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Report from WG3 exotic decays

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Introduction

- Overview of recent progresses in theory and experiment in:

1. H(125)→aa decays
2. Long-lived exotic decays
3. H(125)→mesons decays
4. LFV H(125) decays
5. (Semi-)invisible H(125) decays

1. H→AA

Higgs to SM particles via light bosons

- Higgs boson decays to a pair of new spin-zero particles, decaying each to a pair of SM particles.

- Predicted by many theories of physics BSM:
  - NMSSM
  - Several models of DM
  - Neutral naturalness
  - …

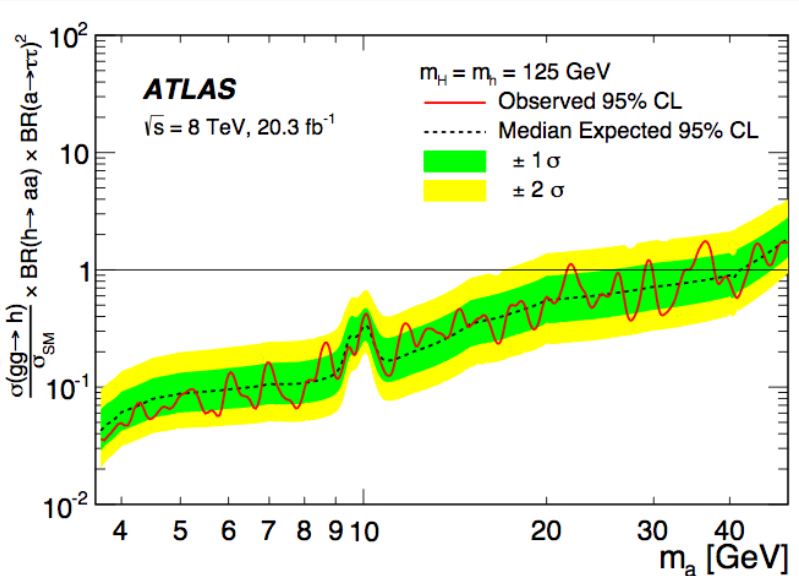
- Several 2HDM+S benchmark models already provided in the WG3 Higgs Exotic Decay (https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGExoticDecay)

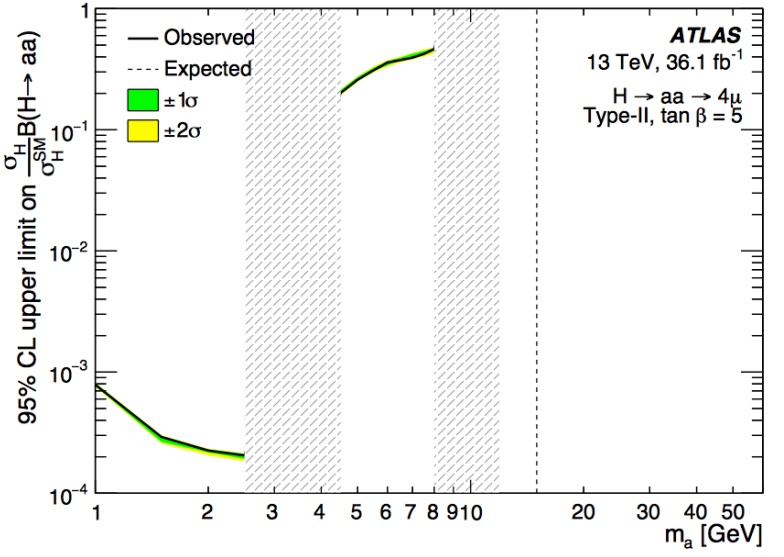
H→aa in ATLAS

- Several final states studied by ATLAS:
  - h→2a→ 4b (arXiv:1606.08391)
  - h→2a→ 2μ2τ (arXiv:1505.01609)
  - h→2Zd / ZZ_d / 2a→ 4ℓ (arXiv: 1505.7645, 1802.03388)
  - h→2a→ 4γ (arXiv:1509.0501)
  - h→2a→2γ2g

NEW

- Work on-going to update analyses and study other final states



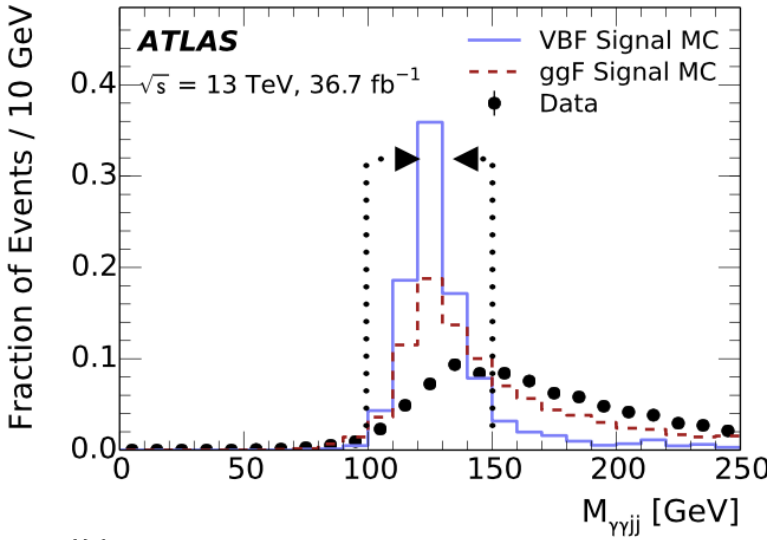


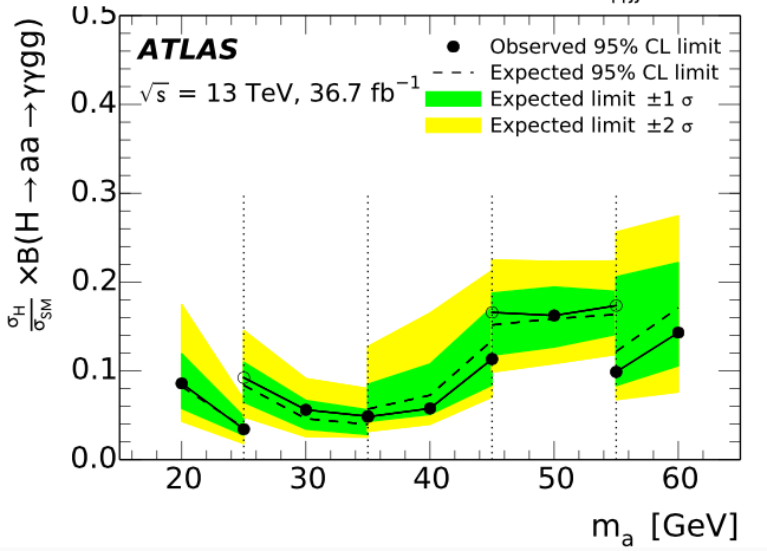
New: H→aa→2γ2g (ATLAS)

- First search in this final state

NEW

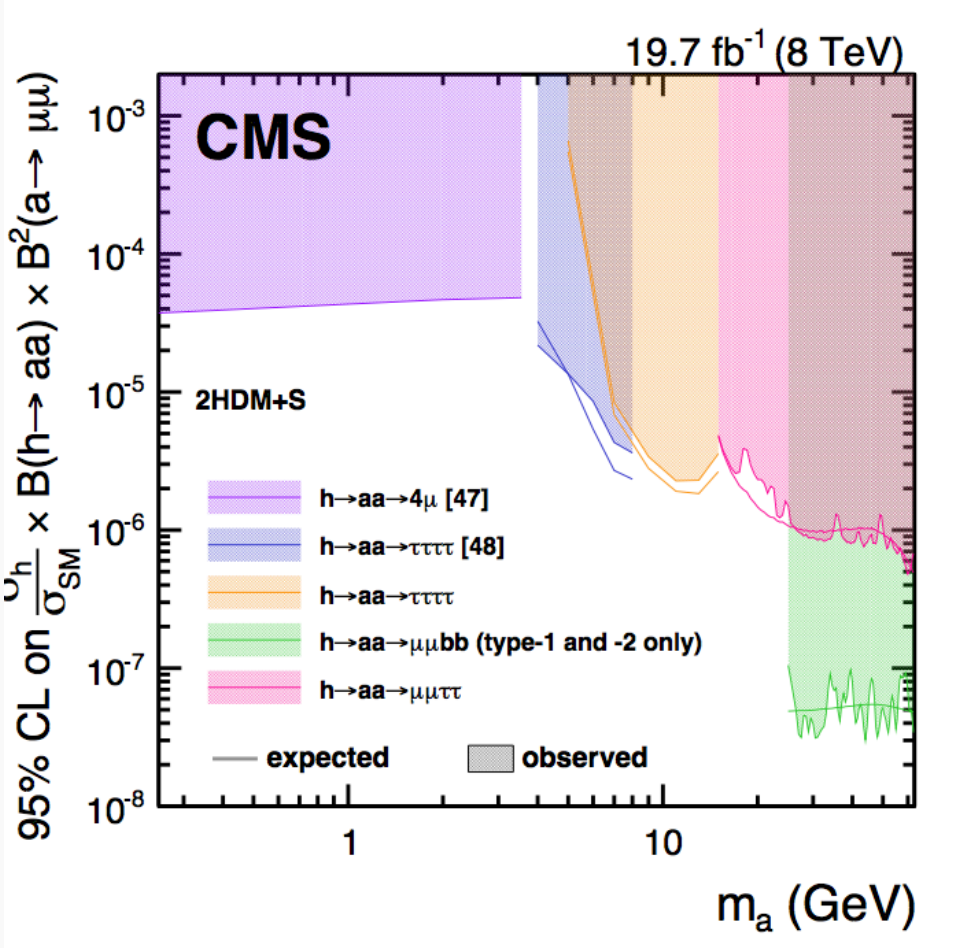
- $20 < m_a < 60$ GeV
- Sensitive in models with suppressed fermionic decays
- Signal selected in the VBF production mode
- $\gamma\gamma$+multi-jet background with 2 mis-identified photons estimated from data in sidebands (ABCD method with photon ID and $|m\gamma\gamma - mjj|$)





H→aa in CMS

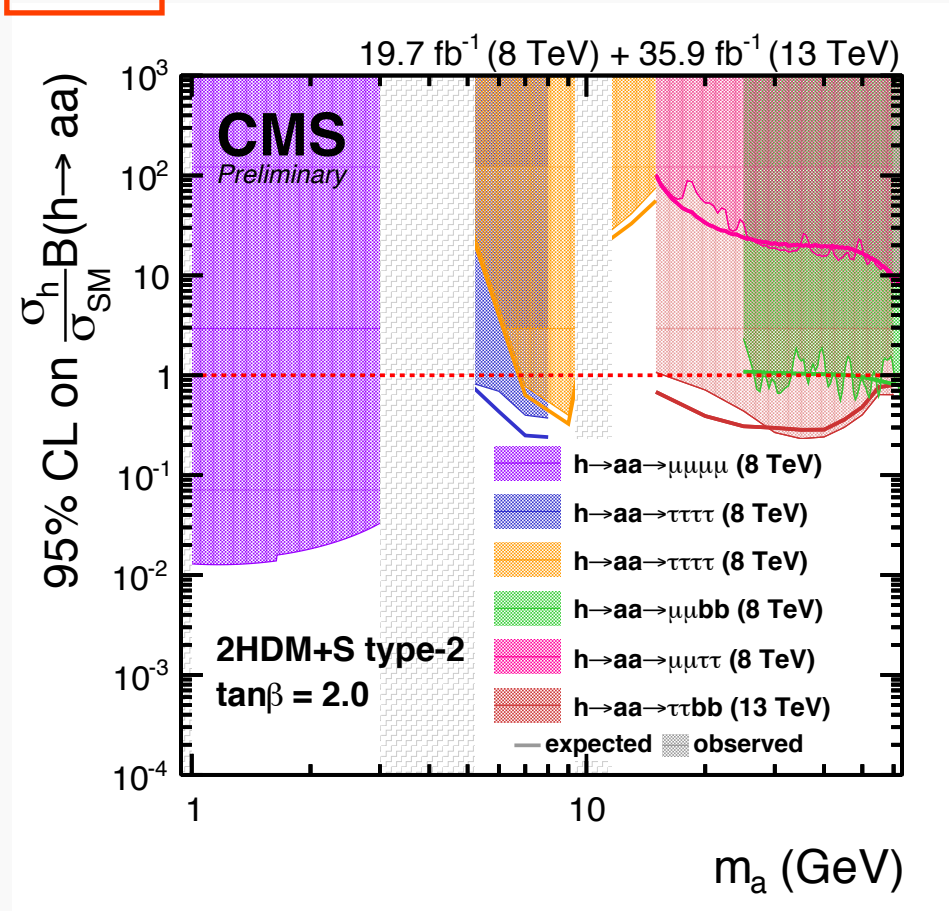
- Searches at 8 TeV:
  - 4μ, low mass
  - 4τ, intermediate mass (arXiv:1701.02032, arXiv: 1510.06534)
  - 2μ2τ, high mass (arXiv: 1701.02032)
  - 2μ2b, high mass (arXiv: 1701.02032)



New: H→aa→2b2τ (CMS)

- 13 TeV result (full 2016 data)
- First time h→aa→bbττ decays are probed: large branching fraction (heavy b and τ), and possible to trigger in ggF production
- In the NMSSM, B(h→aa) > 23% excluded at 95% CL for m_a ~ 35 GeV → most sensitive results so far at the LHC
- Limits improved by several factors in 25 < m_a < 62.5 GeV, and by more than 1 order of magnitude in 15 < m_a < 25 GeV

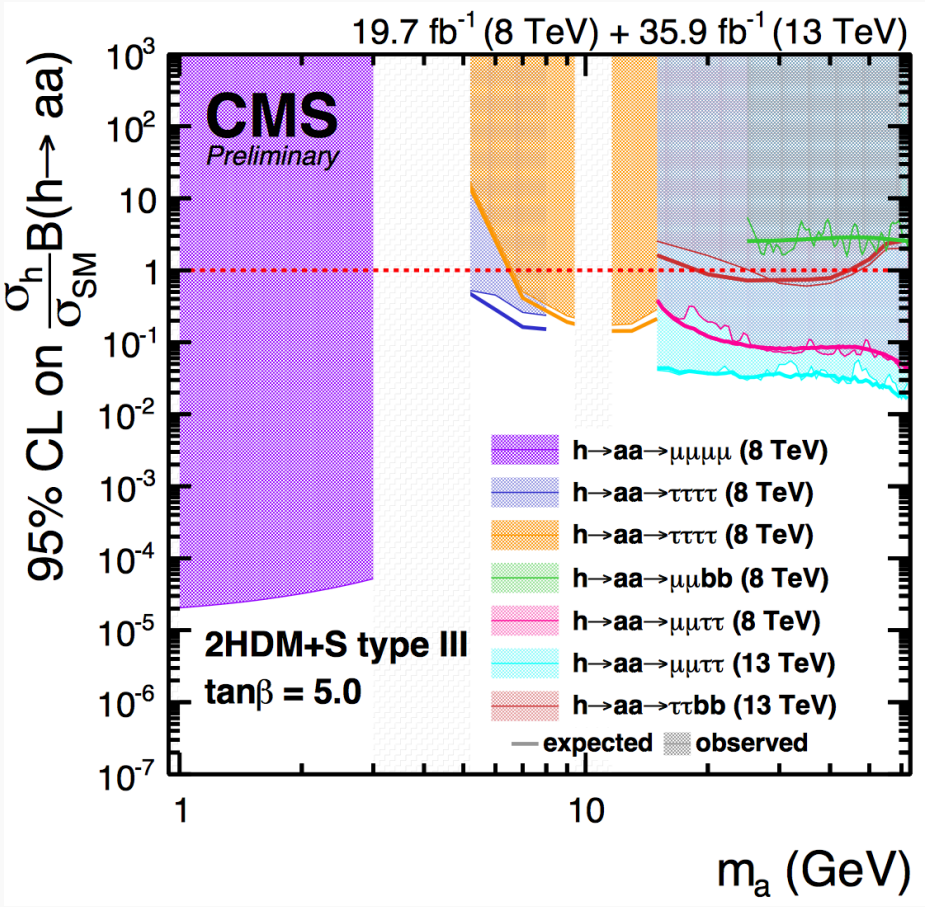
NEW



New: H→aa→2μ2τ (CMS)

NEW

- 13 TeV result (full 2016 data)
- Search for a narrow dimuon resonance over a small flat background
- Same strategy as in run-1
- Limits improved by a factor 2 wrt run-1
- Best limits at high mass in type 3 with large tan β (enhanced couplings to leptons)

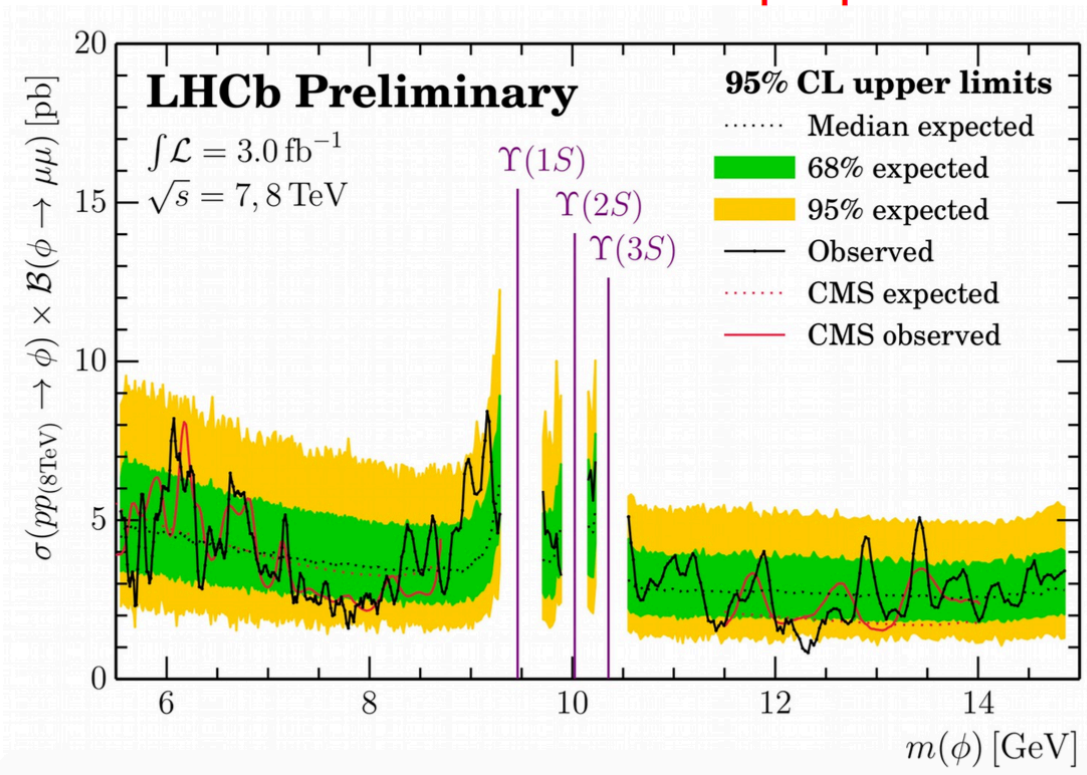


Light pseudoscalars searches at LHCb

- Light Higgs-like spin-0 particle produced in ggF motivated by several models (NMSSM, 2HDM+S).
- NEW search for dimuon resonance in $m_{\mu\mu}$ from 5.5 to 15 GeV.
- First limit in 8.7-11.5 GeV region, competitive with CMS elsewhere

NEW

LHCb-PAPER-2018-008 in preparation



Dark photon searches at LHCb

- Not directly related to exotic Higgs, but interesting technique for pseudoscalar searches in dimuon channel.
- Reconstruction, selection and identification performed online: only interesting events are saved on disk.
- First limit on Dark Photons for m(A') > 10 GeV, and competitive limits on light pseudoscalars as well (arXiv:1802.02156).

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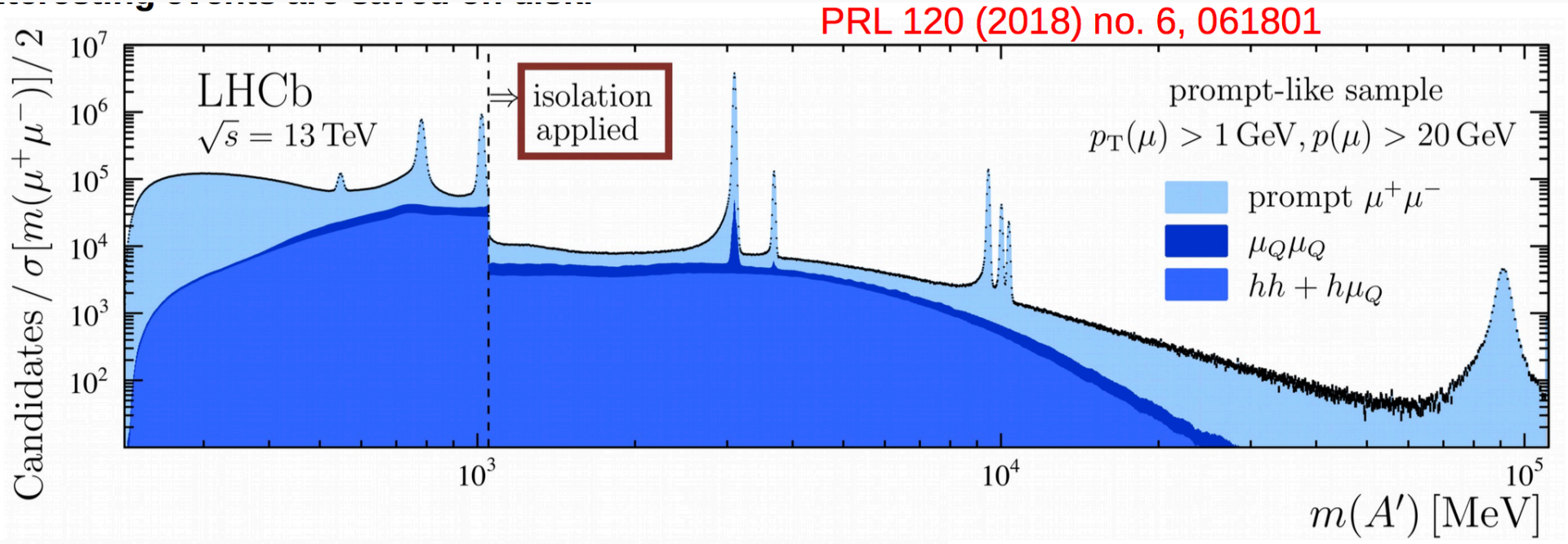


Dark matter motivations

- Exotic Higgs decays in a SM+S type model are the leading LHC signals of a class of simple secluded dark matter models
  - pointed out in [Martin, Shelton, Unwin, 2014]
  - New work [Evans, Gori, Shelton, 2017] defines specific benchmark models and carefully compares constraints/signals in exotic Higgs decays to direct, indirect detection signatures https://arxiv.org/abs/1712.03974

Recent theory work

- Dark matter connection through vectorized fermion portals into dark photons (arXiv:1705.08896); this is recent more thorough discussion on Higgs exotic decays linking to dark matter);

- Higgs to axion-like particles ($H \rightarrow aa$, $H \rightarrow Z$, $H \rightarrow \gamma a$, $a \rightarrow \gamma\gamma$, arXiv:1708.00443, arXiv:1610.02025)

- Complementarity in Higgs two-body and three-body decays ($H \rightarrow SS$ v.s. $H \rightarrow SSS$; arXiv:1609.08127)

- Higgs to more exotic signatures (veto standard signatures after triggering; arXiv:1707.07084) (Higgs has unique advantage as many triggers available)

2. LONG LIVED DECAYS

Long-lived particles

- LHC LLP white paper progressing: draft beginning to circulate for comments

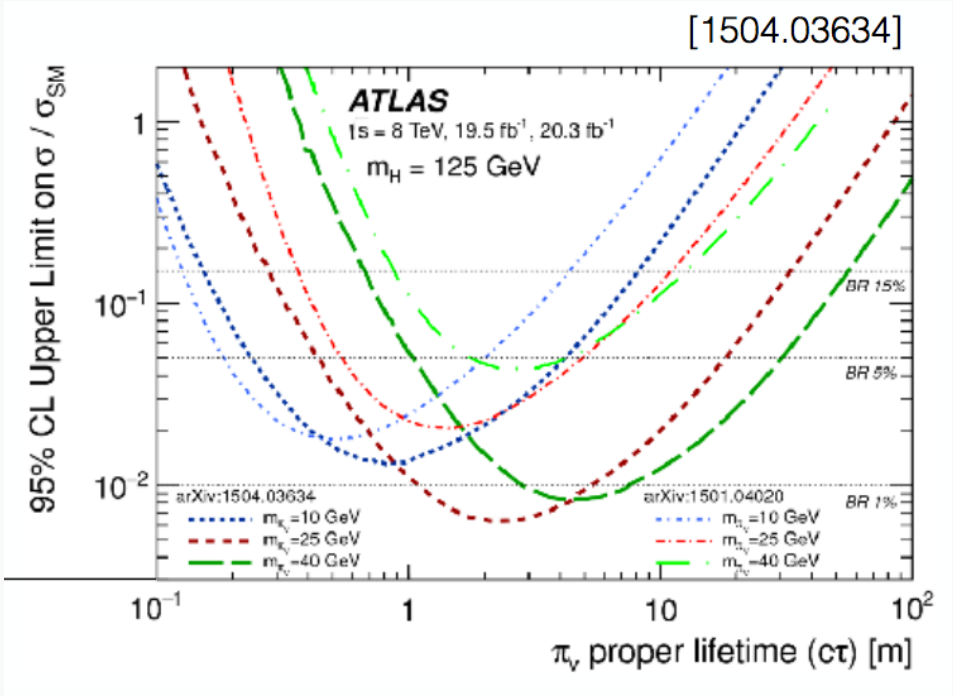
- Includes:
  - recommended simplified models, including production in SM Higgs decay
  - recommendations for presentation of results

- Please contact J. Beacham, B. Shuve, Z. Liu, or J. Shelton if you would like to see a version of the draft

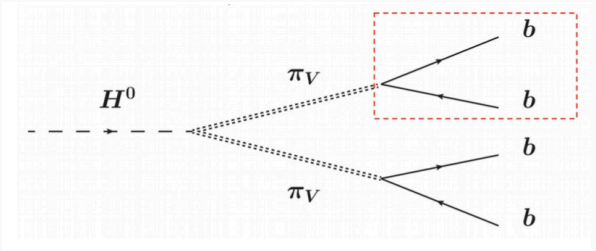
Higgs to long-lived at ATLAS

- Many public results from Run 1 and 2 involving LLPs coming from the Higgs boson, specially exotic signatures looking for:
  - Displaced jets (arXiv:1504.03634, 1501.04020)
  - Displaced lepton-jets (ATLAS-CONF-2016-043)

- New ideas and possible analysis re-interpretations currently being considered.



Higgs to long-lived at LHCb



- Hidden valley dark pions from 125 GeV decays.
- Single displaced dijet signature.
- Search for Higgs decay to a couple of long lived particles.
- ➔ One of the two LLPs is assumed to decay in two jets within the LHCb acceptance.
- No excess found, limit on σ x BR for different dark pions masses and lifetimes.
- Competitive limit with ATLAS and CMS despite factor 10 less luminosity.
- Expected benefit from online identification of displaced dijets in upgrade.

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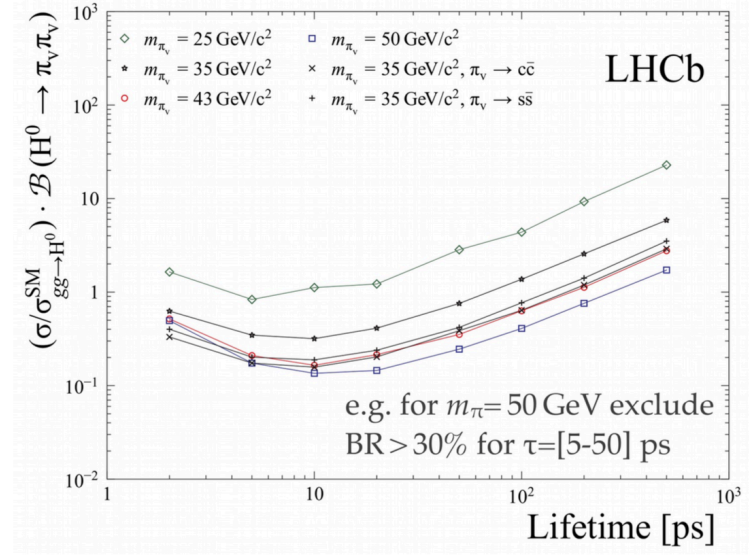
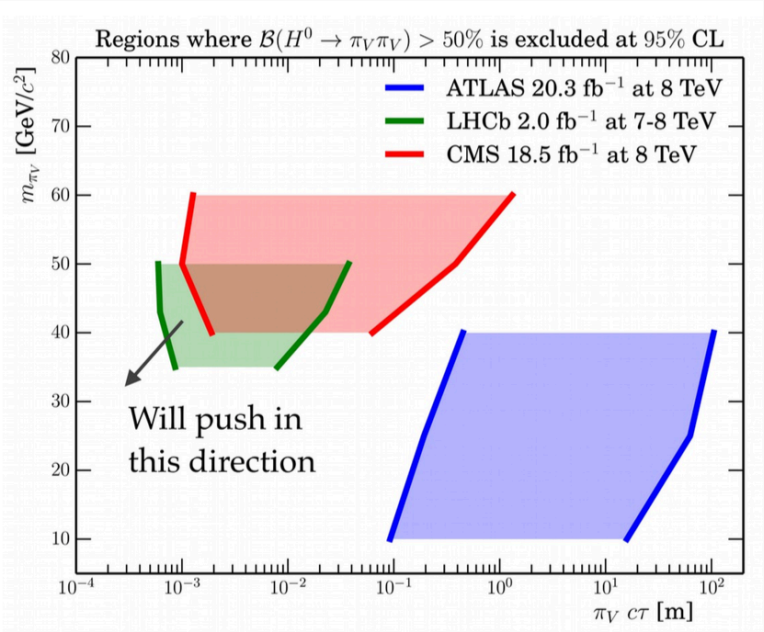




3. H→MESONS

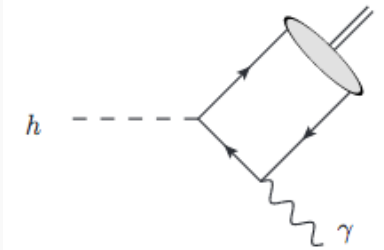
Higgs to mesons

- Rare decays of the Higgs boson to a meson and a photon give a direct window to the Yukawa couplings.

Decay mode	Branching ratio $[10^{-6}]$	Decay constant [MeV]
$h \to \pi^+ W^-$	$4.30 \pm 0.01_f \pm 0.00_{\rm CKM} \pm 0.17_{\Gamma_h}$	130.4 ± 0.2
$h \to \rho^+ W^-$	$10.92 \pm 0.15_f \pm 0.00_{\rm CKM} \pm 0.43_{\Gamma_h}$	207.8 ± 1.4
$h \to K^+ W^-$	$0.33 \pm 0.00_f \pm 0.00_{\rm CKM} \pm 0.01_{\Gamma_h}$	156.2 ± 0.7
$h \to K^{*+} W^-$	$0.56 \pm 0.03_f \pm 0.00_{\rm CKM} \pm 0.02_{\Gamma_h}$	203.2 ± 5.9
$h \to D^+ W^-$	$0.56 \pm 0.03_f \pm 0.04_{\rm CKM} \pm 0.02_{\Gamma_h}$	204.6 ± 5.0
$h \to D^{*+} W^-$	$1.04 \pm 0.12_f \pm 0.07_{\rm CKM} \pm 0.04_{\Gamma_h}$	278 ± 16
$h \to D_s^+ W^-$	$17.12 \pm 0.61_f \pm 0.56_{\rm CKM} \pm 0.67_{\Gamma_h}$	257.5 ± 4.6
$h \to D_s^{*+} W^-$	$25.10 \pm 1.45_f \pm 0.81_{\rm CKM} \pm 0.98_{\Gamma_h}$	311 ± 9
$h \to B^+ W$		
$h \to B^{*+} W$		
$h \to B_c^+ W$		

Decay mode	Branching ratio $[10^{-6}]$	Decay constant [MeV]
$h \to \pi^0 Z$	$2.30 \pm 0.01_f \pm 0.09_{\Gamma_h}$	130.4 ± 0.2
$h \to \eta Z$	$0.83 \pm 0.08_f \pm 0.03_{\Gamma_h}$	$f_\eta^s = -110.7 \pm 5.5$
$h \to \eta' Z$	$1.24 \pm 0.12_f \pm 0.05_{\Gamma_h}$	$f_{\eta'}^s = 135.2 \pm 6.4$
$h \to \rho^0 Z$	$7.19 \pm 0.09_f \pm 0.28_{\Gamma_h}$	216.3 ± 1.3
$h \to \omega Z$	$0.56 \pm 0.01_f \pm 0.02_{\Gamma_h}$	$f_\omega = 194.2 \pm 2.1\,, \quad f_\omega^s = -13.8 \pm 4.8$
$h \to \phi Z$	$2.42 \pm 0.05_f \pm 0.09_{\Gamma_h}$	$f_\phi = 223.0 \pm 1.4\,, \quad f_\phi^s = 230.4 \pm 2.6$
$h \to J/\psi\, Z$	$2.30 \pm 0.06_f \pm 0.09_{\Gamma_h}$	403.3 ± 5.1
	Γ_h	684.4 ± 4.6
	Γ_h	475.8 ± 4.3
	Γ_h	411.3 ± 3.7

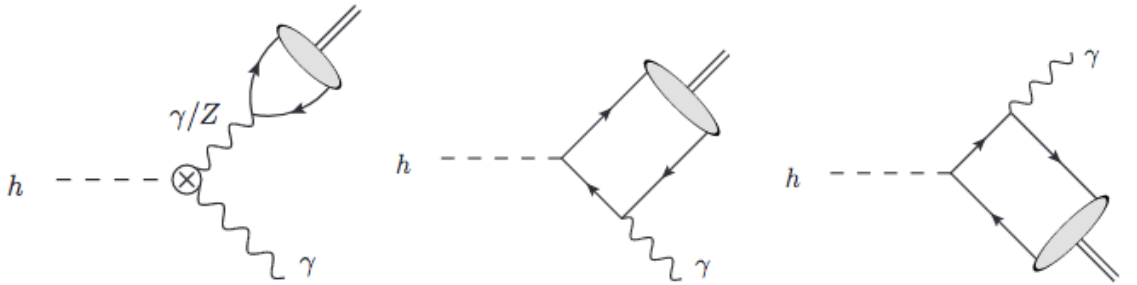
Mode / Method	Branching Fraction $[10^{-6}]$ NRQCD [1486]	LCDA LO [1485]	LCDA NLO [1488]
$\mathrm{Br}(h \to \rho\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(h \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(h \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$

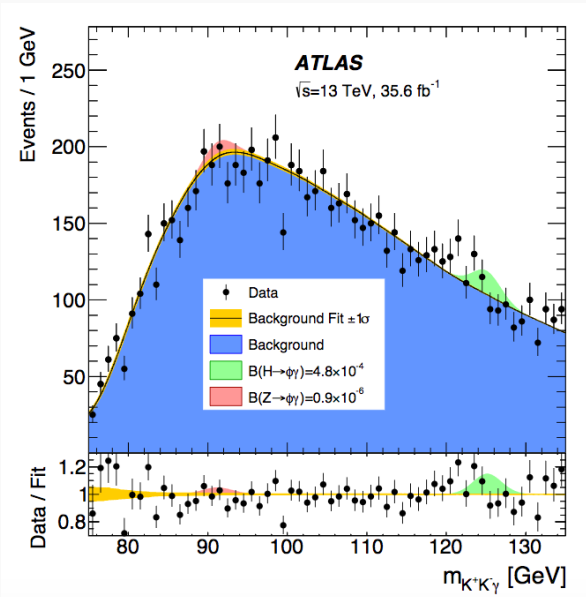


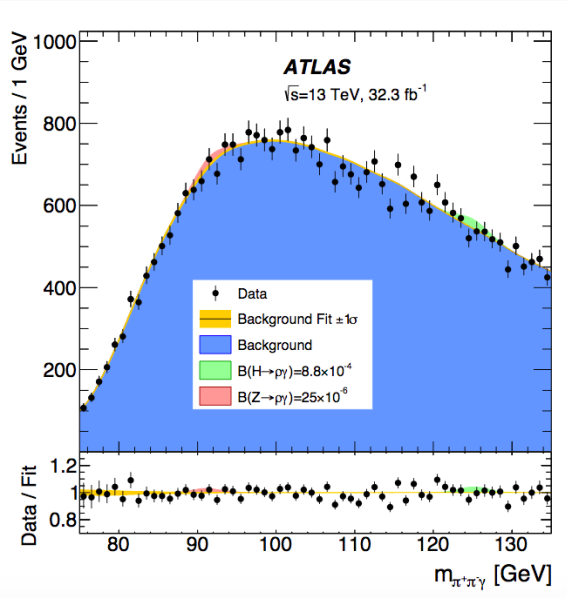
Higgs to mesons at ATLAS

- Several results published:
  - h→$\phi\gamma$ (arXiv:1607.03400, 1507.03031)
  - h→J/$\psi\gamma$, Yγ (arXiv:1501.03276)
  - h→$\phi\gamma$, $\rho\gamma$ (arXiv:1712.02758) **NEW**

- In general far away from being sensitive due to very small branching ratios.

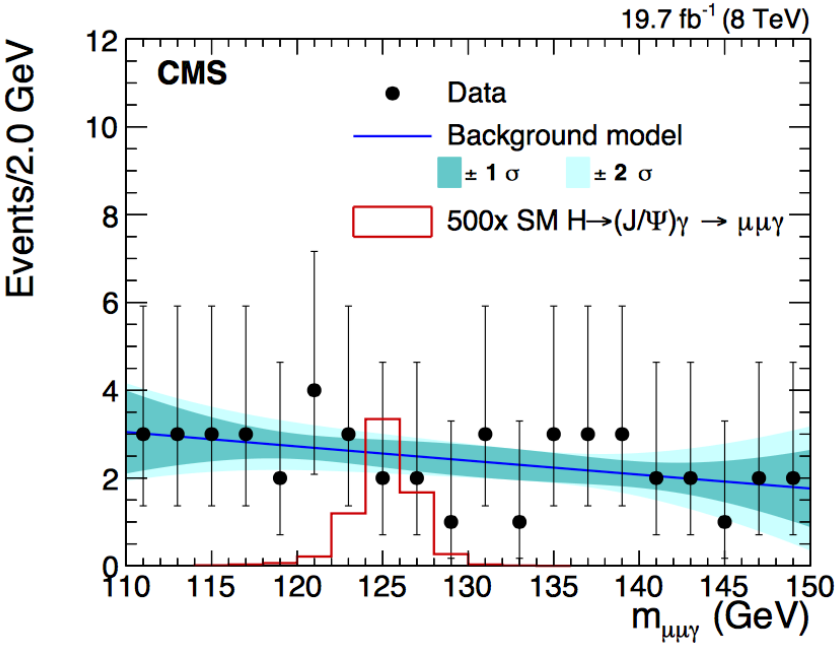


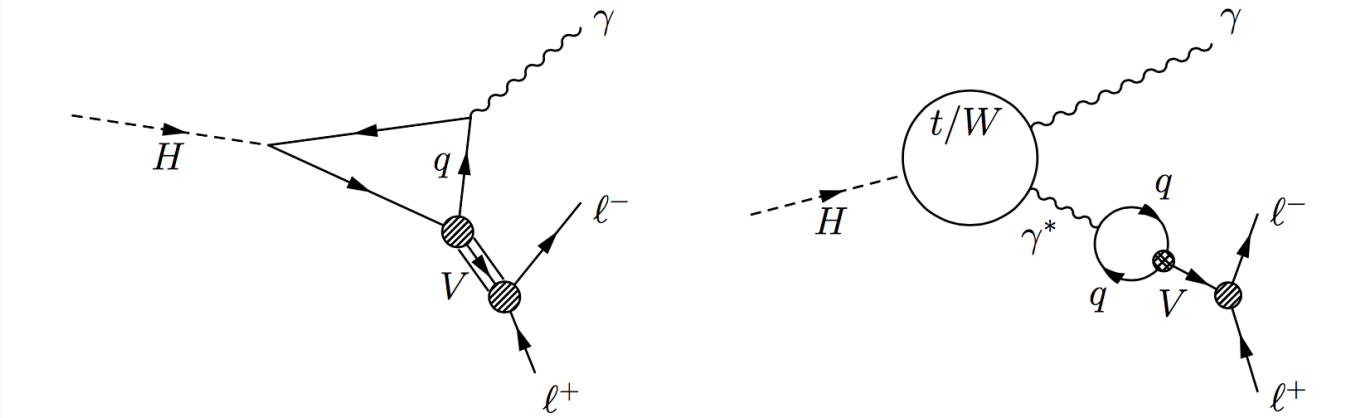




Higgs to mesons at CMS

- arXiv:1507.03031
- Search for a Higgs boson decaying into $\gamma^*\gamma$ to ll γ with low dilepton mass in pp collisions at sqrt(s) = 8 TeV
- Upper limit on B(H→J/psi γ) < 1.5×10^{-3}





Recent theory work

- Higgs to pseudo-scalar mesons plus SM vector boson (arXiv:1705.01112) (new class, harder to search as only third generation decay available if heavy; also complementary to H→Za search when as is around scalar meson mass)

- SM Higgs decays with additional radiations to probe CP properties of individual couplings (arXiv:1610.02025)

- SM Higgs decays with additional radiations to probe light Yukawas (arXiv: 1704.00790) (complementary to Higgs to vector-meson plus photon)

4. LFV HIGGS DECAYS

Higgs LFV

- Lepton Flavor Violating decays of the Higgs boson would be a clear indication of physics BSM.
- Experimental LHC results:
  - **ATLAS**: 8 TeV results for H→μτ/eτ [1604.07730, 1508.03372]
  - **CMS**: H→μτ/eτ: updated with 2016 data (HIG-17-001) and no excess left, H→eμ results only with 2012 data (HIG-14-040)
  - **LHCb**: H→μτ result expected soon

- Current best limits from direct searches:

	With 8 TeV data	With 13 TeV data
BR(H→τμ)	< 1.43% ATLAS	< 0.25% CMS
BR(H→τe)	< 1.04% ATLAS	< 0.61% CMS
BR(H→eμ)	< 0.036% CMS	

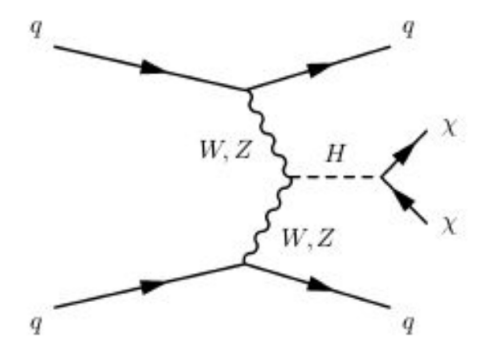
5. (SEMI-)INVISIBLE HIGGS DECAYS

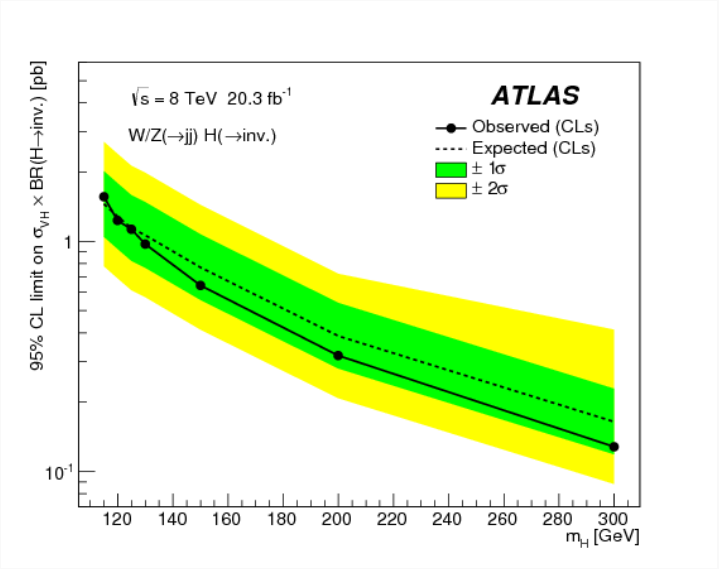
Semi-invisible Higgs decays

- Difficult final states due to particles missing detection
- Many possible topologies
- Possibility for some already existing analyses to interpret their results for models with “slightly different” final states

Invisible Higgs decays at ATLAS

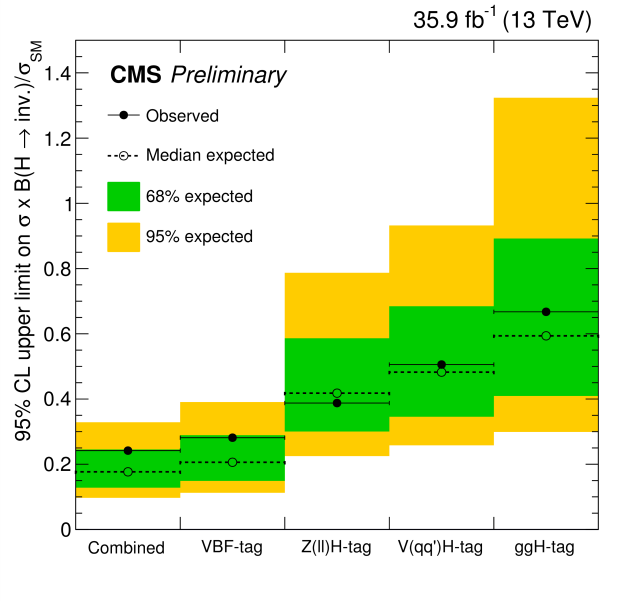
- Several final states studied by ATLAS:
  - Mono-jet analysis (arXiv:1502.015018)
  - Zh(→invisible) (arXiv:1402.3244, 1711.00431, 1708.09624) **NEW**
  - VBF h(→invisible) (arXiv:1508.07869)
  - V(→had)h(→invisible) (arXiv: 1504.04324)
- A handful of interpretations for many BSM models covered, and more to come!

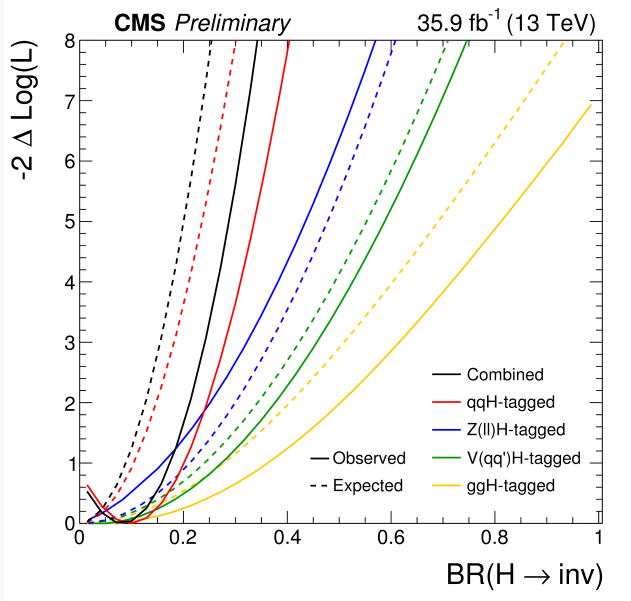




Invisible Higgs decays at CMS

- Invisible:
  - ZH→ll + MET with 2016 data: arXiv:1711.00431
  - VBF with 2012 data: arXiv:1610.09218
  - VBF with 2016 data: CMS-PAS-HIG-17-023 **NEW**
  - Monojet and V→jj with 2016 data: arxiv:1712.02345





CONCLUSIONS

To-do list

- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGExoticDecay

Task	Involved persons	Status	Timescale
Provide final recommendations for h->W/Z+meson		Planned	
Add feasibility studies for Higgs rare decays beyond gamma+J/Psi, gamma+phi, gamma+Upsilon		Planned	
Add feasibility studies for h->2f+MET and develop benchmark scenarios predicting this type of signatures		Planned	
Study feasiblity for searches for Higgs decays involving one or more displaced vertices.		Planned	
What is the best way to present Higgs searches with displaced vertices to allow a simple recast by theorists?		Planned	

- These points can be (partially) addressed by the summer

Conclusions and comments

- Wide exotic Higgs program at the LHC, and recent theory developments
- Several very recent results from CMS, ATLAS, and LHCb
- Different needs from the other Higgs working groups
  - We are not so dependent on how well the cross sections and branching ratios are calculated.
  - We are currently using precise calculations for pp→h, but simplistic h→XY models.
- In general the personpower for experimental searches is very reduced compared to the number of possible analyses:
  - Need to prioritize best-motivated searches and feasibility studies according to theory/phenomenology work
  - Provide recommendations on hw to generate MC for such models so that feasibility studies can be made.

BACKUP

Mono-Higgs searches at ATLAS

- Several final states studied by ATLAS:
  - h($\rightarrow\gamma\gamma$)+E_T^{miss} [1506.01081, 1306.03948]
  - h($\rightarrow$bb)+E_T^{miss} [1707.01302] NEW

- Dark matter connection through vectorized fermion portals into dark photons (arXiv:1705.08896); this is recent more thorough discussion on Higgs exotic decays linking to dark matter);

- Higgs to axion-like particles (H-> a a, H-> Z a, H -> gamma a, a-> gamma gamma; arXiv:1708.00443, arXiv:1610.02025)

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- Higgs to more exotic signatures (veto standard signatures after triggering; arXiv:1707.07084) (Higgs has unique advantage as many triggers available)

H→aa in CMS

- Results at 13 TeV:
  - 4μ with 2015 data (HIG-16-035)
  - 2μ2τ with 2016 data (HIG-17-029): improves corresponding run-1 results by a factor > 2 **NEW**
  - 2b2τ with 2016 data (HIG-17-024): first time this final state is studied, good sensitivity in the NMSSM **NEW**