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Theoretical Opportunities in double Higgs production

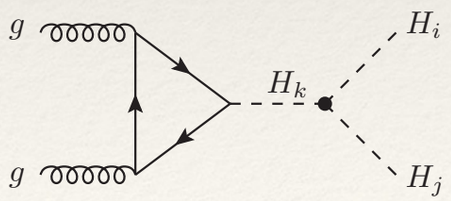
Snowmass EF01/EF02 meeting

27/05/2020

new physics in the Higgs sector

- address shortcomings of the SM
  - dark matter
  - CP violation
  - electroweak phase transition
  - SM fine tuning problems
- any Higgs sector extension necessarily implies non-SM Higgs phenomenology
  - coupling modifications
  - new resonances
  - new kinematics
  - non SM-like decay chains

here: focus on HH



SM

Singlets

Doublets / Triplets

(N)MSSM

....

singlets above threshold

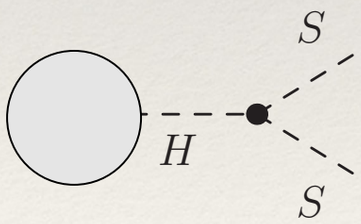
- $\mathbb{Z}_2$-symmetric Higgs portal

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

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

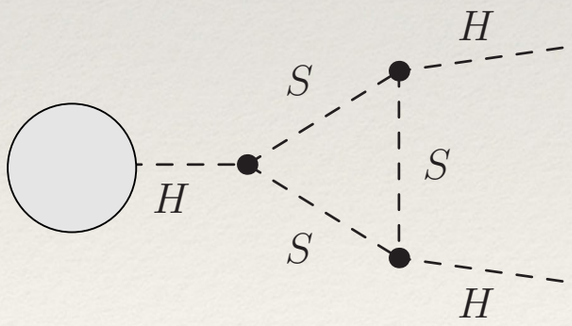
- for $m_S > m_H/2$ no direct SM Higgs decays
- BSM Higgs physics via momentum- or loop-suppressed effects

off-shell production



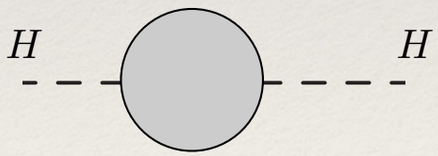
[Craig , Lou. et al.` 14]
[Ruhdorfer, Salvioni, Weiler ` 19]

di-Higgs physics



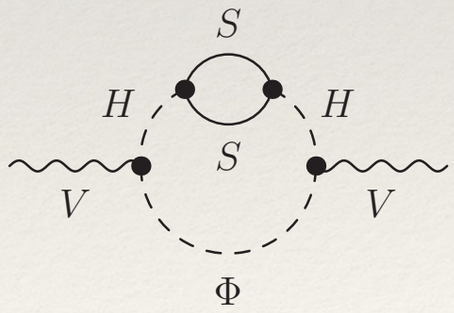
[Curtin, Meade, Yu ` 14]
[He, Zhu ` 16]
[Voigt, Westhoff ` 17]

Higgs couplings



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

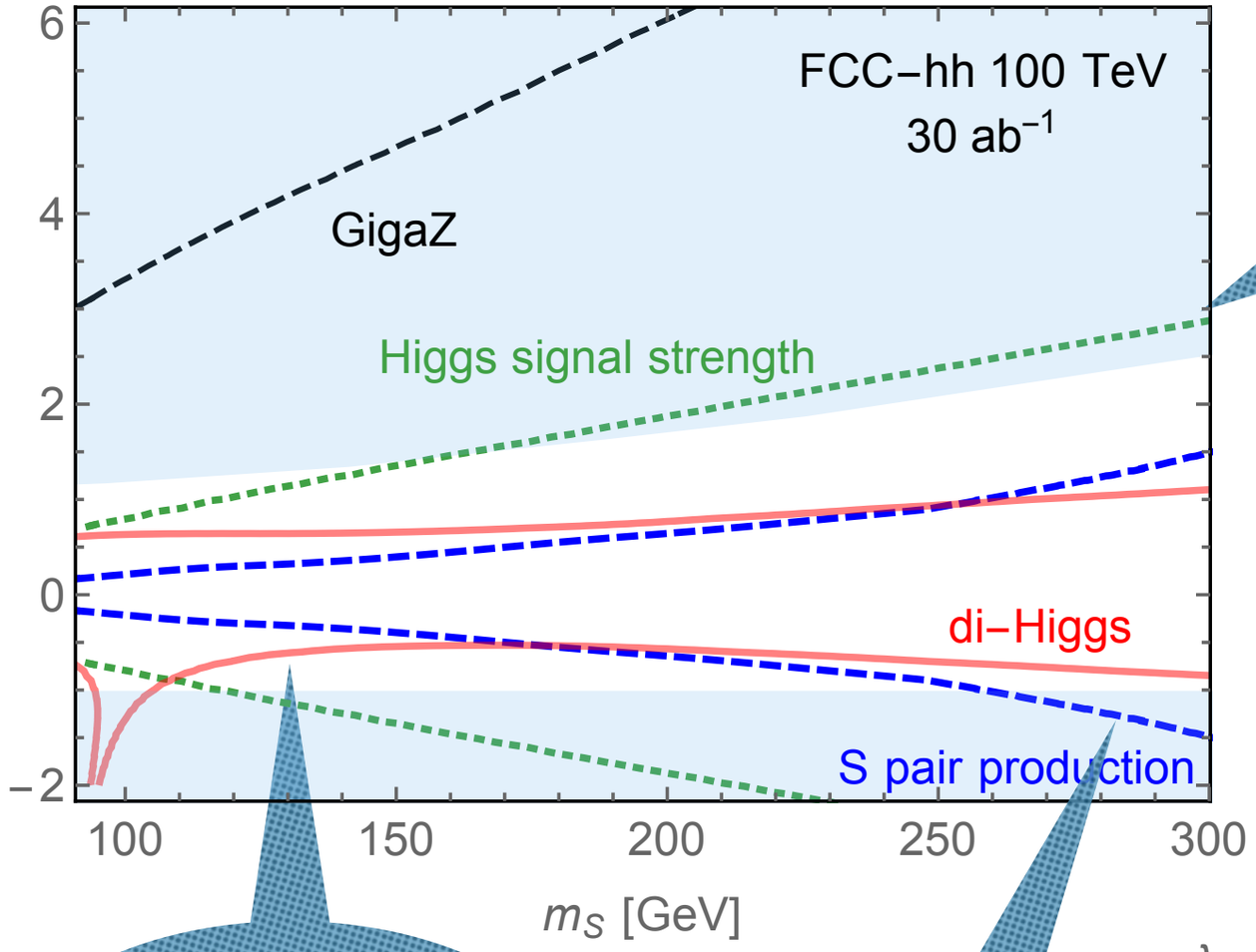
Oblique corrections



[CE, Jaeckel, Spannowsky, Stylianou ` 20]

singlets above threshold

[CE, Jaeckel, Spannowsky, Stylianou `20]

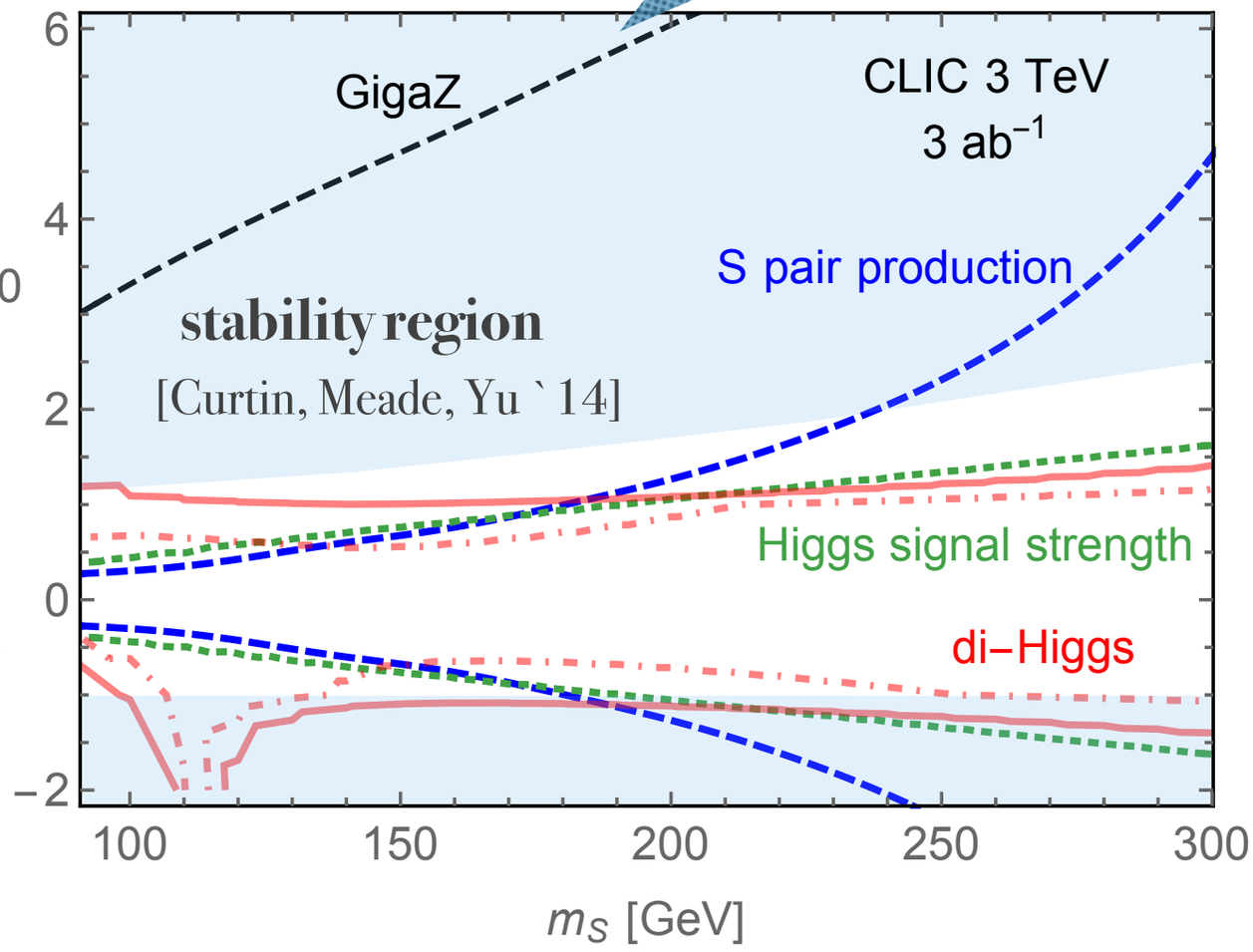


Higgs couplings

Oblique corrections

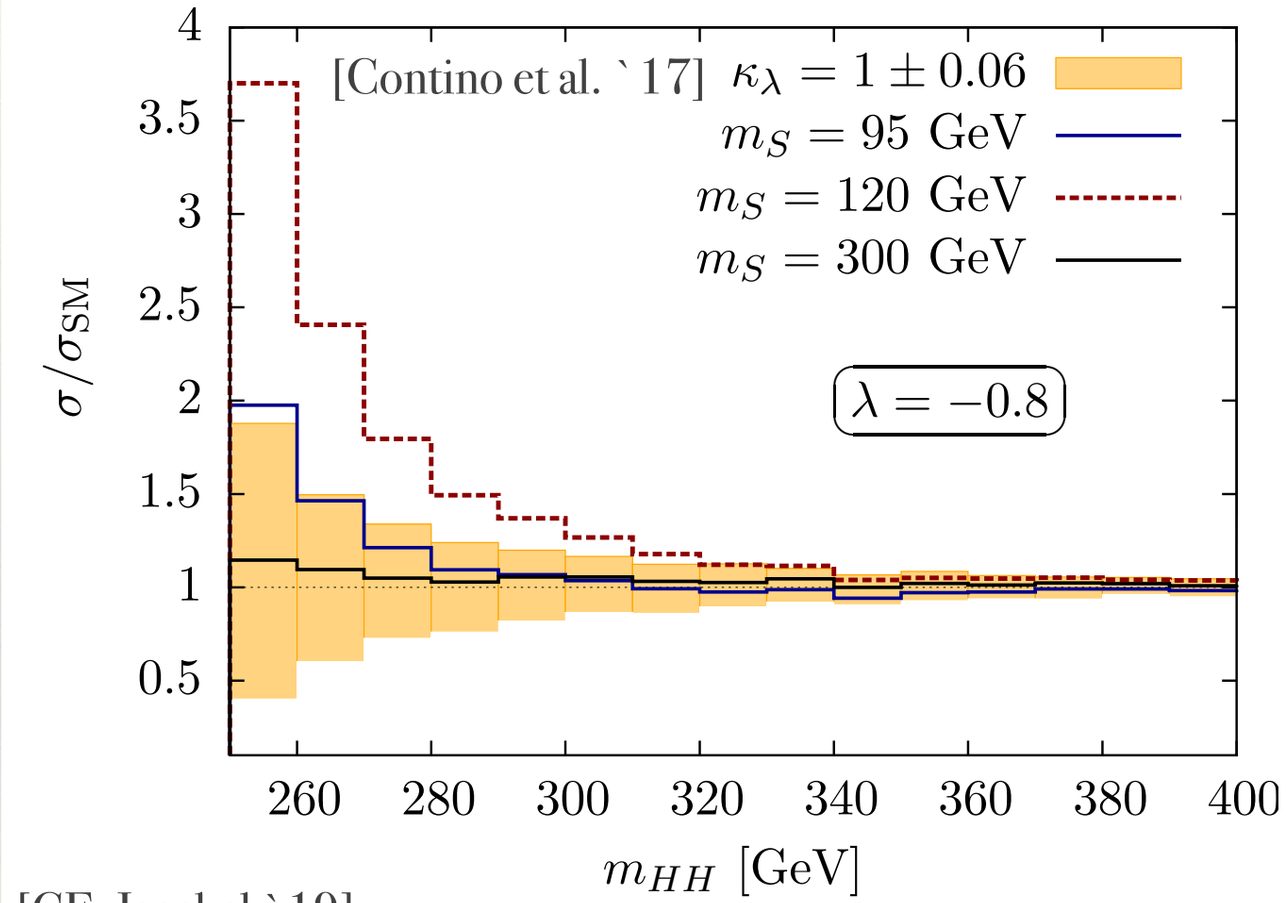
di-Higgs physics

off-shell production



singlets above threshold

- why double Higgs so sensitive?



[CE, Jaeckel `19]

Combination of

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

Good differential control of di-Higgs spectra is key to BSM sensitivity

EFT-based NLO QCD discussion in [Capozi, Heinrich `19]

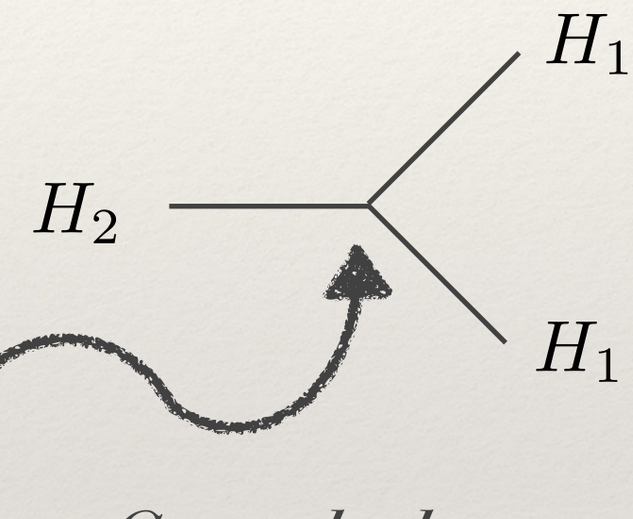
iso-singlet mixing

[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

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



pheno studies:
[Bowen et al. `07]
[CE, Plehn, Zerwas `12]
[Bertoloni, McCullough `12]
...

precision calculations:
[Chen, Dawson, Lewis `14]
[Lopez-Val, Robens `14]
[Bojarski et al. `15]
[Dawson, Sullivan `17]

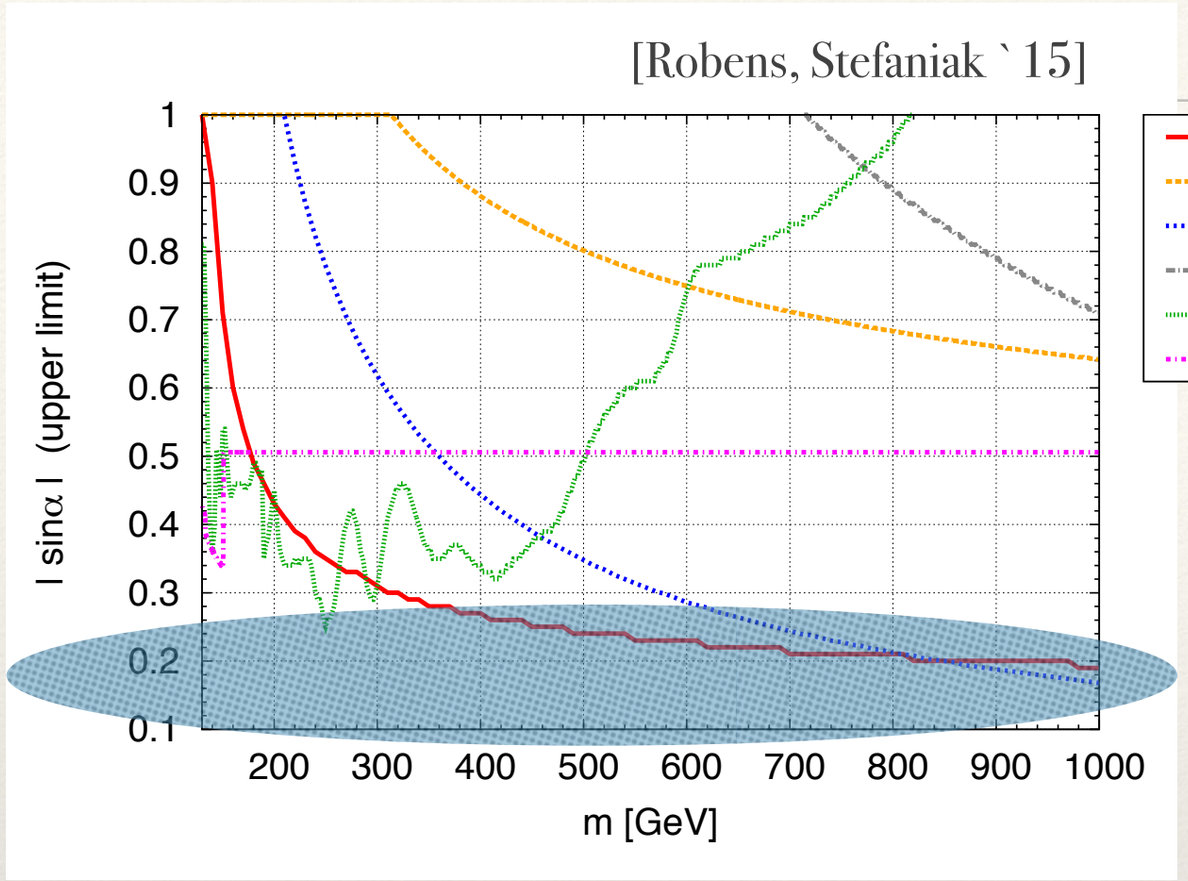
SM-like cross sections & BRs

Cascade decays

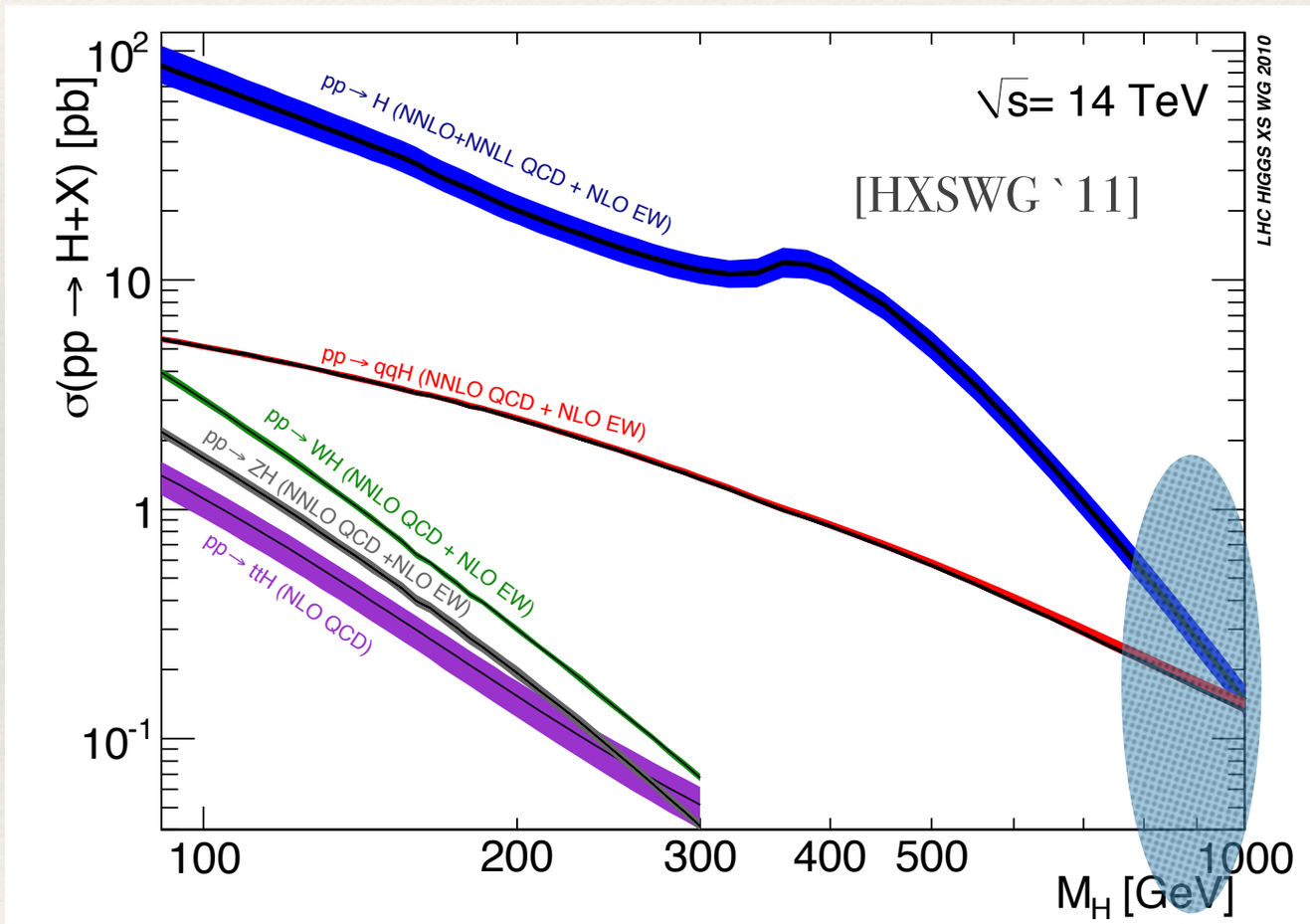
$$\Lambda_{211} = 3\sin 2\chi \left[\cos\chi\,\frac{\lambda_s v_s^2}{v_s} - \sin\chi\,\frac{\lambda_h v_h^2}{v_h}\right]$$
$$- \tan 2\chi\,[\lambda_s v_s^2 - \lambda_h v_h^2]\,\left[(1-3\cos^2\chi)\,\frac{\sin\chi}{v_h} - (1-3\sin^2\chi)\,\frac{\cos\chi}{v_s}\right]$$

- measurement of cascade decay allows us to fully reconstruct the extended Higgs potential

iso-singlet mixing

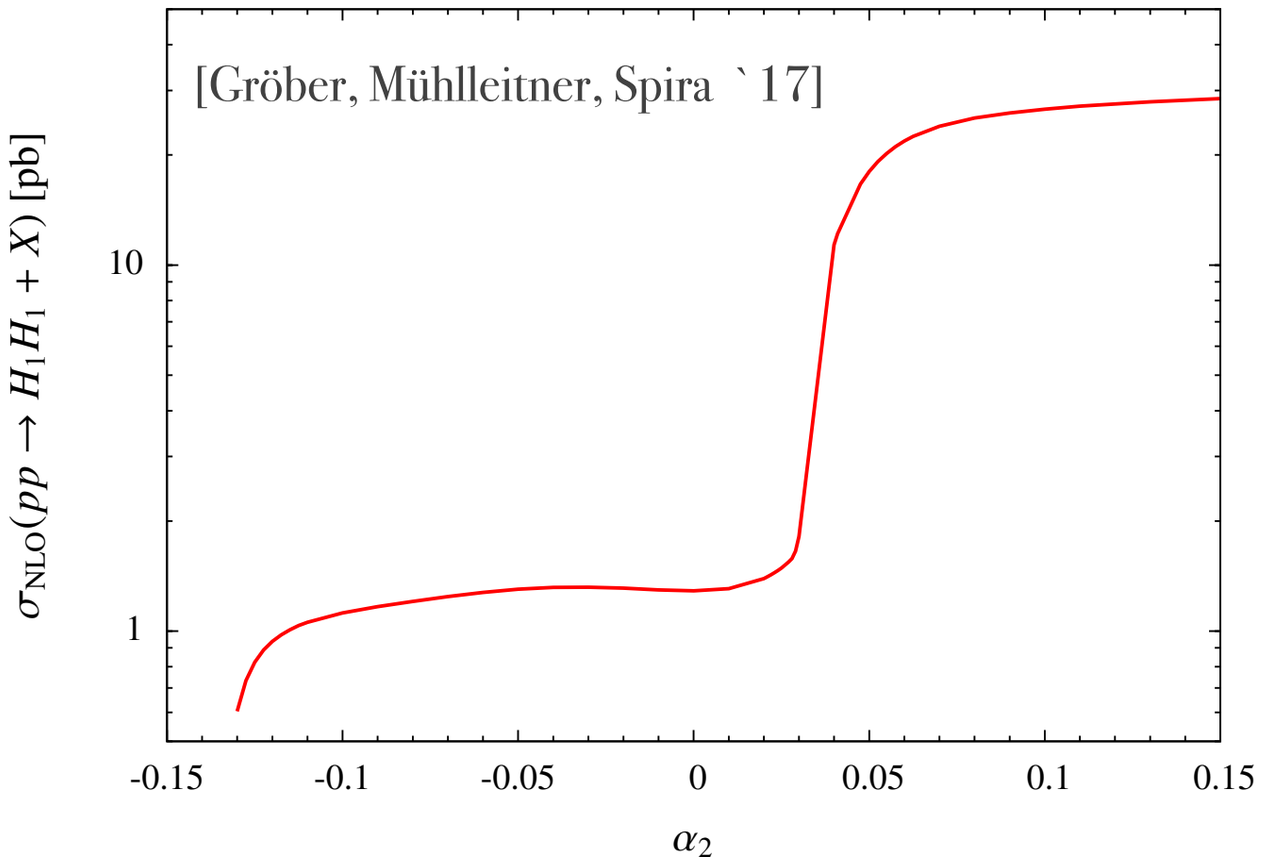


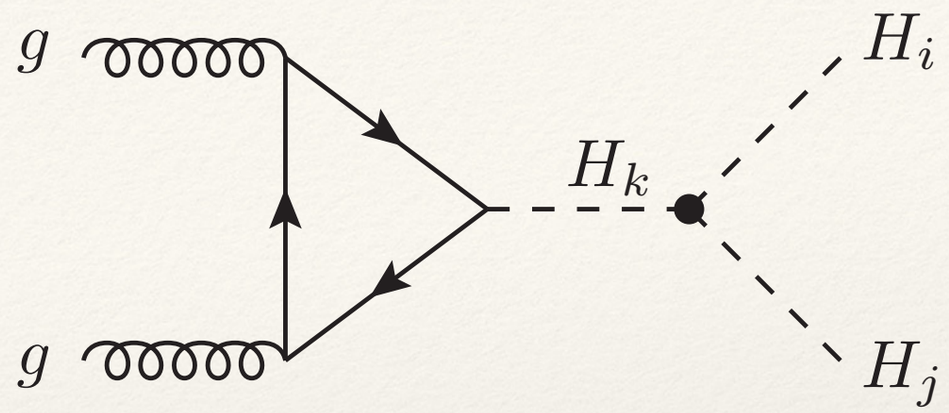
- SM-likeness of 125 GeV selects small mixing angles
- larger masses highlight WBF production on top of GF(+jets)



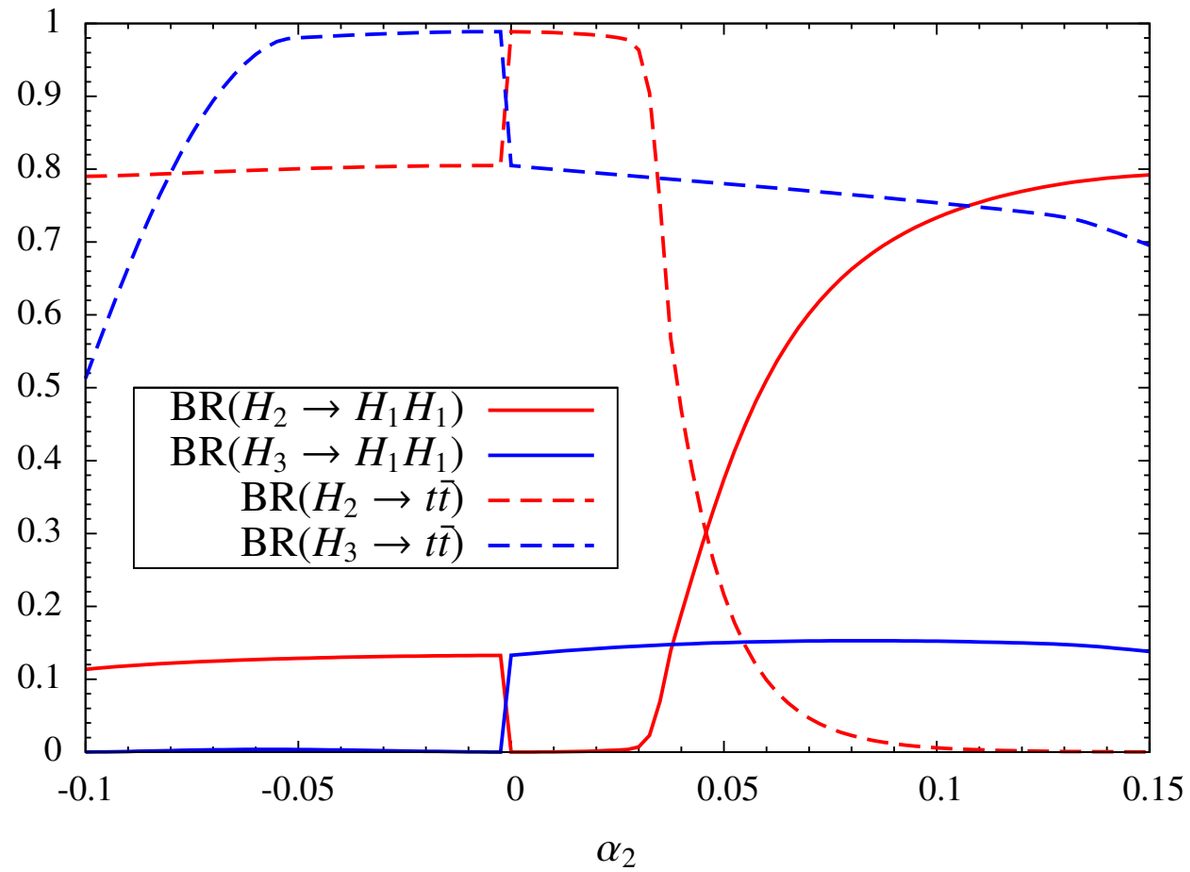
Good coverage of searches for SM-like Higgs and SM HH channels

C2DHMs



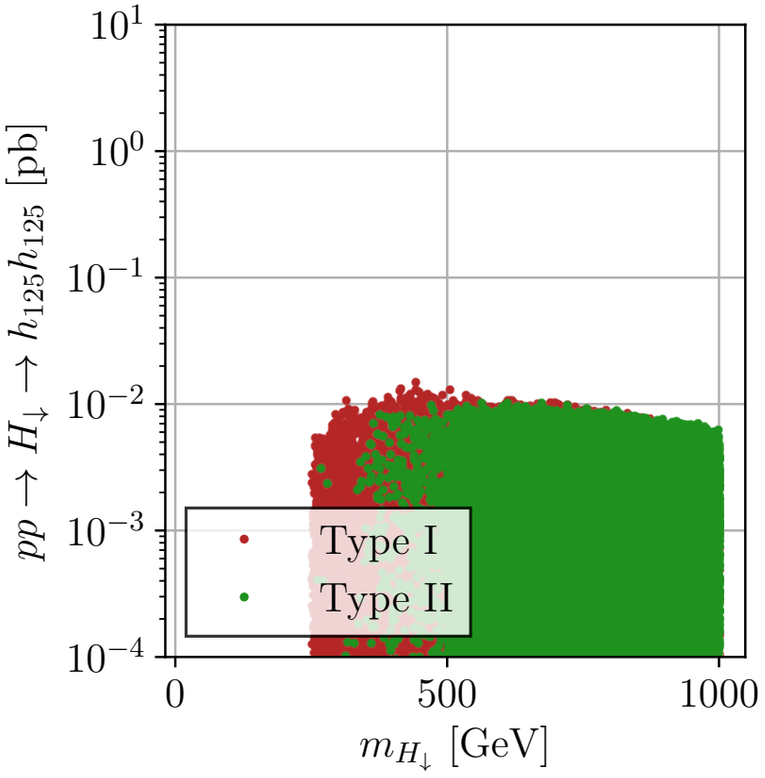


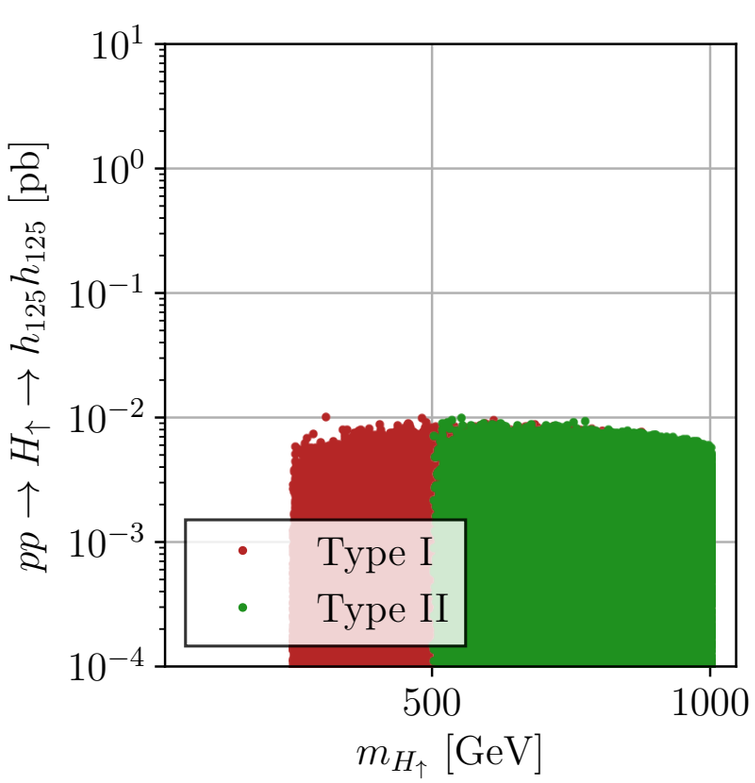
- Higgs pair production can receive large enhancement due to new resonant features
- Higgs pair production as BSM candles however in tension with top pair resonances

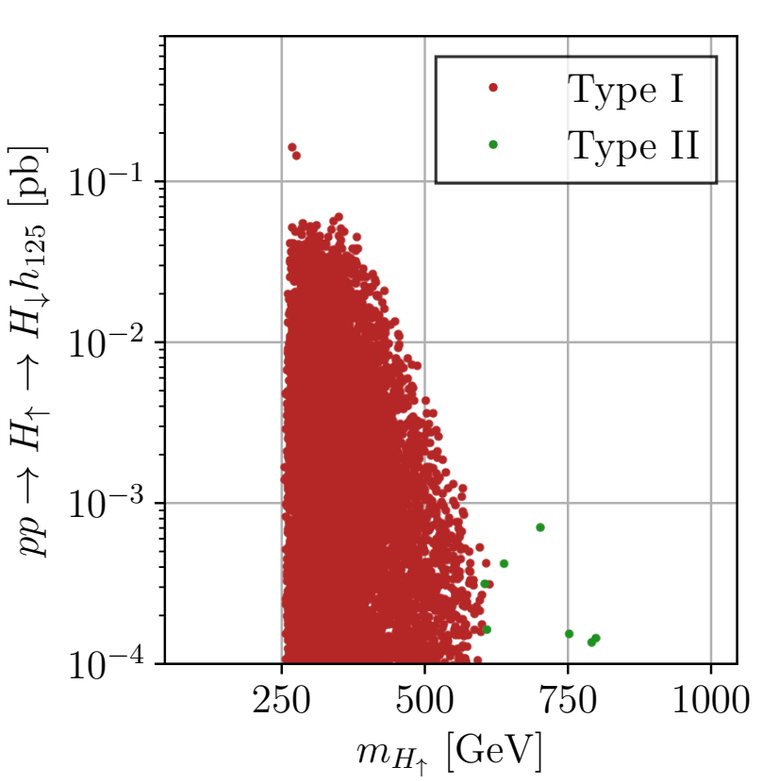


C2DHMs

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







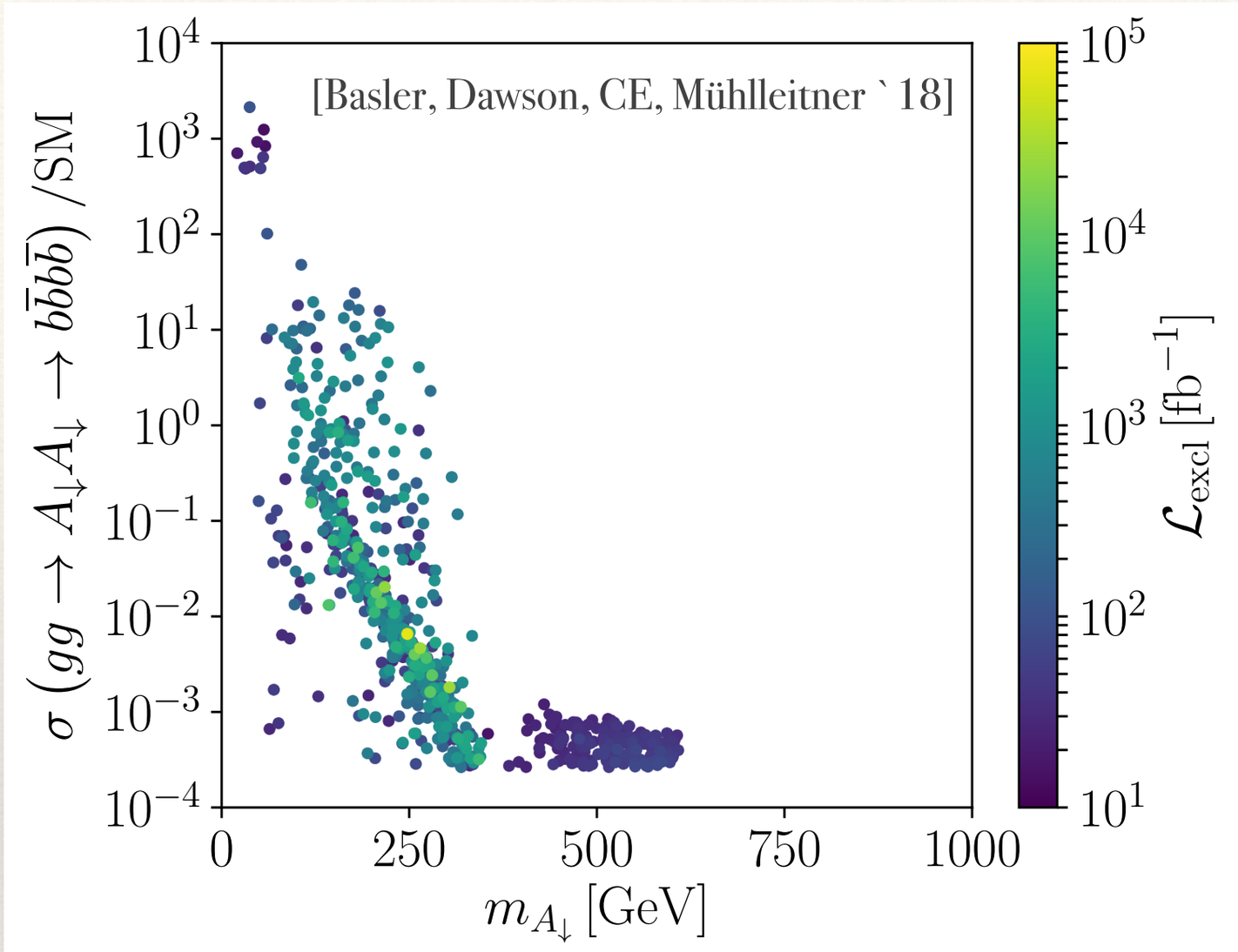
operator	exact AL	$\mathcal{O}(e_2/v)$	$\mathcal{O}(e_3/v)$
$H_1H_1H_1$	$M_1^2/(2v)$	$-e_2M_{H^\pm}^2/v^2$	$-e_3M_{H^\pm}^2/v^2$
$H_1H_1H_2$	$3e_2M_2^2/(2v^2)$	$(2M_{H^\pm}^2 - 2M_2^2 - vq_1)/v$	0
$H_1H_1H_3$	$3e_3M_3^2/(2v^2)$	0	$(2M_{H^\pm}^2 - 2M_3^2 - vq_1)/v$
$H_2H_2H_1$	$(2M_2^2 - 2M_{H^\pm}^2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

NMSSM

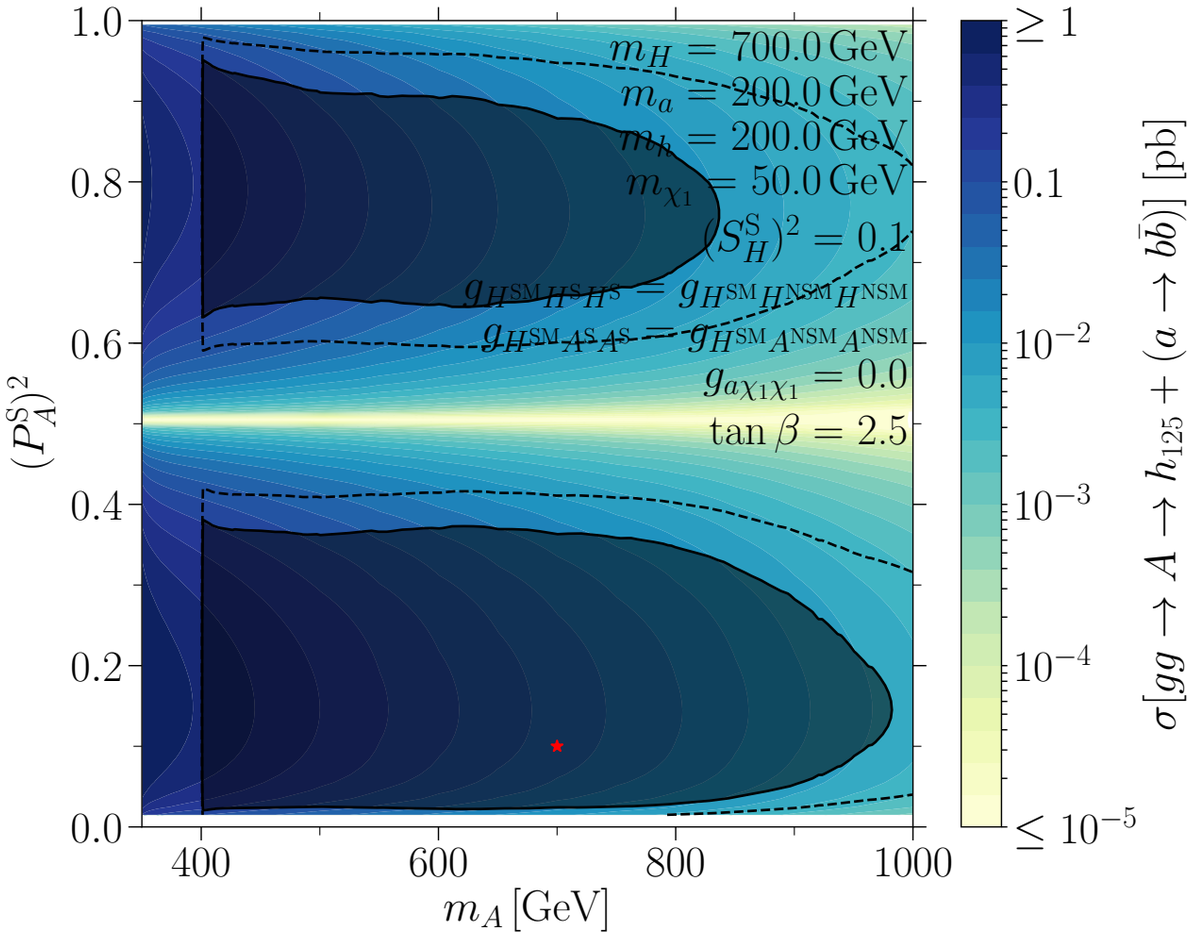
H_iH_j	NMSSM
hh	67
$hH_\downarrow$	26
$hA_\downarrow$	493
$hH_\uparrow$	25
$H_\downarrow H_\downarrow$	4114
$H_\downarrow H_\uparrow$	1.20
$H_\uparrow H_\uparrow$	0.09
$A_\downarrow A_\downarrow$	15894

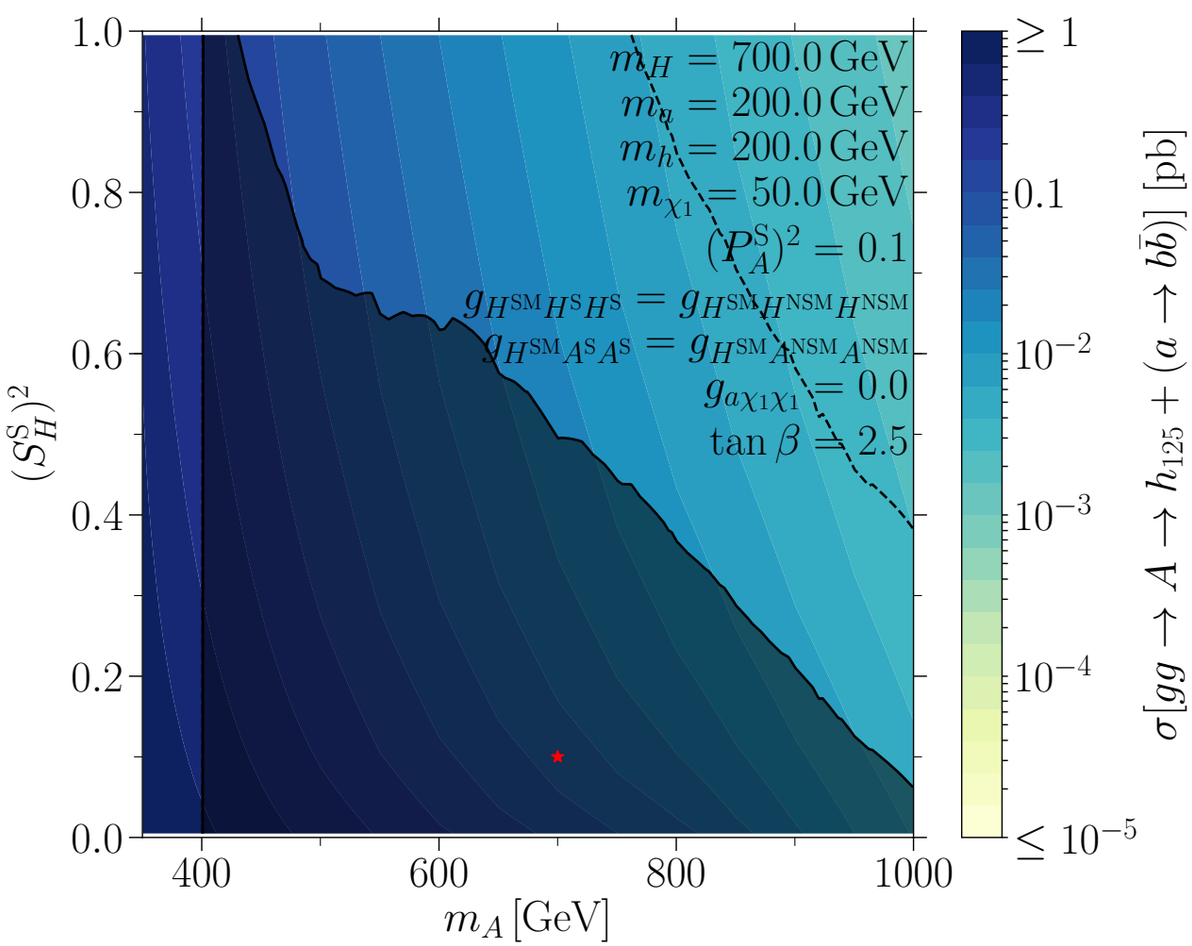
fb at 14 TeV



- SM-like searches, exotics searches and Higgs signal strength extrapolations provide (model-specific) complementary constraints

NMSSM





[Baum, Shah `19]

- large potential of the Higgs decays into different mass Higgs bosons, benchmarks available

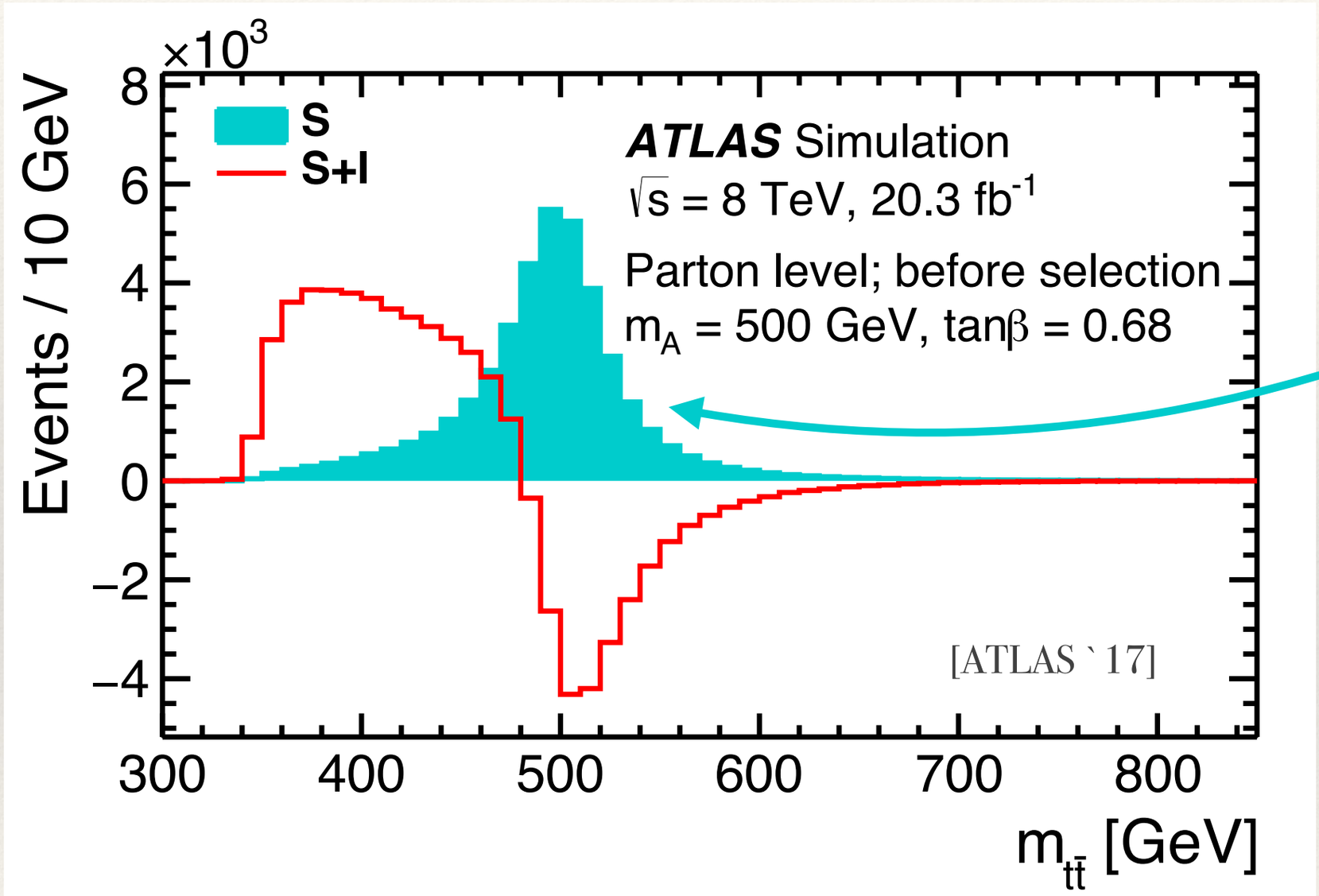
[Basler, Dawson, CE, Mühlleitner `18]
[Baum, Shah `19]

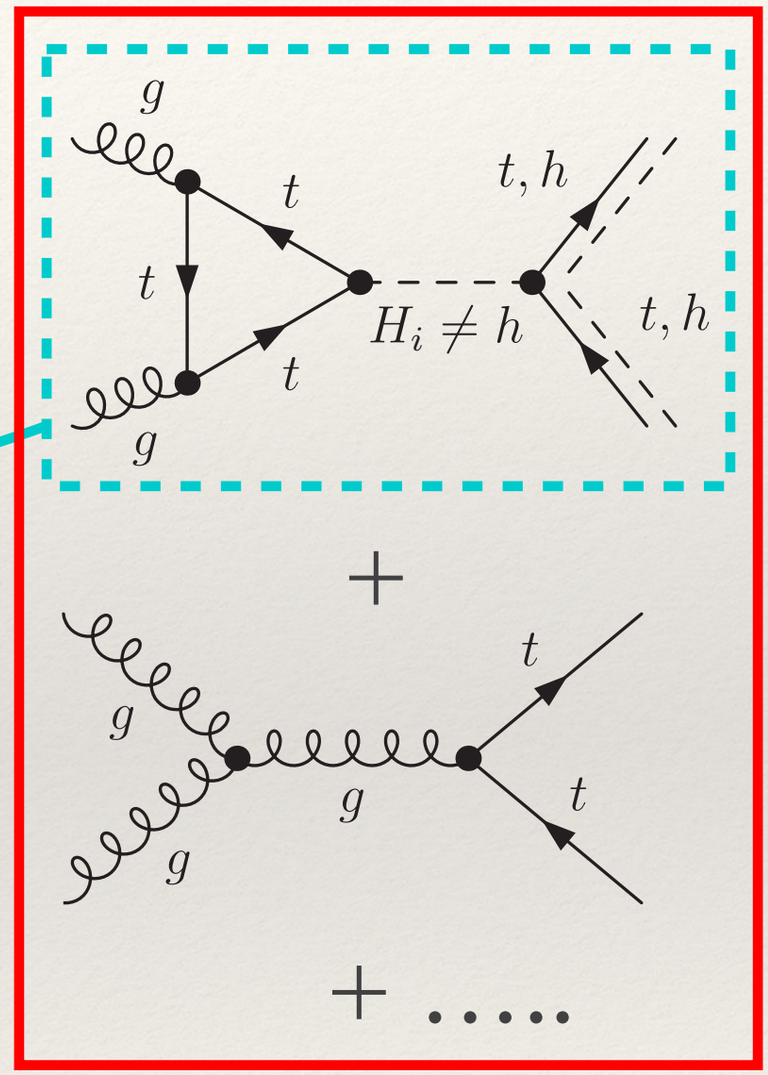
- phenomenological prospect for di-Higgs high, due to insensitivity in in prompt $a \to b\bar{b}$ (large QCD backgrounds, triggers)

special role of top quarks

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

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

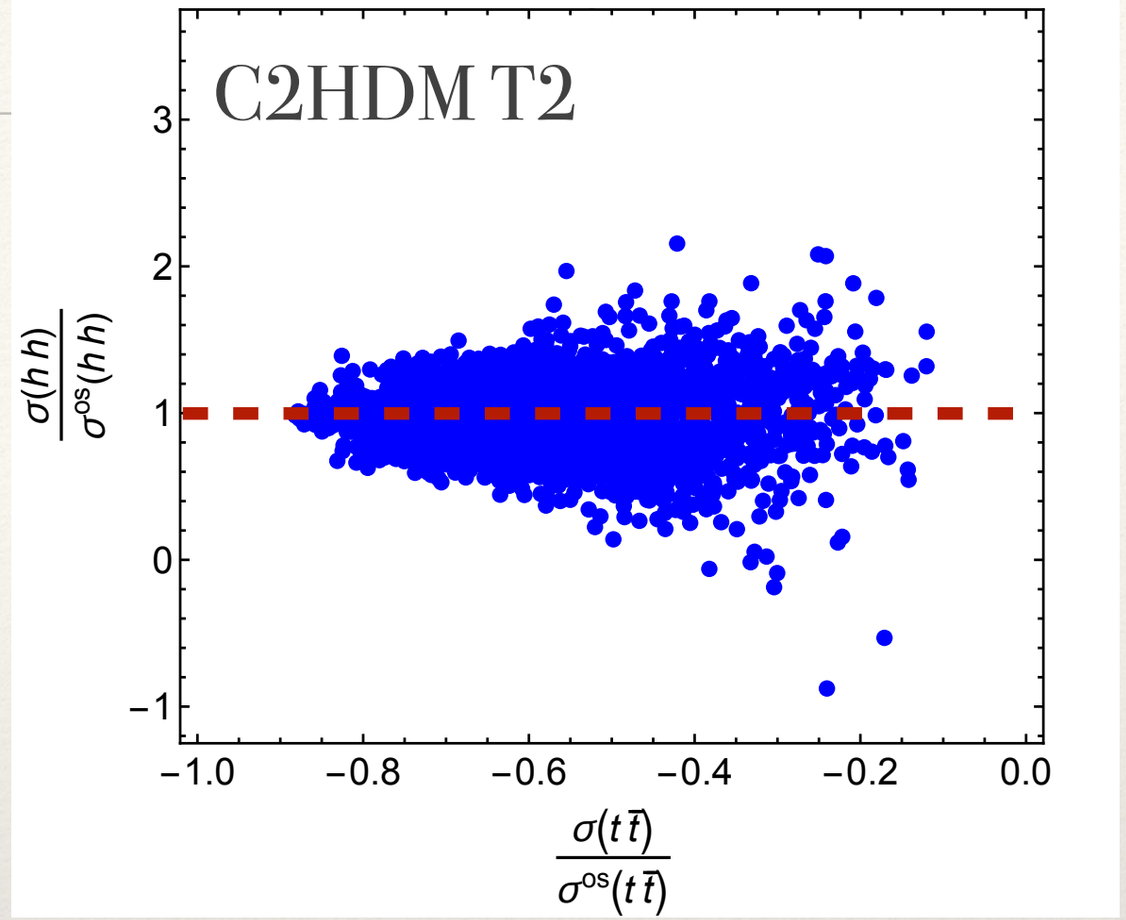


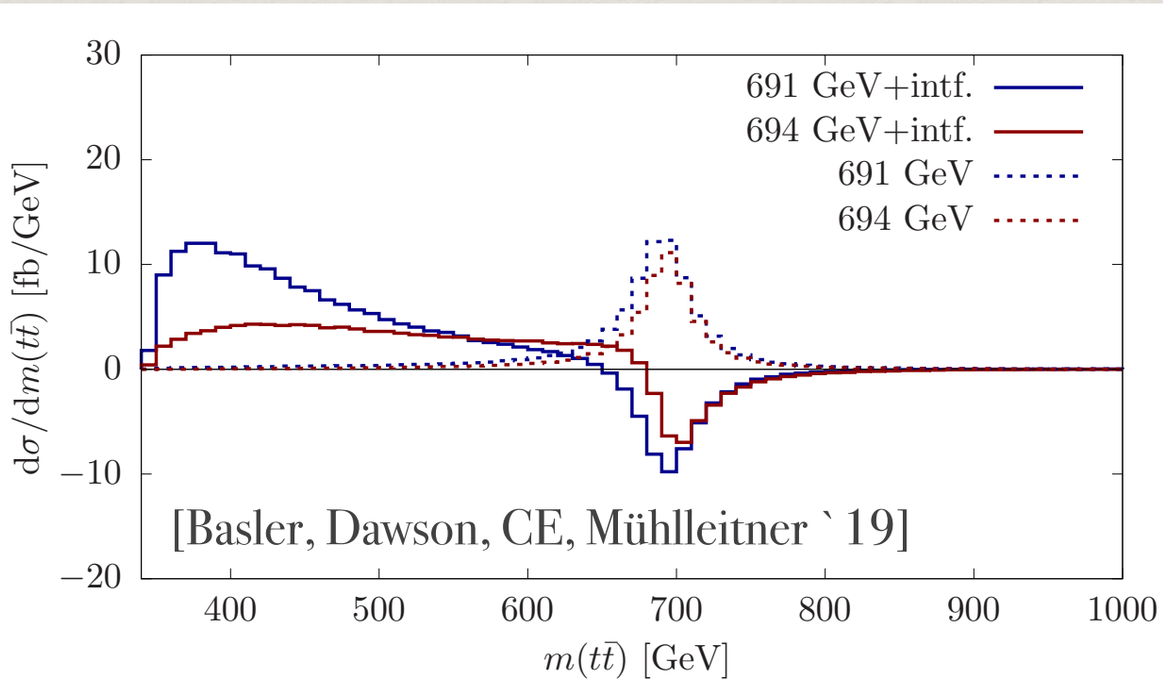


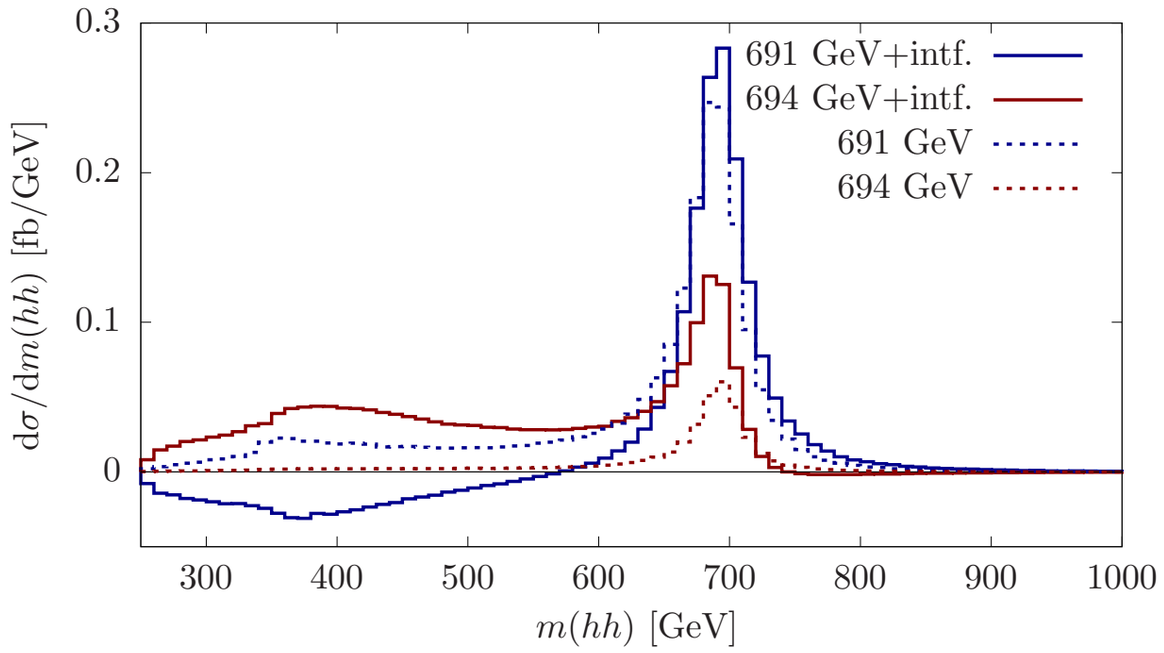
- top resonance searches in Higgs sector extensions with narrow width approximation is inadequate!

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**







phenomenology in perspective

above Higgs pair threshold

- (multi) resonant diHiggs production (hh, hH,...)

opportunity for diHiggs

Higgs interactions dominant

exotics with large couplings to tops

top interactions dominant

above top pair threshold

- tt final states typically preferred
- analysis highly model-dependent due to dedicated S-B interference

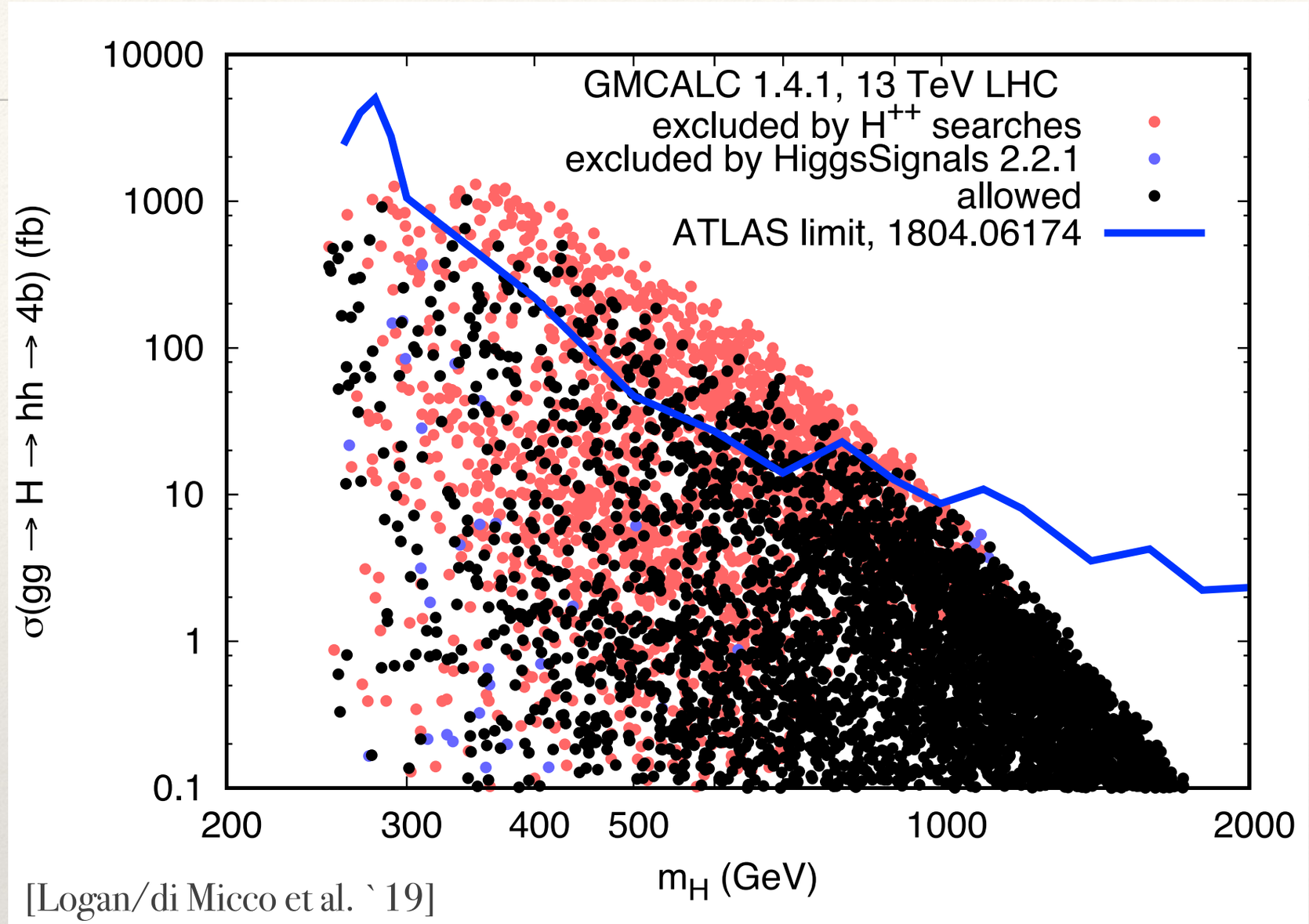
opportunity for diHiggs

below top pair threshold

- compressed spectra
- single Higgs competitive except b-final states (*trigger etc...*)

opportunity for diHiggs

triplets



[Logan/di Micco et al. `19]

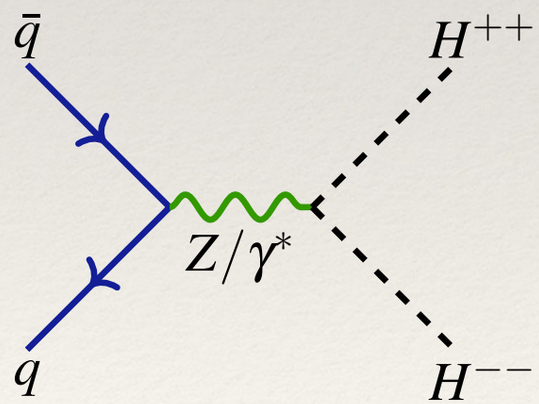
- custodial triplet extensions à la Georgi-Machacek contain an extremely rich Higgs sector phenomenology e.g. [Chang, Chen, Chiang `17]
- not as well explored as 2HDMs but Monte Carlo tool chain and precision predictions well developed [Degrande, Hartling, Logan, Peterson, Zaro `15]

composite triplets

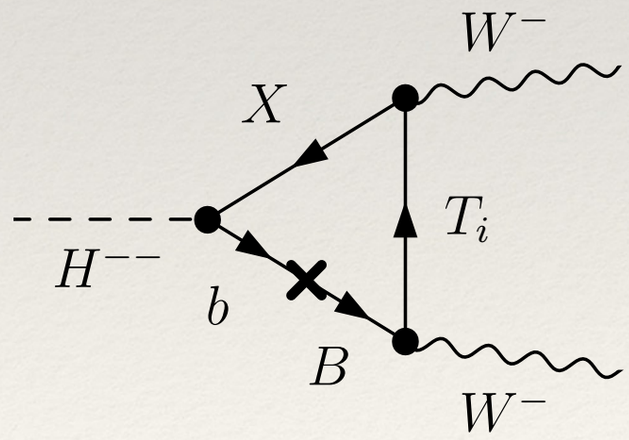
perhaps less appreciated: The GM structure is reproduced in realistic (UV-complete) theories of $SU(4)_c$ Higgs compositeness SU(5)/SO(5)

[Ferretti `14]
[Golterman, Shamir `17]
...

- little a priori knowledge about LEC parameters (baryonic 4-pt correlators massively complicated)
- if no significant triplet vev component, pair production has to proceed through gauge interactions



Drell-Yan pair production

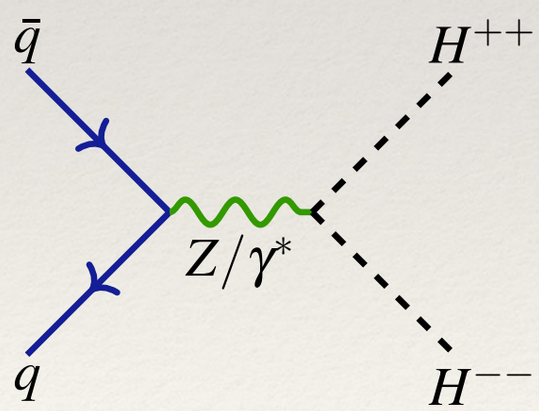


partial compositeness + WZW

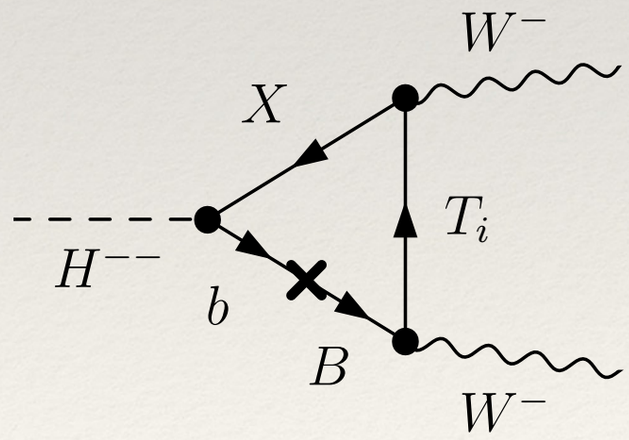
composite triplets

m_H [GeV]	200	300	400	500	600	700	800	900	1000
cut on m_T [GeV]	2.0	2.0	173	234	280	341	367	457	488
$\sigma_{\rm S}$ [ab]	51	25	14	8.1	4.8	2.9	1.9	1.1	0.71
$\sigma_{\rm B}$ [ab]	24	16	11	6.1	3.8	2.3	1.8	1.1	0.79
$\mathcal{L}\,[\text{ab}^{-1}]$ for 95% exclusion	0.11	0.26	0.51	0.85	1.5	2.5	4.2	6.9	12
Z for a $3\,\text{ab}^{-1}$ LHC	10	6.7	4.8	3.7	2.8	2.2	1.7	1.3	1.0
$\text{BR}(H^{\pm\pm} \to W^\pm W^\pm)$	0.44	0.55	0.64	0.73	0.84	0.96	1.1	1.2	1.4
signal modifier μ	0.12	0.21	0.33	0.44	0.63	0.89	1.3	1.8	2.7

[CE, Schichtel, Spannowsky `16]



Drell-Yan pair production



partial compositeness + WZW

3 key questions for the future

- How far can we push the *m(hh)* distribution for different future collider concepts as a BSM tool?
  - theoretical uncertainties/experimental systematics

- How far can we go in mass coverage for di-Higgs resonances? Gluon fusion + jets, weak boson fusion (beyond invisible decays), ...
  - relevance of heavy Higgs-like search > 1 TeV

- Exotic decays, busy high multiplicity final states and challenging kinematics: what is the ultimate experimental sensitivity?
  - multivariate approaches, machine learning, DNNs,...