BSM Higgs Searches at the LHC

Exotic decays of the 125 GeV Higgs boson
Resonant production of the Higgs boson pair
Additional Higgs bosons

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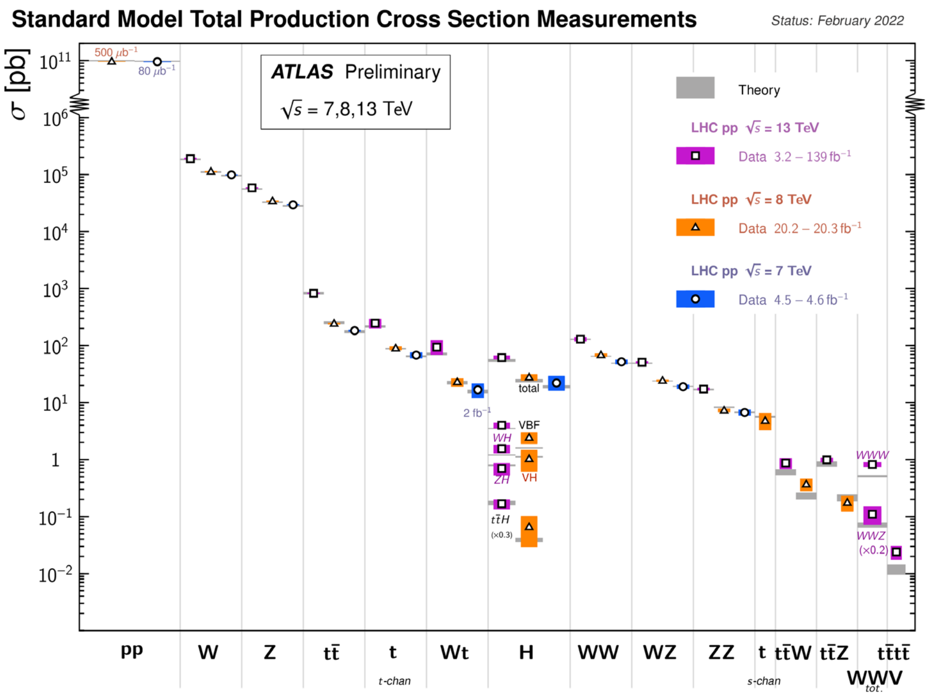
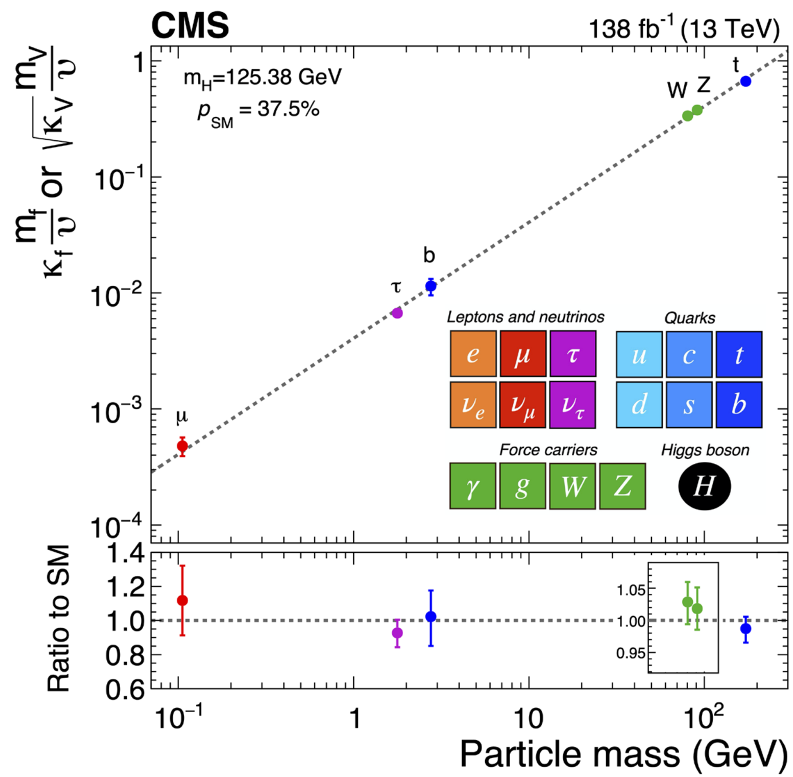
Higgs potential 2022 (Online), July 25-27, 2022

The Standard Model is live and well…





But it does not explain

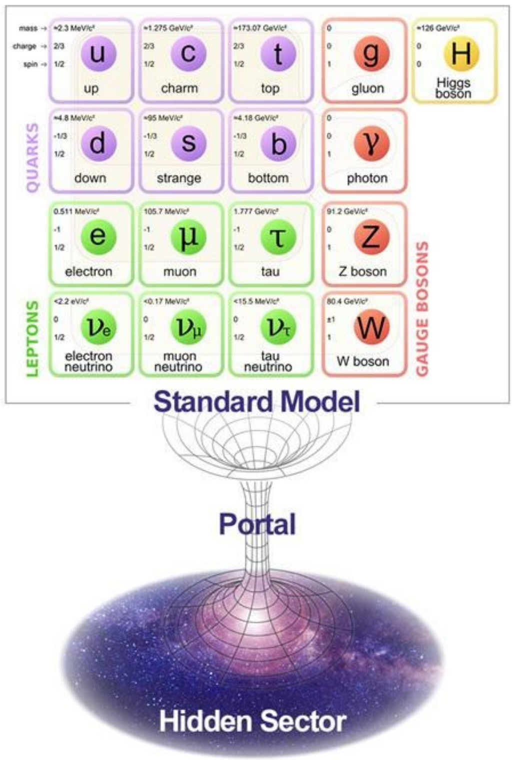
the nature of dark matter, neutrino mass, matter-antimatter asymmetry, …

$\Rightarrow$ Call for BSM physics

unfortunately, none knows where and how BSM physics might show up.

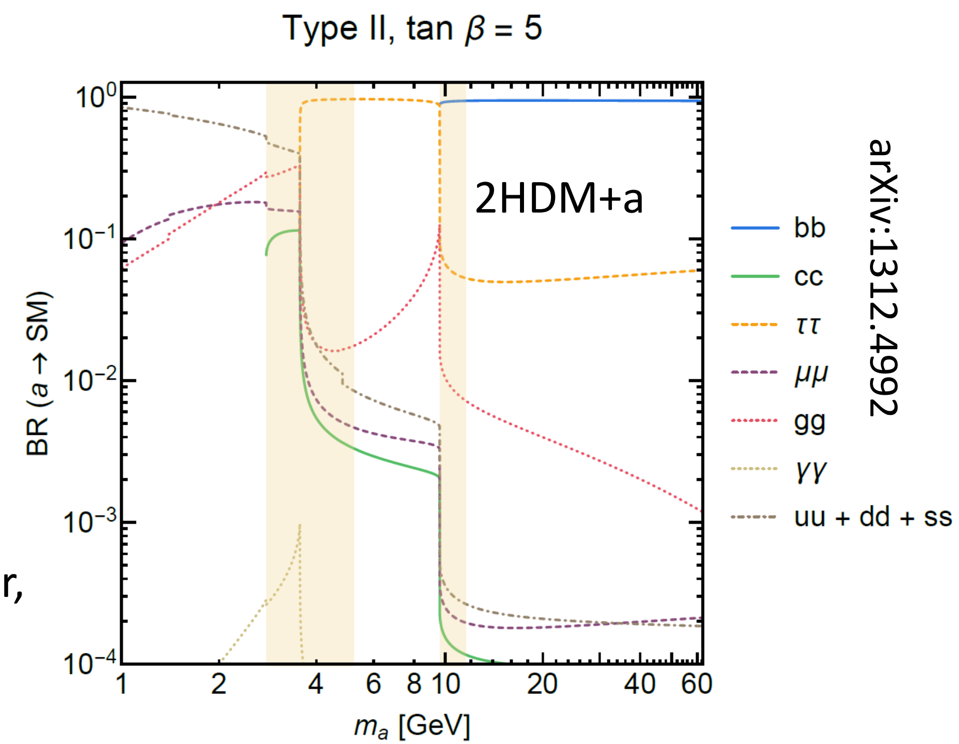
need to cast a wide net…

BSM Higgs boson decays



Higgs portal model:

Higgs boson is the only particle in the SM that interacts with the hidden sector $\Rightarrow$ Higgs boson decay to dark matter particles.

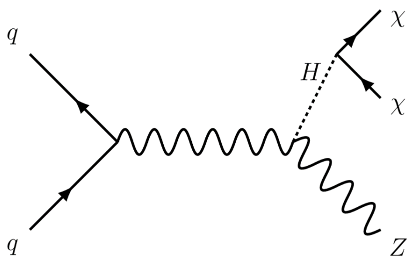


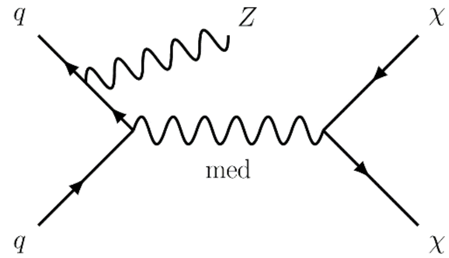
$h \to aa$

SM+scalar/vector, 2HDM(+scalar):

- Simplest extensions to the SM Higgs sector,
- New scalar or vector resonances,
- New decay modes for the Higgs boson

Search for Zh with the h→χχ decay

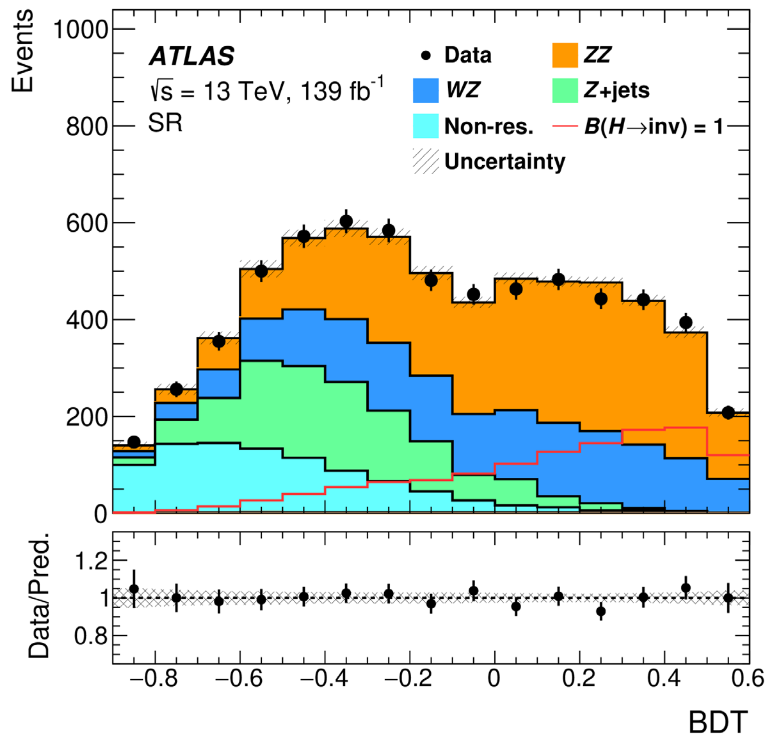


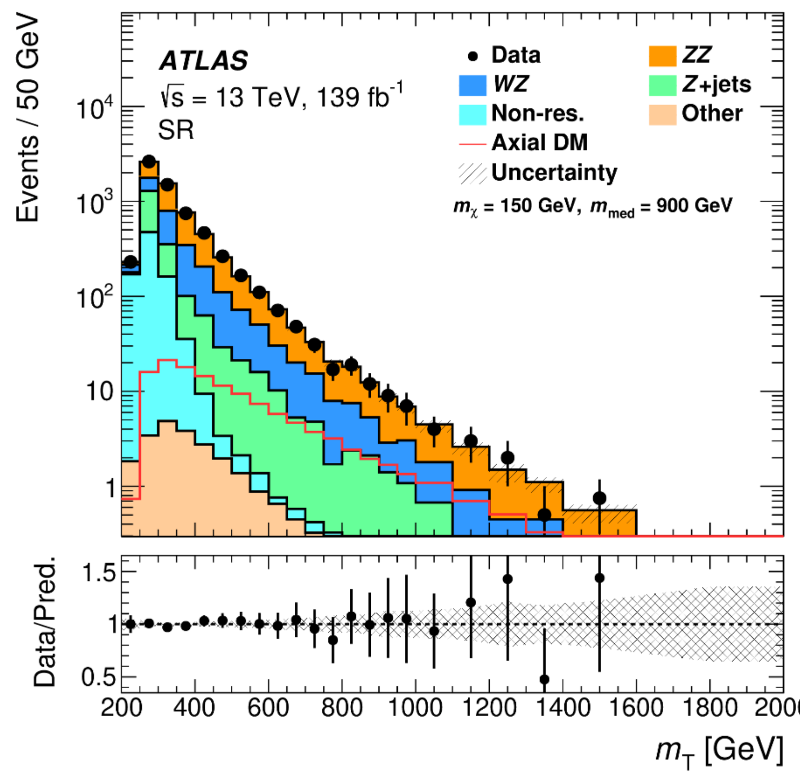


Signature: $Z \to \ell\ell$ events with large E_T^{miss}

Main backgrounds: *ZZ* and *ZW*

BDT for S-B separation and S extraction



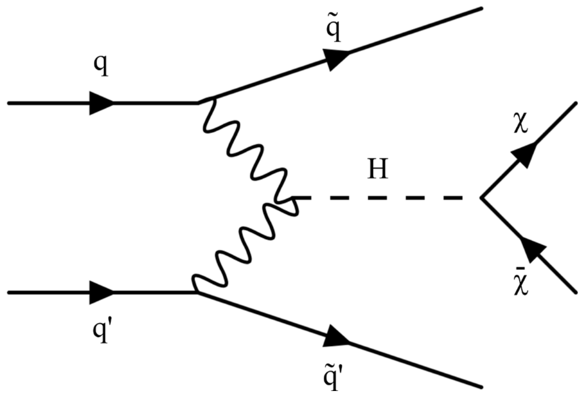


arXiv:2111.08372

Observed (Expected): $B(h \to \text{inv.}) < 19\%(19\%)$ at 95% CL

(Assuming SM Zh production cross section)

Search for VBF h with h→χχ decay

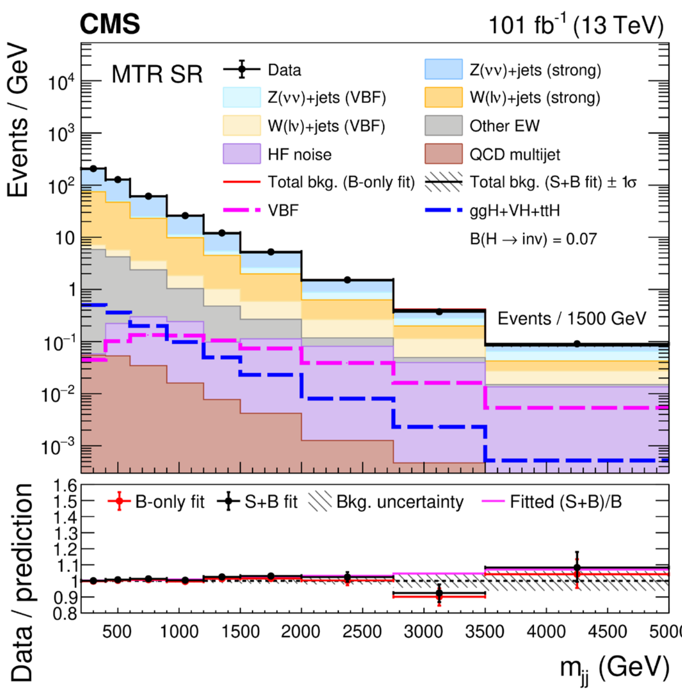


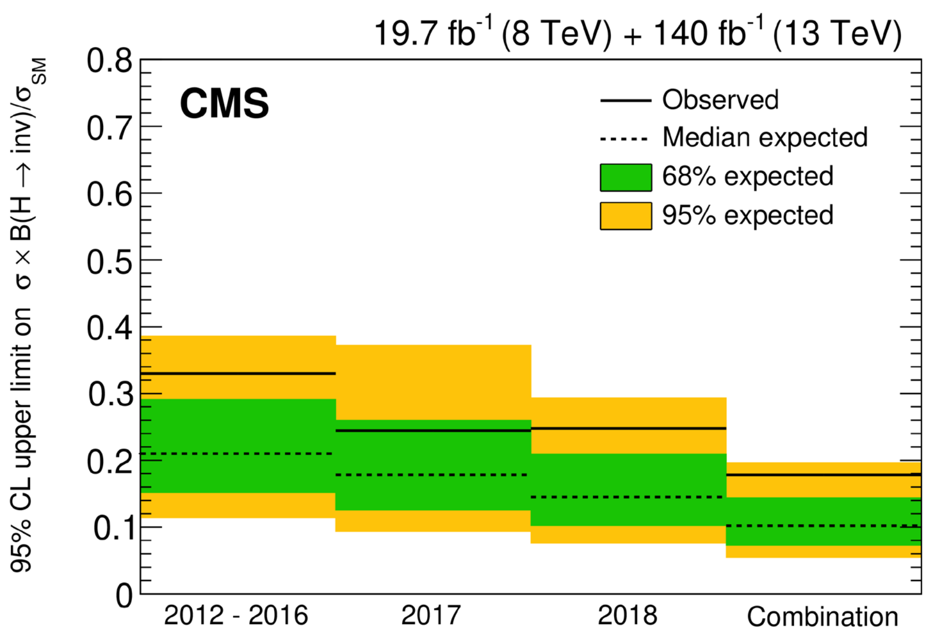
Characterized by two VBF tagging jets with large E_T^{miss}

Main backgrounds: $Z(\nu\nu)+\text{jets}$, $W(\ell\nu)+\text{jets}$

VBF tagging jet mass distribution as the discriminant

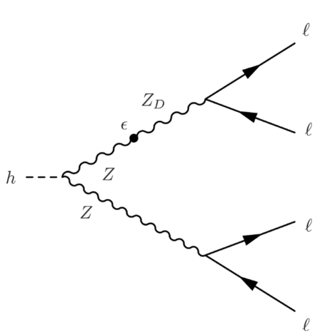
Observed (Expected): $B(h \to inv.) < 18\%(10\%)$ @ 95% CL (assuming SM VBF h production cross section)

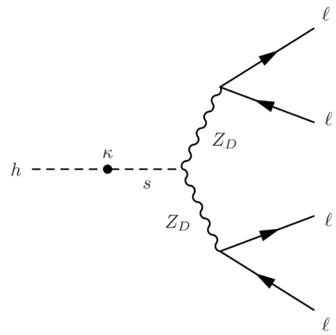




arXiv:2201.11585

Searches for $h \to ZZ_D$ and $h \to Z_DZ_D$





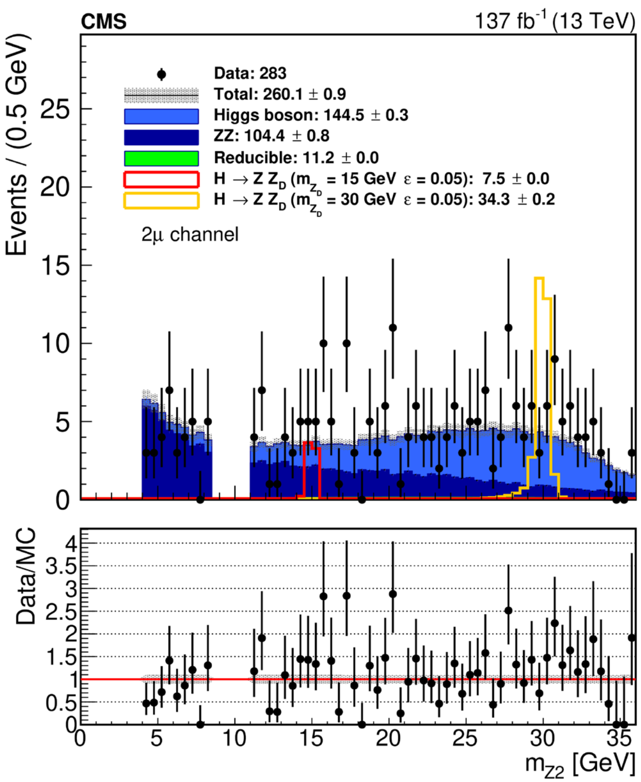
$h \to ZZ_D$ through $Z - Z_D$ mixing and

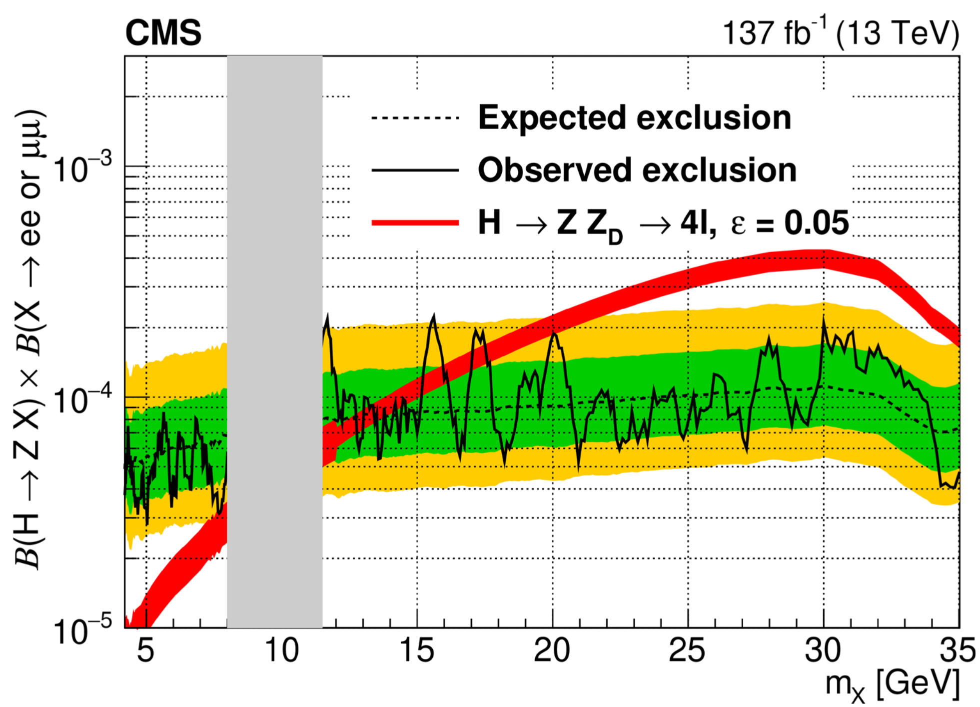
$h \to Z_DZ_D$ through Higgs-to-dark-Higgs mixing

Signatures: 2-3 resonances, full reconstruction

Main backgrounds: $h \to ZZ(!)$ and continum ZZ

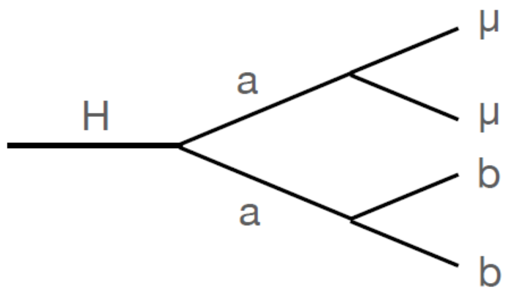
Signal extractions: fit to m_{Z2} for ZZ_D and counting in (m_{Z1}, m_{Z2}) for Z_DZ_D



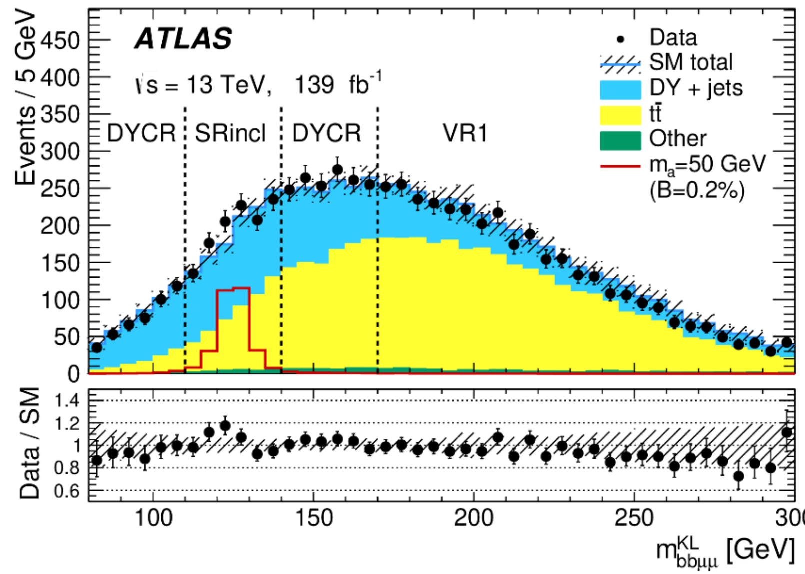


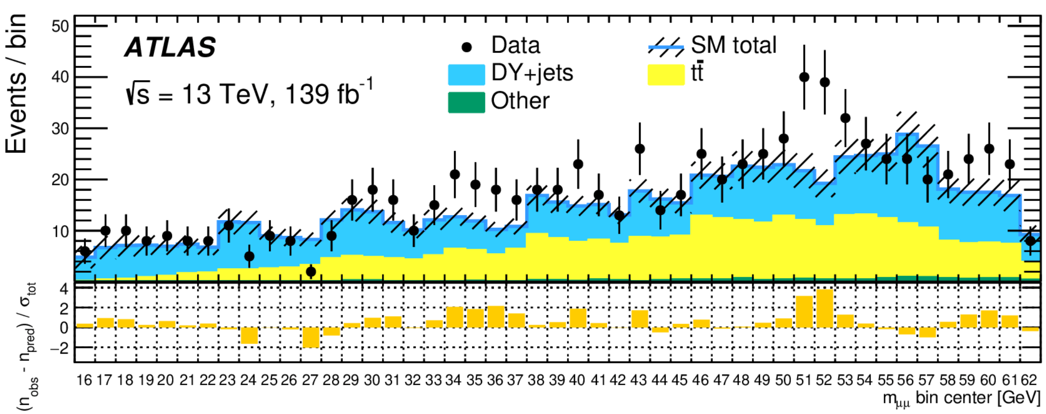
arXiv:2111.01299

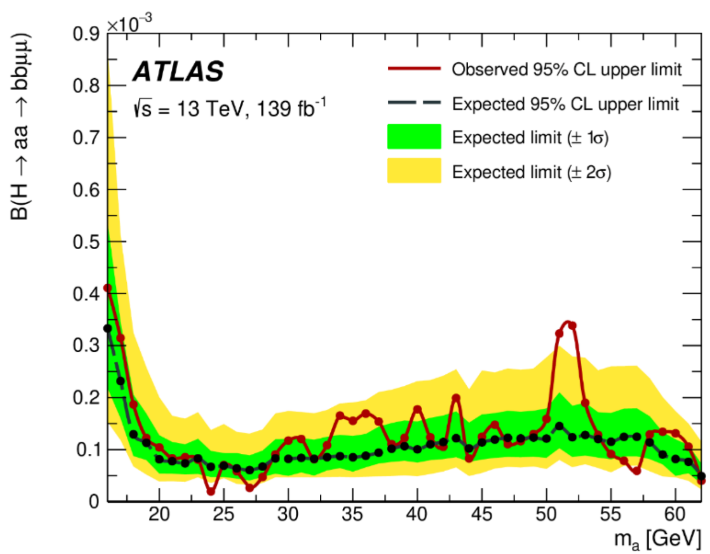
Search for h→*aa*→bbμμ



Scan m_a at steps in 1 or 1.5 GeV steps, requiring $m_{\mu\mu} \approx m_{bb}$ and consistent with m_a, search for excess in $m_{bb\mu\mu}$ distribution at m_H.





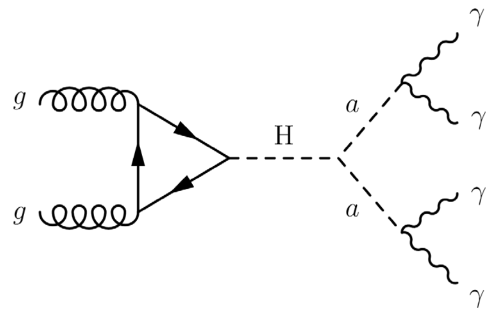


arXiv:2110.00313

Largest excess at $m_a = 52$ GeV:

local (global) significance of $3.3(1.7)\sigma$

Search for h→*aa*→γγγγ

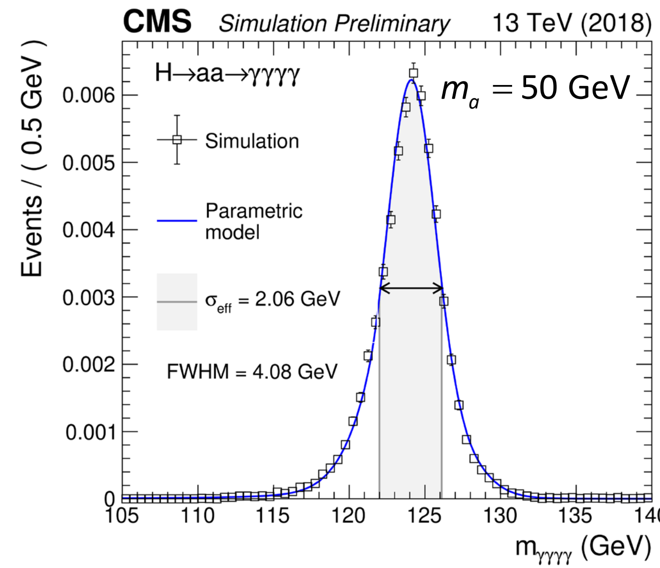


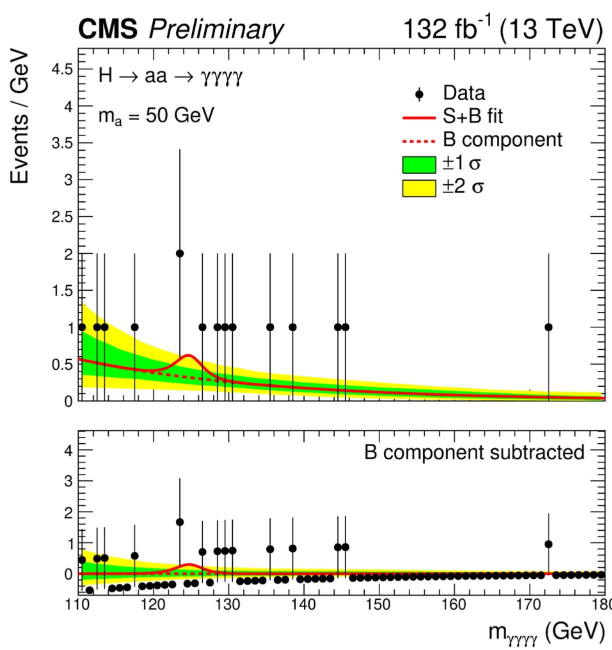
Full reconstruction with good mass resolution

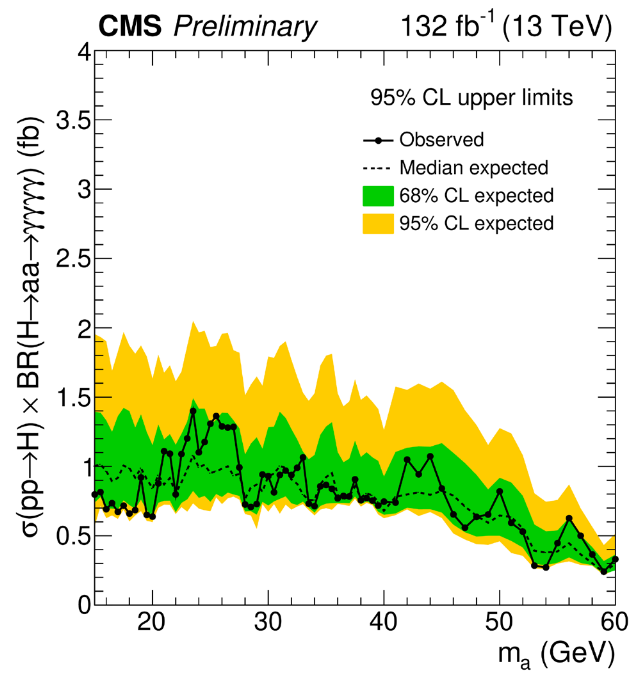
Dominant background: $\gamma(\gamma) + \text{jets}$

BDT for signal-background separation

4γ mass $m_{\gamma\gamma\gamma\gamma}$ as the final discriminant

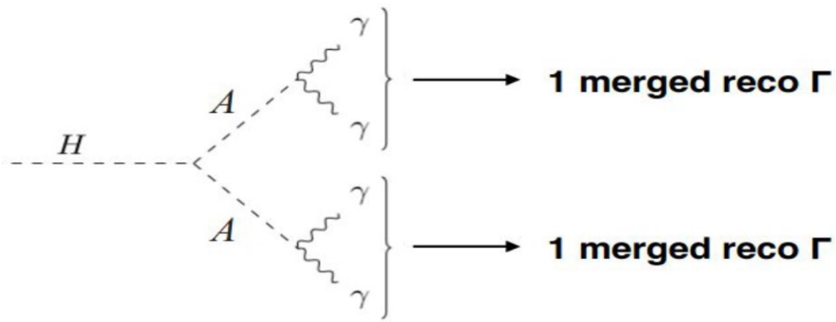






CMS-PAS-HIG-21-003

Search for h→AA→4γ



Light (pseudo)scalar A with $m_A = 0.1 - 1.2$ GeV

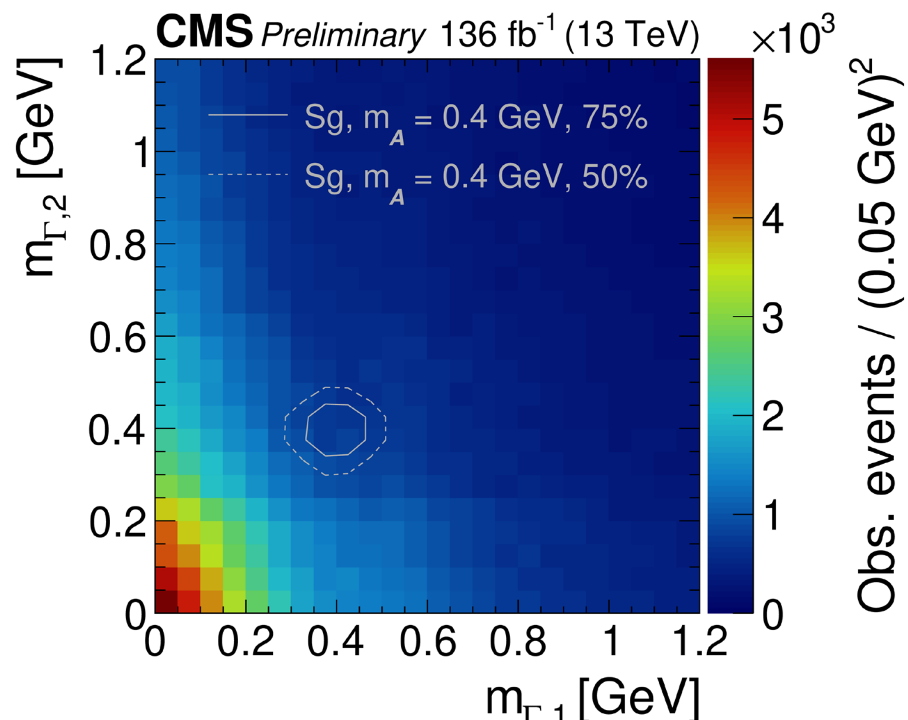
For light A, the $A \rightarrow \gamma\gamma$ decay dominates

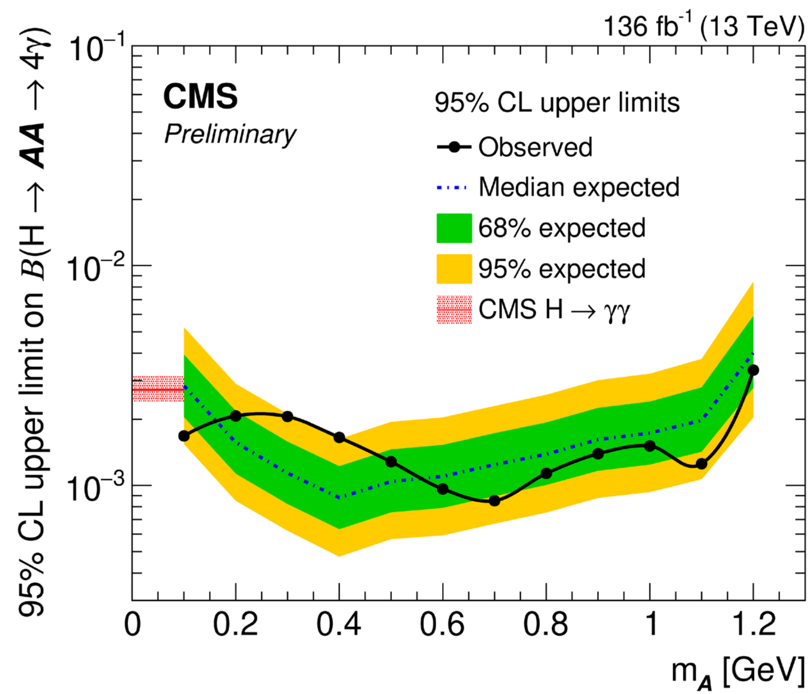
Highly boosted $\Rightarrow$ two photons are merged

Main background: QCD $\gamma\gamma$

Major challenge: Merged $\gamma\gamma$ reconstruction and mass estimation.

2D $\left(m_{\Gamma 1}, m_{\Gamma 2}\right)$ fit to extract potential signal





CMS-PAS-HIG-21-016

(Assuming SM production)

Search for h→(e/μ)τ

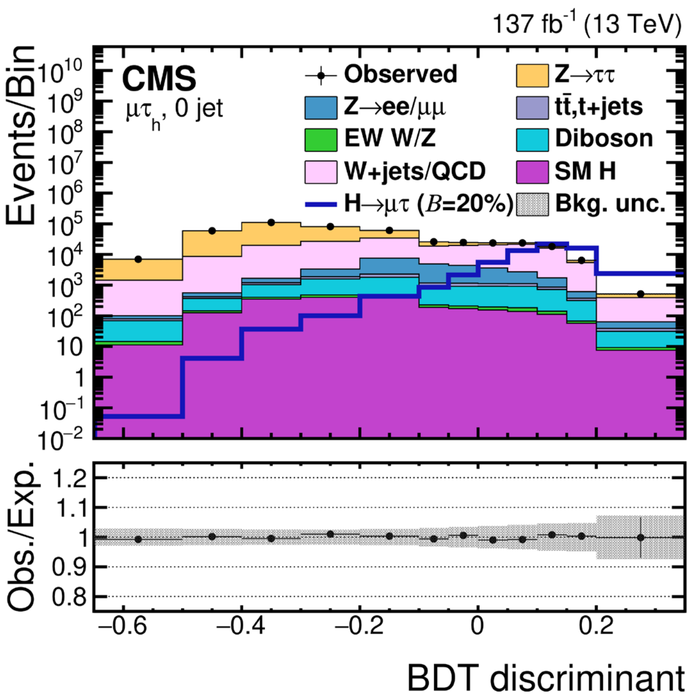
Flavor-changing Higgs boson couplings are predicted in many models with multiple Higgs bosons, particularly those motivated by neutrino oscillations.

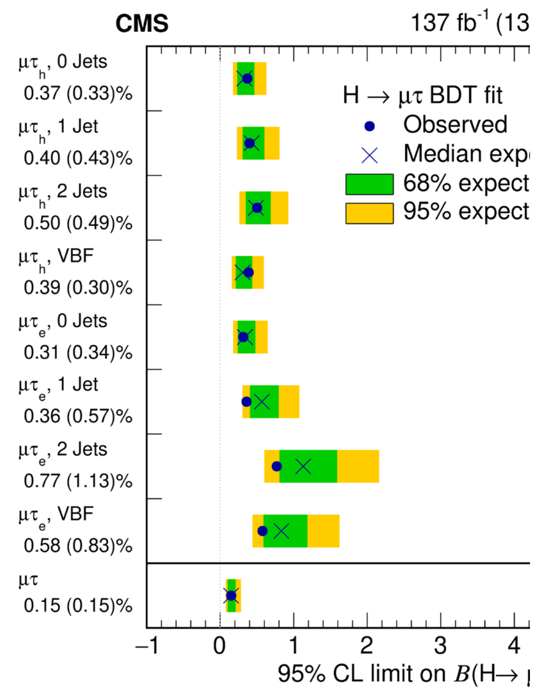
Signatures: $\ell\tau$ final states with $m_{\ell\tau}$ consistent with m_h

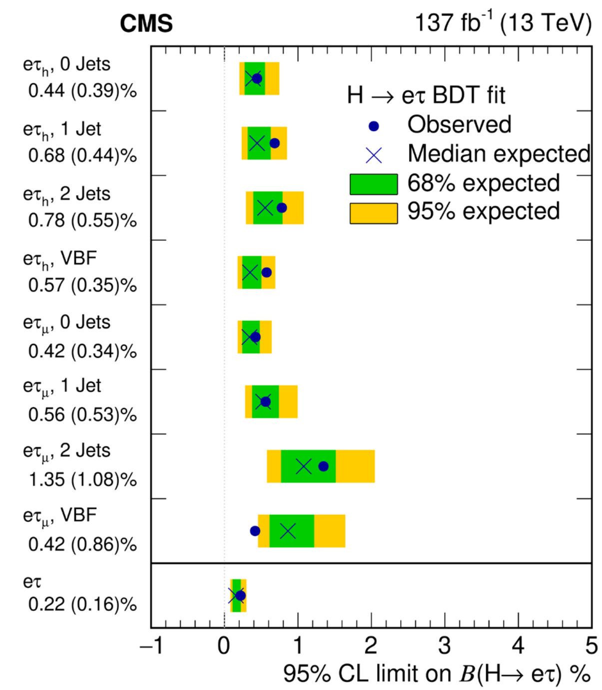
Main backgrounds: $Z \to \tau\tau$ and $W + \text{jets}$

Discriminant: BDT for S-B separation and S extraction

arXiv:2105.03007 (CMS)





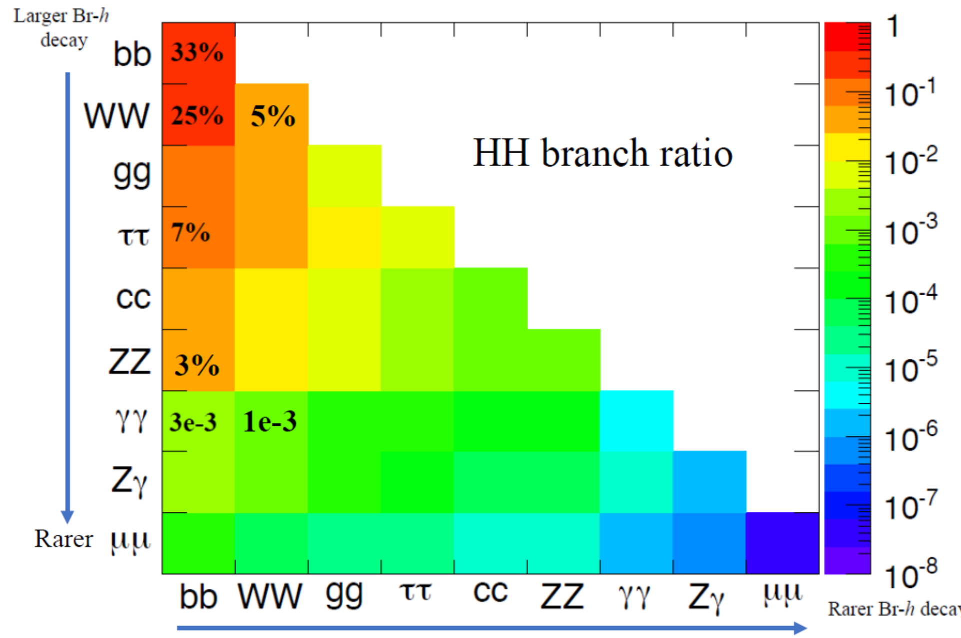


Searches for *hh* resonances

Major efforts in searching for heavy resonances that decay to *hh*:

- different production modes;
- multiple final states

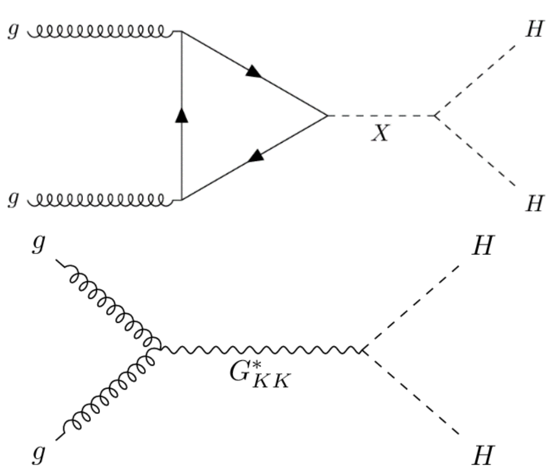
$(bbbb,\ bb\tau\tau,\ bb\gamma\gamma, \ldots)$



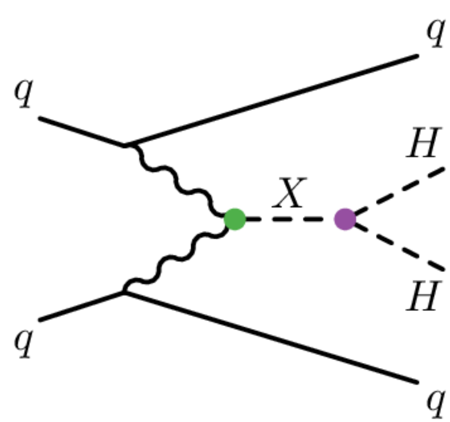
Though the searches are driven by the non-resonant search, *hh* resonances are expected in many BSM scenarios:

- 2HDM
- SM or 2HDM + singlet
- Extra dimensions, …

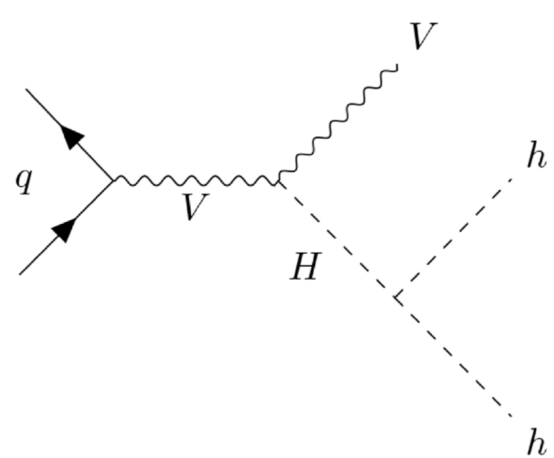
gluon-gluon fusion (ggF)



vector-boson fusion (VBF)



Associated production (VH)

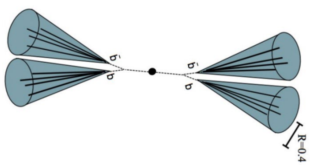


Search for X→hh→bbbb

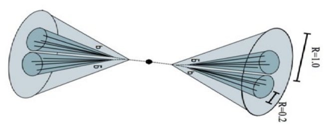
Full X reconstruction, but large multijet background

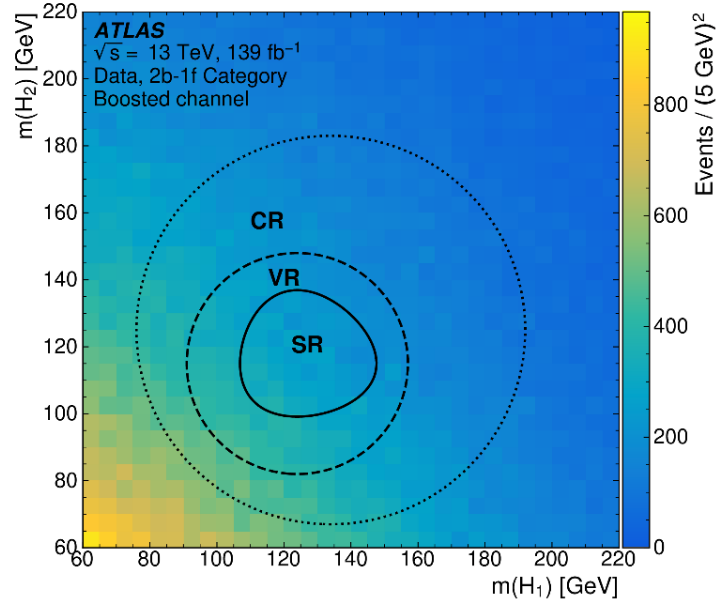
Data 2D side bands to estimate the background

Resolved search for low mass



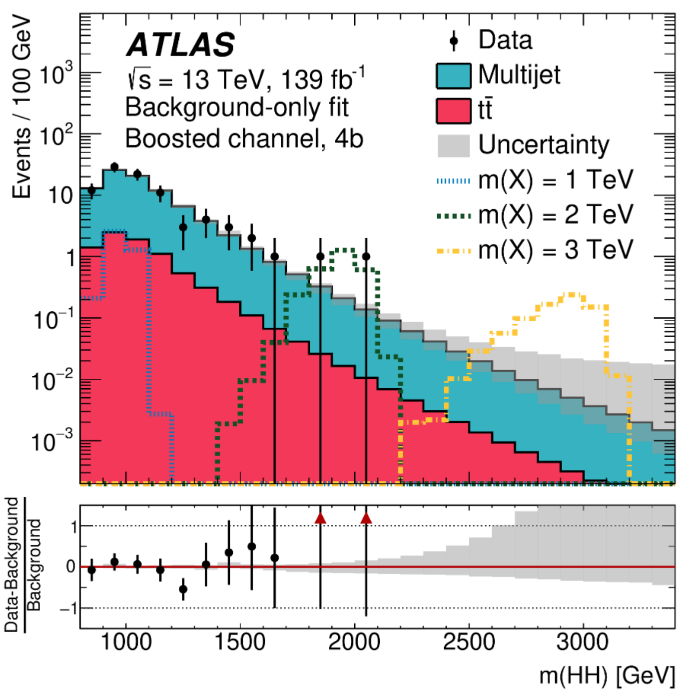
Boosted search for high mass

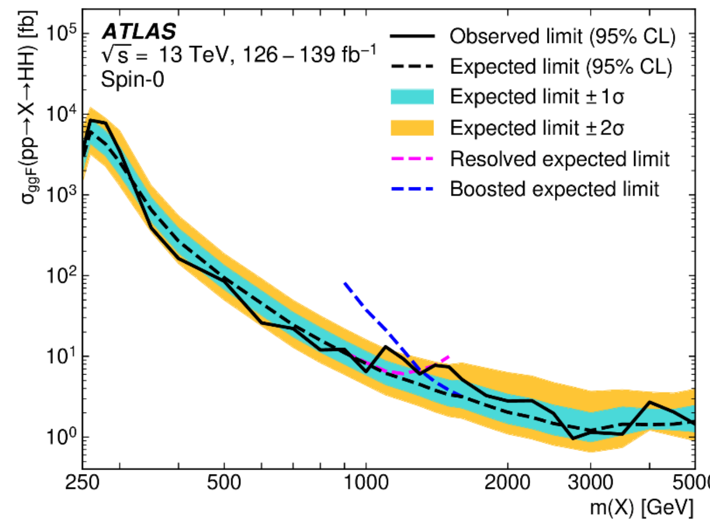




arXiv:2202.07288

Fit the m_{HH} distribution to extract signal



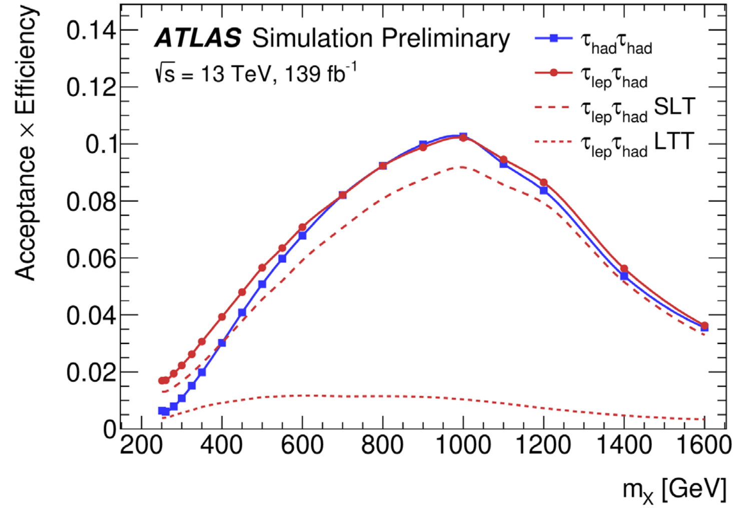


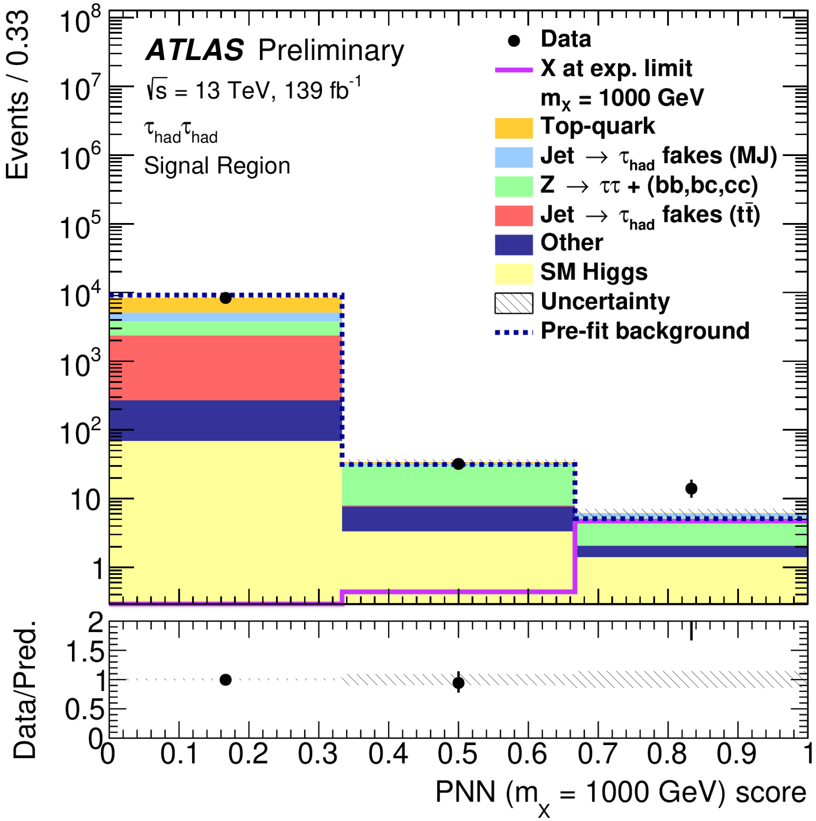
Search for X→hh→bbττ

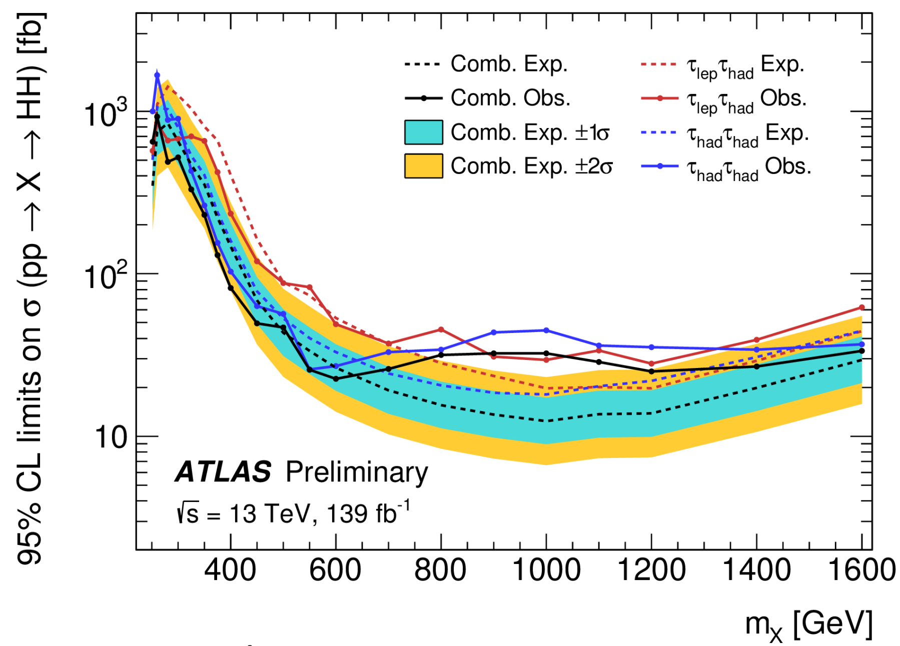
Final states: $bb\tau_h\tau_h$, $bb\tau_\ell\tau_h$

Resolved, losing efficiencies at large m_X

Parameterized NN for S-B separation and S extraction







ATLAS-CONF-2021-030

Broad excess at ~1 TeV:

local (global) significance 3.0 (2.0)σ

Search for X→hh→bbγγ

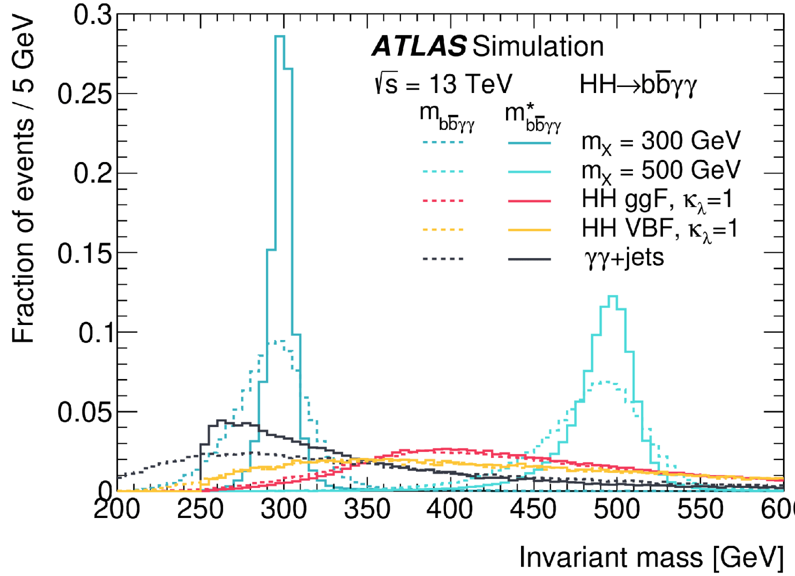
Clean signature, full resonance reconstruction

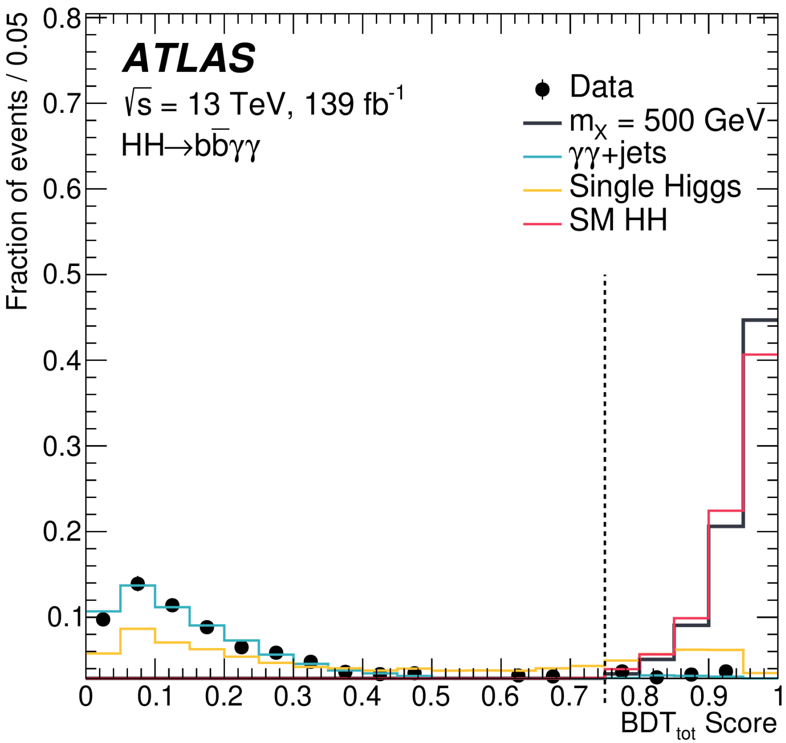
Good mass resolution with m_h constraint

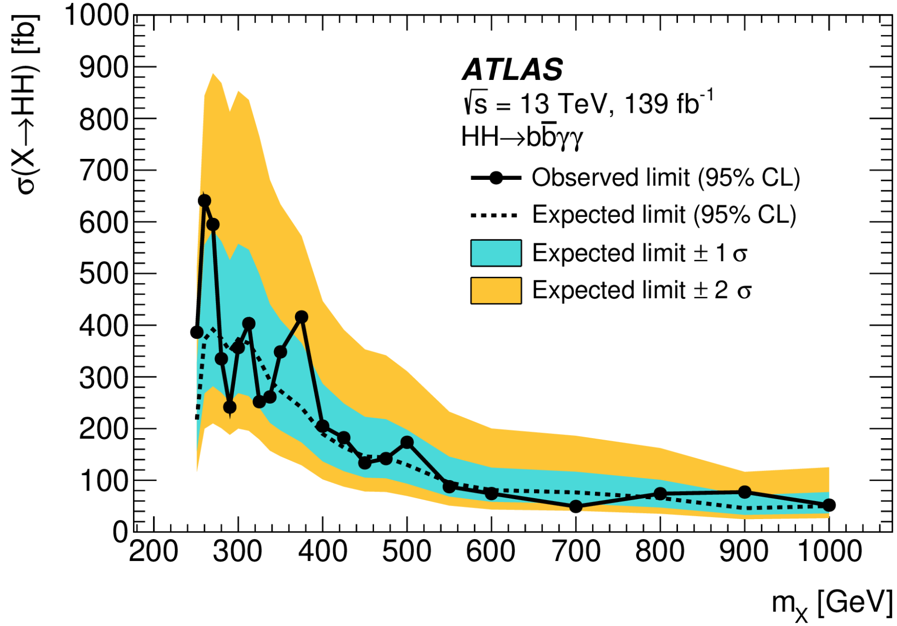
Main backgrounds: $\gamma\gamma$+jets, *ttH*, *ZH*

Separate BDTs for S-$\gamma\gamma$ and S-h discriminations

Combined BDT for signal extraction

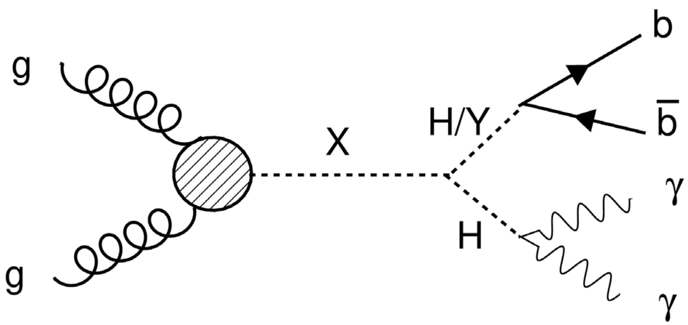






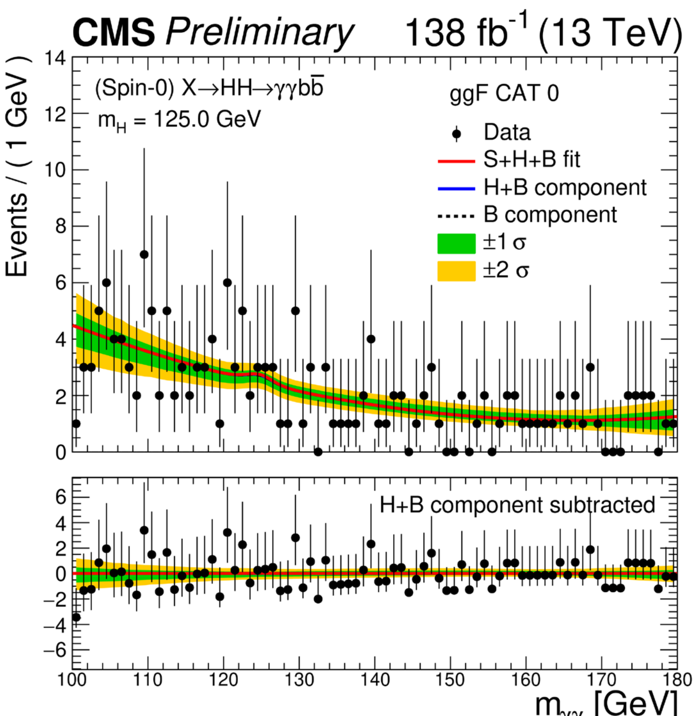
arXiv:2112.11876

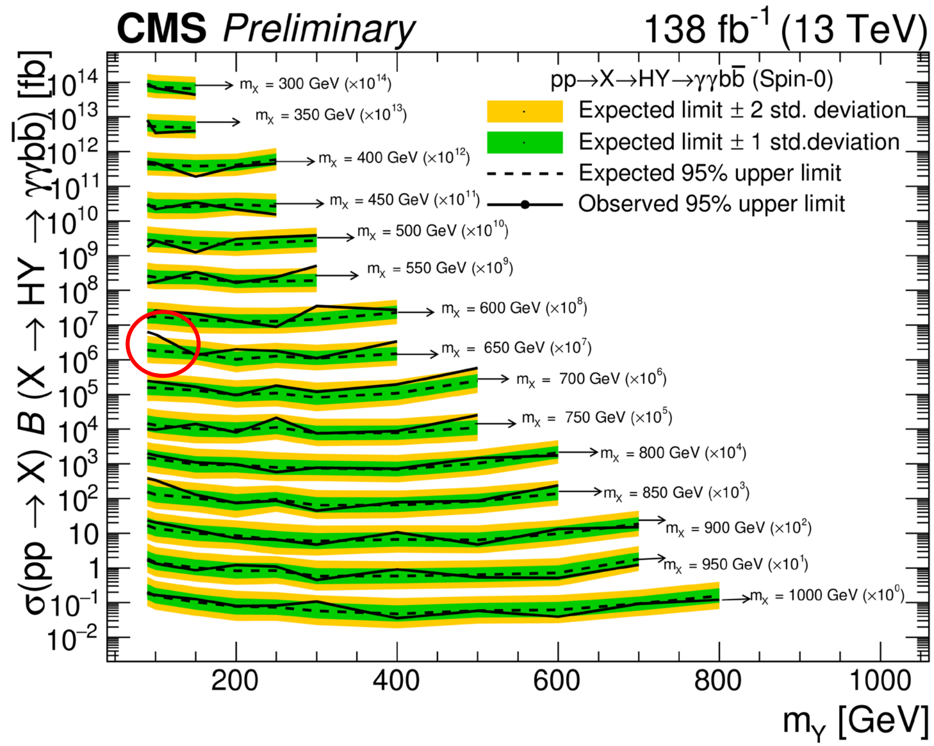
Search for X→h(Y)h→bbγγ



CMS extended the analysis to include another resonance: $Y \to bb$

2D fit to $\left(m_{\gamma\gamma}, m_{jj}\right)$ to extract the signal





CMS-PAS-HIG-21-011

Largest excess at $\left(m_X, m_Y\right) = \left(650, 90\right)$ GeV: local (global) significance of 3.8 $(2.8)\sigma$

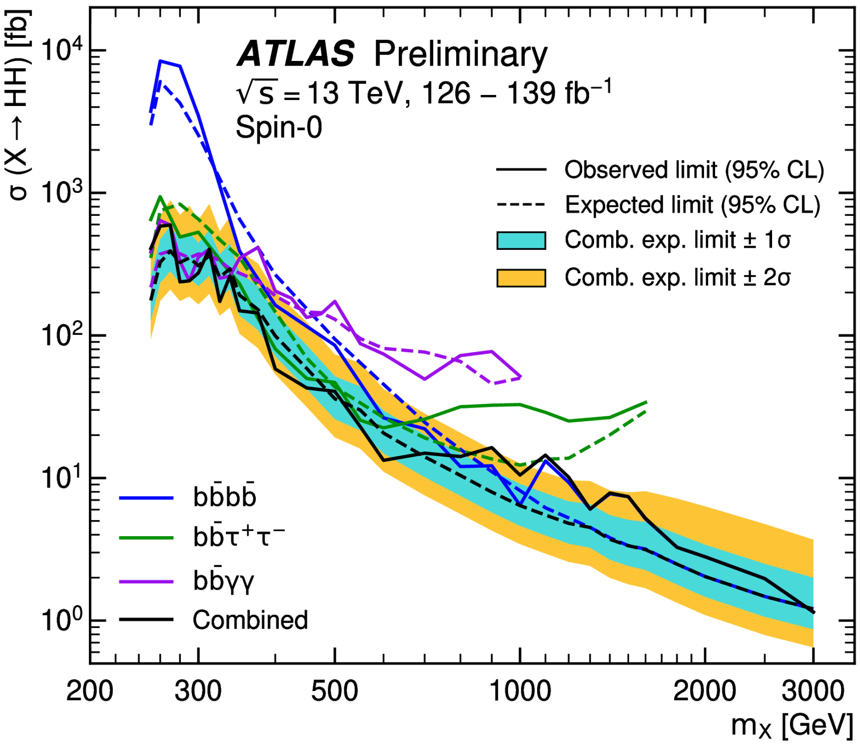
Combined search for X→hh

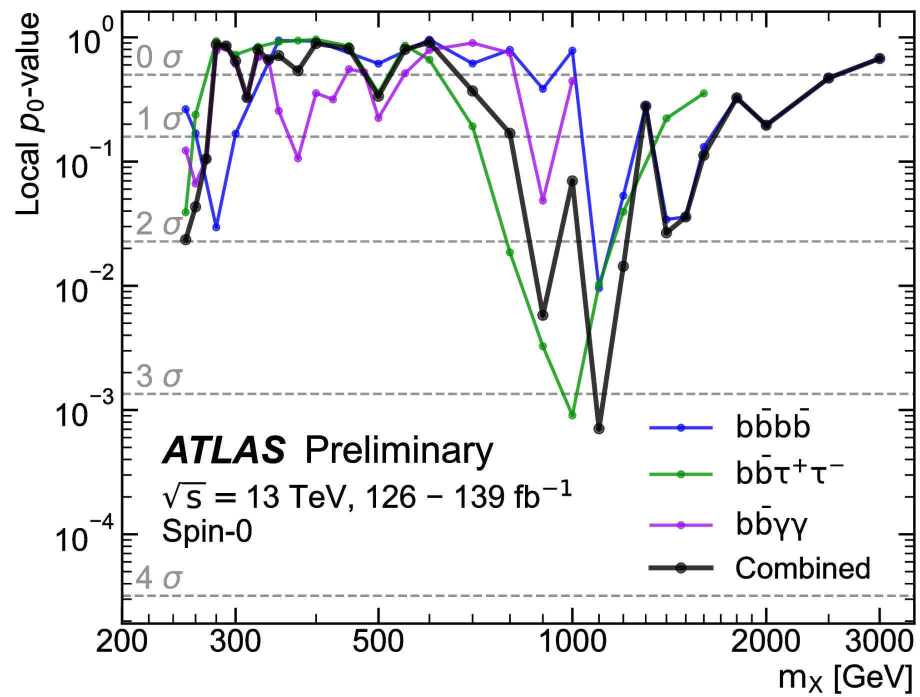
Decay channel sensitivities:

$bb\gamma\gamma$: mass low, $bb\tau\tau$: intermediate mass, $bbbb$: high mass

Most significant excess at $\sim$1.1 TeV: 3.2 $(2.1)\sigma$ local (global)

mostly from the excess observed in the $bb\tau\tau$ channel





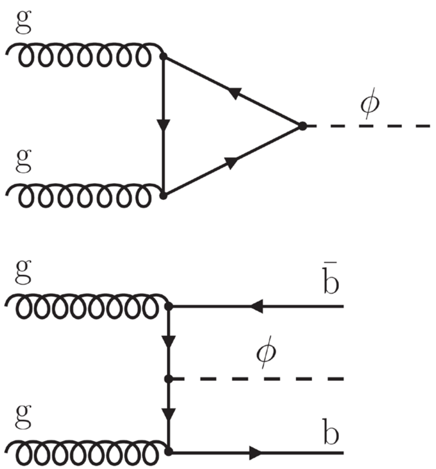
ATLAS-CONF-2021-052

Searches for additional Higgs bosons

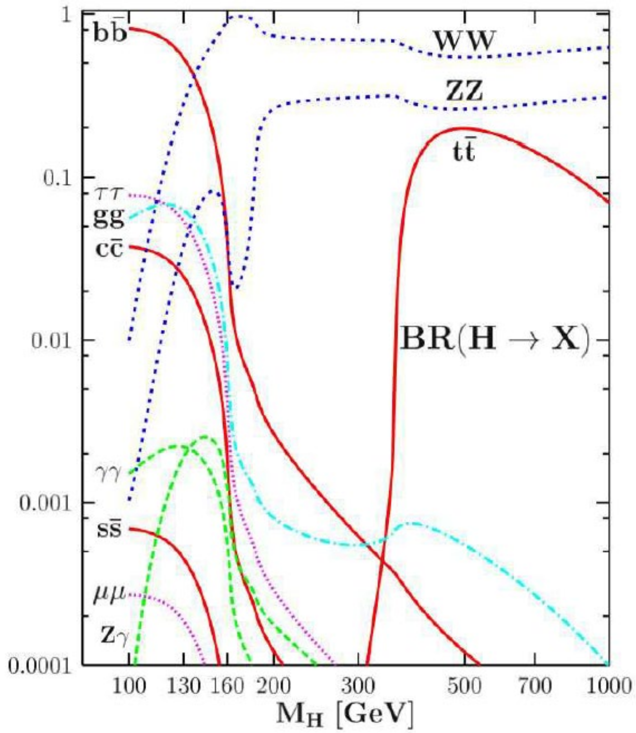
2 Higgs Doublet Models (2HDM) are BSM models of choice for the searches.
With 5 Higgs bosons (two CP-even h and H, one CP-odd A, two charged $H^{\pm}$) and other free parameters, there are many possibilities:

- searches for heavy CP-even Higgs boson H,
- searches for CP-odd Higgs boson A,
- searches for charged Higgs boson $H^{\pm}$.

Similar production and decays as the SM Higgs boson h:



$\phi = h,\ H,\ A$



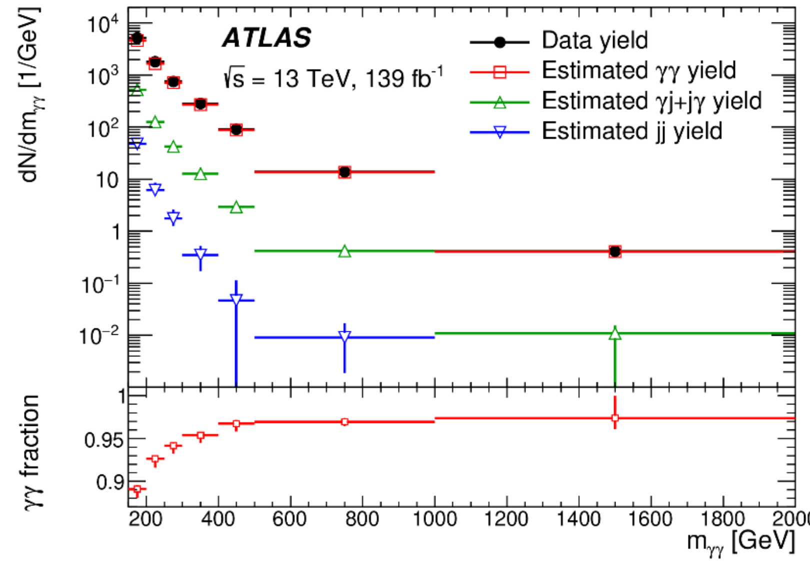
Complications: 2HDM flavors, Higgs boson width, …

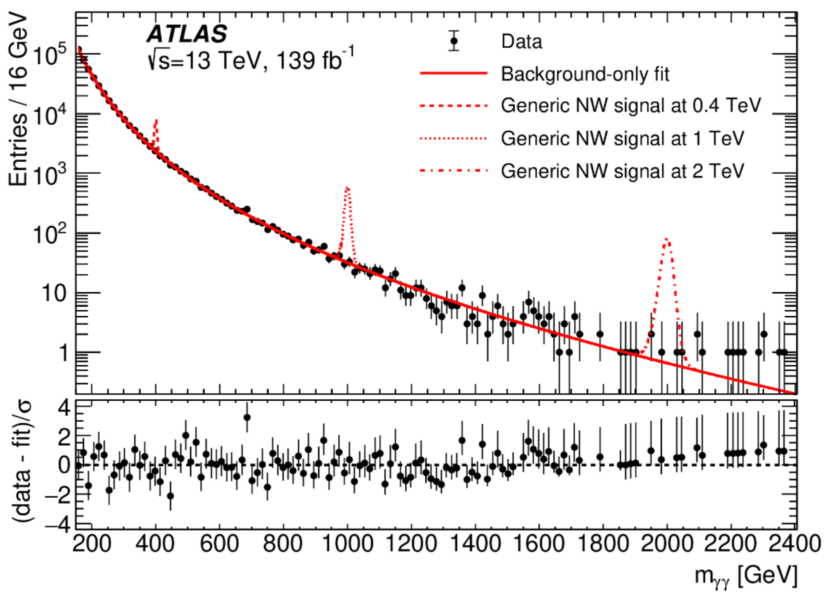
Search for H→γγ

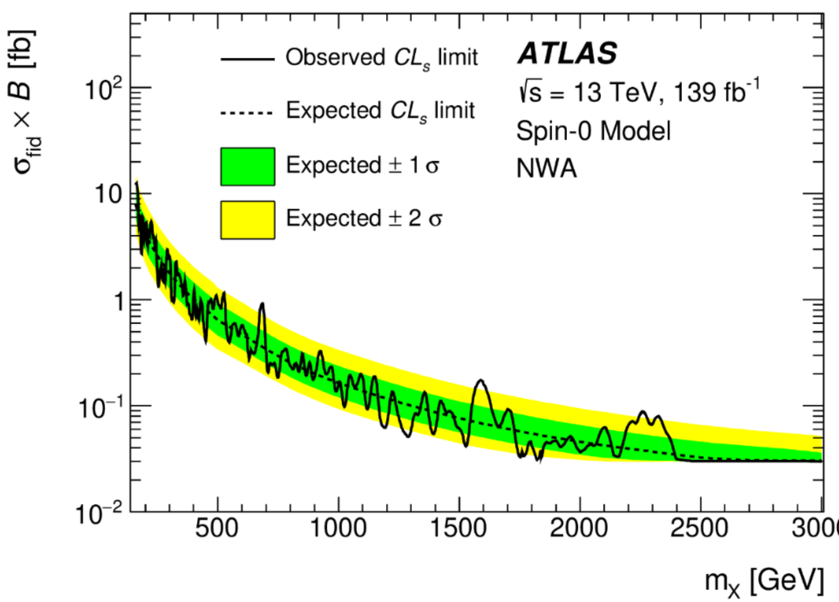
Excellent $m_{\gamma\gamma}$ mass resolution, search for bumps over smooth falling background.

Main backgrounds: QCD $\gamma\gamma$ and γ+jets

Explore resonances with widths up to 10% of their masses.







arXiv:2102.13405

Search for H→WW

Signal model:

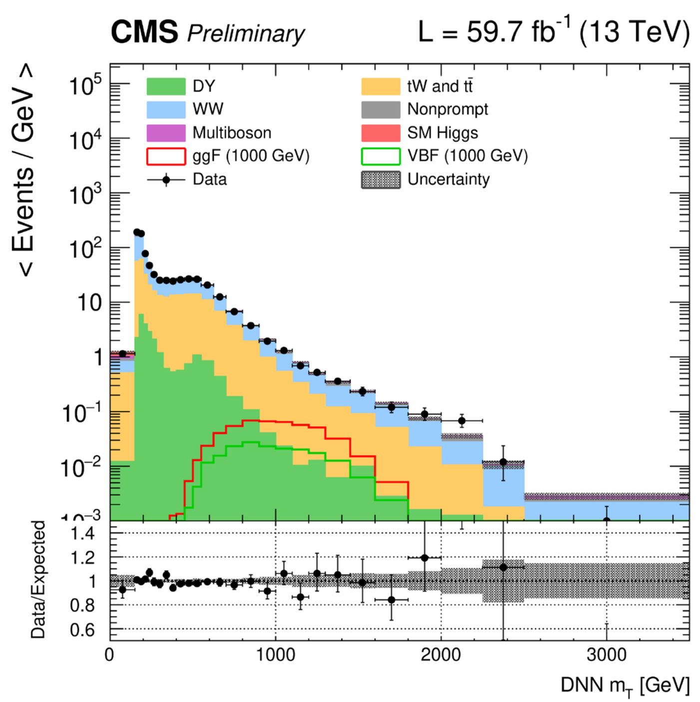
both ggF and VBF production with the varying fraction,

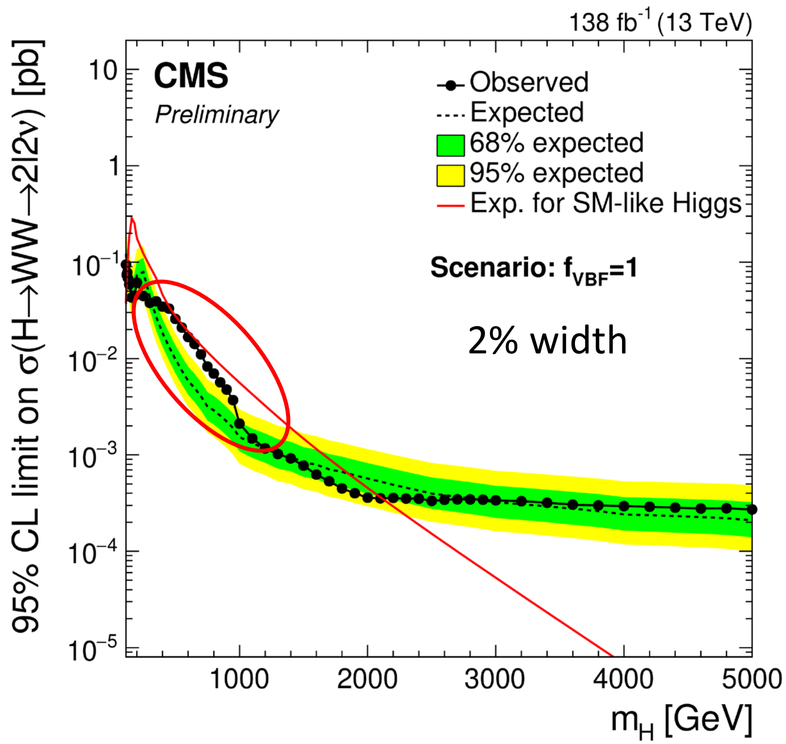
resonance width from 0.1-10%, including interference for $m_H > 300$ GeV

Analysis:

Final states considered: ee, $\mu\mu$, and $e\mu$

mass sensitive DNN as the final discriminant





CMS-PAS-HIG-20-016

Largest excess at $m_H = 650$ GeV for $f_{VBF} = 1$: local (global) significance of $3.8(2.6)\sigma$

Search for H→ZZ

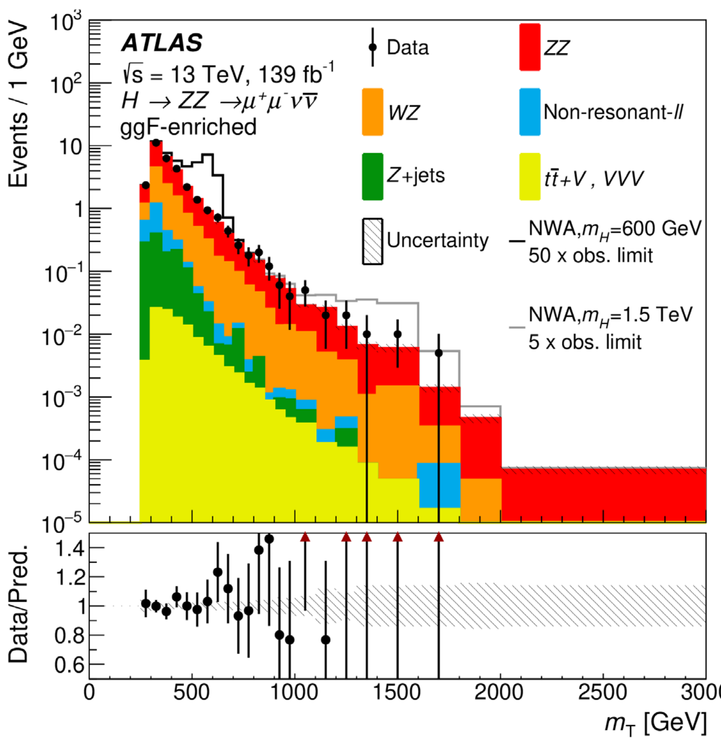
Signal model: *ggF* and *VBF* production

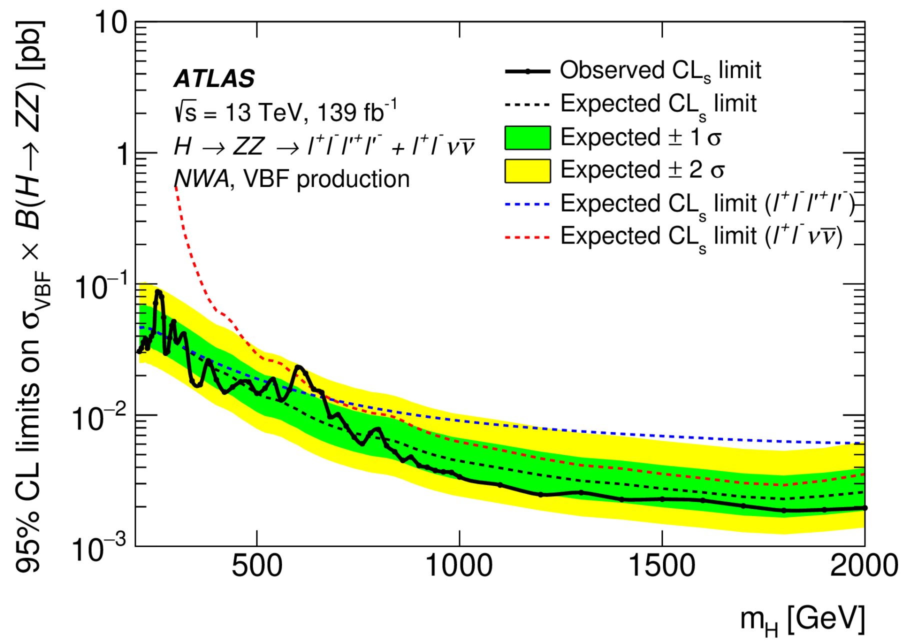
H width from narrow to 15% of its mass

Final states: $ZZ \to 4\ell,\ 2\ell 2\nu$

Clean final states with ZZ and ZW as the main background

Final discriminant: $m_{4\ell}$ for 4ℓ and m_T for $2\ell 2\nu$

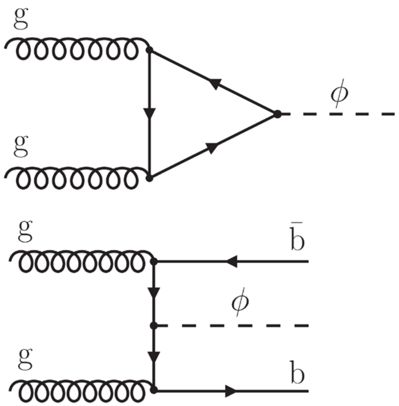




arXIv:2009.14791

$2.4(0.9)\sigma$ observed (expected) at 620 GeV

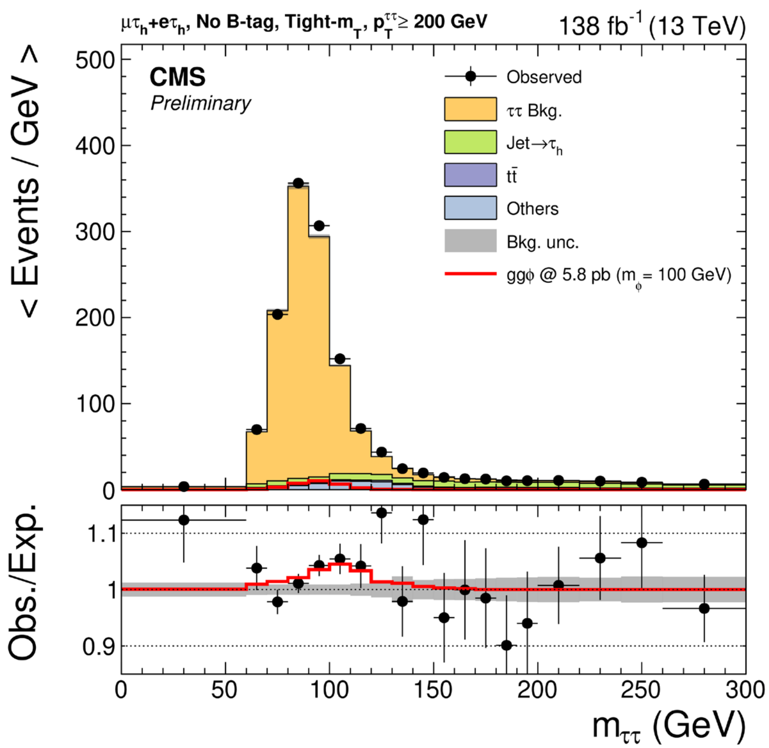
Search for H→ττ

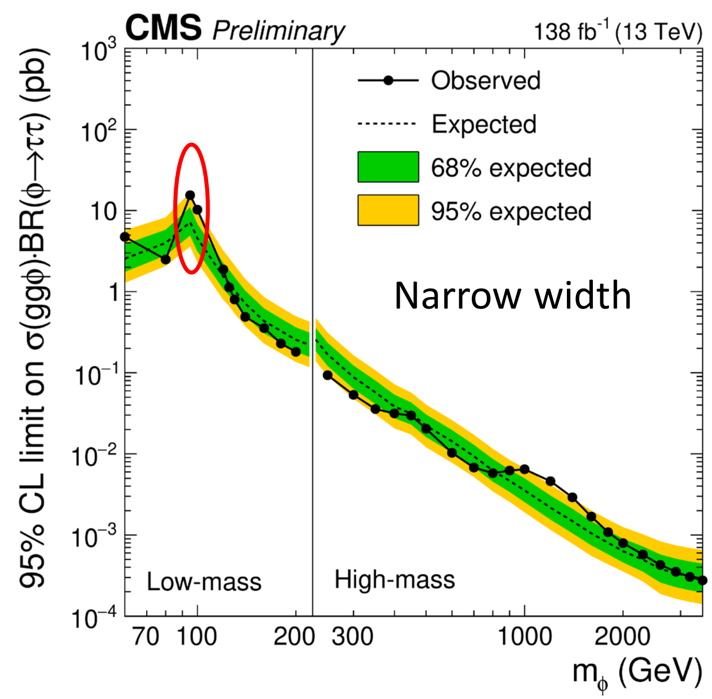


Signal model: $gg\phi$ and $bb\phi$ production

Analysis:

- Final states: $e\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$,
- b-tagging for $gg\phi$ and $bb\phi$ separation,
- Discriminant: $m_{\tau\tau}$ for low mass and m_T^{tot} for high mass



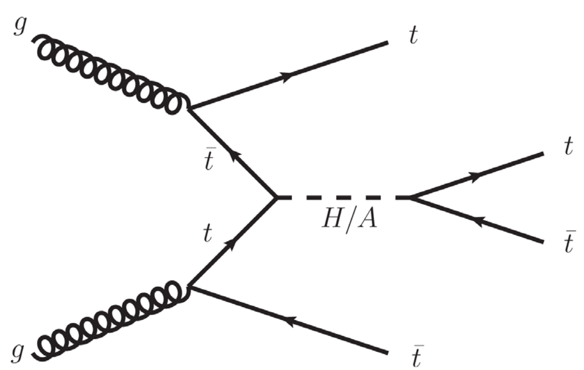


CMS-PAS-HIG-21-001

Largest excess at $m_H = 100$ GeV:

local (global) significance of $3.1(2.7)\sigma$

Search for ttH/A→4t



$$BR\left(4t \rightarrow SSML\right) \approx 12\%$$

Busy and complicated event topology,

Large backgrounds from $tt + (tt,\ V,\ h,\ \text{jets})$

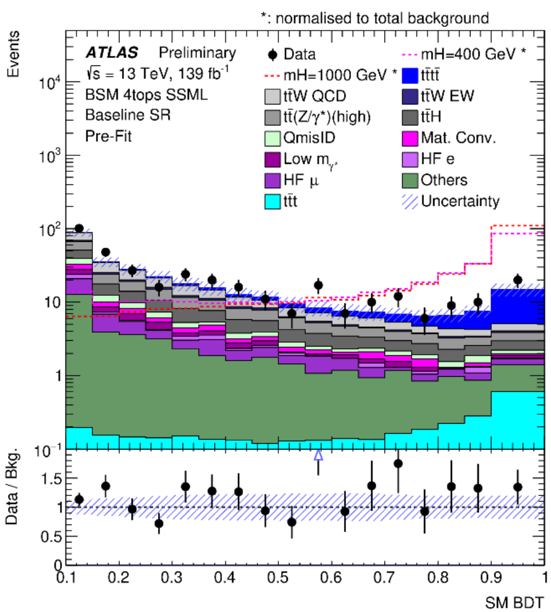
Final states:

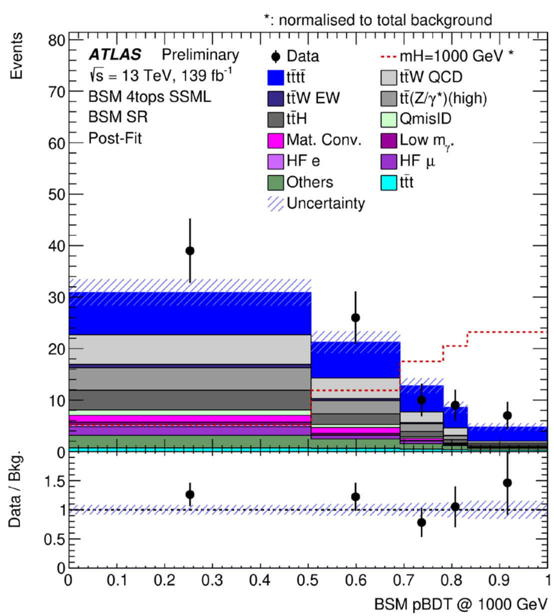
Same-sign dilepton and multilepton (SSML) events

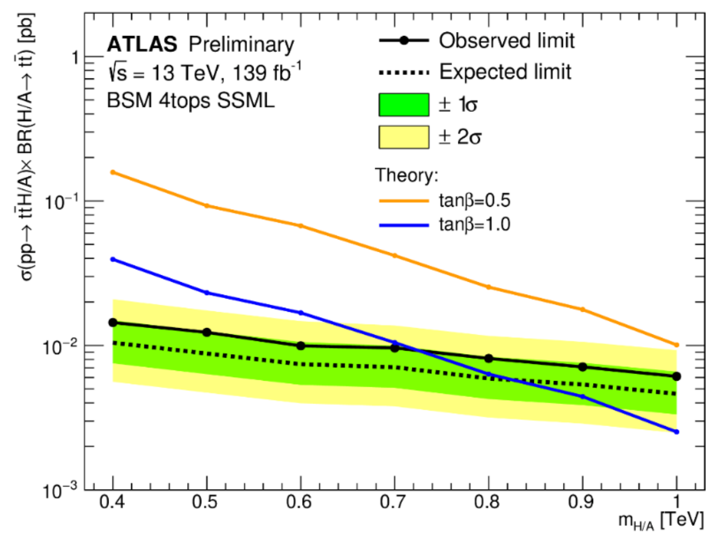
BDTs for S-B discrimination and S extraction:

SM BDT for selecting $4t$ against backgrounds,

BSM BDT for selecting BSM $4t$ signal

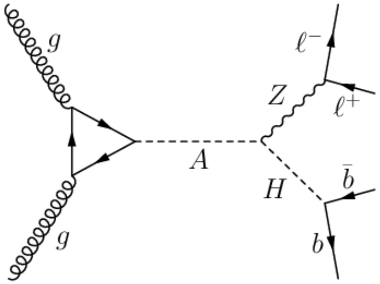




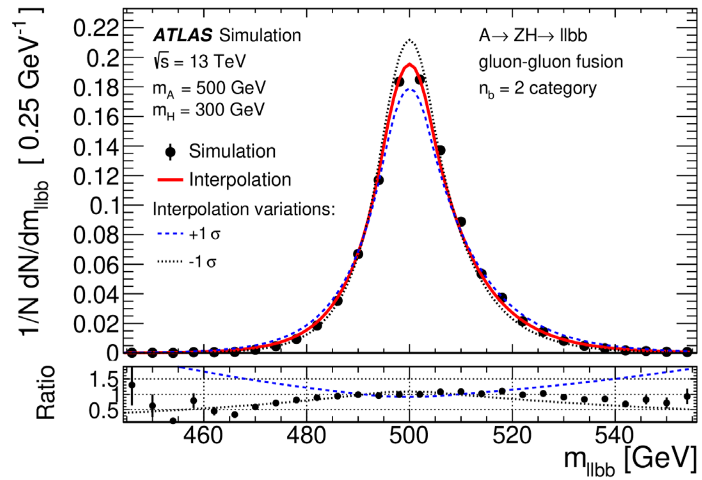


ATLAS-CONF-2022-008

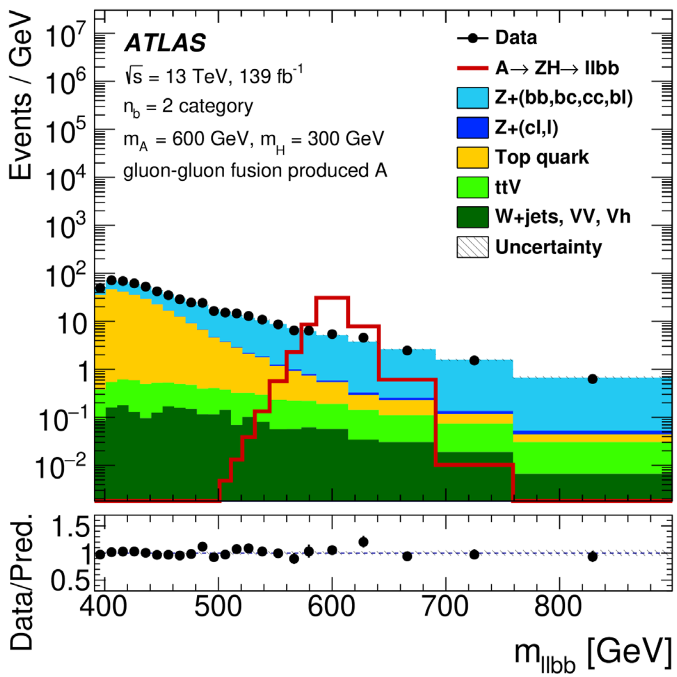
Search for A→ZH with H→bb

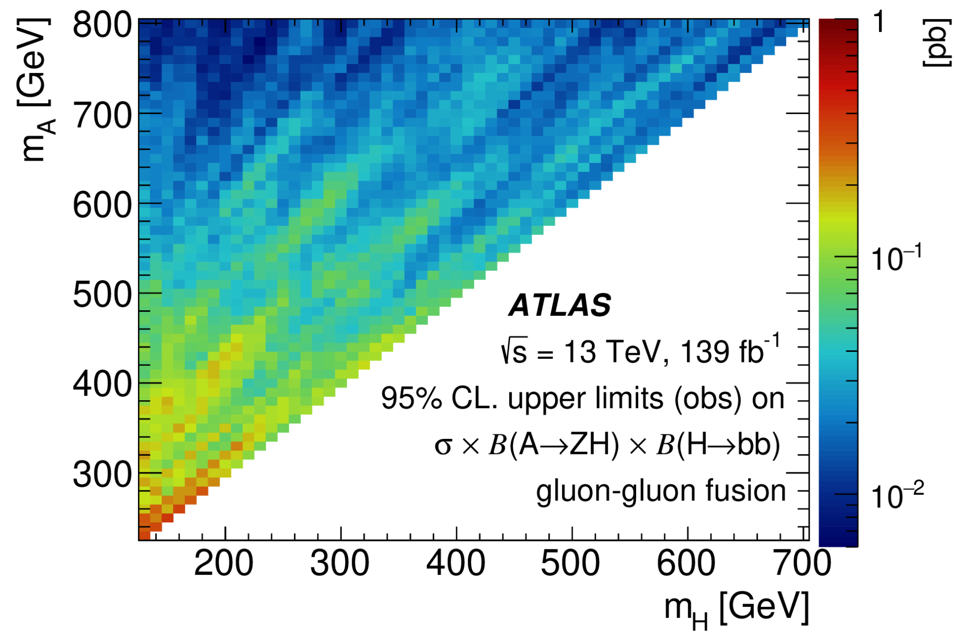


2HDM with $m_A > m_H > m_h$
Widths considered:
narrow for H,
up to 20% for A



Three resonances, full reconstruction
Main backgrounds: Z+jets, $t\bar{t}$
$m_{\ell\ell bb}$ as the final discriminant



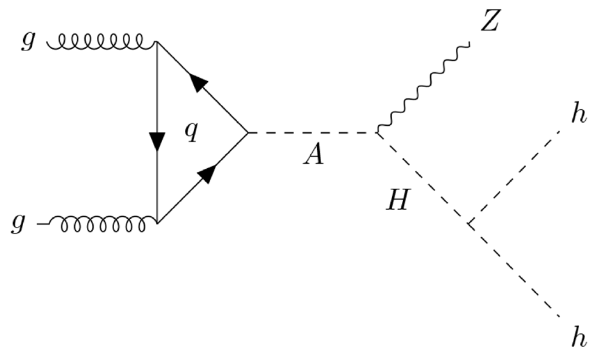


arXiv:2011.05639

Search for A→ZH→Zhh

Signal models: 2HDM, NW H and A width up to 20%

Signatures: 4 resonances, full reconstruction

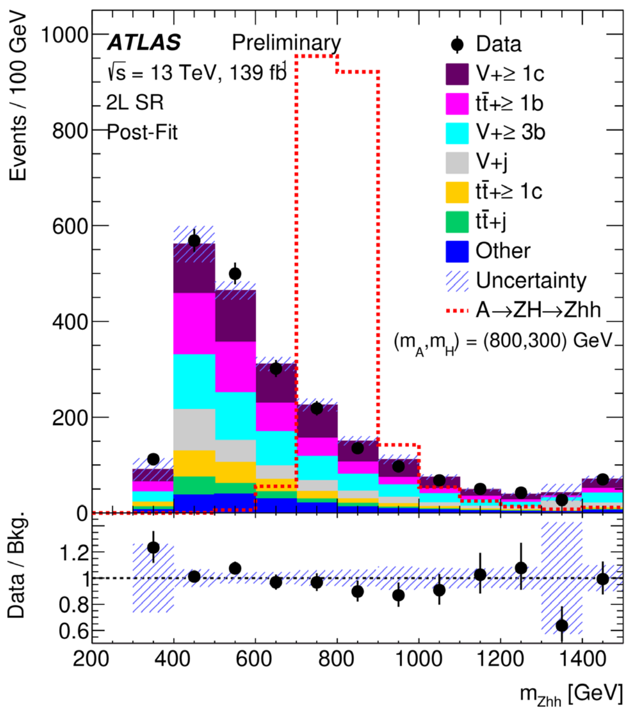


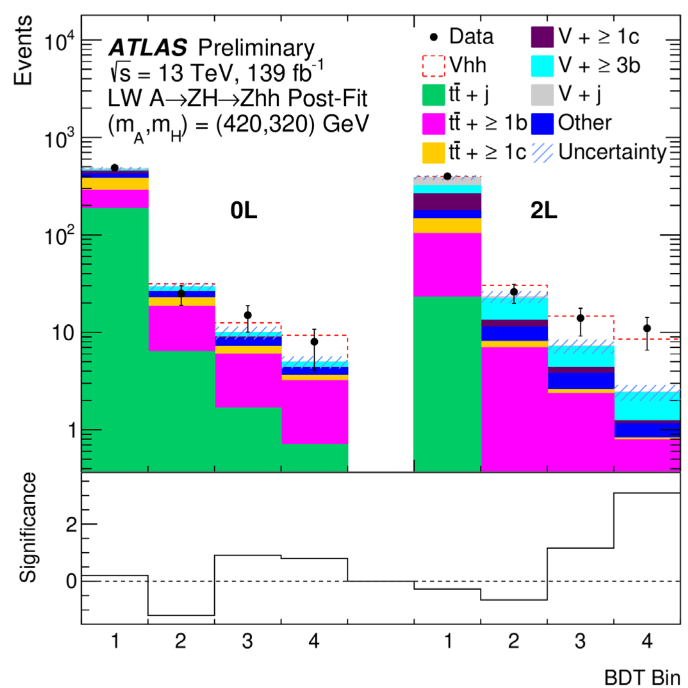
Main backgrounds: Z+jets

BDT for S-B separation and S extraction

Largest excess for a large-width (20%) A

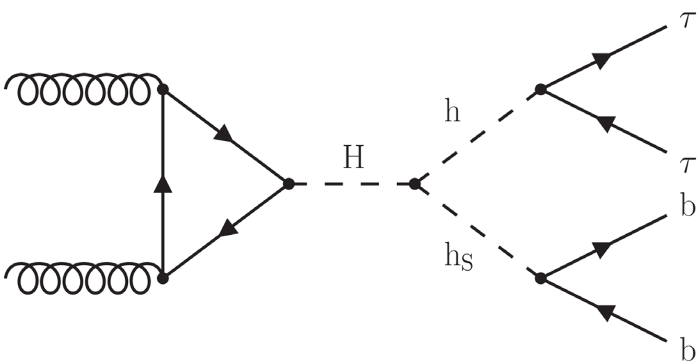
Observed (expected) significance of 3.8 (2.8)σ at $(m_A, m_H) = (420, 320)$ GeV





ATLAS-CONF-2022-043

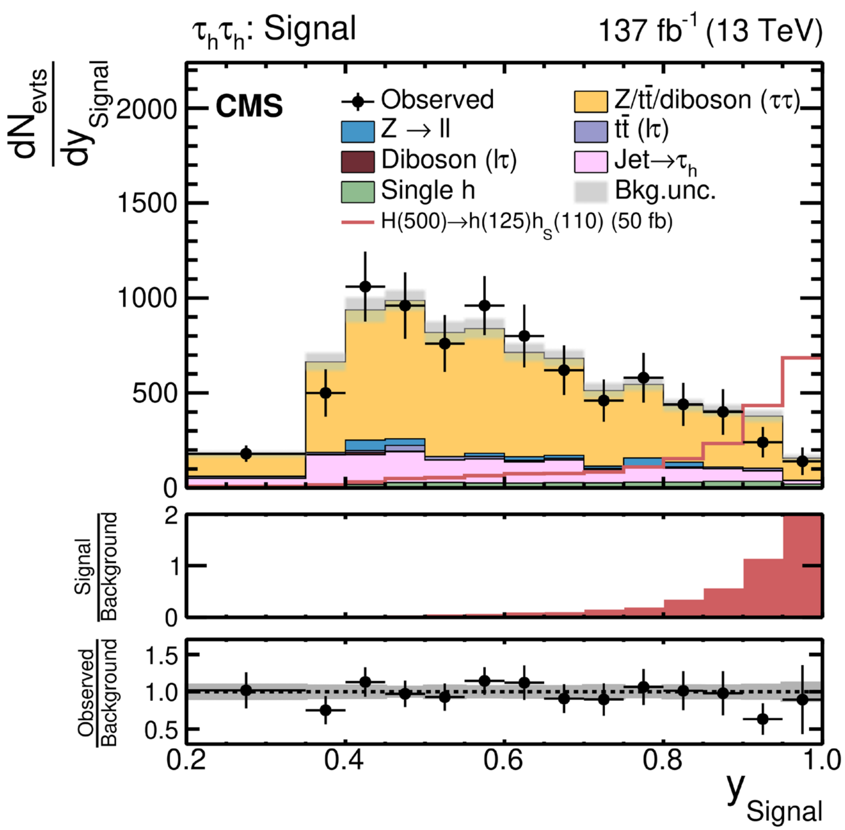
Search for $H \to h + h_s \to \tau\tau bb$

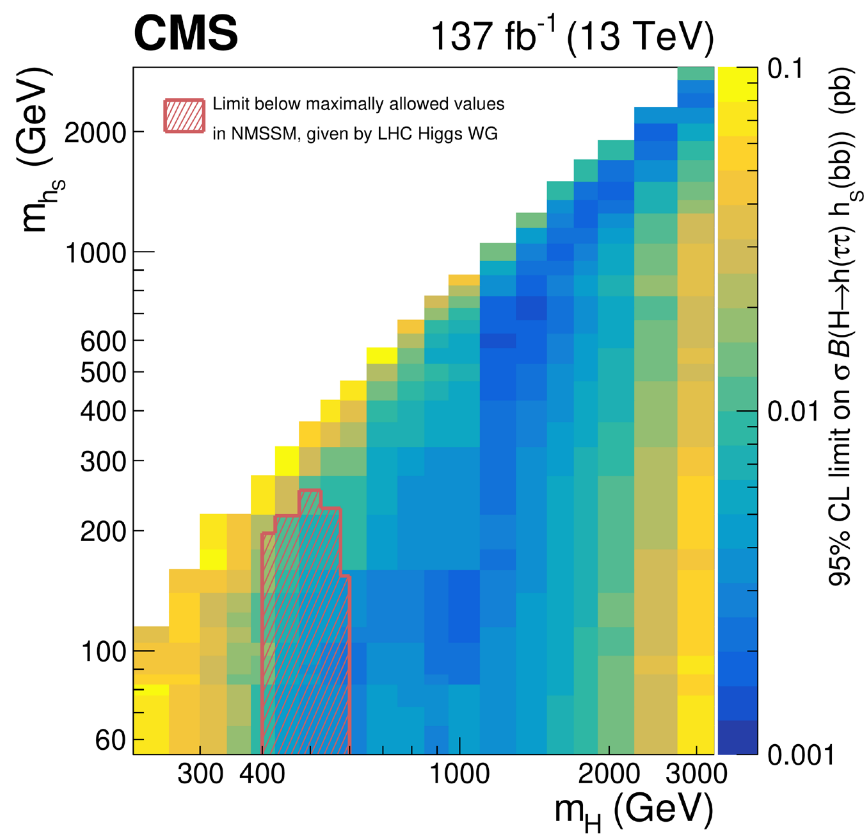


Final states: $(h \to \tau_\ell \tau_h,\ \tau_h \tau_h) + bb$

Main backgrounds: $\tau\tau(t\bar{t}, Z, \ldots) + \text{jets}$

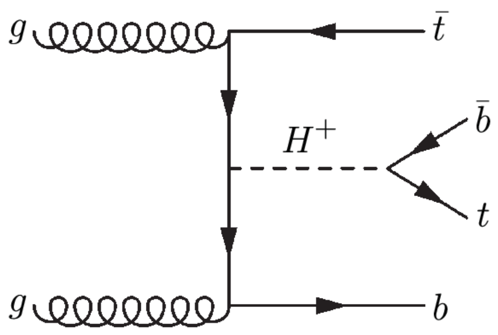
Neural networks to classify signal and background events and to extract signals





arXiv:2106.10361

Search for H±→tb

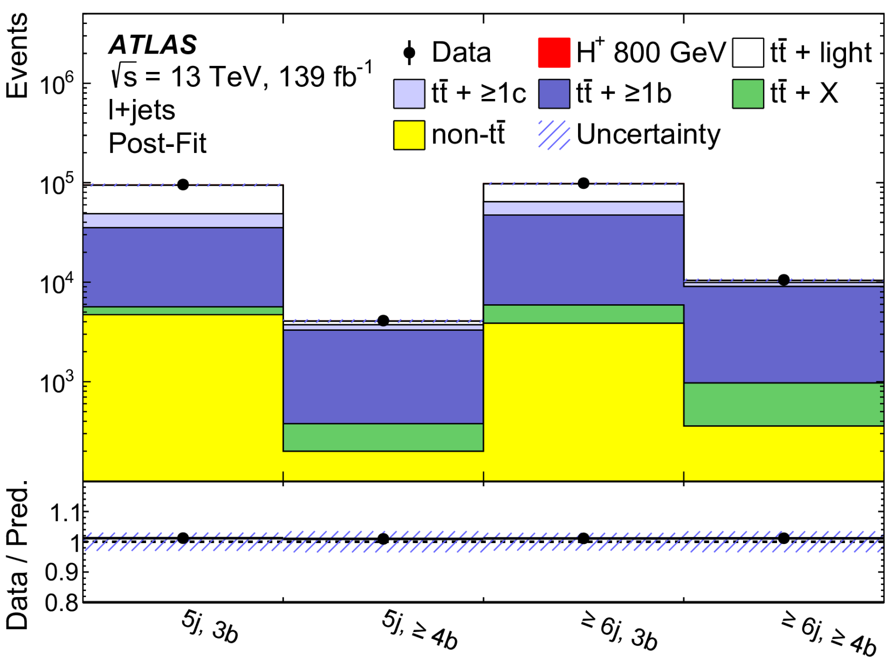


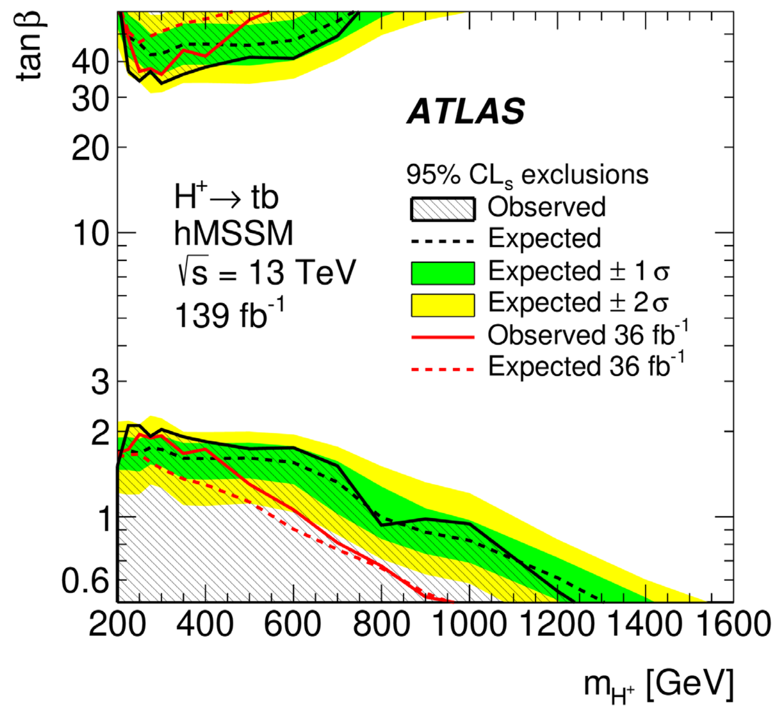
Signal models: MSSM $\left(\text{hMSSM}, m_h^{125}\right)$

Signatures: a (hard to reconstruct) $t\bar{b}$ resonance

Main background: $t\bar{t}$ +jets

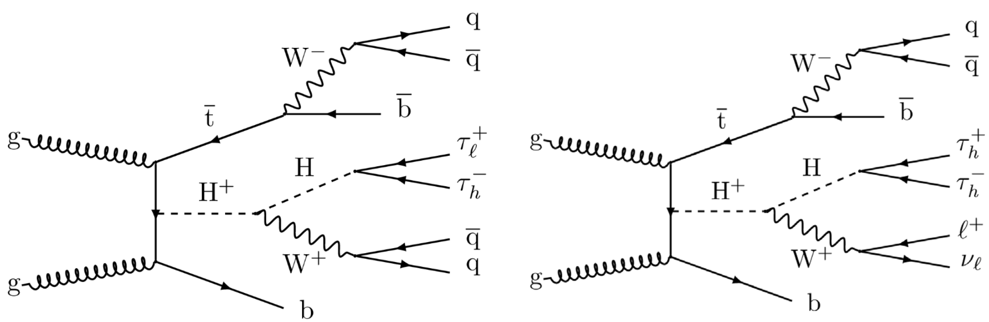
Neural network for S-B separation,





arXiv:2102.10076

Search for tH± with H±→W±h and h→ττ



$gg \to tbH^+,\ H^+ \to W^+h,\ h \to \tau\tau$

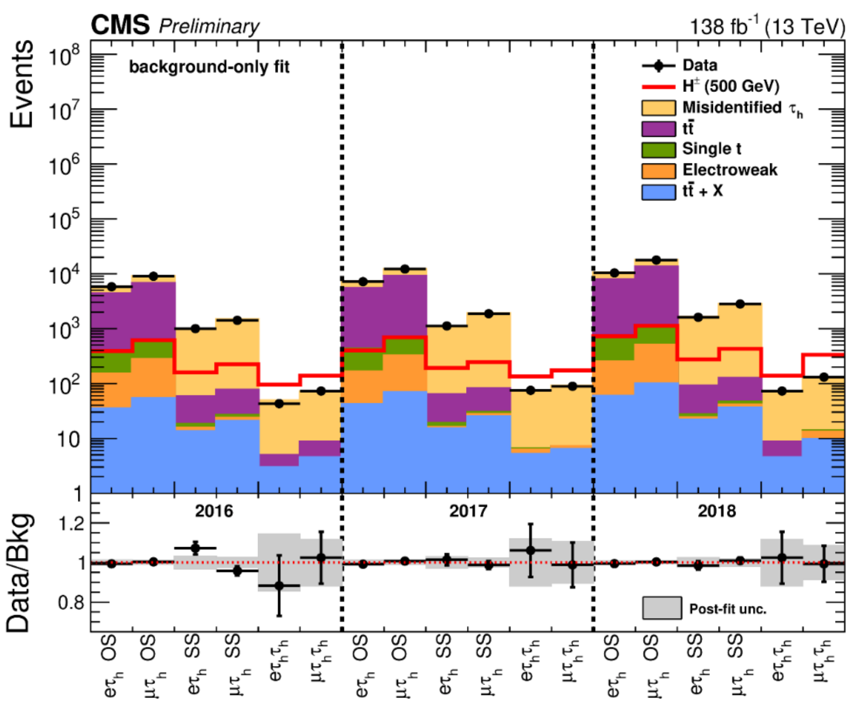
Final states: $\tau_\ell \tau_h (\tau_h)$

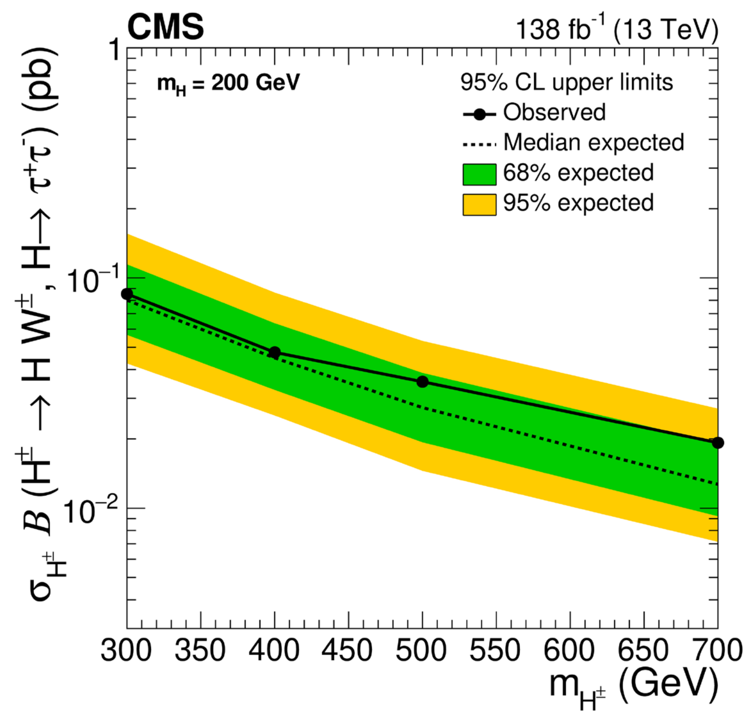
$h \to \tau_\ell \tau_h,\ \tau_h \tau_h$ reconstruction

Main backgrounds: $t\bar{t}$ and fake τ_h

Discriminant: BDT for $\tau_\ell \tau_h$ and

m_T for $\tau_\ell \tau_h \tau_h$





CMS-PAS-HIG-21-010

Summary

Extensive programs in searching for both non-SM decays of the 125 GeV Higgs boson and for additional Higgs bosons.

There are a few excesses here and there that need to be followed up in new data, but no strong evidence to claim BSM physics so far.

Despite of its success, the Standard Model is an incomplete theory. Hopefully cracks will appear sooner than later.

It is important to keep looking, in usual places as well as in unexpected places…