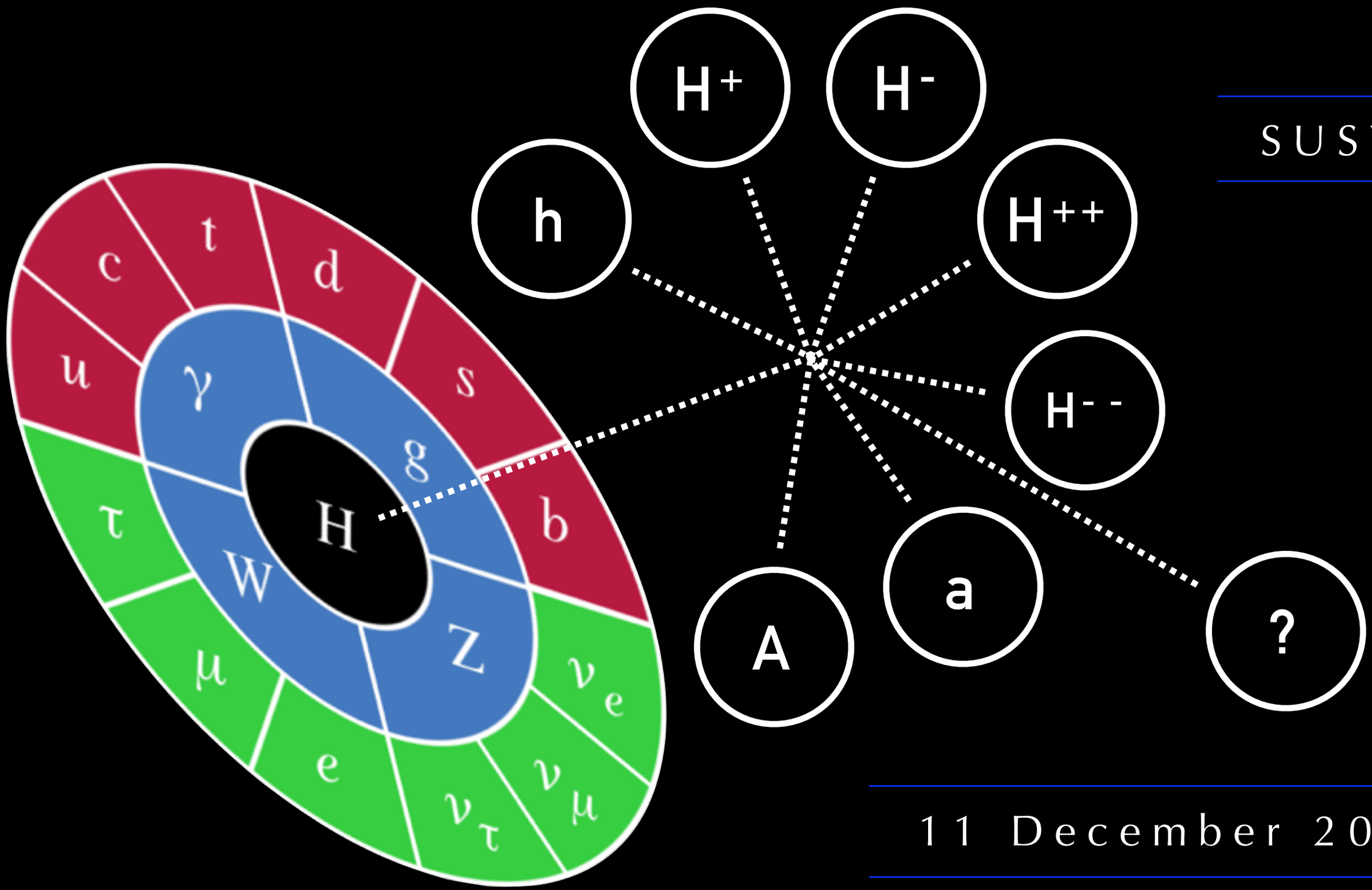
Searching for beyond-the-Standard Model Higgs bosons at ATLAS and CMS

SUSY17



11 December 2017

James Beacham [Ohio State/ATLAS]

tifr Tata Institute of Fundamental Research
टाटा मूलभूत अनुसंधान संस्थान

Open questions before 4 July 2012

Electroweak symmetry breaking
- Does the Higgs boson exist?

Quarks and leptons
- Why three families?
- Why these masses and mixings?
- CP violation in the lepton sector
- Matter/anti-matter asymmetry
- Baryon and charged lepton number violation

Physics toward the Planck scale
- How does gravity play with the other forces?
- Are there more than three dimensions of space?
- Do all forces unify at high energy?
- Are there other forces?

Dark matter
- What is it? WIMP, sterile neutrino, axion, NLSP, other hidden sector particle?
- Only one type?
- Only gravitational or other interactions?
- Are we wrong about gravity? An emergent phenomenon?

Neutrinos
- Why do neutrinos have masses? And what are these masses?
- Majorana or Dirac?
- CP violation
- Are there more (sterile) neutrinos?

Two epochs of Universe's accelerated expansion
- Primordial: Is inflationary model correct? Which (scalar) field? Role of quantum gravity?
- Today: Dark energy (why is Λ so small?) or gravity modification?

Inspired by I. Shipsey

Open questions after 4 July 2012

Electroweak symmetry breaking
- [x] Does the Higgs boson exist?
- [ ] Is m_h natural or fine-tuned?
- [ ] If natural, what new physics/symmetry governs this?
- [ ] Does it regularize divergent V_LV_L cross-section at high $m_{V_LV_L}$? Or new dynamics?
- [ ] Elementary or composite Higgs?
- [ ] Is it alone or does the Higgs have siblings and cousins?
- [ ] Origin of couplings to fermions?
- [ ] Coupling to dark matter?
- [ ] Connection to hidden sectors?
- [ ] Does it violate CP?
- [ ] Cosmological EW phase transition?

Quarks and leptons
- [ ] Why three families?
- [ ] Why these masses and mixings?
- [ ] CP violation in the lepton sector
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Neutrinos
- [ ] Why do neutrinos have masses? And what are these masses?
- [ ] What's the role of h125?
- [ ] Majorana or Dirac?
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- [ ] Are there more (sterile) neutrinos?

Two epochs of Universe's accelerated expansion
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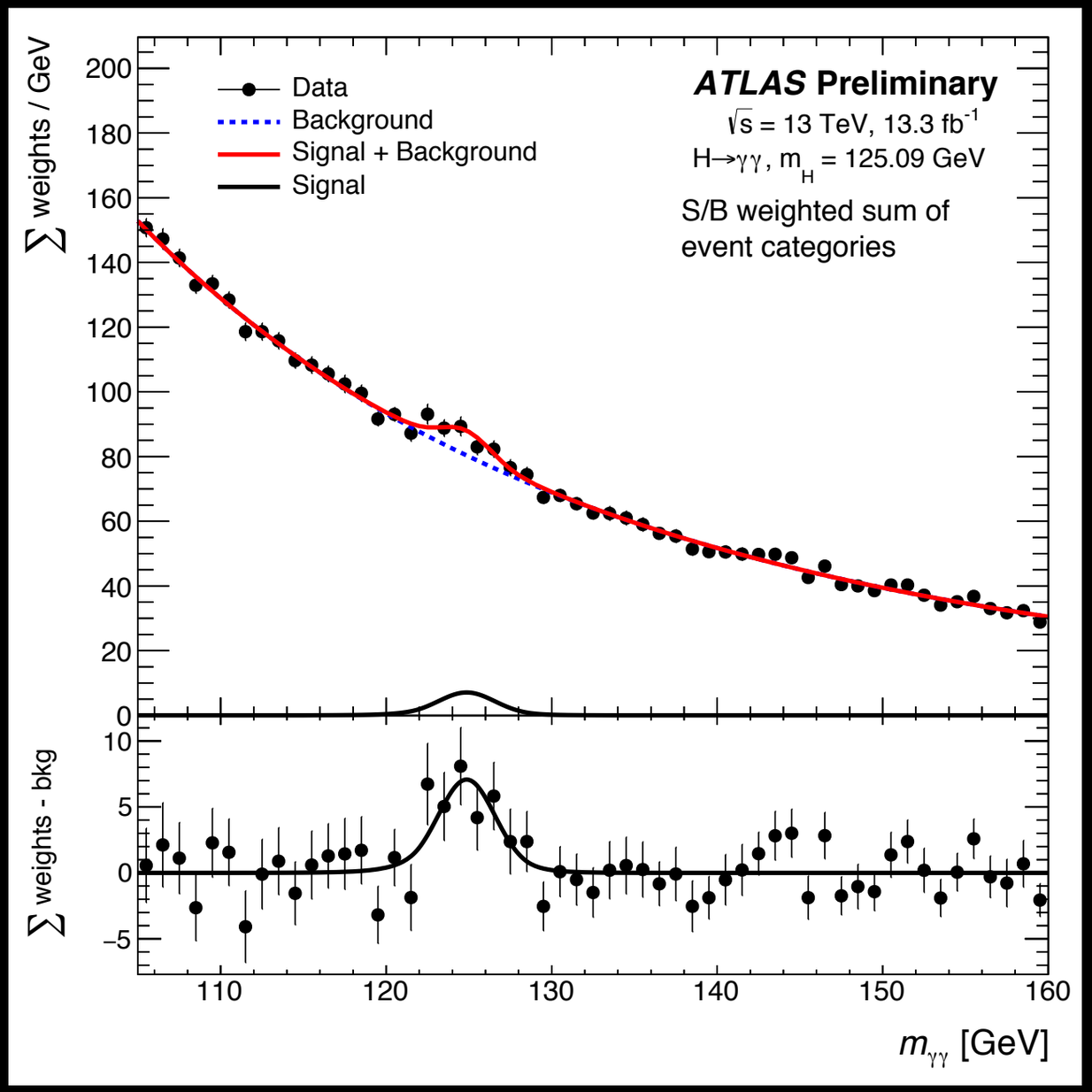
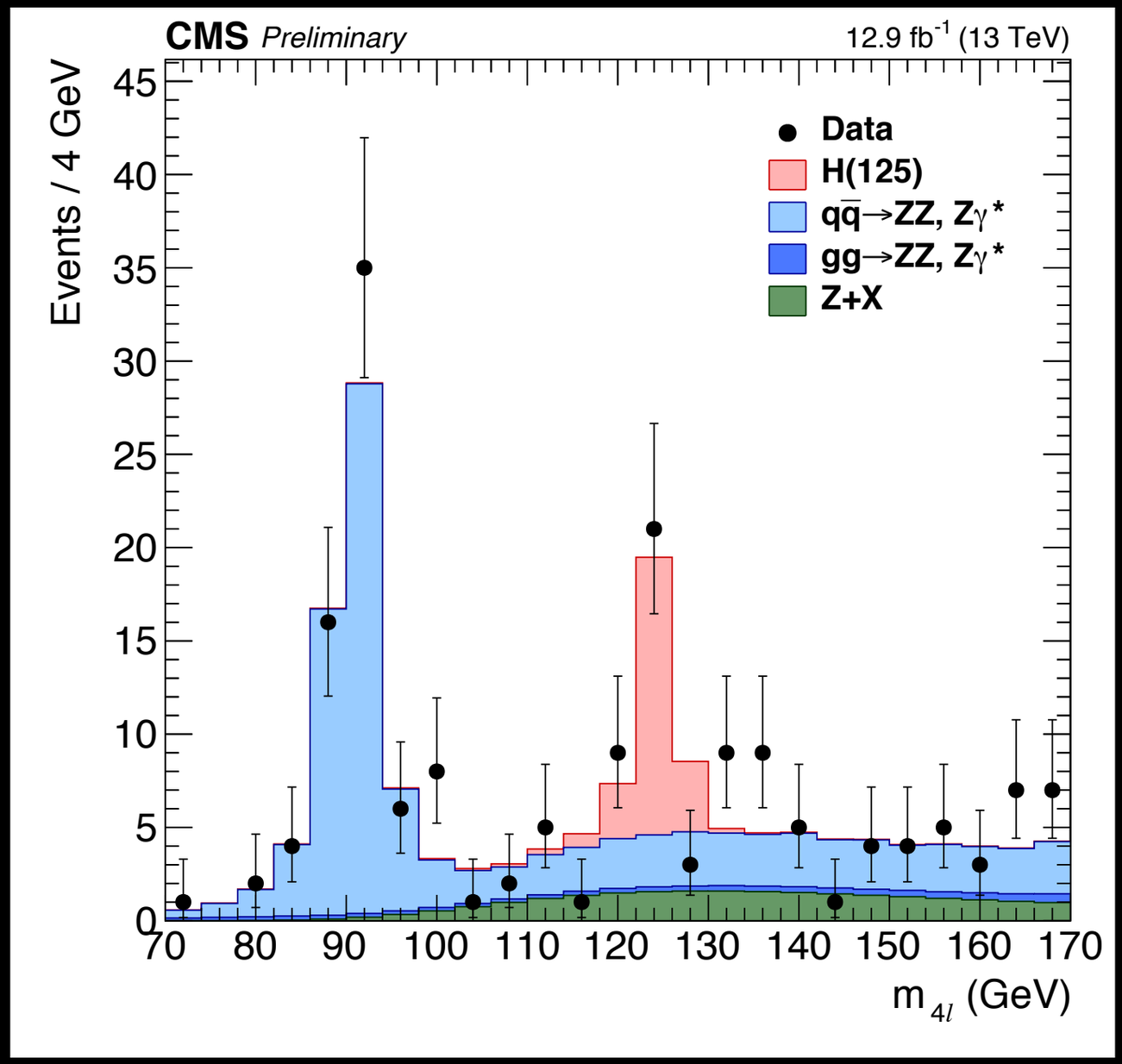
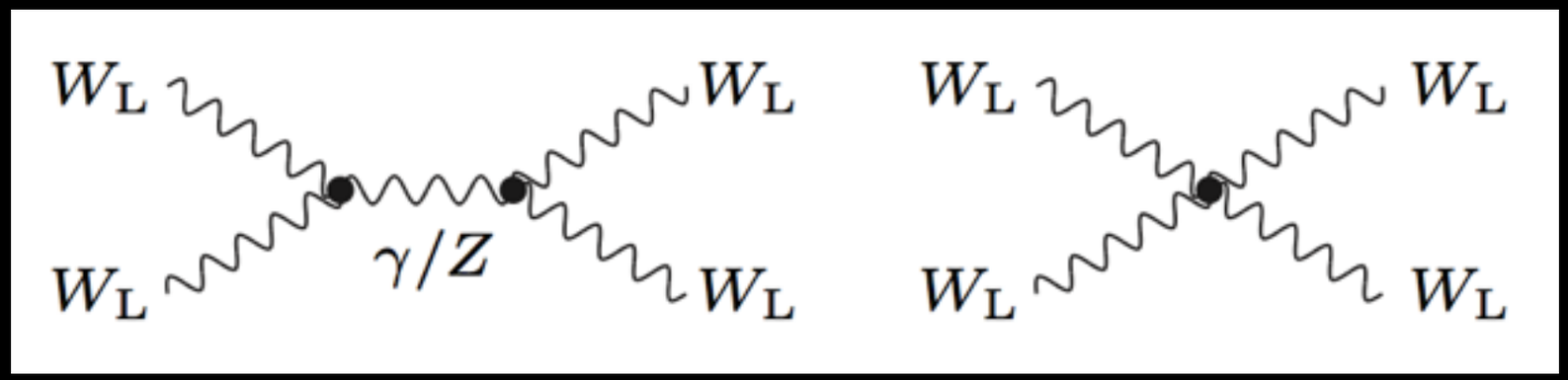
Rediscovering the Higgs at 13 TeV





Is the Higgs alone?



→ Probability > 1 as center-of-mass energy grows

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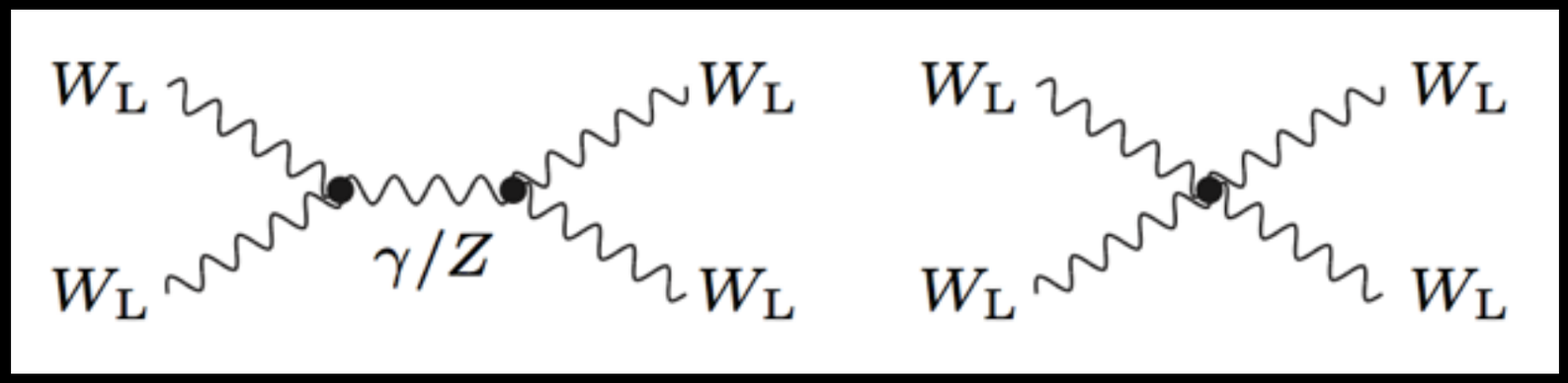

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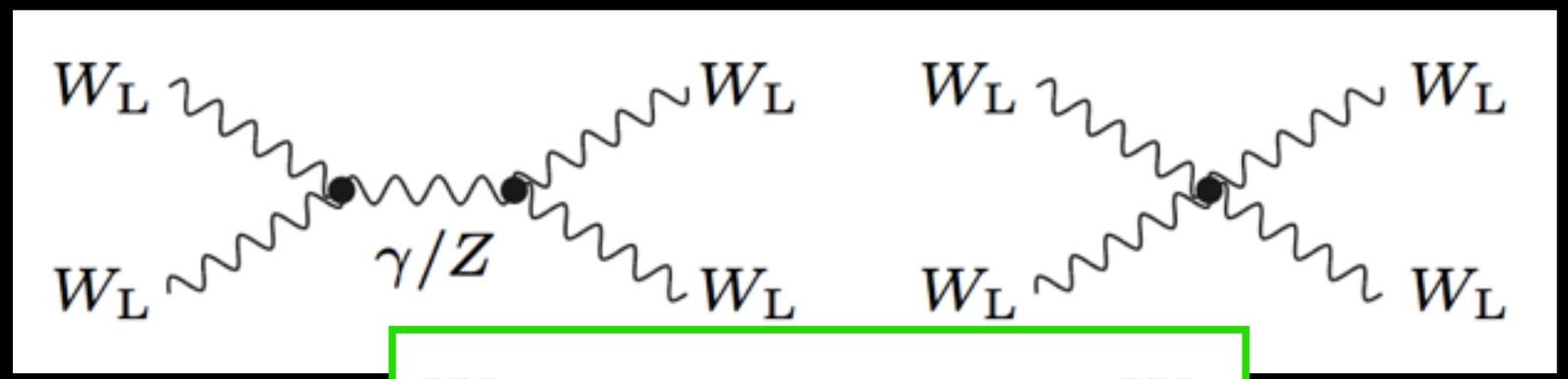
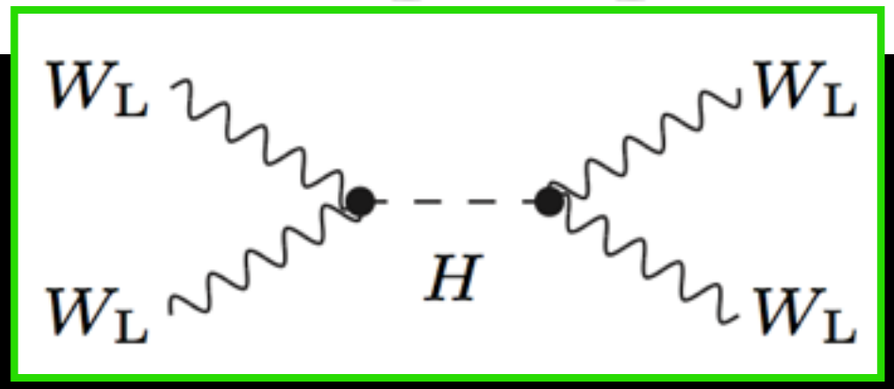
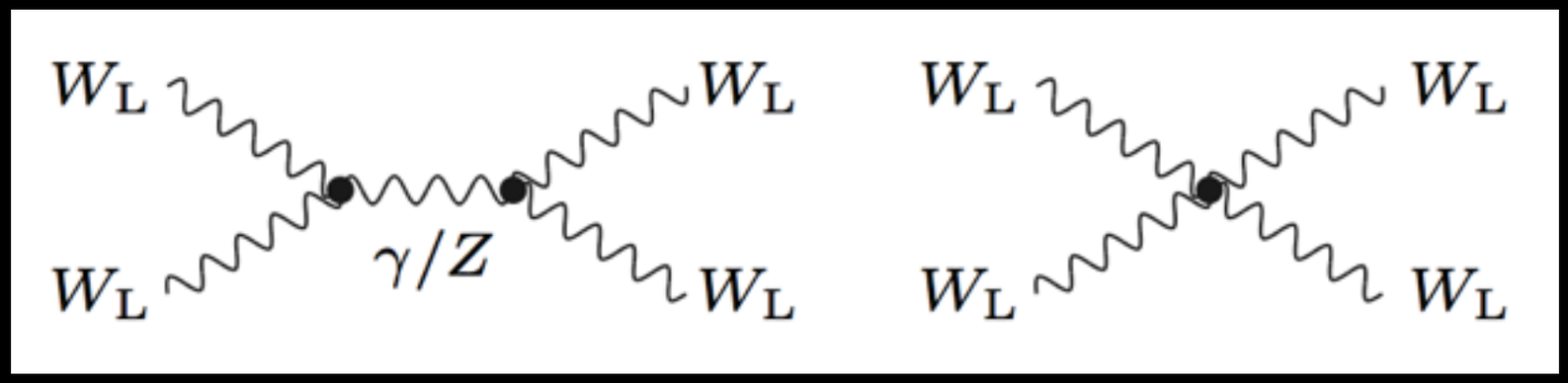




→ The existence of a Standard Model Higgs yields meaningful predictions for vector boson scattering...

Is the Higgs alone?



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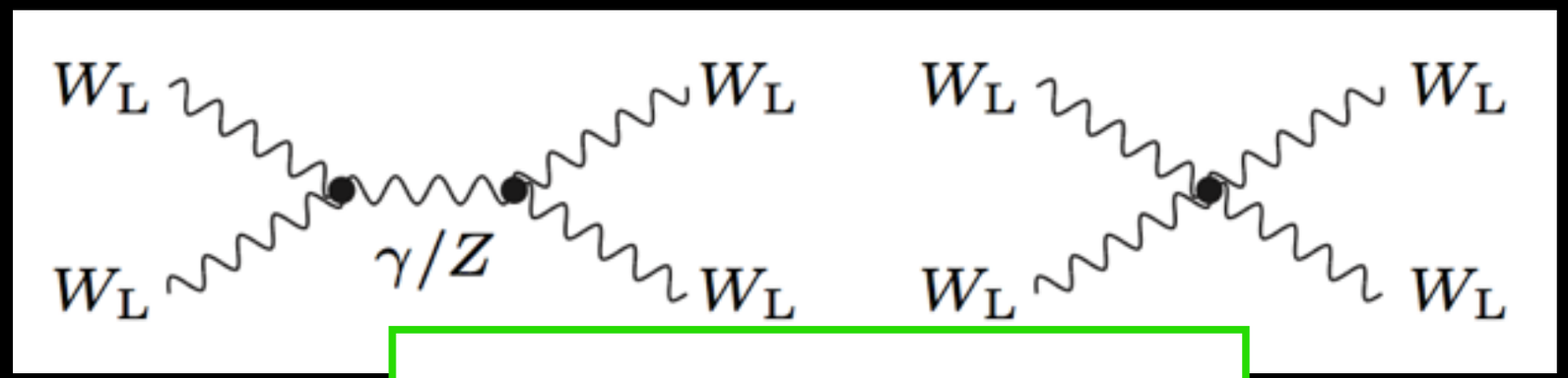
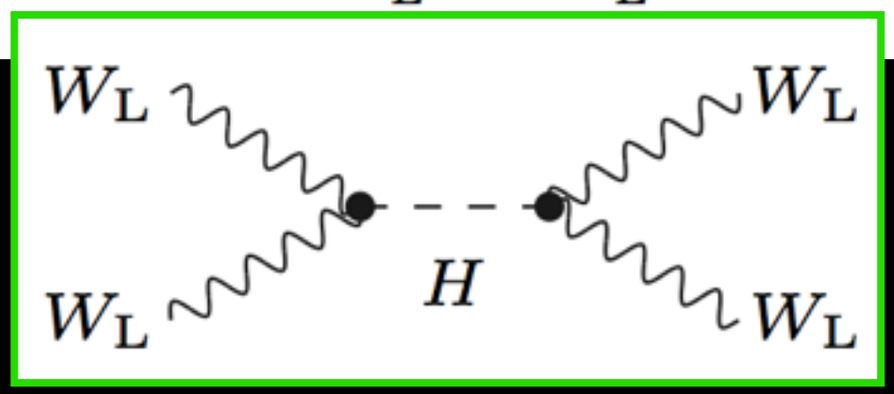




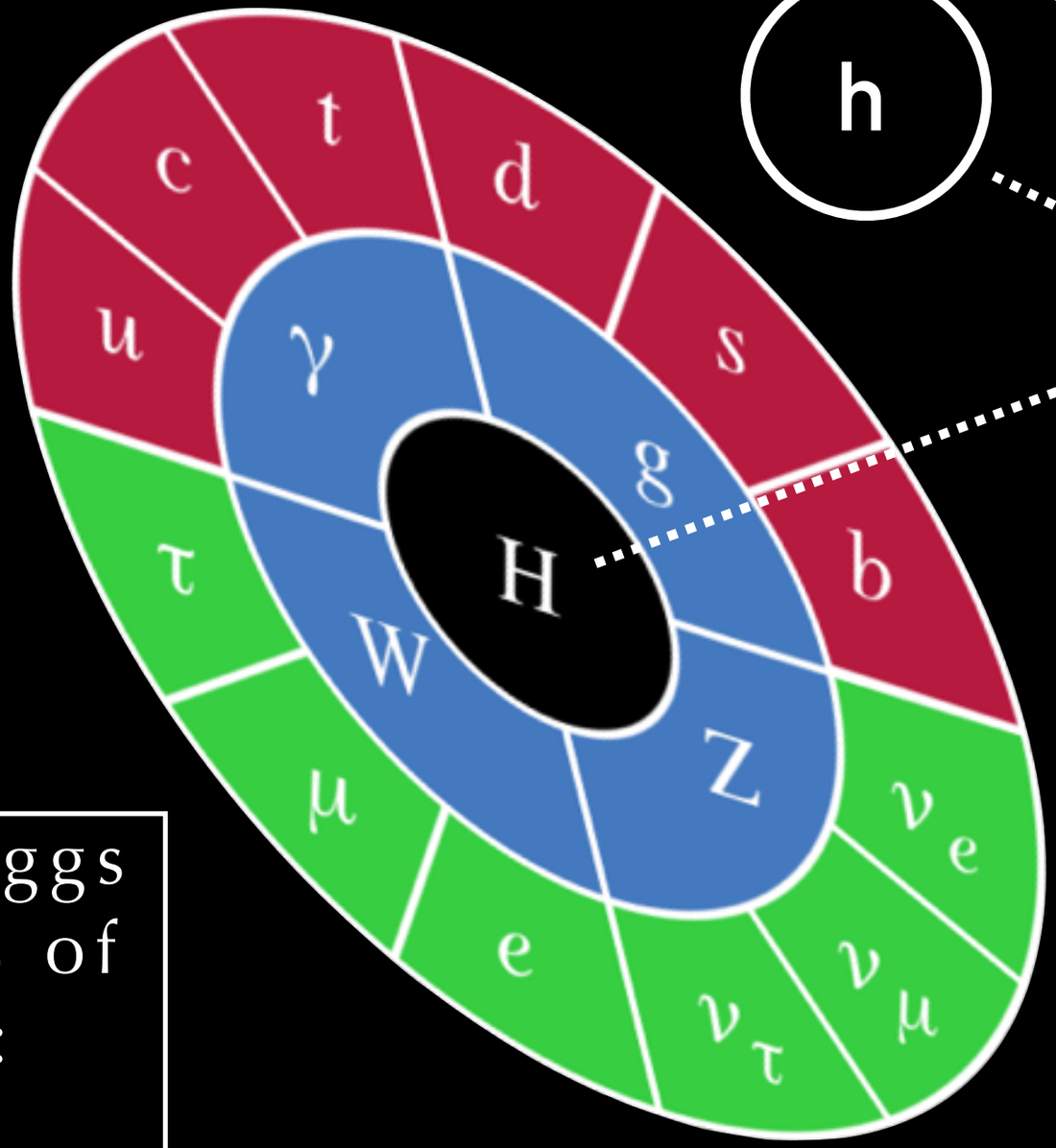
→ The existence of a Standard Model Higgs yields meaningful predictions for vector boson scattering...

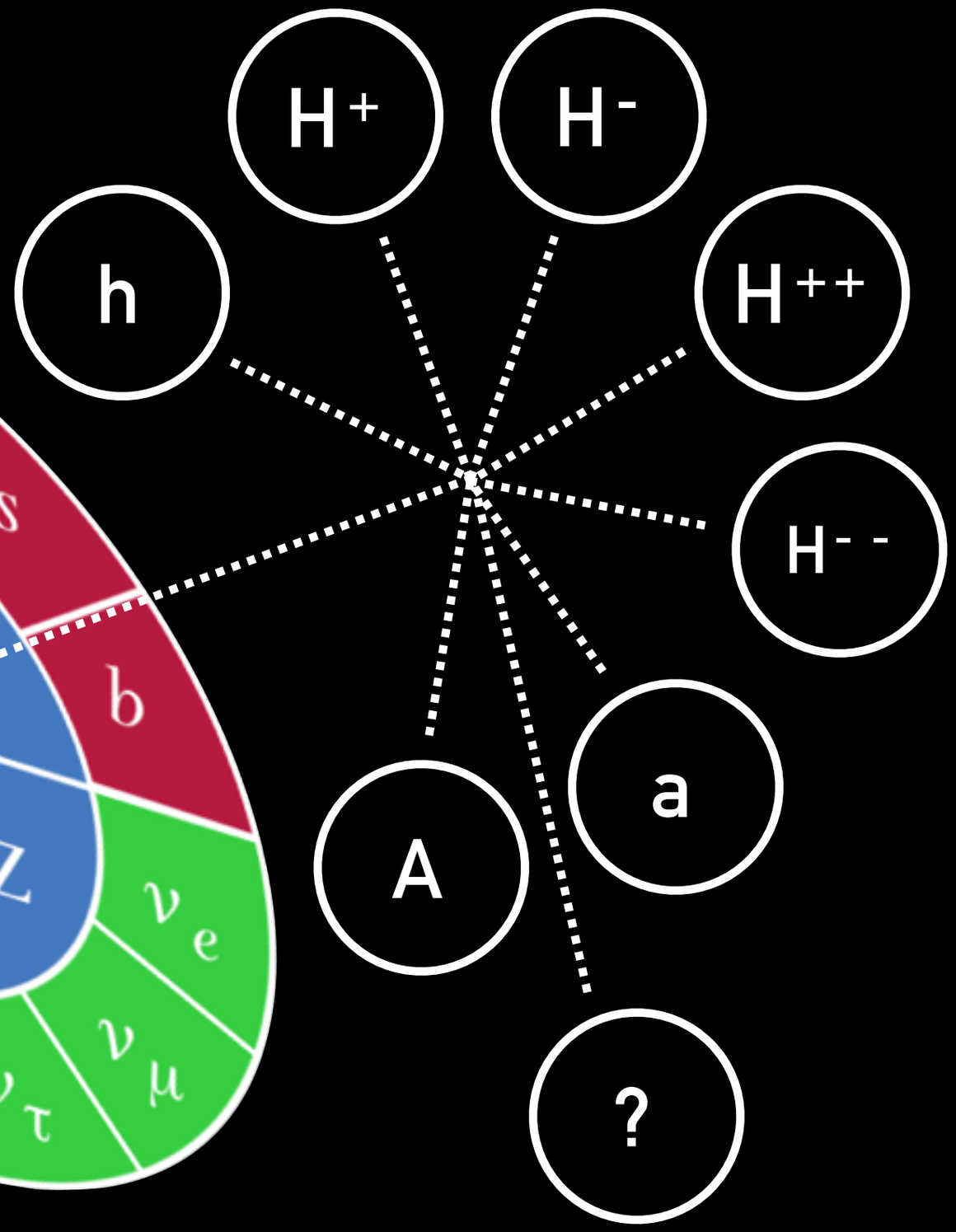
...but are there other Higgs-like particles that help control these nonsense probabilities?

Exotic Higgs bosons

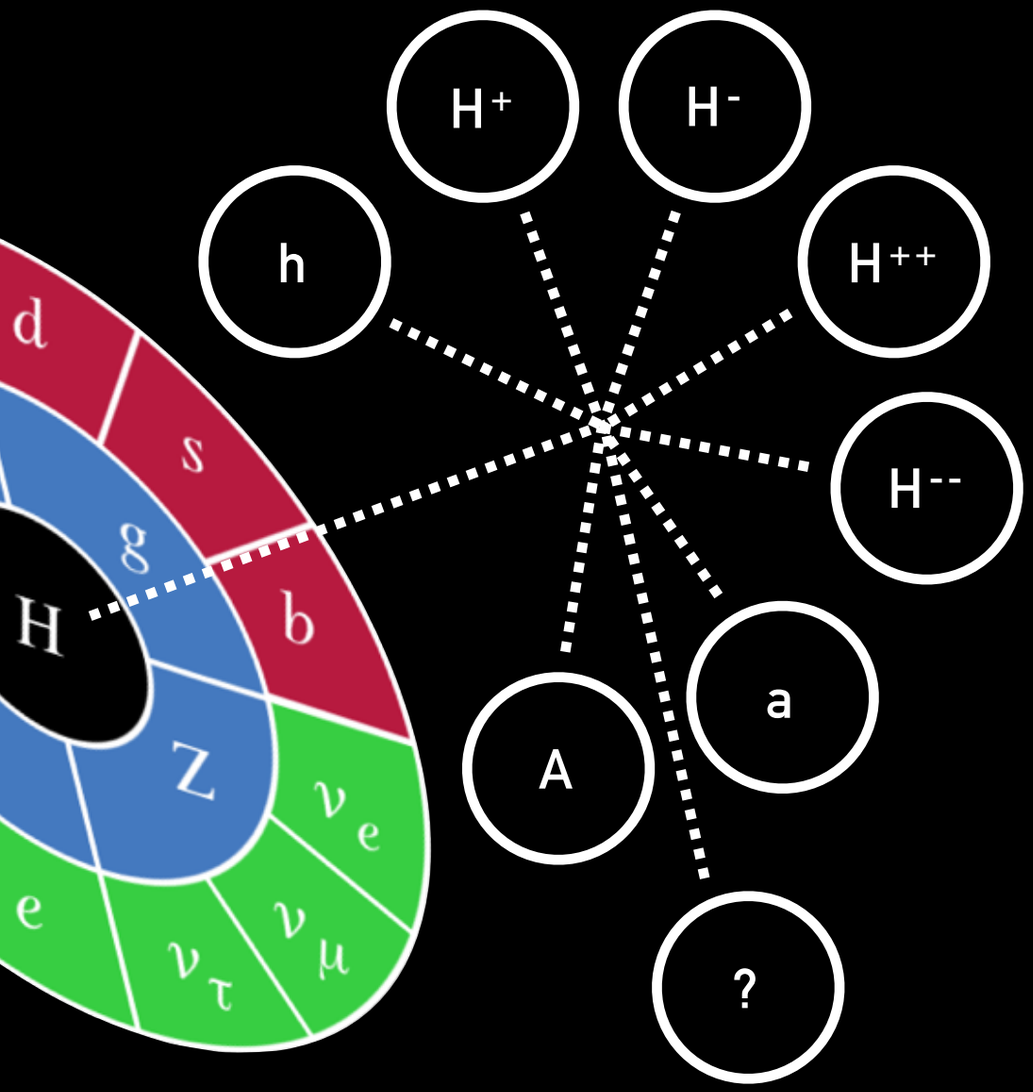
Two Higgs doublet models, Higgs triplet models, MSSM...

Our new Higgs with a mass of 125 GeV: h or H?





BSM Higgs phenomenology at the LHC



Extended scalar sectors appear in many extensions of the SM (SUSY, axion models, electroweak baryogenesis models, grand unification, etc.), but even the "repetition argument" is compelling enough to hypothesize siblings and cousins of h125:

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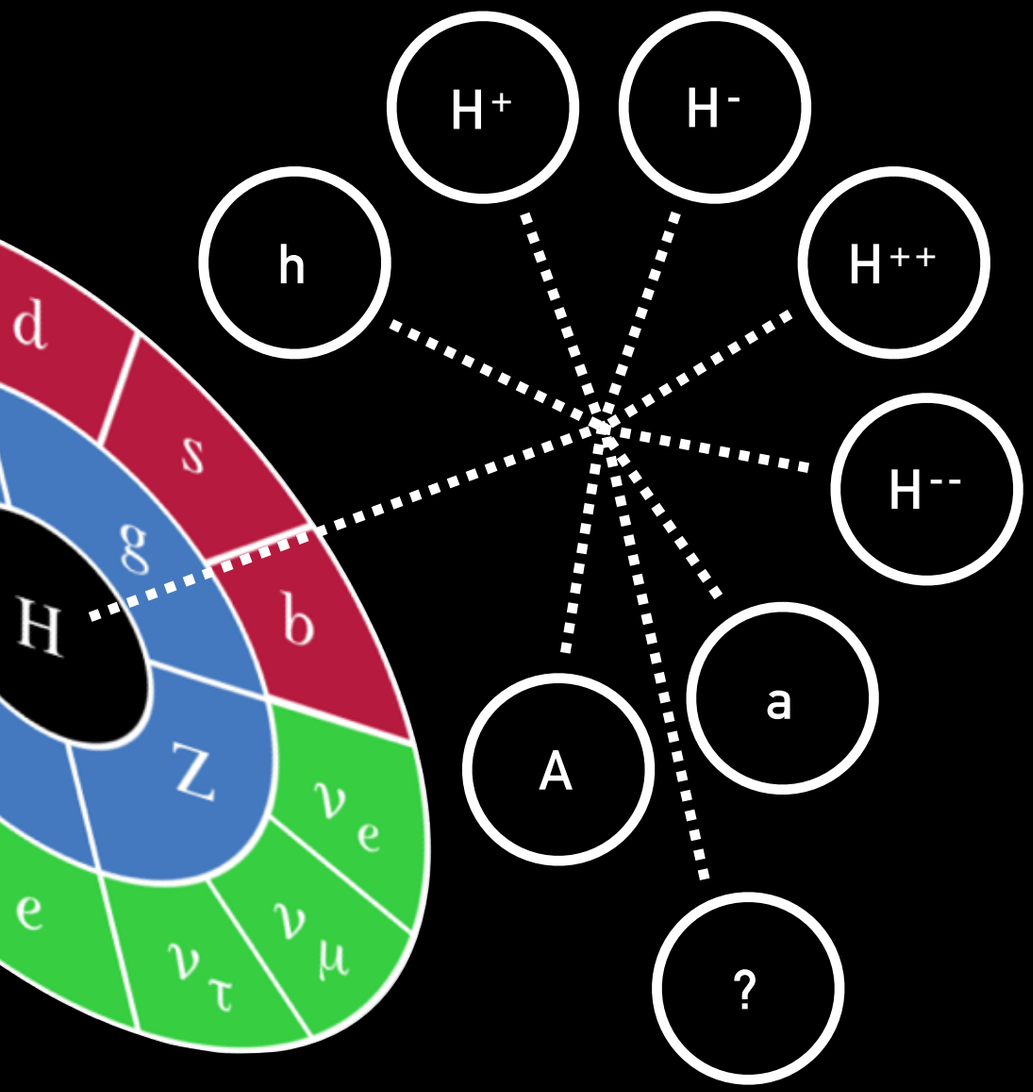

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Three repeated pairs of leptons and of quarks, without any *a priori* reason; why not in the scalar sector, as well?

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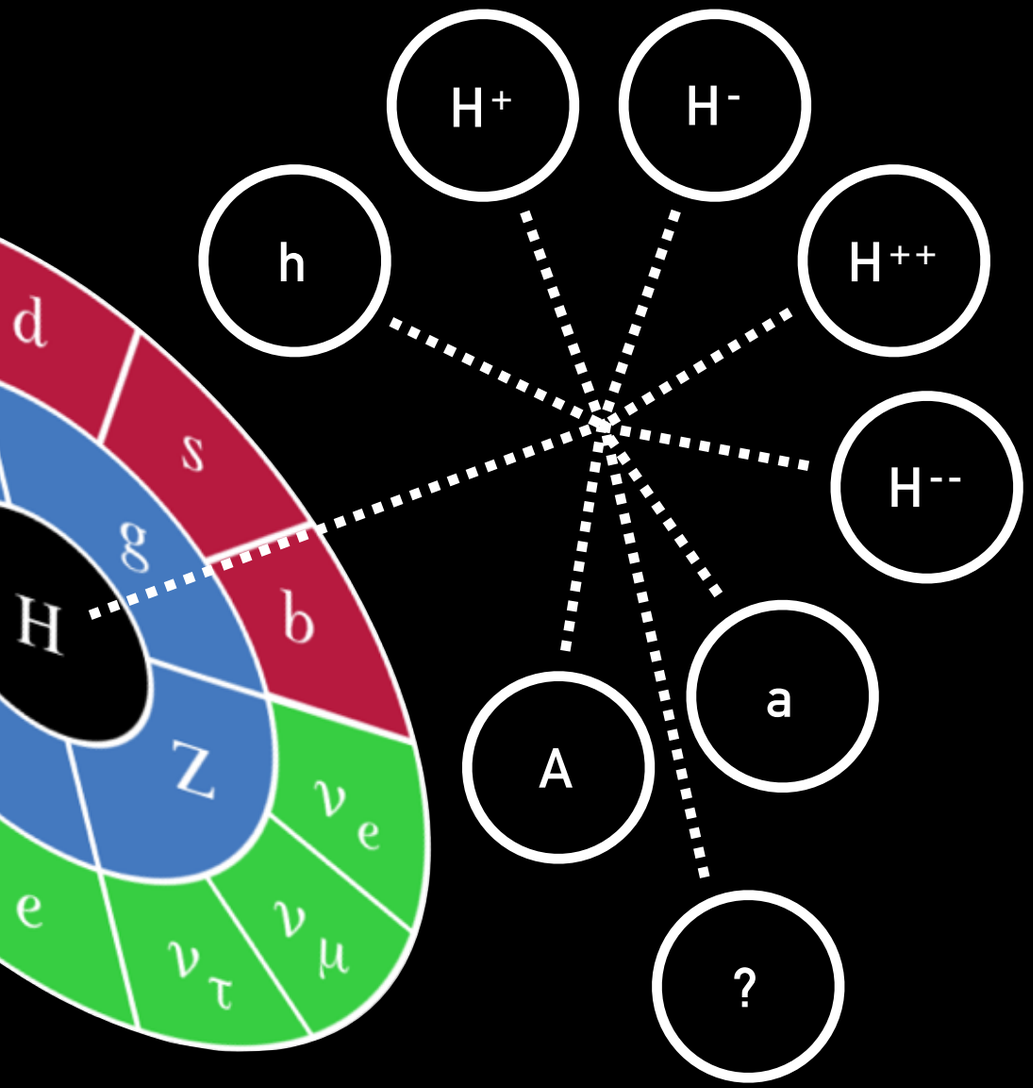

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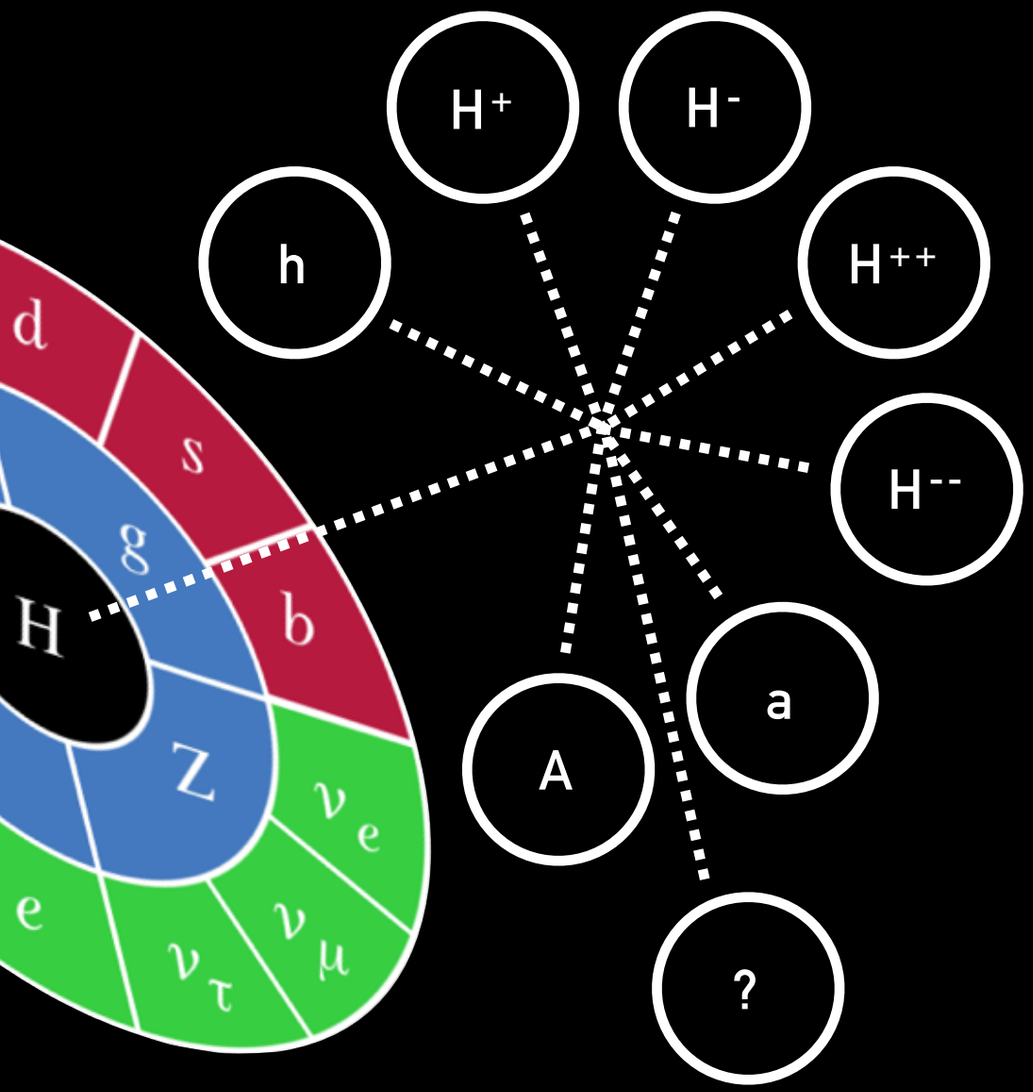

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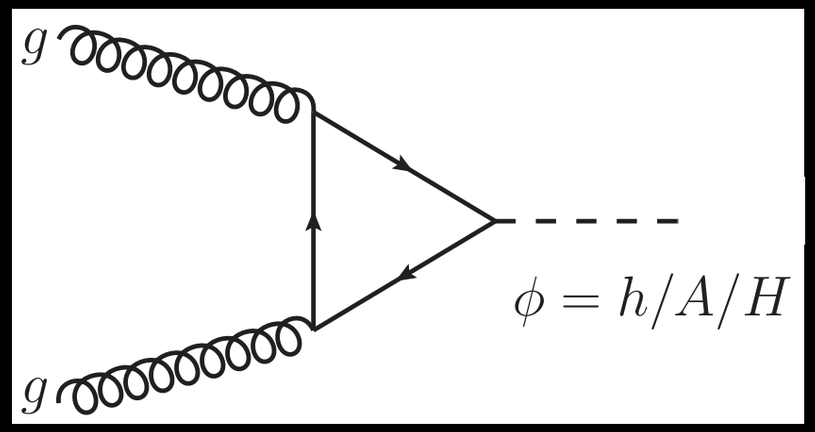
A curated selection of ATLAS/CMS results presented here; we have a multitude of dedicated parallel talks at this conference for more details!

Exhaustive results are available at

CMS
ATLAS

Neutral scalars h/A/H



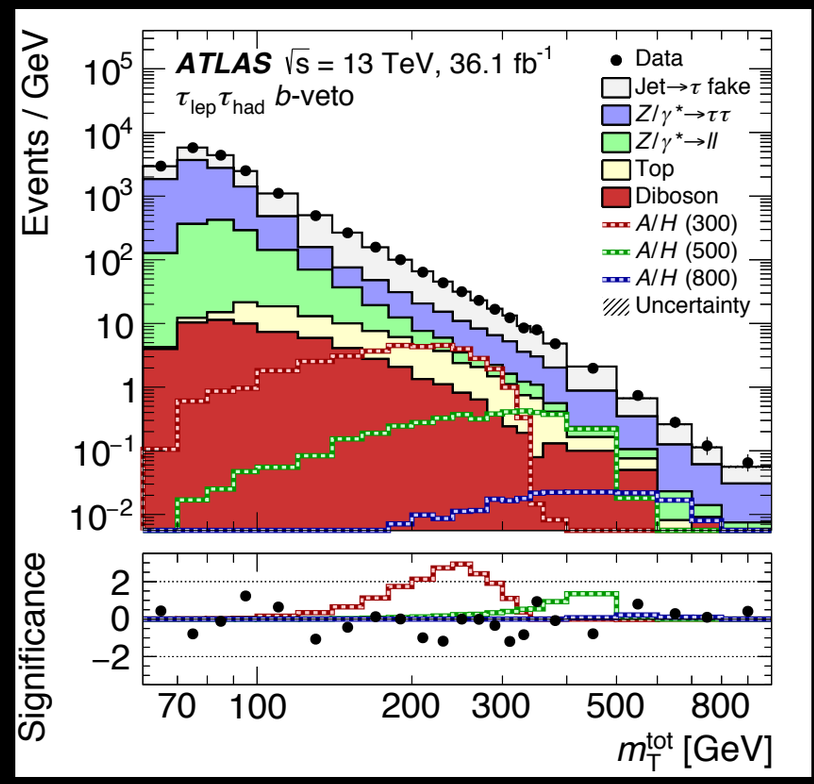
$h/A/H \rightarrow \tau^+\tau^-$

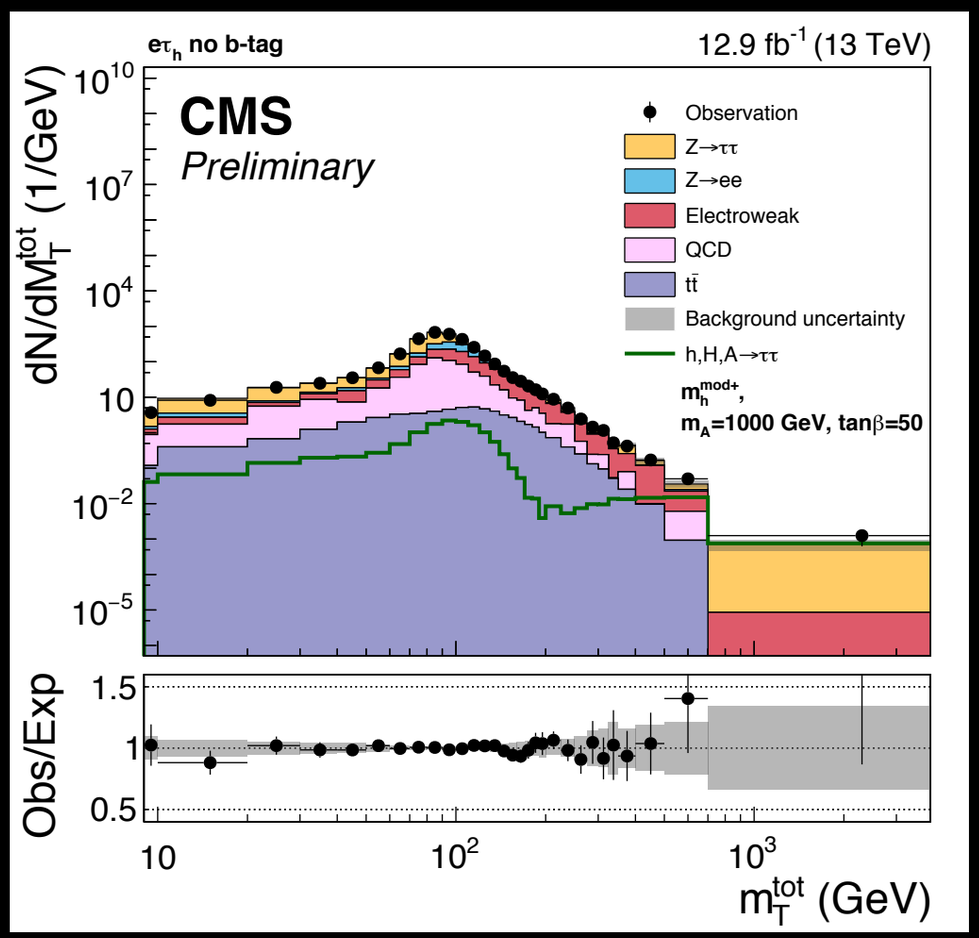
ATLAS: arXiv:1709.07242
CMS-PAS-HIG-16-037

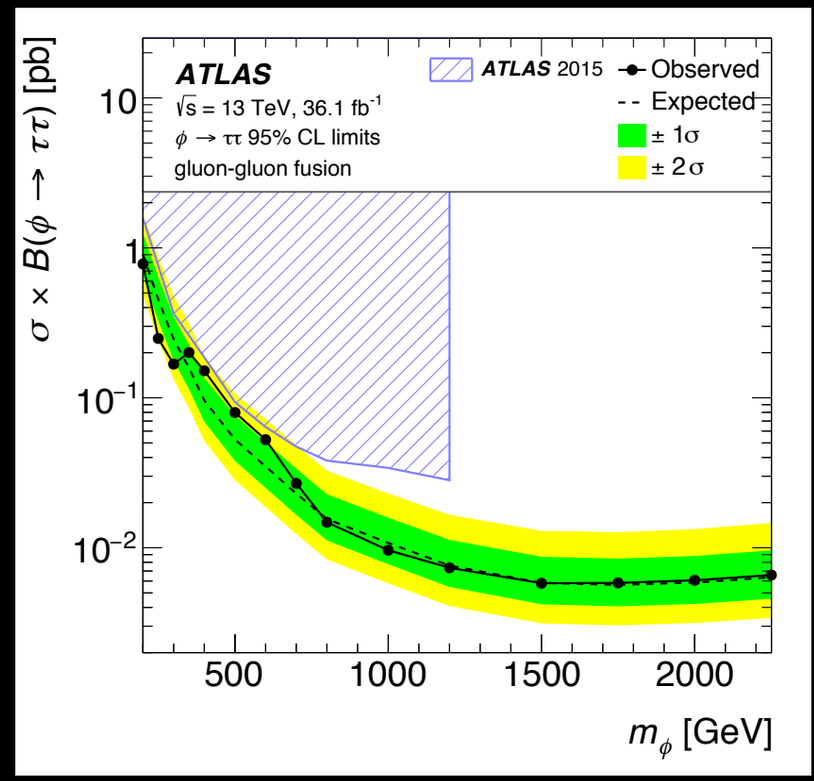
Categorize events based on hadronic / leptonic tau decays & lepton flavor

Search for excesses in total transverse mass spectrum

Background estimate from a combination of data-driven and simulation based methods







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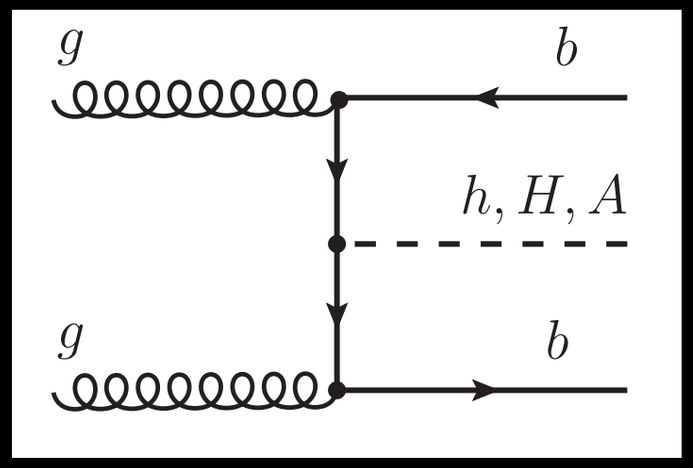
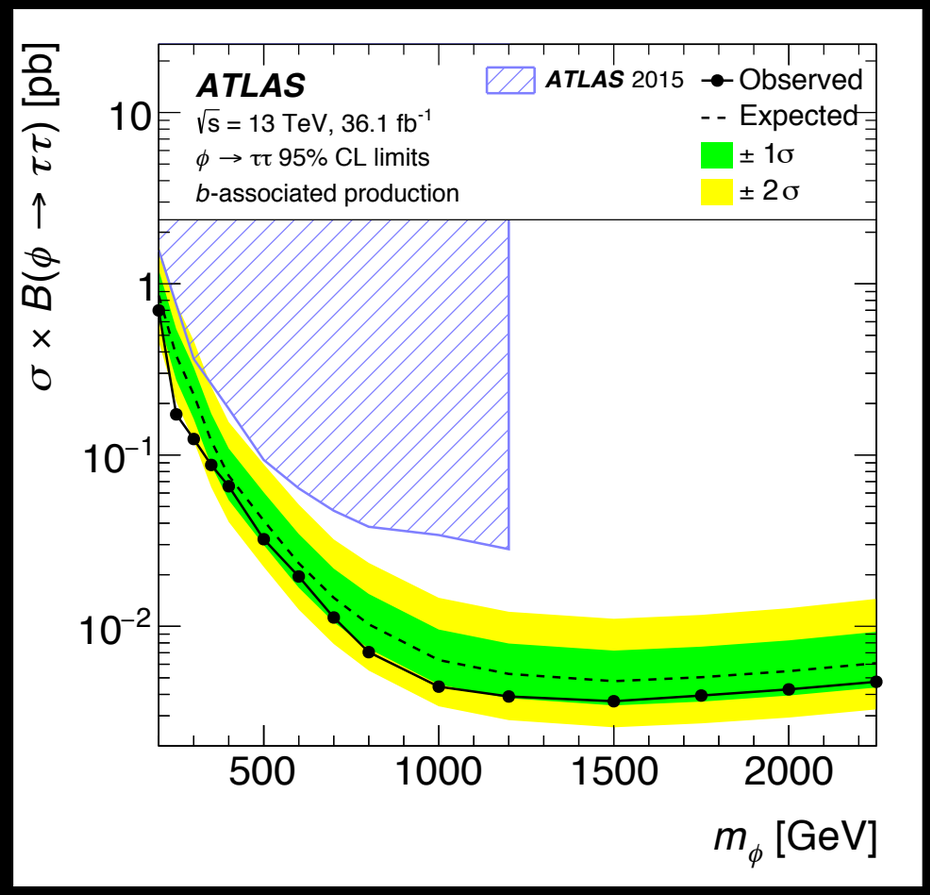


$(bb)h/A/H \rightarrow \tau^+\tau^-$

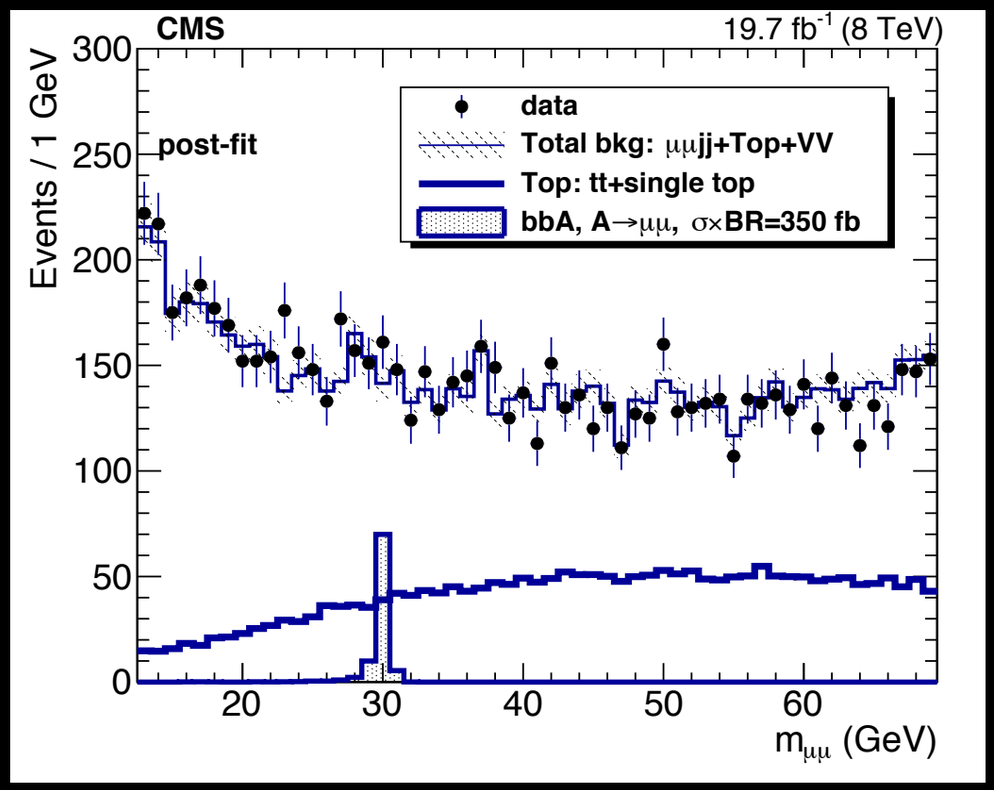
Associated production with b-jets

ATLAS: arXiv:1709.07242



Leptonic and hadronic tau triggers

$(bb)h/A/H \rightarrow \mu^+\mu^-$

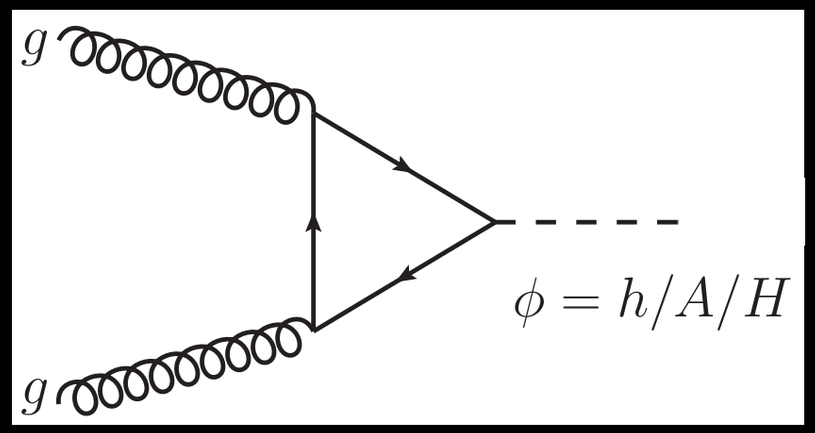


CMS: JHEP 11 (2017) 010

Low-mass di-muon search at 8 TeV

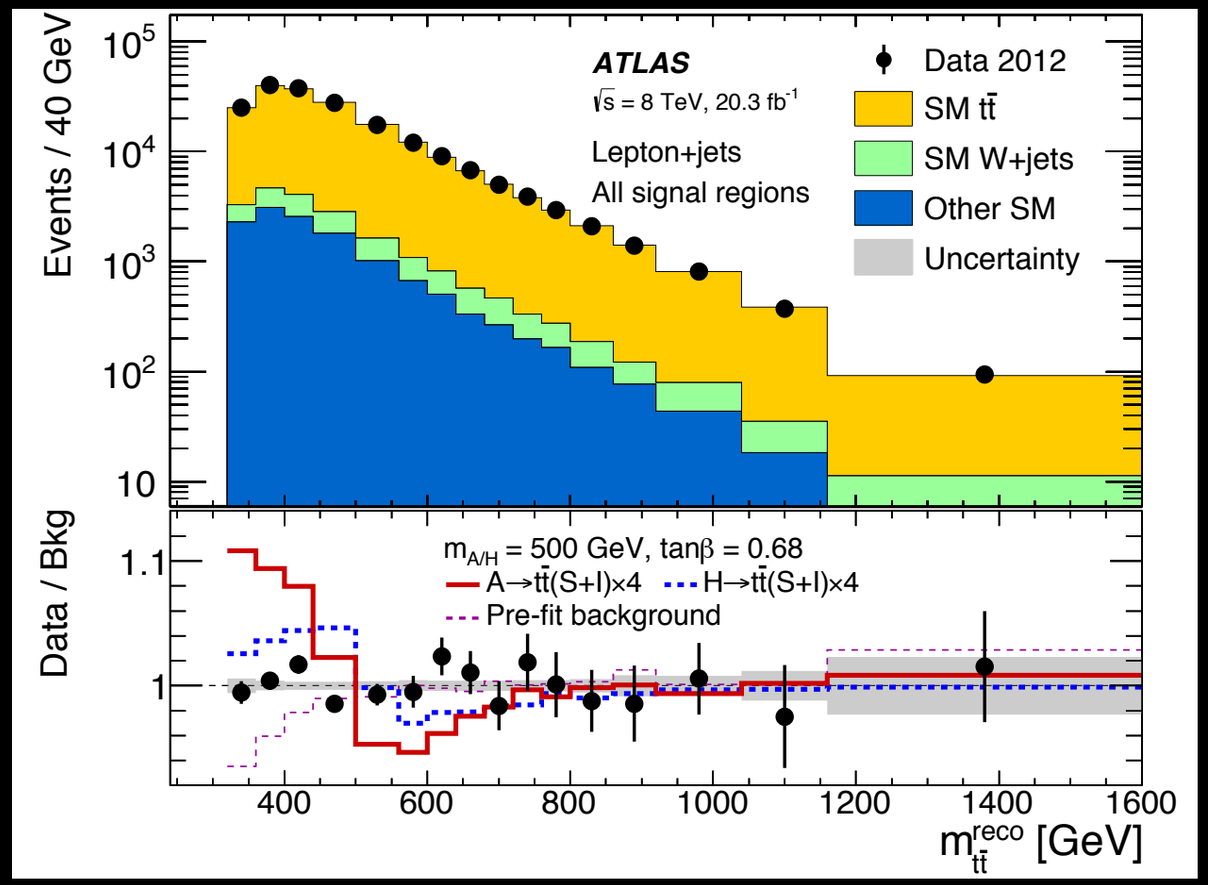
Mass range inspired by 2HDM for a pseudoscalar with 12 GeV < m_A < $m_{h125}/2$

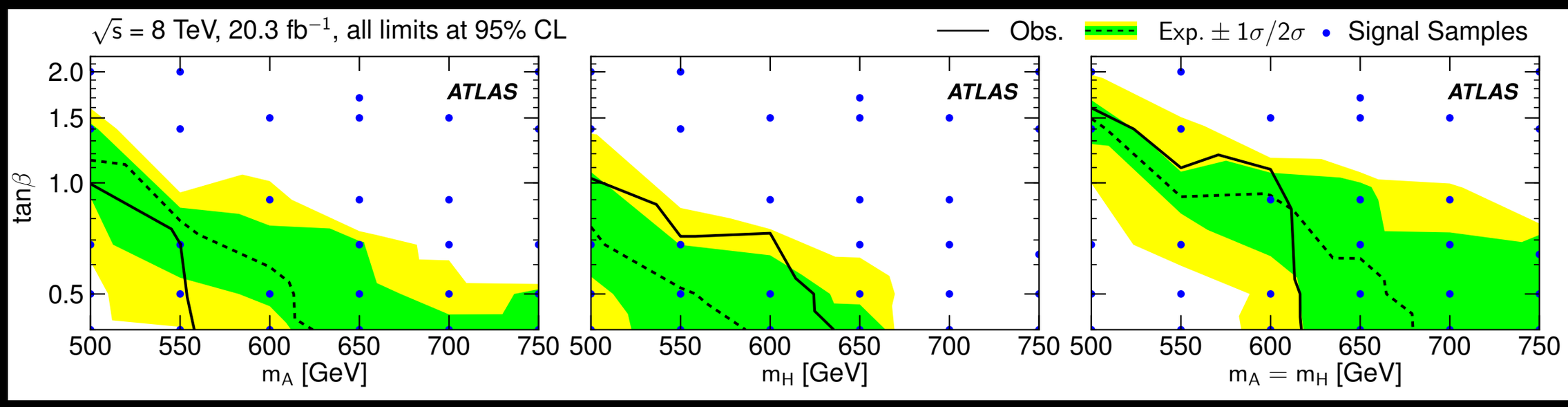
Neutral scalars h/A/H



$h/A/H \rightarrow t\bar{t}$

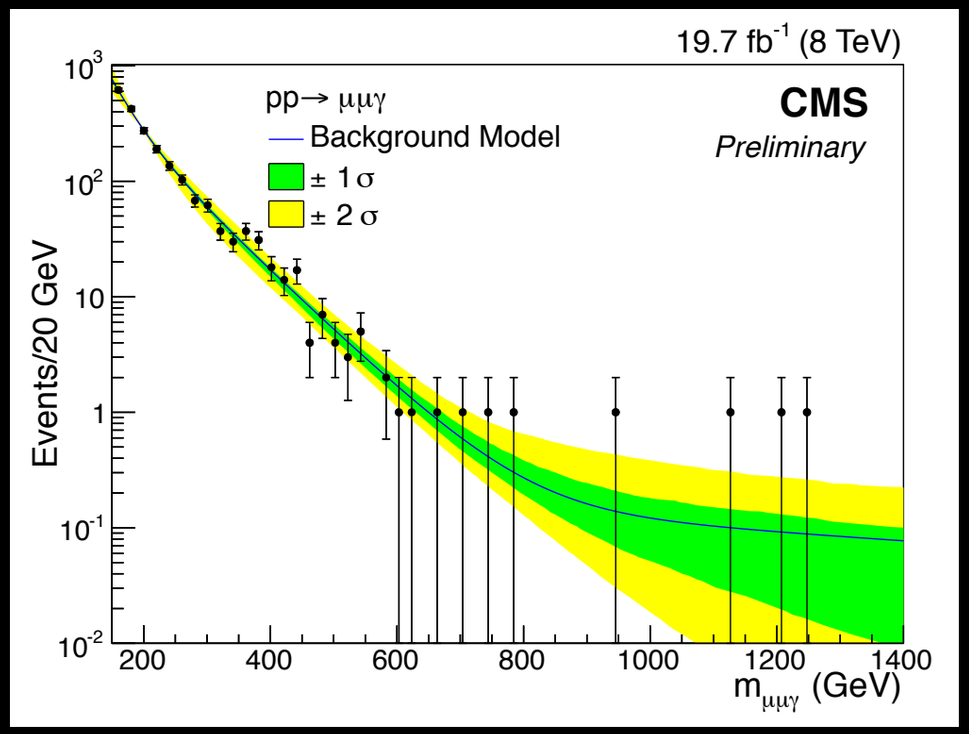
2HDM:
$tan\beta$ = ratio of vevs of the two scalar doublets



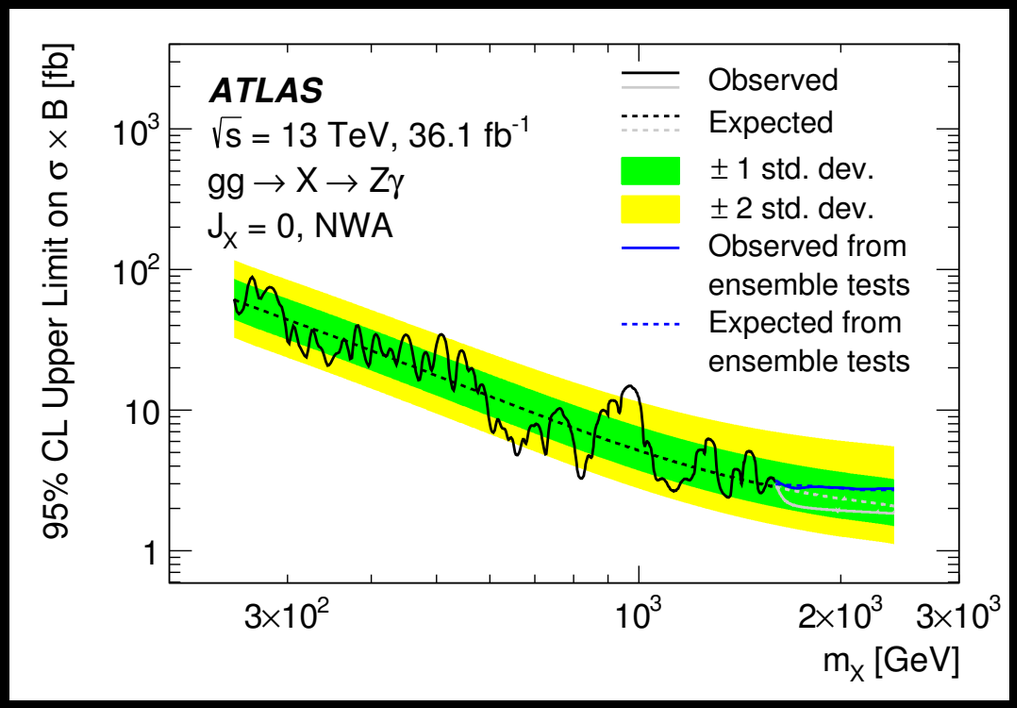


ATLAS: PRL 119 (2017) 191803

A / H —> Z γ



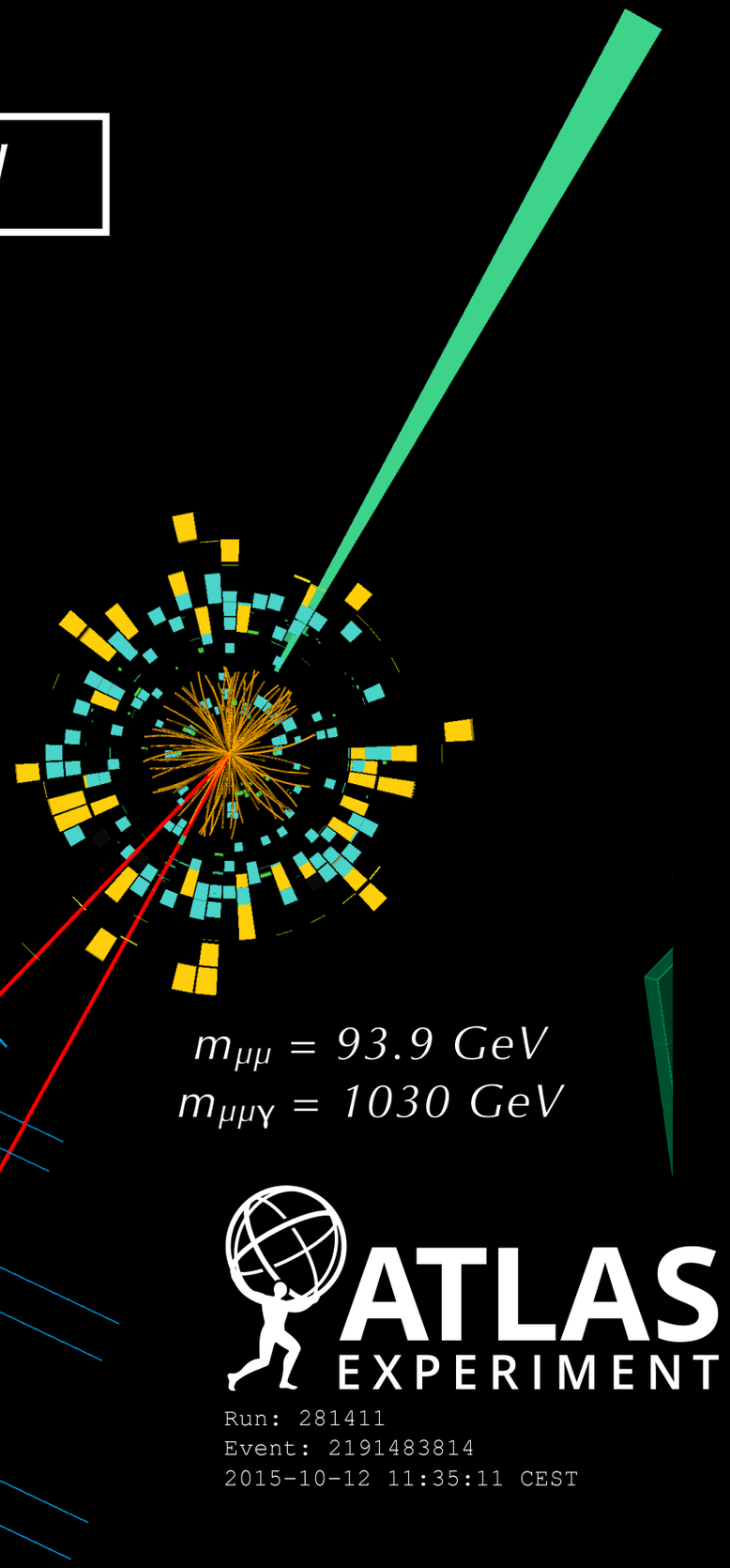
CMS-PAS-HIG-16-014



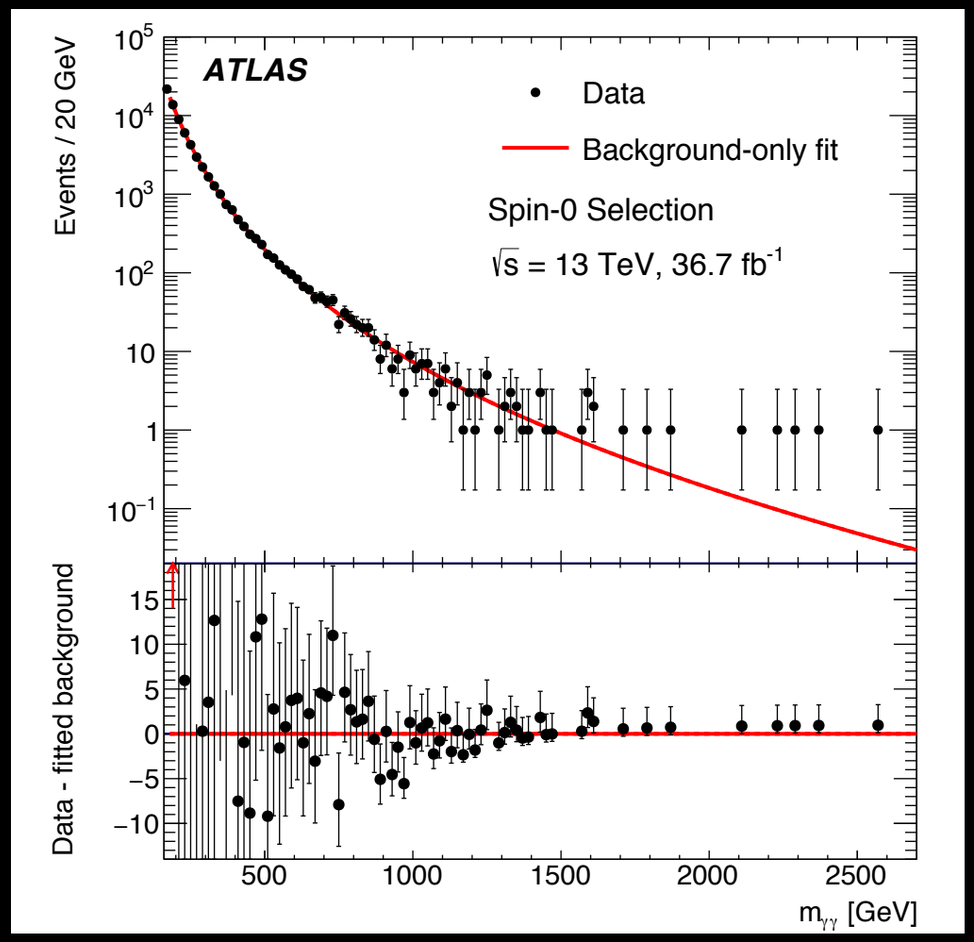
ATLAS: JHEP 10 (2017) 112

$Z \rightarrow ll$

Small branching ratio of h125 —> Zγ in SM, but can be enhanced in some scenarios with higher-mass scalars

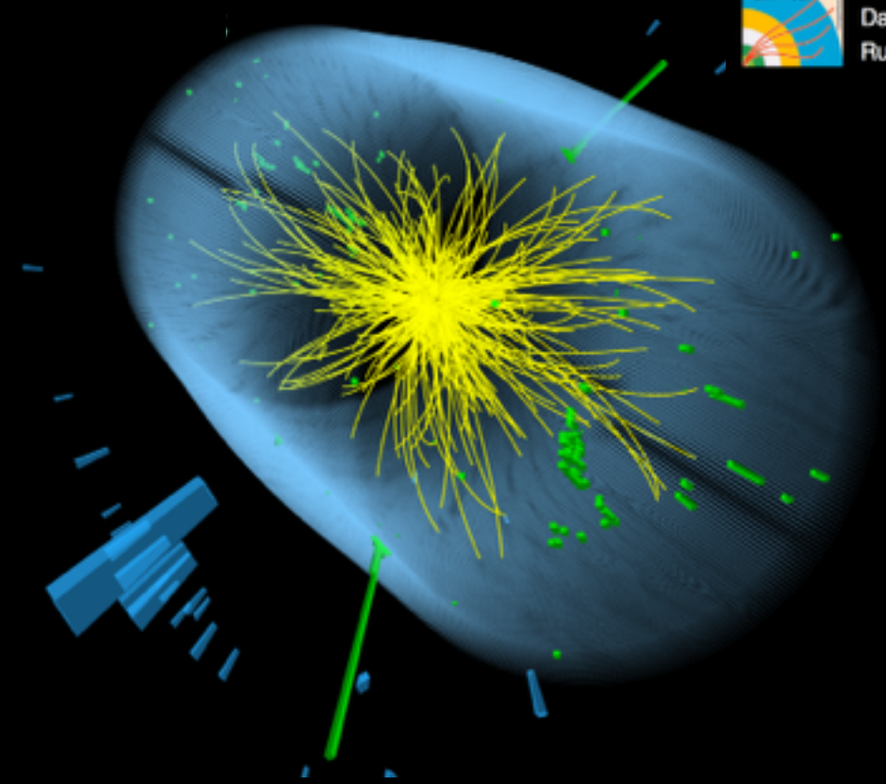


H —> γγ

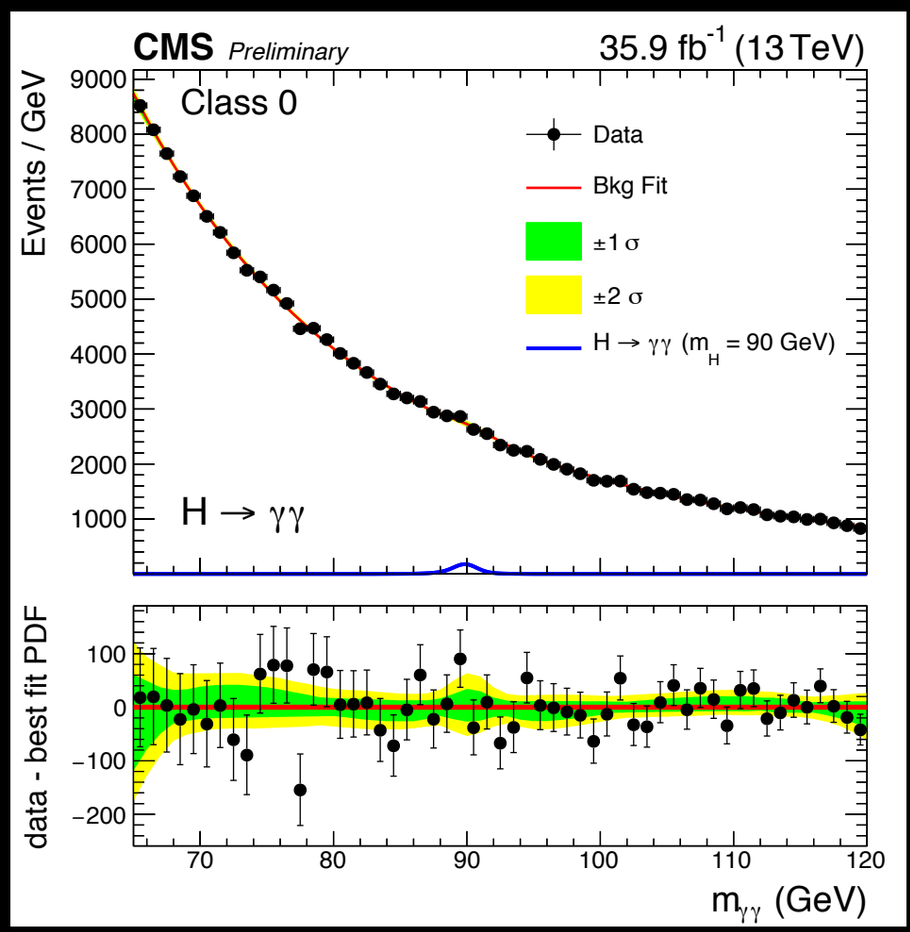


High mass
ATLAS: arXiv:1707.04147
CMS (8 & 13 TeV): PLB 767 (2017) 147

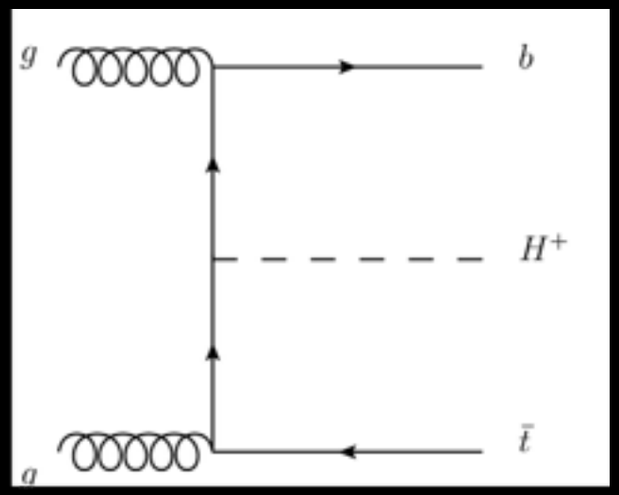
Low mass
ATLAS (8 TeV): PRL 113 171801
CMS (8 & 13 TeV): CMS-PAS-HIG-17-013



$m_{\gamma\gamma}$ = 750 GeV

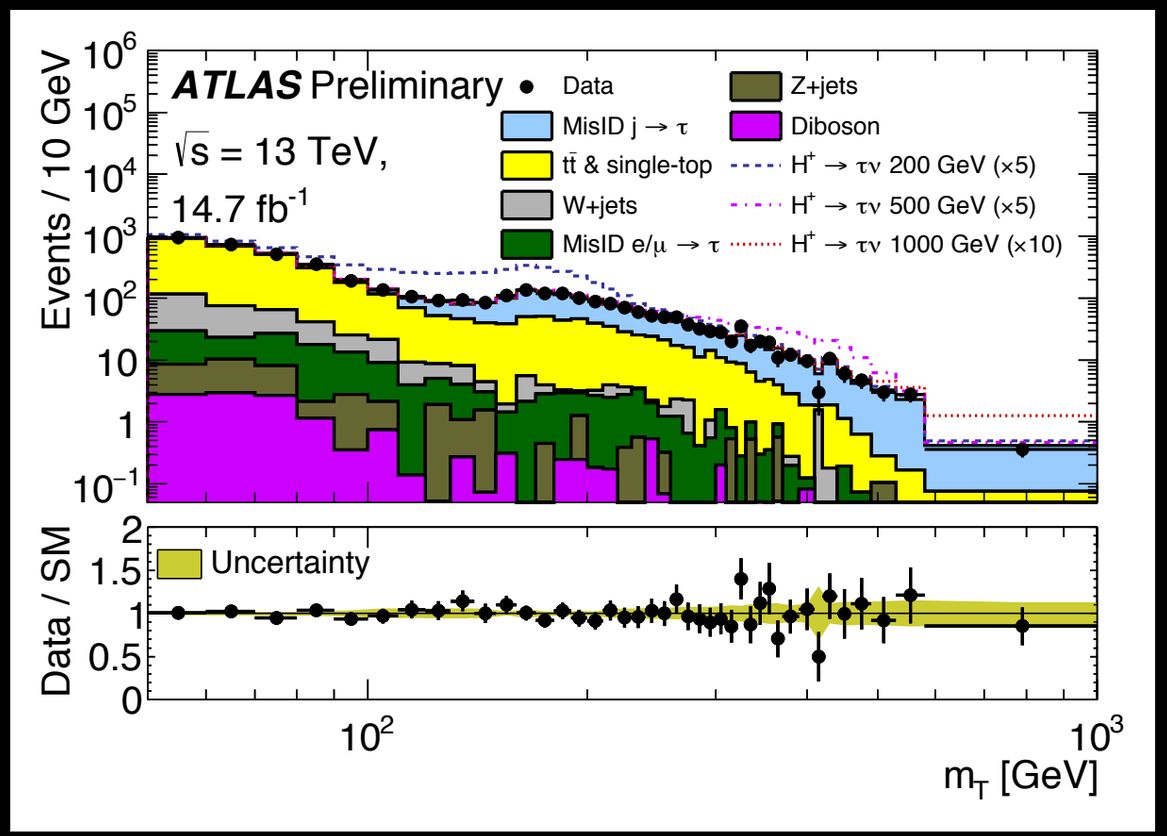


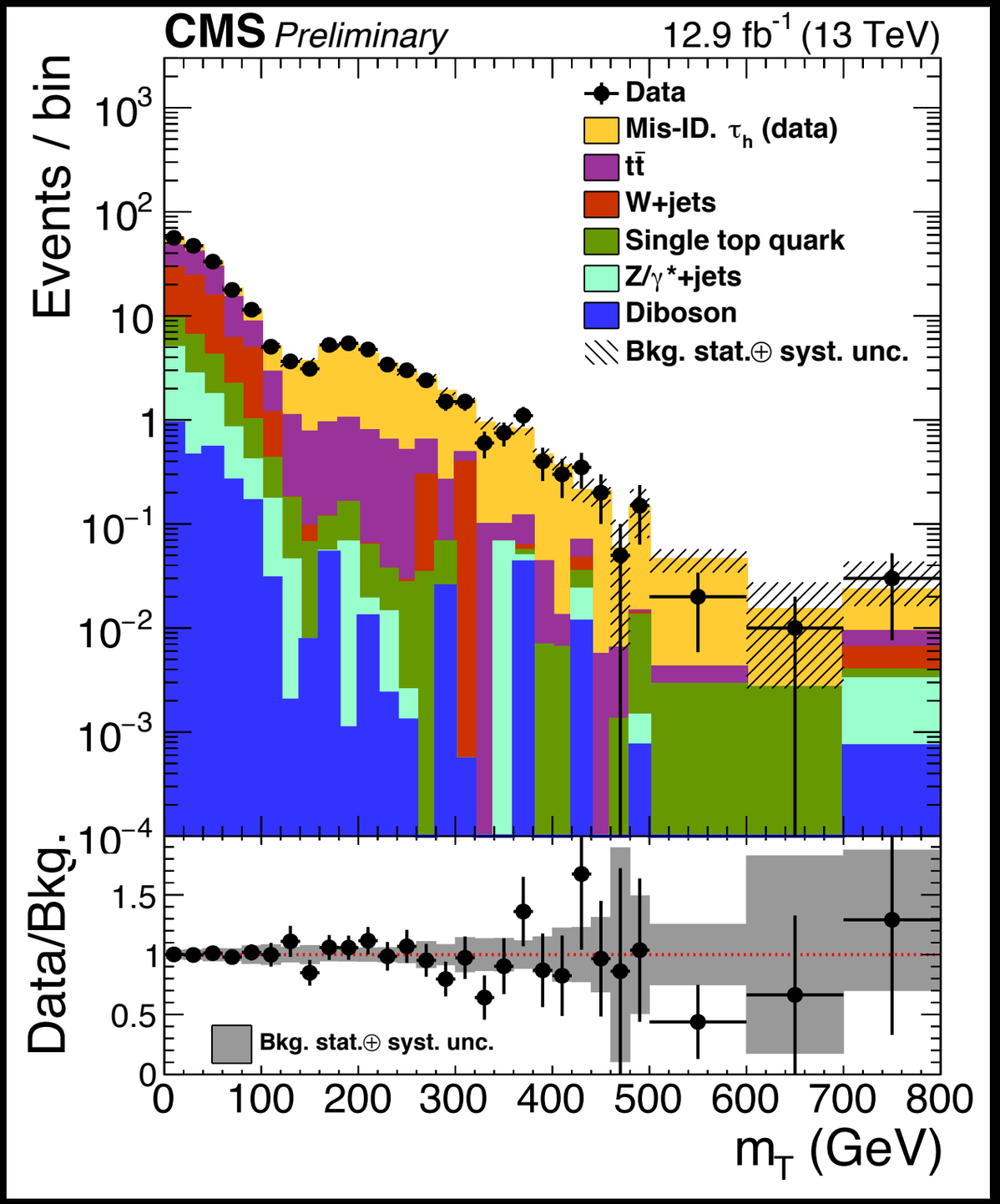
Charged Higgses with hadronic tau final states



$H^{+/-} \rightarrow \tau\nu$

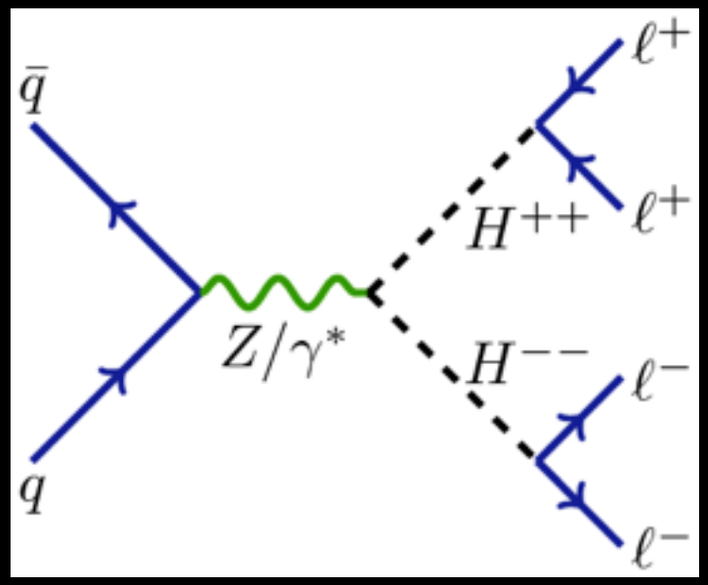
ATLAS-CONF-2016-088





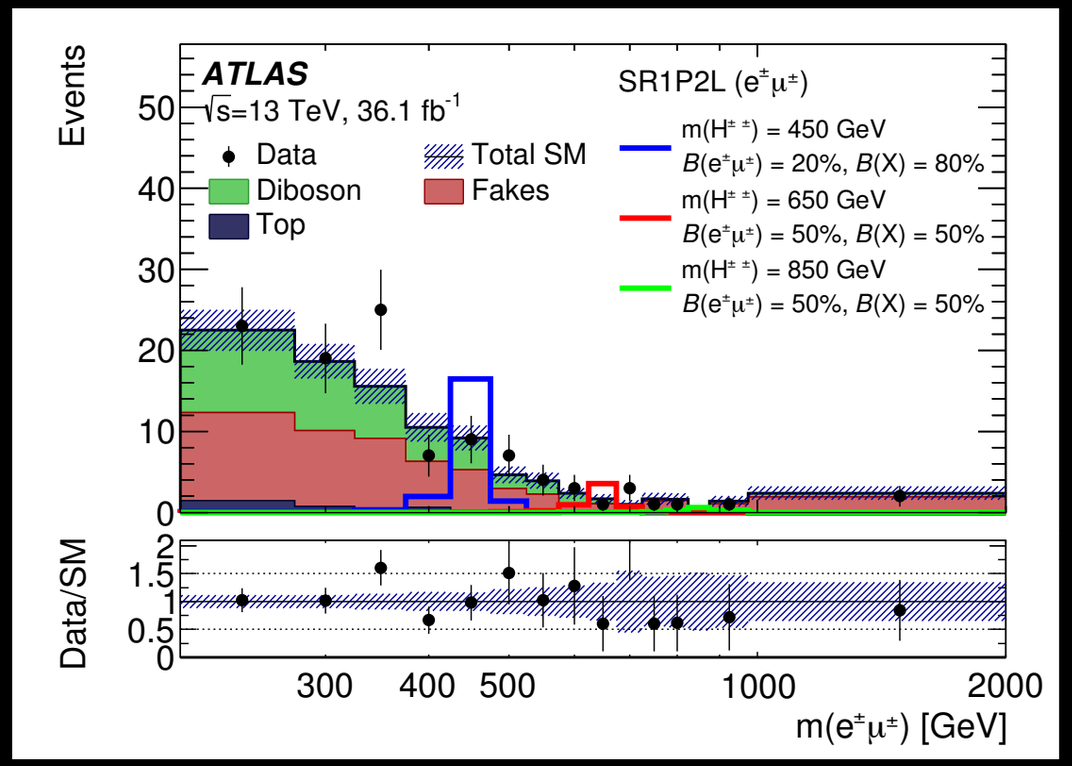
CMS-PAS-HIG-16-031

Charged Higgses to leptons



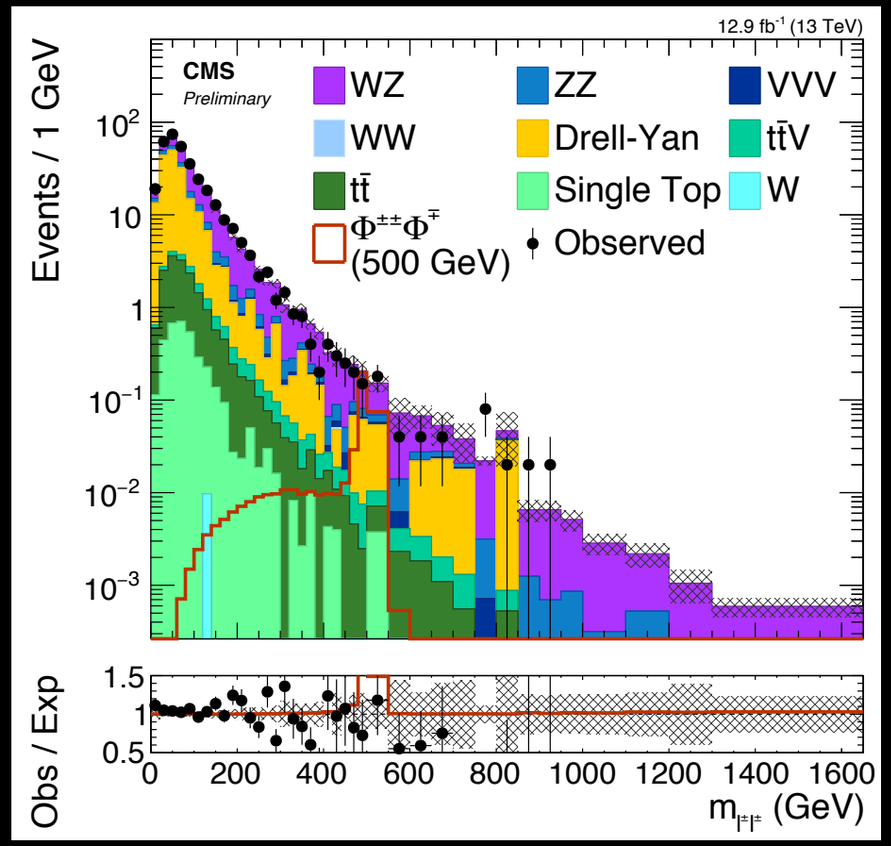
Doubly-charged Higgses can arise in, e.g., Higgs triplet models

ATLAS search for $H^{++/--}$ focusing on same-sign lepton pairs in 4-lepton events

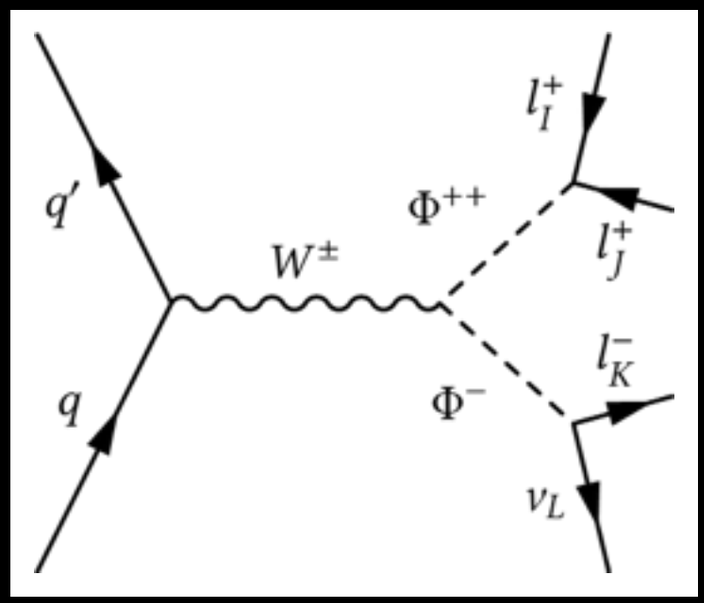


arXiv:1710.09748

CMS-PAS-HIG-16-036



CMS search for $H^{++/--}$ focusing on same-sign lepton pairs in 3-lepton events

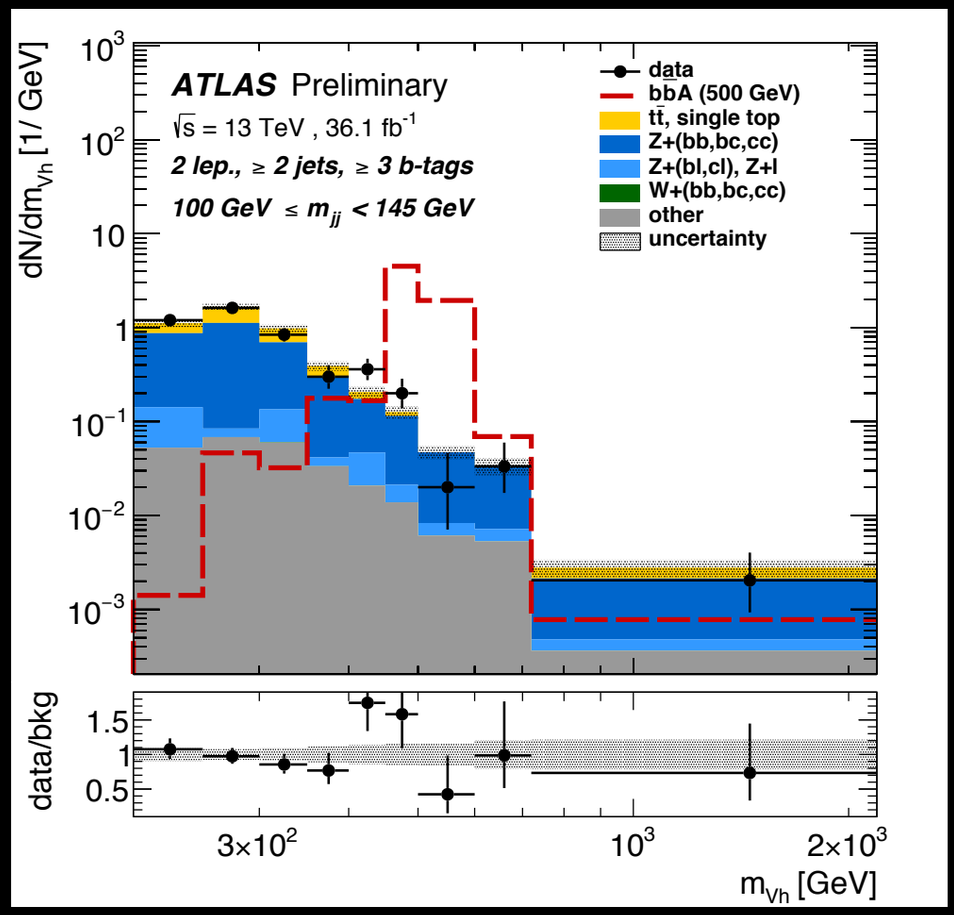


Vh resonances

$Z'/A \rightarrow Zh \rightarrow (ll/\nu\nu)bb$

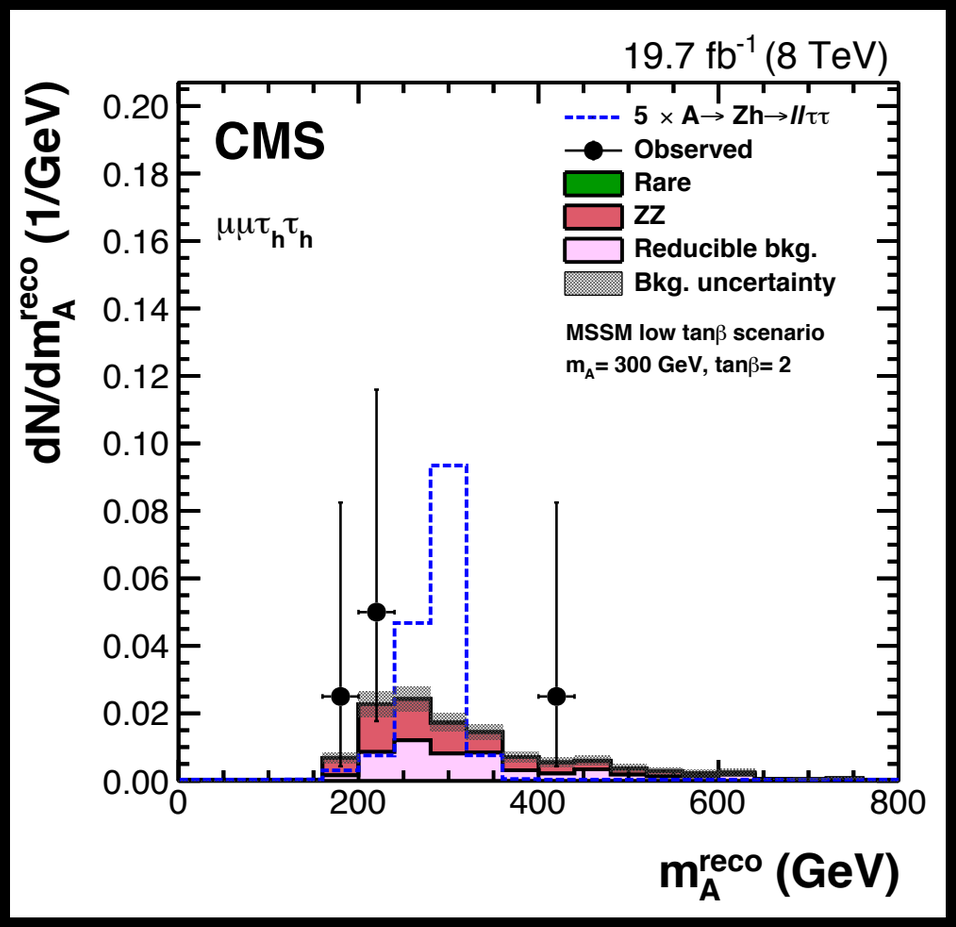
$W' \rightarrow Wh \rightarrow l\nu bb$

ATLAS search with 2015+2016 dataset at 13 TeV focusing on h125 —> bb



ATLAS-CONF-2017-055

CMS search at 8 TeV with h125 —> ττ



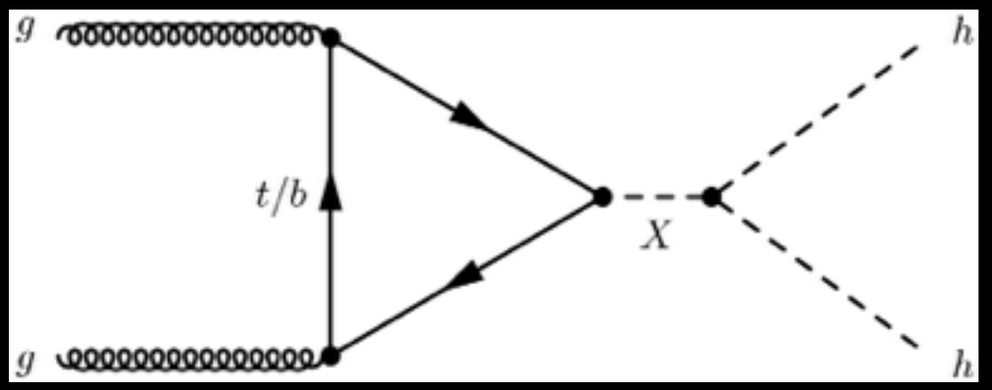
PLB 755 (2016) 217

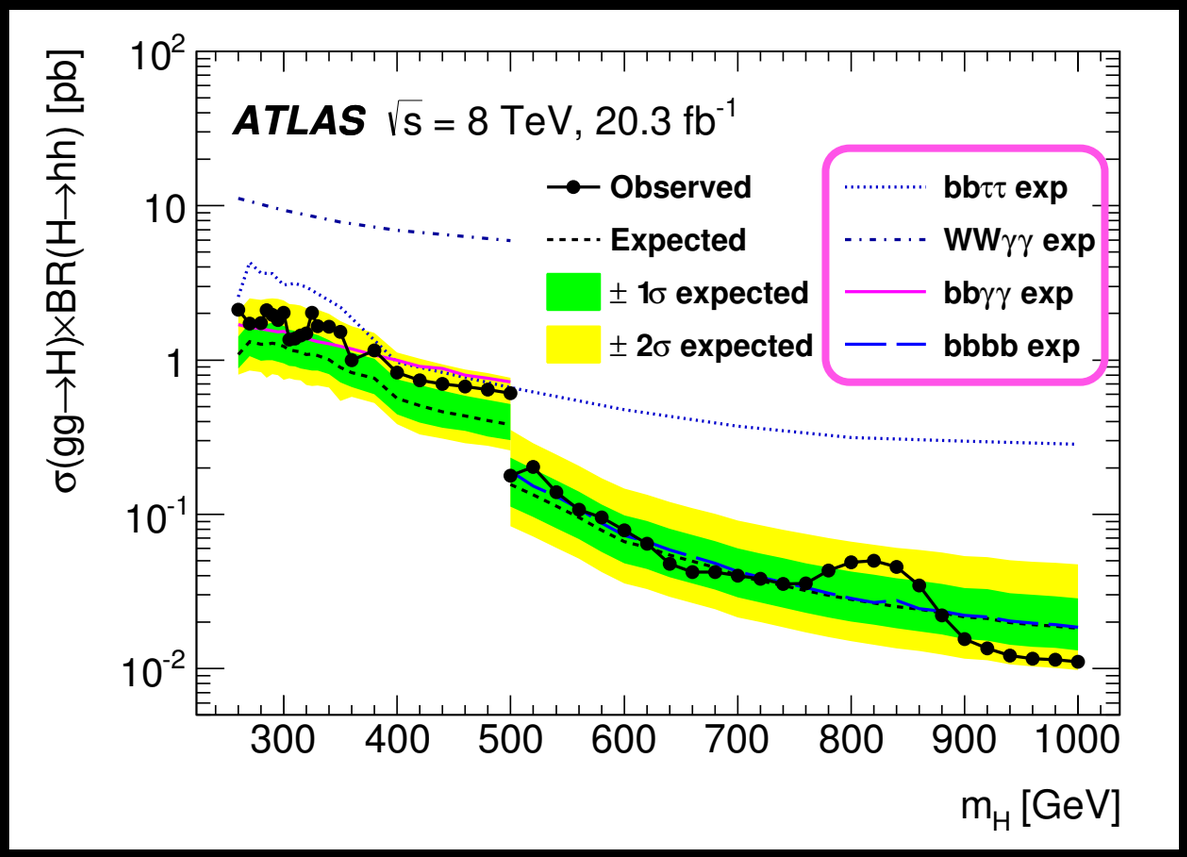
$A \rightarrow Zh \rightarrow ll\tau\tau$

Di-Higgs resonances

$X \rightarrow hh \rightarrow 4SM$

Di-Higgs production is extremely rare in the SM, but new particles can yield di-Higgs resonances

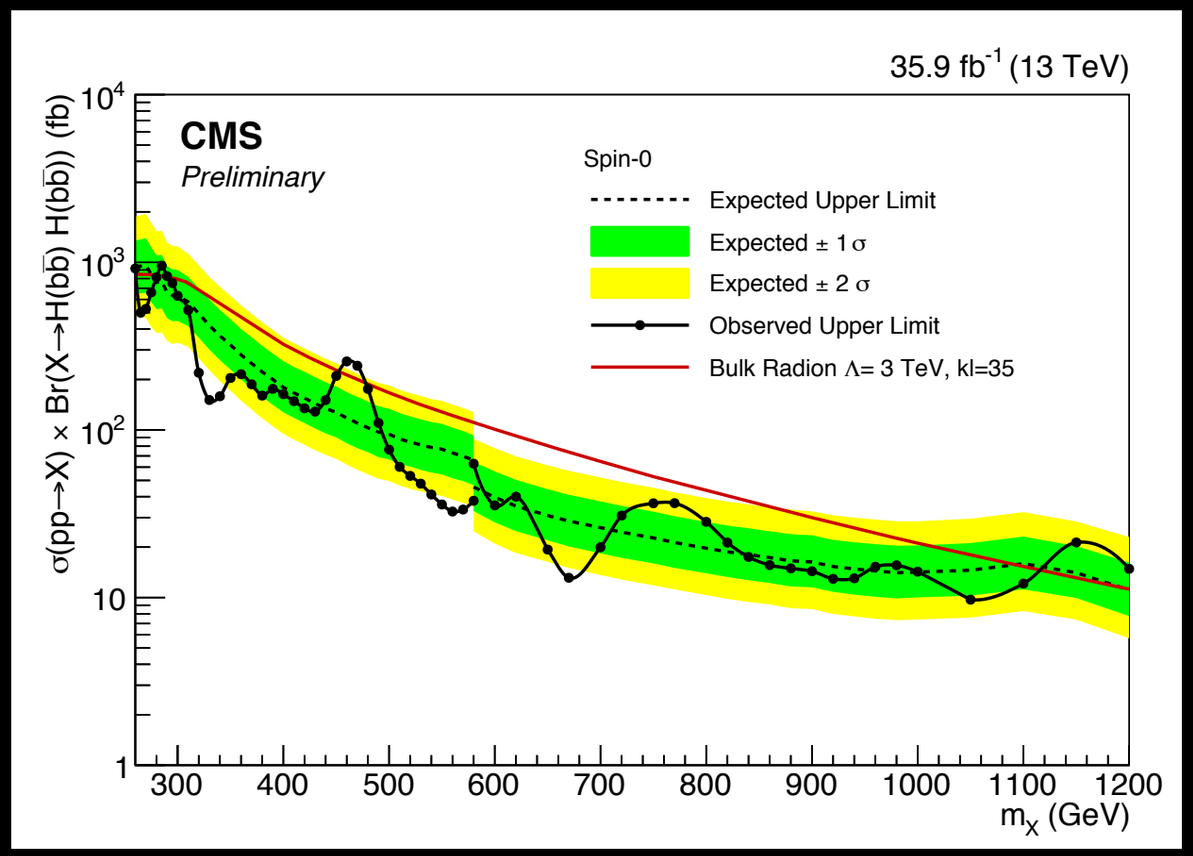




PRD 92, 092004 (2015)

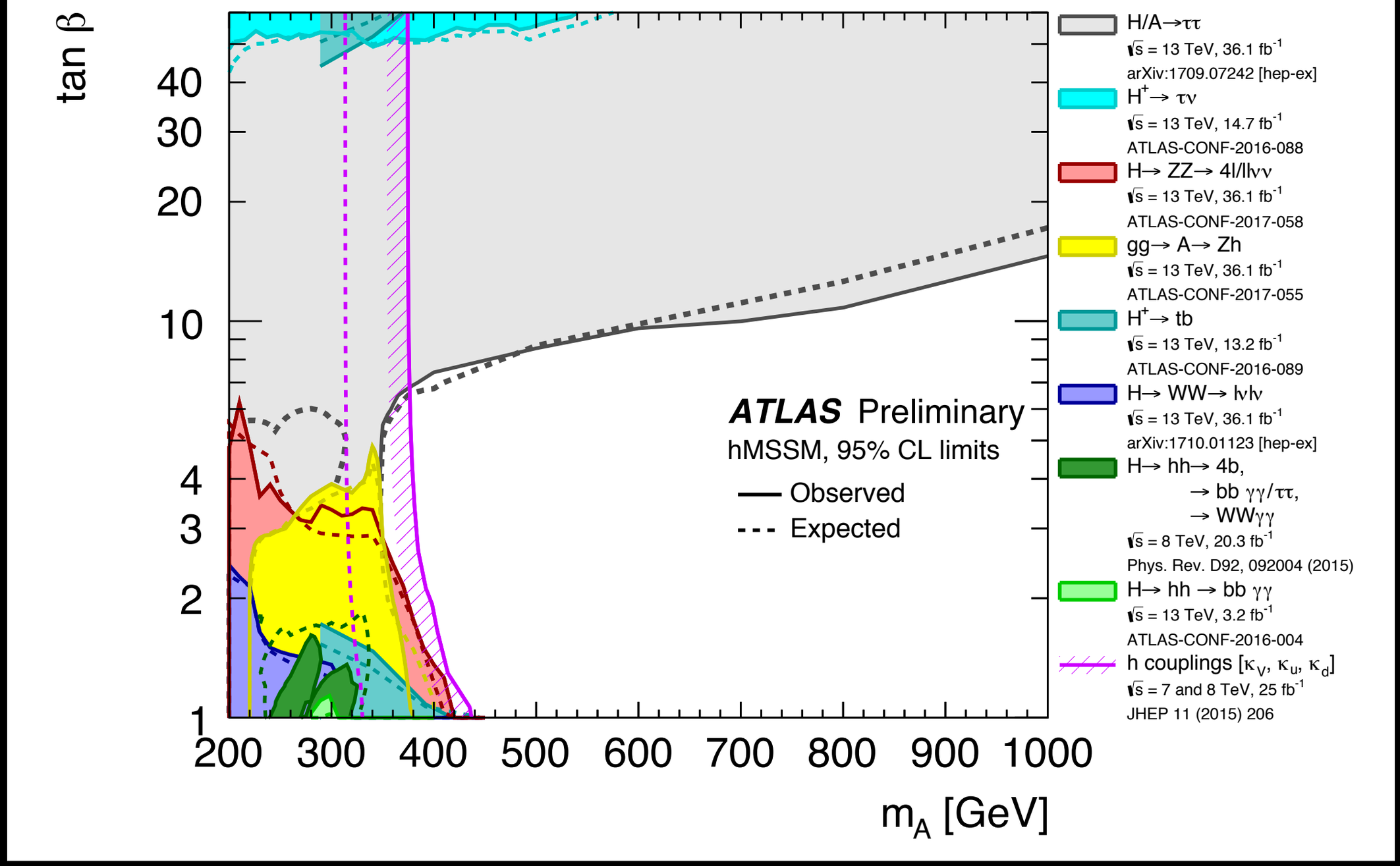
ATLAS combination of four channels at 8 TeV

CMS 4b channel with 2015+2016 13 TeV dataset



CMS-PAS-HIG-17-009

Comparing searches — e.g., in the hMSSM



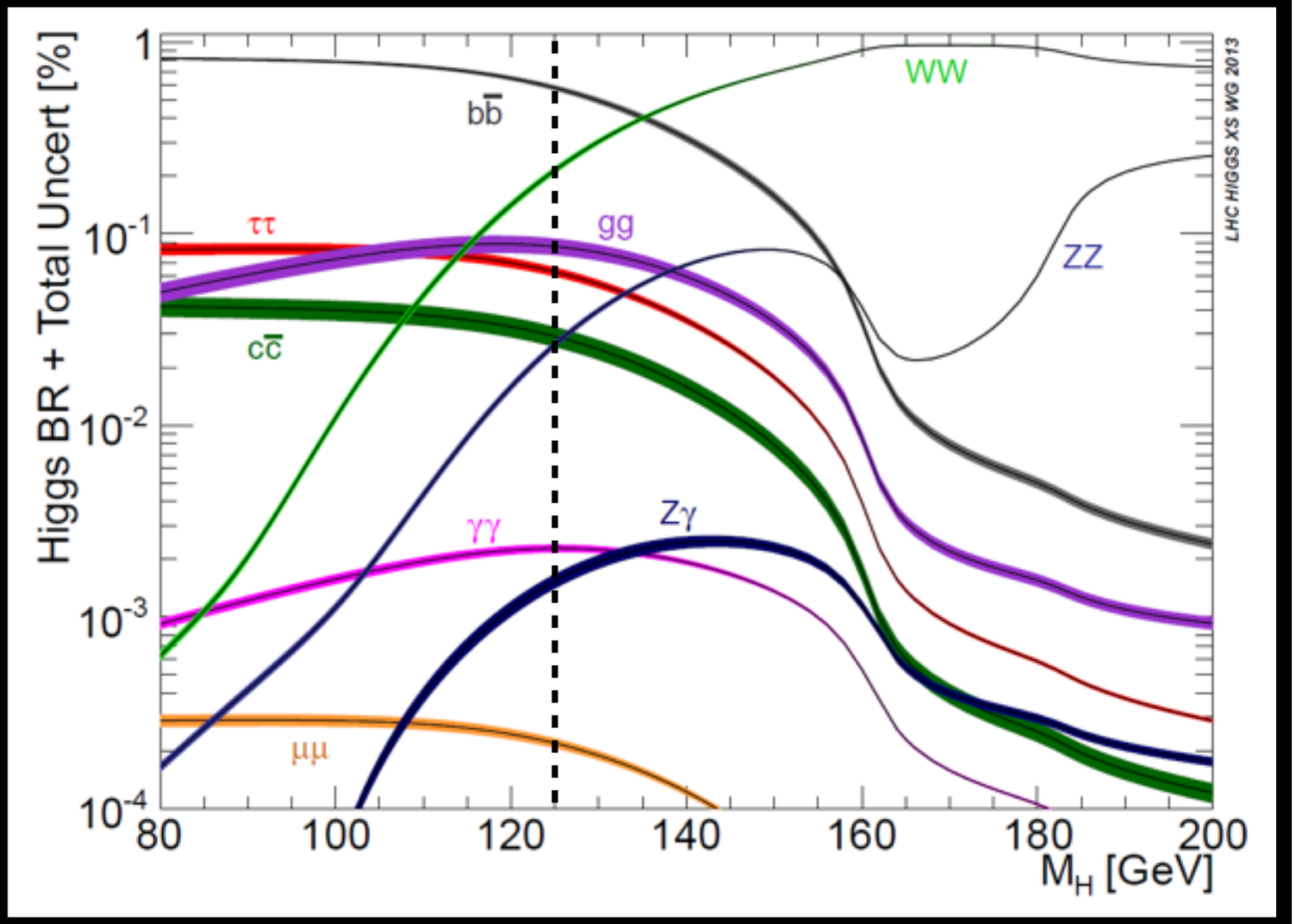
hMSSM

ATLAS Higgs summary plots

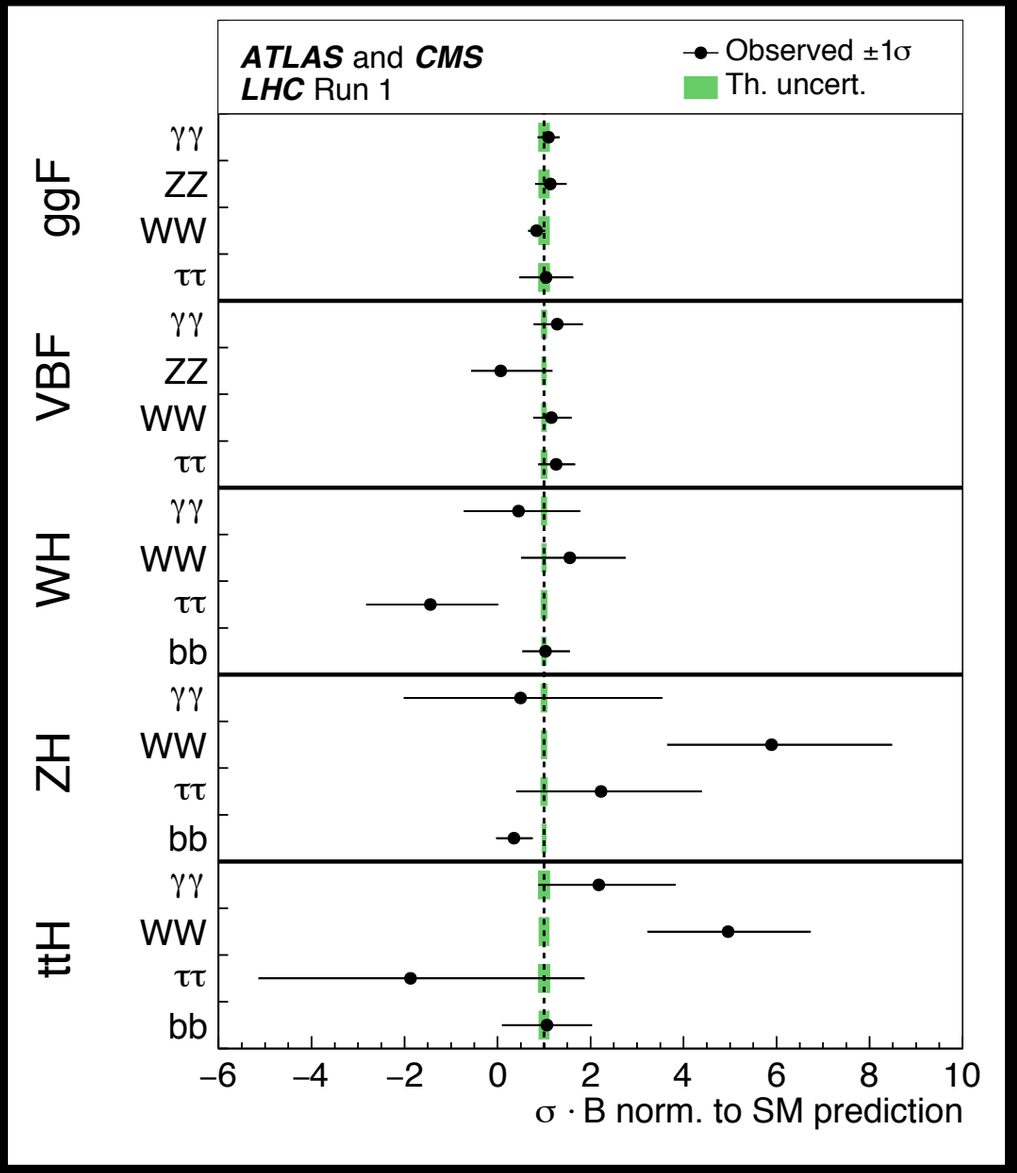
- MSSM framework constrained by h125 measurements

How standard is h125?

Plenty of room for new physics



How can we find evidence of this possible new physics?



JHEP08 (2016) 045

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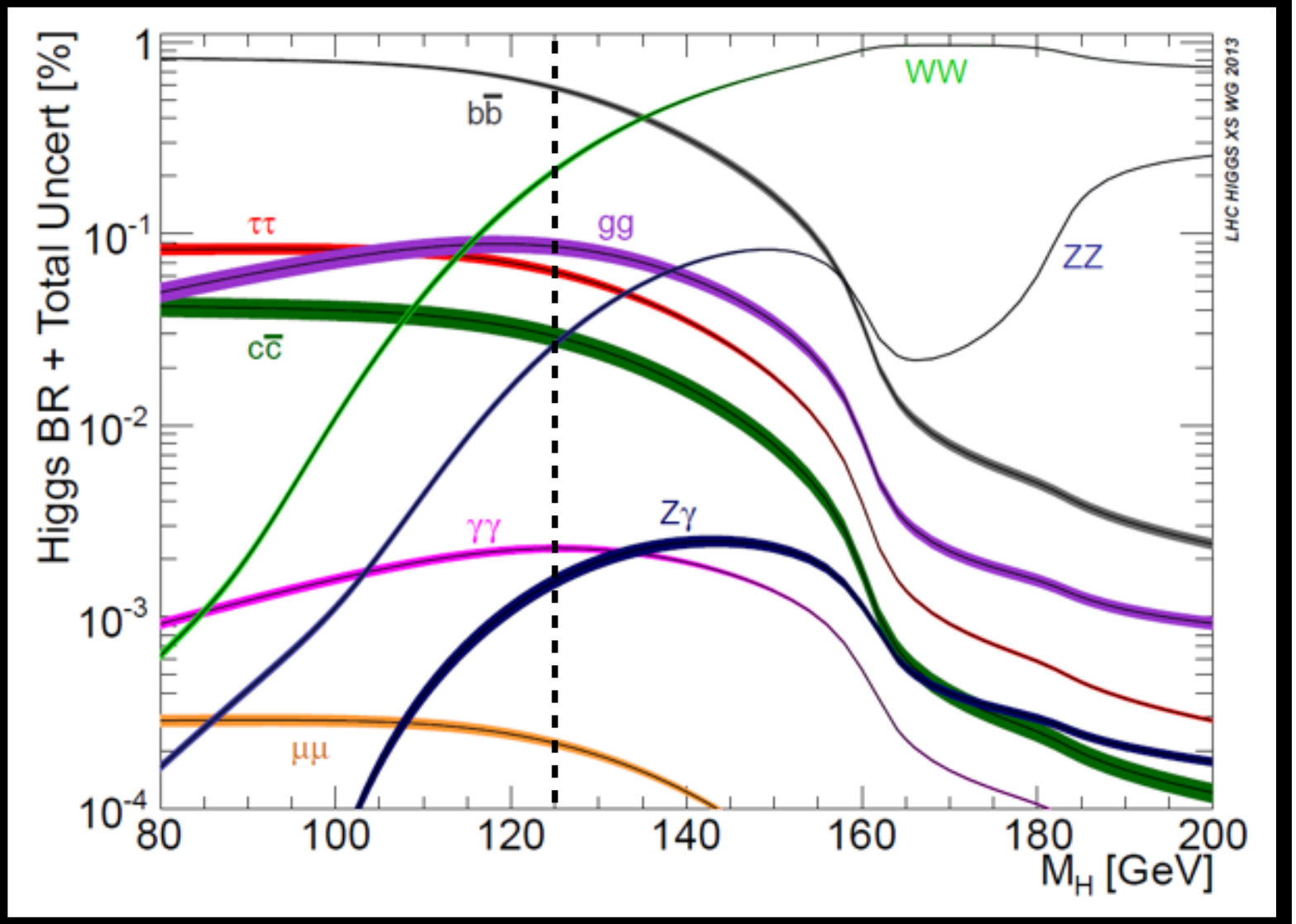

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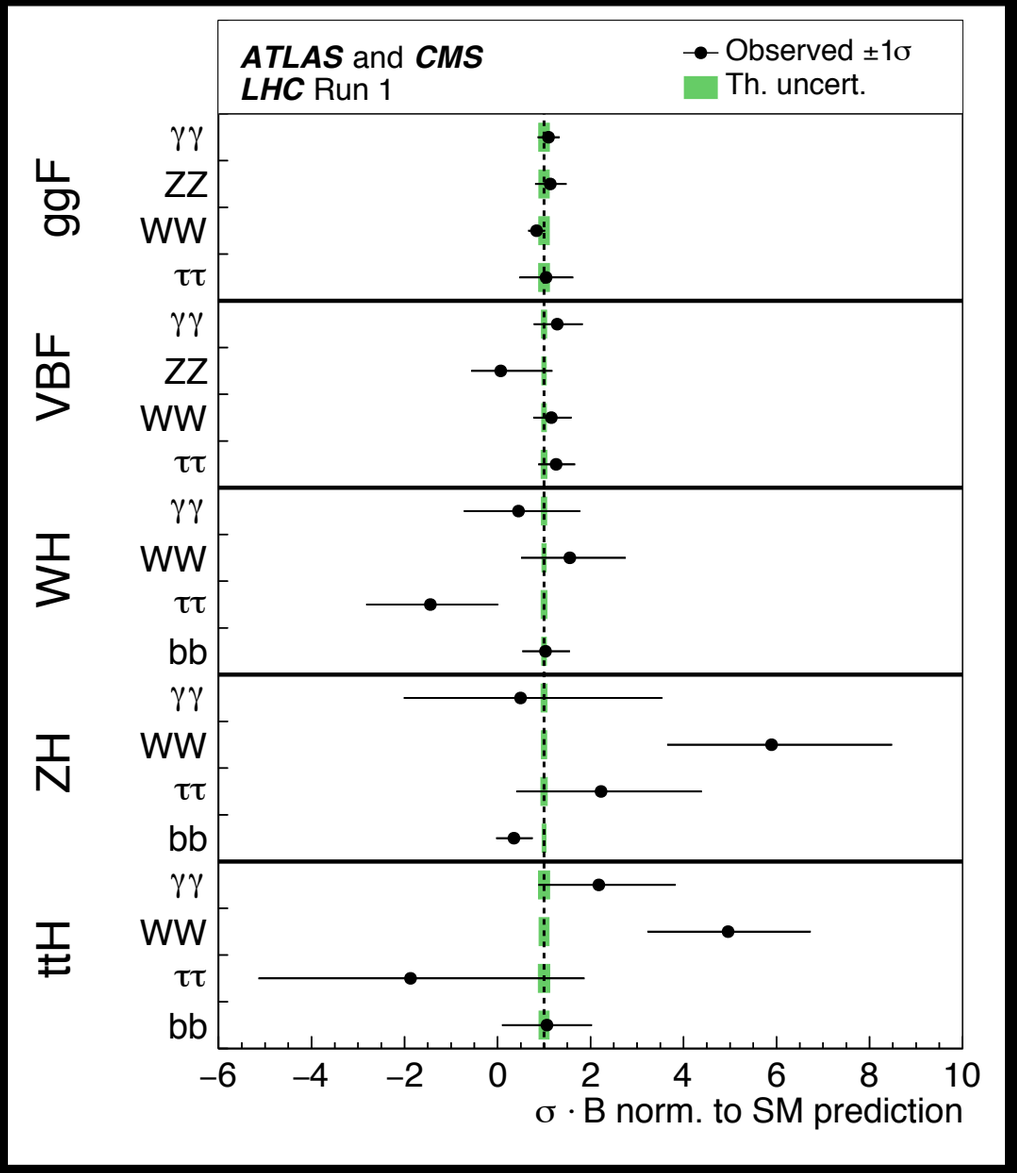
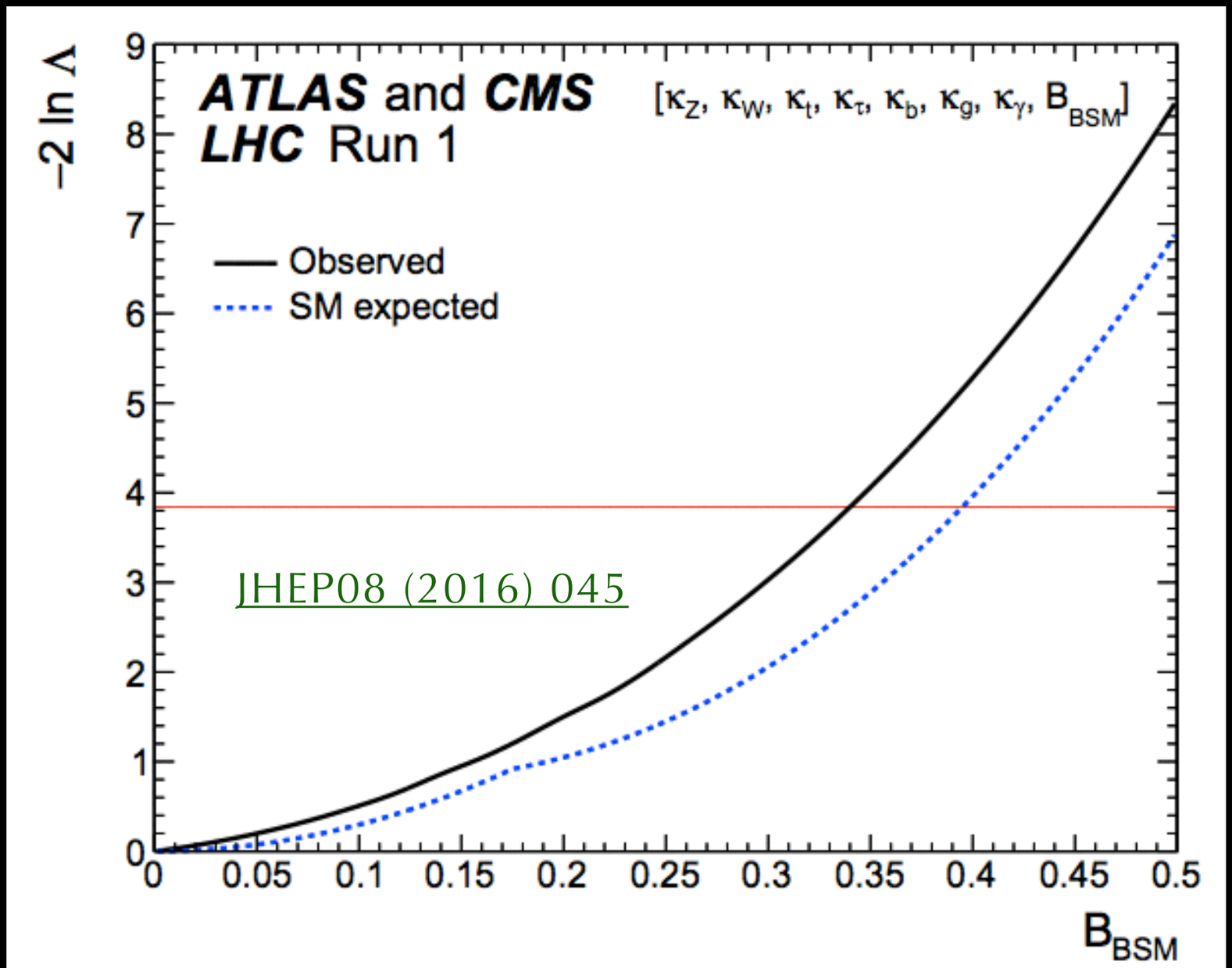


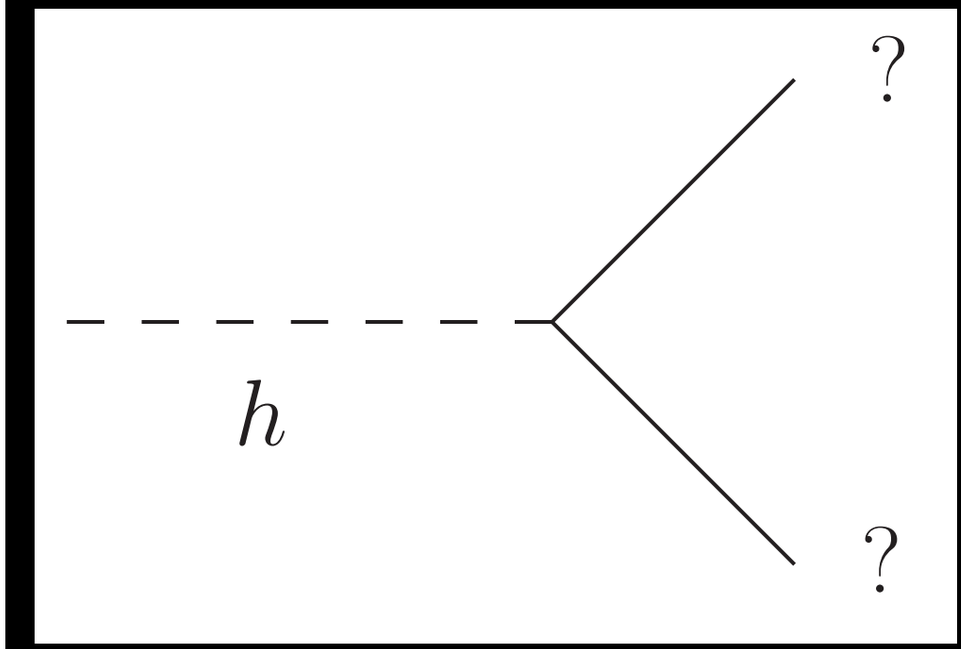
JHEP08 (2016) 045

One way: Wait for the HL-LHC to measure the couplings to ~5/10% and then wait for an e+e- Higgs factory to measure them to <1% by the 2040s or beyond.

How standard is h125?

Another way: Make some basic BSM assumptions and look directly for a new particle that can take up a non-negligible fraction of the total Higgs width

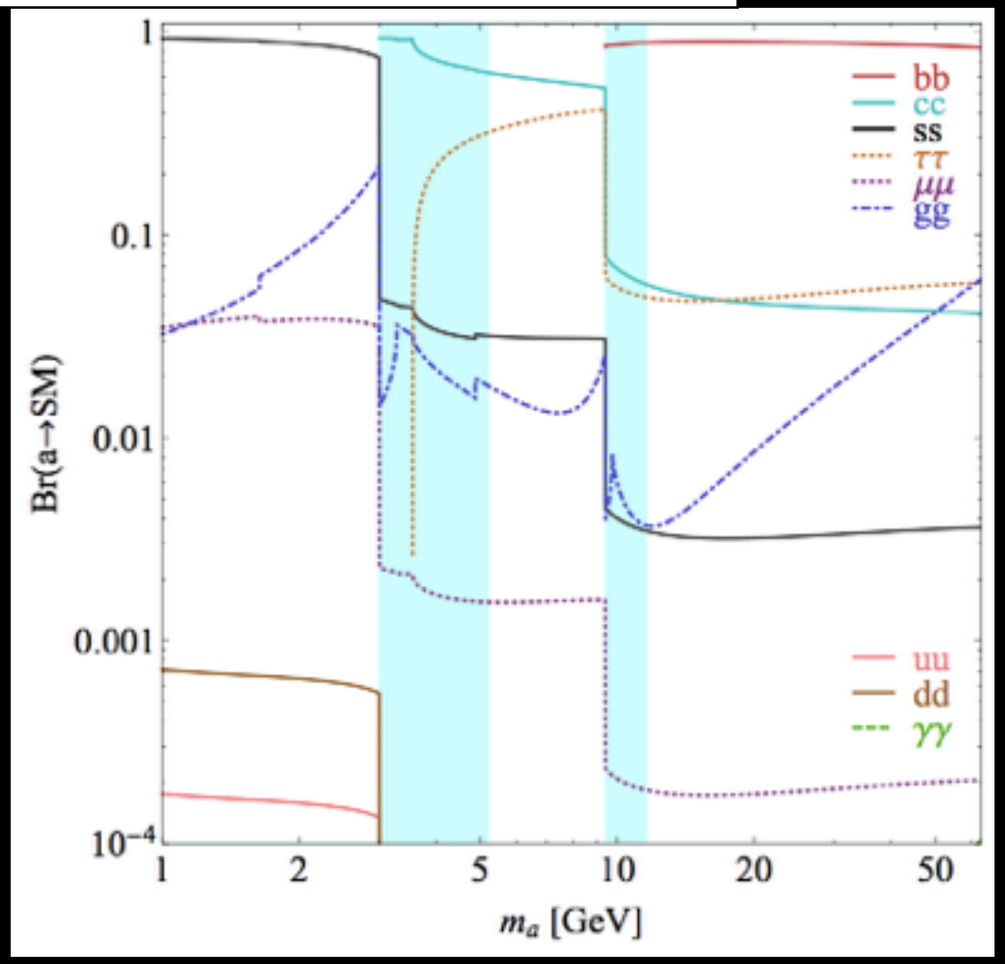




Non-standard decays of h125

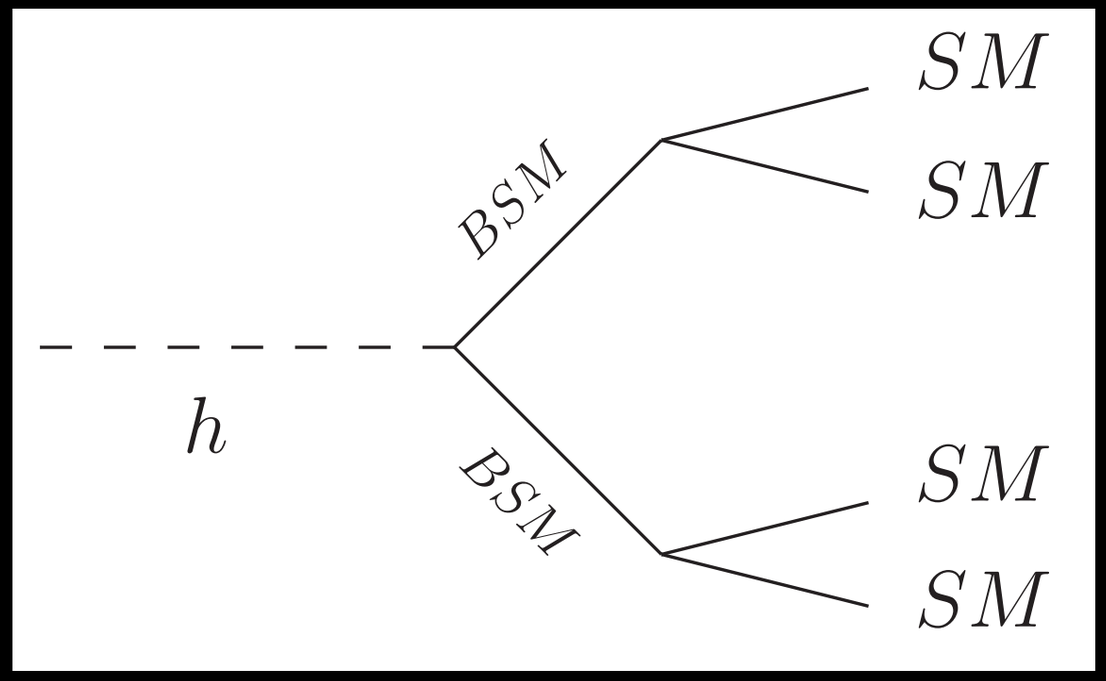
Basic BSM assumptions: Extensions to the SM gauge group that include new light (pseudo)scalars or vectors (Z_{dark}, dark photons) that couple (in some way) to both the Higgs and SM particles

Exotic Decays of the 125 GeV Higgs Boson
arXiv:1312.4992



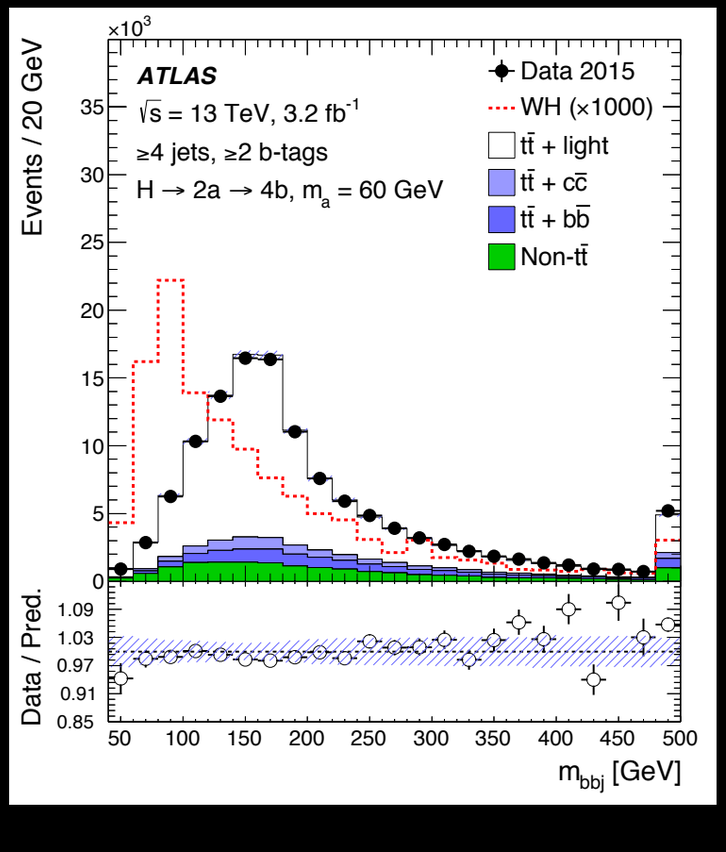
Example:
2HDM+S with
Type 1 Yukawa couplings

Yields a rich set of resonant decay topologies that can be actively searched for!



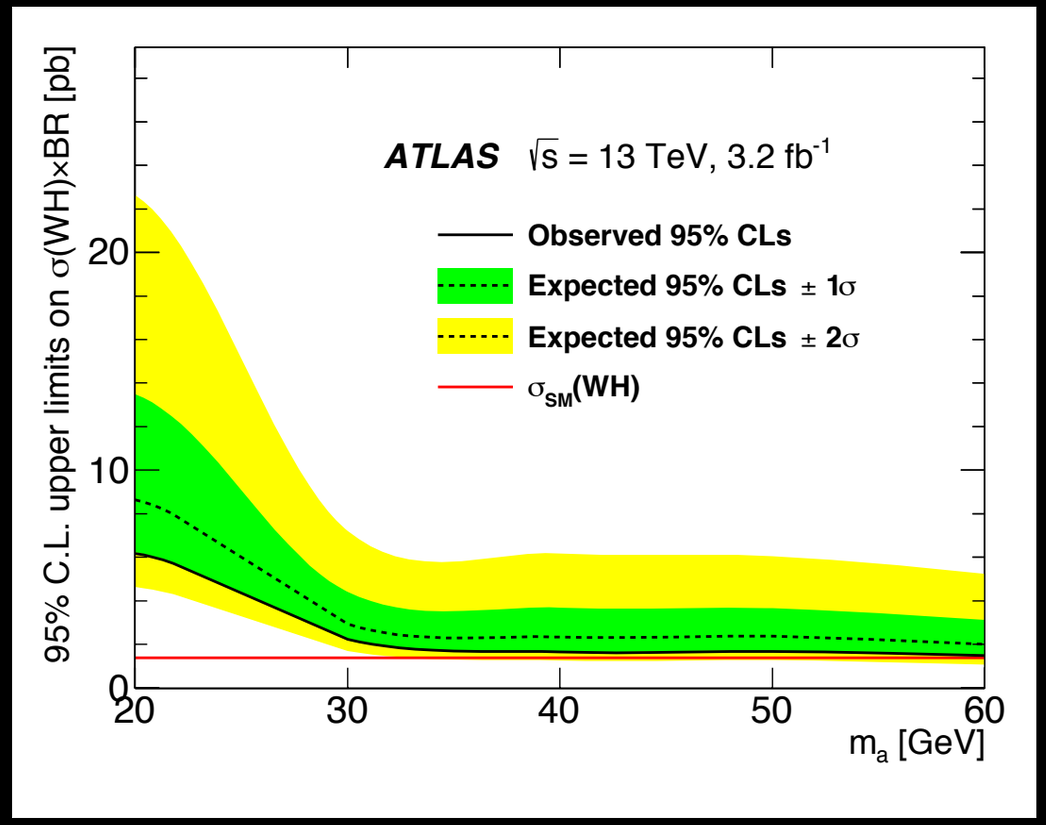
Another example: Models with dark Higgses that mix with h125 and decay to Z_{dark} / dark photons

(W)h125 —> aa —> 4b



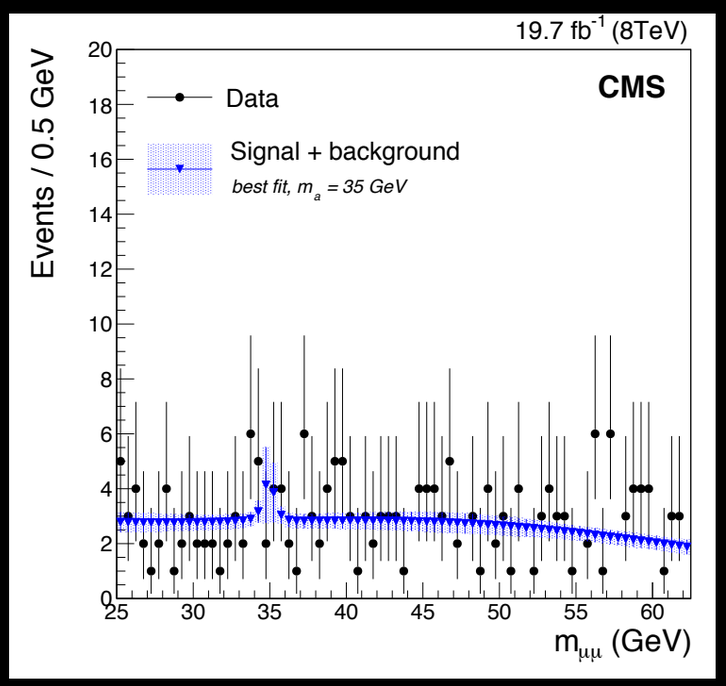
ATLAS search for very challenging signature

Even with only 3.2/fb at 13 TeV start to approach SM WH x-sec



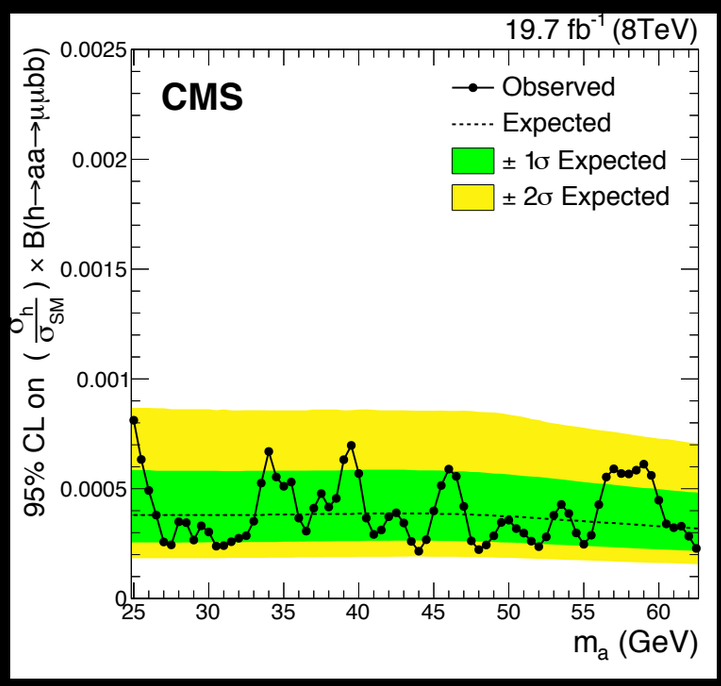
EPJC 76 (2016) 605

aa —> bbμ⁺μ⁻

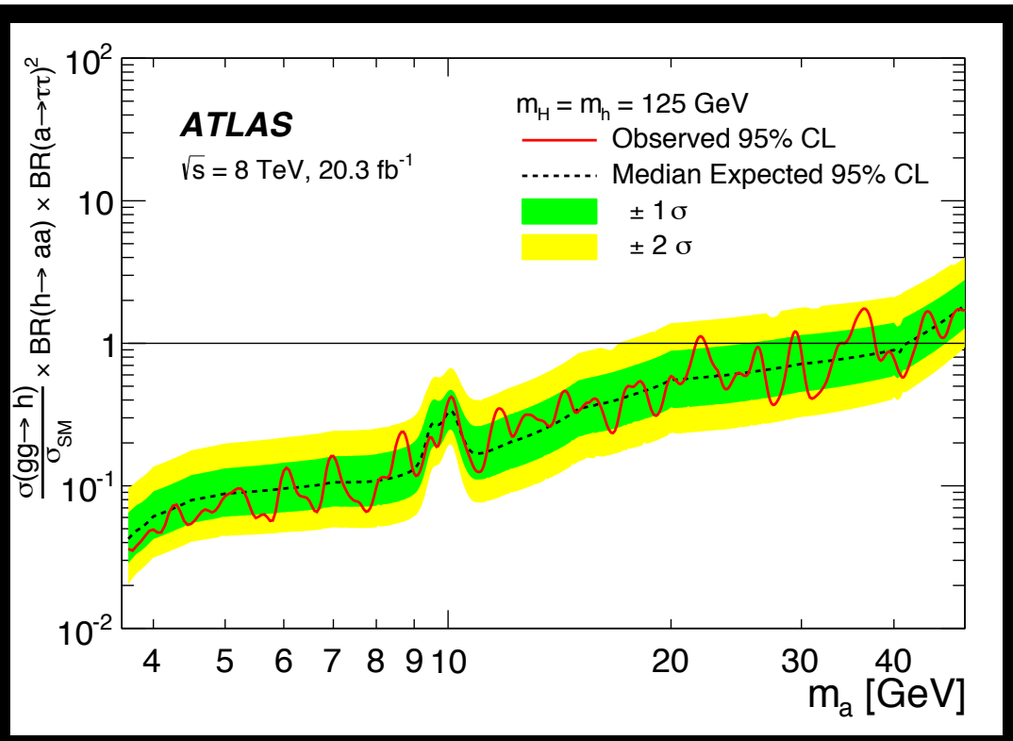


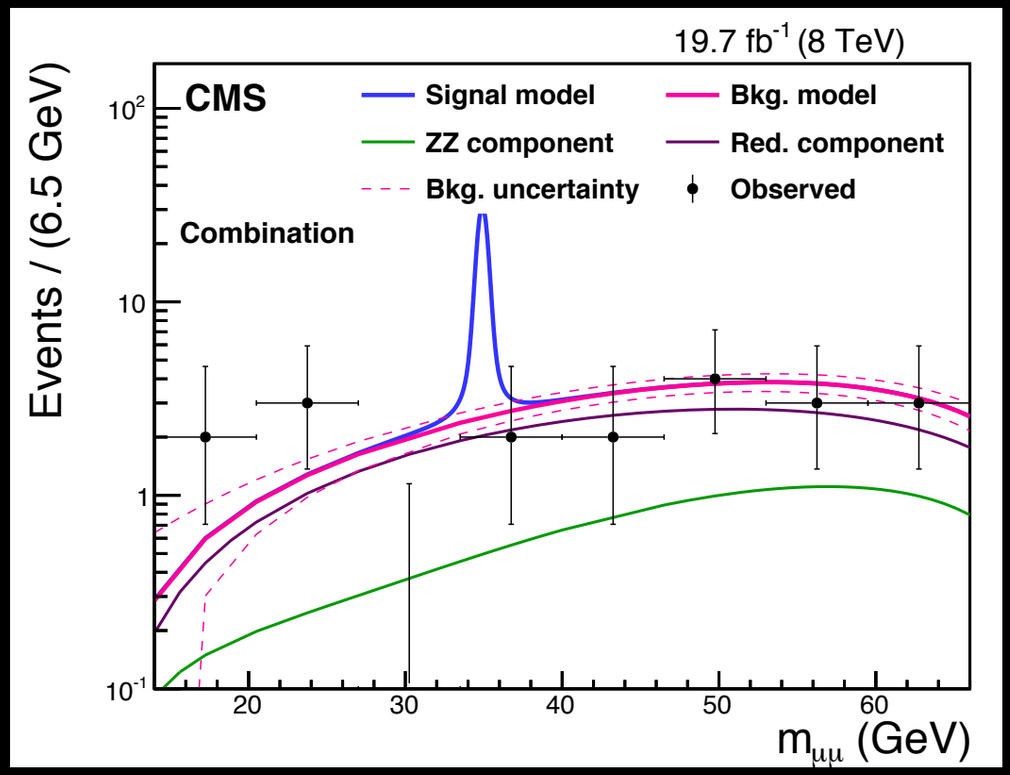
CMS search at 8 TeV

JHEP 10 (2017) 076



$h125 \to aa \to \mu^+\mu^-\tau^+\tau^-$

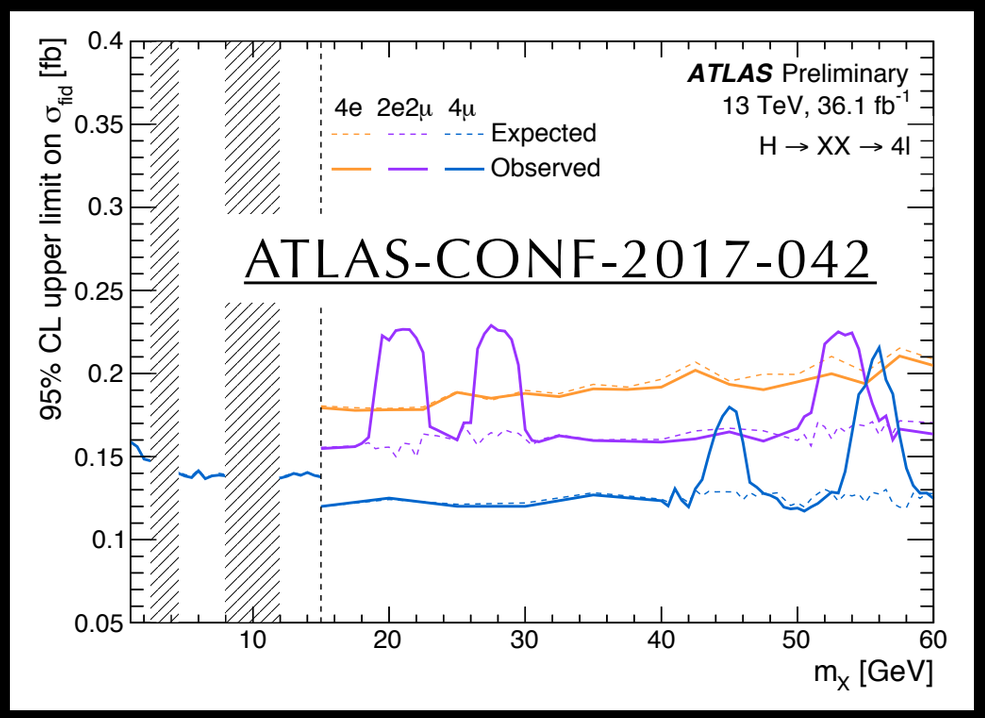




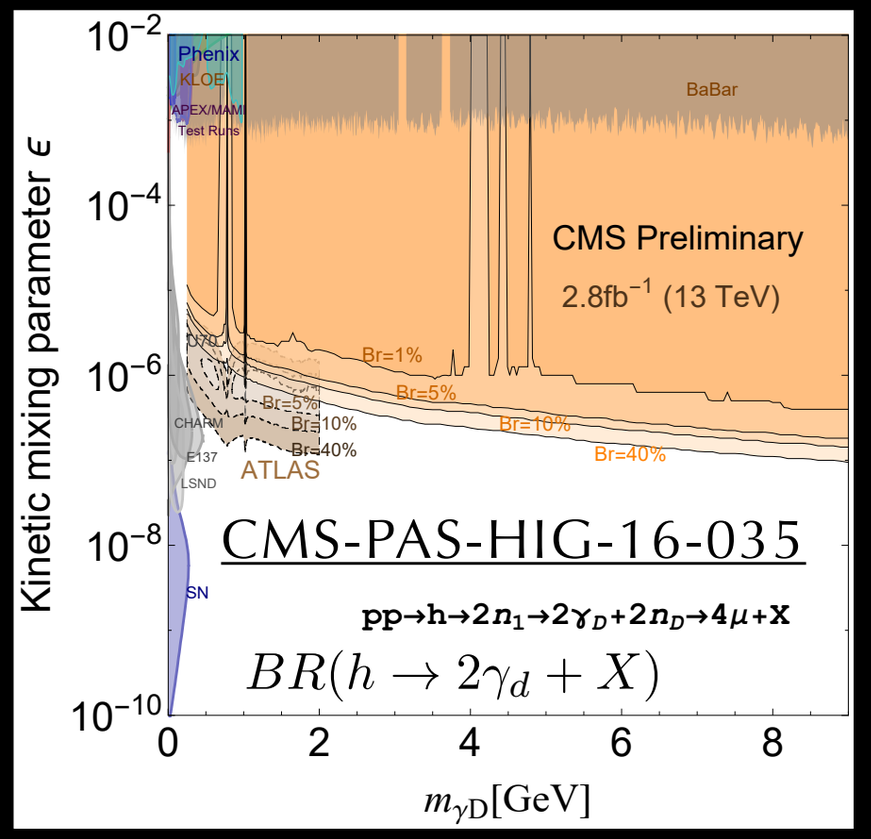
JHEP 10 (2017) 076

PRD 92 (2015) 052002

$h125 \to xx \to 4l$



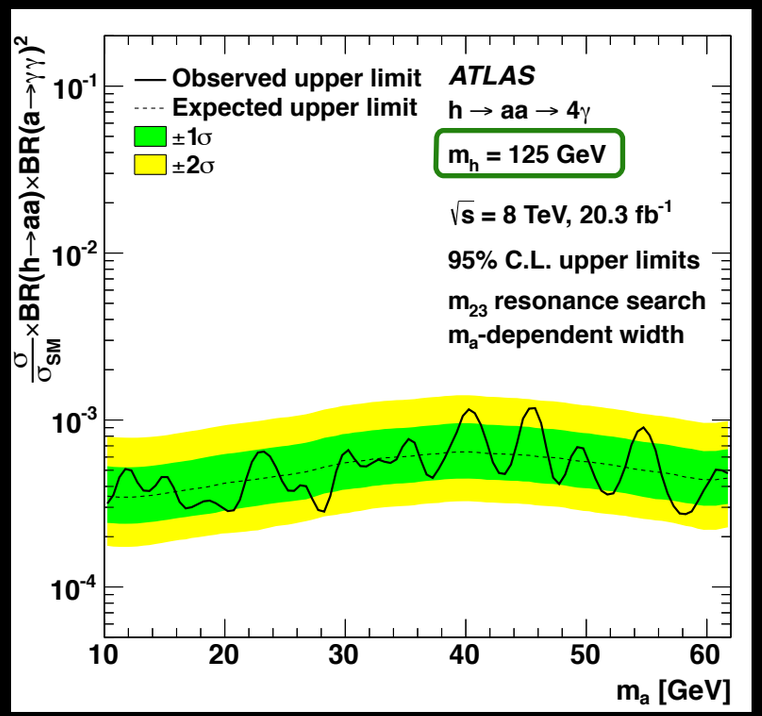
x can be vector
(Z_{dark}, dark photon)
or (pseudo)scalar

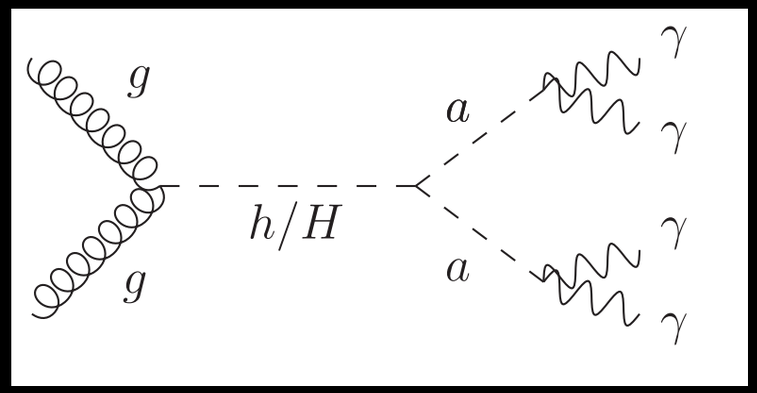


H/h125 —> aa —> 4γ

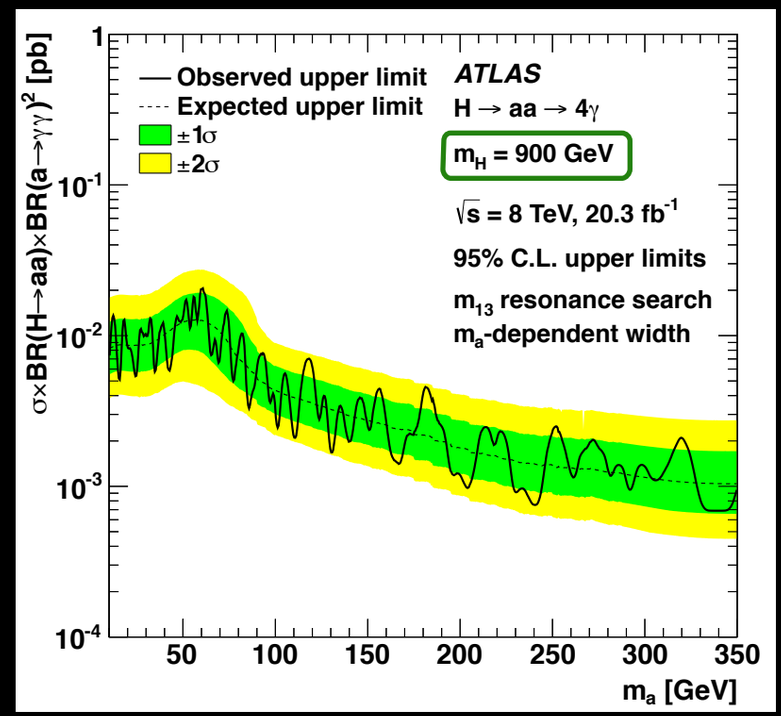
General search for new phenomena in inclusive three-photon events at 8 TeV with ATLAS

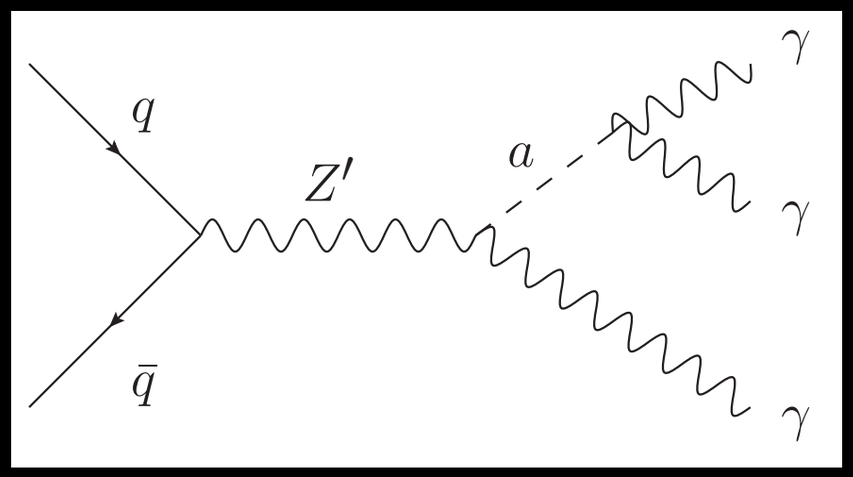
EPJC 76 (2016) 4, 210

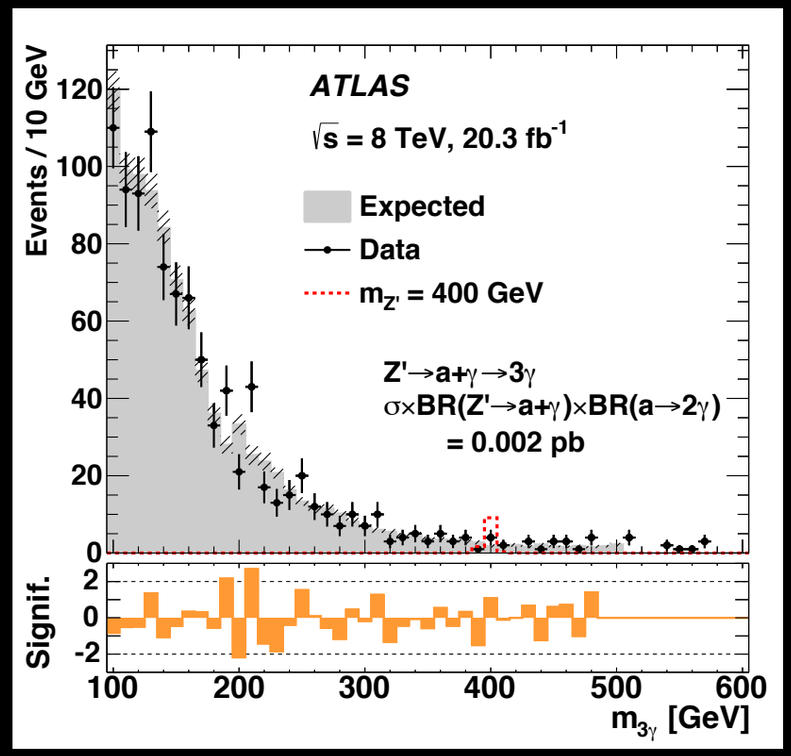




H/h125 —> 4γ one of the main benchmarks

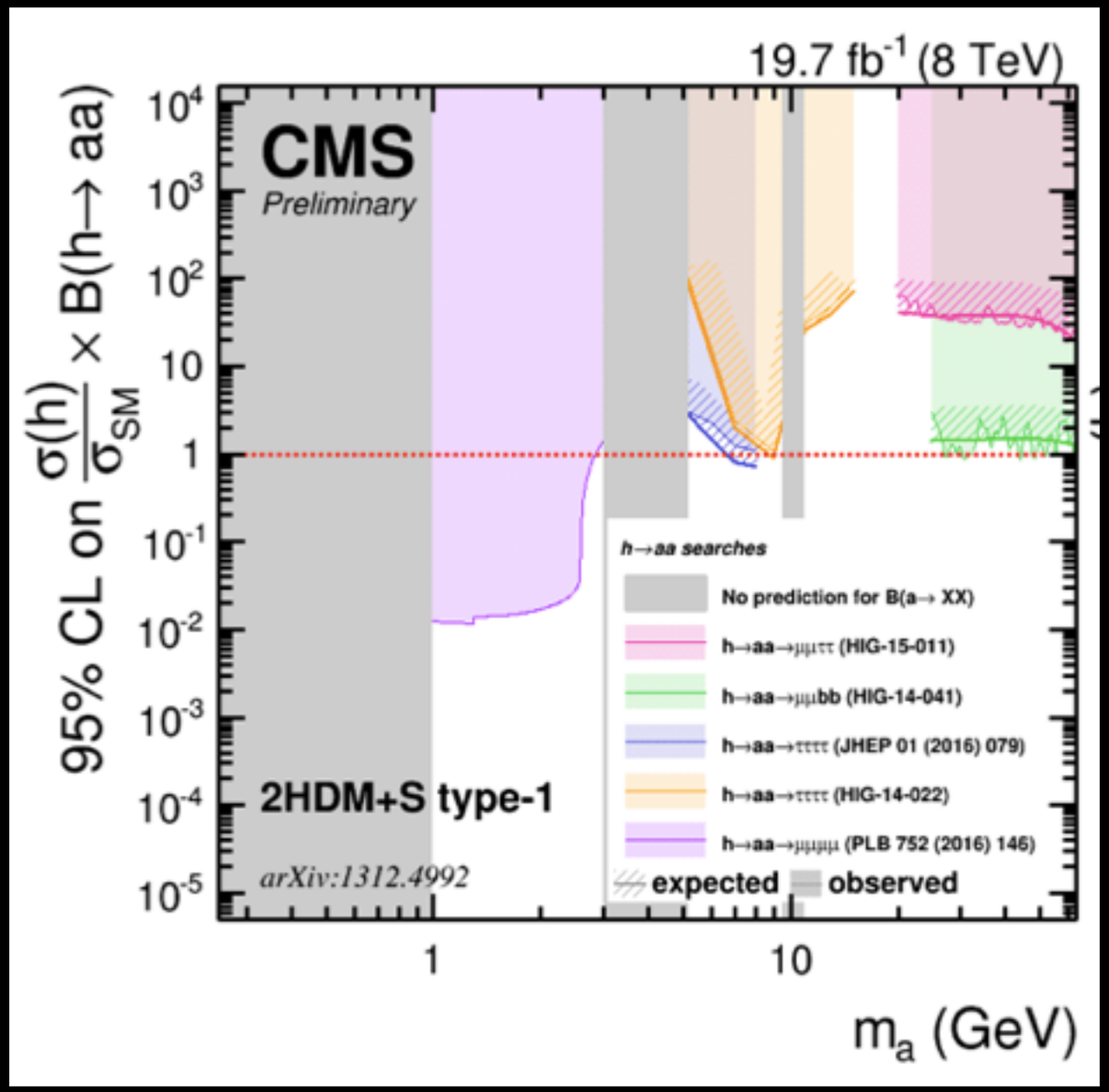






Also sensitive to resonant three-photon final state with an intermediate BSM pseudoscalar

Comparing searches for non-standard decays of h125

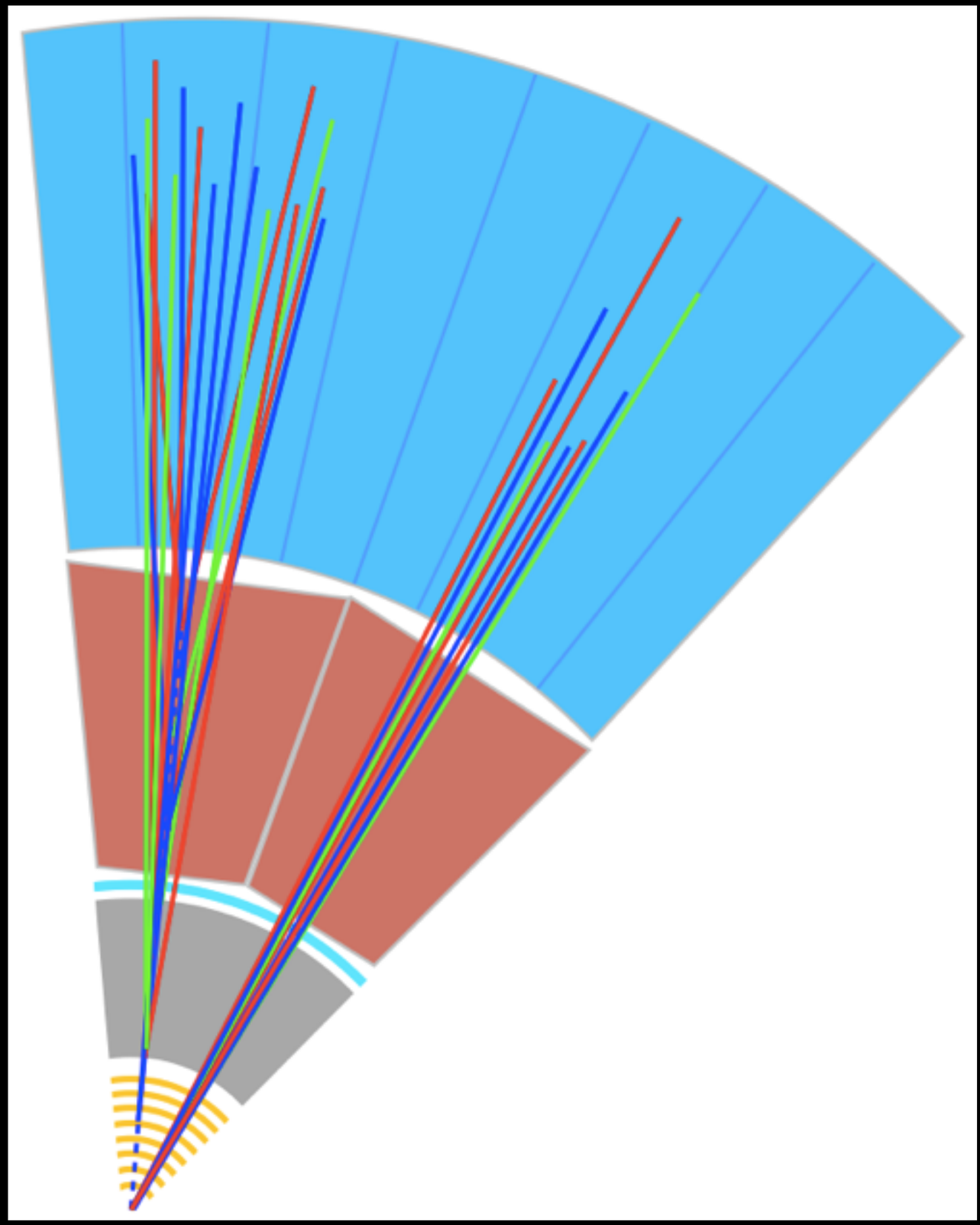


Improvements and expansions in the pipeline:

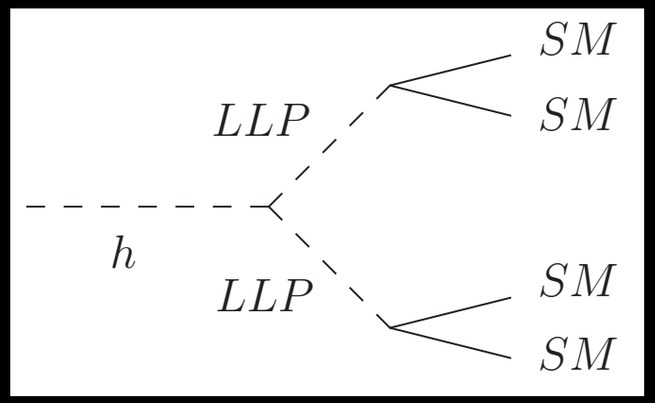
- Challenging low-m_a regime for many final states
- Other channel combinations
- Expansion to higher-mass parent scalars

CMS 2HDM+S summaries

What are we overlooking?



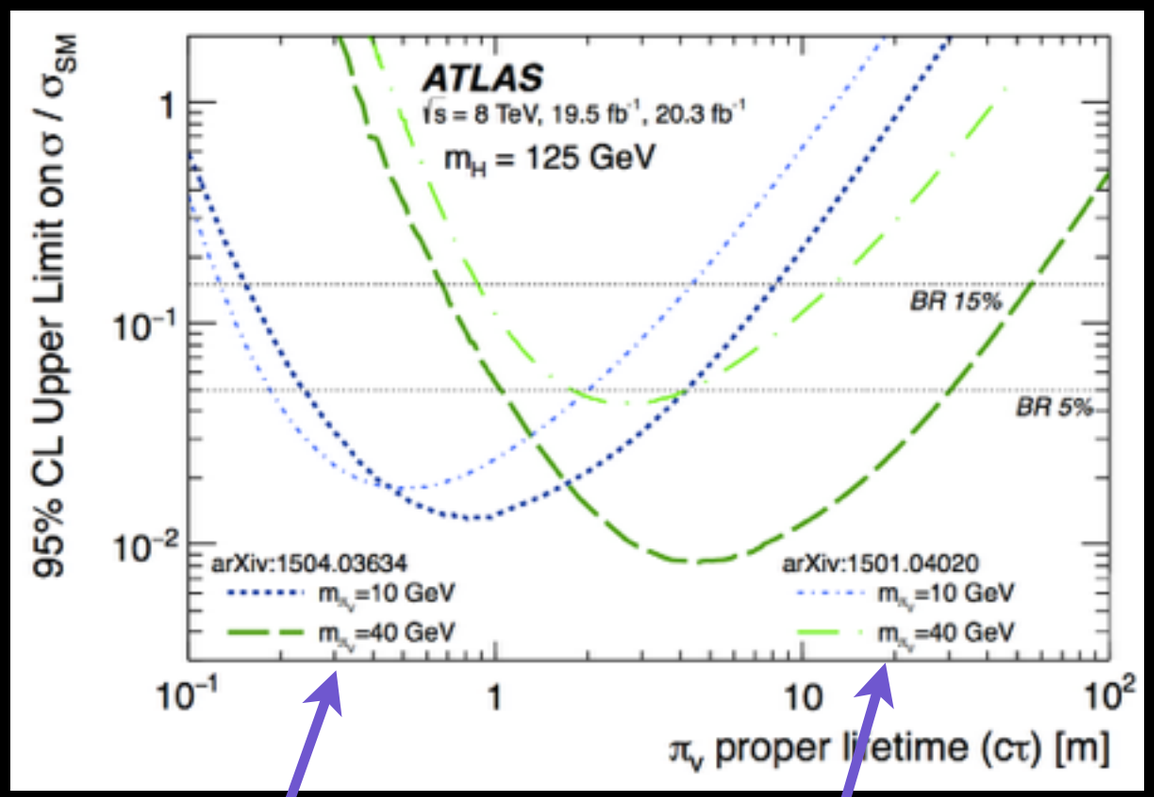
h125 —> long-lived particles



We have a wide range of particle lifetimes in the SM; this means we should include LLPs in any BSM search — non-negligible lifetimes can generically appear!

- Lifetime is best treated as a free parameter
- Rich and challenging set of decay topologies often requiring significantly customized analysis methods

h125 —> LLPs —> jets

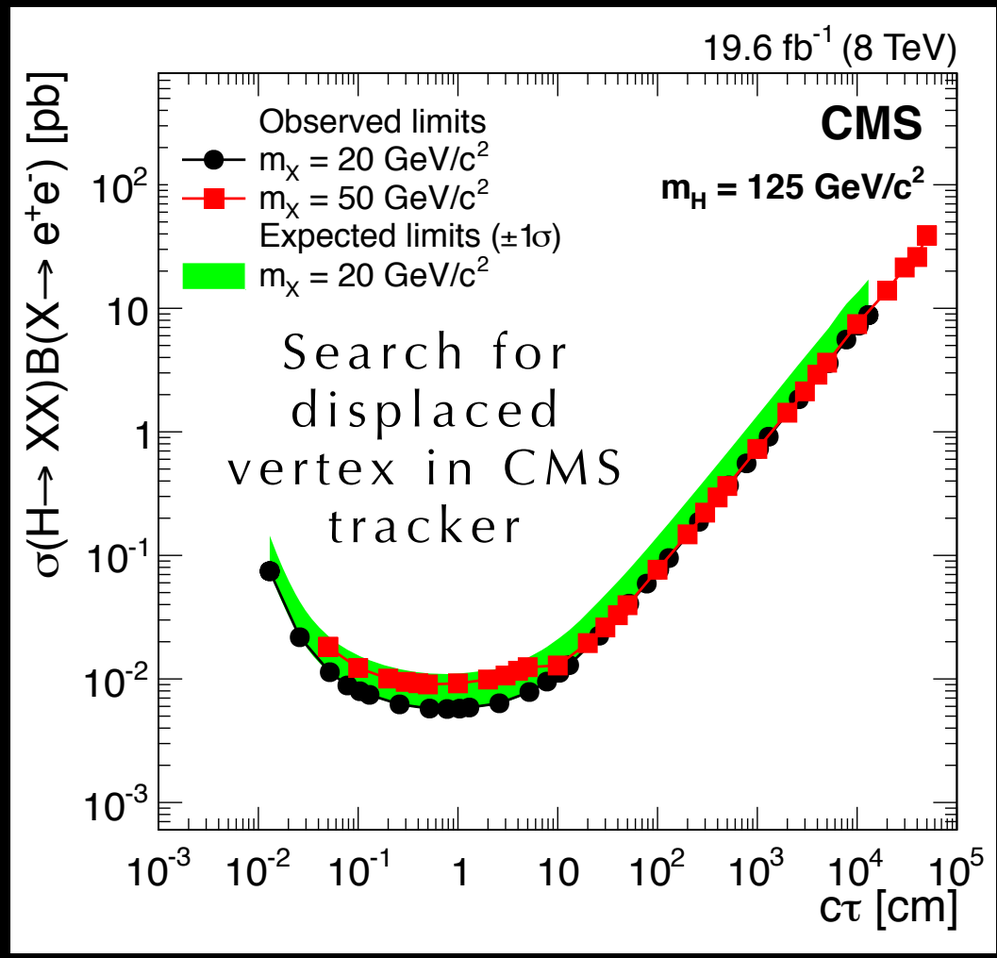


ID/MS search

Just-before-HCal search

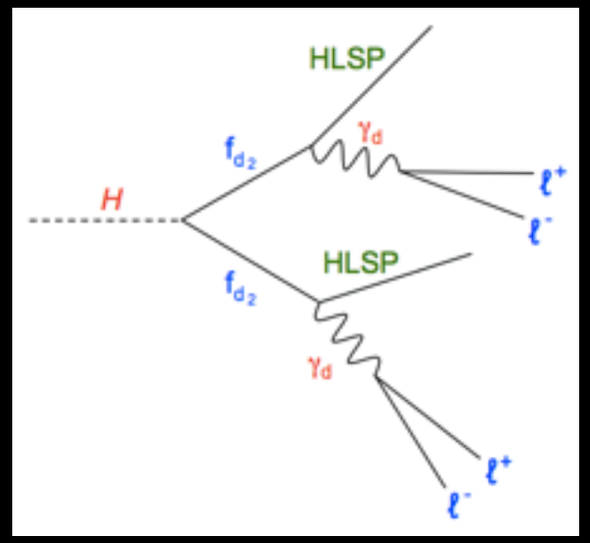
PRD 92 012010 (2015)
PLB 743 (2015) 15-34

h125 —> LLPs —> leptons



PRD 91 (2015) 052012

h125 —> displaced lepton-jets

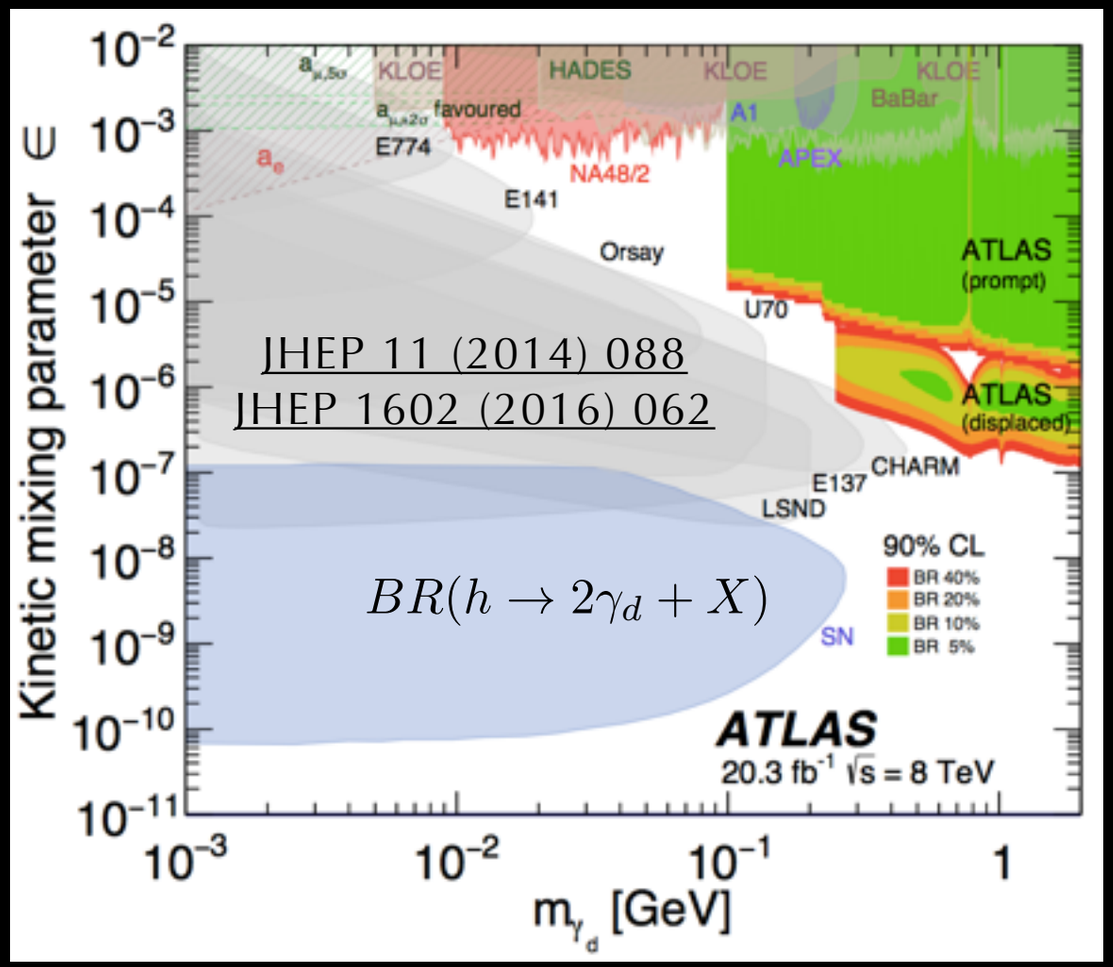


Dark / hidden sector coupled to SM Higgs and leptons via very light dark fermions radiating low-mass dark photons

Very weak interaction —> displaced decay

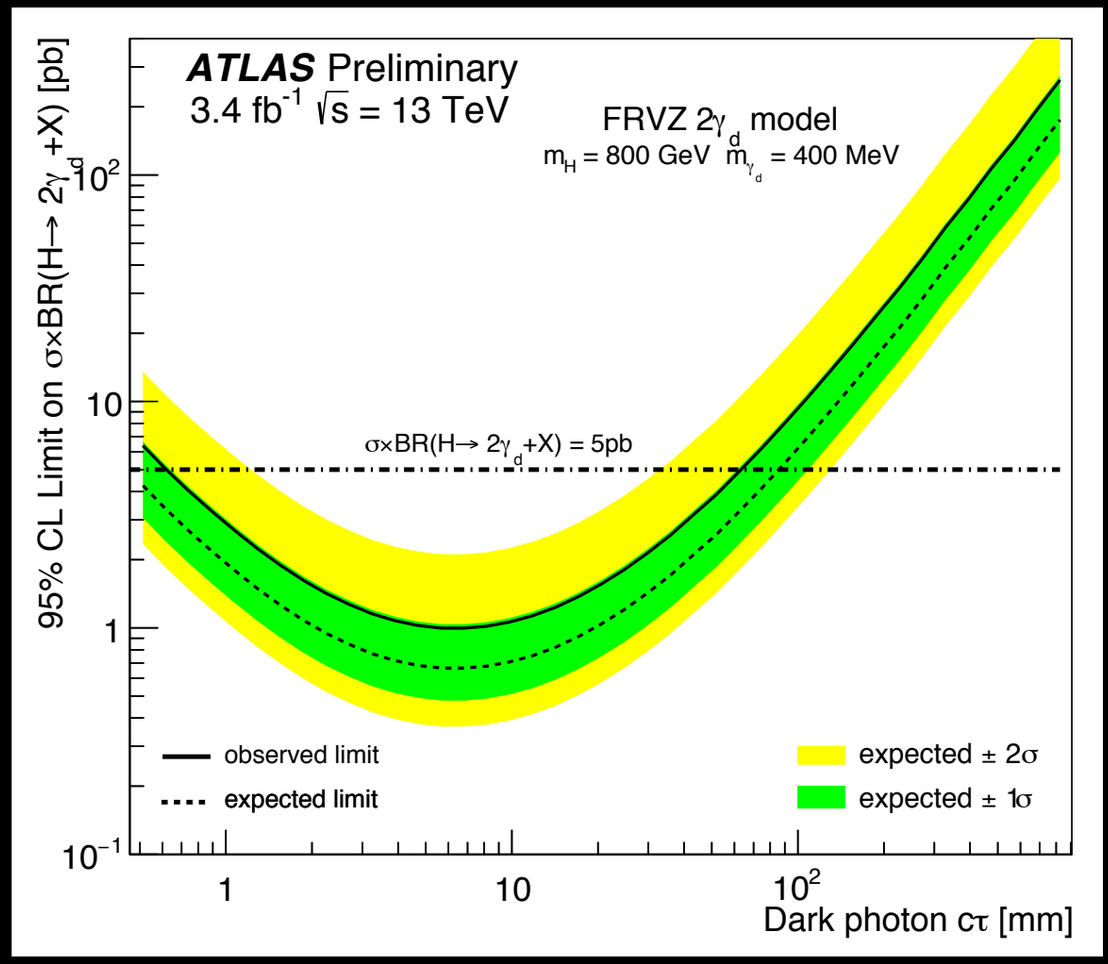
Very light, highly boosted dark photon —> highly collimated groupings of leptons, or *lepton-jets*

h125 —> Lepton-jets



JHEP 11 (2014) 088
JHEP 1602 (2016) 062

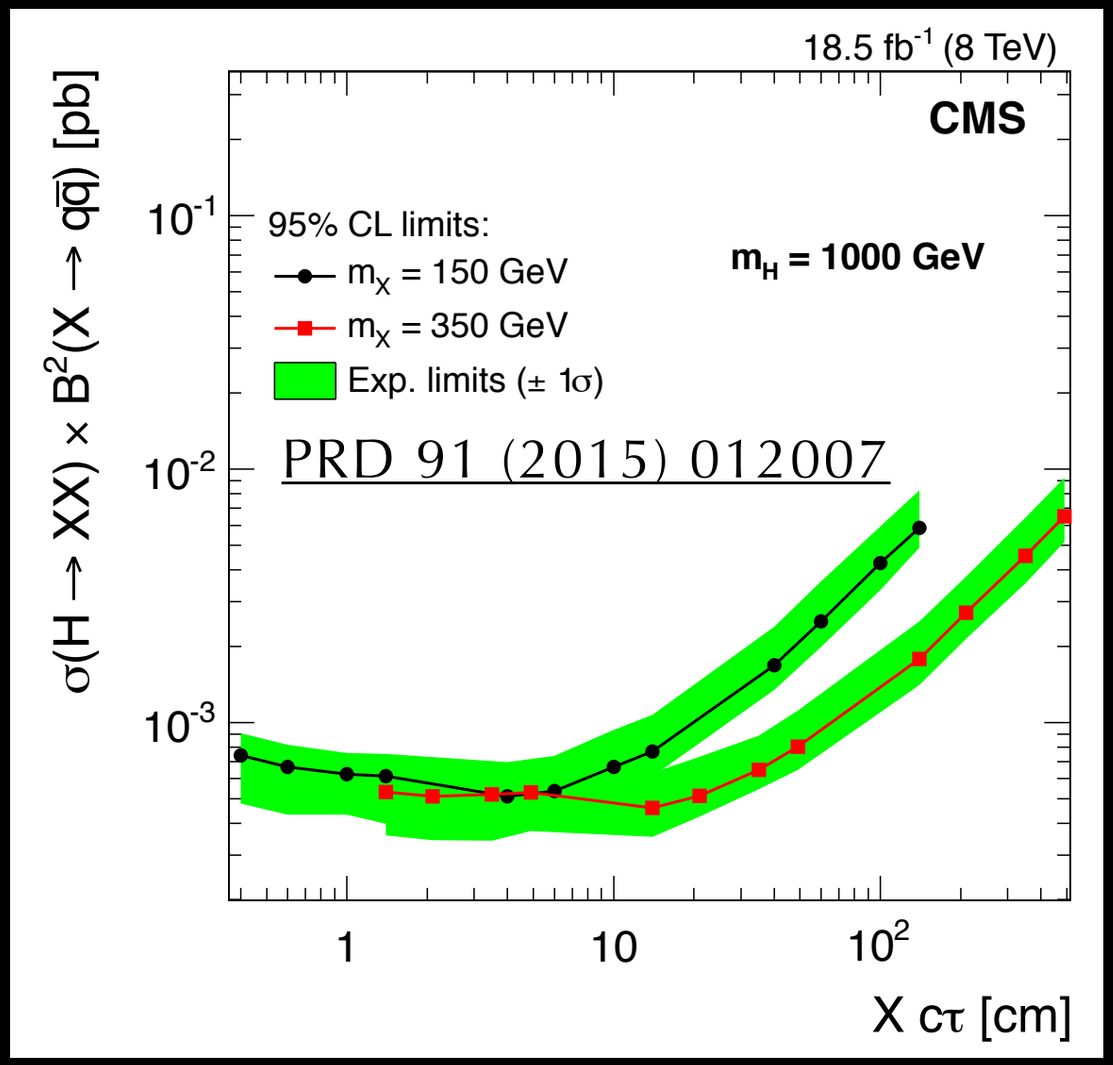
Higher-mass H —> Lepton-jets



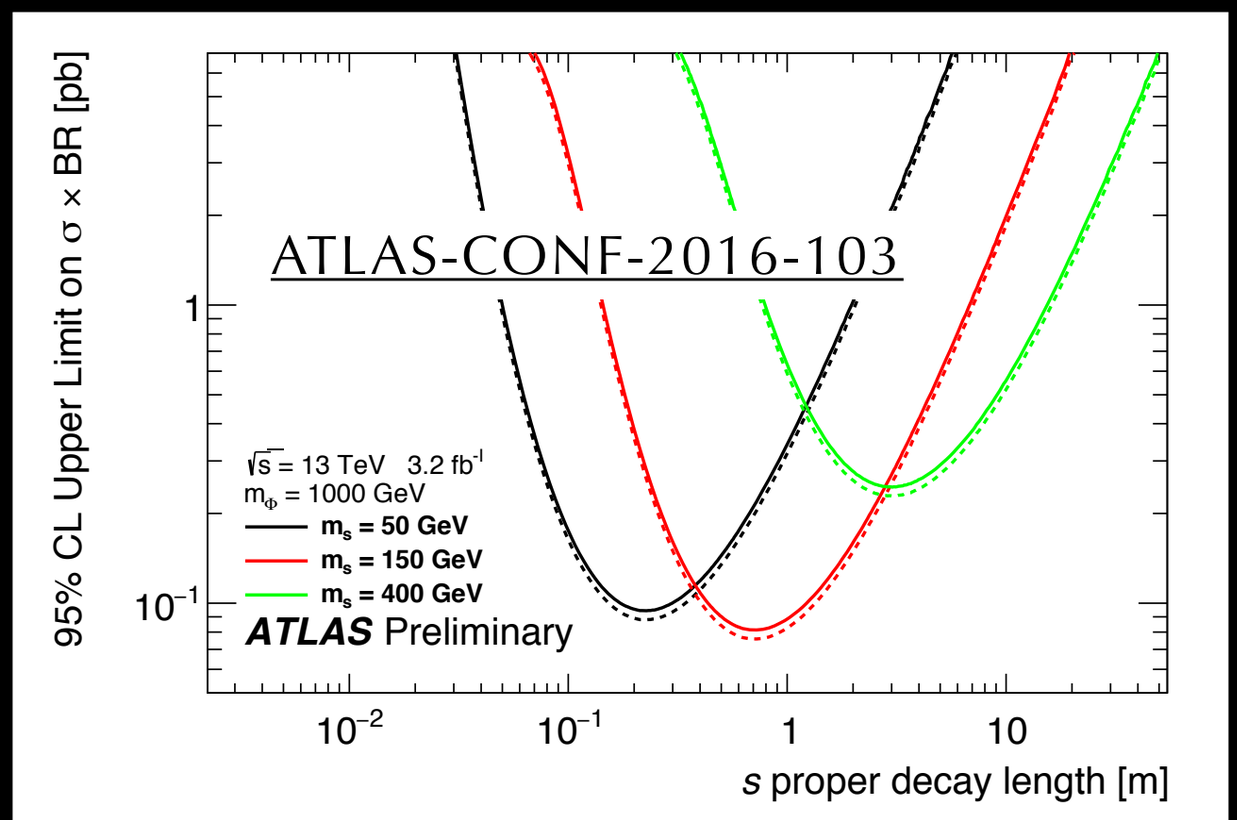
13 TeV: ATLAS-CONF-2016-042

Higher-mass scalars —> long-lived particles

H —> LLPs —> jets



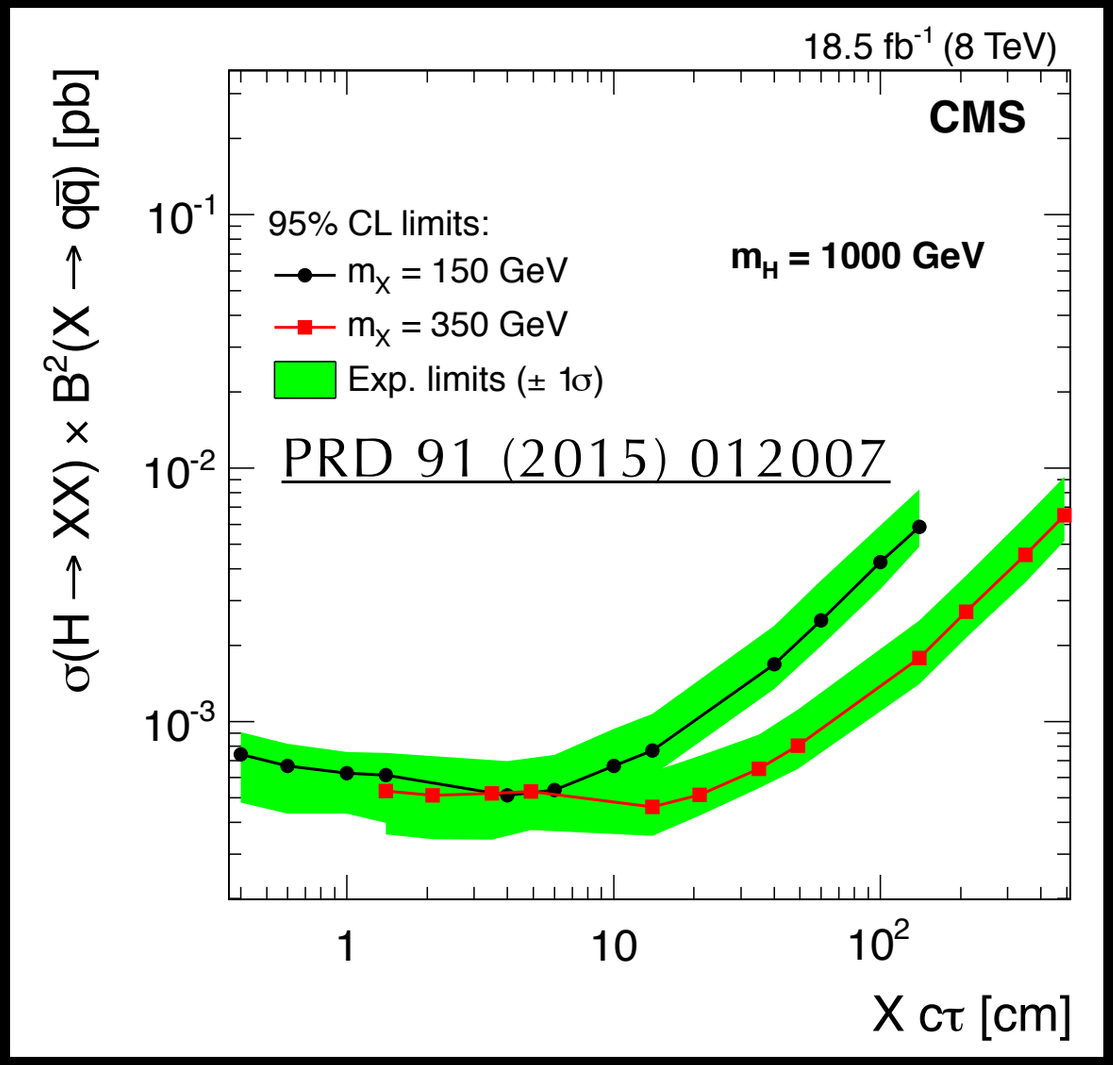
CMS search at 8 TeV for displaced jet pairs



ATLAS search at 13 TeV for displaced jets in the hadronic calorimeter

Higher-mass scalars —> long-lived particles

H —> LLPs —> jets



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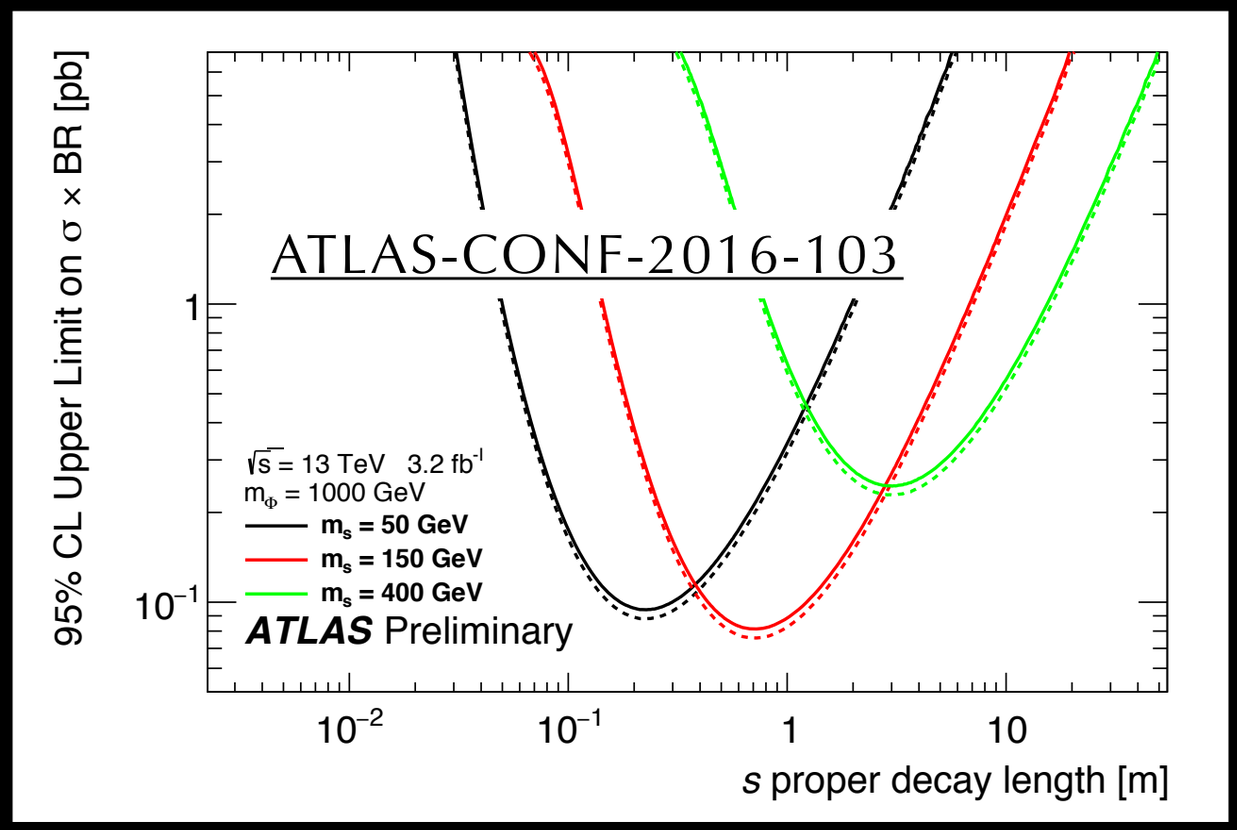


ATLAS search at 13 TeV for displaced jets in the hadronic calorimeter

Mapping the lifetime frontier ongoing right now in the LHC LLP Community initiative; white paper, workshops — join us!

Summary

Neutral scalars h/H/A decaying resonantly to leptons and tops

A/H —> Zγ

H —> γγ

Charged Higgses with hadronic tau final states

Charged Higgses to leptons

Vh resonances

Di-Higgs (h125) resonances

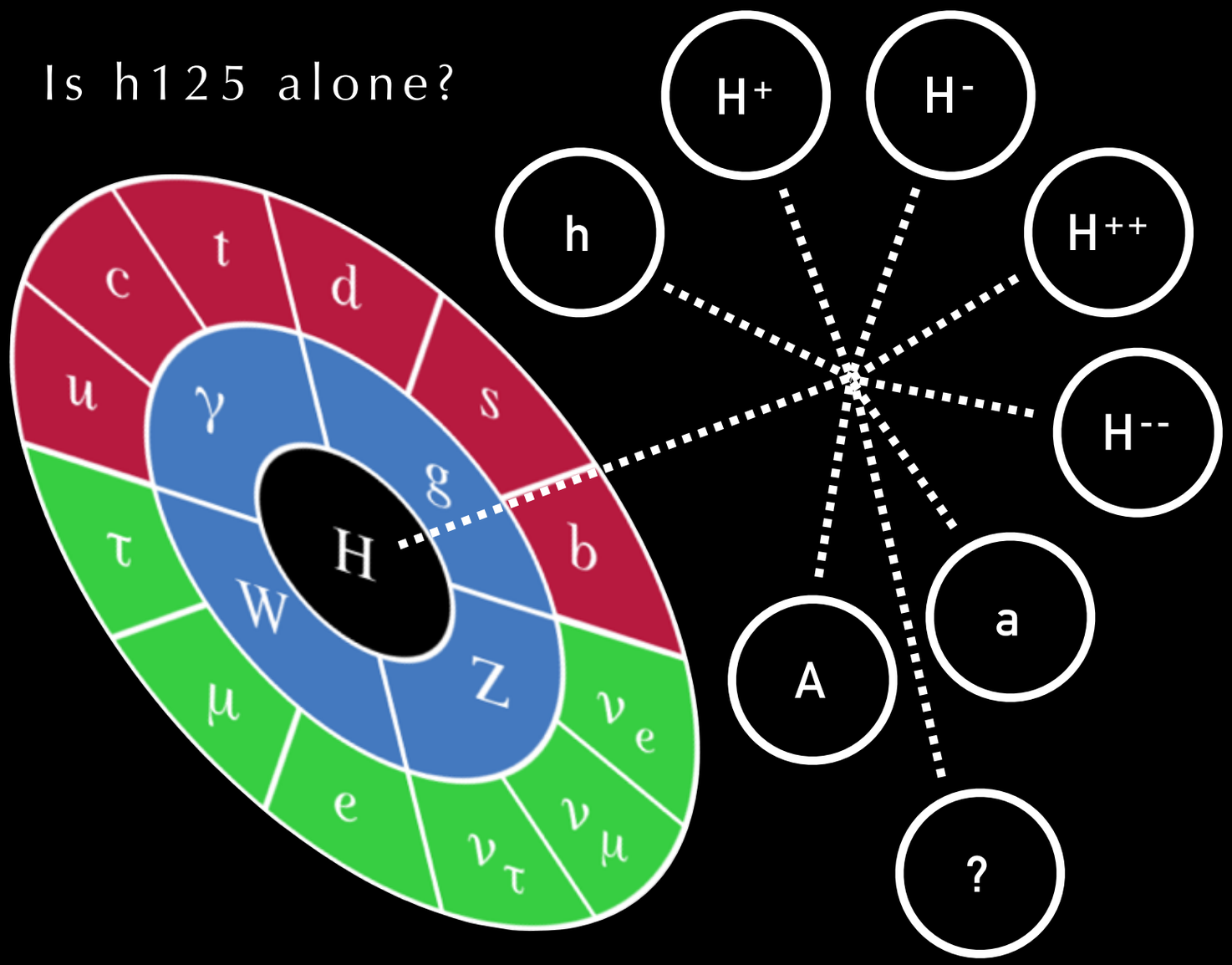
Comparing searches — e.g., in the hMSSM

Non-standard decays of h125 to new, light resonances

The lifetime frontier for h125 and beyond-the-SM scalars

Conclusions

Is h125 alone?



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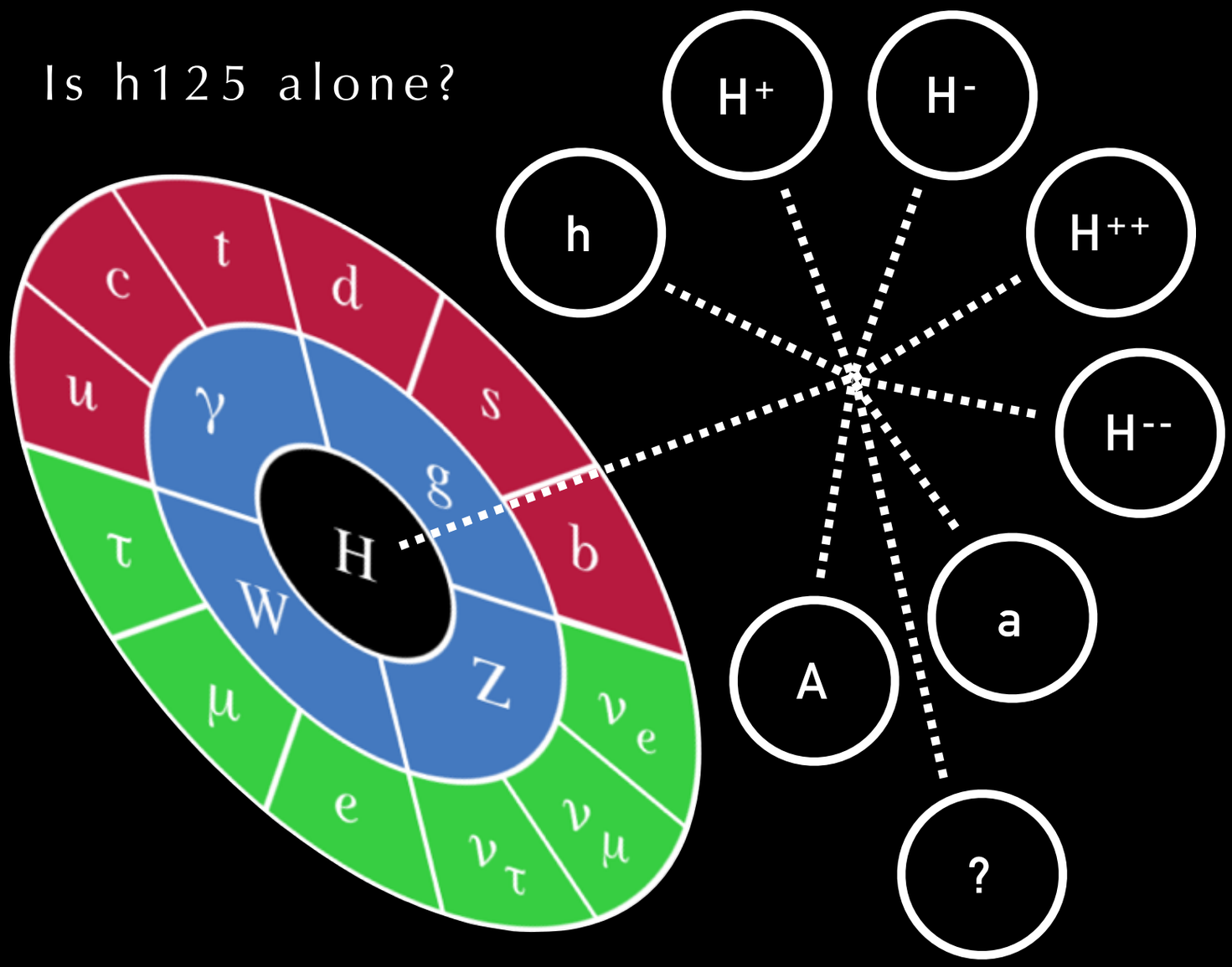

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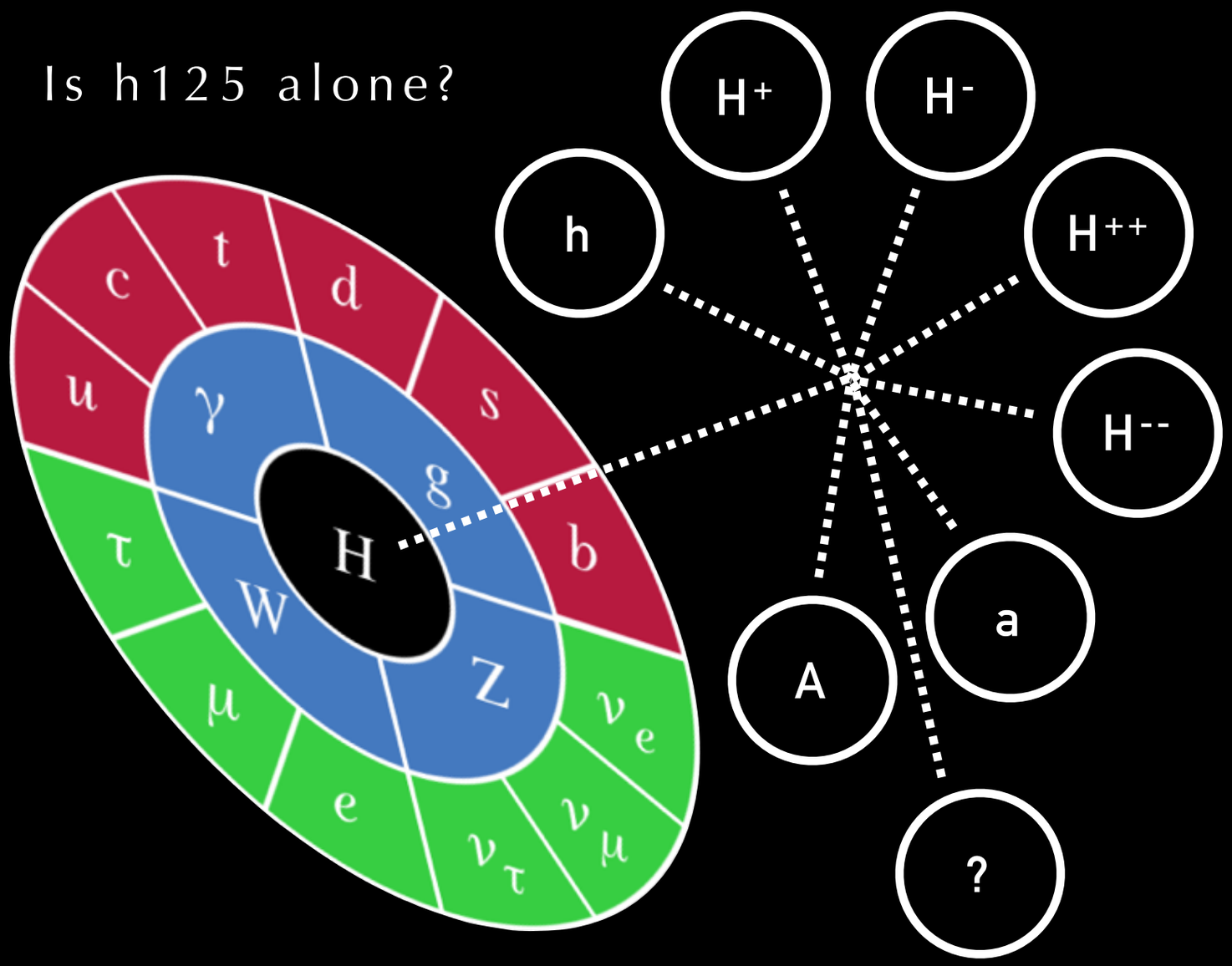

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Is h125 the SM Higgs?

Robust program of BSM Higgs searches at ATLAS and CMS to answer these questions

8 TeV results being updated and expanded now with our first look at 13 TeV

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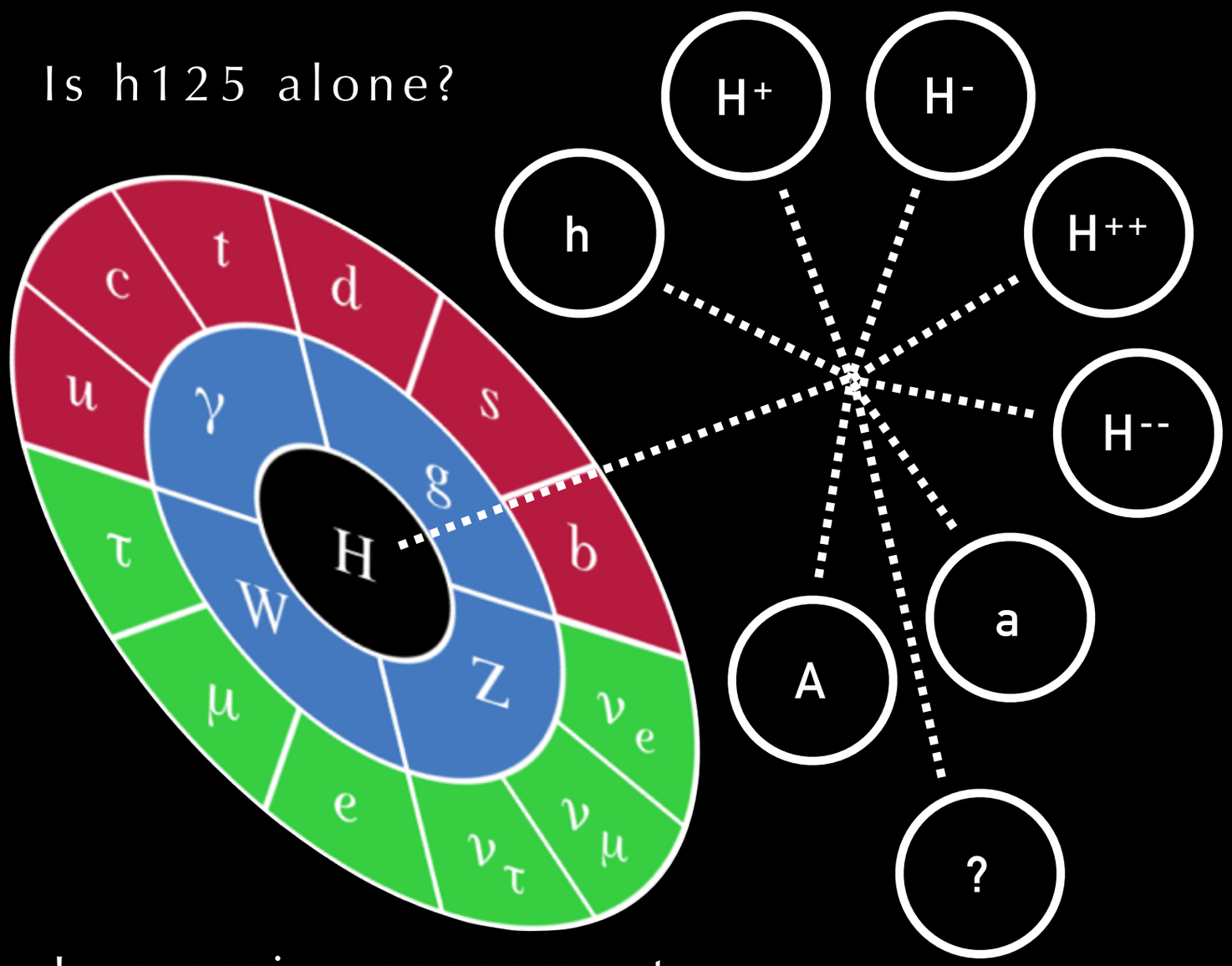

Impressive agreement with SM expectations thus far, but we're just getting started

If h125 has cousins kinematically accessible at the LHC, we'll find them

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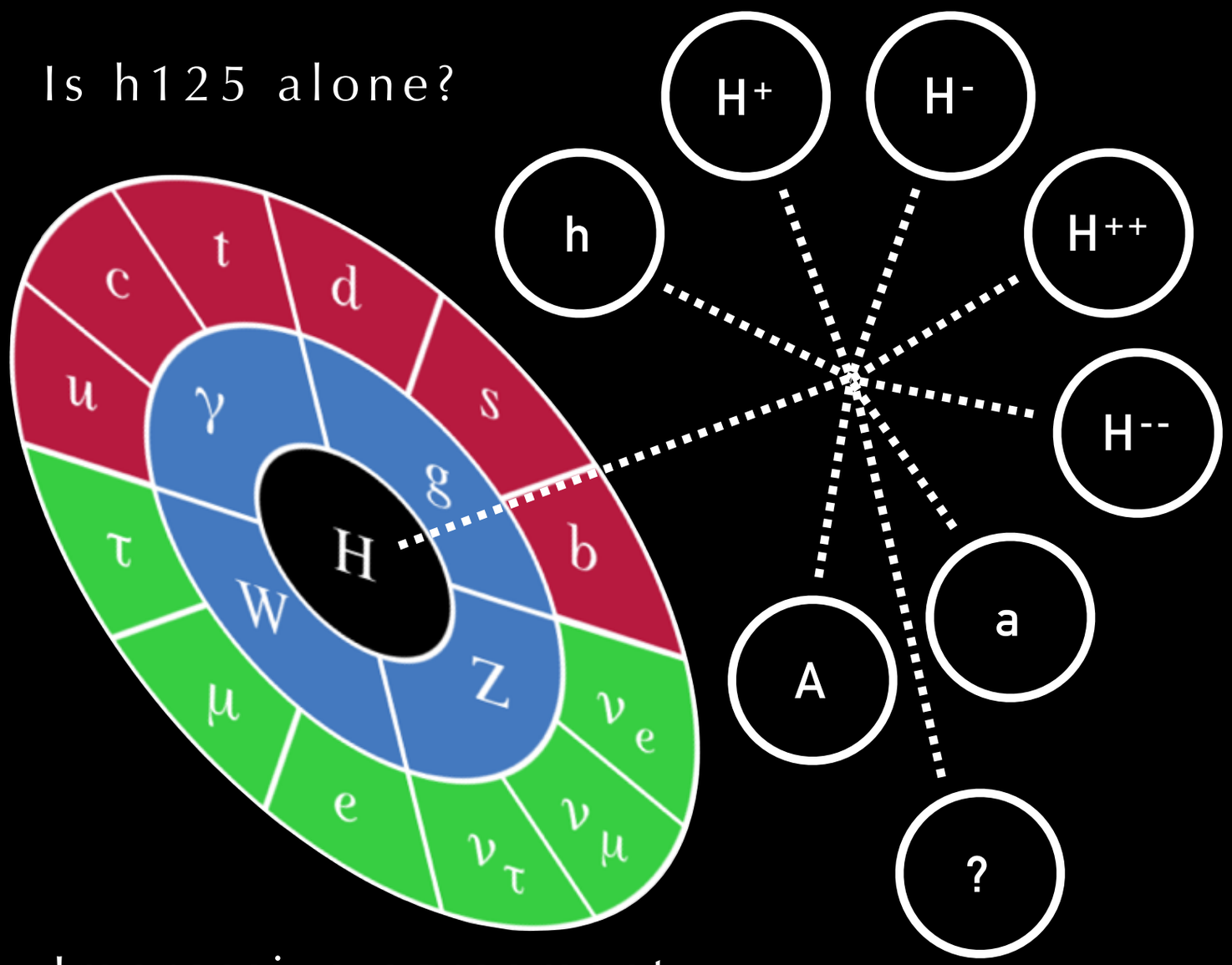

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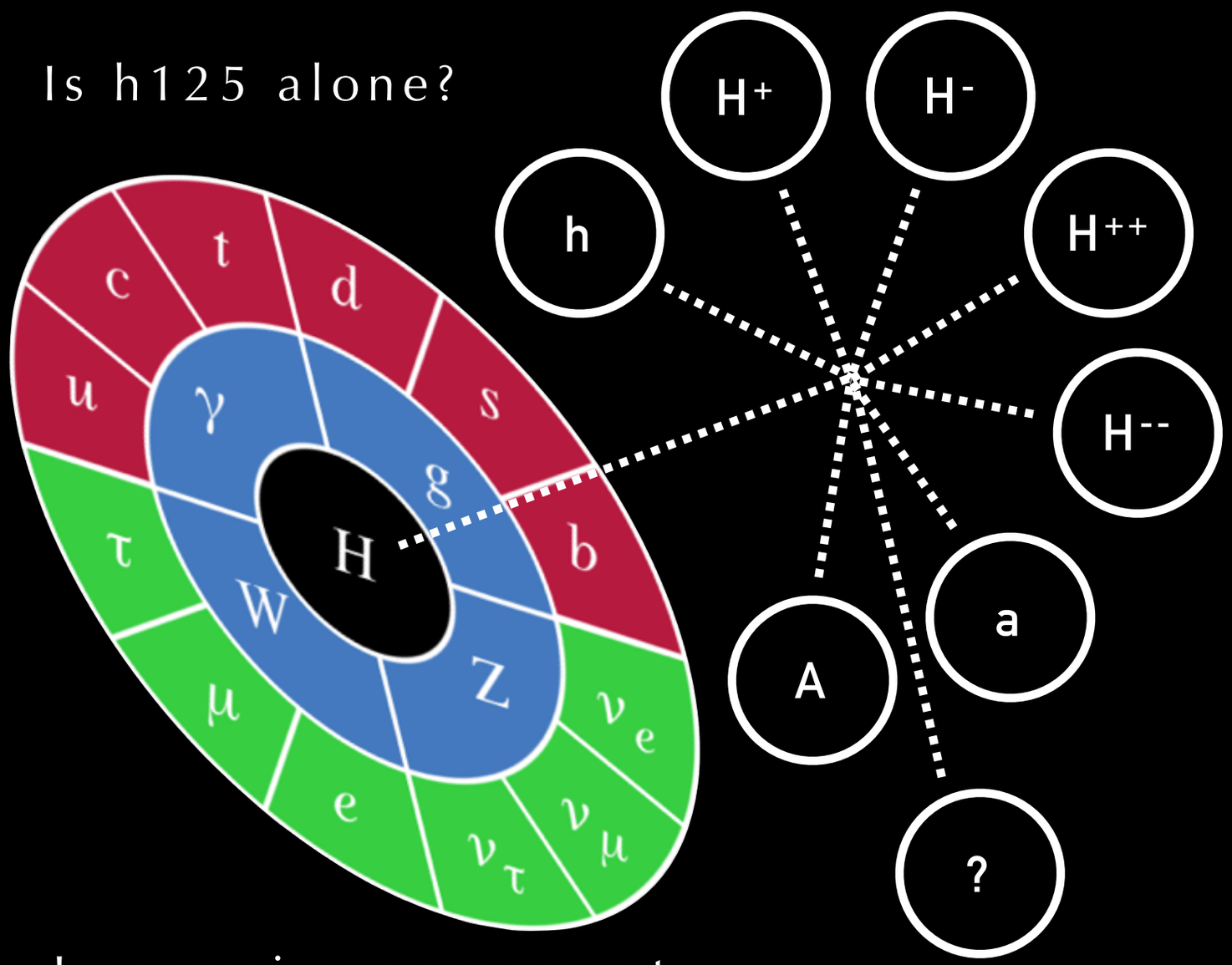

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See the parallel talks for more details!

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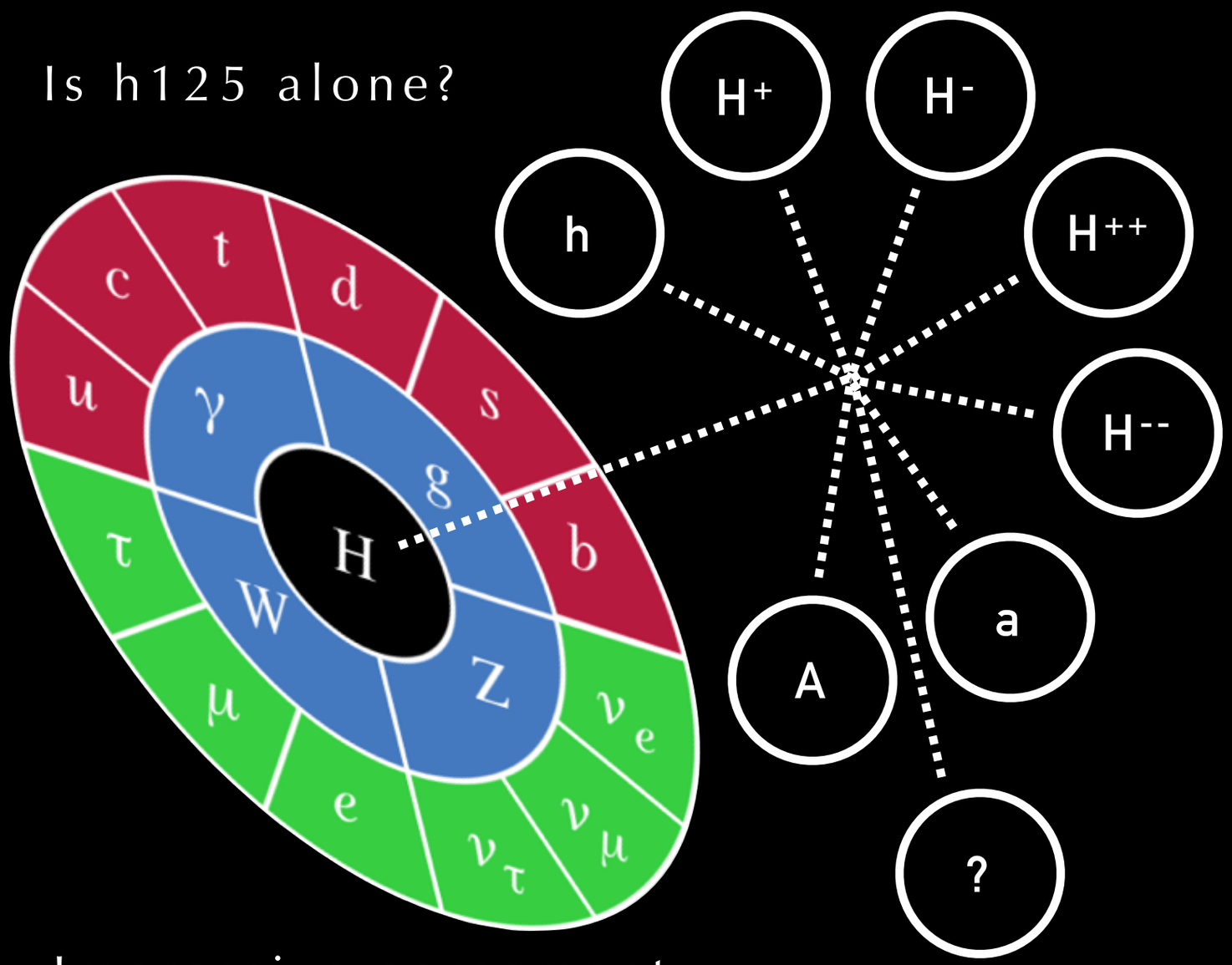

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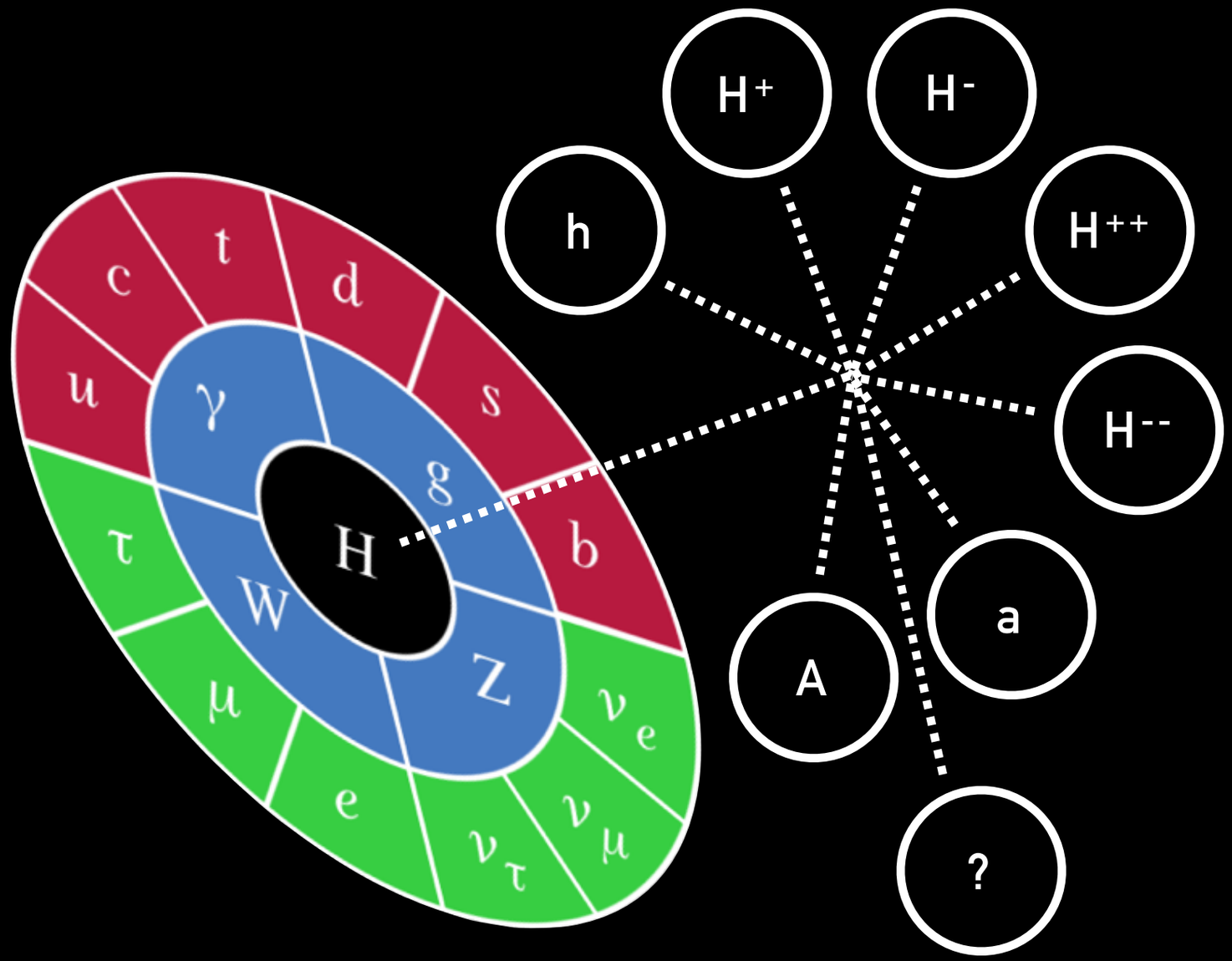
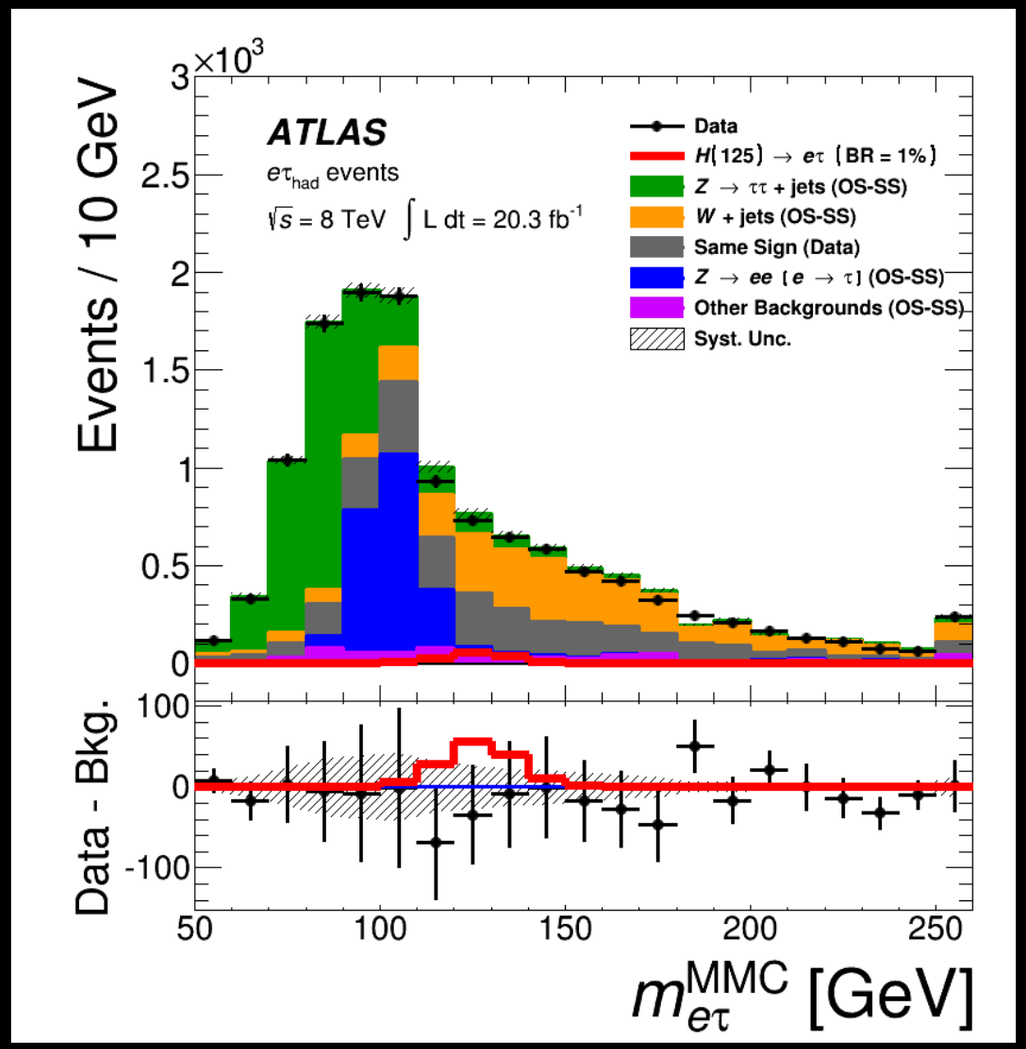
END



Reserve slides

Lepton flavor-violating h decays

h125 —> eτ / μτ

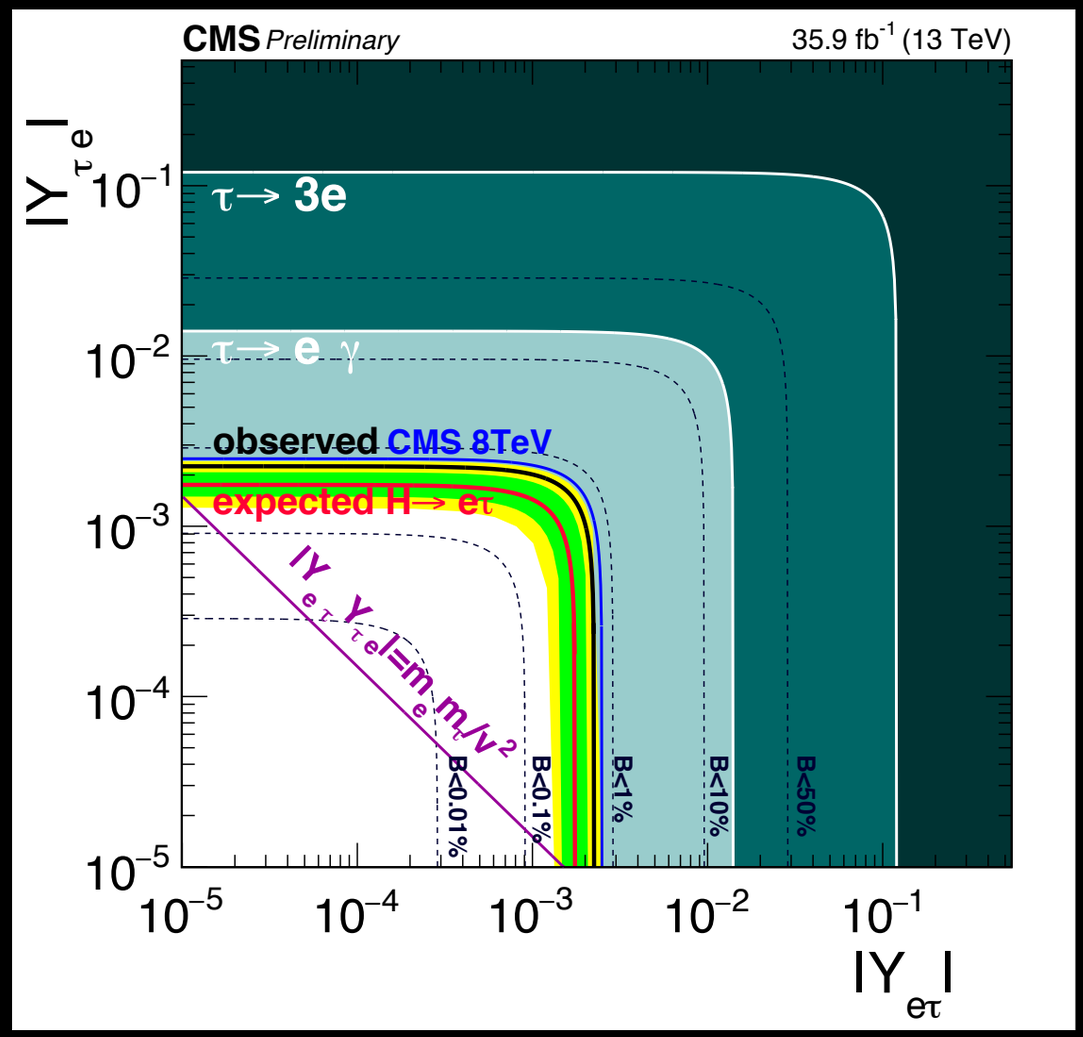


EPJC 77 (2017) 70

ATLAS search at 8 TeV, example of reconstructing m_h as invariant mass of electron, hadronic tau, and E^T_{miss}

LFV decays of h125 can appear generically in 2HDMs, RPV SUSY, etc., and would be an instant sign of BSM physics

CMS search with 2015+2016 dataset at 13 TeV —> Limits on BR(h125 LFV) < 1%



CMS-PAS-HIG-17-001