HH Theory Status

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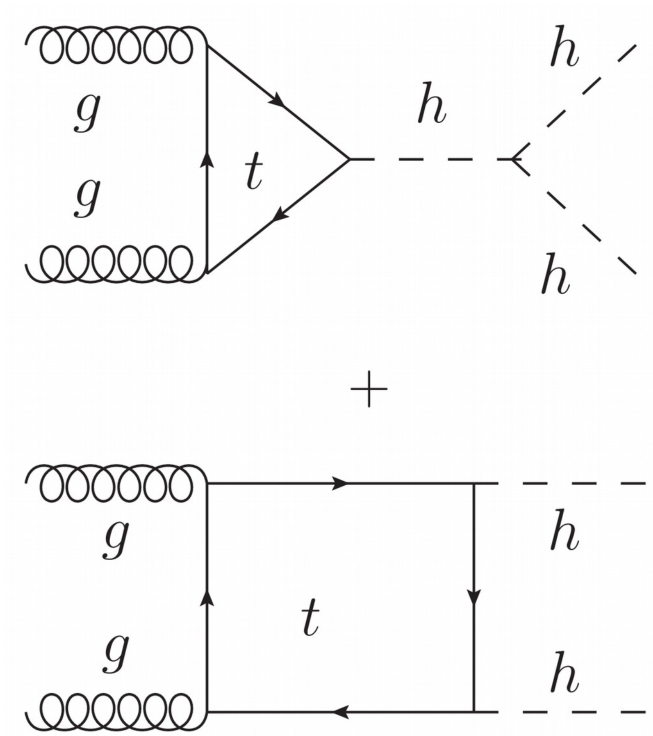
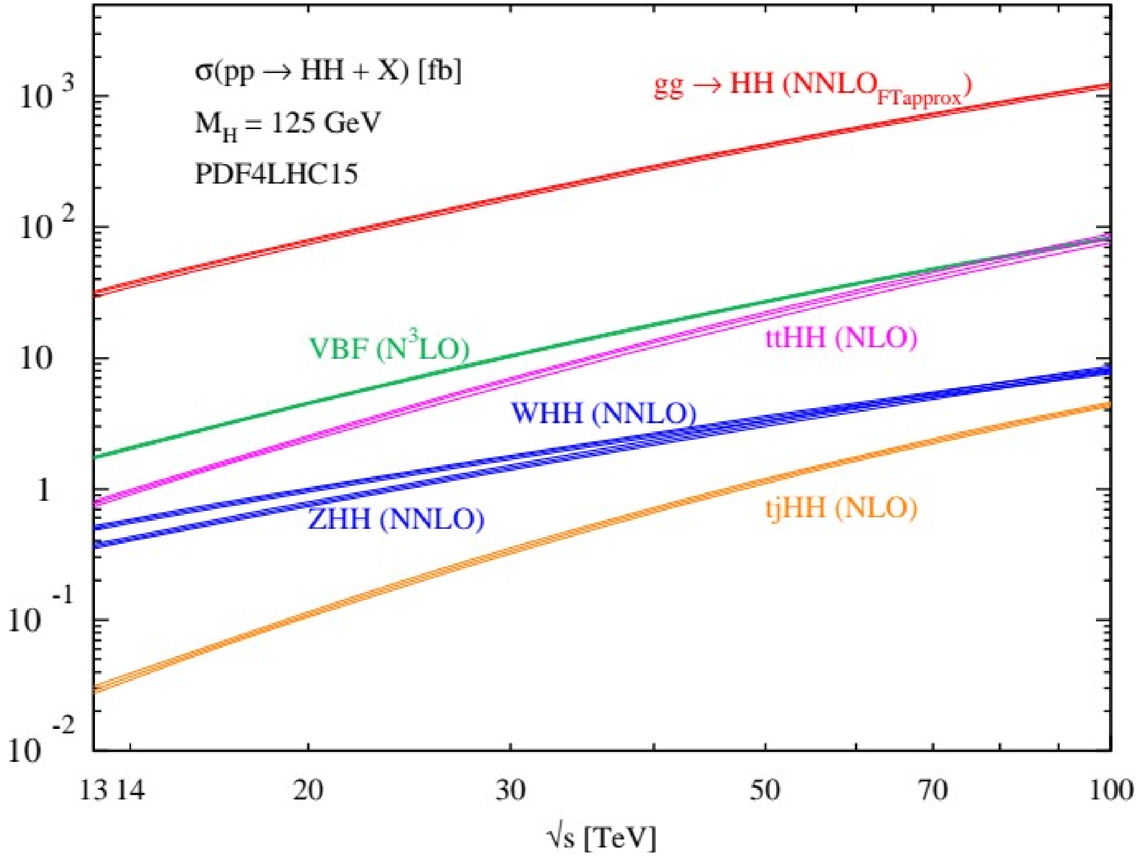
EF01 Jan. 12, 2022

Di-Higgs in SM

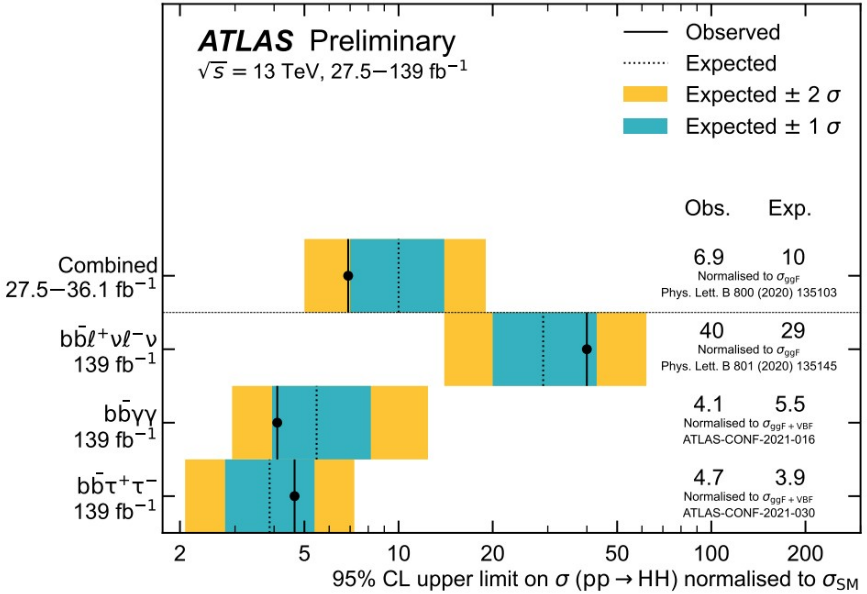


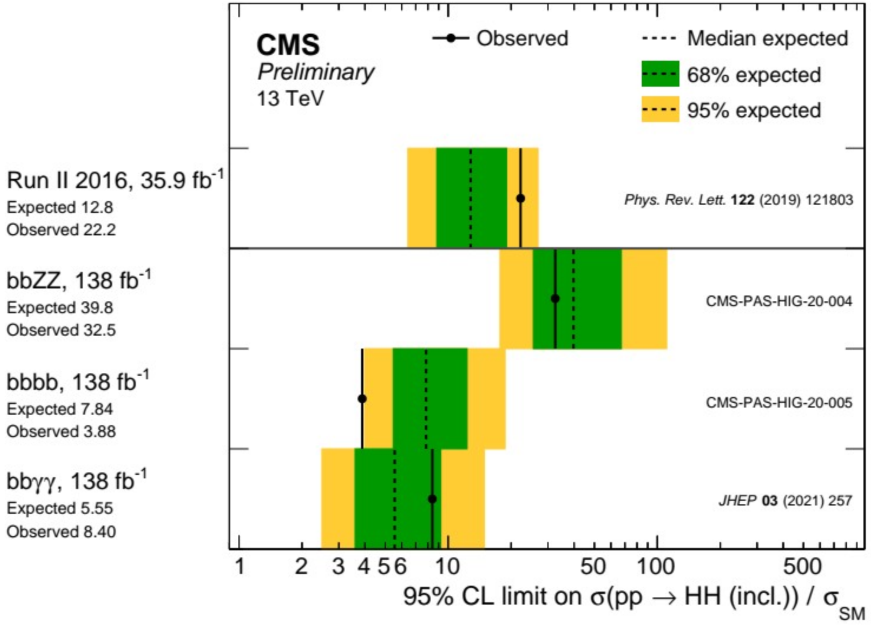


Higgs boson potential at colliders: Status and perspectives, Rev. Phys. 5 (2020) 100045

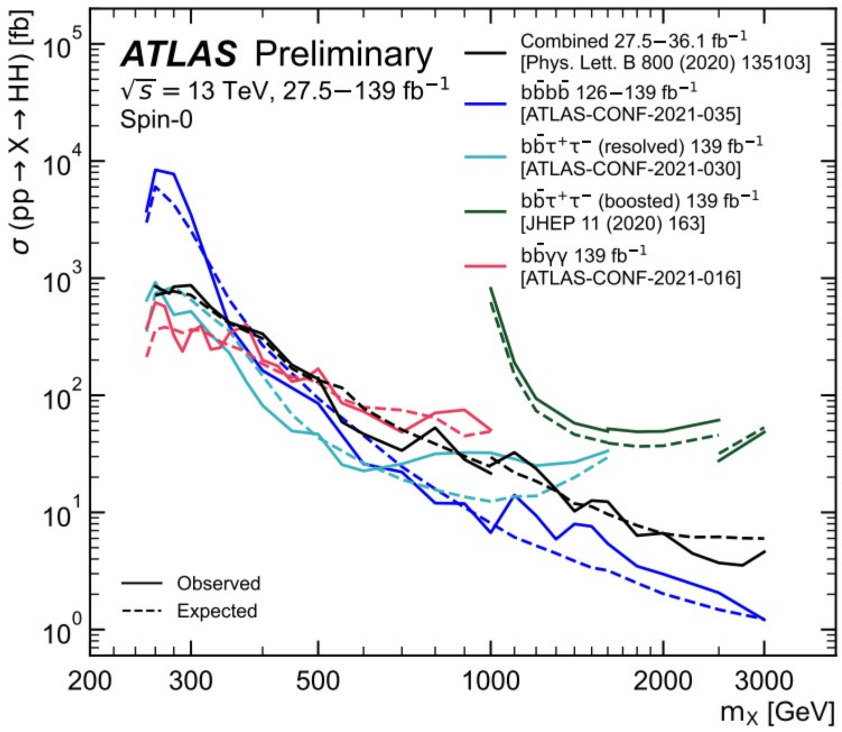
- From now on, will concentrate on gg->hh.

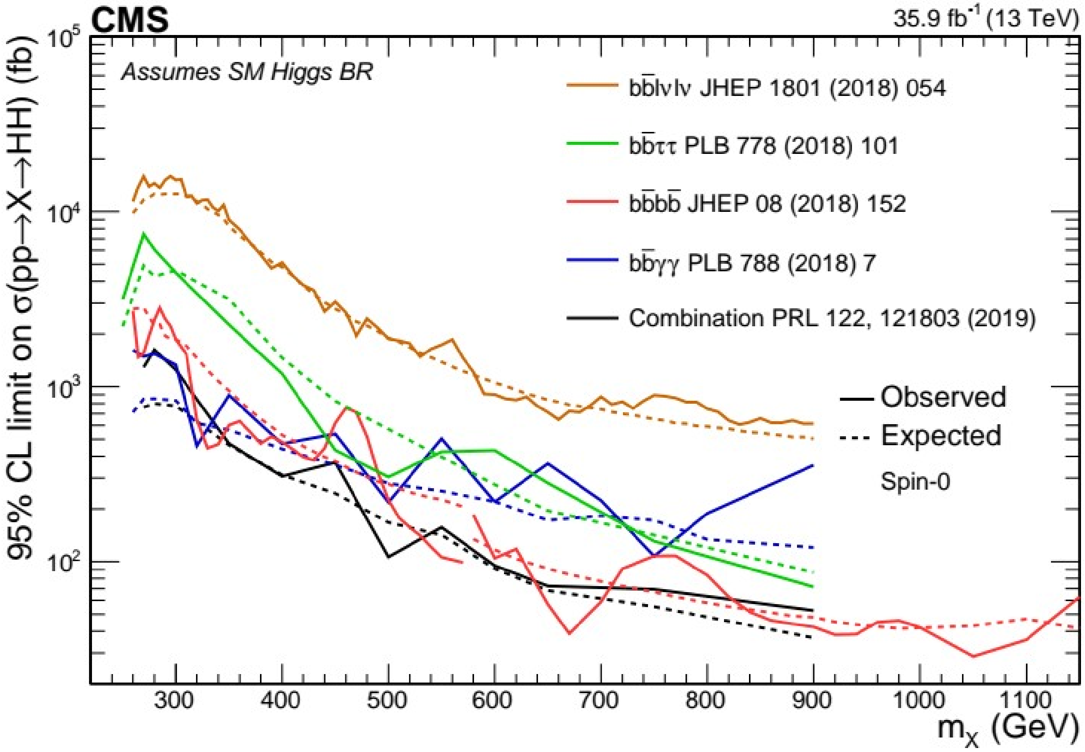
Current Searches: Non-Resonant





Current Searches: Resonance

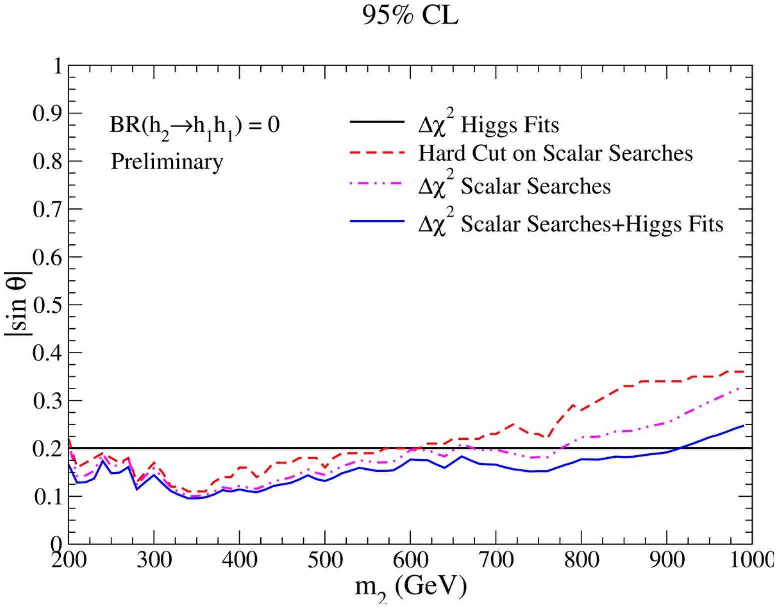


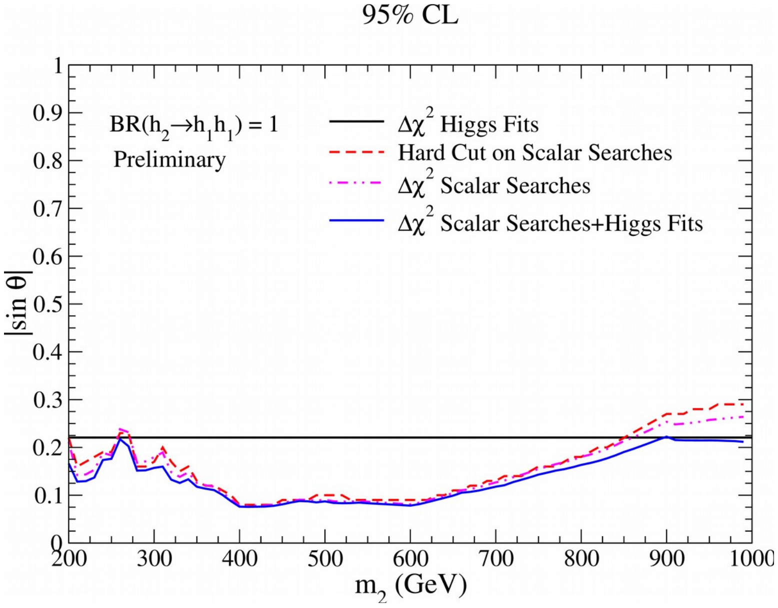


Precision vs. Direct Searches

Singlet Model (No Z_2): Fits to data

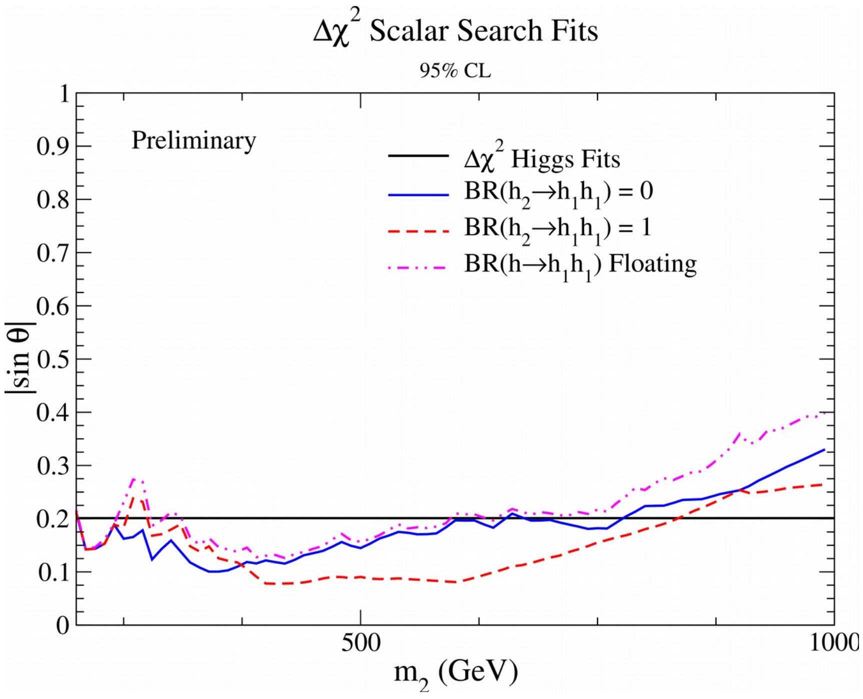
- Compare fits including and not including Di-Higgs resonance searches.
- Including WW/ZZ/hh resonant searches.
- Hard cut: usual method of rejecting a point if it is excluded by any search.
- $\Delta\chi^2$: our proposed method for including searches in a χ^2 fit, see Adhikari, **IML**, Sullivan, PRD 103 (2021) 075027

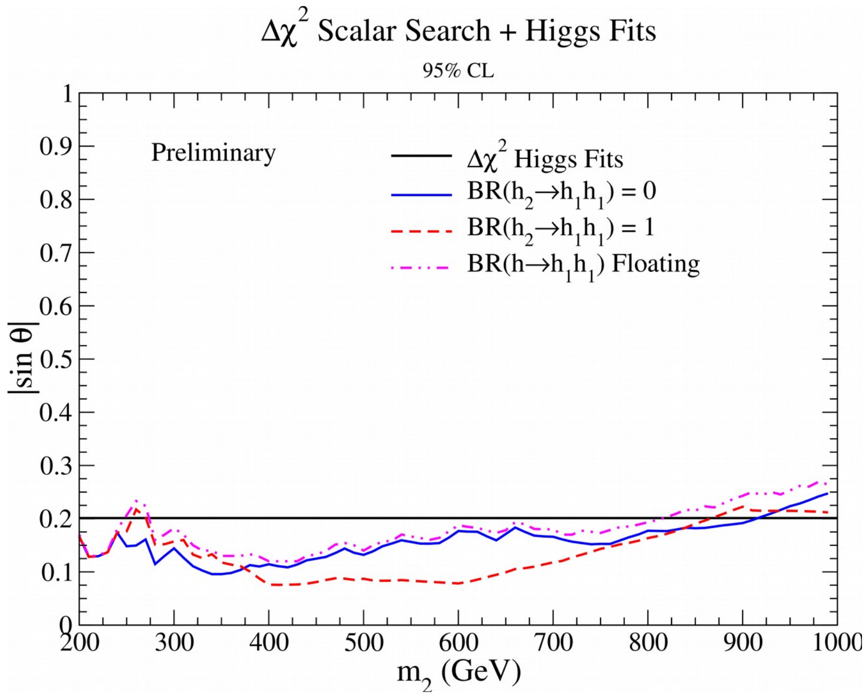




Adhikari, Lane, **IML**, Sullivan, PRELIMINARY

Singlet Model (No Z_2): Fits to data

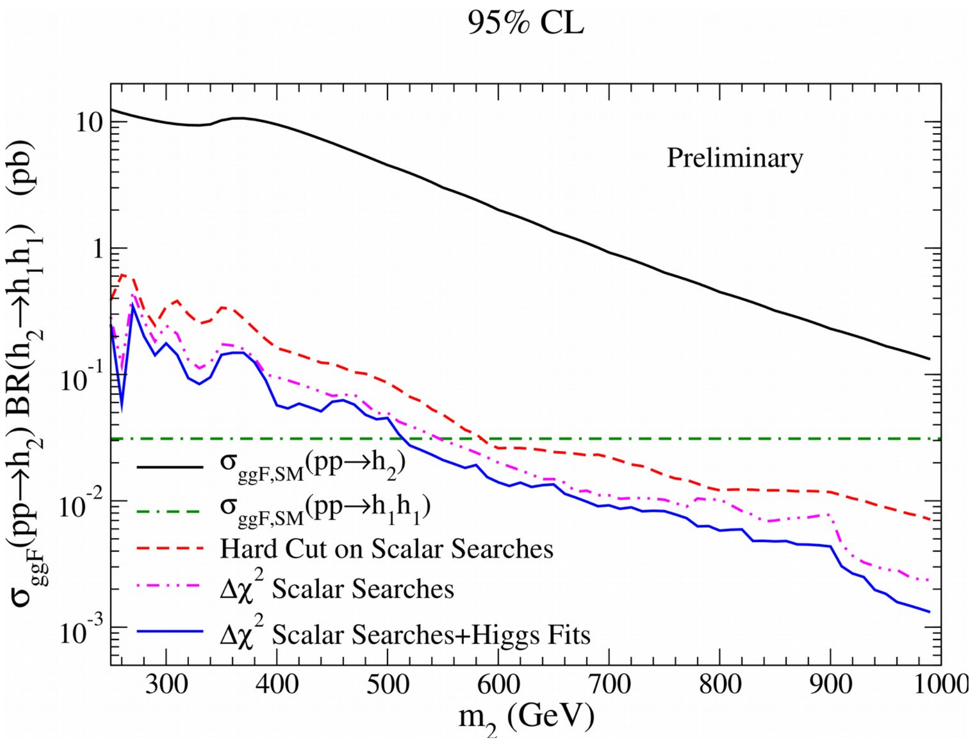




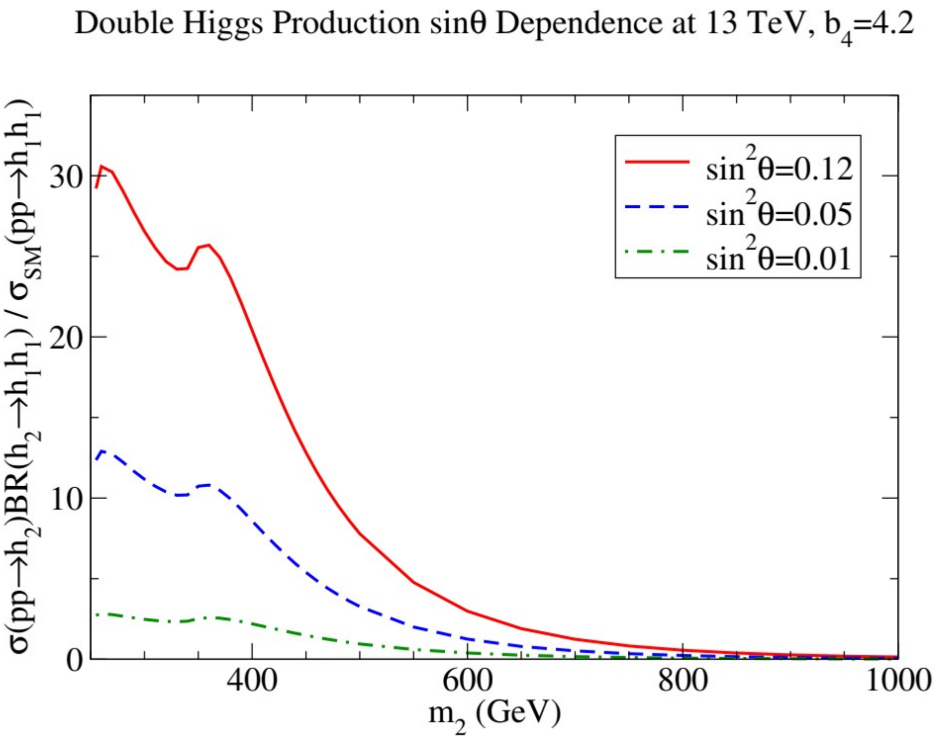
- Comparing 0%, 100%, and floating Di-Higgs branching ratios.

Adhikari, Lane, **IML**, Sullivan, PRELIMINARY

Max Rates in Singlet Model



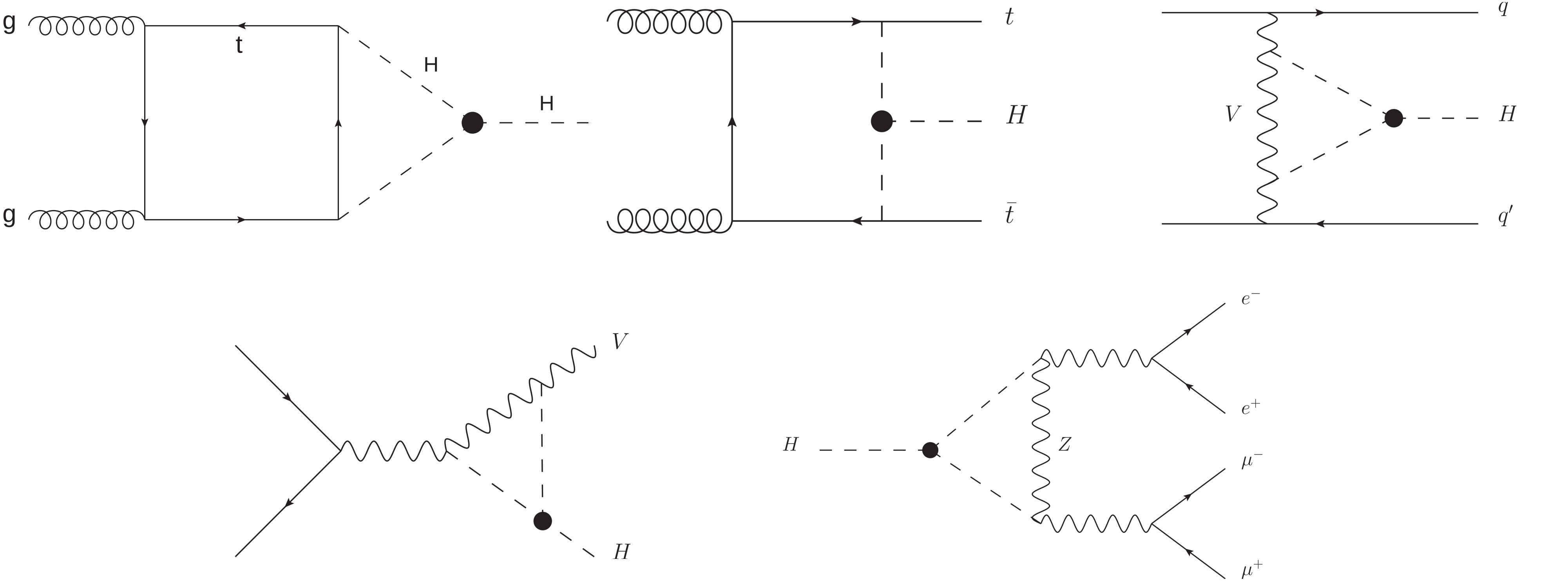
Adhikari, Lane, **IML**, Sullivan, PRELIMINARY



IML, Sullivan, PRD 96 (2017) 035037
See also Robens, Stefaniak, EPJC 76 (2016) 268

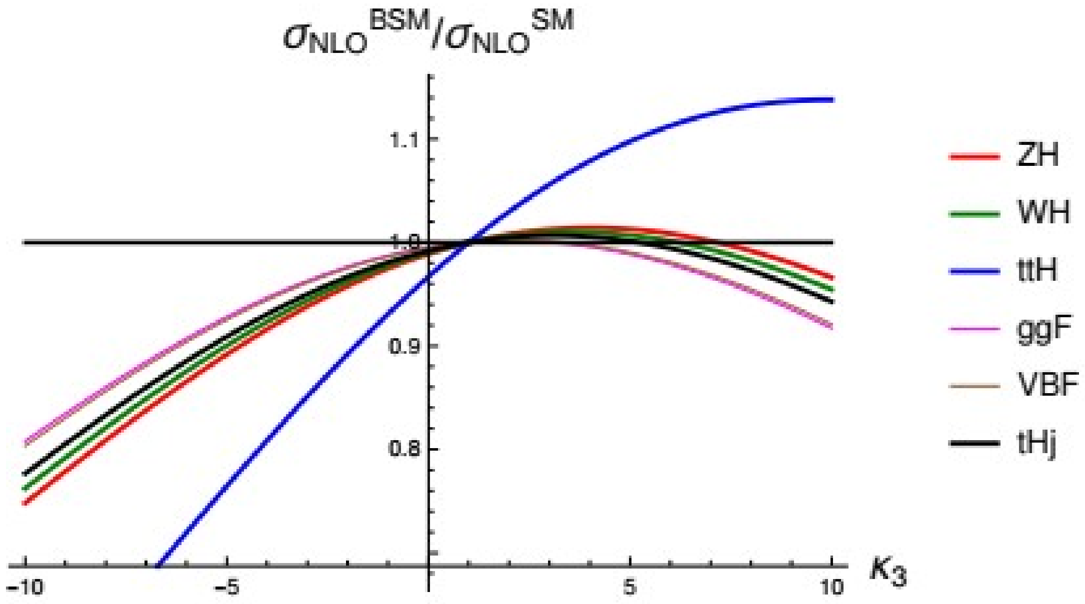
- Current constraints
- Maximum allowed rates

Trilinear: Indirect



- Trilinear Higgs boson coupling can also appear in single Higgs production and decay at loop level. McCullough 2014; Gorbah, Haisch, 2016; Degrassi Guiardinao, Maltoni, Pagain, 2016; Bizon,Gorbahn, Haisch, Zanderighi, 2016; Di Vita, Grojean, Panico, Rimbau, Vantalon, 2017; Maltoni, Pagani, Shivaji, zhao, 2018

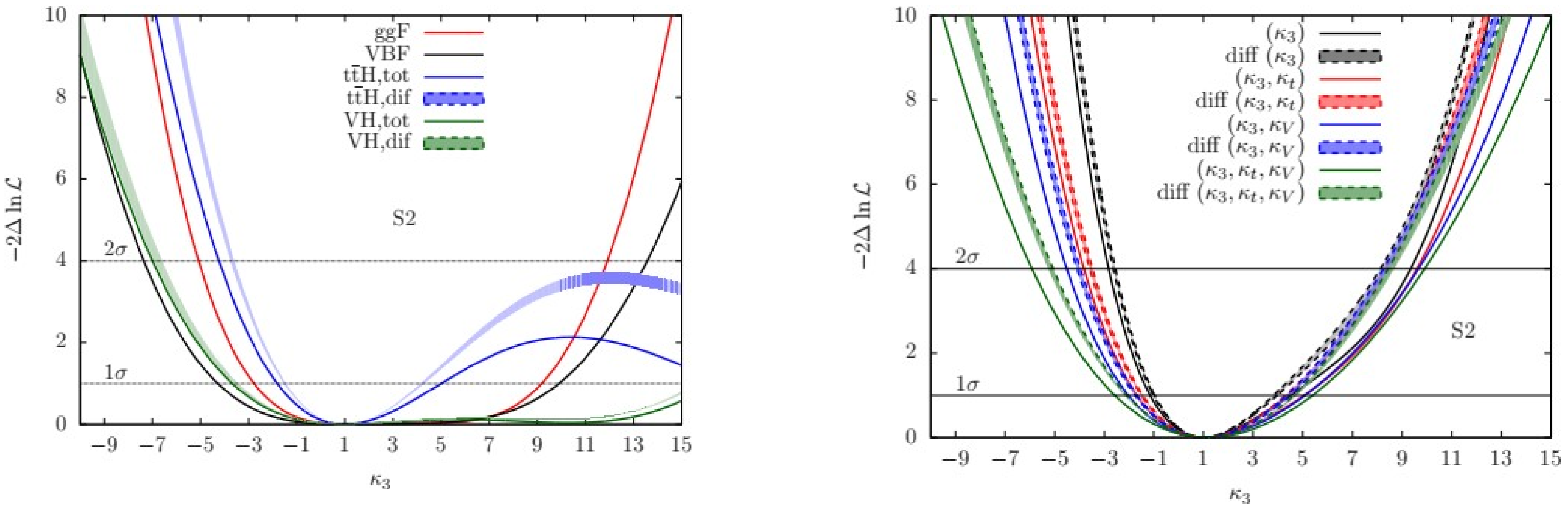
Trilinear in Loops



Maltoni, Pagani, Shivaji, Zhao, EPJC 77 (2017) 887

- Effects of anomalous trilinear Higgs couplings in production and decay.

Loop Level Trilinear



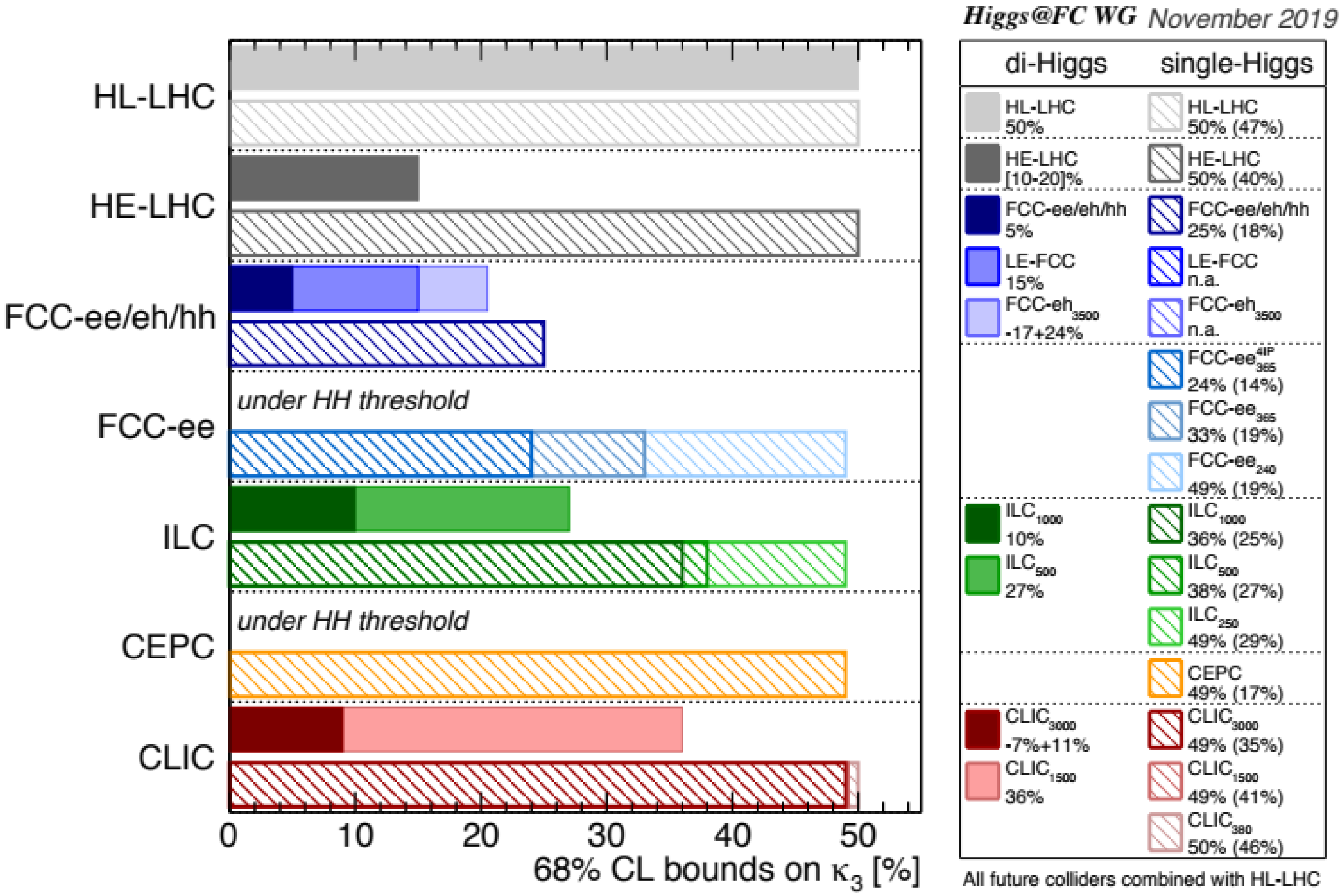
Maltoni, Pagani, Shivaji, Zhao, EPJC 77 (2017) 887

- HL-LHC projections
- Including systematic and theory uncertainties
- κ3 expectations from direct searches at HL-LHC:
  - 1σ: 0.5-1.4

Single Production vs. Double Production: Future Colliders

- Direct: Solid
- Indirect: hashed
- Paranthesis: one parameter fit

Higgs boson potential at colliders: Status and perspectives, Rev. Phys. 5 (2020) 100045



Trilinear from Models

- In SMEFT, have operators $\frac{C_\Box}{\Lambda^2}(\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi) + \frac{C_\phi}{\Lambda^2}(\Phi^\dagger\Phi)^3$
- This give an anomalous trilinear Higgs coupling:

$$\kappa_3 = \frac{\lambda_3}{\lambda_3^{\rm SM}} = 1 - \frac{v^2}{\Lambda^2}\left(C_\phi - 3\,C_\Box\right)$$

- If we integrate out heavy fields, can match onto that operator (small mixing limit)

Dawson, Murphy, PRD 96 (2017) 015041; Dawson, Homiller, Lane, PRD 102 (2020) 055012

 – Singlet model: $\frac{v^2}{\Lambda^2}C_\Box = -\frac{1}{2}\tan^2\theta \qquad C_\phi = -C_\Box\left(\tan\theta\frac{m}{2\,v} - \kappa\right)$

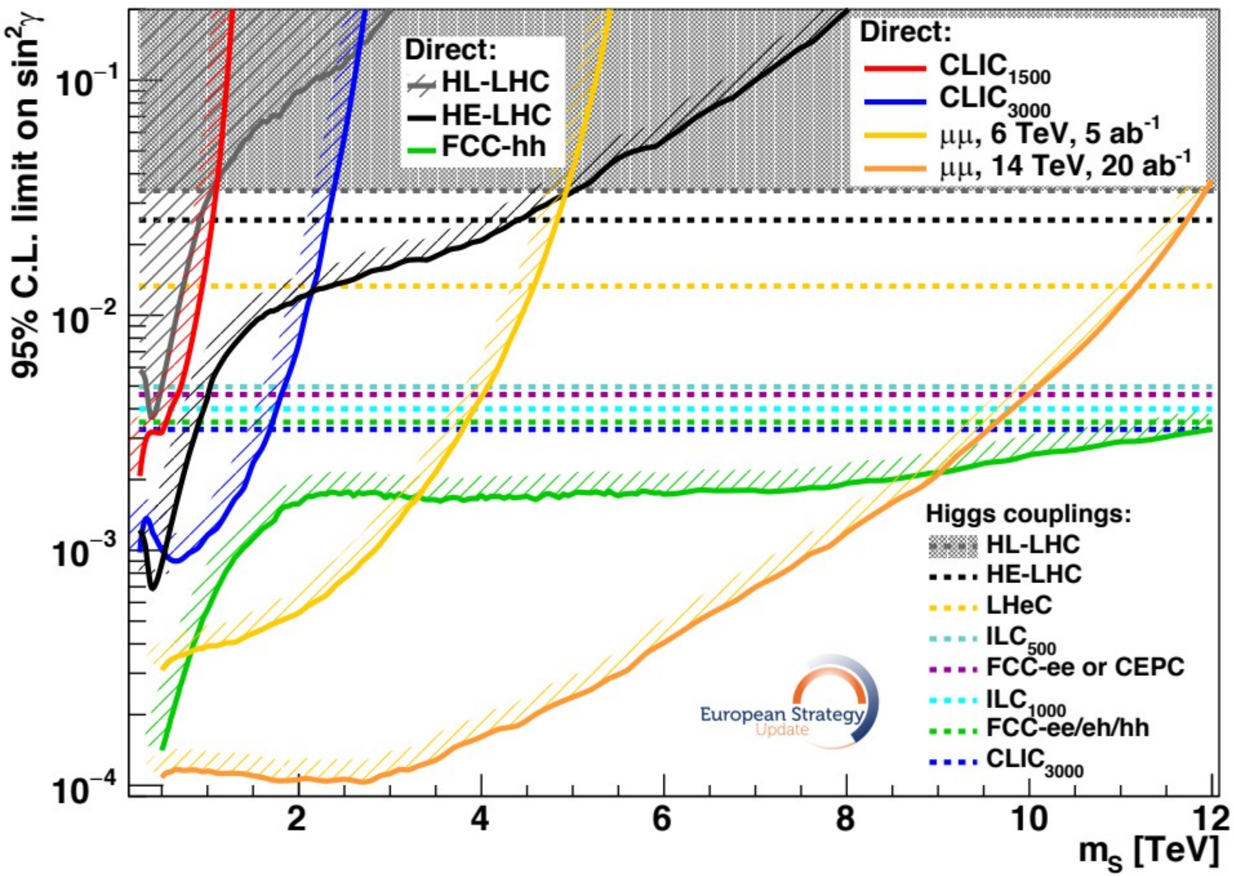
 – 2HDM: $\frac{v^2}{\Lambda^2}C_\phi = \frac{\cos^2(\beta-\alpha)M^2}{v^2}$

 – M is the common mass of the heavy Higgs doublet, m is a Lagrangian mass parameter, κ depends on quartics and mass parameters.

Singlet Constraints from single parameter Trilinear fits

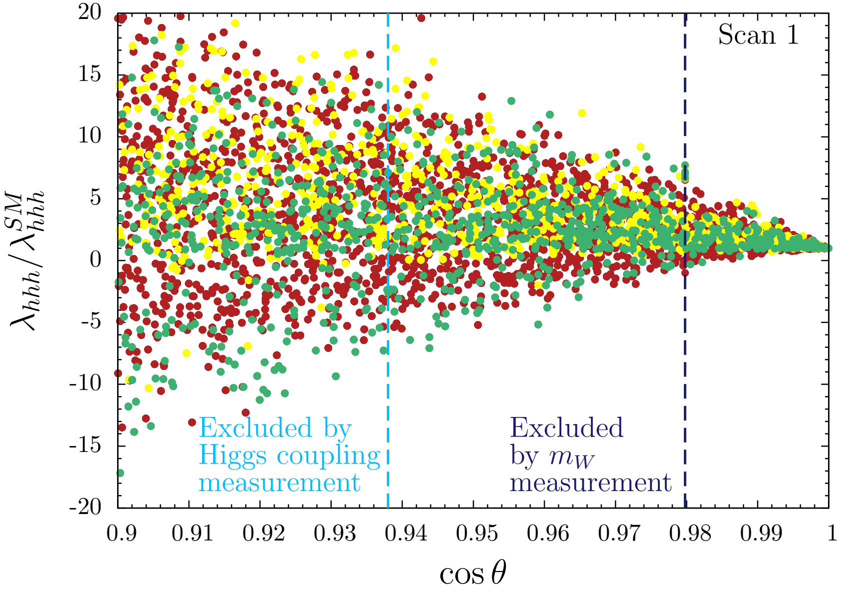
- ILC 240:
  - Single H: $\sin^2\theta \lesssim 0.2 - 0.25$
- ILC-500:
  - Single/Double H: $\sin^2\theta \lesssim 0.19 - 0.24$
- FCC-ee 250:
  - Single H: $\sin^2\theta \lesssim 0.14 - 0.18$
- FCC-ee/eh/hh:
  - Single H: $\sin^2\theta \lesssim 0.14 - 0.17$
  - Double H: $\sin^2\theta \lesssim 0.04 - 0.05$
- Current precision Higgs:

$$\sin^2\theta \lesssim 0.04$$

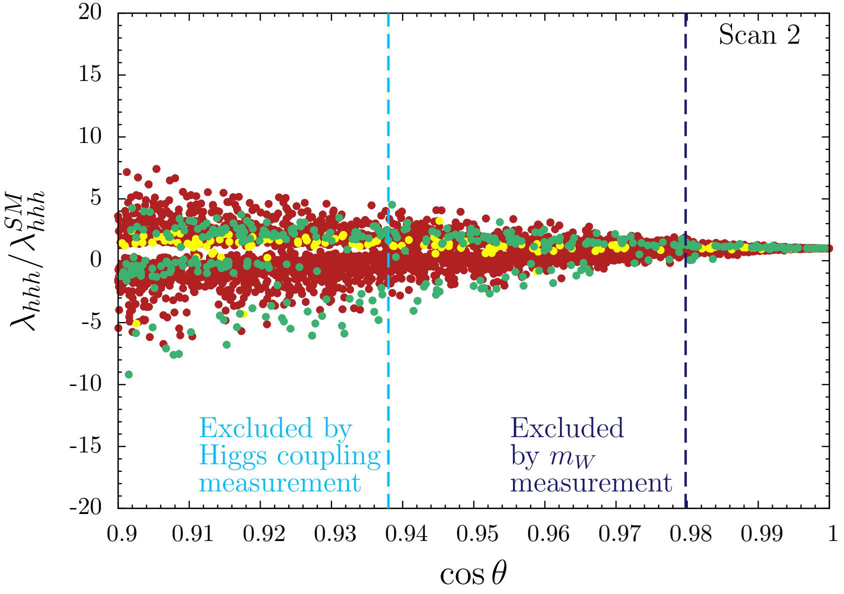


Physics Briefing Book, 1910.11775

How big can trilinear get in Singlet Model?



Strongly Coupled



Weakly Coupled

Di Luzio, Grober, Spannowsky EPJC 77 (2017) 788

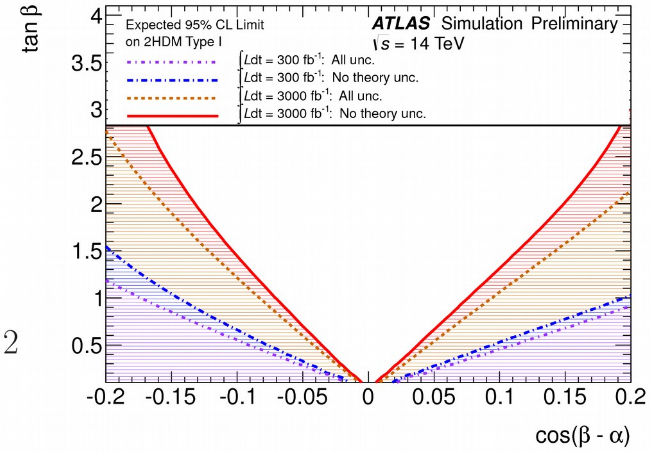
- Current Higgs precision limit: cos θ > 0.98
- Assumed mass about 800 GeV.
- Can still have a variation by a factor of two.

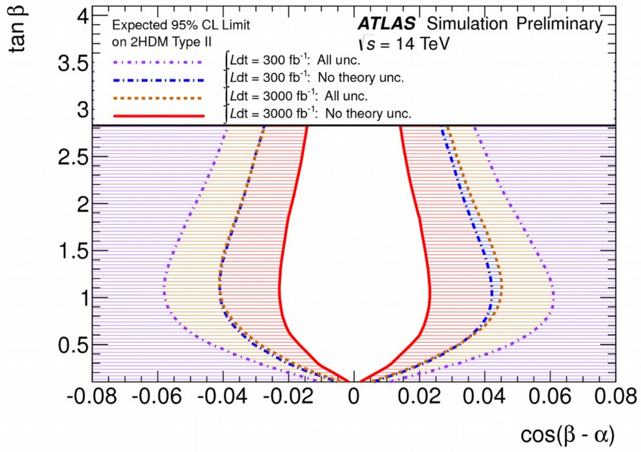
2HDM: HL-LHC Precision Measurements

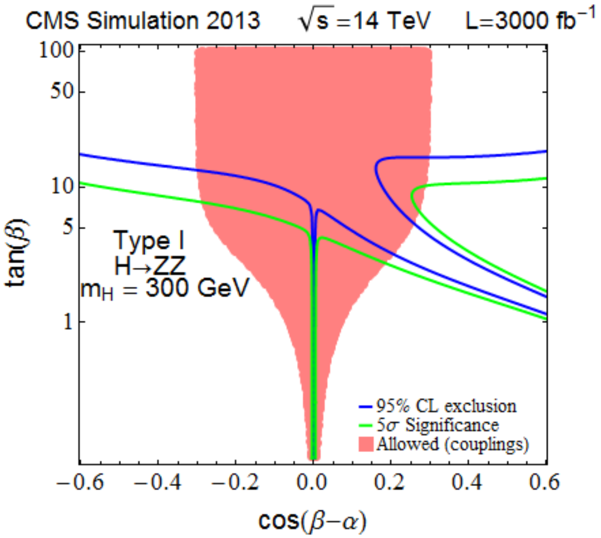
- Variation of trilinear is small unless there are large decoupling effects.
- Due to mixing angle being small from precision measurements.

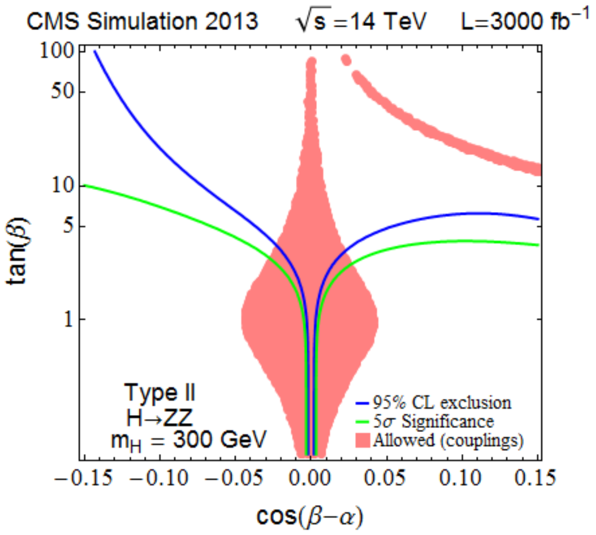
$$\kappa_3 = 1 + 0.17\left(\frac{\cos(\beta-\alpha)}{0.1}\right)^2\left(\frac{M}{\text{TeV}}\right)^2$$

- Would expect HL-LHC to see resonance before variation in trilinear gauge coupling.
- HL-LHC expected to have ~50% measurement of trilinear coupling.
- CEPC and FCC-ee can put 95% CL limit on the variation up to 17-19%







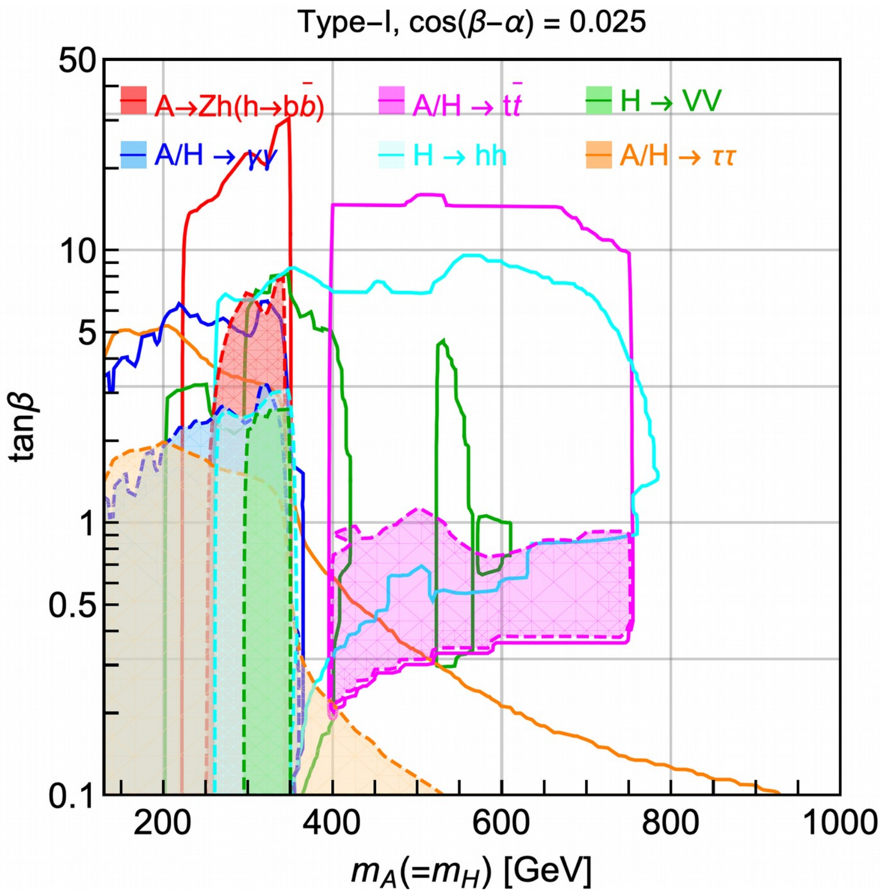


2HDM Type I: HL-LHC

- Solid: HL-LHC
- At $\cos(\beta-\alpha)=0.025$ the trilinear variation is

$$\kappa_3 = 1 - 0.01\left(\frac{M}{\mathrm{TeV}}\right)^2$$

- Sensitive to direct detection before variations in anomalous trilinear Higgs coupling.



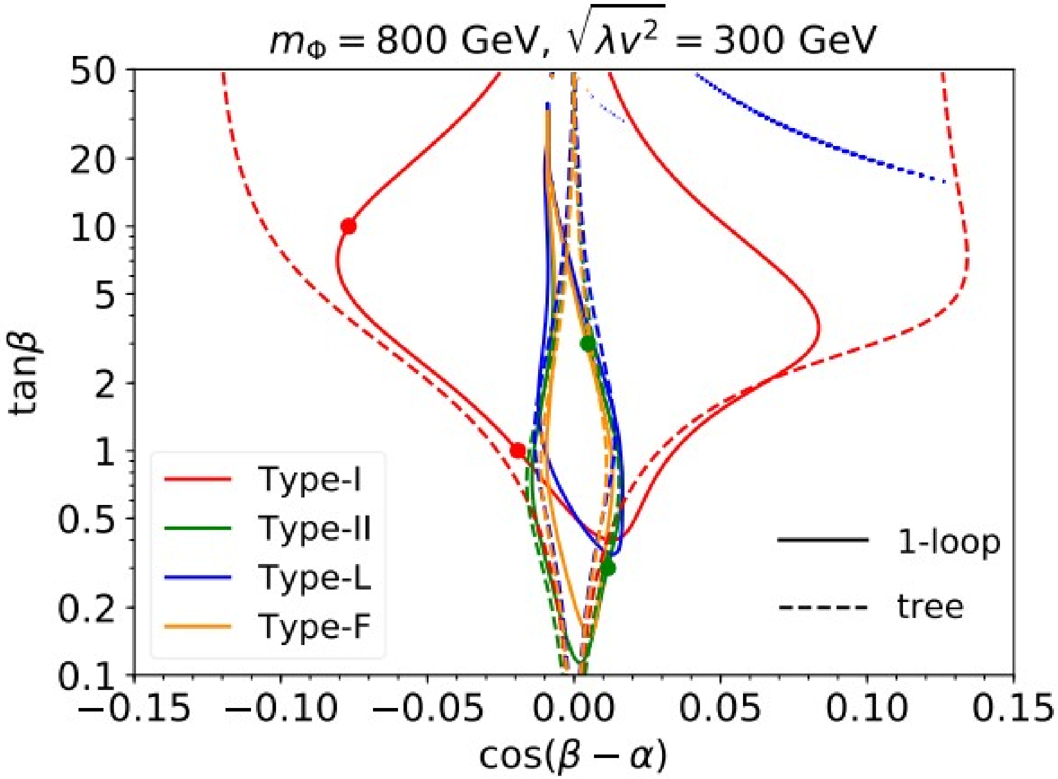
Chen, Han, Li, Su, Su, JHEP 08 (2020) 131

2HDM: CEPC Precision Measurements

- 5 sigma discovery regions
- Can measure triple Higgs coupling indirectly to 17% at CEPC.
- At a mass of 800 GeV, this translates to

$$|\cos(\beta-\alpha)| \lesssim 0.13$$

- Precision Higgs measurements more sensitive.
- Note: parameter point on previous slide is just discoverable at CEPC, depending on tan β



Han, Li, Su, Su, Wu, JHEP 01 (2021) 045

2HDM Benchmarks for Resonant Di-Higgs

- Type-I
- Cos(β-α)=0.11

m_{H_1} [GeV]	m_{H_2} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	α	$\tan\beta$	m_{12}^2 [GeV^2]
125.09	263	622	626	-0.285	2.371	25922

$\lambda_{3H_1}/\lambda_{3H}$	$y_{t,H_1}/y_{t,H}$	$\sigma_{H_1}^{\rm NNLO}$ [pb]	$\sigma_{H_2}^{\rm NNLO}$ [pb]	$\sigma_A^{\rm NNLO}$ [pb]	
0.909	1.042	53.45	1.26	0.55	

$$\begin{aligned}
&{\rm BR}(H_2\to H_1H_1) = 0.504\,, \quad {\rm BR}(H_2\to WW) = 0.342\,, \quad {\rm BR}(H_2\to ZZ) = 0.147\\
&{\rm BR}(A\to ZH_2) = 0.865\,, \quad {\rm BR}(A\to t\bar t) = 0.116\,,\\
&{\rm BR}(H^\pm\to W^\pm H_2) = 0.874\,, \quad {\rm BR}(H^+\to t\bar b) = 0.107\,.
\end{aligned}$$

$$\sigma_{H_2}^{\rm NNLO}\times {\rm BR}(H_2\to H_1H_1) = 635\ {\rm fb}$$

- Type-II
- Cos(β-α)=-0.027

m_{H_1} [GeV]	m_{H_2} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	α	$\tan\beta$	m_{12}^2 [GeV^2]
125.09	528	798	809	-0.695	1.268	130388

$\lambda_{3H_1}/\lambda_{3H}$	$y_{t,H_1}/y_{t,H}$	$\sigma_{H_1}^{\rm NNLO}$ [pb]	$\sigma_{H_2}^{\rm NNLO}$ [pb]	$\sigma_A^{\rm NNLO}$ [pb]	
0.974	0.978	47.02	2.84	0.47	

$$\begin{aligned}
&{\rm BR}(H_2\to H_1H_1) = 0.012\,, \quad {\rm BR}(H_2\to t\bar t) = 0.979\,,\\
&{\rm BR}(A\to ZH_2) = 0.514\,, \quad {\rm BR}(A\to t\bar t) = 0.482\,,\\
&{\rm BR}(H^\pm\to W^\pm H_2) = 0.560\,, \quad {\rm BR}(H^+\to t\bar b) = 0.437\,.
\end{aligned}$$

$$\sigma_{H_2}^{\rm NNLO}\times {\rm BR}(H_2\to H_1H_1) = 34\ {\rm fb}$$

Maximize resonant production rate

Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, Muhlleitner, Santos, arXiv:2112.12515

“Nightmare Scenario”

Resonant vs. Non-Resonant

- Immense amount of work on Di-Higgs resonances.
  - Pair production of SM Higgs and mixed states via resonance: hh, hS, SS
- What about non-resonant production?
  - Case study: singlet model with no Z_2
  - Indeed, there is a diagram that can produce SS that does not decouple in the zero mixing limit.
  - So-called “nightmare-scenario” Curtin, Meade, Yu, JHEP 11 (2014) 127
  - However, if Z_2 is broken or no Z_2, mixing angle does not have to be precisely zero.
  - Then new heavy scalars can decay and give visible signatures.
  - Will have little to no evidence in SM Higgs decays or double SM Higgs production.

Zero Mixing Limit

- Couplings between scalar and Higgs:

$$V(h,S)=\frac{a_1}{4}(h+v)^2S+\frac{a_2}{4}(h+v)^2S^2$$

- Source of Higgs-scalar mixing is:

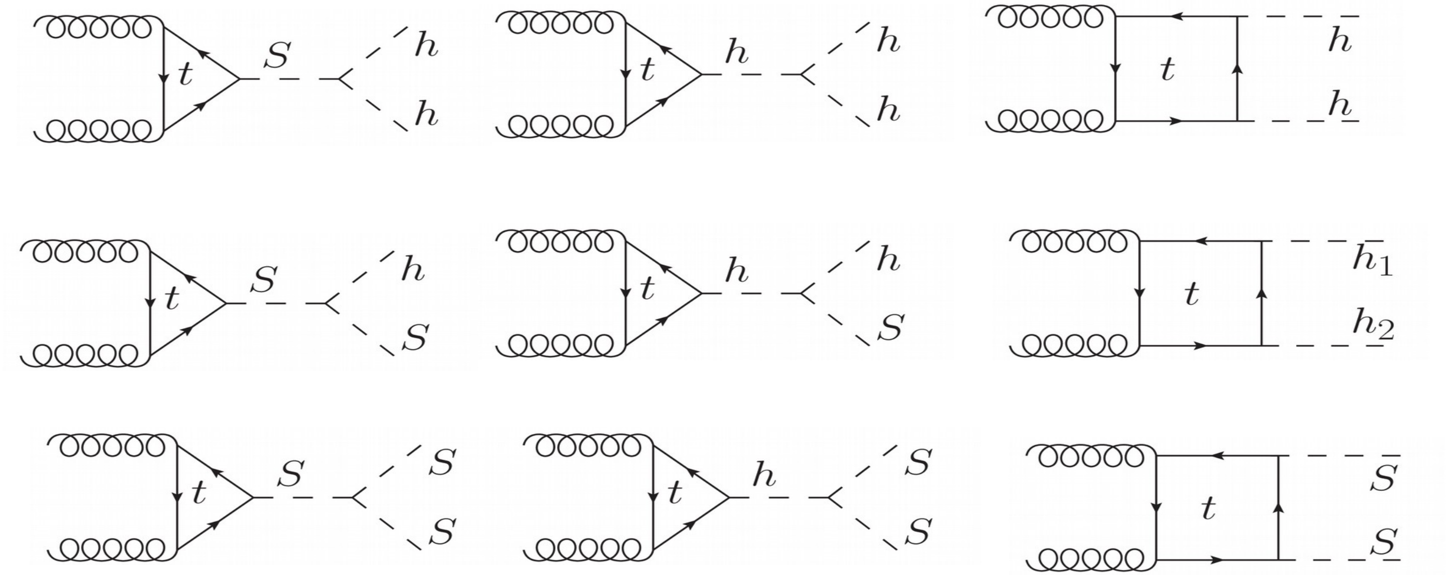
$$V(h,S)\supset\frac{a_1\,v}{2}h\,S$$

- In the limit of zero mixing $a_1 \rightarrow 0$ and only a_2 survives

$$V(h,S)\rightarrow\frac{a_2}{4}(h+v)^2\,S^2=\frac{a_2\,v^2}{4}S^2+\frac{a_2\,v}{2}h\,S^2+\frac{a_2}{4}h^2\,S^2$$

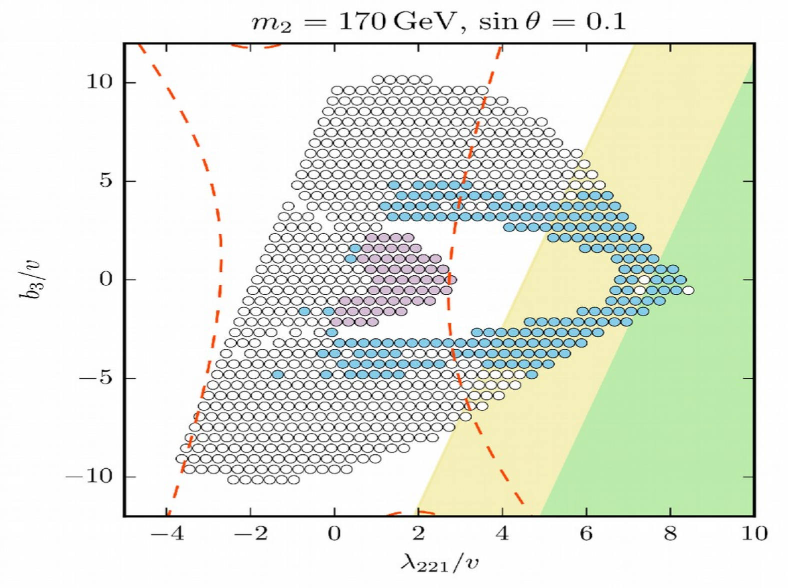
- If the scalar S does not mix with the Standard ModelHiggs, it only couples to the Higgs. Very difficult to produce and can be stable.
- a_2 is the only term to drive the first order phase transition.
  - Lower limit on how large it can be.
  - Gives h-h-S-S and h-S-S couplings, and so we have a lower bound on these.

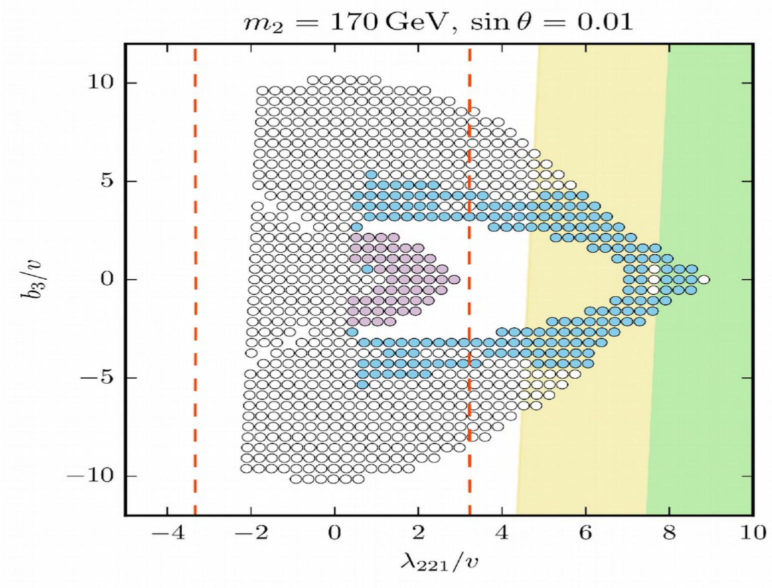
Non-Zero Mixing



- Many di-boson production modes, all with different information about the potential.
  - Can have resonant di-Higgs if allowed.
- SS production depends on h-S-S coupling.
  - This is the coupling that must stay non-zero to hae a strong first order electroweak phase transition.

High Luminosity LHC



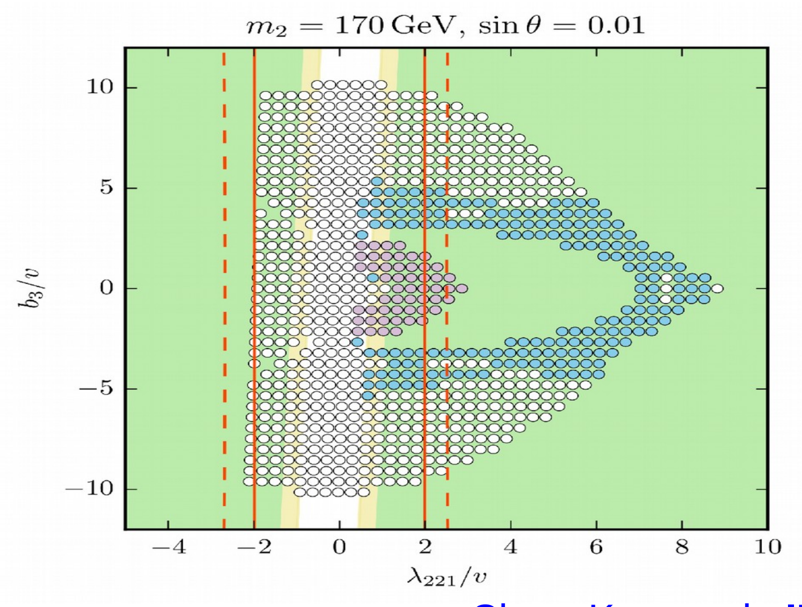


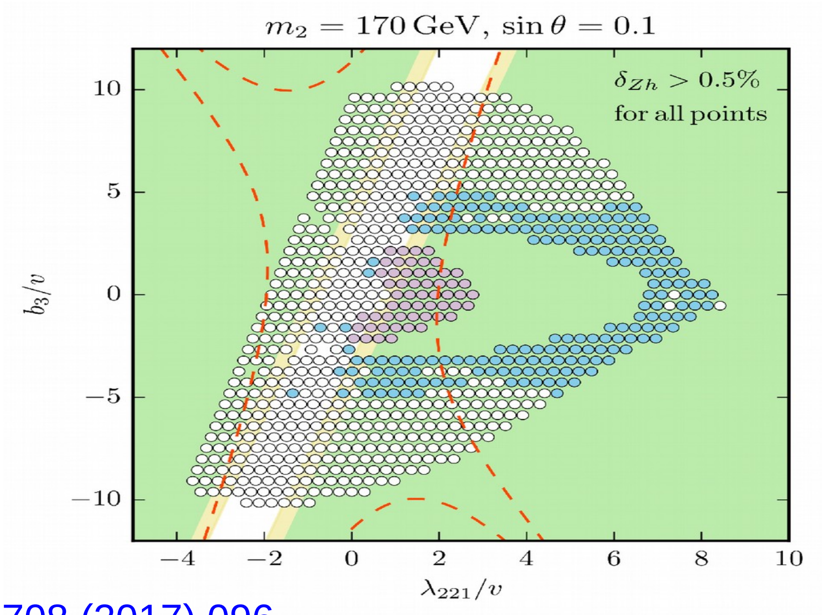
Chen, Kozaczuk, **IML** JHEP 1708 (2017) 096

- 3 ab^{-1} at 14 TeV LHC.
- Comparison of different methods of searching.
- Colored Dots: Compatible with strong first order electroweak phase transition.
- Searches for h_2h_2 production: Yellow: Exclusion, Green: Discovery
- Red dashed curves: Higgs self-coupling limits at 30%.

$$pp \to h_2 h_2 \to 4W \to 2j2\ell^{\pm}\ell'^{\mp}3\nu, \qquad \ell \neq \ell'.$$

100 TeV





Chen, Kozaczuk, **IML** JHEP 1708 (2017) 096

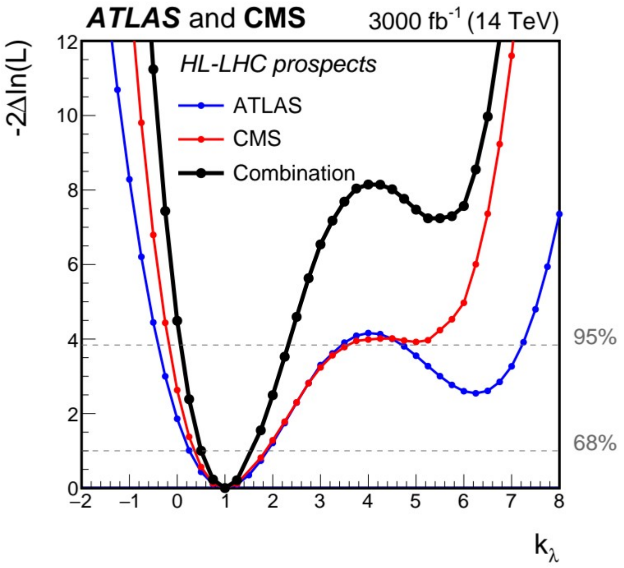
- 30 ab^{-1} at 100 TeV, can probe much of the parameter space.
- Colored Dots: Compatible with strong first order electroweak phase transition.
- Searches for h_2h_2 production: Yellow: Exclusion, Green: Discovery
- Red dashed curves: Higgs self-coupling limits to 15%. Solid lines: Higgs-Z-boson coupling limits to 0.5%

$$pp \to h_2 h_2 \to 4W \to 2j2\ell^\pm \ell'^\mp 3\nu, \qquad \ell \neq \ell'.$$

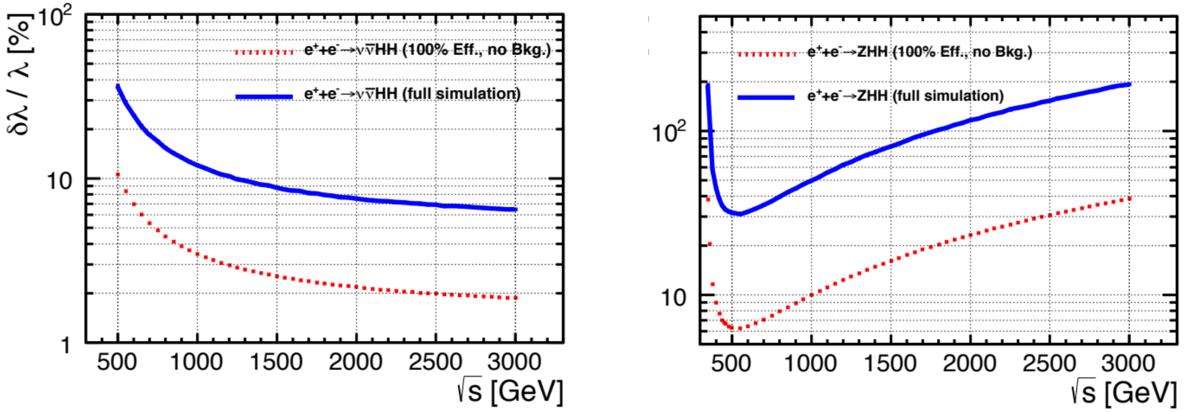
Conclusions

- Complementarity between precision Higgs and direct searches.
- Current double Higgs resonance searches do put meaningful constraints on models.
- Direct searches can be sensitive to regions precision Higgs is not.
  - Some production modes of double scalar do not decouple.
- Many topics not covered:
  - The aforementioned double scalar resonances: hS, SS
  - New particles in the loop.
  - Light quark Yukawas in double Higgs production. Alasfar, Lopez, Grober JHEP 11 (2019) 088

Di-Higgs Projections: Future Colliders



HL-LHC



ILC

	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}ZZ^*$ (4ℓ)	$b\bar{b}WW^*$ $(2j\ell\nu)$	$b\bar{b}b\bar{b}$ +jet
$\delta\kappa_\lambda$	6%	8%	14%	40%	30%

Table 10.4: Precision of the direct Higgs self-coupling measurement in $gg \to HH$ production at $\sqrt{s} = 100$ TeV with $\mathscr{L} = 30$ ab^{-1} for various decay modes.

100 TeV pp

Higgs boson potential at colliders: Status and perspectives, Rev. Phys. 5 (2020) 100045

Thank You