Double Higgs Production in the Singlet Extended SM

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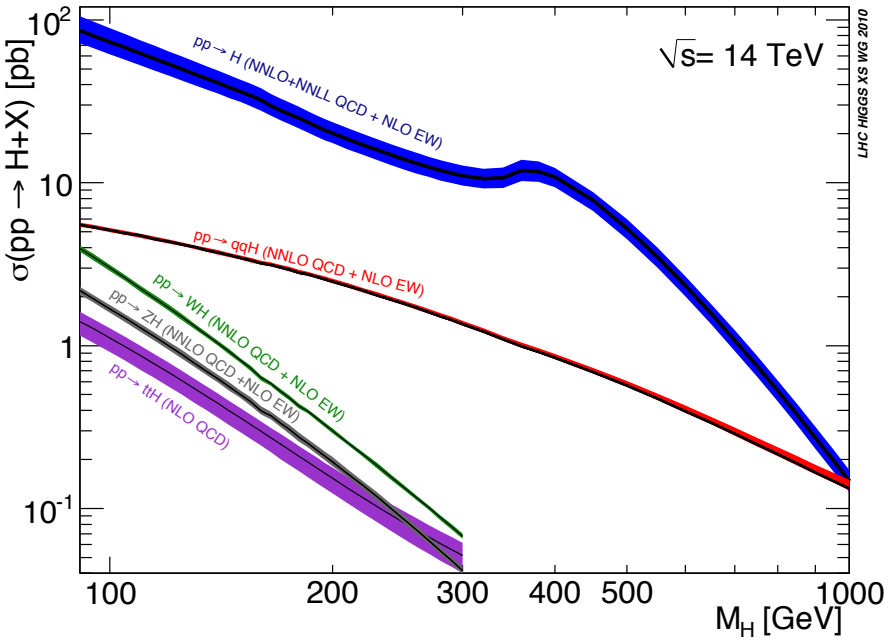
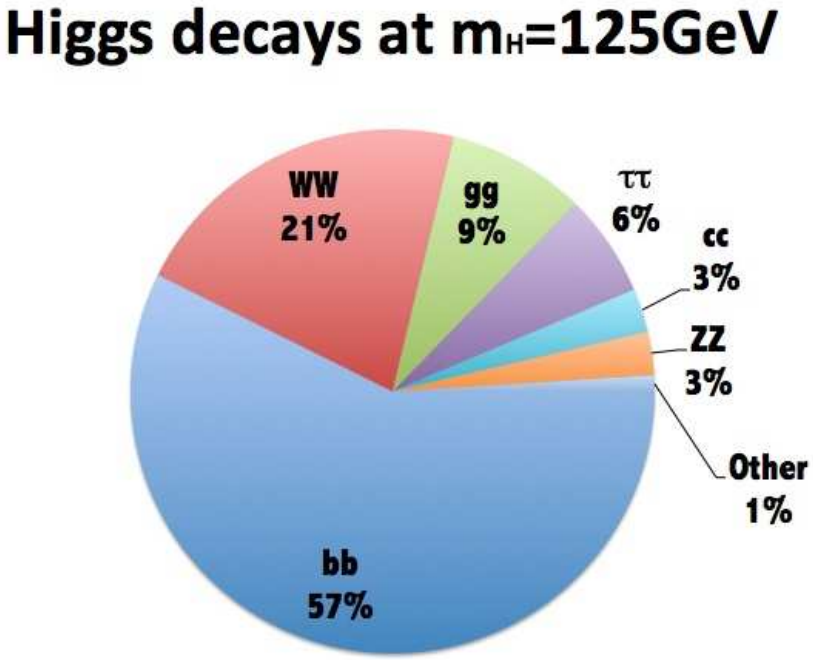
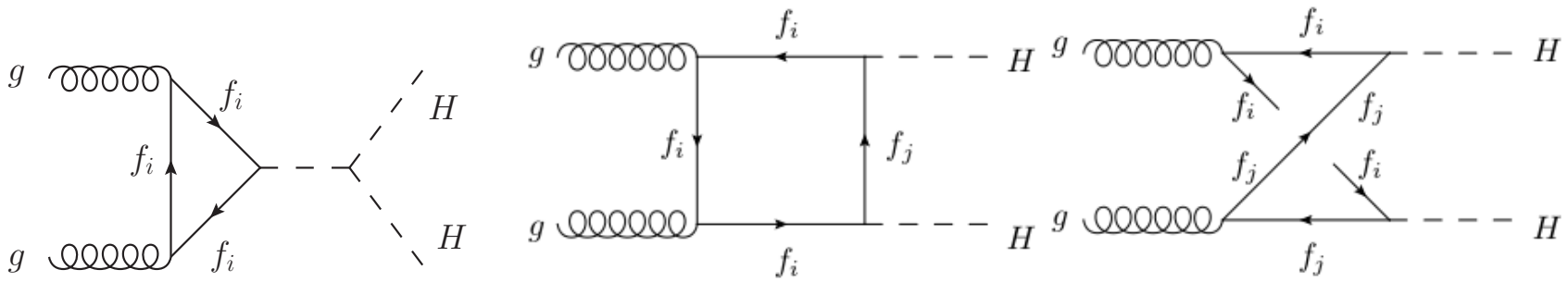
Higgs is Central

- Source of electroweak symmetry breaking in the Standard Model.
- Source of fundamental masses in the Standard Model.
  - Completely predictive.
  - Precision measurements of Higgs boson gives us insights into the nature of electroweak symmetry breaking.





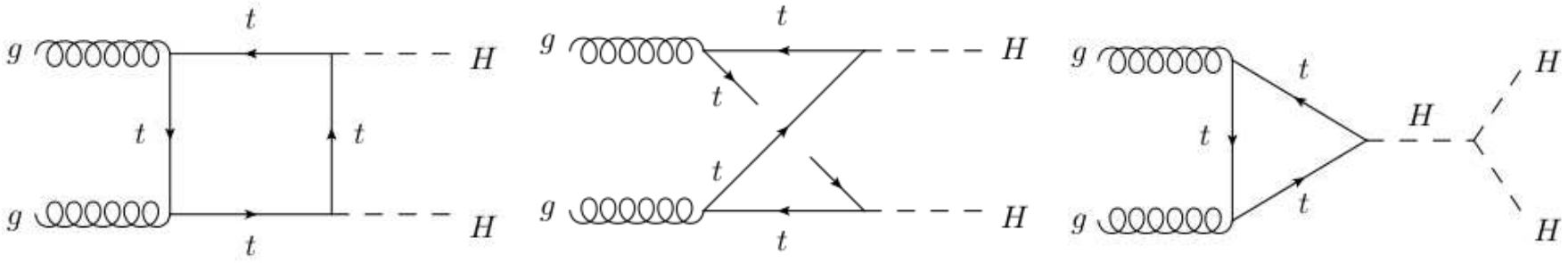
Double Higgs Production



V= -mu^2 |Phi |^2 +lambda |Phi |^4

- In addition, sensitive to Higgs trilinear couplings.
  - In SM, once Higgs mass known can completely solve for terms in potential.
  - Need additional measurement to check the predictions.
  - Directly measure shape of Higgs potential to determine origin of electroweak symmetry breaking.

Standard Model DiHiggs production



- Cross section of ~ 36.8 fb at 13 TeV at NNLO+NNLL de Florian, Mazzitelli PRL111 (2013) 201801, JHEP 1509 (2015) 053
- Small rate due to strong destructive interference between triangle and box diagrams.
- Most likely most sensitive final state is $gg \to hh \to b\bar{b}\gamma\gamma$
  Baur, Plehn, Rainwater, PRD69 (2004) 053004 Snowmass Higgs Working Group; Yao, 1308.6302:

	14 TeV	33 TeV	100 TeV
$S/\sqrt{B}$	2.3	6.2	15.0
Trilinear uncertainty	50%	20%	8%

- ATLAS study showed sensitivity to 1.3σ and $-1.3 \lesssim \lambda/\lambda_{SM} \lesssim 8.7$ in $bb\gamma\gamma$ ATL-PHYS-PUB-2014-019
- CMS showed 1.9σ evidence for $bb\gamma\gamma$, $bb\tau\tau$, $bbWW$ CMS PAS FTR-15-002

Singlet Scalar Extension

Z_2 symmetric limit

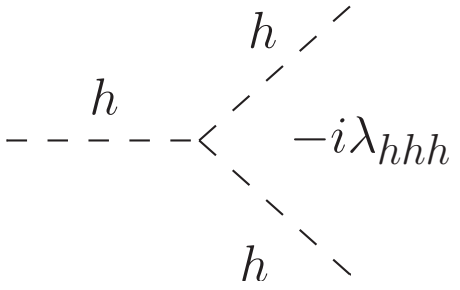
- Introduce a real scalar S singlet under SM gauge group.
- Introduce Z_2 parity: $S \to -S$ and $SM \to SM$
- Start with potential:

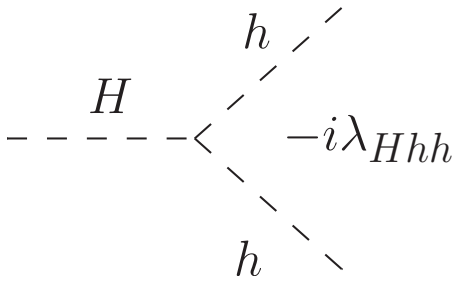
$$V(\Phi, S) = -\mu^2 \Phi^\dagger \Phi - m^2 S^2 + \lambda \left(\Phi^\dagger \Phi\right)^2 + \frac{a_2}{2} \Phi^\dagger \Phi S^2 + \frac{b_4}{4} S^4$$

  - Φ: SM Higgs doublet.
- Two mass eigenstates:
  - h with mass $m_h = 125$ GeV.
  - H with mass $M_H > m_h$.
- 5 degrees of freedom:
  - Masses of physical scalars: $m_h = 125$ GeV, M_H
  - Mixing angle between scalars: θ
    - $h = \cos\theta\, h_{SM} - \sin\theta\, s$
    - $H = \sin\theta\, h_{SM} + \cos\theta\, s$
  - Vevs of the two scalars: $v = 246$ GeV, $\tan\beta = v/x$, where $\langle S \rangle = x/\sqrt{2}$

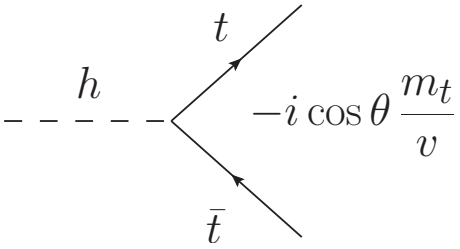
Relevant Feynman Rules in Z_2 Limit

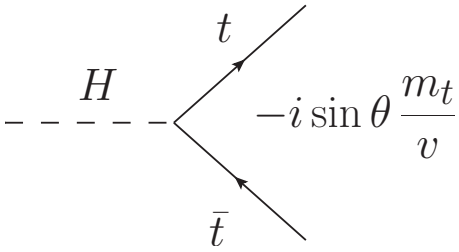
- Trilinear couplings:



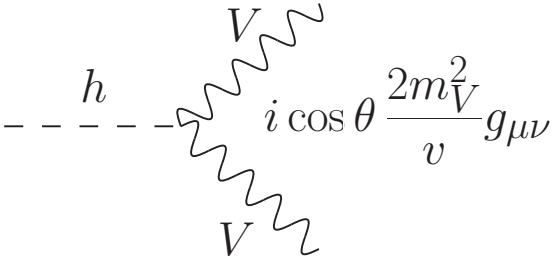


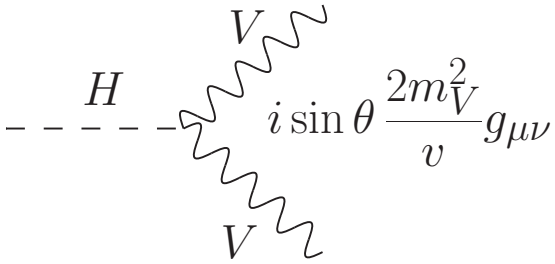
- Couplings to fermions:





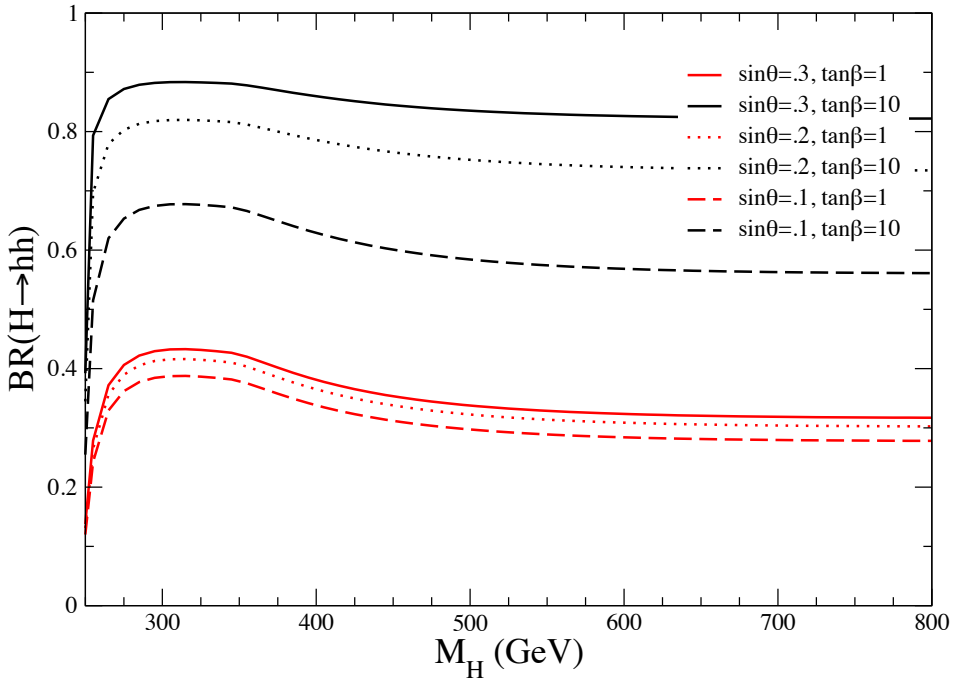
- Couplings to gauge bosons:





  - Since couplings to gauge bosons and fermions proportional to SM couplings, heavy scalar produced through same mechanisms as SM-like scalar.

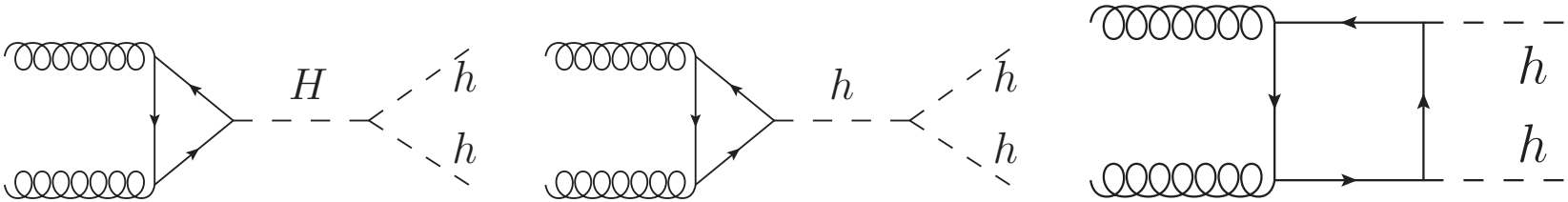
Branching Ratio Into Double Higgs



Dawson, IL PRD92 (2015) 094023

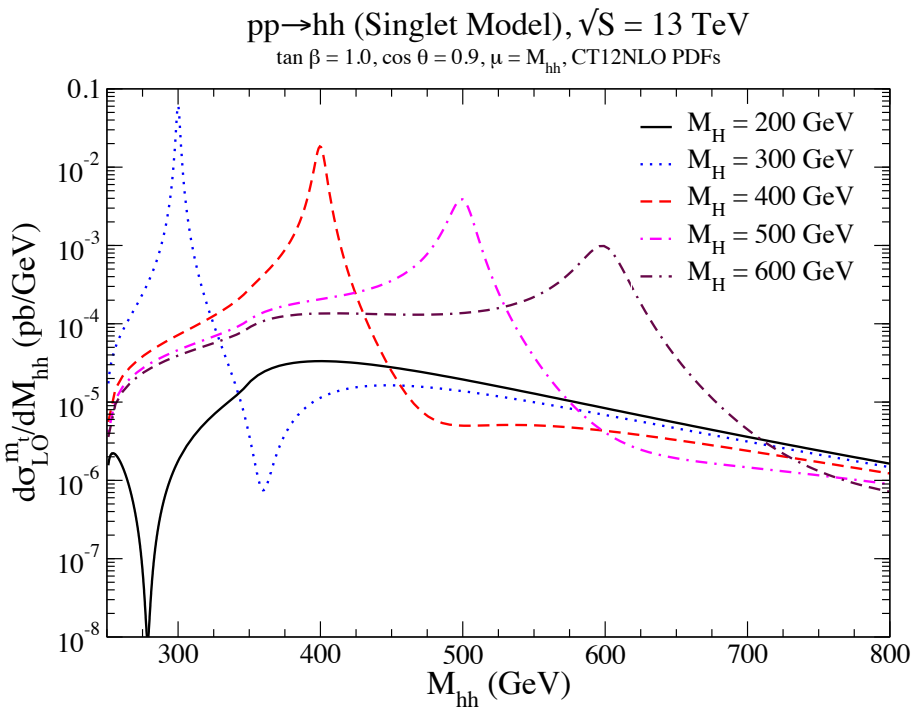
- Black: $\tan\beta = \sqrt{2}v/\langle S\rangle = 10$
- Red: $\tan\beta = \sqrt{2}v/\langle S\rangle = 1$
- Triple coupling: $\lambda_{Hhh} = \dfrac{m_h^2}{v}\sin 2\theta(\cos\theta + \sin\theta\tan\beta)\left(1 + \dfrac{M_H^2}{2m_h^2}\right)$

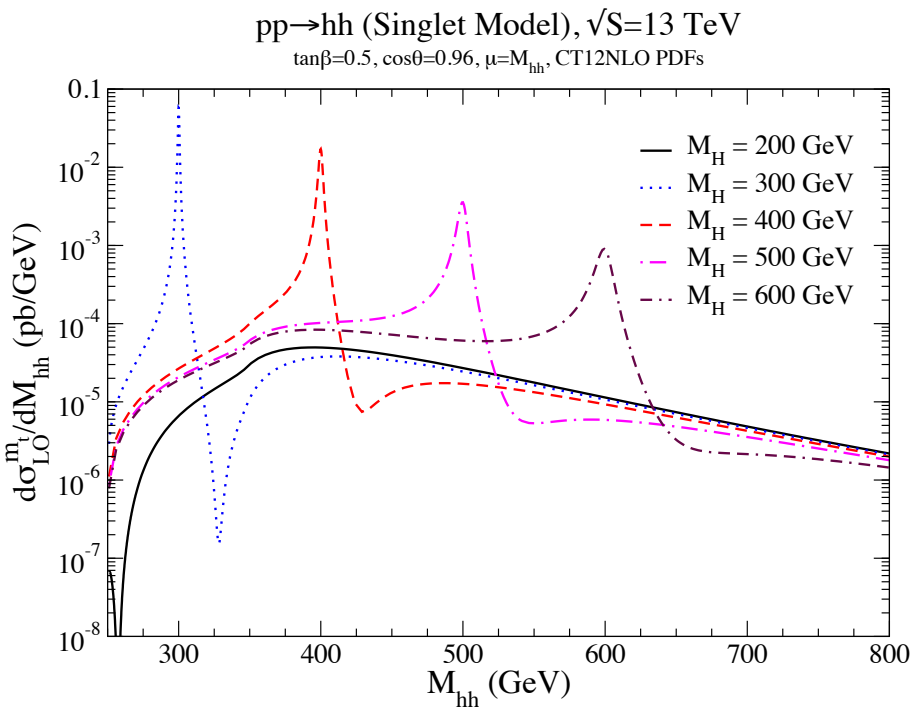
Double Higgs Production



- 3-contributions:
  - Heavy resonance production (H-resonance).
  - Light off-shell resonance (h-resonance).
  - Box diagram.
- Refer to box diagram and h-resonance as "SM-like" contributions.

Invariant Mass Distributions





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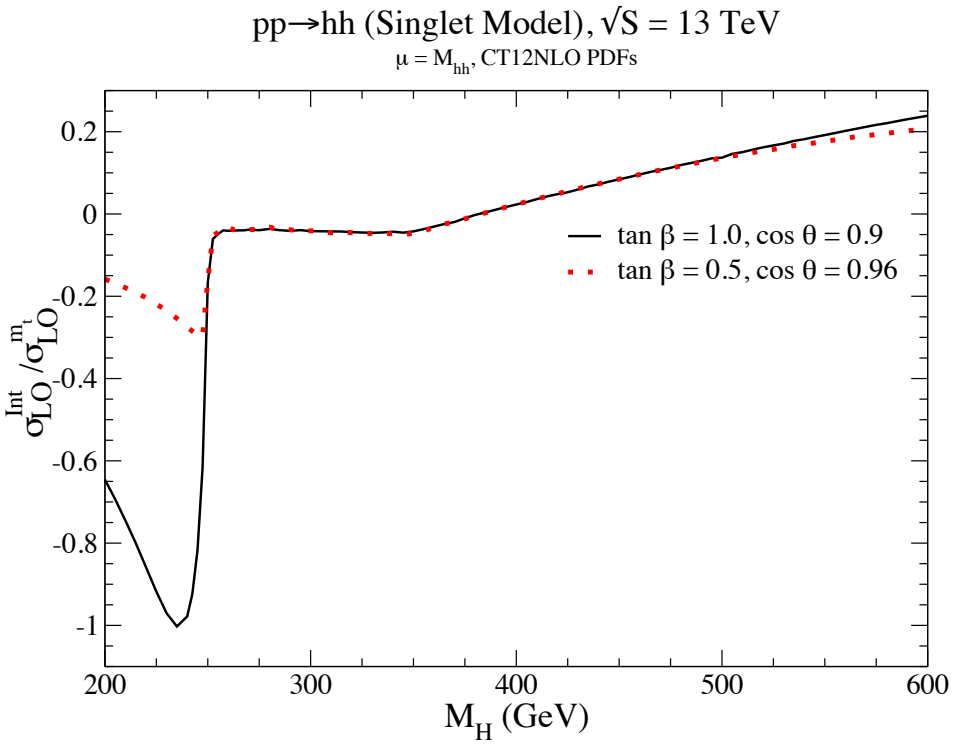
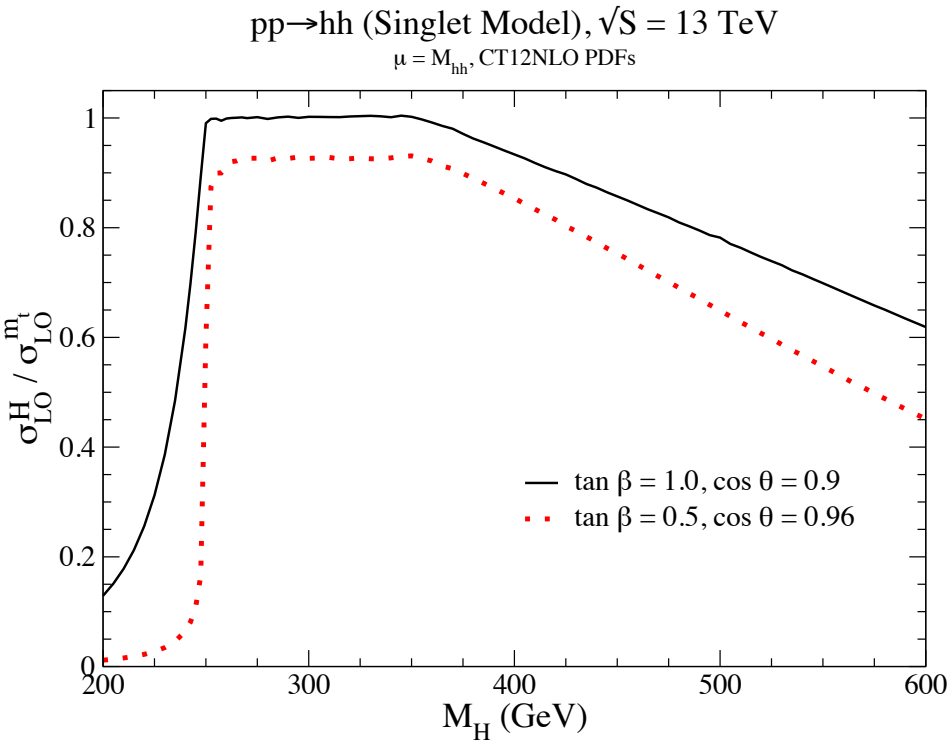
- In limit $M_H \gg m_h$: $\lambda_{Hhh} \to \dfrac{M_H^2}{2v} \sin 2\theta(\cos\theta + \sin\theta \tan\beta)$
- Hence, in limit $s, m_h^2 \ll M_H^2$, have H-propagator and coupling:

$$\frac{\lambda_{Hhh} v}{s - M_H^2 + i\Gamma_H M_H} \to -\frac{\sin 2\theta(\cos\theta + \sin\theta \tan\beta)}{2}$$

- Production through s-channel h and box diagrams have no explicit dependence on M_H.

Total Contribution From Interference





- Fractional contribution from interference of H-resonance with other diagrams to total cross section.
- Fractional contribution of H-resonance to total cross sections.

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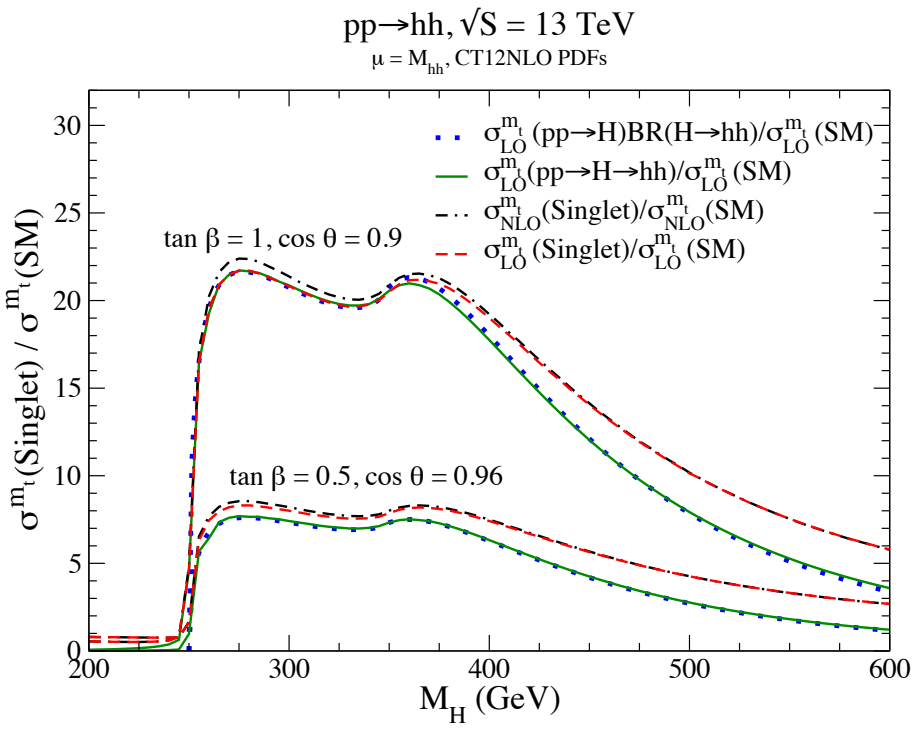
Interference can make substantial contribution to total cross section and should be taken into account in experimental searches.

Resonant Enhancement at $\sqrt{S} = 13$ TeV



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- Can achieve significant enhancement over SM rate.
- Enhancement to rate NLO very similar to enhancement at LO.
- Narrow width approximation describes resonance very well, but not overall rate at high invariant masses.

Non Z_2 Symmetric Case

Non Z_2 Symmetric Case

- More terms in potential:

$$V(\Phi,S) = V_\Phi(\Phi) + V_{\Phi S}(\Phi,S) + V_S(S)$$

- Higgs potential:

$$V_\Phi(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

- Scalar singlet potential:

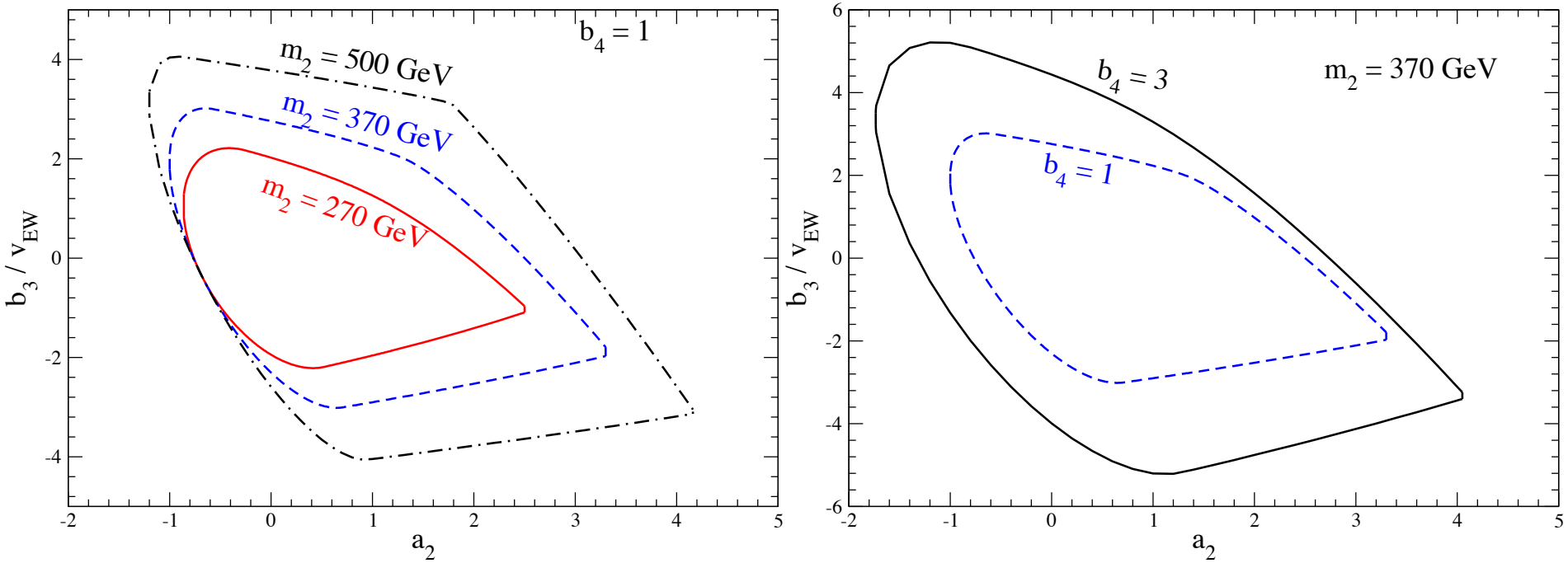
$$V_S(S) = b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

- Mixing terms:

$$V_{\Phi S}(\Phi,S) = \frac{a_1}{2}\Phi^\dagger\Phi S + \frac{a_2}{2}\Phi^\dagger\Phi S^2$$

- Additional terms complicate vacuum structure.
  - Unlike Z_2 case, not all parameters solved in terms of masses,mixing, and vevs.
  - Want to insure that $(\langle\Phi\rangle,\langle S\rangle) = (v/\sqrt{2},0)$ is the global minimum.
  - b_3 and b_4 are completely free.
  - Find a relationship between b_2 and a_2.

Constraints from Global Minimum



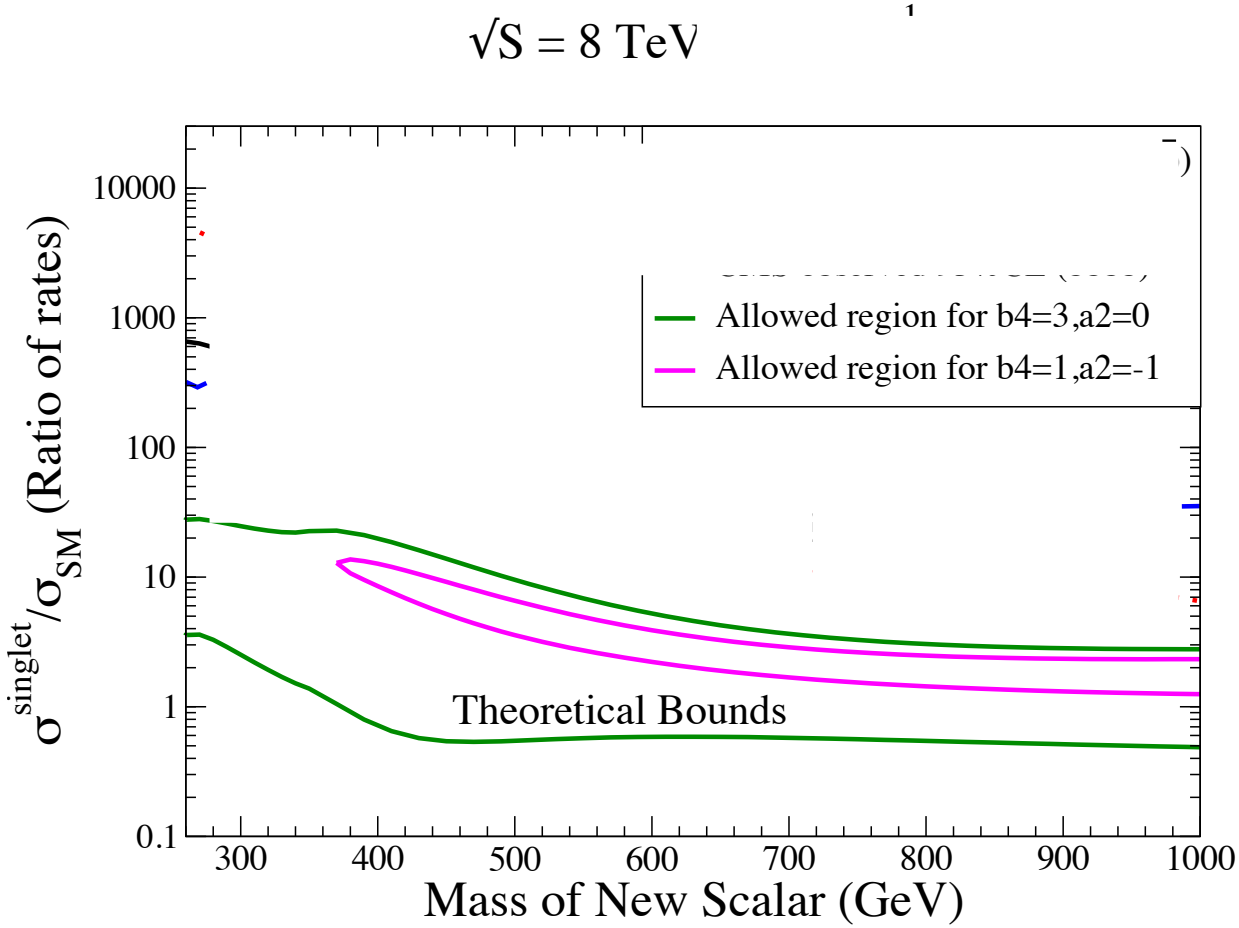
Chen, Dawson, IL PRD91 (2015) 035015

- Area inside curves have correct global minimum.
- Effects phenomenology:
  - Coupling between new heavy scalar and two light (observed) scalars:

$$\lambda_{Hhh} = \sin\theta \left[-\frac{2m_1^2 + m_2^2}{v_{EW}} \cos^2\theta - a_2 v_{EW} (1 - 3\cos^2\theta) + b_3 \sin(2\theta) \right]$$

  - Limits how large $\mathrm{BR}(H \to hh)$ can be.

Current Constraints



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BLACK: ATLAS $\gamma\gamma b\bar{b}$

RED: CMS $b\bar{b}b\bar{b}$

BLUE: CMS $\gamma\gamma b\bar{b}$

GREEN and MAGENTA: theory bounds.

Conclusions

- Discovered a Higgs boson with remarkably SM like properties.

Standard Model double Higgs very hard to measure.
Important for trilinear coupling measurement

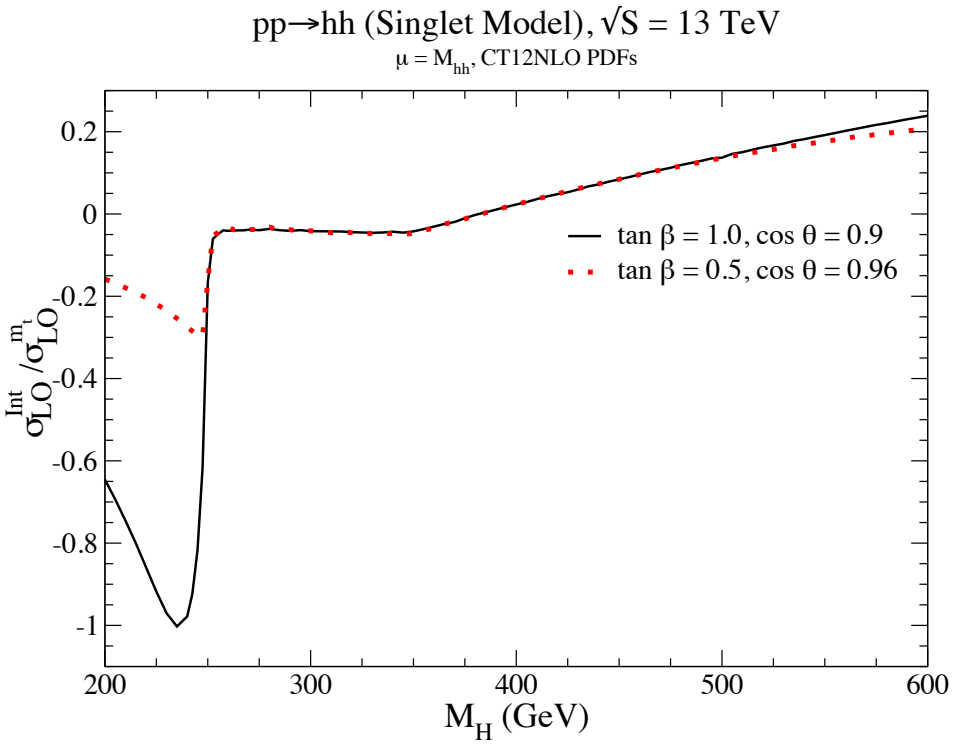
In Singlet models, can get up to a factor of 20 increase over Standard Model double Higgs Production.

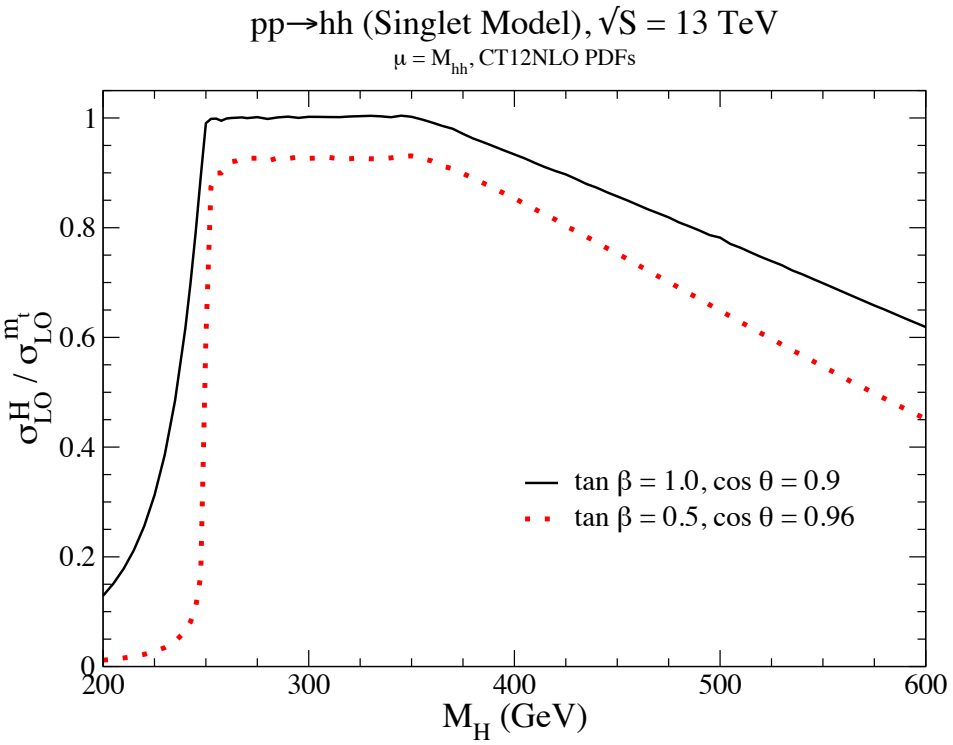
Interference effects between singlet resonance and SM-like contributions can be significant.

NLO QCD corrections increase rate by about a factor of two.

The ratio of the double Higgs rate in the Singlet model to the SM rate is insensitive to NLO corrections.

Total Contribution From Interference





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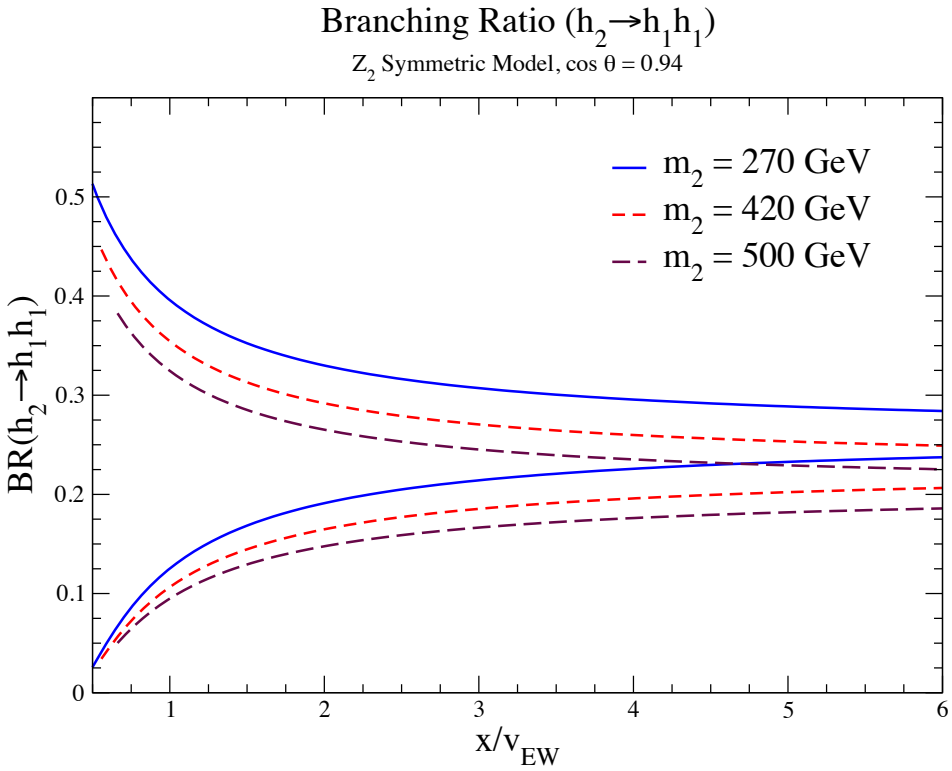
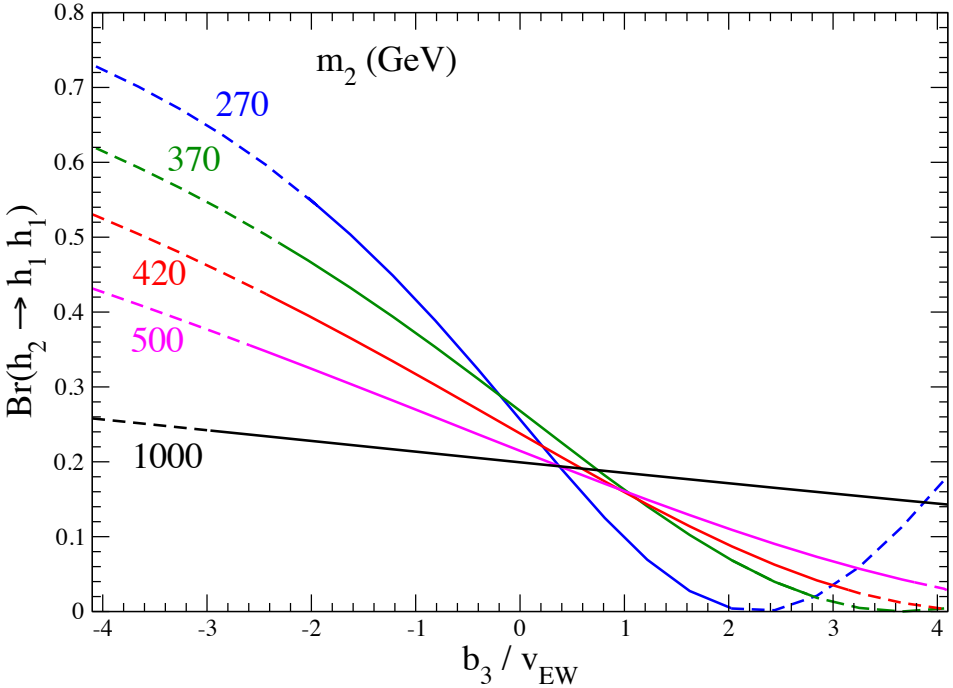
Comparison of Two Cases



Z_2 Symmetric Limit

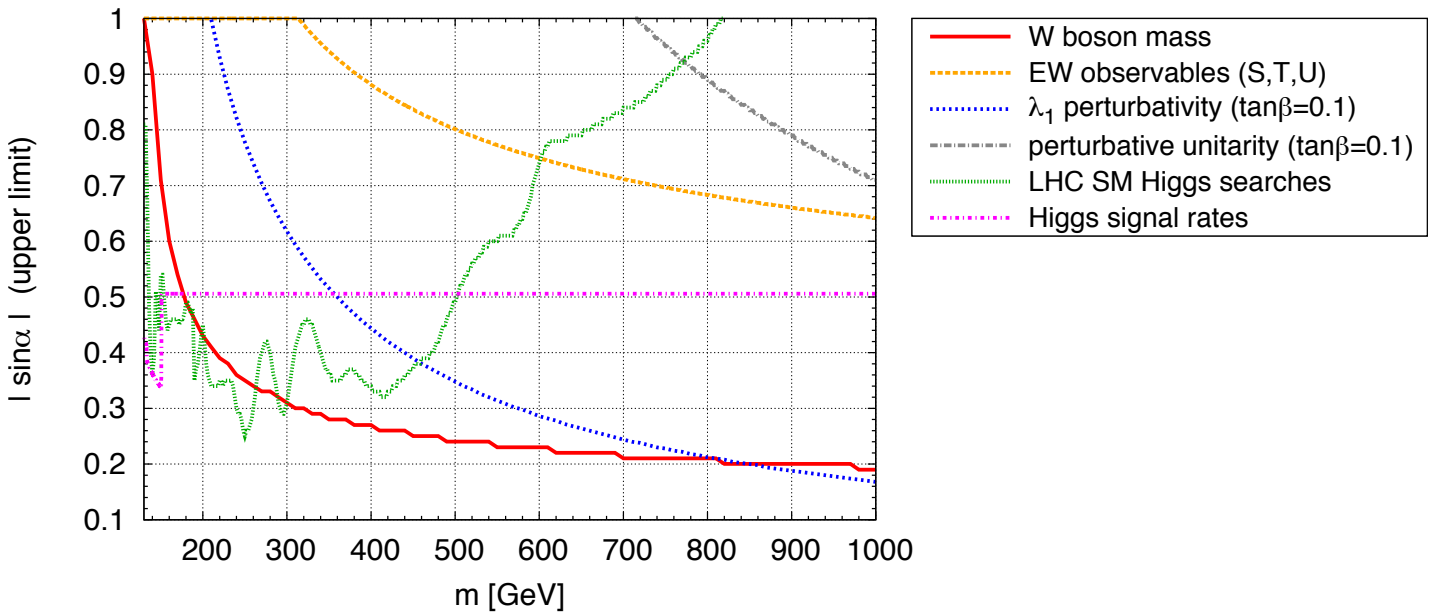


Z_2 Nonsymmetric
$a_2 = 0,\ b_4 = 1$

Chen, Dawson, IL PRD91 (2015) 035015

- Similar branching ratios, so similar conclusions.

Current Limits on Scalar Singlet



Stefaniak, Robens EPJ C75 (2015) 104

- Limits from direct searches, W-mass, and Higgs measurements apply to non-Z_2.
- Limits on $\tan\beta = \sqrt{2}v/\langle S\rangle$ come from perturbativity ($\sin\theta = 0.1$) Stefaniak, Robens EPJ C75 (2015) 104:
  - for $M_H = 200$ GeV $\tan\beta \lesssim 1.5$
  - for $M_H = 500$ GeV $\tan\beta \lesssim 0.5$.
- See also Falkowski, Gross, Lebedev JHEP 1505 (2015) 057, Buttazzo, Sala, Tesi 1505.05488