BSM Higgs Decays and Extended Higgs Sectors in CMS

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on behalf of CMS Collaboration

Boston University

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Outline

Will give a quick overview of several Beyond the Standard Model (BSM) Higgs searches:

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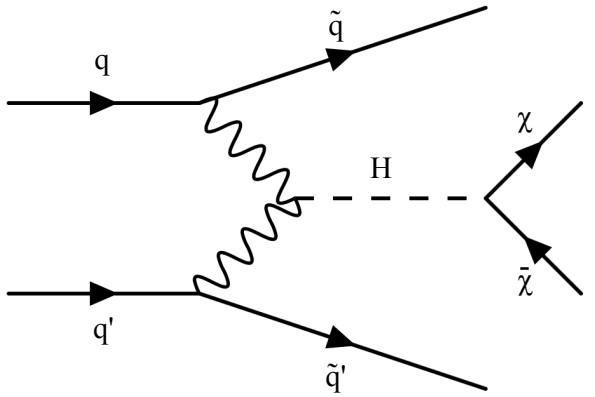
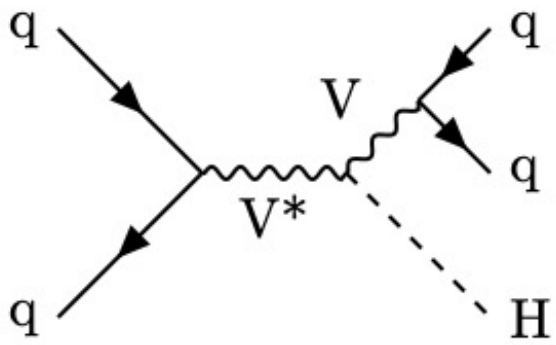
✓ BSM decays of H(125), Higgs portal model

- $VBF\ H$ production
- Monojet + Mono-V
- $Z(\ell\ell) + H$ production

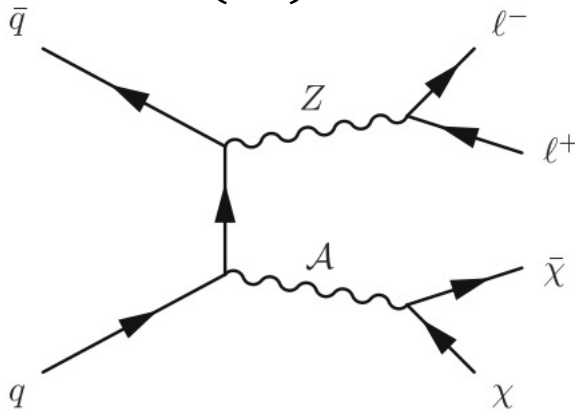
$VBF\ H$



Mono-V



$Z(\ell\ell) + H$



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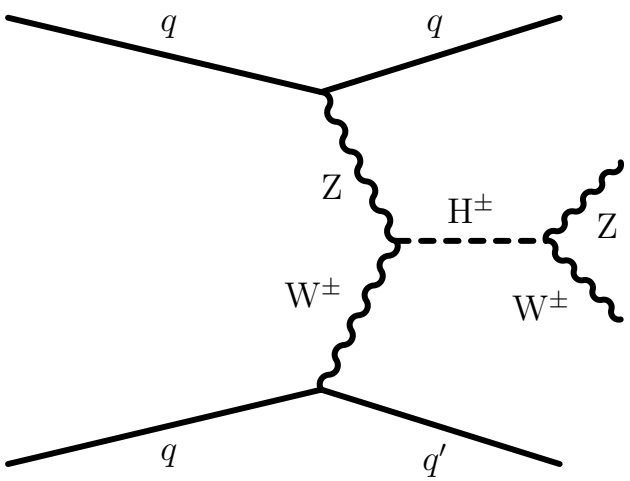
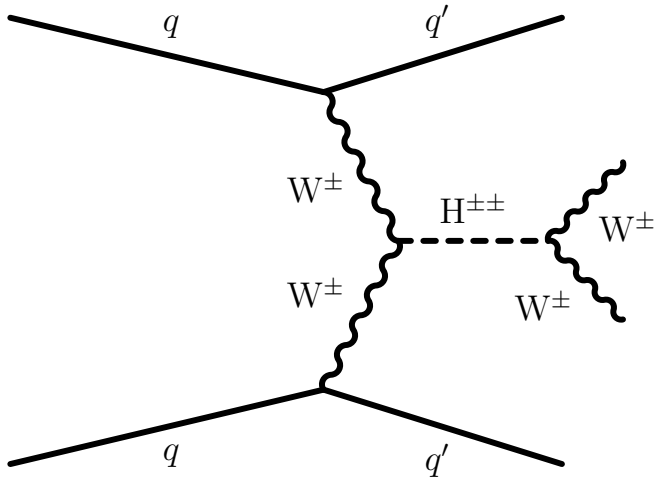
  - $Z(\ell\ell) + H$ production
- ✓ $H^{\pm}$ production

$H^{\pm}$ production with VBF





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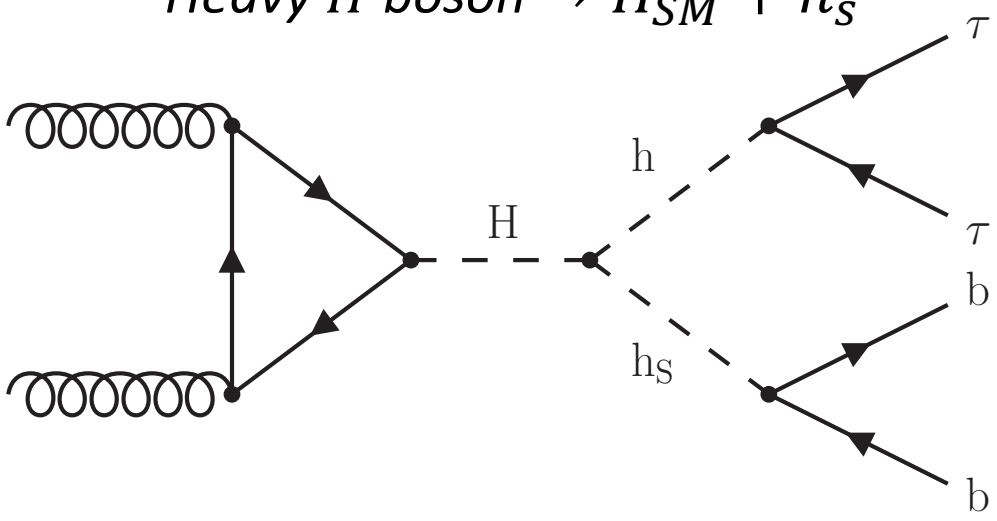
- ✓ $H^{\pm}$ production
- ✓ HH pair production: $H \rightarrow H_{SM} + h_s$

Heavy H boson $\rightarrow H_{SM} + h_s$



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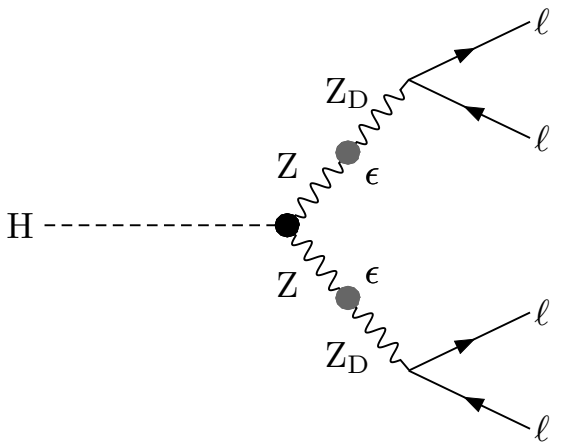
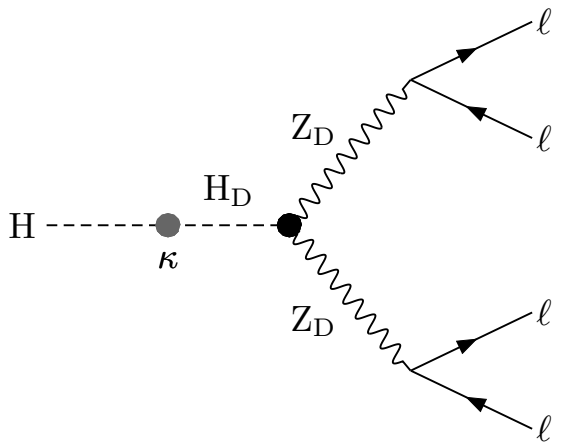
- ✓ $H^{\pm}$ production
- ✓ HH pair production: $H \rightarrow H_{SM} + h_s$
- ✓ $H \rightarrow Z_D Z_D$ (long-lived dark photon)





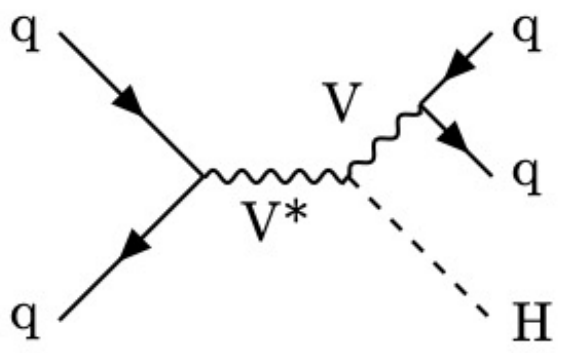
BSM Decays of H(125): Higgs Portal Models

BSM Decays of H(125): Higgs Portal Models

H bosons are the mediator between SM and BSM physics

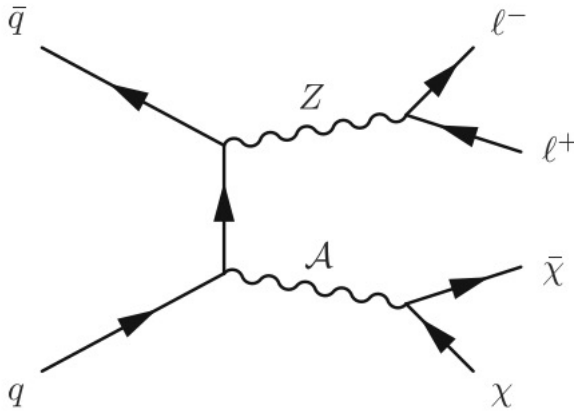
Often interpreted as $BR(H_{SM} \rightarrow inv) \rightarrow$ The only parameter in such models

Searches focus on different production channels:



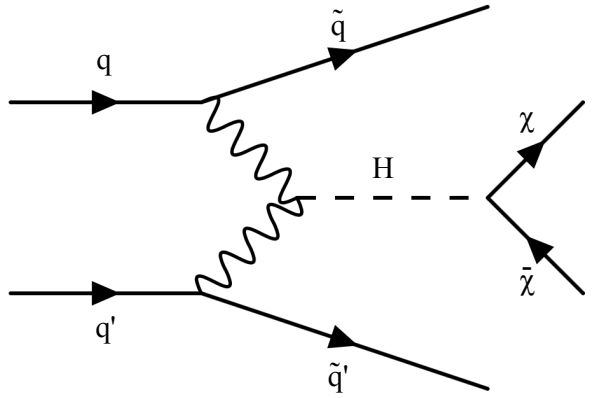
Monojet + Mono-V

JHEP11(2021)153



Mono-Z

EPJC 81, 13 (2021)

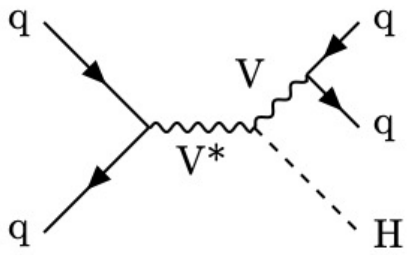


VBF H(inv)

arXiv:2201.11585

BSM Decays of H(125): Monojet + Mono-V

JHEP11(2021)153



Signature:

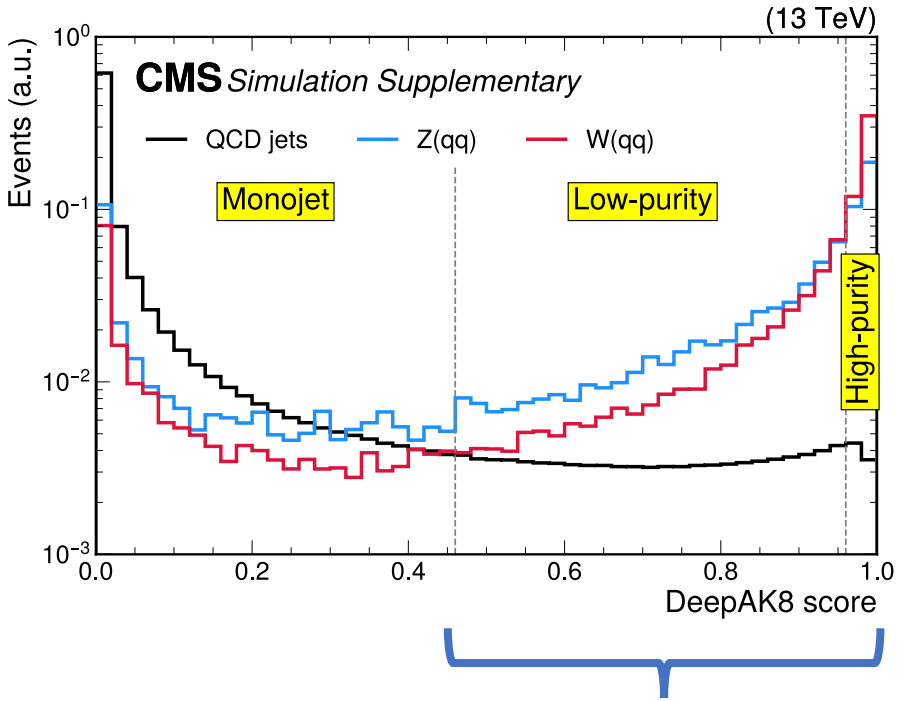
One energetic & central jet

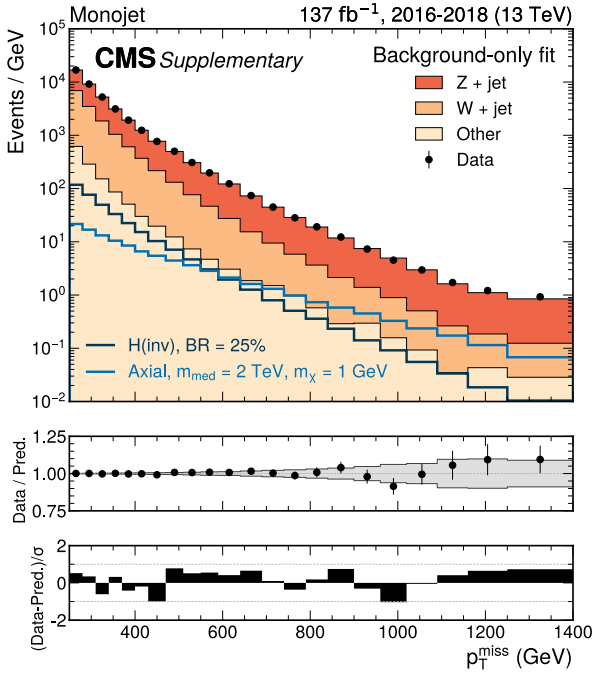
$+ p_T^{miss} > 250\ GeV$

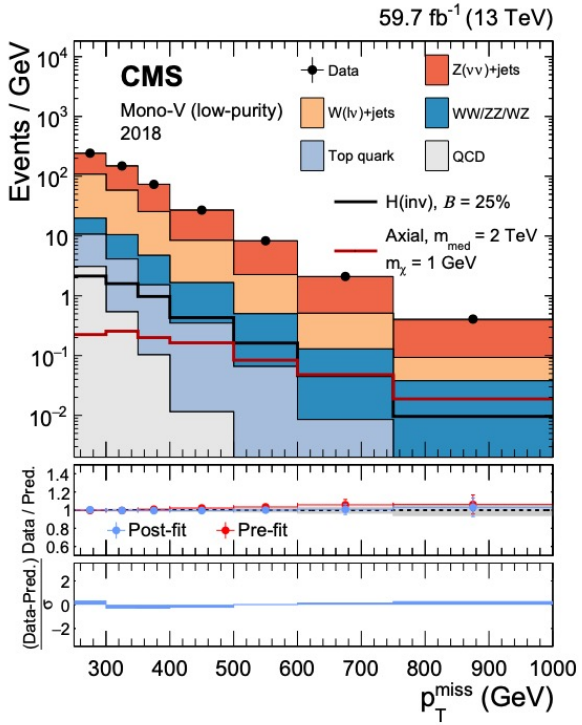
Major backgrounds: $V + jet$

Estimated from dedicated $V \rightarrow leptons + jet$ control regions

Events categorized as monojet/mono-V depending on the AK8 score of the tagged jet:





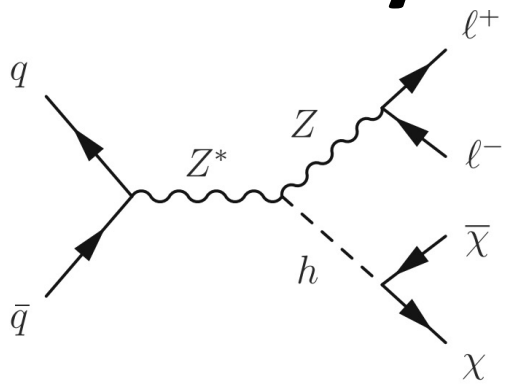


Good agreement between data and background predictions

Mono-V

BSM Decays of H(125): Mono-Z

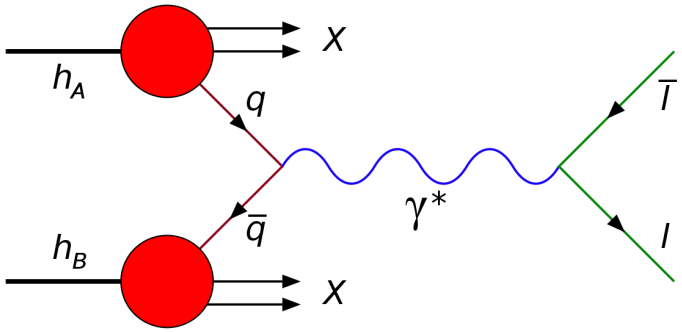
EPJC 81, 13 (2021)



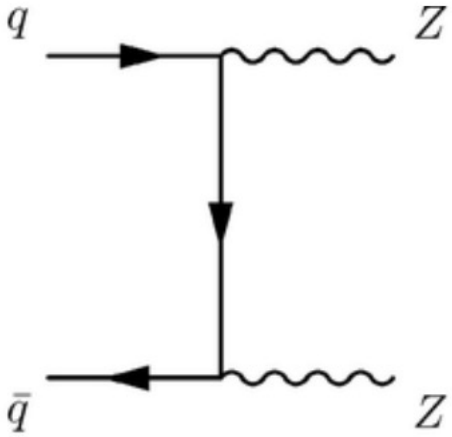
Signature: Two e/μ from Z decay + p_T^{miss}

Major backgrounds:

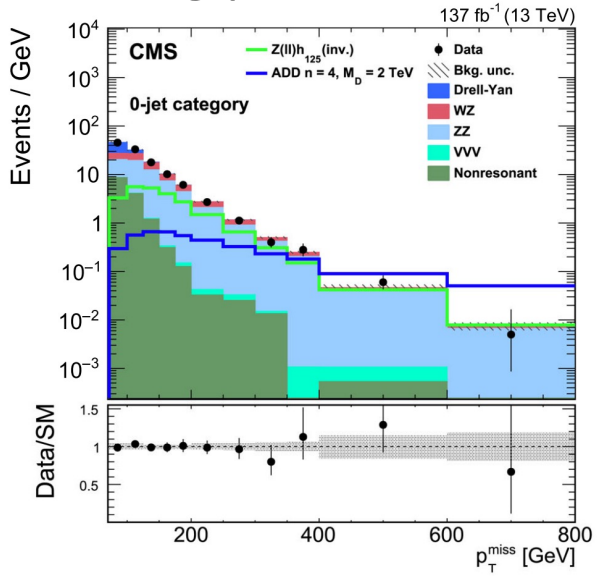
DY production @ low p_T^{miss}



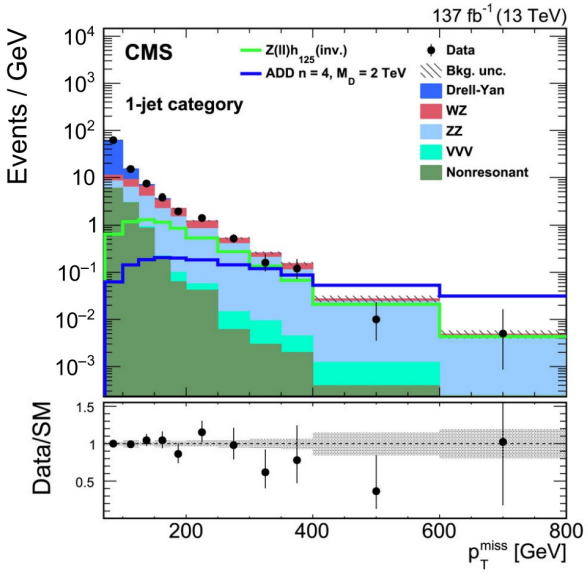
Diboson processes e.g. $ZZ \rightarrow 2\ell, 2\nu$



Good agreement between data & bkg predictions:



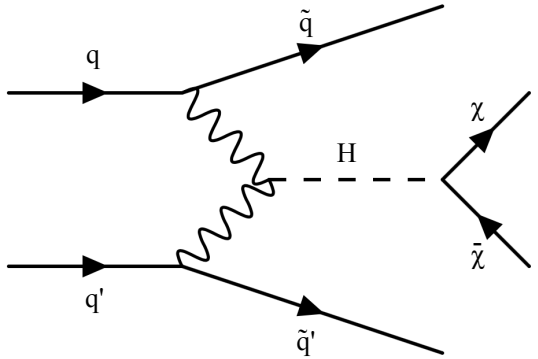
0-jet



1-jet

BSM Decays of H(125): VBF $H \rightarrow inv.$

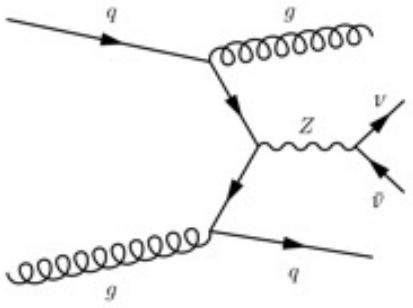
arXiv:2201.11585



Key backgrounds:

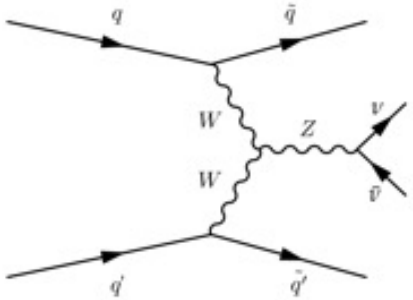
$V + jets$

"QCD" V+jets



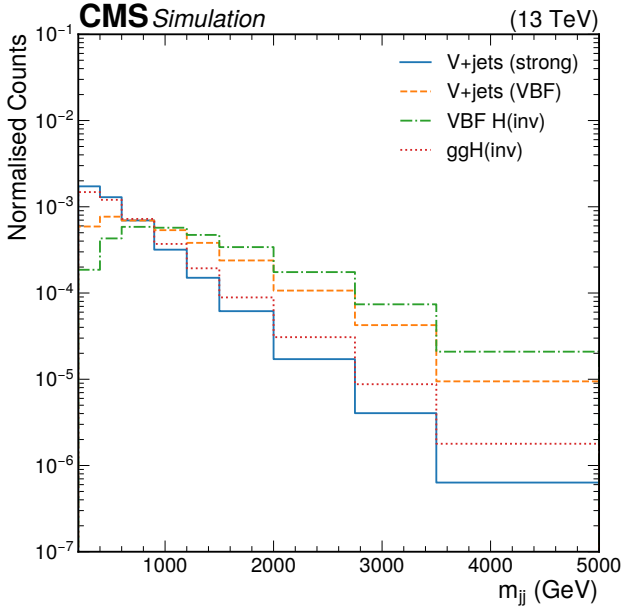
Larger σ, falling m_{jj} spectra

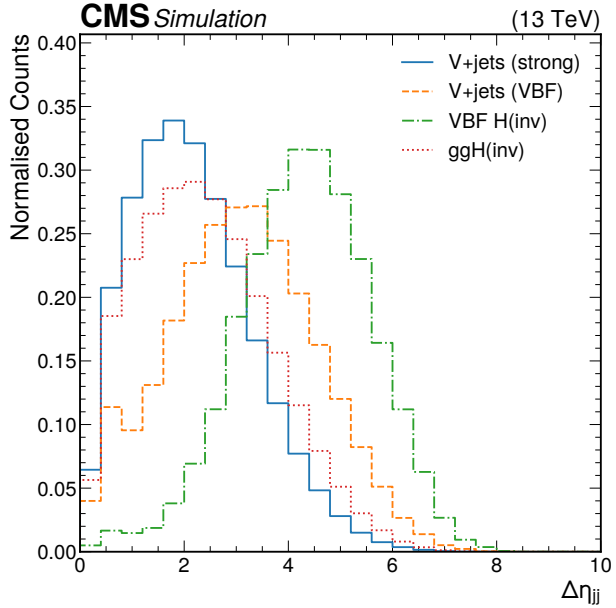
"EWK" V+jets



Important @ high m_{jj}

Dijet variables show discrimination between the VBF H process and major backgrounds:



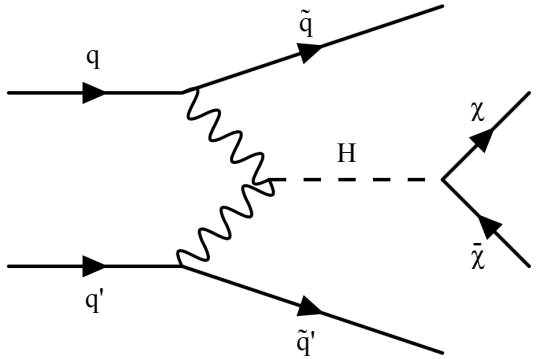


→ Unique signature from VBF H

Strategy: Estimate the backgrounds and do a fit as a function of m_{jj}

BSM Decays of H(125): VBF $H \rightarrow inv.$

arXiv:2201.11585

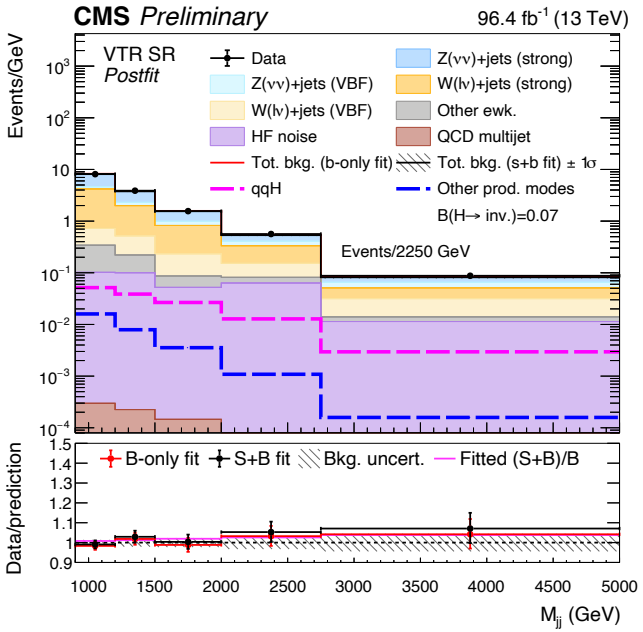


New in 2017+2018 analysis!

Data & background predictions in VBF SR:

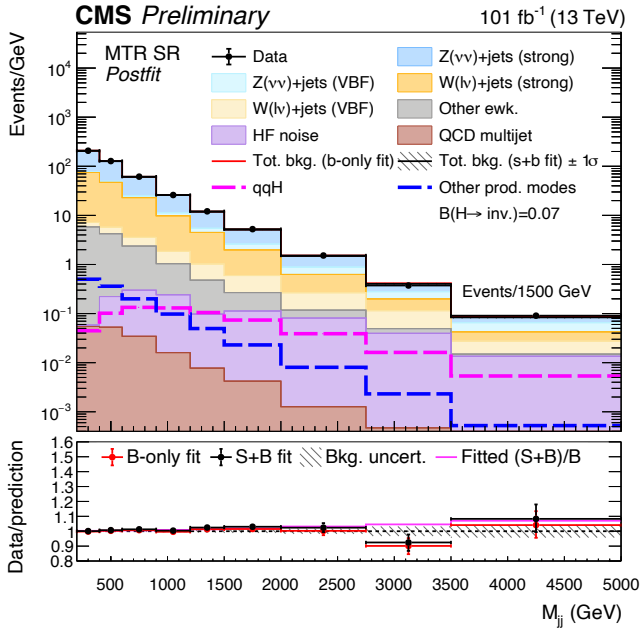
VBF-triggered category

$160 < p_T^{miss} < 250\ GeV$



MET-triggered category

$p_T^{miss} > 250\ GeV$



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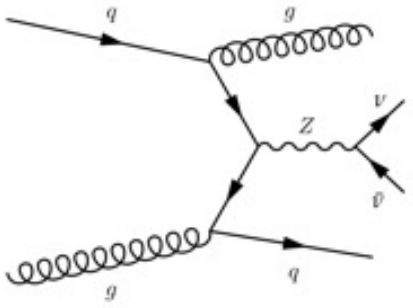

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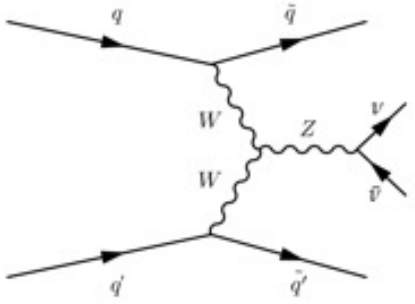


Important @ high m_{jj}

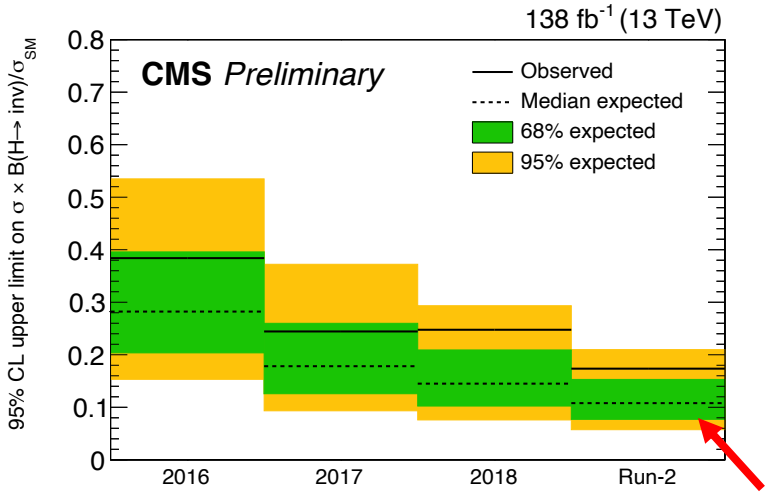
Agreement within $\approx 1\sigma$ between data and background in all regions

Higgs Portal Interpretations

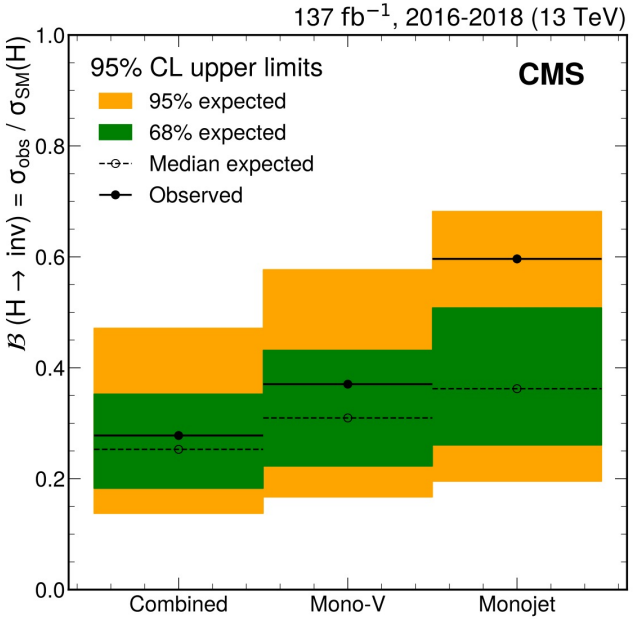
arXiv:2201.11585
JHEP11(2021)153
EPJC 81, 13 (2021)

Results are interpreted as limits on $B(H_{SM} \to inv)$:

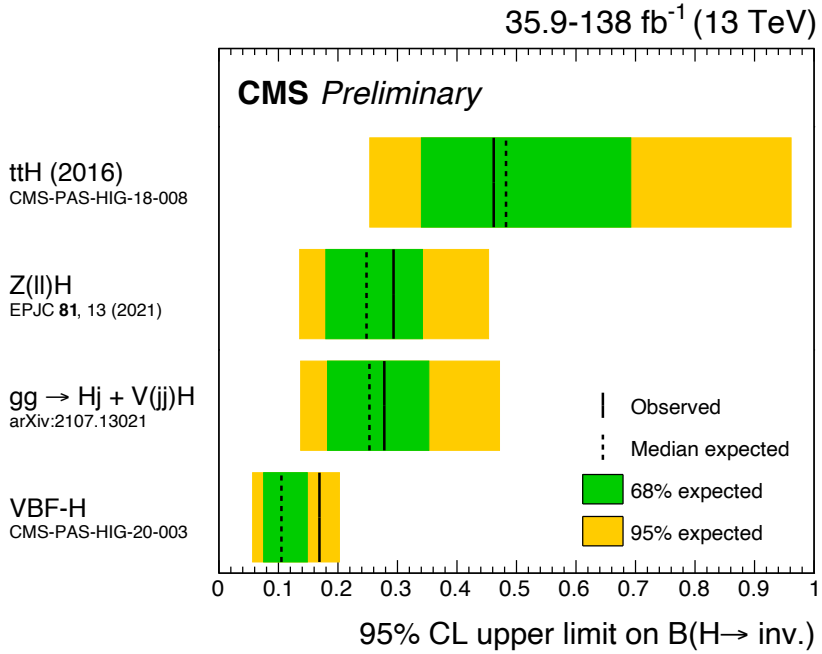
VBF H(inv)



Monojet + mono-V



Summary for all:



VBF H is the leading channel in the sensitivity: Unique dijet signature
→ Reaching to 17% of observed limit (1.5σ above the expected)

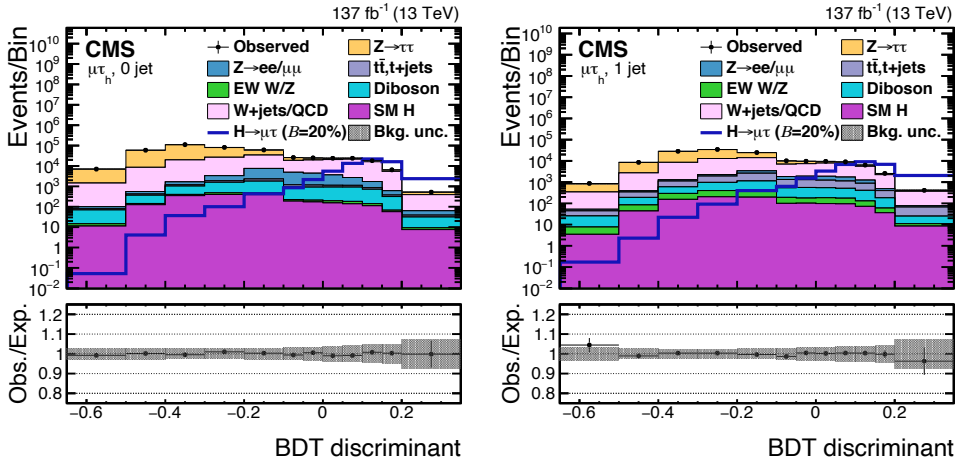
Full Run 2 analyses from CMS are out, combination between channels is ongoing
→ Aiming to probe $\sim 10\%$ for $B(H \to inv)$ with the combination

Other BSM H Decays: LFV Decays

Phys. Rev. D 104 (2021) 032013
JHEP06(2018)001

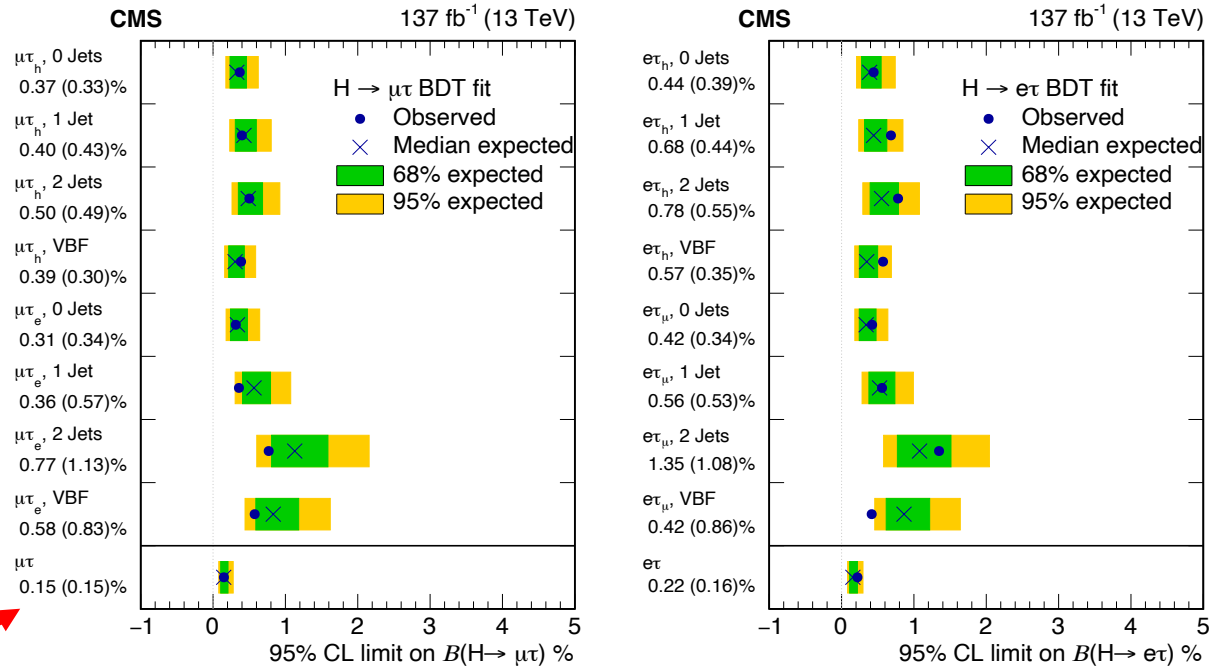
More searches on BSM decays of H_{SM}: Lepton flavor violating (LFV) decays: $H \to e\tau, \mu\tau$

BDTs are used to distinguish signal from backgrounds, fitting done on BDT score:



Different categories based on $N_{jet} = 0,1,2$

Exclusion results from a fit to the BDT score distribution:



All combined

Improvement from earlier results: $B(H \to e\tau) = 0.72\%$

→ Larger dataset, better background estimation/classification with BDTs

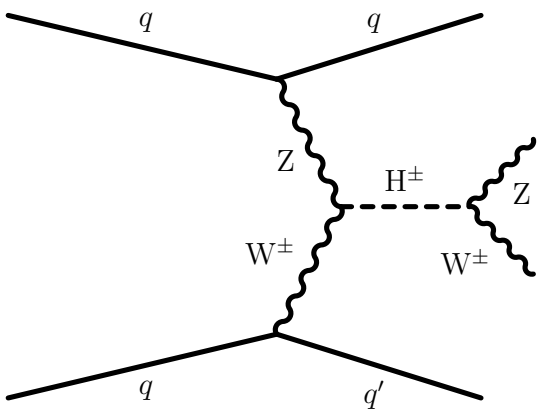
$H^{\pm}$ Search

$H^{\pm}$ Search: $VBF\ H \rightarrow VV$

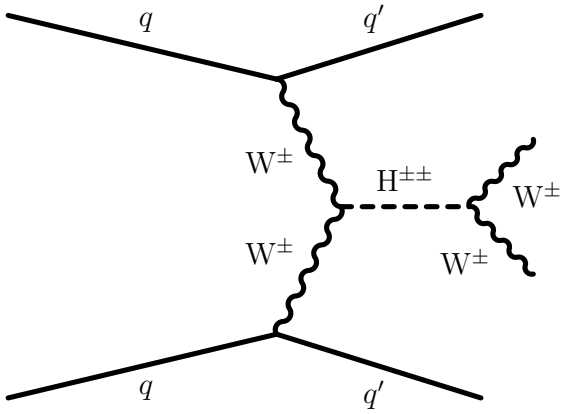
Eur. Phys. J. C (2021) 81:723

$H^{\pm}$ search with VBF production:

Singly charged H



Doubly charged H



Decay modes:

$H^{\pm} \rightarrow W^{\pm}Z, H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$

where $W^{\pm}, Z$ decay leptonically

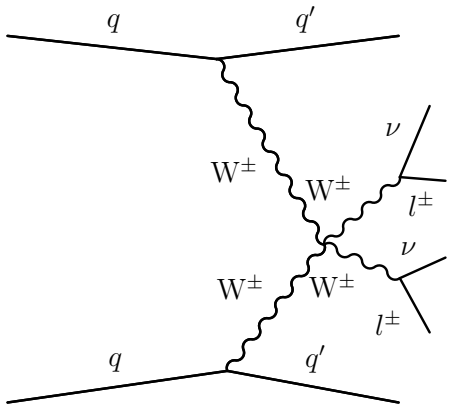
Candidate events:

$N_{\ell} \in \{2,3\}$

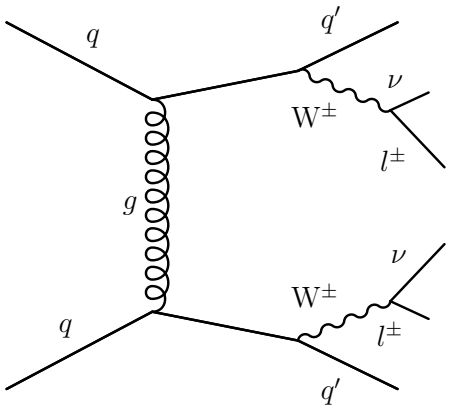
Moderate p_T^{miss}, high $\Delta\eta_{jj}, m_{jj}$

→ Analysis with full Run2 data

Major backgrounds:



EW induced diboson production, $O(\alpha_{EW}^4)$



QCD induced diboson production, $O(\alpha_{EW}^2 \alpha_s^2)$

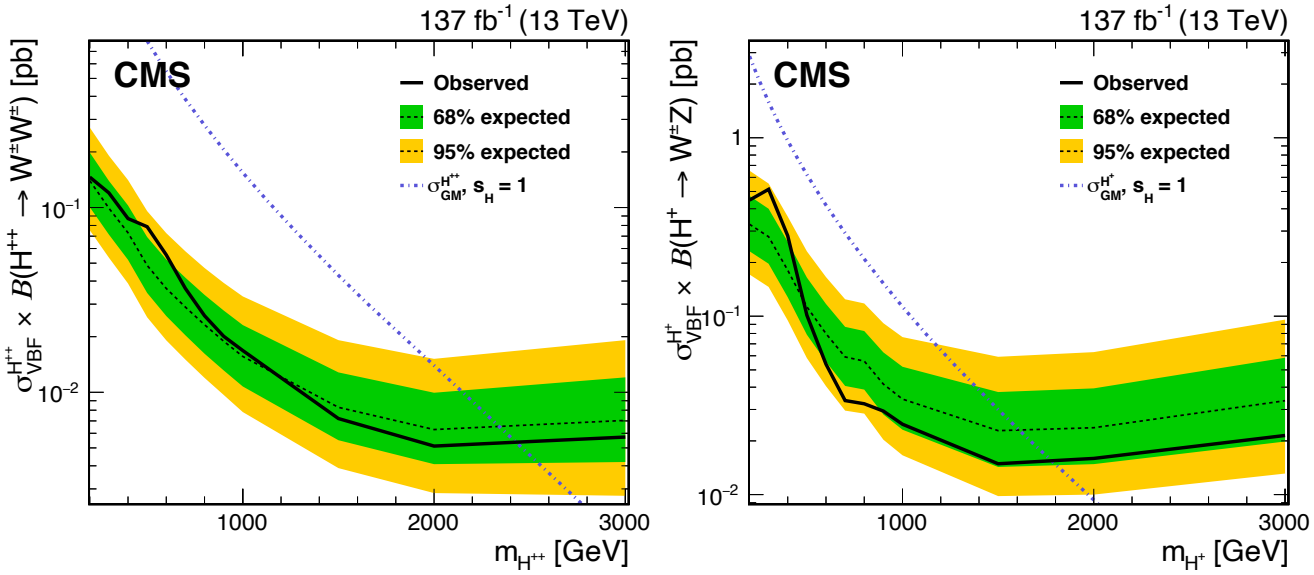
$H^{\pm}$ Search: $VBF\ H \rightarrow VV$

Eur. Phys. J. C (2021) 81:723

Exclusion limits are derived for the cross sections of $H^{\pm}, H^{\pm\pm}$ production

Exclusions up to

$m_{H^+} \approx 1.8\,TeV, m_{H^{++}} \approx 2.4\,TeV$



$H^{\pm}$ Search: $VBF\ H \rightarrow VV$

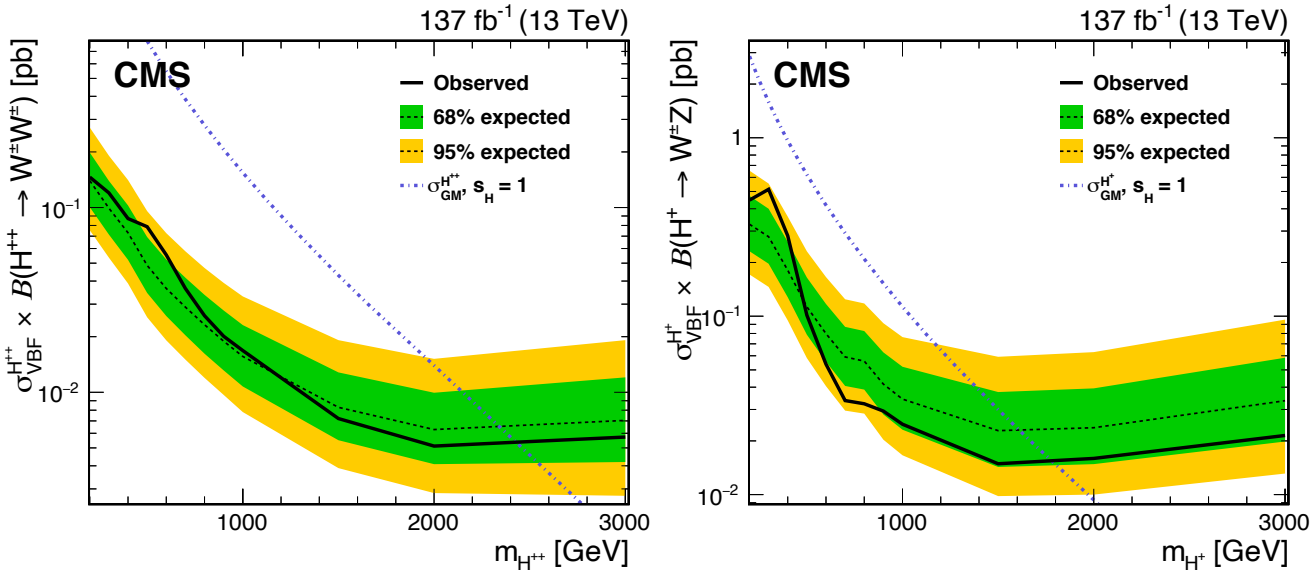
Eur. Phys. J. C (2021) 81:723
Nucl. Phys. B 262, 463

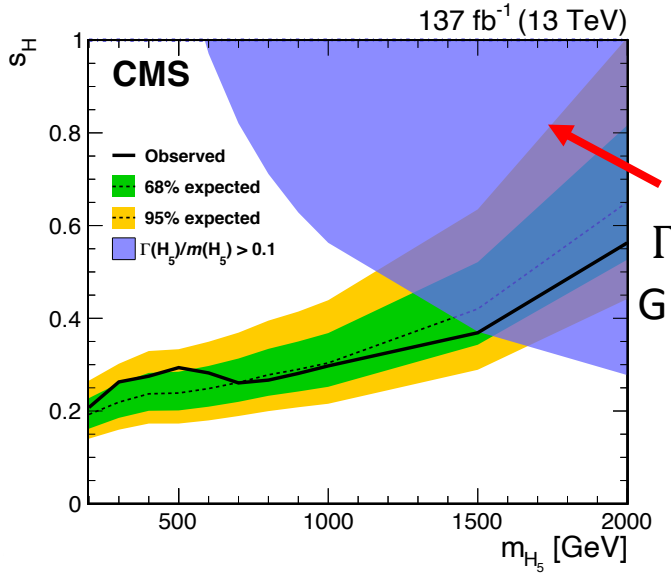
Exclusion limits are derived for the cross sections of $H^{\pm}, H^{\pm\pm}$ production
Exclusions up to
$m_{H^+} \approx 1.8\,TeV, m_{H^{++}} \approx 2.4\,TeV$

Also interpreted in the context of Georgi-Machacek (GM) model
→ 2D parameter grid m_{H_5}, s_H

s_H values $> [0.2 - 0.35]$ range are excluded

→ Improvement over the earlier CMS results which exclude $s_H > [0.4 - 0.5]$ range





$\Gamma_{H_5} > 0.1 \times m_{H_5}$
GM not applicable

HH Pair Production

Pair Production: $H \rightarrow h_S h$

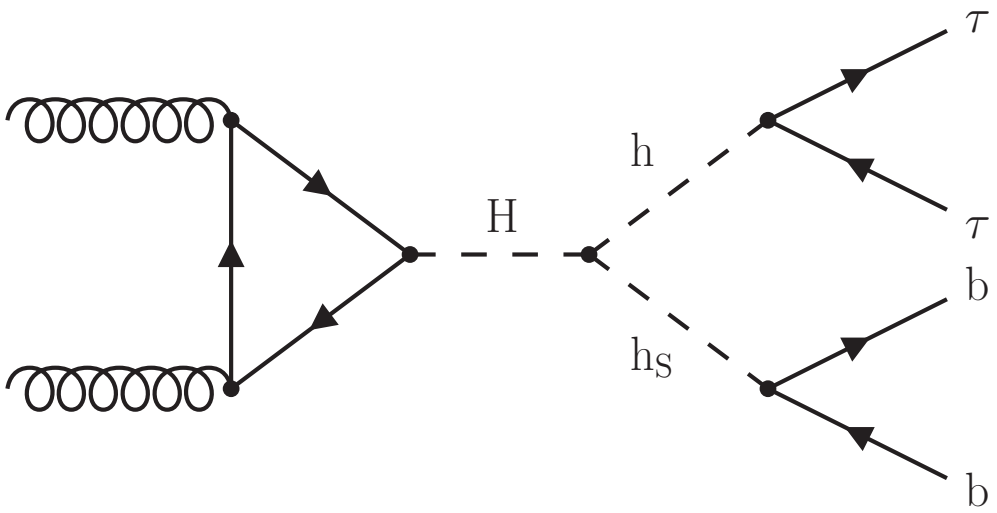
JHEP 11 (2021) 057

$pp \rightarrow H \rightarrow h_s h \rightarrow \tau\tau bb$ search:
h: Observed Higgs boson $\rightarrow \tau\tau$, $h_s \rightarrow bb$

Parameter space:

$60 \leq m_{h_s} \leq 2800\ GeV$

$240 \leq m_H \leq 3000\ GeV$



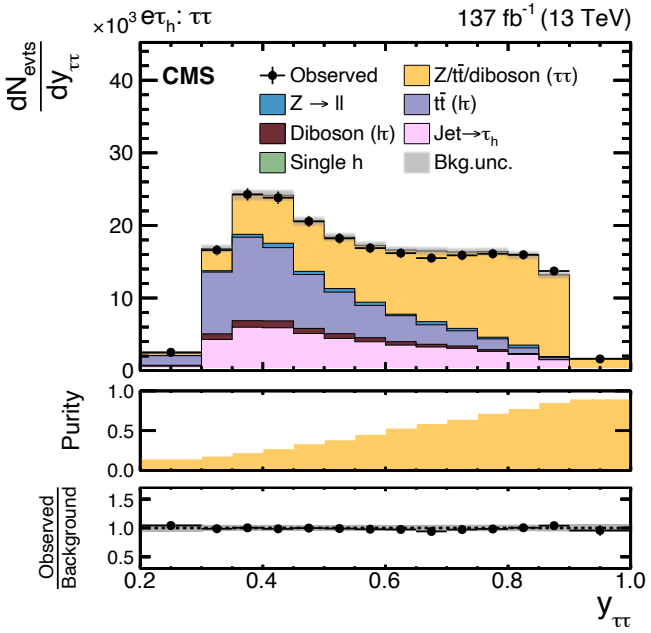
A fully-connected NN is used to group events into signal and multiple background categories

Input features: 20 features including $N_{b-jet}, p_T^{\tau,j}$

Score distributions for some categories shown below:

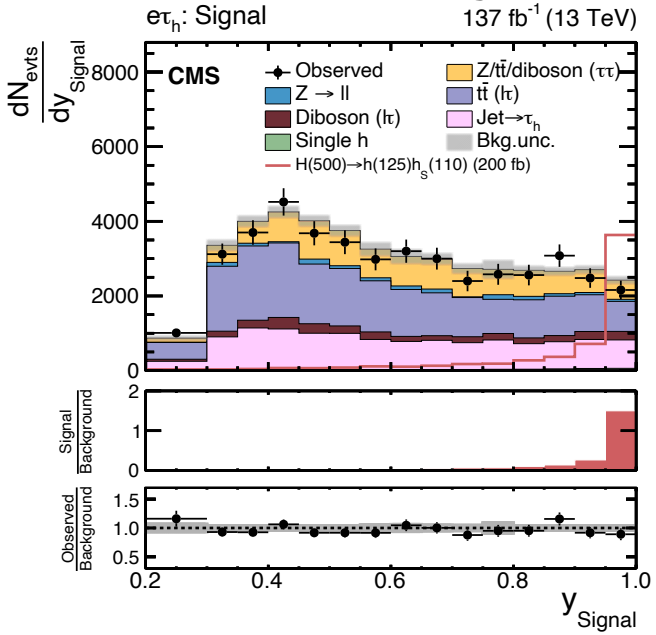
ττ bkg category:

$Z, h \rightarrow \tau\tau$



Signal category:

$H \rightarrow hh_s$



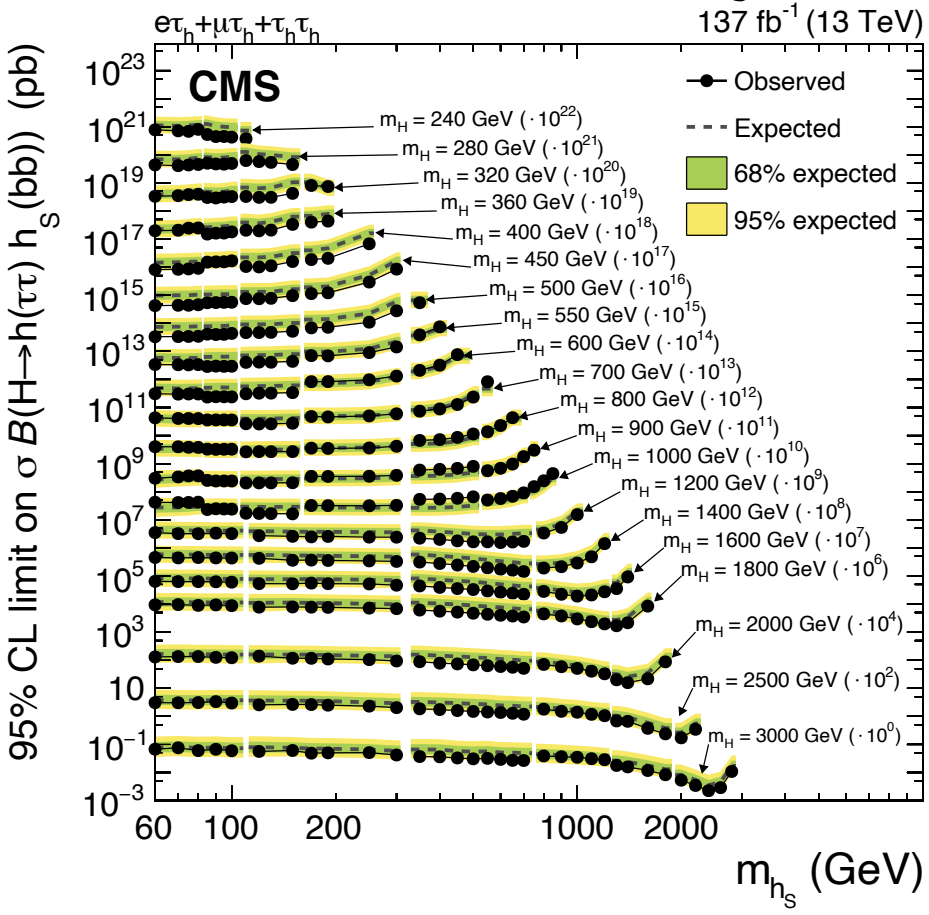
→ Binned likelihood fit over all categories for signal extraction

Pair Production: $H \rightarrow h_S h$

JHEP 11 (2021) 057

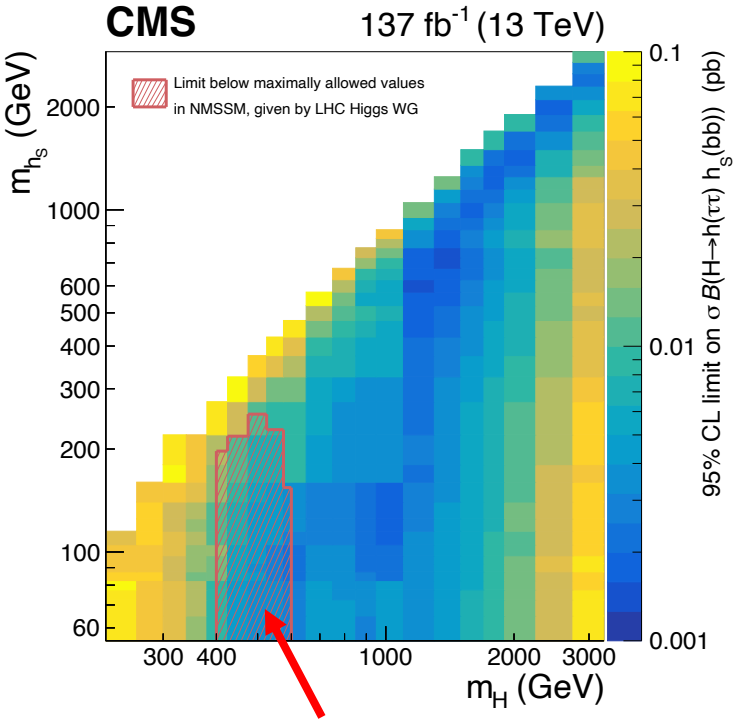
No signal-like excess is observed in data
Limits on $\sigma \times B(H \rightarrow h(\tau\tau)h_s(bb))$ are placed

Exclusion results for (m_H, m_{h_s}) pairs:



First exclusion limits on $H \rightarrow h(\tau\tau)h_s(bb)$ from CMS!

Summary of observed limits:



Observed limit below the maximally allowed value in NMSSM (next-to-minimal SUSY SM)

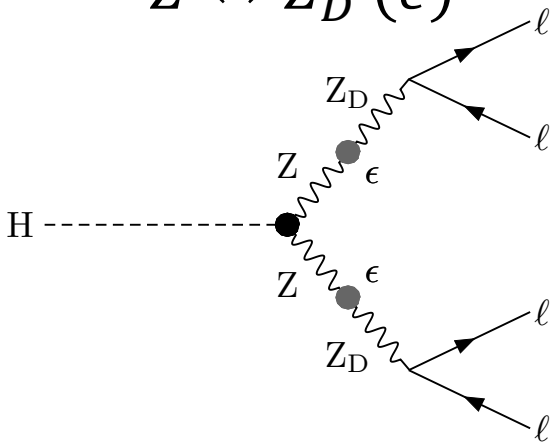
Long-Lived Particle Searches:
$H \rightarrow Z_D Z_D$

LLP Search: $H \rightarrow Z_D Z_D$

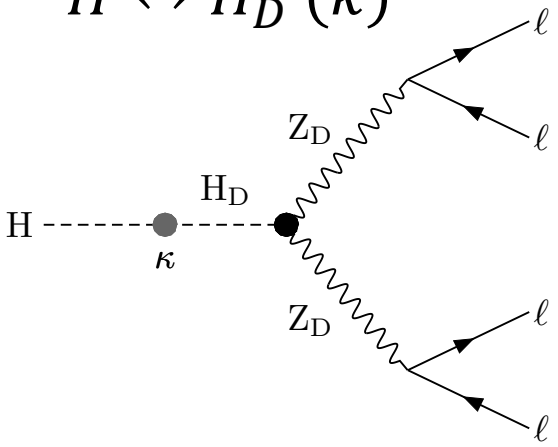
JHEP 04 (2022) 062

Interaction between SM & dark sector through:

$Z \leftrightarrow Z_D\ (\epsilon)$



$H \leftrightarrow H_D\ (\kappa)$



Z_D boson is expected to be long-lived if $\epsilon \lesssim 10^{-4}$

This search:

Long-lived dimuon resonances with 2017+2018 data, 101 fb^{-1}

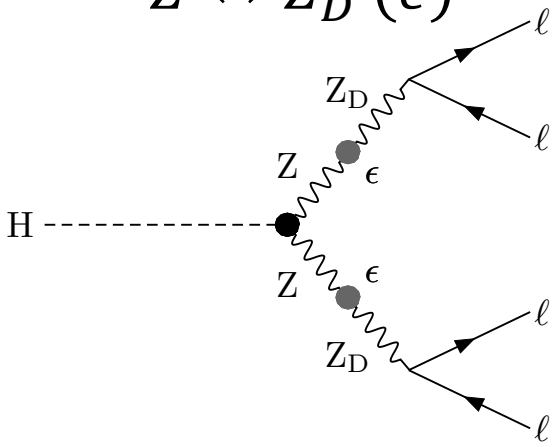
→ Displaced decays of $Z_D(\mu\mu)$

LLP Search: $H \rightarrow Z_D Z_D$

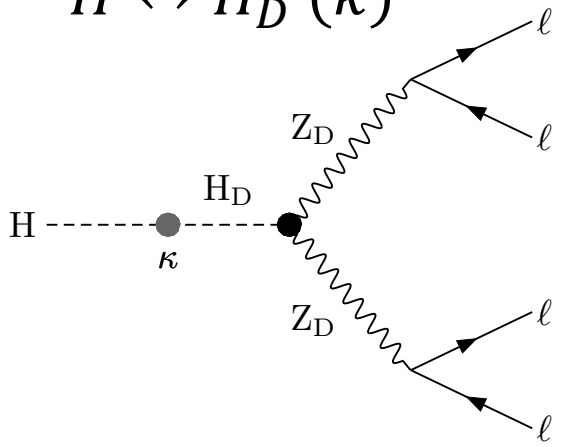
JHEP 04 (2022) 062

Interaction between SM & dark sector through:

$Z \leftrightarrow Z_D\ (\epsilon)$



$H \leftrightarrow H_D\ (\kappa)$



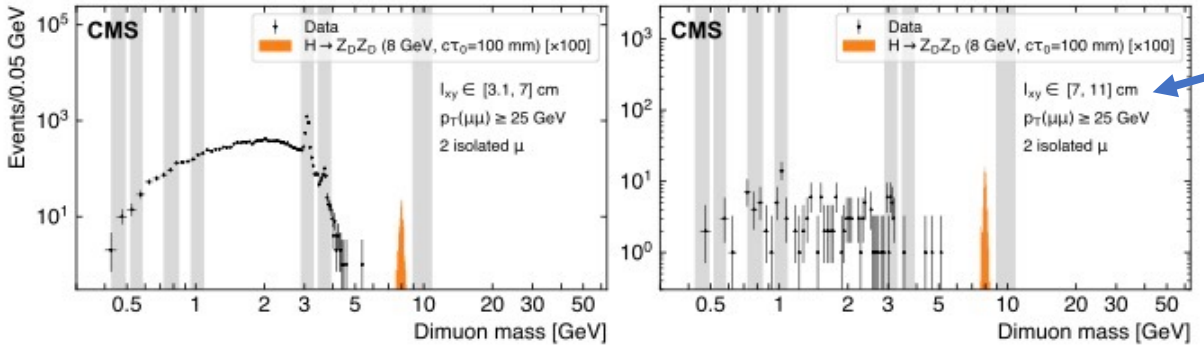
Z_D boson is expected to be long-lived if $\epsilon \lesssim 10^{-4}$

This search:

Long-lived dimuon resonances with 2017+2018 data, 101 fb^{-1}

→ Displaced decays of $Z_D(\mu\mu)$

Observed $m_{\mu\mu}$ distributions and the signal (just 2 categories are shown):



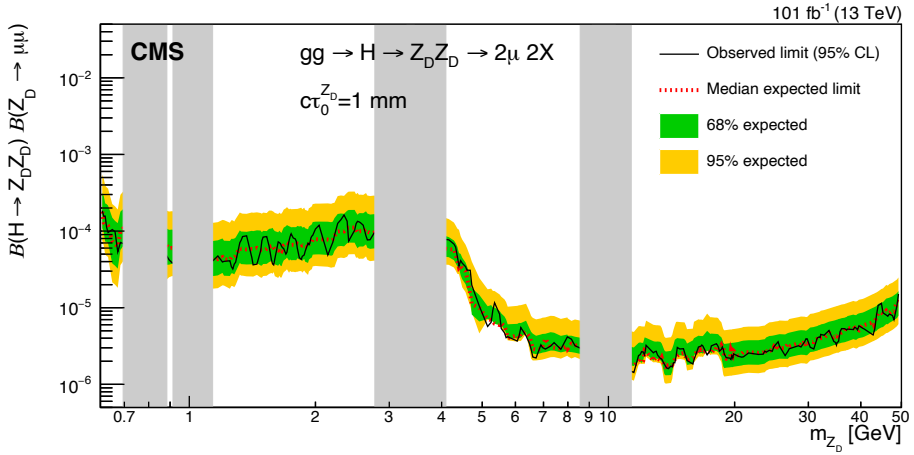
Binned in PV, SV separation

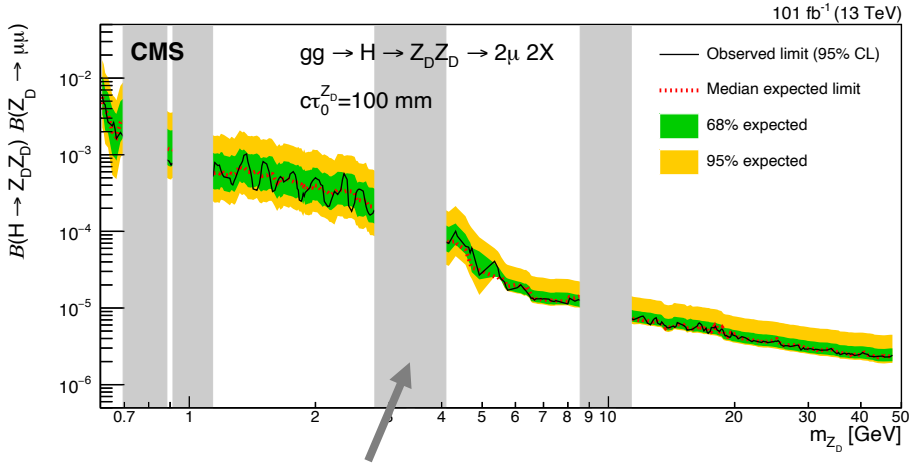
→ No signal-like excess is observed

LLP Search: $H \rightarrow Z_D Z_D$

JHEP 04 (2022) 062

95% CL limits are placed on $B(H \rightarrow Z_D Z_D) \times B(Z_D \rightarrow \mu\mu)$

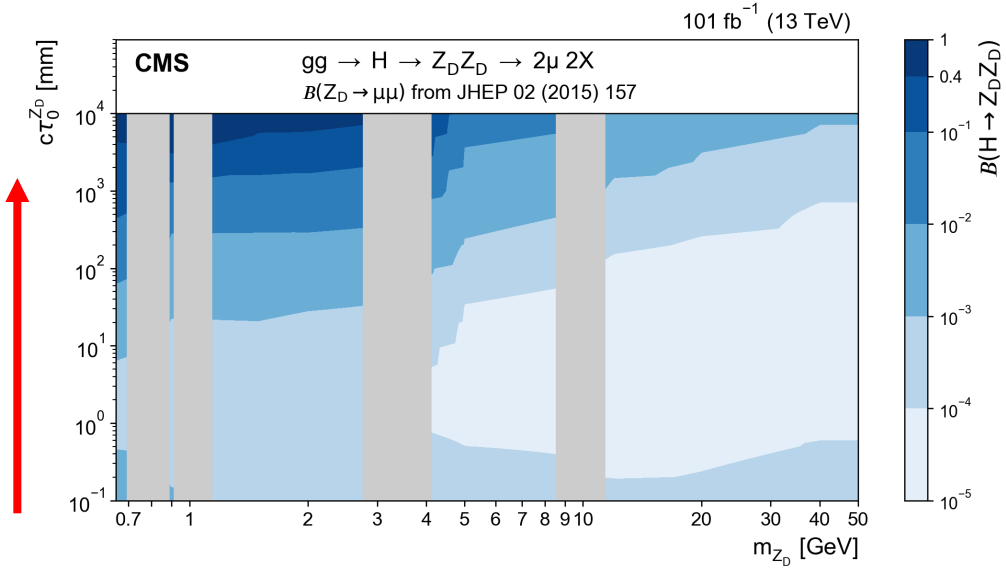




Known SM resonances (masked)

Weaker constraints @ higher τ_0: Decays beyond trigger acceptance

Constrains on $B(H \rightarrow Z_D Z_D)$ as a function of $m_{Z_D}, c\tau_0^{Z_D}$:



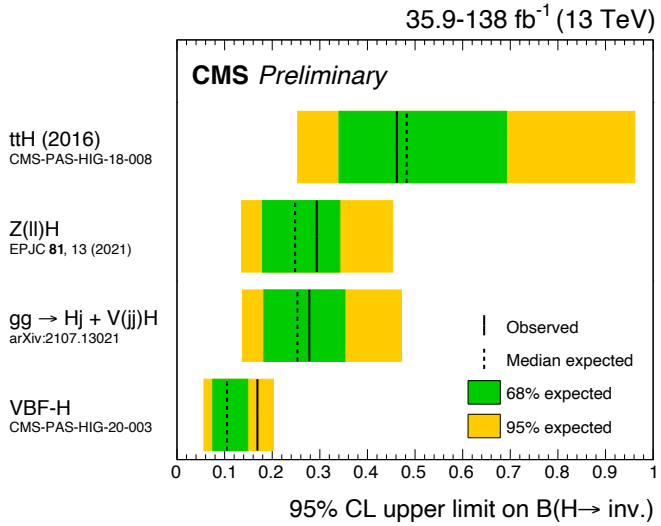
Summary

Presented the latest $BSM\ H$ decays + extended H sector searches from CMS with full Run2 data, $138\ fb^{-1}$

→ No deviation from SM expectation is observed

Developments (amongst many!):

- Pushing to probing $B(H \to inv.) \approx 0.1$ with the $H(inv)$ combination



Summary

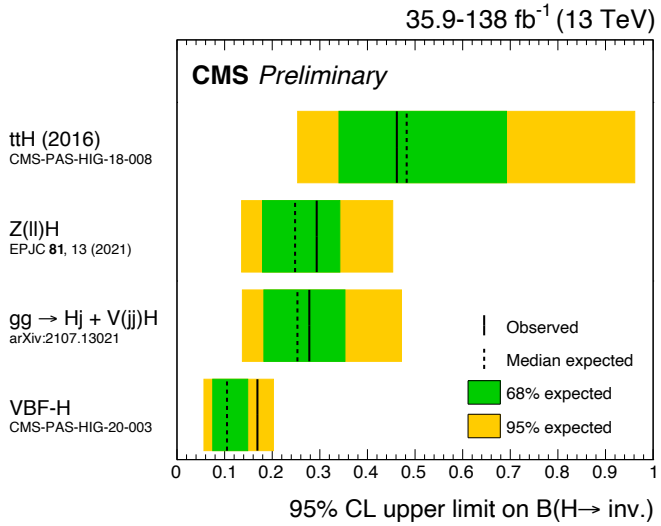
Phys. Rev. D 104 (2021) 032013

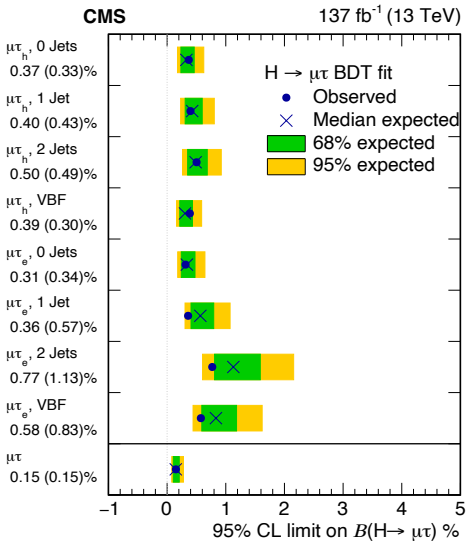
Presented the latest $BSM\ H$ decays + extended H sector searches from CMS with full Run2 data, $138\ fb^{-1}$

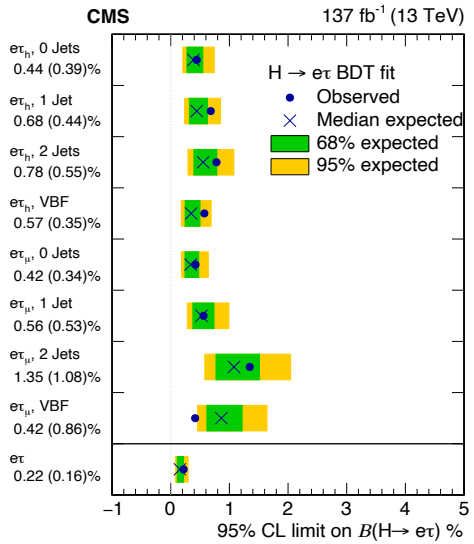
→ No deviation from SM expectation is observed

Developments (amongst many!):

- Pushing to probing $B(H \to inv.) \approx 0.1$ with the $H(inv)$ combination
- Tighter limits on $LFV\ H$ decays with full Run2 data







Summary

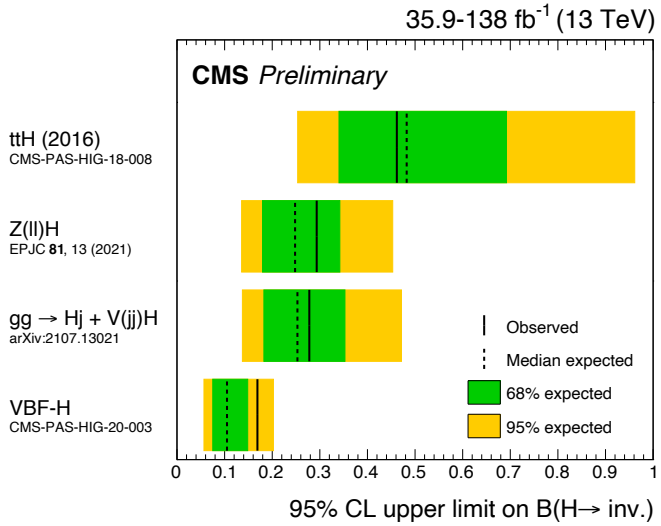
Phys. Rev. D 104 (2021) 032013
JHEP 11 (2021) 057

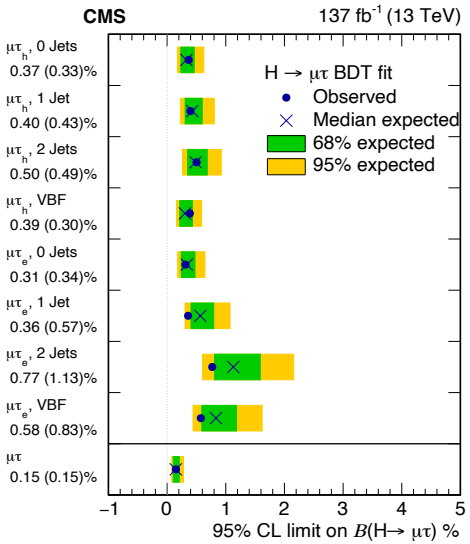
Presented the latest $BSM\ H$ decays + extended H sector searches from CMS with full Run2 data, $138\ fb^{-1}$

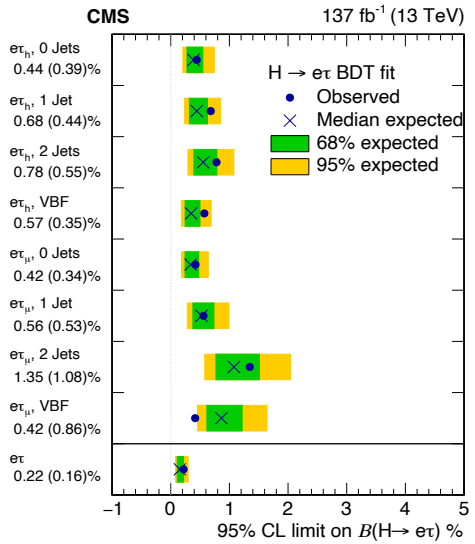
→ No deviation from SM expectation is observed

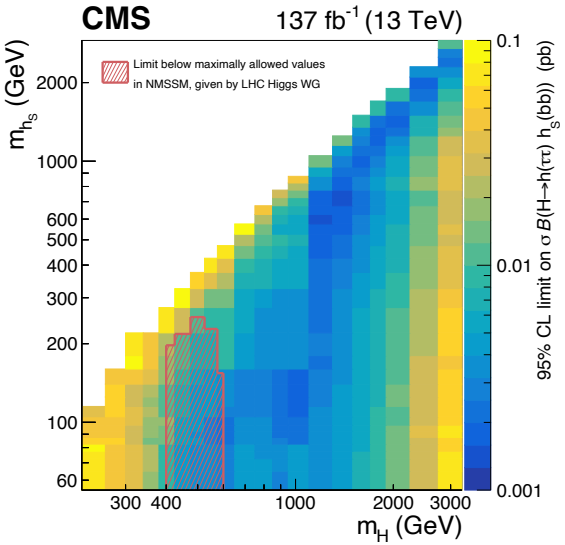
Developments (amongst many!):

- Pushing to probing $B(H \to inv.) \approx 0.1$ with the $H(inv)$ combination
- Tighter limits on $LFV\ H$ decays with full Run2 data
- First results on $H \to h(\tau\tau)h_s(bb)$





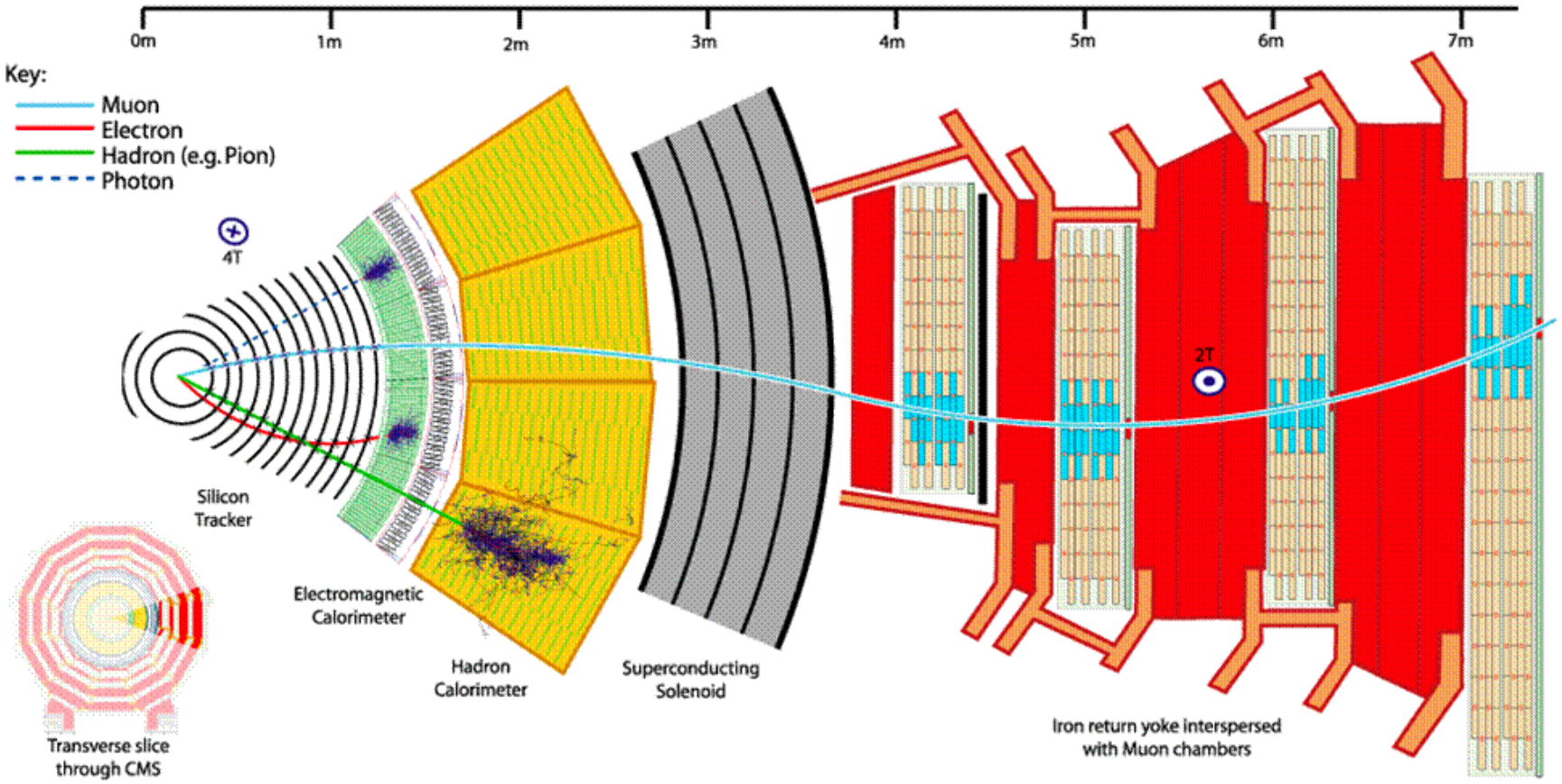




Backup

The CMS Detector

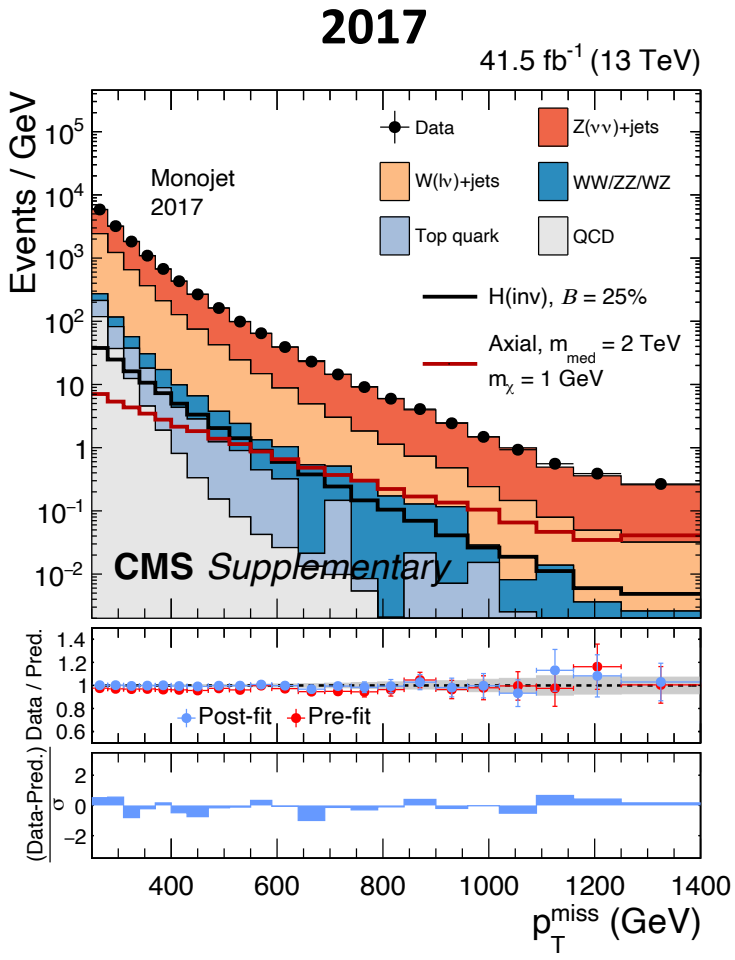
Transverse slice through the CMS detector:

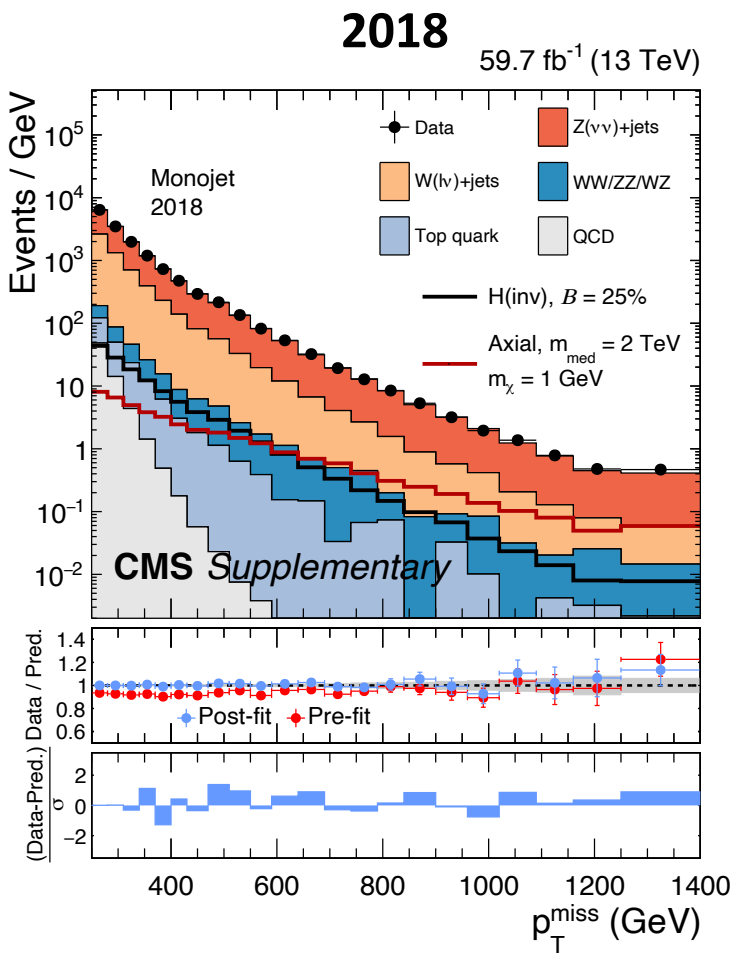


Monojet: Year Separated Results

JHEP11(2021)153

Monojet signal region, shown with 2017 and 2018 data separately:

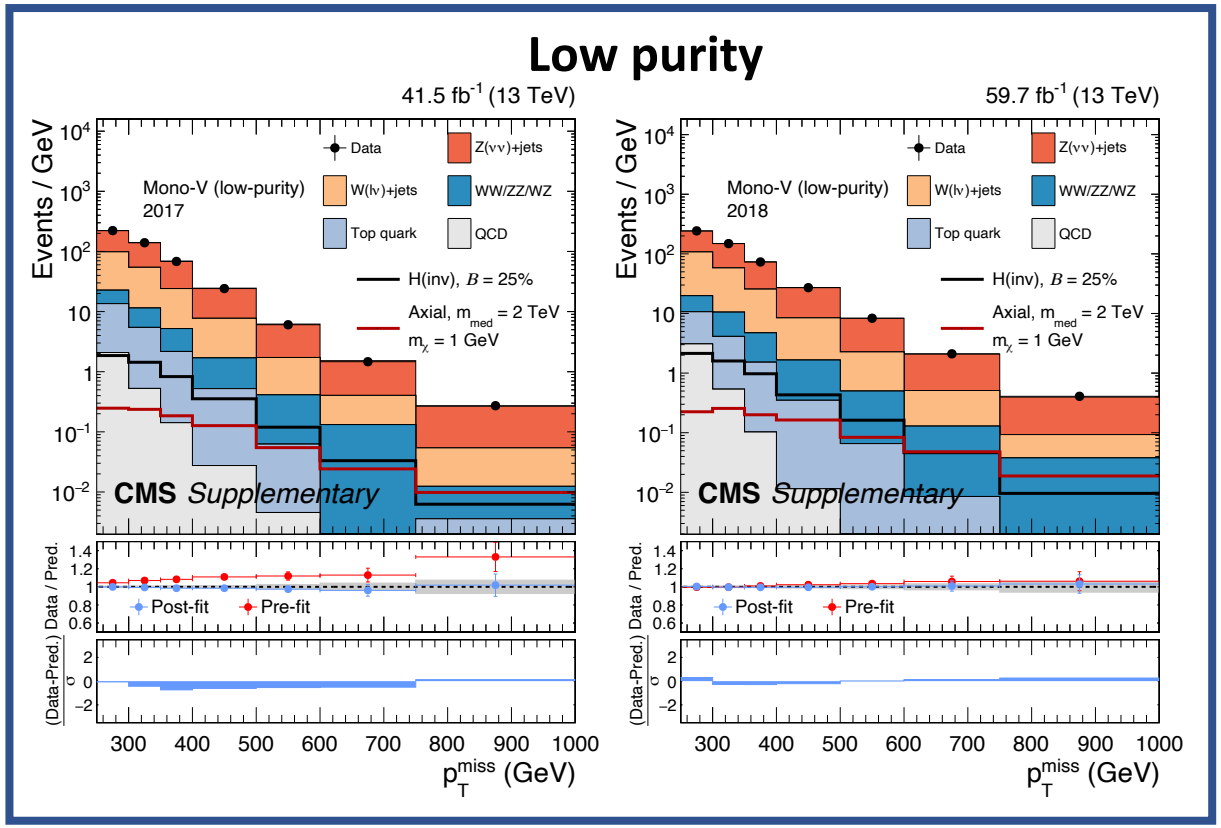


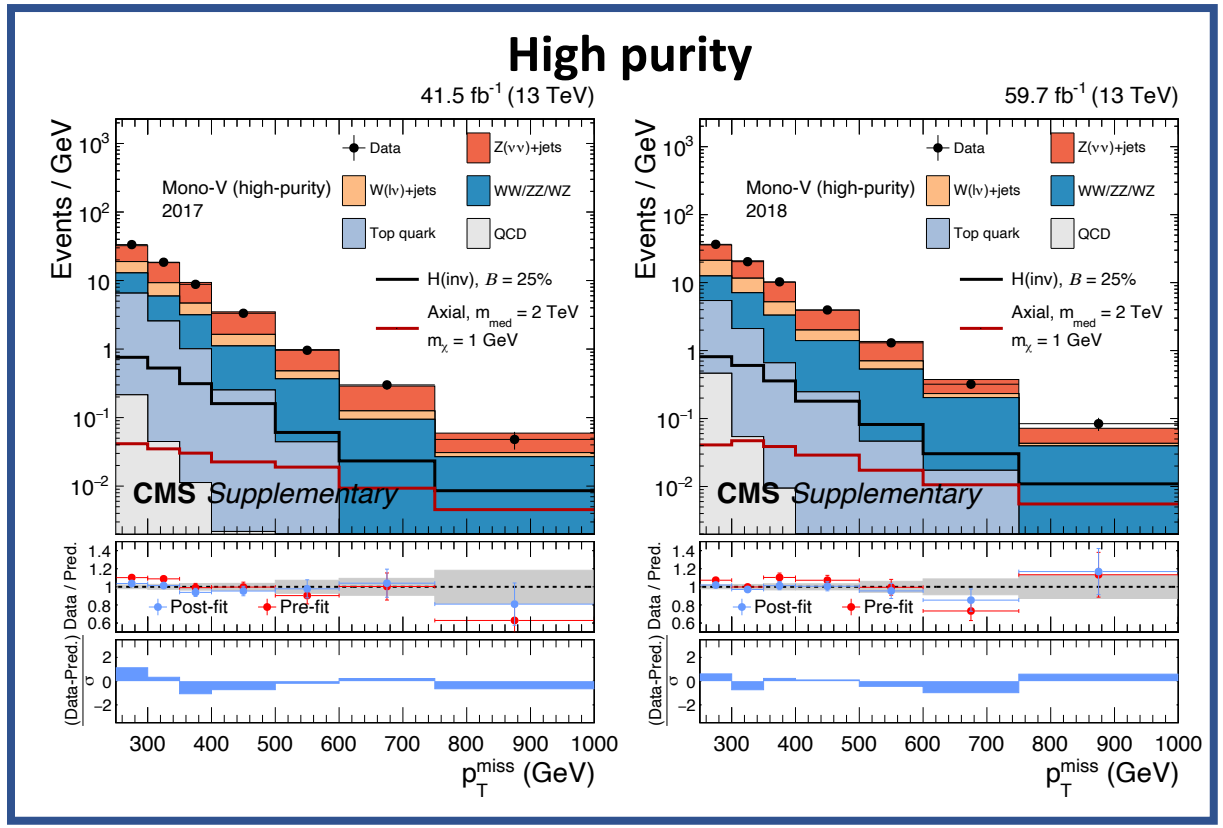


Mono-V: All Results

JHEP11(2021)153

Mono-V results in signal region for both low and high purity categories:





Good agreement between data and bkg predictions after the fit

VBF H(inv): Updates From 2016

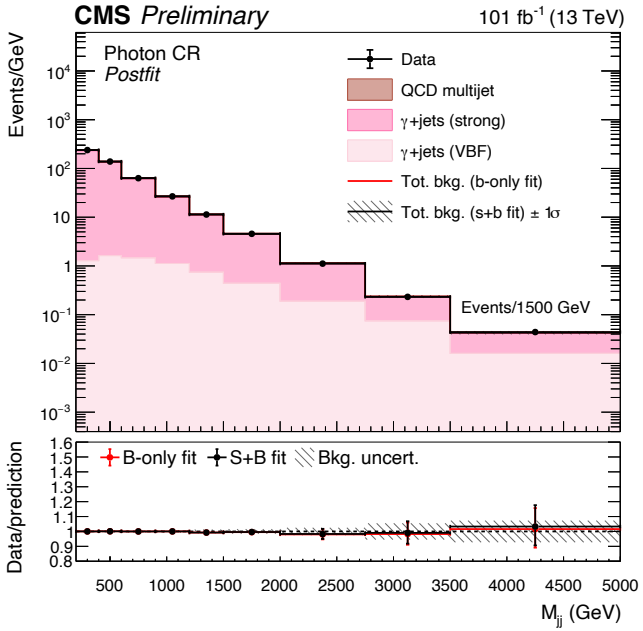
arXiv:2201.11585

Updates from HIG-17-023 in the 2017+2018 VBF analysis:

✓ Addition of photon CR

✓ Inclusion of VBF triggered category (**VTR**) for $p_T^{miss} \in [160,250]\ GeV$

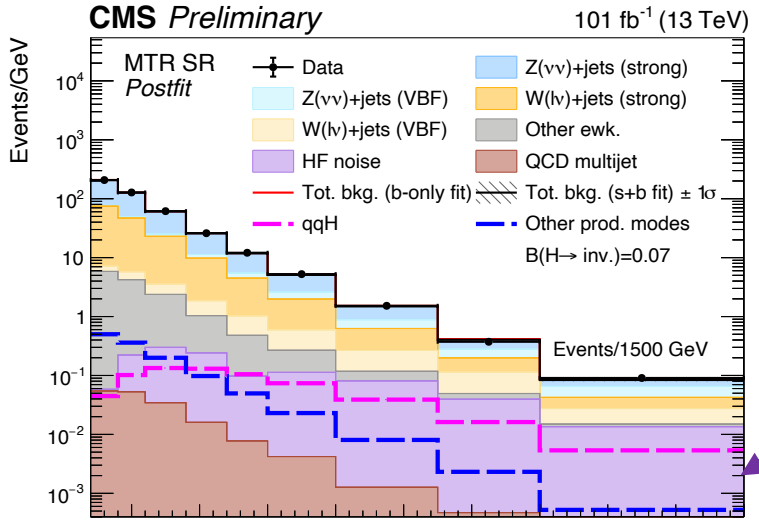
→ In addition to the MET+MHT triggered category (**MTR**)



✓ Addition of HF cleaning cuts

→ The first time we had access to **HF-HF events!**

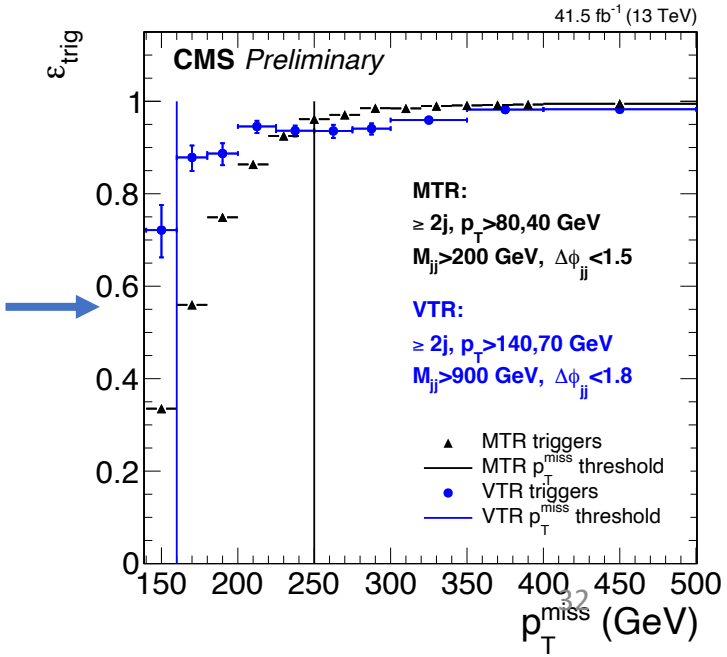
✓ NLO EWK correction on VBF H(inv) signal



HF noise estimate in SR

Trigger efficiencies as a function of MET for MTR & VTR

→ Higher efficiency from lower p_T^{miss} with VBF triggers



VBF H(inv): Noise Cutting + Estimation From Forward Detectors

arXiv:2201.11585

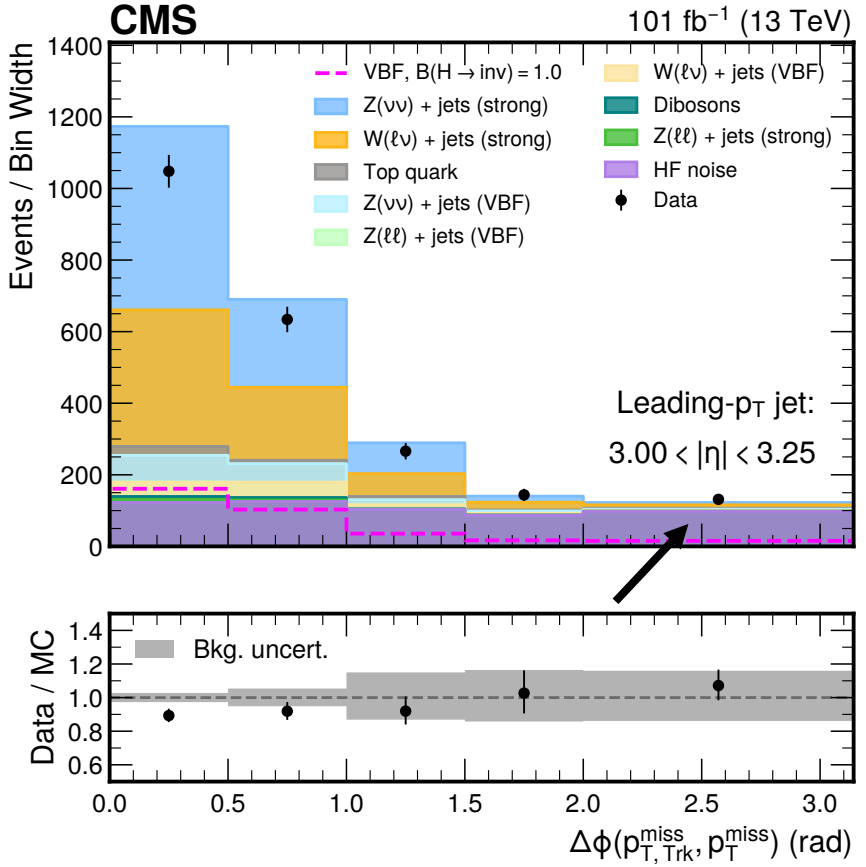
VBF H explicitly gets contributions from events with forward jets, $|\eta| > 3$

→ Results in events with mis-measured jets get into the signal region (high p_T^{miss})

In 2017+2018 analysis, noise reduction + estimation is applied:

- Identify noisy jets with shower shape quantities such as shower widths: $\sigma_{\eta\eta}, \sigma_{\phi\phi}$ (and cut on them)
- Make a leftover noise estimation in signal region, using a control region enriched in noisy events (failing the shower width cuts)

→ Important contribution from noise estimate @ high m_{jj}



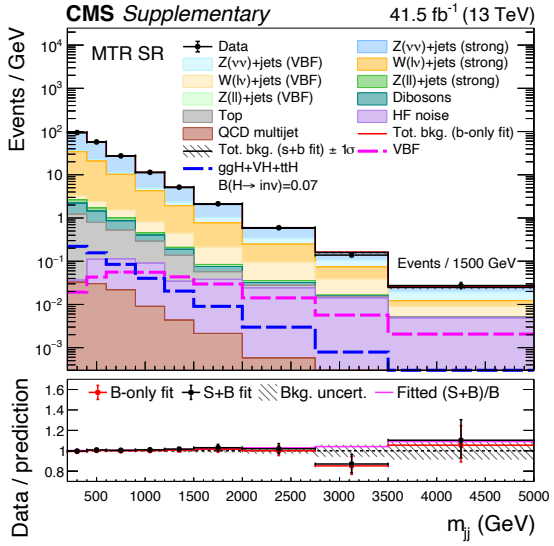
VBF H(inv): Year Separated Results

arXiv:2201.11585

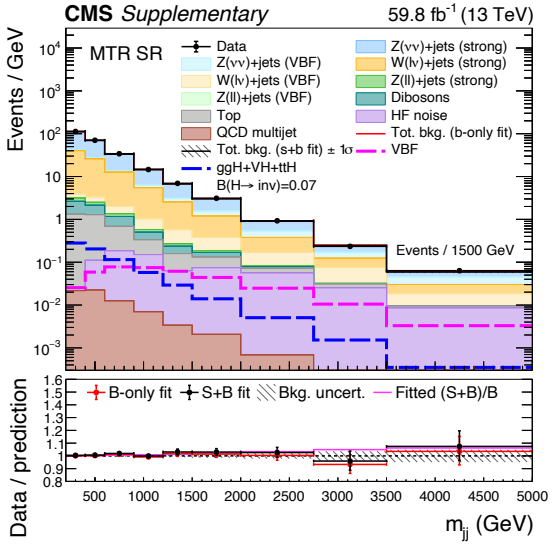
VBF H(inv) signal region, shown with 2017 and 2018 data, and MTR & VTR categories separately:

MTR (MET-triggered)

2017



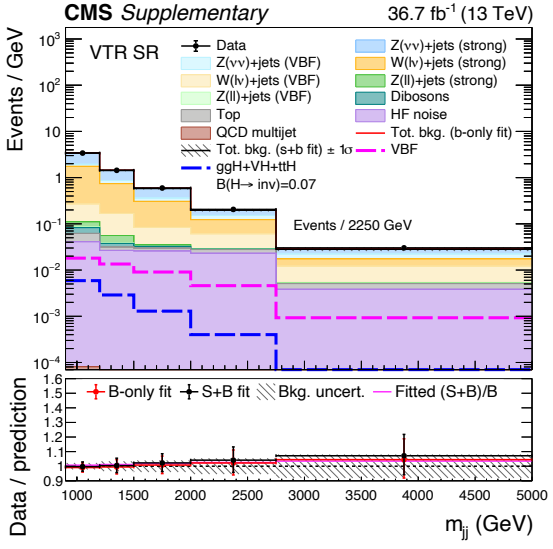
2018



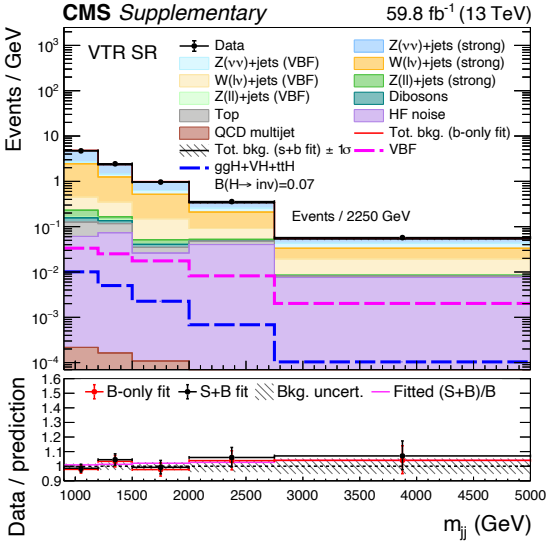
$$p_T^{miss} > 250\ GeV$$

VTR (VBF-triggered)

2017



2018



$$160 < p_T^{miss} < 250\ GeV$$

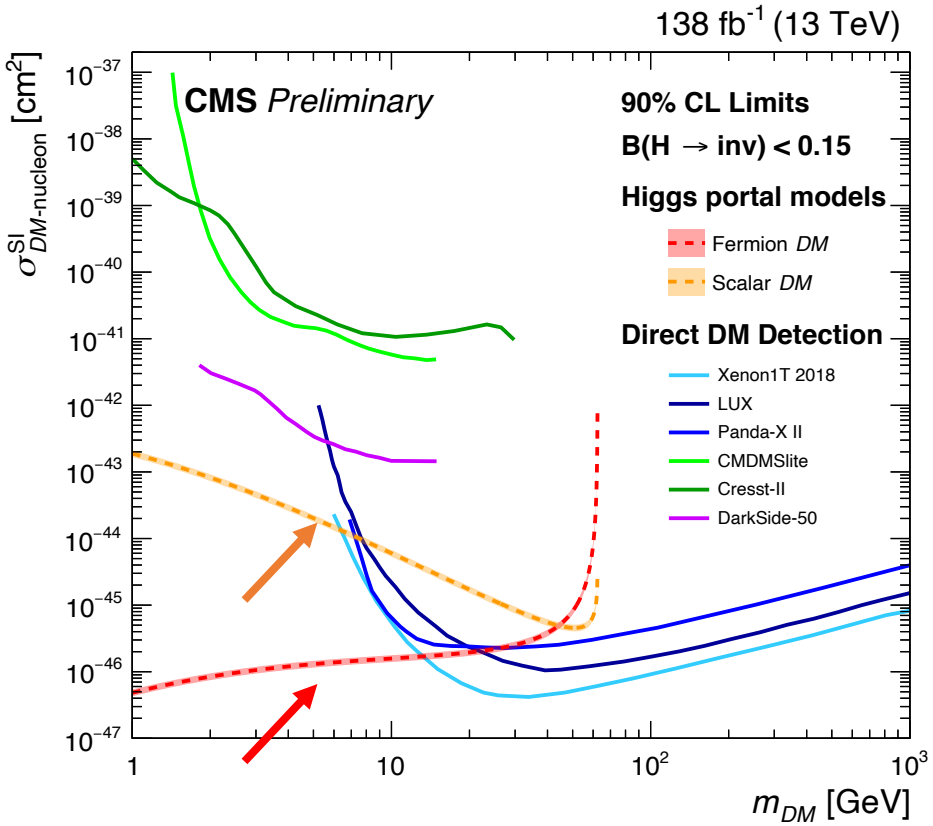
VBF H(inv): Exclusions on σ_{DM}

arXiv:2201.11585

VBF H constraints on $B(H \rightarrow inv)$ interpreted as exclusions on σ_{DM}

Results are compared with the results from direct-detection experiments

→ Results complement the direct-detection experiments nicely for $m_{DM} < O(10\ GeV)$

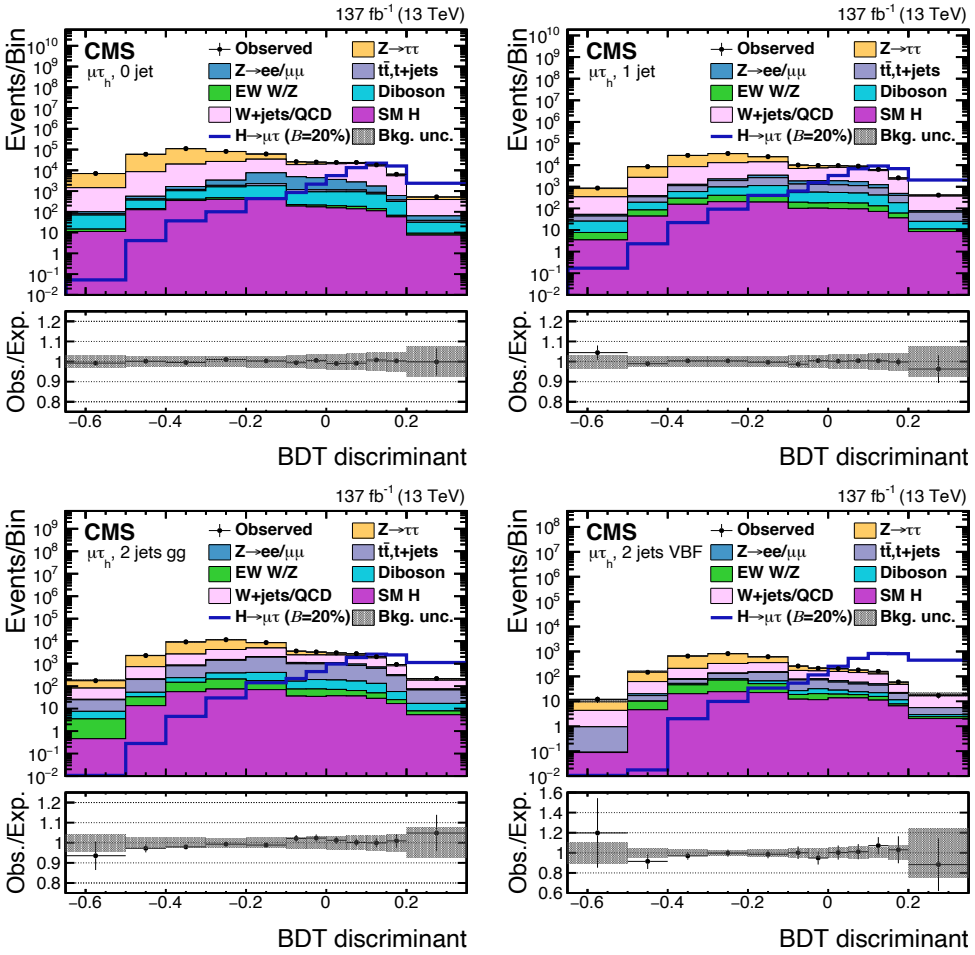


LFV Higgs Decays: BDT Score Distributions

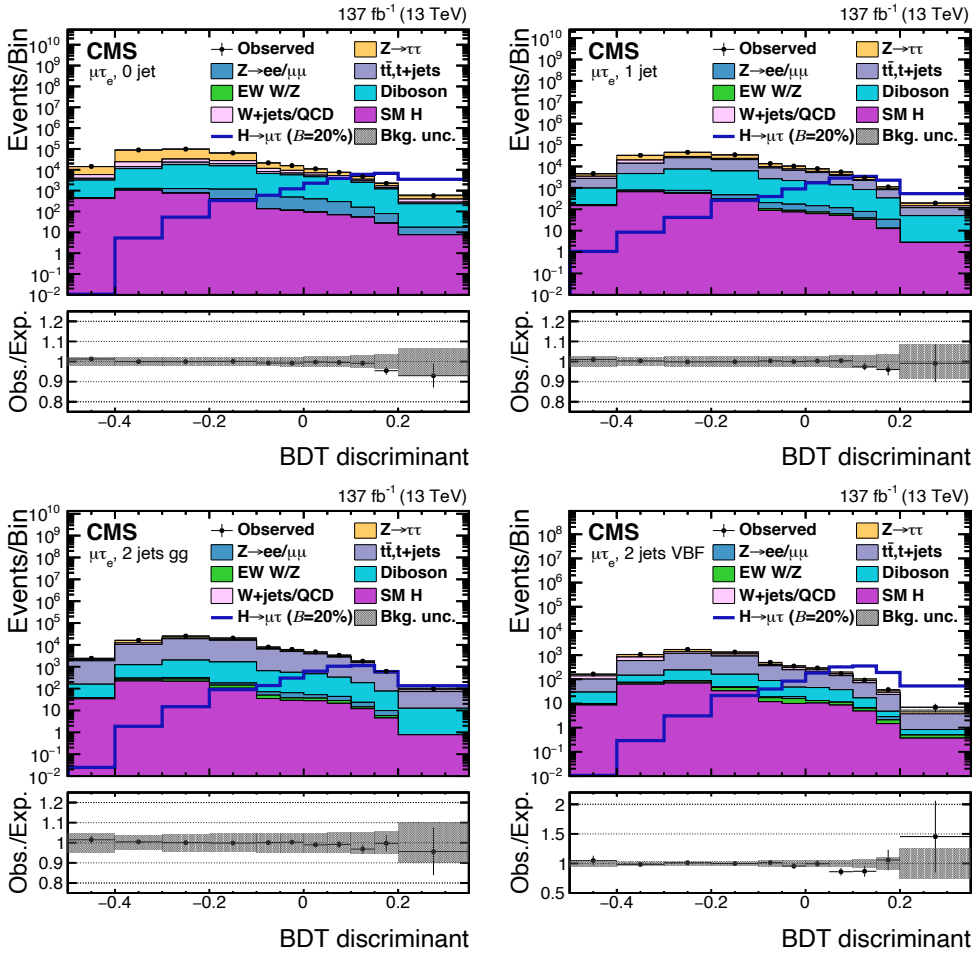
Phys. Rev. D 104 (2021) 032013

The fit has been performed on the BDT score distribution for different channels

$\mu\tau_h$ category



$\mu\tau_e$ category



→ Good agreement is observed between data and SM background predictions

$H^{\pm}$: Event Selection

Eur. Phys. J. C (2021) 81:723

Table of event selection list for:

- $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$
- $H^{\pm} \rightarrow W^{\pm}Z$

VBF topology is targeted by requiring:

- Two high p_T jets
- High $m_{jj}(> 500\ GeV)$
- High $\Delta\eta_{jj}(> 2.5)$

Table 1 Summary of the selection requirements defining the $W^{\pm}W^{\pm}$ and WZ SRs. The looser lepton p_T requirement in the WZ selection refers to the trailing lepton from the Z boson decays. The $|m_{\ell\ell} - m_Z|$ requirement is applied only to the dielectron final state in the $W^{\pm}W^{\pm}$ SR

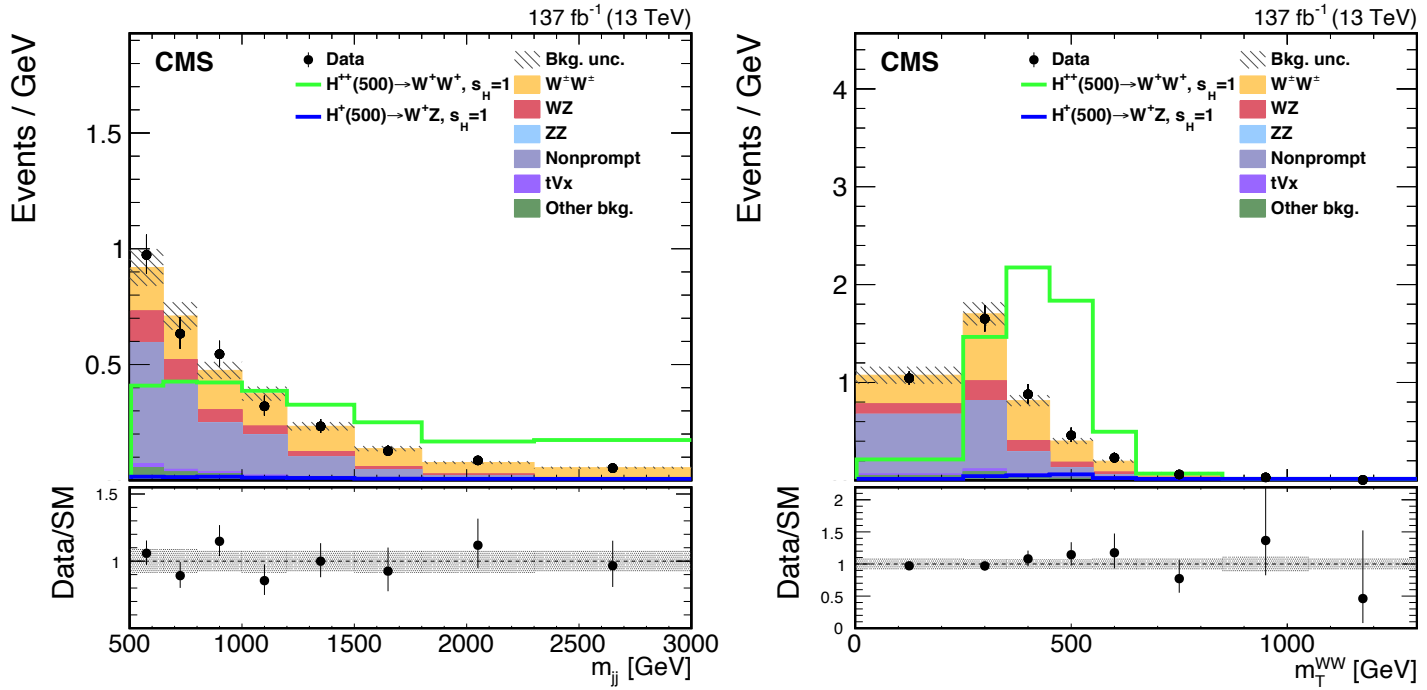
Variable	$W^{\pm}W^{\pm}$	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	>50/30 GeV	>50/30 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)	<15 GeV
$m_{\ell\ell}$	>20 GeV	–
$m_{\ell\ell\ell}$	–	>100 GeV
p_T^{miss}	>30 GeV	>30 GeV
bjet veto	Required	Required
τ_h veto	Required	Required
$\max(z_\ell^*)$	<0.75	<1.0
m_{jj}	>500 GeV	>500 GeV
$\lvert \Delta\eta_{jj} \rvert$	>2.5	>2.5

$VBF\ H^{\pm}$ Search

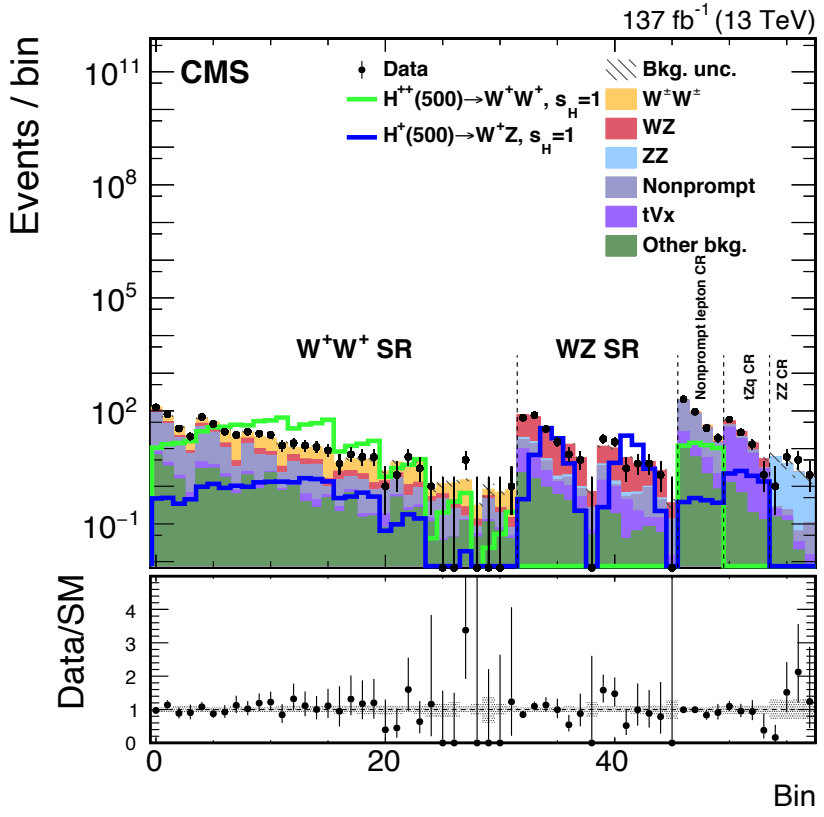
Eur. Phys. J. C (2021) 81:723

$2D$ fit as a function of m_{jj} & m_T^{VV} is performed across ZZ & WZ signal regions and control regions:

WW signal region:



All fitted regions:



→ No excess of data over SM background predictions is observed

$H^{\pm}$: Model Parameters

Eur. Phys. J. C (2021) 81:723

GM model introduces an additional $SU(2)$ triplets
→ Introduces couplings of gauge bosons to charged H

Two key parameters in GM model:

- m_{H_5}: Mass of degenerate $H^{\pm}/H^{\pm\pm}$ state
- s_H: s_H^2 characterizes the fraction of m_W^2 generated by the triplet fields

H_5 states are fermiophobic:
→ $BR(H_5 \to VV) = 1$

Exclusion result from the full-Run2 data analysis: