Christoph Englert

BSM scans of HH final states

Higgs Pairs mini Workshop

29/09/21

Fingerprinting the lack of new physics

coupling/scale separated BSM physics

Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

[Grzadkowski, Iskrzynski, Misiak, Rosiek `10] ...

- benchmarking as part of WGR 4
- limitations known and tackled

→ *Michael's & Gudrun's talk*

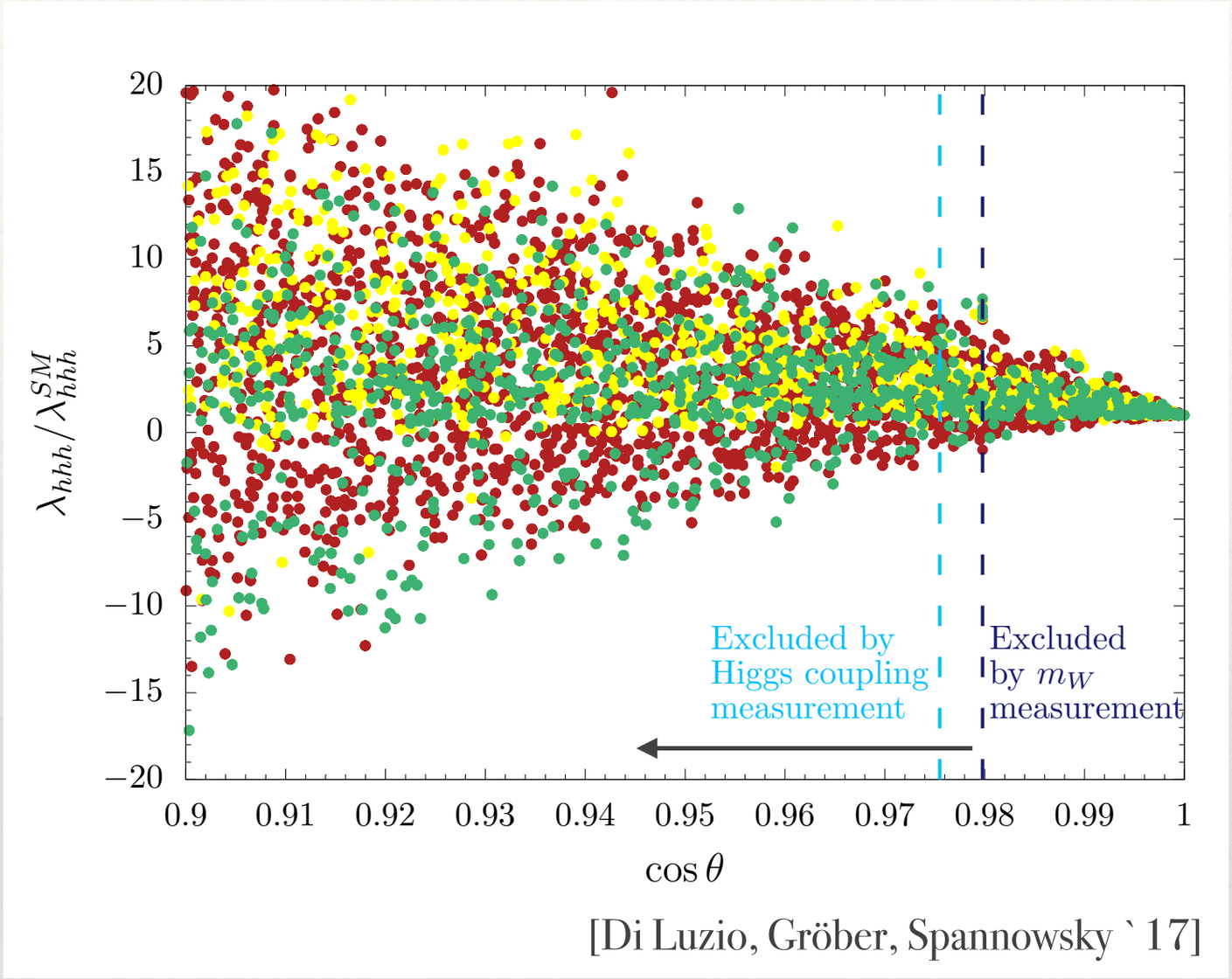
- limits on ad-hoc EFT deformations

HXSWG benchmarks e.g. [CMS `18]

concrete models

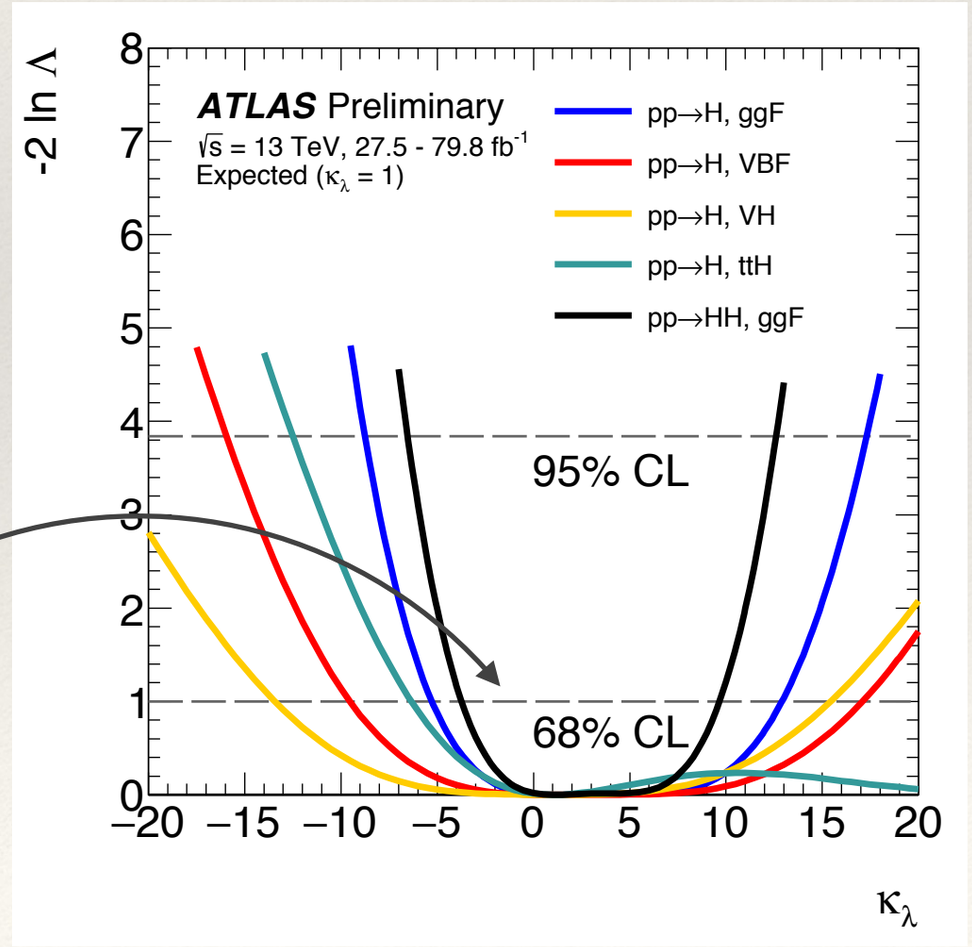
- extended SMEFT
- (ℂ) Higgs portals
- 2HDMs
- simplified models
- compositeness….

Room for EFT deformations?



[Di Luzio, Gröber, Spannowsky `17]

ϕ	$\mathcal{O}_\phi$
$(1,1,0)$	$\phi\Phi\Phi^\dagger$
$(1,2,\frac{1}{2})$	$\phi\Phi\Phi^\dagger\Phi^\dagger$
$(1,3,0)$	$\phi\Phi\Phi^\dagger$
$(1,3,1)$	$\phi\Phi^\dagger\Phi^\dagger$
$(1,4,\frac{1}{2})$	$\phi\Phi\Phi^\dagger\Phi^\dagger$
$(1,4,\frac{3}{2})$	$\phi\Phi^\dagger\Phi^\dagger\Phi^\dagger$



- Higgs pairs do not exist in a phenomenological vacuum…
- …. can be understood as $-1.5 < \kappa_\lambda < 8.7.$

singlets above threshold

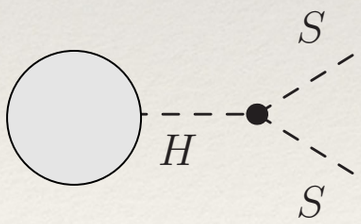
- $\mathbb{Z}_2$-symmetric Higgs portal

[Craig , Lou. et al.` 14]
[Curtin, Meade, Yu ` 14]
...

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2} S^2 - \lambda S^2 (\Phi^\dagger \Phi - v^2/2)$$

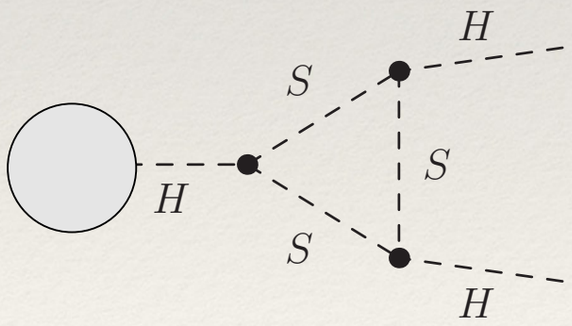
- for $m_S > m_H/2$ no direct SM Higgs decays
- BSM Higgs physics via momentum- or loop-suppressed effects

off-shell production



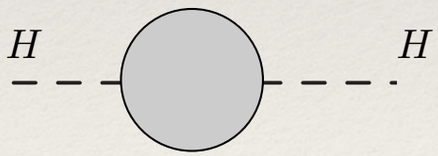
[Craig , Lou. et al.` 14]
[Ruhdorfer, Salvioni, Weiler ` 19]

di-Higgs physics



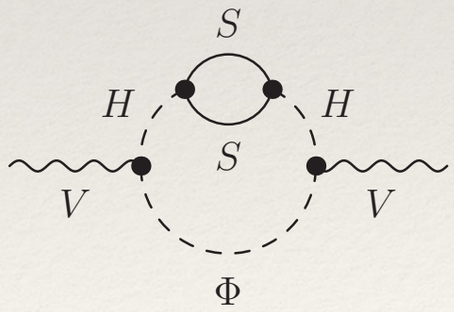
[Curtin, Meade, Yu ` 14]
[He, Zhu ` 16]
[Voigt, Westhoff ` 17]

Higgs couplings



[CE, McCullough ` 13]
[Craig, CE, McCullough ` 13]
[Goncalves, Han, Mukhopadhyay ` 18]

Electroweak precision

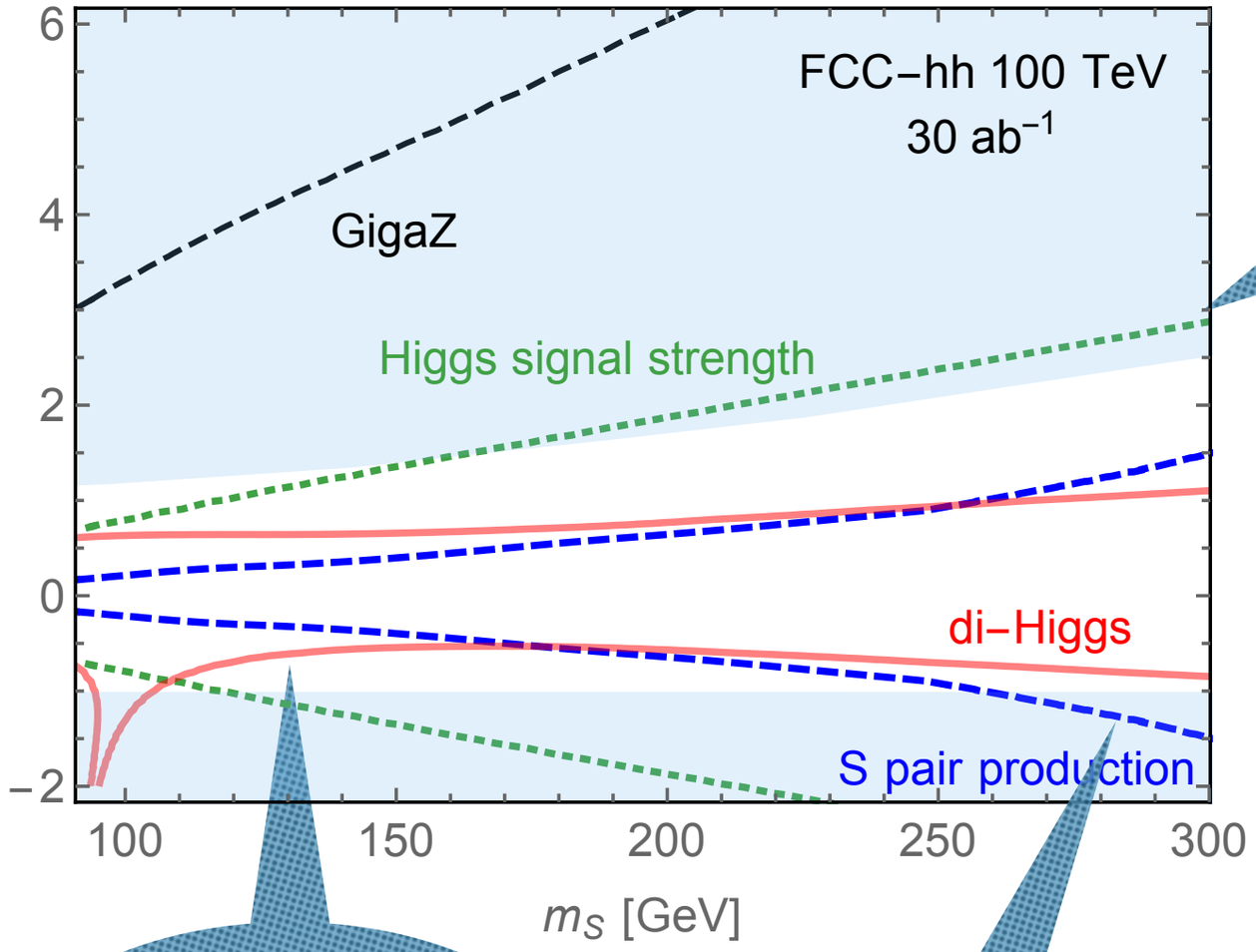


[CE, Jaeckel, Spannowsky, Stylianou ` 20]

→ *Sally's talk*

singlets above threshold

[CE, Jaeckel, Spannowsky, Stylianou `20]

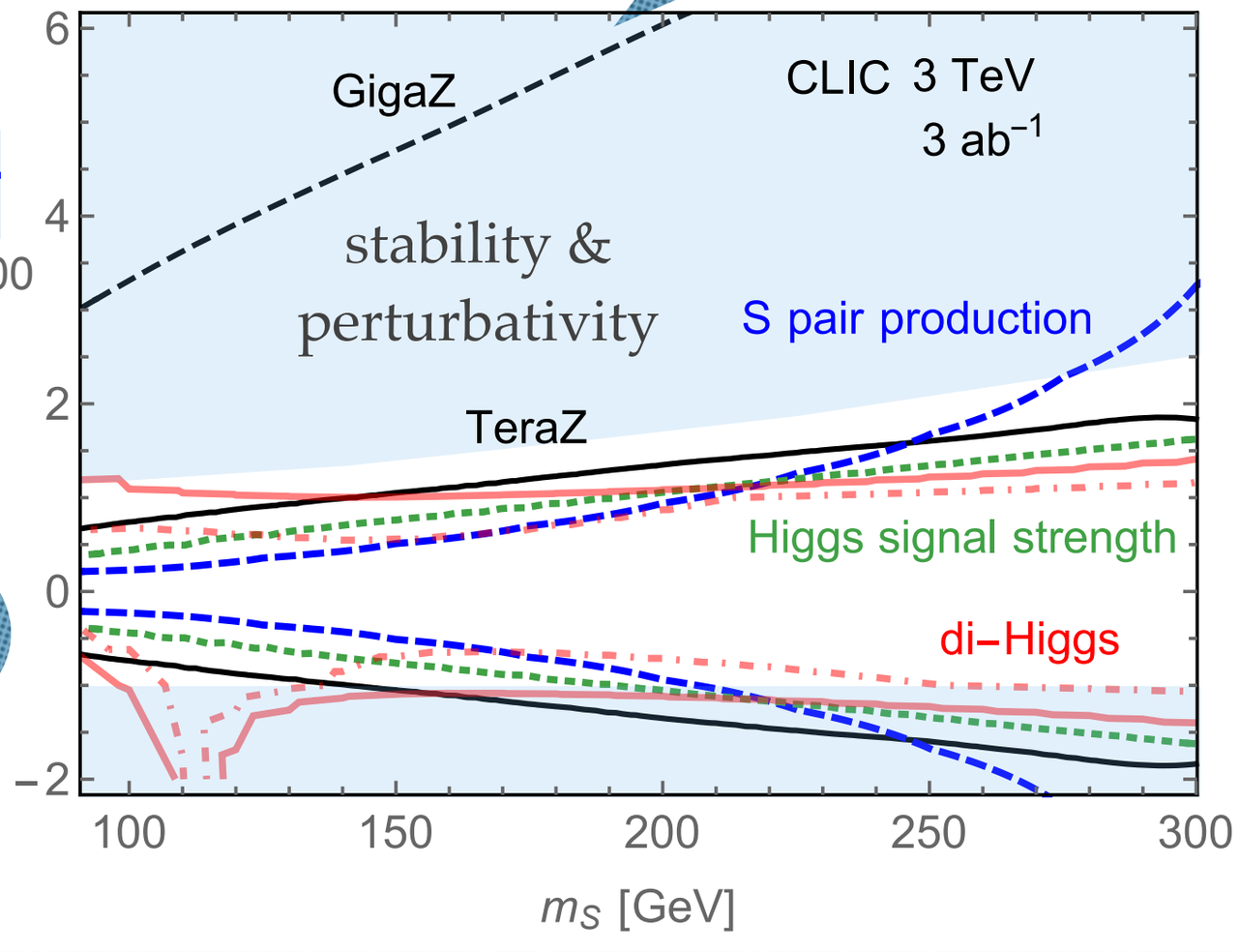


Higgs couplings

Oblique corrections

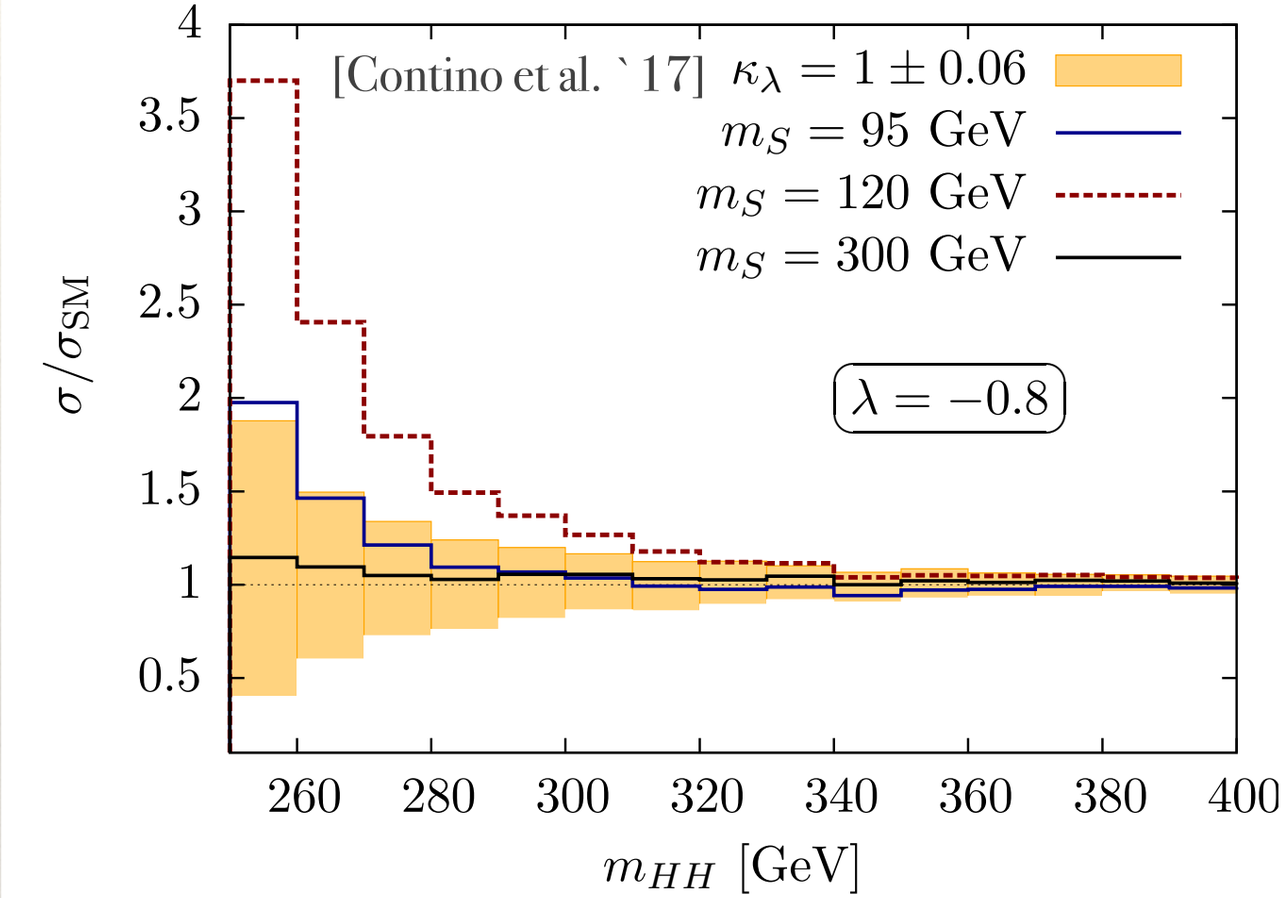
di-Higgs physics

off-shell production



singlets above threshold

- why double Higgs so sensitive?



[CE, Jaeckel `19]

Combination of

- changed threshold behaviour (cf. self-coupling)
- sensitivity of Higgs coupling modification in the tail compared to single Higgs

→ *Michael's & Gudrun's talks*

- **more optimistically**: unique opportunity to discover iso-singlet mixing through WBF di-Higgs resonances @ LHC

[Barman, CE, Goncalves, Spannowsky `20]

iso-singlet mixing

[Binoth, van der Bij `97]
[Schabinger, Wells `05]
[Patt, Wilczek `06]
...

$$V = \mu_s^2|\phi_s|^2 + \lambda_s|\phi_s|^4 \; + \; \mu_h^2|\phi_h|^2 + \lambda_h|\phi_h|^4 \; + \; \eta_\chi|\phi_s|^2|\phi_h|^2$$

- if singlet develops a vev, Higgs phenomenology is parametrised by single mixing angle

$$H_1 = \quad \cos\chi\, H_s + \sin\chi\, H_h$$
$$H_2 = -\sin\chi\, H_s + \cos\chi\, H_h$$

precision pheno studies:
[Bowen et al. `07]
[CE, Plehn, Zerwas `12]
[Bertoloni, McCullough `12]
[Chen, Dawson, Lewis `14]
[Lopez-Val, Robens `14]
[Chako, Cui, Hong `14]
...

SM-like cross sections & BRs

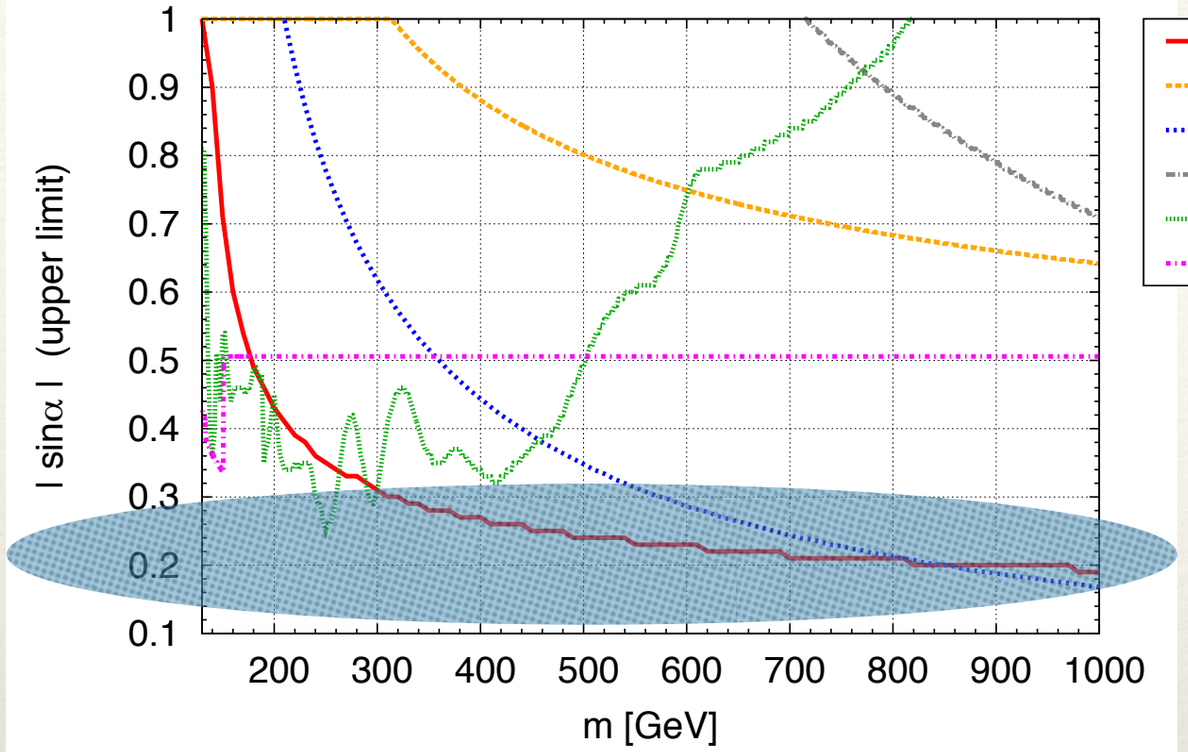
Cascade decays &

modifications of SM trilinear couplings

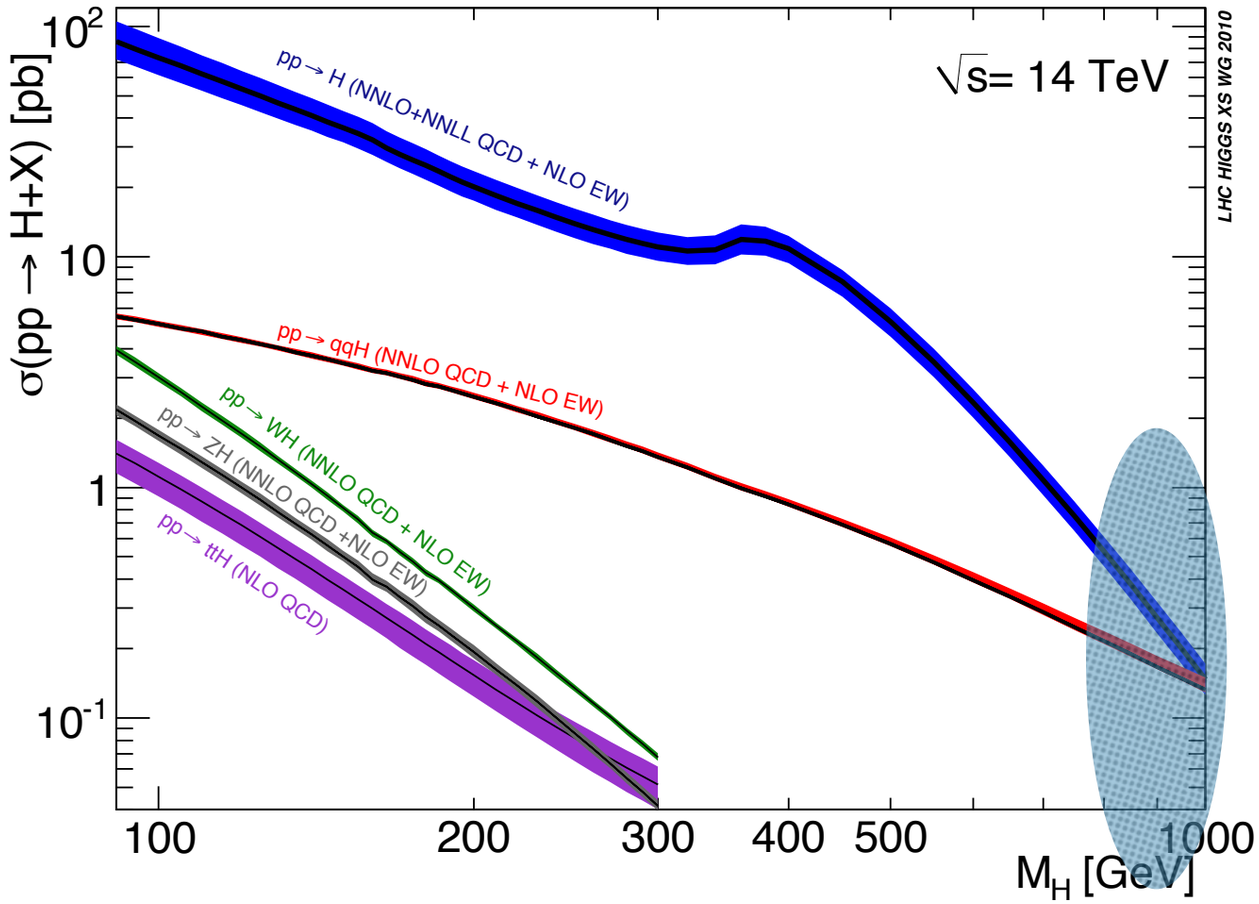
$$\Lambda_{211} = 3\sin 2\chi \left[\cos\chi\,\frac{\lambda_s v_s^2}{v_s} - \sin\chi\,\frac{\lambda_h v_h^2}{v_h}\right]$$
$$- \tan 2\chi\,[\lambda_s v_s^2 - \lambda_h v_h^2]\left[(1-3\cos^2\chi)\,\frac{\sin\chi}{v_h} - (1-3\sin^2\chi)\,\frac{\cos\chi}{v_s}\right]$$

iso-singlet mixing

[Robens, Stefaniak `15]



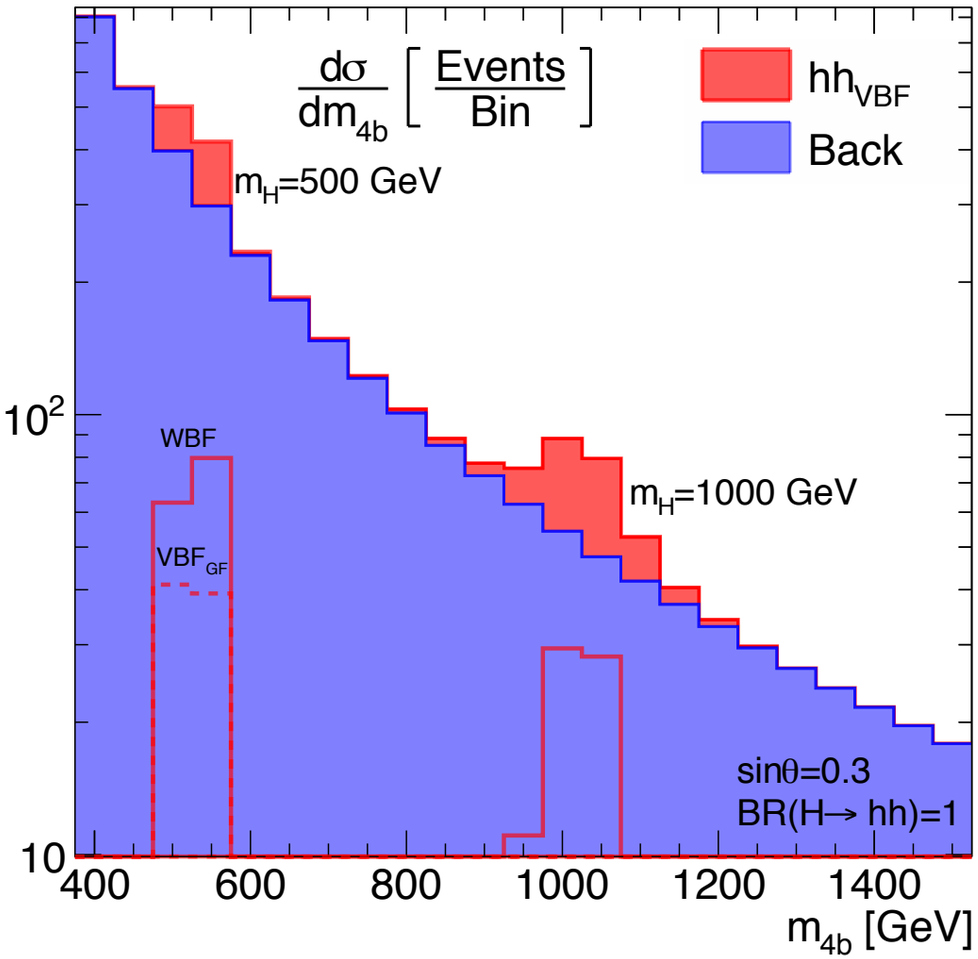
- SM-likeness of 125 GeV selects small mixing angles
- larger masses highlight WBF production on top of GF(+jets): If partner is heavy: **WBF will play an essential role!**



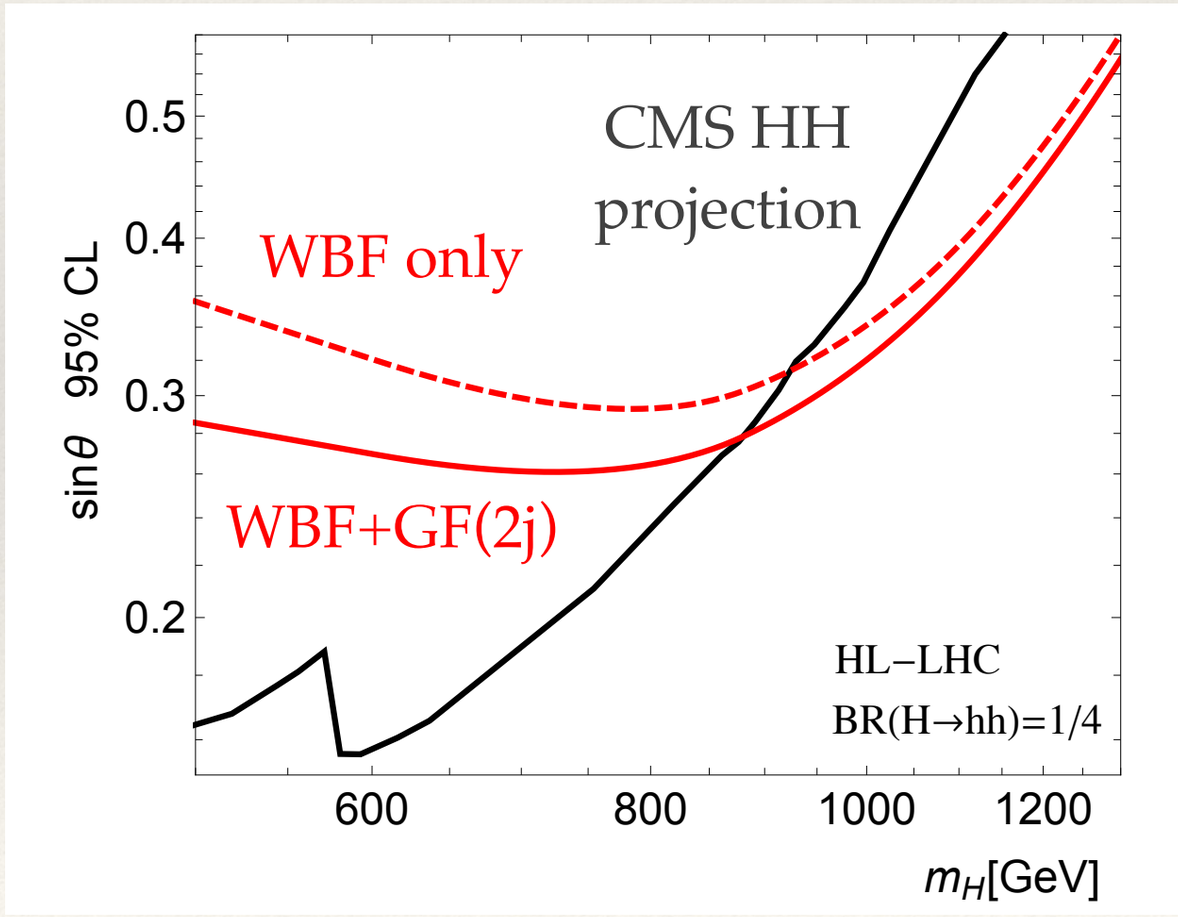
…good coverage of searches for SM-like Higgs and SM HH channels…

Proof-of-principle analyses

[Barman, CE, Goncalves, Spannowsky `20]



- scan over singlet parameter space, taking into account constraints from electroweak precision data, etc.

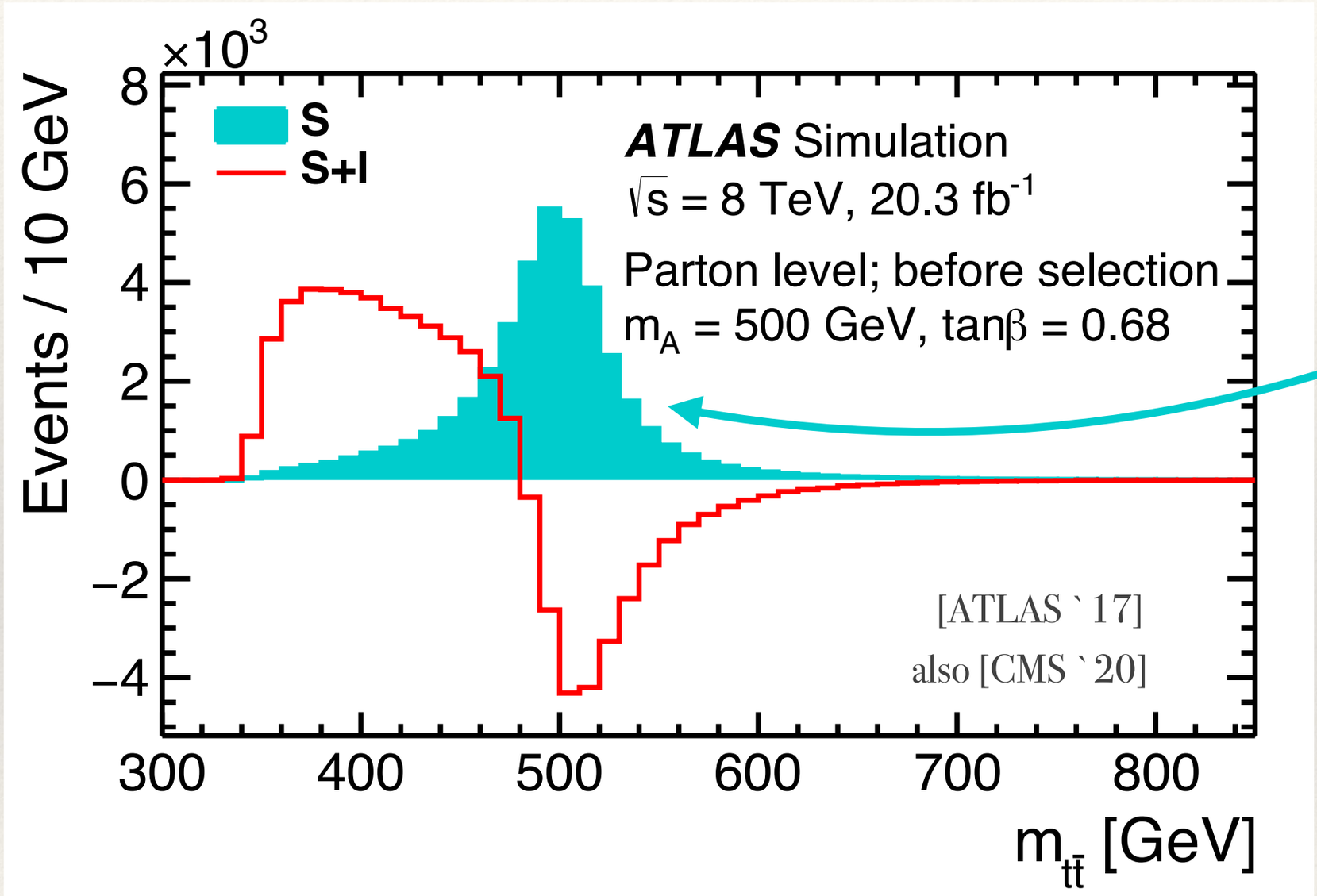


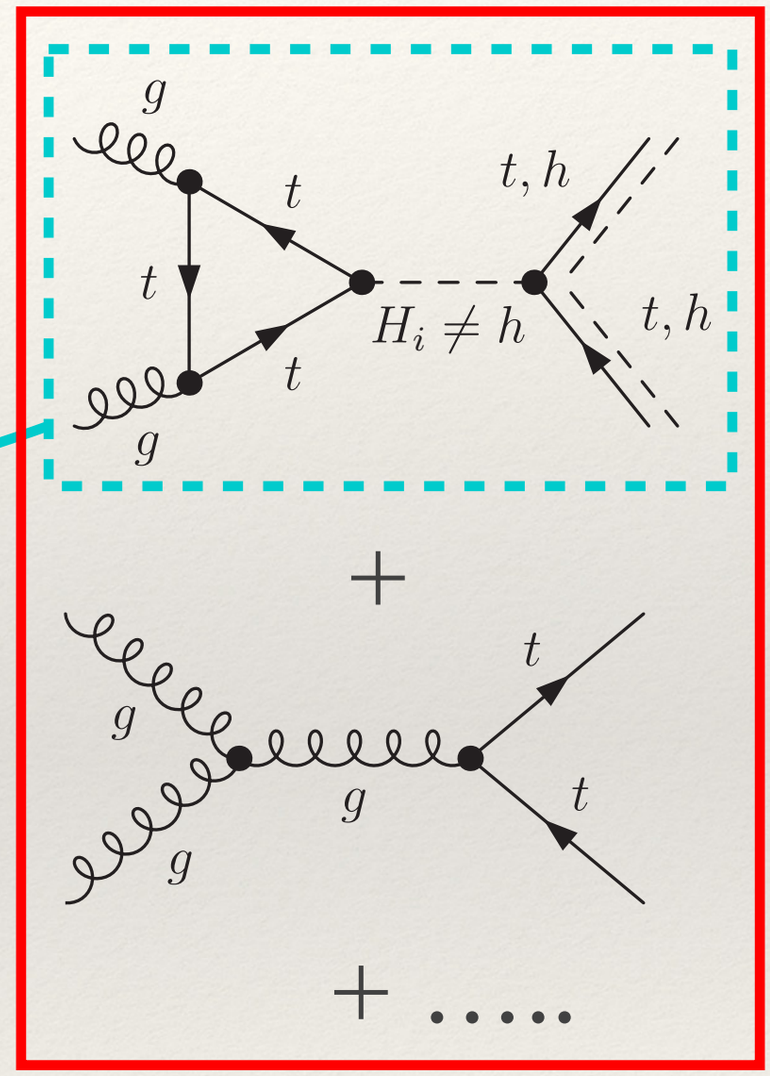
- WBF analysis crucial for heavy resonance searches, GF contribution remains relevant

special role of top quarks

- large interference effects of Higgs "signal" with QCD background

[Gaemers, Hoogeveen `84] [Dicus et al. `94] [Carena, Liu `16]...



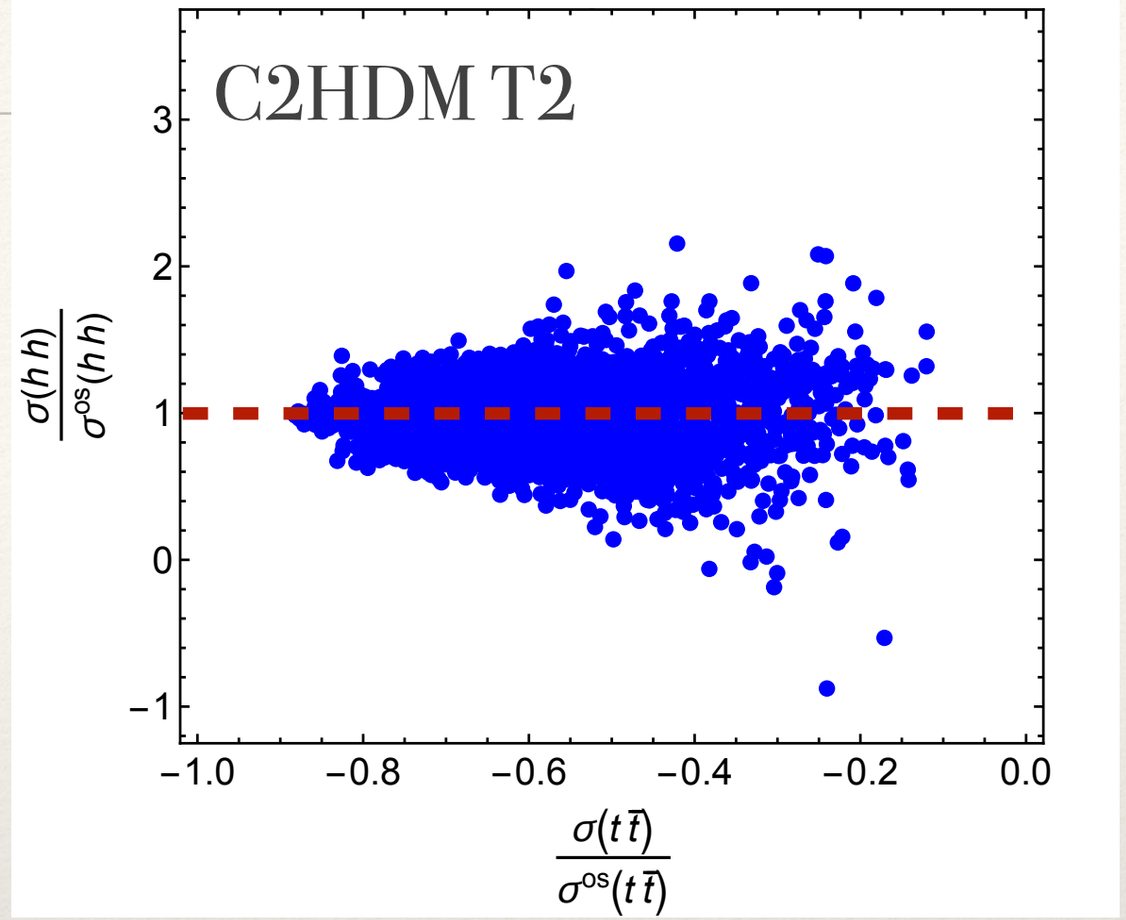


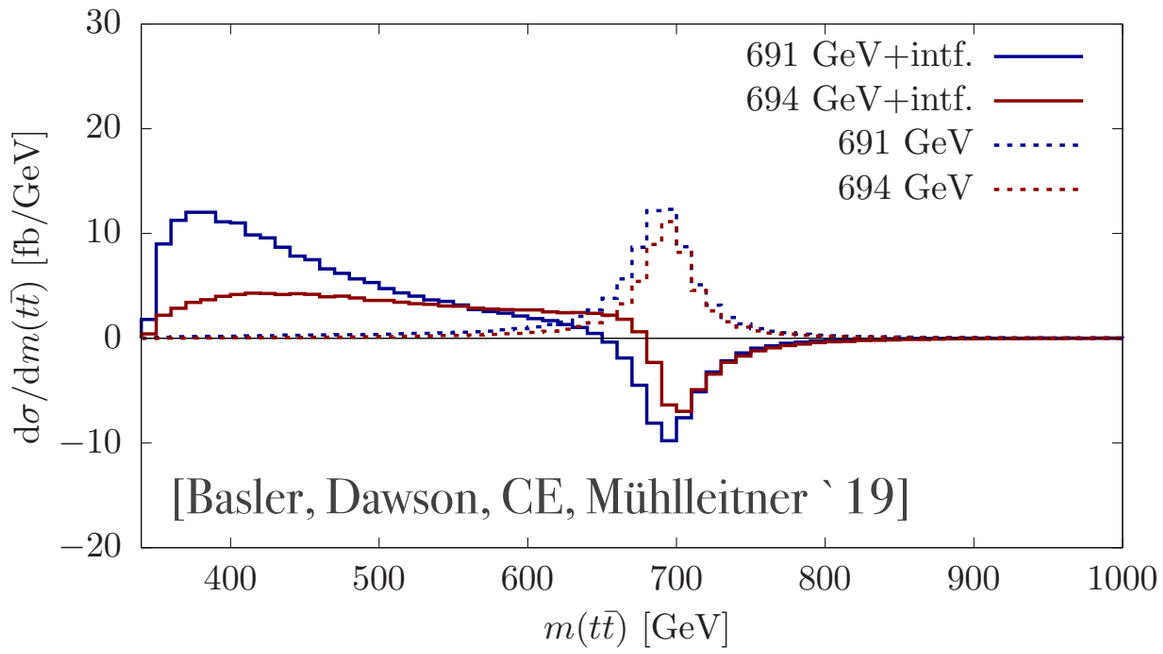
- top resonance searches in Higgs sector extensions with narrow width approximation is inadequate!

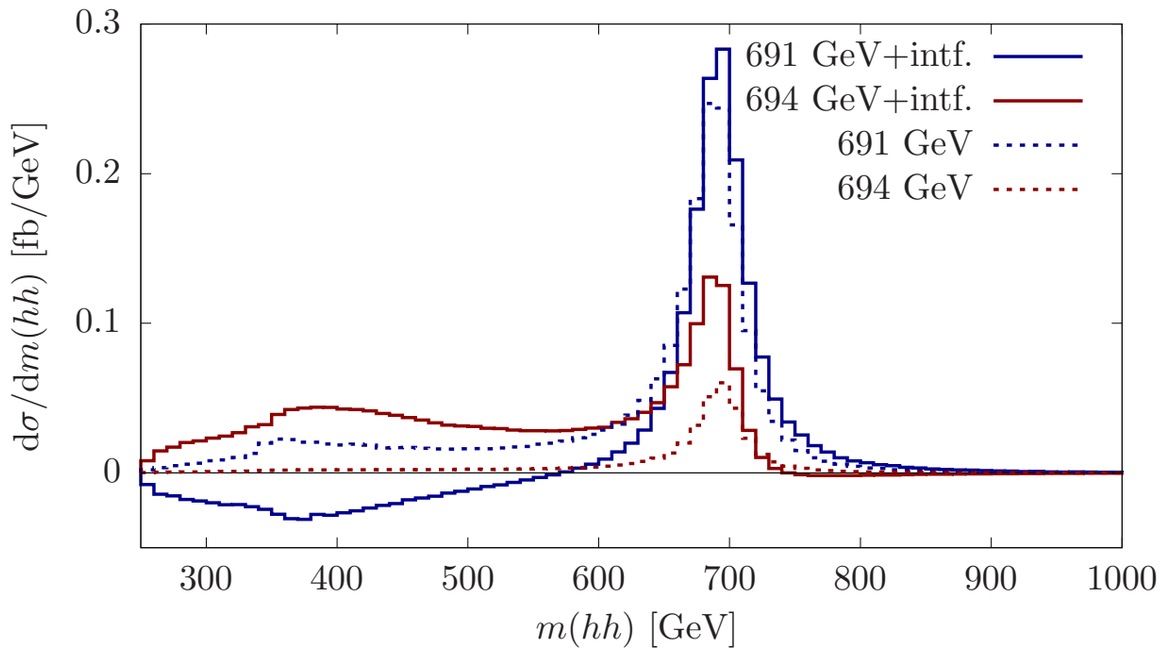
special role of top quarks

- destructive interference in top final states can be correlated with HH enhancement
- phenomenologically viable regions with compressed spectra: **signal-signal interference**

[Basler, Dawson, CE, Mühlleitner `18, `19]

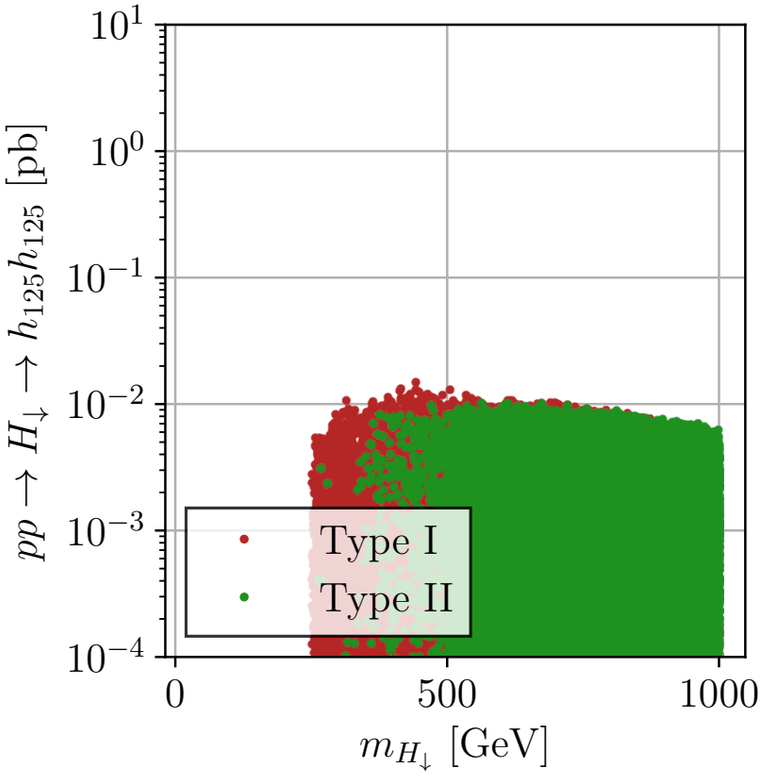


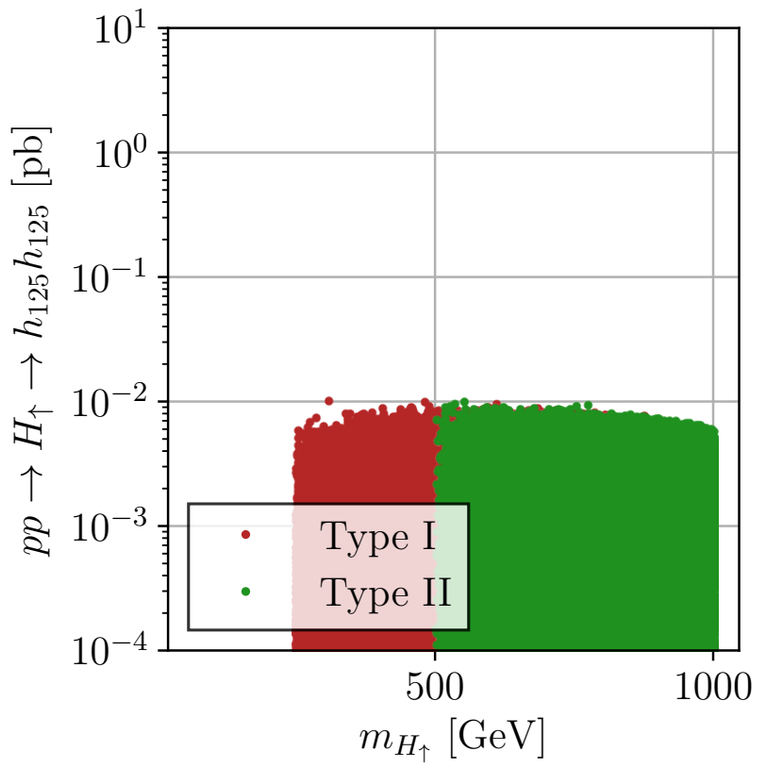


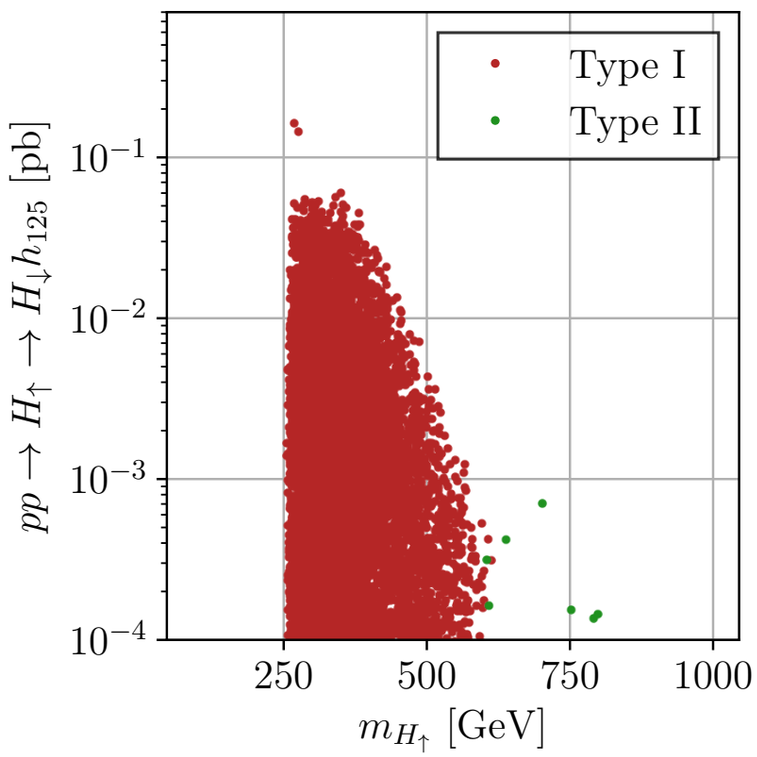


(C)2DHMs

[Fontes, Mühlleitner, Romao, Santos, Silva, Wittbrodt `17]







operator	exact AL	$\mathcal{O}(e_2/v)$	$\mathcal{O}(e_3/v)$
$H_1H_1H_1$	$M_1^2/(2v)$	$-e_2M_{H^\pm}^2/v^2$	$-e_3M_{H^\pm}^2/v^2$
$H_1H_1H_2$	$3e_2M_2^2/(2v^2)$	$(2M_{H^\pm}^2 - 2M_2^2 - vq_1)/v$	0
$H_1H_1H_3$	$3e_3M_3^2/(2v^2)$	0	$(2M_{H^\pm}^2 - 2M_3^2 - vq_1)/v$
$H_2H_2H_1$	$(2M_2^2 - 2M_{H^\pm}^2 + vq_1)/(2v)$	$-q_2 + 2e_2M_2^2/v^2$	0
$H_3H_3H_1$	$(2M_3^2 - 2M_{H^\pm}^2 + vq_1)/(2v)$	0	$-q_3 + 2e_3M_3^2/v^2$
$H_1H_2H_3$	0	$-q_3 + 2e_3M_3^2/v^2$	$-q_2 + 2e_2M_2^2/v^2$

[Grzadkowski, Haber, Ogreid, Osland` 18]

→ *Jonas' talk* [Robens, Stefaniak, Wittbrodt `19]

signal-driven BSM searches

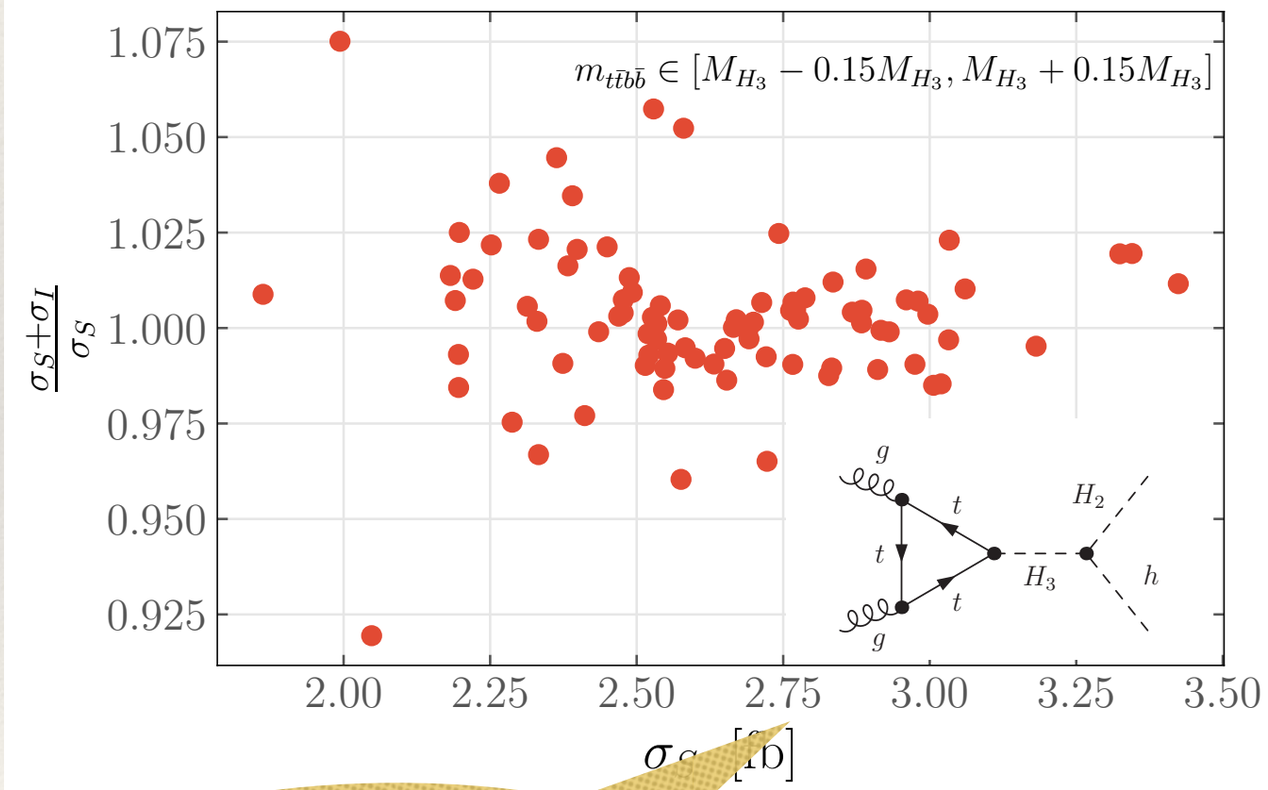
- **new physics could hide efficiently in multi-Higgs final states!**

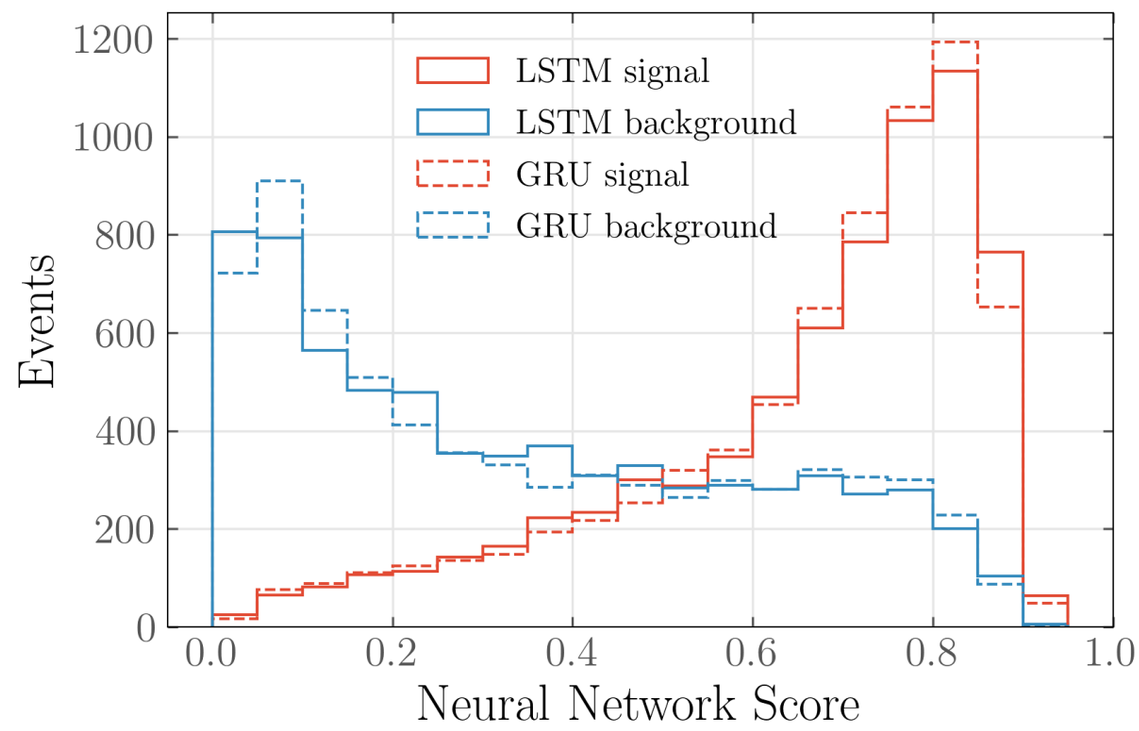
top-philic cascade decays particularly robust against interference effects

[Atkinson, CE, Stylianou `20]

robust signatures

how regain sensitivity?





need maximum information approach → *Elliot's talk*

exploit splitting history patterns similar to natural language processing (RNNs)

[CE, Fairbairn, Spannowsky, Stylianou, Varma `20]

Summary

- Higgs pairs add viable information to the search for new physics in various scenarios

- but an improved understanding of UV limitations is crucial when considering physics approaching the decoupling limit

- resonance structures beyond in GF, WBF remain motivated

- possibility of new physics at lower scales + interference, will need to focus on more exotic and rare final states in such a case