Resonant Double Higgs Production in the Singlet Extended Standard Model

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Singlet Scalar

- Add a Scalar that is a singlet under the SM group.
- Singlet scalar is theoretically motivated.
  - Dark Matter: Need to impose unbroken Z_2 symmetry on scalar, not case studied here.
  - Scalar singlet can help cause strong first order phase transition needed for electroweak baryogenesis Profumo *et al* PRD91 (2015) 035018; Curtin, Meade, Yu JHEP 11 (2014) 127; Espinosa, Konstandin, Riva NPB854 (2012) 592; No, Ramsey-Musolf PRD89 (2014) 095031; Profumo, Ramsey-Musolf, Shaughnessy JHEP08 (2007) 010; Kozaczuk JHEP10 (2015) 135
- Before EWSB, only renormalizable couplings are with Higgs doublet.
- After EWSB, generically can mix with SM Higgs boson.
  - Allows for production and decay through SM particles.

Z_2 Symmetric Case

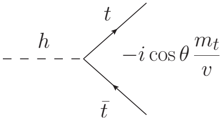
- Introduce a real scalar S singlet under SM gauge group.
- Introduce Z_2 parity: $S \to -S$ and $SM \to SM$
- Start with potential:

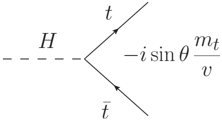
$$V(\Phi, S) = -\mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2 + \frac{a_2}{2} \Phi^\dagger \Phi S^2 - m^2 S^2 + \frac{b_4}{4} S^4$$

  - Φ: SM Higgs doublet.
- Two mass eigenstates:
  - h with mass $m_h = 125$ GeV.
  - H with mass $M_H > m_h$.
- Other degrees of freedom:
  - 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:
    - $\langle \Phi \rangle = v/\sqrt{2} = 174$ GeV
    - $\langle S \rangle = x/\sqrt{2}$
    - $\tan\beta = v/x$

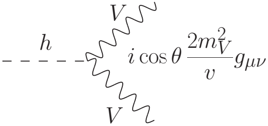
Relevant Feynman Rules

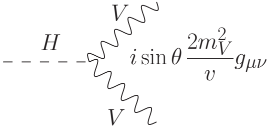
- Couplings to fermions:





- Couplings to gauge bosons:

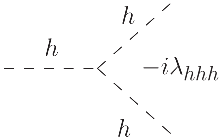


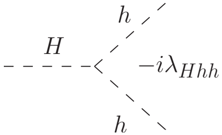


  - Since couplings to gauge bosons and fermions proportional to SM couplings, heavy scalar produced through same mechanisms as SM-like scalar.

Relevant Feynman Rules

- Trilinear couplings:

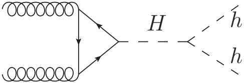


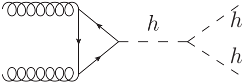


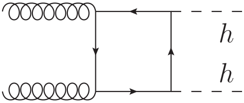
$$\lambda_{hhh} = \frac{3m_h^2}{v}\left(\cos^3\theta - \tan\beta\,\sin^3\theta\right)$$

$$\lambda_{Hhh} = \frac{m_h^2}{v}\sin 2\theta\,(\cos\theta + \sin\theta\,\tan\beta)\left(1 + \frac{M_H^2}{2m_h^2}\right)$$

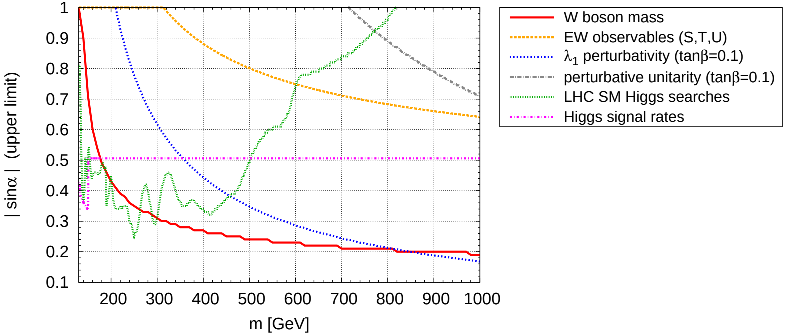
- Double Higgs Production:







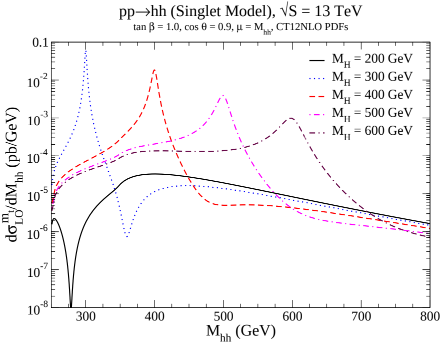
Current Limits on Scalar Singlet



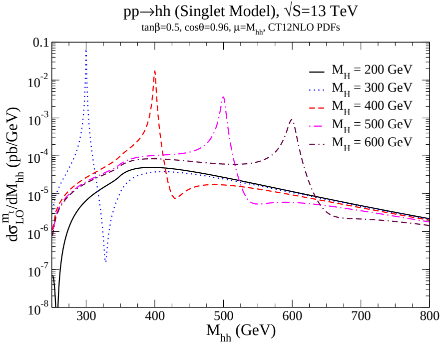
Stefaniak, Robens EPJ C75 (2015) 104

- Limits on $\tan\beta$ 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

Invariant Mass Distributions



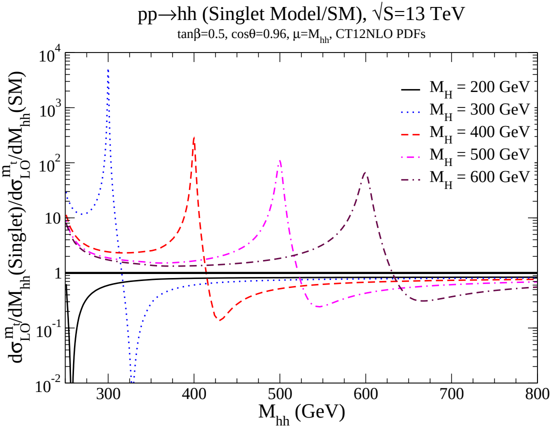
$\tan\beta = 1$
$\cos\theta = 0.9$



$\tan\beta = 0.5$
$\cos\theta = 0.96$

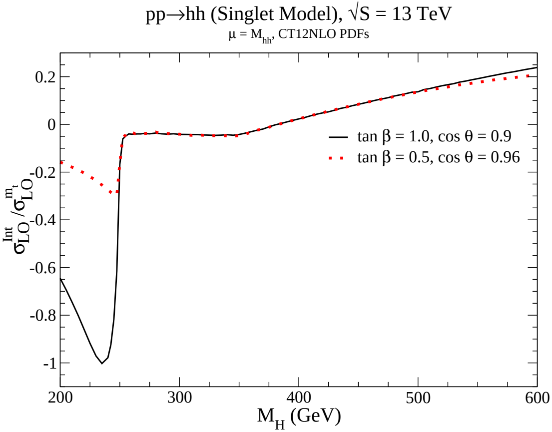
- Destructive interference occurs after the peak.
- Invariant mass distributions appear independent of M_H for $M_{hh} \ll M_H$.

Normalized Invariant Mass Distributions



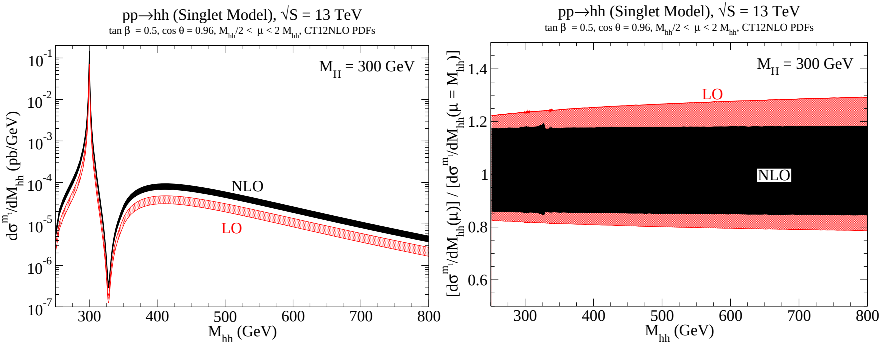
- Ratio of singlet model invariant mass to SM invariant mass distribution.

Total Contribution From Interference



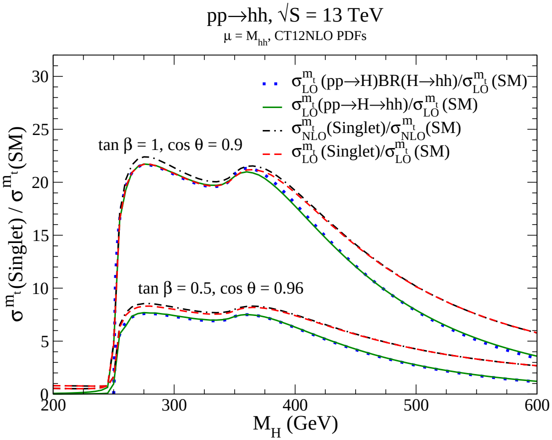
- Fractional contribution from interference of *H*-resonance with other diagrams to total cross section.

Singlet Model at NLO



- K-factor ~ 2 as in SM.
- Scale variation reduced at NLO, and largely independent of distribution.

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



- Can achieve significant enhancement over SM rate.
- Enhancement to rate NLO very similar to enhancement at LO.

Conclusions

- Resonant enhancement possible in singlet Scalar extensions of SM.
  - Can get enhancements of $O(10)$ above SM double Higgs rate.
  - Interference effects that can play a significant role in double Higgs rate for singlet scalars with masses above ~ 400 GeV and below $2m_h$.
  - NLO corrections increase rate by a factor of ~ 2, and decrease scale uncertainty from $\sim 20-30\%$ at LO to $\sim 15\%$ at NLO.