HH in Future Colliders

María Cepeda

Overview

What I will talk about

- Studying the Higgs self-coupling through HH and H production is one of the clear goals of the program of the future colliders, and it has been covered in depth in many detailed presentations before this one :)... including those already shown in the kick-off meetings two weeks ago

- The production of resonant X->hh has also been addressed in past documents, with less complete coverage specially in what regards to more exotic BSM models

- I will give a brief overview on the existing results (starting by current experimental results to set the field and then broaching the future prospects) to focus on what areas can be expanded

  - Asked by the conveners to put focus on resonant and BSM

  - Whenever possible, referring to papers & more complete talks

What follows is a brief recap from my own point of view.
Apologies for any omission (not intentional)

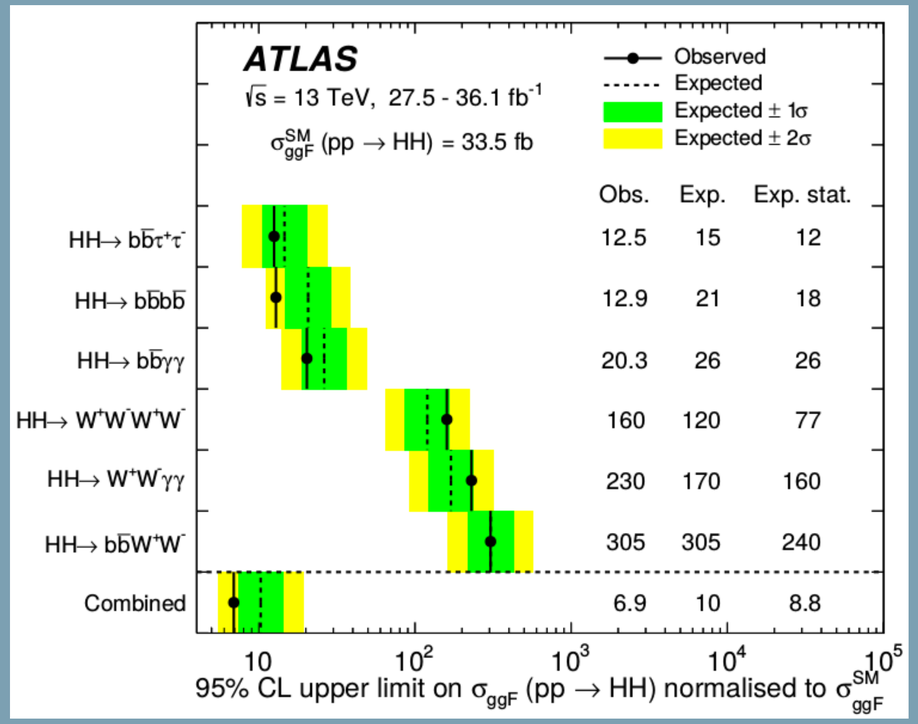
Disclaimer

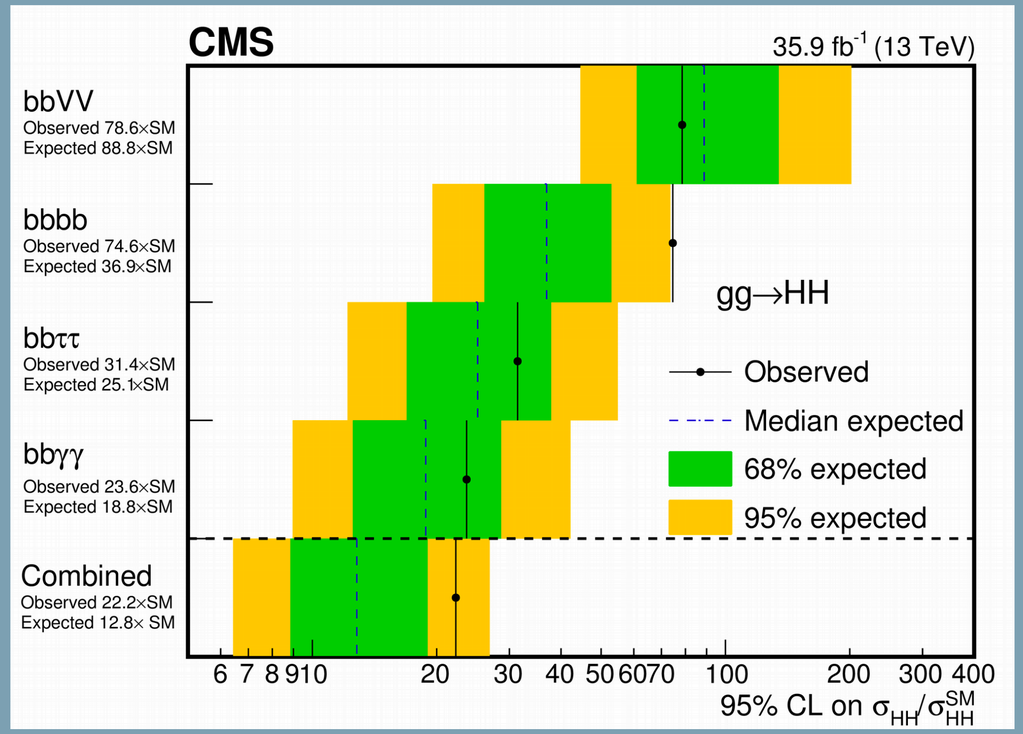
HH & self-coupling

- We will review both **resonant and non-resonant DOUBLE HIGGS PRODUCTION**
  - Any missing experimental studies and unexplored signatures?
    - For resonant: production of different-mass Higgs bosons?
    - **Synergy with EF02 on resonant HH production** : is there any new physics effect that demands a dedicated analysis or signature based analyses are enough?
  - *There is a new FCC-hh study, shall we expect updates from HL-LHC based on full Run 2 analyses?*
    - **VBF HH** not really covered for HL-LHC but first Run 2 results are now available - opportunity for hadronic machines
    - Significant improvements are possible in the context of ILC (M. Peskin)
- For the self-coupling constraints it is important to consider effects on the other Higgs couplings
  - Revise how to optimally combine double Higgs and single Higgs data:
    - ex: differential information, different center of mass of energies for e^+e^- colliders
- Beyond HH: **HHH & quartic coupling?**

In reality Caterina's slide summarised the situation already...

HH today (LHC Run2)





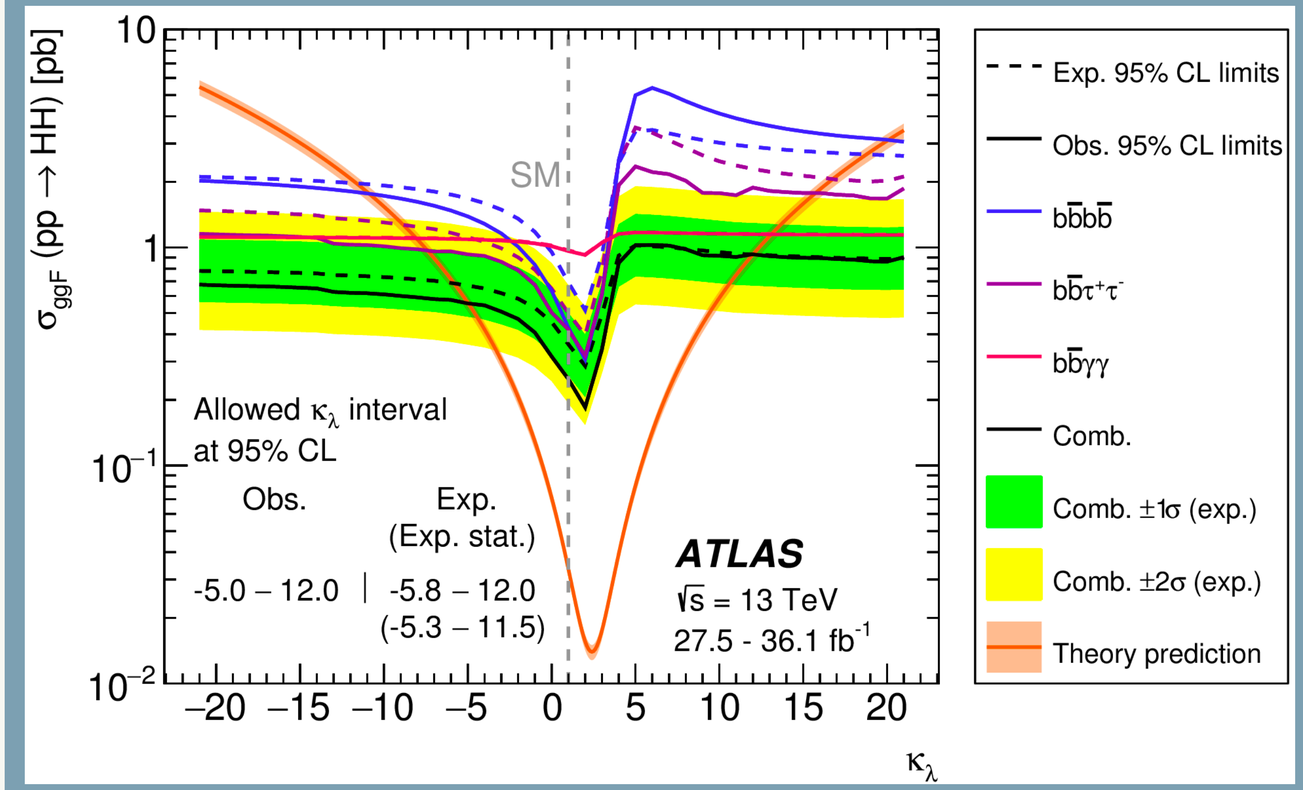
x10 SM with 36fb-1 (waiting for full Run2 results)

LHCP TALK on HH (tomorrow!)

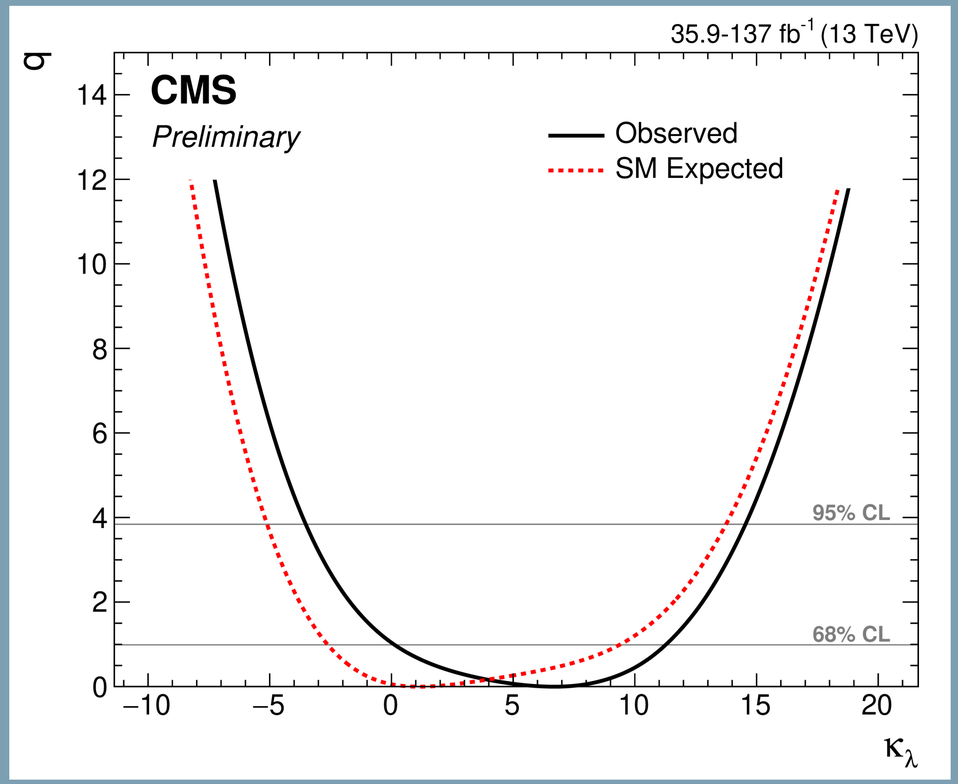
LHCP TALK on Self Coupling (tomorrow)

LHCP TALK on HL-LHC (yesterday)

HH today (LHC Run2)



[-5.0(-5.8), 12.0(12.0)] ATLAS
[-11.8(-7.1), 18.8(13.6)] CMS



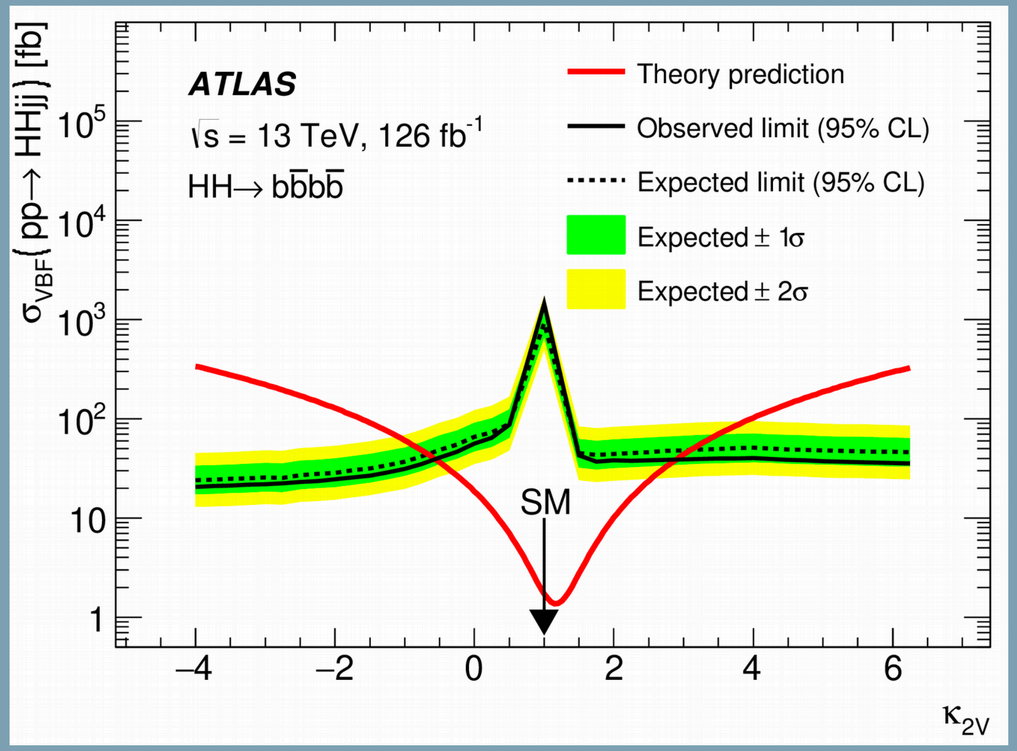
[-3.2, 11.9] (ATLAS) [-3.5, 14.5] CMS

LHCP TALK on HH (tomorrow!)

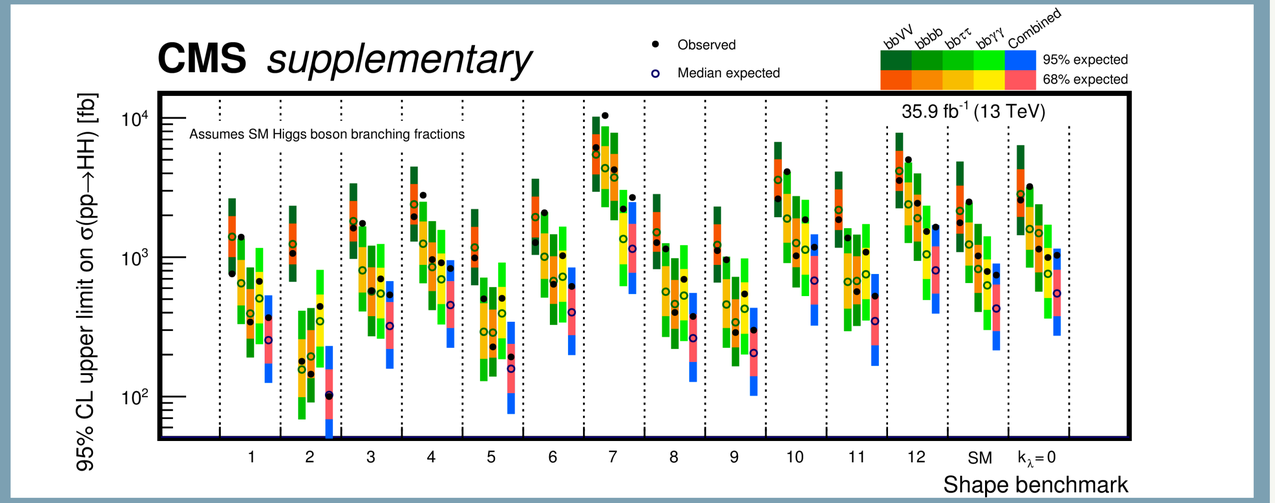
LHCP TALK on Self Coupling (tomorrow)

LHCP TALK on HL-LHC (yesterday)

HH today (LHC Run2)



Starting to probe VBF HH and C2V ttHH?



	SM	$\kappa_\lambda = 0$	1	2	3	4	5	6	7	8	9	10	11	12
κ_λ	1.0	0.0	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0
κ_t	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0
c_2	0.0	0.0	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0
c_g	0.0	0.0	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0
c_{gg}	0.0	0.0	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0

LHCXSWG benchmark modes

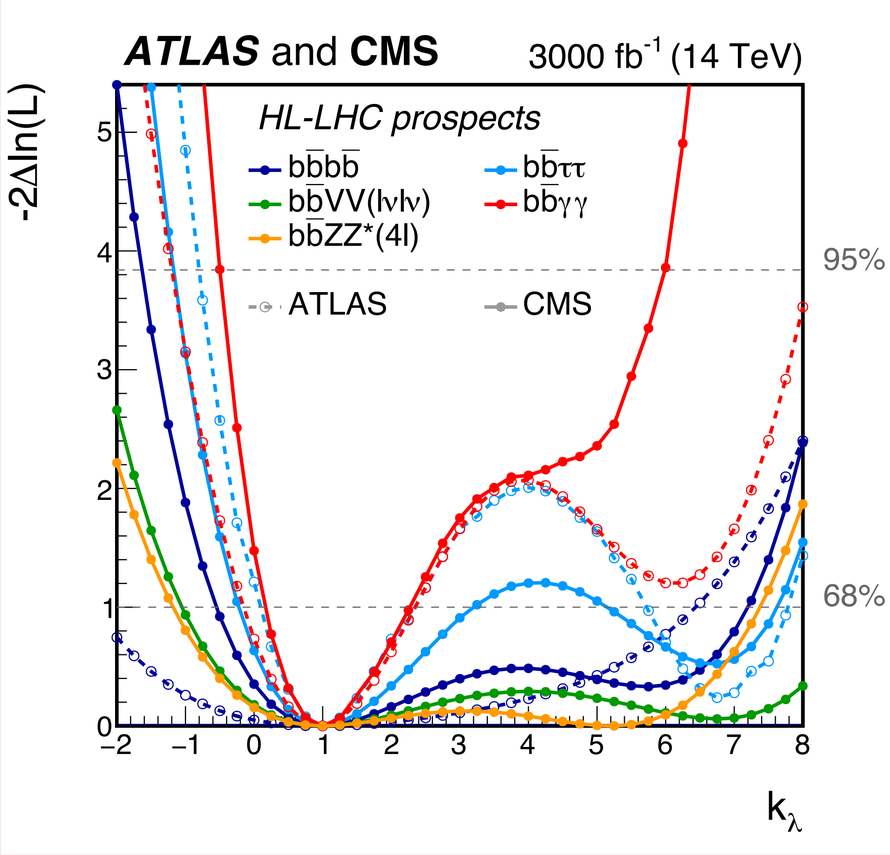
LHCP TALK on HH (tomorrow!)

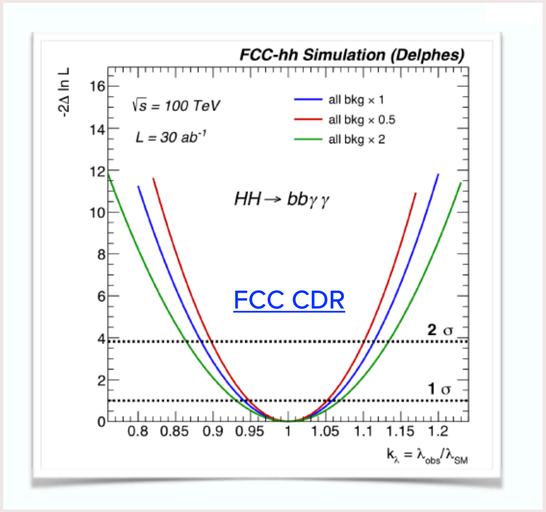
LHCP TALK on Self Coupling (tomorrow)

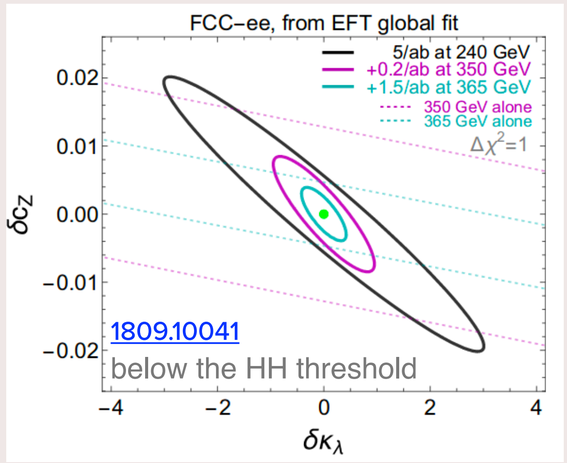
LHCP TALK on HL-LHC (yesterday)

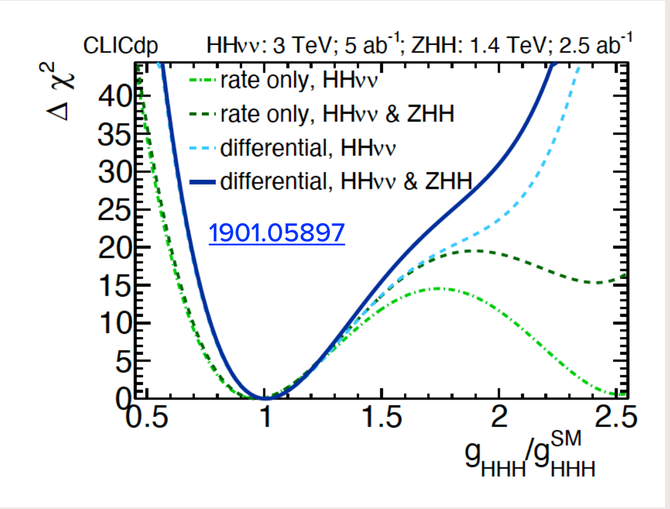
HH & SelfCoupling: the future

ECFA summary presented by Christophe in the kickoff meeting









Full set of references and proper summary both in

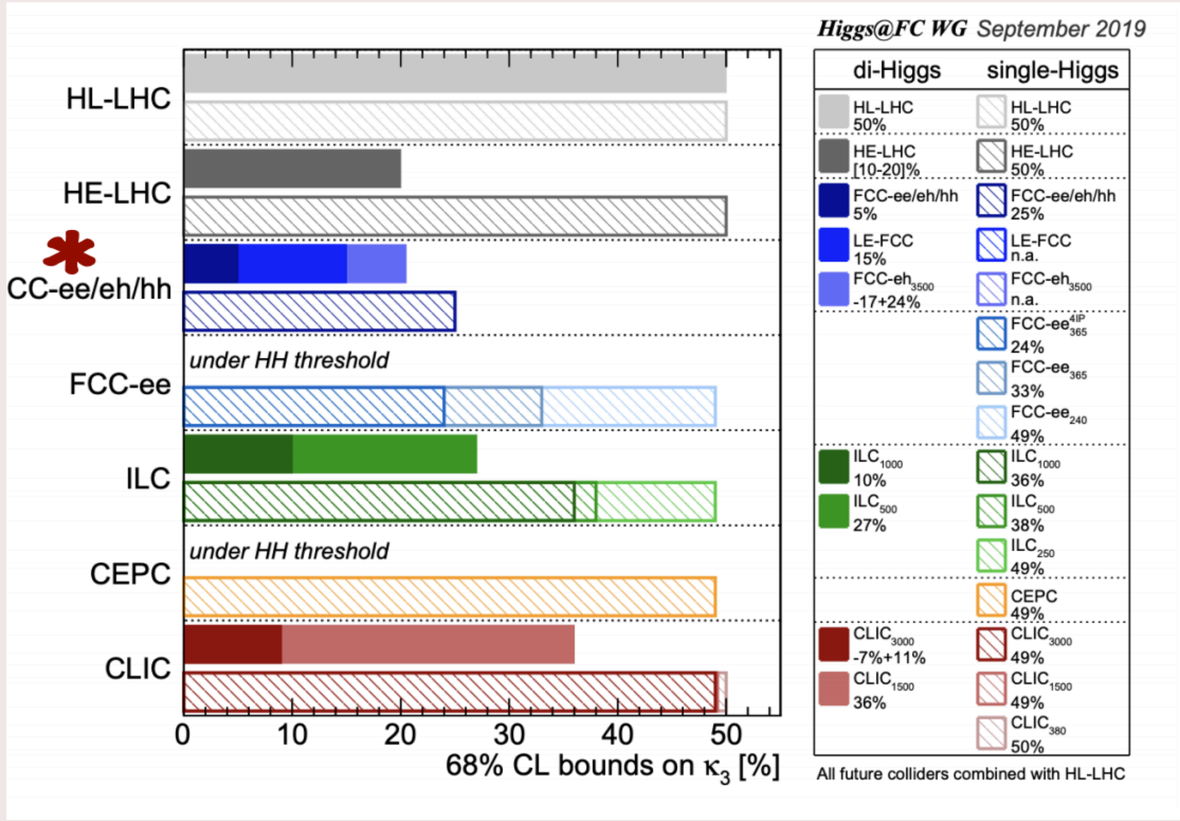
https://arxiv.org/abs/1905.03764 (ECFA Higgs Document)

and

https://arxiv.org/abs/1910.00012 (HH White paper)

Self Coupling in Future Colliders

Higgs ECFA summary (and refs. therein)

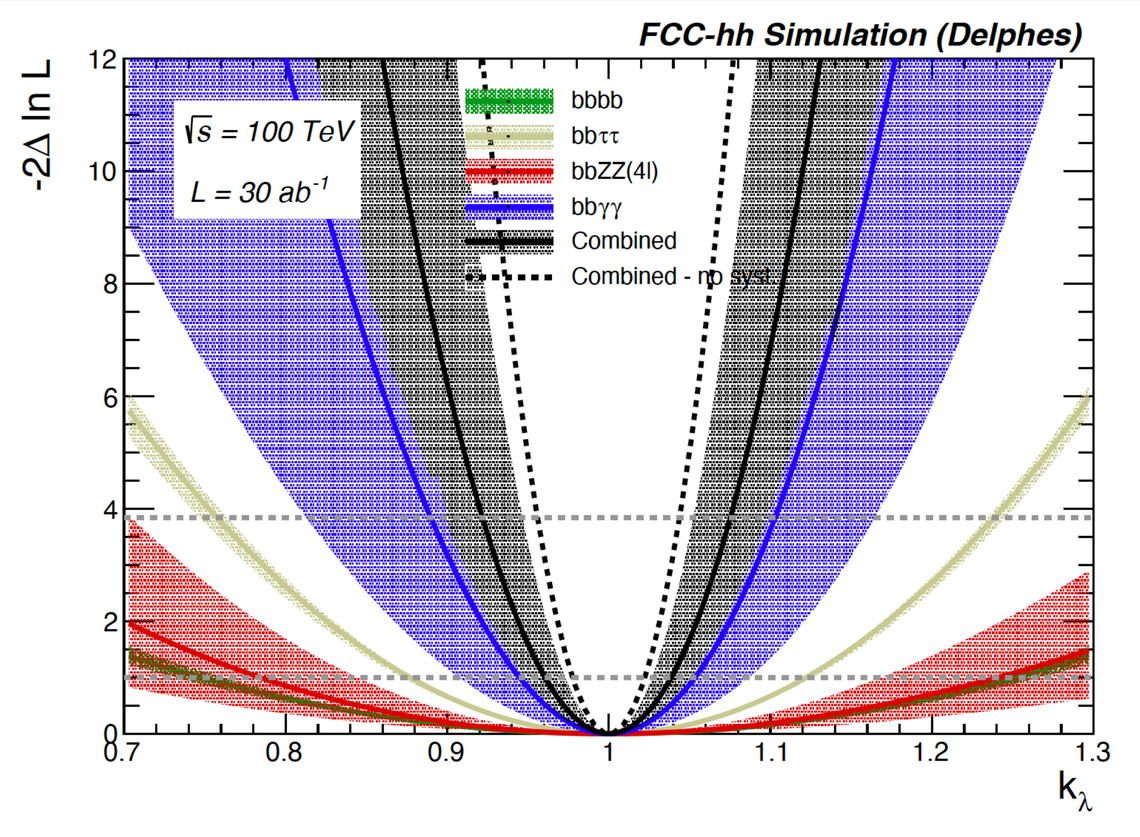


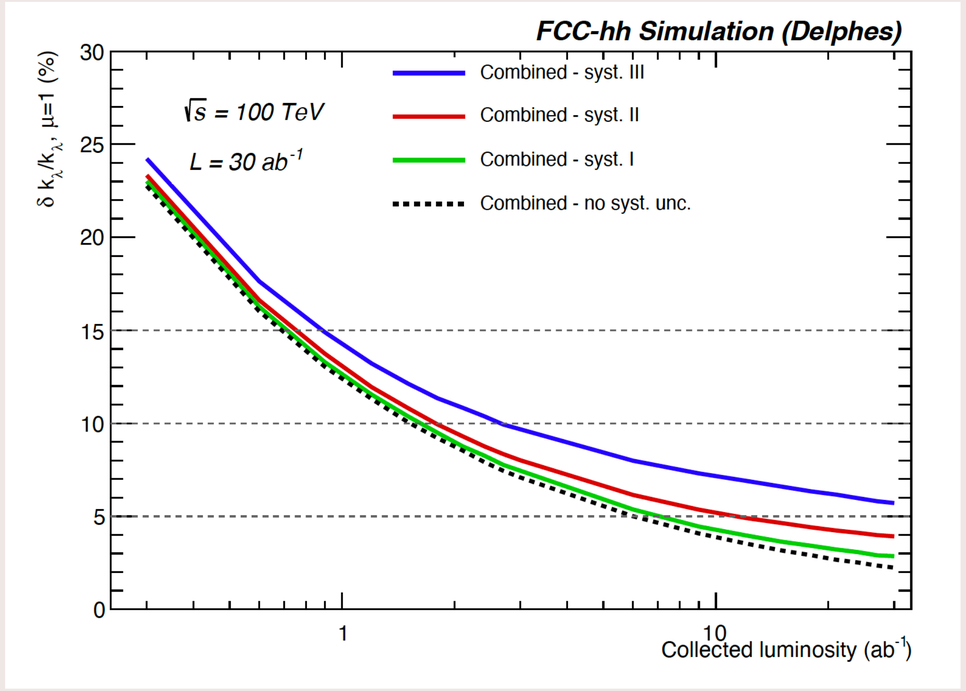
conservative?

collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
$CEPC_{240}$	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh *	-	5%	5%

(* slide stolen from Caterina's introduction)

FCC-hh update - new since ECFA





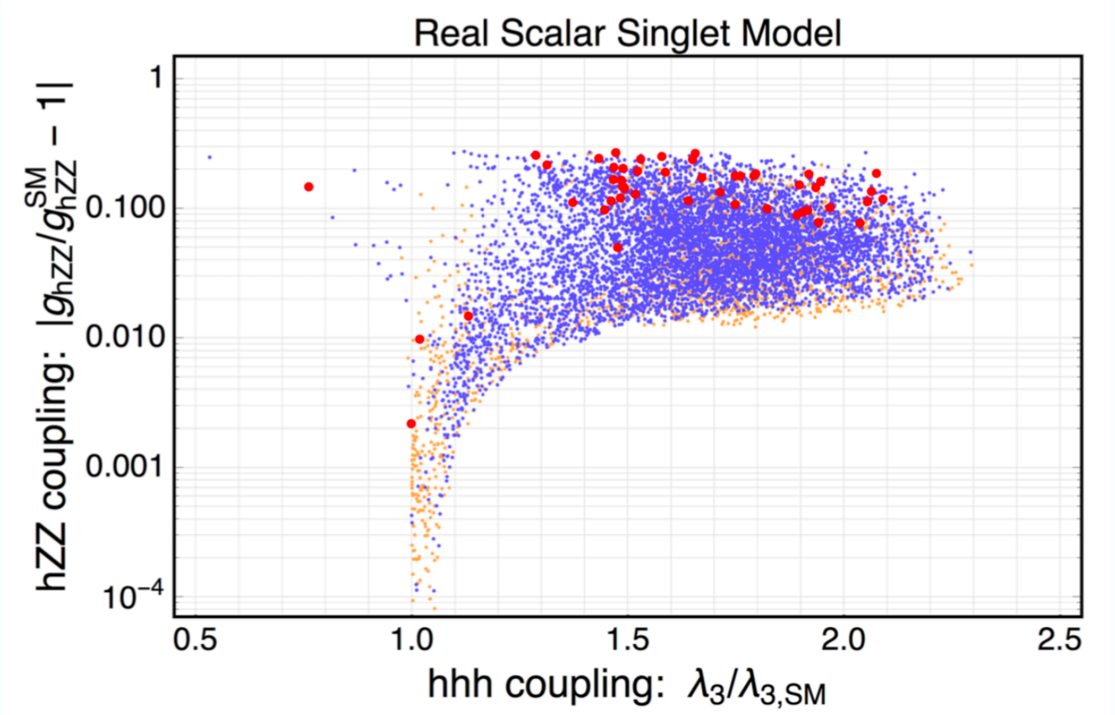
- $\delta\kappa_\lambda$ ~2.9-5.5% with 30 ab^{-1} (10% can be achieved with 2-3 ab^{-1})

https://arxiv.org/abs/2004.06122

Updates from other future colliders?

Borrowing from Peskin's talk

It is important not to consider the Higgs self-coupling in isolation, since BSM models that affect this also typically affect other Higgs couplings



Huang, Long, and Wang

Quartic Higgs Self Coupling?

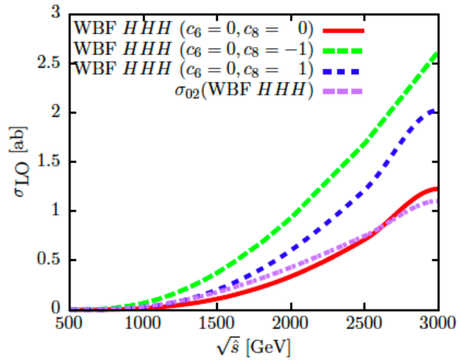
Summarized by F.Maltoni, D. Pagani in the [HH White Paper](#) - see references therein

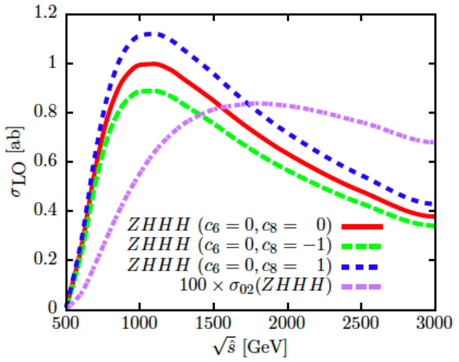
$$\Delta\mathscr{L} = -\frac{\bar{c}_6}{v^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3 - \frac{\bar{c}_8}{v^4}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^4$$

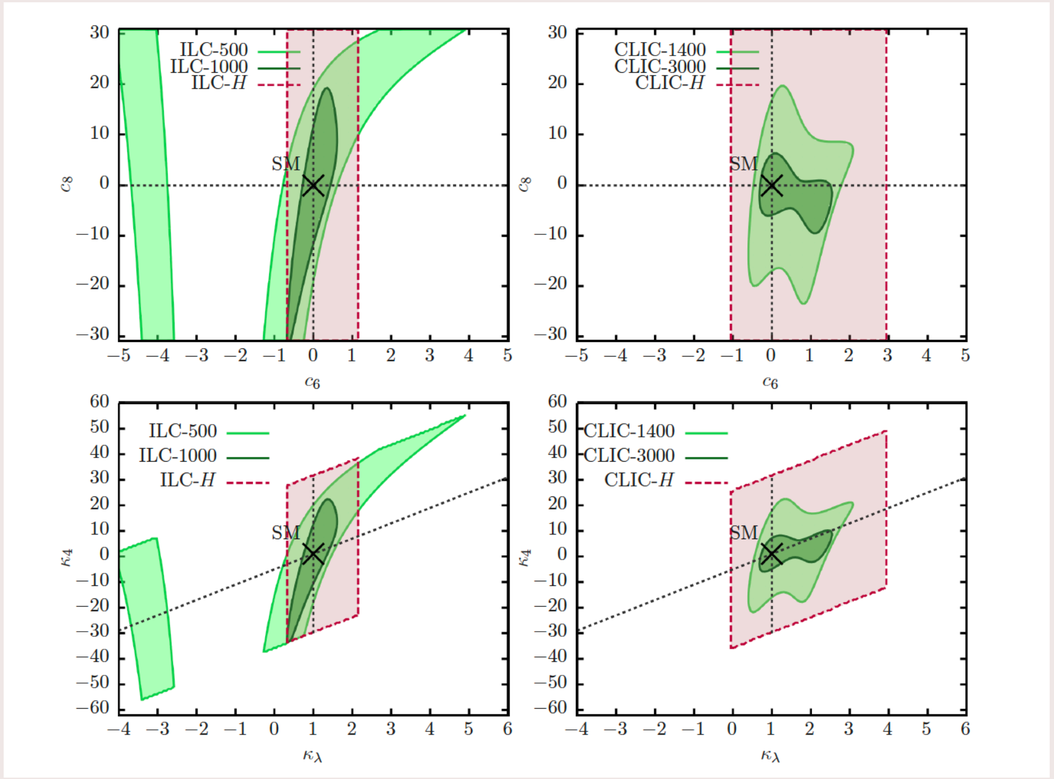
The first coarse bounds on the value of c8, and in turn on λ4, can be set indirectly at future e+e- colliders.

$$c_6 \equiv (2v^2/m_h^2)\bar{c}_6$$
$$c_8 \equiv 4(2v^2/m_h^2)\bar{c}_8 \,.$$

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{SM}} = 1 + c_6$$
$$\kappa_4 \equiv \frac{\lambda_4}{\lambda_4^{SM}} = 1 + 6c_6 + c_8 \,.$$







(FCC-hh also covered in the HH White Paper, see backup)

VBF HH and ttHH at FCChh

Summarized by F.Maltoni, D. Pagani, A. Shivaji, X. Zhao in the HH White Paper - see references therein

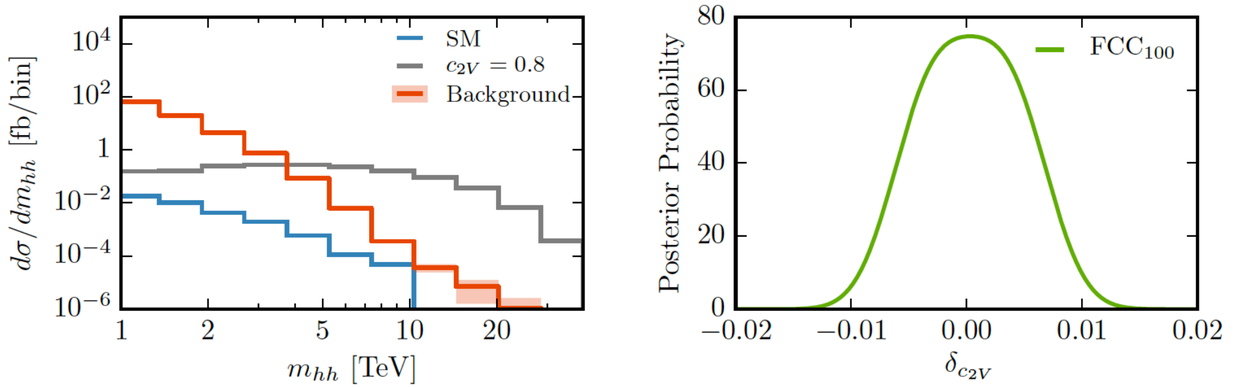


Figure 10.13: Distribution of the m_{HH} (left) and posterior probability on the determination of $\delta_{c_{2V}}$ at the FCC-hh (see Equation 5.16).

Summarized by S. Banerjee, F. Krauss, M. Spannowsky in the HH White Paper - see references therein

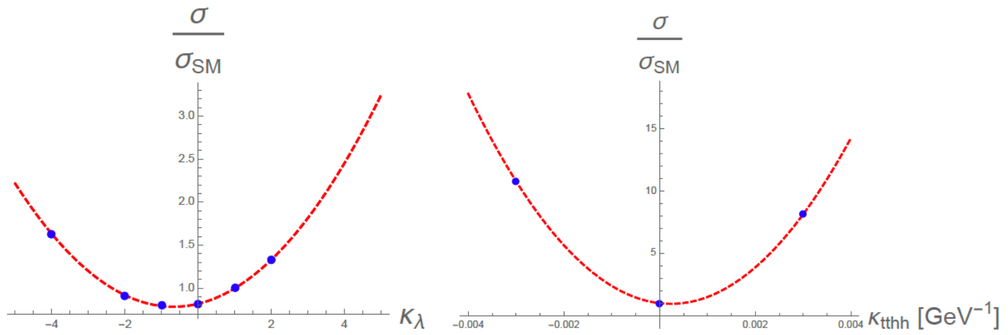
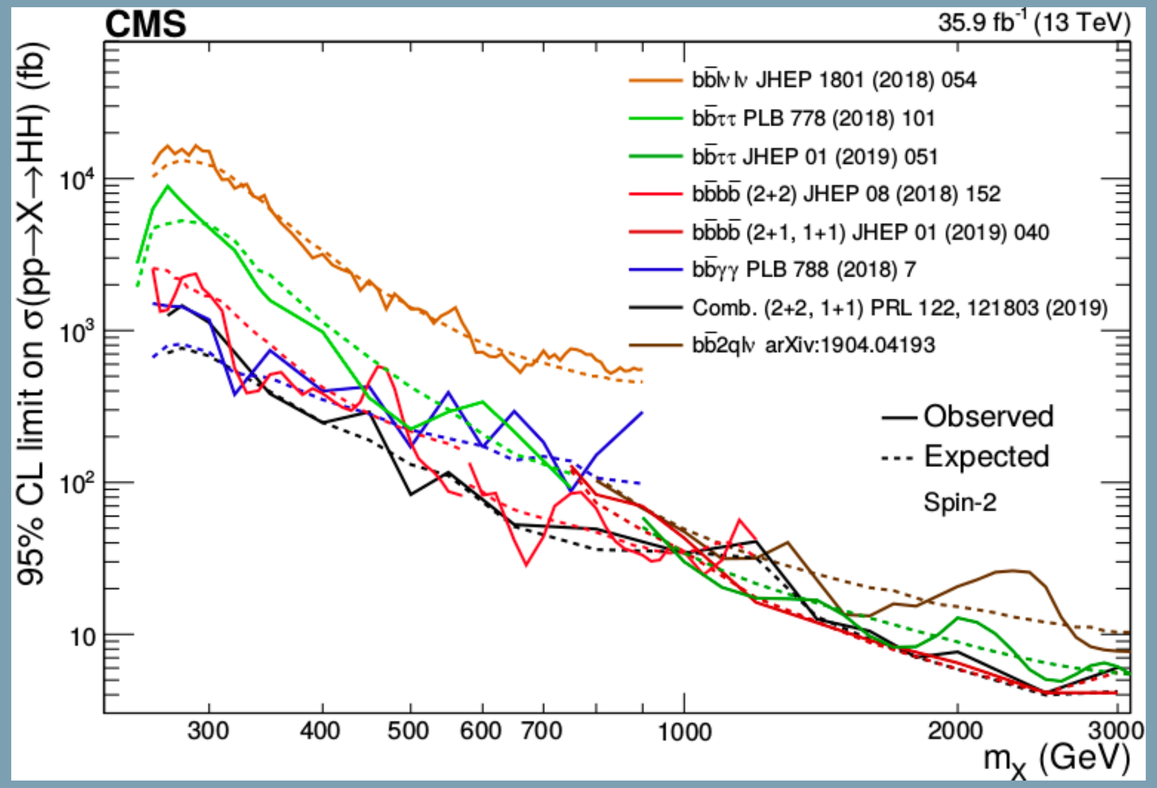
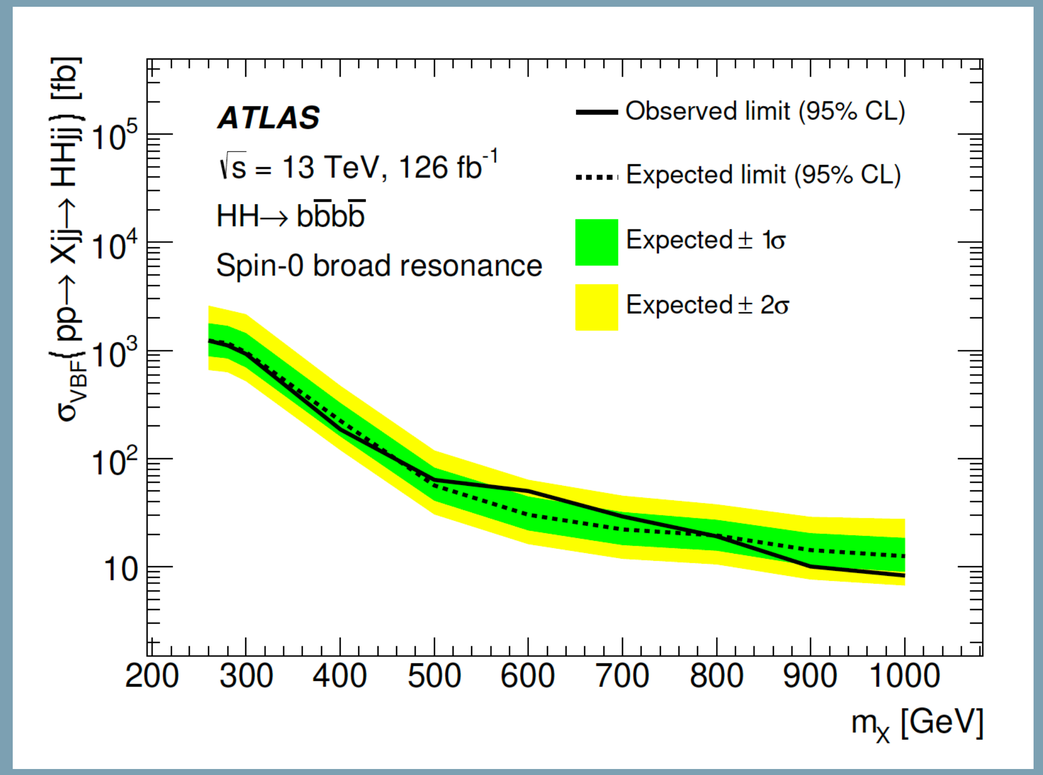


Figure 10.15: $\sigma/\sigma_{\rm SM}$ as a function of κ_λ (left) and $\kappa_{t\bar{t}HH}$ [GeV^{-1}] (right), where $\kappa_{t\bar{t}HH} = -m_t c_{tt}/v^2$.

X->HH today (LHC Run2)

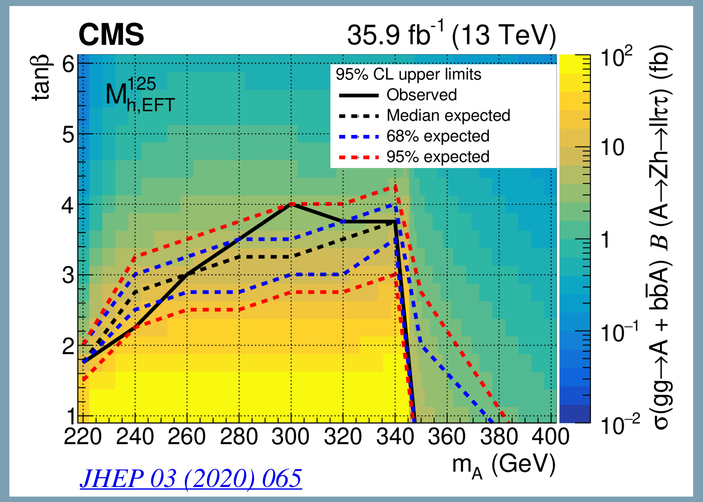




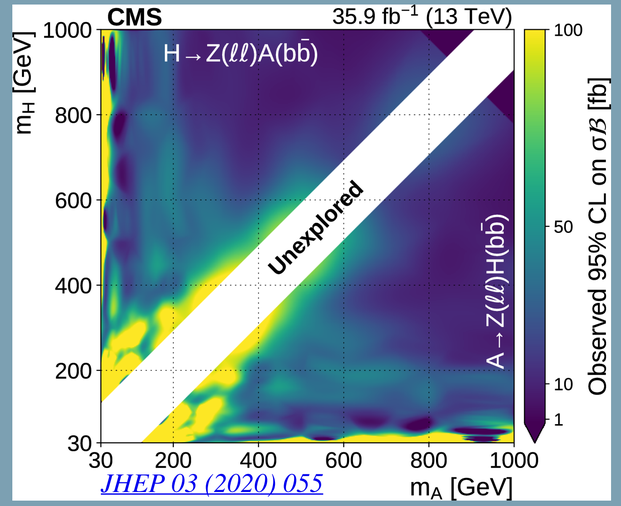
LHCP TALK on BSM Higgs

LHCP TALK on X->HH, X->VH

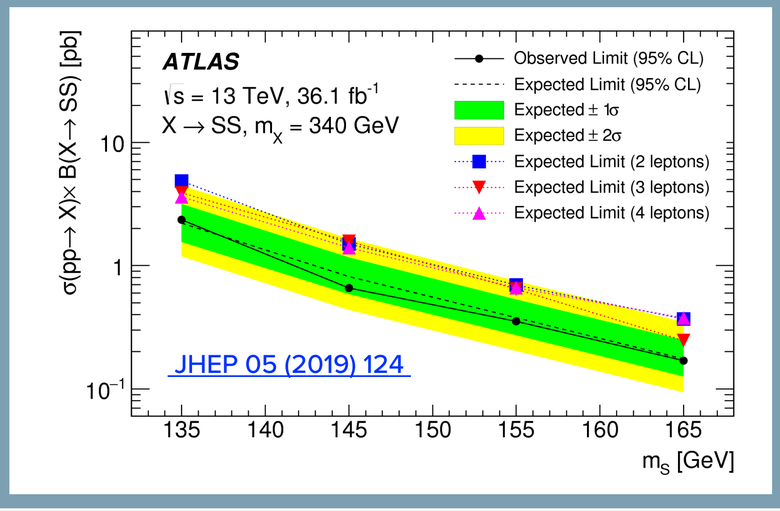
What about X->YH, X->SS, H->aa?



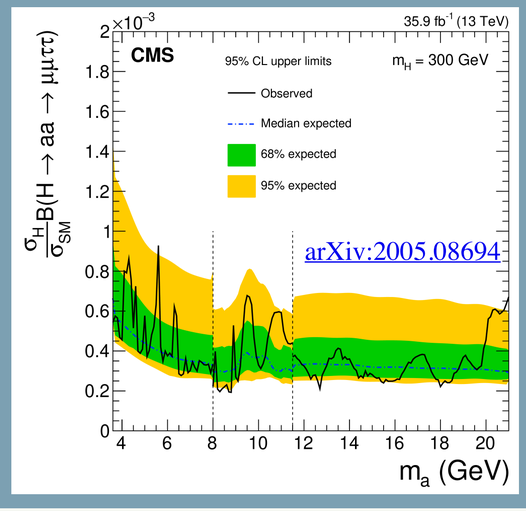
JHEP 03 (2020) 065



JHEP 03 (2020) 055



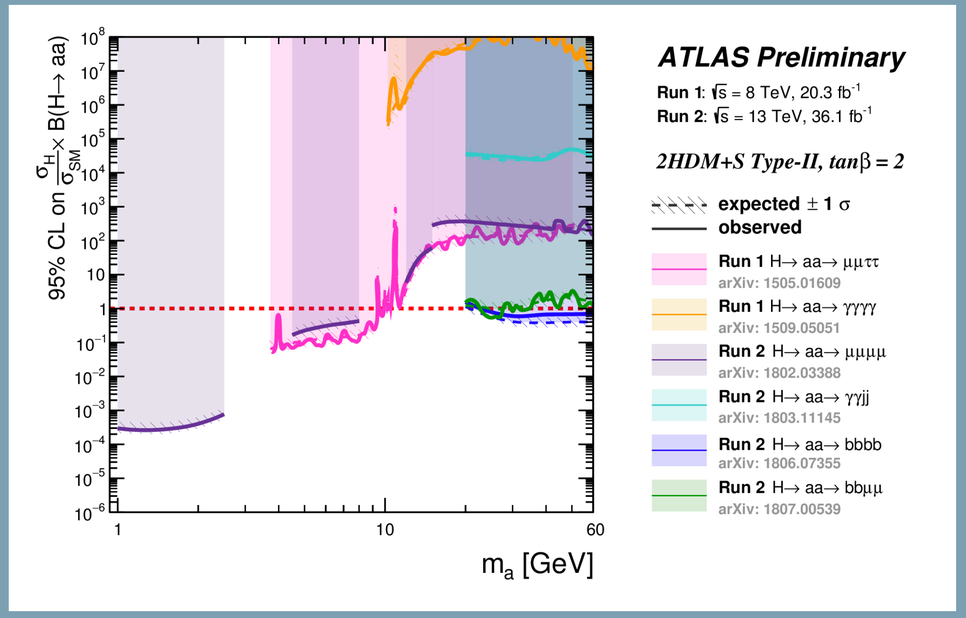
JHEP 05 (2019) 124



arXiv:2005.08694

A->Zh/H->ZA , h(125)->aa reasonably well covered and expanding

X->H1H2 (requested by theo): next challenge?

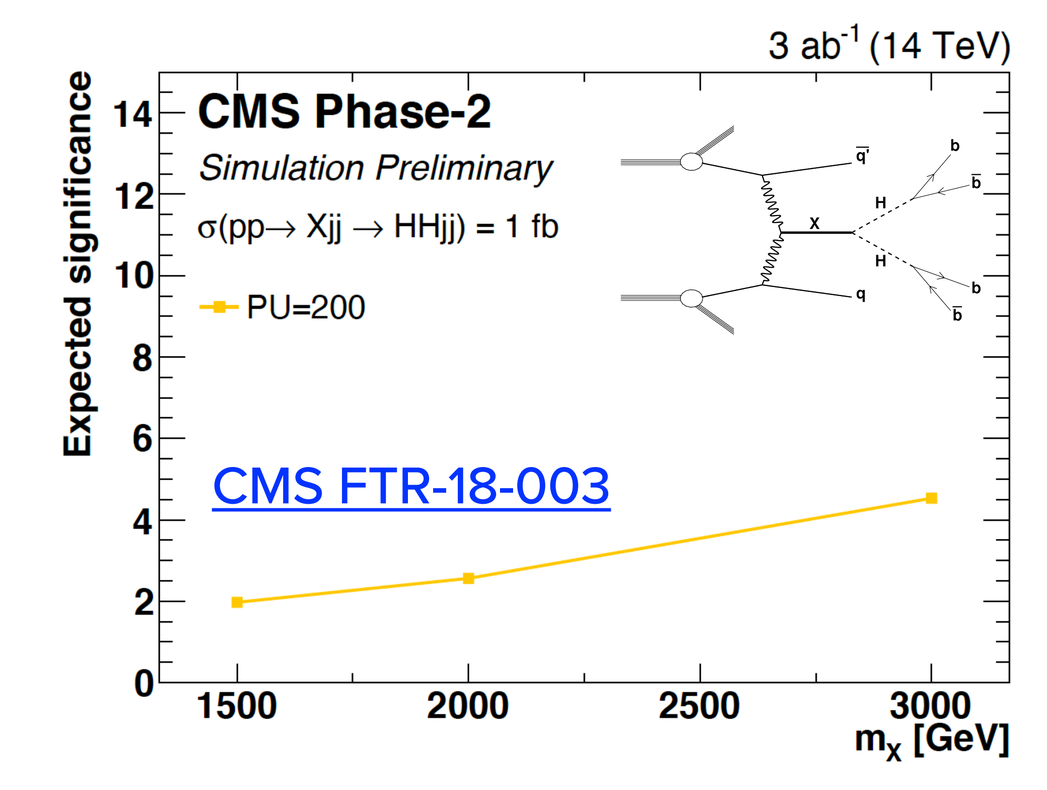


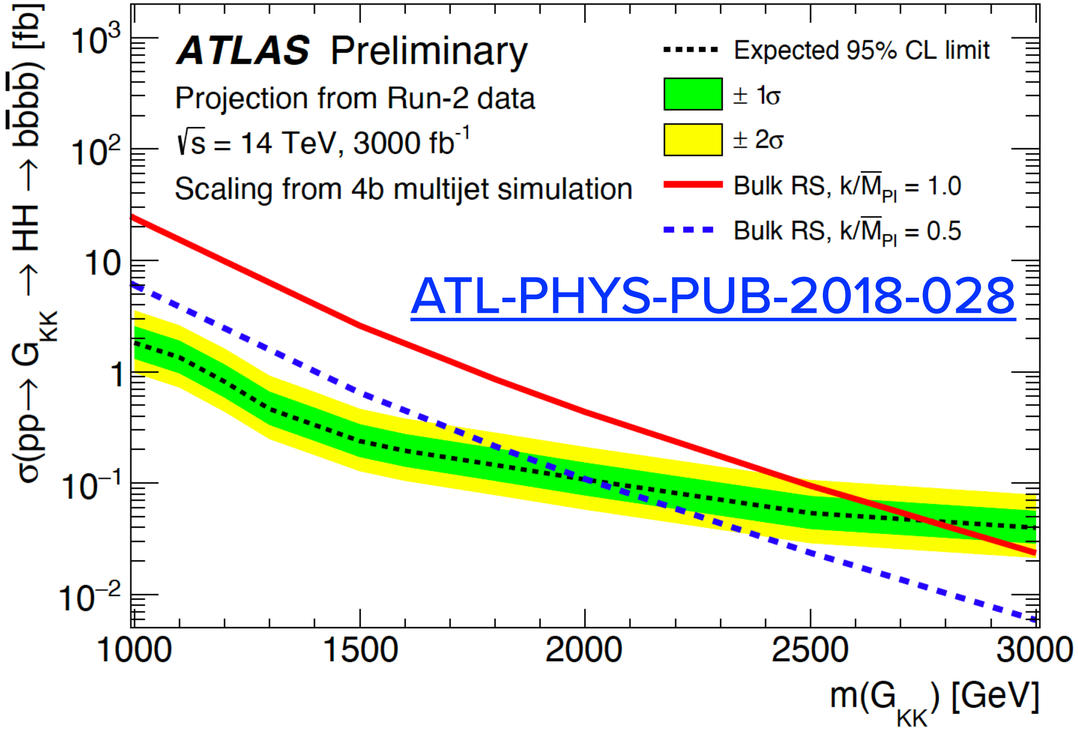
LHCP TALK on BSM Higgs

LHCP TALK on Exotic Higgs Decays

What about X->HH?

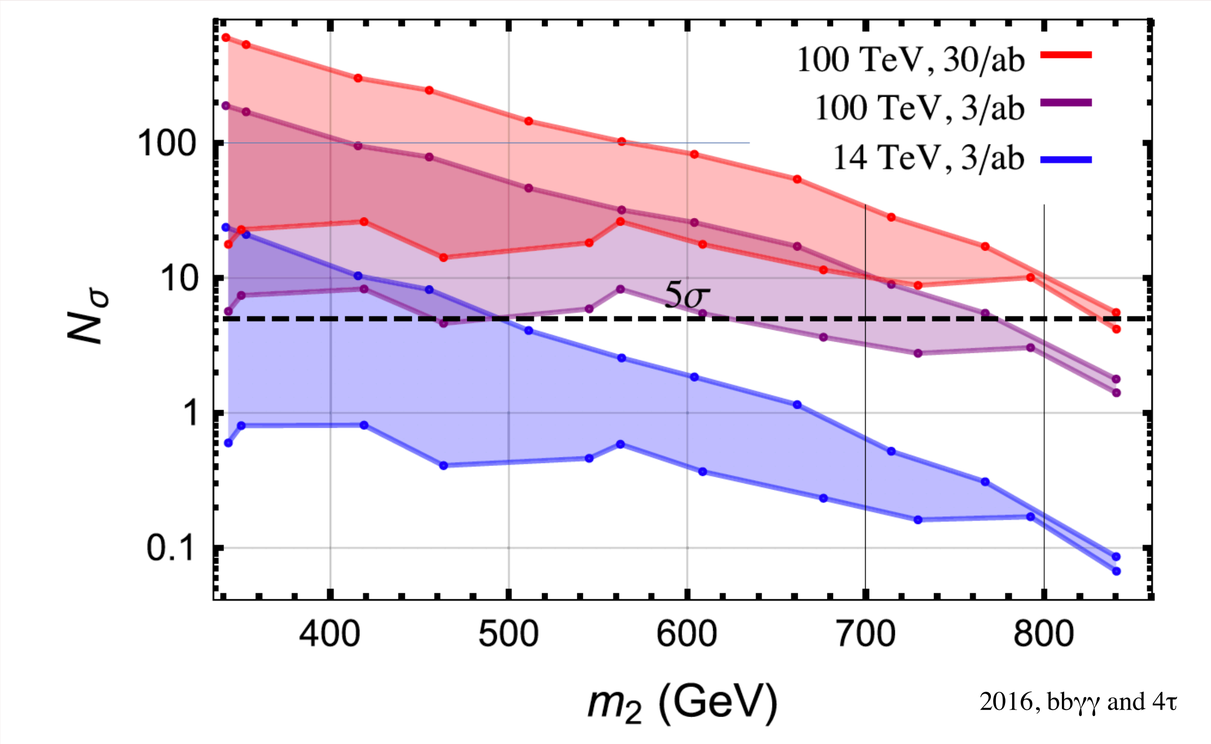
Boosted 4B prospects at HL-LHC available for both ATLAS and CMS
Other final states?



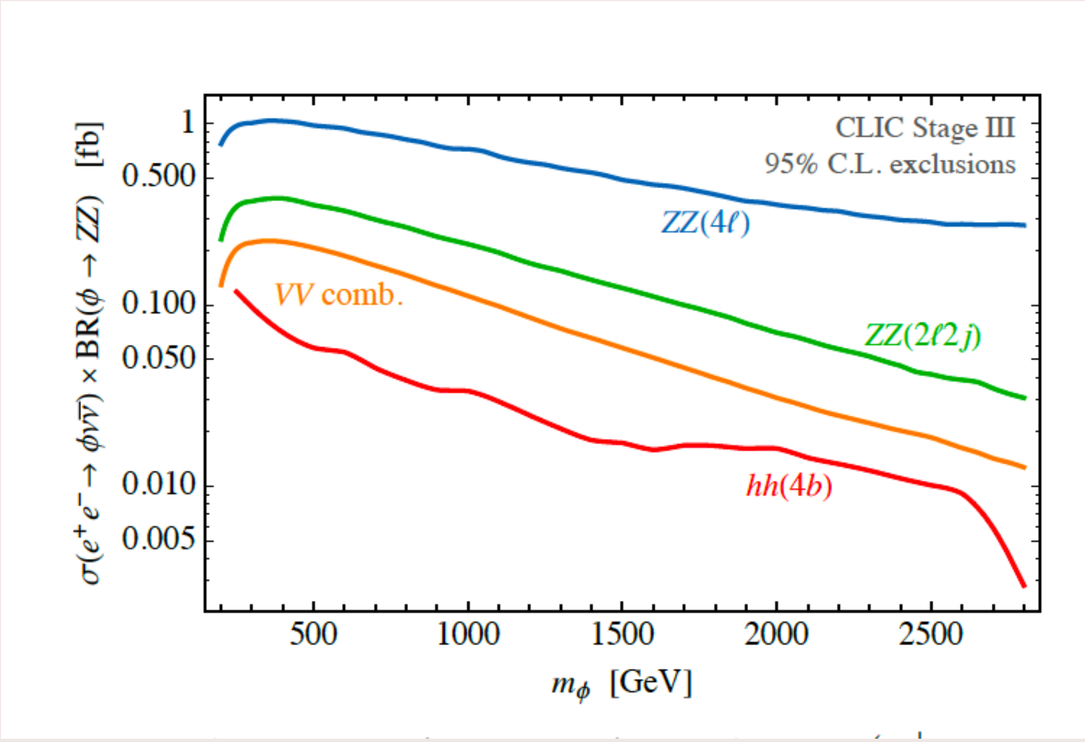


What about X->HH?

What about beyond the HL-LHC ?

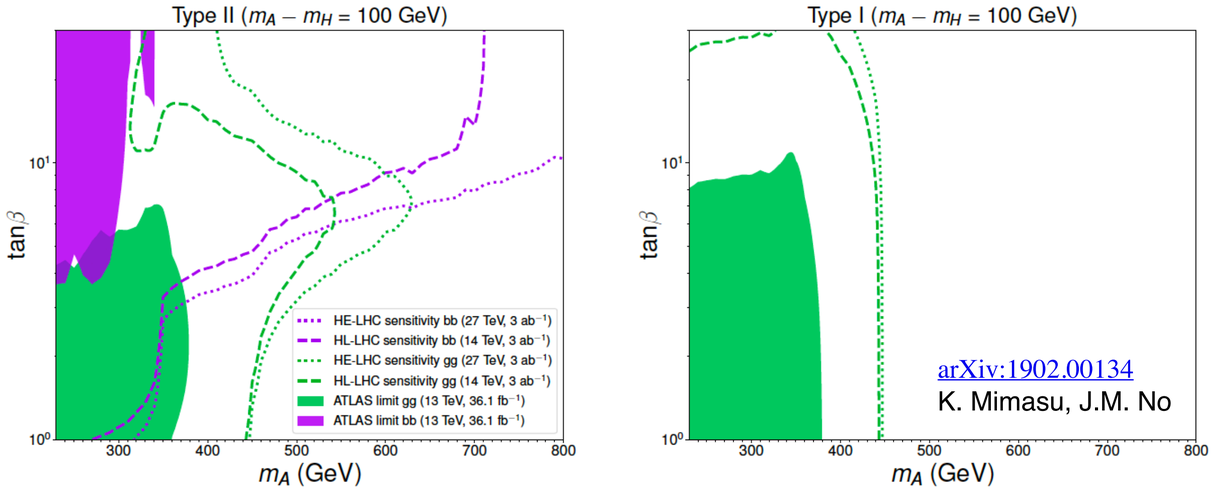


https://doi.org/10.1103/PhysRevD.94.035022



https://link.springer.com/article/10.1007/JHEP11(2018)144

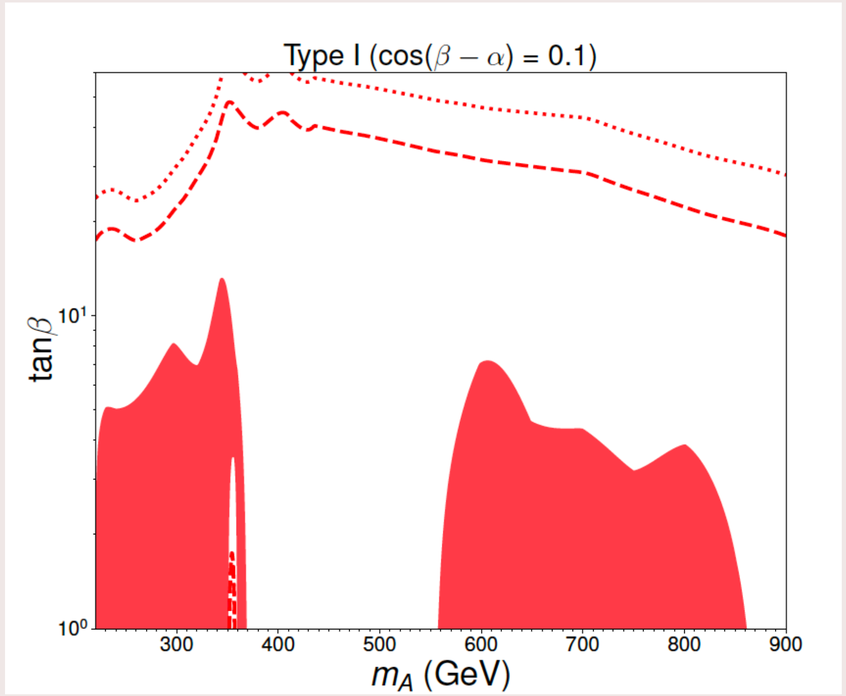
2HDM 'Higgs to Higgs' Decays



arXiv:1902.00134
K. Mimasu, J.M. No

Extrapolation of ATLAS' A->ZH (llbb)

How much can / should the coverage be expanded?



What about X->H1H2 ?

Extended Higgs Sector

Beyond HH but still within EF02…

ECFA Briefing Book

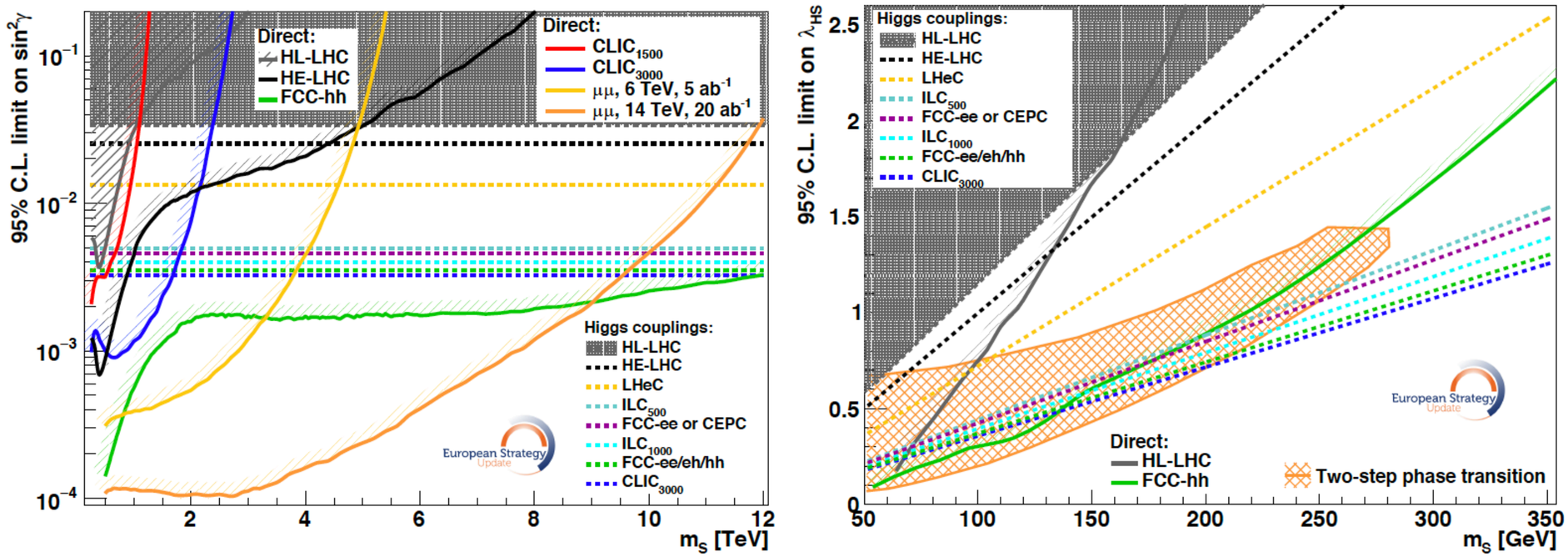


Fig. 8.11: Direct and indirect sensitivity at 95% CL to a heavy scalar singlet mixing with the SM Higgs boson (left) and in the no-mixing limit (right). The hatched region shows the parameters compatible with a strong first-order EW phase transition.

Extended Higgs Sector

Beyond HH but still within EF02…

ECFA Briefing Book

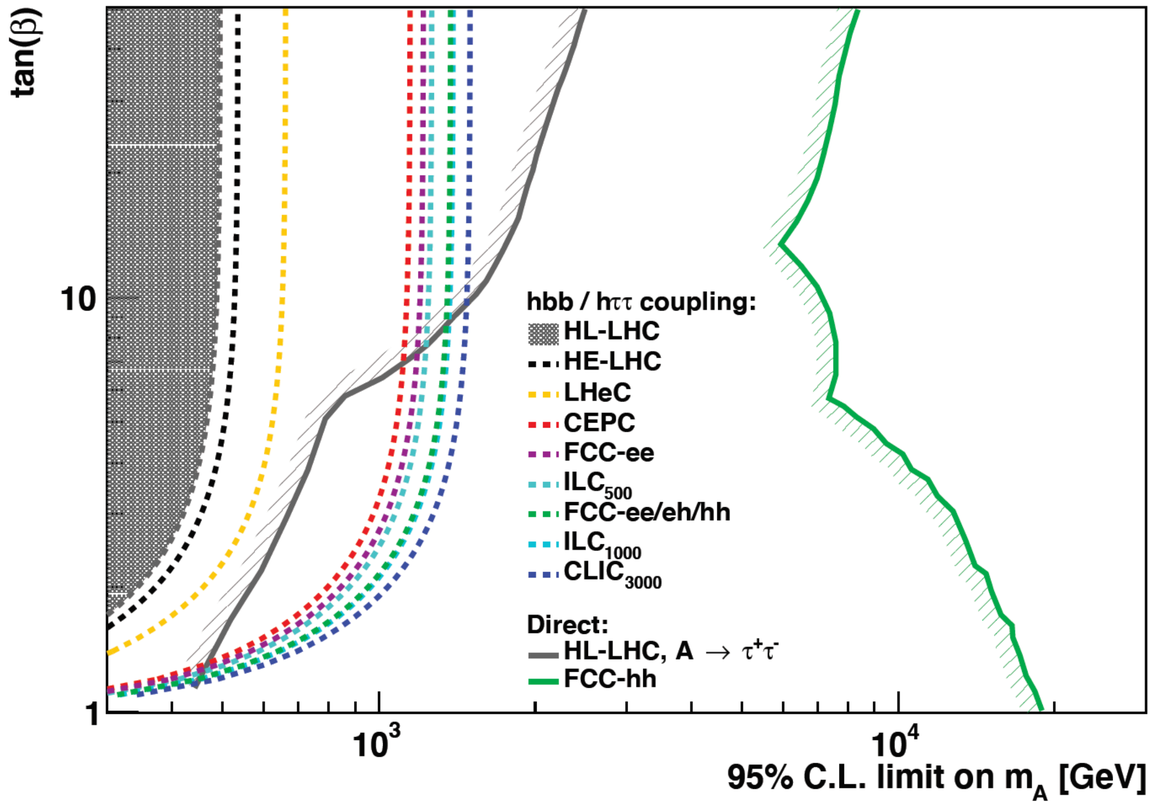


Fig. 8.12: Direct and indirect sensitivity at 95% CL to heavy neutral scalars in minimal SUSY.

Where to expand?

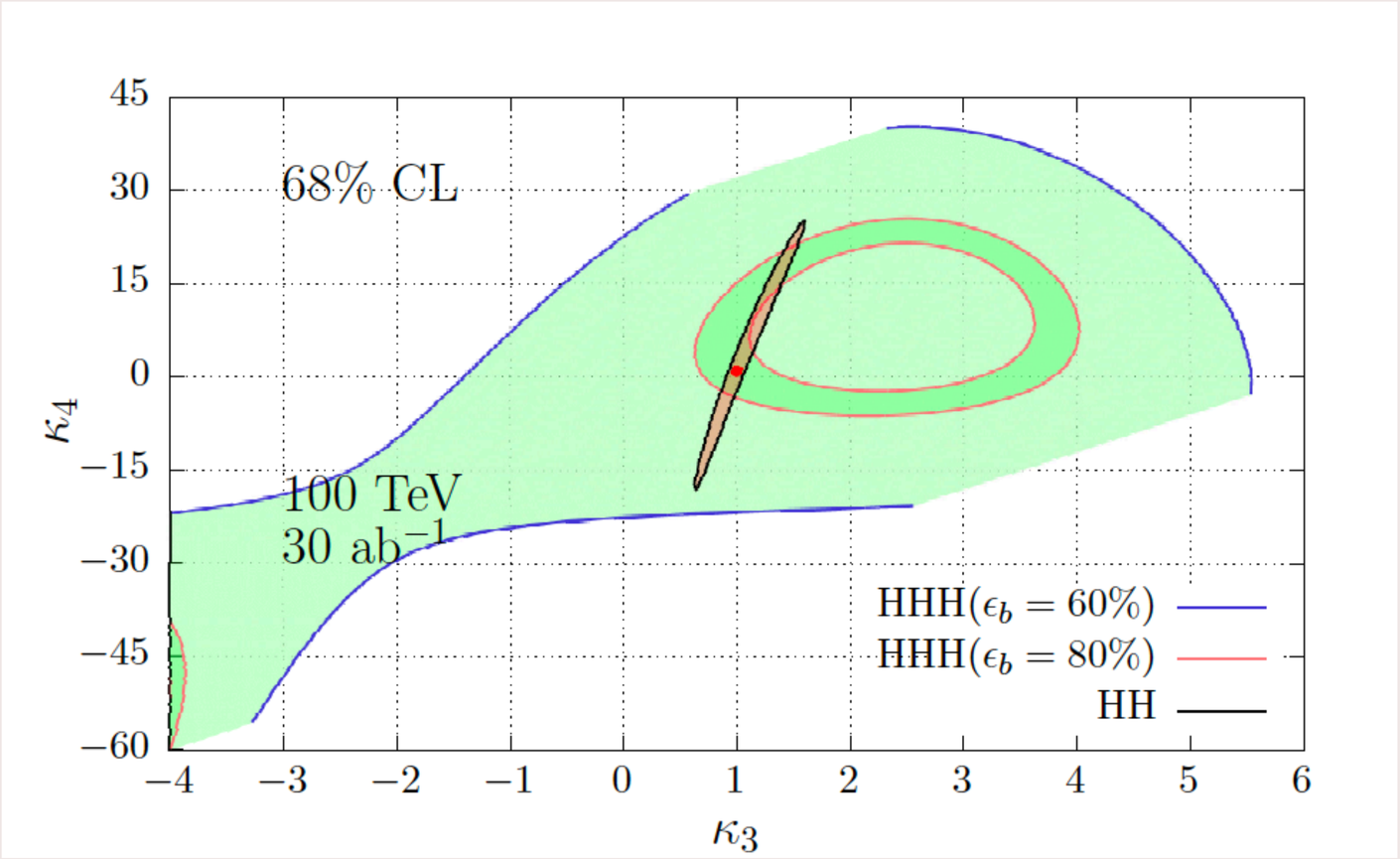
- **HH and self coupling well covered in the past years. What is missing?**
  - Updates? Example, FCC-hh new prospects, what about the other colliders ?
  - VBF / c2v ? ttHH ?
  - Single Higgs + HH combination - exploit kinematics ?
  - Can we go beyond the trilinear ?

- **Resonant HH is not covered uniformly and X->H1H2 very unexplored**
  - Large phase-space that can be probed, but not necessarily all areas interesting. Cross-coverage by different search modes-> what is left open now and what will be still open at the end of the LHC?
  - Guidance from the theoretical community on where to explore critical

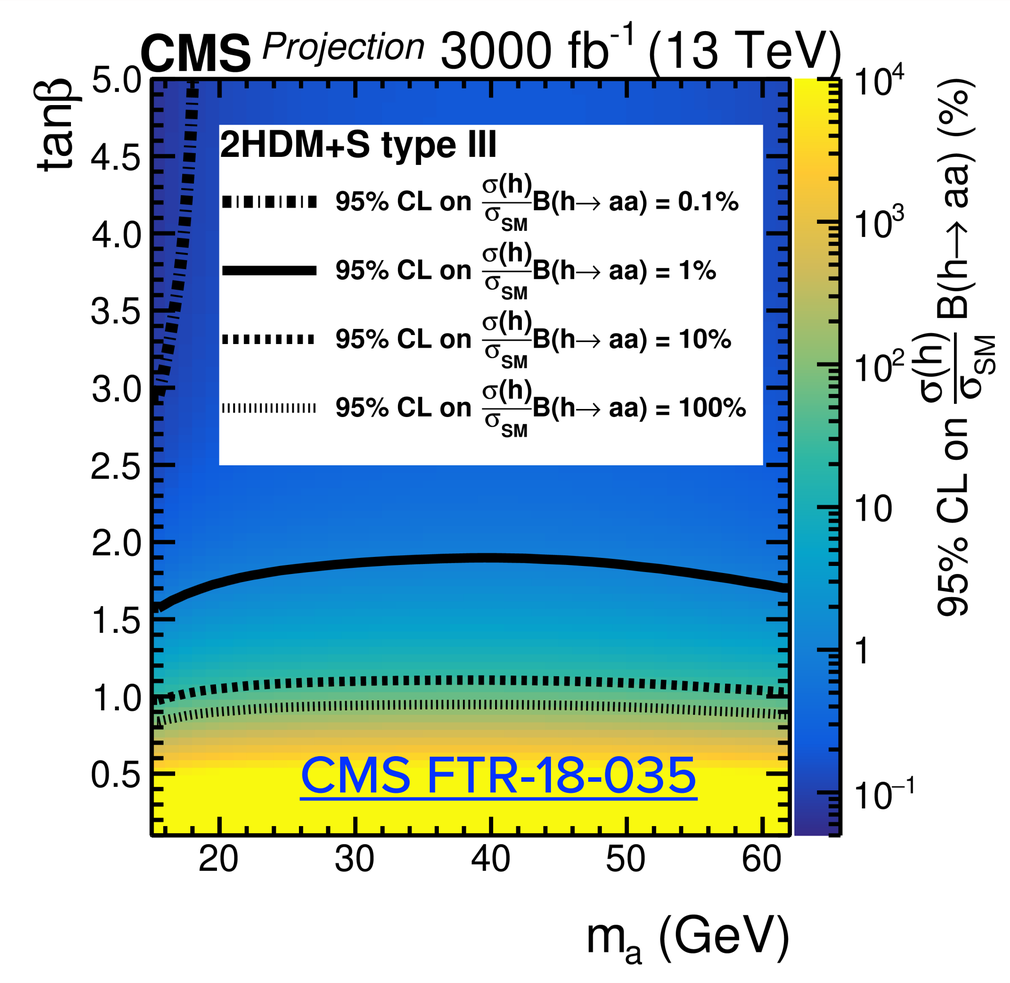
Backup

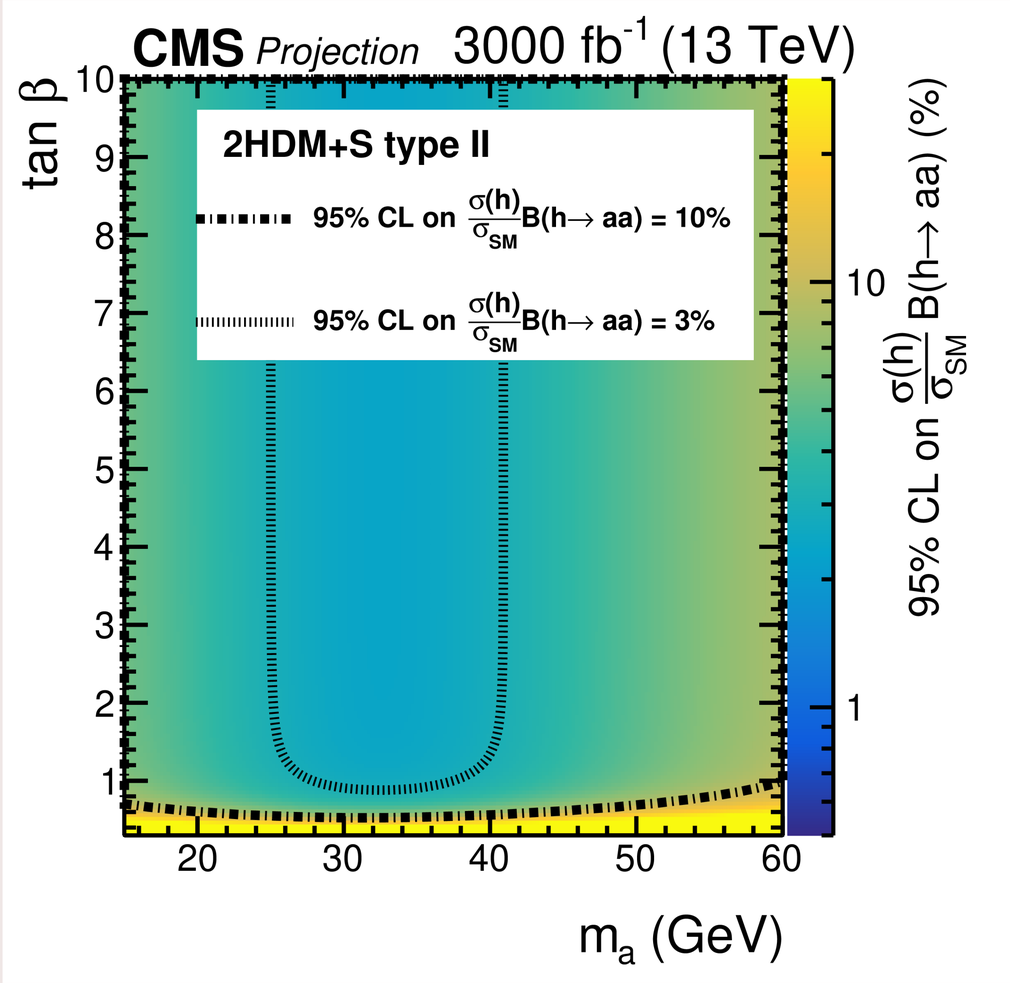
Quartic Higgs Self Coupling at FCChh

Summarized by F.Maltoni, D. Pagani, A. Shivaji, X. Zhao in the [HH White Paper] (see references therein)

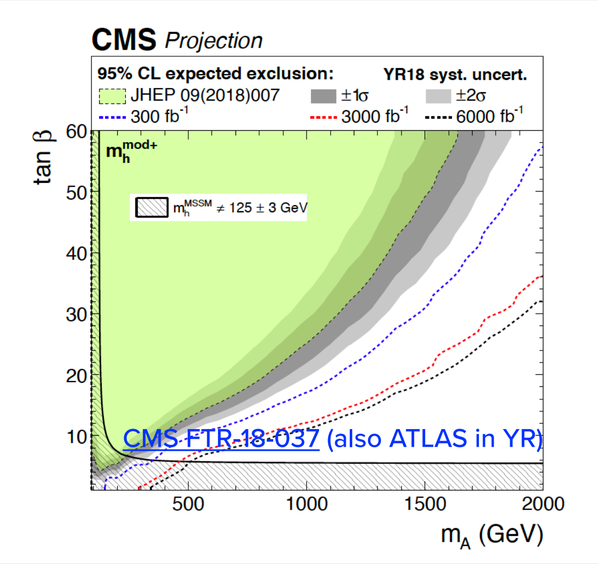


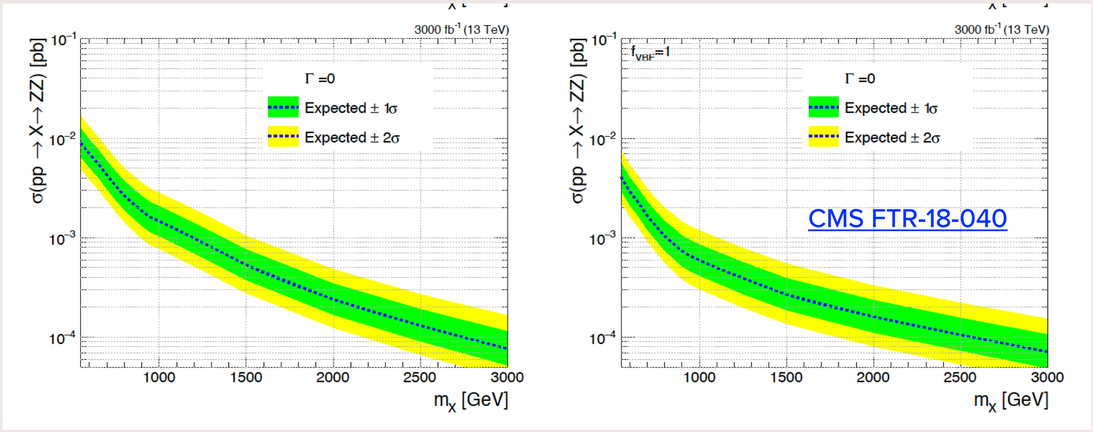
h->aa?

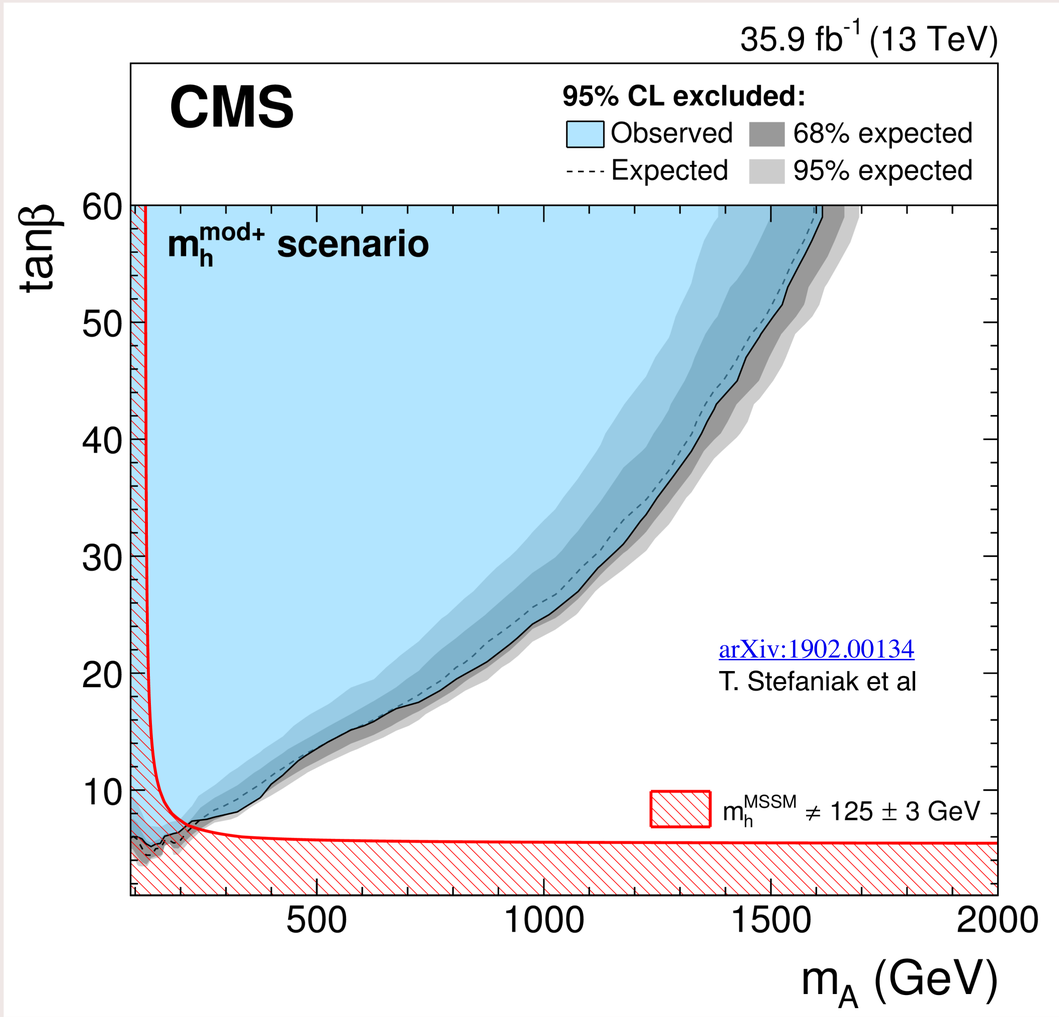

CMS Projection 3000 fb-1 (13 TeV)
2HDM+S type III
95% CL on σ(h)/σSM B(h→ aa) = 0.1%
95% CL on σ(h)/σSM B(h→ aa) = 1%
95% CL on σ(h)/σSM B(h→ aa) = 10%
95% CL on σ(h)/σSM B(h→ aa) = 100%
CMS FTR-18-035
tanβ
ma (GeV)
95% CL on σ(h)/σSM B(h→ aa) (%)


CMS Projection 3000 fb-1 (13 TeV)
2HDM+S type II
95% CL on σ(h)/σSM B(h→ aa) = 10%
95% CL on σ(h)/σSM B(h→ aa) = 3%
tan β
ma (GeV)
95% CL on σ(h)/σSM B(h→ aa) (%)

MSSM


CMS Projection
95% CL expected exclusion:
YR18 syst. uncert.
JHEP 09(2018)007
±1σ
±2σ
300 fb-1
3000 fb-1
6000 fb-1
tan β
mmod+h
mMSSMh ≠ 125 ± 3 GeV
CMS FTR-18-037 (also ATLAS in YR)
mA (GeV)


3000 fb-1 (13 TeV)
Γ =0
Expected ± 1σ
Expected ± 2σ
σ(pp → X→ ZZ) [pb]
mX [GeV]
fVBF=1
CMS FTR-18-040


35.9 fb-1 (13 TeV)
CMS
95% CL excluded:
Observed
68% expected
Expected
95% expected
mmod+h scenario
tanβ
arXiv:1902.00134
T. Stefaniak et al
mMSSMh ≠ 125 ± 3 GeV
mA (GeV)

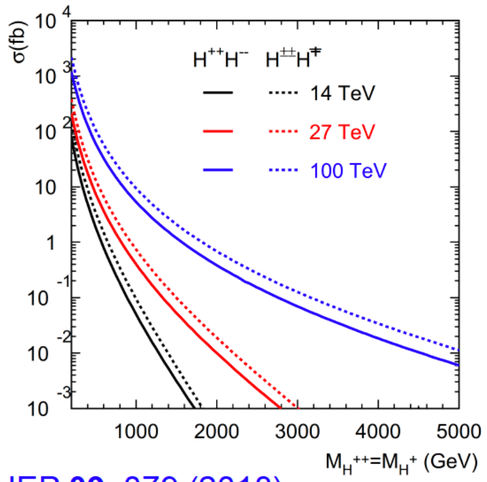
Type II seesaw: hadron colliders

- Type II seesaw: new scalar triplet couples to SM leptons to produce the light neutrino masses (no sterile neutrinos)

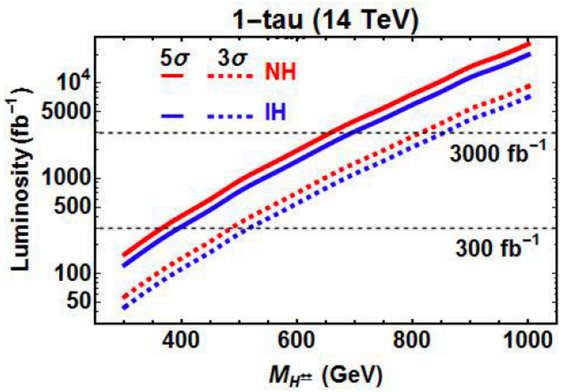
- Doubly charged Higgs production in hadron collisions: $pp \to Z^*/\gamma^* \to H^{++}H^{--}$ and $pp \to W^* \to H^{++/--}H^{-/+}$

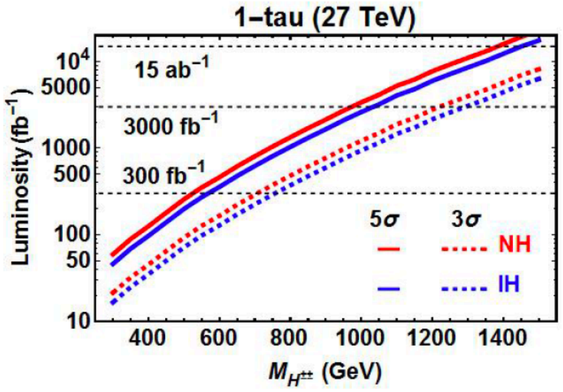
- **Benchmark:** $H^{++}H^{--} \to \tau_h \ell^{+/-}\ell^{-/+}\ell^{-/+}$; $\tau^\pm \to \pi^\pm\nu$

$\to$ tau polarisation can help to discriminate between different heavy scalar mediated neutrino mass mechanisms



JHEP **09**, 079 (2018)
Sec. 5.1 of CERN-LPCC-2018-005





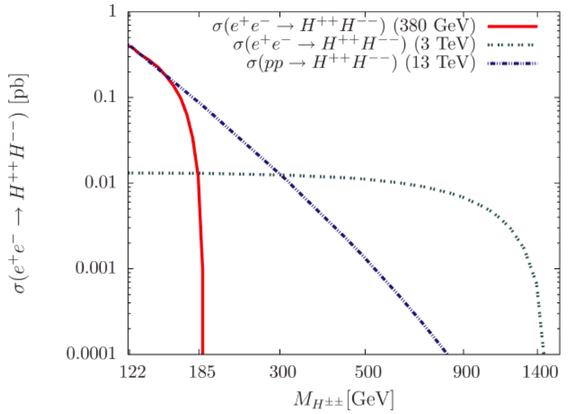
M(H±±) > 1930 GeV / 2070 GeV for NH / IH using 3 ab^{-1} at 100 TeV (3 sigma)

Type II seesaw: lepton colliders

• Pair production cross section almost flat up to the kinematic limit: $e^+e^- \to H^{++}H^{--}$

Benchmark: triplet vev $v_\Delta = 10^{-2}$ GeV
→ BR($H^{++} \to W^+W^+$) = 100%
(cross section in VBF at LHC very small)

• CLIC study for 380 GeV and 3 TeV (Delphes) shows sensitivity almost up to the kinematic limit
(also expected for other e^+e^- colliders)



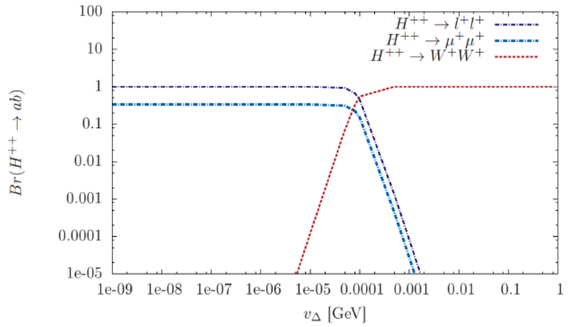
$\sqrt{s}$ = 380 GeV:

$e^+e^- \to H^{++}H^{--} \to N_j \geq 7j$		
Mass (GeV)	n_s	$\mathcal{L}$ (fb^{-1})
121	1.54	1054.14
137	4.48	124.56
159	10.48	22.76
172	10.15	24.26
184	2.69	345.48

$\sqrt{s}$ = 3 TeV:

$e^+e^- \to H^{++}H^{--} \to W^+W^+W^-W^- \to Nj_{\rm fat}$		
Masses (GeV)	n_s (2, 3-tagged $\mathcal{L} = 500$ fb^{-1})	$\mathcal{L}$(fb^{-1})(with 2,3-tagged)
800	17.96(2-tag)	38.75
1000	13.95(2-tag)	64.23
1120	11.49(2-tag)	94.68
1350	5.48(3-tag)	416.24
1400	3.95(3-tag)	801.15

→ Luminosity for 5σ discovery smaller than expectation at CLIC



NB: M(H^{++}) < M(H^+)

NB: FCC-hh would be sensitive to $H^{++}H^{--} \to W^+W^+W^-W^-$ below ≈1.7 TeV for $v_\Delta > 10^{-4}$ GeV JHEP 01, 101 (2019)

Phys. Rev. **D 98**, 015024 (2018)
Sec. 7.1 of CERN-2018-009-M