WG3 Exotic Higgs decays sub-group report

Georgia Karapostoli (*CMS*), Lily Morvaj (*ATLAS*), Lorenzo Sestini (*LHCb*), Matthias König (*theory*), Brian Shuve (*theory*)

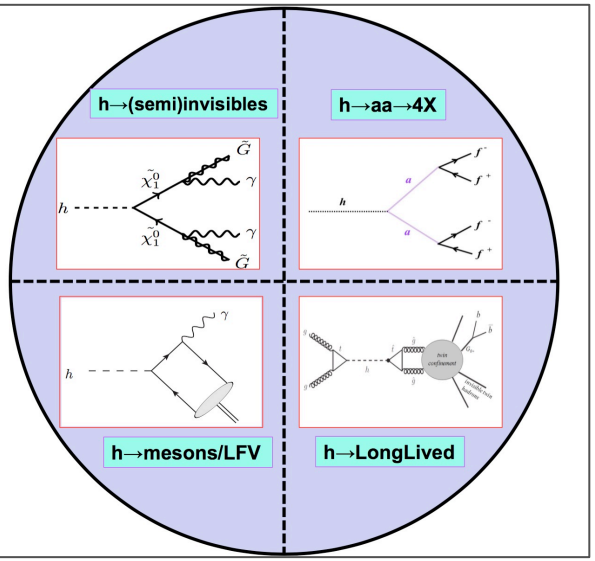
17th Workshop of the LHC Higgs XS group
9-11 Nov, 2020

Introduction

- **Exotic Higgs Decays sub-group twiki**:
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGExoticDecay

Exotic Higgs Decays **contact persons**

- ATLAS: Lily Morvaj (2018)
- CMS: Georgia Karapostoli (2020)
- LHCb: Lorenzo Sestini
- Theory: Brian Shuve, Matthias Konig
- Dedicated twiki with all the latest information is here
- email all the conveners here
- Tasks discussed in the group and timelines: slide 24



- **In this talk**:
  - Overview of recent experimental and theory results covering Exotic decays of the 125 GeV Higgs
  - Only most recent results will be presented (published after last 16th Workshop of the LHCHXS group in November 2019)

Exotic H: prompt decays

- **Many searches proposed in Exotic Higgs decay paper (1312.4992, PRD 90 (2014)). How we stand now, 7 years later?**

- *H to SS to 4 fermions*: pretty good coverage with 4b, 2b + 2lepton, 4 lepton (taus & muons)
  - e.g. ATLAS 1806.07355; CMS 1812.06359; CMS 2005.08694
- *H to SS to 4 gauge bosons*: some searches for 2 photon + 2 gluon, 4 photons
  - e.g. ATLAS 1509.05051, ATLAS 1803.11145
- *H to two dark photons, Z + A'*: extensive searches with leptonic decays of dark photon
  - e.g. ATLAS 1802.03388, CMS 1812.00380, ATLAS 2004.01678
- *Flavor violating decays*: $h \to \ell\ell'$, e.g. ATLAS 1909.10235, CMS 1911.10267

- **What are the gaps?**
  - Partially visible signatures, like $h \to bb$ + MET

  D.Curtin et al, 1312.4992, PRD 90 (2014)
  - High multiplicity decays like $h \to ss \to A'A'A'A'$, $h \to NN \to 6f$

  e.g. E.Izaguirre, D.Stolarski, 1805.12136, PRL 121 (2018)
  - Interesting more exotic flavour violation like $h \to e^+e^-\mu^+\mu^-$

  J.Evans, P.Tanedo, M.Zakeri, 1910.07533, JHEP 01 (2020)

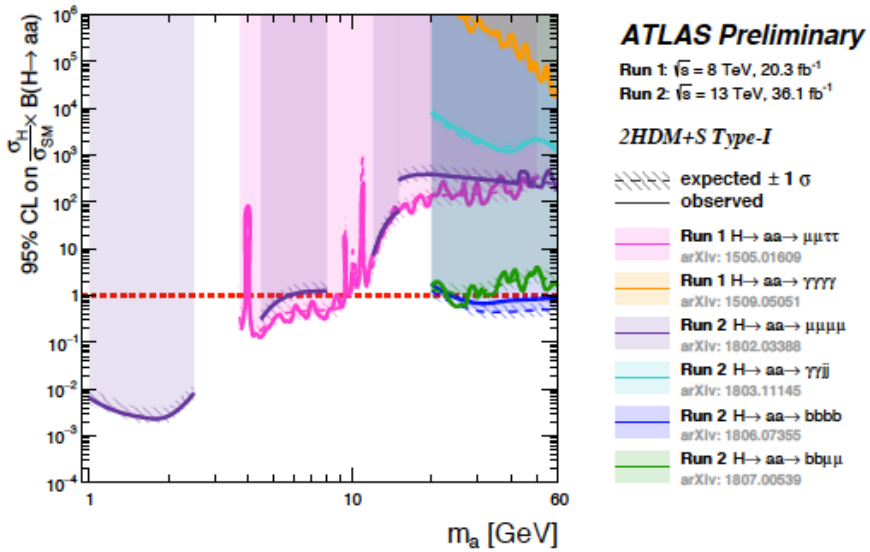
* See Brian's Shuve talk in Higgs 2020: "Exotic Higgs decays"

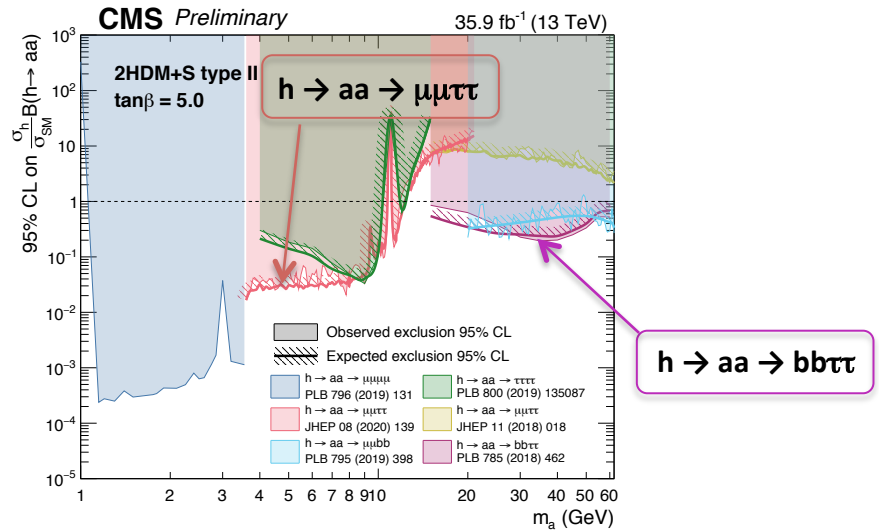
H → aa: summary

- Model-dependent results: assume BR(a → XX)

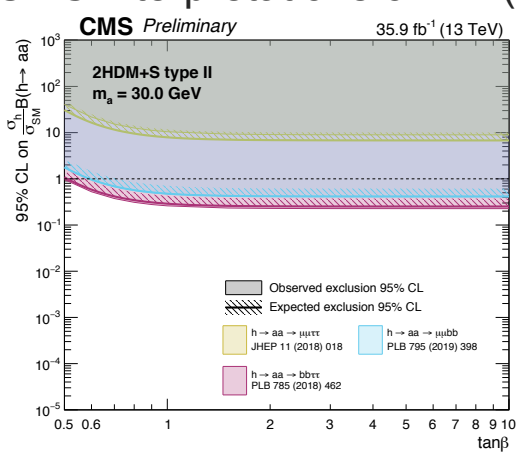
2HDM+s Type I and Type II, tanβ=5

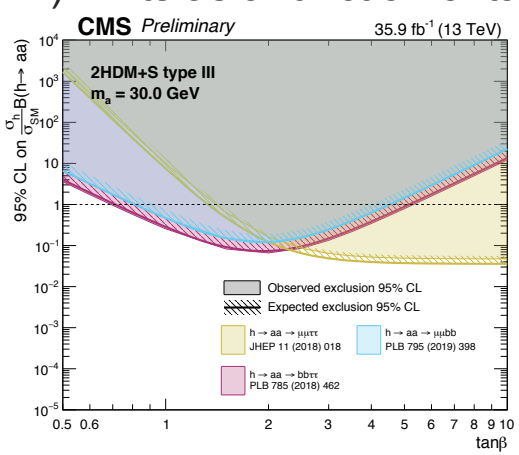
Theory calculations from JHEP3 (2018) 178





- Very recent CMS interpretations of BR (a → XX) limits as a function of tanβ:

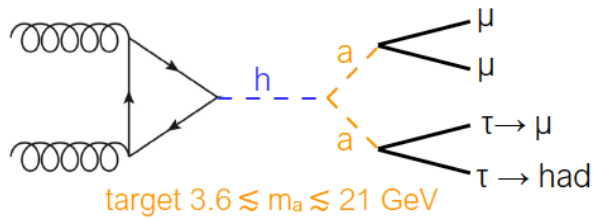


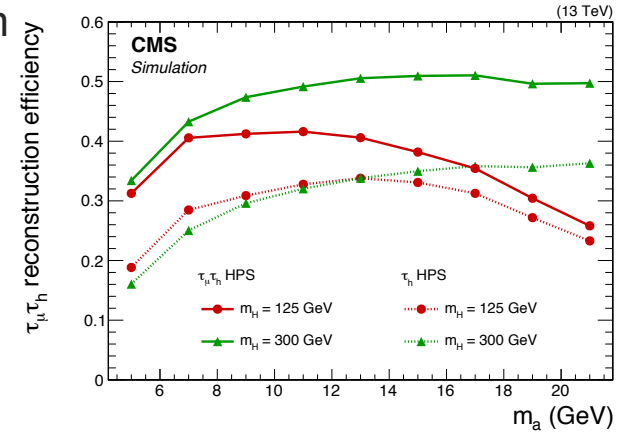


ATLAS: https://cds.cern.ch/record/2650740/files/ATL-PHYS-PUB-2018-045.pdf
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2

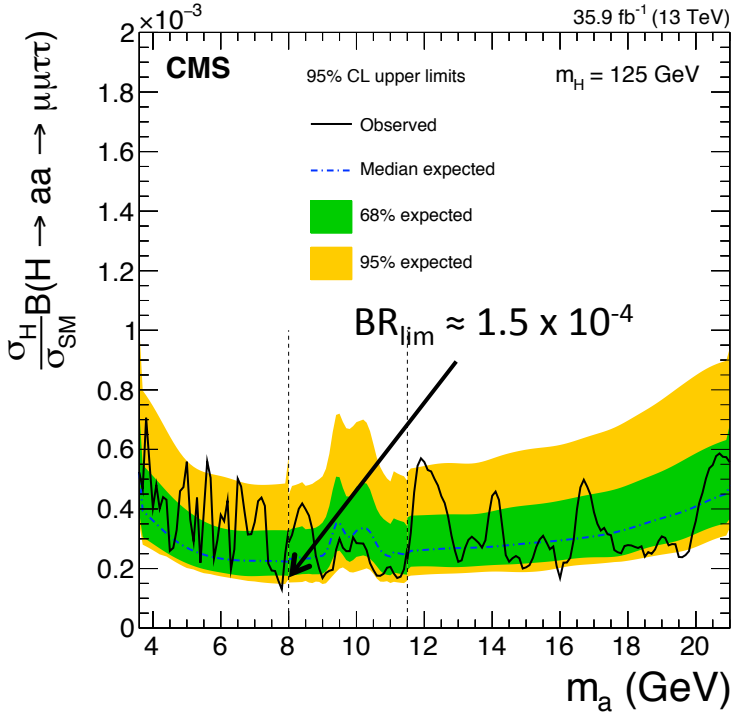
H → aa → (μμ)(ττ), boosted

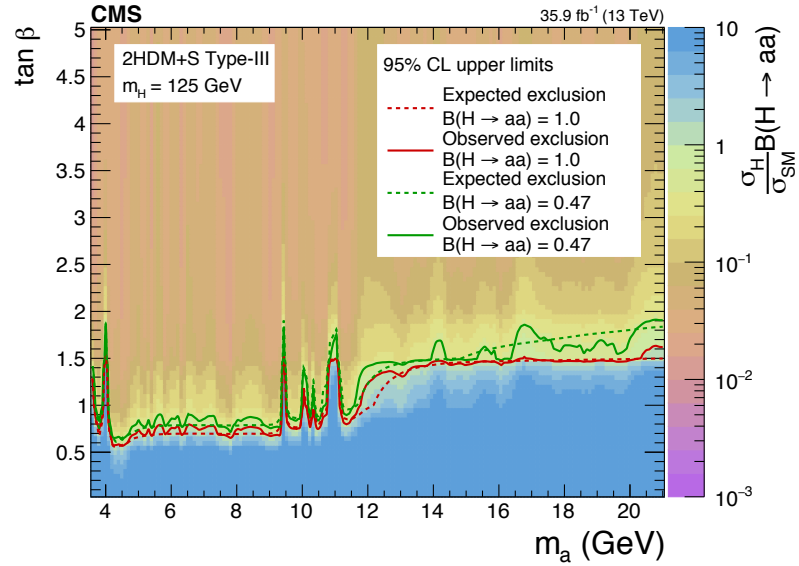
- Pseudo-scalar mass between 3.6 and 21 GeV; form two pairs of boosted systems (arXiv:2005.08694).
- 2D un-binned fit to the m(μμ) x m ($\mu\mu\tau_h\tau_\mu$) spectrum.





Boosted ττ system identified with dedicated $\tau_\mu\tau_h$ reconstruction technique

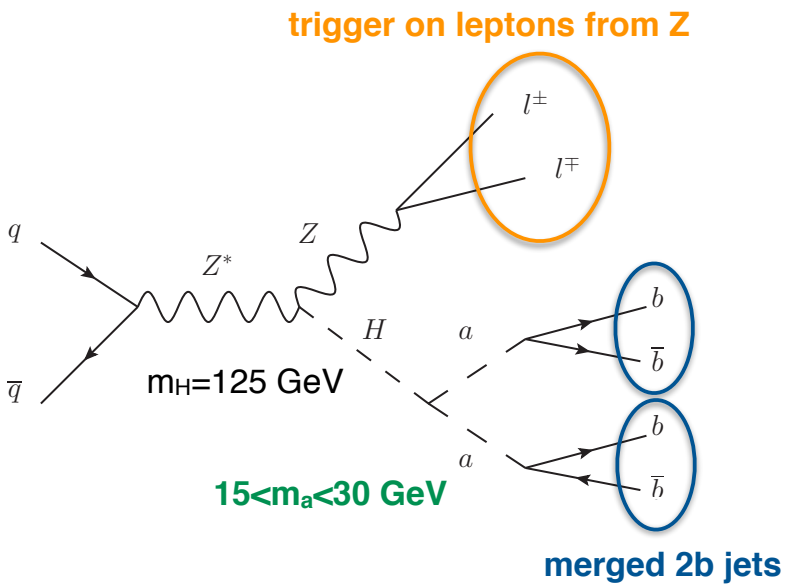


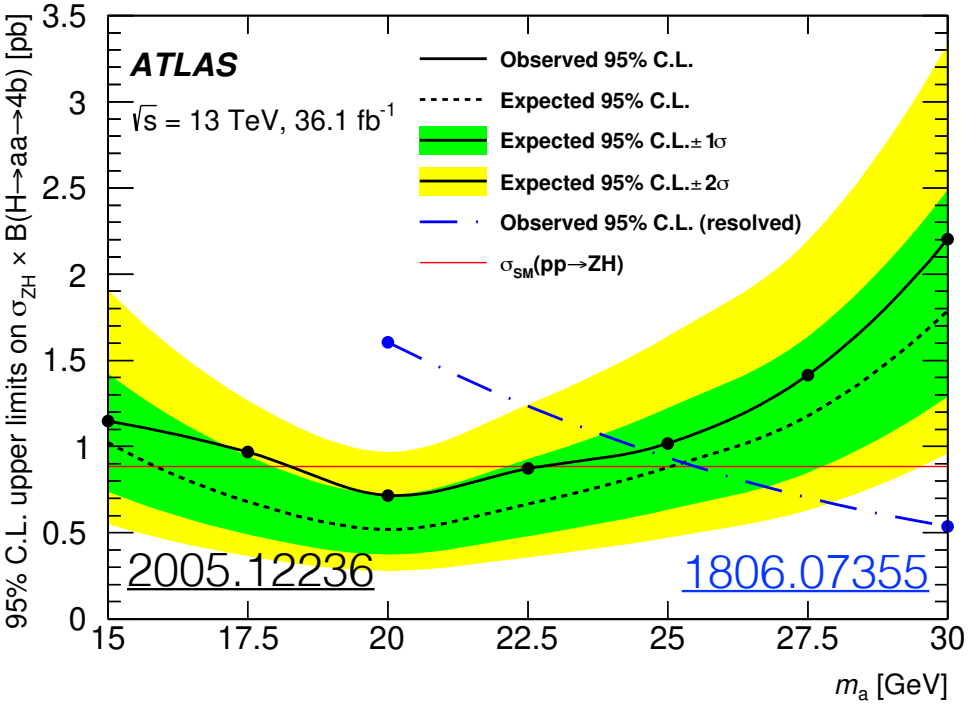


+ Model-dependent limits on BR(H→aa)

H → aa → 4b (merged)

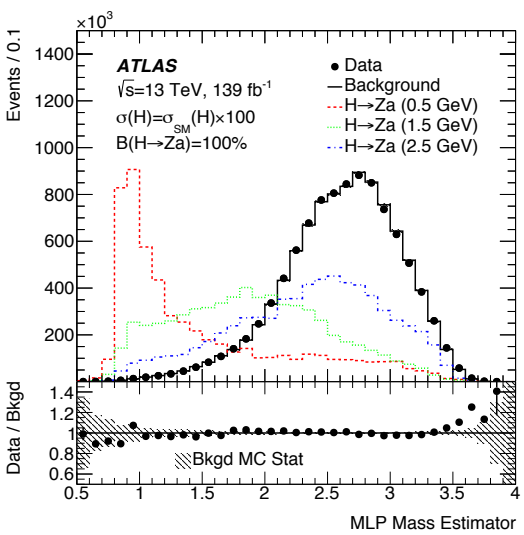
- **Targeting low-mass region (15<m_a<30 GeV) where b-jets are overlapping** (2005.12236)
  - First search in this mass range tagging merged b-jets
- Complementary to the resolved analysis sensitive to 25<m_a<60 GeV range (1806.07355)
- **Developed dedicated low-mass a→bb tagger**
  - Using multivariate technique with substructure
  - Calibrated in data using g→bb events

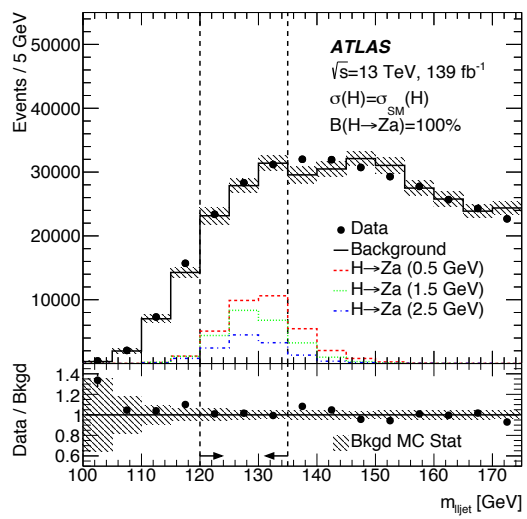




H → Za → (2e/μ) jj

- **Targeting 500 MeV<m_a<4 GeV** (2004.01678)
  - Using multivariate technique to tag the merged a→jj
  - Select a calo jet ΔR=0.4, using tracks and substructure variables to build MLPs
- Limits set on $\sigma(pp \to H)\mathcal{B}(H \to Z(Q/a))$ assuming 100% a→gg or a→ss
- Interpretation for $H \to Z\eta_c$ & $H \to ZJ/\psi$ also provided





limits on $\sigma(pp \to H)\mathcal{B}(H \to Z(Q/a))$

a mass [GeV]	$a \to gg$ Exp	$a \to gg$ Obs	$a \to s\bar{s}$ Exp	$a \to s\bar{s}$ Obs
0.5	16^{+6}_{-5}	17		
0.75	19^{+7}_{-5}	20		
1.0	17^{+7}_{-5}	18		
1.5	20^{+8}_{-6}	22	19^{+7}_{-5}	20
2.0	26^{+10}_{-7}	27	23^{+9}_{-6}	24
2.5	38^{+15}_{-11}	40	32^{+12}_{-9}	33
3.0	75^{+29}_{-21}	78	65^{+25}_{-18}	68
3.5	110^{+40}_{-30}	120		
4.0	320^{+130}_{-90}	340		

$H \to Z\eta_c$	100^{+40}_{-30} pb (exp)	110 pb (obs)
$H \to ZJ/\psi$	100^{+40}_{-30} pb (exp)	100 pb (obs)

H → Za → (2e/μ) jj

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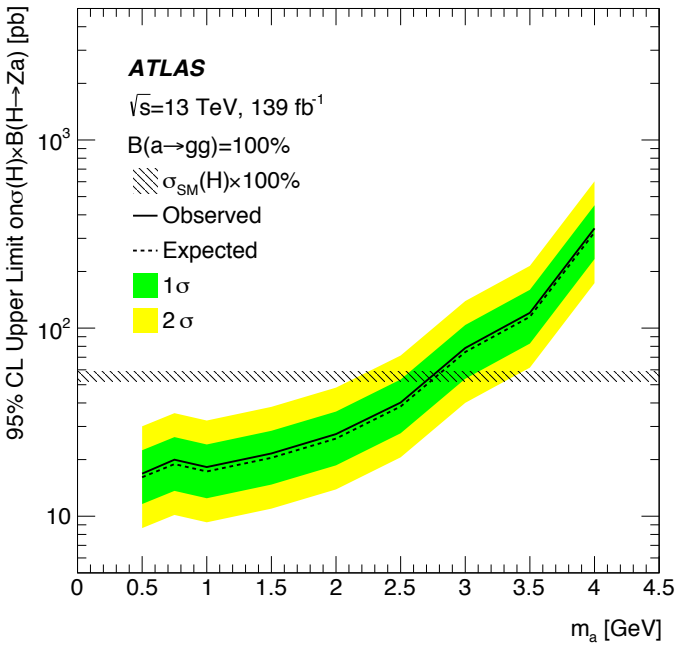
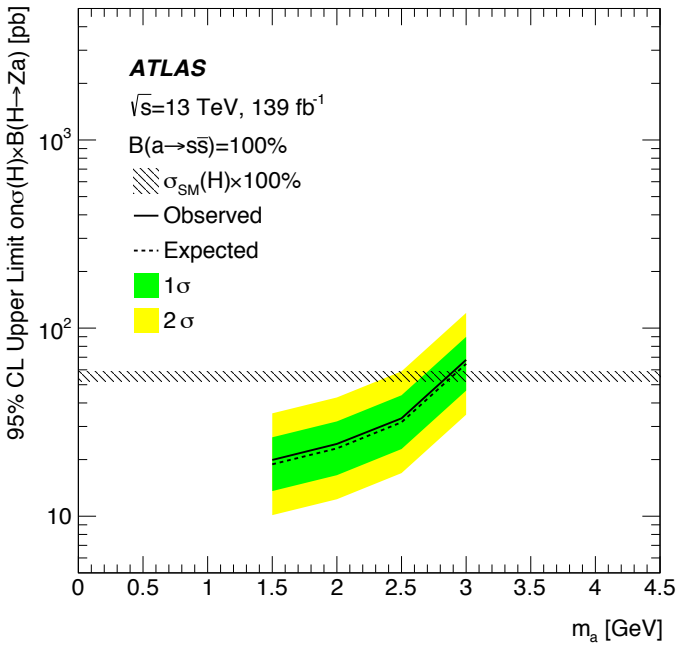
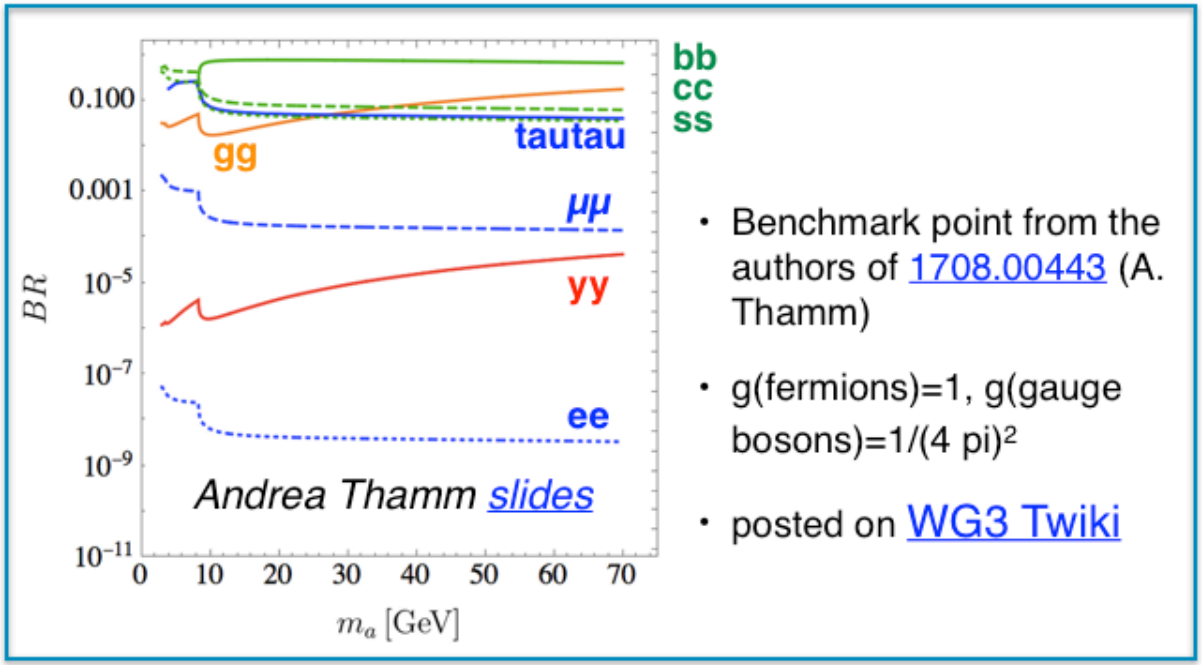




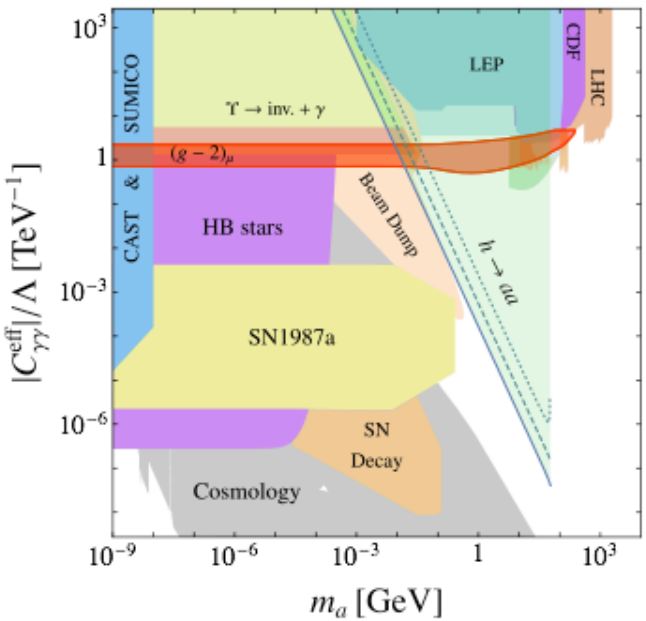
New benchmark: ALPs

- **New benchmark** point posted on WG3 Twiki: **ALPs**
  - Couplings generally proportional to mass, but always interesting for yy/gg final states
- Interest from theorists to interpret searches for light pseudoscalars in ALPs model:
  - All channels on 1 plot (using the benchmark for Br(a→xx))
  - Limit on Br(H→aa) assuming Br(a→xx)=1, 0.1,…
  - Coupling vs mass plot



- Benchmark point from the authors of 1708.00443 (A. Thamm)
- g(fermions)=1, g(gauge bosons)=1/(4 pi)²
- posted on WG3 Twiki

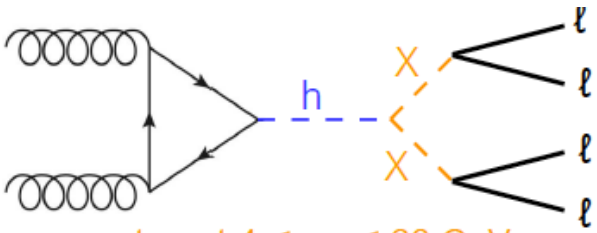
1708.00443 : H→aa→4γ



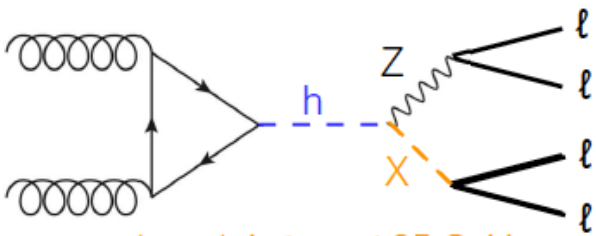
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWGExoticDecay/Thamm_ALP_Signatures.pdf

H → XX / ZX → (ℓℓ)(ℓℓ)

- Search for low-mass di-lepton resonances in *4e, 2e2μ, 4μ* final states (arXiv:2005.08694).
- Backgrounds: Higgs and ZZ from simulation, non-prompt background from fake-lepton method.



target $4 \lesssim m_X \lesssim 60$ GeV



target $4 \lesssim m_X \lesssim 35$ GeV

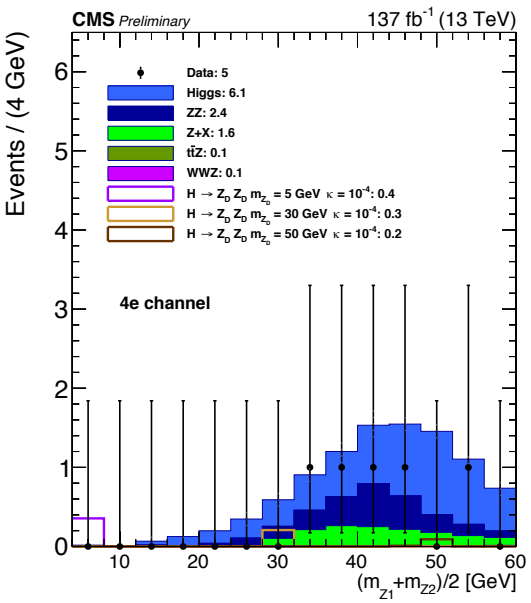
H -> XX:

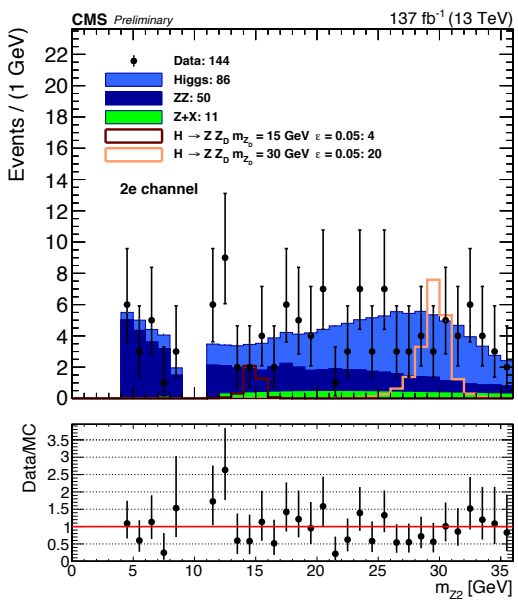
Binned fit in m_{X1} x m_{X2} spectrum

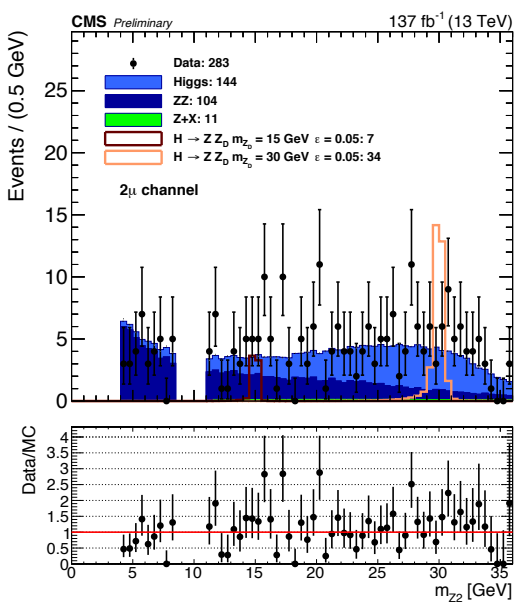
H -> ZX:

Binned fit in m_X spectrum

Exclude narrow mass window around Z candidate

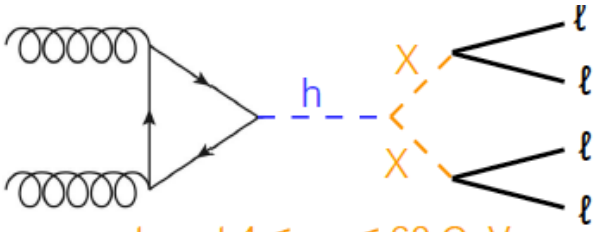




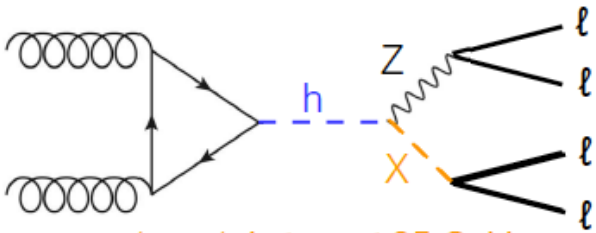


H → XX / ZX → (ℓℓ)(ℓℓ)

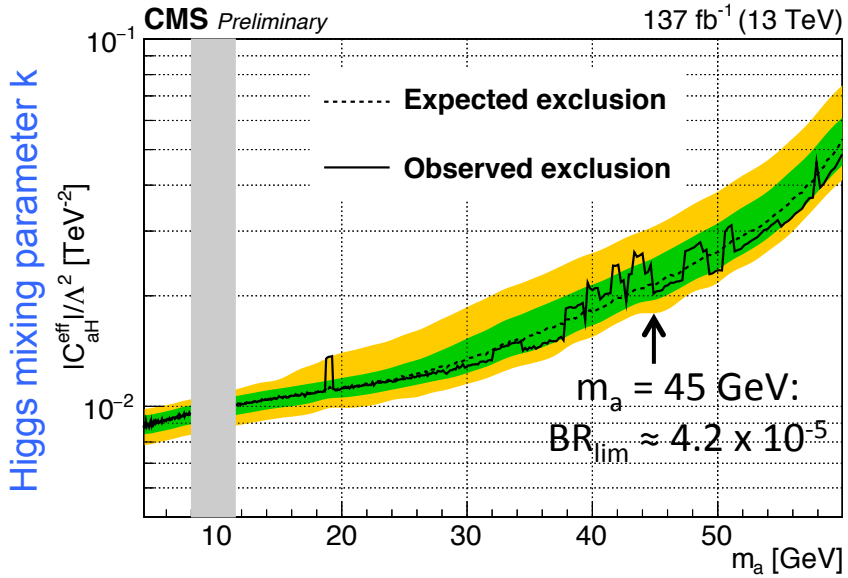
- **The search reports constraints on**:
  - Model-independent branching fraction, model parameters in dark photon model, model parameters in ALP model

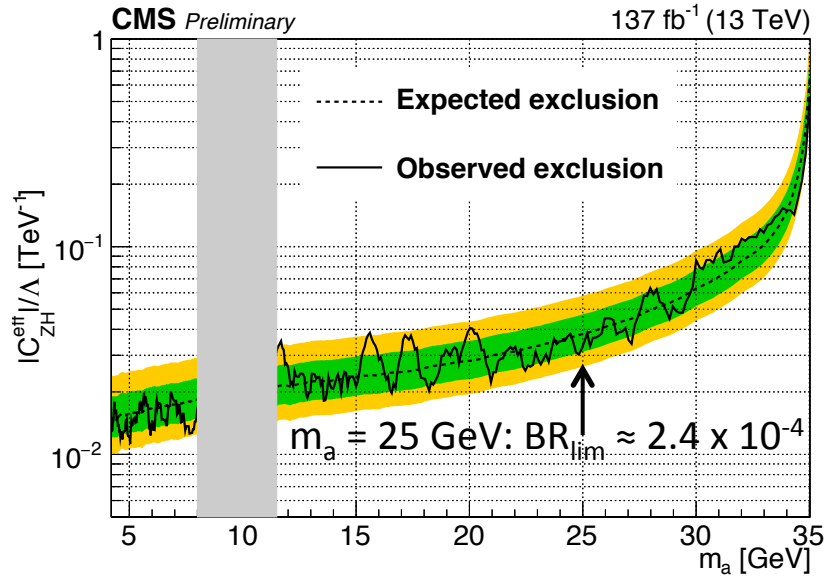


target $4 \lesssim m_X \lesssim 60$ GeV



target $4 \lesssim m_X \lesssim 35$ GeV





$$\Gamma(\mathrm{H} \to \mathrm{aa}) = \frac{v^2 m_h^3}{32\pi} \frac{c_{\mathrm{ah}}^{\mathrm{eff}2}}{\lambda^4} \left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

Interpretation in ALP model

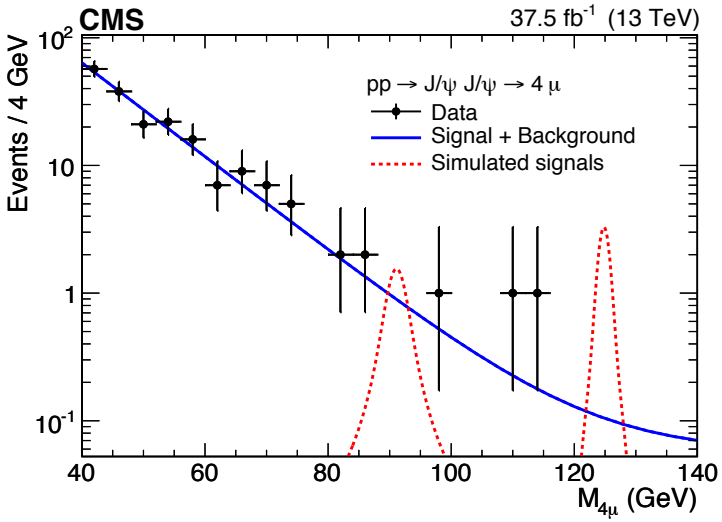
$$\Gamma(\mathrm{H} \to \mathrm{Za}) = \frac{m_h^3}{16\pi} \frac{c_{\mathrm{Zh}}^{\mathrm{eff}2}}{\Lambda^2} \lambda^{3/2} \left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2}\right)$$

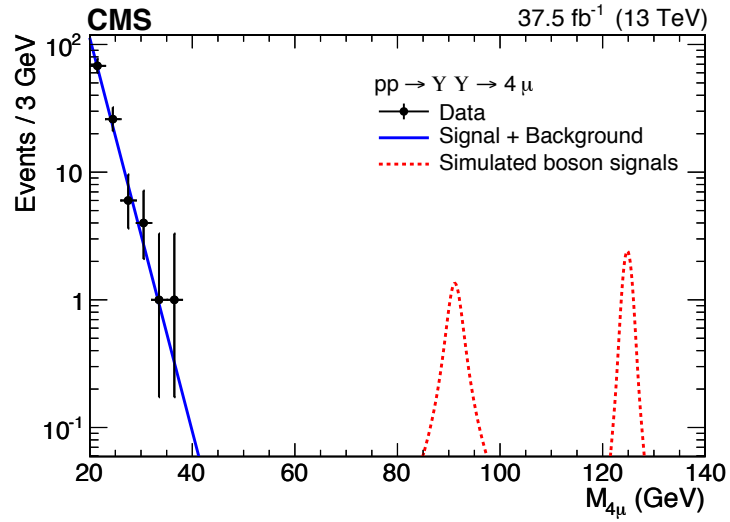
Assumes BR(a → ll) = 1

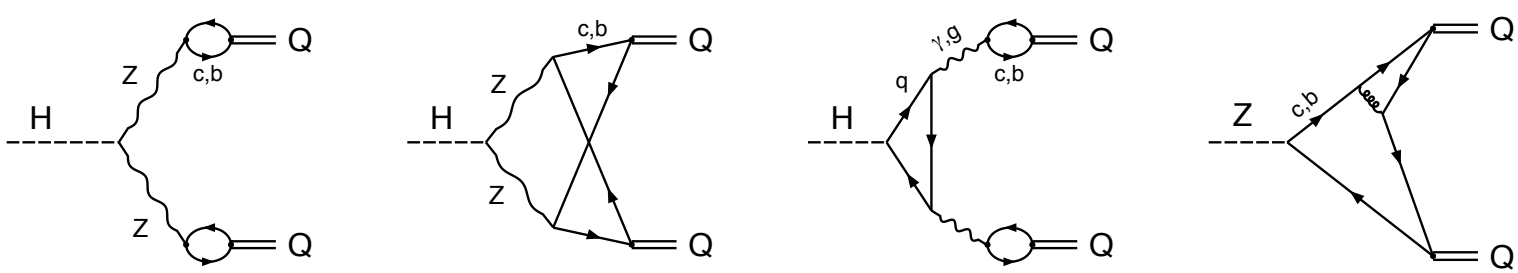
H → J/ψ J/ψ and H → YY

- In 4-muon final state; dedicated di-muon+J/ψ, trimuon+Y triggers in 2017 (arXiv:1905.10408)

Process	Observed	Expected
$\mathcal{B}(\mathrm{H} \to \mathrm{J}/\psi\mathrm{J}/\psi)$	1.8×10^{-3}	$(1.8^{+0.2}_{-0.1}) \times 10^{-3}$
$\mathcal{B}(\mathrm{H} \to \mathrm{YY})$	1.4×10^{-3}	$(1.4 \pm 0.1) \times 10^{-3}$

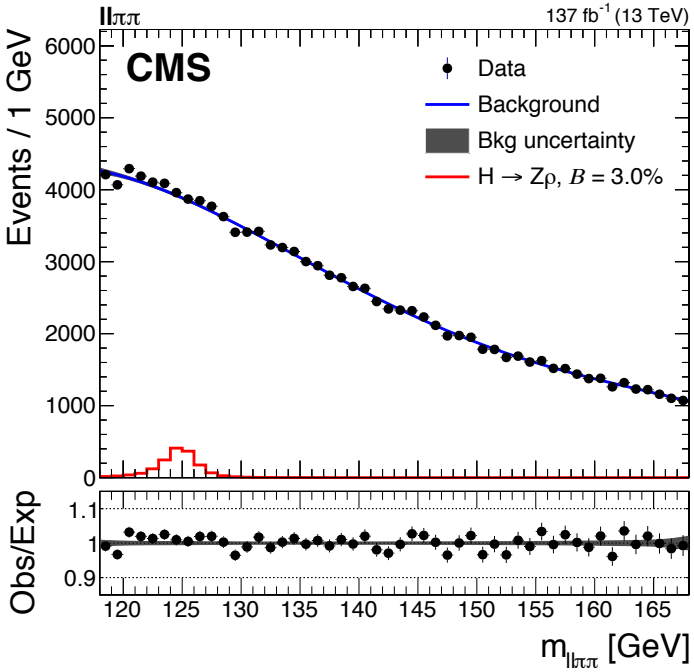


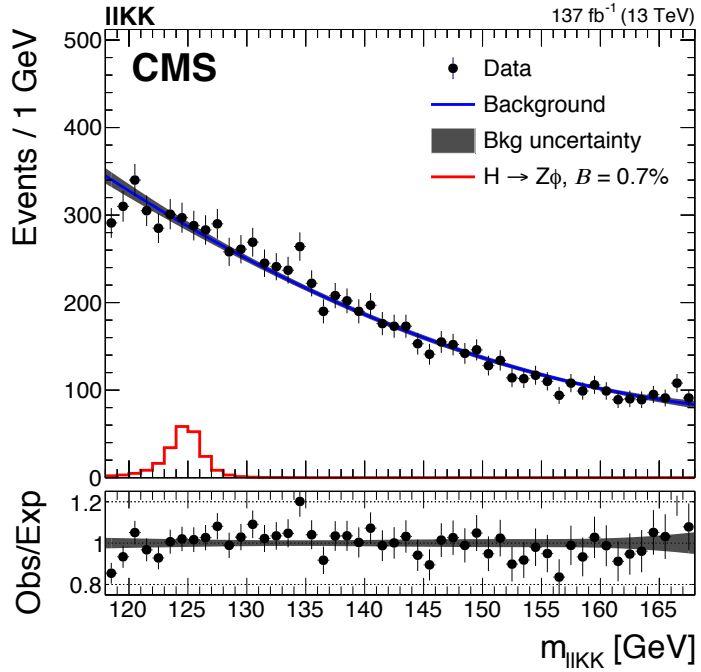




H → Zρ and H → Zϕ

- Four final states targeted: μμππ, μμKK, eeππ, eeKK (arXiv: 2007.05122).





- $B(H \to Z\rho)_{lim} \approx$ 1-1.9%
(710-1360 x SM expectation)

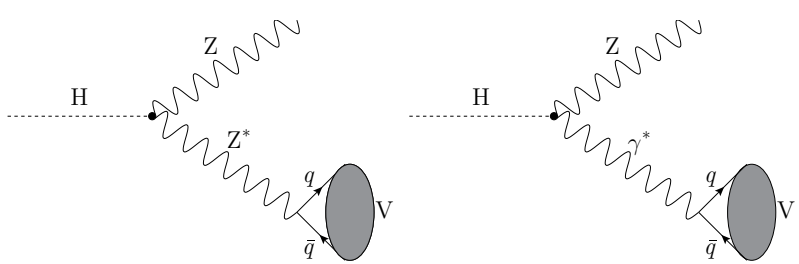
- $B(H \to Z\phi)_{lim} \approx$ 0.5-0.92%
(1190-2190 x SM expectation)

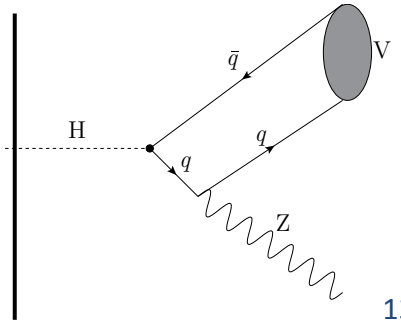
Indirect: VV*(VM)

Complementary to standard VV* analyses

Direct: Yukawa coupling

Access to BSM effects

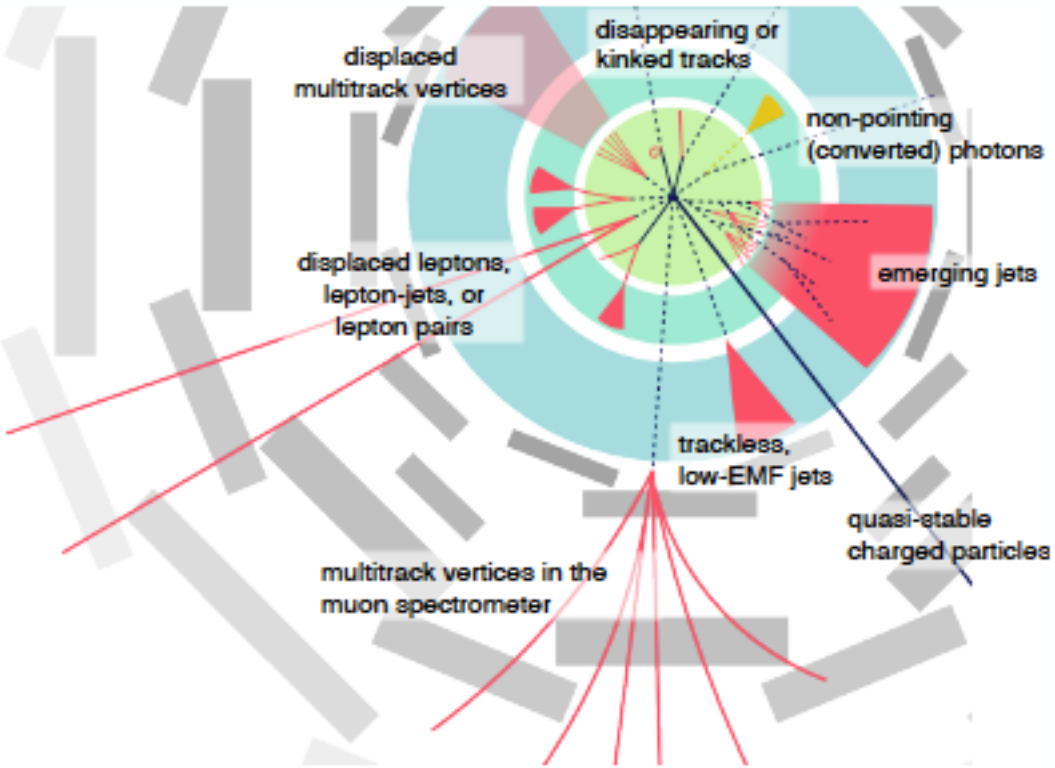




Higgs + long-lived

- Long-Lived Particle (LLP) searches are very promising right now:
  - LLPs provide exciting discovery avenues for new physics in view of LHC Run3

- Recently published LLP white paper (arXiv:1903.04497, J.Phys.G 47 (2020)) takes a comprehensive look at coverage / gaps in LLP signatures, including from Higgs decay



H. Russell, LHC LLP Community workshop, 2017

- **Higgs exotic decays characterized by low transverse momentum final states**

- **Challenging to trigger and reconstruct!**

- **Motivates new searches, triggers, detectors**

Higgs + long-lived

- Where coverage is currently pretty solid:
  - LLP produced in Higgs decays and decaying to muons (some coverage of other flavor combinations too)

ATLAS, 1808.03057, PRD 99 (2019); CMS, 1409.4789, PRL 114 (2015); ATLAS, 1504.05162, PRD 92 (2015)

  - Multiple lepton jets (collimated sprays of leptons + pions)

ATLAS, 1909.01246, EPJC 80 (2020)

  - 1 or 2 LLPs produced in Higgs decays and decaying hadronically, provided they live long enough to reach HCAL and/or MS

ATLAS, 1911.12575, PRD 101 (2020)

- What are the major gaps / opportunities to-date:
  - Leptonically decaying LLPs with low p_T, different flavor combinations
  - Hadronically decaying LLPs with proper lifetimes < 0.1m
  - Hadronically decaying taus from LLPs
  - High multiplicities (6-8 final-state particles!), including Majorana neutrinos (3-body, semi-leptonic decays)
  - Compressed scenarios (e.g. inelastic dark matter)
  - Delayed photons (little to no MET), photon jets
  - Emerging jets & dark showers

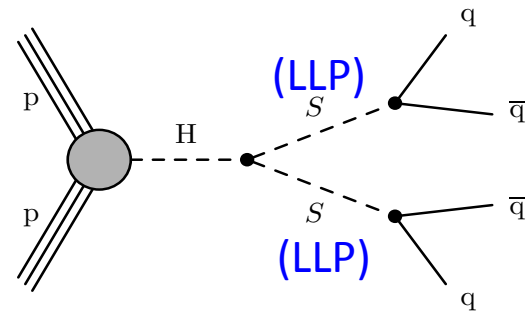
* See Brian's Shuve talk in Higgs 2020: "Exotic Higgs decays"

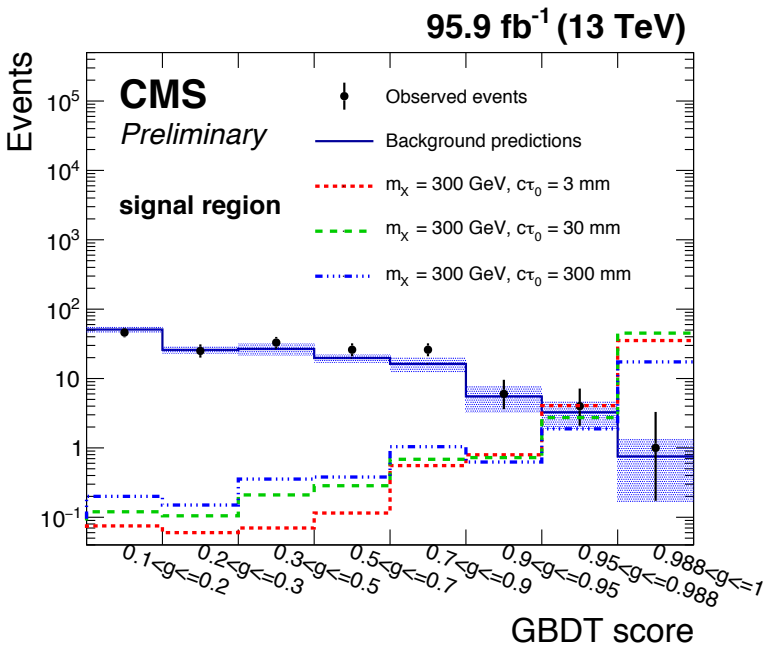
LLP decays: H → displaced jets

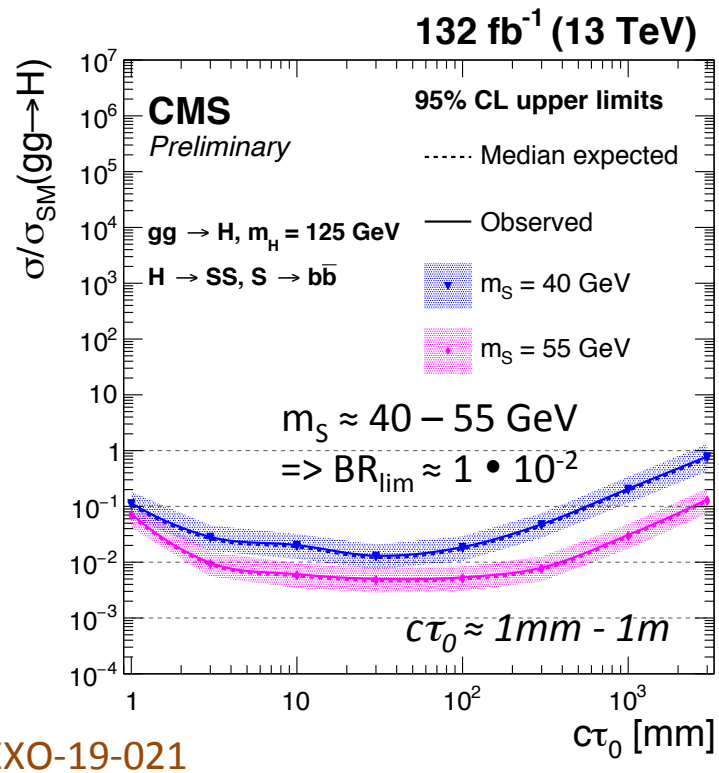
- Built as model independent search covering a large variety of BSM models.
- Strategy:
  - Displaced-jet triggers to lower HT threshold
  - Combined offline tracking information in a Gradient BDT (GBDT)
  - Multi-jet background: data-driven, used real data in control regions for BDT training

Exotic decay of the Higgs bosons

pp → H, H → SS, S → *jj*



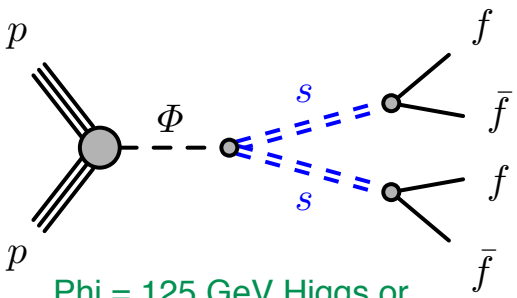




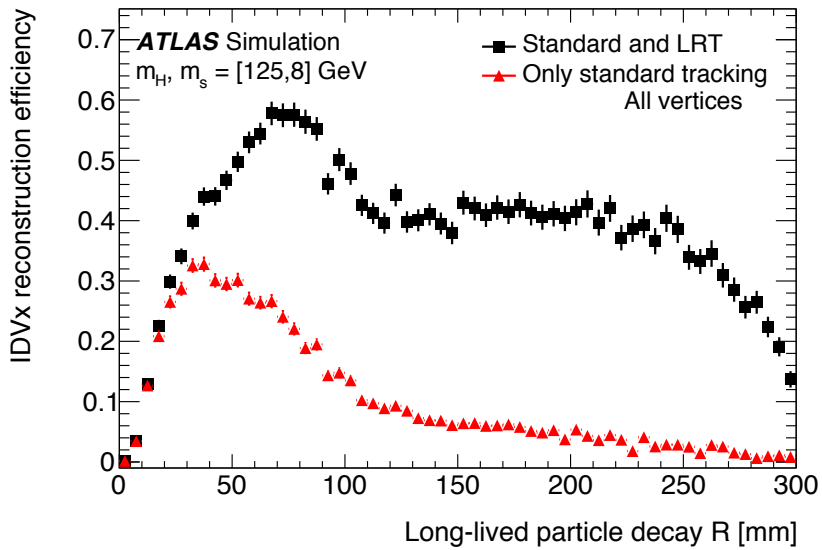
CMS-PAS-EXO-19-021

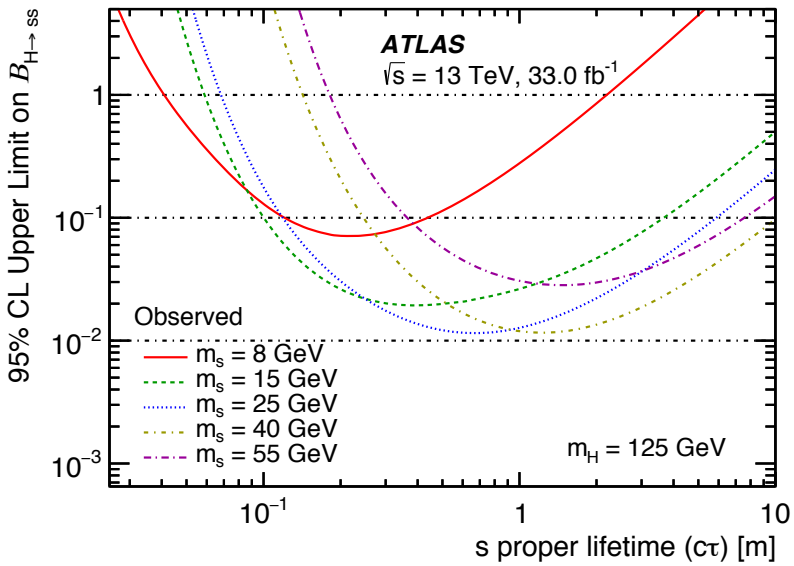
H → displaced jets

- **Search for hadronic decays in the inner tracking detector (ID) and muon spectrometer (MS)** (1911.12575)
- Use special trigger for displaced hadronic decays in MS (Muon RoI Cluster trigger)
- Dedicated ID & MS vertex reconstruction algorithms using large-radius tracks (LRT = tracks not pointing to the IP)
- Select events with 1 ID vertex and 1 MS vertex
  - Sensitive to proper lifetimes from a few cm to several meters



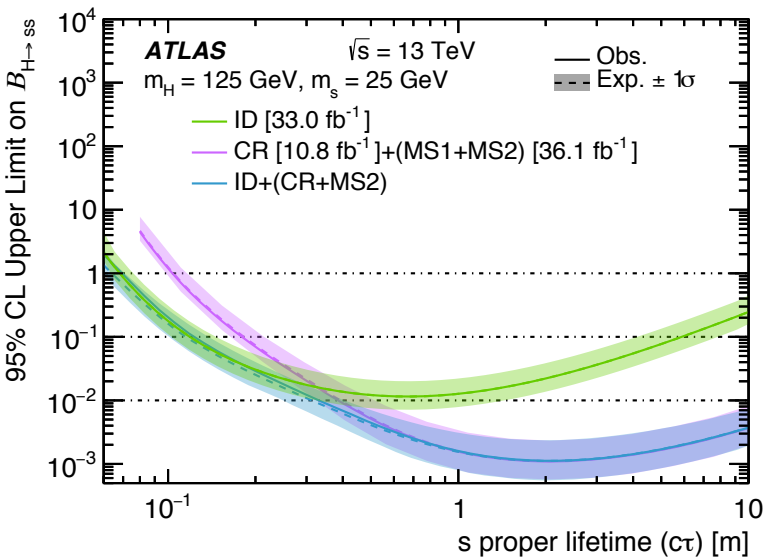
Phi = 125 GeV Higgs or [200,1000] GeV mediator

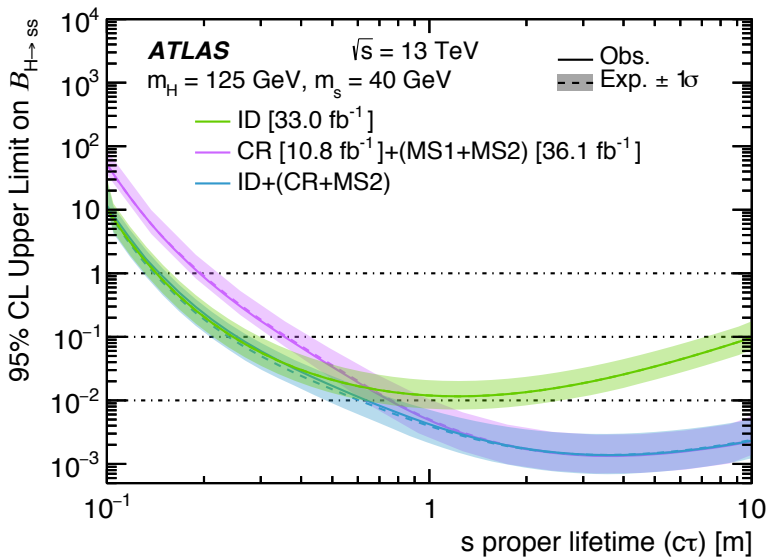




H → displaced jets: combination

- **Combination with searches for displaced jets in the calorimeter (1902.03094) and MS only (1811.07370)**
- **green** = ID (1 ID & 1 MS vertex) analysis (previous slide)
- **purple** = combination of CR (2 displaced jets in the calo) & MS (2 MS vertices) analyses
- **blue** = ID + CR + MS combination





- **ID analysis** better than the combination of **CR+MS** for proper lifetimes 0.05-0.7 m
  - ➡ Requiring both an ID & MS vertex suppresses the background

H → displaced jets: reinterpretation

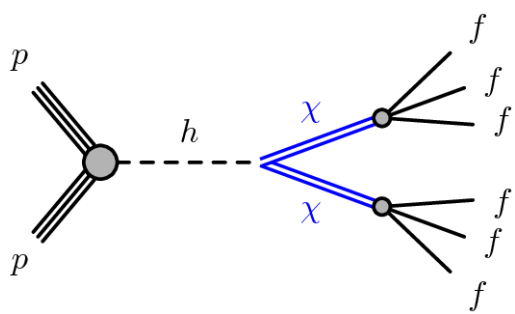
- **CalRatio (CR) analysis with displaced jets in the calorimeter** (1902.03094) **is preserved in RECAST**
  - Used to reinterpret the analysis in several other models, setting the limits in a previously unconstrained part of parameter space

➡ **The importance of analysis preservation**

Higgs portal baryogenesis model

- The singlet boson X mixes with the SM Higgs and decays to decays to SM violating baryon and/or lepton number

$$\chi \to \tau^+\tau^-\nu_\ell,\ \chi \to cbs,\ \chi \to \ell^\pm cb,\ \chi \to \nu b\bar{b}$$



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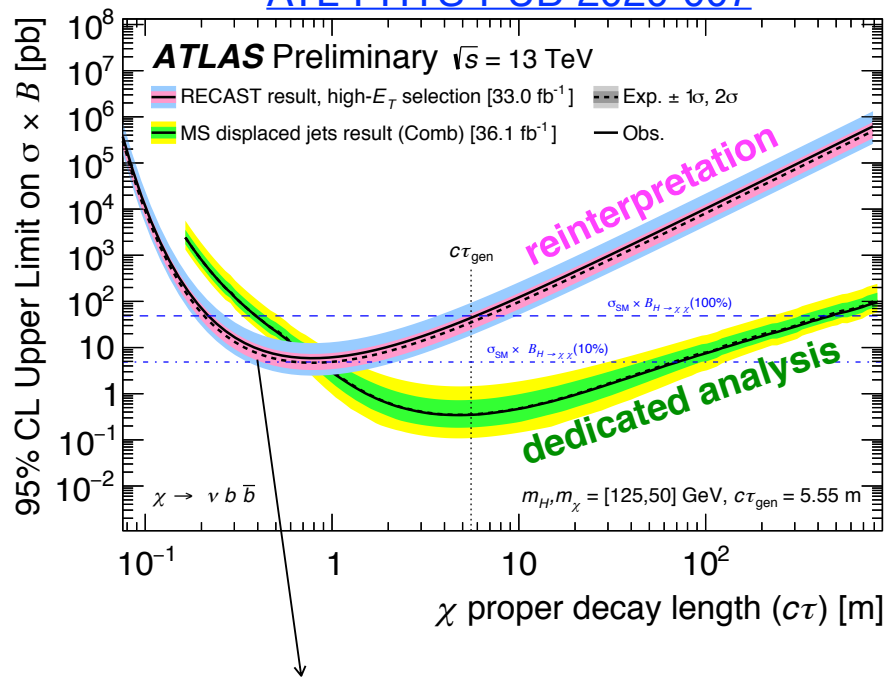


✓ **The existing limits are improved & extended at shorter decay lengths**

H → displaced jets: reinterpretation

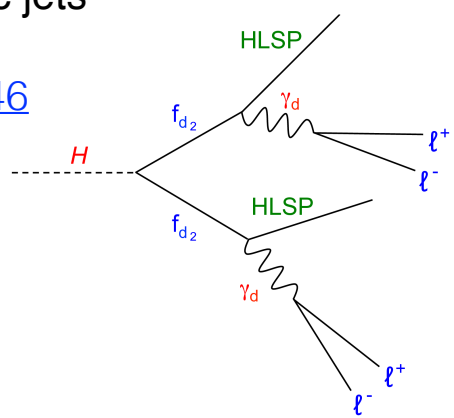
- **CalRatio (CR) analysis with displaced jets in the calorimeter** (1902.03094) **is preserved in RECAST**
  - Used to reinterpret the analysis in several other models, setting the limits in a previously unconstrained part of parameter space

➡ **The importance of analysis preservation**

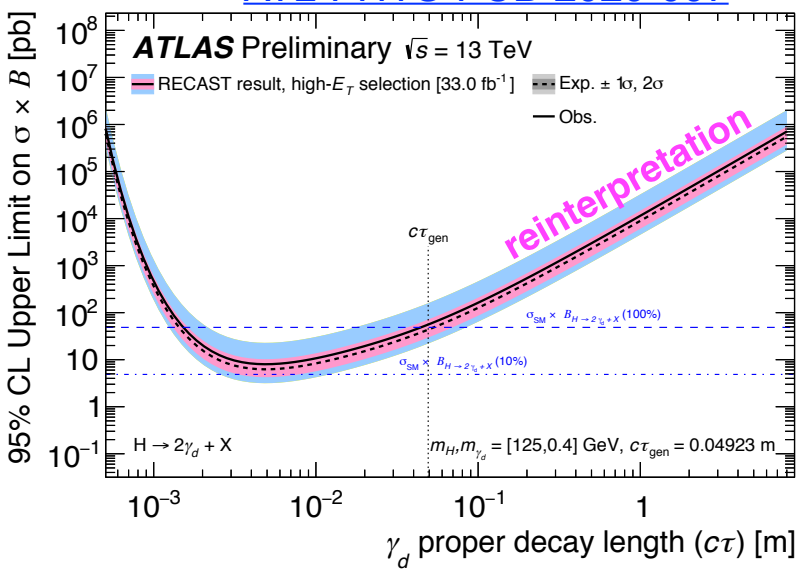
Dark photon model (FRVZ)

- Dark photons decay to displaced lepton or hadronic jets

1909.01246



ATL-PHYS-PUB-2020-007



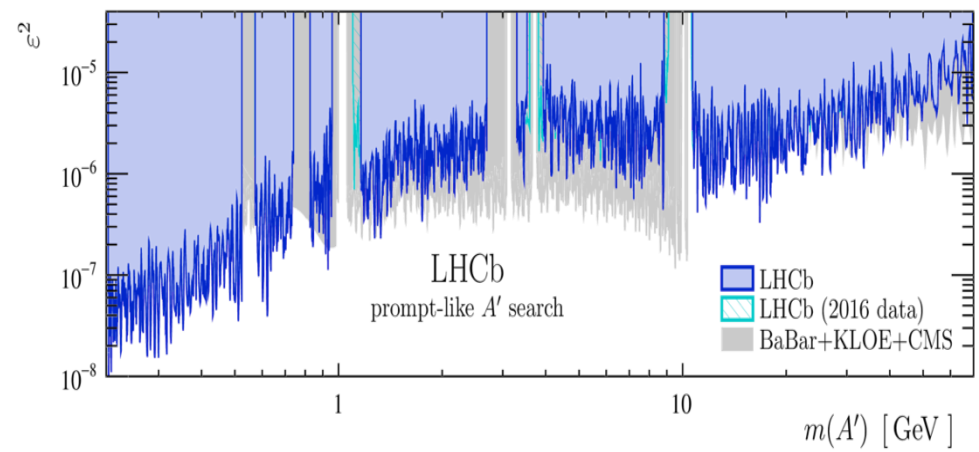
- The original analysis targeting FRVZ model (1909.01246) didn't have any sensitivity for dark photons decaying to collimated hadron jets in the case m_H=125 GeV

✓ **RECAST analysis set first limits in this channel**

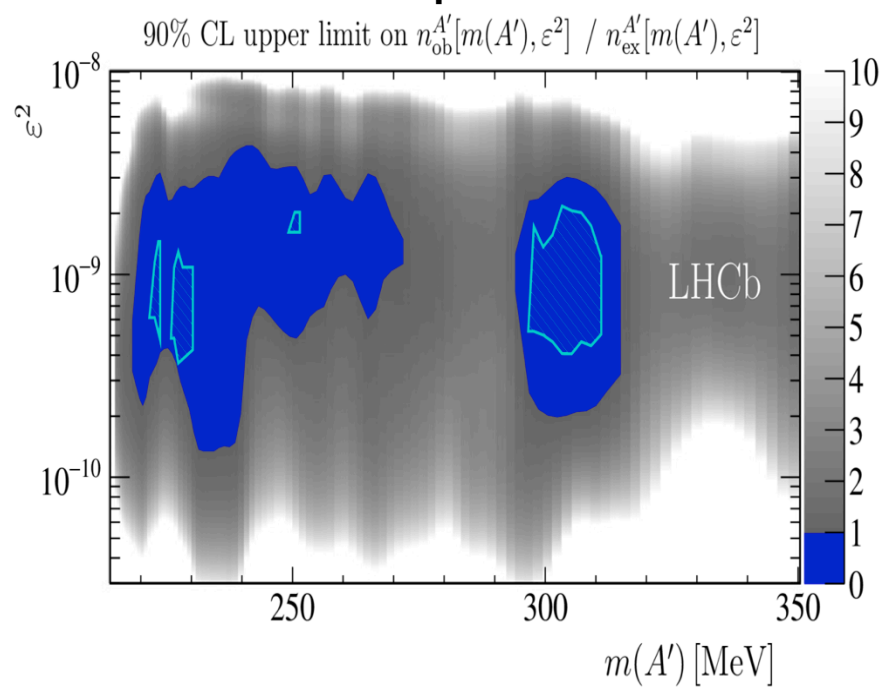
Search for Dark Photons

- Recently we haven't got new results on direct Higgs Exotic decays searches.
- **But we have a couple of $\mu^+\mu^-$ searches that could be used for reinterpretations.**
- **Search for prompt and displaced Dark Photons** (A') in dimuons using full Run 2 dataset, limits at 90% CL: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.041801
- For prompt search, best constraint in the range [214,740] MeV and [10.6,30] GeV for m(A').
- Best limit for displaced low-mass A', with a O(1 ps) lifetime.

Prompt search



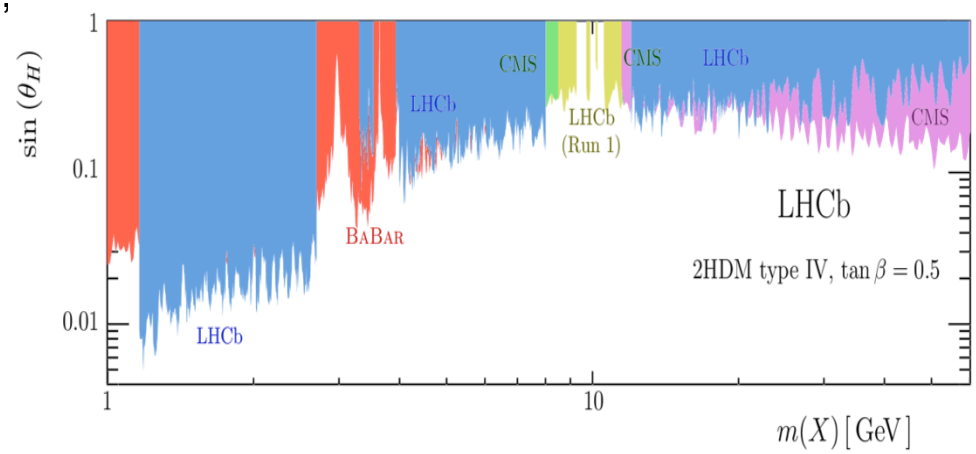
Displaced search



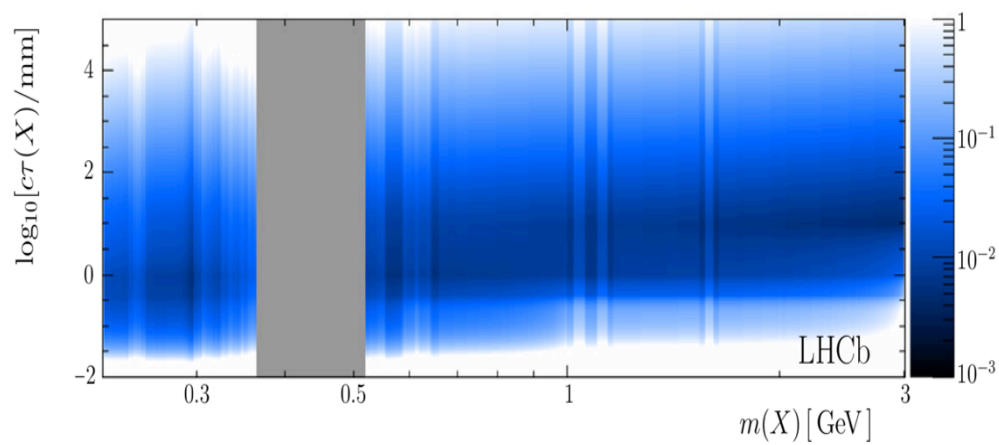
Inclusive search $X \to \mu^+\mu^-$

- Search for low-mass dimuon resonances, with Run 2 dataset: https://arxiv.org/abs/2007.03923.
- **Selection similar to the Dark Photon analysis, but model-independent approach.**
- Prompt search explore X masses up to 60 GeV, displaced search up to 3 GeV.
- Inclusive $X \to \mu^+\mu^-$ and associated X + b-jets production have been considered.
- These results have been used to set limits on the X-H mixing angle (θ_H) in the 2HDM scenario, and to the γ-Z_{HV} mixing in a hidden valley scenario.

90% CL limits on X-H mixing angle



90% CL limits on γ-Z_{HV} mixing strength



On-going activities, LHCb

- As follow-up of the “STEALTH physics at LHCb” workshop in February (https://indico.cern.ch/event/849862/timetable/), where LHCb physicist discussed with theorists on new physics searches, **a White Paper is in preparation**: a section will be dedicated to Exotic Higgs decays at LHCb!

- We are working on new Run 3 trigger lines for long-lived particles searches.

- Search for model-independent bb and cc production is on-going (includes also H→bb and H→ cc at LHCb)

Tasks list and timelines

- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3#Exotic_Higgs_Decays

Task	Involved persons	Status	Timescale
Provide a benchmark for interpretations of h->aa->4y/2g2y searches	Andrea Thamm	DONE	ALP benchmark
Add feasibility studies for h->2f+MET and develop benchmark scenarios predicting this type of signatures	All	planned	lower priority
List uncovered, but well motivated, Higgs decays searches involving one or more displaced vertices.	Brian Shuve	In progress	Spring 2021
What is the best way to present Higgs searches with displaced vertices to allow a simple recast by theorists?	Theorists	In progress	winter 2021
Reinterpret prompt decays results for LLP signatures	Experimentalists	In progress within collaborations	Full Run 2 papers
List of high priority channels for inclusion into BSM H fits and for which experimentalists are highly encouraged to publish likelihood scans (see p7-9). In the form of slides or a short document.	Theorists	In progress	Spring 2021
Parameter calculations for Higgs rare decays beyond gamma+J/Psi, gamma+phi, gamma+Upsilon	Matthias Koenig	DONE	Parameter_calculations
Provide final recommendations for h->W/Z+meson: link	Zhen Liu, Stefan Alte	under review	

Benchmark models

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

Benchmark models

Signature	Motivation	Parameter calculations	MC implementation	Contact
H → ALPs	1708.00443 nice benchmark for H(125)→aa (ss) → 4y/2j2y	ALP BRs for 1 benchmark point: g(fermions)=1; g(gauge bosons)=1/(4 pi)^2, BR figure		Andrea Thamm
H(125)→aa (ss) →XXYY	1312.4992	Br(a(s)→XX) for plots from the paper, outside of the quarkonia regions plotdata.zip		Stefania Gori, Yiming Zhong
H(125)→aa (ss) →XXYY	1802.02156	BR.tgz. Calculations provide Br(a->xx) values for multiple tan(beta) values and cover also the quarkonia regions. Please read the README.txt to know how to use them.		Ulrich Haisch
H(125)→hh	1601.07880, 1501.02234 ,slides	see the quoted papers	available, contact the authors	Tania Robens, Tim Stefaniak
H(125)→h1h2	1908.08554, slides, slides	see the quoted paper	available, contact the authors	Tania Robens, Tim Stefaniak, Jonas Wittbrodt
H(125)→hh	EWPT: 1911.10210, 1911.10206	Br(S->ff) have been calculated using HDECAY, see the attached plot: s_Brs_1911.10210.pdf		paper authors
H(125)→2Zd→4 lep	1412.0018	Table2 of 1412.0018	hahm_mg	Jessie Shelton, Stefania Gori, David Curtin, Rouven Essig
H(125)→2Hd→4Ad→8 lep	Hto8lepChannel_Stolarski	Table2 of 1412.0018	hahm_mg	Daniel Stolarski
H(125)→aa (ss) →XXYY/invis	mixture of visible & invisible (DM) decays			

Conclusions

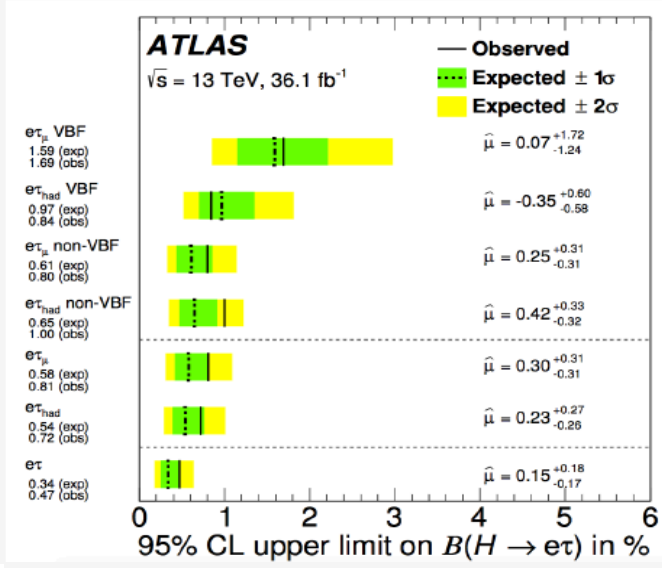
- Higgs sector provide incredible tool for testing models of New Physics
- Exotic Higgs decay searches remain a top priority of the BSM search program, as we face new challenges and opportunities at HL-LHC
- Still a lot of room for new discoveries in signatures we have not covered yet!
- Exciting possibilities for full Run2 and Run3 analyses, with new searches and strategies, e.g.
  - Open to new benchmark ideas…
  - New trigger / reconstruction techniques for low p_T objects (boosted regimes, collimated decay products).
  - new Run 3 triggers being developed for LLP searches.
  - etc

Backups

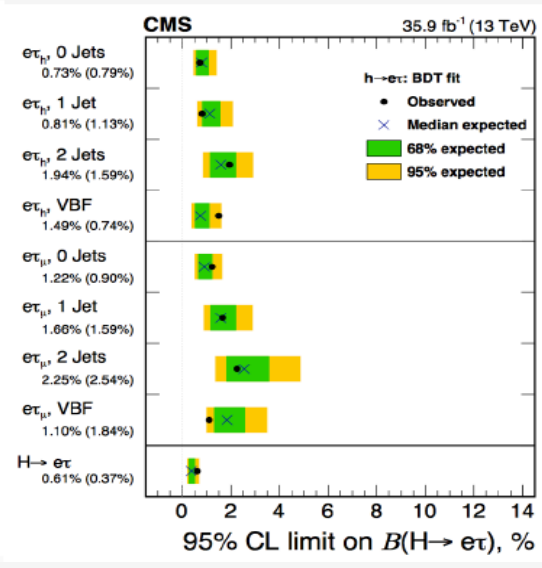
LFV decays

- Lepton flavor violating decays: H → eτ and H → μτ, both from ATLAS and CMS
- **H → eτ** : comparable expected sensitivity, much tighter constraints than in Run1
- **H → μτ** : CMS a bit better on expected sensitivity, tighter constraints than in Run1
- Presented last year by C.S.Caillol

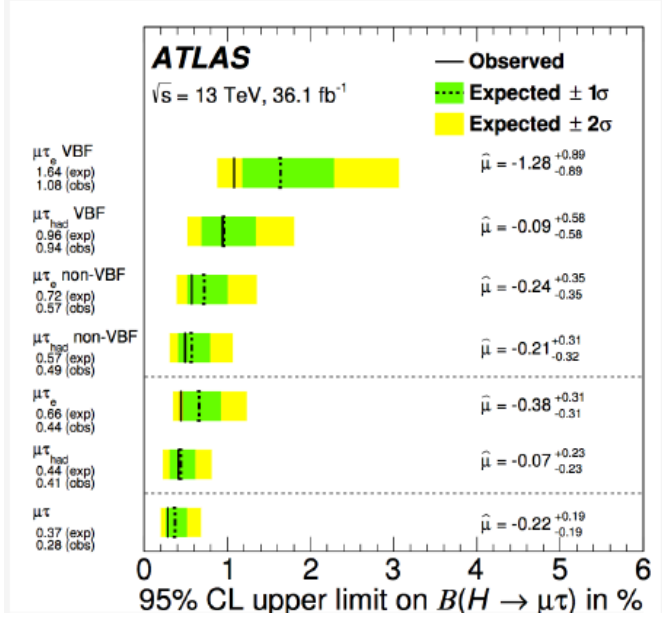
arXiv:1907.06131



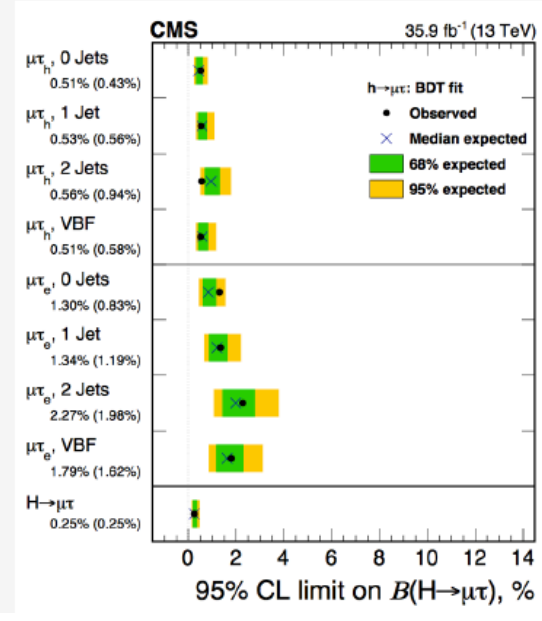
arXiv:1712.07173



arXiv:1907.06131



arXiv:1712.07173

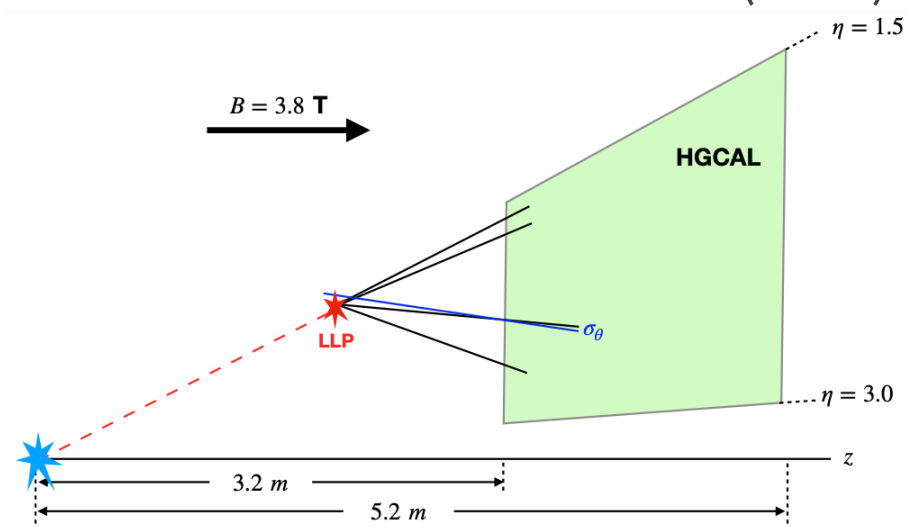


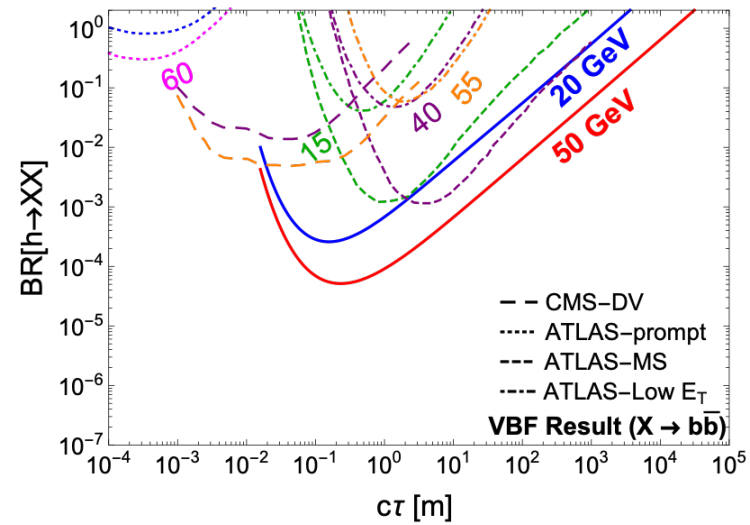
J. Liu *et al.*, 2005.10836

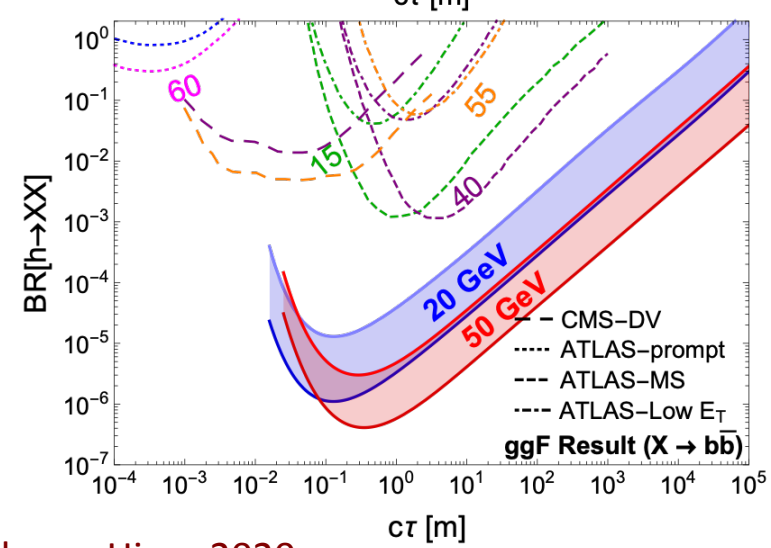
UPGRADED CMS HGCAL

- Propose using HGCAL to reconstruct LLPs in Higgs decays
- Employ VBF trigger, and/or proposed L1 displaced track trigger

see Y. Gershtein, 1705.04321, PRD 96 #3 (2017)





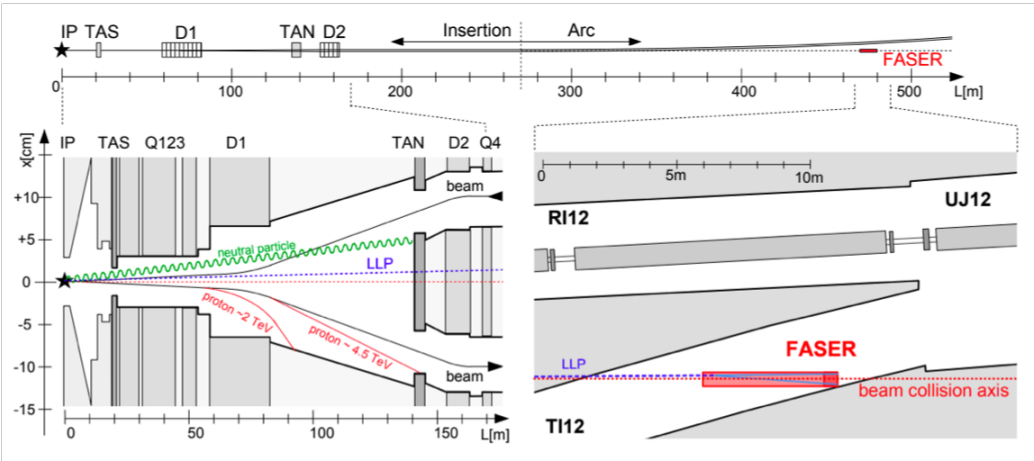


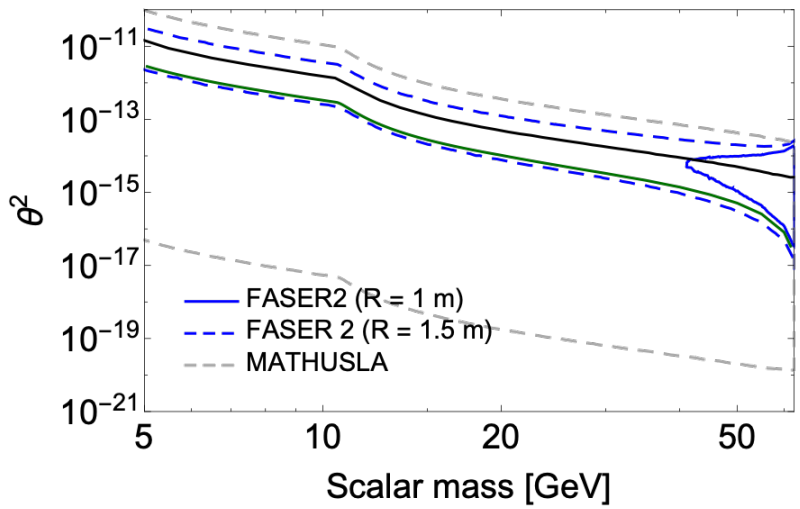
Brian Shuve, Higgs 2020

I. Boiarska *et al.*, 1908.04635, JHEP 05 (2020) 049

DISTANT DETECTORS

- Upgrades of existing dedicated LLP detectors like FASER, or proposed detectors like MATHUSLA, can reconstruct LLPs produced in exotic Higgs decays



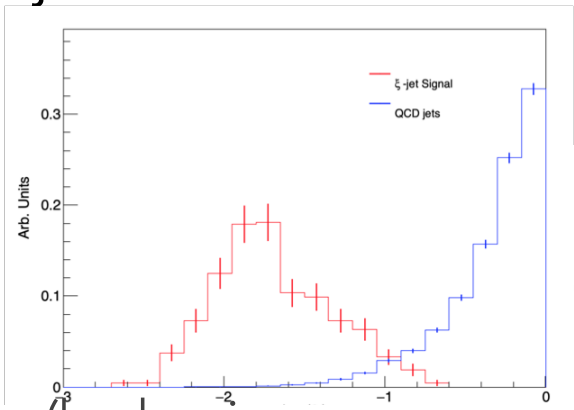


Brian Shuve, Higgs 2020

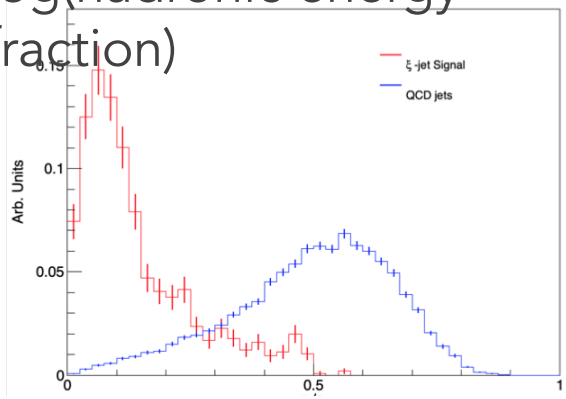
S. Ellis, T. Roy, J. Scholtz, 1210.3657, PRD 87 (2013); B. Sheff, N. Steinberg, J. Wells, 2008.10568

PHOTON JETS

- If the Higgs decays into low-mass scalars that in turn decay to photons, we get collimated "photon jets" (or "xi jets") that are not covered by existing searches - use jet substructure instead!

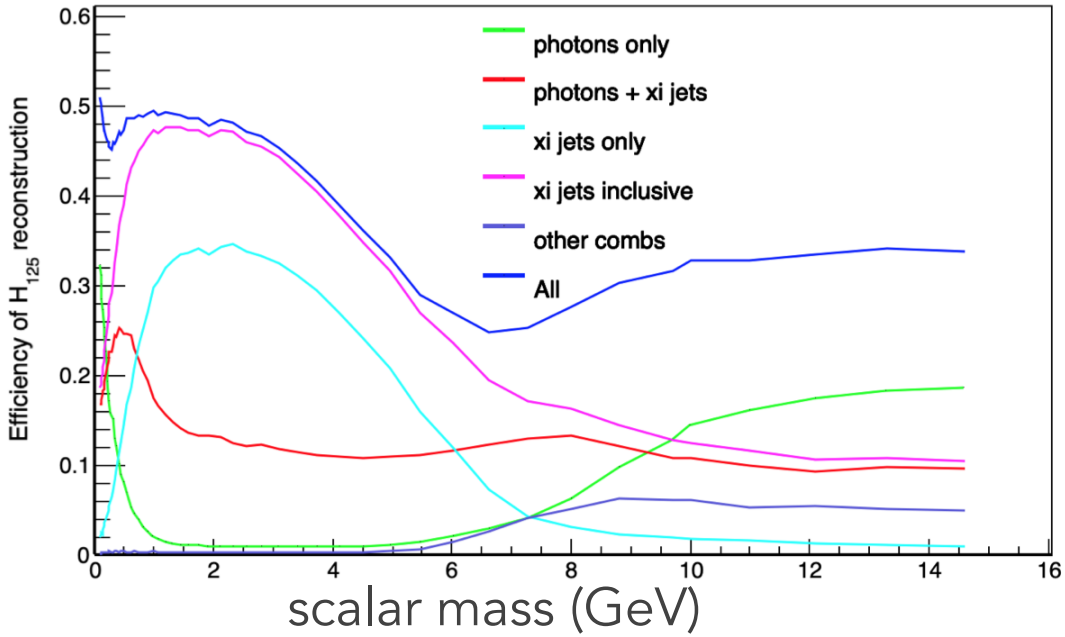


log(hadronic energy fraction)



2-subjettiness ratio

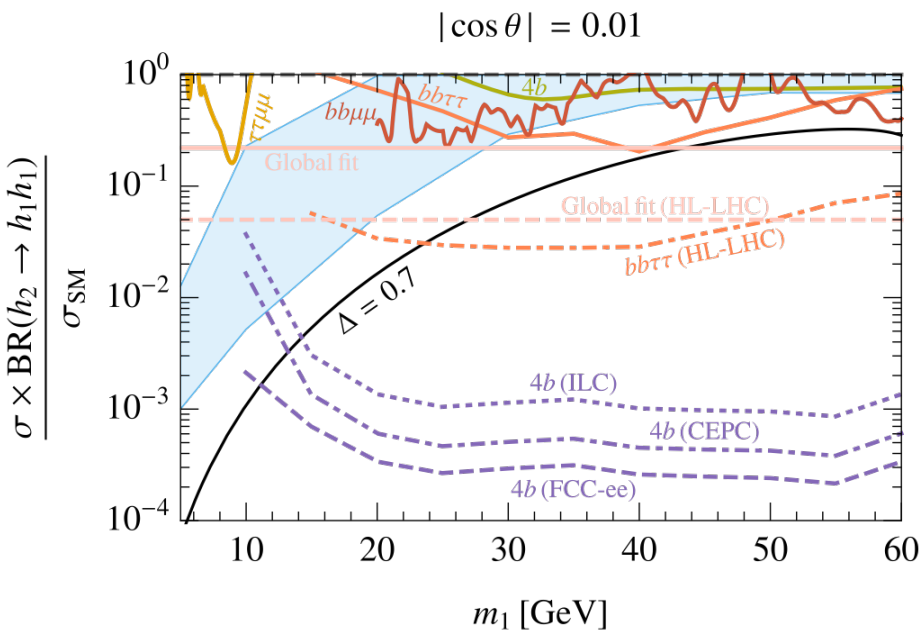
B. Sheff, N. Steinberg, J. Wells, 2008.10568



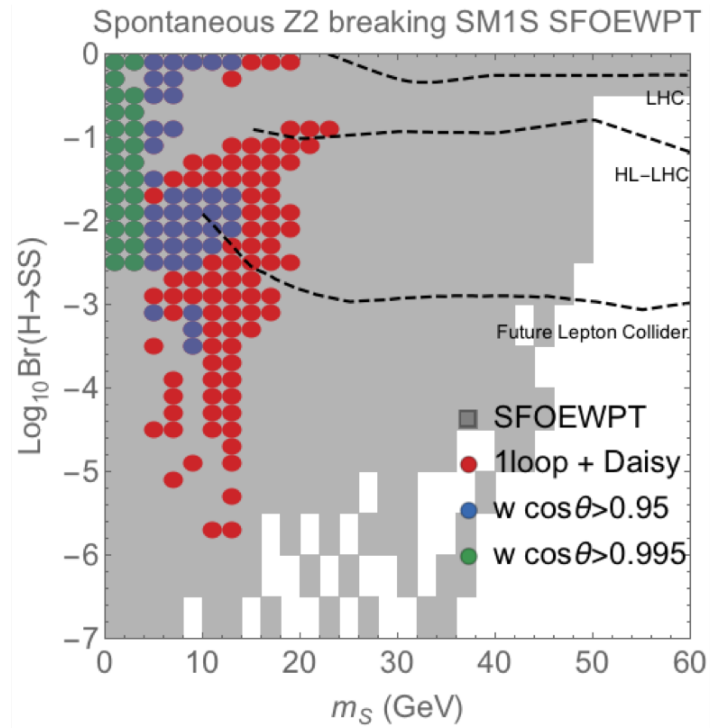
Brian Shuve, Higgs 2020

ELECTROWEAK PHASE TRANSITION

- A low-mass scalar produced in exotic Higgs decays could facilitate a strongly first-order electroweak phase transition!



J. Kozaczuk, M. Ramsey-Musolf, J. Shelton, 1911.10210, PRD 101 (2020)



M. Carena, Z. Liu, L. Wang, 1911.10206, JHEP 08 (2020)

Brian Shuve, Higgs 2020