Complex Single Benchmarks at Future Collider Experiments

arXiv: 2203.07455, 2211:XXXXX

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AEI Workshop for BSM / KIAS Workshop on Particle Physics & Cosmology

Outline

- Introduction/Motivation
- Model
- Constraints
- Analytical Expectations
- Results
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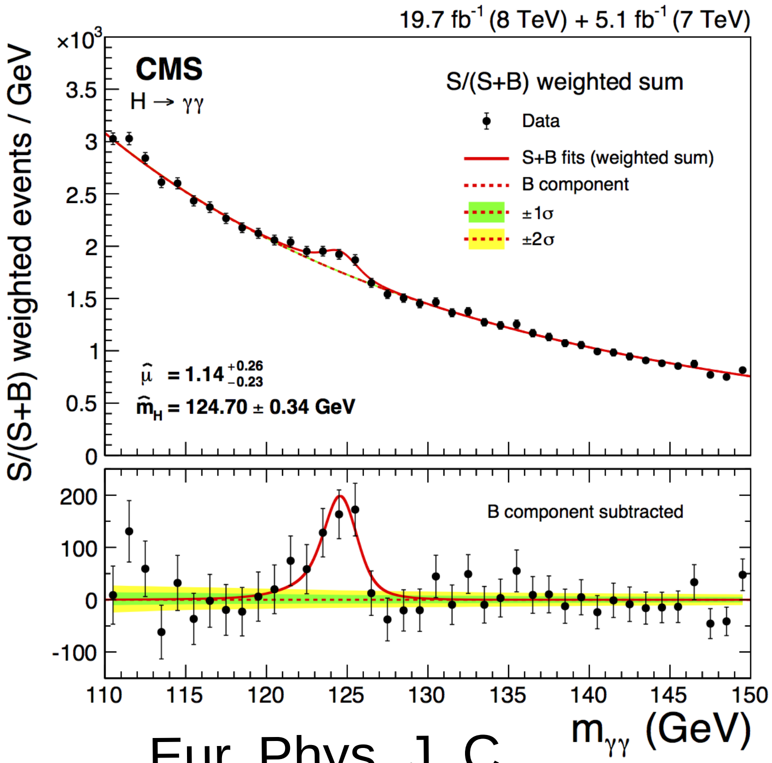
Introduction

- 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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Motivation

- Scalars are some of the simplest SM extensions
- They have been studied extensively in literature
  - arXiv: 1512.05355, 2007.02985, 1908.08554, 2101.0003, ...
- Most of these will assume additional symmetries
  - We take no symmetry assumptions
- The complex scalar introduces two new scalar resonances
  - Can lead to interesting discalar resonances
  - Under right assumptions this is equivalent to two real singlets

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The General Complex Singlet

- Add a new complex scalar uncharged under SM and with no new symmetries.
- $S_c = (S_0 + i\,A)/\sqrt{2}$

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

- $\langle S_c\rangle = 0$ without loss of generality.

Couplings and Production

- h_2 couples to fermions and gauge bosons like a SM Higgs boson of mass m_2 but suppressed by $\sin\theta_{1.}$
- h_2 produced via ggF and VBF like SM higgs
- h_3 couplings to fermions and gauge bosons are doubly suppressed by $\sin\theta_1 \sin\theta_2$
- Expect h_3's main production mechanism to be via decays of h_2 ($h_2 \rightarrow h_1 h_3$ or $h_2 \rightarrow h_3 h_3$)

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

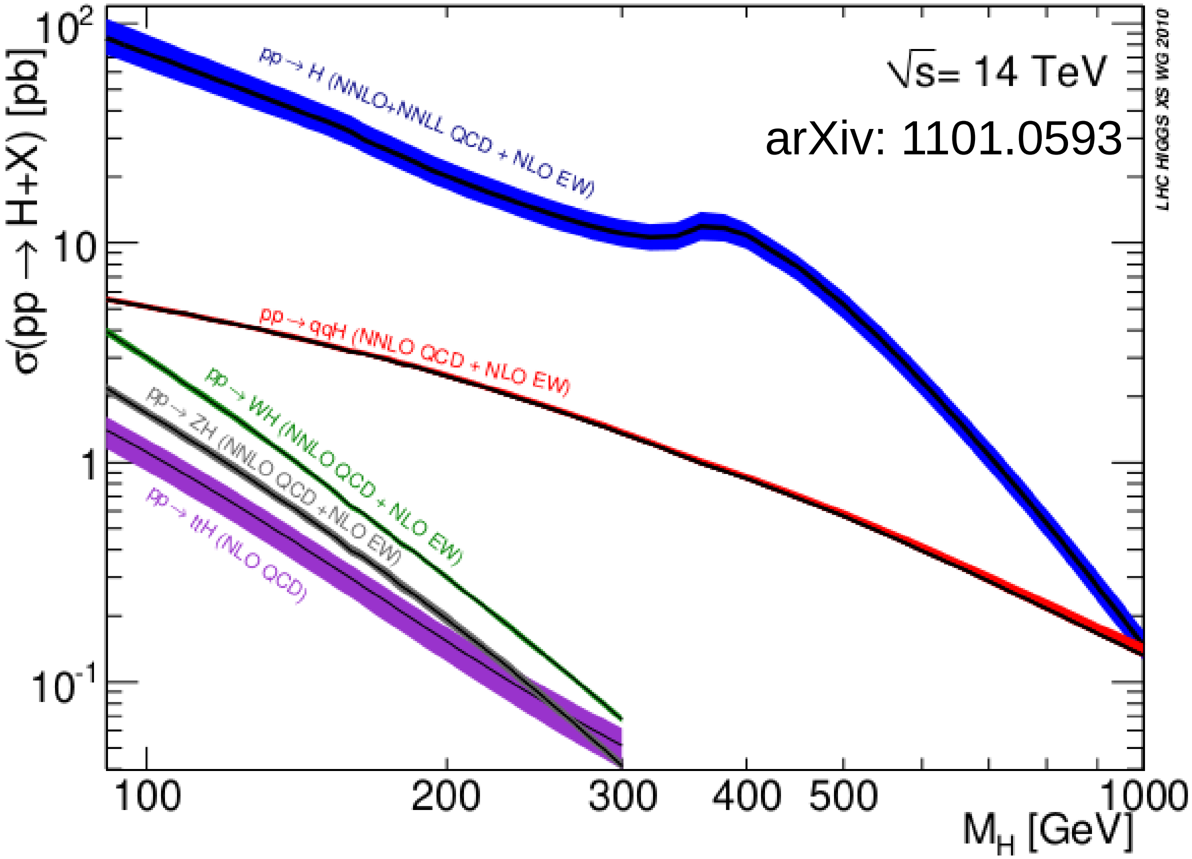
Mass range: 0.3 to ~10 TeV
Couplings to vector bosons and fermions ~ $\sin(\theta_1)$

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

Mass Eigenstates

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

$\sin^2(\theta_1)$



Scalar Trilinear Couplings

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

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

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

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Theory Constraints

- Narrow widths (10% of Mass)
  - Can be used to place upper bound on particular channels
- 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

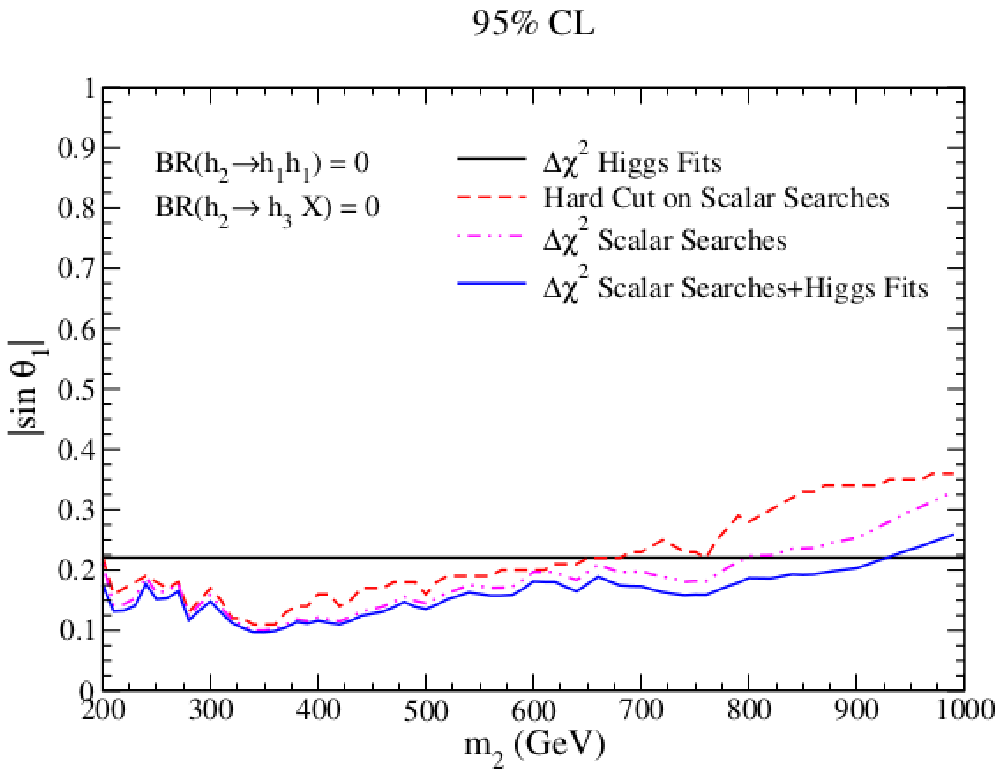
$$\mathcal{M} = 16\pi \sum_{j=0}^{\infty} (2j+1) a_j P_j(\cos\theta), \quad \Rightarrow \quad \begin{aligned} |\delta_2|, |\Re(\delta_3)|, |\Im(\delta_3)| &\leq 16\sqrt{\frac{2}{3}}\pi \\ |\lambda| \leq \frac{16\pi}{3}, \quad |d_2| &\leq 8\pi, \end{aligned}$$

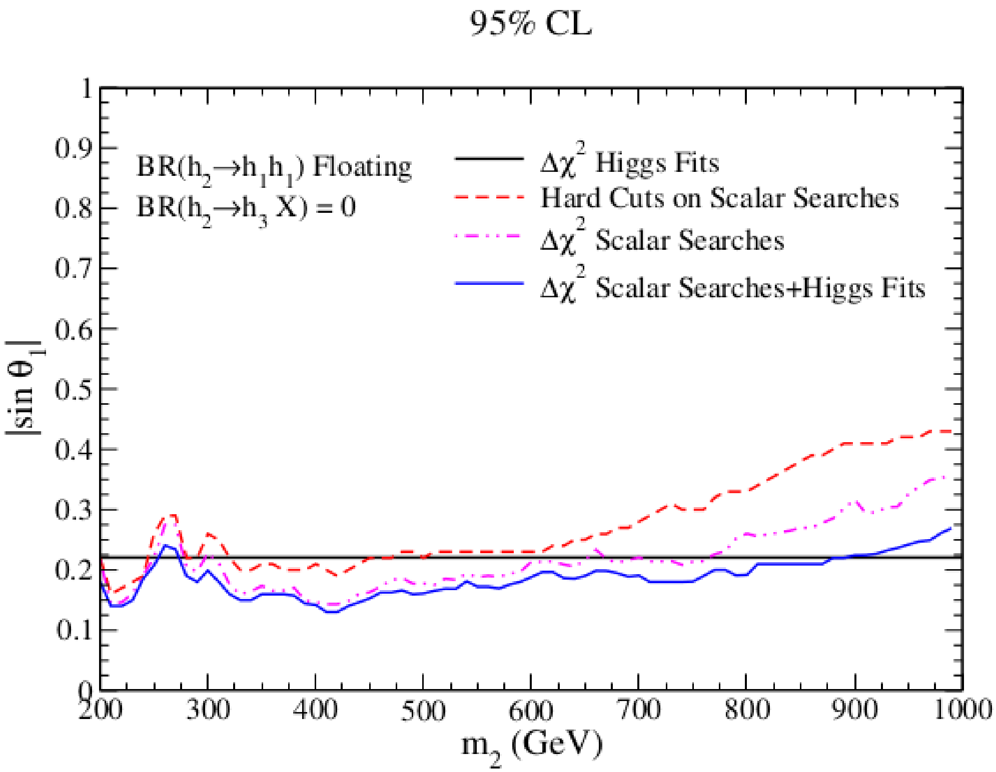
Current Experimental Constraints

- 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
- Heavy resonance chi square

$$\left(\chi^f_{i,h_2}\right)^2 = \begin{cases} \left(\dfrac{\sigma_i(pp\to h_2)\mathrm{BR}(h_2\to f)+\hat{\sigma}^f_{i,Exp}-\hat{\sigma}^f_{i,Obs}}{\hat{\sigma}^f_{i,Exp}/1.96}\right)^2 & \text{if } \hat{\sigma}^f_{i,Obs}\geq\hat{\sigma}^f_{i,Exp} \\ \left(\dfrac{\sigma_i(pp\to h_2)\mathrm{BR}(h_2\to f)}{\hat{\sigma}^f_{i,Obs}/1.96}\right)^2 & \text{if } \hat{\sigma}^f_{i,Obs}<\hat{\sigma}^f_{i,Exp}. \end{cases}$$

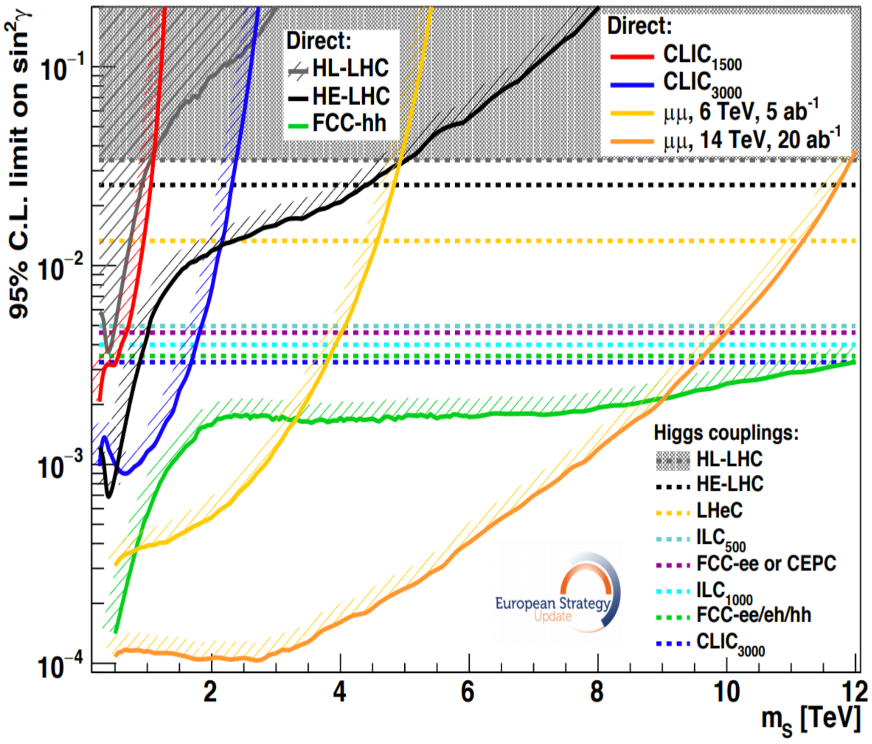
Current Experimental Constraints





Projected Future Constraints

- Take as inputs
  - HL-LHC upgrade
  - HL-LHC + FCC-ee
  - HL-LHC + ILC500
- Maximize Production rates for various discalar resonance



European Strategy 2020, arXiv 1910.11775

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Analytic Expectations

- Narrow Width places upper bound on new BR
  - $\Gamma_{tot} = \Gamma_{SM\text{-}like} + \Gamma_{new} < 0.1*m_2$
  - $BR_{new} < 1 - \Gamma_{SM\text{-}like} / (0.1*m_2)$
- We can also use narrow width to find constraints on sin θ
  - First lets look at $h_2 \rightarrow h_1 h_1$
  - Then we will look at $h_2 \rightarrow h_1 h_3$ and $h_2 \rightarrow h_3 h_3$
  - Lets label the SM like decay width as $\Gamma_{SM}(h_2)$
    - It will depend on the mass m_2

Analytic Expectations: h2 → h1 h1

- $\sigma / \sigma_{SM} = \sin^2\theta \, \mathrm{BR}(h_2 \to h_1 h_1)$
- Let us assume $\Gamma(h_2 \to h_3 h_3) = \Gamma(h_2 \to h_1 h_3) = 0$
- Assume we saturate the total width bound
  - $\Gamma_{tot}(h_2) = \Gamma(h_2 \to h_1 h_1) + \sin^2\theta \;\Gamma_{SM}(h_2) = 0.1\, m_2$
  - $\sigma / \sigma_{SM} = \sin^2\theta \,(1 - 10 \sin^2\theta \;\Gamma_{SM}(h_2)/ m_2)$
- At very high energy (m_2) GBET takes over
  - $\Gamma_{SM}(h_2) = \Gamma_{SM}(h_2 \to ZZ) + \Gamma_{SM}(h_2 \to WW) = 3 \;\Gamma_{SM}(h_2 \to ZZ)$
  - $\Gamma(h_2 \to h_1 h_1) = \sin^2\theta \,\Gamma_{SM}(h_2 \to ZZ) = \sin^2\theta \;\Gamma_{SM}(h_2) / 3$
- $\mathrm{BR}(h_2 \to h_1 h_1) = 1/4$ and $\sigma / \sigma_{SM} = (3/16)\,(0.1\, m_2)/ \Gamma_{SM}(h_2)$

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Collider Scenarios

- Current Limits (arXiv 2203.07455)

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

PRELIMINARY

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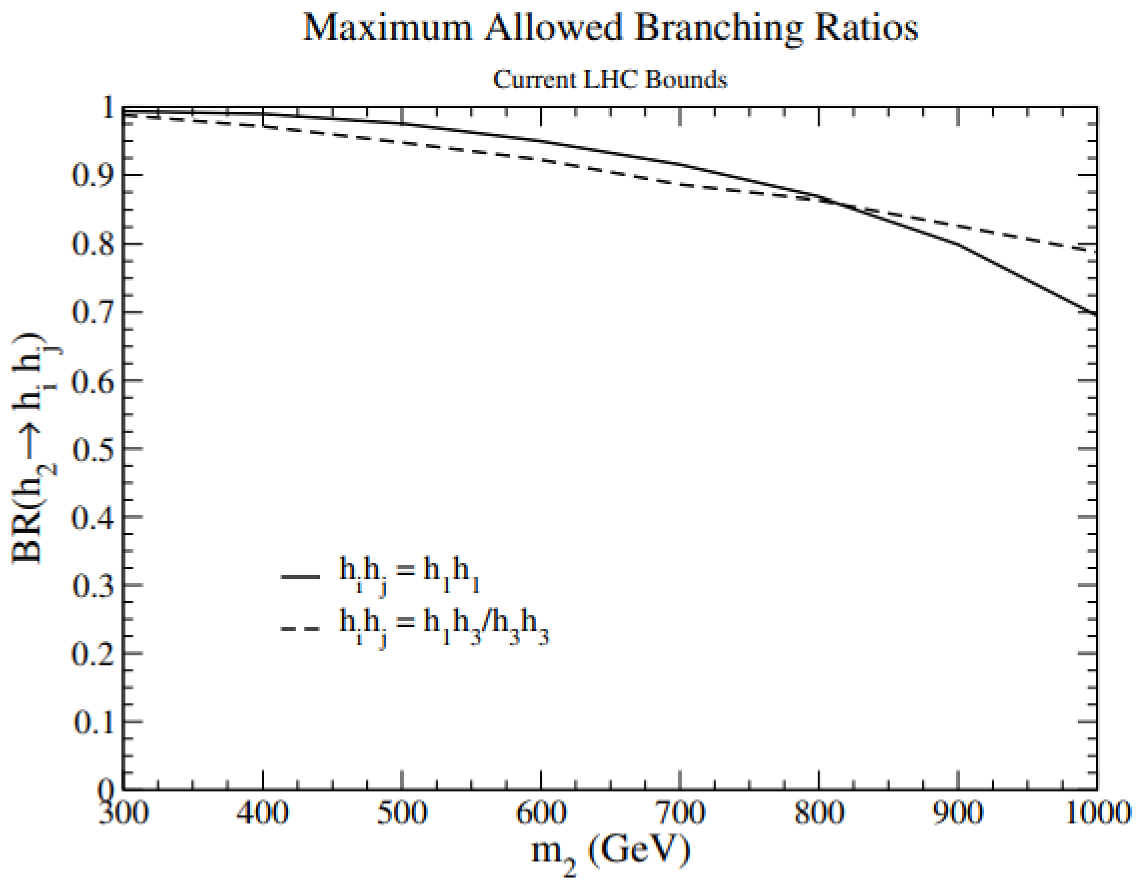
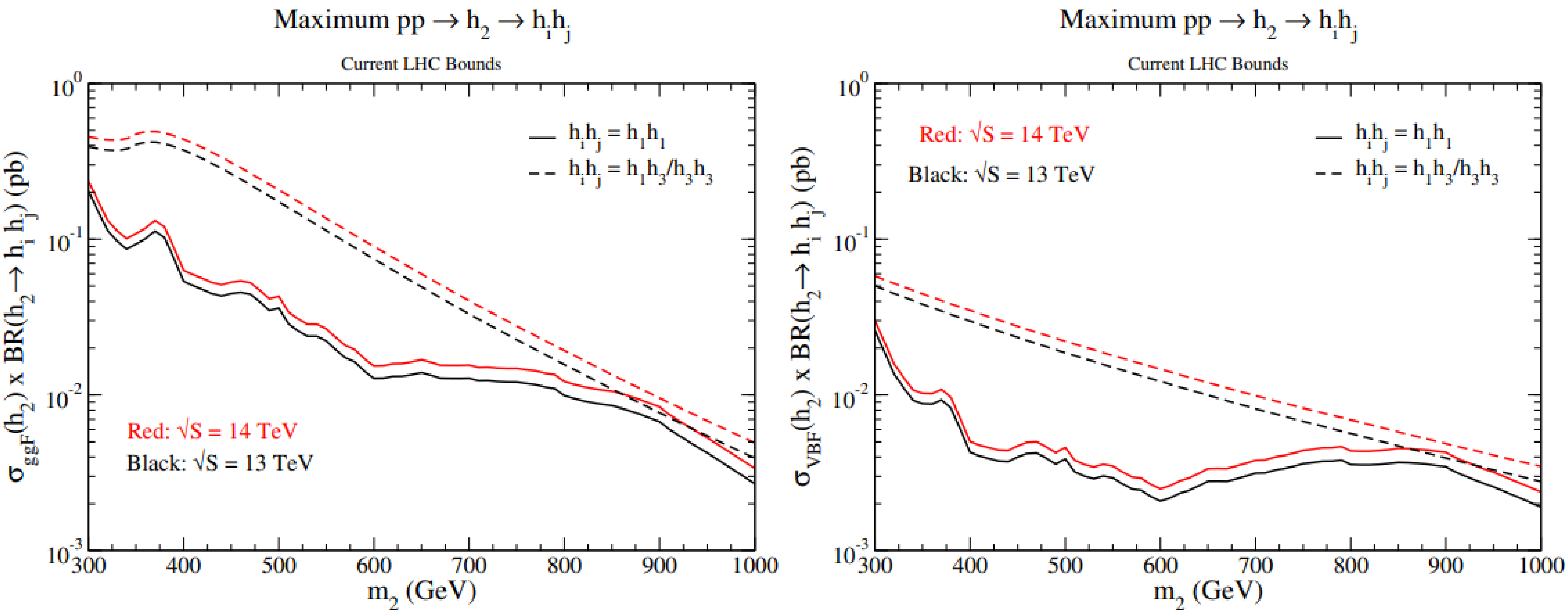
PRELIMINARY

Maximum Branching Ratio



Production Cross Sections



Collider Scenarios

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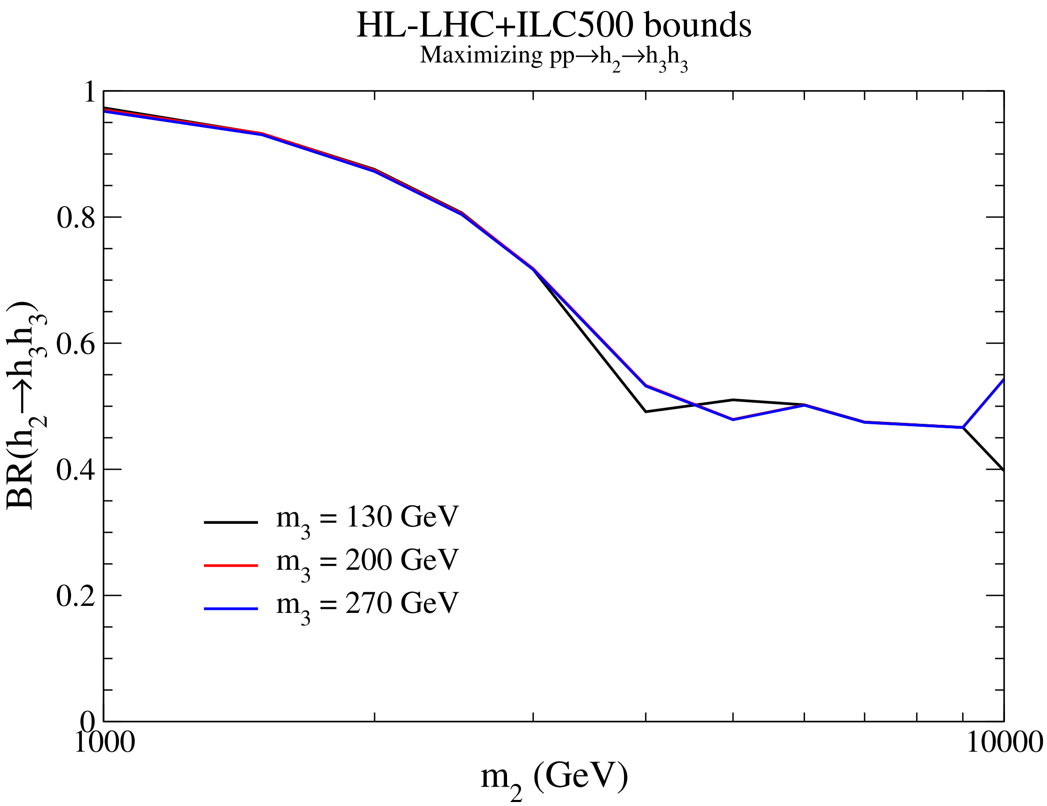
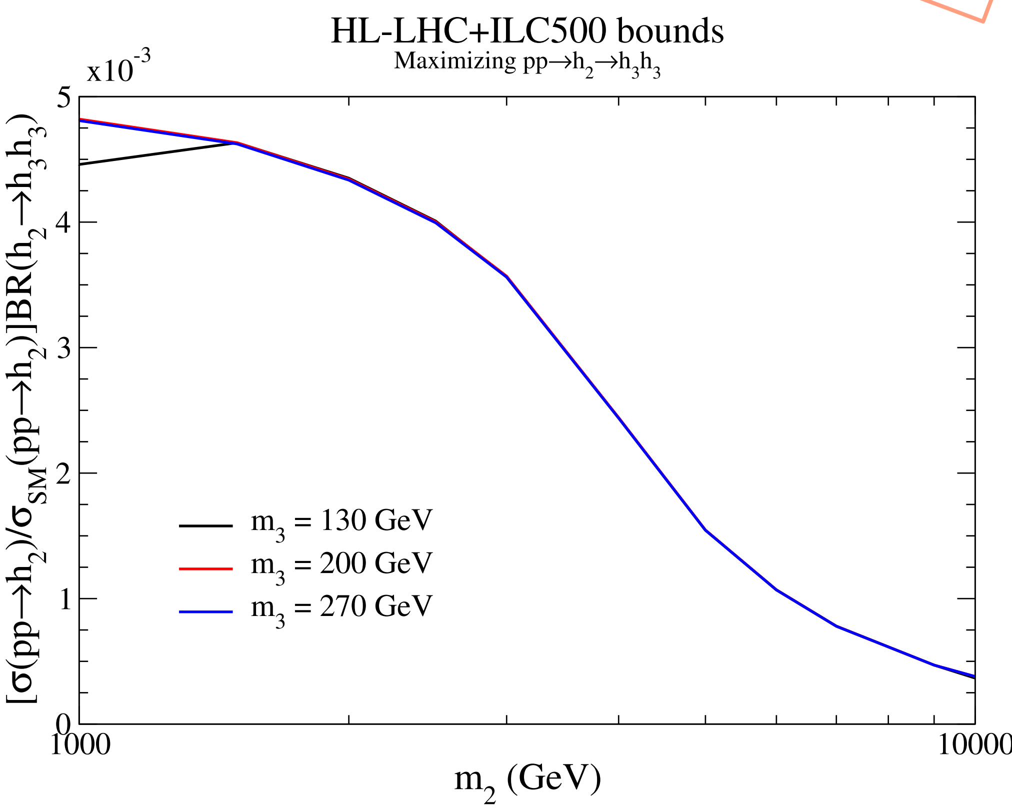
PRELIMINARY

HL-LHC + ILC500

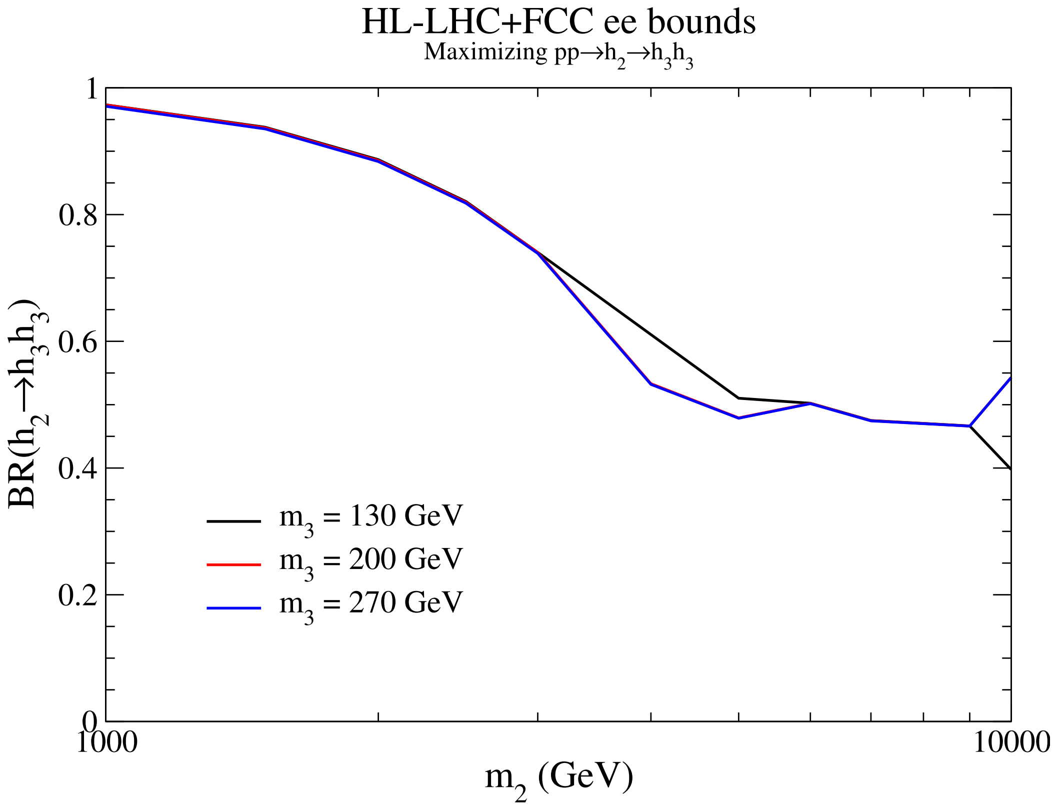
PRELIMINARY

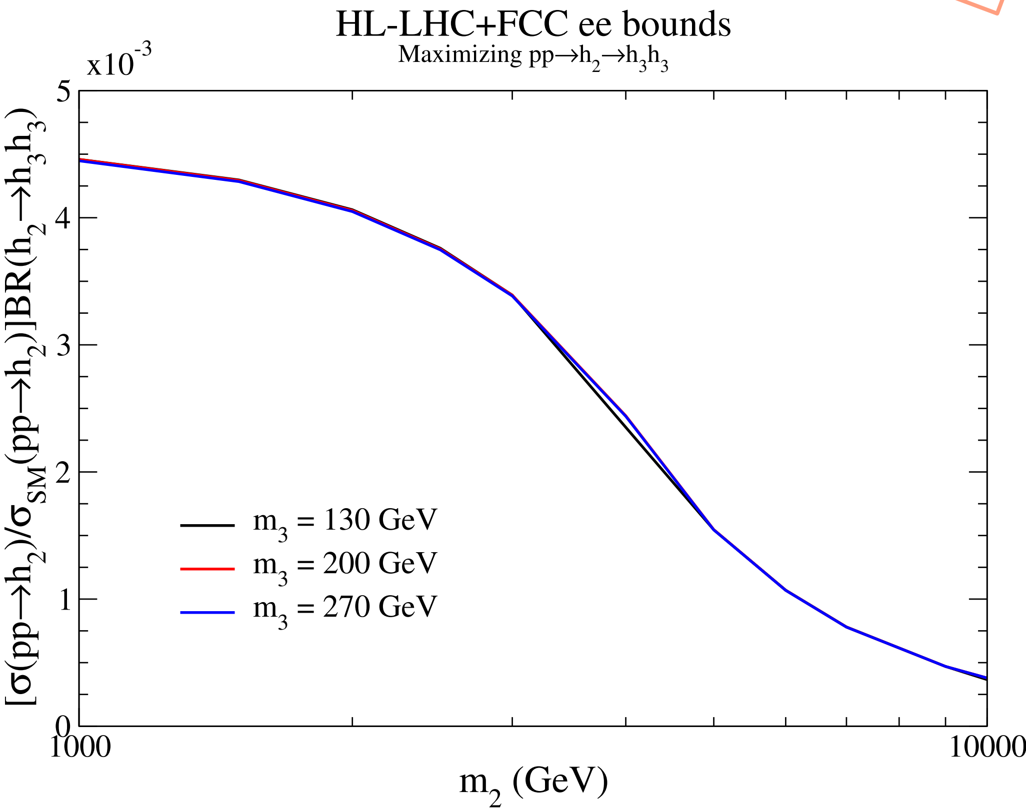




HL-LHC + FCCee

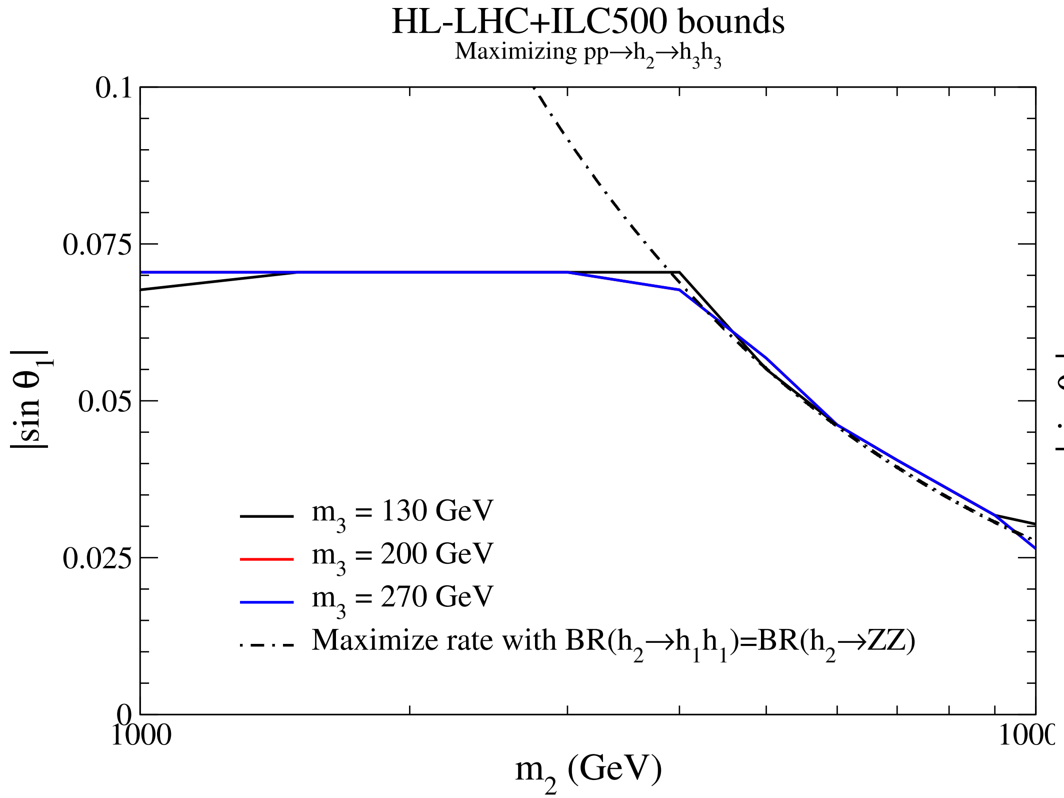
PRELIMINARY

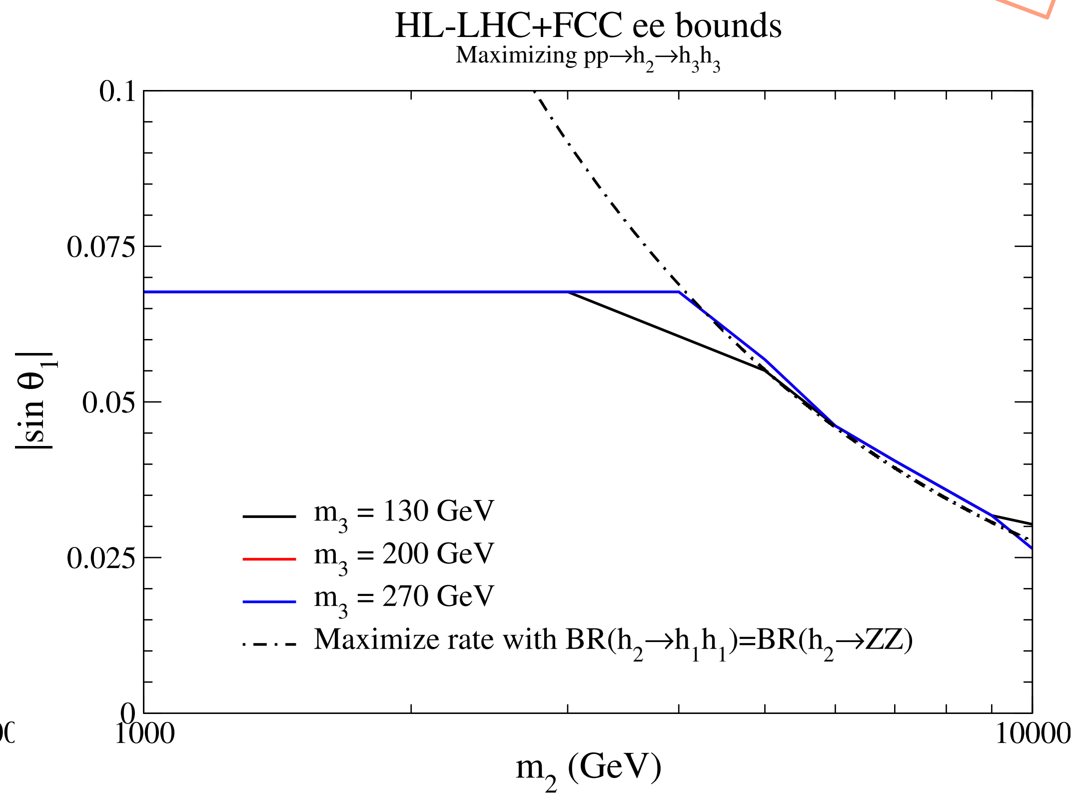




sin θ vs m_2

PRELIMINARY





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- The complex singlet extension allows for resonant production of multi scalar final states.
- The narrow width constraint has significant implications for the Branching ratios into these states in the high energy (m_2) limit
- Can find mass points with substantial branching ratios > 0.25 in the high mass regime
- The generalized double Higgs channels could be an essential discovery channels for the general complex singlet

Thanks for your attention!