Exotic Higgs searches at LHC

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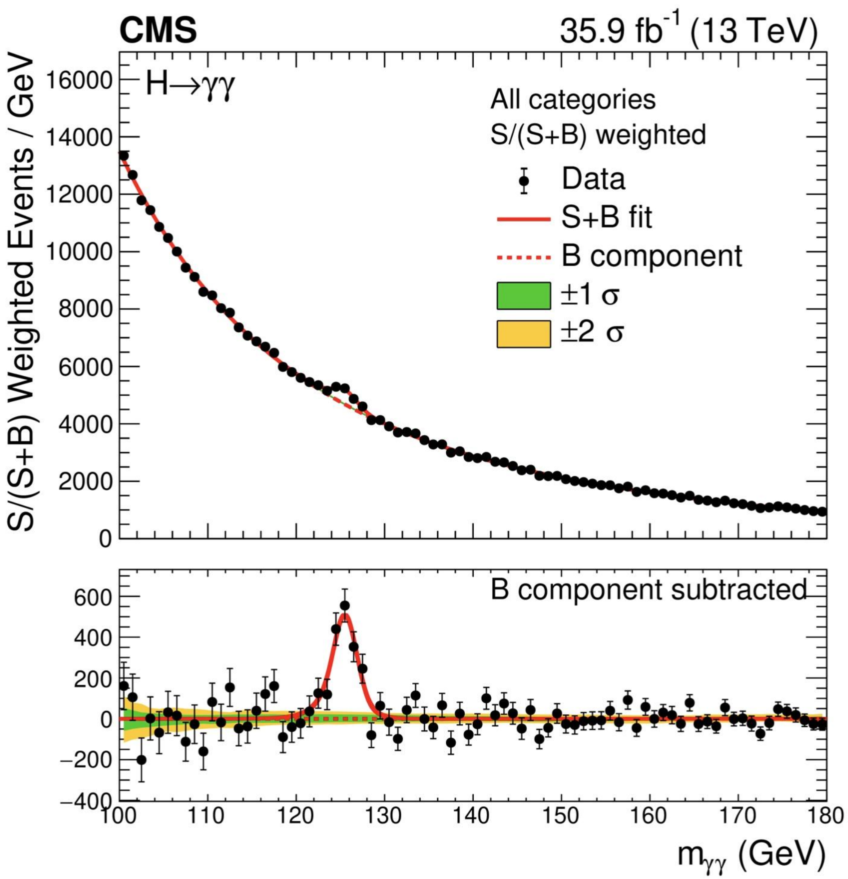
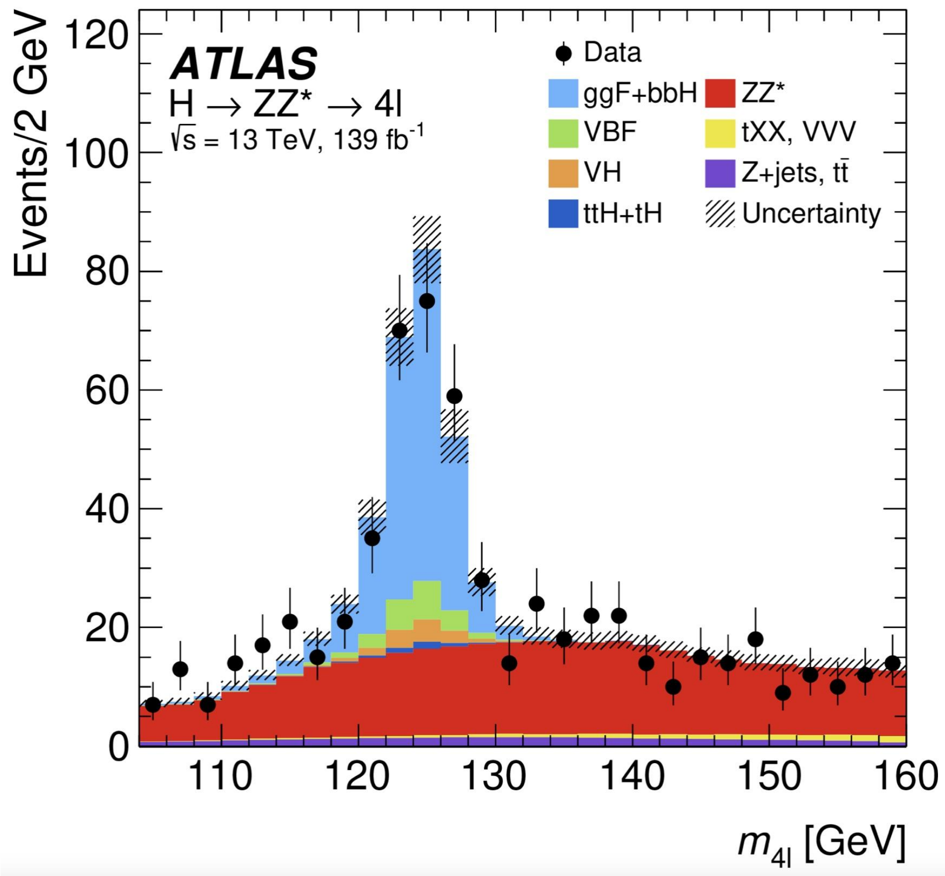
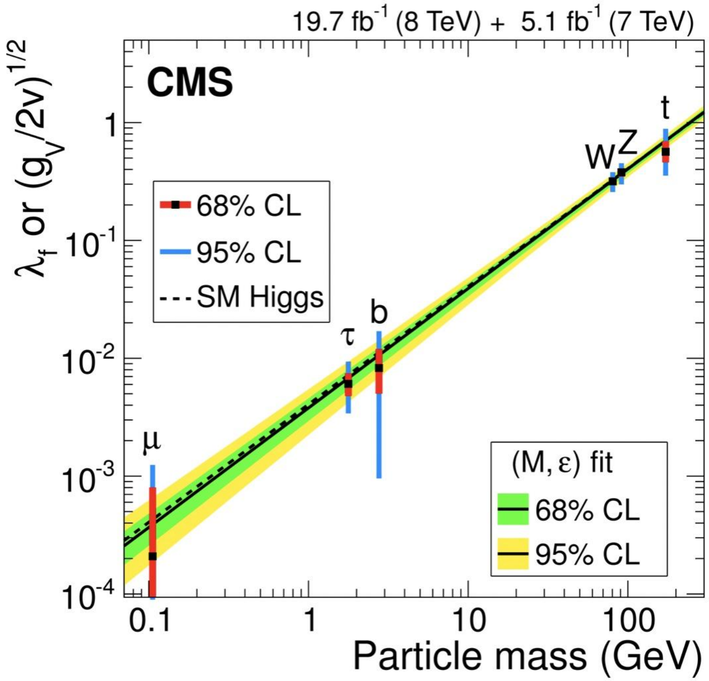
The story so far

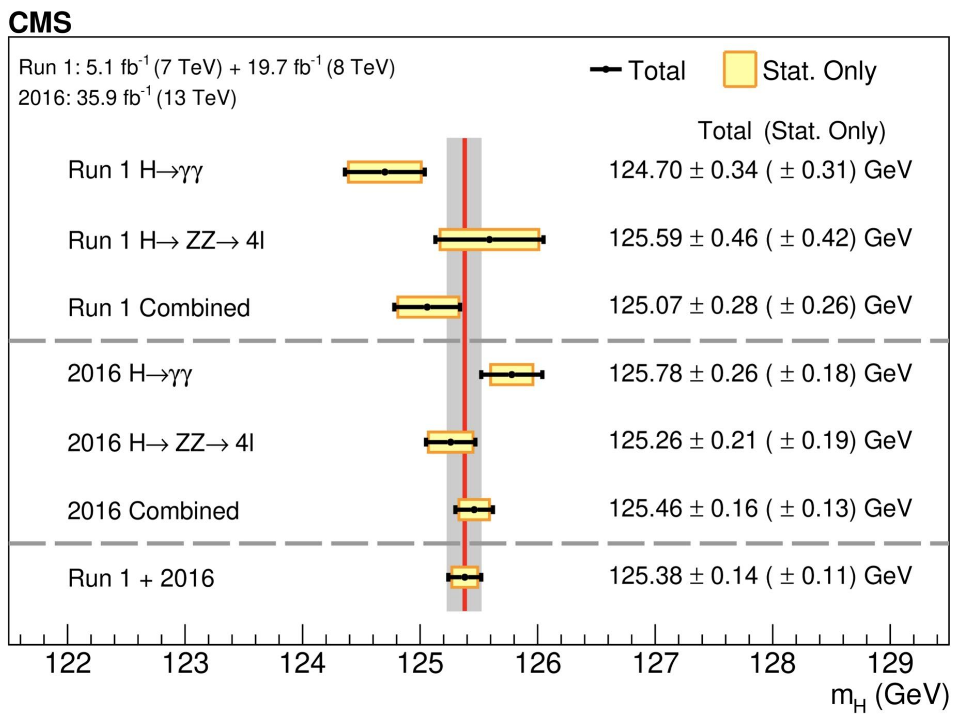


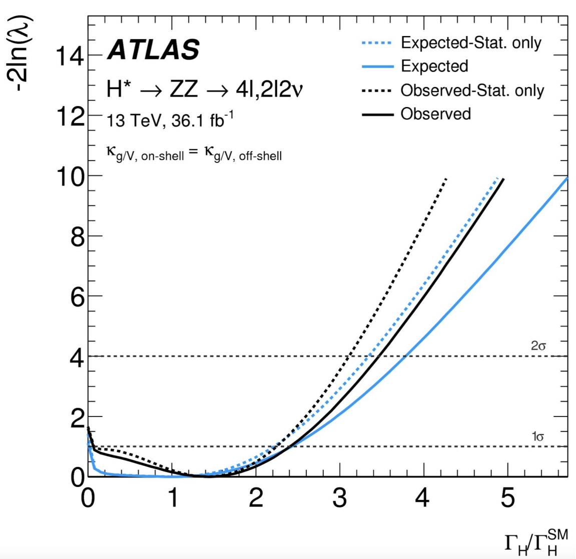


Clear signature of a particle with m = 125 GeV
Observed in many final states
Compatible with SM Higgs boson within 10-20% precision (depends on final states and observables)

Measuring properties







Extensive physics program to measure properties of h_{125} up to the end of HL-LHC

Will bring precision down to a few % in most cases

Not the only way to test the Higgs sector of the SM!

Problems

Issues with the SM (that *could* be fixed/observed by the Higgs sector)

- Higgs mass
- Dark matter
- Neutrino masses
- Hierarchy problem
- Large number of parameters

Looking elsewhere

- Many BSM theories require modifications to Higgs sector modelling
  - Most of SUSY incarnations
  - “Non minimal” SM
- Large overlap of signatures with searches not related to Higgs sector
- Common framework and benchmarks with properties of h_{125} (for example hh production)

Definition of exotic Higgs obviously arbitrary

Review studies of interest (for physics or techniques)

Disclaimer: from a CMS member perspective

Two exotic paths

Exotic: signature/group of signatures not present in SM predictions

Two main routes:

- Search for new Higgs bosons
- Search for new decays of h_{125}

Higgs multiplets

The Higgs sector in the SM

In SM, minimal request is one electroweak doublet

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_0 + i\phi_3 \end{pmatrix}$$

- Necessary to provide mass (L polarization) to $W^{\pm}$ and Z
- The extra d.o.f. originates the Higgs scalar

Many of the BSM scenarios deal with extra singlets/doublets/triplets

Next-to-minimal-ish: 2HDM

Additional electroweak doublet

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \qquad \phi' = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_7 + i\phi_8 \end{pmatrix}$$

5 degrees of freedom available

➔ **CP-even (h, H) CP-odd (A), $H^\pm$**

With few assumptions, free parameters of the theory: m_h, m_H, m_A, $m_{H\pm}$, tanβ, α

α is the mixing parameter between h and H

$$\tan(\beta) = \frac{<\varphi>_0}{<\varphi'>_0}$$

Somewhat problematic to produce common benchmarks with all these parameters

⟶ Extensive work of theory/experiment within the LHC HXSWG

Parameters can be constrained in particular incarnations of 2HDM

⟶ In MSSM, d.o.f. reduced to two parameters ⟶ m_A and tanβ

Personal note: very "mild" BSM if no SUSY ⟶ sideways SM!

Couplings in 2HDM

All mass eigenstates couple to both h and H in all configurations, but couplings depend on model

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$

Different scaling of up and down fermions

Different scaling of leptons and quarks

Different scaling of up and down quarks, leptons flipped

$$g_{h,VV} \propto \sin(\beta - \alpha) \qquad g_{H,VV} \propto \cos(\beta - \alpha)$$

Typical topologies

Signatures depend on mass hierarchy

High mass:

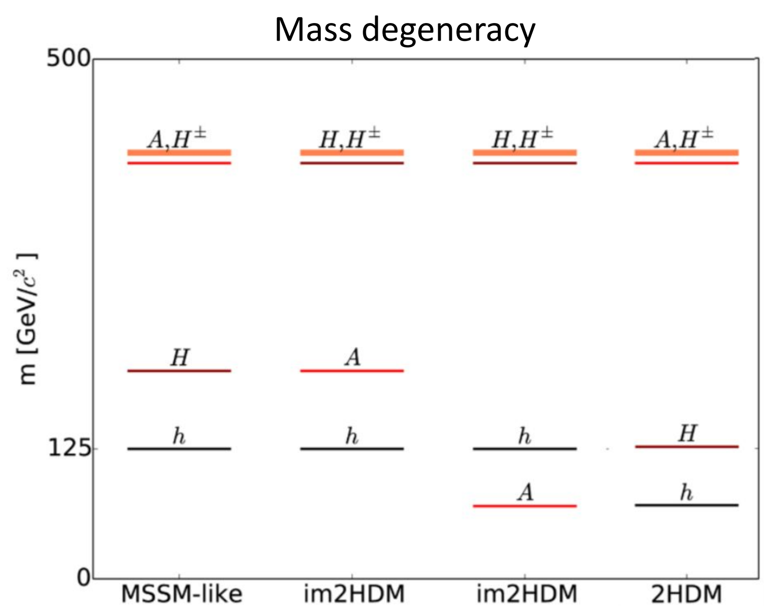
- $H \to hh$, $H^{\pm} \to W^{\pm}Z$, $H \to AZ$, $A \to Zh$, $H \to tt$ …

Mid-high mass:

- $A/H \to \tau\tau/bb/\mu\mu/WW/ZZ$

Low mass:

- $A \to \tau\tau/bb/\mu\mu$
- Overlap with NMSSM (see later)



A/H → ττ

Phys. Rev. Lett. 125 (2020) 051801

Search in the $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ in range [0.2,2.5] TeV

→ Single lepton triggers ~ 25 GeV, single τ around 150 GeV

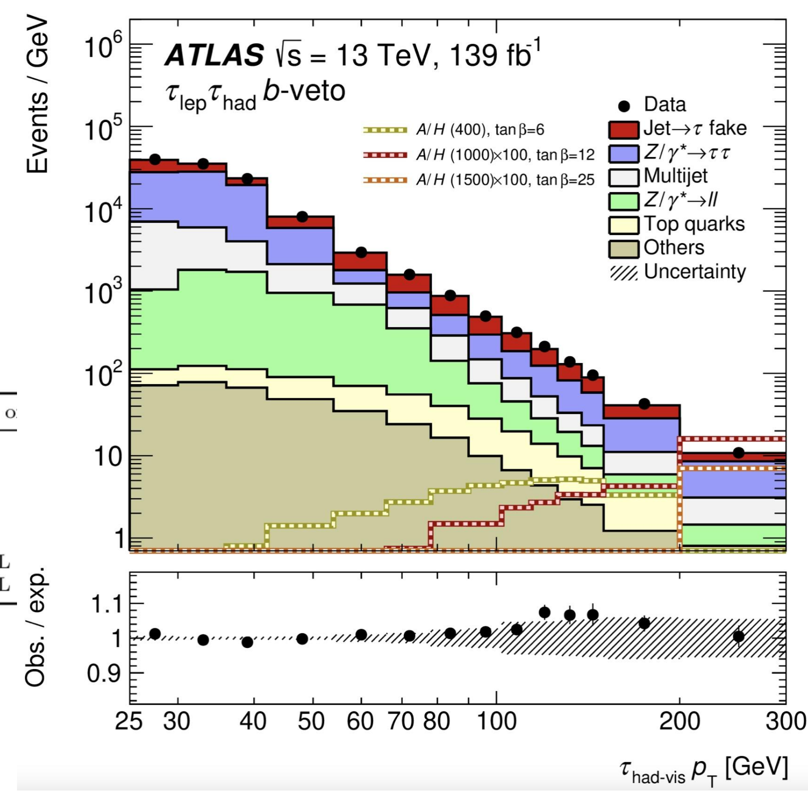
"Bump" hunting over the transverse mass spectrum defined with missing energy

$$m_T^{\mathrm{tot}} = \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{\mathrm{miss}})^2 - (\boldsymbol{p}_T^{\tau_1} + \boldsymbol{p}_T^{\tau_2} + \boldsymbol{E}_T^{\mathrm{miss}})^2}$$

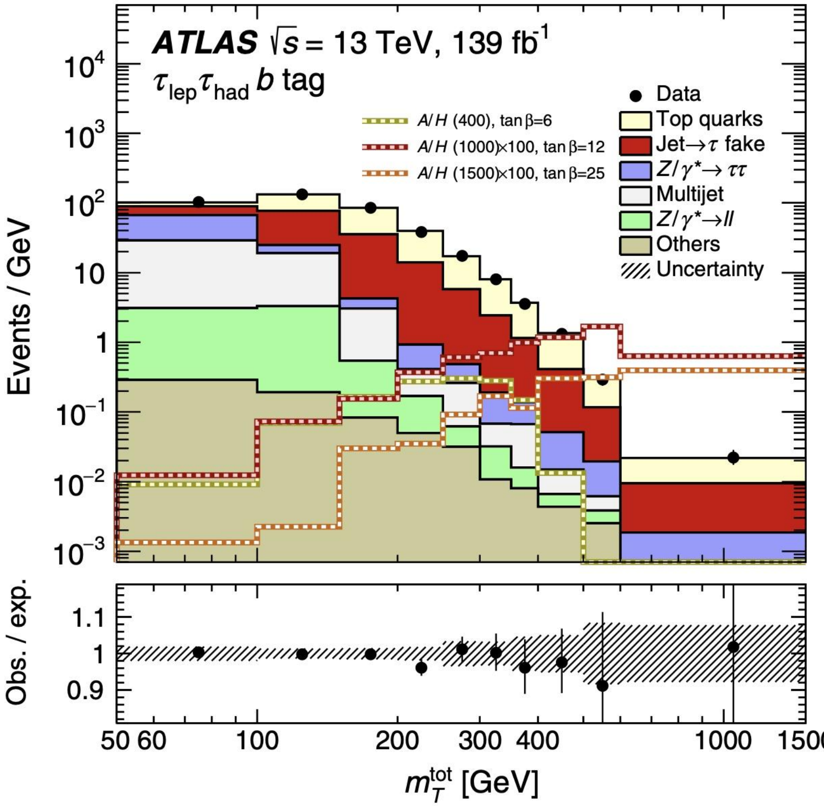
N_{bjet} categorization to exploit different production mechanisms

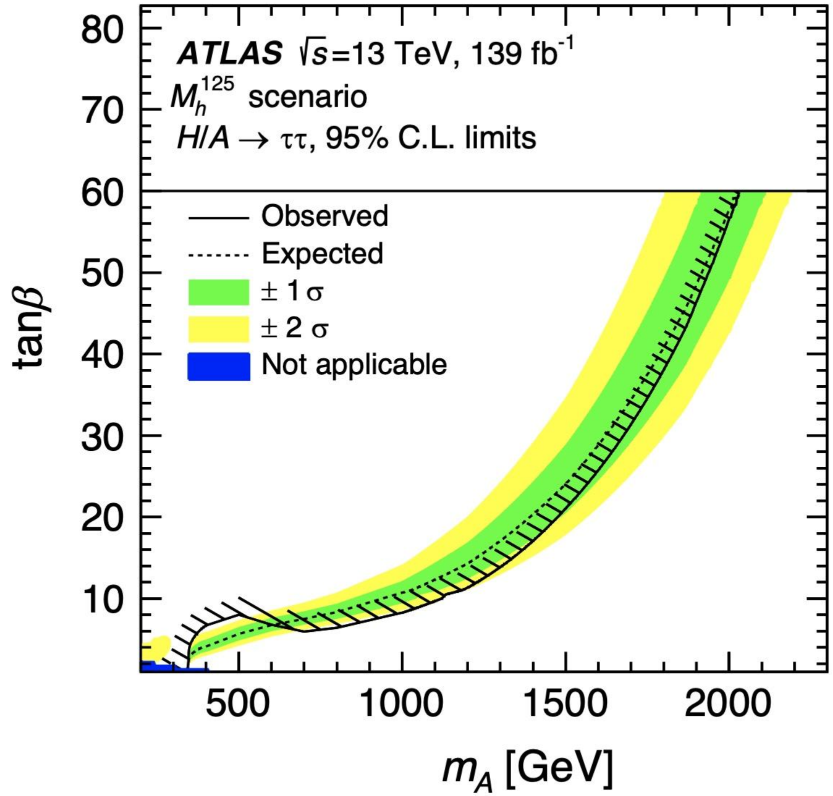
→ Dependence on tanβ for both b and τ

Process	Generator	PDF	UEPS	Cross-section o
ggF	Powheg-Box v2 [61,62,63,64,65]	CT10 [66]	Pythia 8.1 [67]	See text
bbH	MG5_aMC@NLO 2.1.2 [68,69]	CT10	Pythia 8.2 [70]	See text
W+jets	Sherpa 2.2.1 [71]	NNPDF 3.0 NNLO [72]	Sherpa 2.2.1 [73]	NNLO [74]
Z+jets	Powheg-Box v1 [61,62,63,75]	CT10	Pythia 8.1	NNLO [74]
$VV/V\gamma^*$	Sherpa 2.2	NNPDF 3.0 NNLO	Sherpa 2.2	NLO
$t\bar{t}$	Powheg-Box v2 [76,61,62,63]	NNPDF 3.0 NLO	Pythia 8.2	NNLO+NNLL
Single t	Powheg-Box v2 [84,85,86,61,62,63]	NNPDF 3.0 NLO	Pythia 8.2	NNLO+NNLL



A/H → ττ





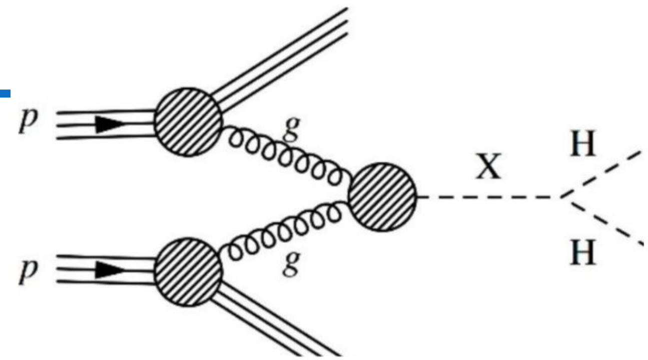
Source	ggF (400 GeV)	ggF (1 TeV)	bbH (400 GeV)	bbH (1 TeV)
Tau id. efficiency	0.14	0.16	0.12	0.08
Tau energy scale	0.33	0.09	0.22	0.03
Z+jets bkg. modeling	0.27	0.19	0.08	0.04
Mis-id. $\tau_{\text{had-vis}}$ bkg.	0.22	0.01	0.14	0.03
Others	0.09	0.04	0.11	0.02
Total	0.54	0.28	0.45	0.13

hh production

Can be done non-resonant (self coupling) or resonant

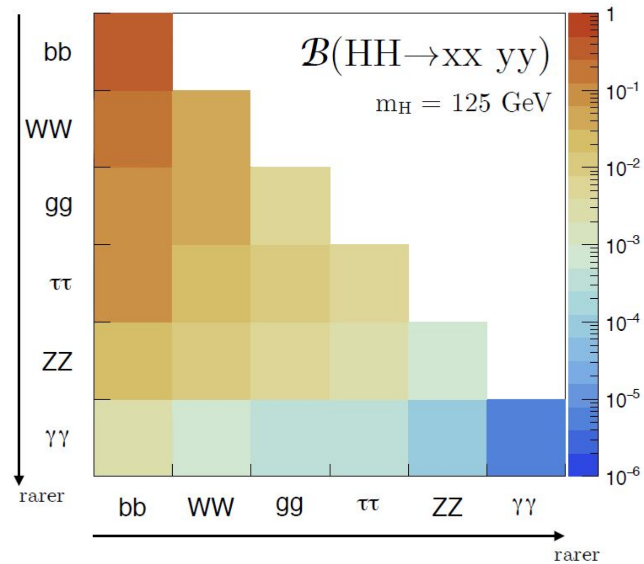
- The latter more relevant in these models

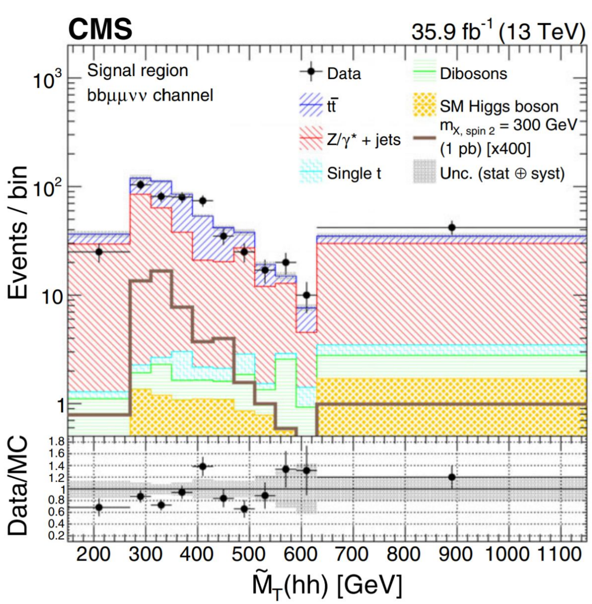
Strong compromise between statistics and purity

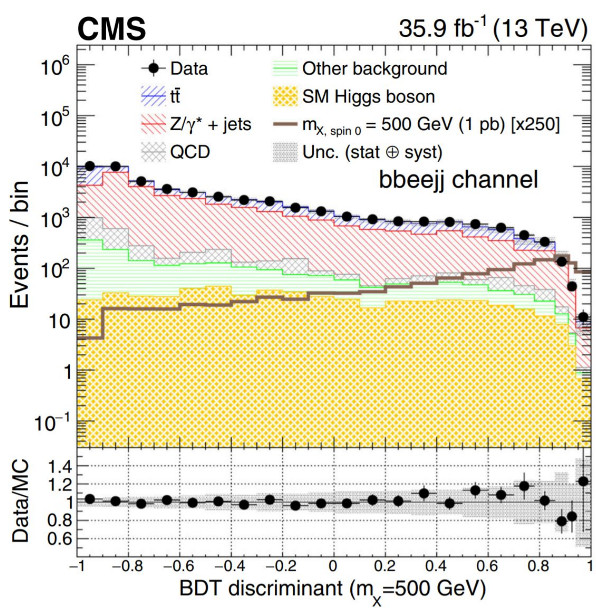


A case study: **hh → bbZZ** at CMS

- Z(ll) + Z($\nu\nu$/jj)
- Fit (pseudo)transverse mass in neutrino channel and BDT output in hadronic

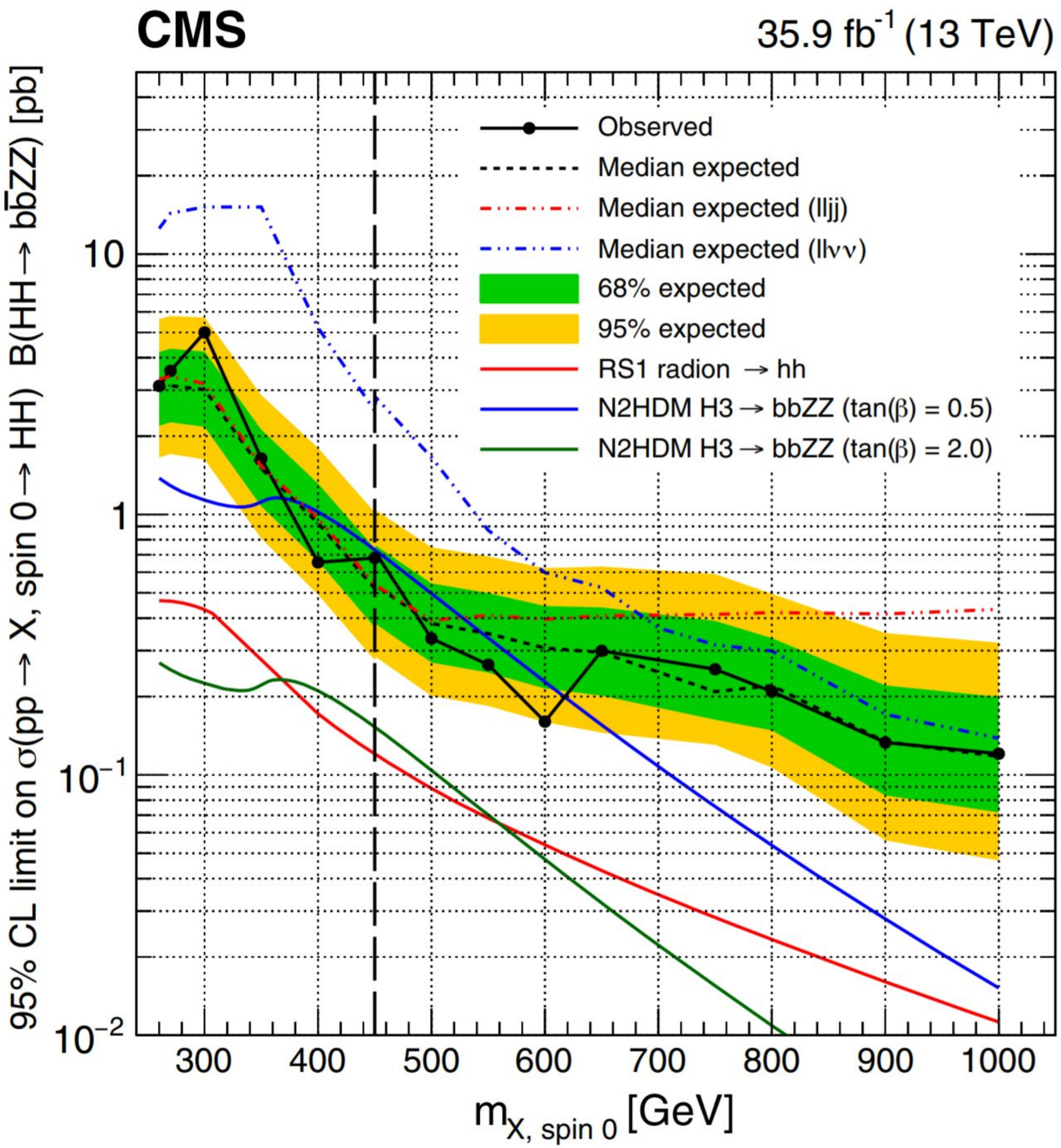






Phys. Rev. D 102 (2020) 032003

hh → bbZZ results

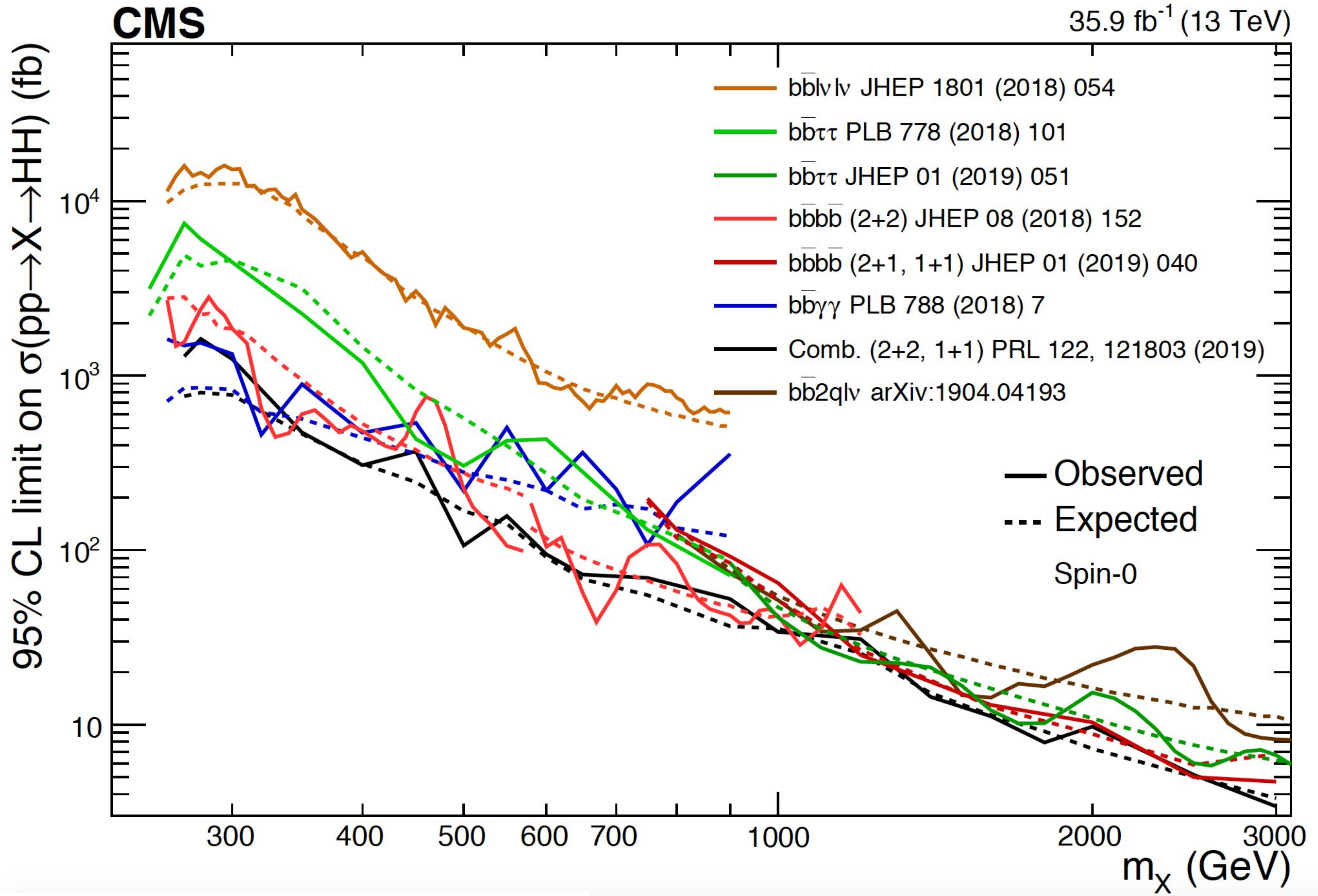


For tan□ = 0.5 exclude H → hh in 360-620 GeV range

Discontinuity at 450 because of different BDT setup for “high” mass

Also reinterpreted for spin-2 resonance for graviton searches

Intermezzo: hh combinations



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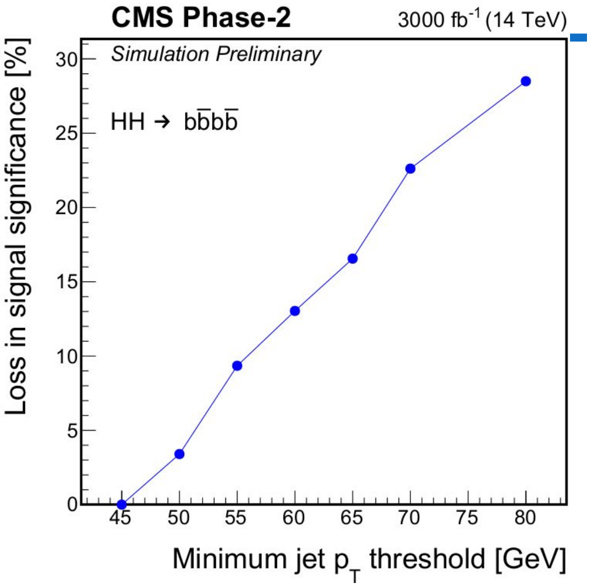
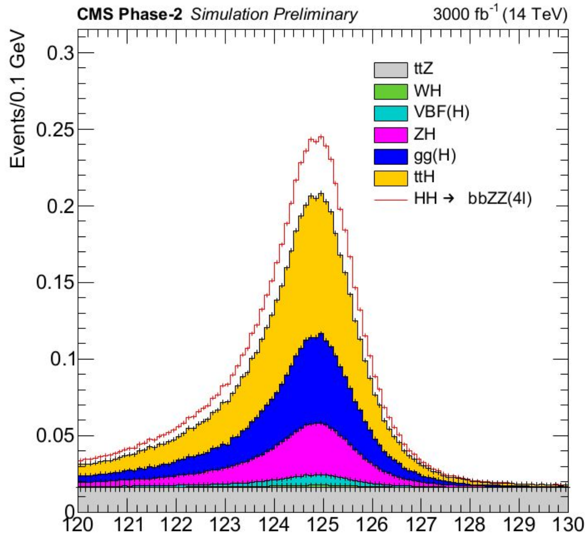
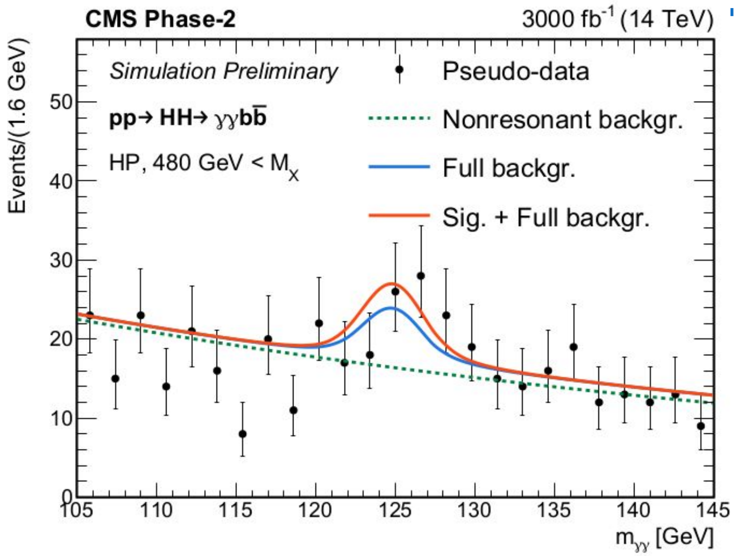
hh at HL-LHC

CMS-FTR-18-019



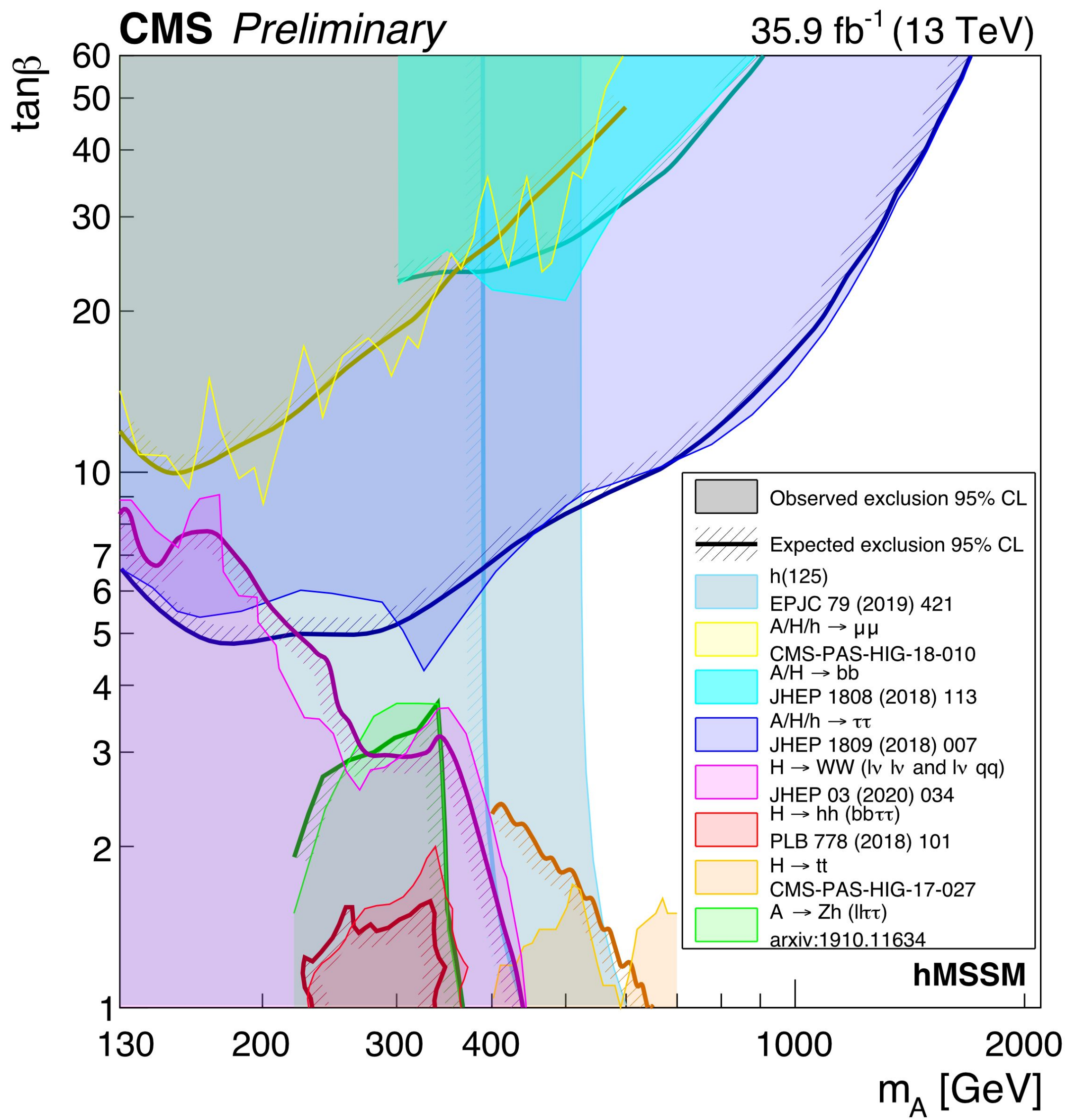




Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bb$\tau\tau$	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bb$\gamma\gamma$	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

Combination shows LHC won't provide a complete picture on di-Higgs physics

Combining into hMSSM

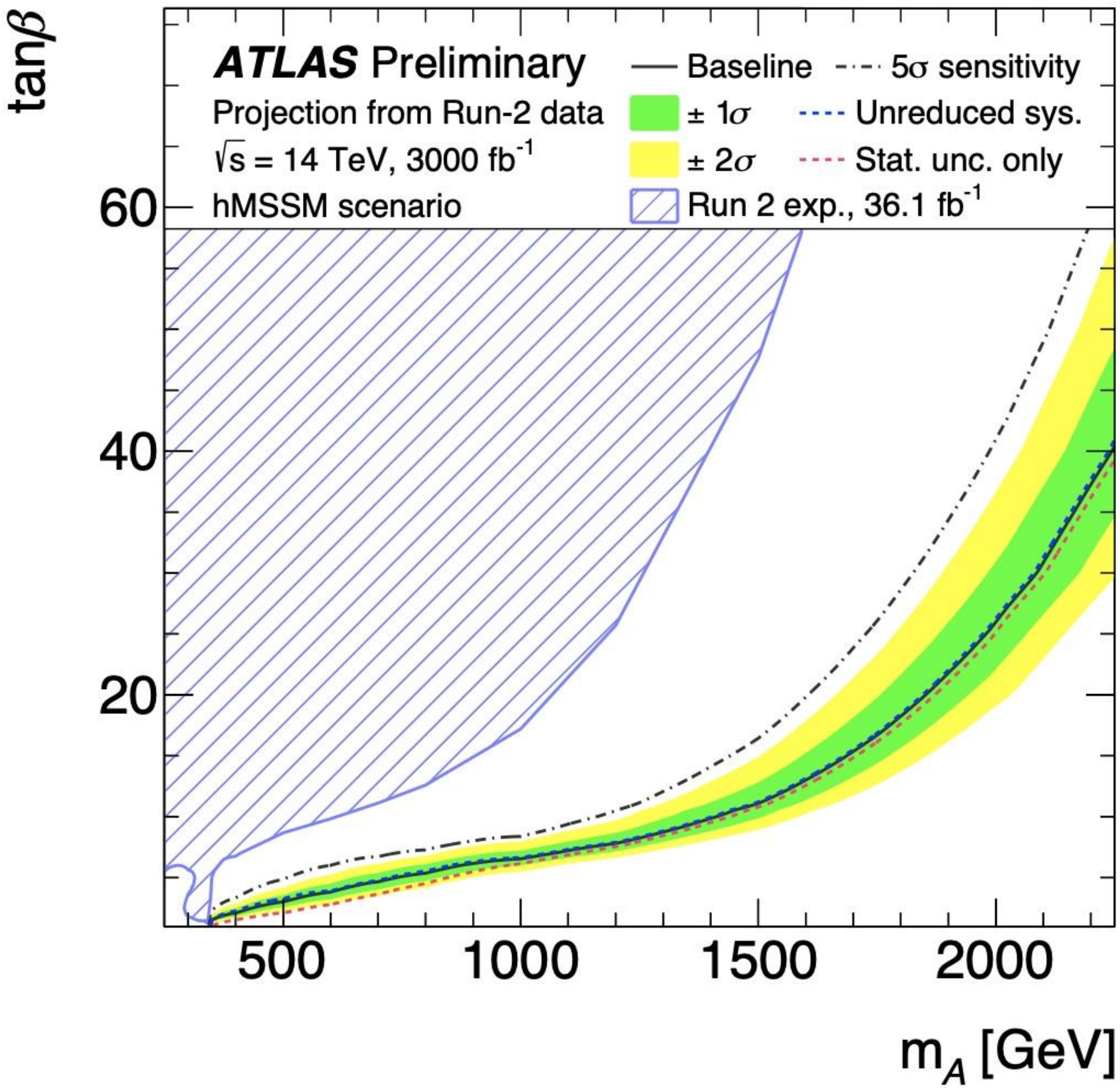


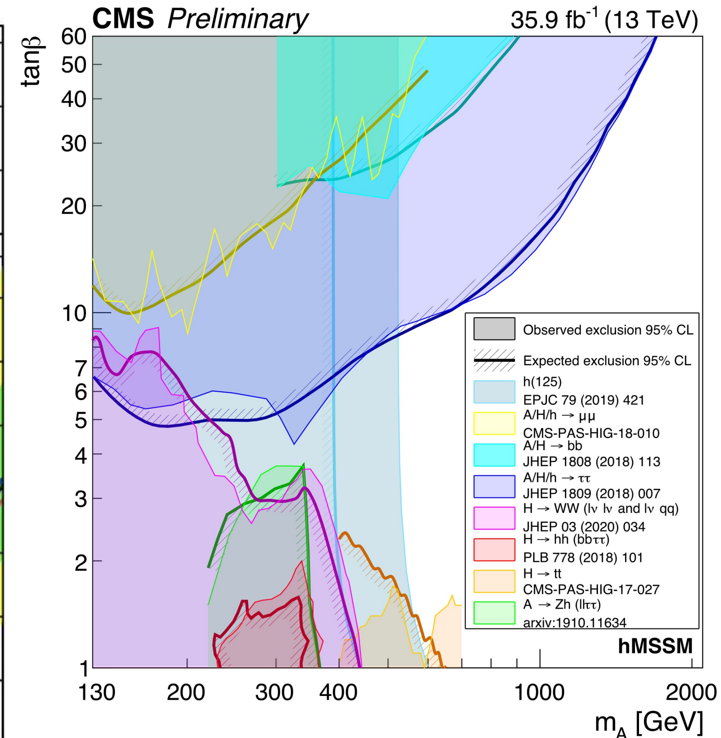
hMSSM:

- h_{125} interpreted as lower mass Higgs boson
- CP conserving Higgs sector
- Superpartners too heavy to contribute to production and decay

Strong limit provided by constraints from h_{125}

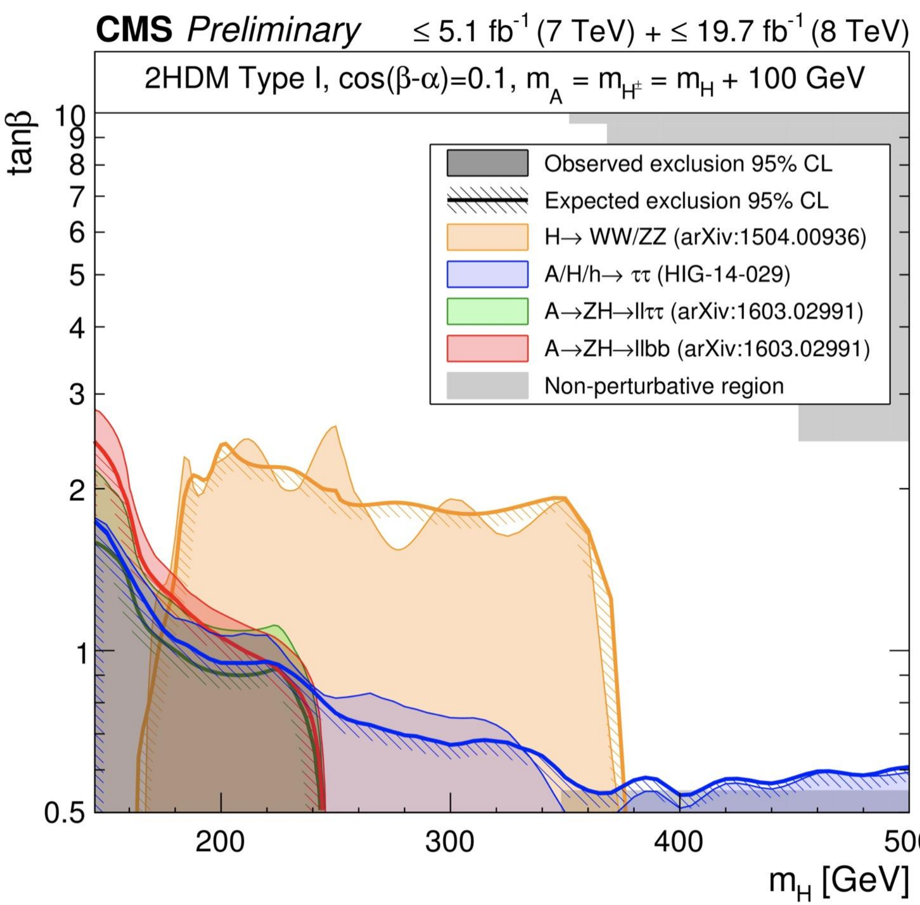
H/A→ττ at HL-LHC

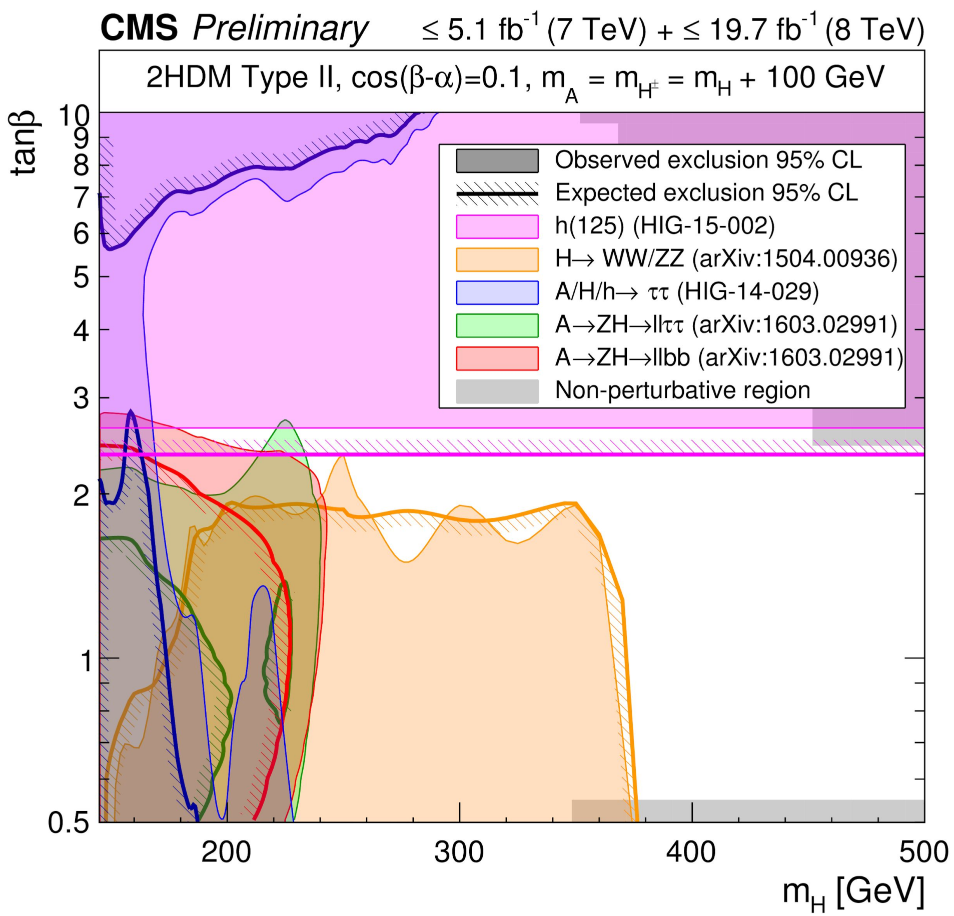




Good complementarity with H->tt and h_{125} measurements, some analyses like H ->WW and hh become less competitive in this particular scenario

General 2HDM combination





Sensitivity strongly dependent on the choice parameters (and solution to ambiguities)

Still missing a full update to RunII of a generic 2HDM interpretation

LHC HXSWG: Yellow Report 4

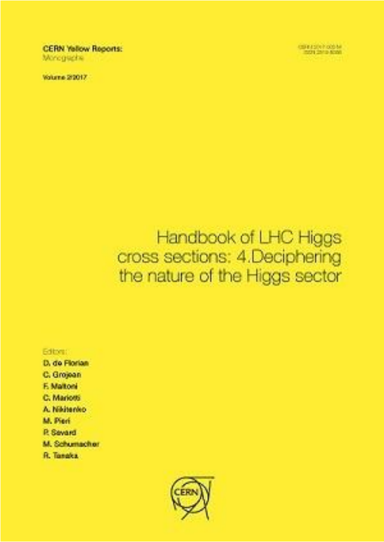
Collaboration of theory/experiments to produce common guidelines for techniques and interpretation of results

Benchmark scenarios:

→Large fraction dedicated to definition of topologies and parameter space for future searches

→ Define ~ 10 scenarios for analyses possible at LHC

→ A "wishlist" of what theory wants and experiments can do



https://cds.cern.ch/record/2227475

2HDM + S

Common extension (see for example NMSSM)

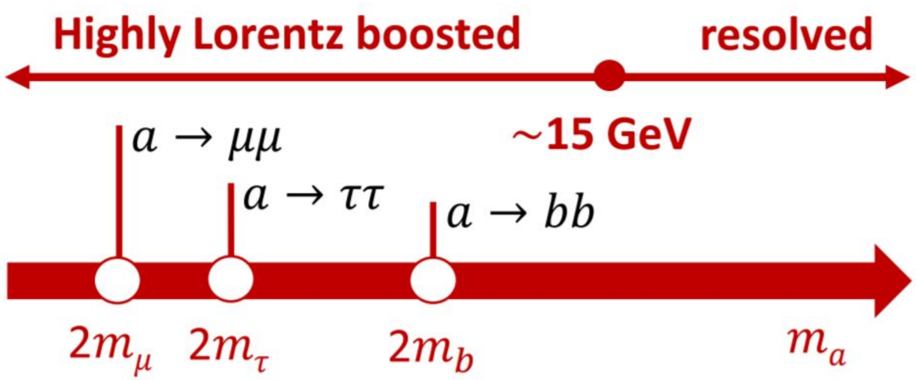
Helps solving the “μ-problem”

Add one singlet (2 d.o.f.)

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} \quad \phi' = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_5 + i\phi_6 \\ \phi_7 + i\phi_8\end{pmatrix} \quad +\phi_S$$

Typically searched in a “lower” mass boson in μμ/ττ/bb

- Of particular interest in **h** $\longrightarrow$ **aa** decays



$h/H \rightarrow aa \rightarrow \mu\mu\tau\tau$

Search for collimated dilepton pairs

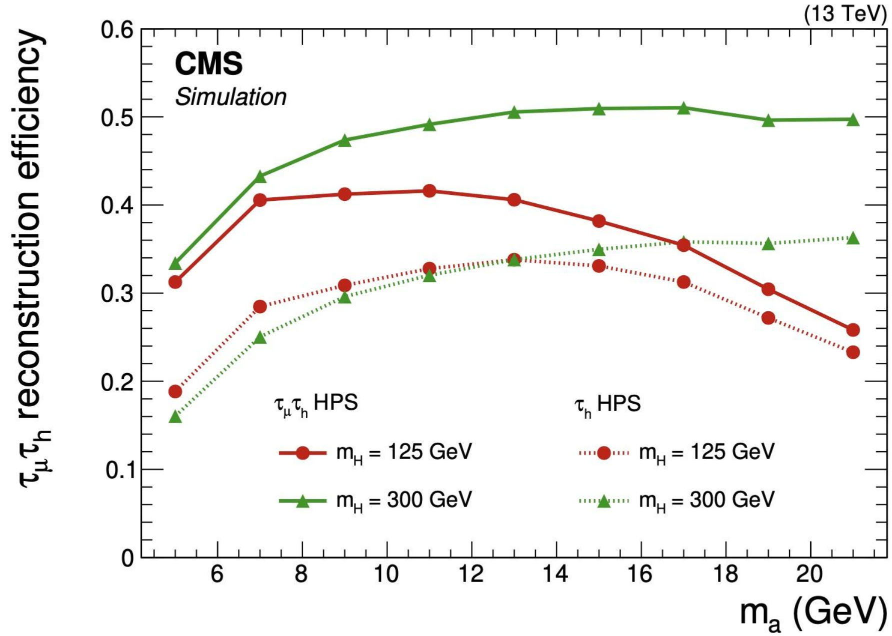
$3.6 < m_a < 21$ GeV

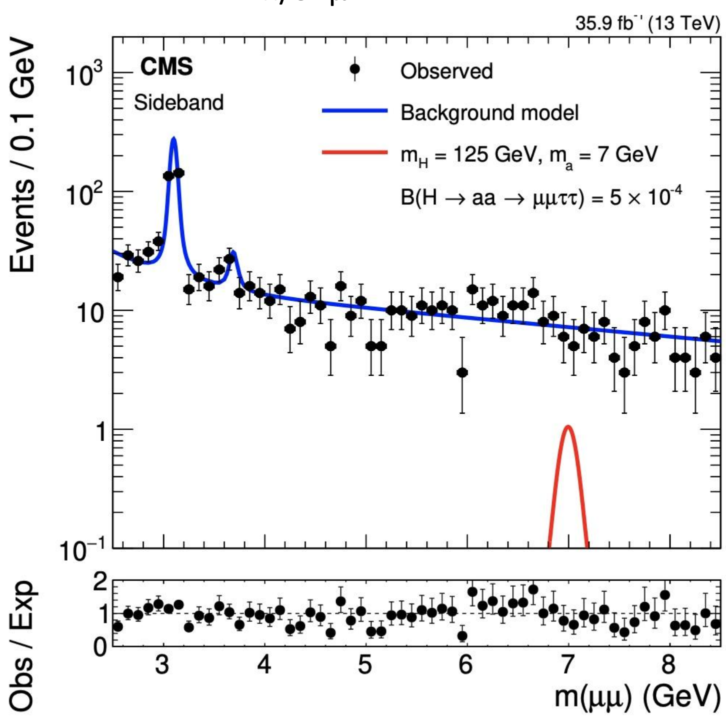
Require isolated μ trigger with $p_T > 24$ GeV

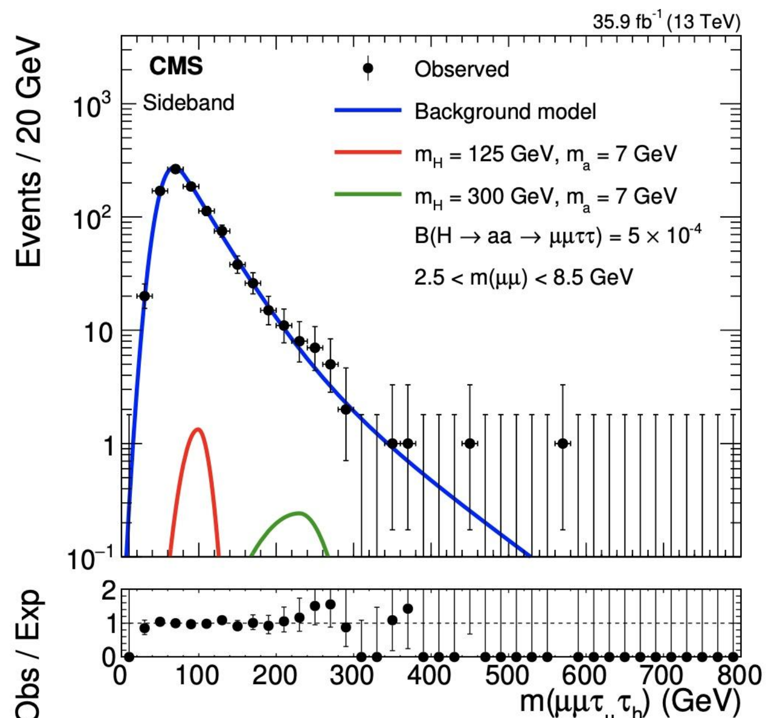
Custom τ-pair algo for collimated objects

→ allow for a non-isolated μ in one τ decay

Final state is $\mu\mu\tau_{h/e}\tau_\mu$







h/H → aa → μμττ

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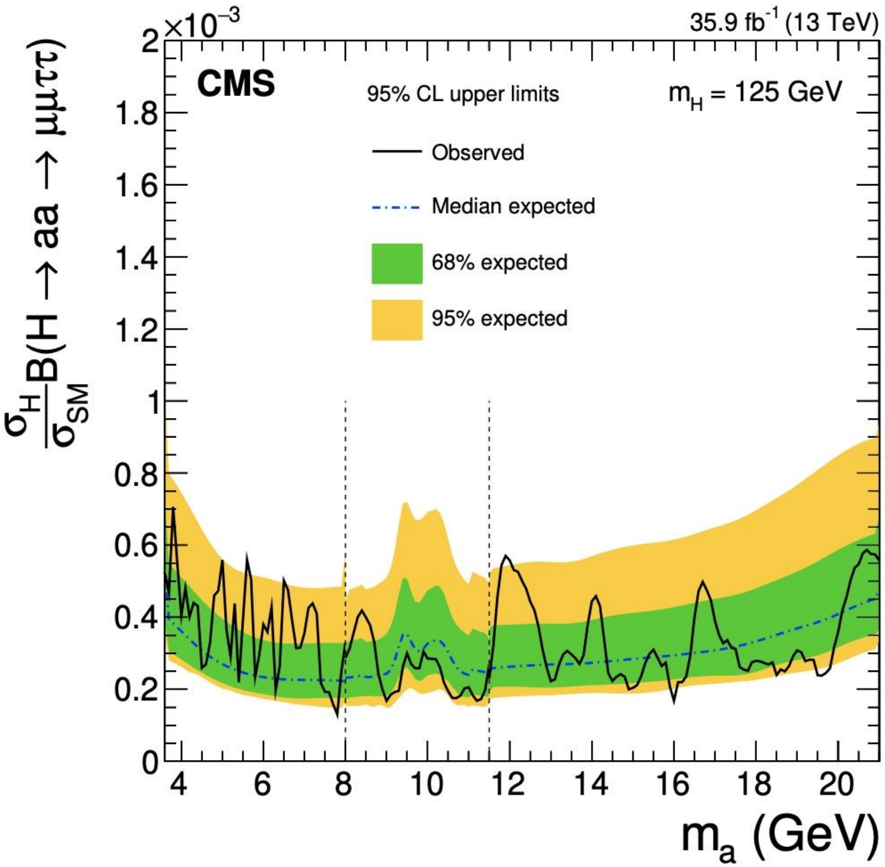
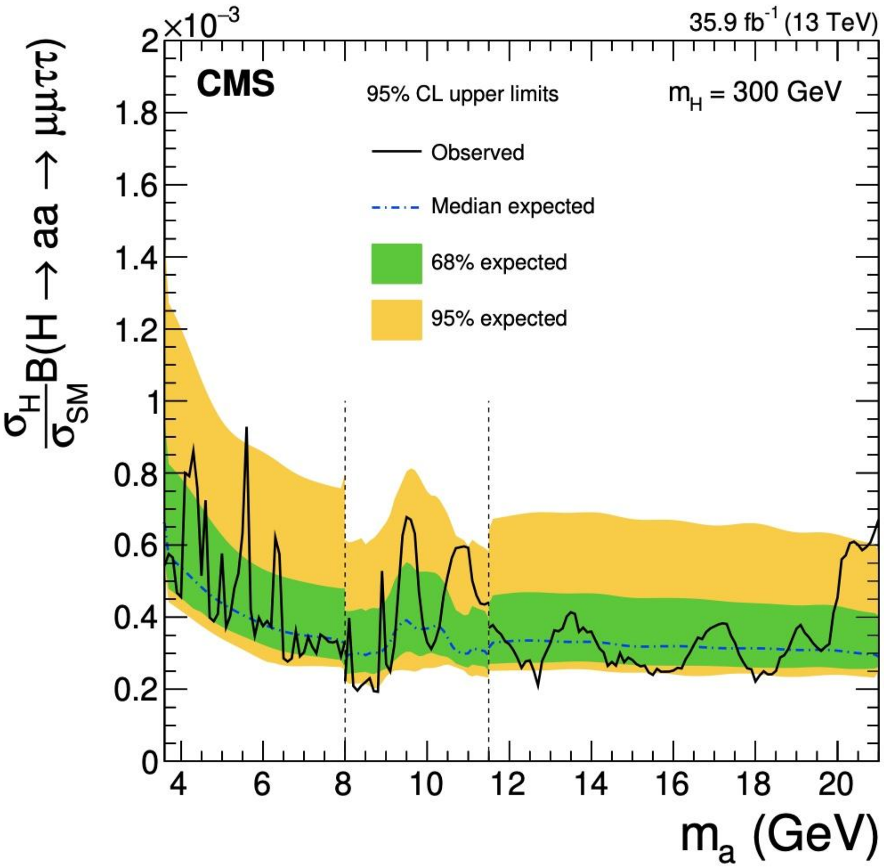
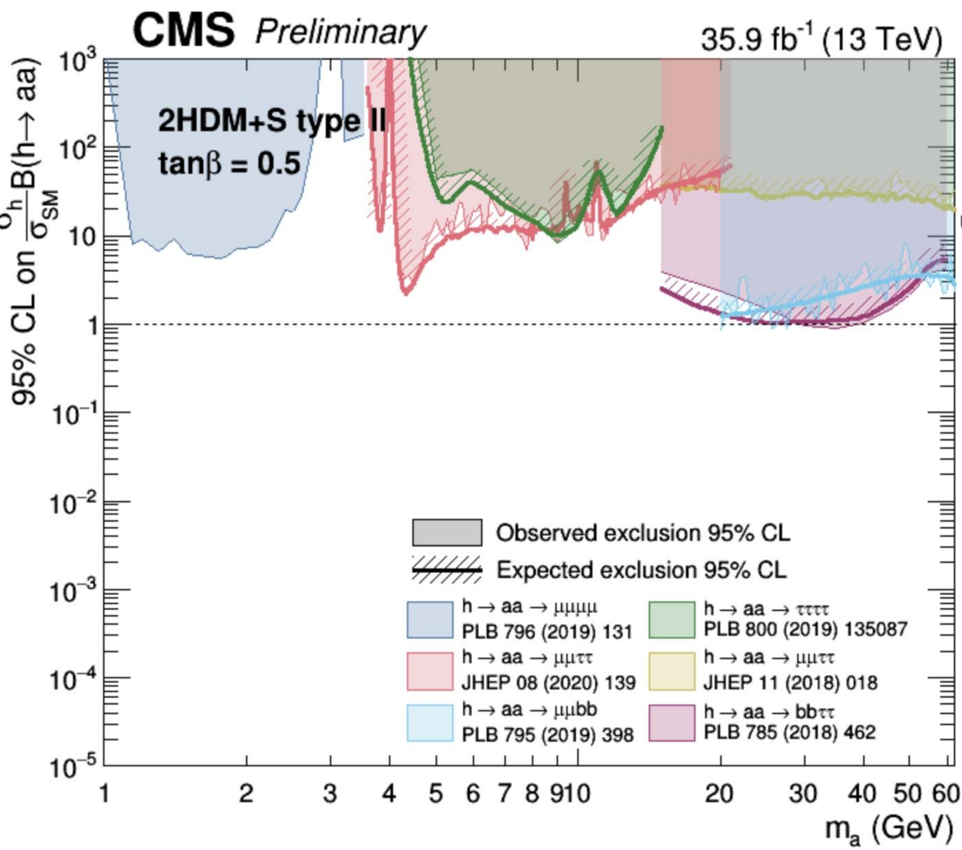
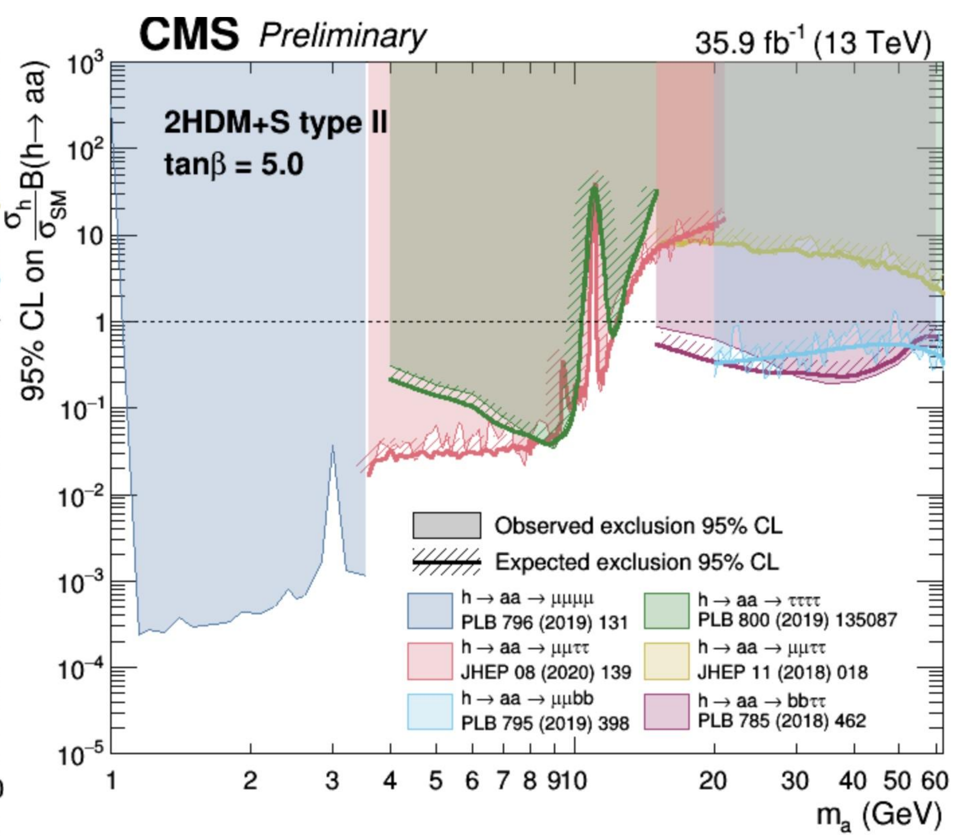




2HDM+S h⟶ aa combination





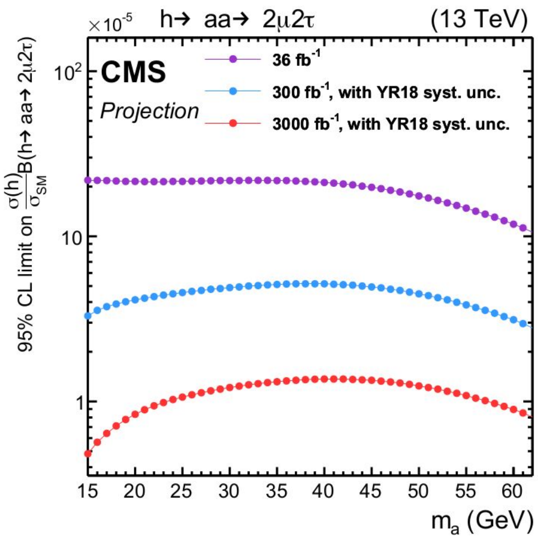
Strong dependence on tan□ and sign choice for couplings
All topologies necessary to fully investigate the spectrum
Most are statistically limited

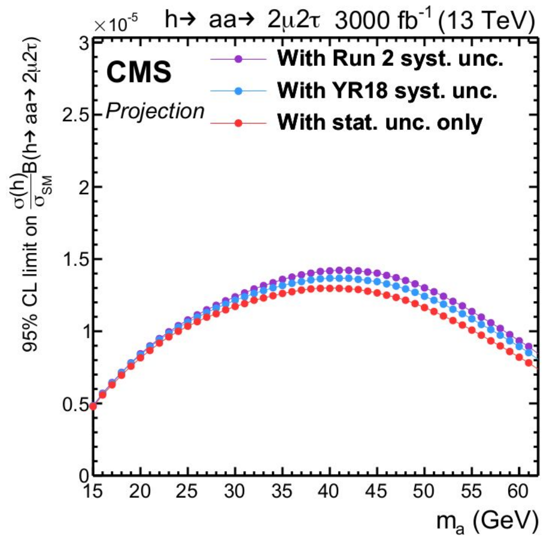
2HDM+S at HL-LHC

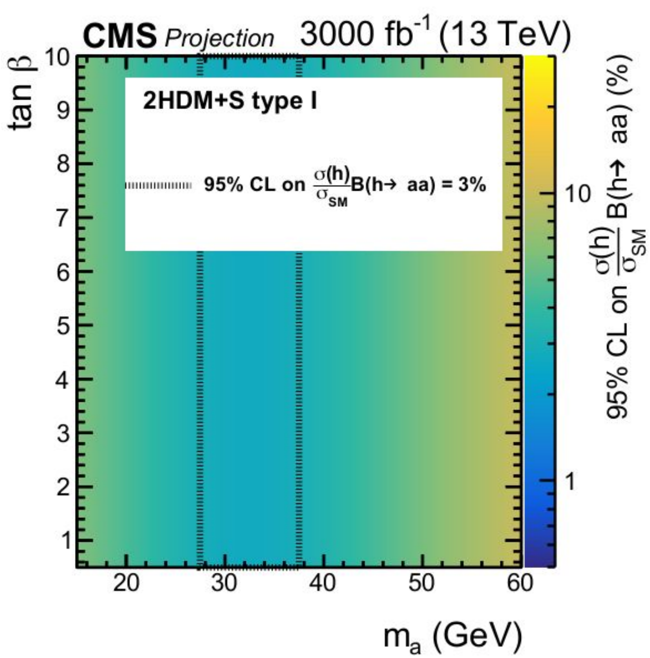
CMS-FTR-18-035

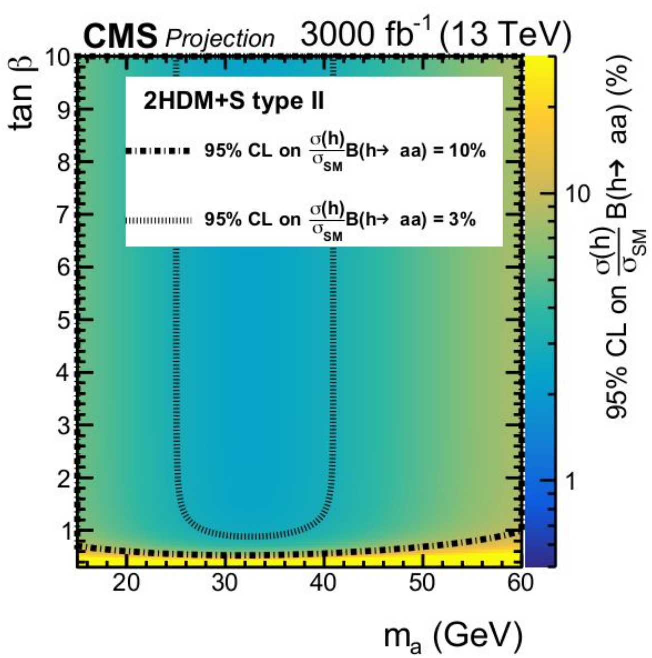
Projections for h⟶ aa⟶ 2μ2τ and 2b2τ channels

Analyses are completely statistically limited









BR limits will mostly get to < 10%

Difficult to be competitive at future (lepton) colliders

Higgs triplets

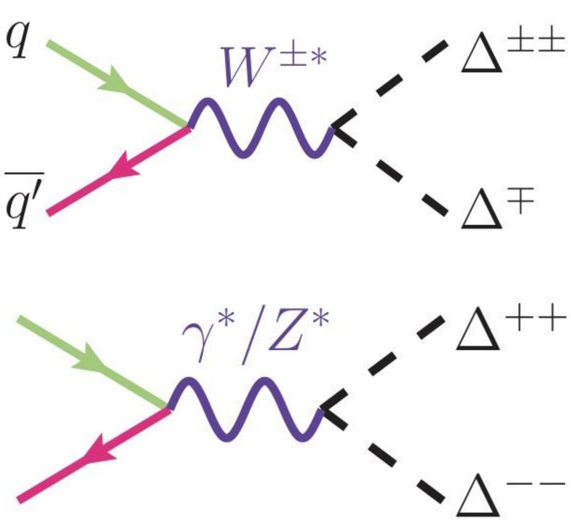
Higgs sector organized in triplets: a nice way to provide neutrino masses via type-II seesaw mechanism

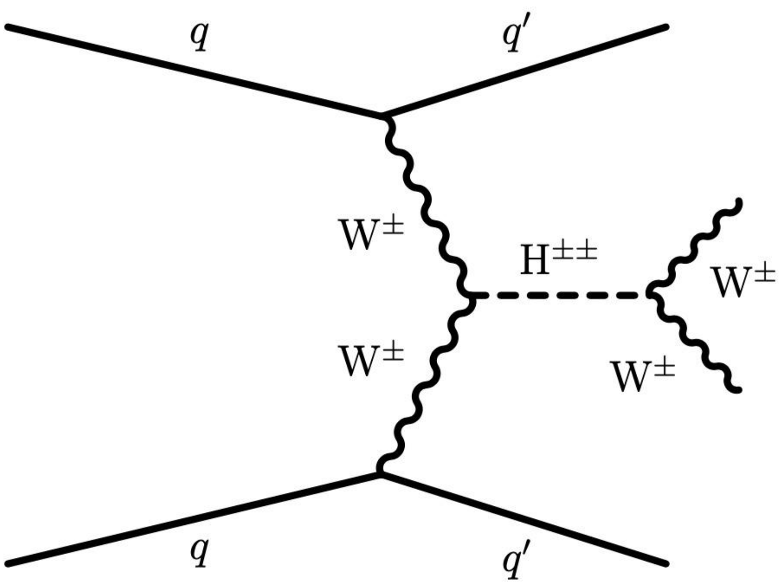
→ Generic forms suffer for large radiative corrections

Georgi-Machacec: two triplets, one real and one complex

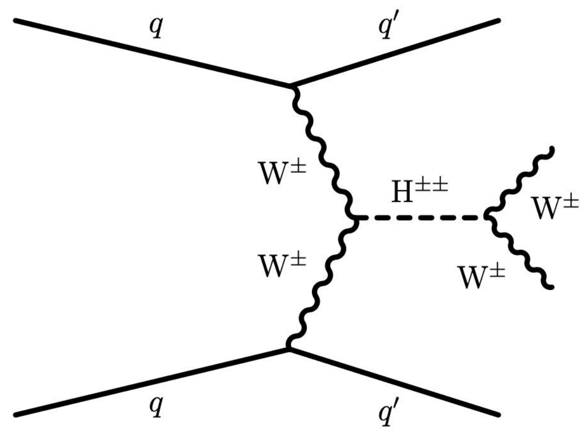
corrections preserved via custodial symmetry

Generates two scalars, $H_{1,2}^{+}$, H^{++}





$H^{+(+)} \rightarrow$ vector bosons



VBF $H^{+} \rightarrow W^{+}Z$ and $H^{++} \rightarrow W^{+}W^{+}$ in leptonic decays

Mass degeneracy

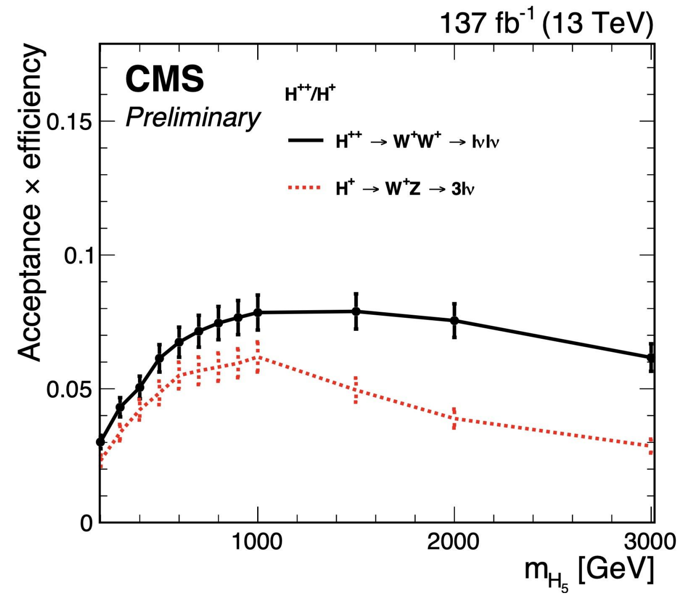
$\rightarrow$ simultaneous search in $200 < m_{H5} < 2000$ GeV range

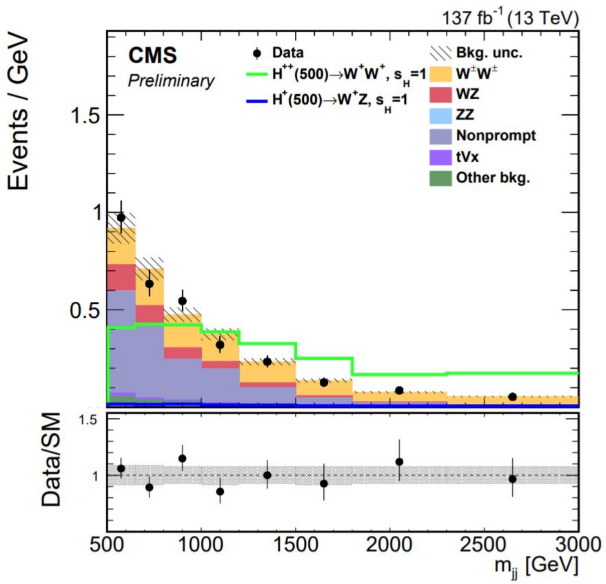
tt, tZq and ZZ backgrounds estimated from data

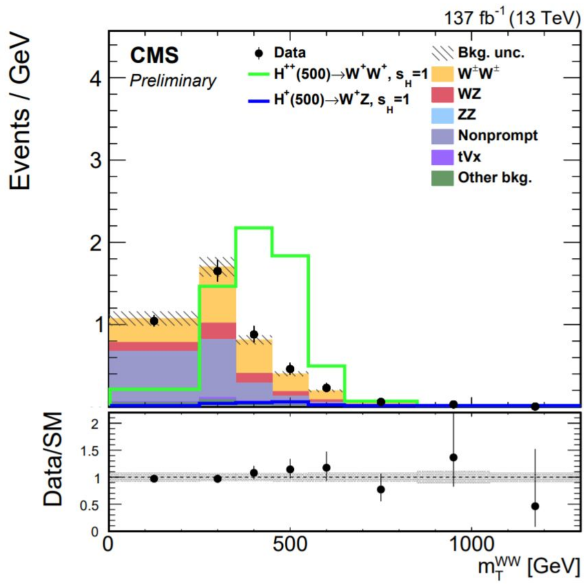
inverting b-tag and same-sign selections

Fit m_{jj}, m_T^{VV}

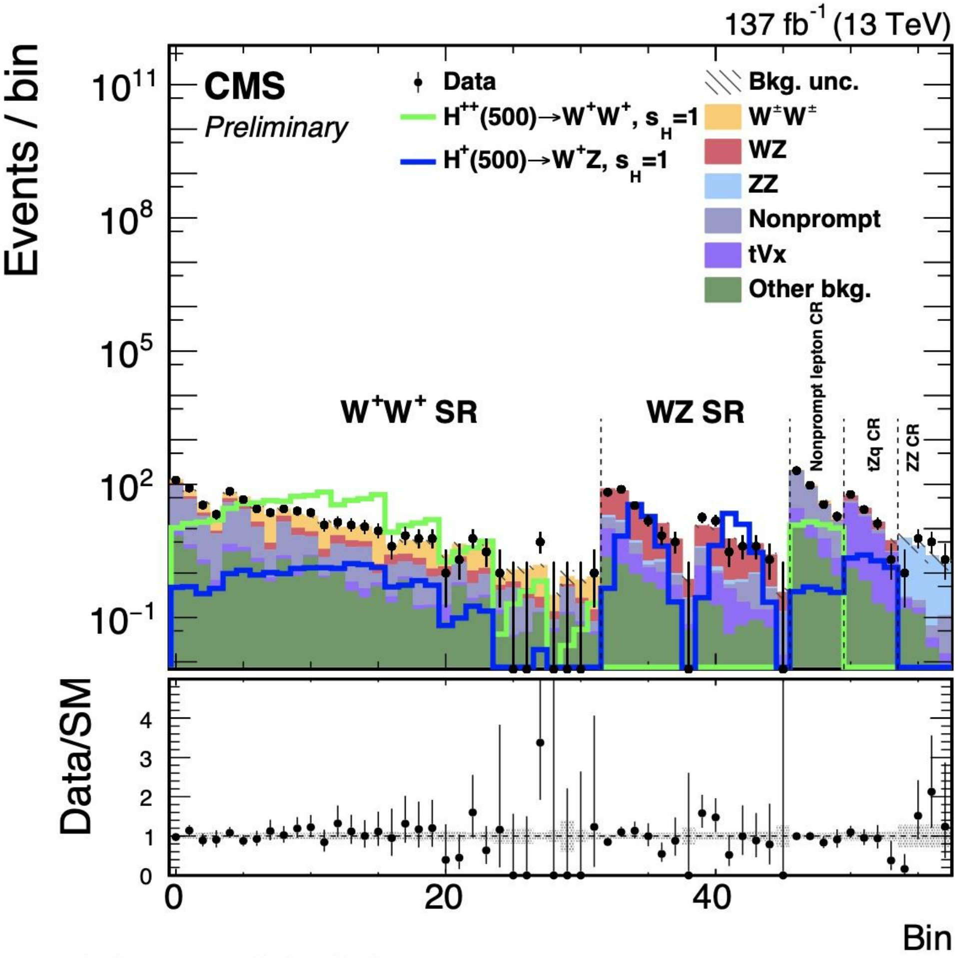
$$m_{\mathrm{T}}^{\mathrm{VV}} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$$





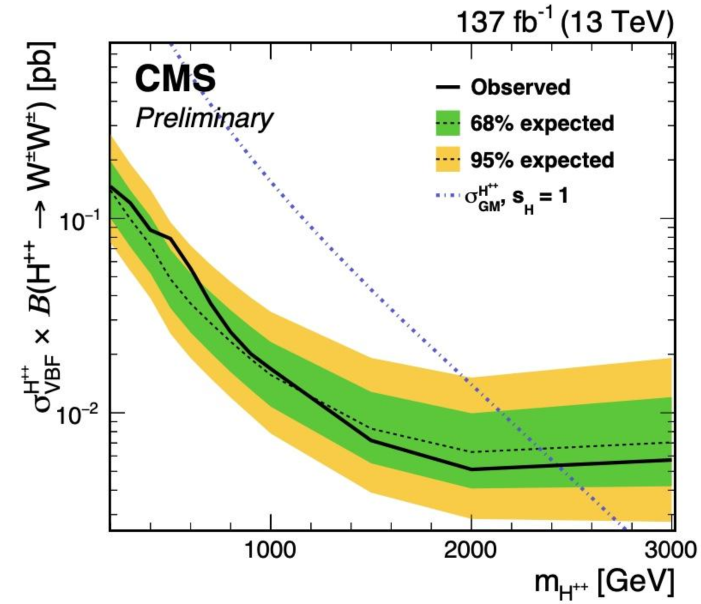


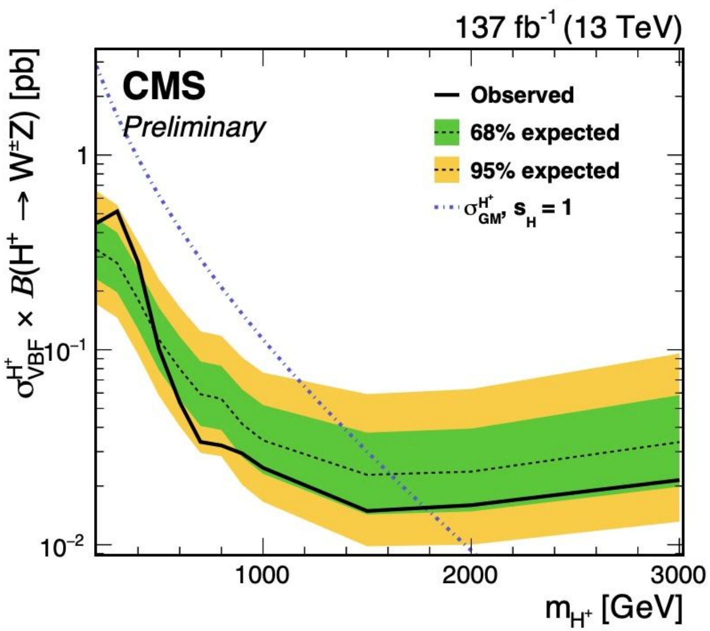
$H^{+(+)} \longrightarrow$ vector bosons

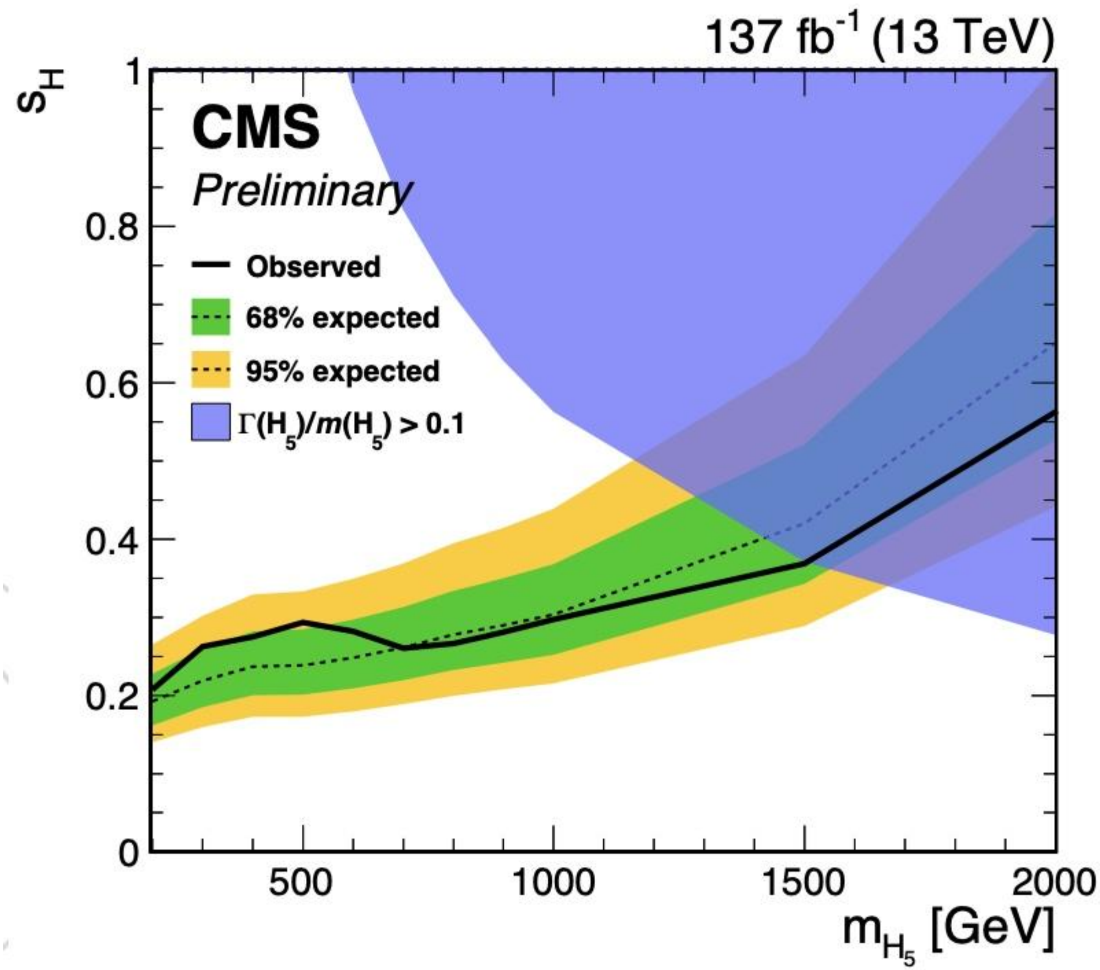


Source of uncertainty	$\Delta\mu$ background-only
Integrated luminosity	0.002
Lepton measurement	0.003
JES and JER	0.003
Pileup	0.001
b tagging	0.001
Trigger	0.001
Limited sample size	0.005
Nonprompt rate	0.002
$W^\pm W^\pm$/WZ rate	0.014
Other prompt background rate	0.002
Signal rate	—
Total systematic uncertainty	0.016
Statistical uncertainty	0.021
Total uncertainty	0.027

$H^{+(+)} \rightarrow$ vector bosons







Exotic decays of h_{125}

LFV in Higgs decays

LFV strongly suppressed in SM

In Higgs decays, mediated by Yukawa couplings $Y_{e\mu}$, $Y_{e\tau}$, $Y_{\mu\tau}$

Scenarios include

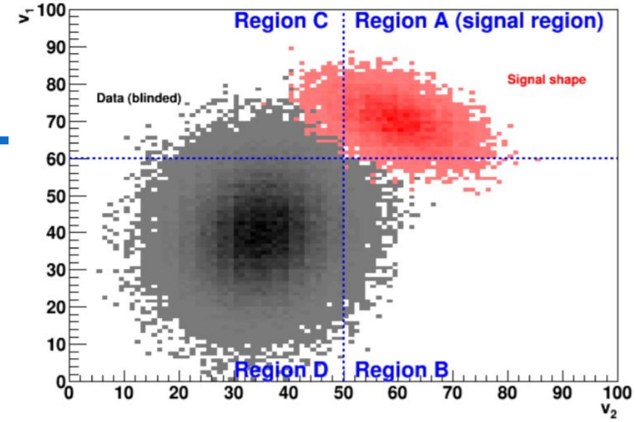
- Higgs multiplets
- SUSY
- composite Higgs
- RS extra dimensions
- ...

$H\longrightarrow \mu e$ strongly constrained by indirect measurements

❖ concentrate on $H\longrightarrow\mu\tau$ and $e\tau$

H → eτ,μτ

CMS-PAS-HIG-20-009



Four final states: $\ell\tau_h$, $\ell\tau_{\ell'}$

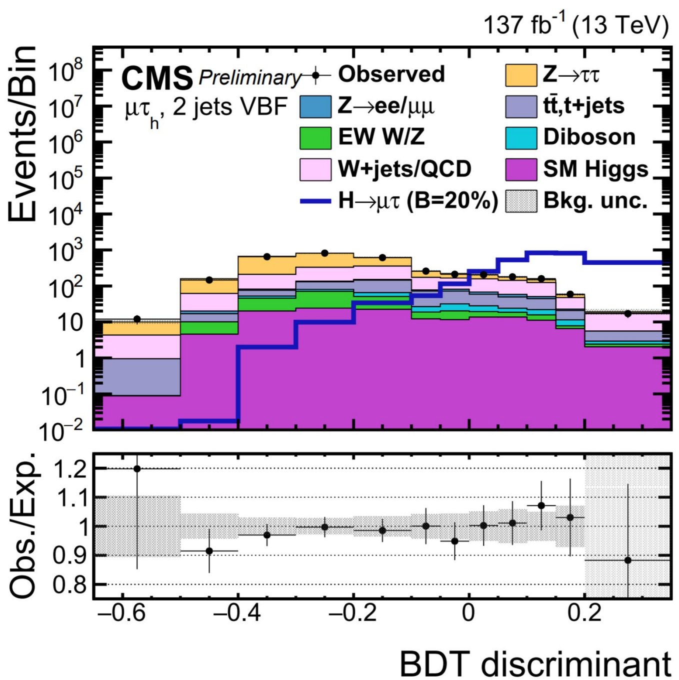
- Limit DY Z->$\ell\ell$ contributions

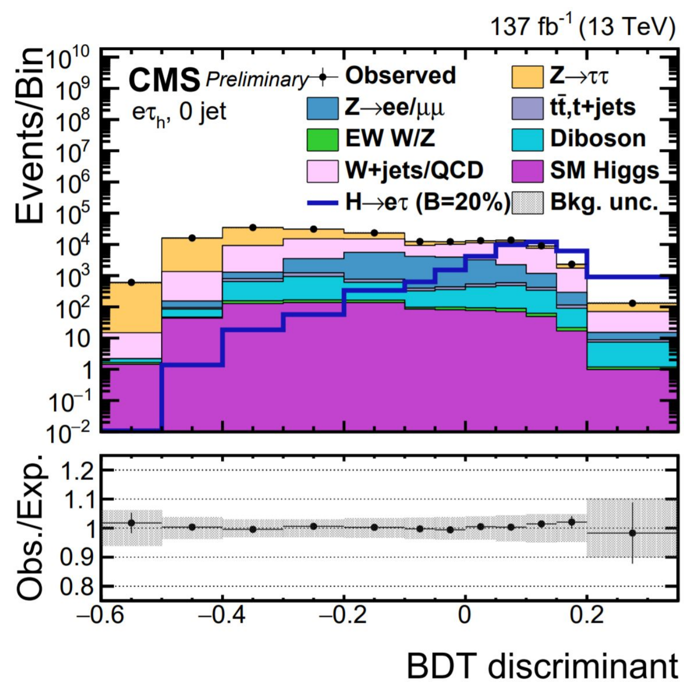
Samples characterized with BDT that is fitted to extract BR

- Binned in number of jets

Backgrounds: Z/H→ττ , Z→$\ell\ell$, H→ WW, mis-ID background

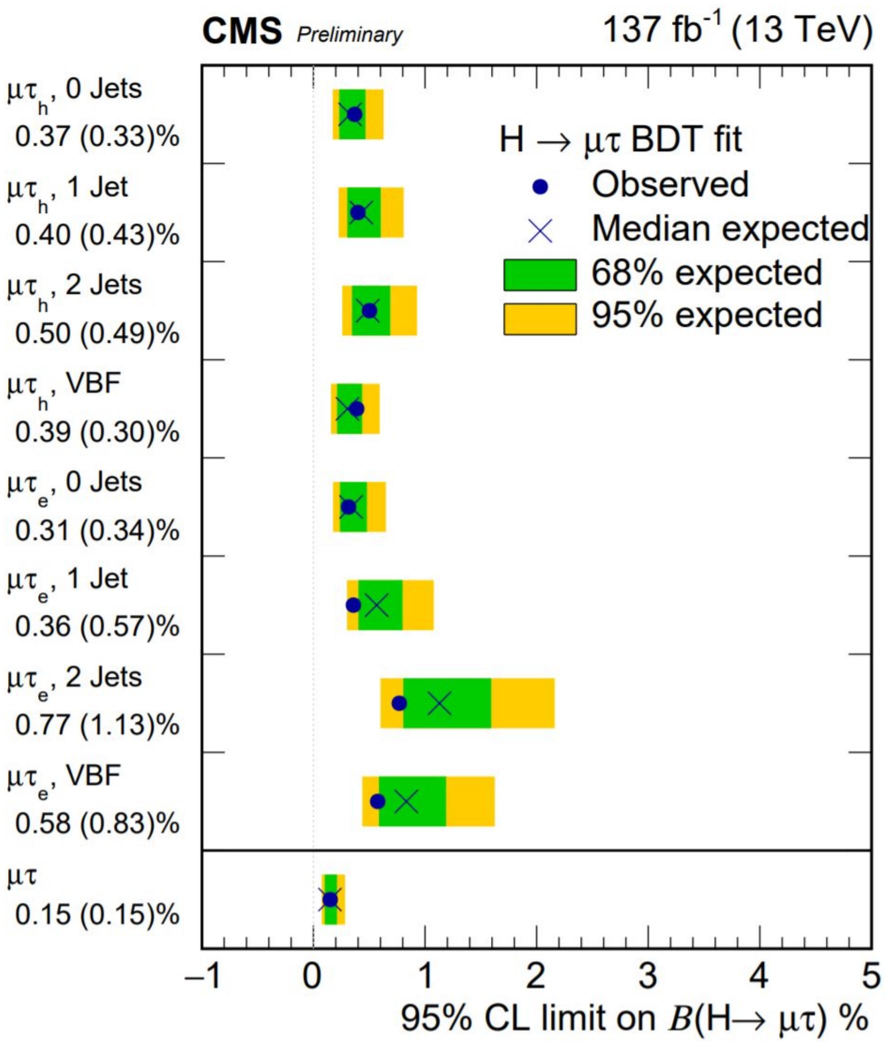
Use of embedded and ABCD methods for background estimate

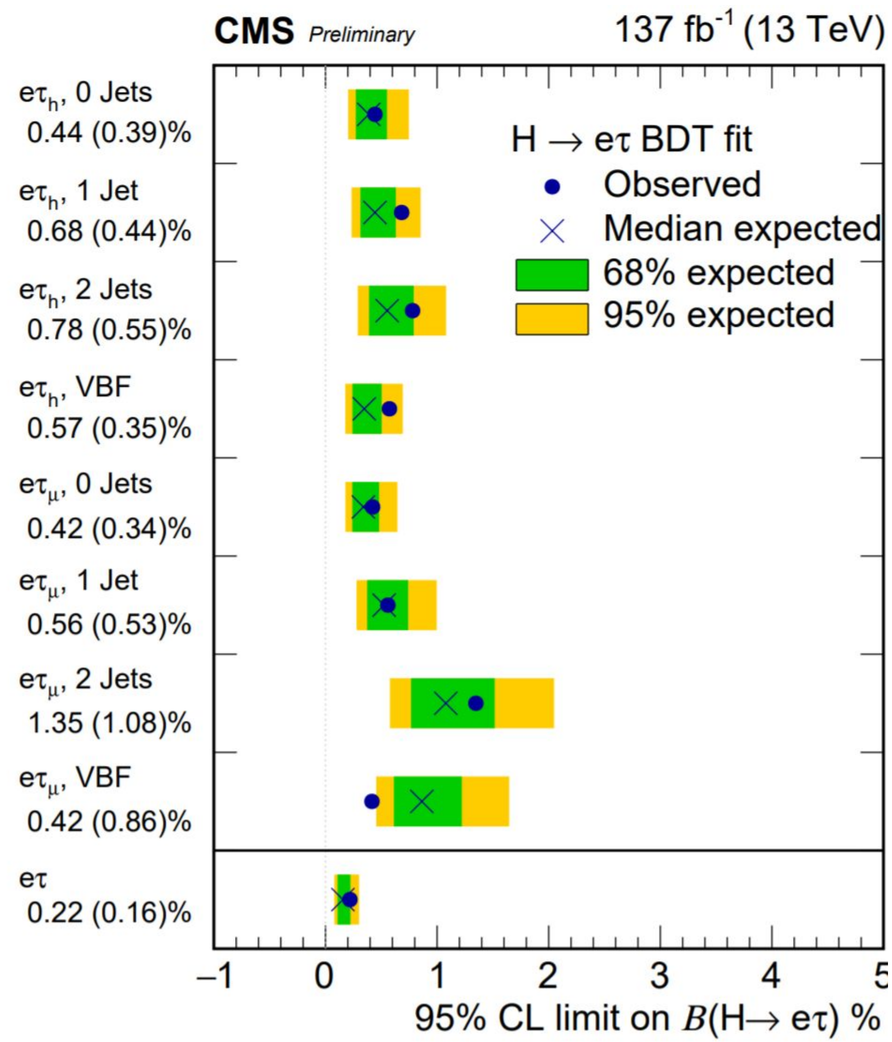




H → eτ,μτ

CMS-PAS-HIG-20-009

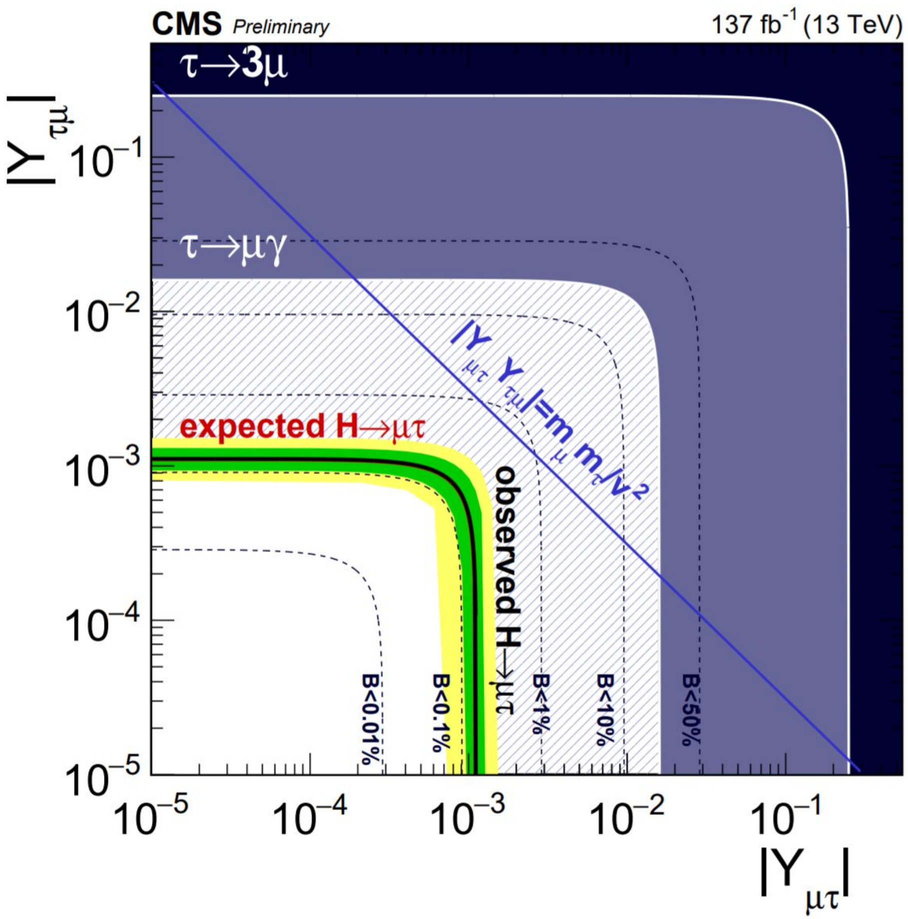


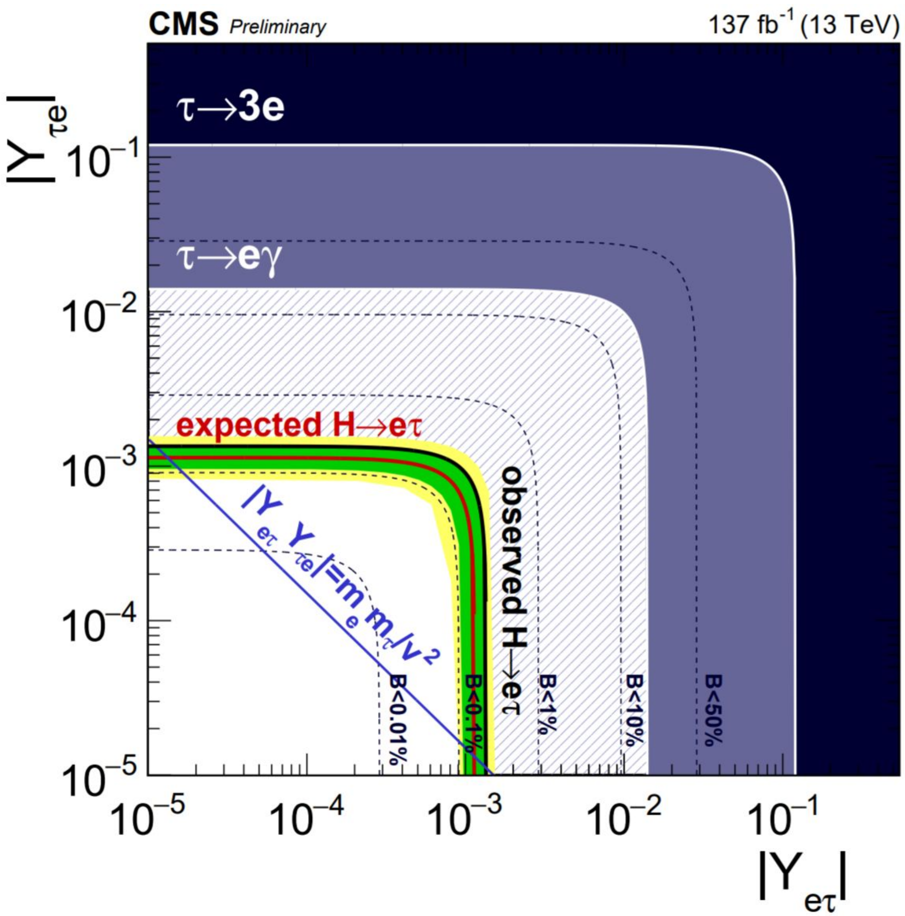


$H \rightarrow e\tau, \mu\tau$

CMS-PAS-HIG-20-009

Derived from $\Gamma(H \rightarrow \ell^\alpha \ell^\beta) = \frac{m_H}{8\pi}(|Y_{\ell^\alpha \ell^\beta}|^2 + |Y_{\ell^\beta \ell^\alpha}|^2)$





H⟶ invisible

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Search for missing energy associated with H production

- VBF, ZH, WH signatures

Analysis	$\sqrt{s}$	Int. luminosity	Observed	Expected
Run 2 VBF	13 TeV	36.1 fb^{-1}	0.37	$0.28^{+0.11}_{-0.08}$
Run 2 $Z(\text{lep})H$	13 TeV	36.1 fb^{-1}	0.67	$0.39^{+0.17}_{-0.11}$
Run 2 $V(\text{had})H$	13 TeV	36.1 fb^{-1}	0.83	$0.58^{+0.23}_{-0.16}$
Run 2 Comb.	13 TeV	36.1 fb^{-1}	0.38	$0.21^{+0.08}_{-0.06}$
Run 1 Comb.	7,8 TeV	4.7, 20.3 fb^{-1}	0.25	$0.27^{+0.10}_{-0.08}$
Run 1 + 2 Comb.	7,8,13 TeV	4.7, 20.3, 36.1 fb^{-1}	0.26	$0.17^{+0.07}_{-0.05}$

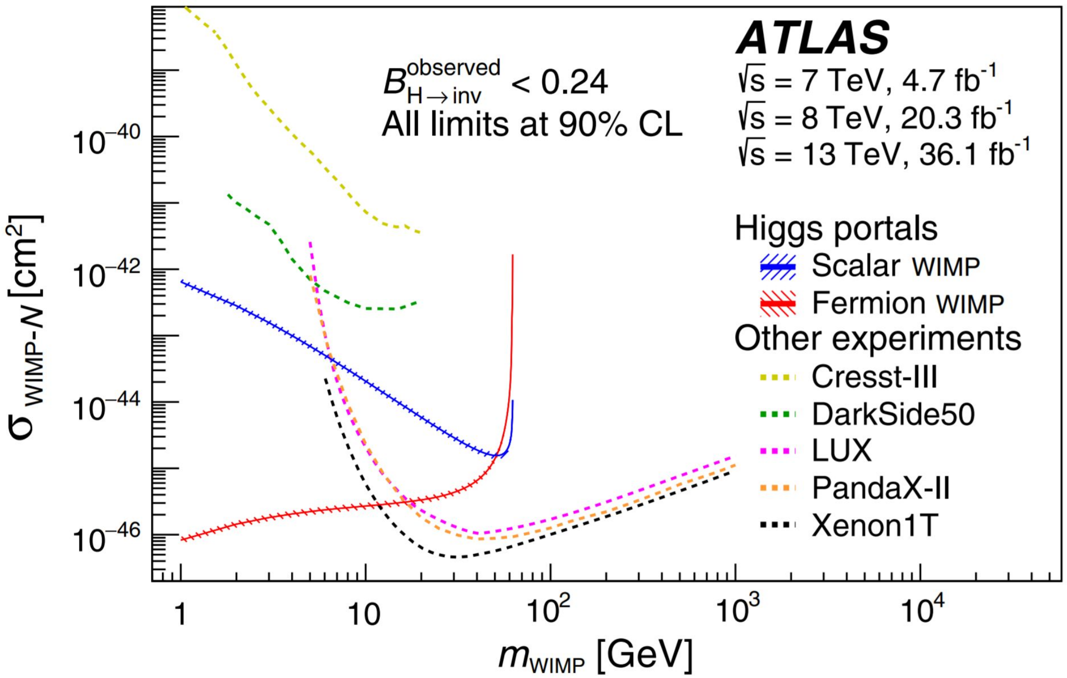
Interpret in the context of Higgs portal models

Translate limit into DM-N cross section in EFT

Very competitive and complementary search

…. but many assumptions on this plot!

Unfortunately, systematics will limit future prospects of these measurements



$H \rightarrow$ invisible at HL-LHC

CMS-FTR-18-016

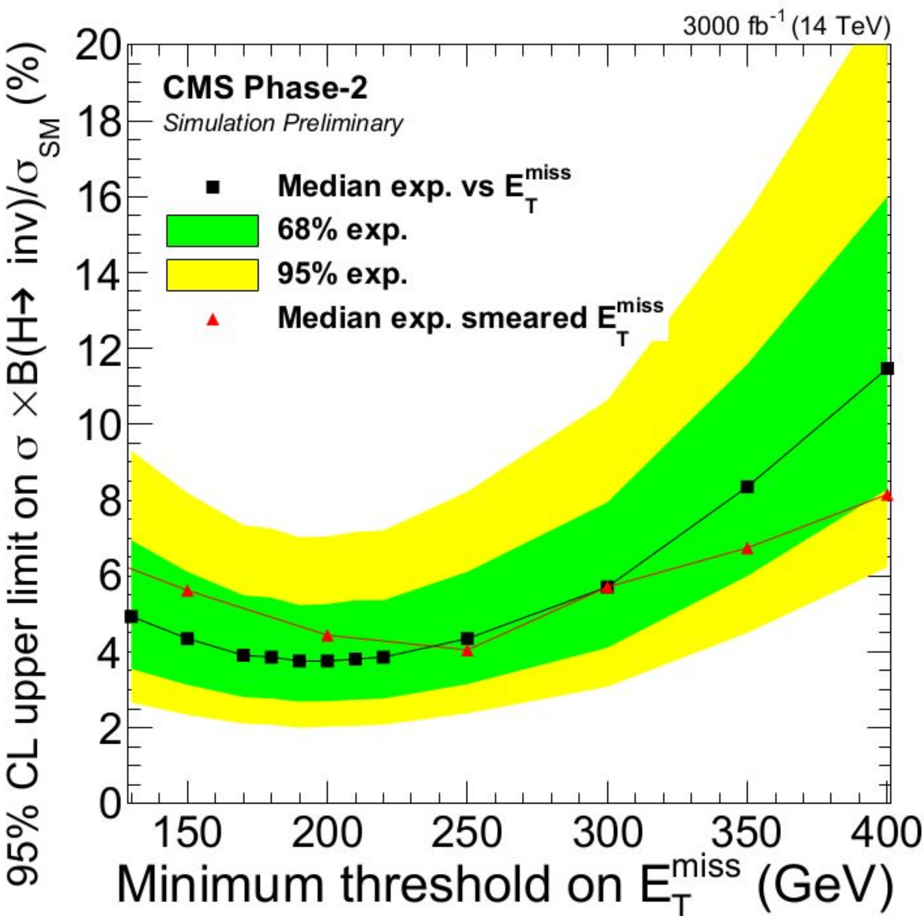
- Projections to 3 ab^{-1} show search limited by systematic uncertainties
- Not the biggest surprise: tough analysis in pp environment, with great experimental challenges

Interesting exercise:

- Test scenario with missing mass resolution worse by factor 2
    - Case of *extreme* PU conditions

Conclusion:

- Analysis is flexible enough to yield similar limits with selection re-optimization



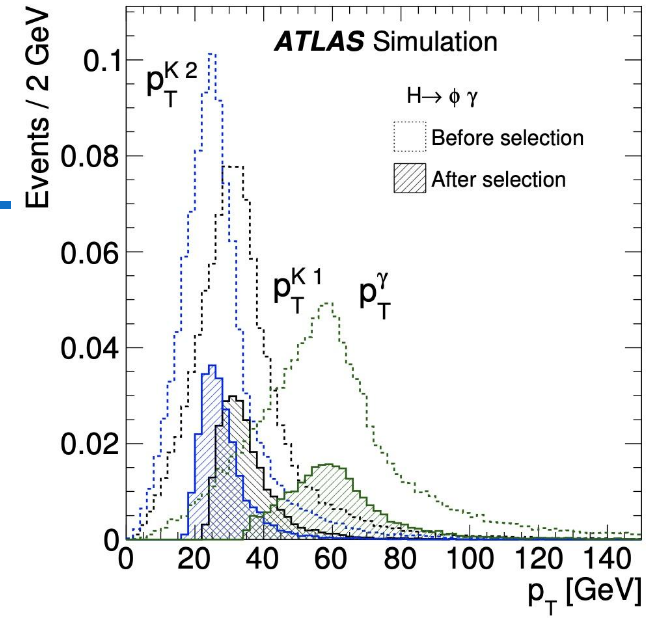
$H \rightarrow \phi/\rho + \gamma$

Coupling to first and second generations (and up-type quarks) for Higgs multiplets test

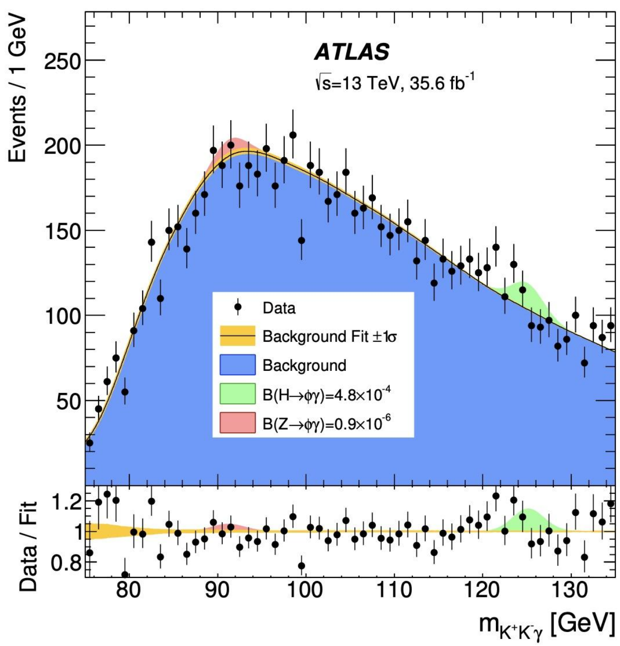
- Greatly suppressed in SM

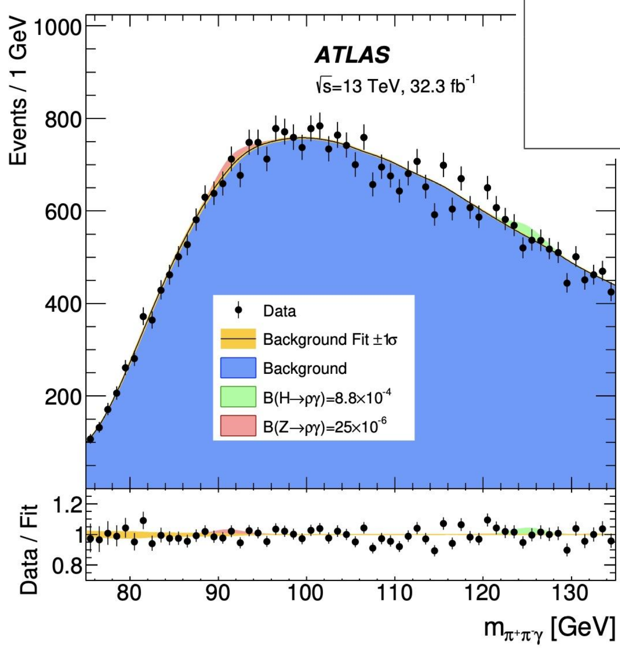
Experimental difficulty in trigger at LHC

- ATLAS: use photon + modified τ trigger



Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \rightarrow \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \rightarrow \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \rightarrow \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \rightarrow \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25





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Considerations on future colliders

- Studies emerging to provide more complete view on Higgs perspectives in future colliders
- Fundamental step into decision making process for next generation accelerators
- Many scenarios, difficult to summarize all considerations, but...

Expected relative precision

kappa-0	HL-LHC	LHeC	HE-LHC	ILC_{250}	ILC_{500}	CLIC_{380}	CLIC_{1500}	CLIC_{3000}	CEPC	FCC-ee_{240}	FCC-ee_{365}	FCC-ee/eh/hh
κ_W (%)	1.9	0.75	1.0	1.8	0.29	0.86	0.17	0.11	1.3	1.3	0.43	0.15
κ_Z (%)	1.6	1.2	0.95	0.29	0.23	0.5	0.26	0.23	0.13	0.2	0.17	0.12
κ_g (%)	2.4	3.6	1.5	2.3	0.97	2.5	1.3	0.9	1.5	1.7	1.0	0.52
κ_γ (%)	1.9	7.5	1.2	6.7	3.4	98⋆	5.0	2.2	3.7	4.7	3.9	0.35
$\kappa_{Z\gamma}$ (%)	10.6	–	4.0	99⋆	86⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.7
κ_c (%)	–	4.0	–	2.5	1.3	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t (%)	2.8	–	2.1	–	6.9	–	–	2.6	–	–	–	1.0
κ_b (%)	3.5	2.1	2.3	1.8	0.58	1.9	0.48	0.38	1.2	1.3	0.67	0.45
κ_μ (%)	4.6	–	1.9	15	9.4	320⋆	13	5.8	8.9	10	8.9	0.42
κ_τ (%)	1.8	3.3	1.3	1.9	0.7	3.0	1.3	0.89	1.3	1.4	0.73	0.49

Di-Higgs: cubic self-coupling

collider	(1) di-H excl.
HL-LHC	$^{+60}_{-50}$% (50%)
HE-LHC	10-20% (n.a.)
ILC_{250}	–
ILC_{350}	–
ILC_{500}	27% (27%)
CLIC_{380}	–
CLIC_{1500}	36% (36%)
CLIC_{3000}	$^{+11}_{-7}$% (n.a.)
FCC-ee_{240}	–
FCC-ee_{365}	–
FCC-ee/eh/hh	5% (5%)
CEPC	–

Upper bounds from rarer decays

	HL-LHC	+LHeC	+HE-LHC	$+\text{ILC}_{500}$	$+\text{CLIC}_{3000}$	+CEPC	$+\text{FCC-ee}_{240}$	+FCC-ee/eh/hh
κ_u	570.	320.	420.	330.	430.	290.	310.	280.
κ_d	270.	150.	200.	160.	200.	140.	140.	130.
κ_s	13.	7.3	9.4	7.5	9.9	6.6	7.	6.4
κ_c	1.2		0.87	measured directly				

from arXiv:1905.03764

Conclusions

- Since the discovery of h_{125}, a rich and varied physics program to test the structure of the Higgs sector
- These studies are complementary both to the understanding of h_{125} and to many different fields outside Higgs physics
- Experimental difficulties can motivate to really push the capabilities of LHC detectors

So far, no new evidence, BUT the parameter space is vast (and worth exploring)

Projections show LHC will remain a relevant tool to explore these physics topics until the end of HL-LHC

THANKS!