HH production
is there something left to do?

0. you have one, why not look for two?

1. "kappa-style" Higgs trilinear coupling measurements

2. break degeneracies in the dim 6 extended SM

3. measure/constrain BSM scenarios with a SM-like Higgs

- LHC-relevant analyses approx. 3 years ago from theory side

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  - lots of progress: boosted techniques, MT2, realistic taus…

- some resonant models constrained with 8 TeV

- issues in "easy" channels for SM-like production

  $b\bar{b}\gamma\gamma$

process	ATLAS	CMS
SM HH→bbγγ	8.4± 0.1	9.9
Total background	47.1 ± 3.5	22.6

The signal is not the issue here

- where are the performance studies for other channels?

  - boosted regime (bbtautau, bbWW)

  - what limits sensitivity? margin for improvement?

viable channels:

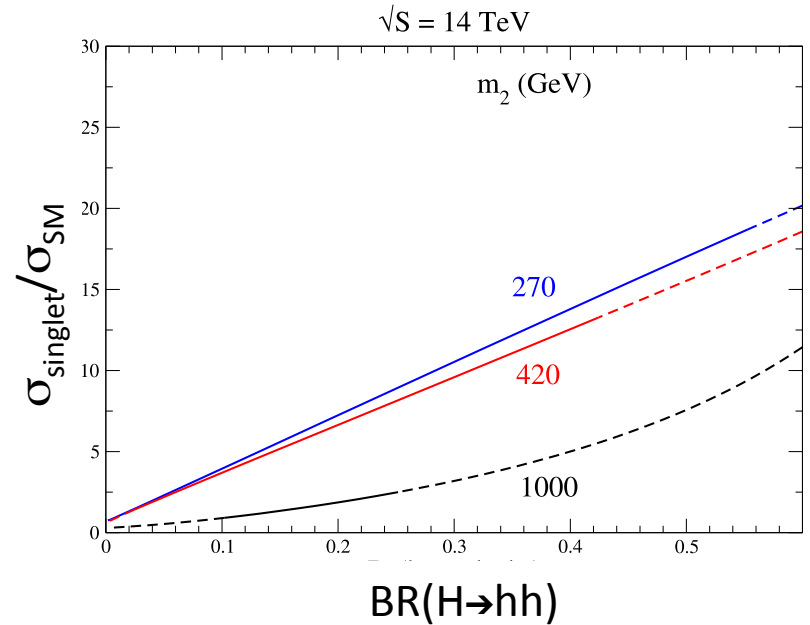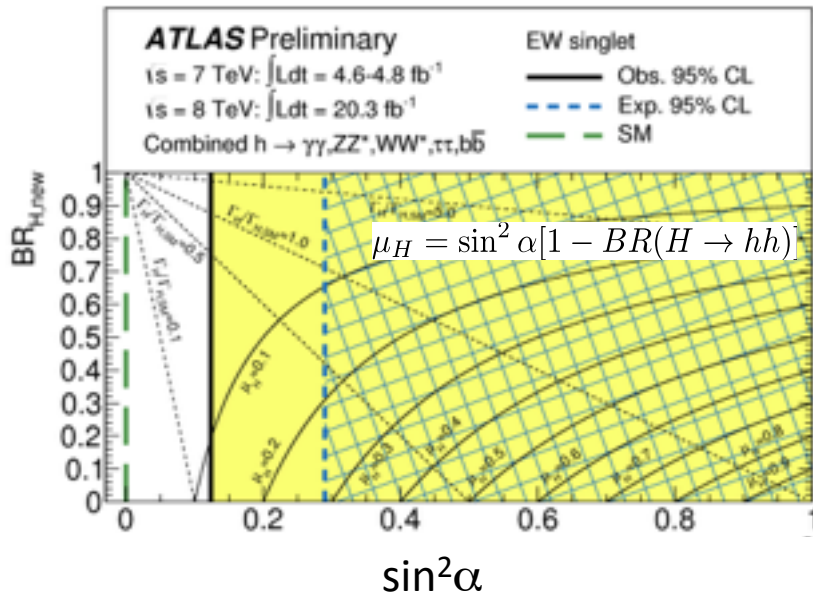| Decay	Issues	Expectation 3000 ifb	References
$b\bar{b}\gamma\gamma$	• Signal small • BKG large & difficult to asses • Simple reconst.	$S/B \simeq 1/3$ $S/\sqrt{B} \simeq 2.5$	[Baur, Plehn, Rainwater] [Yao 1308.6302] [Baglio et al. JHEP 1304]
$b\bar{b}\tau^+\tau^-$	• tau rec tough • largest bkg tt • Boost+MT2 might help	**differ a lot** $S/B \simeq 1/5$ $S/\sqrt{B} \simeq 5$	[Dolan, Englert, MS] [Barr, Dolan, Englert, MS] [Baglio et al. JHEP 1304]
$b\bar{b}W^+W^-$	• looks like tt • Need semilep. W to rec. two H • Boost + BDT proposed	**differ a lot** best case: $S/B \simeq 1.5$ $S/\sqrt{B} \simeq 8.2$	[Dolan, Englert, MS] [Baglio et al. JHEP 1304] [Papaefstathiou, Yang, Zurita 1209.1489]
$b\bar{b}b\bar{b}$	• Trigger issue (high pT kill signal) • 4b background large difficult with MC • Subjets might help	$S/B \simeq 0.02$ $S/\sqrt{B} \leq 2.0$	[Dolan, Englert, MS] [Ferreira de Lima, Papaefstathiou, MS] [Wardrope et al, 1410.2794]
others	• Many taus/W not clear if 2 Higgs • Zs, photons no rate		

[M. Spannowsky, Mainz workshop]

Leaving behind byzantine models

- LHC HXSWG seeks input.

1.) Higgs singlet
- Fix mixing angle to largest allowed by precision EW
- Free parameters: $M_H, \Gamma(H \to hh), BR(h \to \text{invisible})$

2.) Non-resonant 2HDM
- Small tan β, $M_H < 2m_h$
- Free parameters: $M_H, \cos\alpha, M_A, M_{H+}, tan\beta, m_{12}^2$

3.) Enhanced b, τ 2HDM
- Large tan β

4.) EFT following Higgs Cross section working group
- Neglect b's, assume no CP or flavor /violation
- Free parameters: $c_{gg}, \ \delta y_t, \ y_t^{(2)}, \ \delta\lambda_3$

HH x-group [Dawson, Englert,Gouzevitch, Salerno, Slawinska]

Benchmarks

- **B1: Higgs singlet model with Z$_2$ symmetry**

  - 5 parameters:
  $$m_h, M_H, \cos\alpha, v, \Gamma(H \to hh), BR(h \to \text{invisible})$$

  - α parameterizes mixing of SM Higgs with singlet; BR(H→hh) depends on parameters in potential

  - Pros: Simple to implement, captures resonance features, limits on cos α from single Higgs decays and precision EW

  - Cons: Only SM and invisible Higgs decays, can get larger enhancements in 2HDM, MSSM, NMSSM
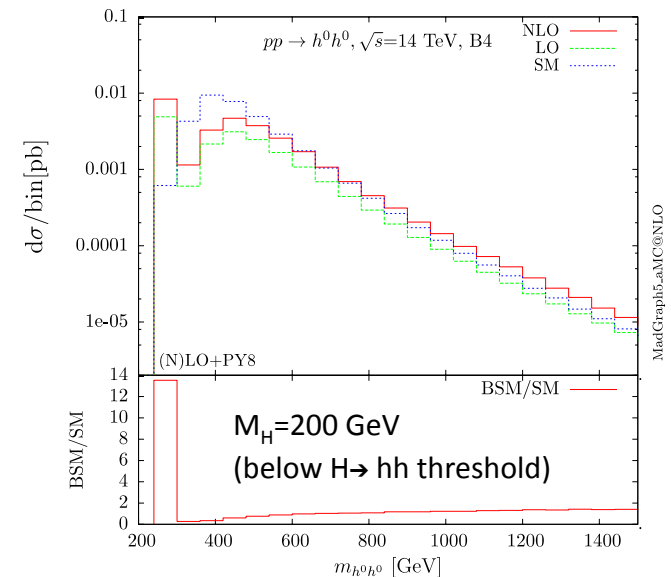
Benchmark #1 (Singlet)

ATLAS Preliminary
$\sqrt{s}$ = 7 TeV: $\int$Ldt = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int$Ldt = 20.3 fb^{-1}
Combined h → γγ,ZZ*,WW*,ττ,b$\bar{b}$

EW singlet
— Obs. 95% CL
- - - Exp. 95% CL
- - - SM

$\mu_H = \sin^2\alpha[1 - BR(H \rightarrow hh)]$

$\sin^2\alpha$

$\sqrt{S}$ = 14 TeV

m_2 (GeV)

270
420
1000

BR(H→hh)

- Precision EW: $\sin^2\alpha$ < .12
- Proposal: Fix cos α=.95
- New parameters in singlet model:

$$M_H, \Gamma(H \rightarrow hh), BR(h \rightarrow \text{invisible})$$

Benchmark #2 (non-resonant)

- 2HDM $m_h, M_H, \cos\alpha, M_A, M_{H^+}, tan\beta, m_{12}^2$

- Pros: Multiple channels probed - hh, hH, HH, hA, H$^+$H$^-$

- Benchmarks B4 of arXiv:1407.0281

  - Rate not dominated by resonant decay H→hh (M$_H$=200 GeV)

  - tan β=1.2, enhanced hhh, Hhh couplings, Type-I fermion-Higgs couplings

  - $\sigma \sim .7\ \sigma_{SM}$

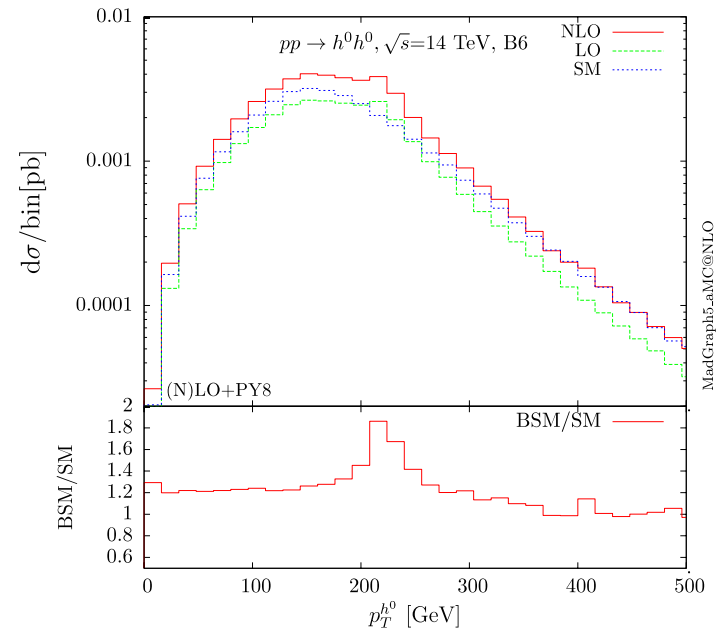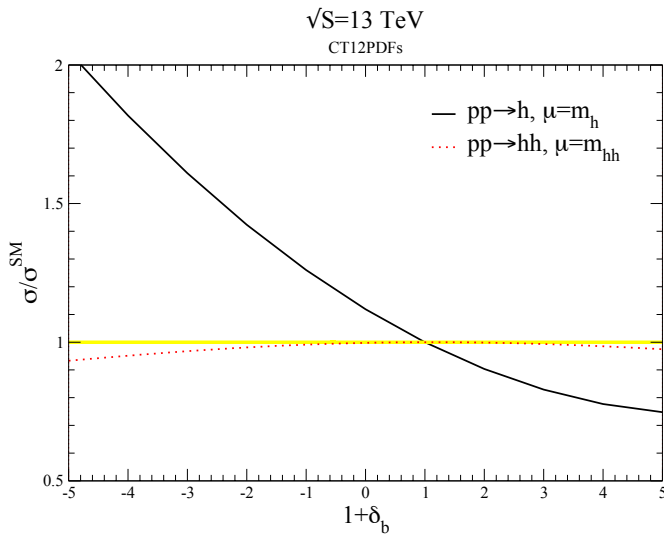 - Interference effects change shapes

Similar to Stahl, Scenario A, Type-I Benchmark

[Hespel, Lopez-Val, Vryonidou, arXiv:1407.0218]

Benchmark #3 (Enhanced bbh)

- Similar to MSSM (NMSSM) large tan β benchmarks

- tan β=20, M_H=500, large enhancement of bbh couplings

[B6 2HDM benchmark from 1407.0281]

Benchmark #4 (EFT)

- All resonances heavy, use EFT

- HXSNWG2 recommendation: linear representation (Higgs couplings from doublet)

$$L = L_{SM} + \left(\frac{h}{v} + \frac{h^2}{2v^2} \right) c_{gg} \frac{g_s^2}{4} G^A_{\mu\nu} G^{A,\mu\nu} - \frac{h}{v} \Sigma_f \Sigma_i m_{f_i} [\delta y_f]_i \overline{f}_i f_i$$

$$- \frac{h^2}{2v^2} \Sigma_f \Sigma_i m_{f_i} [y_f^{(2)}]_i \overline{f}_i f_i + \delta\lambda_3 h^3$$

- Assume no flavor violation in Higgs sector and CP conservation, neglect anomalous b couplings

- Free couplings: $c_{gg}, \; \delta y_t, \; y_t^{(2)}, \; \delta\lambda_3$

- Can be related to your favorite basis…..