Searches for exotic, invisible and rare decays of the Higgs boson

Sven Dildick
Texas A&M University

On behalf of the CMS and ATLAS Collaborations

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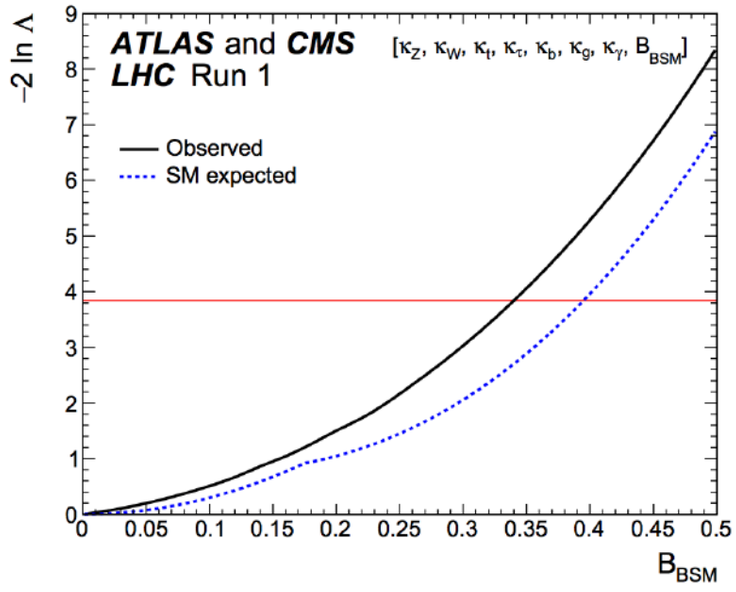
Overview

- Introduction
- SM Higgs to light boson decays
- Lepton Flavor Violation
- Invisible decays of SM Higgs
- Rare decays
- Plans for the Yellow Report
- Summary

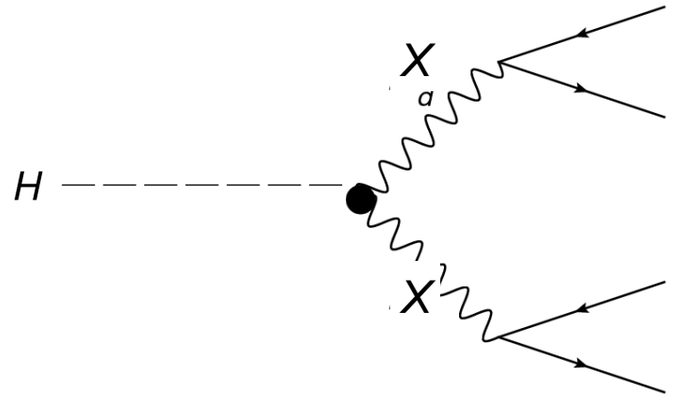
Introduction

- Scalar boson discovered in 2012 consistent with SM Higgs boson
- **New physics searches** and **precision measurements** at LHC, HL/HE-LHC to determine is true nature
- Focus on Higgs decays: 3 big & interesting fields



1) Exotic decays

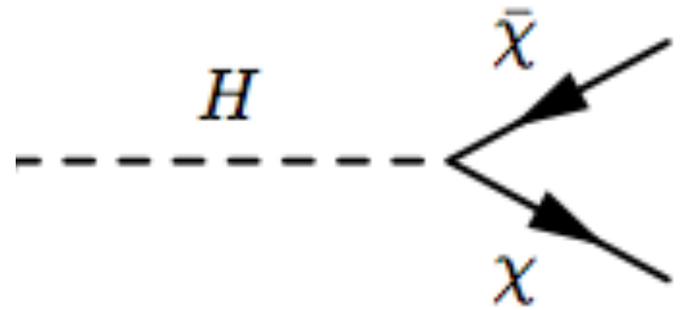
- Higgs to BSM particles or forbidden SM decays
- Currently $B_{BSM}<34\%$ at 95% CL (ATLAS+CMS)
  - Sets upper limit to all exotic branching ratios
- Popular set of models include **Higgs decays to light bosons, $h \to 2x$, with $m_X < m_h/2$**
  - NMSSM: CP-odd pseudo-scalar light boson
  - 2HDM + S: extra singlet scalar
  - Dark sector models with $U(1)_D$: extra dark vector boson
- **Many** different final states! 2b2μ, 4τ, 4b, 2τ2b, 2τ2μ,…



Introduction

2) Invisible decays

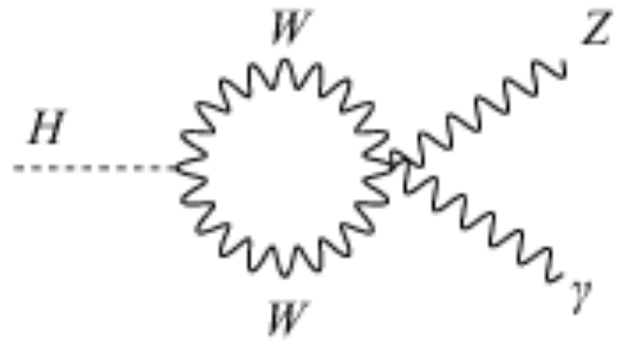
- Higgs decays to particles that leave a detector unseen
  - Higgs decay to unseen SM particles
    - Example: H →ZZ →4ν
  - Higgs decay to weakly interacting massive particles
    - Example: WIMP dark matter



- Currently **B_{inv}<24%** at 95% CL (CMS)
  - Note: exotic decays can become “invisible” when particle becomes long-lived
    - Decays to SM particles after it left the detector

3) Rare SM decays

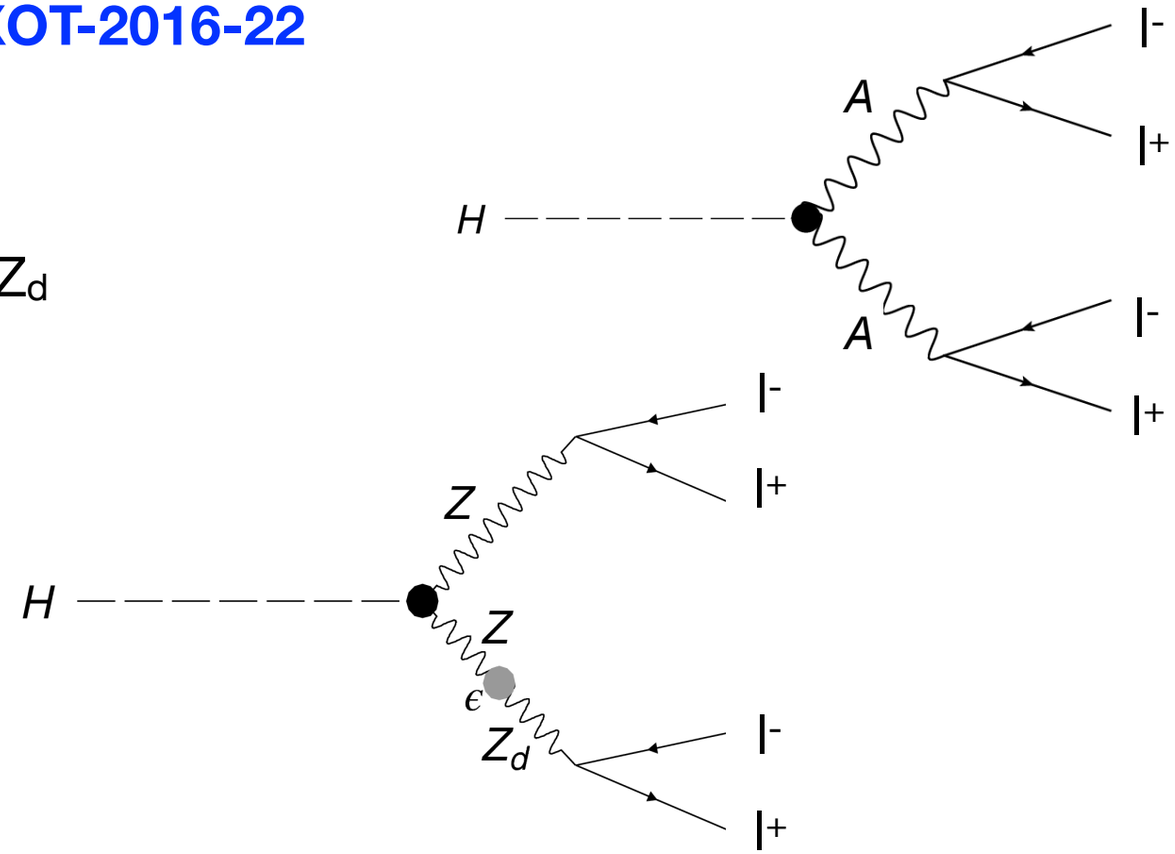
- H →Zγ
- H →φγ
- H →ργ

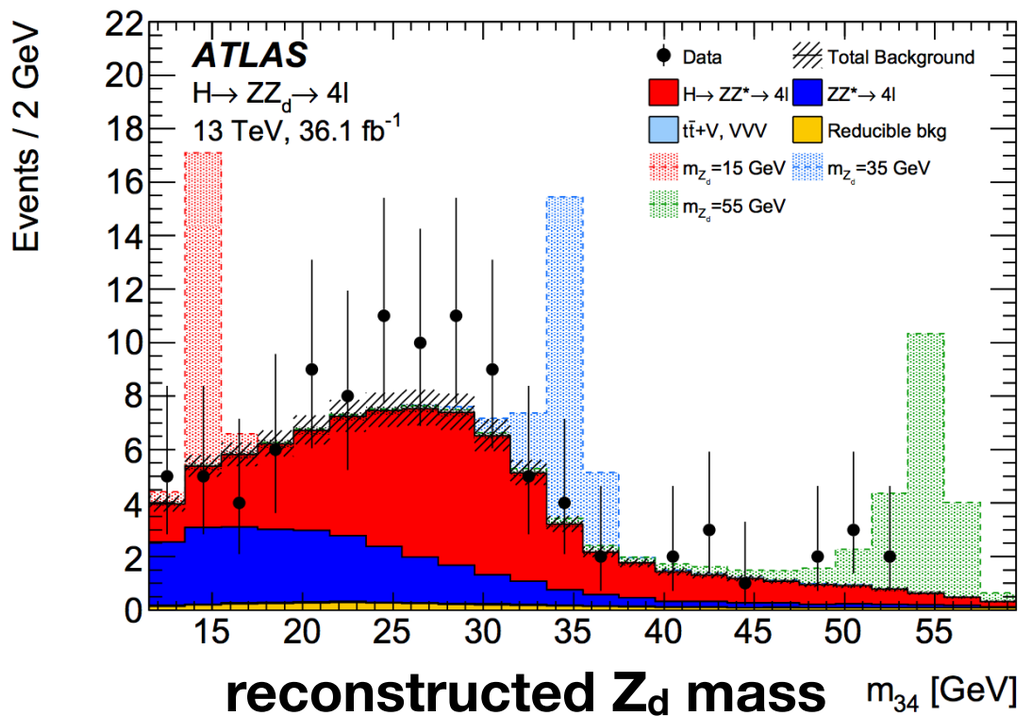


Higgs to boson: h(125) → aa/$Z_{(d)}Z_d$ → 4l

Run-2 (2016) data: 36.1 fb^{-1} @ 13 TeV **ATLAS-EXOT-2016-22**

- Three different searches for new bosons a and Z_d
  - pseudo-scalar “a” (2HDM+S)
  - vector boson “Z_d“ (U(1) dark sector)
- Channels: aa, ZZ_d and Z_dZ_d
- Final states: 4μ, 4e and 2e2μ
- Largest backgrounds:
  - pp → ZZ* → 4l and pp → h → ZZ* → 4l
- Limits at 95% CL:
  - B(h → ZZ_d → 4l) ≈ 0.1%
    - Also valid for h → Za → 4l, with a necessarily pseudo-scalar if CP is conserved
  - B(h → Z_dZ_d → 4l) ≈ 0.01%
  - B(h → aa → 4l) ≈ 1%
    - Also valid in case light boson is scalar



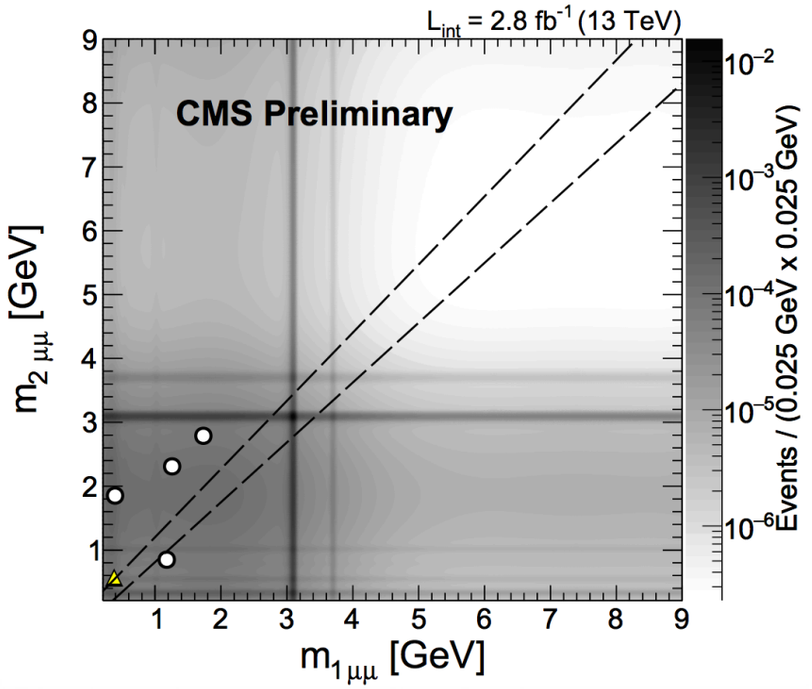


Higgs to light boson:

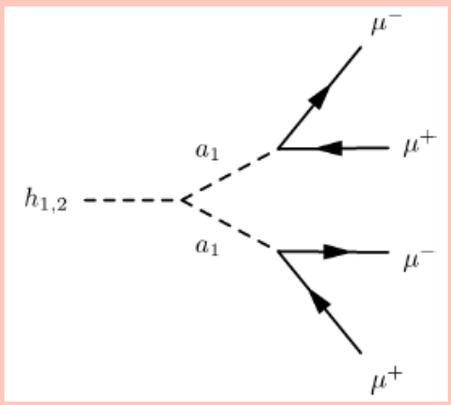
$h(125) \rightarrow 2a_1 \rightarrow 4\mu$, $h(125) \rightarrow 2n_1 \rightarrow 2\gamma_1 2n_D \rightarrow 4\mu 2n_D$

Run-2 (2015) data: 2.8 fb^{-1} @ 13 TeV **CMS-HIG-16-035**

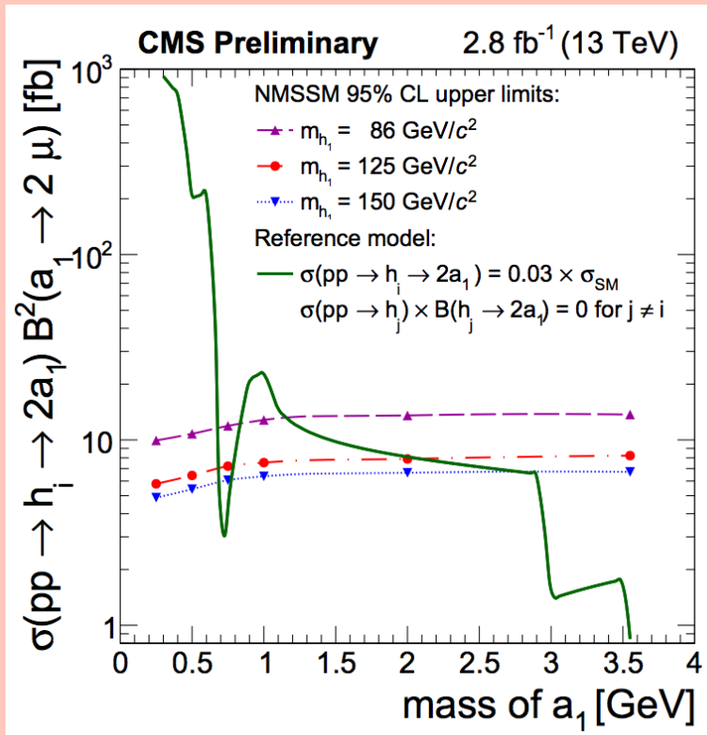
- Light boson decays to pair of opposite-sign muons
  - Search for enhancement in 2D mass spectrum
- No significant excess of events over the SM background prediction
- Model independent limit on $\sigma(h \rightarrow 2a) \times B(a \rightarrow 2\mu)^2 \times$ GEN-acceptance
- Interpreted in context of two benchmark models:
  - NMSSM: a_1 is pseudo-scalar
  - Dark SUSY: γ_D is vector boson
    - long-lived if it mixes with photon → **displaced muons**



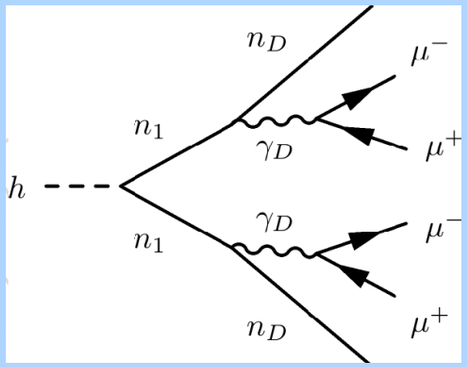
NMSSM



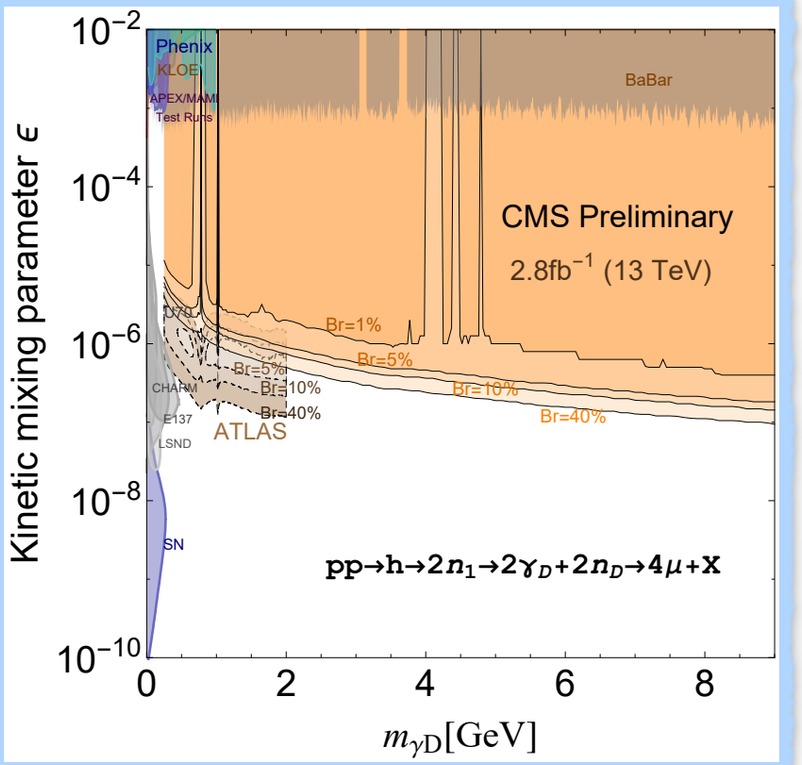
$0.25 < m_{a1} < 3.55$ GeV



Dark SUSY



$0.25 < m_{\gamma D} < 8.5$ GeV



Higgs to light boson:
$h(125) \rightarrow 2n_1 \rightarrow 2\gamma_1 2n_D \rightarrow 4\mu 2n_D$

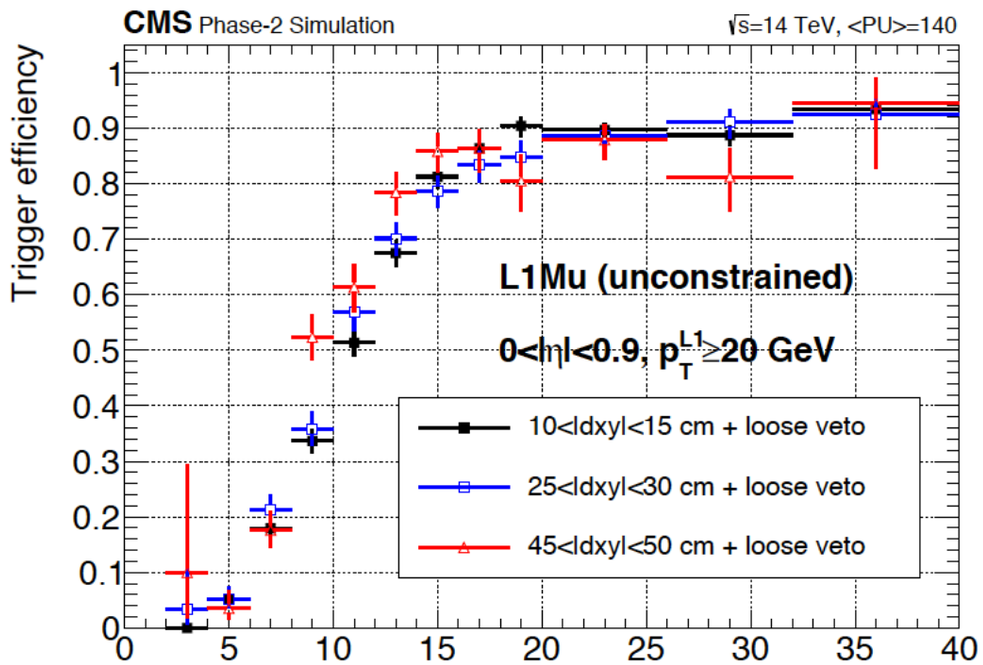
- This analysis is one of the benchmark ones considered for the Phase-2 upgrade of the CMS Muon detector

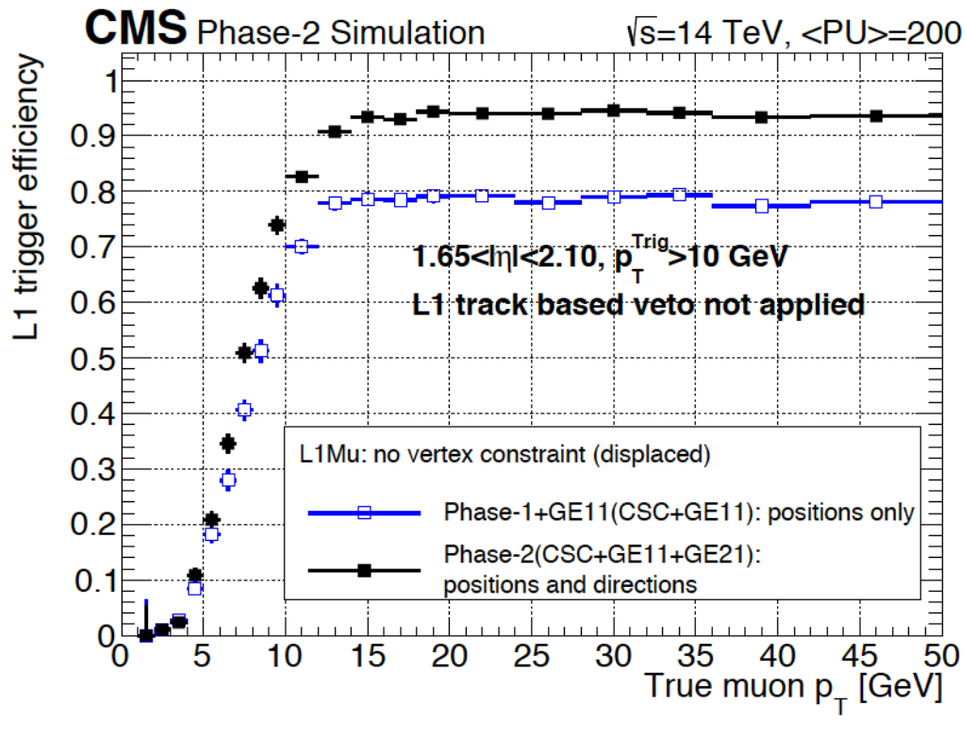
- Displacement in this study limited by trigger and reconstruction capabilities by CMS
  - impact parameter d_{xy} < 10 cm

- Analysis can be significantly improved in Phase-2 with dedicated **displaced muon trigger**

- Requires
  - upgrade of Muon system (GEMs)
  - upgrade of Tracker system (Track-Trigger)

- Such displaced muon trigger would allow for displacements d_{xy} ~10 to ~100 cm (and beyond)





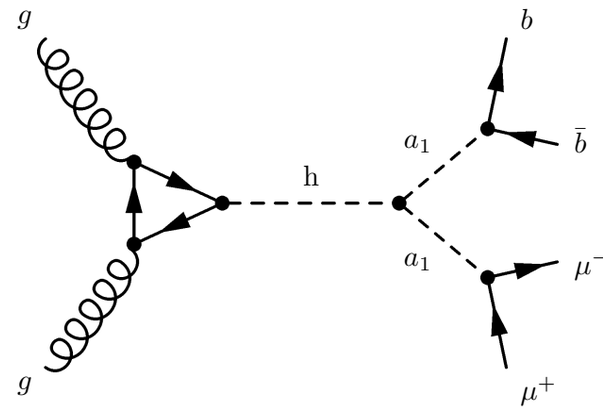
CMS-TDR-17-003

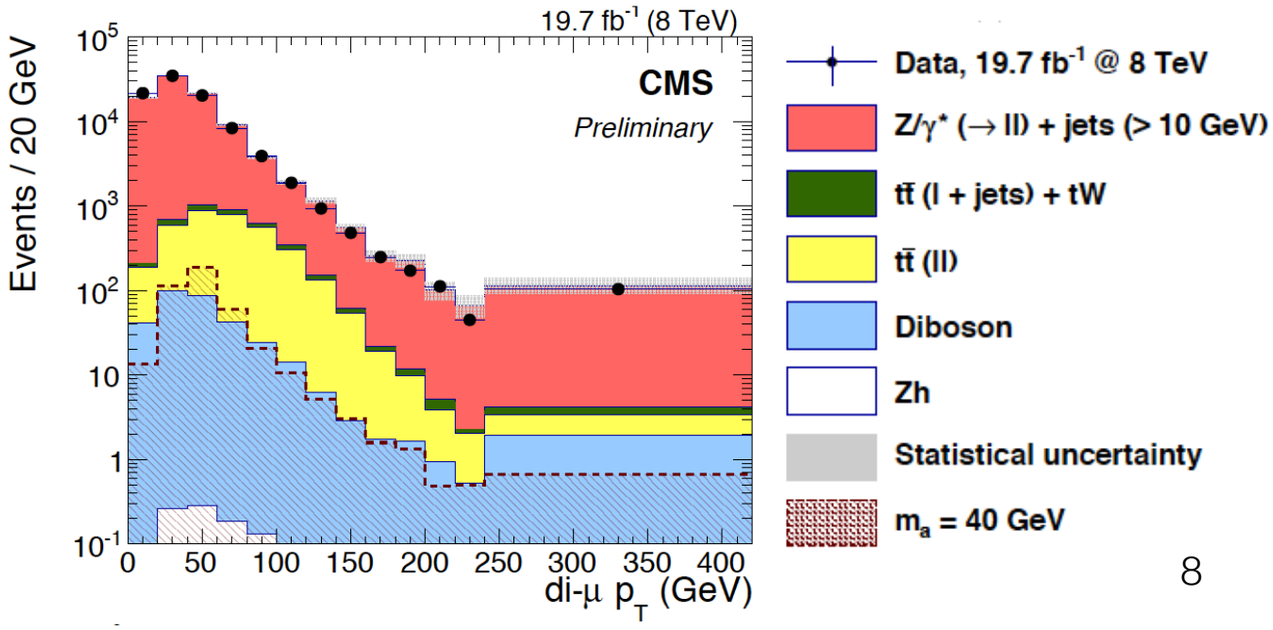
CMS-TDR-17-004

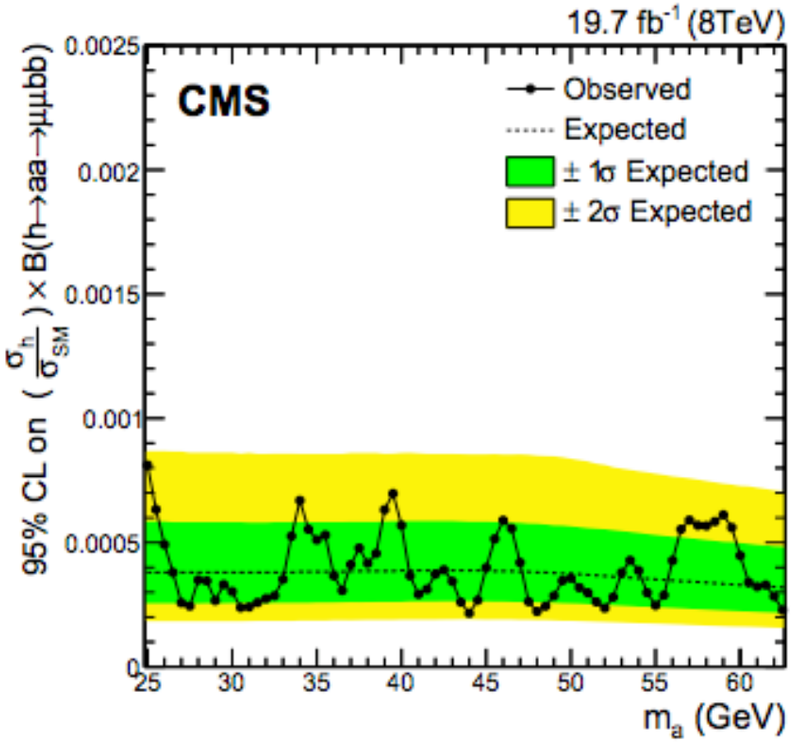
Higgs to light boson: h(125) → 2a → 2μ2b

Run-1 (2012) data: 19.7 fb^{-1} @ 8 TeV **CMS-HIG-14-041**

- Light boson with mass between $25 < m_a < 65$ GeV
- Selection:
  - 2 opposite sign muons and 2 b-jets
  - $|m(\mu\mu bb) - 125\ \text{GeV}| < 25$ GeV
- Good agreement between MC and data
- No significant excess of events over the SM background prediction
- Limits evaluated in context of 2HDM+S, assuming 100% ggh production, B(h → 2a) = 10% and B(2a → 2b2μ) = 0.17%
- $\sigma(pp \to h)/\sigma_{SM} \times B(h \to 2a \to 2b2\mu) \sim 0.04\%$



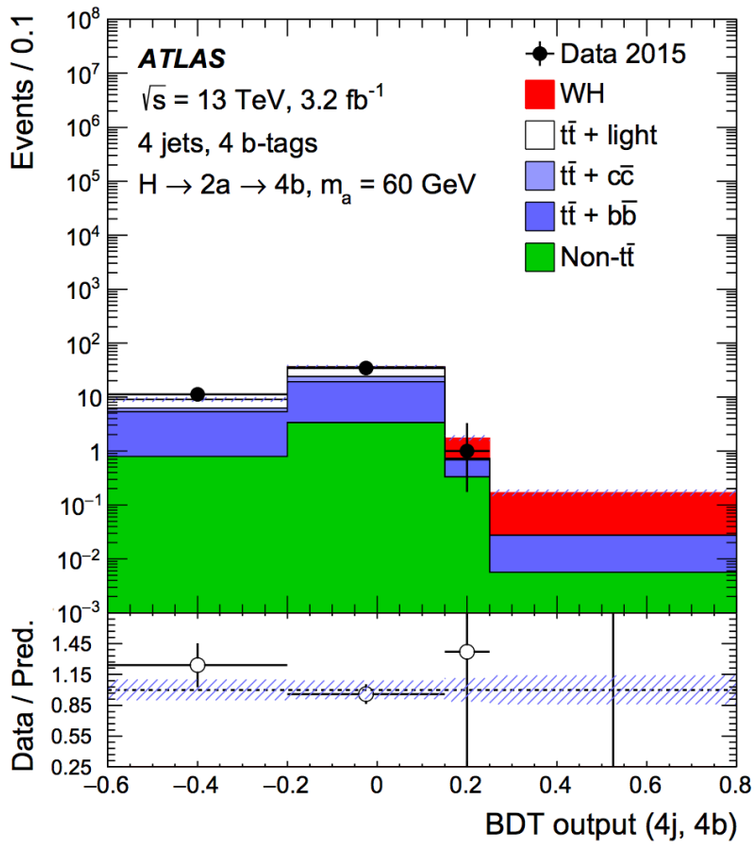


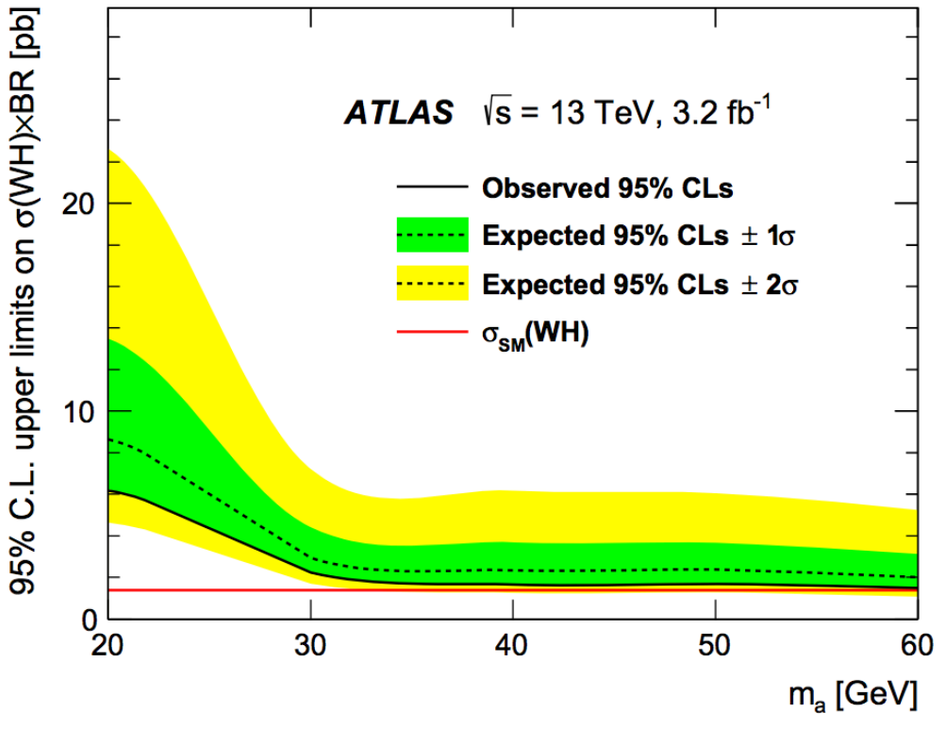


Higgs to boson: h(125) → aa → 4b

Run-2 (2015) data: 3.2 fb^{-1} @ 13 TeV ATLAS-HIGG-2016-01

- Search for (pseudo-) scalar boson with mass between 20 and 60 GeV
- Focus on the Wh production channel, with W →lν
  - Extra lepton (l=e,μ) powerful handle to reduce the large QCD multi-jet background
- Signal region is split up in sectors depending on #jets and #b-tagged
- Dominant background: top quark pair production
- Kinematic variables feed into a BDT to discriminate signal from background
  - m_{bb}, m_{bbbb}, H_T, $p_T(W)$,…
- Limits at 95% CL
  - σ(pp → Wh) x B(h → aa → 4b) < 1.5 - 6.2 pb

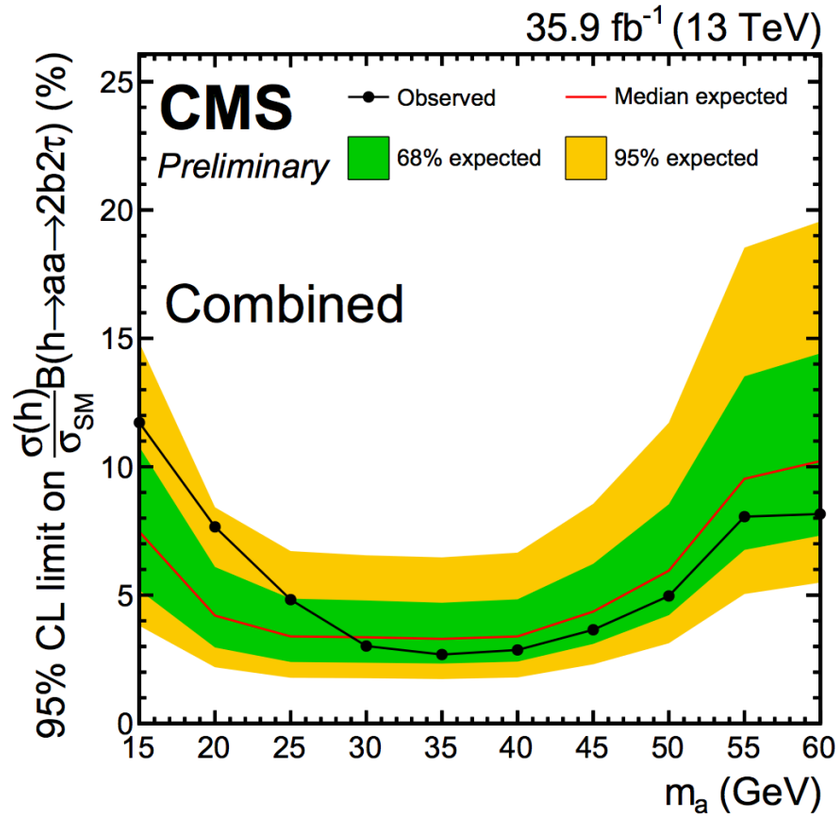


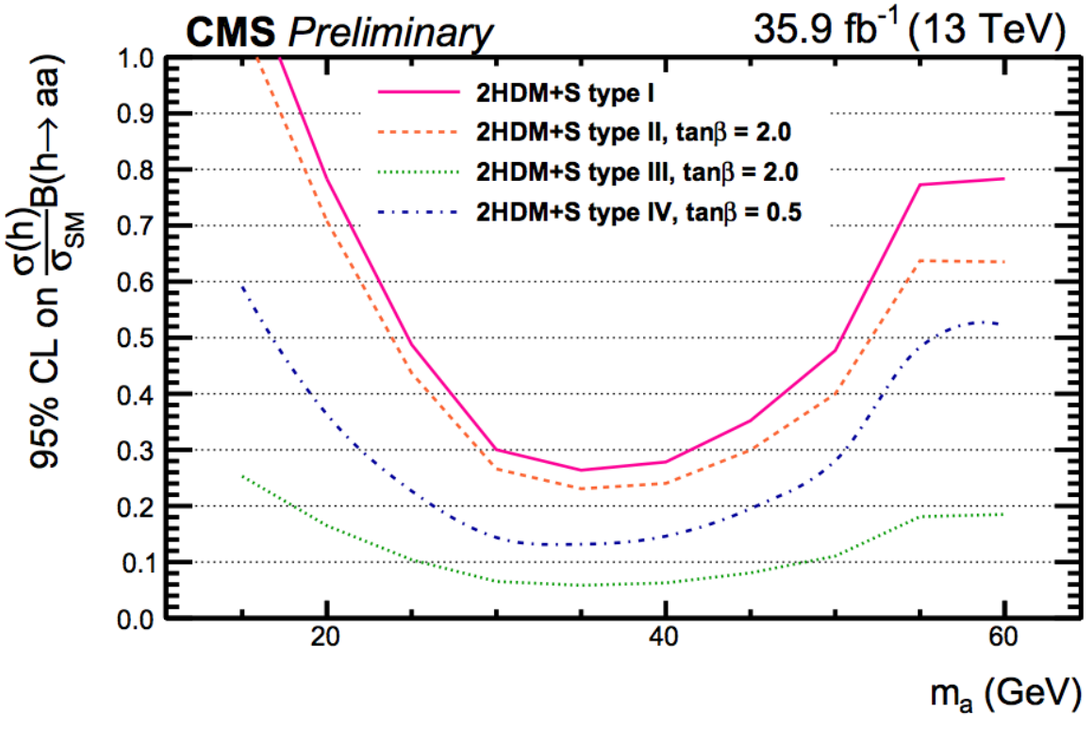


Higgs to light boson: h(125) → 2a → 2τ2b

Run-2 (2016) data: 35.9 fb^{-1} @ 13 TeV **CMS-HIG-17-024**

- Masses of the pseudo-scalar boson between 15 and 60 GeV in context of 2HDM+S
- Production modes: ggh, Vh, and VBF
- Three final states studied: bbτ$_e$τ$_h$, bbτ$_μ$τ$_h$, bbτ$_μ$τ$_e$
  - τ$_h$: tau decaying to hadrons
- Require at least one b-jet.
- Events must have good separation between lepton and τ$_h$
- Largest backgrounds:
  - ttbar + jets, Z → ττ
- Results are interpreted in the context of different 2HDM+S models





Higgs to light boson: h(125) → 2a → 4τ

Run-1 (2012) data: 19.7 fb^{-1} @ 8 TeV **CMS-HIG-14-019** **CMS-HIG-14-022**

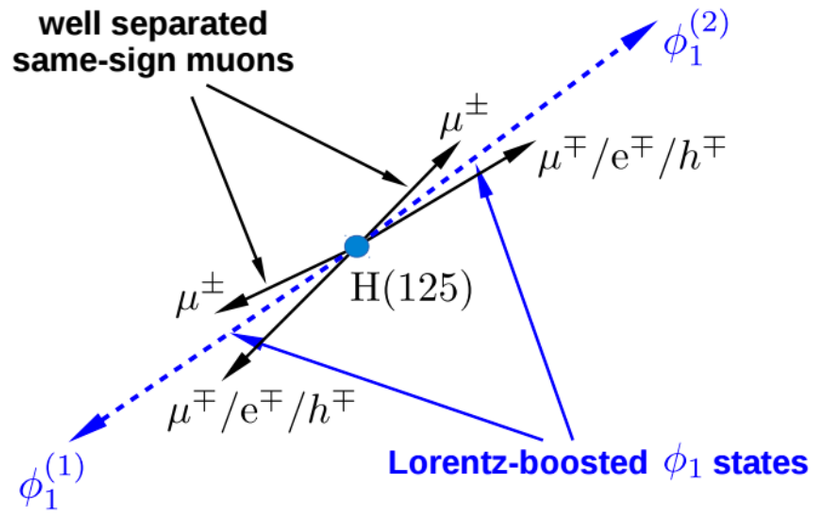
- Masses of the pseudo-scalar boson between 5 and 15 GeV in context of NMSSM

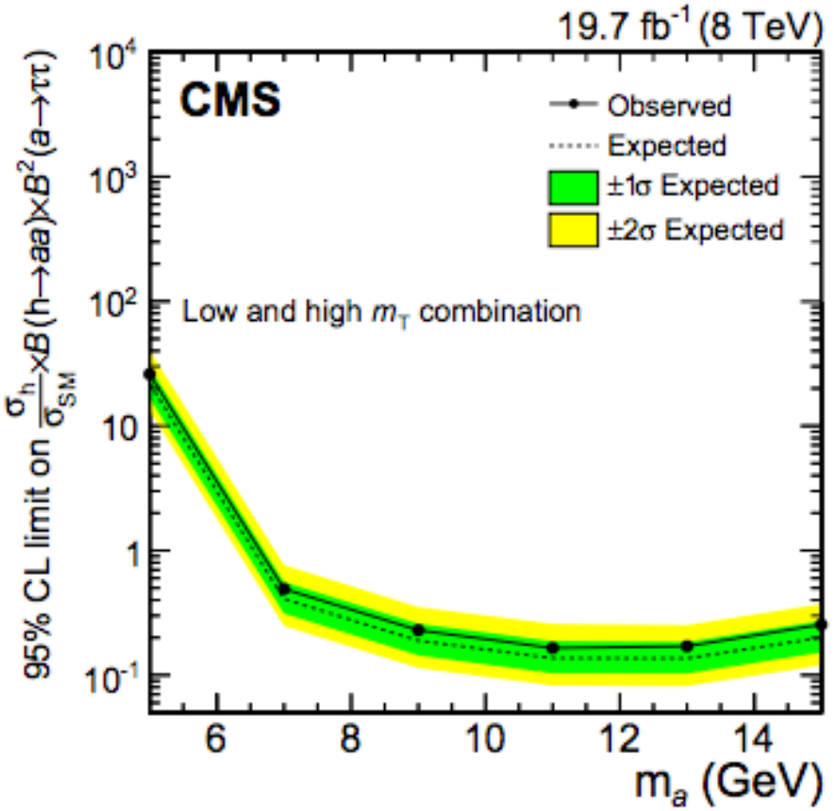
- Low mass light boson
  → dedicated algos to distinguish the overlapping τ

- To reduce QCD multi-jet background, require at least 2 muons in final state
  - other τ leptons decay to μ/e/hadrons

- 2 search regions based on m_T formed from high-p_T trigger muon and missing p_T
  → ensure high sensitivity to signal in each region
  - low m_T (≤ 50 GeV): mainly ggh
  - high m_T (> 50 GeV): equal parts ggh and Wh

- 95% CL limits on $\sigma(pp \to h)/\sigma_{SM} \times B(h \to 2a) \times B(a \to 2\tau)^2$ between 20 to 0.3 for m_a from 5 to 15 GeV

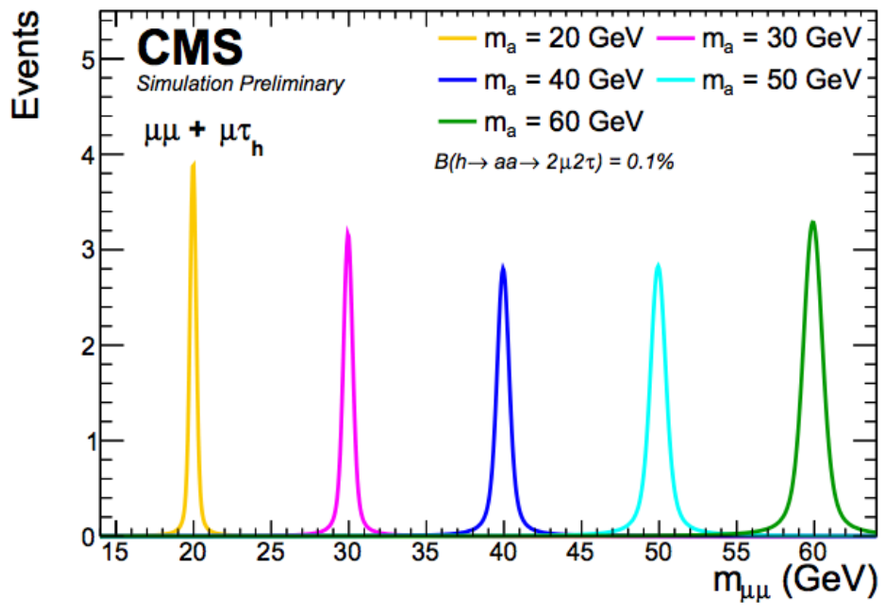




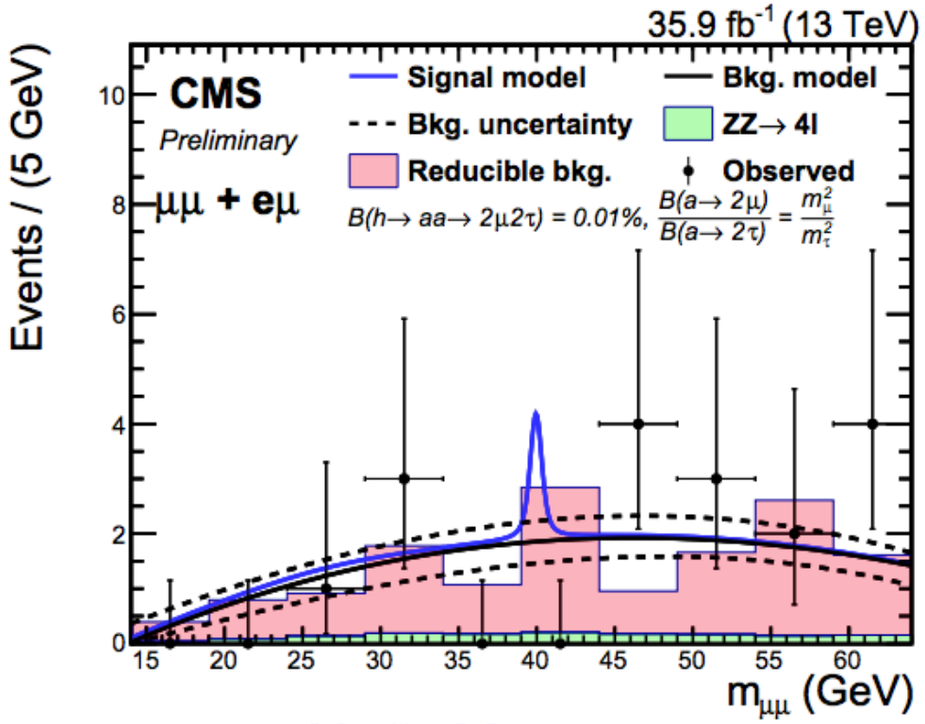
Higgs to light boson: h(125) → 2a → 2μ2τ

Run-2 (2016) data: 35.9 fb^{-1} @ 13 TeV **CMS-HIG-17-029**

- a_1 in mass range 15 to 62.5 GeV
  → good separation between tau leptons
- Four final states studied: μμτ$_e$τ$_\mu$, μμτ$_e$τ$_h$, μμτ$_\mu$τ$_h$, μμτ$_h$τ$_h$
- μμτ$_e$τ$_e$ and μμτ$_\mu$τ$_\mu$ not considered
  - smaller branching fractions
  - large contribution from pp → ZZ* → 4e/4μ
- Dominant backgrounds: ZZ, Z+jets, WZ+jets
- No significant excess over the SM prediction
- 95% CL limits on σ(pp→ h)/σ$_{SM}$ x B(h → 2a → 2μ2τ) between 2.8e-4 and 1.2e-4 for m_a from 15 to 62.5 GeV
- Interpretation in context of NMSSM and 2HDM+S



Signal dimuon invariant mass



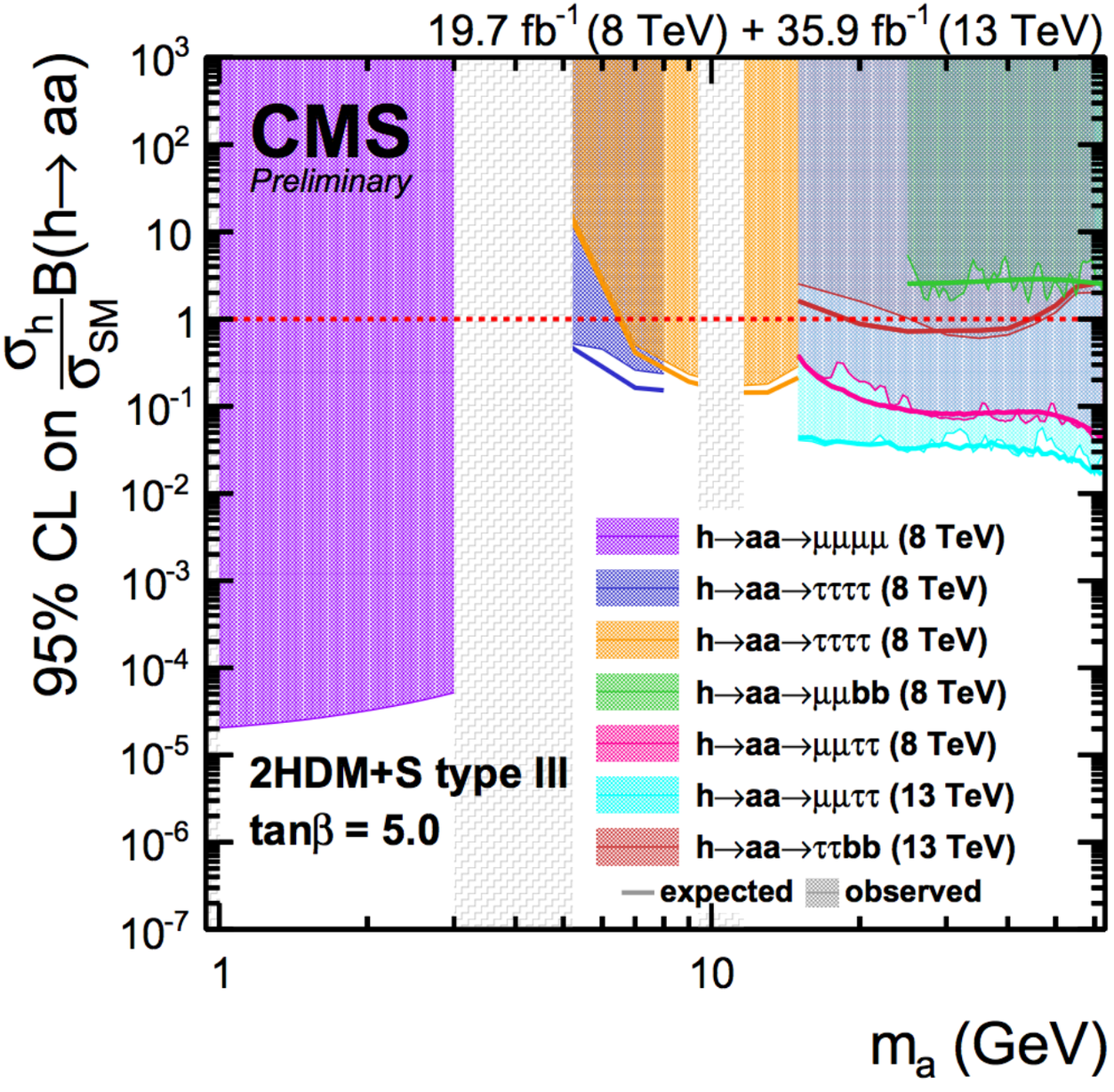
m$_a$ = 40 GeV

Higgs to light boson: combination

Run-1 (2012) + Run-2 (2016): 19.7 fb^{-1} @ 8 TeV + 35.9 fb^{-1} @ 13 TeV **CMS-HIG-17-029**

- Combined results from CMS searches: h(125) → 2a

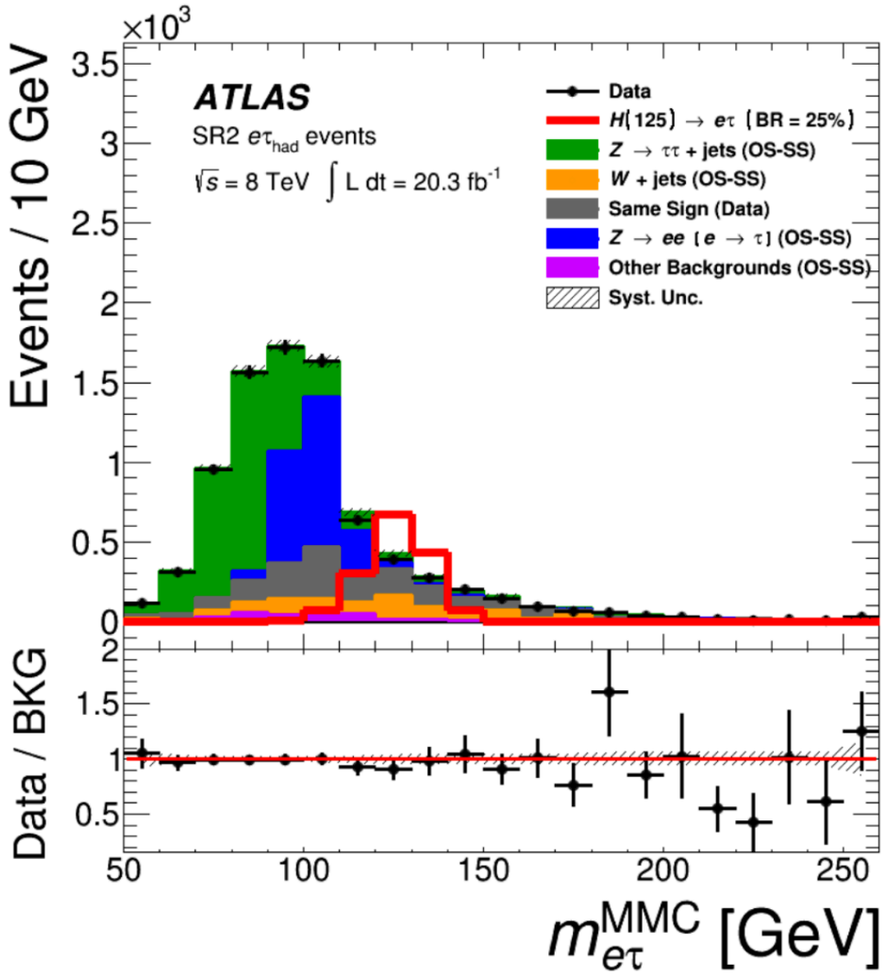
- Extra results at 13 TeV expected soon:
  - h(125) → 2a → 4μ
  - h(125) → 2a → 4τ

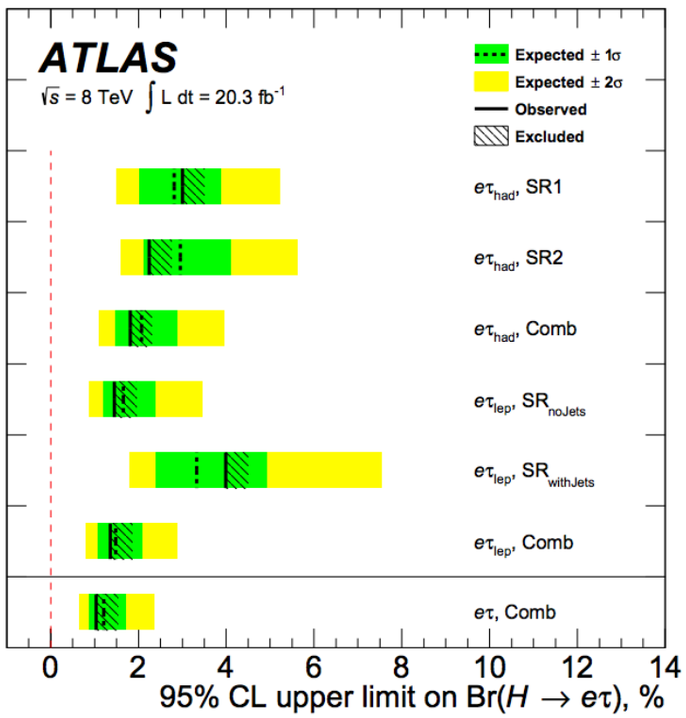


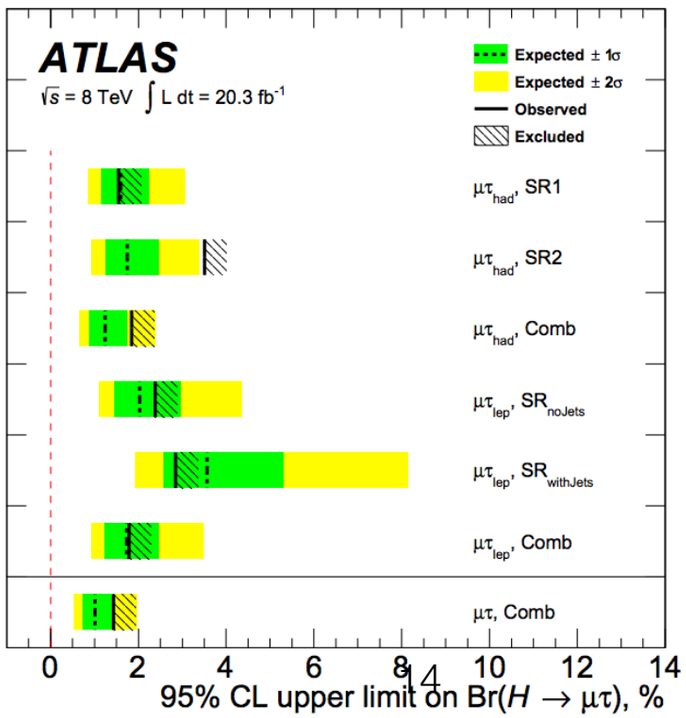
Lepton flavor violation: h(125) → eτ/μτ

Run-1 (2012) data: 20.3 fb^{-1} @ 8 TeV **ATLAS-HIGG-2015-09**

- Three searches: h → eτ$_h$, h → eτ$_{lep}$ and h → μτ$_{lep}$
- Use Missing Mass Calculator (MMC): more sophisticated version of the collinear approximation
- Largest background from Z boson production with misidentified lepton in the decay
- Results at 95% CL
  - B(h → eτ) < 1.04% (1.21% exp.)
  - B(h → μτ) < 1.43% (1.01% exp.)







Lepton flavor violation: h(125) → eτ/μτ

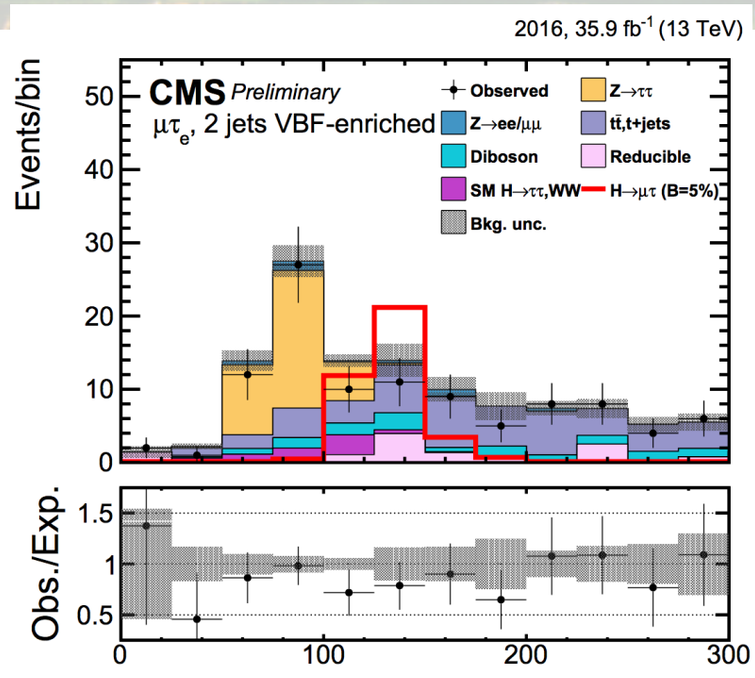
Run-2 (2016) data: 35.9 fb^{-1} @ 13 TeV **CMS-HIG-17-001**

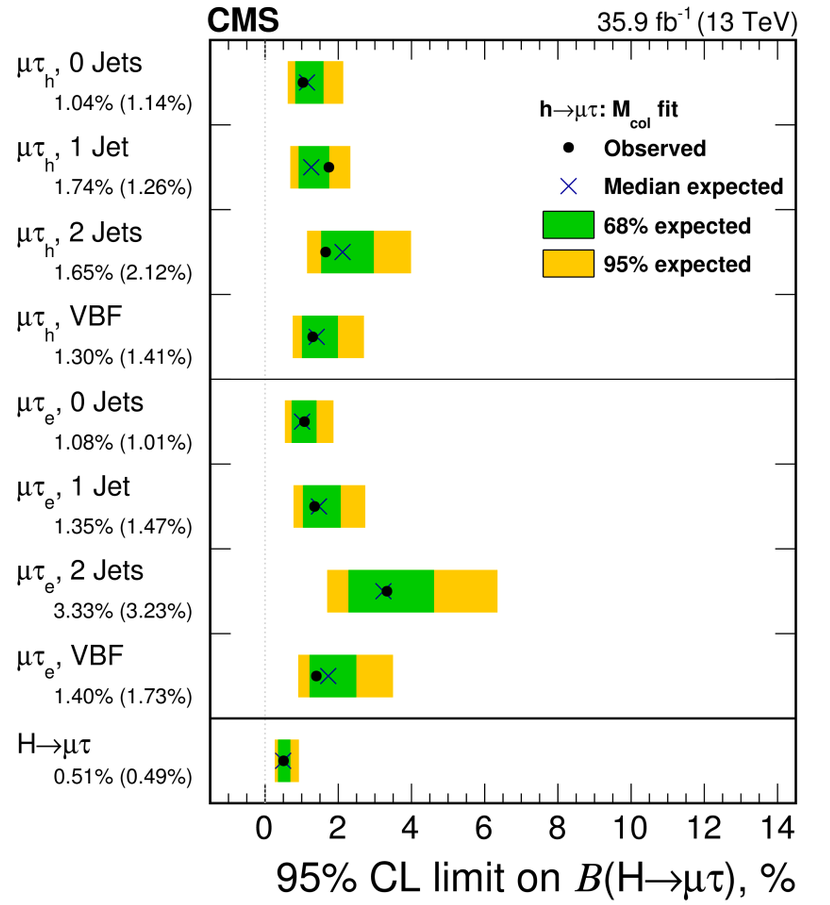
- Four decay channels: eτ$_h$, eτ$_\mu$, μτ$_h$, μτ$_e$
  - eτ$_e$ and μτ$_\mu$ not considered (large Z →ee/μμ background)

- Two complementary analyses:
  1. Template fit to collinear mass as estimated for m$_h$
  2. Boosted decision tree

- Most prominent backgrounds: Z →ττ, QCD and W+jets
  - For W+jets use the m$_T$ as discriminator
  - Smaller backgrounds: ttbar, SM Higgs decays, VV

- Results at 95% CL:
  - B(h → eτ) < 0.61% (0.37% expected)
  - B(h → μτ) < 0.25% (0.25% expected)



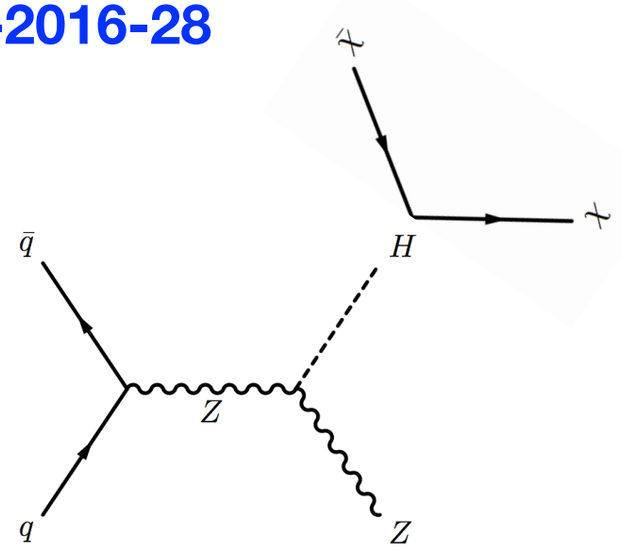


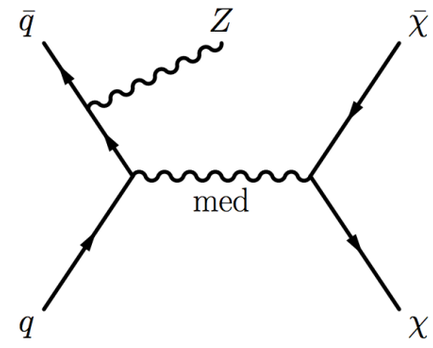
Invisible decays: ATLAS

Run-2 (2016) data: 36.1 fb^{-1} @ 13 TeV **ATLAS-HIGG-2016-28**

- ATLAS search for h→ invisible decay or dark matter candidates with associated Z→ll

- Dark matter model includes axial-vector mediator that decays to pair of WIMPs
  - Z is radiated off in ISR

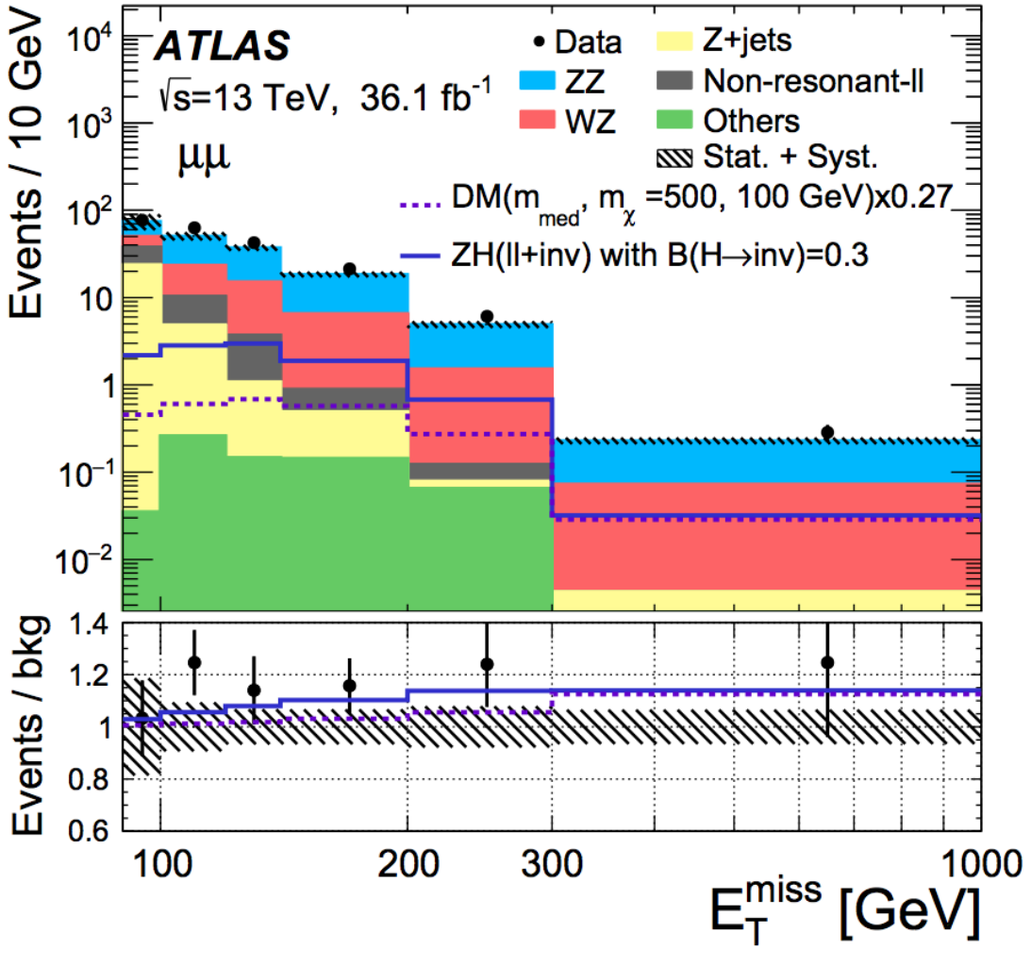




- "Cut-and-count" analysis relies on accurate understanding of missing E_T
  - Requires good understanding of leptons and jets

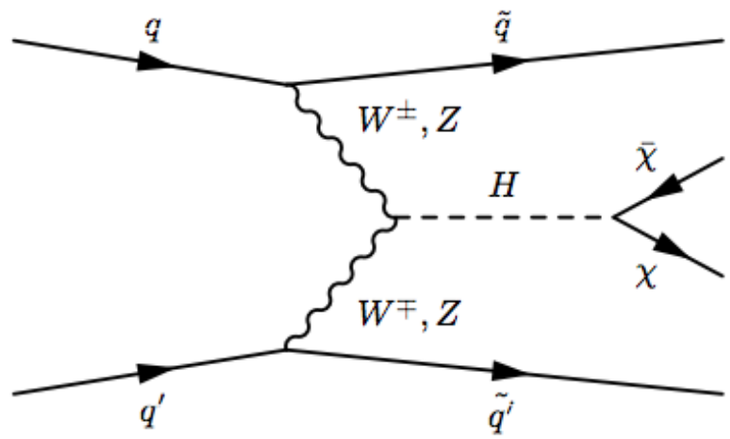
- Result at 95% CL:
  - B(h→ invisible) < 67% (39% exp.)

- Sensitivity limited due to large systematic uncertainties
  - Theory predictions qqZZ and ggZZ
  - Data-driven estimation of the WZ and Z + jets



Invisible decays: CMS

Run-2 (2016) data: 35.9 fb^{-1} @ 13 TeV **CMS-HIG-17-023**

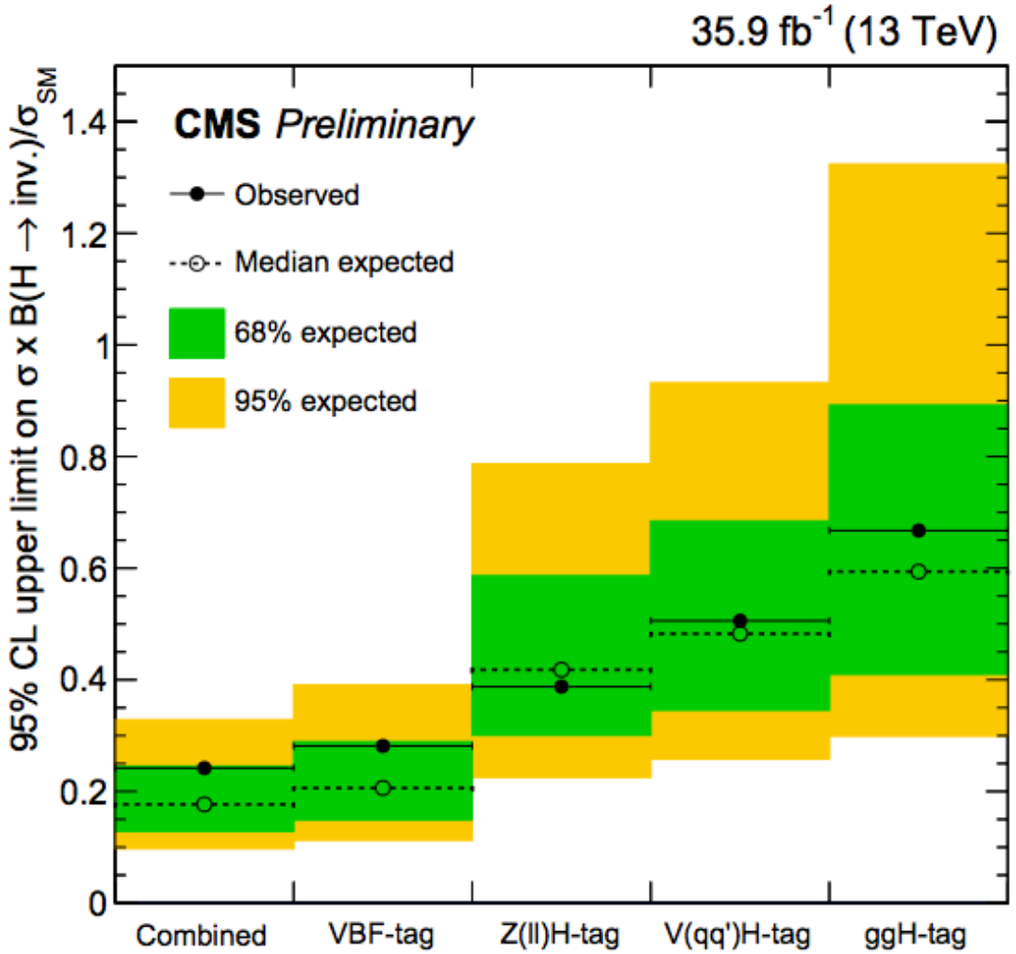


- h(125) → χχ (χ invisible) production through VBF
  - Two jets with large $\Delta\eta_{jj}$ powerful discriminator against QCD

- Two complementary analyses:
  - **Cut-and-count**: signal extraction with fit to events passing selection based on kinematic differences
  - **Shape analysis**: more relaxed selection, template to binned dijet mass

- Result (assuming SM production through VBF)
  - B(H→ invisible) < 0.28% at 95% CL (21% exp.)

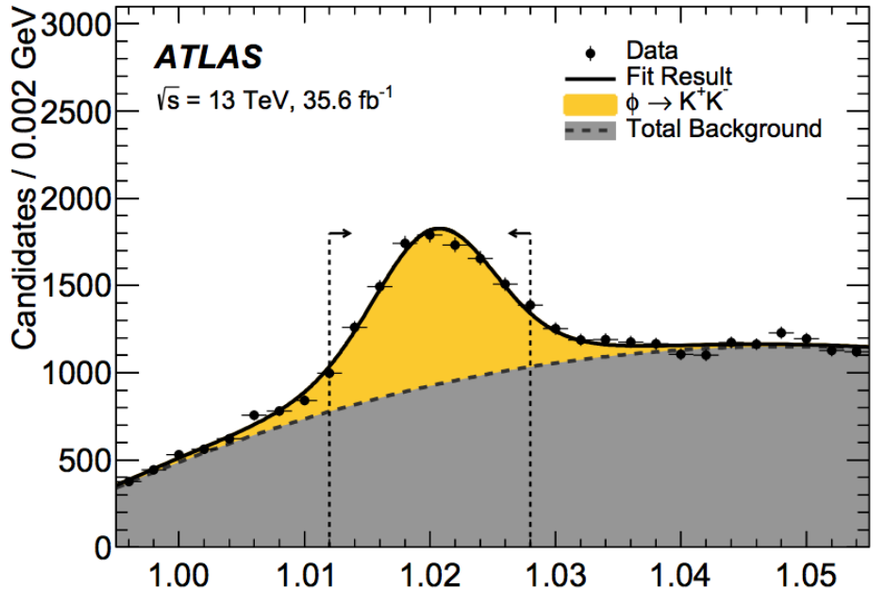
- Combination also available from searches with qqH, ZH (with Z boson decaying to pair of lepton VH (with hadronically decaying boson) and ggH modes
  - B(H→ invisible) < 24% at 95% CL (24% exp.)

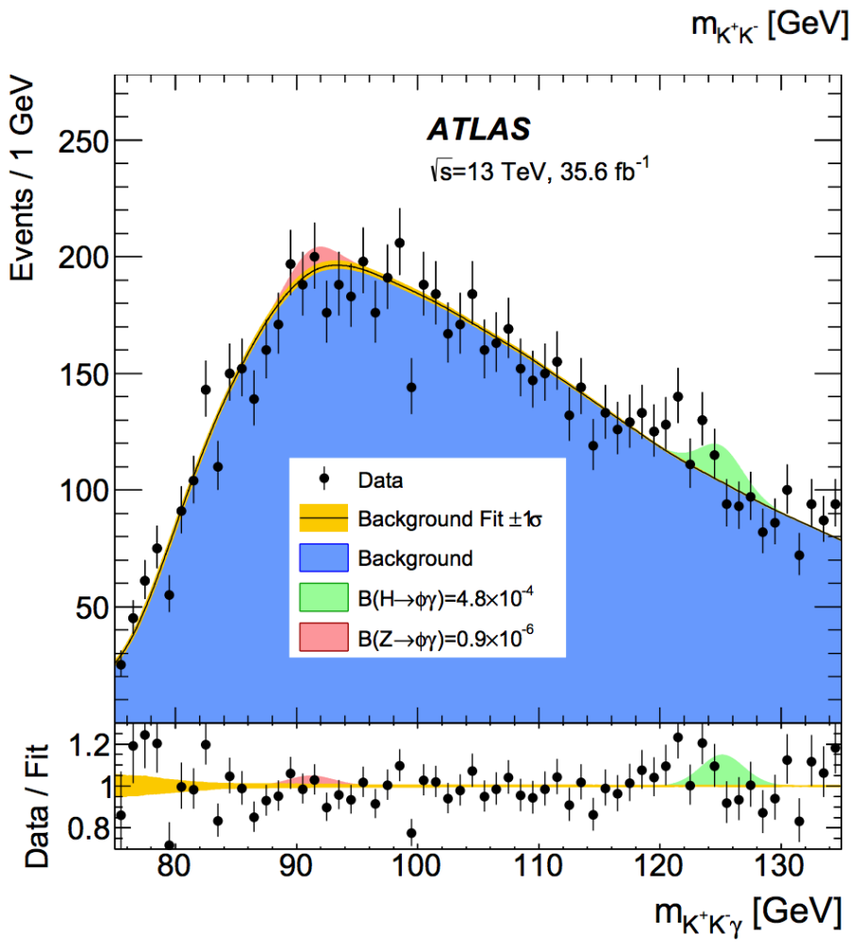


Rare decays: h(125) → ργ/φγ

Run-2 (2016) data: 35.6 fb^{-1} @ 13 TeV **ATLAS-HIGG-2016-13**

- φ and ρ meson decay to pairs of K^+K^- and $\pi^+\pi^-$
  - Reconstruct φ and ρ meson mass
- Events are selected with dedicated triggers derived from the τ-lepton trigger
- Require an isolated photon with $p_T > 35$ GeV and two isolated tracks
- Background: inclusive photon + jet or multijet processes
  - Use $K^+K^-\gamma$ and $\pi^+\pi^-\gamma$ enriched sample
  - Data-driven background determination with templates
- Results at 95% CL
  - $B(h \to \phi\gamma) < 4.8 \times 10^{-4}$ (4.2 x 10^{-4} exp.)
  - $B(h \to \rho\gamma) < 8.8 \times 10^{-4}$ (8.4 x 10^{-4} exp.)

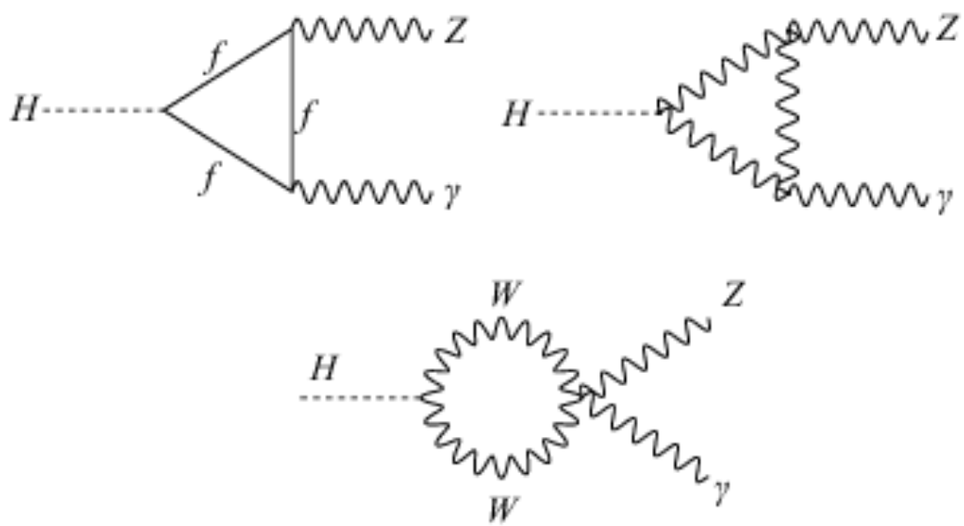


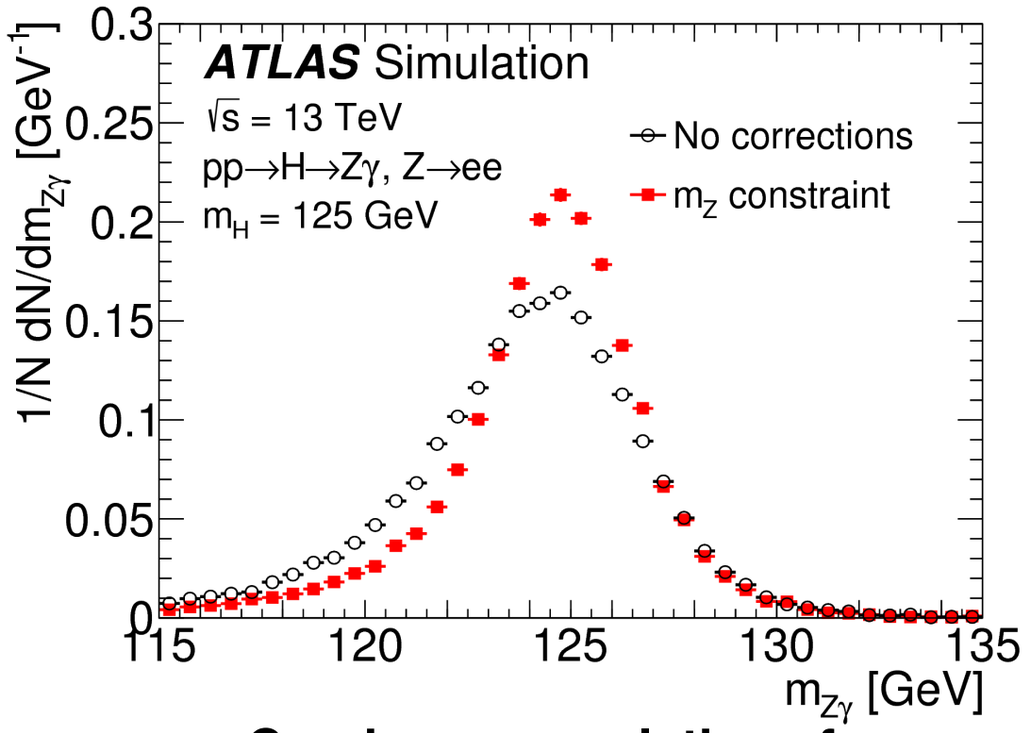


Rare decays: h(125) → Zγ →eeγ/μμγ

Run-2 (2015+2016) data: 36.1 fb^{-1} @ 13 TeV **ATLAS-HIGG-2016-14**

- h(125) → Zγ through ggh, VBF or Vh
- Event selection: Two isolated leptons and an isolated photon
- Analysis is limited by small branching fraction B(h → Zγ) x B(Z →ll)
  - B(h → Zγ) similar to B(h → γγ), but B(Z →ll) only 3.63%
- Can fully reconstruct the invariant mass of the Higgs boson
  - Apply final-state-radiation corrections + constrained kinematic fit to Z boson mass
- Result:
  - B(h → Zγ) < 1% at 95% CL





Good mass resolution of dilepton-photon system

Plans for the Yellow Report

- Plans were outlined in HL-LHC Higgs Yellow Report Preparation meeting: https://indico.cern.ch/event/714119/

- Preliminary wishlists:

ATLAS plans for Yellow Report studies
h → invisible
h(125) → Zγ h(125) → ργ/φγ (Extrapolation of Run-2 result should be done by summer)
No plans for studies on exotic decays of the Higgs boson

CMS plans for Yellow Report studies
h → invisible
h(125) → φφ → 4jets (φ long-lived boson, https://arxiv.org/pdf/1705.04321.pdf) h(125) → $2n_1$ → $2\gamma_D 2n_D$ → $4\mu 2n_D$ (see muon TDR CMS-TDR-17-003) h(125) → $Z_d Z_d$ → 4l
LFV Higgs decays

Summary

- Study of exotic, invisble and rare decays is a very exciting field to explore the properties of the SM(?) Higgs boson!
- Many channels and final states have been studied by ATLAS and CMS
- Yellow Paper wish lists for ATLAS and CMS are taking shape
- Looking forward to including the projections in the Yellow Paper

Backup

Higgs to light boson:

$h(125) \rightarrow 2a_1 \rightarrow 4\mu$, $h(125) \rightarrow 2n_1 \rightarrow 2\gamma_1 2n_D \rightarrow 4\mu 2n_D$

Run-2 (2015) data: 2.8 fb^{-1} @ 13 TeV **CMS-HIG-16-035**

- CMS search for light boson decays to pair of opposite-sign muons

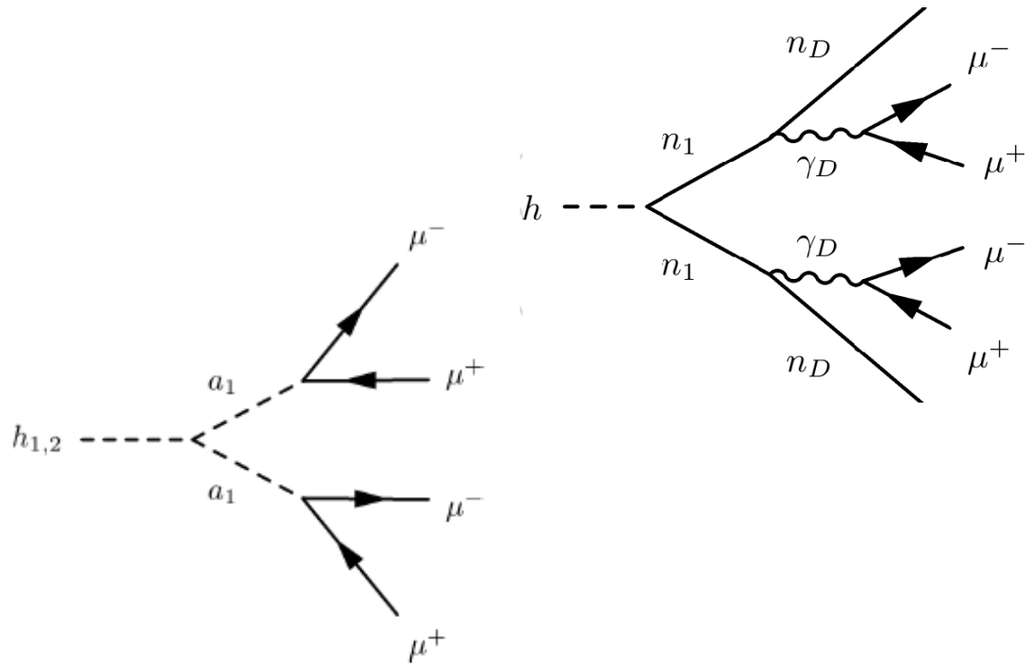
- Two different benchmark models:
  - NMSSM: a_1 is a pseudo-scalar boson
  - Dark SUSY: γ_D is a vector boson that mixes kinetically with the SM photon

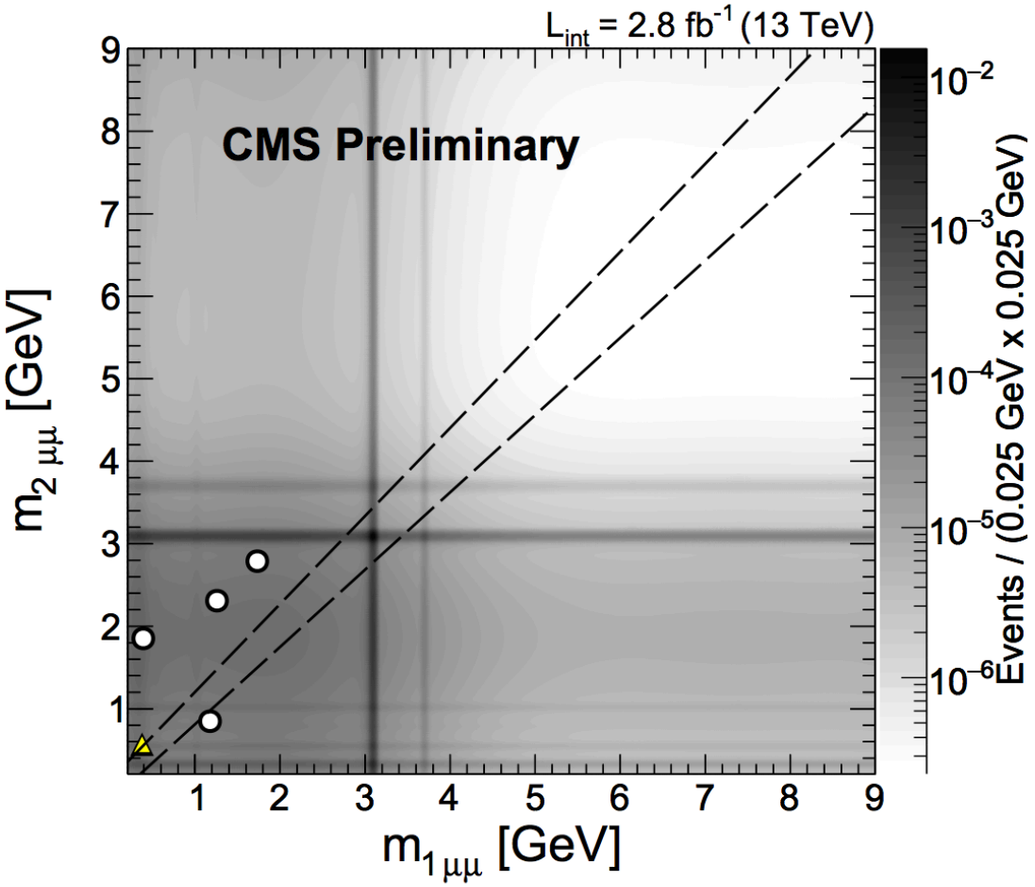
- Kinetic mixing between γ and γ_D can result in long-lived dark photons
  - Detector registers pairs of displaced muons in the muon system

- Light boson masses:
  - m(a_1): 0.25 - 3.55 GeV
  - m(γ_D): 0.25 - 8.5 GeV

- Search for enhancement in selected events over background in 2D dimuon-dimuon mass spectrum

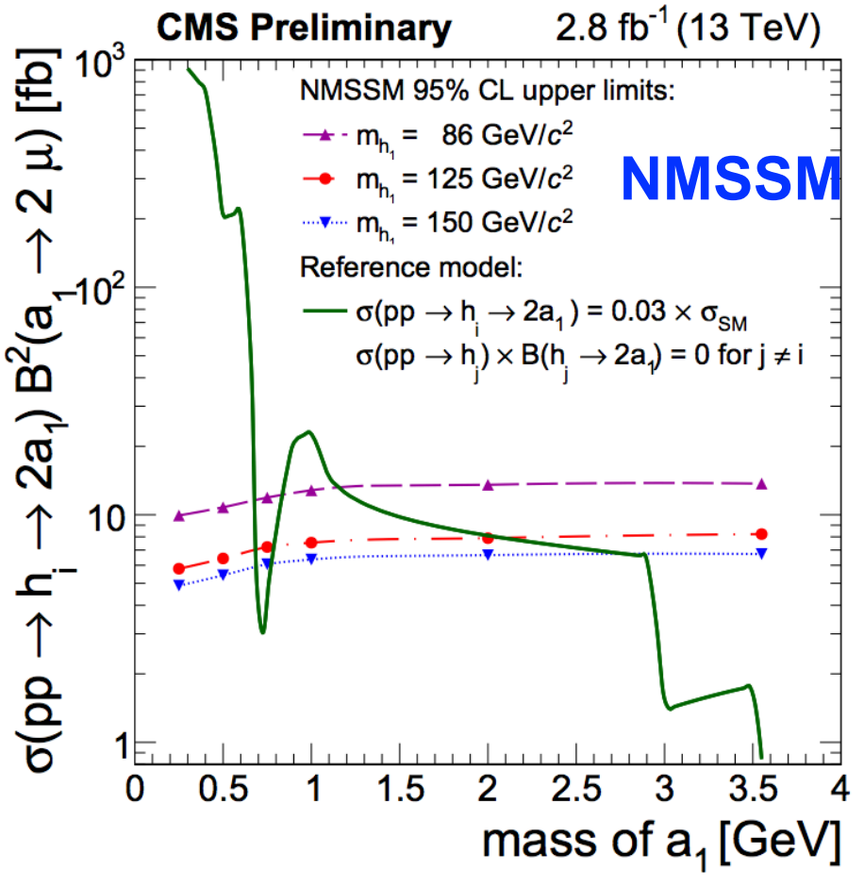
- No significant excess of events over the SM background prediction

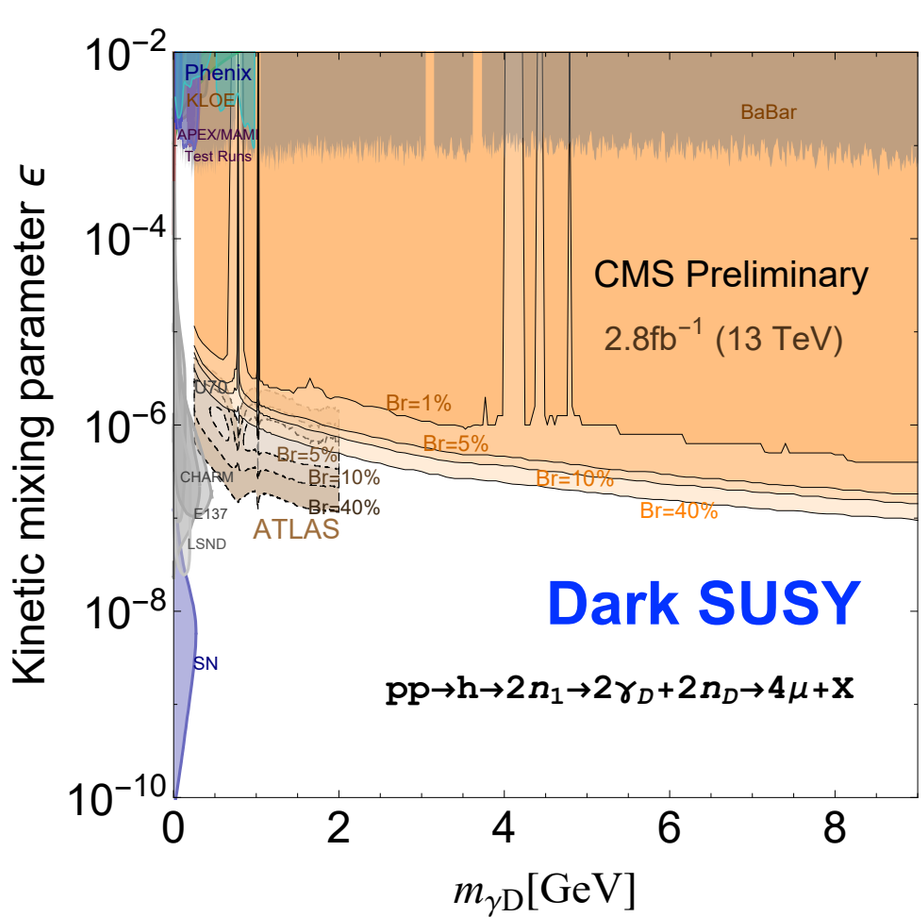


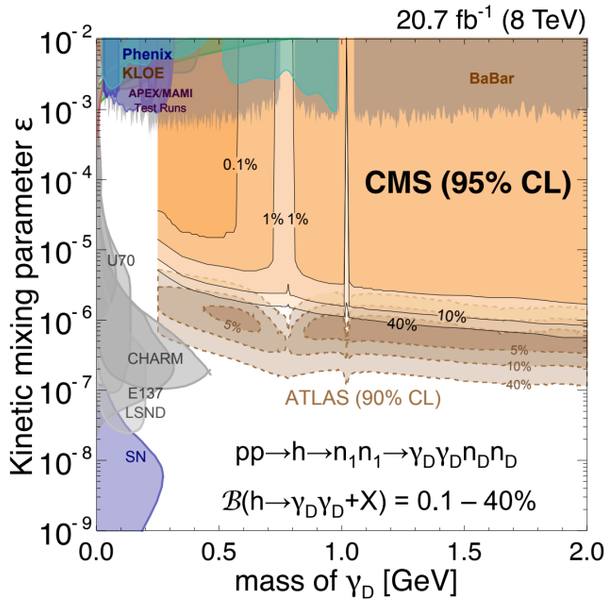


Higgs to light boson:
$h(125) \rightarrow 2a_1 \rightarrow 4\mu$, $h(125) \rightarrow 2n_1 \rightarrow 2\gamma_1 2n_D \rightarrow 4\mu 2n_D$

- Model independent limit on $\sigma(pp \rightarrow h \rightarrow 2a + X) \times B(a \rightarrow 2\mu)^2 \times$ GEN-level acceptance
- Interpreted in context of NMSSM and dark SUSY
  - Limits on dark SUSY greatly improved (both in mass and coupling) compared to 8 TeV results



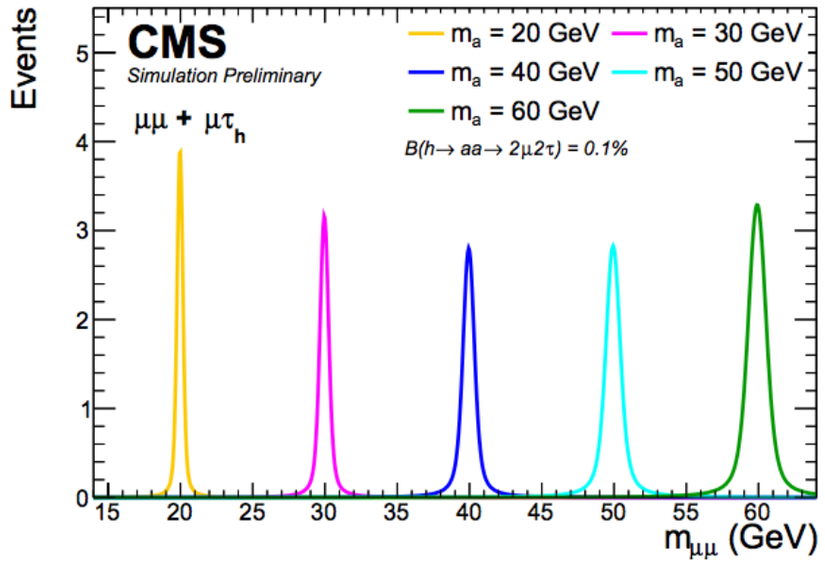




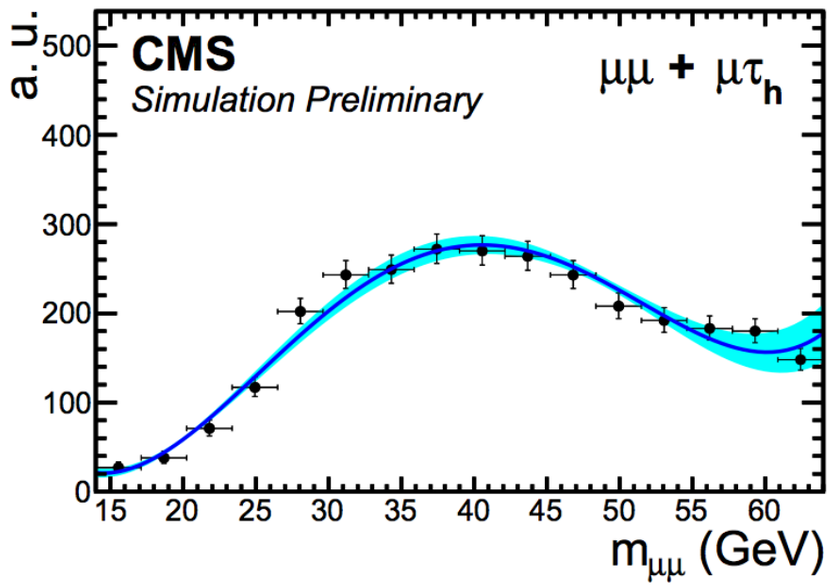
Higgs to light boson: h(125) → 2a → 2μ2τ

Run-2 (2016) data: 35.9 fb^{-1} @ 13 TeV **CMS-HIG-17-029**

- CMS Search for a_1 with mass in range $15 < m_a < 62.5$ GeV
  - Context of NMSSM and 2HDM+S
  - Lowest mass point (15 GeV) was chosen from requirement to have good signal selection efficiency
- a_1 relatively heavy → good separation between tau leptons
- Four final states studied:
  - $\mu\mu\tau_e\tau_\mu$, $\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$, $\mu\mu\tau_h\tau_h$ (τ_h: tau decaying to hadrons)
  - $\mu\mu\tau_e\tau_e$ and $\mu\mu\tau_\mu\tau_\mu$ not considered
    - smaller branching fractions
    - large contribution from irreducible pp → ZZ* → 4e and pp → ZZ* → 4μ
- Selections:
  - 2 muons with p_T: 18-9 GeV
  - Well separated from electrons or hadronic jets
  - m(visible) ~< 120 GeV to suppress background
- Dominant background from ZZ and reducible processes (Z+jets, WZ+jets)



Signal dimuon invariant mass

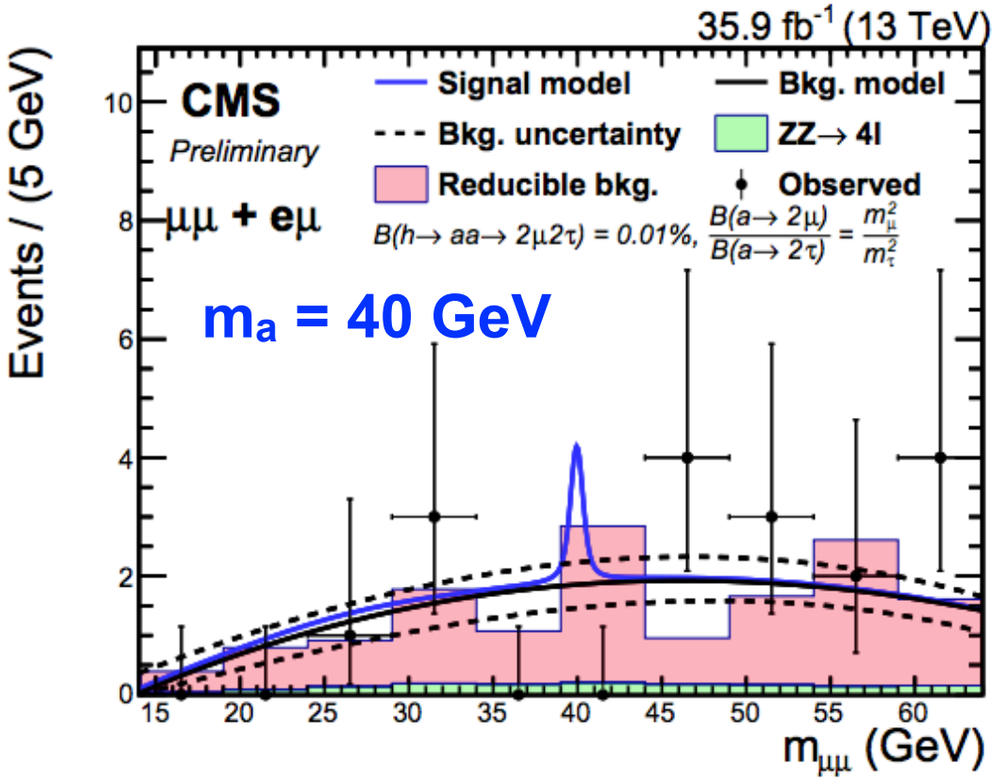


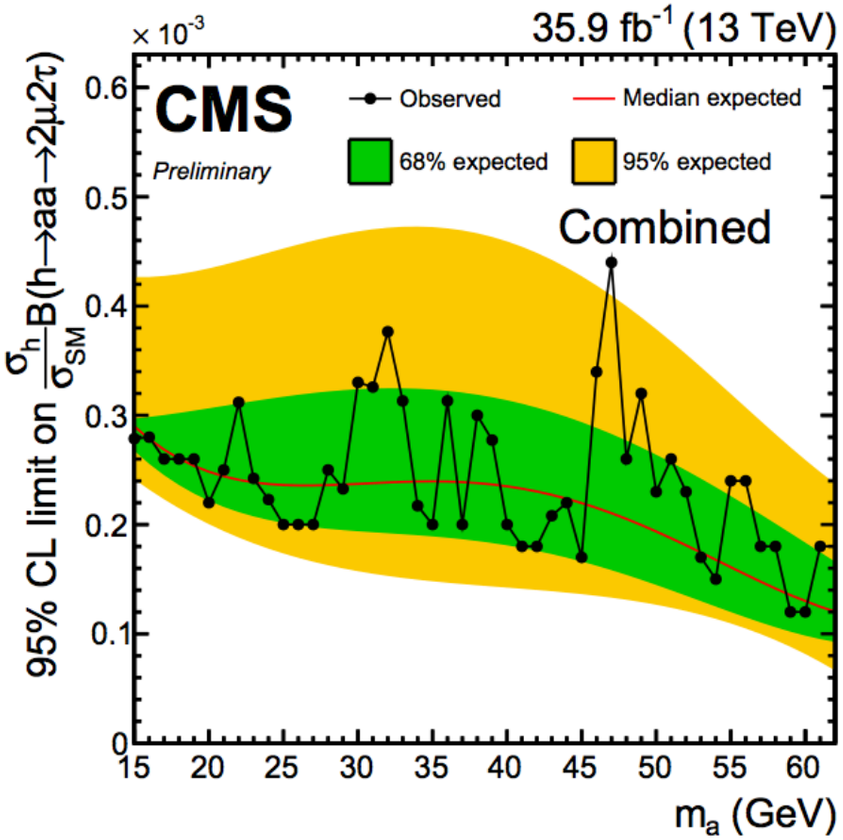
Background dimuon invariant mass

25

Higgs to light boson: h(125) → 2a → 2μ2τ

- No significant excess of events over the SM background prediction
- Results are interpreted as upper limits on the production of pp → relative to the SM Higgs boson production, scaled by B(h → 2a → 2μ2τ)
  - Run-1 results were interpreted in terms of B(h → 2a) x B(a →2τ)^2 **(CMS-HIG-15-011)**
- Limits between 2.8e-4 and 1.2e-4 at 95% CL for m_a from 15 to 60 GeV
- Interpretations are also provided in context of 2HDM+S models

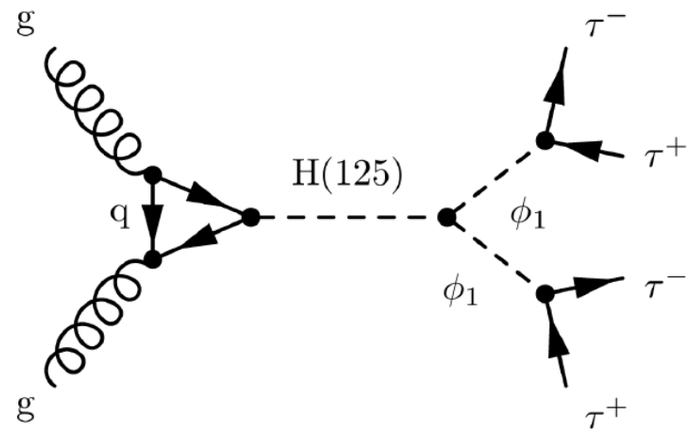




Higgs to light boson: h(125) → 2a → 4τ

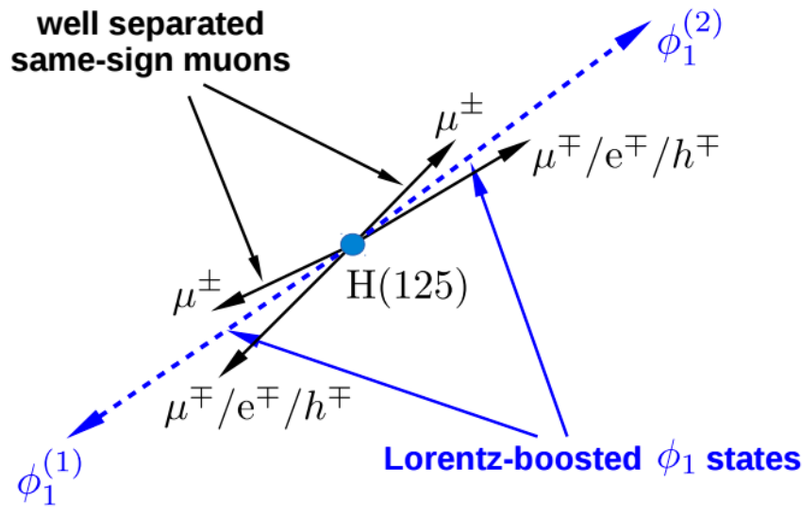
Run-1 (2012) data: 19.7 fb^{-1} @ 8 TeV **CMS-HIG-14-019** **CMS-HIG-14-022**

- CMS searches for a pseudo-scalar in mass range 5 to 15 GeV decaying to pairs of tau leptons
- Relatively light boson → boosted tau leptons → dedicated algorithms to distinguish the overlapping taus



- Tau decays into μ/e/hadrons
- To reduce QCD multi-jet background, require at least 2 muons in final state
- 2 search regions defined based on m_T formed from a high-p_T trigger muon and the missing p_T
  → ensure high sensitivity to signal in each region
  - low m_T (≤ 50 GeV): mainly ggh
  - high m_T (> 50 GeV): equal parts ggh and Wh

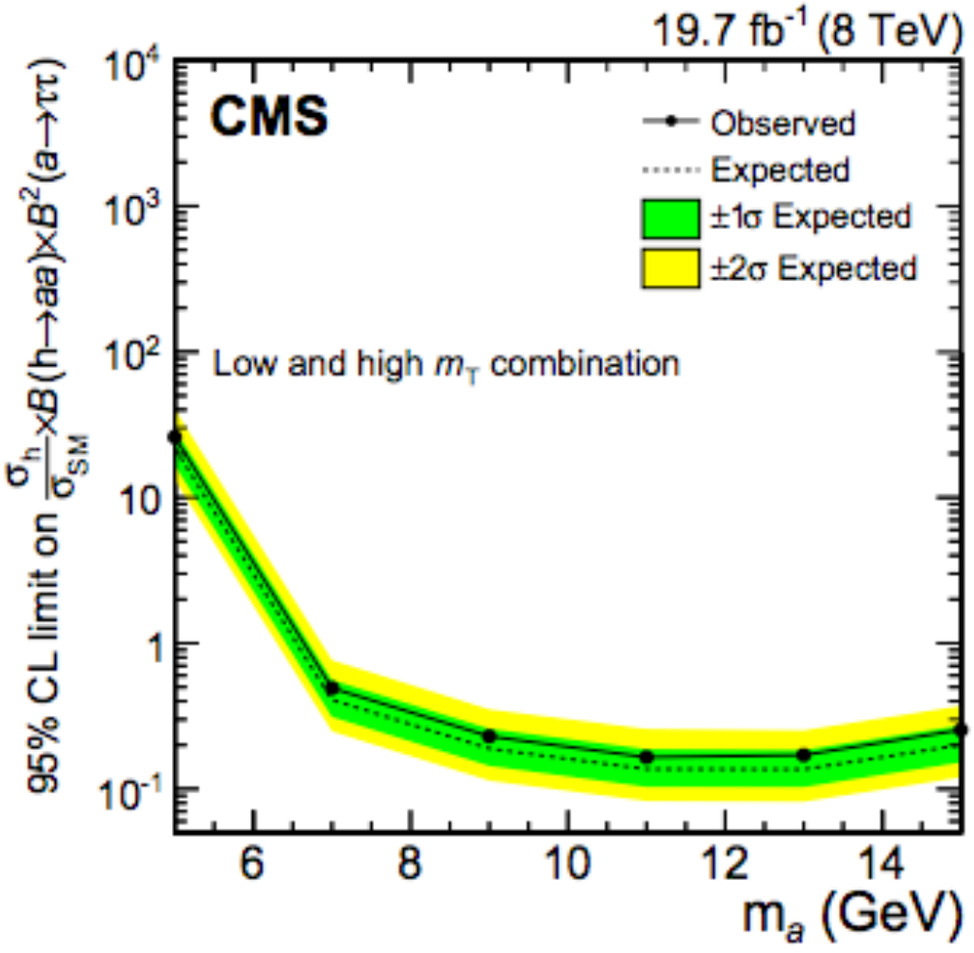
$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\mu_{\mathrm{trg}}} E_{\mathrm{T}}^{\mathrm{miss}} [1 - \cos \Delta\phi(\mu_{\mathrm{trg}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})]},$$



Higgs to light boson: h(125) → 2a → 4τ

- Do a counting experiment on tau pair invariant mass m(ττ) in each search region
- SM production cross sections are taken for ggh, Vh, and VBF processes
- Expected yields in each search region shown below (assuming B(h → 2a) x B(a →2τ)^2 = 0.1)

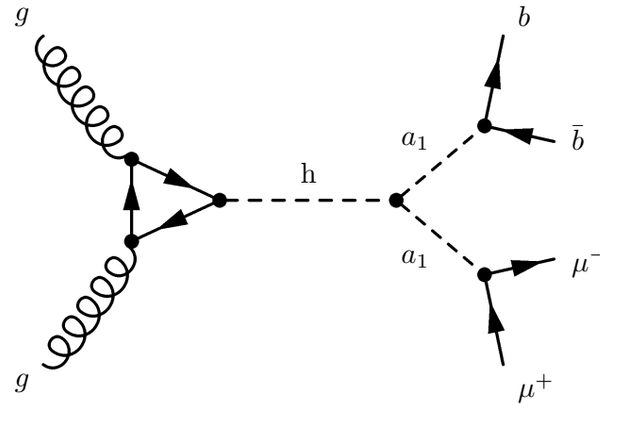
	$m_T \leq 50\,\text{GeV}$	$m_T > 50\,\text{GeV}$
ggh	4.6 ± 0.3	0.8 ± 0.1
Wh	0.27 ± 0.02	0.70 ± 0.03
Zh	0.068 ± 0.005	0.19 ± 0.01
VBF	0.51 ± 0.03	0.09 ± 0.01
SM background	$5.4 \pm 1.0\,(\text{stat})^{+4.2}_{-4.6}\,(\text{syst})$	$6.1 \pm 1.6\,(\text{stat})^{+3.7}_{-3.6}\,(\text{syst})$
Observed	7	14



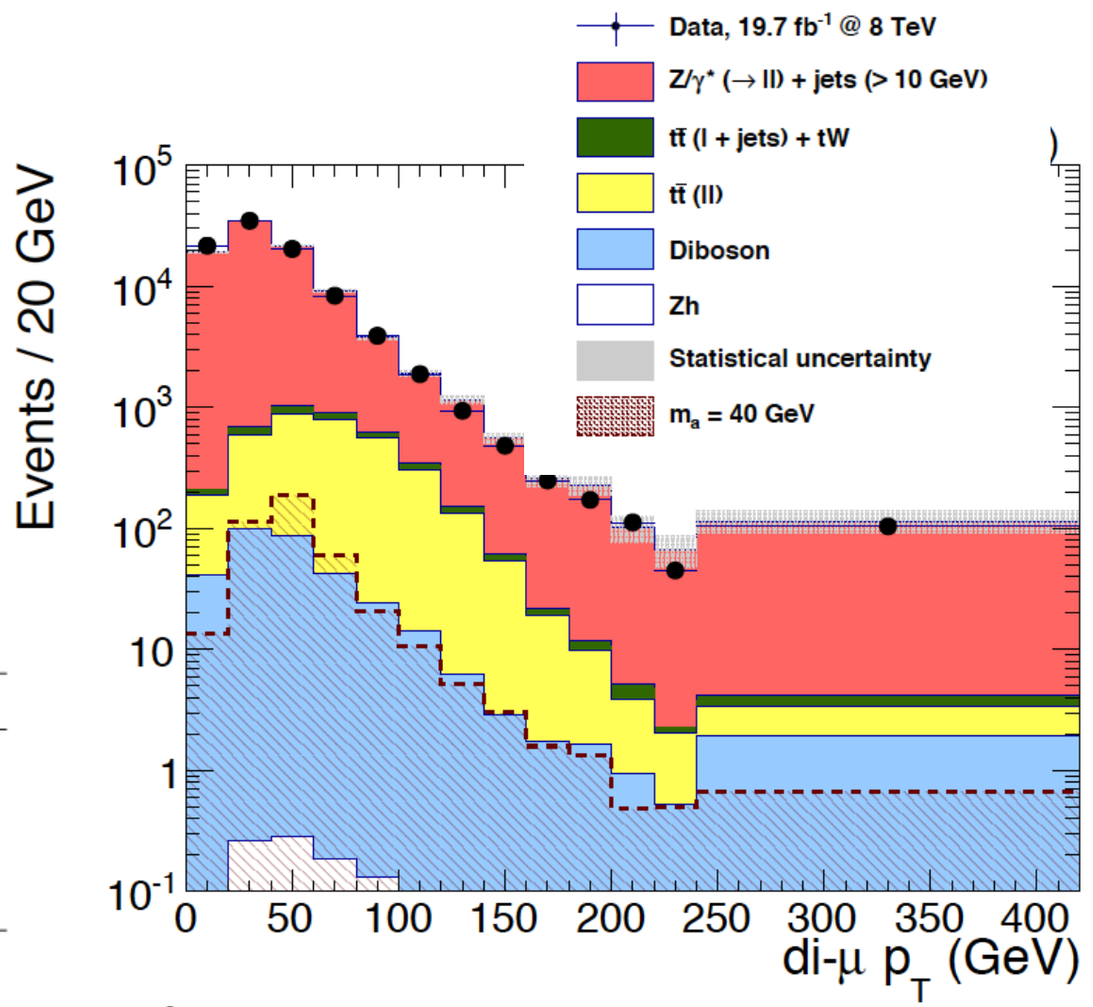
- No significant excess of events over the SM background prediction
- Results are interpreted as upper limits on the production of pp→ h relative to the SM Higgs boson production, scaled by B(h → 2a) x B(a →2τ)^2
- Limits between 20 and 0.3 at 95% CL for m_a from 5 to 15 GeV

Higgs to light boson: h(125) → 2a → 2μ2b

Run-1 (2012) data: 19.7 fb^{-1} @ 8 TeV **CMS-HIG-14-041**



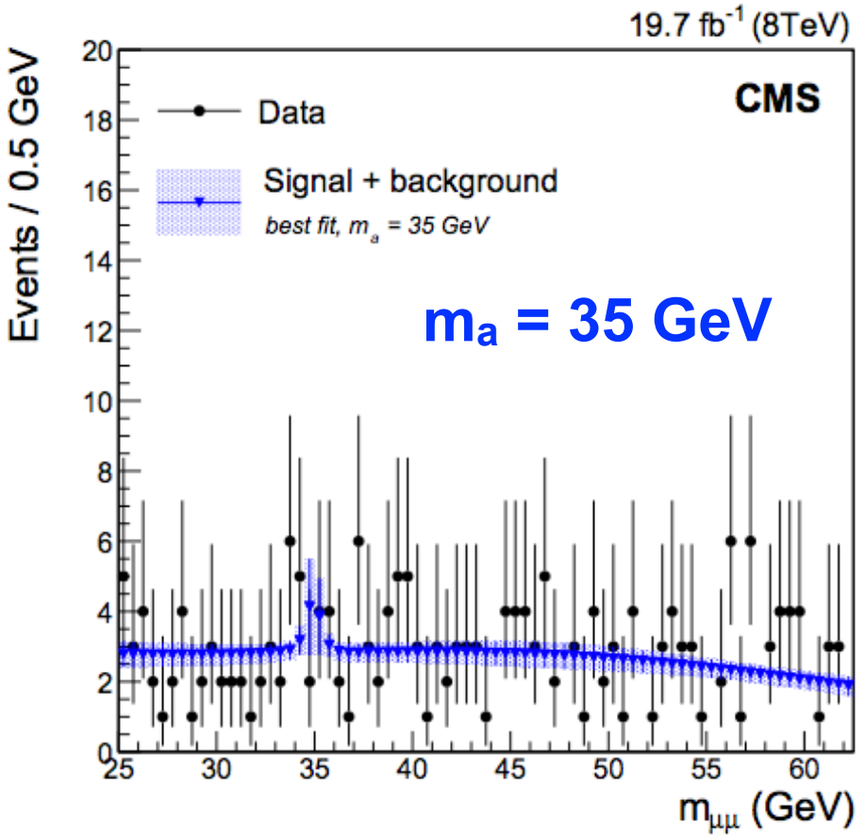
- Search for a with mass in range 25 < m_a < 62.5 GeV
- Selection:
  - 2 opposite sign muons with $p_{T,1}$ > 24 and $p_{T,2}$ > 9 GeV
  - 2 b-jets with p_T > 15 GeV
  - |m(μμbb) – 125 GeV| < 25 GeV
- Good agreement between MC and data
- Signal yield is calculated assuming 100% ggh production and B(h → 2a) = 10% and B(2a → 2b2μ) = 1.7e-3 (type-3 2HDM+S with tan β = 2)

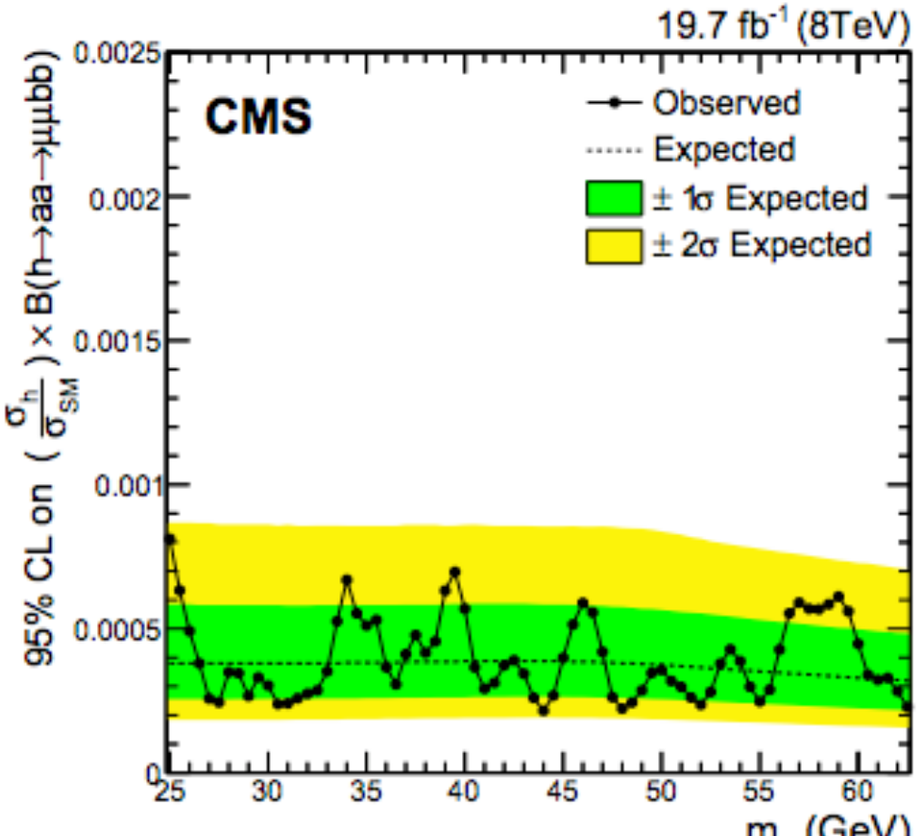


	Z/γ^*+jets ($m_{\ell\ell} > 10$ GeV)	$t\bar{t}$ ($\ell\ell$)	Other
Backgrounds	210 ± 35	22 ± 1	3 ± 1
Total	235 ± 35		
Data	252		

	$m_a = 30$ GeV	$m_a = 40$ GeV	$m_a = 50$ GeV	$m_a = 60$ GeV
Signal	1.18	0.97	1.11	1.49

Higgs to light boson: h(125) → 2a → 2μ2b

- No significant excess of events over the SM background prediction
- Smooth shape + gaussian to model dimuon mass distribution was used for signal search and limit setting
- Observed and expected limits on h boson production normalized to the SM prediction times B(h → 2a → 2b2μ) ~ 0.04%
- 



Lepton flavor violation: h(125) → eμ

Run-1 (2012) data: 19.7 fb^{-1} @ 8 TeV **CMS-HIG-14-040**

- Most prominent background
  - Drell-Yan
  - Tau lepton pairs
  - Electroweak diboson production
- No excess over SM prediction
- Results at 95% CL:
  - B(h → eμ) < 0.048% (0.035% expected)