Complex Singlet Benchmarks

PRELIMINARY

Snowmass contribution ArXiv: 2203.07455
Preliminary work ArXiv: 2206.XXXXX

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Outline

- Introduction
- Model
- Collider Scenarios
- Results
- Conclusion

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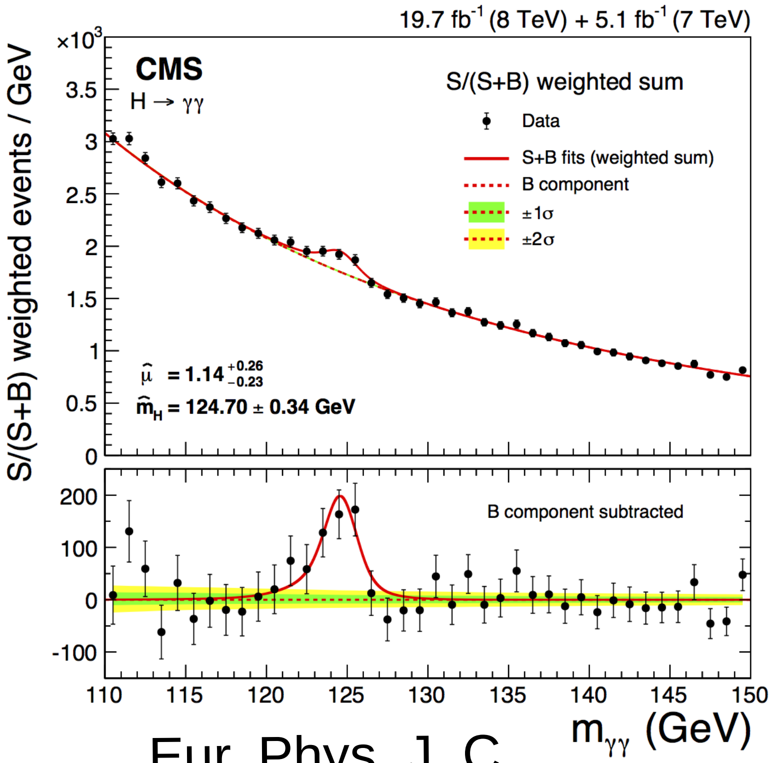
Introduction

- The Higgs solidified the widely successful SM
- But there are many unanswered questions: Dark Matter, baryon asymmetry, naturalness
- Future colliders could find first evidence of new physics



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The Singlet Extension

- One of the simplest extensions of the SM is to add one or more new scalar states uncharged under SM gauge symmetries.
- These new singlets can be used to help solve some unanswered questions (dark matter candiates, etc.)
- Add a new complex scalar uncharged under SM and with no new symmetries

$$S_c = (S_0 + i\,A)/\sqrt{2}$$

- S_0 and A are CP even scalars
- One can relate the complex singlet to two real singlets

Goal

- Maximize production of new scalars states (h_2, h_3)
- We can show
- h_2 $\sigma_i(pp \to h_2) = \sin^2\theta_1 \sigma_{i,\mathrm{SM}}(pp \to h_2)$
- Want to maximize $\sin(\theta_1)$ for maximum production of h_2
  - Additional Di-higgs production from $h_2 \longrightarrow h_1 h_1$
- h_3 comes from decays of h_2
  - Maximize $Br(h_2 \to h_1 h_3)$ and $Br(h_2 \to h_3 h_3)$

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The Scalar Potential

- Write the most general potential (19 real params)

$$V(\Phi, S_c) = \frac{\mu^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^4 + \frac{b_2}{2}|S_c|^2 + \frac{d_2}{4}|S_c|^4 + \frac{\delta_2}{2}\Phi^\dagger\Phi|S_c|^2$$
$$+ \left(a_1 S_c + \frac{b_1}{4} S_c^2 + \frac{e_1}{6} S_c^3 + \frac{e_2}{6} S_c|S_c|^2 + \frac{\delta_1}{4}\Phi^\dagger\Phi\, S_c + \frac{\delta_3}{4}\Phi^\dagger\Phi\, S_c^2\right.$$
$$\left. + \frac{d_1}{8} S_c^4 + \frac{d_3}{8} S_c^2|S_c|^2 + \text{h.c.}\right)$$

- Appropriate choice of parameters $\langle S_c \rangle = 0$

$$\langle \Phi \rangle = (0, v_{EW}/\sqrt{2})^{\mathrm{T}}$$

Mass Eigenstates

- Rotate to the mass eigenstates via

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} \Longleftarrow R(\theta_1,\theta_2,\theta_3) \Longrightarrow \begin{pmatrix} h \\ S_0 \\ A \end{pmatrix}$$

Mass Eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} \leftarrow R(\theta_1, \theta_2, \cancel{\theta_3}) \rightarrow \begin{pmatrix} h \\ S_0 \\ A \end{pmatrix}$$

- Can remove one mixing angle using phase of singlet

Mass Eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} \Leftarrow R(\theta_1,\theta_2) \Rightarrow \begin{pmatrix} h \\ S_0 \\ A \end{pmatrix}$$

Mass Eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} \leftarrow R(\theta_1, \theta_2 \ll 1) \rightarrow \begin{pmatrix} h \\ S_0 \\ A \end{pmatrix}$$

- Take expansion in terms of small θ_2

Mass Eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & \sin\theta_2 \\ \sin\theta_1 \sin\theta_2 & \cos\theta_1 \sin\theta_2 & -1 \end{pmatrix} \begin{pmatrix} h \\ S_0 \\ A \end{pmatrix} + \mathcal{O}(\sin^2\theta_2)$$

Mass Eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

SM Higgs, mass 125 GeV
Couples in usual way

Mass range ~ 0.3 to ~10 TeV
Couplings to vector bosons and fermions ~ $\sin(\theta_1)$

Masses 130, 200, 270 GeV
Couplings to vector bosons and fermions ~ $\sin(\theta_1)\sin(\theta_2)$

Scalar Trilinear Couplings

$$h_1 h_1 h_2 \;:\; \sin\theta_1 \frac{m_2^2 + 2\, m_1^2 - [\mathrm{Re}(\delta_3) + \delta_2]\, v^2}{v} + \mathcal{O}(\sin^2\theta_1),$$

$$h_1 h_2 h_3 \;:\; \frac{\mathrm{Im}(\delta_3)}{2} v + \mathcal{O}(\sin\theta_1),$$

$$h_2 h_3 h_3 \;:\; -\frac{1}{\sqrt{2}}\left(\mathrm{Re}(e_1) - \frac{1}{3}\mathrm{Re}(e_2)\right) + \mathcal{O}(\sin\theta_1).$$

Theory Constraints

- Bounded Below and Electroweak global minimum
  - Enforced numerically on the scalar potential
  - Reject parameter points which don’t satisfy these constraints
- Perturbative Unitarity at tree level
  - Calculate J = 0 partial wave matrix for two-to-two scalar scattering through the quartic couplings

$$\mathcal{M} = 16\pi \sum_{j=0}^{\infty} (2j+1) a_j P_j(\cos\theta),$$

$$\Rightarrow$$

$$|\delta_2|, |\Re(\delta_3)|, |\Im(\delta_3)| \leq 16\sqrt{\frac{2}{3}}\pi$$

$$|\lambda| \leq \frac{16\pi}{3}, \quad |d_2| \leq 8\pi,$$

Theory Constraints

- Narrow widths (10% of Mass)
  - Can be used to place upper bound on particular channels
  - $\Gamma_{tot} = \Gamma_{SM\text{-}like} + \Gamma_{new} < 0.1*m_2$
  - $BR_{new} < 1 - \Gamma_{SM\text{-}like} / (0.1*m_2)$

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Collider Scenarios

- Current Limits (arXiv 2203.07455)

- HL LHC
- HL LHC + FCCee
- HL LHC + ILC500

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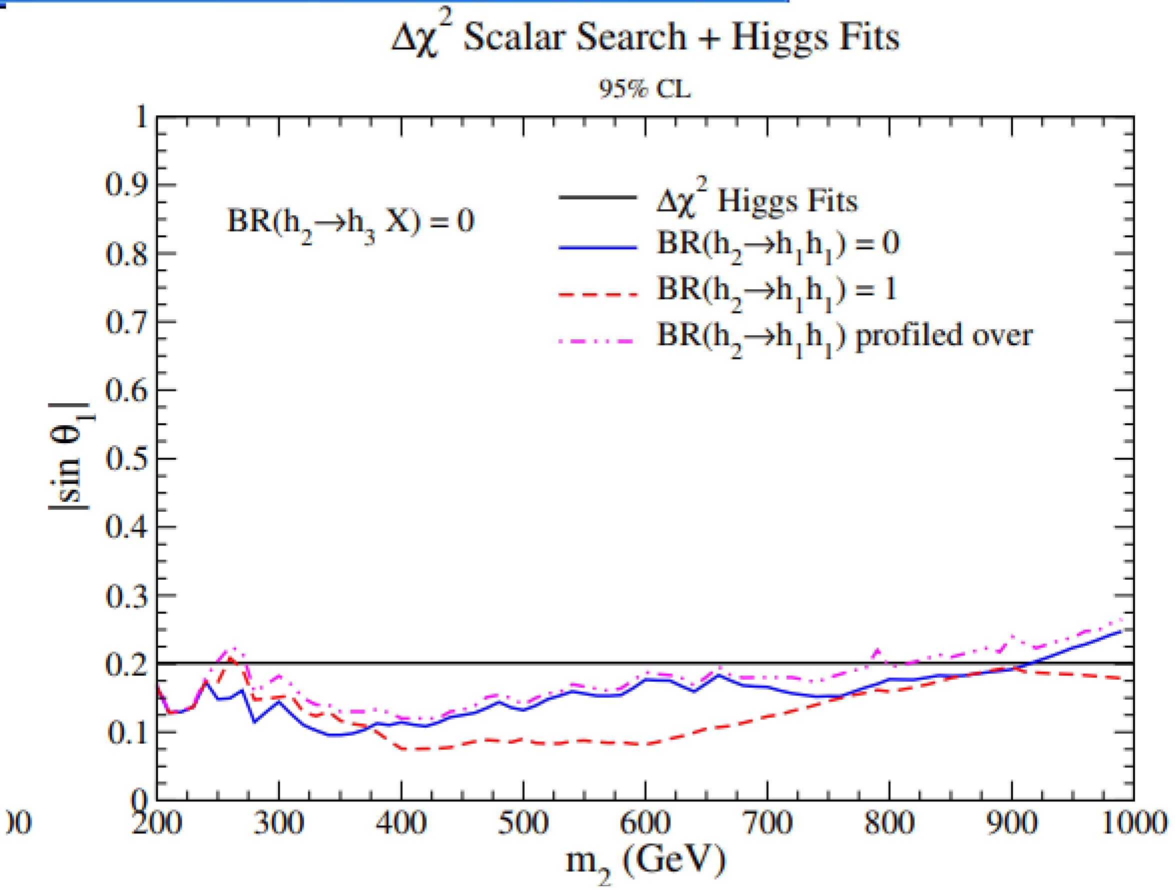
Current Constraints

- Can combine direct searches and higgs signal strengths to place limit on $\sin\theta_1$ see Phys. Rev. D 103, 075027 for details and assumptions



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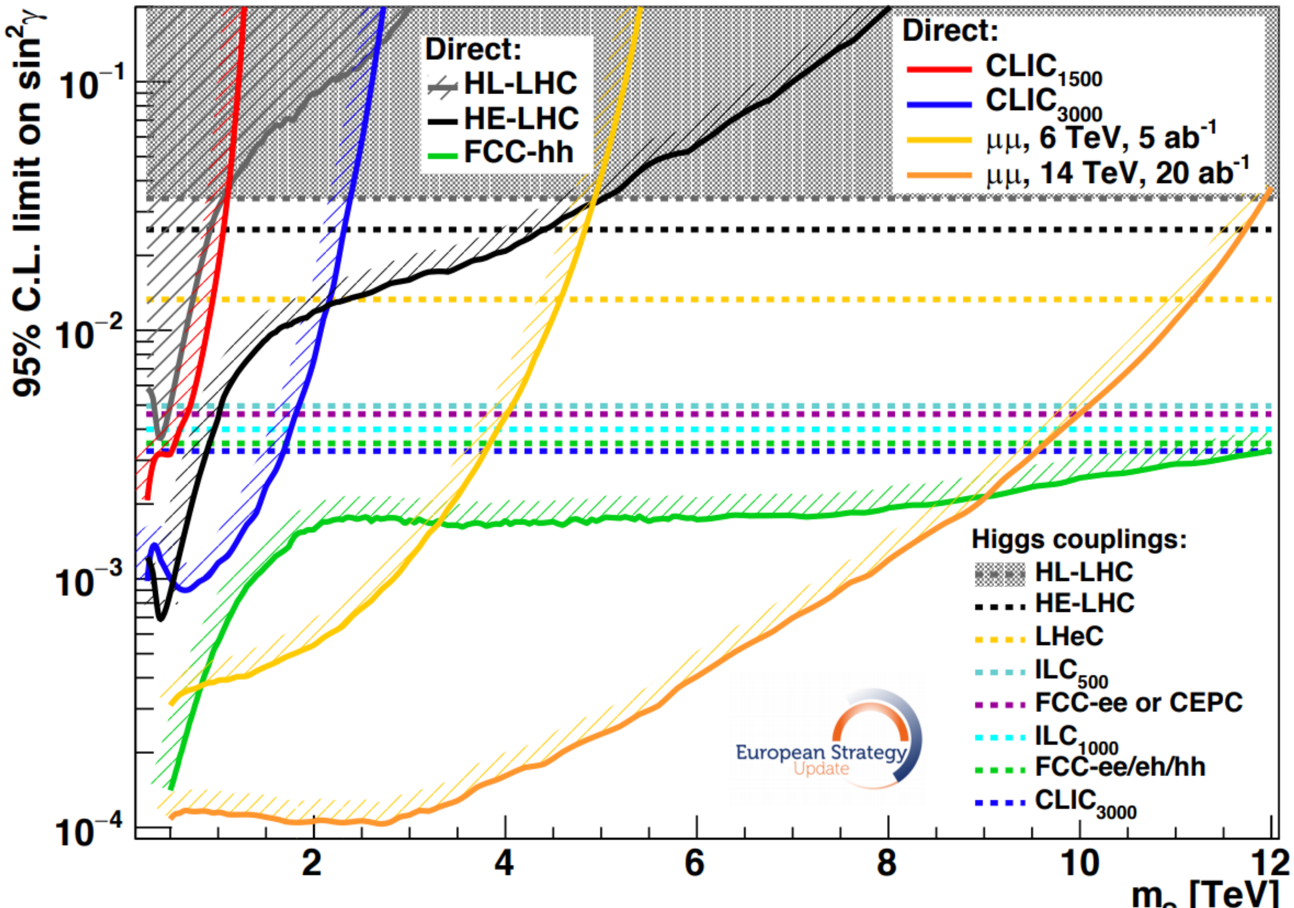
Projected Limits from ESR



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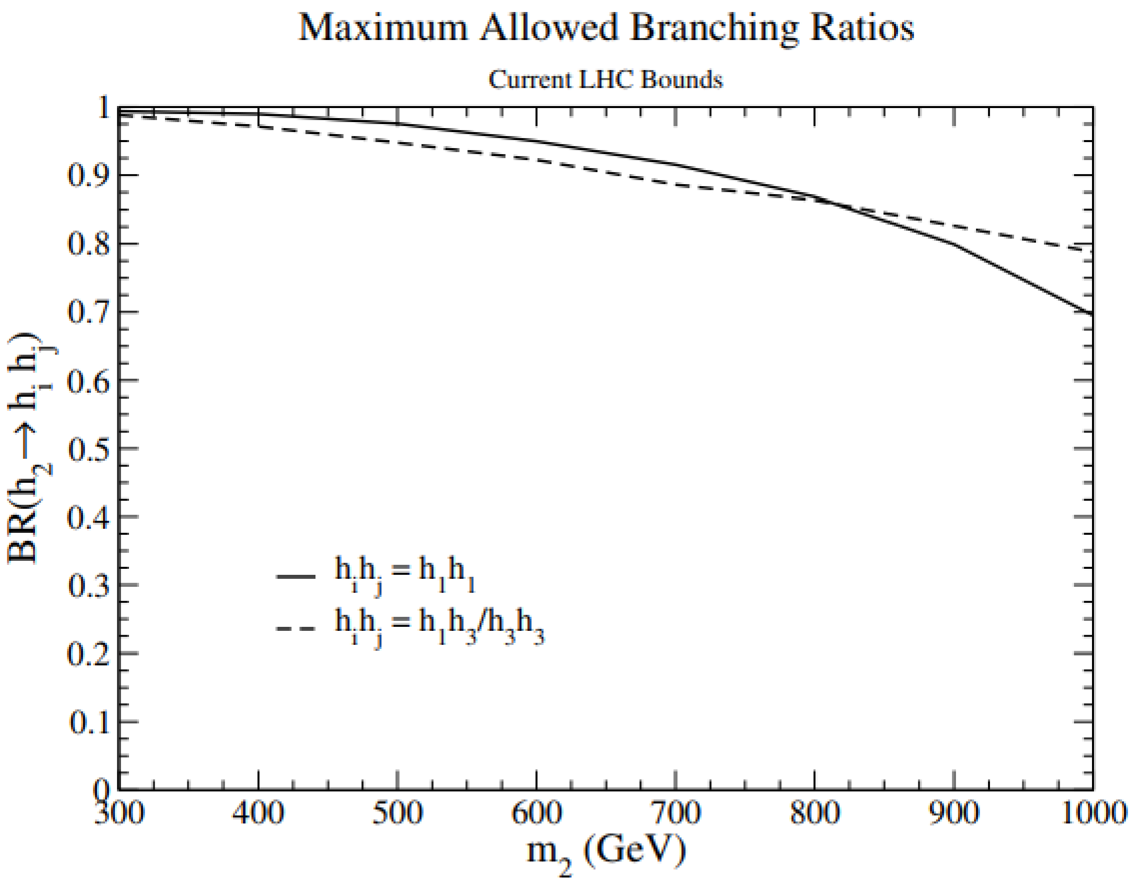
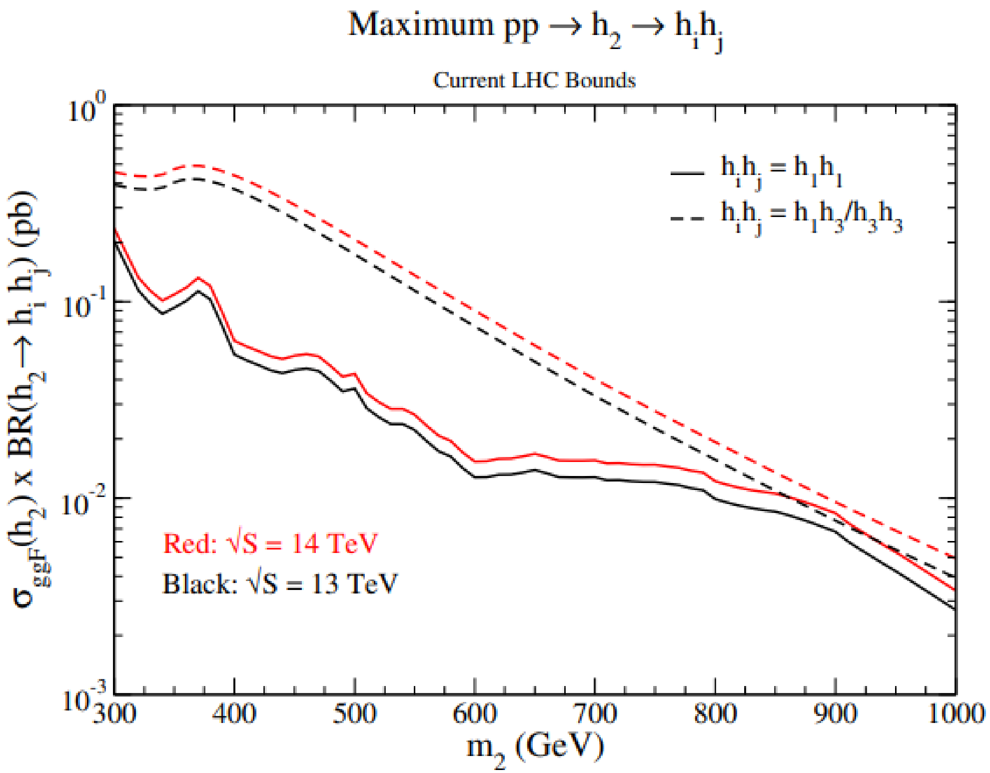
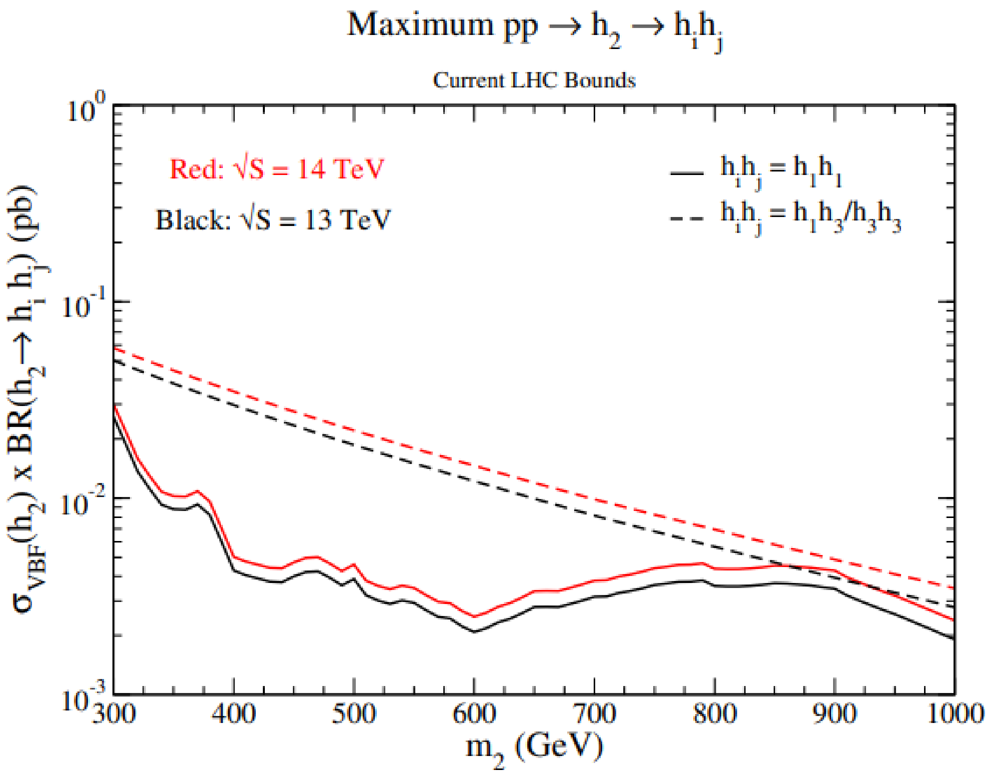
Maximum Branching Ratio



Production Cross Sections





Collider Scenarios

- Current Limits (arXiv 2203.07455)

- **HL LHC (1)**
- **HL LHC + FCCee (2)**
- **HL LHC + ILC500 (3)**

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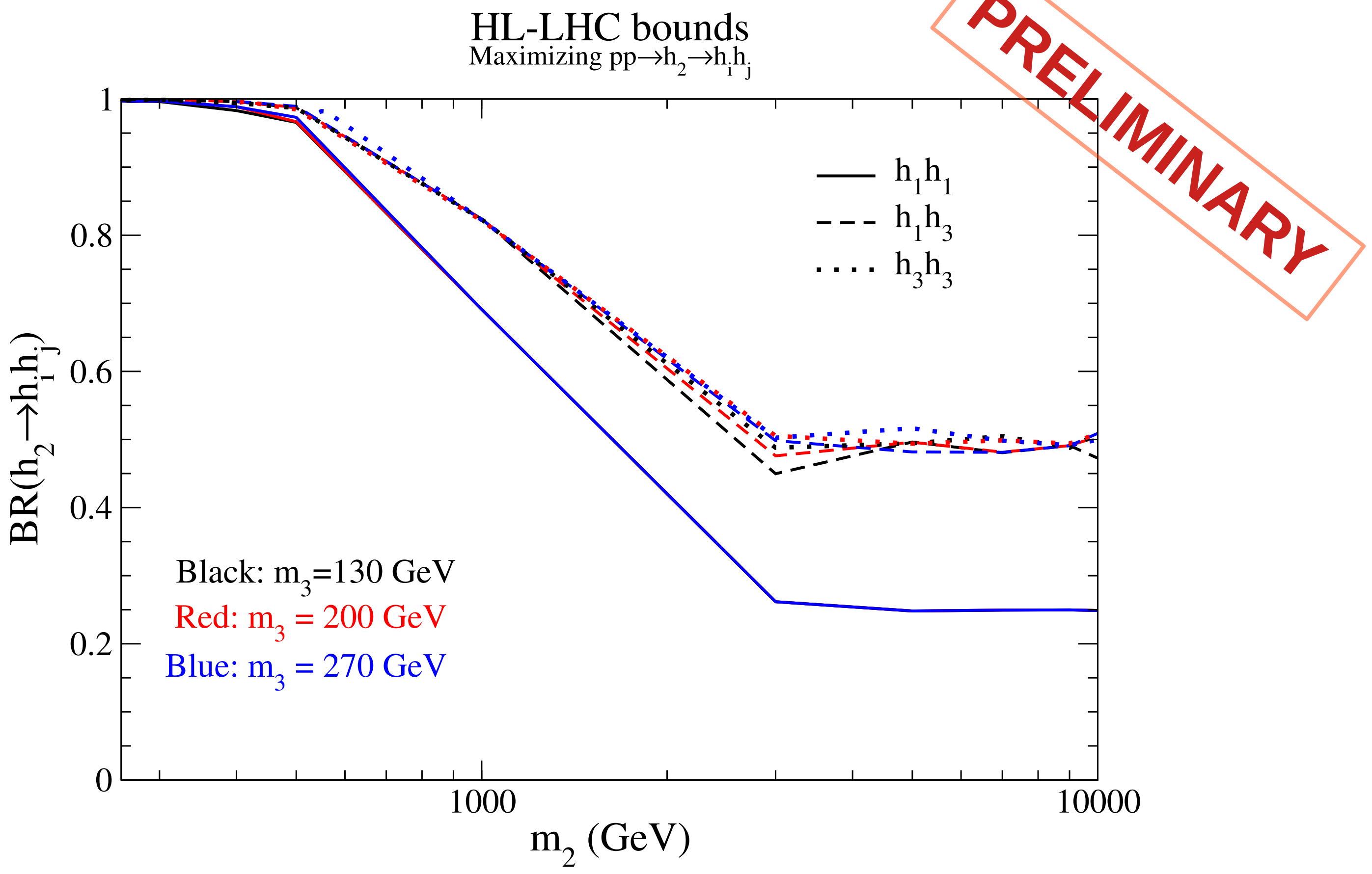
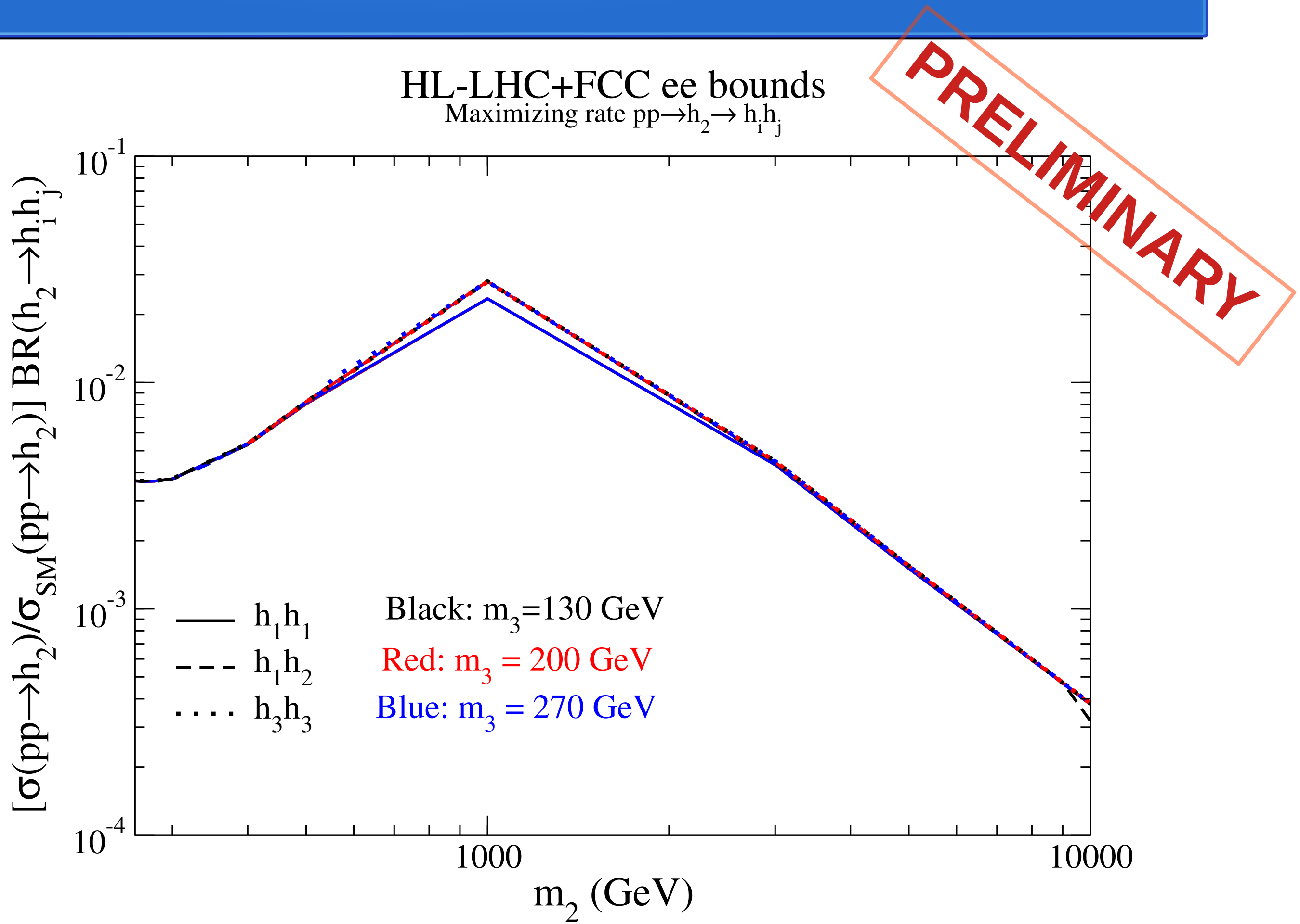
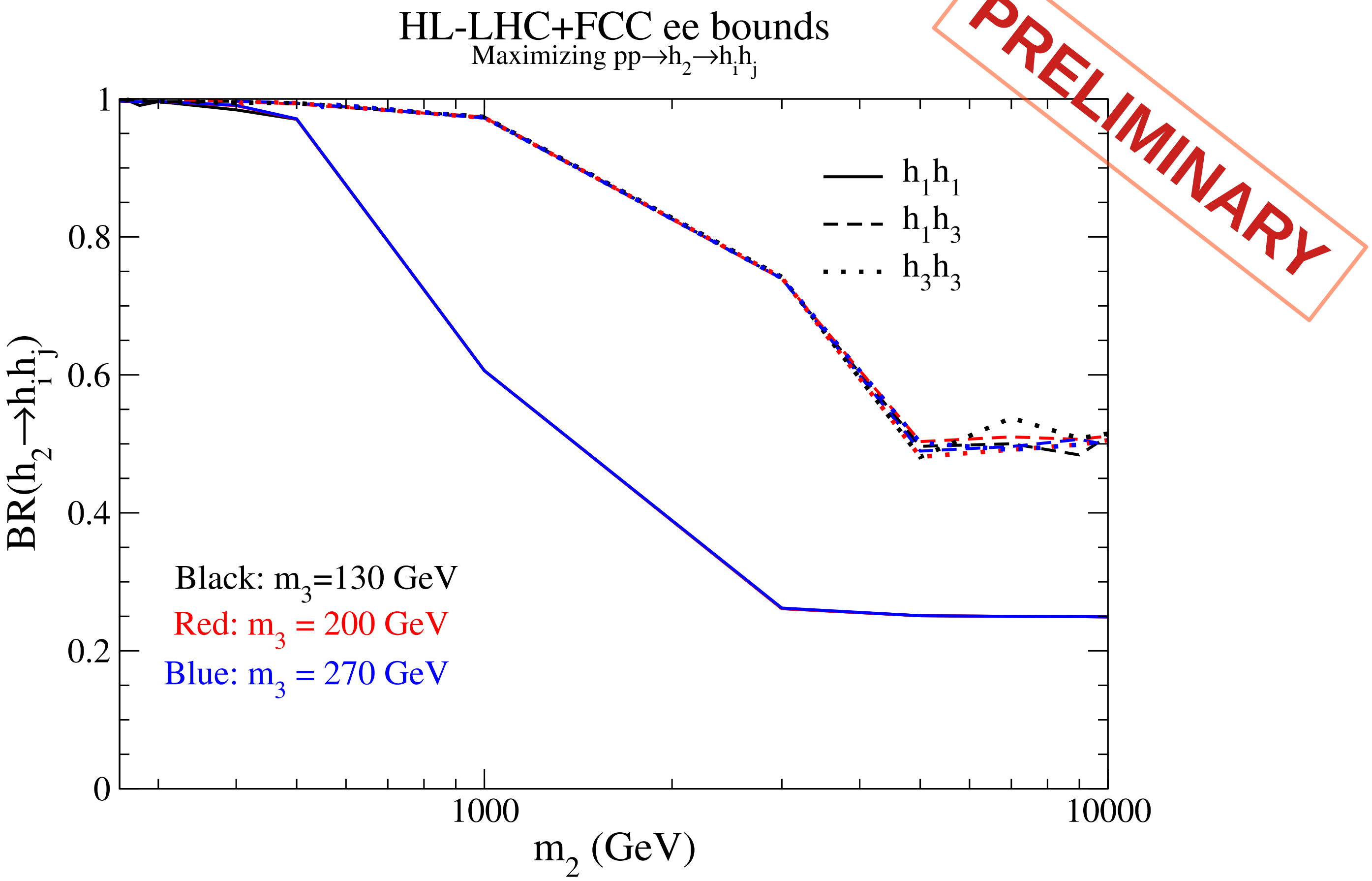
Maximum Branching Ratios (1)



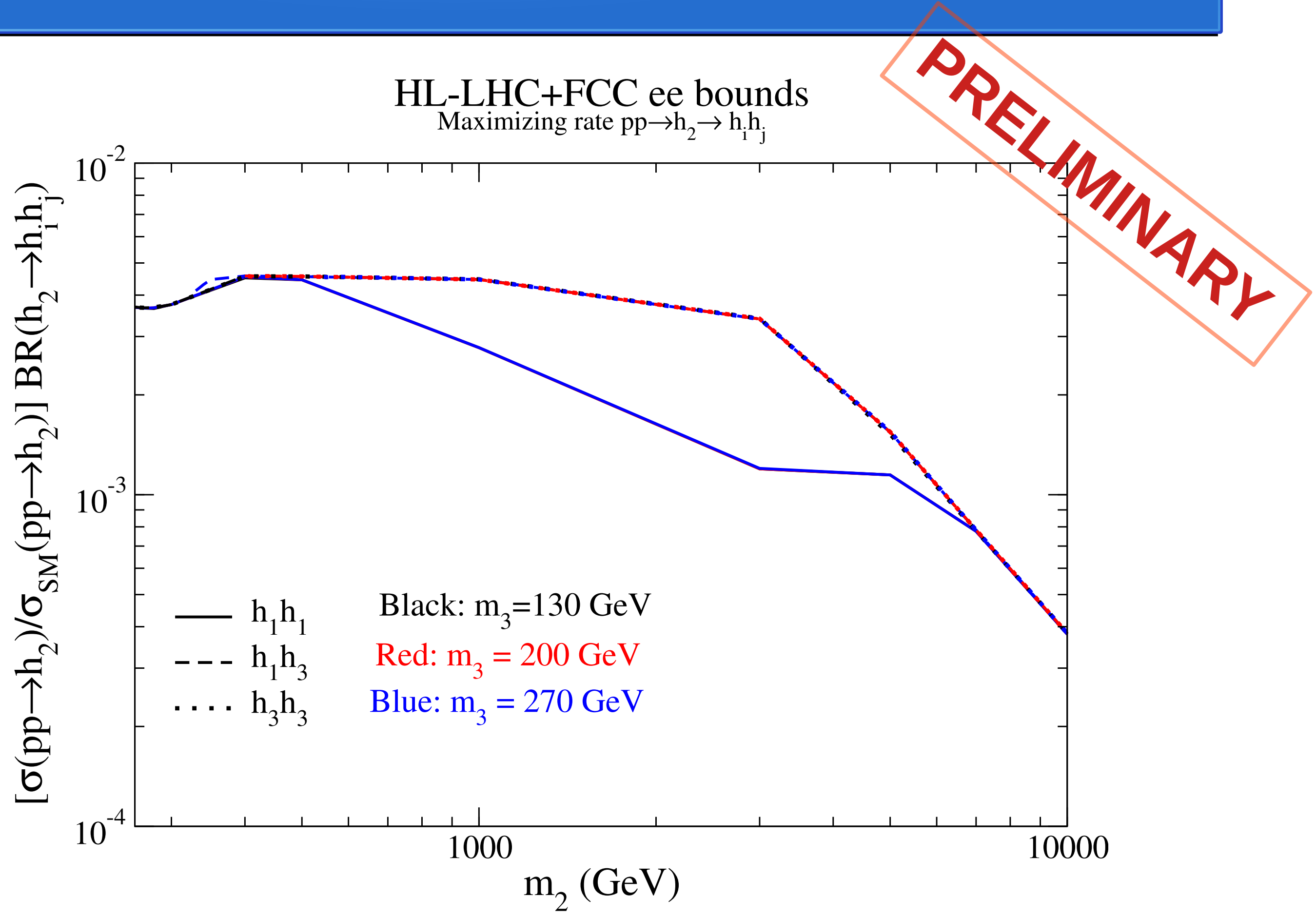
Production Rates (1)



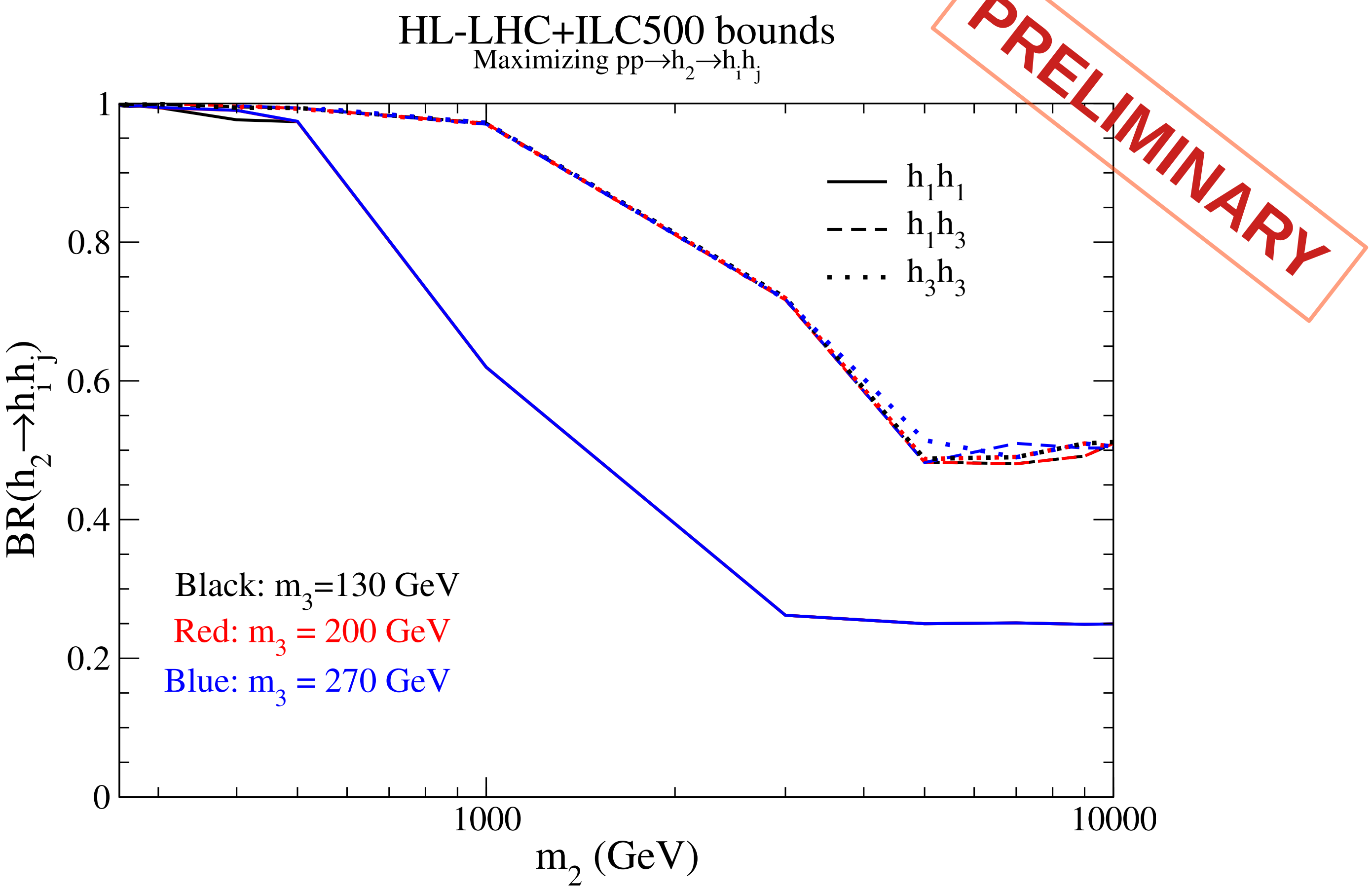
Maximum Branching Ratios (2)



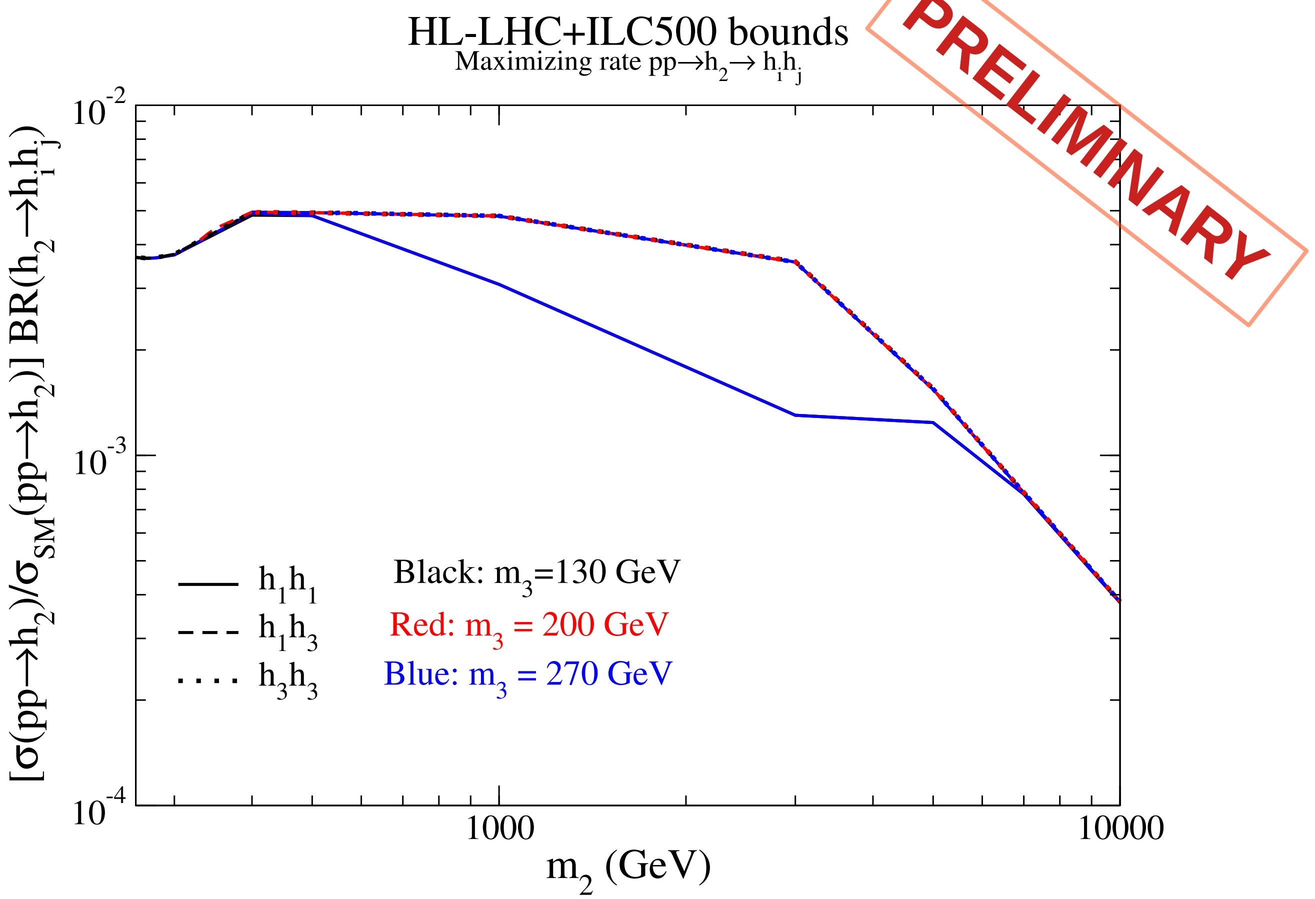
Production Rates (2)



Maximum Branching Ratios (3)



Production Rates (3)



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Conclusion

- The complex singlet extension allows for resonant production of multi scalar final states.
- we found benchmarks for resonant production and decays
- $pp \rightarrow h_2 \rightarrow h_i h_j$
- Branching ratios are substantial in the high mass regime > 0.25
- These points show the these generalized double Higgs channels could be an essential discovery channels for the complex singlet

Thanks for your attention!