Light Scalars and Exotic Higgs Decays LHC Run 2 and Run 3

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PITT PACC

Apr 9th, 2021

INTRODUCTION

- Please allow ample time for questions, and try to structure your talks in a way that provokes questions. Talks that are listed at 30 min = 20 + 10. 40 = 25 + 15.
- Guiding themes:
  - How do we design future analyses to fully utilize a doubled dataset, beyond the naive sqrt(2) improvement?
  - What lessons have been learned from Run 2 analyses and how we apply them to Run 3?
  - What new SM measurements would you like to see, or how would you like to see measurements improved beyond the current state-of-the-art?
- Specific ideas that may be useful:
  - How might we benefit the most by using new triggers or trigger techniques?
  - How can special runs or dedicated configurations play a role (for example, low pileup data or heavy ions)?
  - How can improvements in offline reconstruction, including ML techniques be utilized?
  - How can novel ideas from ML be utilized in the analysis of data?

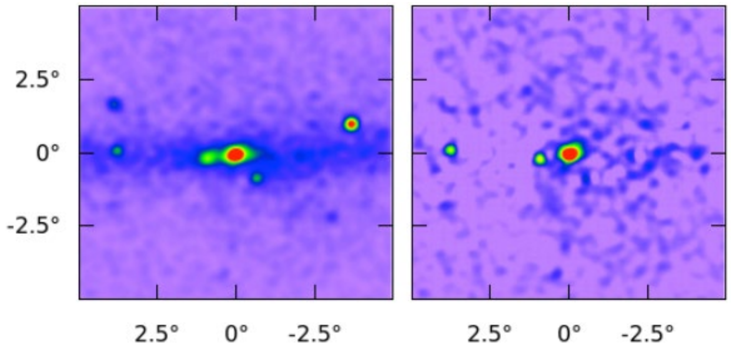
Motivation

- Recently we have seen a lot of excitement related to possible new light scalars
- They are present in models for **naturalness**, **thermal dark matter**, **electroweak baryogenesis**, **axions**.
- Various anomalies can be explained by the presence of light scalars (and several by coupling it to the Higgs):
  - Gamma-ray excess at the center of the galaxy
  - Antiproton excess in cosmic rays
  - KOTO anomaly
  - Excess in excited Beryllium decay

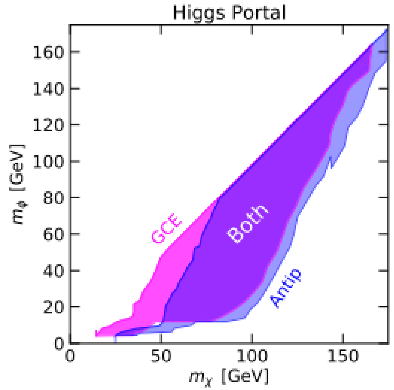
$O(10-100\ GeV)$ (gamma-ray excess, antiproton excess)

$O(10-100\ MeV)$ (KOTO anomaly, Beryllium decay)

Fermi-LAT Collaboration, Phys. Rev. D **89**, 042001



D. Hooper et al. arXiv:1912.08821

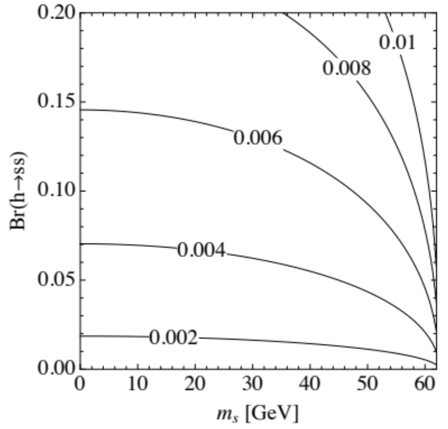


How to search for these states?

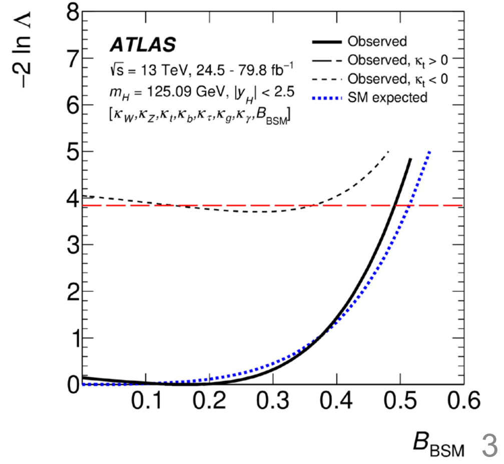
- These states have to be very weakly coupled, otherwise we would have seen them already.
- So, even though direct searches for these scalars are possible, it is usually quite challenging and these searches are usually limited by trigger.
- Another idea is to look for the new scalar in the decay of the Higgs boson.
  - The Higgs boson is a very narrow resonance. Even very weakly-coupled new particles may yield a sizeable branching ratio.
  - ATLAS and CMS have a lot of Higgs events on their tapes.
- The constraints on the total Higgs width are quite weak.

D. Curtin et al, Phys. Rev. D 90 , 075004

Coupling in units of v



ATLAS Collaboration, Phys. Rev. D 101 (2020) 012002



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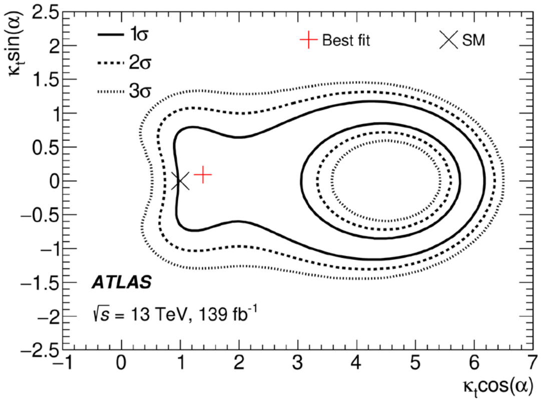
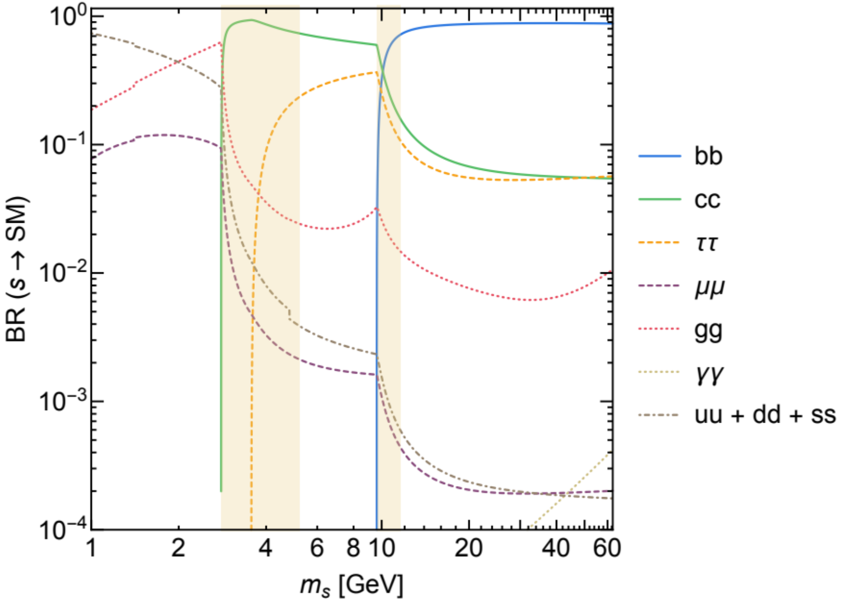
How to search for these states?

- A new light scalar mixes with the Higgs boson inheriting the Yukawa couplings
- In several DM models, a pseudo-scalar is favored to avoid constraints from direct-direction experiments.
  - Requires a CP-odd component of the Higgs
  - Also very weak constraints



ATLAS Collaboration, Phys. Rev. Lett. 125 (2020) 061802

D. Curtin et al, Phys. Rev. D 90 , 075004



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How to look for these states?

- Favors "heavy" final states.
  - bb for $m_S > 10$ GeV
  - $\tau\tau$ for $m_S > 4$ GeV
  - $\mu\mu$ otherwise.
- Other types of couplings may favor different decays.
- For instance, in ALP models, dimension-5 couplings to $\gamma\gamma$ and gg are favored.
  - But in these models exotic Higgs decays are either higher order (dimension 6) or loop-suppressed, so we won't cover it here.
  - See, *eg*, Bauer *et al.*, JHEP 12 (2017) 044

Existing analyses with LHC Run 2 data

	bb	$\tau\tau$	$\mu\mu$
bb	ATLAS EXPERIMENT		
$\tau\tau$	CMS		
$\mu\mu$	ATLAS EXPERIMENT, CMS	CMS	ATLAS EXPERIMENT, CMS

CMS has an $H \to aa \to (\mu + \text{track})(\mu + \text{track})$ search (PLB 800 (2019) 135087) that can be interpreted as both $2\mu 2\tau$ and 4τ. It is not included in the table above.

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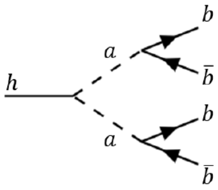
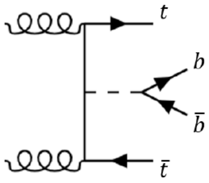
Is there another way?

- If the new light scalar inherits the Higgs boson Yukawa couplings then it should interact strongly with top quarks.
- Search for tta production can provide complementary information (see, *eg*, Casolino *et al.*, Eur.Phys.J.C 75 (2015)). $H \to aa$ depends on both the Haa exotic coupling and on the aff coupling. The tta process depends only on the aff coupling.
- Performing both analyses simultaneously can provide unique information.



$\propto g_{haa} \times g_q^2$



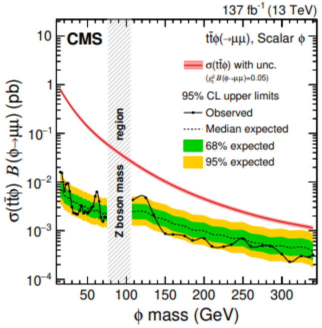
$\propto g_q^2$

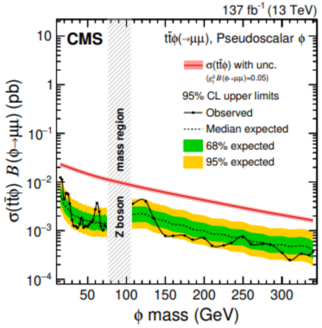
Existing analyses with LHC Run 2 data

bb	$\tau\tau$	$\mu\mu$

Note the CMS analysis (published in JHEP 03 (2020) 051) is not a targeted analysis.

The predicted cross section can vary significantly between scalar and pseudoscalar hypotheses.





REVIEW OF RECENT RESULTS

Preliminary result ATLAS-CONF-2021-009

ATLAS EXPERIMENT

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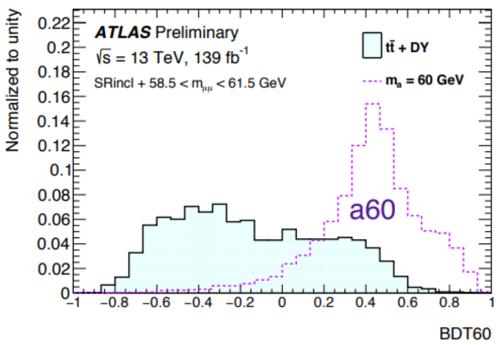
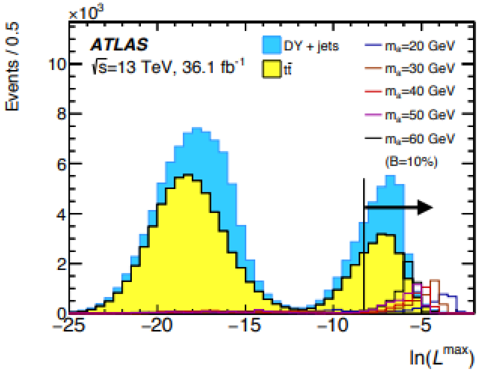
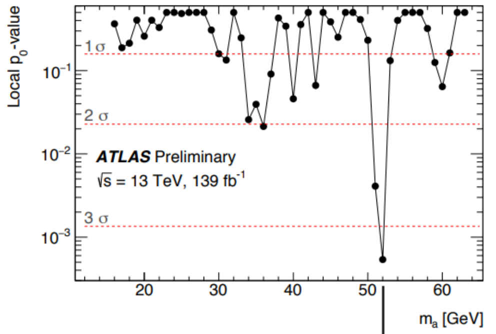
Light scalars in $H \rightarrow aa \rightarrow (bb)(\mu\mu)$

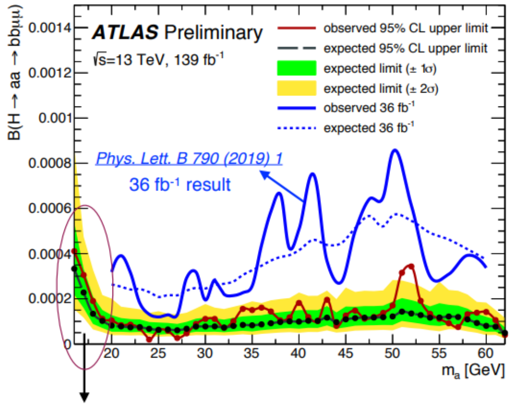
- Search for $H \rightarrow aa \rightarrow 2b2\mu$ targeting ggF production
- Covers the mass range $16 < m_a < 62$ GeV
- Introduces a maximum likelihood $m_{\mu\mu} = m_{bb}$ constrain to improve the dijet mass resolution and to select events.
- Additional event selection performed with BDT to reject DY and $t\bar{t}$ events. Different BDTs trained for different mass regimes.







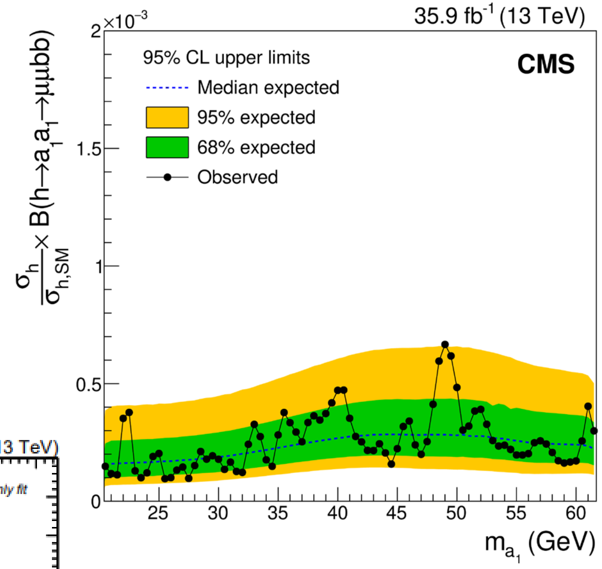
p-val = 0.0005 (0.048) local (global)

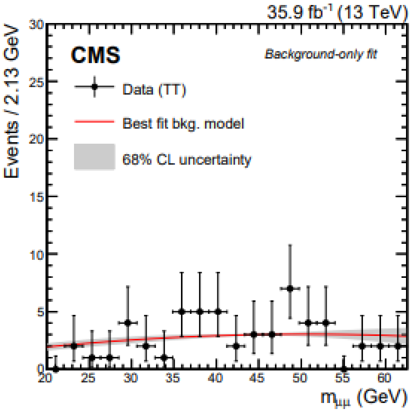


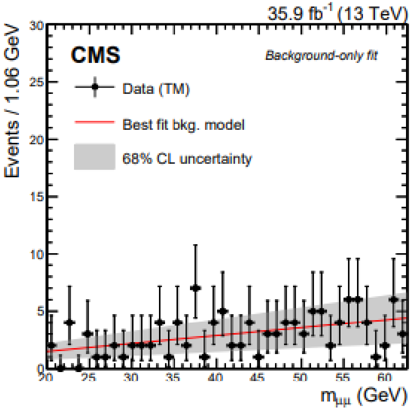
b-jets start merging/falling below reco threshold

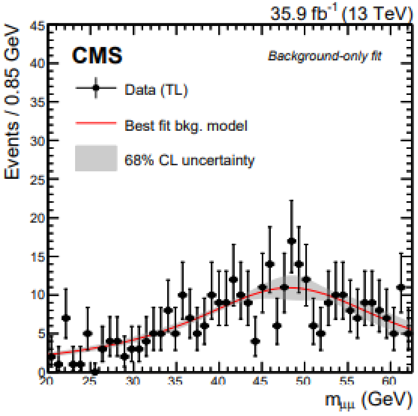
Light scalars in $H \to aa \to (bb)(\mu\mu)$

- Search for $H \to aa \to 2b2\mu$ targeting ggF production
- Covers the mass range $20 < m_a < 62.5$ GeV
- Similar kinematic constraint $m_{\mu\mu} = m_{bb}$ used to select events.
- Several SR depending on the value of the b-tagging discriminator of the two jets in the event.
- Analysis performed with an unbinned fit to data.









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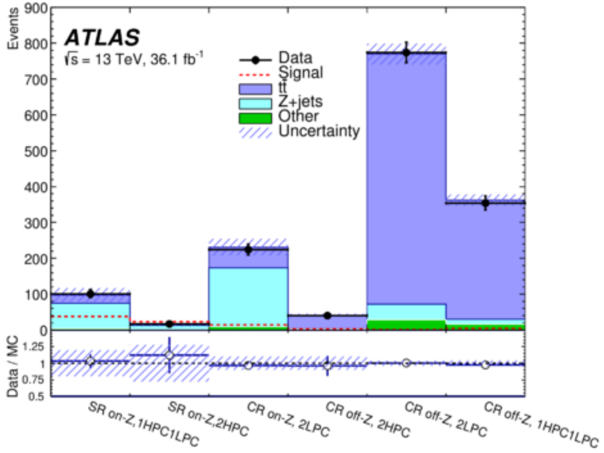
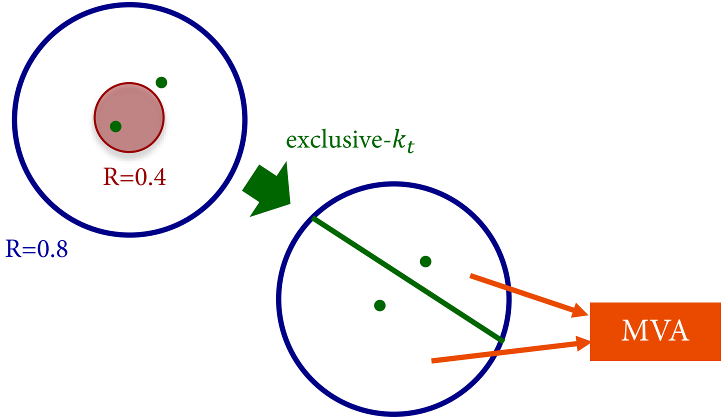
Light scalars in $H \rightarrow aa \rightarrow (bb)(bb)$

- Search for $H \rightarrow aa \rightarrow 4b$ using the WH/ZH production mechanism.
- Two analyses: one targeting the mass range $15 < m_a < 30$ GeV (ZH only) and another one for $25 < m_a < 60$ GeV.
- Z/W-boson provides strategy for triggering and background estimate
- For low masses, $a \rightarrow bb$ decays produce merged jets. Dedicated MVA with substructure, b-tagging, and kinematic information to distinguish $a \rightarrow bb$ decays from background.

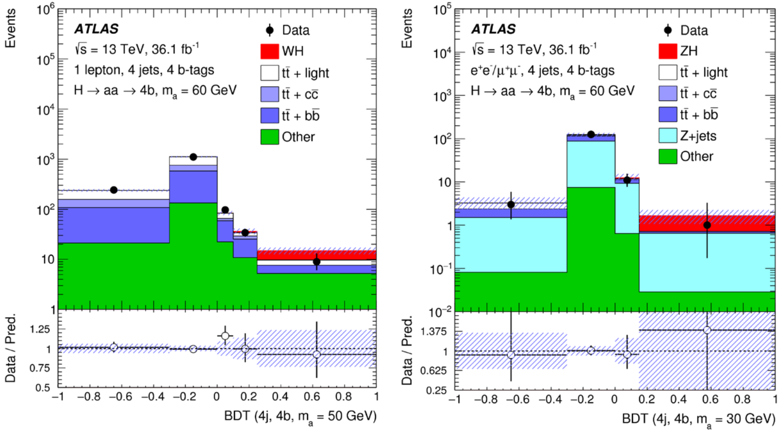


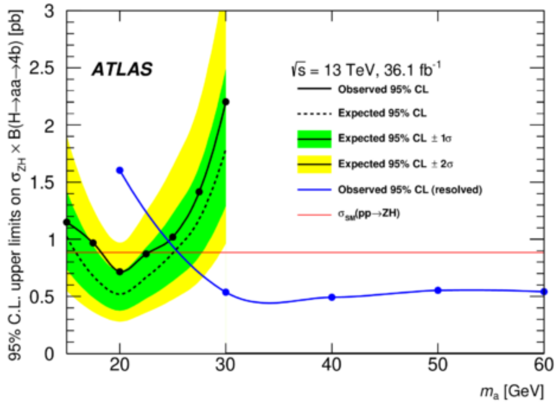


Phys. Rev. D 102 (2020) 112006 **and** JHEP 10 (2018) 031

Light scalars in $H \to aa \to (bb)(bb)$

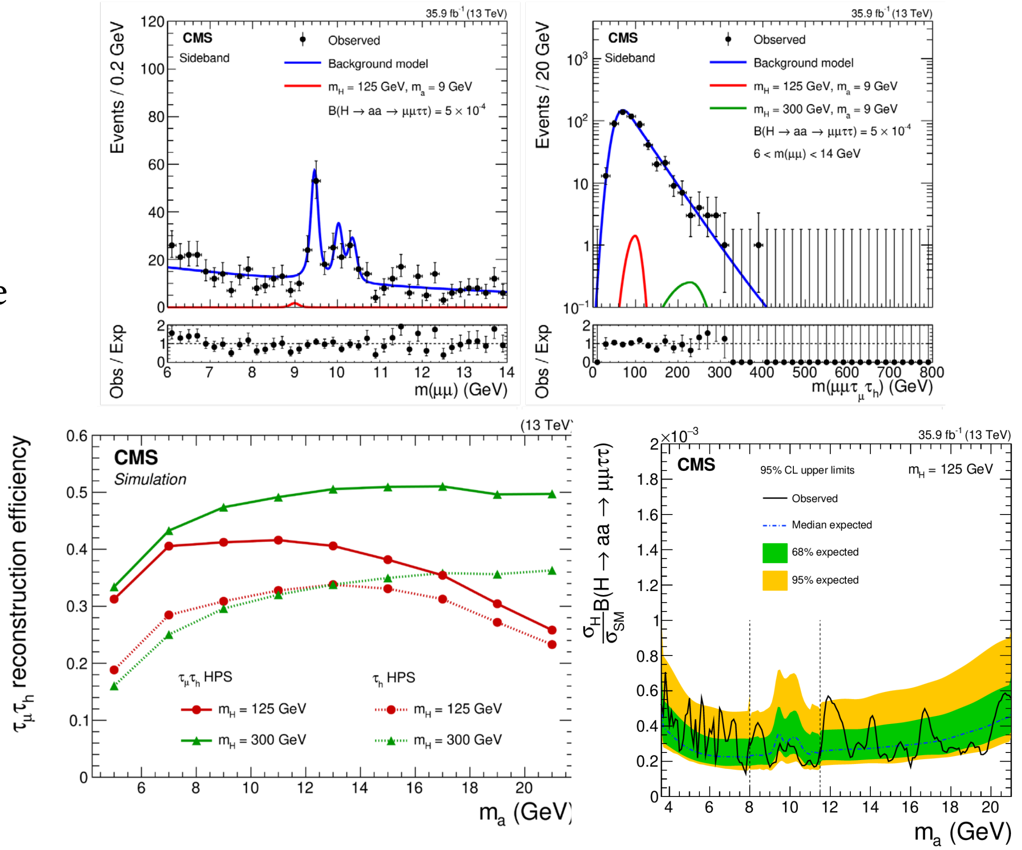
- Search for $H \to aa \to 4b$ using the WH/ZH production mechanism.
- Two analyses: one targeting the mass range $15 < m_a < 30$ GeV (ZH only) and another one for $25 < m_a < 60$ GeV.
- Z/W-boson provides strategy for triggering and background estimate
- For low masses, $a \to bb$ decays produce merged jets. Dedicated MVA with substructure, b-tagging, and kinematic information to distinguish $a \to bb$ decays from background.





Light scalars in $H \to aa \to (\mu\mu)(\tau\tau)$

- Search for decays $H \to aa \to (\mu\mu)(\tau\tau)$.
- Focus on the case $\tau_h\tau_\mu$ to be able to identify boosted τ-decays with high efficiency and low misidentification.
- Search performed with 2D unbinned fit to the $m(\mu\mu) \times m(\mu\mu\tau_\mu\tau_h)$ spectrum.
- Background model obtained from sideband with non-isolated $\tau_\mu\tau_h$ candidates and loose-to-tight factors measured in $Z(\to \mu\mu)$+jets events.
- Modeling of low-mass resonances improved by use of a low-mass $\mu\mu$ CR without additional $\tau_\mu\tau_h$.

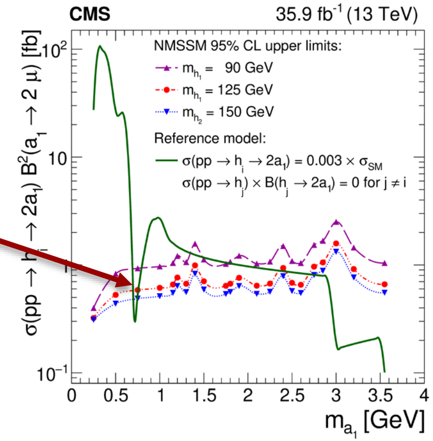


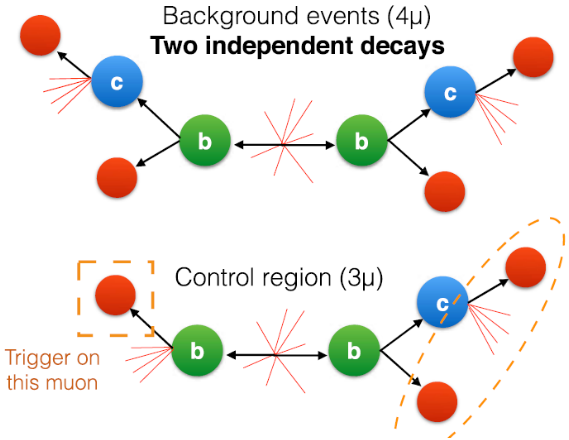
Phys. Lett. B 796 (2019)

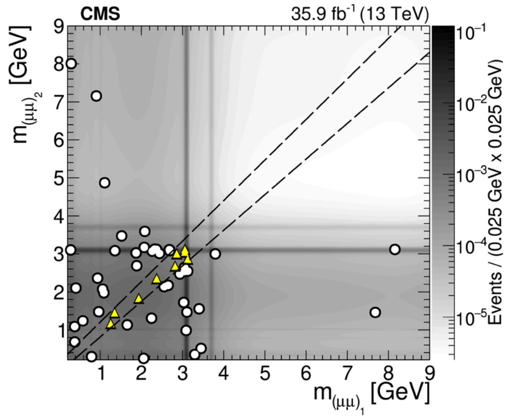
Light scalars in $H \to aa \to (\mu\mu)(\mu\mu)$

- Search for decays $H \to aa \to (\mu\mu)(\mu\mu)$.
- Search for isolated, low mass, di-muon pairs.
- Non-prompt background $bb + X$ estimated from a sample with 3 muons.
- Prompt background estimated from isolation sidebands in 4 muon events selected with J/ψ trigger.
- Negligible electroweak background.

$BR_{\text{lim}} \approx 1 \cdot 10^{-5}$





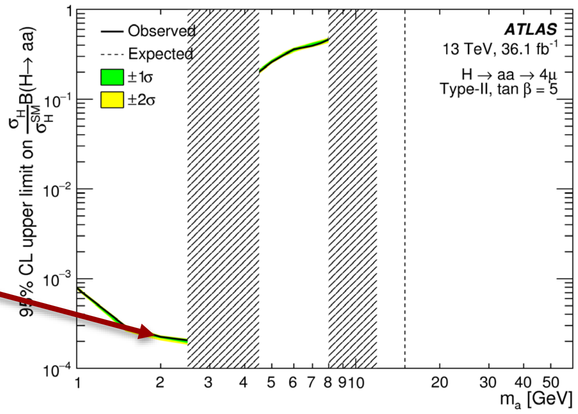


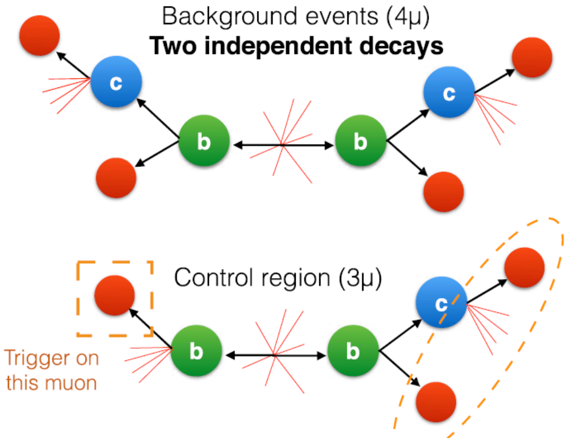
JHEP 06 (2018) 166

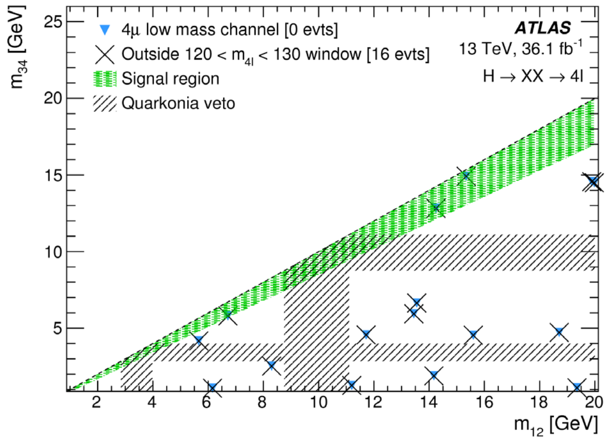
Light scalars in $H \to aa \to (\mu\mu)(\mu\mu)$

- Search for decays $H \to aa \to (\mu\mu)(\mu\mu)$
- Same background method (3 muon sample) as used by CMS.
- But veto resonance regions $(\omega, \rho, J/\psi, \Upsilon)$.
- Imposes Higgs mass constraint explicitly

$BR_{\text{lim}} \approx 1 \cdot 10^{-5}$
[if you translate this to $BR(H \to aa \to 4\mu)$]







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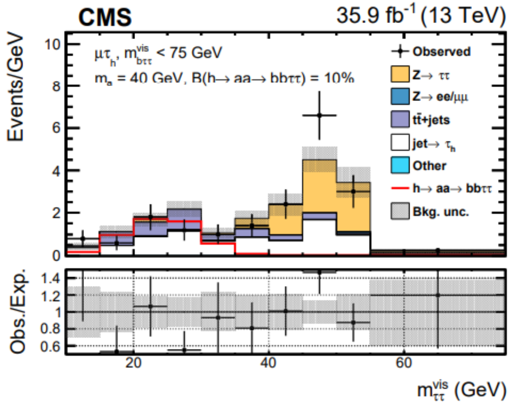
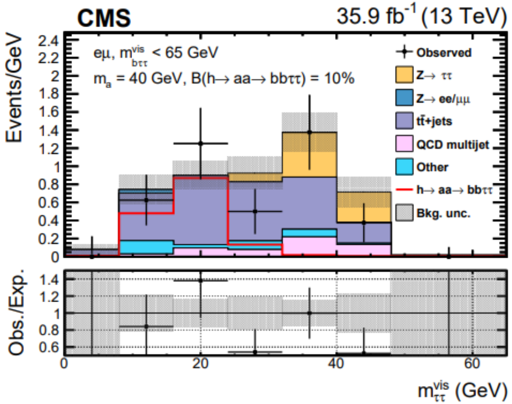
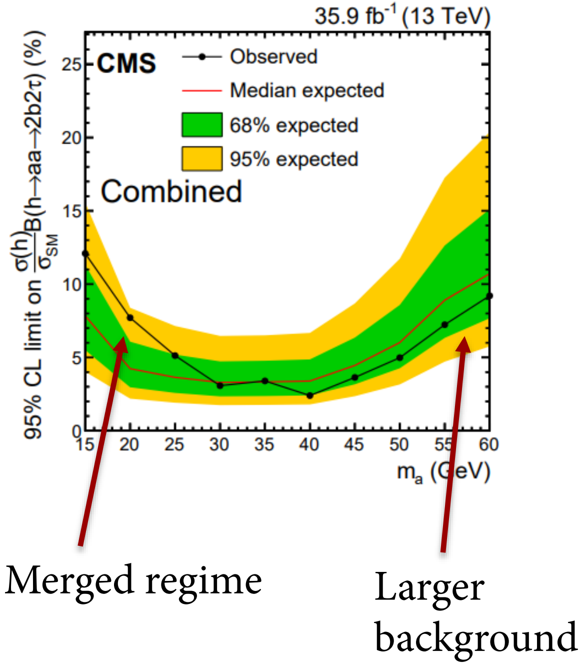
Light scalars in $H \to aa \to (\tau\tau)(bb)$

- Search for decays $H \to aa \to (\tau\tau)(bb)$ where at least one of the τ decays leptonically.
- Targeting the high-mass regime $15 < m_a < 60$ GeV with a completely resolved final state.
- Analysis is challenging due to the large $t\bar{t}$ and Z + jets background.



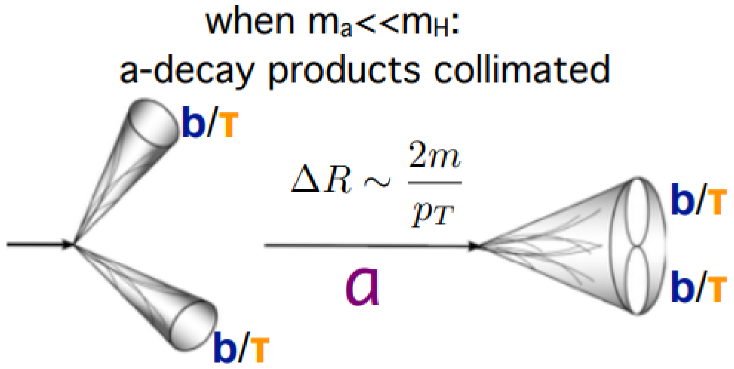




IDEAS FOR RUN 3

Looking forward: objects

- Why are these analyses difficult? Because the final state particles can be close together in the detector. This is specially true for low scalar masses.
- We will discuss some of the ideas that are being pursed for the future. Right now, these ideas as experimental and, when used in analysis, a series of customized/dedicated work is necessary,
- The best way to extend the reach of the LHC searches for the search for light scalars in Run 3 is for these technique to become standard and widely supported by the collaborations.



Merged bb reconstruction

- During the last 10 years, several bb-jet identification techniques were developed, calibrated, and are now widely supported by CMS and ATLAS.
- Well known examples are the family of algorithms DeepAK8, DeepDoubleB, and DeepDoubleC from CMS (see, for instance, EPJ Web Conf. 214, 06010 (2019)) and the $X \to bb$ taggers in ATLAS (see, for instance, ATL-PHYS-PUB-2020-019).
- These algorithms use advanced ML methods to identify merged bb-jets **using large-R jets.**
- **Large-R jets** are only defined at **high-$\boldsymbol{p_T}$** and **high mass**. However, the merged jets in $H \to aa \to (bb)(XX)$ are **low-$\boldsymbol{p_T}$** and **low mass**.
- Most of the searches currently being pursued use **large-R track jets**, and novel double-b tagging algorithms developed for this kind of jets.
- **But large-R track jets are way less studied and understood than "regular" (PFlow, UFO, …) large-R jets.**

Merged $\tau\tau$ reconstruction

- The situation with merged $\tau\tau$ is similar: there are some merged $\tau\tau$ identification algorithms available and partially supported by the collaborations.
- However, they were all developed in the context of SUSY searches and most of them use **high-p_T large-R jets**.
- Current low-p_T, merged $\tau\tau$ reconstruction is limited to the $\tau_h\tau_\mu$ channel, where the muon has little influence on the tau hadronic jet. CMS showed the power of the PFlow-based reconstruction in the $H \to aa \to (\mu\mu)(\tau\tau)$ search where the reconstruction of the $\tau_h\tau_\mu$ mode was obtained with minimal modification over the standard τ_h reconstruction.
- There are some on-going attempts to reconstruct $\tau_h\tau_h$ and $\tau_h\tau_e$ at low p_T, but they are very much R&D at this point and this is a strong limiting factor for $(\tau\tau)$ final states.

Take-home message

- There is a lot of **unexplored** potential in the CMS and ATLAS data.
- So far, there is only one preliminary analysis that has used the full Run 2 dataset (ATLAS $H \rightarrow aa \rightarrow (bb)(\mu\mu)$) and this analysis focuses on a completely resolved phase-space.
- In order to explore the full potential of the two very large datasets for discovery of Higgs exotic decays, new reconstruction algorithms will have to be developed for low-p_T merged bb and $\tau\tau$ states.
- Dedicated reconstruction and isolation for close-by muon may also be necessary to explore the very low mass region ($m_a < 1$ GeV).
- Right now, each analysis has to "rediscover" each of these reconstruction, identification, and isolation methods. And many times, this makes the analysis very challenging.
- We can do better in Run 3.

Looking forward: topologies

- So far, the only topology explored has been $H \to aa \to (XX)(YY)$ where both X and Y are visible.
  - First, and foremost, we have to make sure to explore all possible final states to have a complete picture in all accessible mass ranges.
- Looking forward to Run 3, we should start exploring other topologies:
  - tta topologies, as discussed in the introduction
  - $H \to aa \to (XX) + E_T^{\text{miss}}$, *ie*, when the Y particle is invisible (a DM candidate, for instance)
  - Cascade decays in models with multiple new light scalar $H \to a_1 a_2 \to a_2 a_2 a_2 \to (XX)(YY)(ZZ)$. In this case, particles become very low p_T even in the completely resolved regime (see, *eg*, Robens et al., Eur.Phys.J.C 80 (2020))
  - Lepton flavor violating decays of new light scalars (see, *eg*, Evans et al., JHEP 01 (2020) 028)
  - etc, etc, etc… this is a vast and unexplored field.

Looking forward: topologies

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  - tta topo...
  - $H \rightarrow aa$ ... for instance)
  - Cascade d... new light scalar $H \rightarrow a_1 a_2 \rightarrow a_2 a_2 a_2 \rightarrow (XX)(YY)$ ... case, particles become very low p_T even in the completely resolved regime.
  - Lepton flavor violating decays of new light scalars (see, for instance JHEP 01 (2020) 028)
  - etc, etc, etc… this is a vast and unexplored field.

There are several other directions that are currently being explored and will continue to be explored by both CMS and ATLAS:

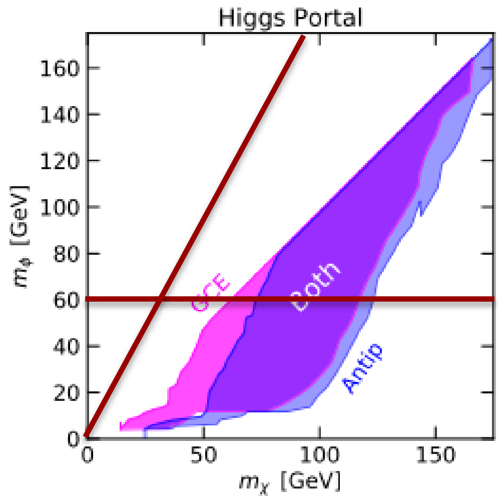
Axion-like particles

Long-lived particles (see, for instance, the talk by J. Alimena)

However, they are outside the scope of this talk.

Looking forward: phase-space

- All the analyses discussed here have a common limitation: $m_\phi < m_H/2$
- Above $m_\phi \simeq 60$ GeV, the on-shell decay $H \to \phi\phi$ is not allowed and the power of searches decreases quite quickly.
- However, for several of the motivations discussed here (see figure), the region $m_\phi > m_H/2$ may be favored.
- The region favored in this study also disfavors $\phi \to \chi\chi$ decays.
- In this case, new ideas will be required. Is it possible to search for these light states using Run 3 data?



D. Hooper et al. arXiv:1912.08821

Conclusions

- New light scalars have strong phenomenological motivation
- CMS and ATLAS are good experiments to search for these new light scalars in the range $0.5 < m_a < 120$ GeV
- Searches so far have focused on $H \rightarrow aa \rightarrow (XX)(YY)$ final state. Several analyses still being performed with full Run 2 data.
- In order to fully explore the data collected (and to be collected in Run 3), new reconstruction algorithms will have to be developed.
- New topologies and new search strategies will also be explored.

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