SM Higgs with singlet variations

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LHC Early Phase for the ILC

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SM Higgs + 1 Scalar Singlet

Add one scalar singlet to SM Higgs potential

- Higgs can be indistinguishable from SM
- Singlet obtains no VEV

$$V = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_1}{2}H^\dagger H S + \frac{\delta_2}{2}H^\dagger H S^2 + \left(\frac{\delta_1 m^2}{2\lambda}\right) S + \frac{\kappa_2}{2}S^2 + \frac{\kappa_3}{3}S^3 + \frac{\kappa_4}{4}S^4,$$

O'Connell, Ramsey-Musolf, Wise

$\Longrightarrow$ Singlet interacts only with Higgs

Two cases of singlet:

- Case A: Singlet mixes with SM Higgs (O'Connell et al.)
- Case B: Reflection Symmetry $S \to -S$ (McDonald & Burgess et al.)

Case A: Singlet and Higgs mix

Higgs Bf same as SM

Exception: If $m_H > 2\, m_S$, then H→ S S is open

$$\mathrm{BF}(H \to X_{SM}) = \frac{\mathrm{BF}(h_{SM} \to X_{SM})}{1 + \Gamma(H \to SS)/\Gamma(H \to X_{SM})}$$

Higgs couplings reduced universally by
mixing parameter (like radion-higgs mixing)

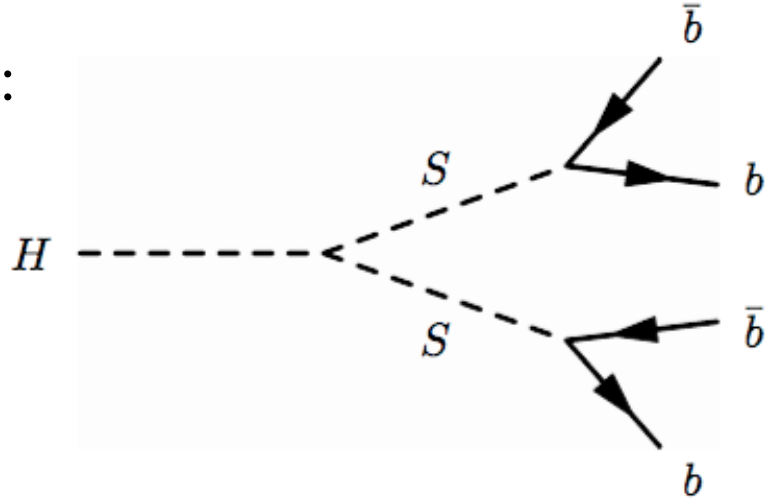
BF of light S same as Higgs of equal mass

Case A: New Higgs decay modes

Extended decays through singlet:

$W\,H \to l\nu + 4b$

$W\,H \to l\nu + 2b + 2\tau,$

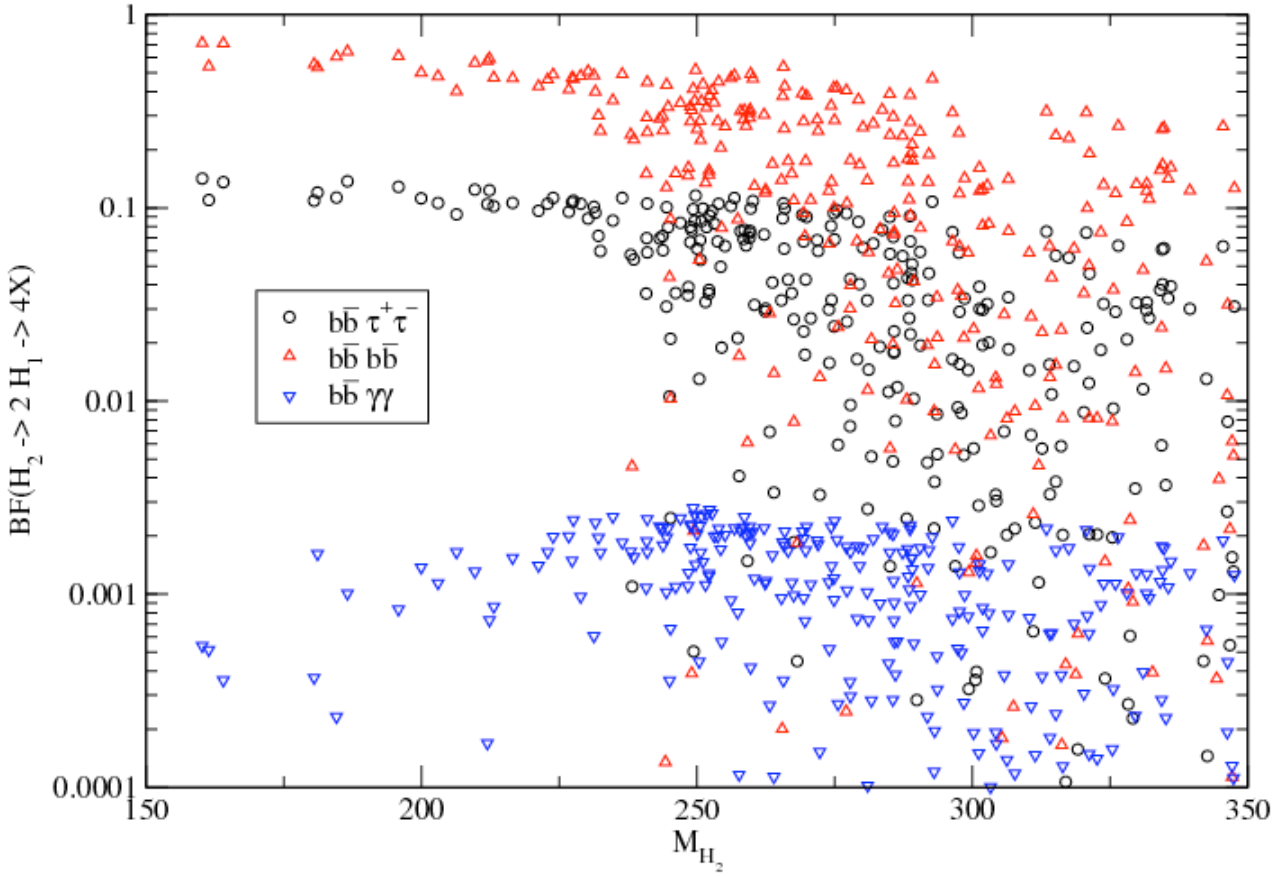


Similar to $h \to aa$ searches in Singlet + MSSM

Carena, Han, Huang, Wagner
Cheung, Song, Yan
Gunion, Dermisek
Chang, Fox, Weiner
Graham, Pierce, Wacker

Case A: New Higgs decay modes

Higgs may escape detection through usual search modes (CMS, 30 fb^{-1})



But may be observable in new modes

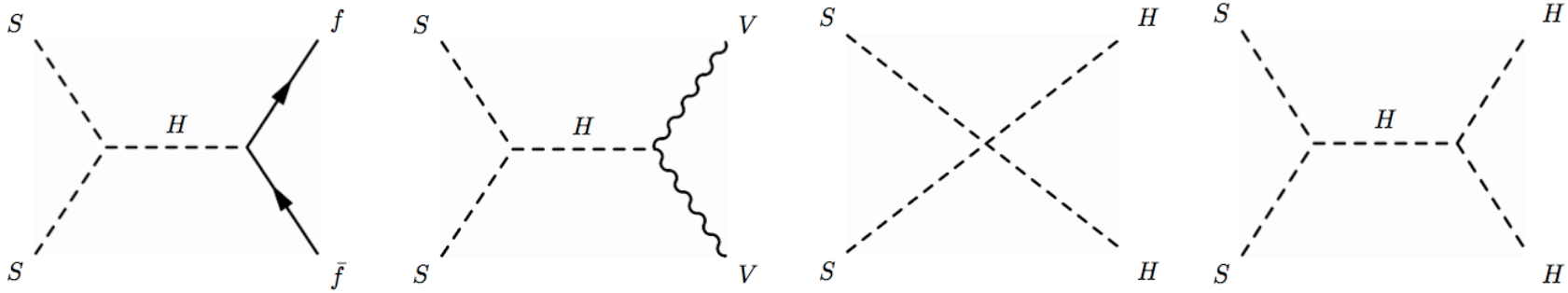
Case B: S →-S (stable singlet)

- S → -S symmetry prevents S decay
  ⇒DM candidate

- DM singlet annihilates through Higgs boson

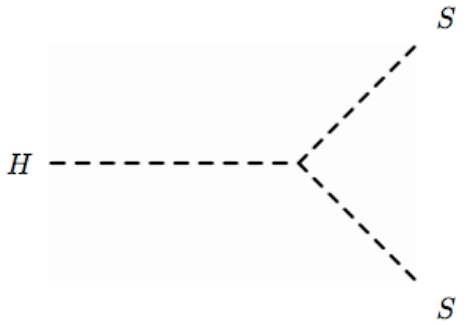
$$\frac{\delta_2}{2} H^+ H S^2$$

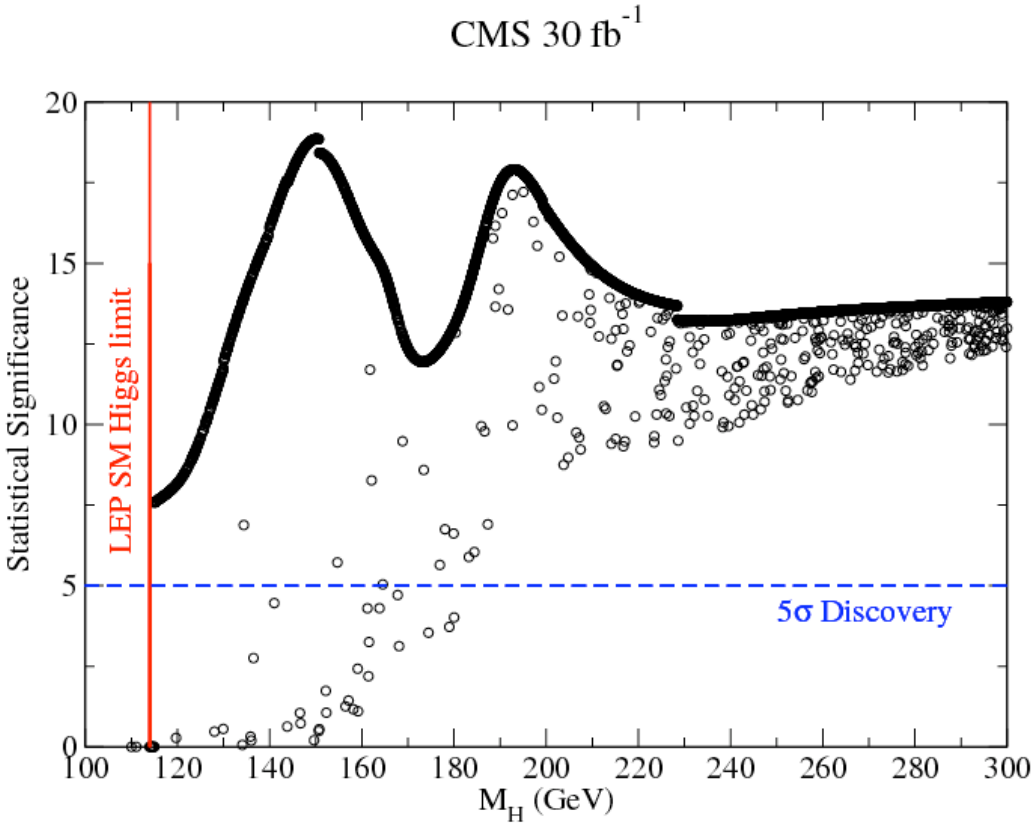
Annihilation processes:



Case B: Higgs decay to singlet

- May greatly affect Higgs discovery potential
  - Higgs decays to invisible states
  - Decrease rate of traditional Higgs modes





Case B: Finding an invisible Higgs

Weak boson fusion:

Extract signal with cuts on azimuthal correlation of forward jets and large missing p_T

Eboli and Zeppenfeld

Z-Higgstrahlung:

Cuts on dilepton separation and inv. mass extract signal

Combined → model independent mass determination

Davoudiasl, Han, Logan

ILC: invisible Higgs can be discovered rather easily via Z-recoil spectrum in $Z+H_{inv}$ production

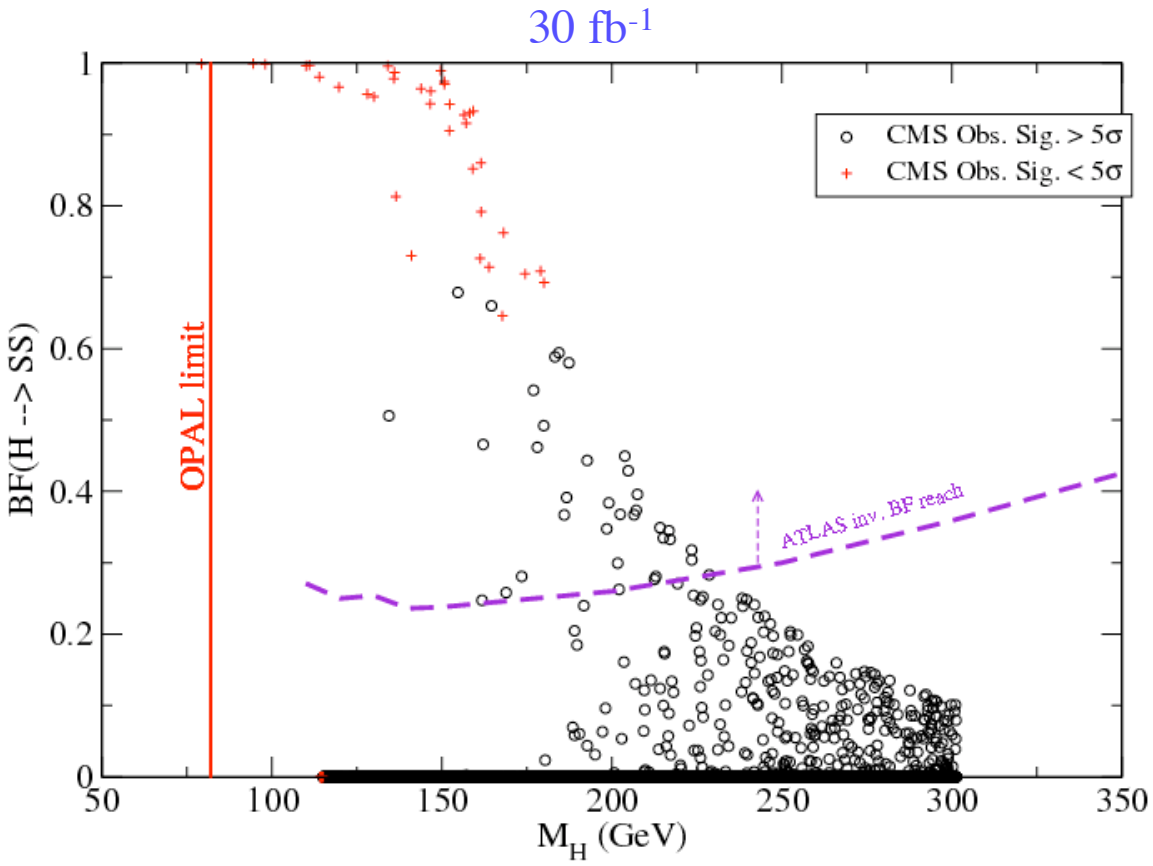
Case B: H discovery via stable S

OPAL: Higgs w/ SM couplings $m_h > 82$ GeV

ATLAS reach on Bf(H→inv) to ~20%

Red: not disc. with visible mode

Black: disc. with visible modes



Higgs boson discoverable using either method with early LHC data!

Summary

SM Higgs + 1 scalar singlet:

Case A: Singlet mixes with SM Higgs

- Traditional discovery modes weakened if H→SS open
- H discovery may be possible via 4b or 2b+2τ modes

Case B: S → -S (stable singlet)

- DM candidate
- H → inv:
  - Discovery potential reduced (traditional modes)
  - Opportunity for discovery via invisible modes

Parameter Scan Range

Case A:

Min		Max
0	λ	3
0	$\lambda_S = \delta_2 + \kappa_2 / v^2$	3
-200 GeV	δ_1	200 GeV
-1 TeV	κ_3	1 TeV

Case B:

Min		Max
0	λ	3
–200 GeV	δ_1	200 GeV
–3	δ_2	3
-(200 GeV)^2	κ_2	-(200 GeV)^2
–1 TeV	κ_3	1 TeV

Finding an invisible Higgs

Weak boson fusion:

Major cuts include azimuthal angle of forward jets, $\phi_{jj} < 1$ with a rapidity cut of $|\Delta\eta| > 4.4$ and large missing $p_T > 100$ GeV

Signal rate estimated by fraction of events with $\phi_{jj} < 1$

Eboli and Zeppenfeld

Z-Higgstrahlung:

$Z+H_{inv}$ signal can be isolated from backgrounds with cut on dilepton separation and invariant mass

Combining these two modes allows model-independent determination of Higgs mass

$m_H = 120$ GeV 5σ discovery in $Z+H_{inv}$ with 10 fb^{-1}

$\Delta m_H \sim 15$ GeV with 100 fb^{-1} with ZH and WBF (SM production strength)

Davoudiasl, Han, Logan

At the ILC, an invisible Higgs can be discovered rather easily via Z-recoil spectrum in $Z+H_{\rm inv}$ production