LHC-Higgs XS WG3 (BSM) Report

Jana Schaarschmidt (University of Washington)

Charged2018 – Uppsala, 25.09.2018

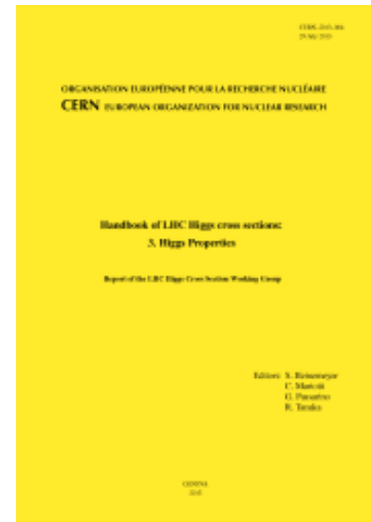
Outline

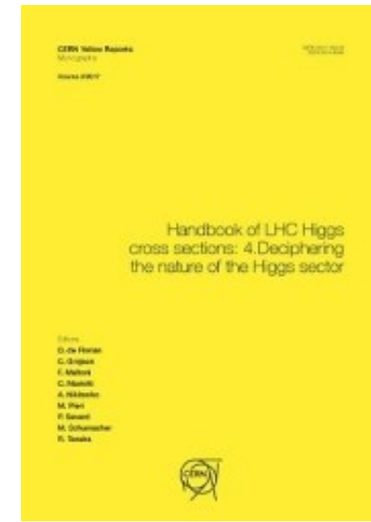
- Overview of the LHC HXS WG
- Brief overview of each working group (and cross groups)
- Activities in each WG3 sub-group
  (Extended+Charged, MSSM, NMSSM, Exotic decays)

This talk contains lots of material from other people's talks:
Many thanks to Stefan Liebler, Jose Santiago Perez, Rui Santos and Nikos Rompotis!

Twiki: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

- The LHXSWG was created in 2010 to produce agreement on cross sections, branching ratios and pseudo observables relevant for the SM and MSSM Higgs boson(s).
- It has evolved over the years including new (sub)groups to study properties of the SM Higgs boson in the SM, and explore more BSM models
- One of its main purposes is to provide the experimental collaborations with information in various forms (reference xsecs and BR, benchmarks, recommendations, codes, …).
- 4 CERN reports have been produced: “Inclusive Observables” (‘11), “Differential Distributions” (‘12), “Higgs Properties” (‘13) and “Deciphering the Nature of the Higgs sector” (‘16).





Pages: 153 → 275 → 404 → 849 (!!)

LHC Higgs XS WG – Group Structure

- Steering committee (SC): In charge of coordinating and overseeing the activities of the whole WG and organizing general assembly meetings

ATLAS		CMS		THEORY			
Michael Duehrssen (CERN)	Bill Murray (STFC/Warwick)	Roger Wolf (KIT)	Guillelmo Gomez Ceballos	Jose Santiago (Granada)	Massimiliano Grazzini (Zürich)	Nathaniel Craig (Santa	Laura Reina (Florida State U.)

- 3 Working groups: Structured in subgroups and task force groups
  - Higgs XS&BR
  - Higgs Properties
  - BSM Higgs
- Two cross-groups: bbH/bH and HH
- Theory advisory committee (TAC): Advise on theory related issues, nominate SC theory members.
- Mode of operation: Objective, transparent, results publicly available (subject to approval)
- Submission of requests/proposals: through SC or WG conveners → SC starts approval procedure.

Next General Assembly Meeting:

10-12 December at CERN: https://indico.cern.ch/event/740110/ Please register!

LHC Higgs XS WG1: Cross sections and branching ratios

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG1

Group Conveners

Mail to conveners	ATLAS	CMS	THEORY	
Mail	Paolo Francavilla (INFN-Pisa)	Alicia Calderon (Universidad de Cantabria) (2018)	John Campbell (Fermilab)	Fabrizio Caola (IPPP)

Subgroups:
- BR
- ggF
- VBF
- VH
- ttH/tH
- Offshell

Recent progress:

Input from WG1 recently requested by the HL/HE LHC WG

The predictions of production cross sections (including uncertainty projections) for the HE-LHC (27 TeV). Most of the results already finished, they will be publicly available soon.

YR4-like predictions for HL/HE

E_{CM}	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}}$ $\left(^{+4.27\%}_{-6.49\%}\right)$	$\pm 0.89\,\text{pb}\,(\pm 1.85\%)$	$^{+1.24\text{pb}}_{-1.26\text{pb}}$ $\left(^{+2.59\%}_{-2.62\%}\right)$
14 TeV	54.72 pb	$^{+2.35\text{pb}}_{-3.54\text{pb}}$ $\left(^{+4.28\%}_{-6.46\%}\right)$	$\pm 1.00\,\text{pb}\,(\pm 1.85\%)$	$^{+1.40\text{pb}}_{-1.41\text{pb}}$ $\left(^{+2.60\%}_{-2.62\%}\right)$
27 TeV	146.65 pb	$^{+6.65\text{pb}}_{-9.44\text{pb}}$ $\left(^{+4.53\%}_{-6.43\%}\right)$	$\pm 2.81\,\text{pb}\,(\pm 1.95\%)$	$^{+3.88\text{pb}}_{-3.82\text{pb}}$ $\left(^{+2.69\%}_{-2.64\%}\right)$

LHC Higgs XS WG2: Higgs properties

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG2

Convenors:

ATLAS	CMS	THEORY	
Chris Hays (Oxford) (2015)	Mingshui Chen (CN) (2016)	David Marzocca (Zürich) (2017)	Francesco Riva (CERN) (2017)

Subgroups:

– Fiducial/Differential and Simplified Template Cross Sections (STXS)
– Pseudo Observables
– EFT

Recent (and expected future) progress:

– Production of benchmark models for EFT analyses

– EFT parametrization of STXS

– Global fit in EFT framework (combining with top, EW, …)

– EFT interpretation workflow summary

– Benchmark exercise of EFT codes

LHC Higgs XS WG3: BSM Higgs

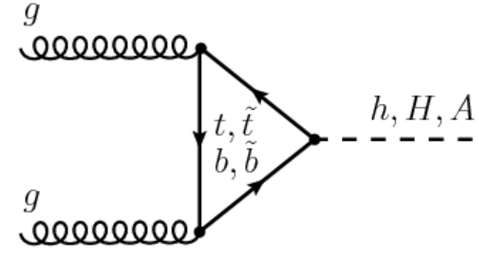
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3

Convenors:

ATLAS	CMS	THEORY	
Liron Barak (CERN) (2016)	David Sperka (Boston University) (2018)	Stefania Gori (Cincinnati) (2016)	Pietro Slavich (LPTHE) (2017)

Subgroups:

- Extended Higgs Sector (neutral+charged, recently merged)
- MSSM Higgs
- NMSSM Higgs
- Exotic Higgs decays

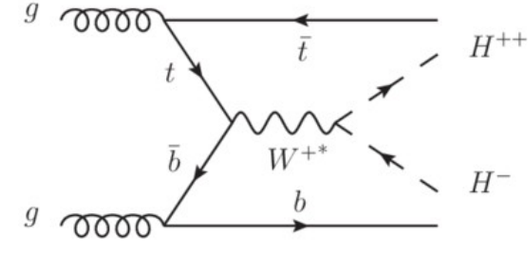


Recent progress/highlights (more details later in this talk):

- New MSSM scenarios available!

- Theory predictions for H→aa that close some gaps

- Intermediate mass range prediction for MSSM H^+, have been used to set limits

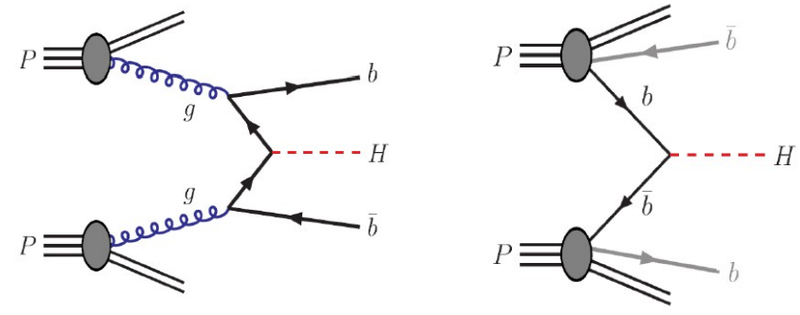


bbH/bH cross group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGBBH

Convenors:

ATLAS	CMS	THEORY	
Lei.Zhang (Freiburg)	Alexandre Nikitenko (IC, London)	Michael Spira (PSI)	Marius Wiesemann (Zürich)



The goal of the group is to provide inclusive and exclusive cross-sections for bbh production and Monte-Carlo generation tools. The cross-section calculation in BSM is the shared responsibility with WG3/MSSM.

Status:

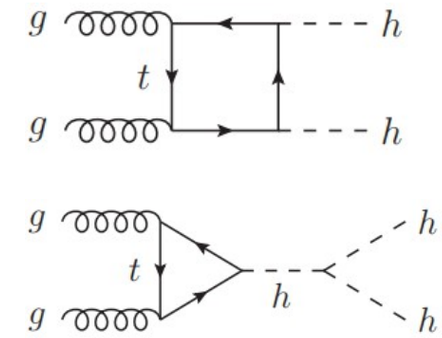
– Theory predictions in good shape: several NLO MC implementations available.
Experimentalists in contact with MC developers to test and compare predictions.

– Currently working on gluon fusion production of bbH, larger than expected in SM (Wieseman et al.)

– No major new development (beyond the results of the comparisons of different codes) expected in the near future.

HH cross group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGHH



Convenors:

ATLAS	CMS	THEORY		
Magdalena Slawinska (NIKHEF)	Maxime Gouzevitch (Lyon)	Sally Dawson (BNL)	Ramona Gröber (Durham)	Javier Mazzitelli (Zurich)

SM non-resonant HH cross-section and uncertainties recently updated (including HE-LHC projections):

√s	7 TeV	8 TeV	13 TeV	14 TeV	27 TeV	100 TeV
$\sigma_{NNLO\ FTapprox}$ [fb]	6.572 -6.5%+3.0%	9.441 -6.1% + 2.8%	31.05 -5.0% + 2.2%	36.69 -4.9% +2.1%	139.9 -3.9% +1.3%	1224 -3.2% +0.9%
mt unc.	±2.2%	±2.3%	±2.6%	±2.7%	±3.4%	±4.6%
PDF unc.	±3.5%	±3.1%	±2.1%	±2.1%	±1.7%	±1.7%

Higgs boson pair production at NNLO with top quark mass effects

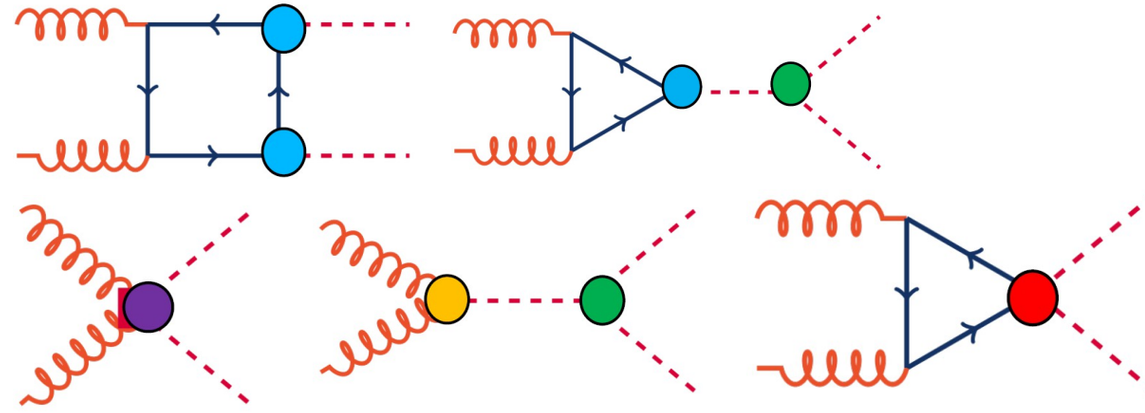
M. Grazzini, G. Heinrich, S. Jones, S. Kallweit, M. Kerner, J. Lindert, JM [arXiv:1803.02463]

HH cross group: Recent work (BSM)

- Many discussions (exp+theory) at the HH workshop at Fermilab

- Regarding BSM non-resonant searches: EFT approach

$$L_{hh} = \frac{1}{2}\partial_\mu \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3$$
$$- \frac{m_t}{v}\left(v + k_t h + \frac{c_2}{v} hh\right)(\bar{t}_L t_R + h.c.)$$
$$+ \frac{\alpha_S}{12}\left(c_{1g} h - \frac{c_{2g}}{2v} hh\right) G^A_{\mu\nu} G^{A\mu\nu}$$

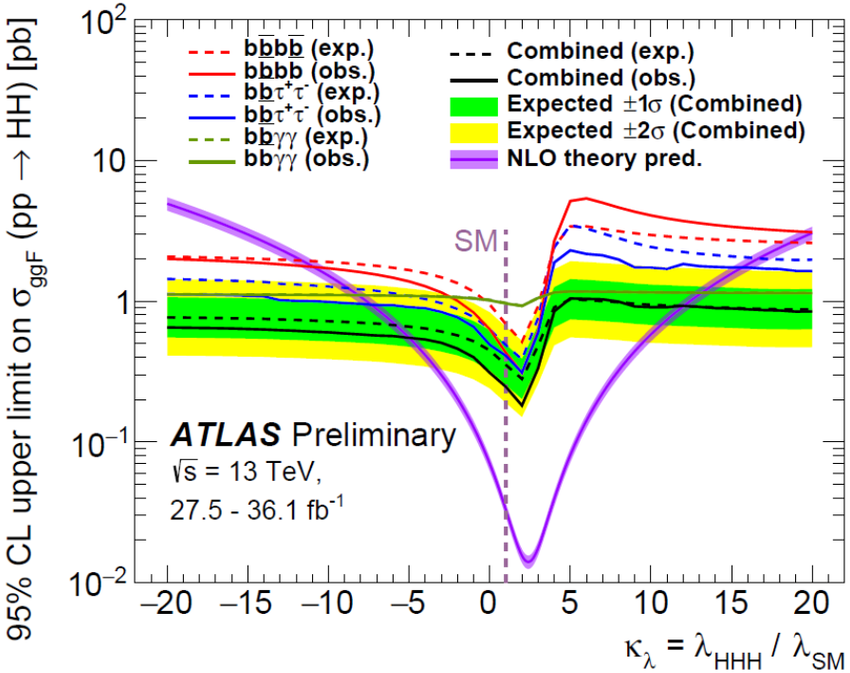


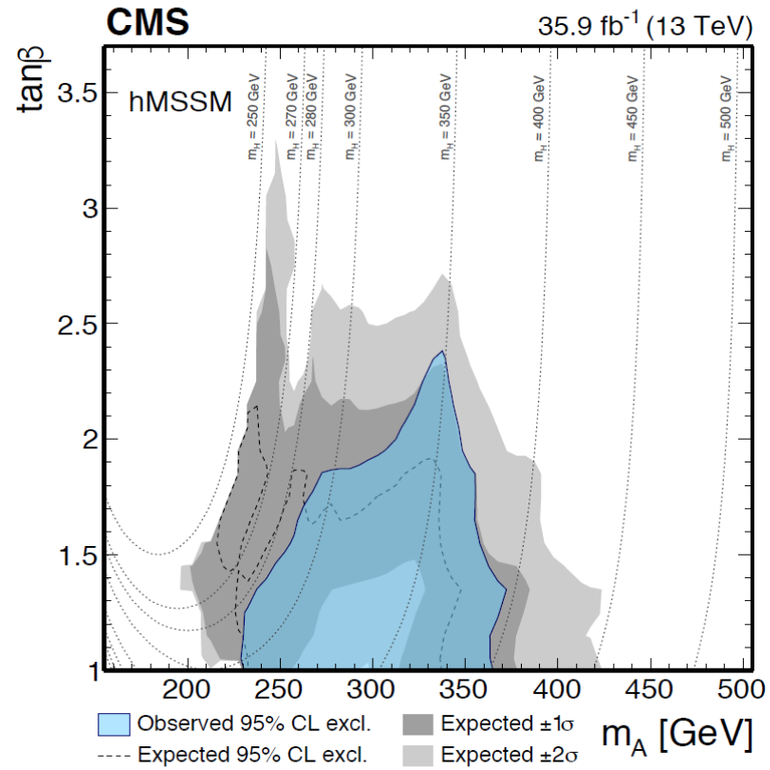
Plans exist to look into some concrete models in order to motivate ranges for EFT coefficients

- Discussions about the usage of shape benchmarks for EFT, and how to map the limits obtained for these benchmarks to a given combination of Wilson coefficients (see this talk by Alexandra Carvalho)

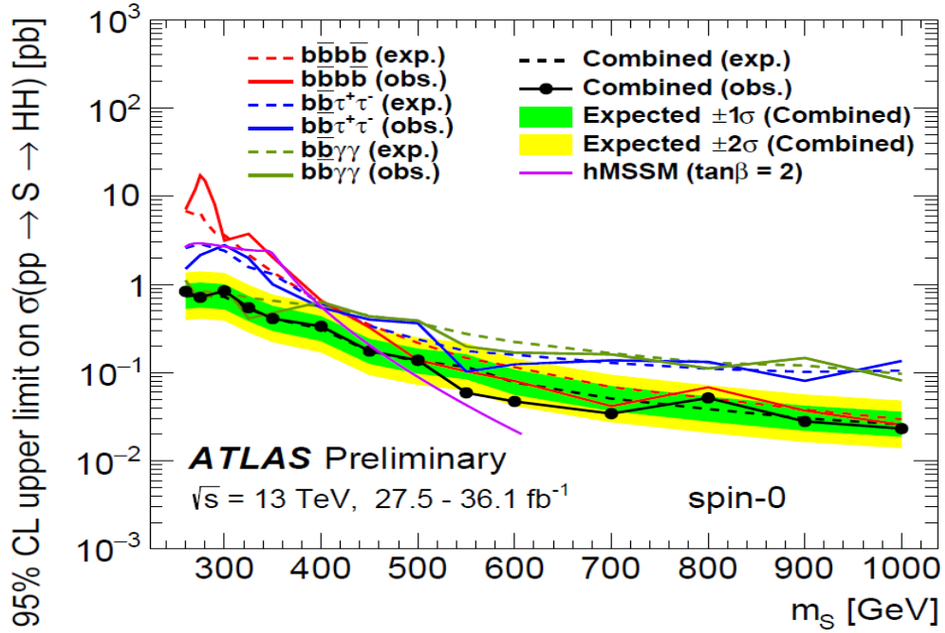
- For resonant HH production:
  - RS Bulk Graviton models with various values of $k/\overline{M}_{Pl}$
  - Heavy Higgs benchmarks within the singlet model and 2HDM in YR4
  - plan is to find more benchmarks in other models, e.g. MSSM, NMSSM, or beyond that
  - recently discussed: $X \rightarrow S\, H_{125}$

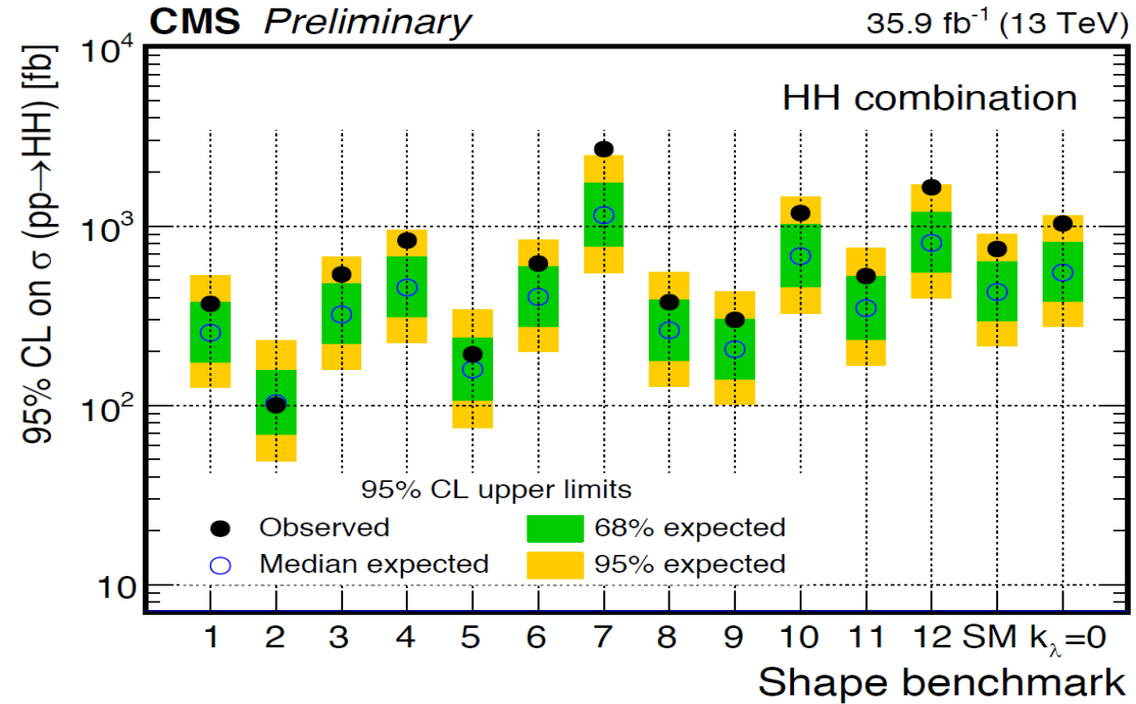
HH: Recent results





BM	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0	0.0	0.0
Box	0.0	1.0	0.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0





WG3: Extended Higgs Sector and Charged Higgs

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3#Extended_Higgs_Sector_neutral_ch

Used to be two separate groups, but has been merged to one group in summer 2018

Contacts: Xiangyang Ju, JS (ATLAS); Raffaele Gerosa, Martin Flechl (CMS);
Heather Logan, Rui Santos, Shufang Su (Theory)

Initial mandate of the Charged Higgs group:

- Provide theory recommendations (cross sections, BR) for MSSM benchmarks (done!)
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGMSSMCharged

- Theory recommendations of the intermediate mass range (where $m_{H+} \sim m_{top}$) (mostly done!)

Possible extensions:
Sub-leading and/or uncovered channels, extended models (beyond MSSM), interference studies

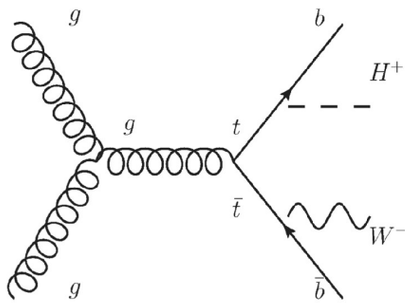
Extended Higgs Sector:

Provide recommendations, benchmarks and tools for 2HDM, Flavorful 2HDM, Complex 2HDM, 3HDM, Georgi-Machacek, …

→ Lots of possibilities (and lots of work) !

Charged Higgs: Overview of the Recommendations

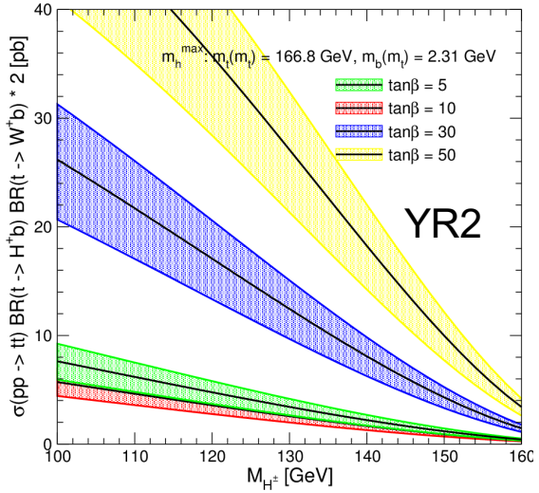
Low mass



$\sigma(pp \rightarrow tt) * BR(t \rightarrow bH^+) * BR(t \rightarrow bW)$

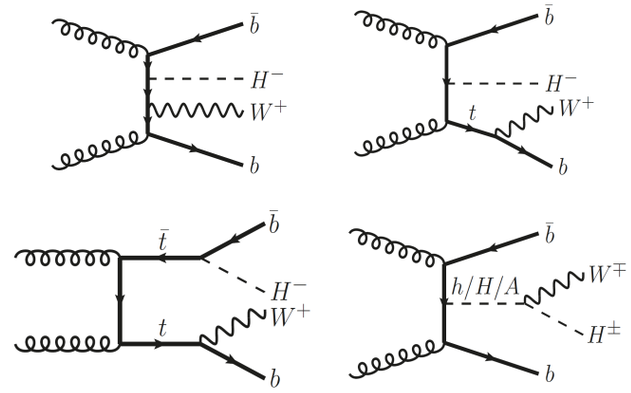
NNLO
PRL 110 (2013)

NLO: Phys. Rev. D76 (2007), hep-ph/9301237
NNLO: eg. hep-ph/9806244

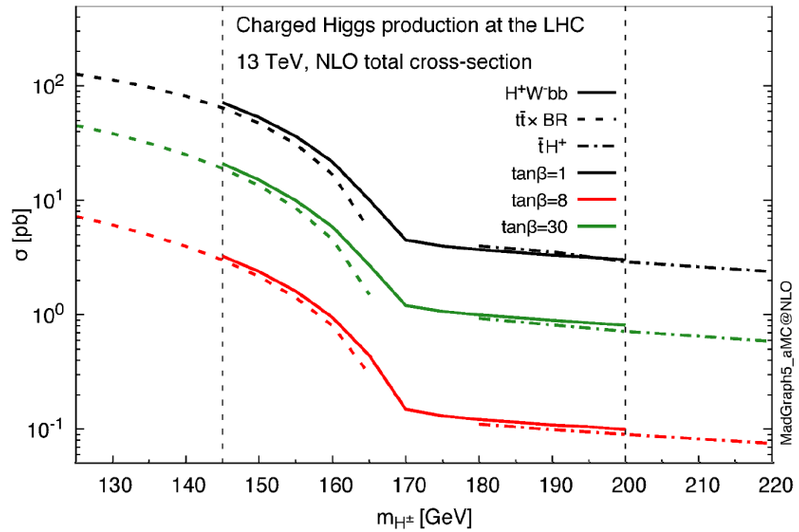


Intermediate mass

NLO $pp \rightarrow H^+W^-bb$

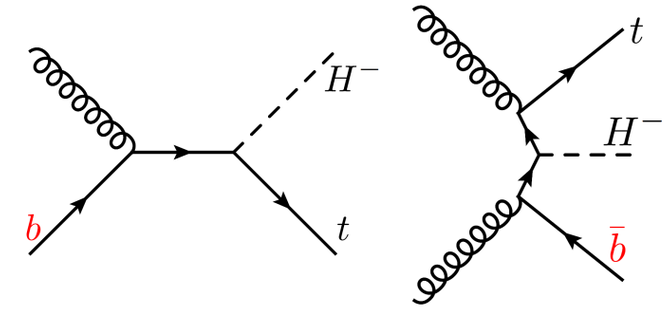


https://arxiv.org/abs/1607.05291

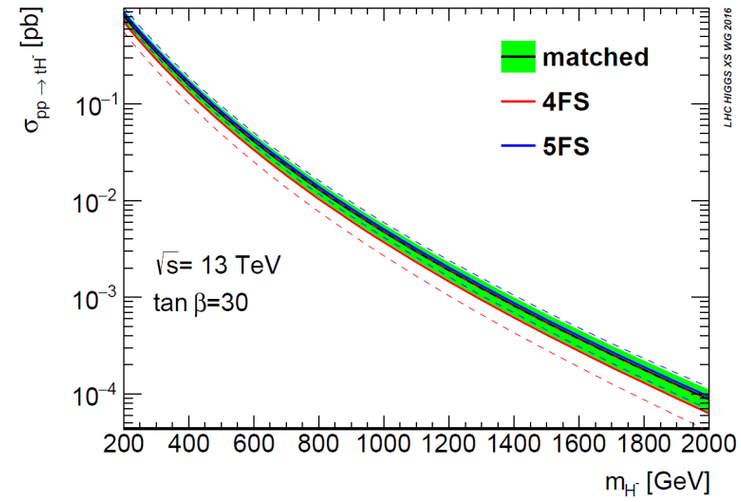


Differential cross sections at LO

High mass



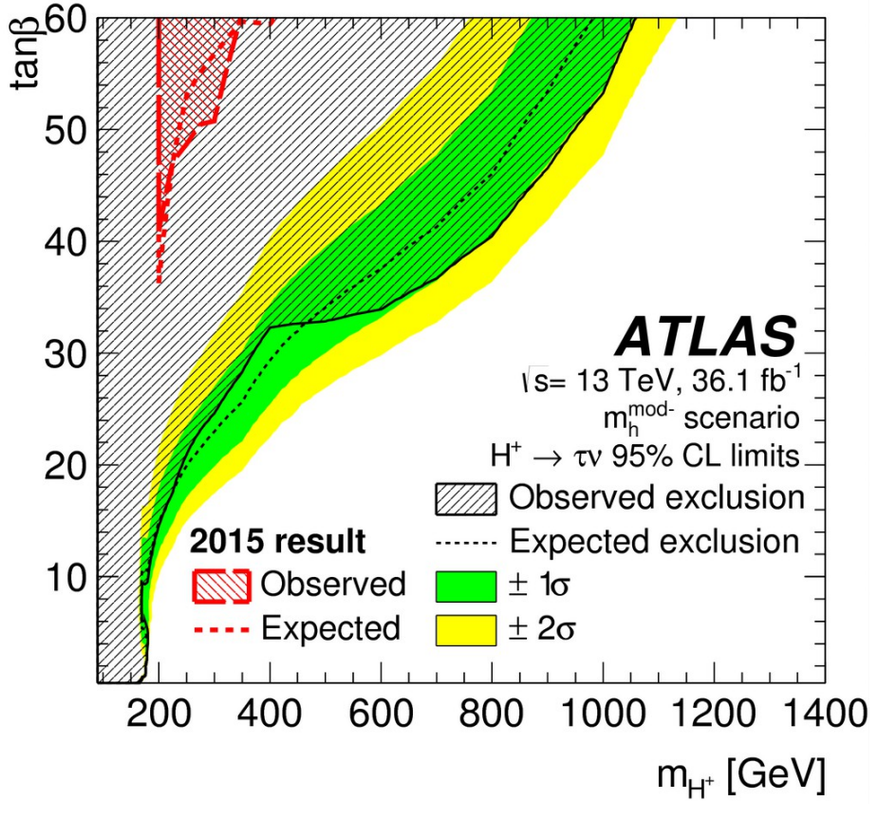
Tools: 4FS: MG5_aMCatNLO,
5FS: Prospino

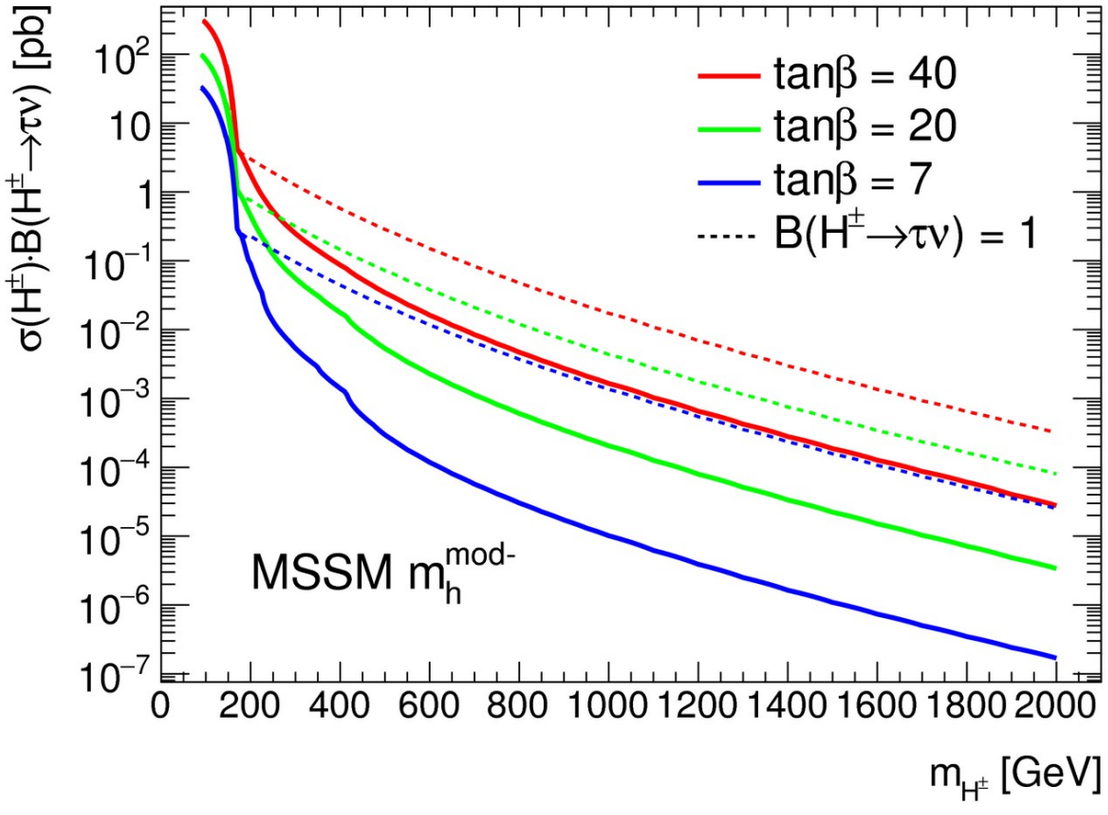


Differential cross sections at NLO

Charged Higgs: Intermediate region

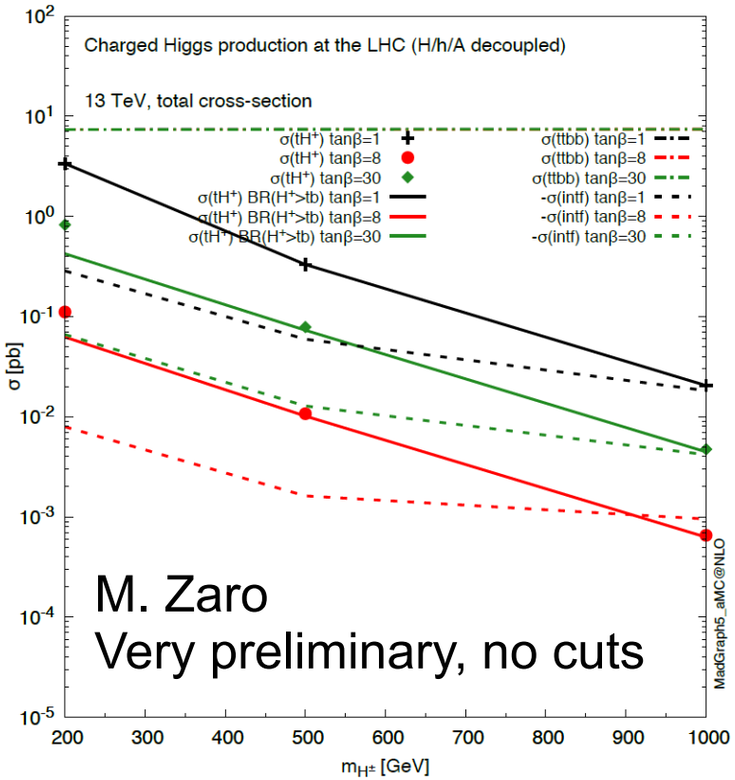
- Theory talk by M. Zaro this Thursday
- ATLAS has results in the intermediate mass range, explored for the first time





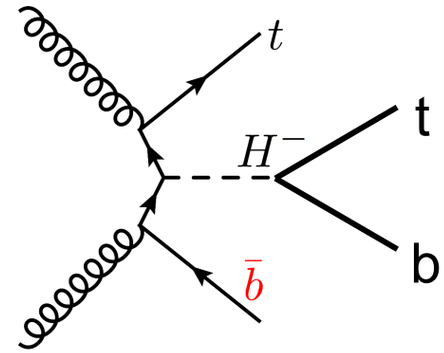
- CMS?

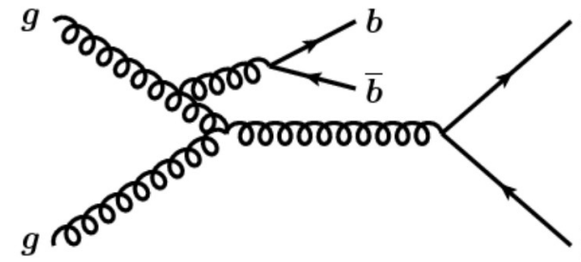
Charged Higgs: Signal-background Interference



In models where the H^+ width is not negligigble:

Interference between H^+ signal and ttbar background





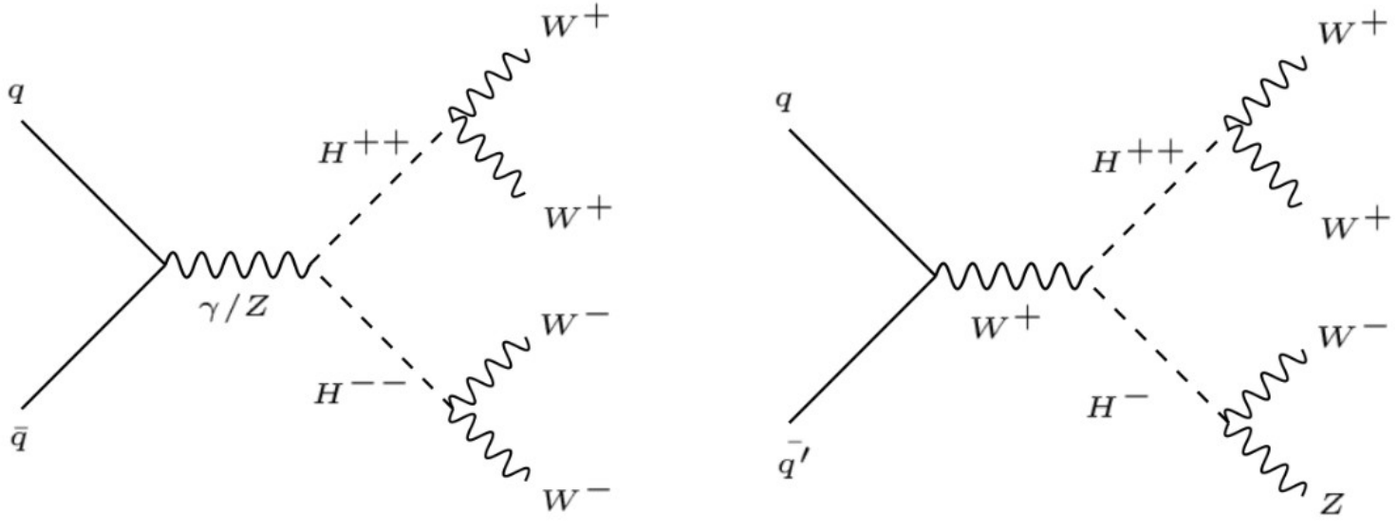
In absence of recommendations, has been neglected in the model-dependent limits (interpretations) of the searches

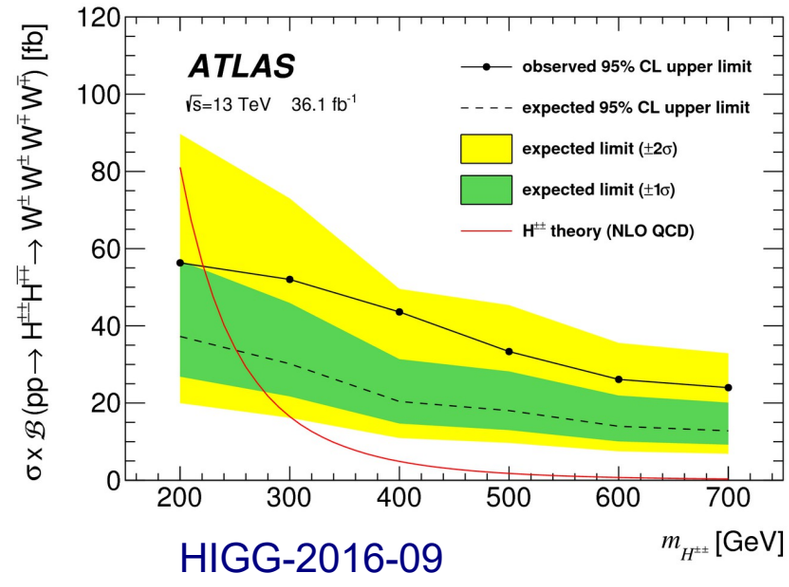
- Study of interference in pp → tH → tWbb (signals: Wh(bb), WH(bb), WA(bb) and tb)
  A. Arhrib, R. Benbrik, S. Moretti, Rui Santos, P. Sharma: arXiv:1712.05018
  → for **H^+→WH using 5FS signal**: interference was found to be very large up to O(100%), and negative in 6 out of 8 studied benchmarks, but negligible impact on shapes

- Work is now continued by R. Santos, Riley Patrick, Duarte Azevedo, for the hMSSM
  → expect results for the December meeting!

- In arXiv:1604.04965 it was found, that interference between the signal contributions is negligible

Charged Higgs: H^{++}





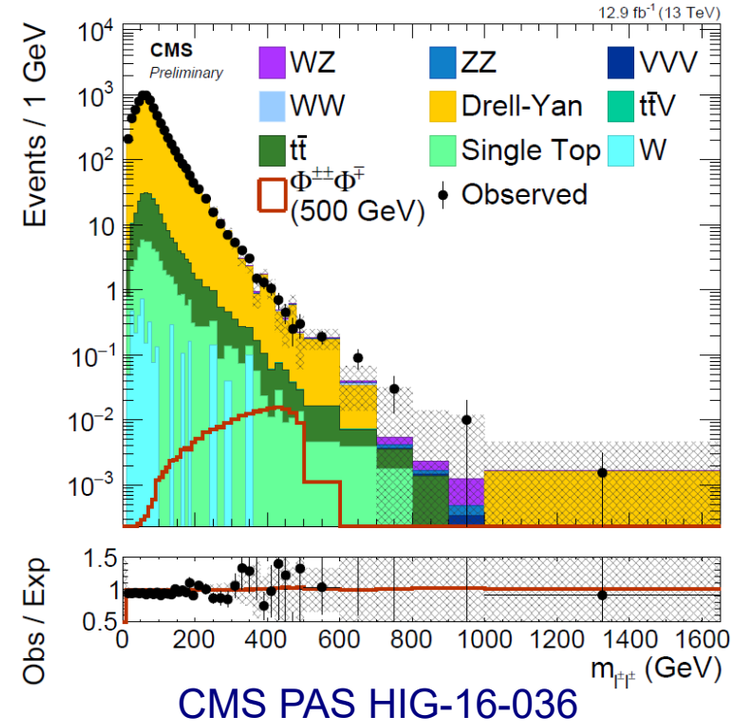
HIGG-2016-09

Recent Activity: (H. Logan et al)

Updated the MadGraph5 model file for doubly-charged Higgs production that can generate
$pp \rightarrow H^{++} H^{--} \rightarrow W^+W^+W^-W^- \rightarrow 8f$ at NLO-QCD

In the process of validating this model.

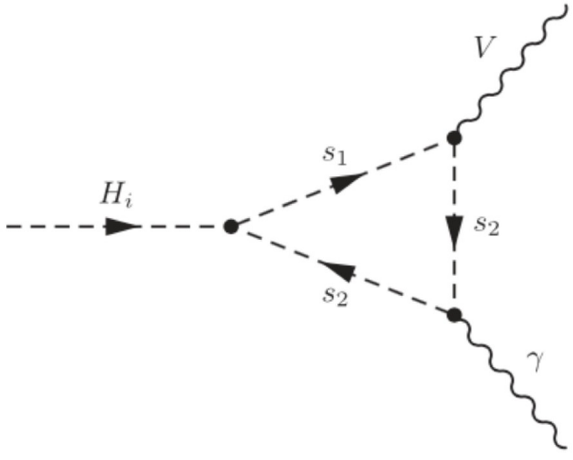
Work ongoing to develop a benchmark in the Georgi-Machacek model for H^{++} masses below 200 GeV, that is consistent with other searches and h(125) measurements.



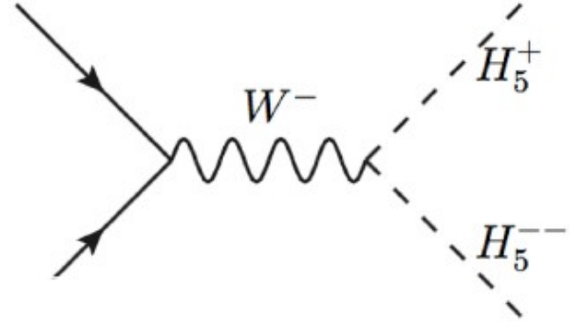
CMS PAS HIG-16-036

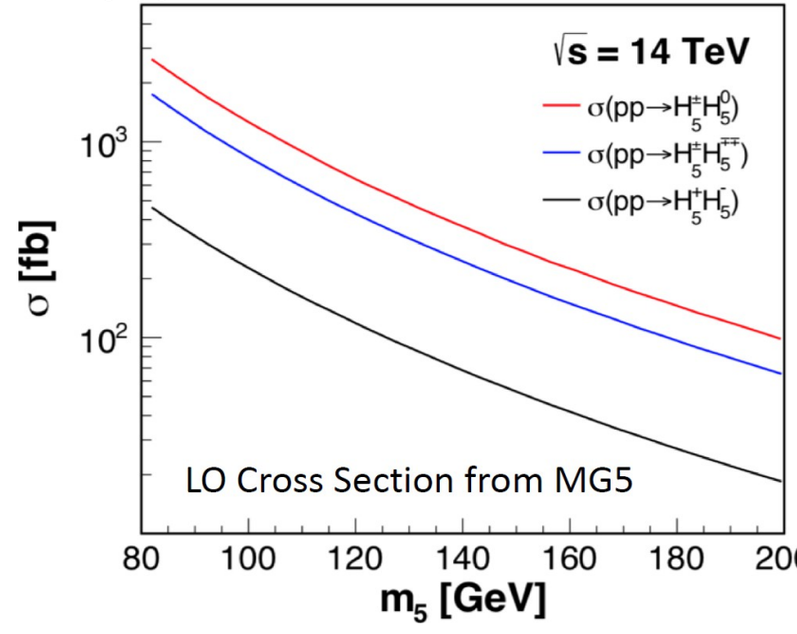
Charged Higgs: New Channel $H^+ \to W\gamma$

- In the 2HDM, there are no tree couplings of H^+ to WZ or $W\gamma$, but these decays can be induced on 1-loop level (similar to $H \to \gamma\gamma$, or $H \to Z\gamma$), BR ~ 10^{-3}
- In Higgs Triplett models these decays can occur on tree level → large cross sections
- Recent studies in GM model → See talk by Heather Logan at this workshop (on Wednesday)!



Drell-Yan production $pp \to H_5 H_5$:

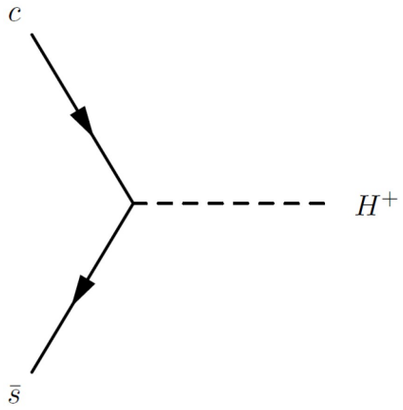




Dominant decay in fermiophobic models
Not searched for by LHC

- Also potential other models: eg. „Stealth Model“ https://arxiv.org/abs/1311.4367
  Two scalar doublets and broken Z_2 symmetry (generalized Inert Doublet Model),
  one doublet is the Higgs doublet and provides EWSB, the other doublet is fermiophobic.

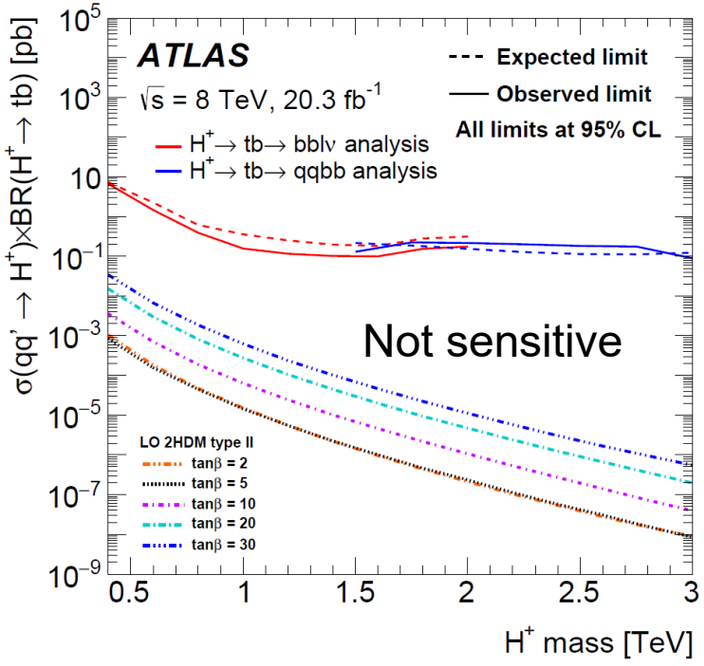
Charged Higgs: New Channels (qq' production)



s-channel production

No associated top → easier from the experimental point of view:
- Mass reconstruction,
- background reduction
- can profit from W ' searches

Recasting W'→tb to H⁺:



HIGG-2013-28

8 TeV LO σ* BR (H⁺→tb) for type-II 2HDM:

Computed using MG5 + NLOCT (1406.3030)

m_{H^+} [GeV]		tan β 0.5	1	2	10	20	30	50
400	σ × BR [fb]	14	3.8	1.1	3.6	15	34	94
	Γ [GeV]	60	15	3.8	0.72	2.3	5.2	14
800	σ × BR [fb]	0.72	0.17	0.047	0.19	0.82	1.9	5.3
	Γ [GeV]	140	36	9.0	1.6	5.2	11	32
1000	σ × BR [fb]	0.24	0.055	0.015	0.063	0.28	0.63	1.8
	Γ [GeV]	145	80	11	2	6.4	14	39
1600	σ × BR [ab]	23	3.9	0.96	4.6	20	47	140
	Γ [GeV]	280	69	17	3.1	9.9	22	61
2000	σ × BR [ab]	6.9	0.96	0.21	1.1	4.7	11	36
	Γ [GeV]	340	85	21	3.8	12	27	74
3000	σ × BR [ab]	0.89	0.07	0.0088	0.039	0.20	0.55	2.5
	Γ [GeV]	490	120	31	5.5	17	39	110

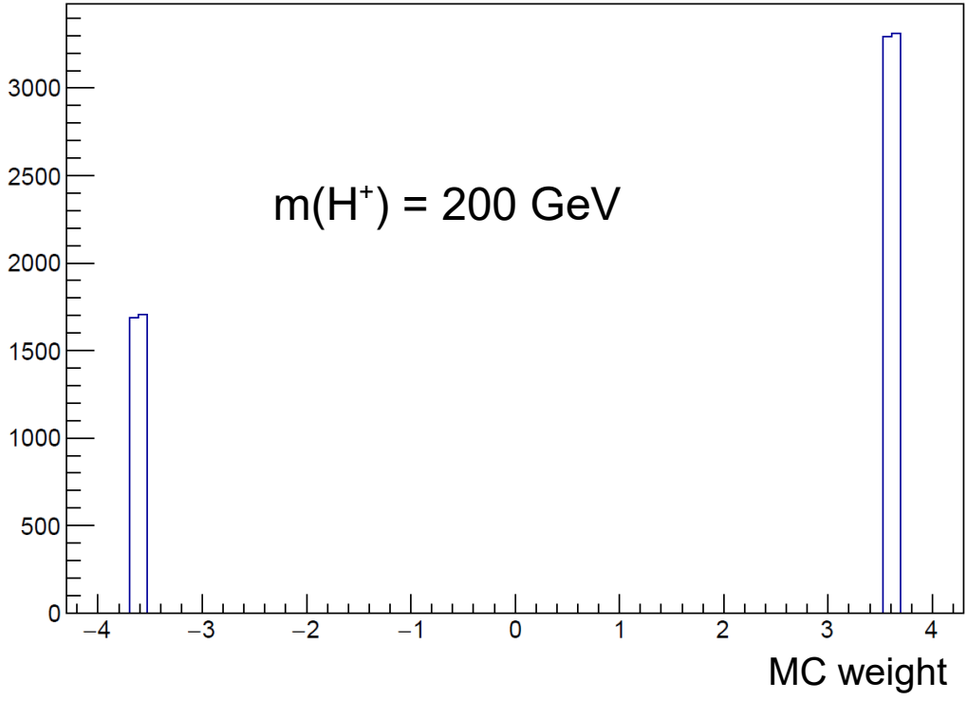
At tanβ=50 1 TeV, only factor 1.5 smaller than tH⁺ x-sec

H⁺ width becomes very large for low tanβ and high mass

Goal is to get official recommendation, but no progress due to lack of interests from the experiments (?)

Charged Higgs: Negative weights in MG5_aMC@NLO

- The issue of large negative weights was raised at the last General Assembly meeting in March



- Large fraction of MC events with negative weights leads to a strong decrease of available MC statistics
- Example: 35% neg. weights
  → up to 70% of the events cancel each other out
- This forces the analysers to produce more events, which is expensive and slow

News:

MG authors are aware of this and are working on a solution to this problem!

S. Frixione, in an email from 24.09.2018:
„There is significant progress. But I can't commit to give you a deadline.“

Extended Scalars:

2HDM Benchmarks (reported in YR4)

LHCHXSWG3Benchmarks2HDM

Shown here is just the overview table, all details are in YR4

Considered theories:

- 2HDM non-alignment
- 2HDM with SM-like H
- 2HDM with degenerate h and A
- Higgs-to-higgs cascades
- EW cosmology
- Light pseudoscalars
- Inert Doublet Model
- Fermiphobic Higgs
- Complex 2HDM
- Higgs flavour changing decays

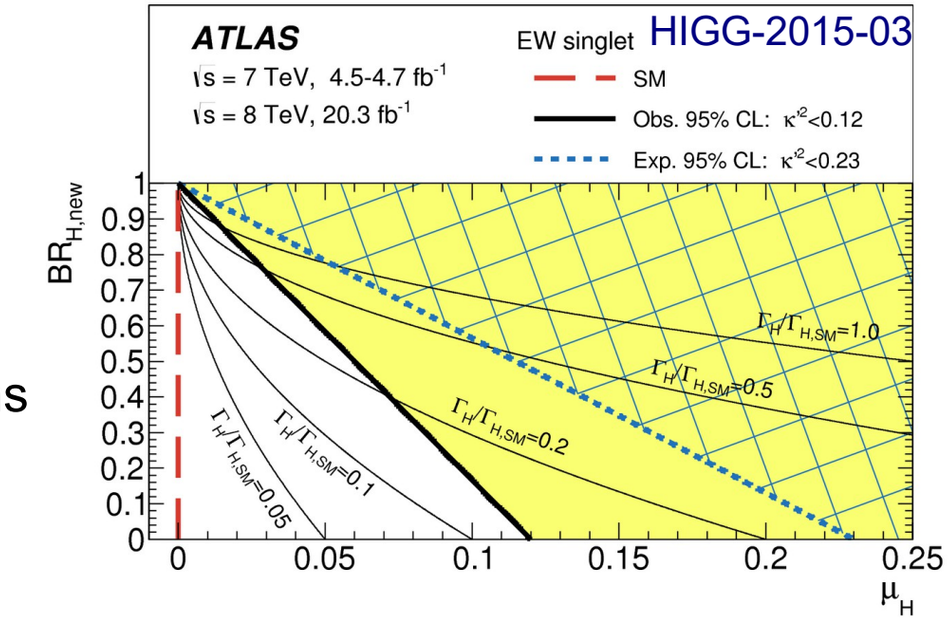
$BP1_A$	2HDM, non-alignment, h approximately SM-like; plane: $1 < \tan\beta < 60$, $150 < M_H < 600$ GeV signatures: type-I $H \to hh, t\bar{t}, WW, ZZ$; type-II: $H \to b\bar{b}, t\bar{t}$
$BP1_B$	2HDM, H is SM-like; line of $65 < M_h < 120$ GeV; signatures: $h \to b\bar{b}, \tau\tau$
$BP1_C$	2HDM, $M_h = M_A = 125$ GeV; line $1 < \tan\beta < 10$ for $M_H = M_{H^\pm} = 300$ GeV large deviations from the SM value of $\tau\tau$ for the 125 GeV Higgs boson
$BP1_D$	2HDM short cascades, $M_h = 125$ GeV, exact alignment; line $250 < M_H < 500$ GeV signatures: $H \to ZA, W^\pm H^\pm, H^\pm H^\mp, AA$
$BP1_E$	2HDM long cascades, $M_h = 125$ GeV, exact alignment; line $200 < M_H < 300$ GeV signatures: $H^\pm \to W^\pm A \to W^\pm ZH$, $A \to W^\pm H^\mp \to W^\pm W^\mp H$
$BP1_F$	2HDM, $M_h = 125$ GeV, opposite sign coupling to down-type fermions; plane: $5 < \tan\beta < 50$, $150 < M_H < 600$ GeV; signatures: $H \to WW, ZZ$
$BP1_G$	2HDM, $M_h = 125$ GeV, with an MSSM-like Higgs sector; signatures $H \to hh$ and $H, A \to t\bar{t}$ or $H, A \to \tau\tau$ for large $\tan\beta$
BP2	Exotic decays in the 2HDM alignment limit; planes provided
BP3	2HDM, $M_h = 125$ GeV, large mass splitting between H and A for electroweak baryogenesis signatures: $A \to ZH$ with $H \to WW, b\bar{b}, t\bar{t}$
BP4	2HDM, $M_h = 125$ GeV, A is very light ($M_A \lesssim M_Z$); signatures: $h \to ZA$ with $A \to b\bar{b}, \tau\tau, \mu\mu$
BP5	Inert 2HDM, $M_h = 125$ GeV and SM-like, H dark matter candidate, $M_H > 45$ GeV signatures: $A \to ZH$, $H^\pm \to W^\pm H$; H will give missing transverse energy in the event
BP6	Fermiophobic 2HDM, $M_h = 125$ GeV and SM-like, H fermiophobic; various planes are suggested signatures: $pp \to HA, HH^\pm$, and has large branching ratios to $H \to WW, ZZ$
BP7	C2HDM, $M_h = 125$ GeV and SM-like, CP-violation detected by the simultaneous existence of 3 decay channels signatures: e.g. $h_3 \to h_2 Z$, $h_2 \to h_1 Z$, $h_3 \to h_1 Z$ simultaneously
BP8	BGL models: Higgs bosons with flavour changing decays; plane: $\tan\beta$ versus $\cos(\beta - \alpha)$ signatures: $t \to hc$, $h \to \tau\tau, b\bar{b}, bs, \mu\tau$

Extended Scalars: Singlets and Triplets

- Discussed in detail in YR4

- **Singlets:**

  - Both real and complex singlets
  - In depth phenomenological examination
  - Explicit recommendations for the Higgs bosons cross sections and branching ratios
  - Benchmarking discussion



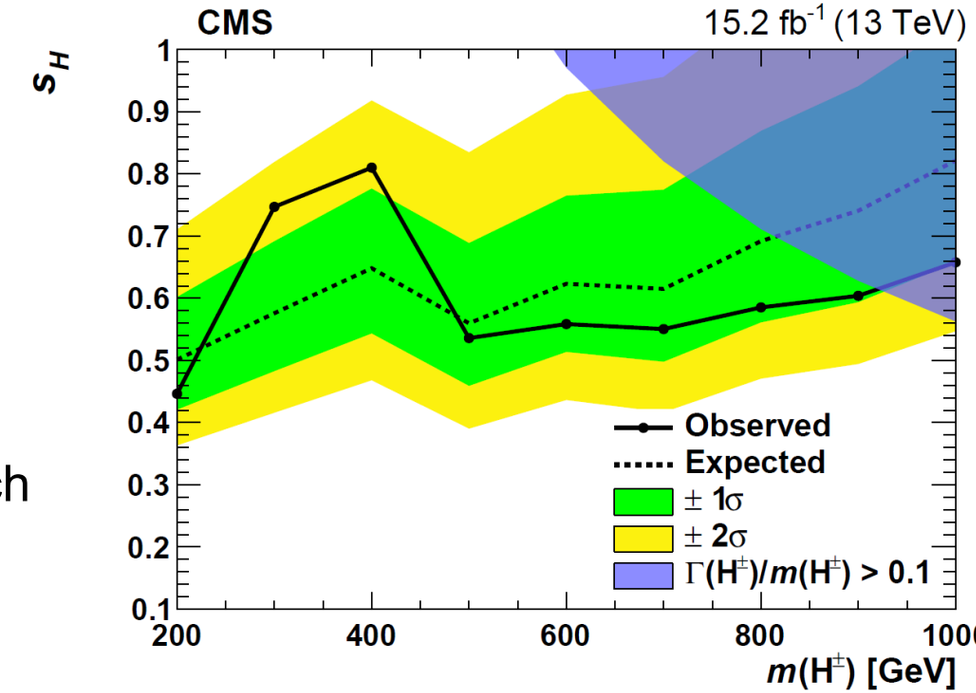
- **Triplets (GM)**

  - adds two $SU(2)_L$-triplet scalars to the Standard Model

  10 Higgs bosons: Singlets: H^0, H'^0
  5-plet: H_5^{++}, H_5^{+}, H_5^{0}
  3-plet: H_3^{+}, H_3^{0}

  - "H5" plane benchmark to facilitate the five-plet state search LHCHXSWGGM/h5plane-benchmark.pdf

  - Explored at LHC, for example through $H^+ \rightarrow WZ$



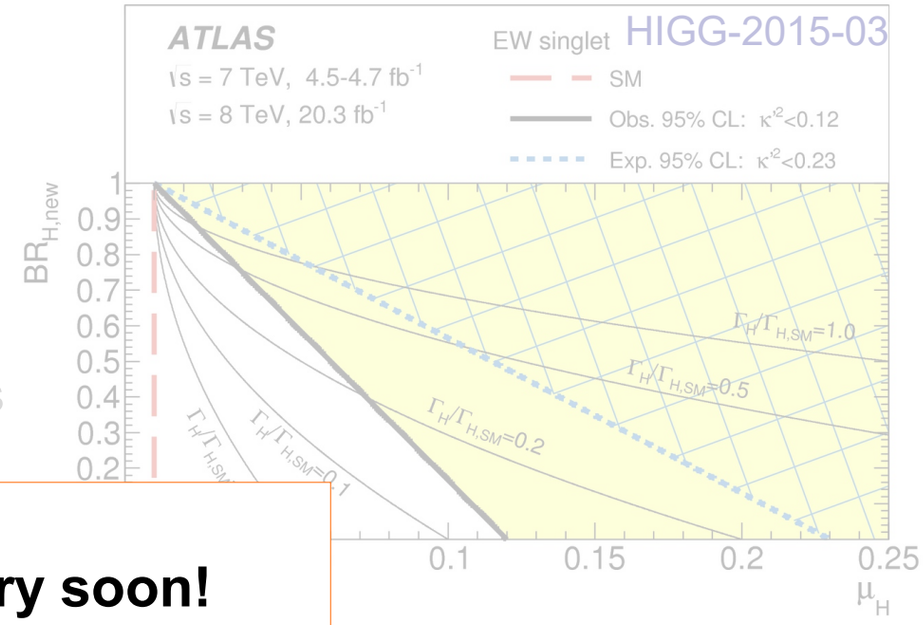
Extended Scalars: Singlets and Triplets

- Discussed in detail in YR4
- **Singlets:**

  - Both real and complex singlets
  - In depth phenomenological examination
  - Explicit recommendations for the Higgs bosons cross sections and branching ratios
  - Benchmark

A call for new benchmarks for the Extended Higgs Sector will be sent out very soon!

Please submit your proposals, they will be discussed in an open meeting afterwards.



- **Triplets (GM**

  - adds two S

  10 Higgs bosons: Singlets: H^0, H'^0
  5-plet: H_5^{++}, H_5^{+}, H_5^{0}
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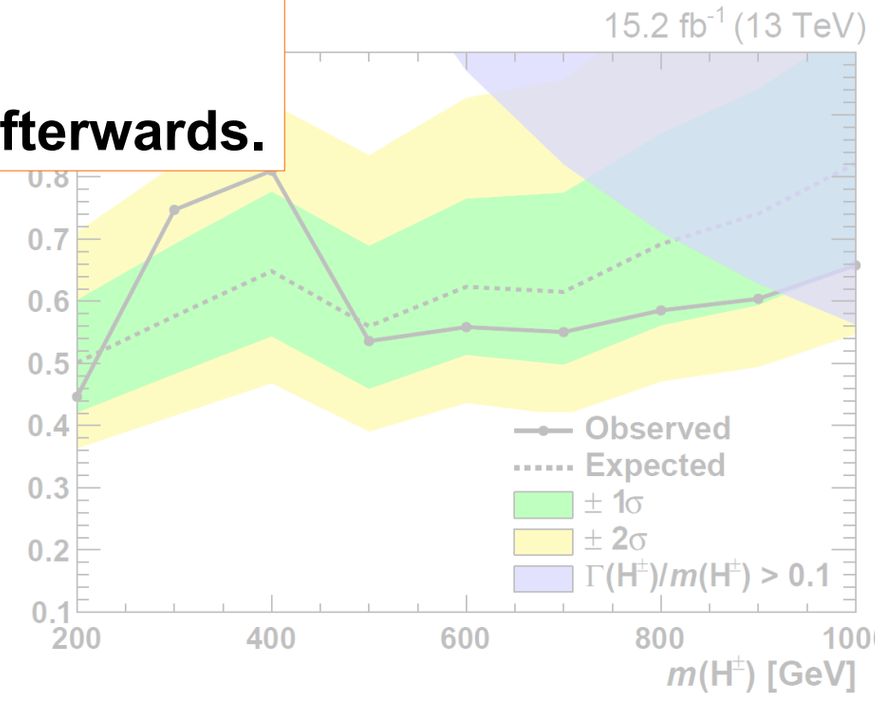


Extended Scalars: Useful tools

https://2hdmc.hepforge.org/

2HDMC

2HDMC is a general-purpose calculator for the two-Higgs doublet model. It allows parametrization of the Higgs potential in many different ways, convenient specification of generic Yukawa sectors, the evaluation of decay widths (including higher-order QCD corrections), theoretical constraints and much more.

http://people.physics.carleton.ca/~logan/gmcalc/

GMCALC

A calculator for the Georgi-Machacek model

GMCALC is a FORTRAN program that, given a set of input parameters, calculates the particle spectrum and tree-level couplings, checks theoretical and indirect constraints on the model, and computes the branching ratios and total widths of the scalars. It also generates a param_card.dat file for MadGraph5 (both LO and NLO versions) to be used with the corresponding FeynRules model implementation.

BSMPT - Beyond the Standard Model Phase Transitions –

A Tool for the Electroweak Phase Transition in Extended Higgs Sectors

BASLER, MUHLLEITNER; 1803.02846

https://github.com/phbasler/BSMPT

ScannerS

https://scanners.hepforge.org/

ScannerS alows general scalar potential with automatic:

- Analysis of tree level local minimum/stability
- Detection of tree level scalar spectrum and mixing
- Tree level unitarity test

Interfaces to:

- HDECAY, sHDECAY, N2HDECAY, C2HDECAY
- HIGGSBOUNDS/SIGNALS (collider bounds/measurements)
- MICROMEGAS (dark matter observables)
- SUSHI (+ internal numerical tables for gluon fusion)
- SUPERISO (flavour physics observables)

Extended Scalars: Useful tools

sHDECAY

The program sHDECAY is a modified version of the latest release of HDECAY 6.50.
It allows for the calculation of the partial decay widths and branching ratios of the
Higgs bosons in the real and in the complex singlet extensions of the Standard Model,
both in the broken and the dark matter phase of the models.

https://www.itp.kit.edu/~maggie/sHDECAY/

N2HDECAY

The program N2HDECAY is a modified version of HDECAY 6.51.
It allows for the calculation of the partial decay widths and branching ratios of the
Higgs bosons of the N2HDM, i.e. the CP-conserving 2HDM extended by a real scalar singlet field.

https://www.itp.kit.edu/~maggie/N2HDECAY/

C2HDM_HDECAY

The program C2HDM_DHECAY is a modified version of HDECAY 6.51.
It allows for the calculation of the partial decay widths and branching ratios of the Higgs bosons in the complex 2HDM

https://www.itp.kit.edu/~maggie/C2HDM/

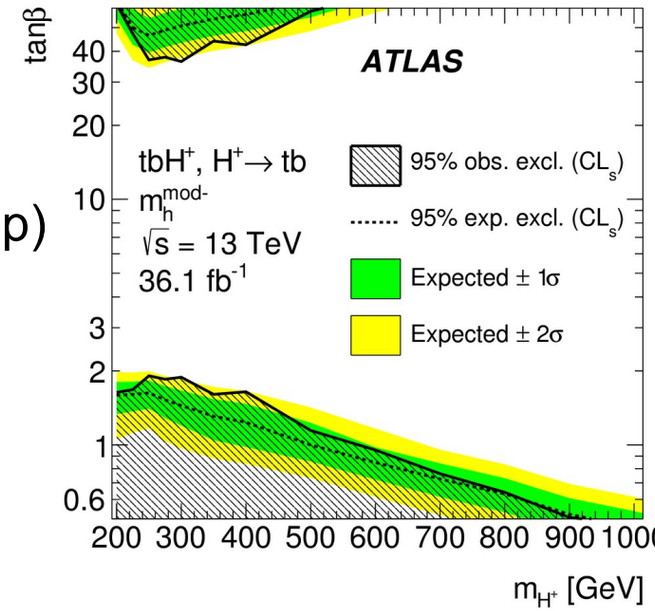
VBF @ NNLO

Cross-Section Calculator via a structure-function approach

http://vbf-nnlo.phys.ucl.ac.be/vbf.html

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGMSSMNeutral

Contacts: Guillermo Hamity (ATLAS), Andrew Gilbert (CMS),
Stefan Liebler, Pietro Slavich, Michael Spira (Theory)



Activities until YR4:

- Classic scenarios (mhmax, mhmod+, mhmod-, tauphobic, light stau, light stop)
- low tanβ scenarios (hMSSM, „low-tanβ-high“)
- low m_H scenario
- EFT approaches (ongoing)
- Higgs pT spectrum for gluon-fusion production

Tools:

Feynhiggs (Higgs masses, BR), ggh@nnlo and HIGLU (ggF cross section), bbh@nnlo (5FS bbh cross section), SusHi

Recent work:

New MSSM benchmark scenarios, with updated inputs:

For details, refer to Stefan's talk

α_s = 0.118, m_b = 4.18 GeV, N^{3}LO precision for gg→h, new bbΦ 4 and 5 flavour matching scheme, more precise BSM Higgs boson mass calculations, extendes sparticle boundaries from the experiments

MSSM: New benchmark scenarios

scenario	m_A [GeV]	$\tan\beta$	$\sqrt{s}$ [TeV]	authors
M_h^{125}	$70 - 2000$	$0.5 - 60$	$8, 13(, 14)$	[1808.07542]
$M_h^{125}(\tilde{\tau})$	$70 - 2000$	$0.5 - 60$	$8, 13(, 14)$	[1808.07542]
$M_h^{125}(\tilde{\chi})$	$70 - 2000$	$0.5 - 60$	$8, 13(, 14)$	[1808.07542]
M_h^{125}(alignment)	$100 - 1000$	$1 - 20$	$8, 13(, 14)$	[1808.07542]
M_H^{125}	$m_{H^\pm} = 150 - 200$	$5 - 6$	$8, 13(, 14)$	[1808.07542]
$M_{h_1}^{125}(\mathrm{CPV})$	$m_{H^\pm} = 120 - 1000$	$1 - 20$	$8, 13(, 14)$	[1808.07542]
hMSSM	$130 - 2000$	$1 - 60$	$8, 13(, 14)$	[Maiani et al. '13; Djouadi et al. '13 '15]
2HDM-EFT	$- - -$	$- - -$	$8, 13(, 14)$	[in progress]

[1808.07542 by Bahl, Fuchs, Hahn, Heinemeyer, Liebler, Patel, Slavich, Stefaniak, Wagner, Weiglein]

Strategy for the definition of new scenarios:

- They all feature a scalar with mass and couplings compatible with the observed Higgs boson

- a significant portion of their parameter space is not yet ruled out by the searches for additional Higgses and SUSY

MSSM: New benchmark scenarios

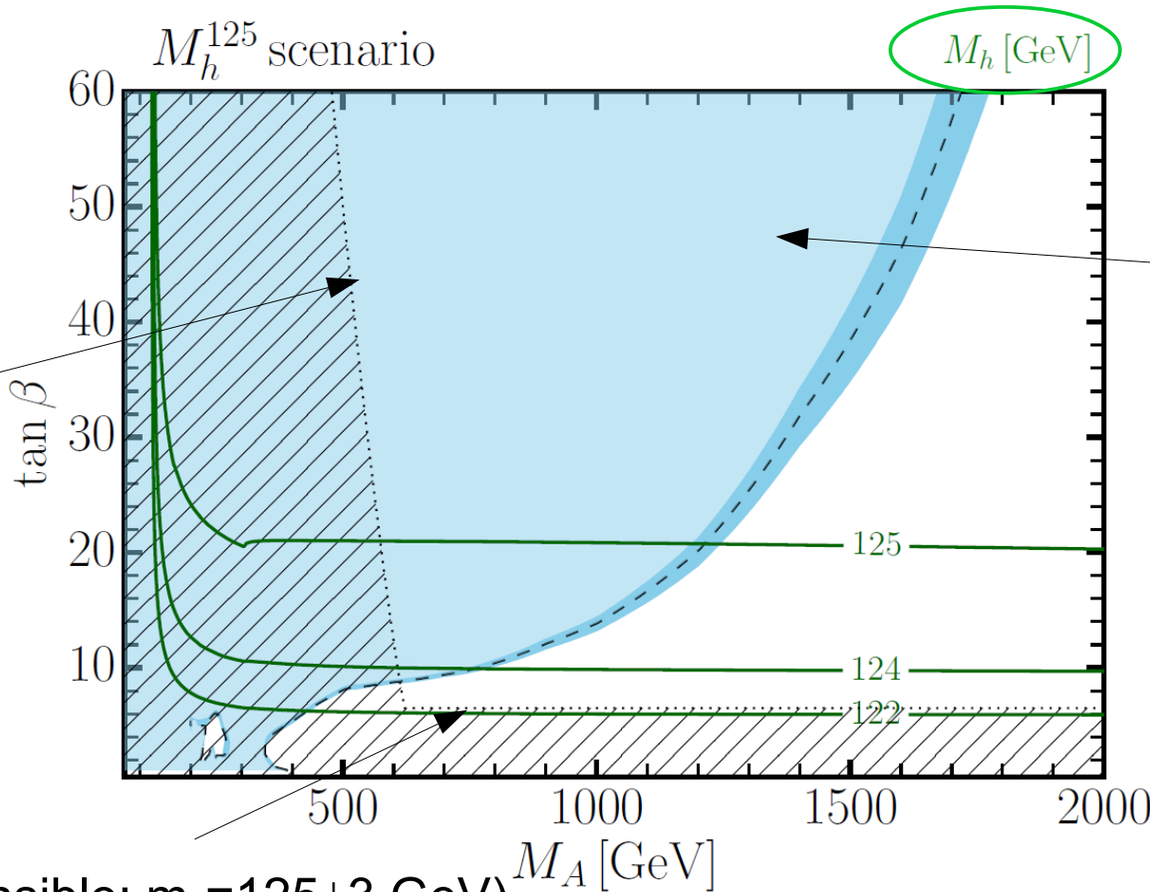
Classic scenarios: with SUSY < 2.5 TeV

M_h^{125} scenario: $M_{\rm SUSY} = 2\,\text{TeV}, \quad M_{Q_3} = M_{U_3} = M_{D_3} = 1.5\,\text{TeV}, \quad \mu = 1\,\text{TeV}$

$M_1 = 1\,\text{TeV}, \quad M_2 = 1\,\text{TeV}, \quad M_3 = 2.5\,\text{TeV}$

$X_t = 2.8\,\text{TeV}, \quad A_\tau = A_b = A_t$

2HDM Higgs sector with SUSY properties, i.e. SUSY ≥ 1 TeV, No influence on BRs of Higgs bosons for m_Φ < 2 TeV.



Bounds from direct searches (Tautau, taunu, ...) (HiggsBounds 5.2.0 beta)

Bounds from SM Higgs couplings (HiggsSignals 2.2.0 beta)

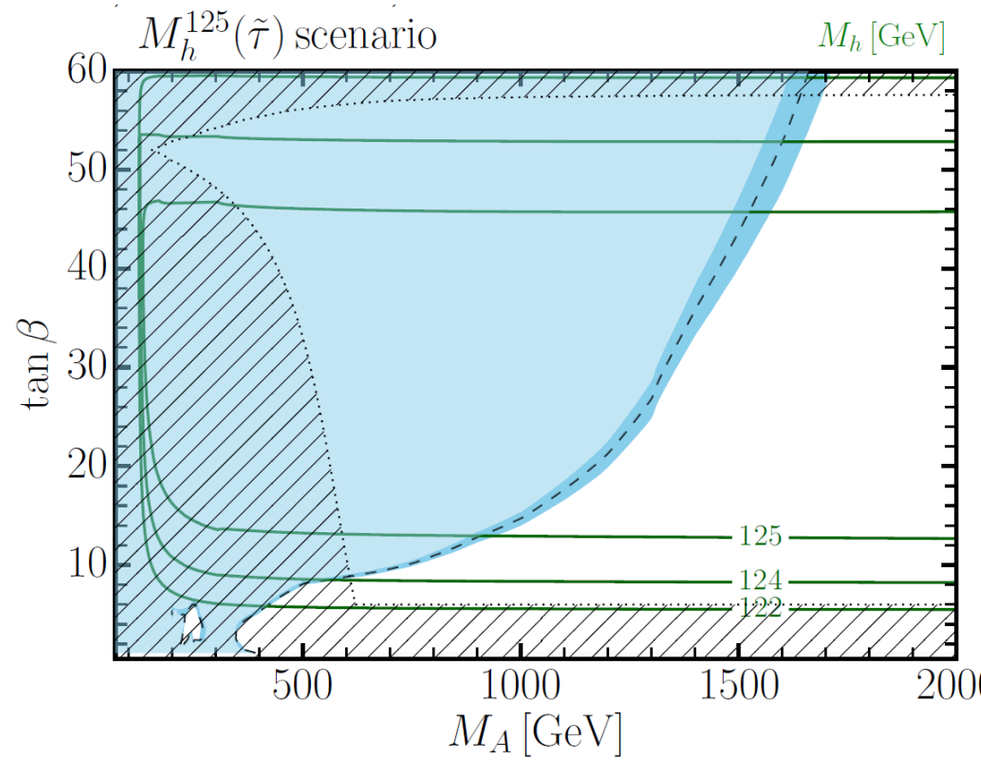
M_h = 122 contour (sensible: m_h=125±3 GeV)

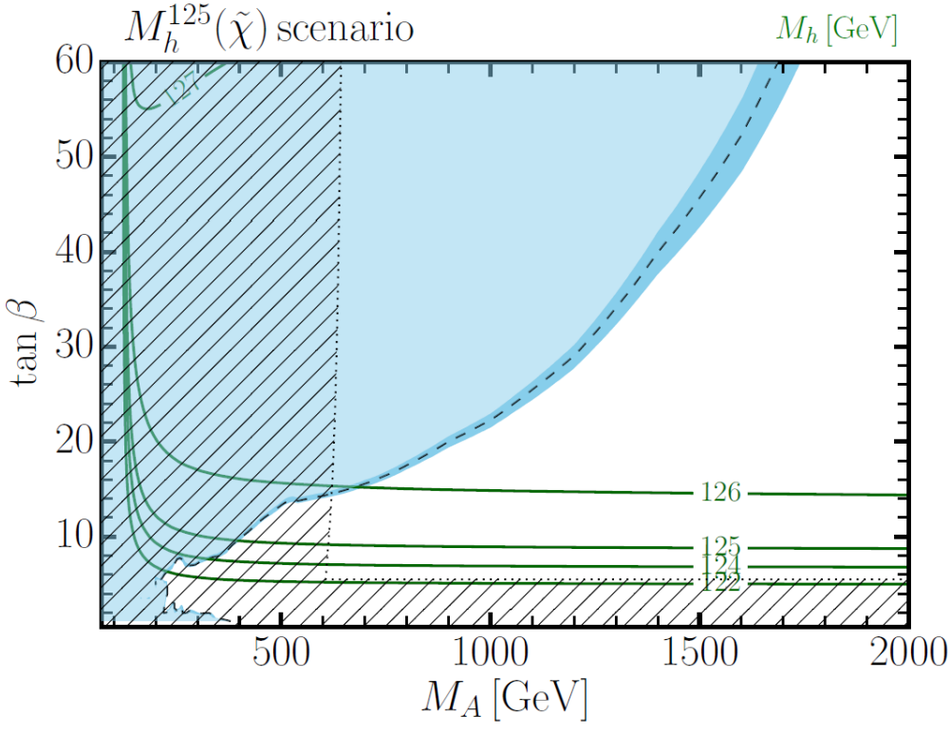
MSSM: New benchmark scenarios

$M_h^{125}(\tilde{\tau})$ scenario →

features light staus that influence h → γγ and open BR(H/A → staus) for large values of tanβ

$$M_{\text{SUSY}} = 2\,\text{TeV}, \quad M_{Q_3} = M_{U_3} = M_{D_3} = 1.5\,\text{TeV}, \quad \mu = 1\,\text{TeV}$$
$$M_1 = 180\,\text{GeV}, \quad M_2 = 300\,\text{GeV}, \quad M_3 = 2.5\,\text{TeV}$$
$$M_{L_3} = 350\,\text{GeV}, \quad M_{E_3} = 350\,\text{GeV}$$
$$X_t = 2.8\,\text{TeV}, \quad A_b = A_t, \quad A_\tau = 800\,\text{GeV}.$$





← $M_h^{125}(\tilde{\chi})$ scenario

with light electroweakinos that open BR(H/A → $\tilde{\chi}_i\tilde{\chi}_i$).

Features: Enhanced BR(h → γγ) at low tanβ.
Motivates search for decay modes H/A/$H^{\pm}$→ $\tilde{\chi}_i\tilde{\chi}_i$ in the future.

$$M_{\text{SUSY}} = 2\,\text{TeV}, \quad M_{Q_3} = M_{U_3} = M_{D_3} = 1.5\,\text{TeV}, \quad \mu = 180\,\text{GeV}$$
$$M_1 = 160\,\text{GeV}, \quad M_2 = 180\,\text{GeV}, \quad M_3 = 2.5\,\text{TeV}$$
$$X_t = 2.5\,\text{TeV}, \quad A_\tau = A_b = A_t\,.$$

MSSM: New benchmark scenarios

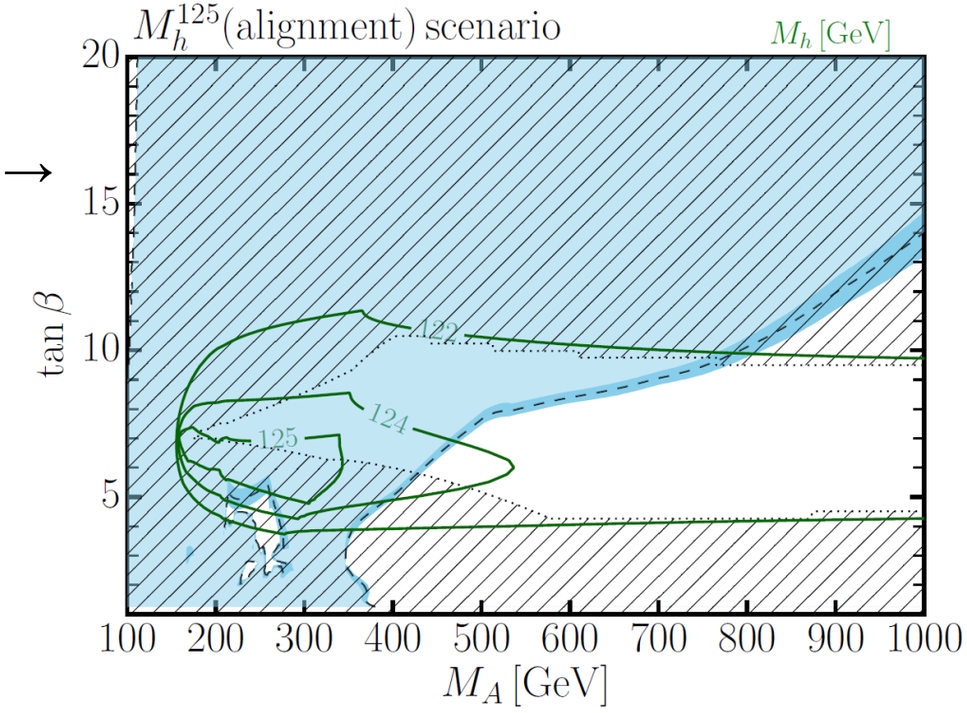
Two exotic scenarios: Alignment without decoupling

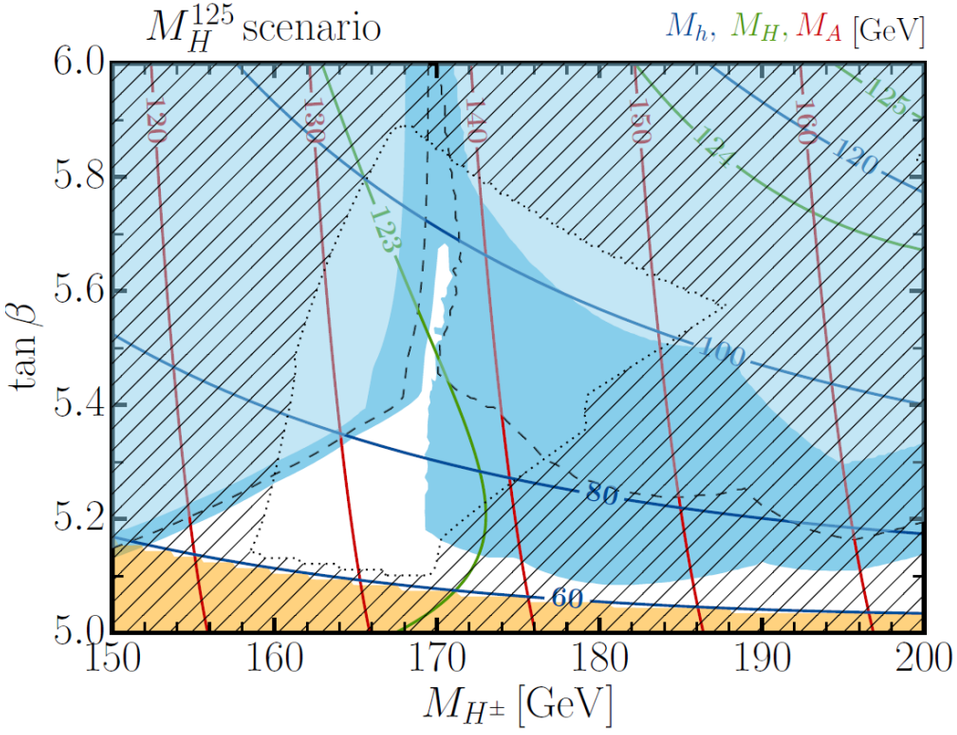
Alignement:
One of the CP-even scalars has SM-like couplings.

Decoupling:
lighter CP-state, h, is SM-like, and H is heavy

M_h^{125} (alignment) scenario →

$$M_{Q_3} = M_{U_3} = M_{D_3} = 2.5\,\text{TeV}$$
$$M_1 = 500\,\text{TeV},\ M_2 = 1\,\text{TeV},\ M_3 = 2.5\,\text{TeV}$$
$$\mu = 7.5\,\text{TeV}, \quad A_b = A_\tau = A_t = 6.25\,\text{TeV}.$$





← M_H^{125} scenario 125 GeV Higgs is H and not h, h is lighter

$$M_{Q_3} = M_{U_3} = M_{D_3} = 750\,\text{GeV} - 2\,(M_{H^\pm} - 150\,\text{GeV})$$
$$\mu = [5800\,\text{GeV} + 20\,(M_{H^\pm} - 150\,\text{GeV})]\ M_{Q_3}/(750\,\text{GeV})$$
$$M_1 = M_{Q_3} - 75\,\text{GeV}, \quad M_2 = 1\,\text{TeV}$$
$$M_3 = 2.5\,\text{TeV}, \quad A_t = A_b = A_\tau = 0.65 M_{Q_3}.$$

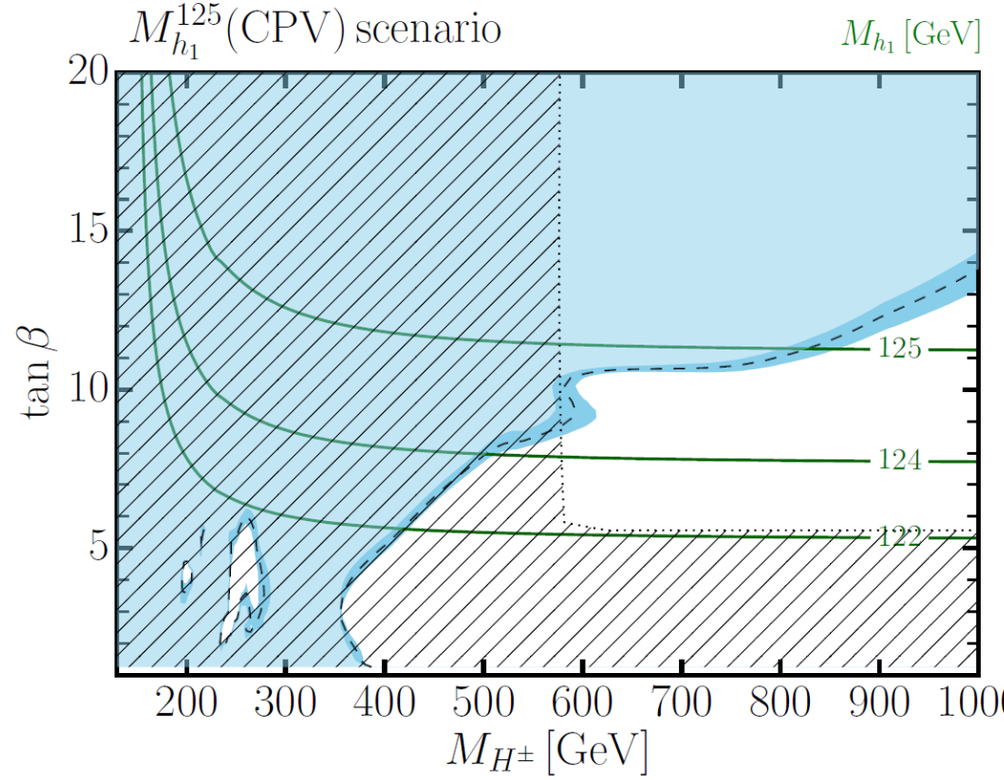
Light h → Decay of H^+ → Wh becomes relevant

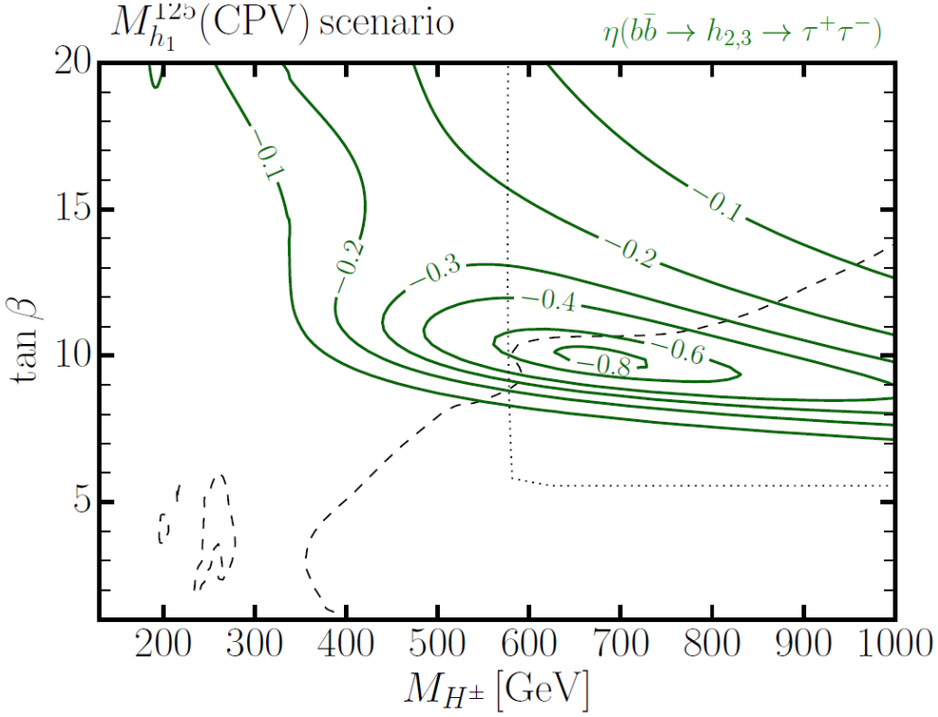
MSSM: New benchmark scenarios

One CP-vialoting scenario: M_h^{125} (CPV)

H/A/h mix to three mass eigenstates h_i through phase in trilinear couplings A_f → interference

$$M_{\text{SUSY}} = 2\,\text{TeV}, \quad \mu = 1.65\,\text{TeV}, \quad M_1 = M_2 = 1\,\text{TeV}$$
$$M_3 = 2.5\,\text{TeV}, \quad |A_t| = \mu/\tan\beta + 2.8\,\text{TeV}$$
$$\phi_{A_t} = \tfrac{2\pi}{15}, \quad A_b = A_\tau = |A_t|$$





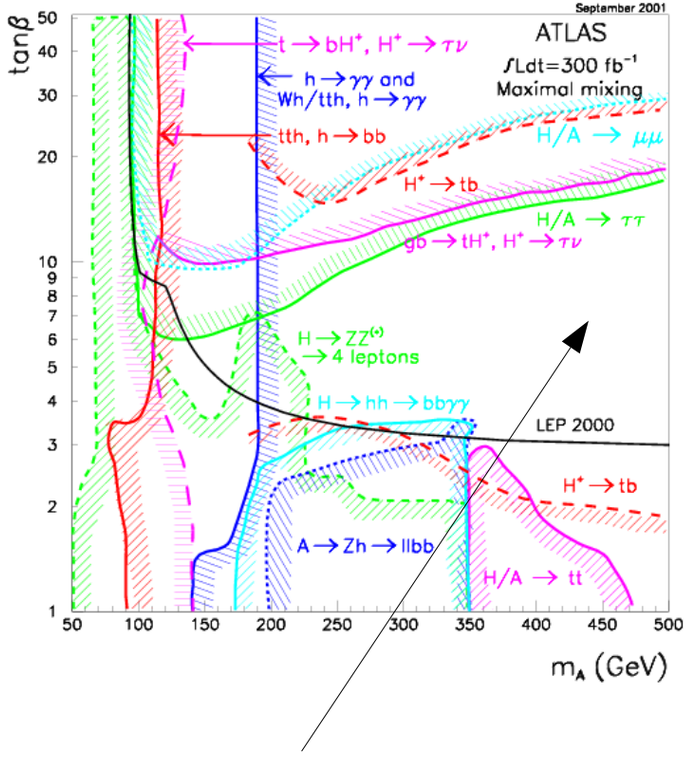
Interference factor: $\eta_{\text{IF}} = \dfrac{2\text{Re}[A_{h_2} A_{h_3}^*]}{|A_{h_2}|^2 + |A_{h_3}|^2}$

→ weakens the exclusions

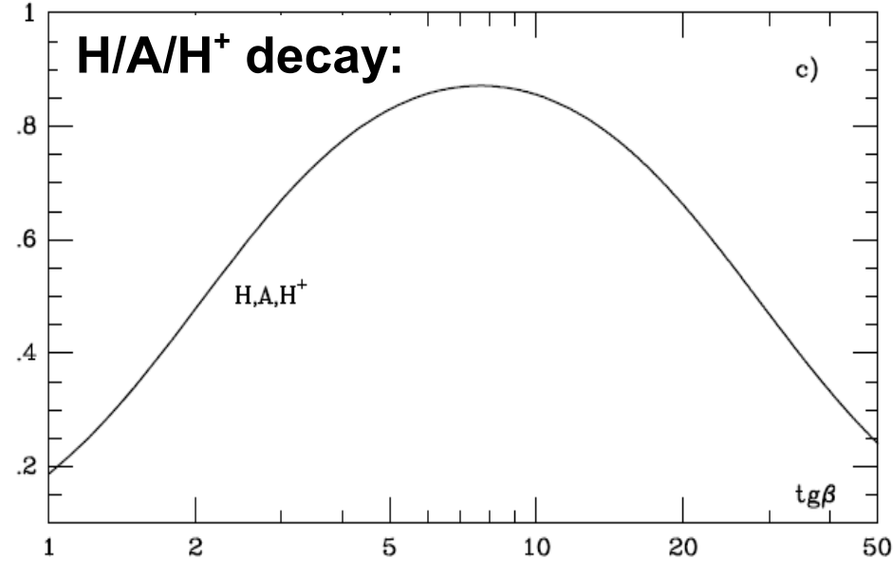
MSSM: Higgs to SUSY

Theoretical wok ongoing from S. Gori, B. Shakya and Z. Liu, to point out new possible searches for electroweak SUSY particles produced from MSSM heavy Higgs decays, ie. H → neutralinos, H → staus

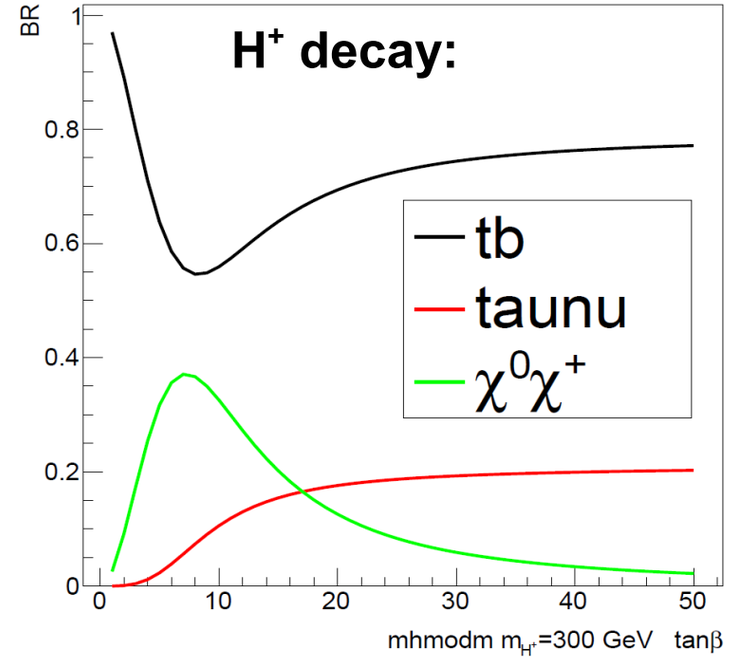
Paper coming soon!



How to cover the wedge?



Djouadi: https://cds.cern.ch/record/340786



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGNMSSM

Contacts: Nikos Rompotis (ATLAS), Nadjieh Jafari (CMS),
Ulrich Ellwanger, Margarete Mühlleitner, Florian Staub (Theory)

Activities and work presented in YR4:

- Benchmark points (see also https://twiki.cern.ch/twiki/bin/view/LHCPhysics/NMSSMBenchmarkPoints)

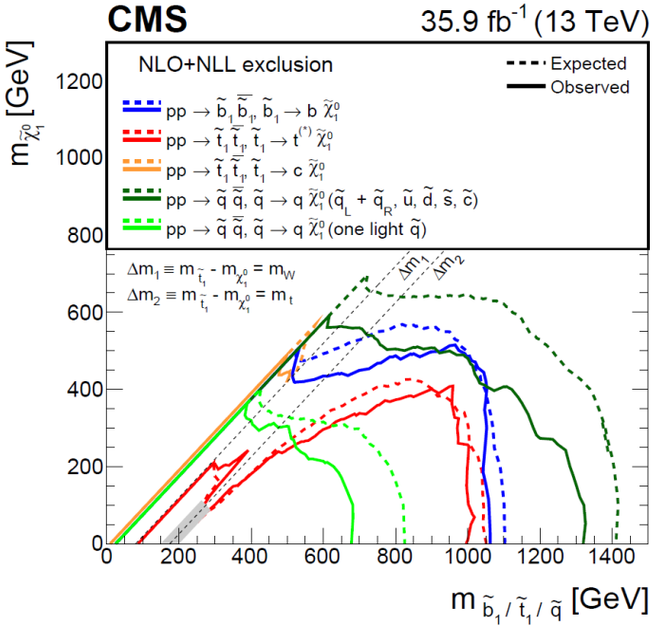
  - 125 GeV Higgs decays
  - Production of a light additional Higgs boson
  - Production of a heavy additional Higgs boson
  - Higgs bosons in sqark/gluino/chargino/neutralino decays
  - Displaced vertices

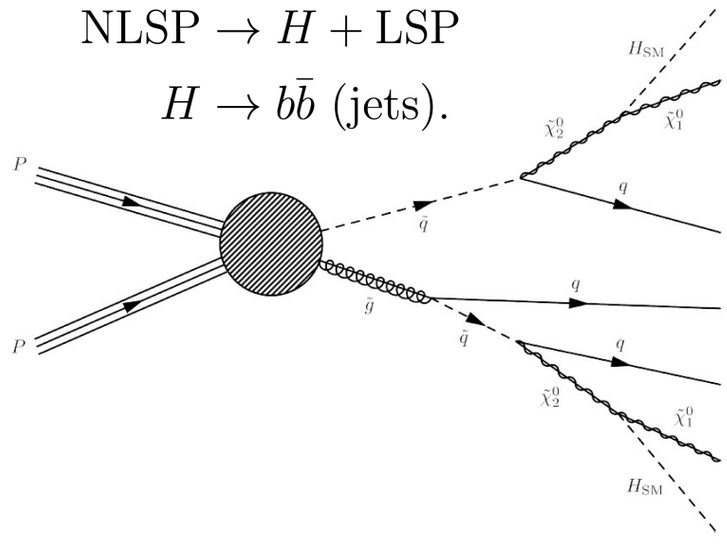
  The BP were meant to be some test points to compare the experimental sensitivity.
  But some of the benchmarks from YR4 are out of reach for LHC, to be updated (perhaps in a white paper)

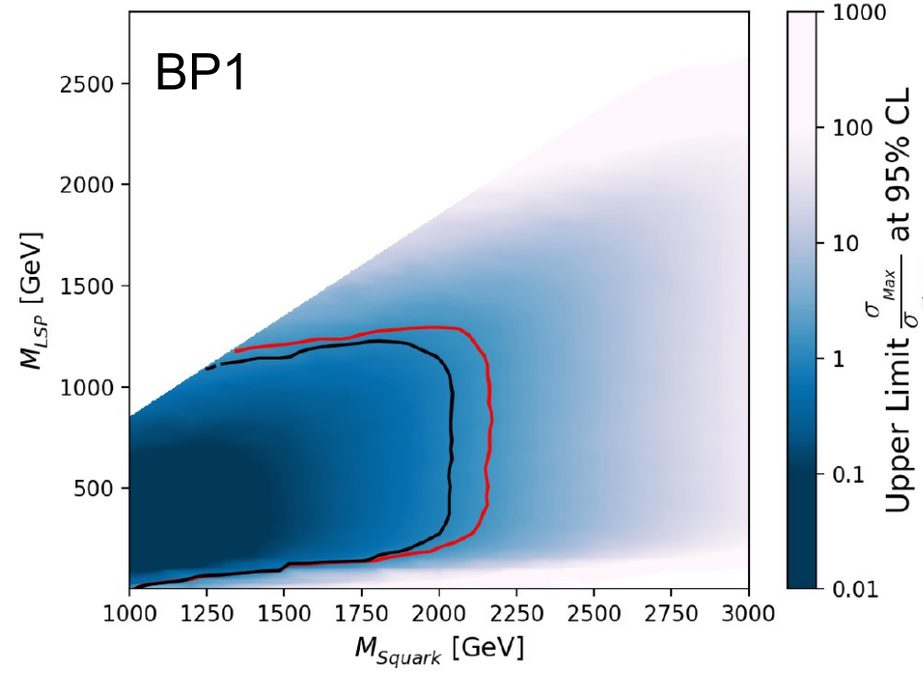
- **Tools:**
  NMSSMTools (Higgs & sparticle spectrum), CalcHEP (cross sections), MircOMEGAS (LSP cross sections and relic density), Spheno (sparticle decay amplitudes), WHIZARD (MC), SuperIso (flavor observables), SusHi (cross sections), NMSSMCalc (Higgs spectrum and decays)

NMSSM: Recent work and plans

A paper by Ellwanger et al.:
"Exploring Sensitivity to NMSSM Signatures with Low Missing Transverse Energy at the LHC"
(recasting CMS limits on squarks/gluinos in BPs of the NMSSM), arXiv:1807.10672







Plans:

- Searches for ggF → H_3 → H_2+H_1, with either H_1 or H_2 mostly SM- or singlet-like

- Re-interprete searches for ggF → H → γγ by ATLAS/CMS in the NMSSM (with H mostly singlet-like)

- Re-interprete searches for H_{SM} → aa in the NMSSM

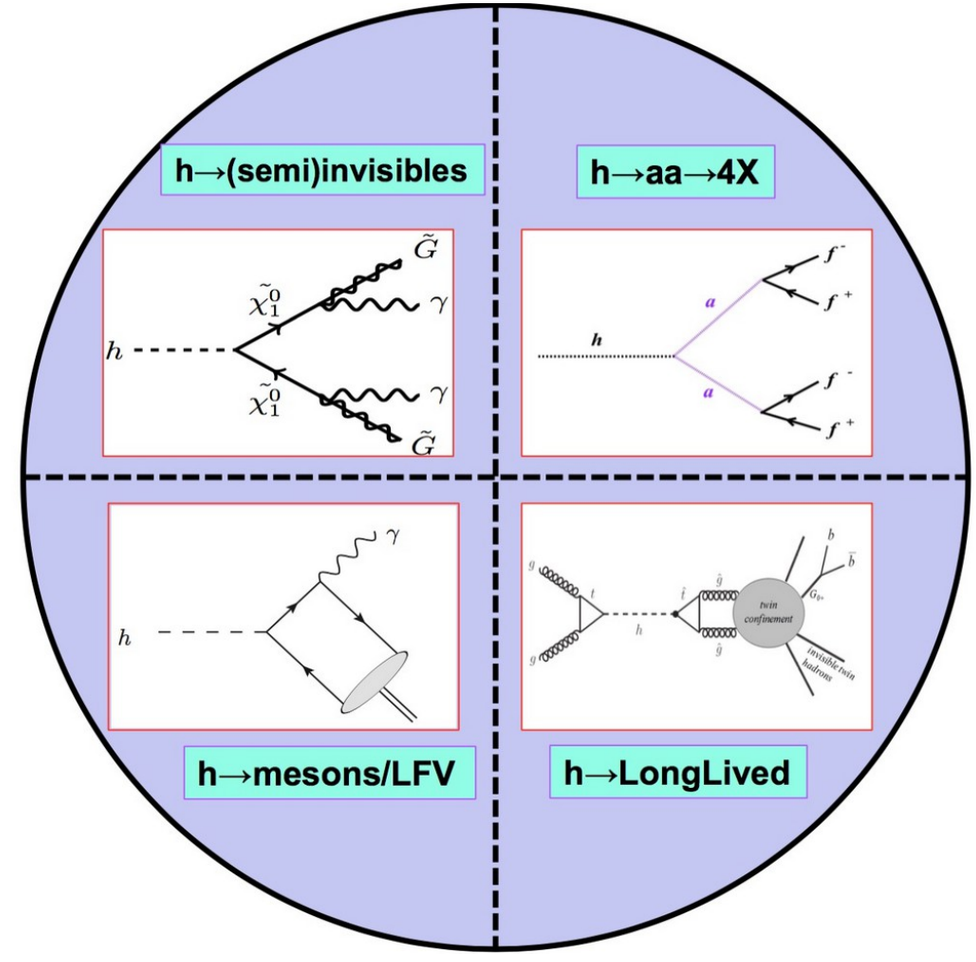
Exotic Higgs Decays

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGExoticDecay

Contacts: Lily Morvaj (ATLAS), Cecile Caillol (CMS), Lorenzo Sestino (LHCb), Jesse Shelton, Zhen Liu (Theory)

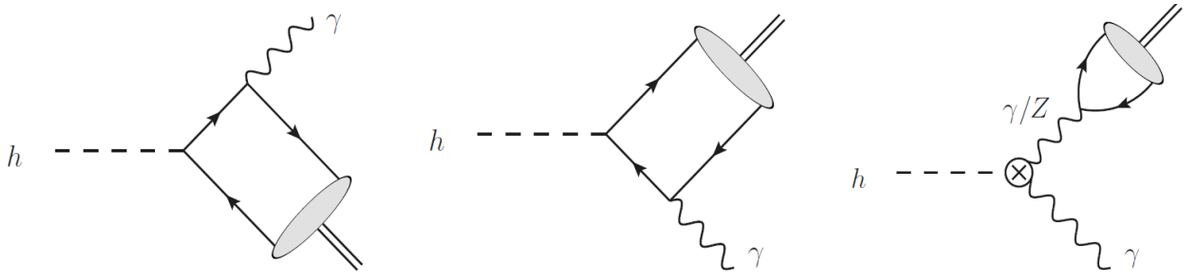
Topics discussed in YR4:

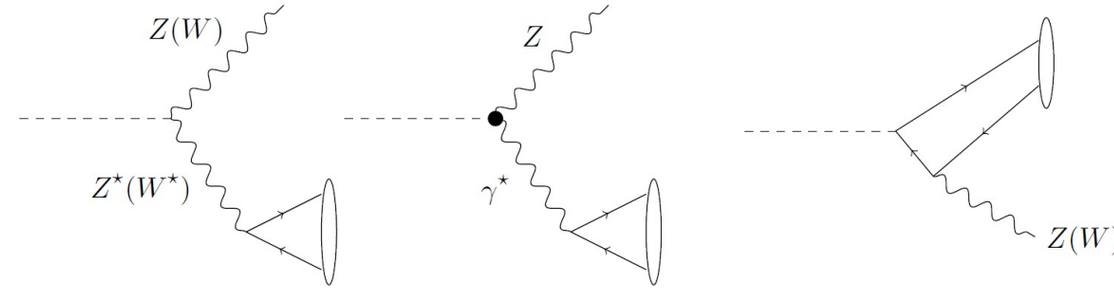
- mesonic Higgs decay, such as h → Mγ, or h → MV
- flavour-violating Higgs, eg. h → eμ
- Higgs to light resonances: h → aa → 4b/4μ/bbττ/...
- Higgs to (semi-)invisibles, such as h → γγ + MET
- Higgs decays to long-lived particles h → XX



Exotic Higgs Decays

Rare Higgs decays Brachning ratios (in collaboration with the BR sub-group) documented in YR4:



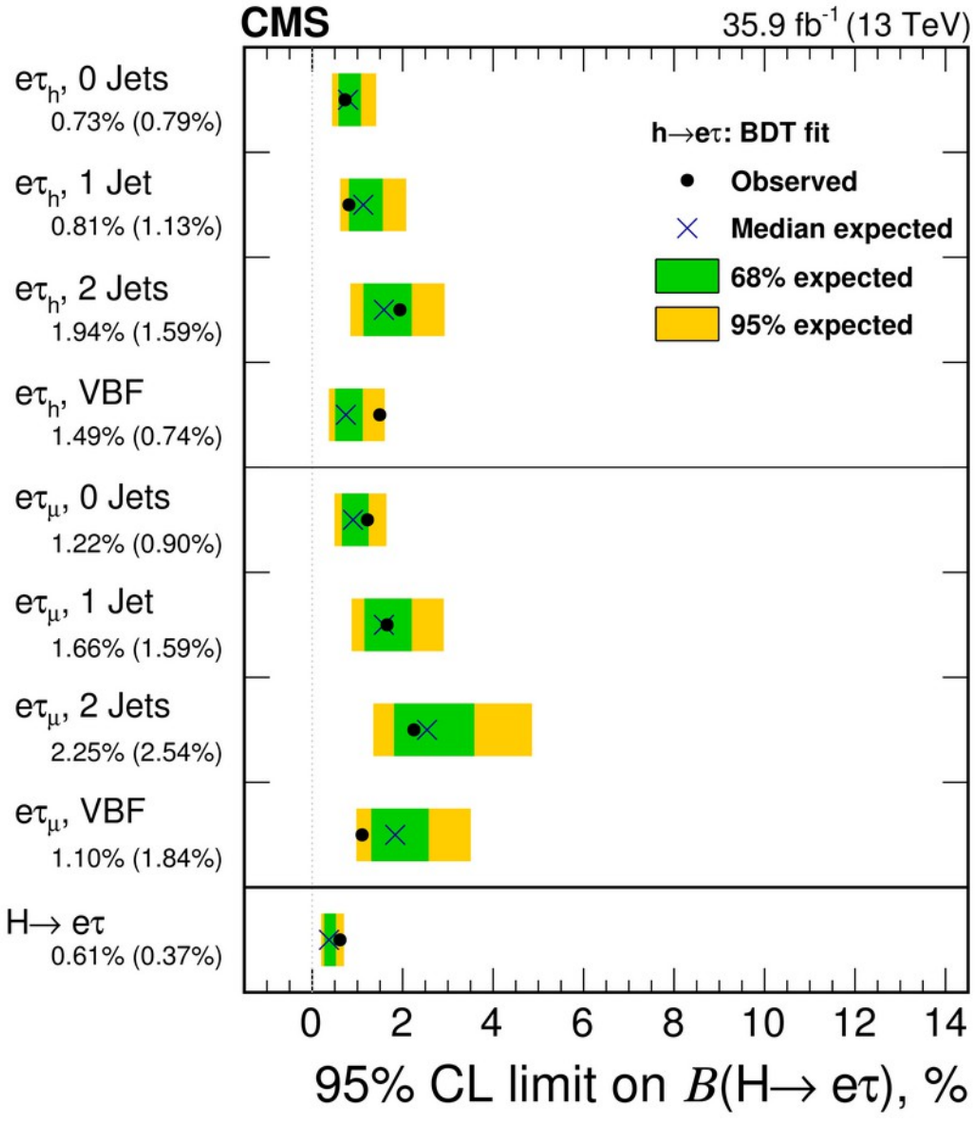


Mode Method	Branching Fraction $[10^{-6}]$ NRQCD [1487]	 LCDA LO [1486]	 LCDA NLO [1489]
$\mathrm{Br}(h \to \rho\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(h \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(h \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$

VP mode	P mass	F_P	$\mathcal{B}^{\mathrm{SM}}$	Th. Error
$W^-\pi^+$	139.57018 ± 0.00035 MeV	126.6 ± 1.4 MeV	0.42×10^{-5}	$\pm 5\%$
W^-K^+	493.677 ± 0.016 MeV	35.2 ± 0.3 MeV	0.33×10^{-6}	$\pm 4\%$
$W^-D_s^+$	1968.30 ± 0.11 MeV	248.6 ± 2.4 MeV	1.6×10^{-5}	$\pm 4\%$
W^-D^+	1869.61 ± 0.09 MeV	47.07 ± 2.4 MeV	0.58×10^{-6}	$\pm 11\%$
W^-B^+	5279.29 ± 0.15 MeV	0.79 ± 0.10 MeV	1.6×10^{-10}	$\pm 26\%$
$W^-B_c^+$	6275.1 ± 1.0 MeV	7.82 ± 0.42 MeV	1.6×10^{-8}	$\pm 11\%$
$Z\pi^0$	134.9766 ± 0.0006 MeV	92.1 ± 1.0 MeV	0.23×10^{-5}	$\pm 5\%$
$Z\eta_c$	2984.3 ± 0.84 MeV	197.4 ± 0.30 MeV	1.0×10^{-5}	$\pm 5\%$

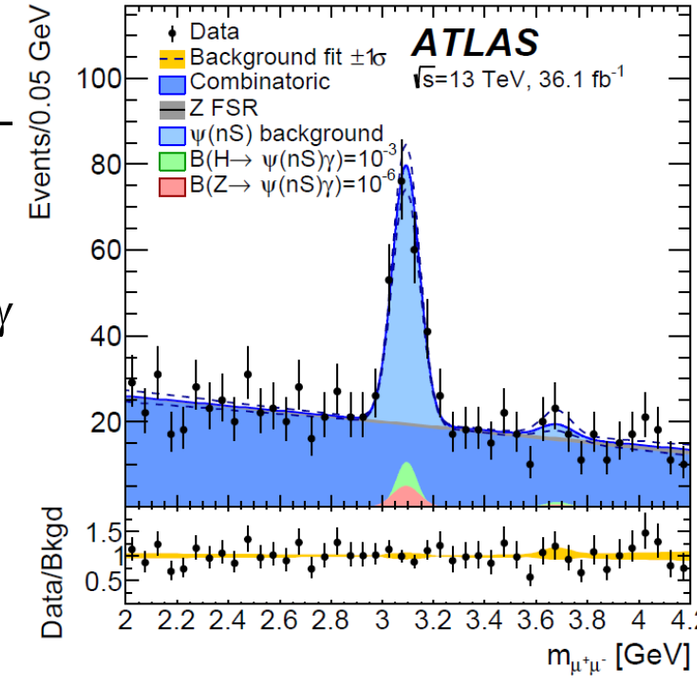
Exotic Higgs Decays

LFV Higgs: HIG-17-001



H → J/ψγ, ψ(2S)γ and Υ(nS)γ

HIGG-2016-23



Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi(2S)\,\gamma)\,[\,10^{-4}\,]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(Z \to J/\psi\,\gamma)\,[\,10^{-6}\,]$	$1.1^{+0.5}_{-0.3}$	2.3
$\mathcal{B}(Z \to \psi(2S)\,\gamma)\,[\,10^{-6}\,]$	$6.0^{+2.7}_{-1.7}$	4.5
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.5}_{-1.4}$	5.7
$\mathcal{B}(Z \to \Upsilon(1S)\,\gamma)\,[\,10^{-6}\,]$	$2.8^{+1.2}_{-0.8}$	2.8
$\mathcal{B}(Z \to \Upsilon(2S)\,\gamma)\,[\,10^{-6}\,]$	$3.8^{+1.6}_{-1.1}$	1.7
$\mathcal{B}(Z \to \Upsilon(3S)\,\gamma)\,[\,10^{-6}\,]$	$3.0^{+1.3}_{-0.8}$	4.8

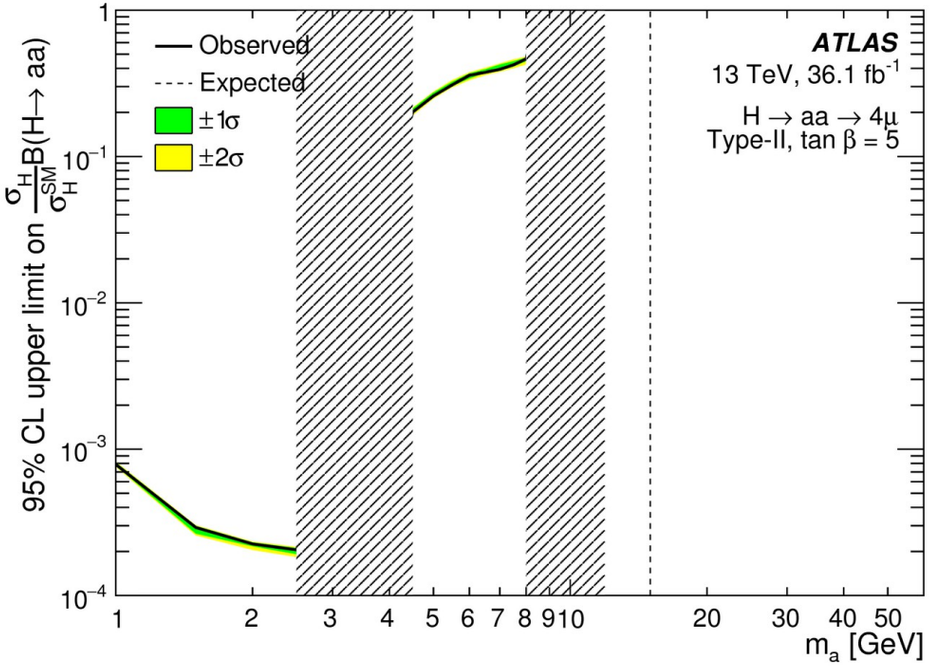
Exotic Higgs Decays

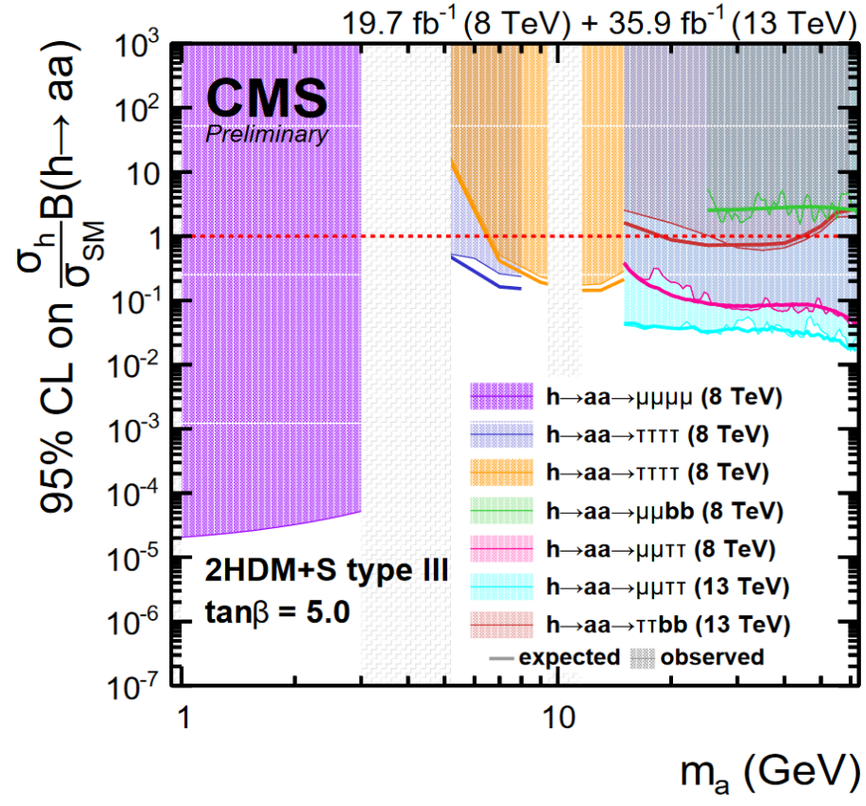
Theory work:

„Exotic Decays of the 125 GeV Higgs Boson“, https://arxiv.org/abs/1312.4992 (Curtin, Essig, Gori, et. al.)

„Collider constraints on light pseudoscalars“
U. Haisch, J. Kamenik, A. Malinauskas, M. Spira: https://arxiv.org/abs/1802.02156

Makes theory predictions in particular for the mass regions [3,5] GeV and [9,11] GeV (quarkonia regions), in which a meaningful theoretical description has to include estimates of non-perturbative effects such as the mixing of the pseudoscalar with QCD bound states.



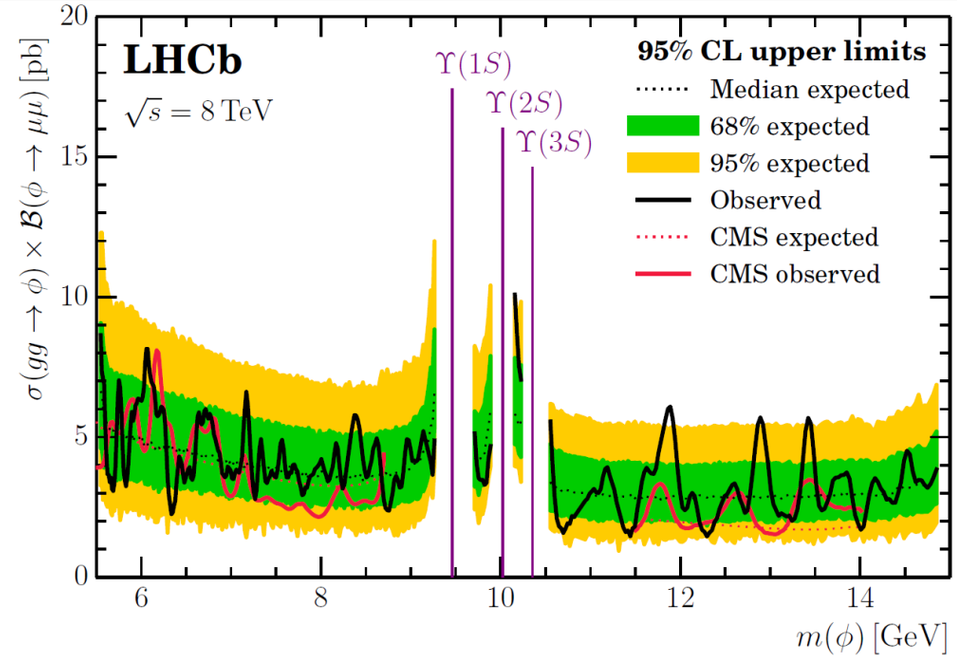


Exotic Higgs Decays: Latest news

Input for interpretations available:

a → XX BRs for various 2HDM and tanβ values, including the quarkonia regions, based on the mentioned theory papers now available on the twiki!

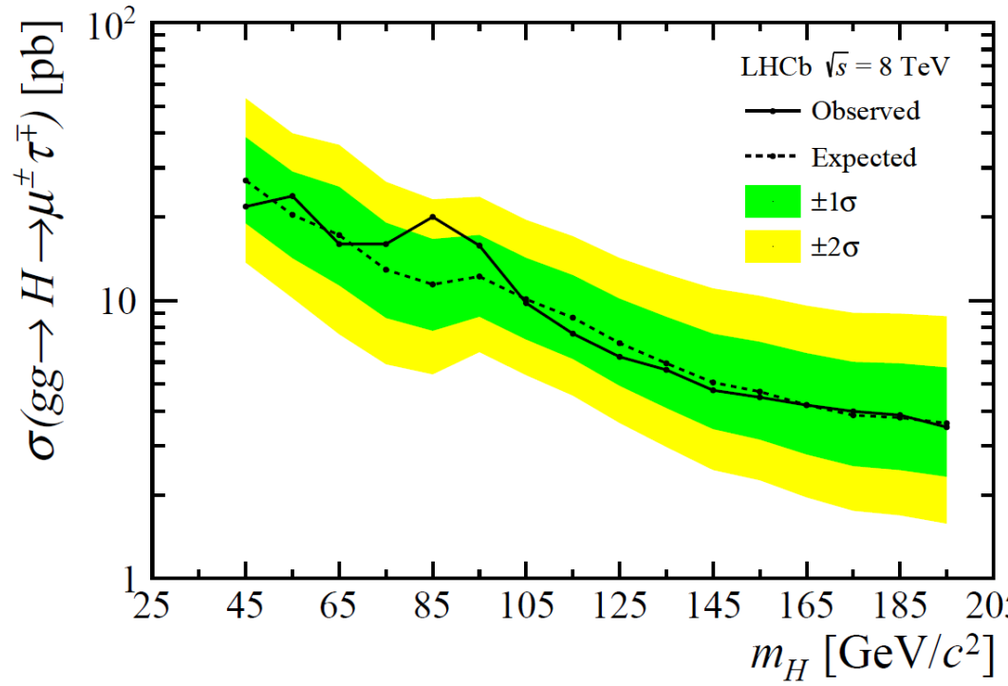
→ analysers are working to update their plots/produce interpretations



New results from LHCb:

The search for a higgs-like boson in μμ, in the upsilon region: https://arxiv.org/pdf/1805.09820.pdf

The search for a lepton flavour violating H → mu tau: https://arxiv.org/abs/1808.07135



Summary

- After the big YR4 effort no new large CERN reports expected in the near future, but the work of course continues on all topics
- Experimental collaborations still need important (and sometimes urgent) input
- LHC HXS WG is a well-defined, mature structure but it is flexible to achieve the goal: to be really useful for the particle physics community
- 15th General LHXSWG assembly meeting in December 2018. Excellent opportunity to get an update on the latest results and discuss the structure and future prospects of the WG.
- Input and new ideas from the community are more than welcome, please join in!

Next General Assembly Meeting:

10-12 December at CERN: https://indico.cern.ch/event/740110/ Please register!