Searches for rare and exotic Higgs boson decays at ATLAS and CMS

Moriond EW (24th - 31st March 2024)

Andy Chisholm (University of Birmingham)
on behalf of the ATLAS and CMS collaborations

It's been over 10 years since the Higgs boson was discovered and all experimentally observed decay properties remain in line with expections from the SM...

Could surprises still be waiting in the form of very rare or exotic decays?

I will focus on ATLAS and CMS results which are new since last year's Rencontres de Moriond

- Combination of $H \rightarrow Z\gamma$ searches
- Searches for exclusive radiative Higgs boson decays to mesons
- Searches considering exotic Higgs boson decays to new light scalar particles

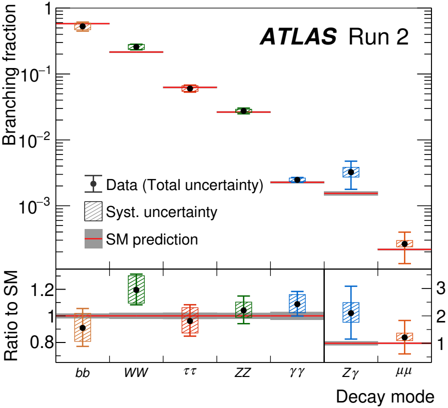
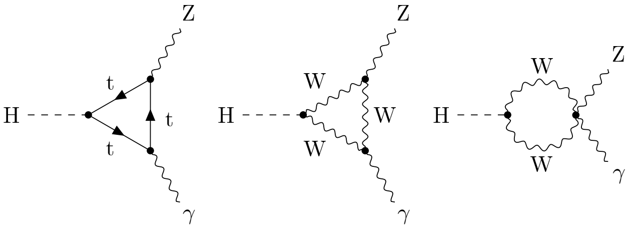


Figure from ATLAS [Nature 607 (2022) 52], see also [Nature 607 (2022) 60] from CMS

Much more information can be found on the respective public results web pages of ATLAS and CMS

For a 125 GeV Higgs boson, $H \to Z\gamma$ is a rare decay in the SM, with a branching fraction of $\mathcal{B}(H \to Z\gamma) = (1.5 \pm 0.1) \times 10^{-3}$



- It occurs through loop diagrams and is sensitive to modifications in various BSM scenarios (e.g. extended Higgs sector, composite models, new particles in loops)

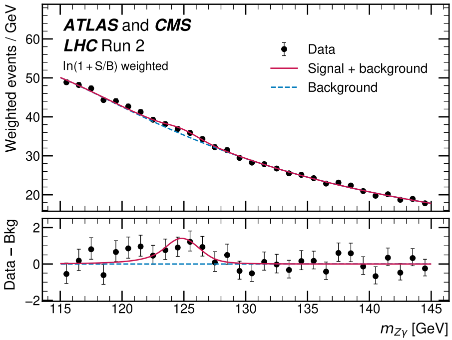
Experimental Situation

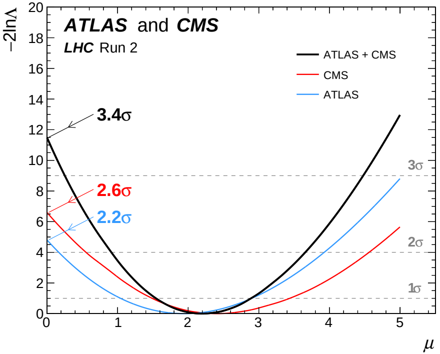
- Searches for $H \to Z\gamma$ decays (with $Z \to e^+e^-, \mu^+\mu^-$) have been performed by ATLAS† and CMS‡ with the full LHC Run 2 dataset
- **Both experiments observed a modest excess of events ($2.2 - 2.6\sigma$)**, where signal significances of around $\approx 1\sigma$ were expected based on the SM prediction

Recently, a statistical combination of the ATLAS and CMS results was performed...

† Phys. Lett. B 809 (2020) 135754 ‡ JHEP 05 (2023) 233

Search for $H \to Z\gamma$ at ATLAS and CMS [Phys. Rev. Lett. 132 (2024) 021803]



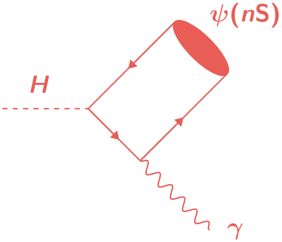


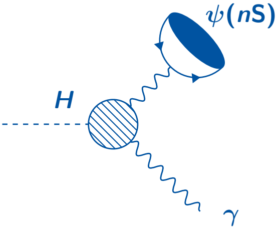
- Combination yields a signal strength of $\mu = 2.2 \pm 0.7\,(1.0 \pm 0.6)$ observed (exp.)
- **Evidence for $H \to Z\gamma$ decay** is established with an observed significance of 3.4σ, where 1.6σ is expected based on the SM prediction
- Measurement agrees with expectation from SM prediction within 1.9σ

Combined sensitivity remains statistically limited, clear prospects to clarify this intriguing excess with the LHC Run 3 datasets currently being collected!

The decays $H \to \psi(nS)\,\gamma$ are very rare in the SM, but provide a clean probe of the charm quark Yukawa couplings at the LHC via $\psi(nS) \to \mu^+\mu^-$

- **Interference** between **direct** ($H \to c\bar{c}$) and **indirect** ($H \to \gamma\gamma^*$) contributions
- **Direct** amplitude **sensitive to magnitude and sign of $Hc\bar{c}$ coupling**, enhancements possible in BSM scenarios
- **Indirect** amplitude largest contribution to decay width, **insensitive to Yukawa coupling**
- **Analogous decays of the Z boson** expected to have branching fractions of $\mathcal{O}\left(10^{-8}\right)$





SM Branching Fraction Predictions

$$\mathcal{B}\left(H \to J/\psi\,\gamma\right) = (2.95 \pm 0.17) \times 10^{-6} \quad \dagger$$

$$\mathcal{B}\left(H \to \psi(2S)\,\gamma\right) = (1.03 \pm 0.06) \times 10^{-6} \quad \ddagger$$

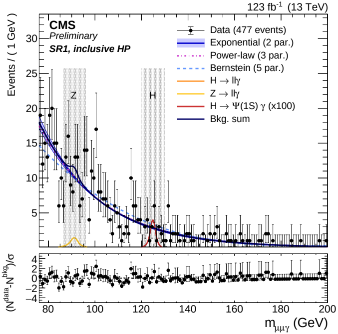
† JHEP 1508 (2015) 012 ‡ Phys. Rev. D 96, 116014 (2017)

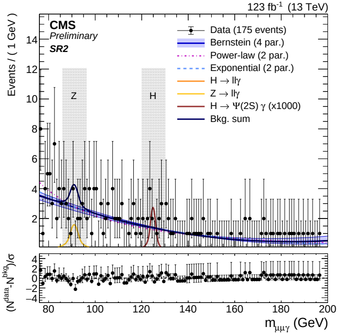
Other (numerically similar) predictions include: Phys. Rev. D 100 (2019) 054038 and Chin. Phys. C 40 (2016) 123105

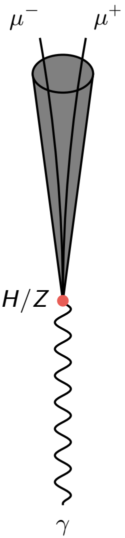
Search for $H/Z \to \psi(nS)\gamma$ at CMS [CMS-PAS-SMP-22-012]

With $\psi(nS) \to \mu^+\mu^-$, a distinctive signature of an isolated and collimated di-muon recoiling against an isolated photon is achieved

- Events categorised to target Higgs production mechanisms and distinct angular distribution of the signal (spin correlations)
- 4 categories for J/ψ search and single category for $\psi(2S)$, associated with lower statistics from factor of $\approx 7.5\times$ lower $\mathcal{B}(\to \mu^+\mu^-)$
- Background modelled with analytic functions in $m_{\mu\mu\gamma}$ likelihood fit



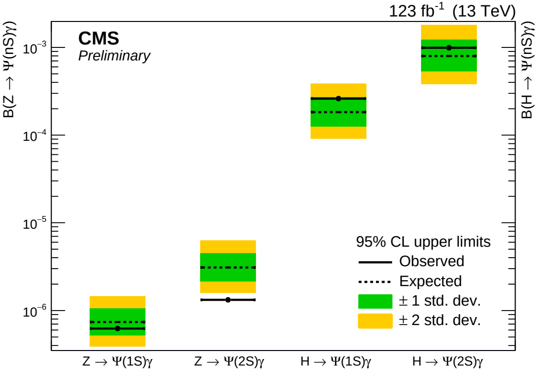




↑ **Fitted $m_{\mu\mu\gamma}$ distribution for high purity J/ψ (left) and $\psi(2S)$ (right) categories**

Up to a factor of 2× improvement on earlier CMS limits [Eur. Phys. J. C 79 (2019) 94]

95% CL upper limit (obs.) on branching fraction	
$H \to J/\psi\,\gamma$	$\mathbf{2.6 \times 10^{-4}}$
$H \to \psi(2S)\,\gamma$	$\mathbf{9.9 \times 10^{-4}}$
$Z \to J/\psi\,\gamma$	$\mathbf{0.6 \times 10^{-6}}$
$Z \to \psi(2S)\,\gamma$	$\mathbf{1.3 \times 10^{-6}}$



The fitted $H \to J/\psi\,\gamma$ signal strength is also interpreted in the context of the κ-framework to derive constraints on the $Hc\bar{c}$ coupling

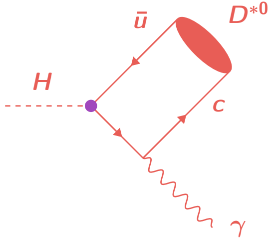
- The signal strength ratio $\mu(H \to J/\psi\,\gamma)/\mu(H \to \gamma\gamma)$ is sensitive to κ_c/κ_γ (c.f. interfering diagrams shown earlier) while avoiding assumptions on Γ_H
- With input from latest CMS $H \to \gamma\gamma$ result [JHEP 07 (2021) 027], an **observed 95% CL interval of $(-157 < \kappa_c/\kappa_\gamma < 199)$** is obtained

Both branching fraction limits and κ_c/κ_γ constraints are comparable to the corresponding ATLAS results in this channel [Eur. Phys. J. C 83 (2023) 781]

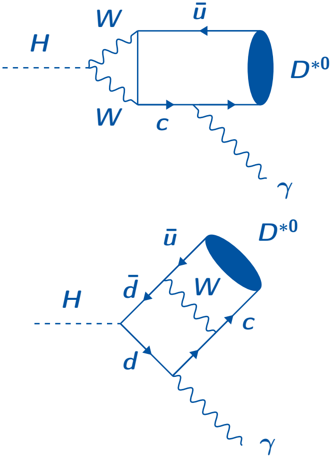
Exclusive radiative Higgs boson decays to flavoured mesons

Analogously to the quarkonium case, decays to flavoured mesons can provide an experimentally clean probe of potential flavour changing Yukawa interactions

- Examples include $H \to \{K^{*0}, D^{*0}, B^{*0}, B_s^{*0}\}\ \gamma$
- D^{*0} case particularly interesting since it's the rarest in the SM, with a branching fraction estimated at $\mathcal{O}\left(10^{-27}\right)$! [arXiv:2312.11211]
- Observation of this decay at any rate accessible at the LHC would likely indicate the presence of physics beyond the SM!



↑ Non-SM diagram involving a flavour changing neutral current $Hc\bar{u}$ interaction



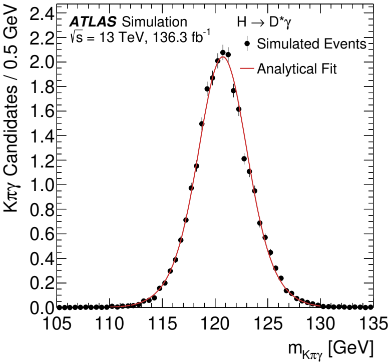
↑ Two examples of SM diagrams for the $H \to D^{*0}\gamma$ decay

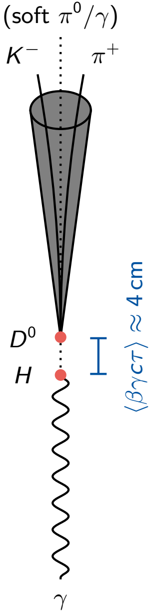
Three channels involving a long-lived flavoured meson investigated

- Datasets collected with dedicated triggers based on modified hadronic τ decay algorithm
- Distinct signature of two isolated tracks recoiling against an isolated photon, displaced meson decay vertex exploited to reduce backgrounds

$H \to D^{*0}\gamma$ channel

- Almost all D^{*0} decays proceed via $D^0\{\pi^0, \gamma\}$
- Reconstruction of $D^0 \to K^-\pi^+$ decay targeted ($\mathcal{B} \approx 4\%$)
- No attempt to reconstruct soft photons in $D^{*0} \to D^0\{\pi^0, \gamma\}$ decays (very small impact on Higgs mass resolution)





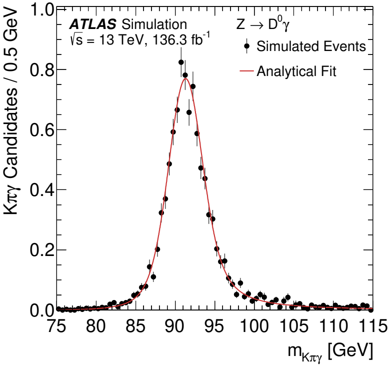
Expected signal for $\mathcal{B}(H \to D^{*0}\gamma) = 10^{-3}$ (around 25 events) ↑

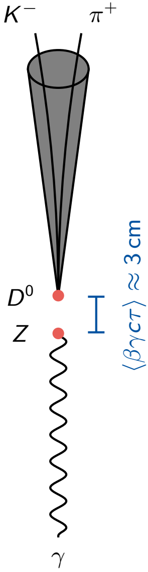
Three channels involving a long-lived flavoured meson investigated

- Datasets collected with dedicated triggers based on modified hadronic τ decay algorithm
- Distinct signature of two isolated tracks recoiling against an isolated photon, displaced meson decay vertex exploited to reduce backgrounds

$Z \to D^0\gamma$ channel

- Reconstruction of $D^0 \to K^-\pi^+$ decay targeted ($\mathcal{B} \approx 4\%$)

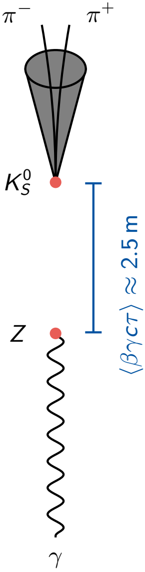




Expected signal for $\mathcal{B}(Z \to D^0\gamma) = 10^{-6}$ (around 10 events) ↑

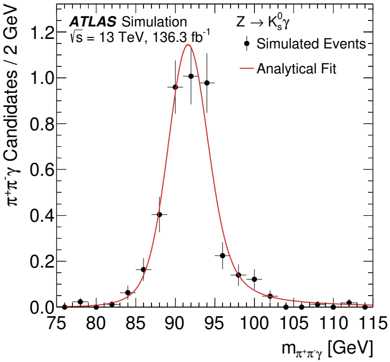
Three channels involving a long-lived flavoured meson investigated

- Datasets collected with dedicated triggers based on modified hadronic τ decay algorithm
- Distinct signature of two isolated tracks recoiling against an isolated photon, displaced meson decay vertex exploited to reduce backgrounds



$Z \to K_S^0\gamma$ channel

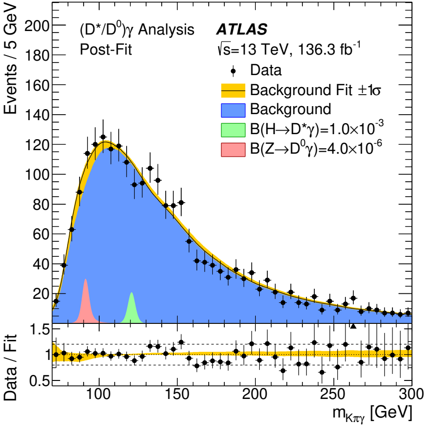
- Reconstruction of $K_S^0 \to \pi^-\pi^+$ decay targeted ($\mathcal{B} \approx 69\%$)
- Most K_S^0 decays occur deep into the tracker, substantially reducing signal acceptance

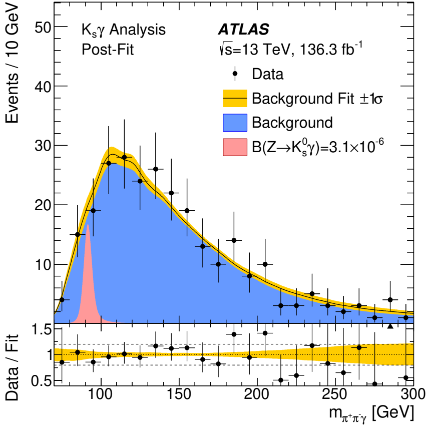


Expected signal for $\mathcal{B}(Z \to K_S^0\gamma) = 10^{-6}$ (around 4 events) ↑

Search for $H \to D^{*0}\gamma$ and $Z \to \{D^0, K_S^0\}\gamma$ at ATLAS

[2402.18731]
Sub. to PLB





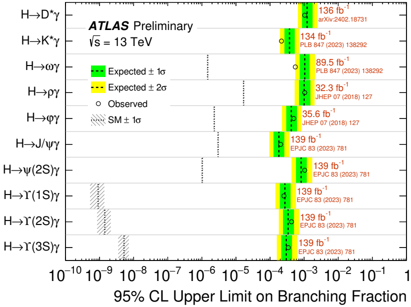
- Background dominated by $\gamma +$ jet and multi-jet processes, modelled with data-driven technique providing finely binned templates for background PDF
- Presence of signal quantified with un-binned likelihood fit to $m_{D^0\gamma}$ and $m_{K_S^0\gamma}$ distributions
- Main systematic uncertainties associated with modelling of background shape and signal efficiency, though sensitivity statistically limited

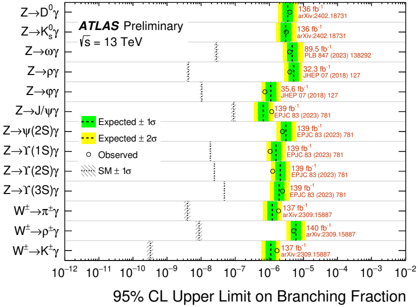
First limits on $H \to D^{*0}\gamma$ and $Z \to K^0_S\gamma$ decays!

- Substantial improvement (500×) on existing $Z \to D^0\gamma$ limit from LHCb

[arXiv:2212.07120]

	95% CL upper limit	
	Expected	**Observed**
$\mathcal{B}\left(H \to D^{*0}\gamma\right)$	$\left(1.2^{+0.5}_{-0.3}\right) \times 10^{-3}$	$\mathbf{1.0 \times 10^{-3}}$
$\mathcal{B}\left(Z \to D^{0}\gamma\right)$	$\left(3.4^{+1.4}_{-1.0}\right) \times 10^{-6}$	$\mathbf{4.0 \times 10^{-6}}$
$\mathcal{B}\left(Z \to K^0_S\gamma\right)$	$\left(3.0^{+1.3}_{-0.8}\right) \times 10^{-6}$	$\mathbf{3.1 \times 10^{-6}}$





These latest limits complement a much broader programme of Higgs and W/Z boson exclusive decay searches in ATLAS, see ATL-PHYS-PUB-2023-004

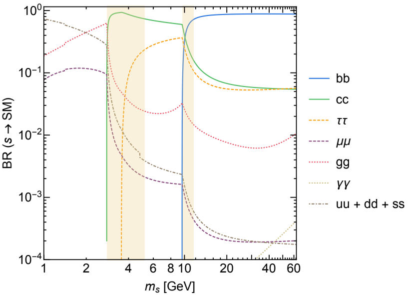
Various models for physics beyond the SM predict the existance of new light (pseudo-)scalar particles, *a*, including:

- **Axion-like particles** - potential solution to strong CP problem and muon $g-2$ anomoly
- **Extended Higgs sector** - Additional Higgs fields beyond the single doublet of the SM, can lead to light (pseudo-)scalars (e.g. 2HDM and 2HDM+S models)

Most of these models also allow decays of a heavier *CP*-even Higgs boson (i.e. $H(125)$) to the (pseudo-)scalar *a* particles:

- $\boldsymbol{H \to Za}$ - Kinematically allowed for $m_a < 33.8$ GeV
- $\boldsymbol{H \to aa}$ - Kinematically allowed for $m_a < 62.5$ GeV
- Experimental characteristics of H and a decays depend strongly on m_a

Scalar branching fractions in SM + singlet model, from Phys. Rev. D 90, 075004 (2014) →

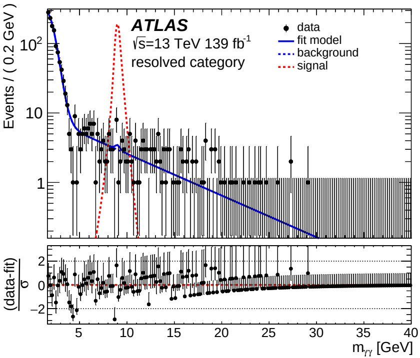


Many earlier searches performed by ATLAS and CMS, now extending with larger datasets and evolving to target more challenging regions of parameter space

Search split into two regimes, based on the angular separation of the photons

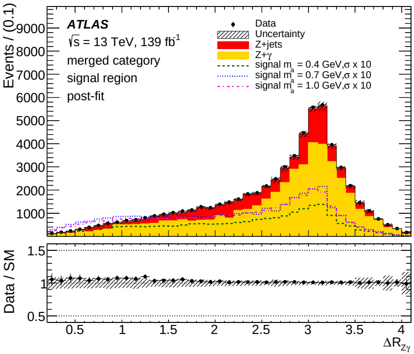
- Main backgrounds from $Z+$jets (π^0 decays) and $Z+\gamma$, composition varies between regimes (90:10 in resolved, 25:75 in merged)

Resolved Category - $m_a > 2$ GeV



- Two distinct photons reconstructed
- $m_{\gamma\gamma}$ used as S/B discriminant

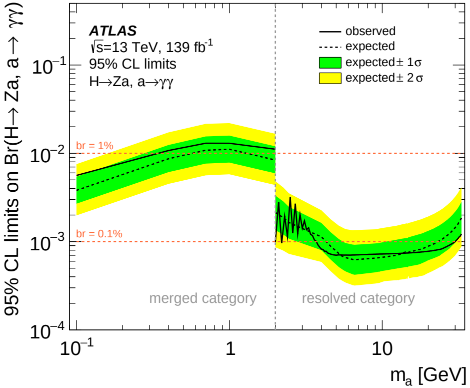
Merged Category - $m_a < 2$ GeV

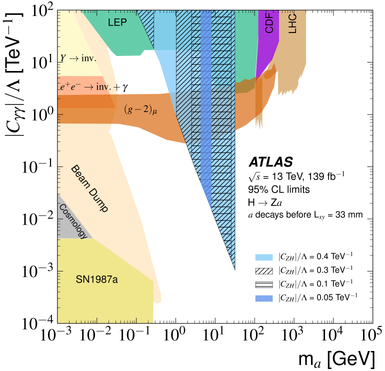


- EM showers merged in calorimter, reconstructed as single photon
- $\Delta R_{Z\gamma}$ used as S/B discriminant

Broad range in m_a covered: 0.1 - 33 GeV

- Limits on $\mathcal{B}(H \rightarrow Za) \times \mathcal{B}(a \rightarrow \gamma\gamma)$ range from around 1% for the merged analysis to below 0.1% for the resolved analysis





Interpretation in context of Axion-Like Particle models

[JHEP 12 (2017) 044]

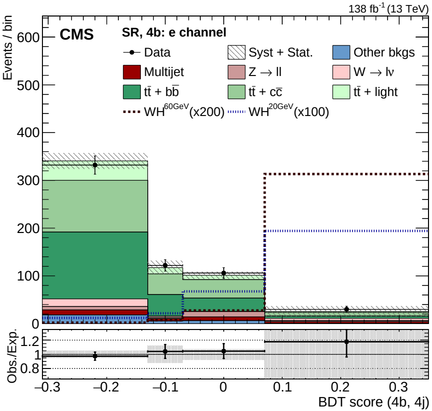
- Sensitivity to short-lived axions very complementary to existing bounds

CMS also have results in this channel (comparable sensitivity for $m_a > 1$ GeV), preliminary results shown last year, now submitted to PLB [arXiv:2311.00130]

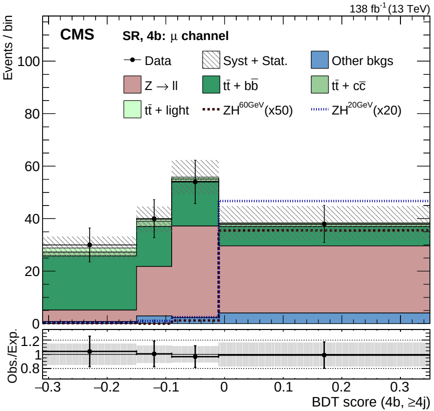
Search for $VH, H \to aa \to b\bar{b}b\bar{b}$ at CMS [arXiv:2403.10341] Submitted to JHEP

Striking event signature of up to 4 b-jets and a $Z \to \ell\ell$ and $W \to \ell\nu$ decay

- Categories for events with 3 or 4 b-tagged jets
- Two BDT discriminants (WH and ZH) trained with event kinematic variables
- Main backgrounds from $t\bar{t} + \{b\bar{b}, c\bar{c}\}$ production and W/Z + jets



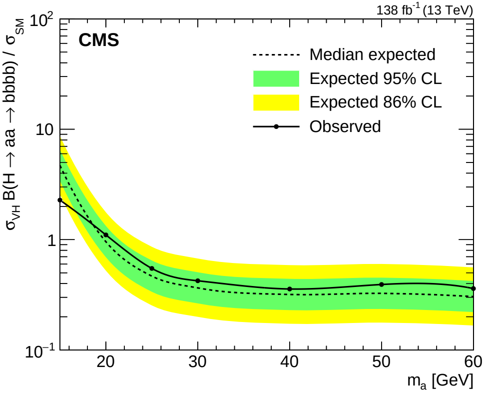
Example BDT score distribution in $W(e\nu)H$ 4 b-jet category



Example BDT score distribution in $Z(\mu\mu)H$ 4 b-jet category

Search sensitive to broad m_a range between 15 and 60 GeV

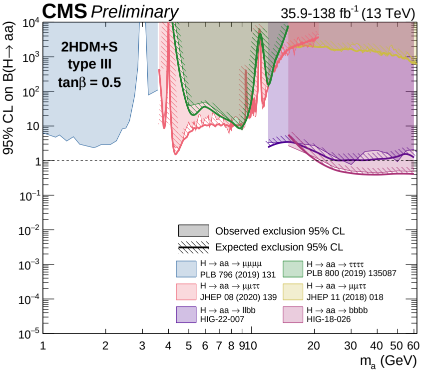
- Sensitivity reduced at low m_a where b-jets tend to merge, reducing signal efficiency
- Searches in WH and ZH channels combined to deduce limits on signal strength†
- Very important in context of 2HDM+S models where $a \to b\bar{b}$ is usually the dominant decay for m_a above the $b\bar{b}$ threshold



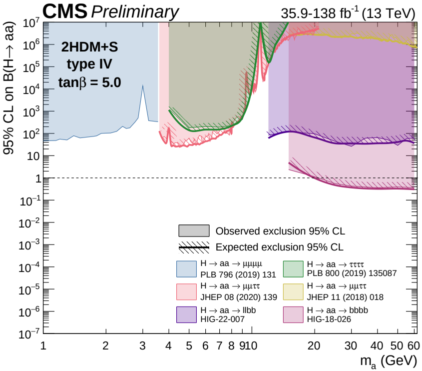
Interesting region where signal strength limit is below unity ($m_a > 20$ GeV), corresponding to SM VH production, $\mathcal{B}(H \to aa) = 1$ and $\mathcal{B}(a \to b\bar{b}) = 1$

† Signal strength can be interpreted as $\mathcal{B}(H \to aa) \times \mathcal{B}(a \to b\bar{b})^2$ if SM VH production assumed

Summaries of exclusion limits in 2HDM+S models recently updated with latest CMS results (including $VH, H \to aa \to b\bar{b}b\bar{b}$)



Type III - Leptons couple to H_1 field, quarks couple to H_2



Type IV - Down-type fermions couple to H_1 field, up-type to H_2

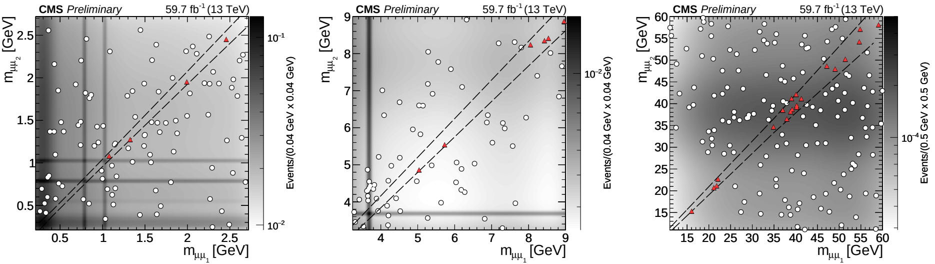
New regions of 2HDM+S parameter space excluded by $VH, H \to aa \to b\bar{b}b\bar{b}$ result (HIG-18-026) for Type III and IV models

For more information and other model variations, see here and [Phys. Rev. D 90, 075004 (2014)] for details on the 2HDM+S model

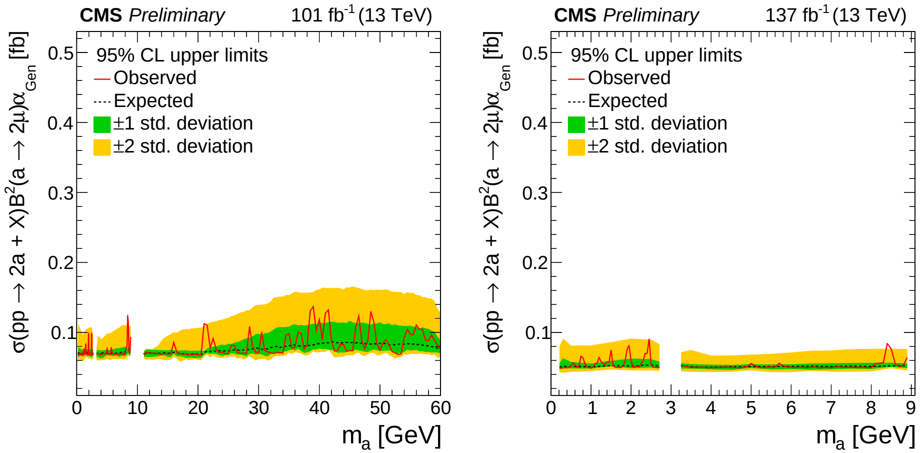
Model-independent search for *aa* → muons at CMS [CMS-PAS-HIG-21-004]

New for Moriond! **Search for $aa \rightarrow \mu^+\mu^-\mu^+\mu^-$ with 2017+2018 dataset (101 fb^{-1}), improving result based on 2016 (35.9 fb^{-1}) data [Phys. Lett. B 796 (2019) 131]**

- Search strategy agnostic to *aa* production mode, but sensitive to $H \rightarrow aa$ decays in ALP and MSSM scenarios
- Experimental signature of two isolated dimuons, each with good dimuon vertex proability, displaced $a \rightarrow \mu^+\mu^-$ decay vertices also considered for 2018 data
- **Signal region** defined by expected mass resolution (90% efficient window) in $m_1 - m_2$ plane (dashed lines in figures), dimuons required to have consistent mass
- Background from multi-jet (below Υ) and Drell-Yan / EW (above Υ) processes, modelled with data-driven techniques

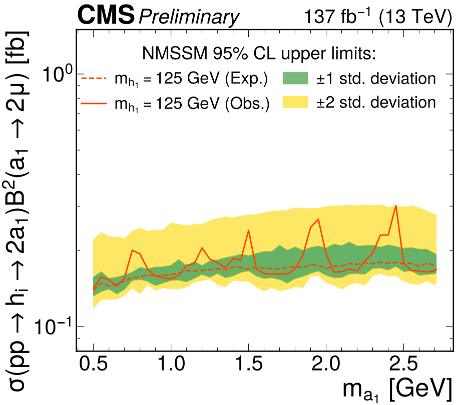


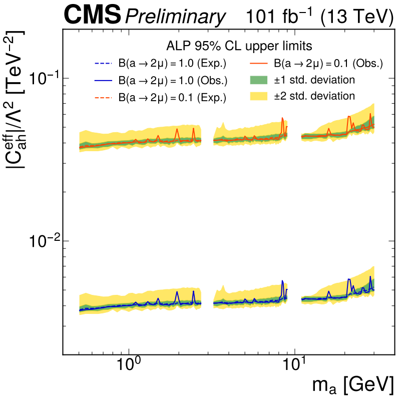
Broad mass range considered, from 0.21 – 61 GeV, excluding J/ψ and Υ regions



The limits from this new analysis (left) are also combined with the 2016 data result [Phys. Lett. B 796 (2019) 131] for masses below 9 GeV (right)

Limits are also interpreted in the context of a variety of BSM scenarios, including: ALP, NMSSM, vector dark portal and dark SUSY (see backup or CMS note)





↑ Cross-section times branching fraction constraints in NMSSM interpretation with $m_{h_1} = 125$ GeV

↑ Constraints on the effective coupling of an axion-like particle to the Higgs boson

(Very) rare SM decays of the Higgs boson

- $H \rightarrow Z\gamma$ - Combination of ATLAS and CMS Run 2 results establishes evidence for the decay at 3.4σ, intriguing excess w.r.t. SM prediction
- $H \rightarrow \psi(nS)\gamma$ - New CMS search dramatically improves upon earlier branching fraction upper limits to $\mathcal{O}(10^{-4})$ level and adds κ_c interpretation

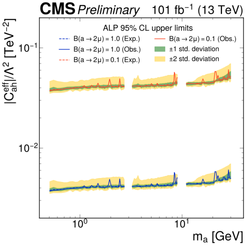
Exotic decays of the Higgs boson

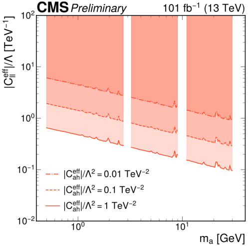
- $H \rightarrow D^{*0}\gamma$ - ATLAS perfoms first search for this exotic flavour violating Higgs boson decay, excluding branching fractions above $\mathcal{O}(10^{-3})$ level
- $H \rightarrow Za, a \rightarrow \gamma\gamma$ - ATLAS extend limits to cover most of allowed m_a region, excluding $\mathcal{B}(H \rightarrow Za) \times \mathcal{B}(a \rightarrow \gamma\gamma)$ down to $\mathcal{O}(10^{-3})$ level for $m_a > 3$ GeV
- $VH, H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$ - Recent CMS limits exclude new regions of 2HDM+S parameter space
- $H \rightarrow aa \rightarrow \mu^+\mu^-\mu^+\mu^-$ - **New for Moriond!** CMS result extends to full Run 2 dataset and interpreted in a variety of BSM scenarios

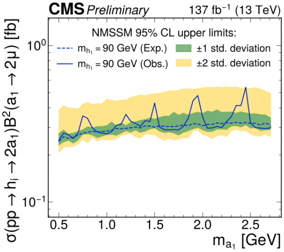
Most of these searches are limited by the statistical power of the datasets used, bright prospects for futher exploration of these channels with the LHC Run 3 data currently being collected!

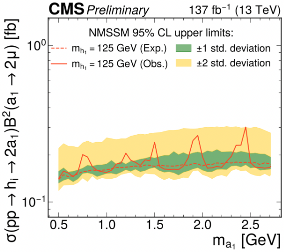
Additional Slides

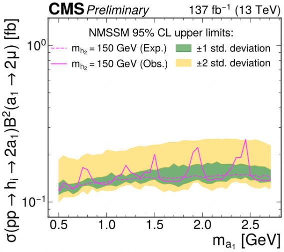
Top: Constraints on ALP effective coupling to both *H* and leptons



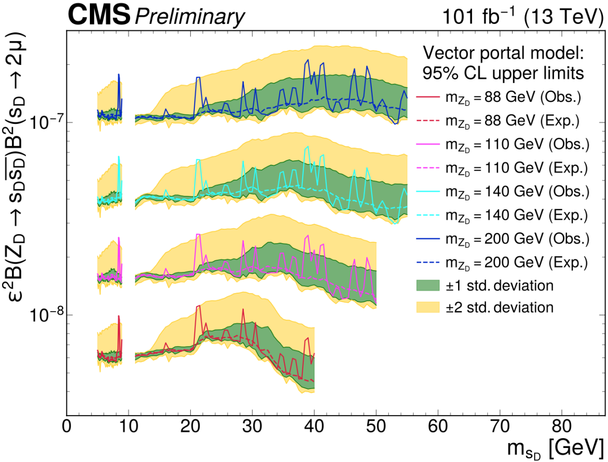




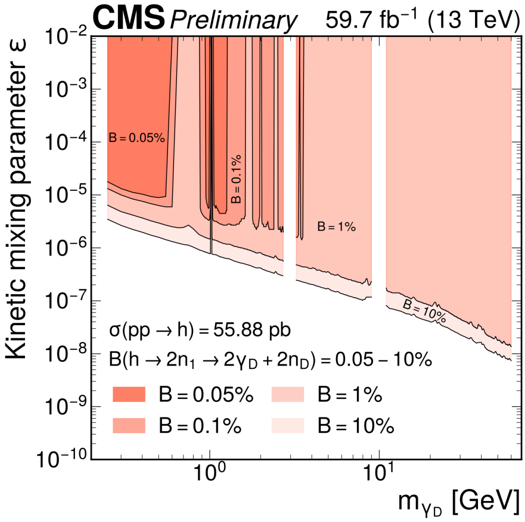




Bottom: Other h_1 and h_2 mass assumptions in MSSM interpretation



Constraints in vector dark portal model



Constraints in dark SUSY model