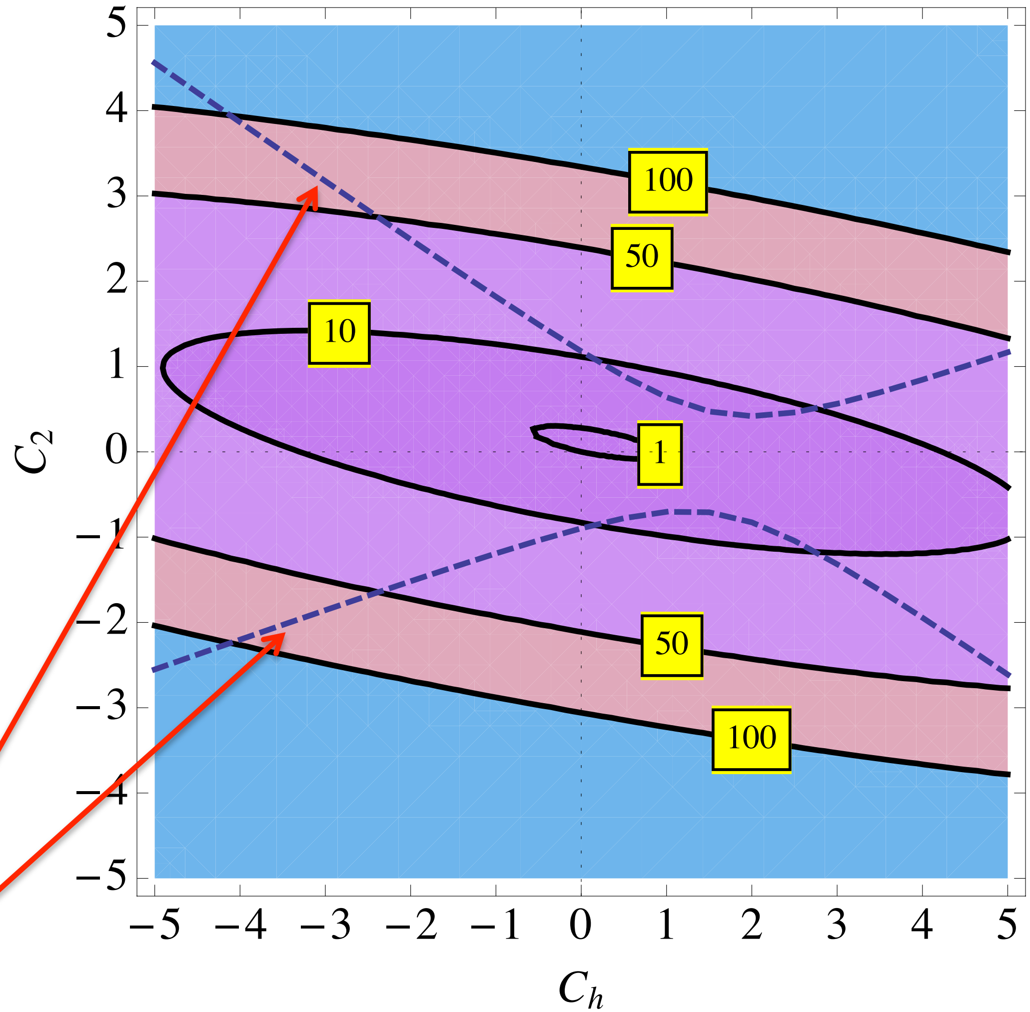
$$\sigma(pp \to hhjj)_{SM} \simeq 1.6 \text{ fb at } 14 \text{ TeV}$$



Higgs pair from vector boson fusion



Higgs pair via VB fusion pp->hhjj @LHC



$$\sigma(pp \to hhjj) = \sigma(pp \to gg \to hh)$$

Higgs pair via VB fusion ee->hhvv @ILC

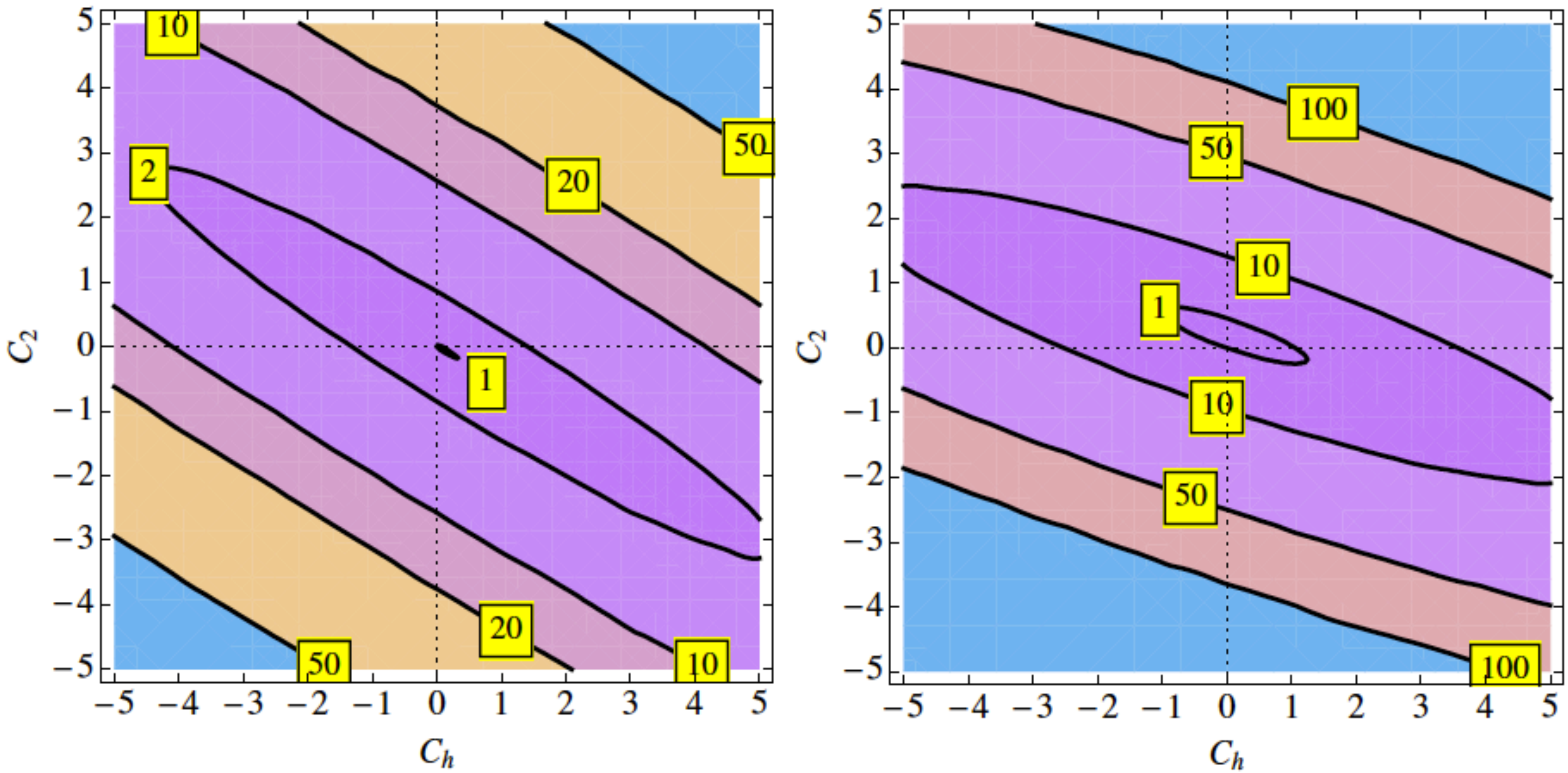


Figure 4: The contour plots of the ratio of the cross section, $\sigma(C_h, C_2)/\sigma(C_h = C_2 = 0)$ of $e^+e^- \to hh\nu\bar{\nu}$. Left ($\sqrt{s} = 500$ GeV), and right ($\sqrt{s} = 1$ TeV).

Higgs pair via Higgsstrahlung ee->Zhh @ILC

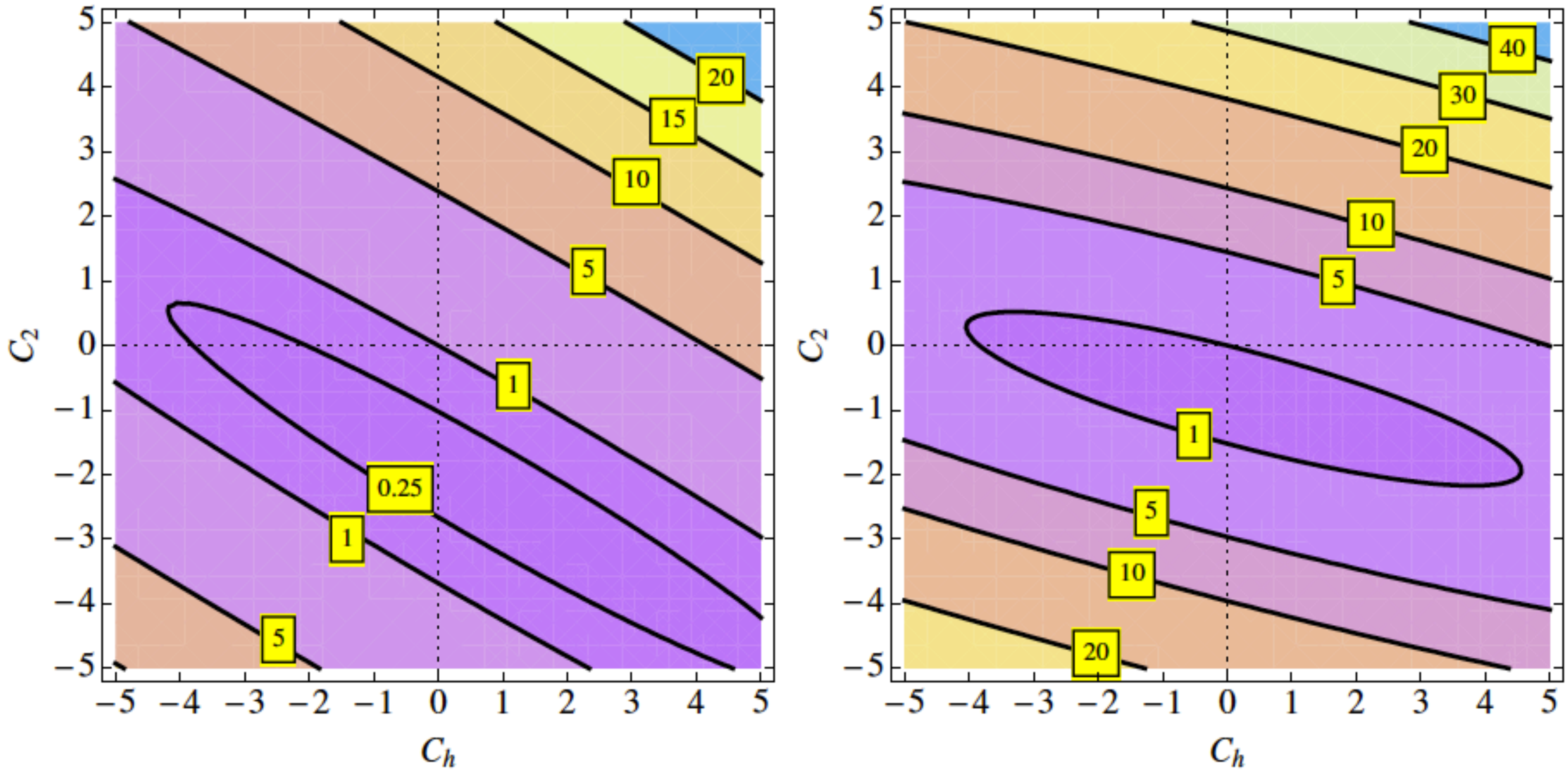


Figure 5: The count our plots of the ratio of the cross section, $\sigma(C_h, C_2)/\sigma(C_h = C_2 = 0)$ of $e^+e^- \to Zhh$. Left ($\sqrt{s} = 500$ GeV), and right ($\sqrt{s} = 1$ TeV).

Diff x-sec for ee->Zhh .vs. scaled Z energy @ILC

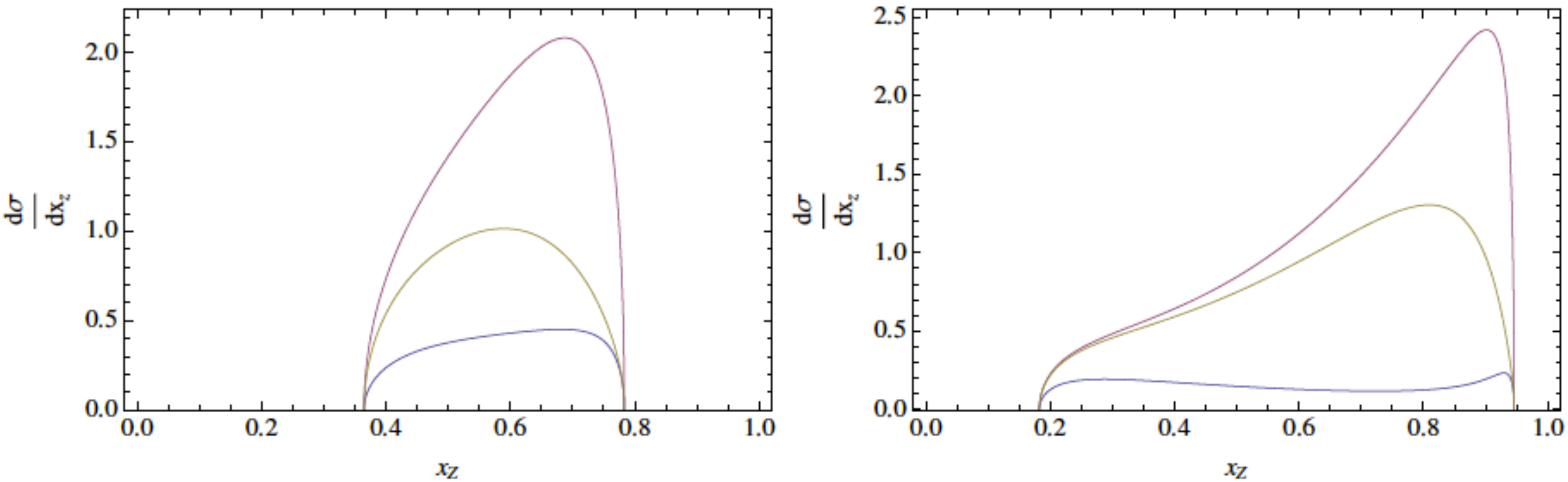


Figure 6: The differential cross section (in fb) of $e^+e^- \to Zhh$. Left ($\sqrt{s} = 500$ GeV), and right ($\sqrt{s} = 1$ TeV). x_Z is a scaled energy of Z boson in the final state : $x_Z = 2E_Z/\sqrt{s}$. $(C_h, C_2) = (0,0), (-2,2), (0,2)$ from below to top in each graph.

$$-\mathcal{L} \supset \frac{m_h^2}{2v}(1+C_h)h^3 + \left(M_W^2 W^+W^- + \frac{M_Z^2}{2}ZZ\right)\left((1+C_1)\frac{2h}{v} + (1+C_2)\frac{h^2}{v^2}\right)$$

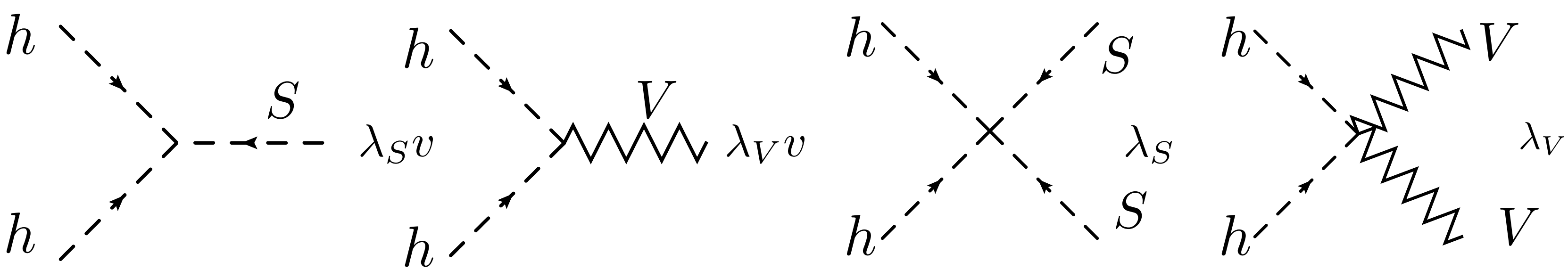
Color-octet vector & scalar particles

Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}(S,V)_{kin} + \mathcal{L}(S,V)_{int} - \lambda_S |S|^2 |H|^2 + \lambda_V V_\mu V^{\mu *} |H|^2$$

Complex → (above)

Real → $$-\frac{\lambda_S}{2} S^2 |H|^2 + \frac{\lambda_V}{2} V_\mu V^\mu |H|^2$$



Odd operators in S & V ➔ Prompt decay

$$V^\mu \bar{q} \gamma_\mu q, \quad S^3, \quad V^\mu S D\mu S, \quad V^\mu V_\mu S$$

$$S V^\mu g_\mu, \quad \epsilon_{\mu\nu\sigma\rho} V^\mu \partial^\rho S \partial^\sigma W^\nu, \quad S \partial_\mu V_\nu \partial^\nu W^\mu \ldots$$

Higgs productions Color-octet vector & scalar particles

$$\sigma_{gg\to h} = \frac{G_F \alpha_s^2}{126\sqrt{2}\pi} \left| \frac{1}{2} A_{\frac{1}{2}}(x_t) + C_s \frac{\lambda_S v^2}{4m_S^2} A_0(x_S) + C_v \frac{\lambda_V v^2}{4m_V^2} A_1(x_V) \right|^2$$

$$\begin{aligned} A_1(x) &= -\left(2 + 3x + 3x(2-x) f(x)\right), \\ A_{1/2} &= 2x\left(1 + (1-x) f(x)\right), \\ A_0 &= -x\left(1 - x f(x)\right), \\ f(x) &= \begin{cases} \arcsin^2\left(1/\sqrt{x}\right), & \text{if } x \geq 1 \\ -\frac{1}{4}\left(\log \frac{1+\sqrt{1-x}}{1-\sqrt{1-x}} - i\pi\right)^2, & \text{if } x < 1 \end{cases} \end{aligned}$$

$$\frac{A_1(x)}{A_2(x)} \sim -19 \qquad \text{for} \qquad x = \frac{4m^2}{m_h^2} \gtrsim 4$$

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)

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

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

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

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

Contributions from colored vectors

G. V. Jikia, Nucl.Phys. B412 (1994) 57-75

$$F_{tri}^{V} = \frac{s+2m_h^2}{s-m_h^2}\frac{C_v\lambda_v v^2}{m^2}\left(8sC_{AB} + (6m^2+m_h^2)\left(1+2m^2C_{AB}\right)\right)$$

$$F_{box}^{V} = C_v\left(\frac{\lambda_v v^2}{m^2}\right)^2\frac{m^2}{2s}\left(4sm^2\left(D_{abc}+D_{bac}+D_{acb}\right) - 4sC_{AB}\right.$$
$$+\frac{m_h^4-2m_h^2m^2+12m^4}{2sm^2}\left((t-m_h^2)m^2C_{ac}+(u-m_h^2)C_{bc}\right.$$
$$\left.\left.-(tu-m_h^4)D_{acb}\right)-2sm^2\left(D_{abc}+D_{bac}+D_{acb}\right)\right)$$

$$G_{box}^{V} = -C_v\left(\frac{\lambda_v v^2}{m^2}\right)^2\frac{m^2}{2s}\left(2(tu-m_h^4)\left(D_{abc}+D_{bac}+D_{acb}\right)-4sC_{ab}\right.$$
$$\frac{1}{2m^2(tu-m_h^4)}\left((4m^2(t-m_h^2)^2-M^4t)(2(t-m_h^2)C_{ac}+(t-m_h^2)^2D_{bac}\right)$$
$$(4m^2(u-m_h^2)^2-M^4t)(2(u-m_h^2)C_{ac}+(u-m_h^2)^2D_{abc}))$$
$$+\frac{M^4+4m^2s}{2m^2}\left(\frac{s}{tu-m_h^4}((s-2m_h^2)m^2C_{ab}+(s-4m_h^2)C_{cd})\right.$$
$$\left.\left.-(t-2m_h^2)D_{bac}-(u-2m^2)D_{abc}+2m^2D_{acb}-2C_{cd}\right)\right)$$

Calculation: Higgs pair production via gluon fusion at LHC

- ✧ Higgs pair production in the presence of colored scalars and vectors are implemented in MG5
- ✧ The rate was calculated scanning over the masses

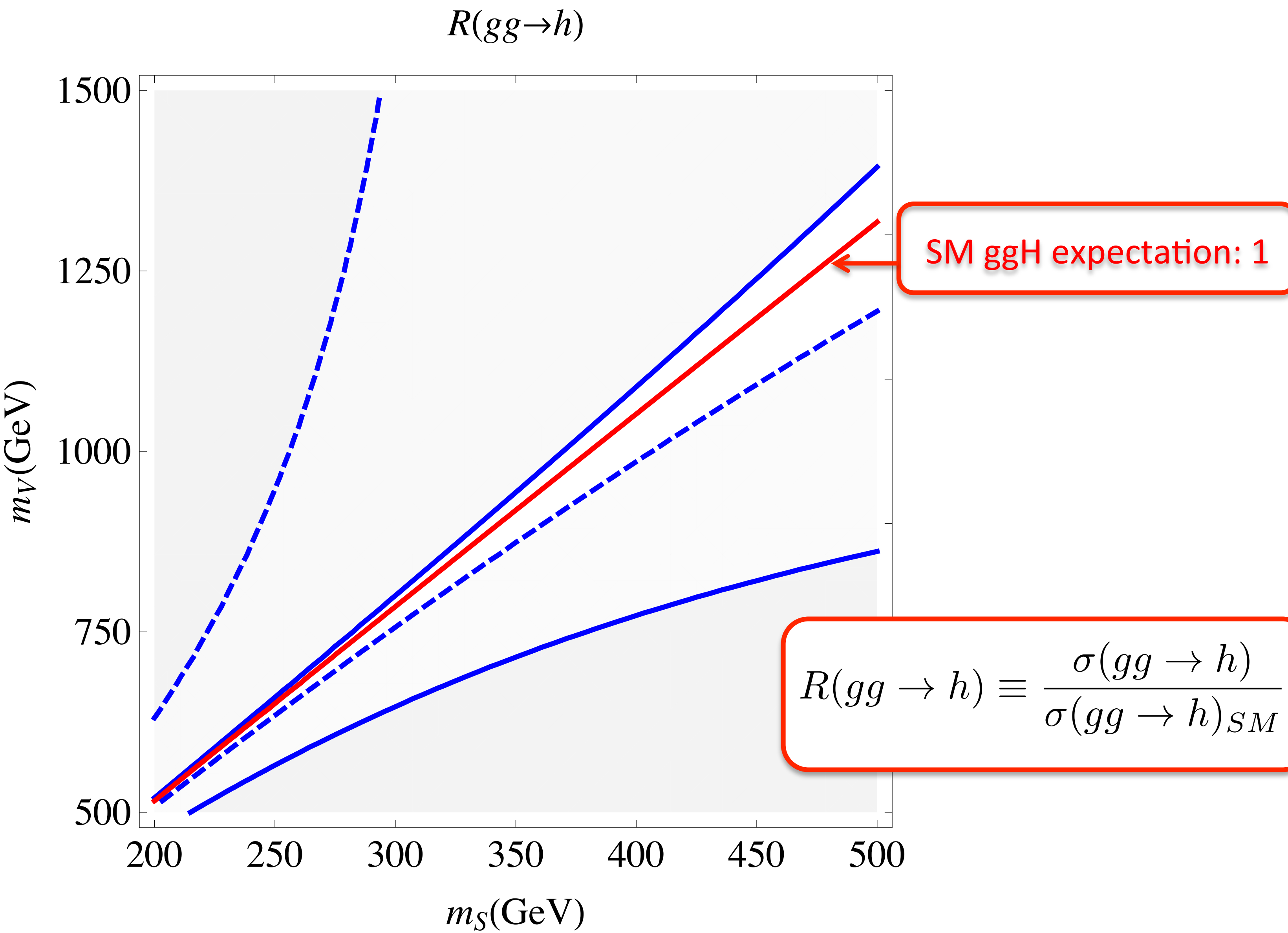
  m_S & m_V

  and their portal couplings

  λ_S & λ_V

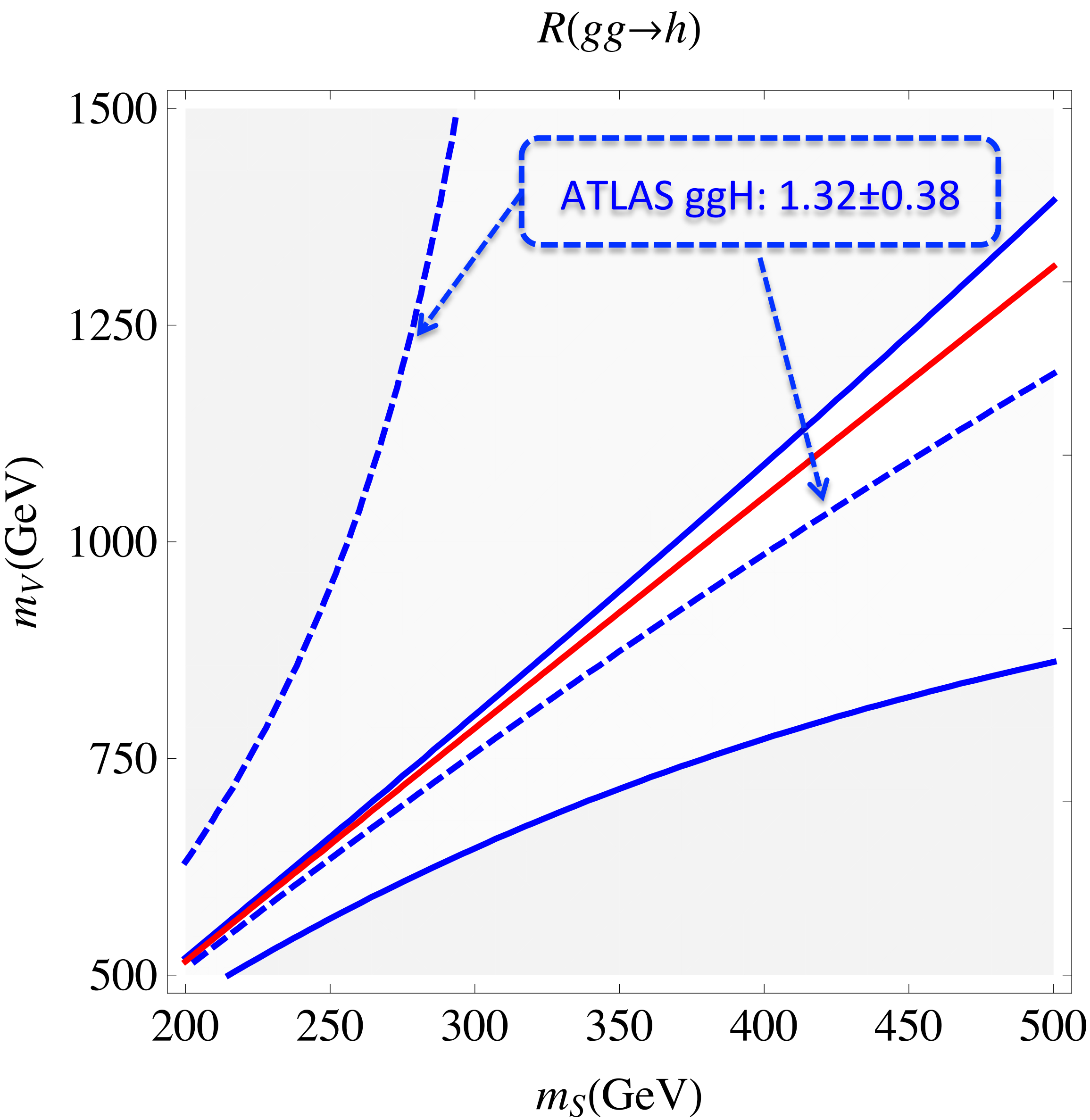
  of the color octet scalar & vector particles for three cases:
  - Real S & V
  - Complex S & V
  - Real V & complex S
- ✧ The constraints of the single Higgs production via gluon gluon fusion from ATLAS & CMS are put on these parameters

Scan over vector & scalar octet masses:

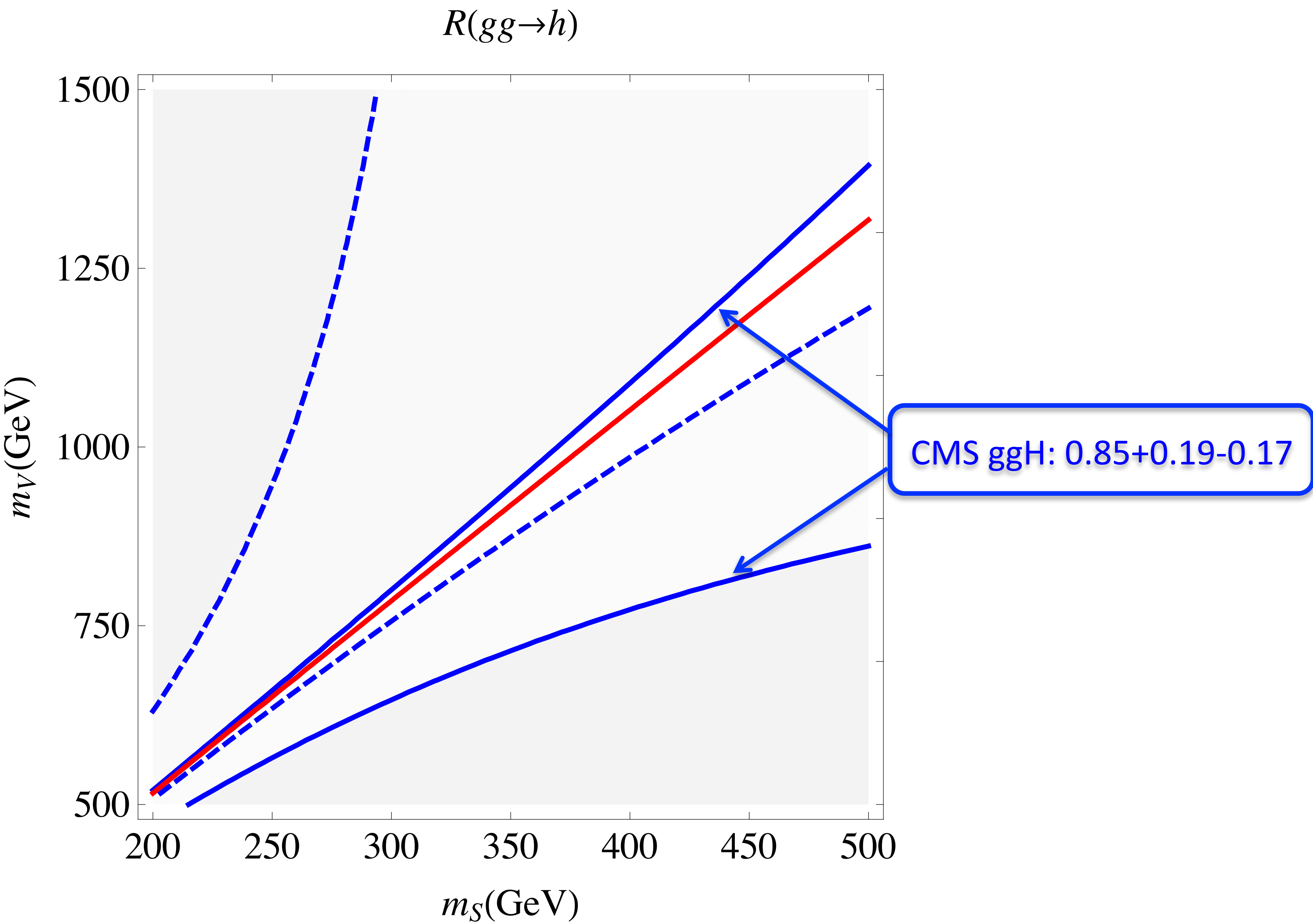


$$R(gg \to h) \equiv \frac{\sigma(gg \to h)}{\sigma(gg \to h)_{SM}}$$

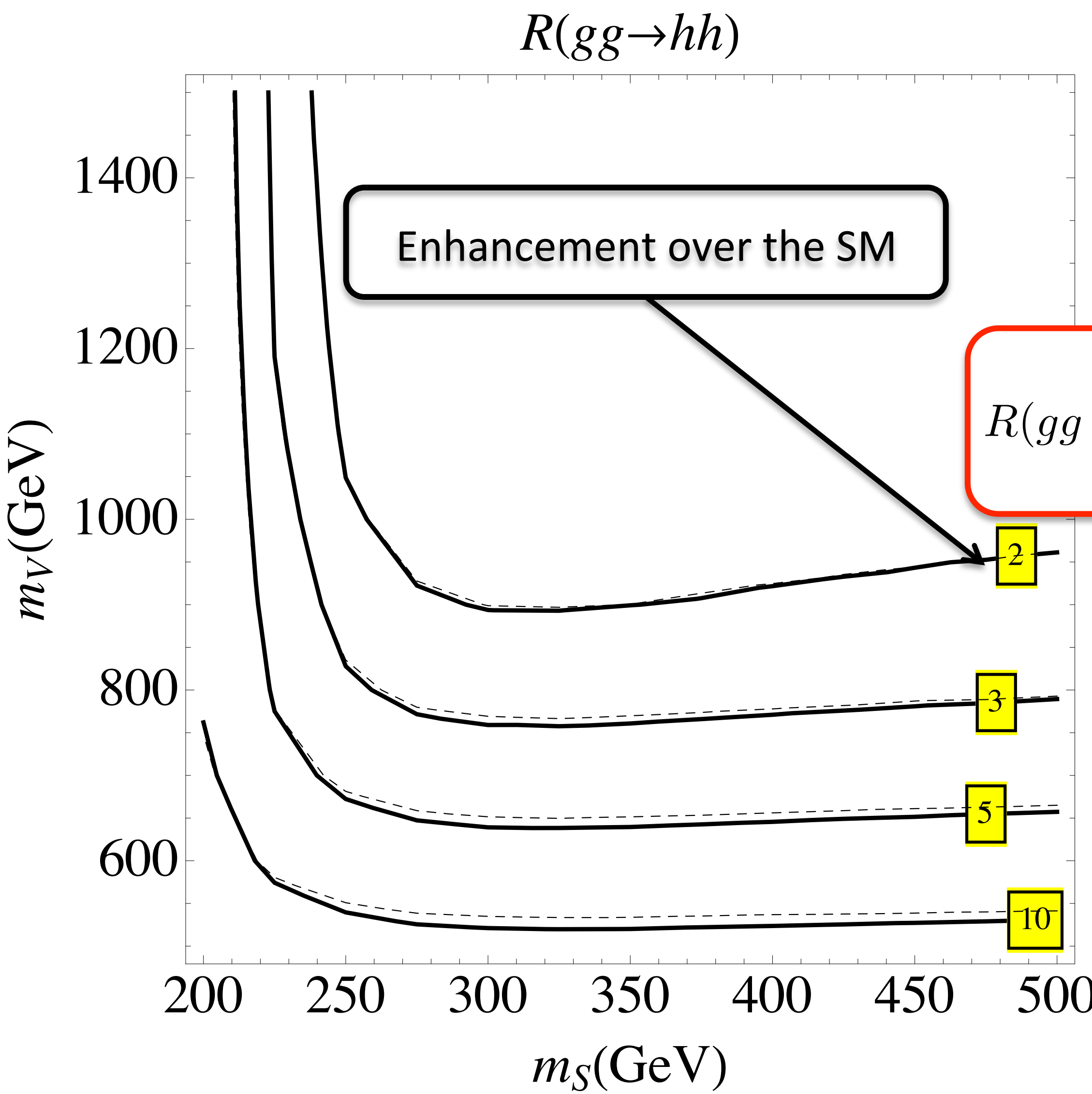
Scan over vector & scalar octet masses:



Scan over vector & scalar octet masses:

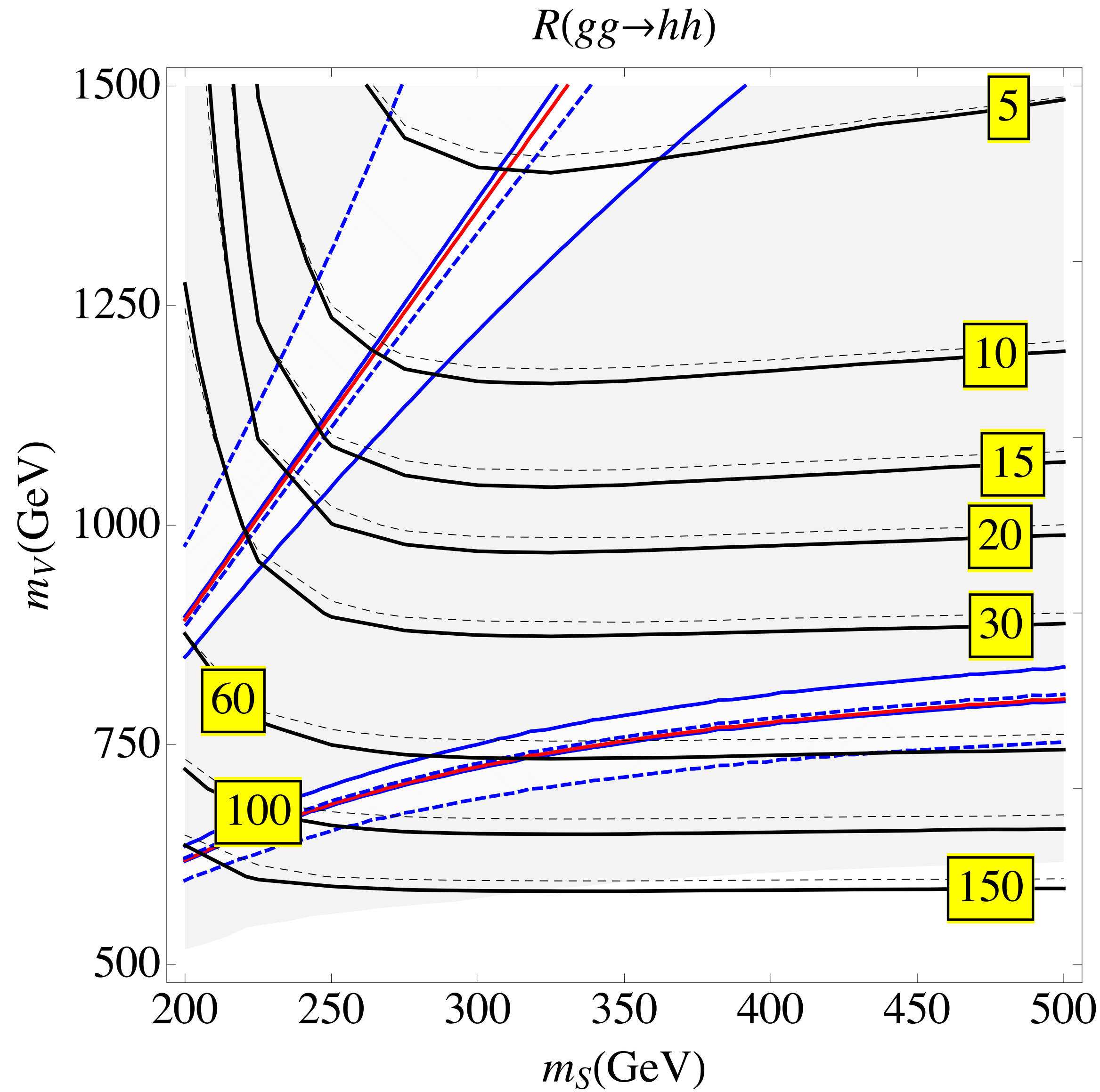


Scan over vector & scalar octet masses:



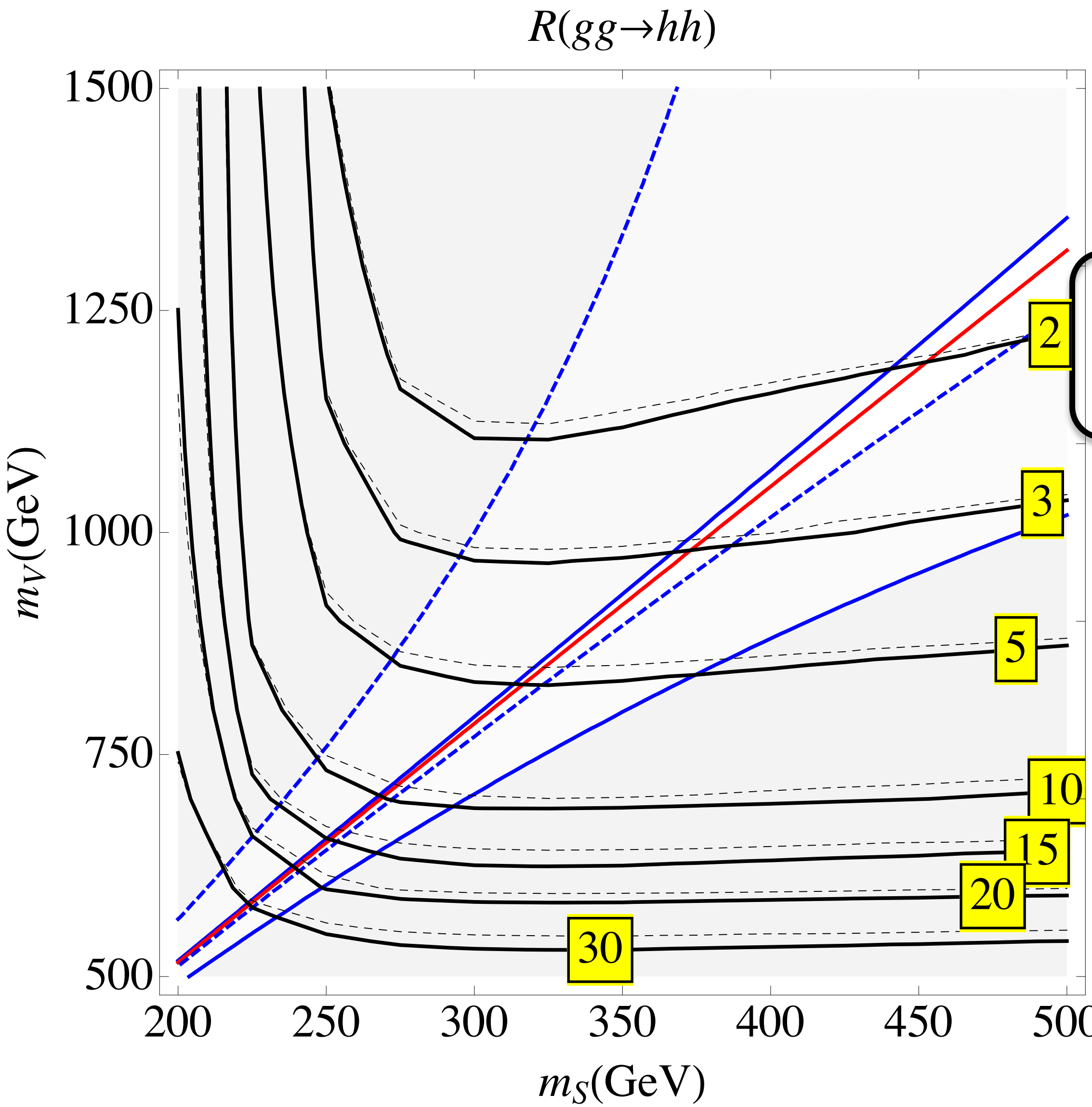
$$R(gg \to hh) \equiv \frac{\sigma(gg \to hh)}{\sigma(gg \to hh)_{SM}}$$

Scan over vector & scalar octet masses: Complex S & V



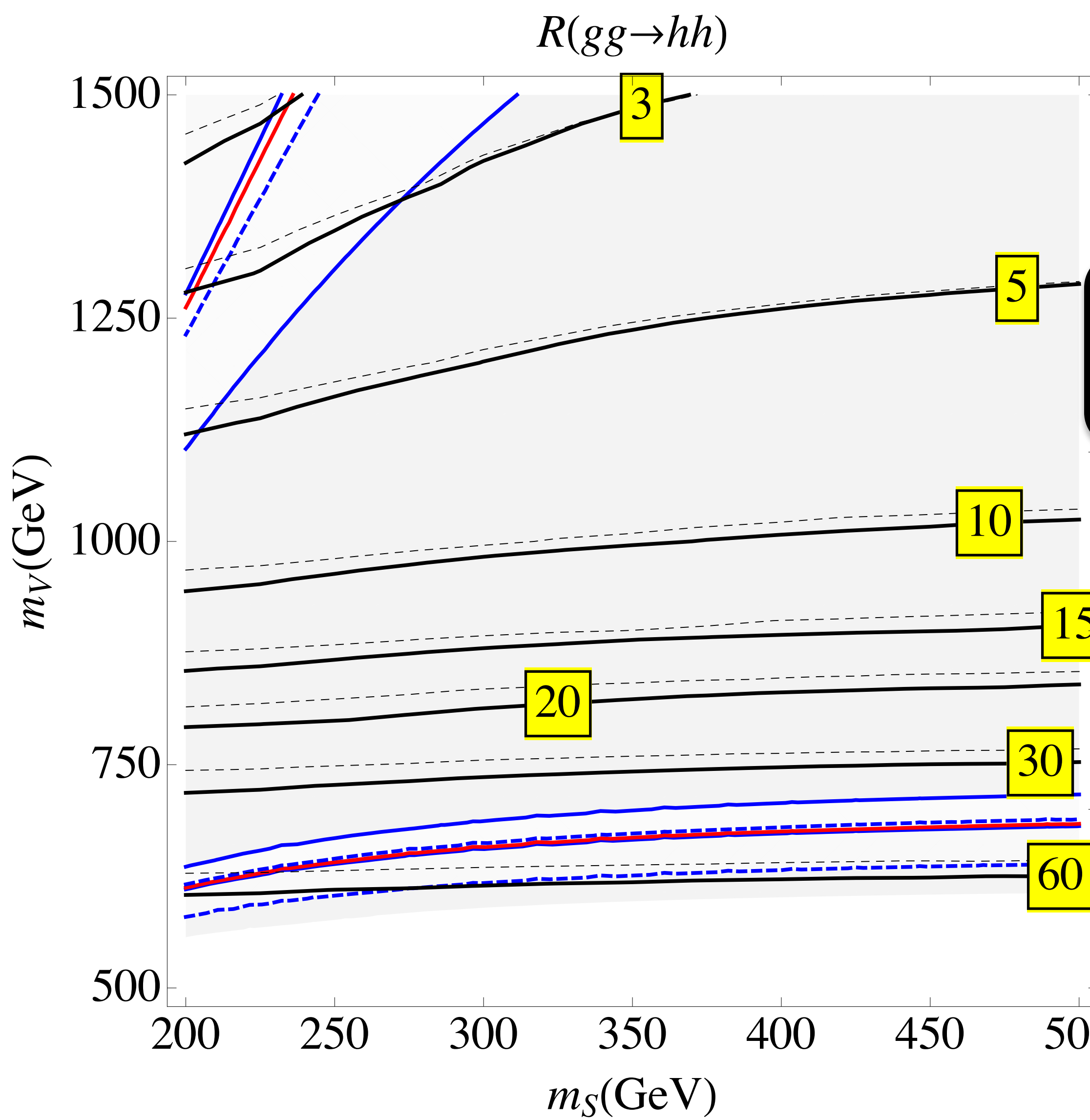
Portal Couplings:
λ_s=1.5
λ_V=1.5

Scan over vector & scalar octet masses: Complex S & V



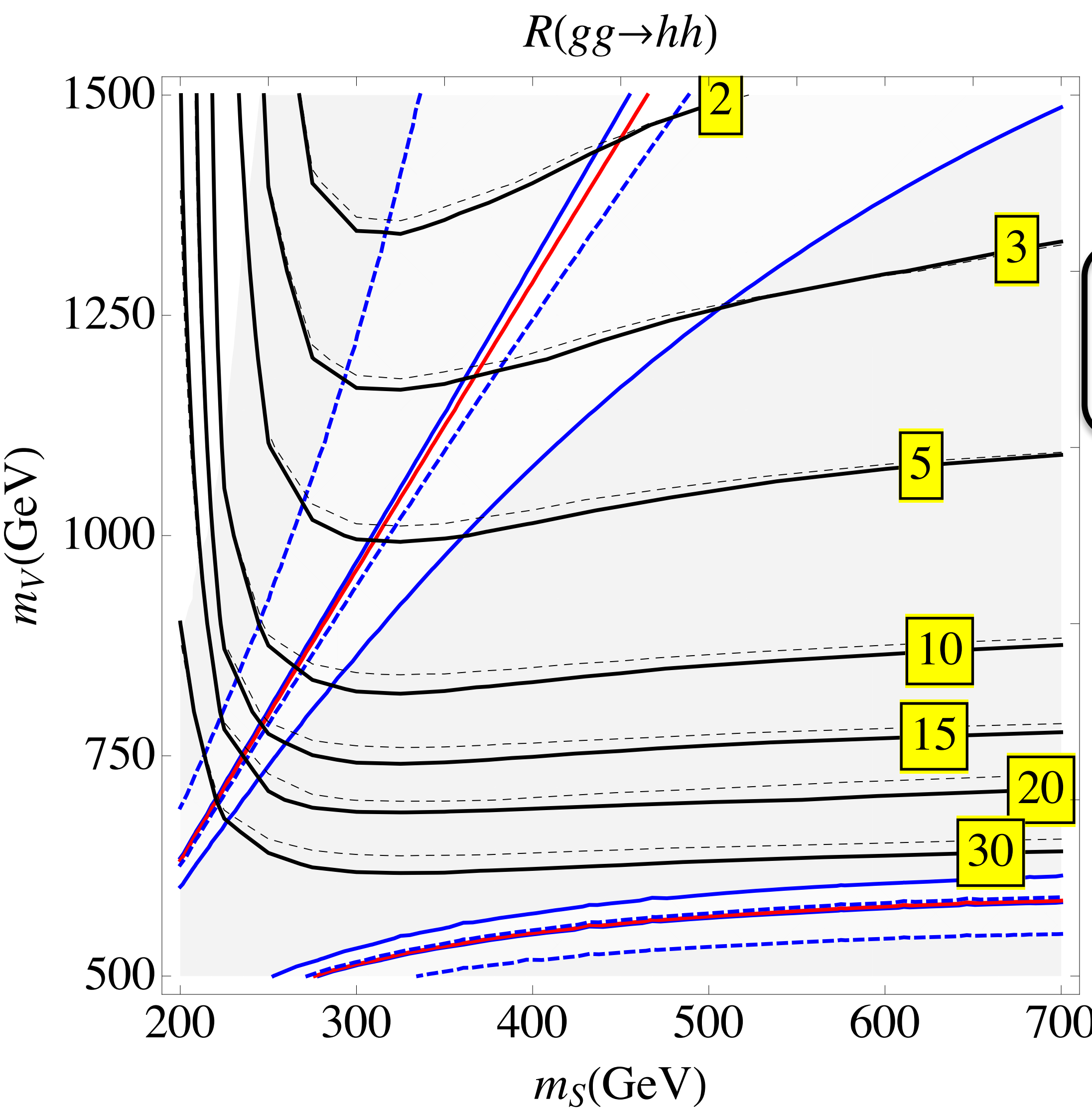
Portal Couplings:
λ_s=1.5
λ_V=0.5

Scan over vector & scalar octet masses: Complex S & V



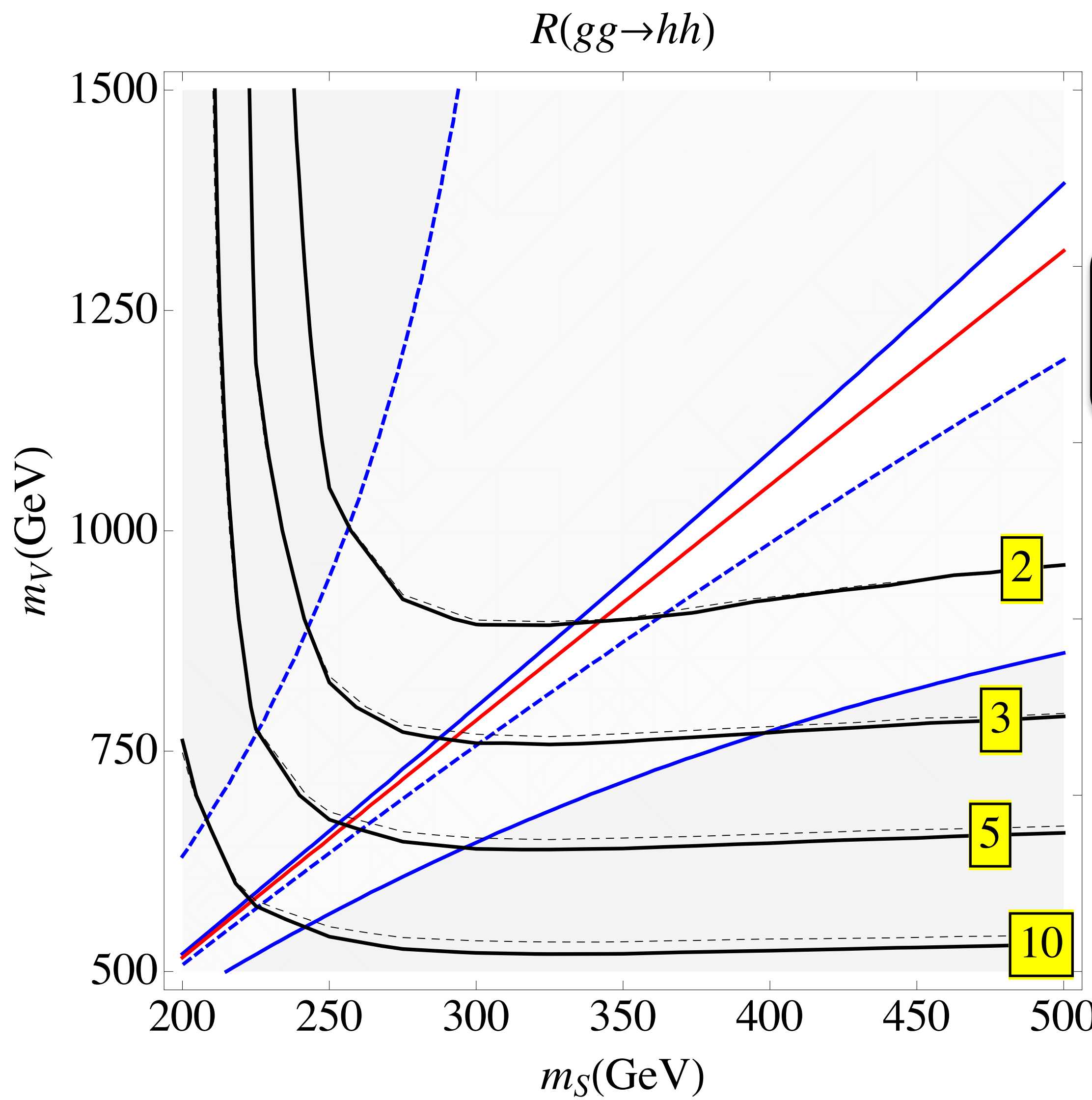
Portal Couplings:
λ_s=0.5
λ_V=1.

Scan over vector & scalar octet masses: Real V & Complex S



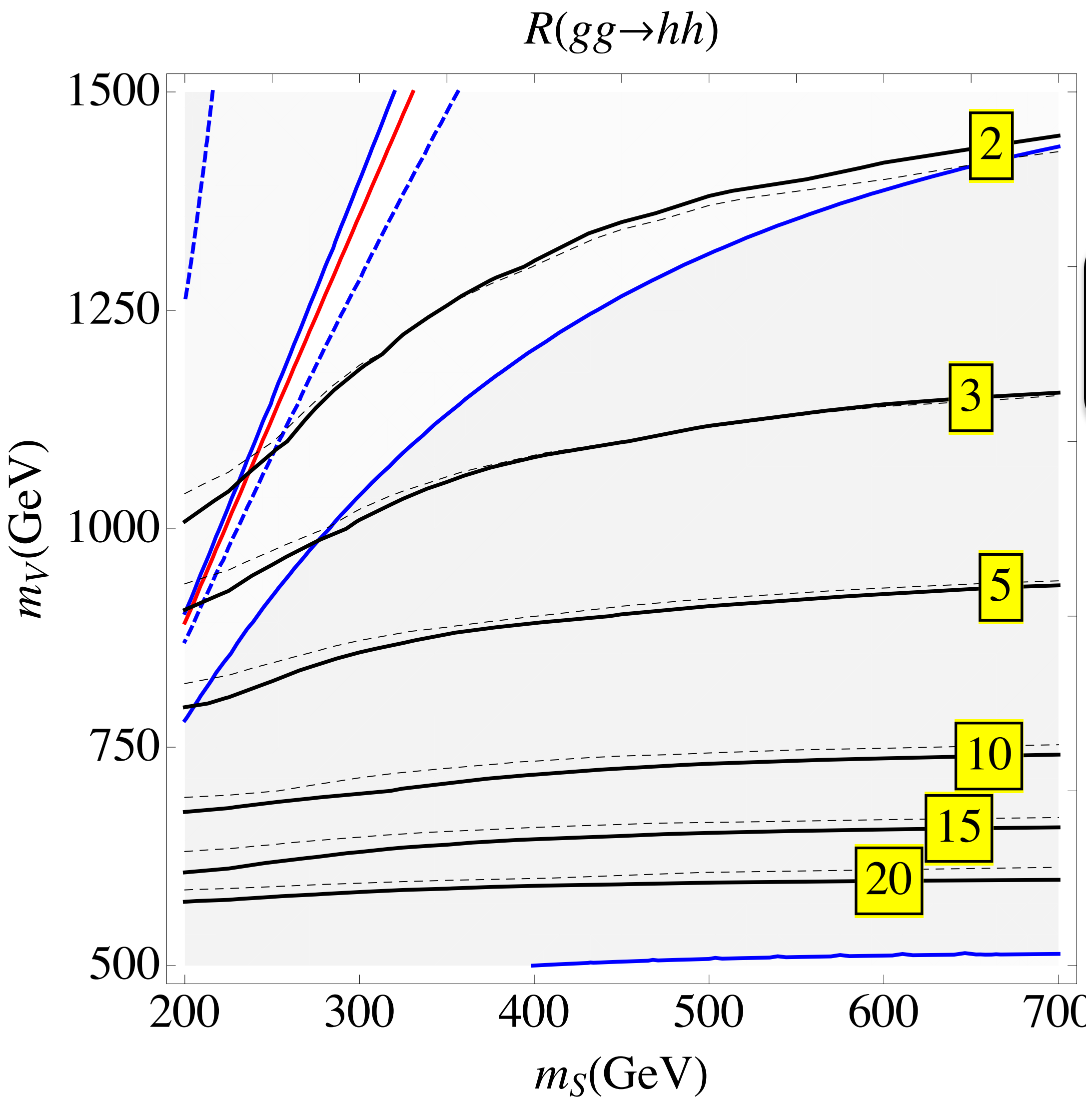
Portal Couplings:
λ_s=1.5
λ_V=1.5

Scan over vector & scalar octet masses: Real V & Complex S



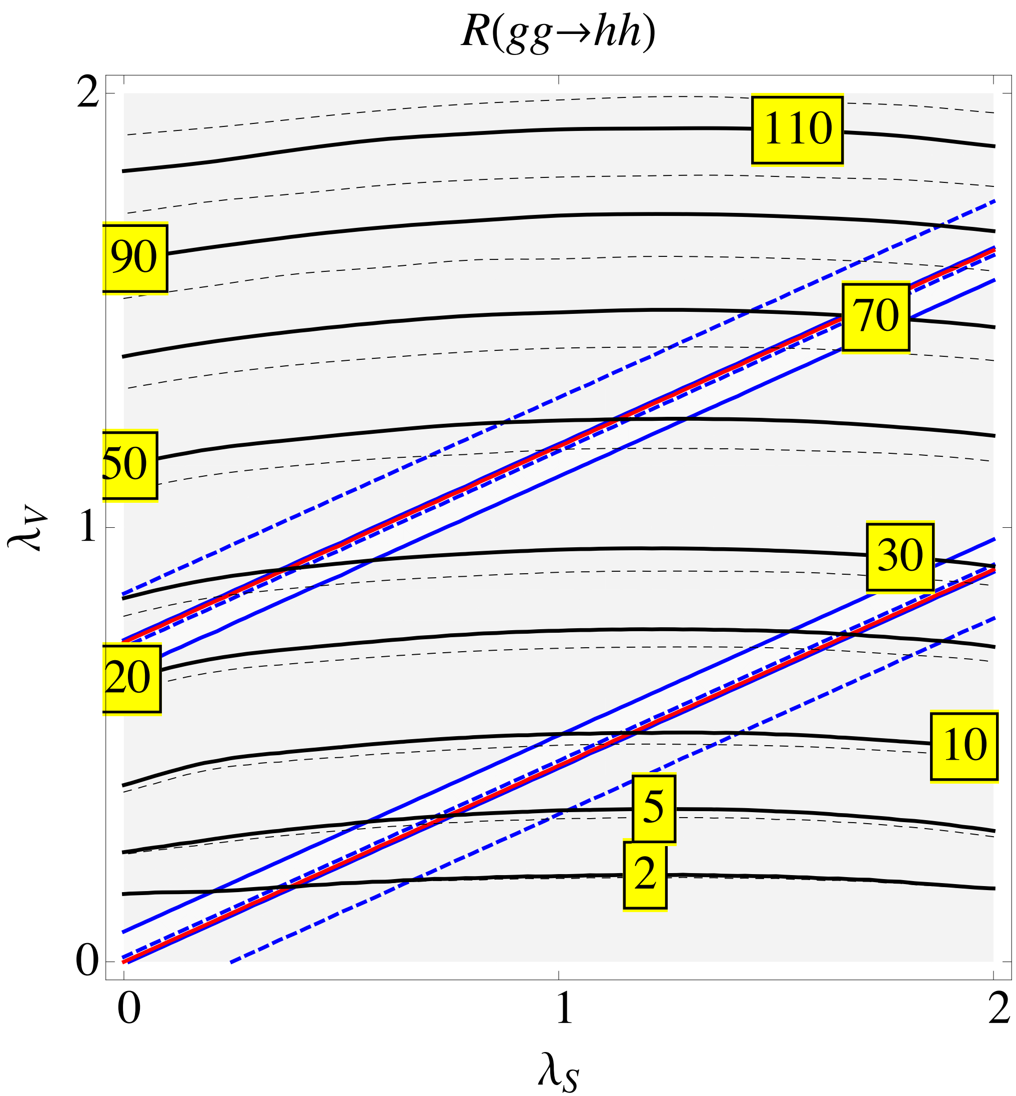
Portal Couplings:
λ_s=1.5
λ_V=0.5

Scan over vector & scalar octet masses: Real V & Complex S



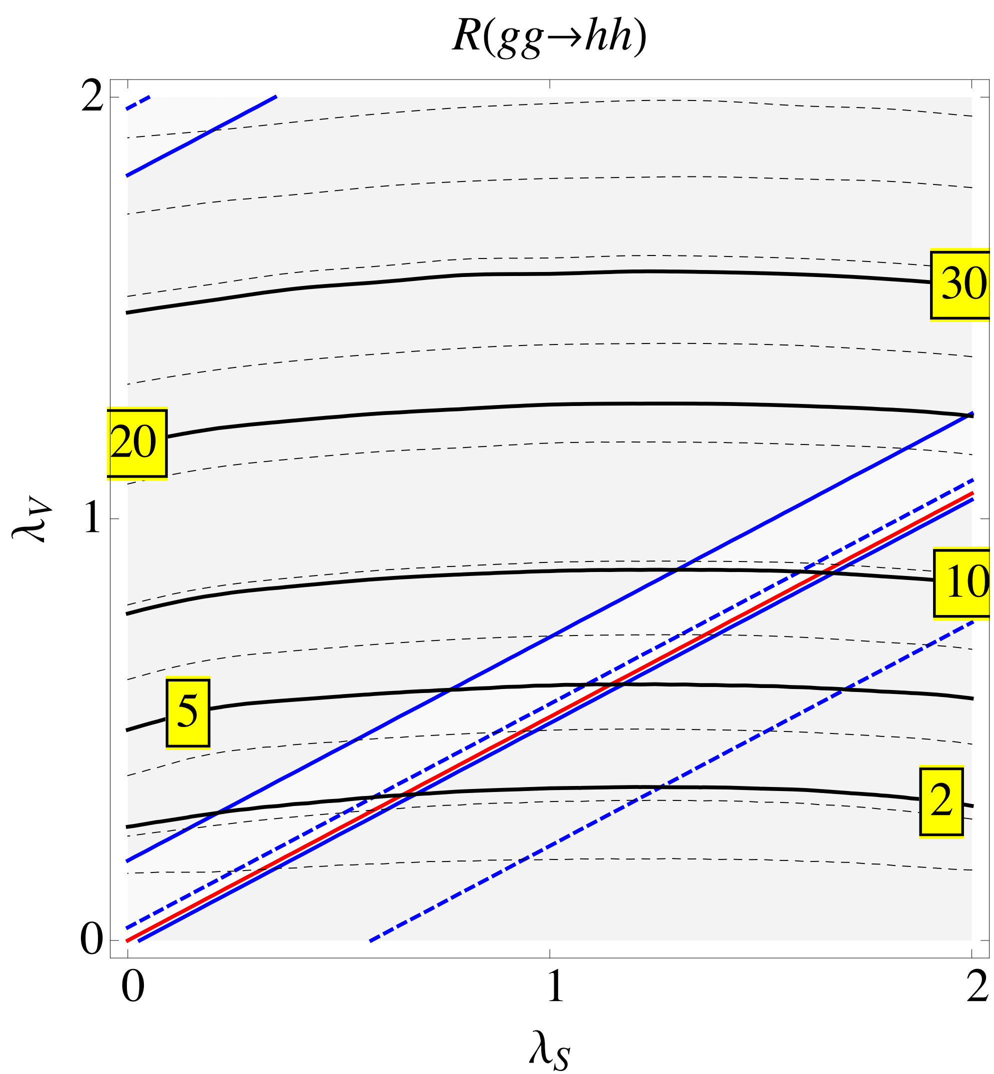
Portal Couplings:
λ_s=0.5
λ_V=1.

Scan over portal couplings: Complex V & S



Masses:
m_s=300 GeV
m_V=700 GeV

Scan over portal couplings: Real V & Complex S



Masses:
m_s=300 GeV
m_V=700 GeV

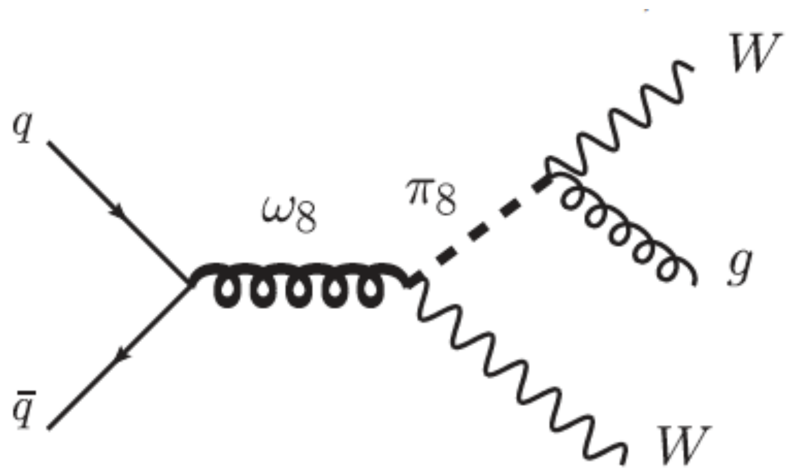
Example Model of Octet V & S

K. Ishiwata & M. B. Wise, PRD 83 (2011) 074015
T. E, W-S. Hou & H. Yokoya, PRD 84 (2011) 094013
J. Alwall, T. E., W-S. Hou & H. Yokoya, PRD 86 (2012) 074029
A. Idilbi et al, PRD 82 (2010) 075017

✧ SU(2)-singlet SU(3)-octet vector ω_8, SU(2)-triplet SU(3)-octet scalar π_8

ω_8 -> W π_8 (Z π_8) ->WWg (ZZg)

Experimental signals for color octets



✧ CMS Collaboration, JHEP 09 (2015) ω_8 -> W π_8 (Z π_8)->WWg (ZZg) 50%+bb 50%

Example Model of Octet V & S

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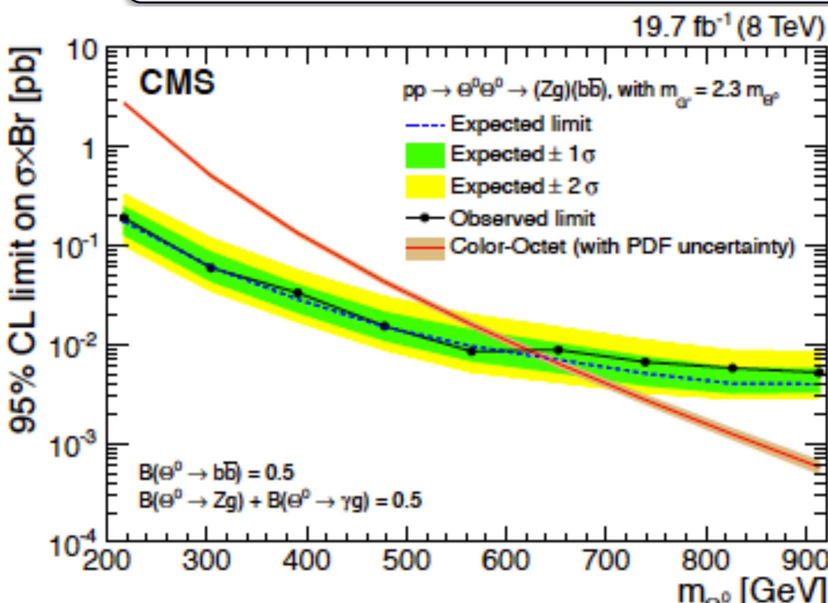
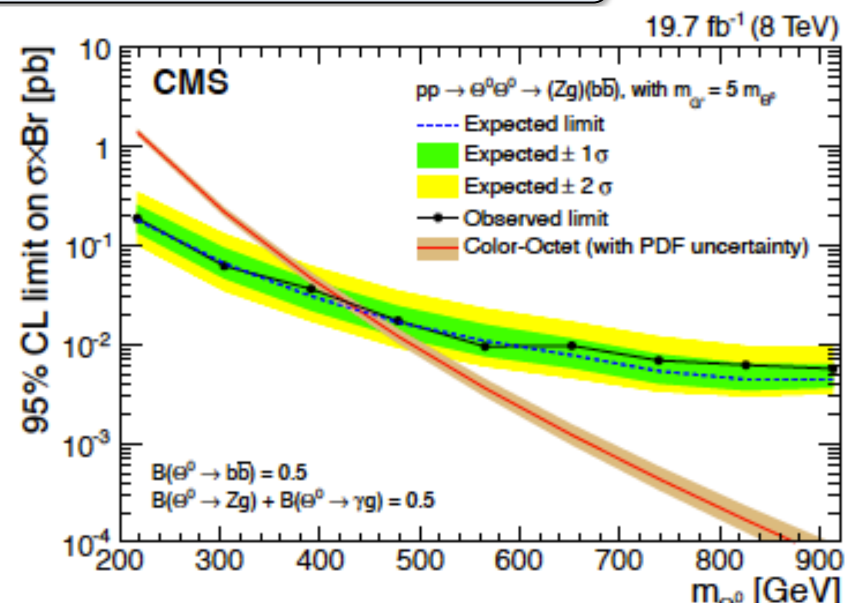
✧ SU(2)-singlet SU(3)-octet vector ω_8, SU(2)-triplet SU(3)-octet scalar π_8

ω_8 -> W π_8 (Z π_8) ->WWg (ZZg)

Experimental search for pair produced colorons





✧ CMS Collaboration, JHEP 09 (2015)

ω_8 -> W π_8 (Z π_8)->WWg (ZZg) 50%+bb 50%

Conclusion

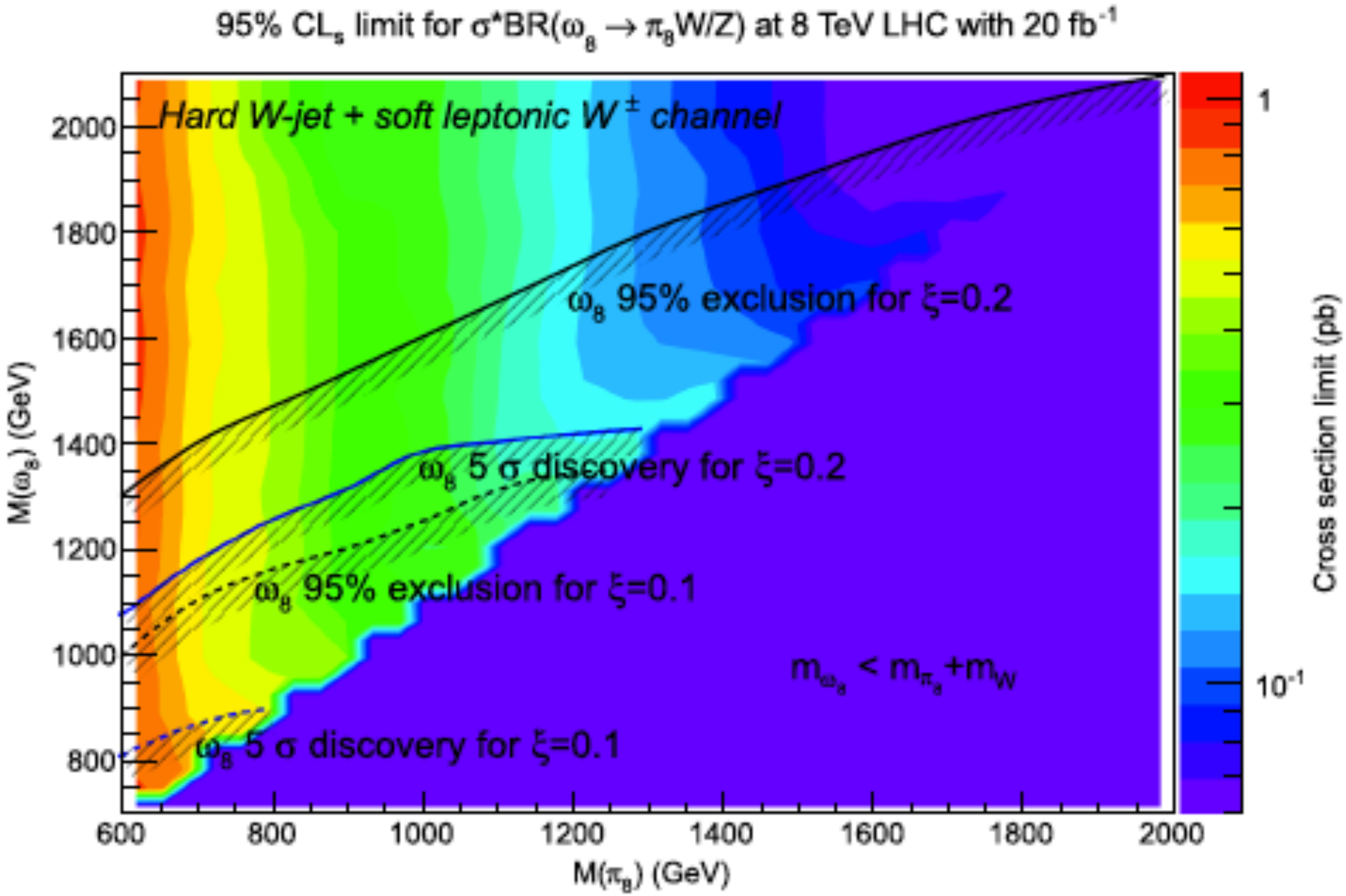
- ✧ The Higgs pair production is studied for general potential and in the presence of Scalar and Vector octets for LHC.
- ✧ Single Higgs production constraint on the effective operator & Scalar & Vector octet masses and portal couplings have been studied by scanning over them.
- ✧ Several set of parameters & portal couplings are chosen which are consistent with the current data.
- ✧ They have been found to be affected for some values even the single Higgs production receives moderate correction.

Thank you for

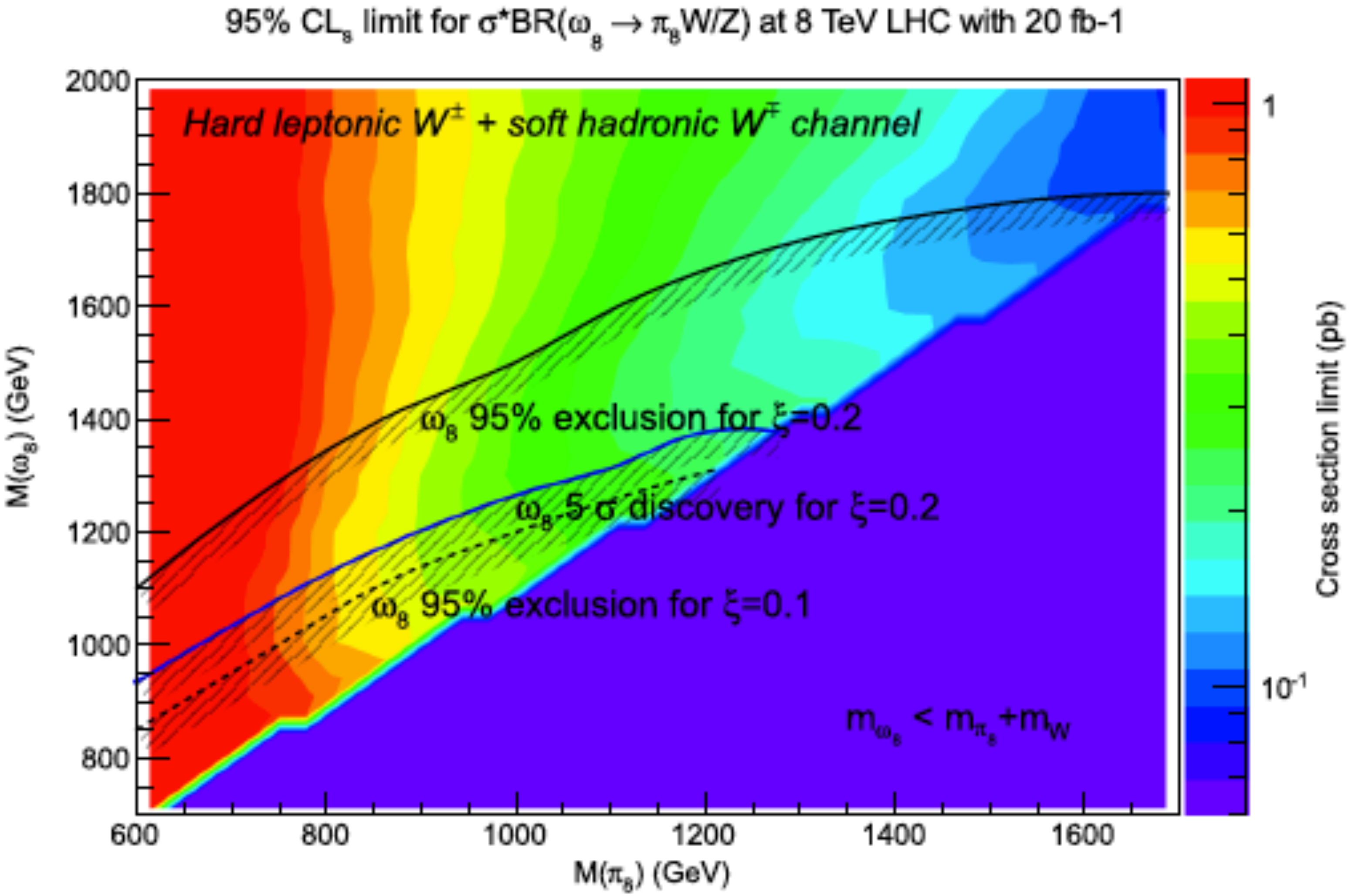
your Attention!

Thank you, organizers!

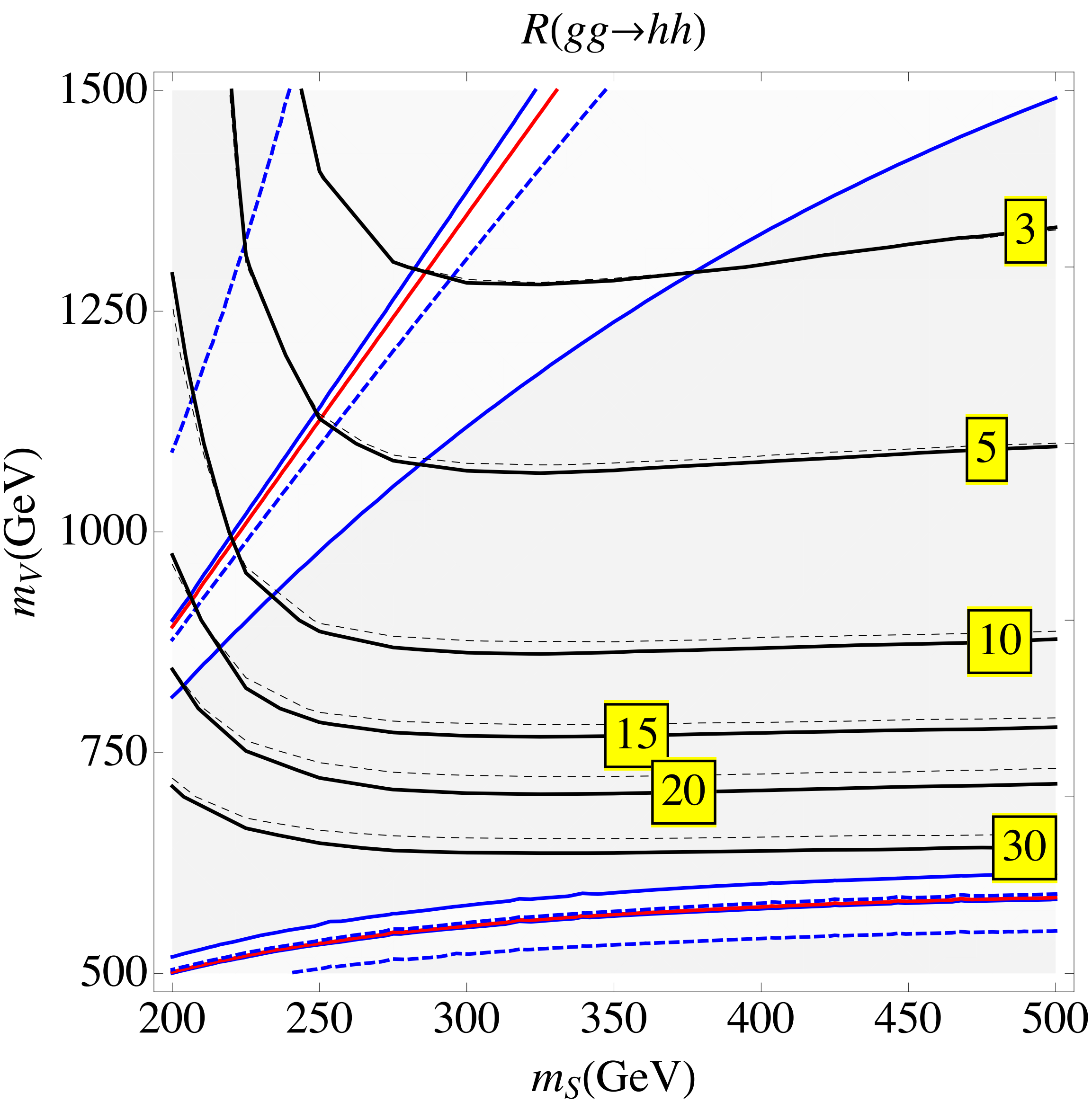
Jet tagged W channel



Hard leptonic W channel

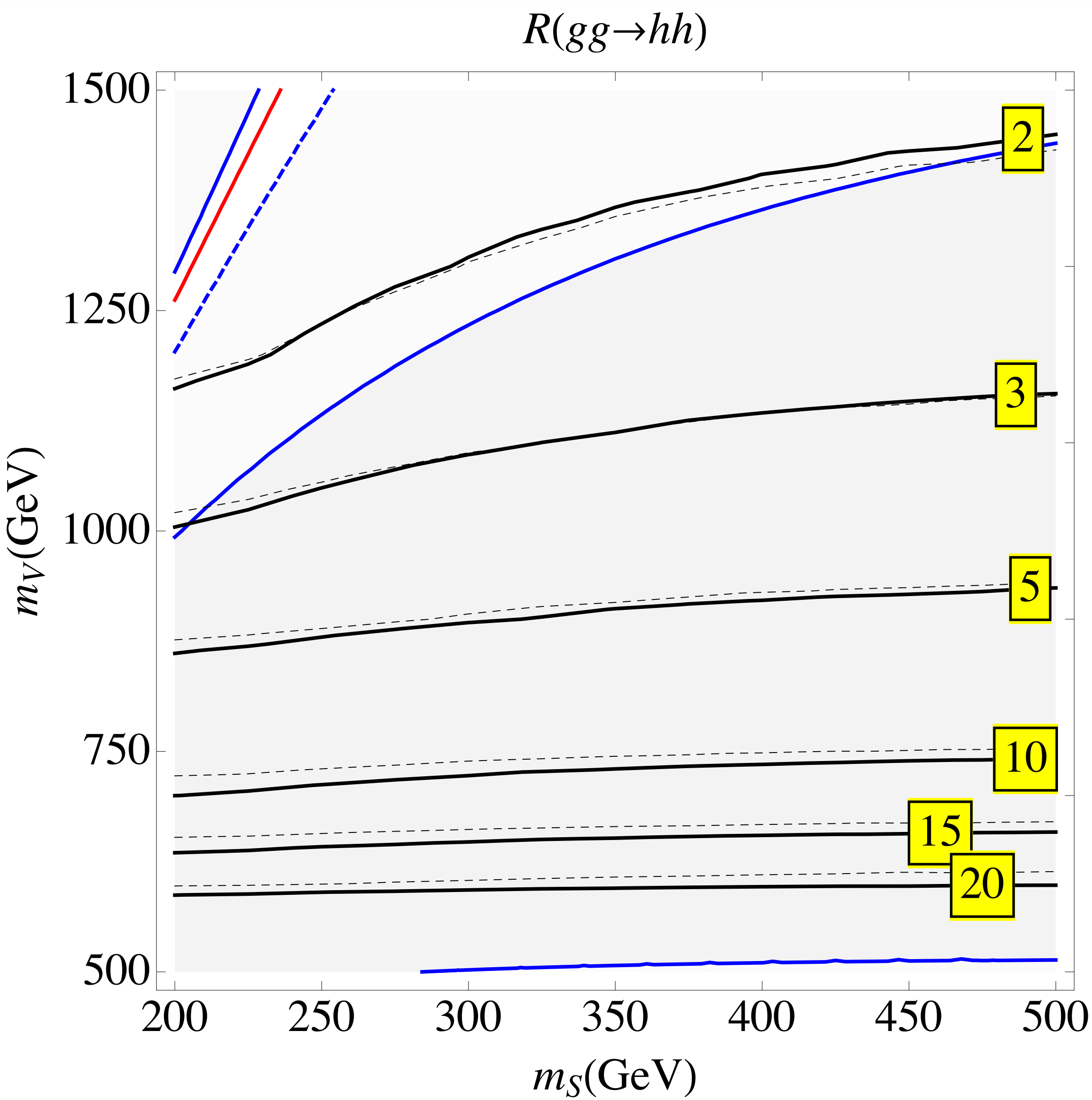


Scan over vector & scalar octet masses: Real S & V



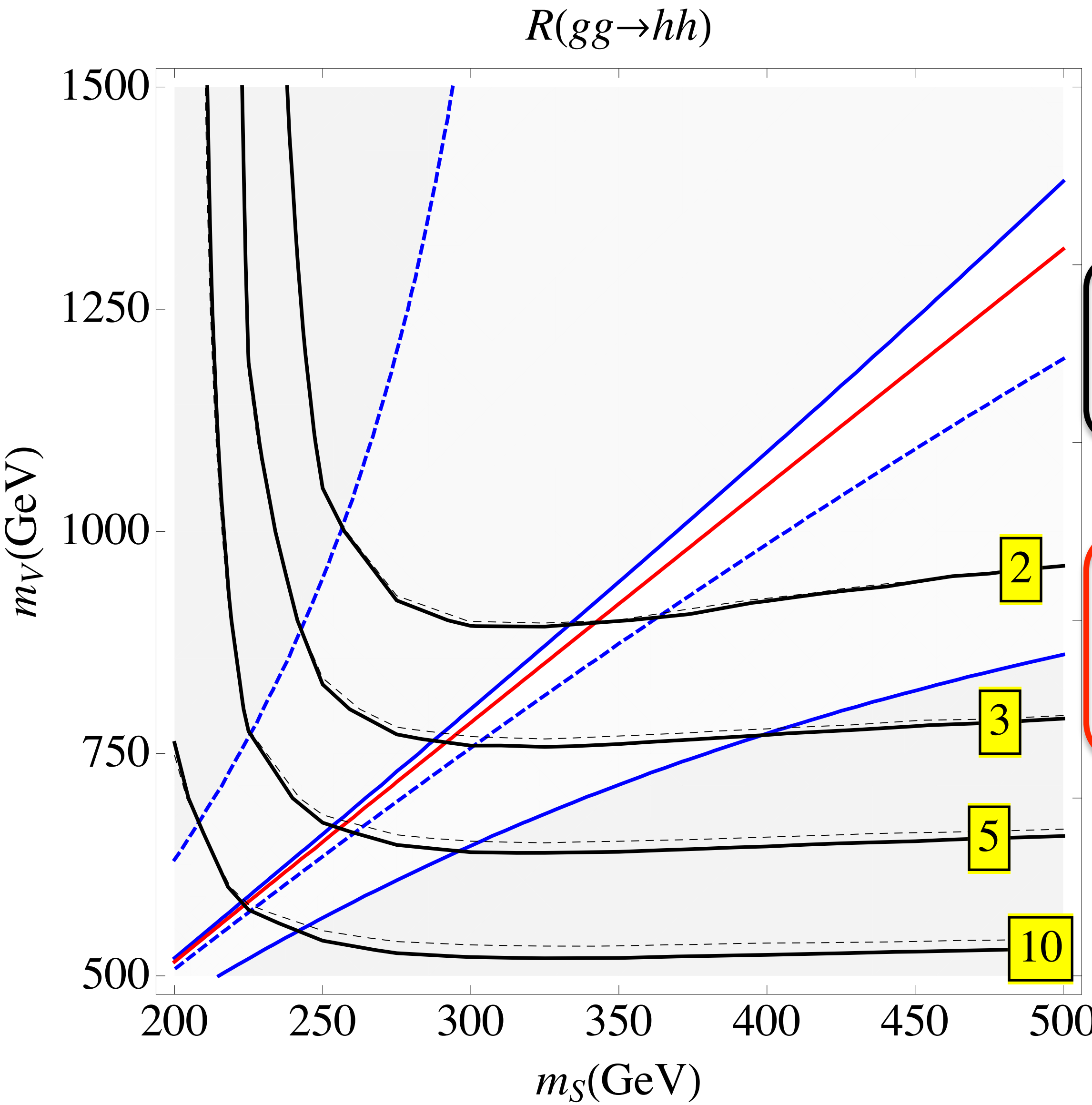
Portal Couplings:
λ_s=1.5
λ_V=1.5

Scan over vector & scalar octet masses: Real S & V



Portal Couplings:
λ_s=0.5
λ_V=1.

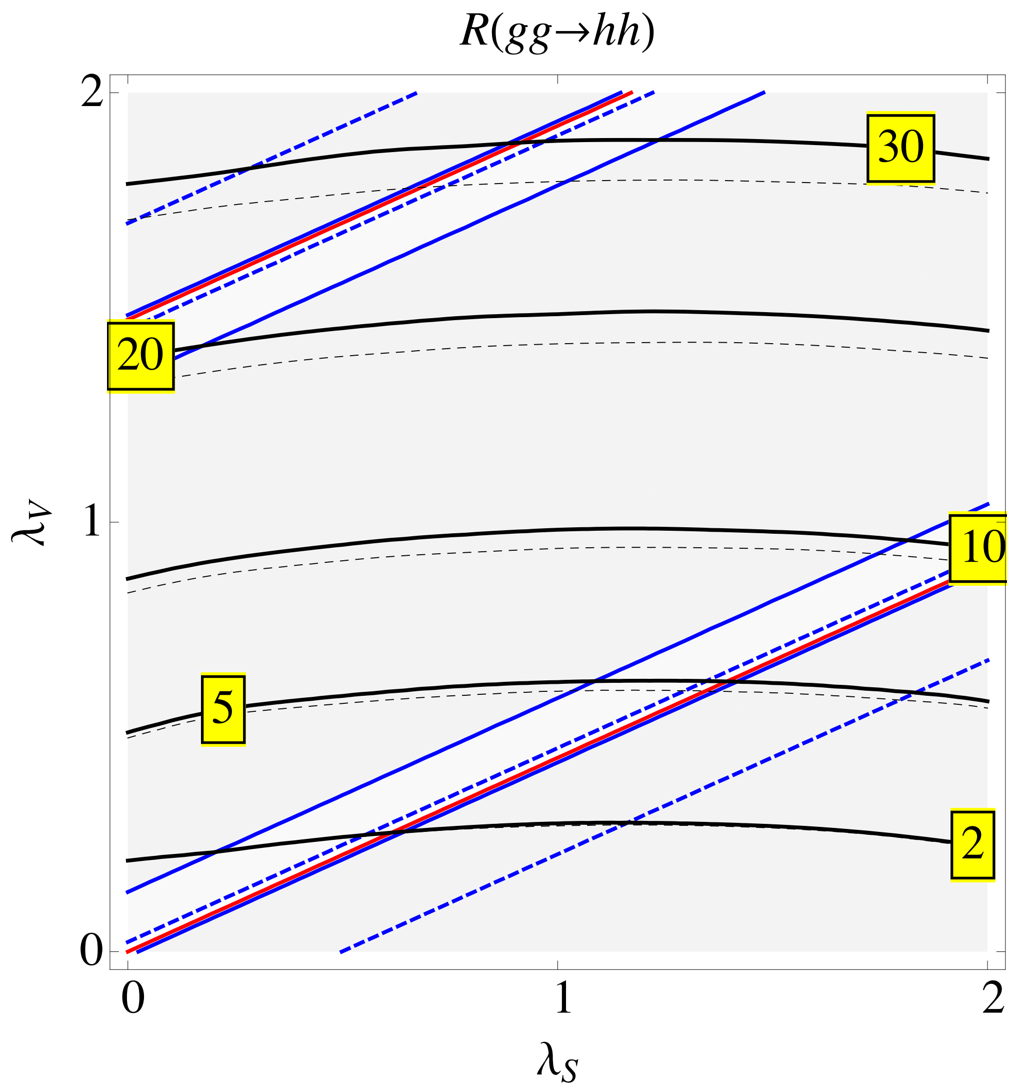
Scan over vector & scalar octet masses: Real S & V



Portal Couplings:
λ_s=1.5
λ_V=0.5

The SM NLO expect.:
σ_s=30-40fb at 14 TeV

Scan over portal couplings: Real V & S



Masses:
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