Searches for exotic Higgs boson decays at CMS

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On behalf of the CMS Collaboration

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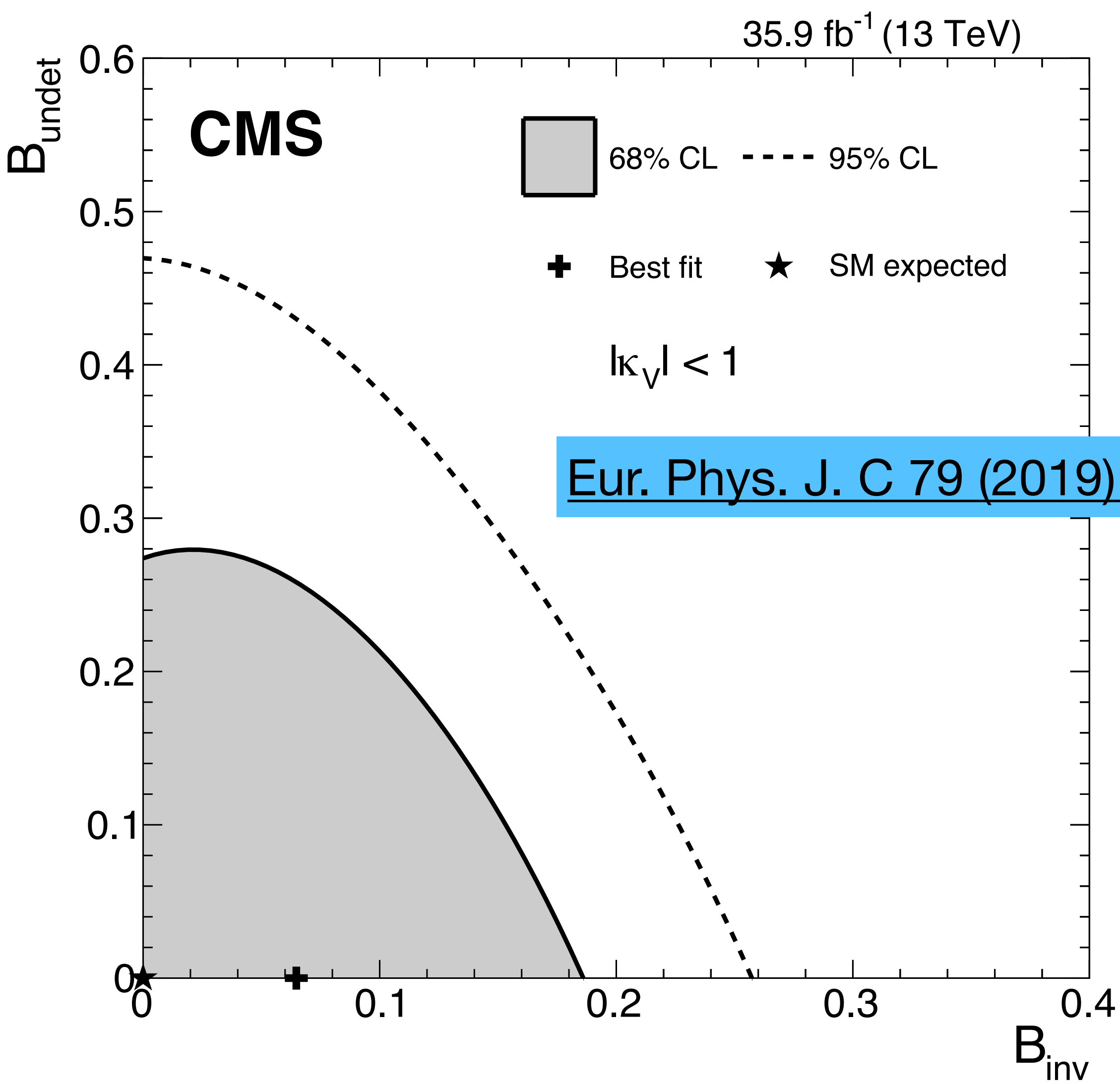
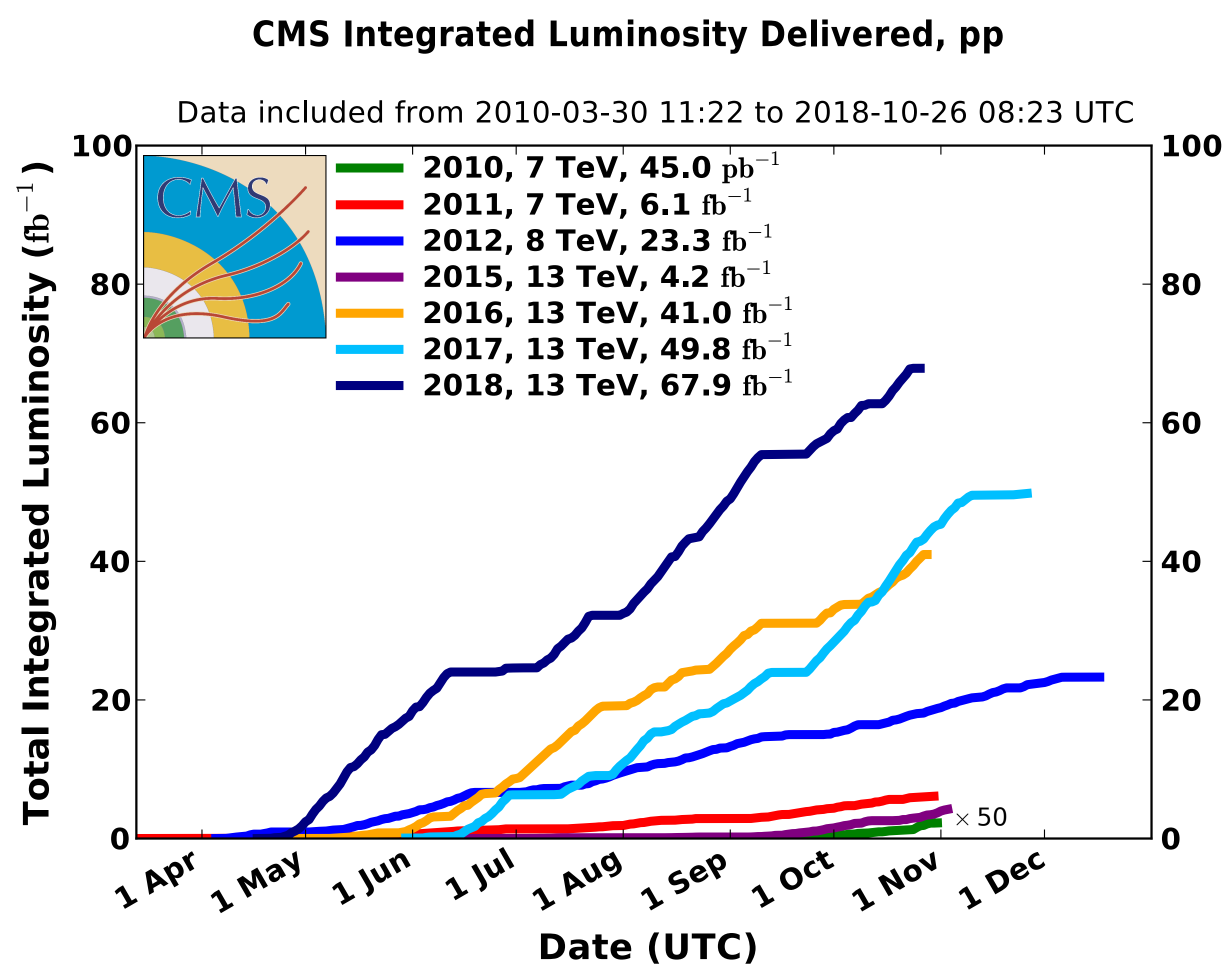
Motivation

- Higgs boson (125 GeV — scalar sector):
  - Discovery in 2012 completed the Standard Model (SM) theory
  - Measurements of Higgs coupling to SM particles consistent with predictions for the moment
  - Beyond Standard Model decays (BSM) not completely excluded by current physics limits
    - Deviations from the SM predictions might give a hint of BSM
    - Upper limits of branching ratio of H→ undet (assuming $B_{inv} = 0$) as 47% at 95% confidence level have been determined with CMS RunII results



Eur. Phys. J. C 79 (2019) 421

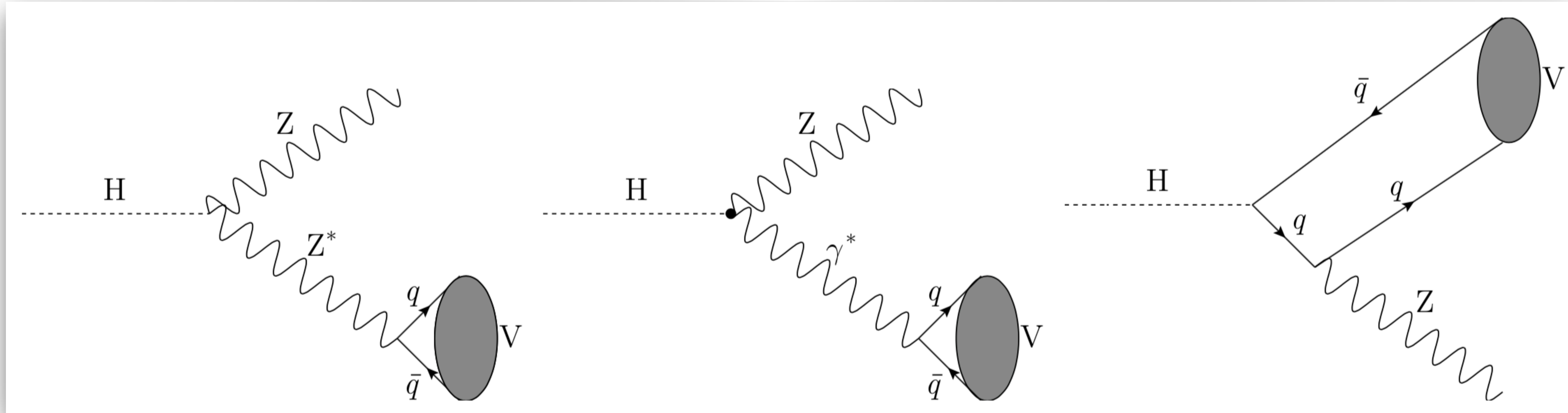


CMS searches for exotic & rare decays of Higgs boson

- H → $\mu\mu$: CMS-HIG-19-006 (talk given by Vukasin Milosevic)
- H → J/ψ J/ψ
- H → cc
- H → YY
- **H → Z + ρ(770) / ϕ(1020)**
- **H → aa → 2μ2τ**
- H → aa → 4μ
- H → aa → 4τ
- H → aa → 2μ2b
- H → aa → 2τ2b
- **H → ZX & H→XX (X = dark photon)**
- H → invisible: CMS-EXO-19-003 (talk given by Vukasin Milosevic)
- H → invisible + photon: CMS-EXO-19-005 (ZH), CMS-EXO-20-005 (VBF) (talk given by Raman Khurana)
- H → μτ & H → eτ (lepton flavor violation)

$H \rightarrow Z + \rho(770) / \phi(1020)$

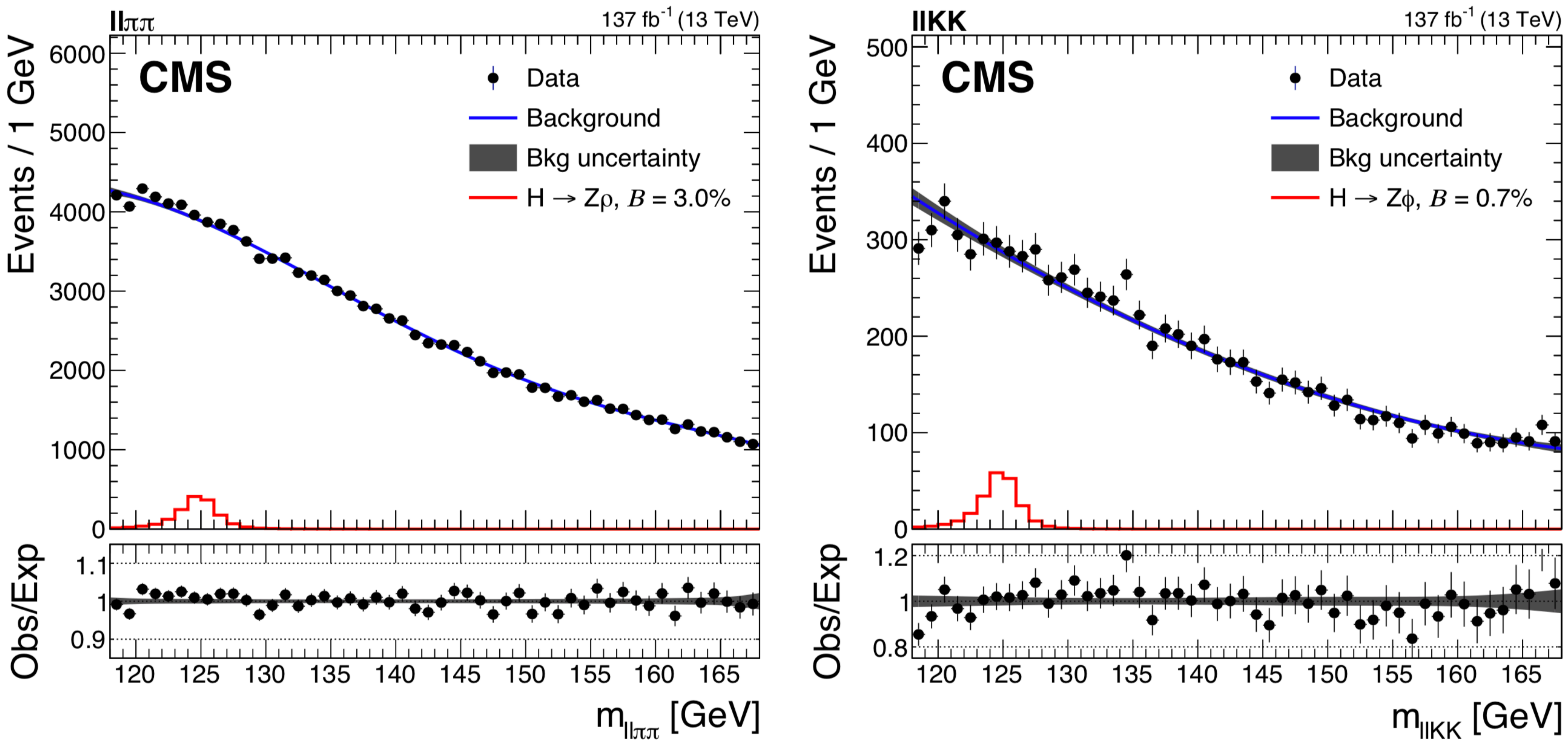
arXiv:2007.05122



- These processes provide with important information about Yukawa couplings between Higgs boson and light flavor fermions
- Branching fraction:
  - $B(H \rightarrow Z\rho) = (1.4 \pm 0.1) \times 10^{-5}$
  - $B(H \rightarrow Z\phi) = (4.2 \pm 0.3) \times 10^{-6}$
- Signal samples were generated at next-to-leading order
- The selected events with two leptons (from Z boson decay) + two reconstructed isolation tracks

H → Z + ρ(→π±) / ϕ (→ K±)

arXiv:2007.05122



- The signal is modeled by a binned template
- Chebyshev polynomials are used to describe the backgrounds
- A maximum likelihood fit of signal and background models is performed
- The largest uncertainty is from tracking efficiency (4.6% - 4.8%)

- The first experimental limits are set in the two decay channels in 95% CLs:
  - Zρ: 1.04% - 1.31%
  - Zϕ: 0.31% - 0.4%

Exotic decays in 2HDM + S

- **Two-Higgs-Doublet Model (2HDM)**: two doublets of scalar fields (ϕ_1,ϕ_2) in the SM Lagrangian
  - Type-2 : **minimal supersymmetry model (MSSM)**
  - Type-3**: enhanced couplings to leptons at large tanβ**

- Further extension: **a scalar singlet (2HDM + S)**
  - Type-2 : **Next-to-minimal-supersymmetry-model (NMSSM)**
  - **Light pseudoscalars are natural**

- Symmetry breaking → seven physical states are predicted:
  - Neutral scalars: h_1, h_2, h_3
  - Neutral pseudoscalars: a_1, a_2
  - Charged scalars: $H^{\pm}$

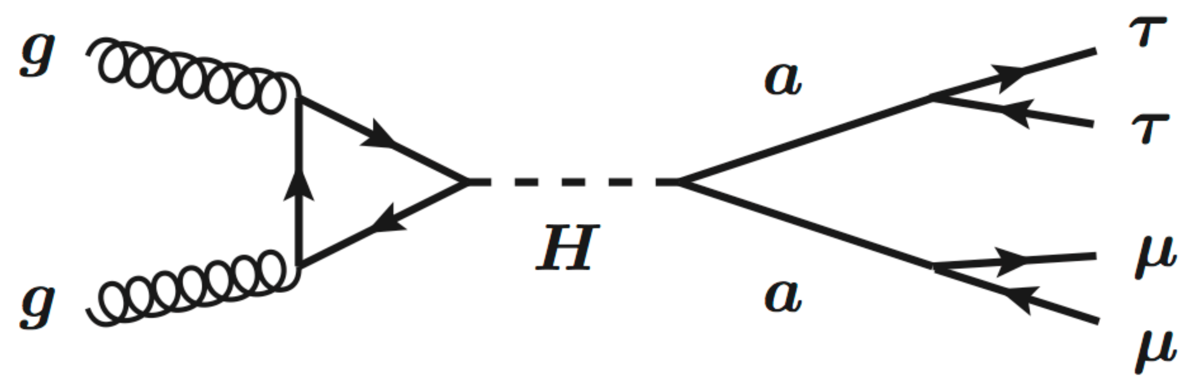
- Four types of 2HDM (doublets couplings to fermions):

	Type-1	Type-2	Type-3 (lepton-specific)	Type-4 (flipped)
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1
Charged leptons	Φ_2	Φ_1	Φ_1	Φ_2

H → aa → μμττ

arXiv:2005.08694

Accepted by JHEP



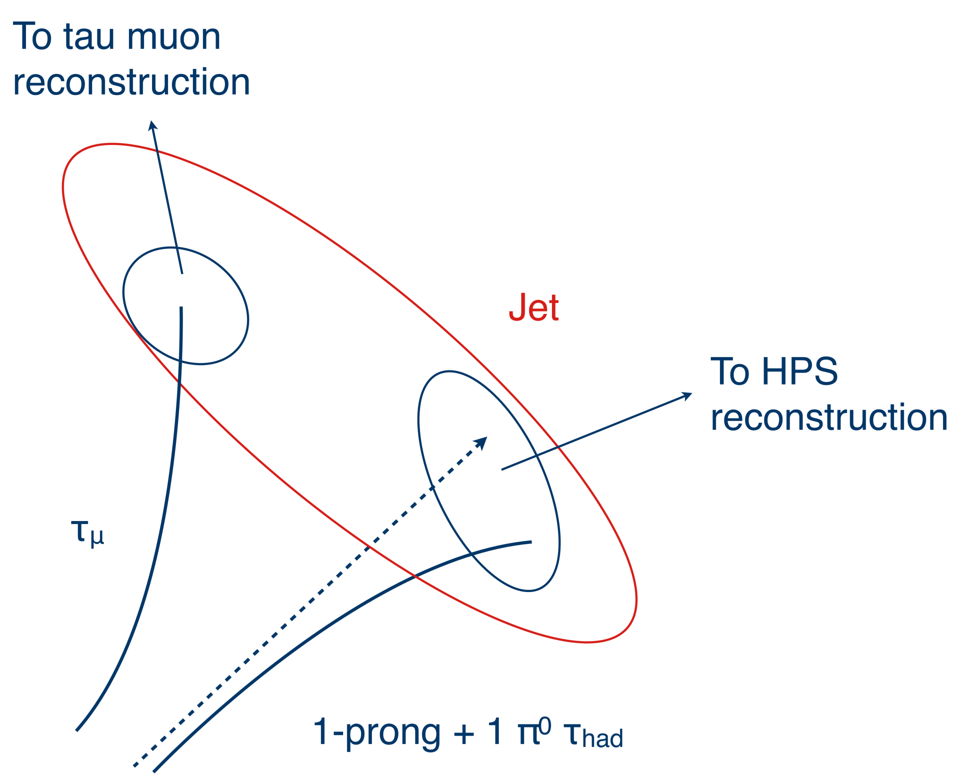
$$\frac{\Gamma(\mathrm{a} \to \mu^+\mu^-)}{\Gamma(\mathrm{a} \to \tau^+\tau^-)} = \frac{m_\mu^2\sqrt{1-(2m_\mu/m_\mathrm{a})^2}}{m_\tau^2\sqrt{1-(2m_\tau/m_\mathrm{a})^2}}$$

- a→μμ gives clean signature
- a→ττ has large branching ratio

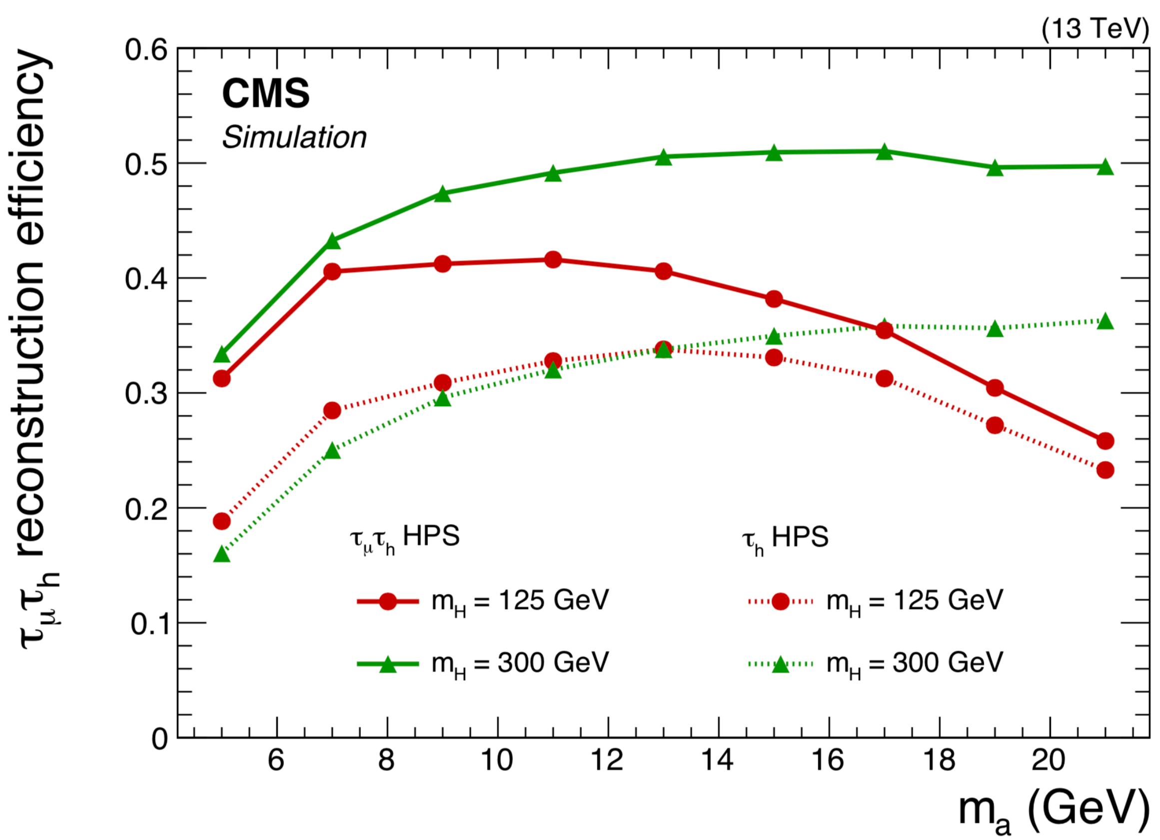
- Compatibility with a SM **Higgs boson decay or heavier Higgs boson decay**
- Pseudoscalar boson mass range: [3.6, 21] GeV
  - **Boosted muons and taus**
- Final states with different **tau decay modes**:
  - **μμ +** $\boldsymbol{\tau_\mu \tau_h}$

$H \to aa \to \mu\mu\tau\tau$

arXiv:2005.08694



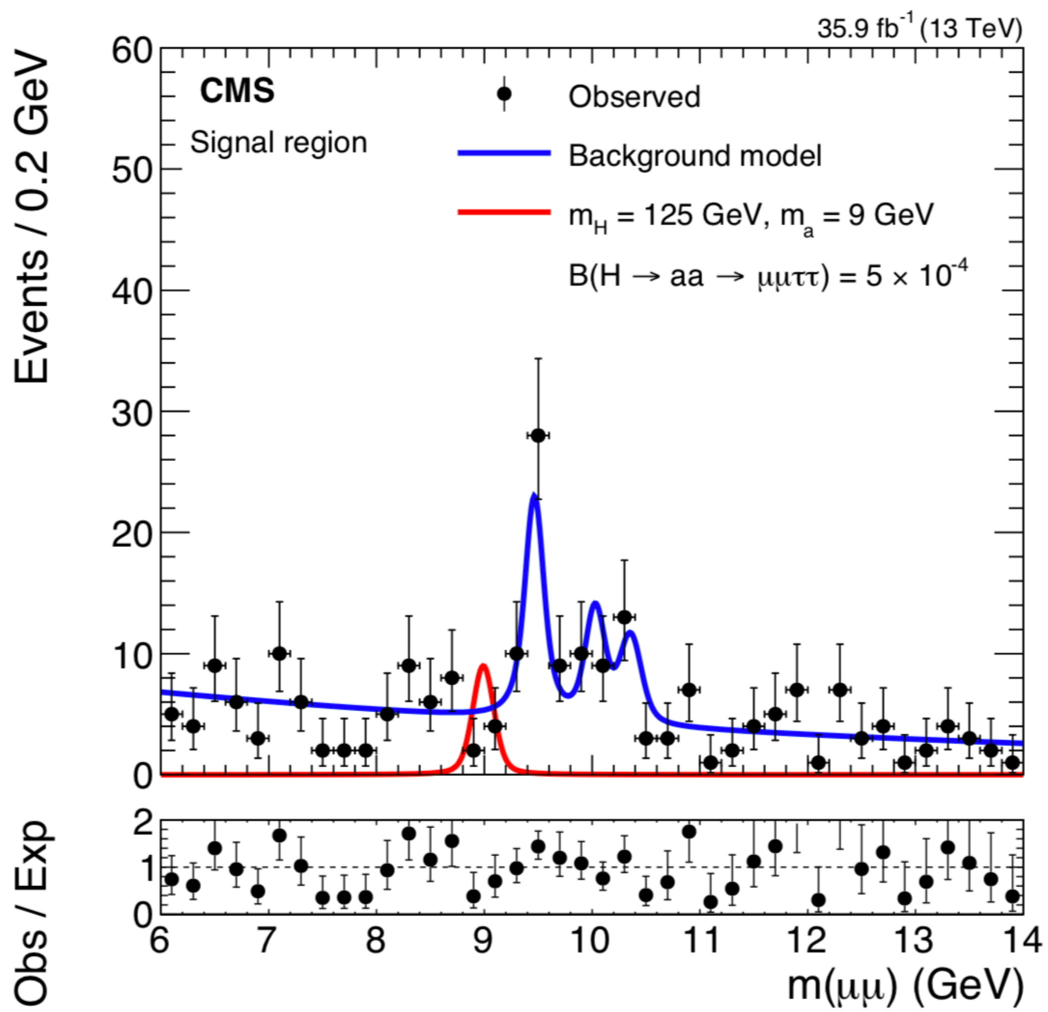
- In order to cope with boosted $\tau_\mu\tau_h$ pair topology, muons are cleaned from jets which seeds hadronic tau reconstruction
- The reconstructed τ_h can have 1 prong or 3 prongs (+ π^0 s)

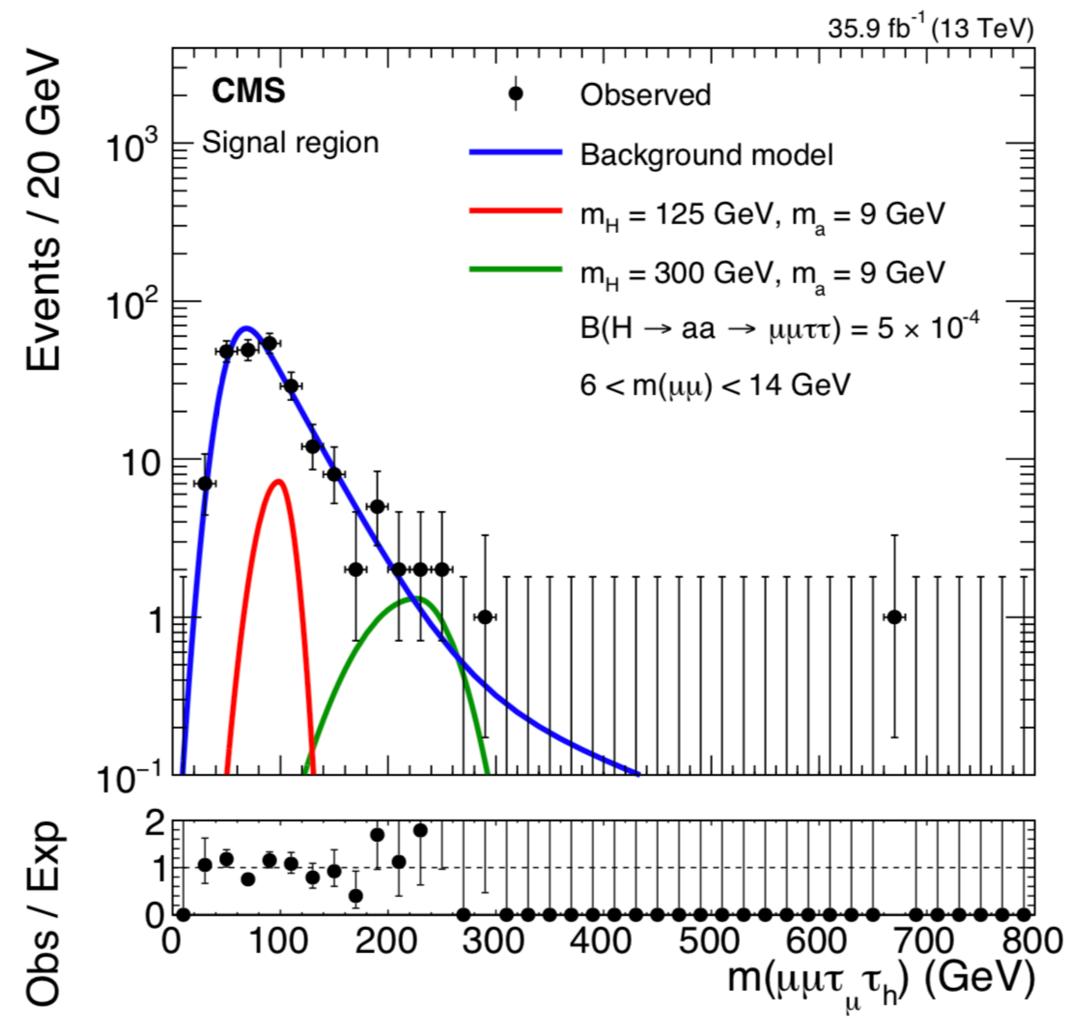


- Comparison:
  - Standard tau reconstruction (τ_h HPS)
  - Muon-Cleaned tau reconstruction ($\tau_\mu\tau_h$ HPS)
- Reduced efficiency at low a mass:
  - Muon collinear with a charged hadron from tau

$H \to aa \to \mu\mu\tau\tau$

arXiv:2005.08694





- The dominant background is Drell-Yan $\mu\mu$ + jet(s)
- Parametrized signal & background distribution:
  - Perform a 2-dimensional **unbinned maximum likelihood fit**
  - Use a polynomial function to interpolate between the generated masses
- Variables used for simultaneous fit:
  - **Di-muon mass**
  - **Four body visible mass ($\mu\mu\tau_\mu\tau_h$)**

$H \to aa \to \mu\mu\tau\tau$

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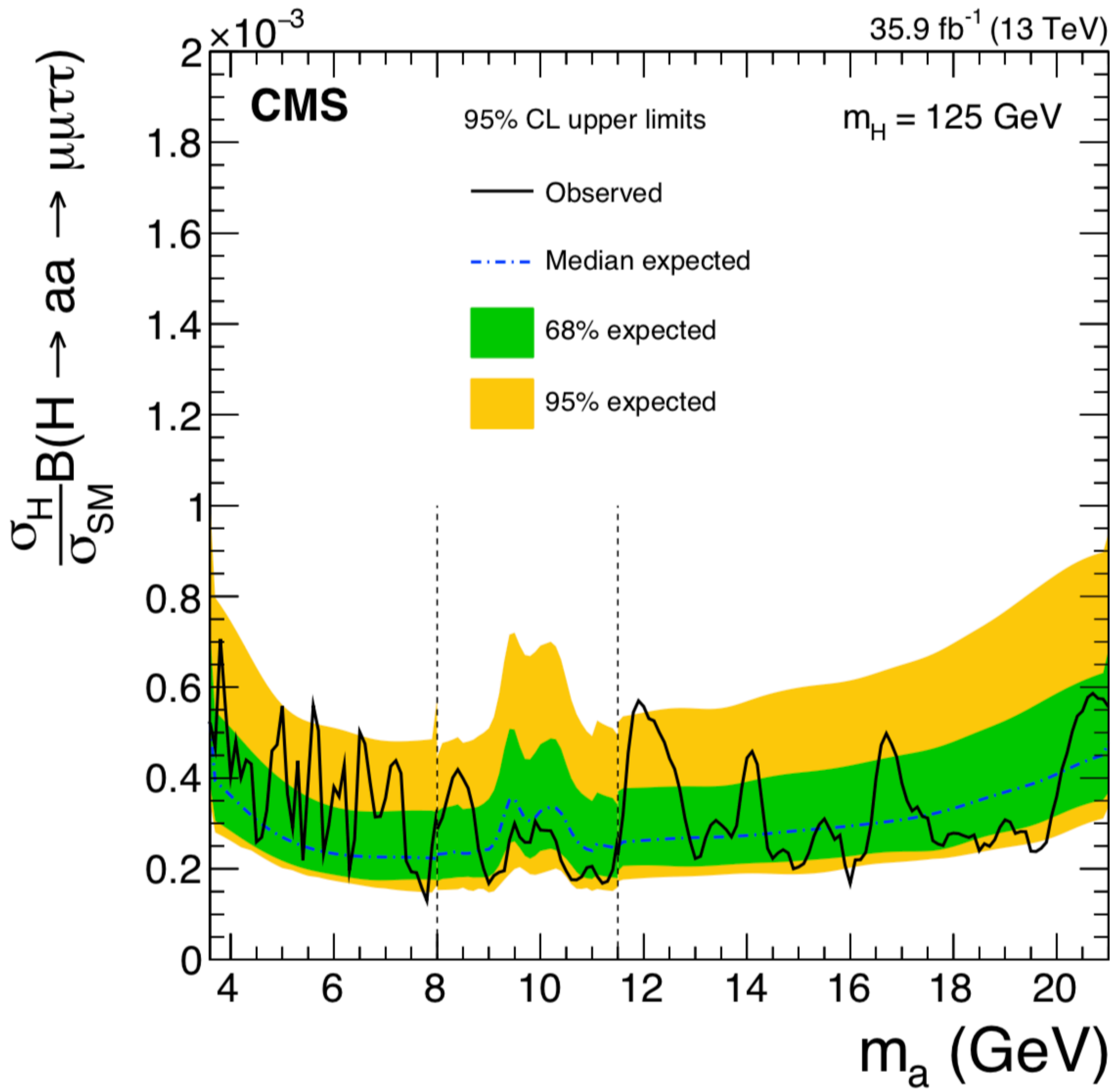
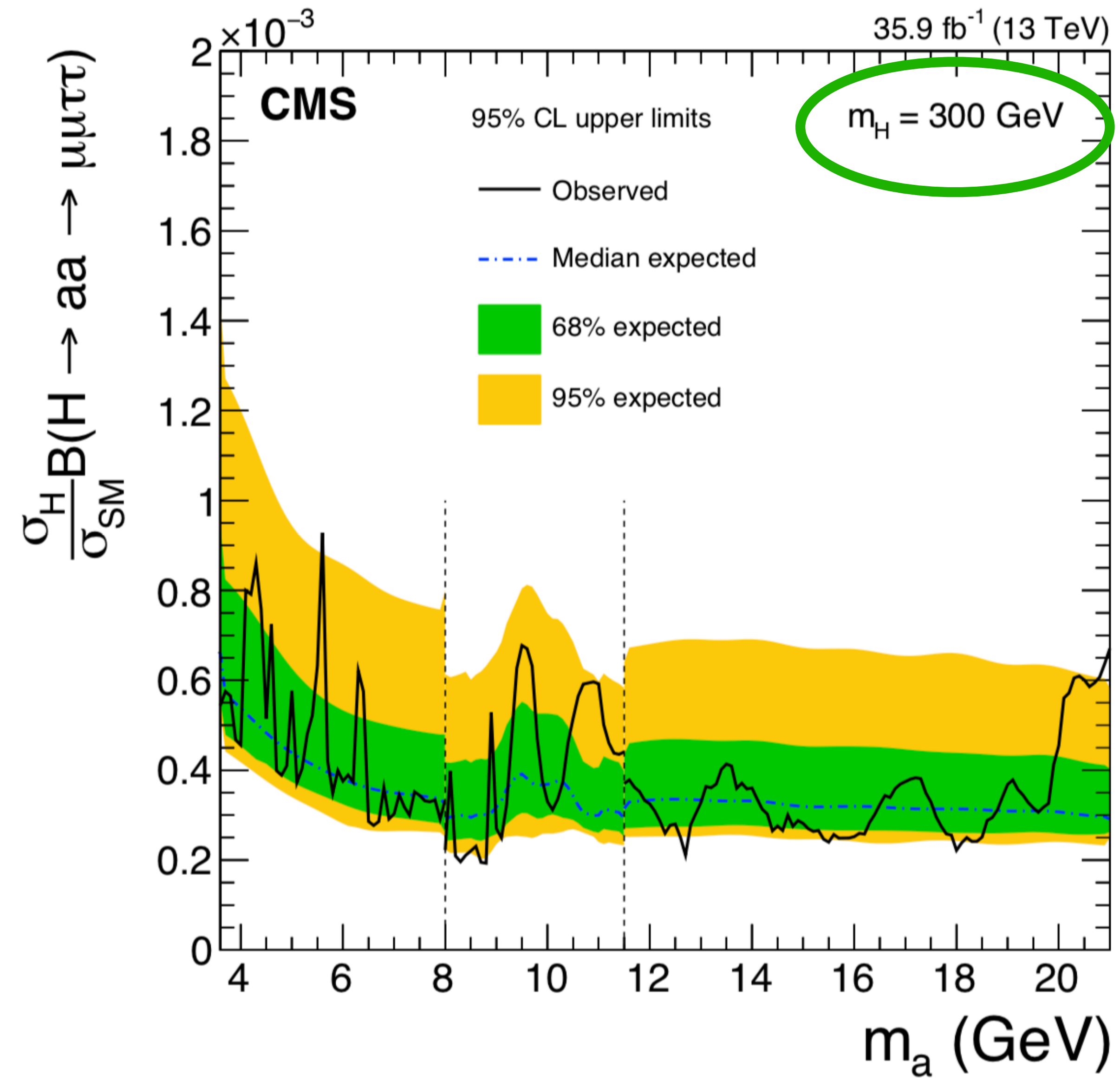
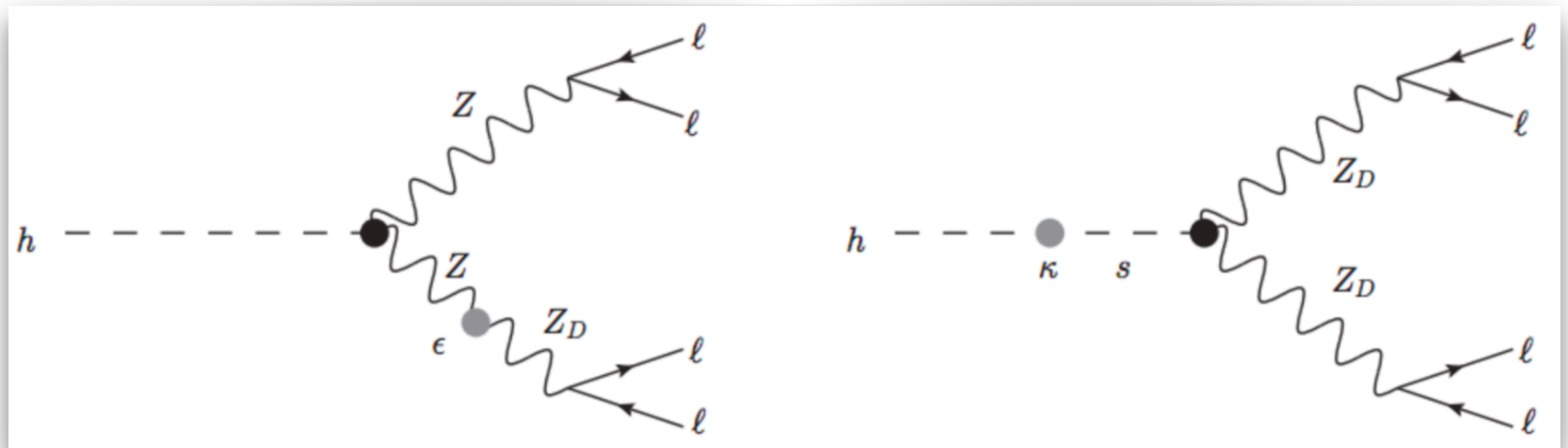




- Model independent limits set in M(H) = 125 GeV for light pseudoscalars
- First model independent limits set in heavy Higgs mass (300 GeV) for $H \to aa$ in 95% CLs
- The three peaks in the middle are due to the influence of upsilon resonances
- The dominant uncertainty is from the background model around upsilon resonances (5-20%)
- 2HDM + S model limits are also set

H→ZX & H→XX

CMS-PAS-HIG-19-007

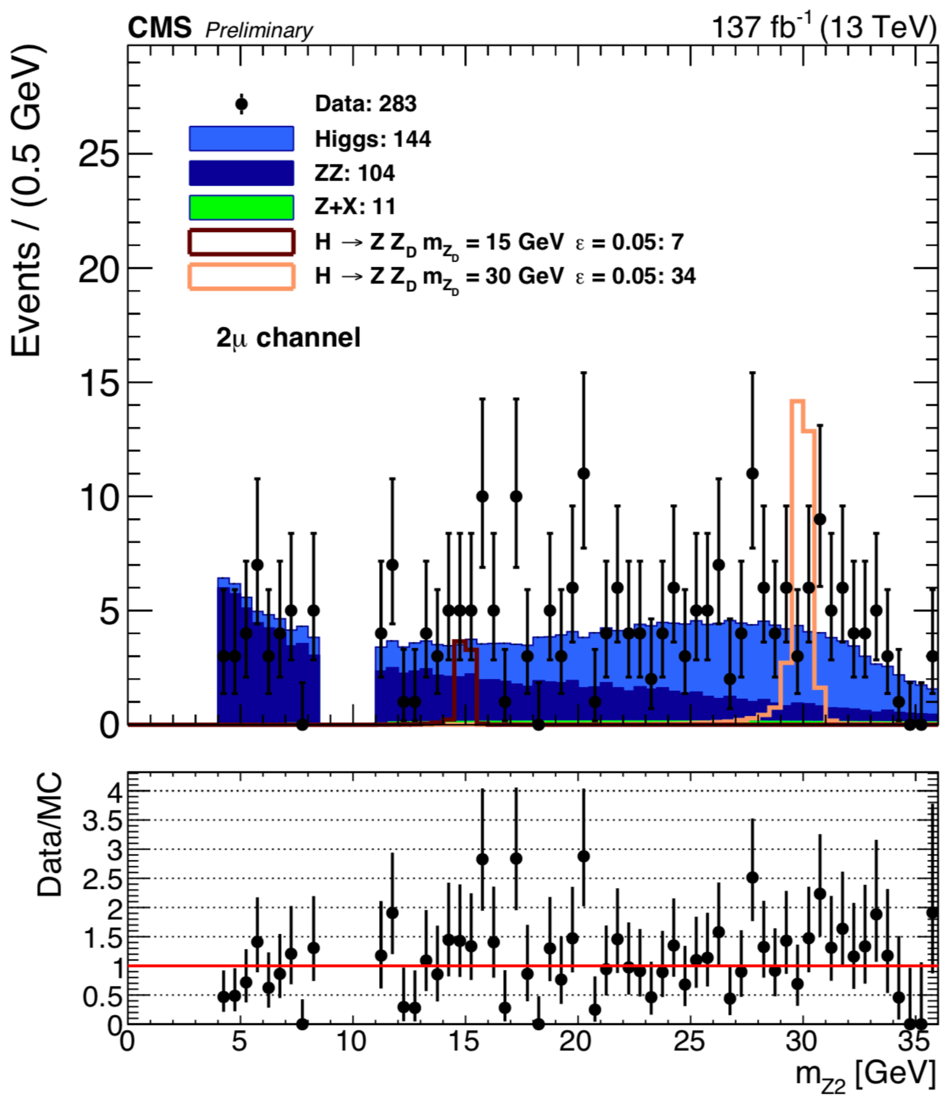


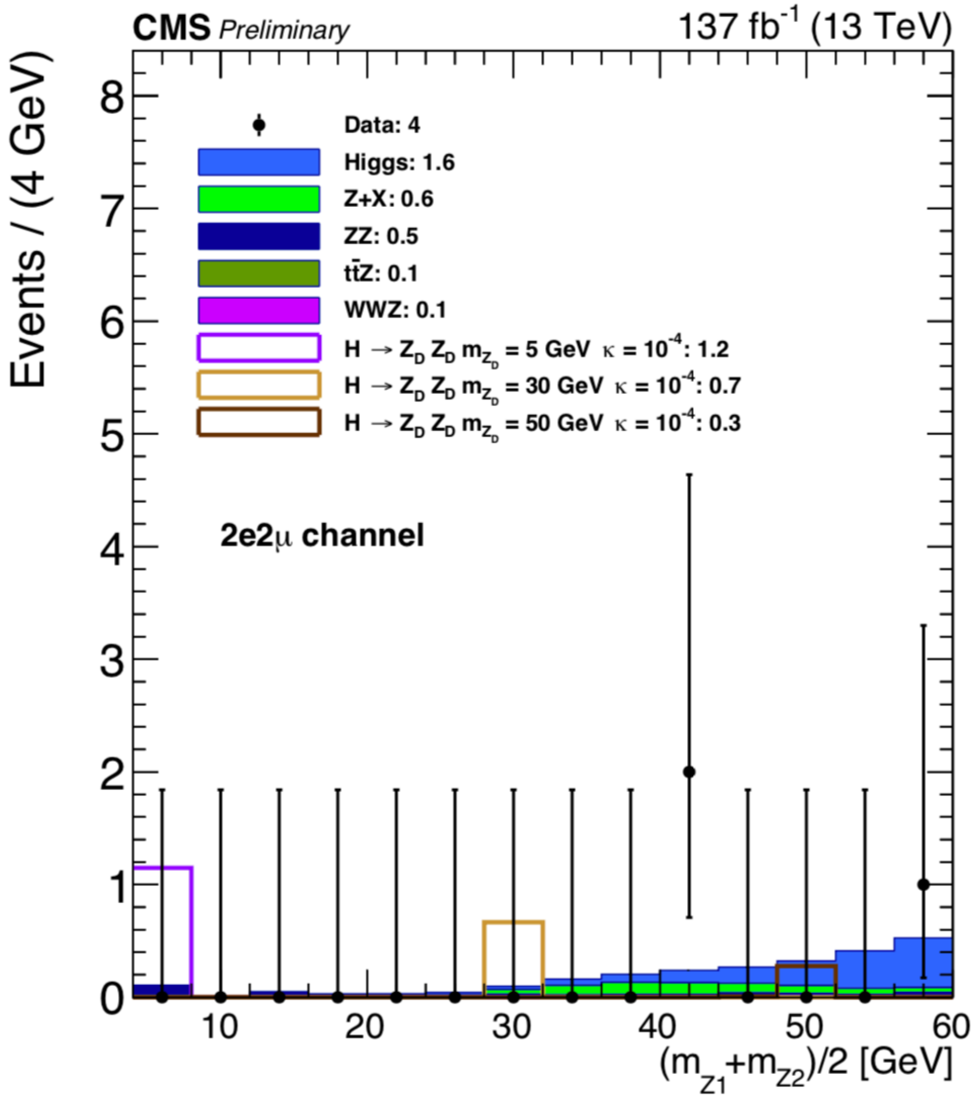
- **Dark photon model:**
  - **Z_D: mediates a dark $U(1)_D$ gauge symmetry, simultaneously broken by dark Higgs mechanism**
  - **Interaction type:**
    - **Hypercharge portal via kinematical mixing coupling**
    - **Higgs portal via Higgs mixing coupling**

H→ZX & H→XX

CMS-PAS-HIG-19-007

- **Generated Next-to-leading order (NLO)** for the signal process
- Four final-state lepton categories: ***4μ*, *2μ2e*, *2e2μ*, 4e**
- The main background (Z + jets) estimated from data

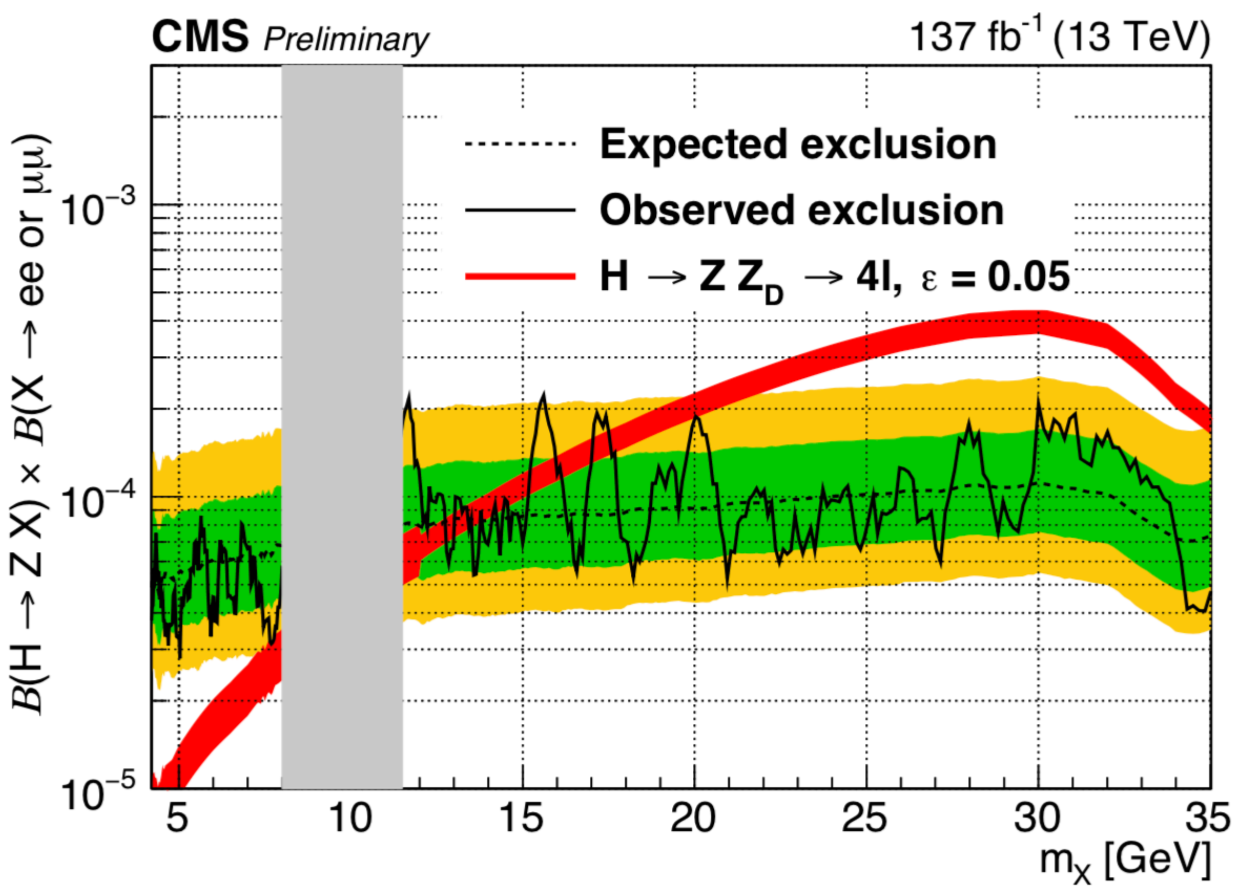


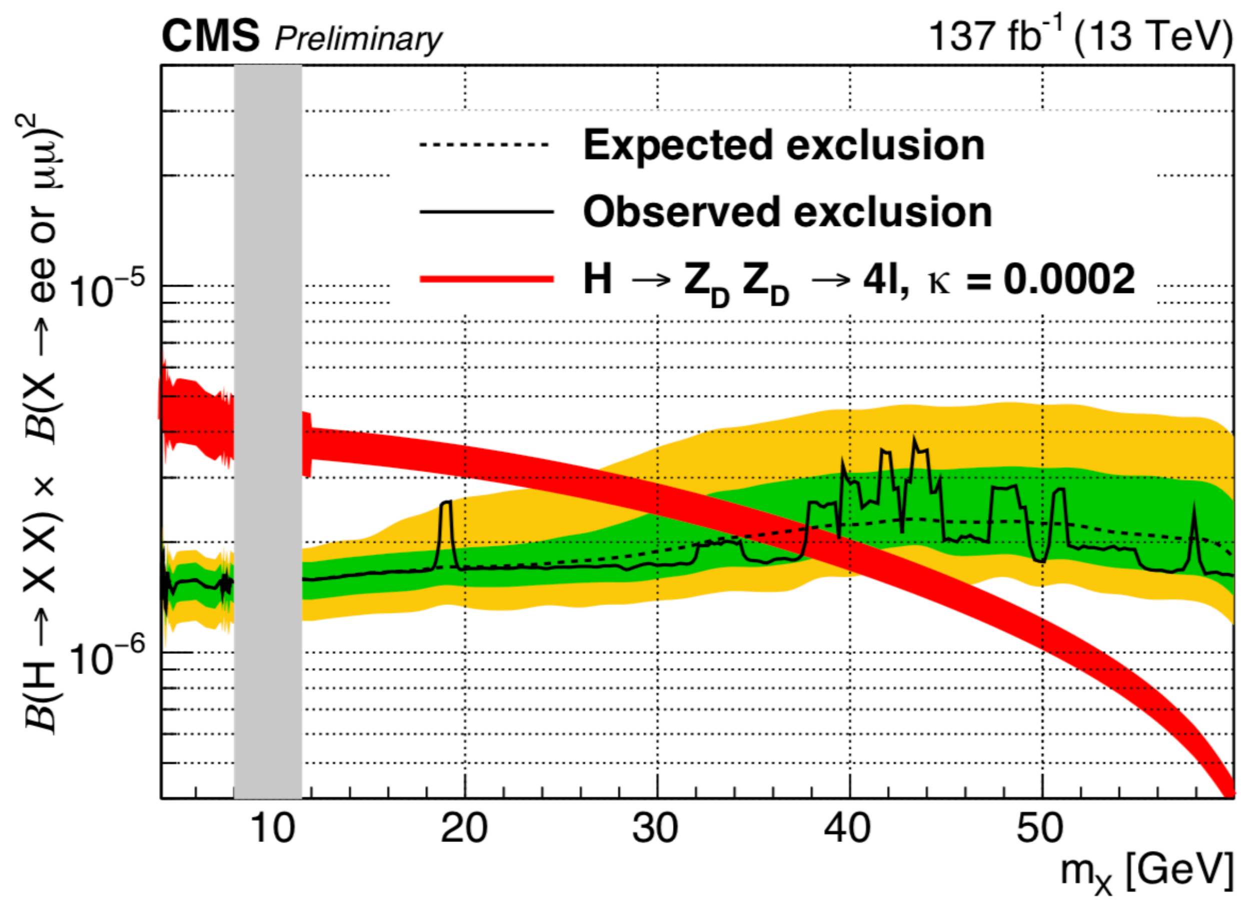


- **No significant deviation from SM background prediction**
- **Other channels' results can be found in backup pages**

H→ZX & H→XX

CMS-PAS-HIG-19-007





- **The mass range of upsilon meson states is excluded**
- **The normalization of Higgs background is allowed to float freely in the likelihood fit**
- **The largest uncertainty is Z + jets background estimation (48 -100 %)**

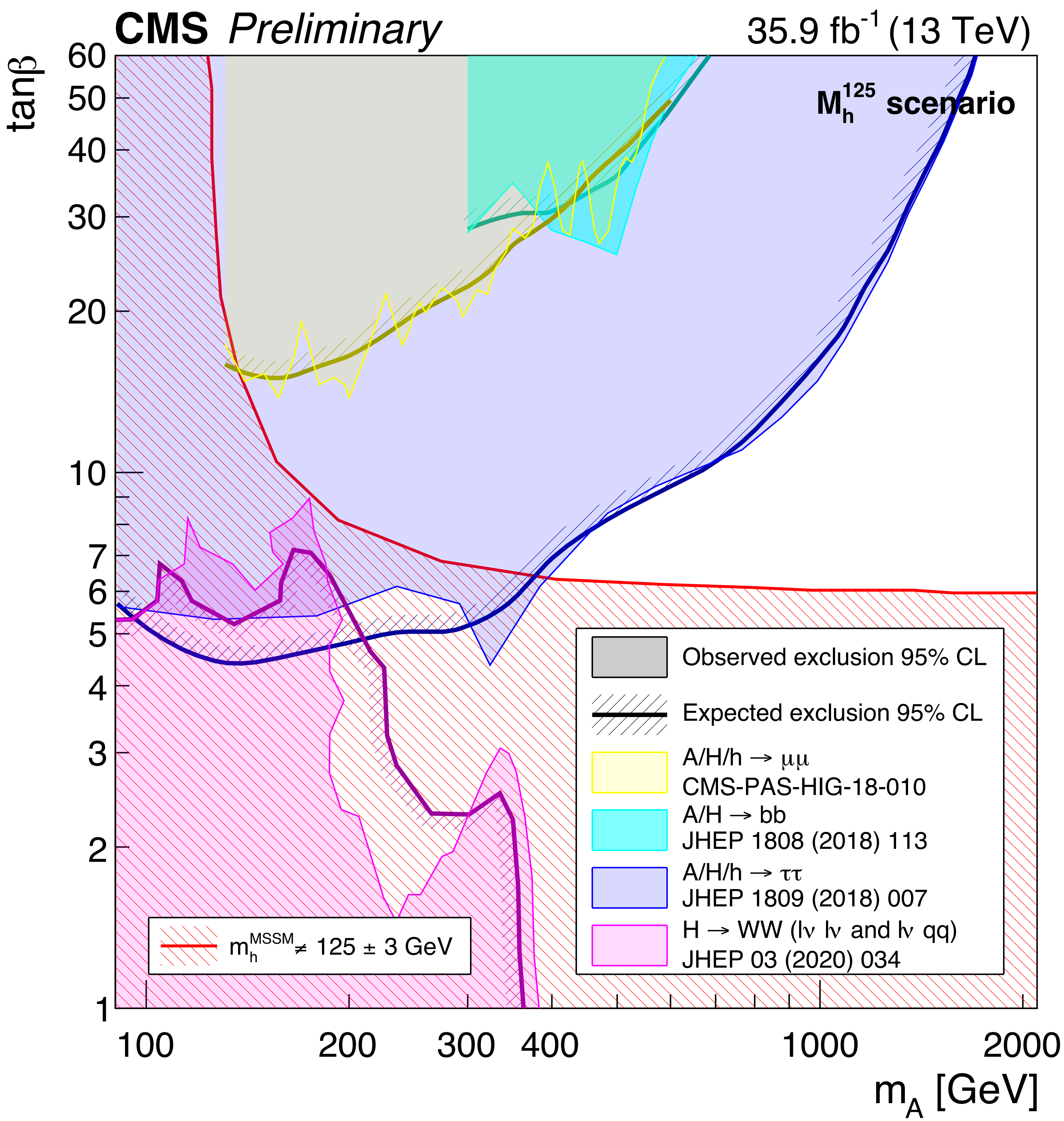
Summary & Conclusion

- CMS has made good progress in Higgs exotic decay searches
  - **No significant excess** above SM prediction has been found
  - Increased Run II data sets allow more stringent constraints
- Presented results:
  - **First limits on $H \to Z + \rho/\phi$ channels**
  - **Upper limits on light pseudoscalars for M(H) = 125, 300 GeV**
  - **Search for dark photons in Higgs exotic decay**
- More interesting results are coming out with full Run II data
- In a longer term, we will achieve higher sensitivity with large data sets in Run III and beyond

Stay tuned!

Backup

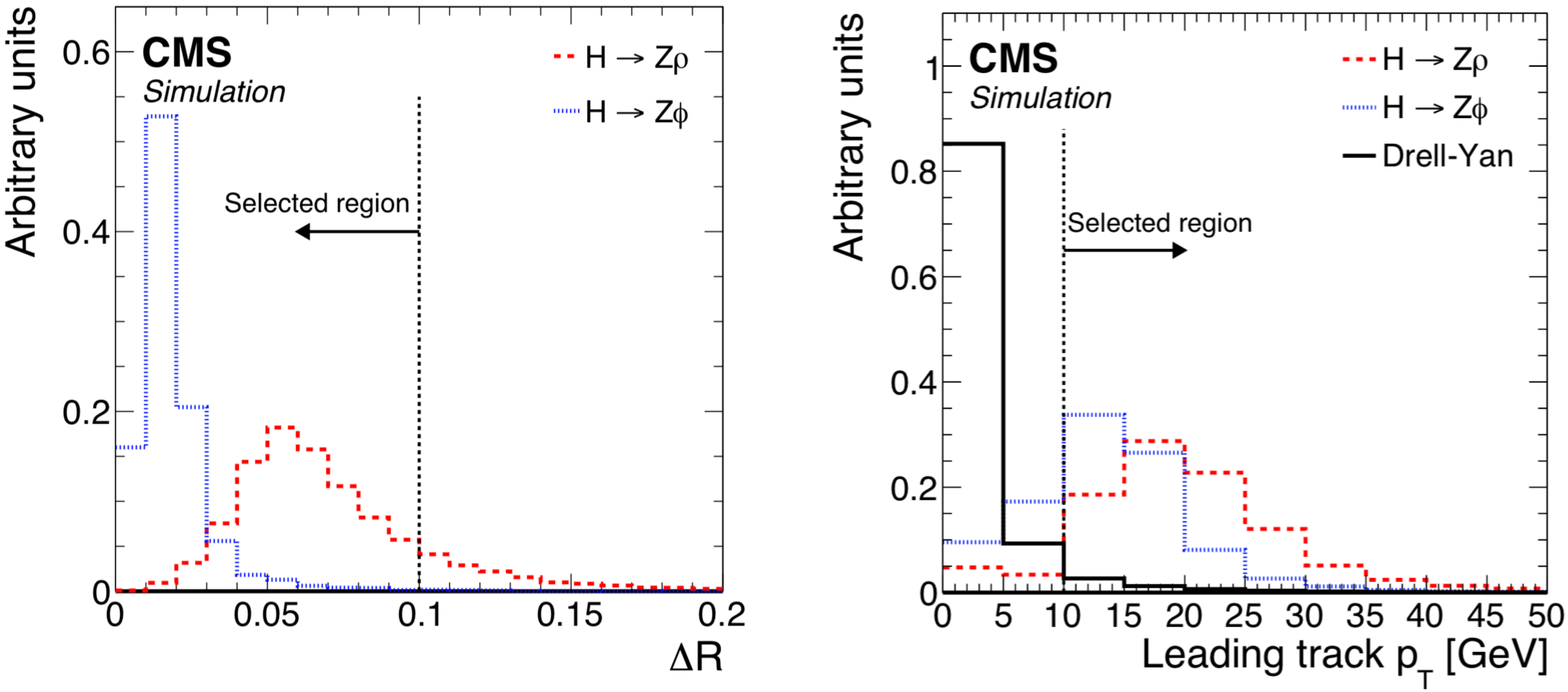
2HDM + S type II Summary



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

H → Z + ρ/ϕ

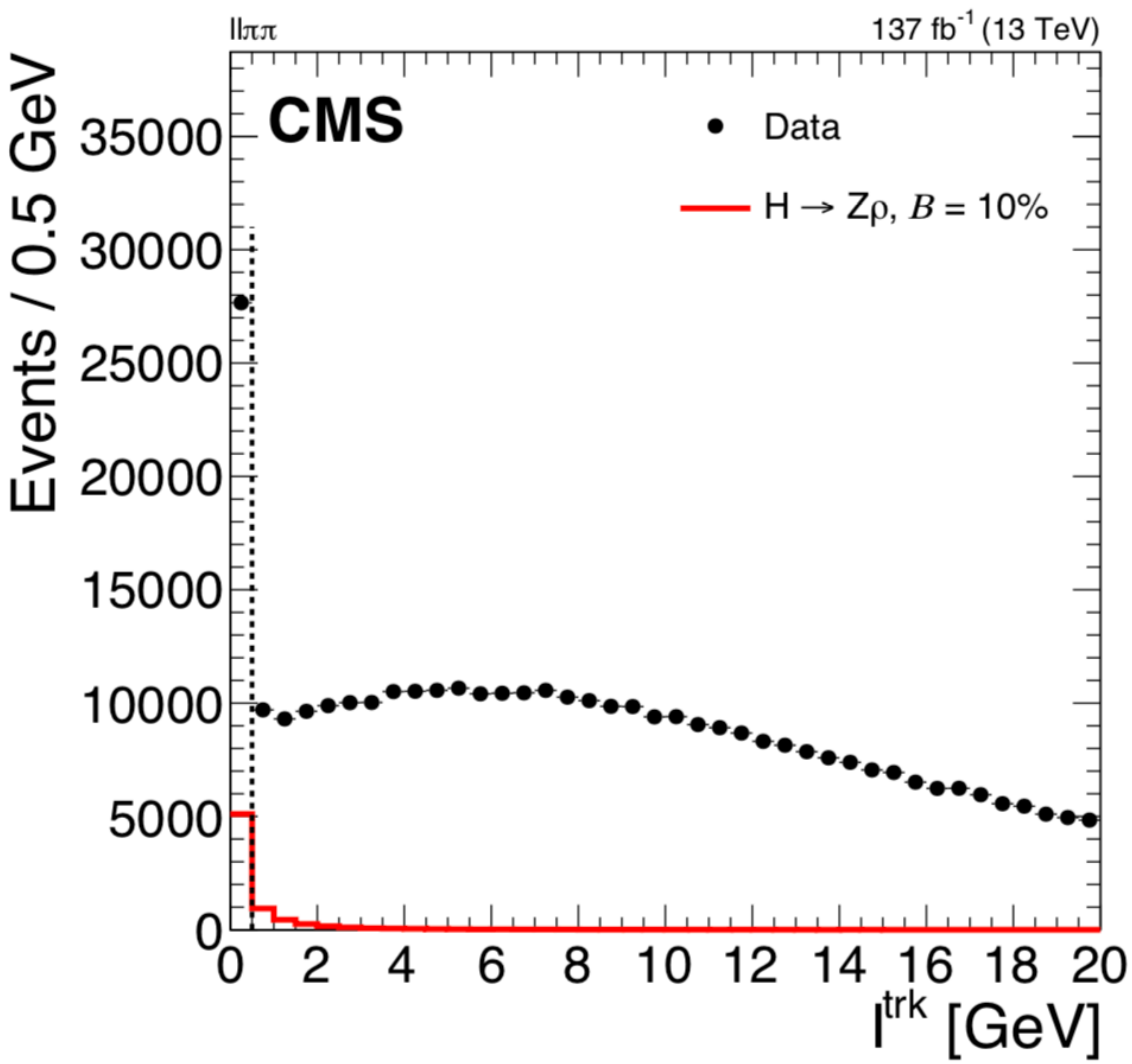
arXiv:2007.05122

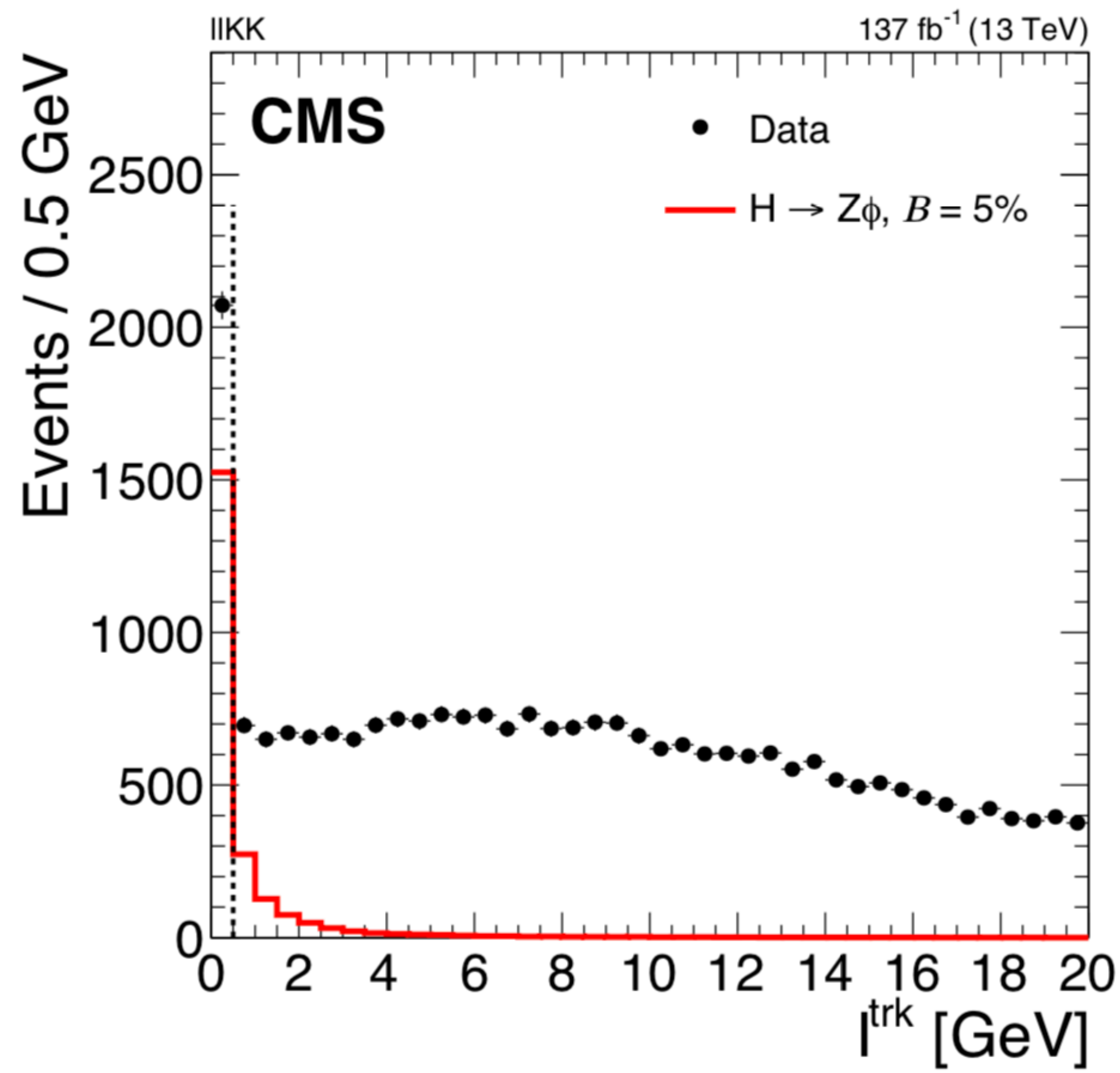


- The two charged particles produced in the decay are emitted with small angular separation
- The meson candidate is selected as a pair of oppositely charged particle tracks
- One of the tracks is required to have pT above 10 GeV

H → Z + ρ/ϕ

arXiv:2007.05122

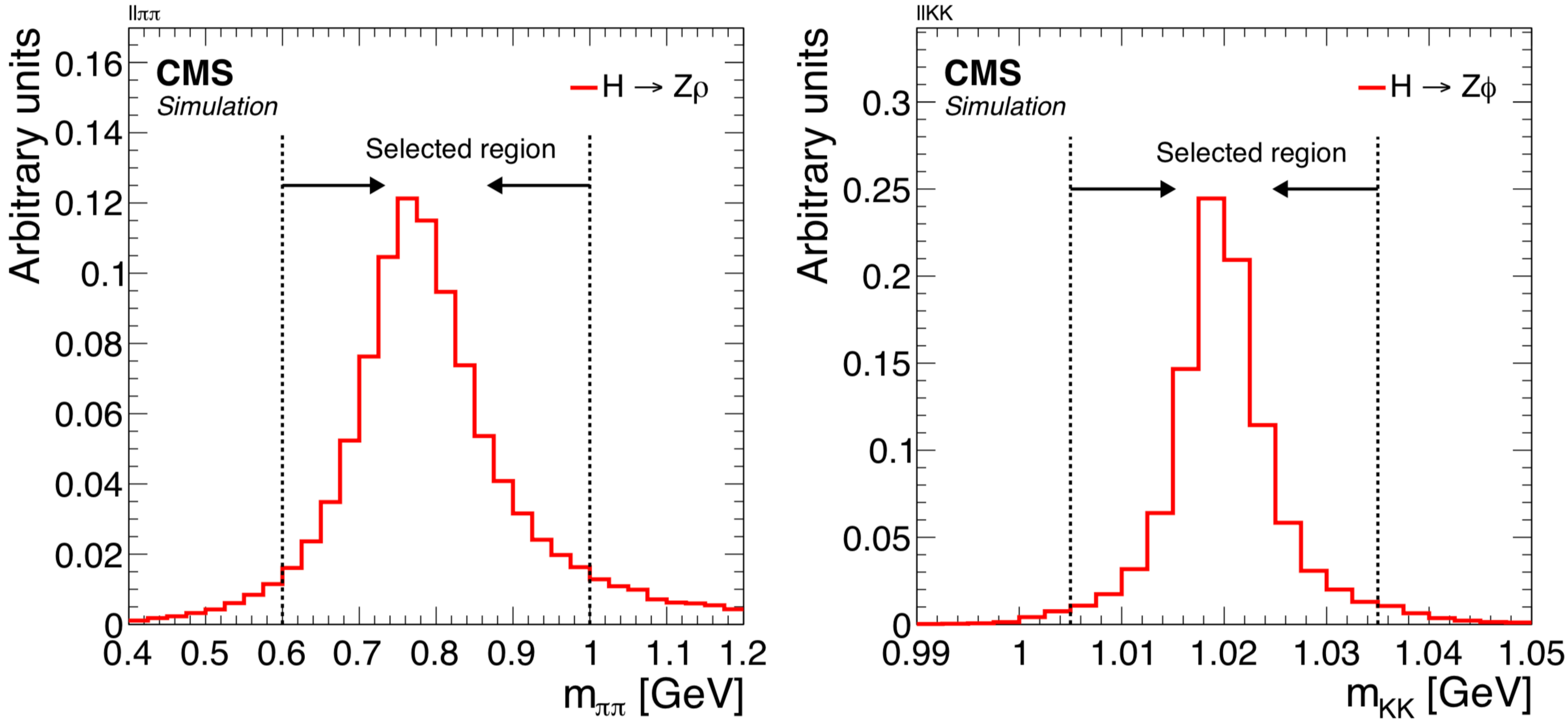




- The ditrack system is required to be isolated in a cone of ΔR (0.3) around the direction of ditrack
- Only events in which the dilepton and ditrack four-body mass is in the range 120–130 GeV are shown, which is expected to contain 95% of the simulated signal

$H \to Z + \rho/\phi$

arXiv:2007.05122



- The invariant mass of ditrack system is also used to reduce the contamination from background events

$H \to Z + \rho/\phi$

arXiv:2007.05122

Table 1: The effect on the signal yields of reweighting to the extreme polarization scenarios, described in more detail in the text, relative to the scenario with isotropic decays. The change in the fraction of signal events that pass the selection criteria affects the final results of the analysis.

Polarization state	Effect on yield			
	$\mu\mu\pi\pi$	$\mu\mu$KK	ee$\pi\pi$	eeKK
Longitudinally polarized	+16%	+17%	+23%	+21%
Transversely polarized	−8%	−9%	−11%	−11%

- The signal templates are weighted to both of these polarized distributions simultaneously

H → Z + ρ/ϕ

arXiv:2007.05122

Uncertainty source	Type	Effect on simulated signal yield
Integrated luminosity	Normalization	2.3–2.5%
Muon efficiency	Normalization	1%
Muon energy scale	Shape	<0.3%
Electron efficiency	Normalization	2–3%
Electron energy scale	Shape	<0.3%
Tracking efficiency	Normalization	4.6–4.8%
Ditrack isolation efficiency	Normalization	2%
Ditrack isolation efficiency extrapolation	Shape	1–6%
Production cross sections	Normalization	0.4–3.9%
Choice of PDF and α_S	Normalization	1.6–3.2%
Inelastic cross section	Shape	0.5–1.5%
Limited size of simulated samples	Shape	Bin-dependent

- The largest possible bias from the choice of the function modelling the background is included in the likelihood as a modification of the number of expected events
- The observed upper limits on B(H → $Z\rho$) and B(H → $Z\phi$) are 1.04–1.31% and 0.31–0.40%, respectively, depending on the polarization scenario considered
- These values correspond to 740–940 times the SM expectation for the H → $Z\rho$ decay and 730–950 times the SM expectation for the H → $Z\phi$ decay

$H \to Z + \rho/\phi$

arXiv:2007.05122

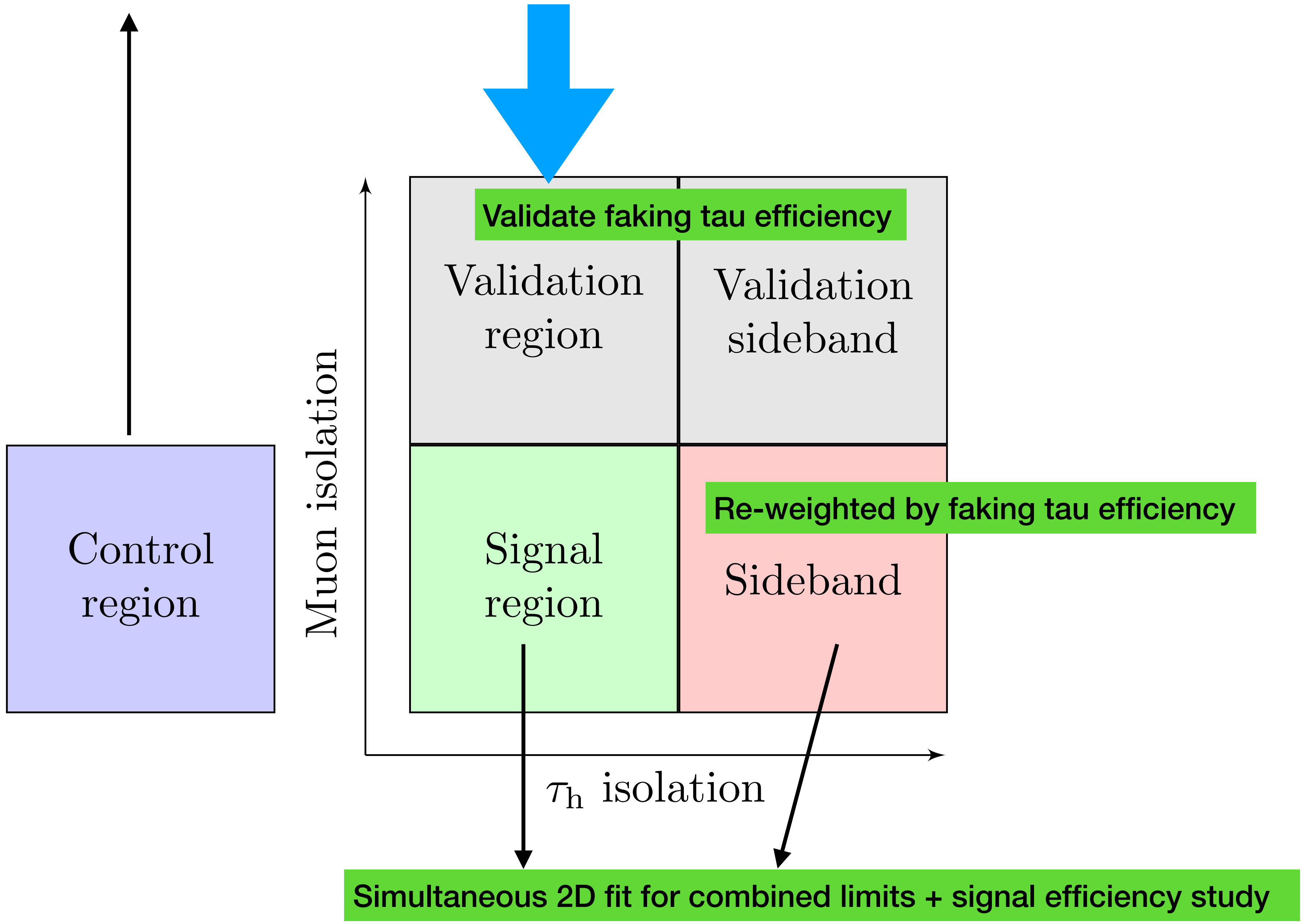
	Observed	Median expected	±68% expected	±95% expected
Isotropic decay	0.0121	0.0073	0.0052–0.0104	0.0038–0.0141
Z and ρ longitudinally polarized	0.0104	0.0063	0.0044–0.0089	0.0032–0.0120
Z and ρ transversely polarized	0.0131	0.0080	0.0057–0.0114	0.0041–0.0154

	Observed	Median expected	±68% expected	±95% expected
Isotropic decay	0.0036	0.0033	0.0023–0.0046	0.0018–0.0061
Z and ϕ longitudinally polarized	0.0031	0.0027	0.0020–0.0039	0.0015–0.0052
Z and ϕ transversely polarized	0.0040	0.0036	0.0026–0.0050	0.0019–0.0068

$H \to aa \to \mu\mu\tau\tau$ analysis strategy

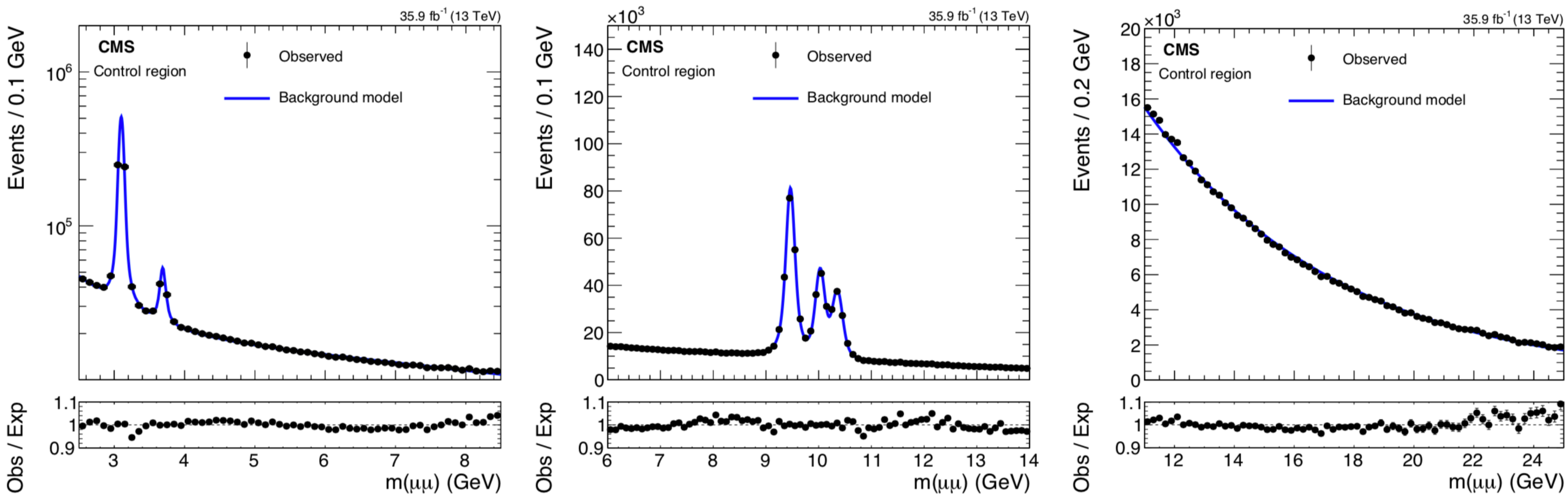
arXiv:2005.08694

- Constrain the simultaneous 2D fit
  - Select $\mu^+\mu^-$ (smallest ΔR), no $\tau_\mu + \tau_h$
- Jet faking tau efficiency study:
  - Select ($Z \to \mu^+\mu^-$) + τ_μ + τ_h



H → aa → μμττ analysis strategy

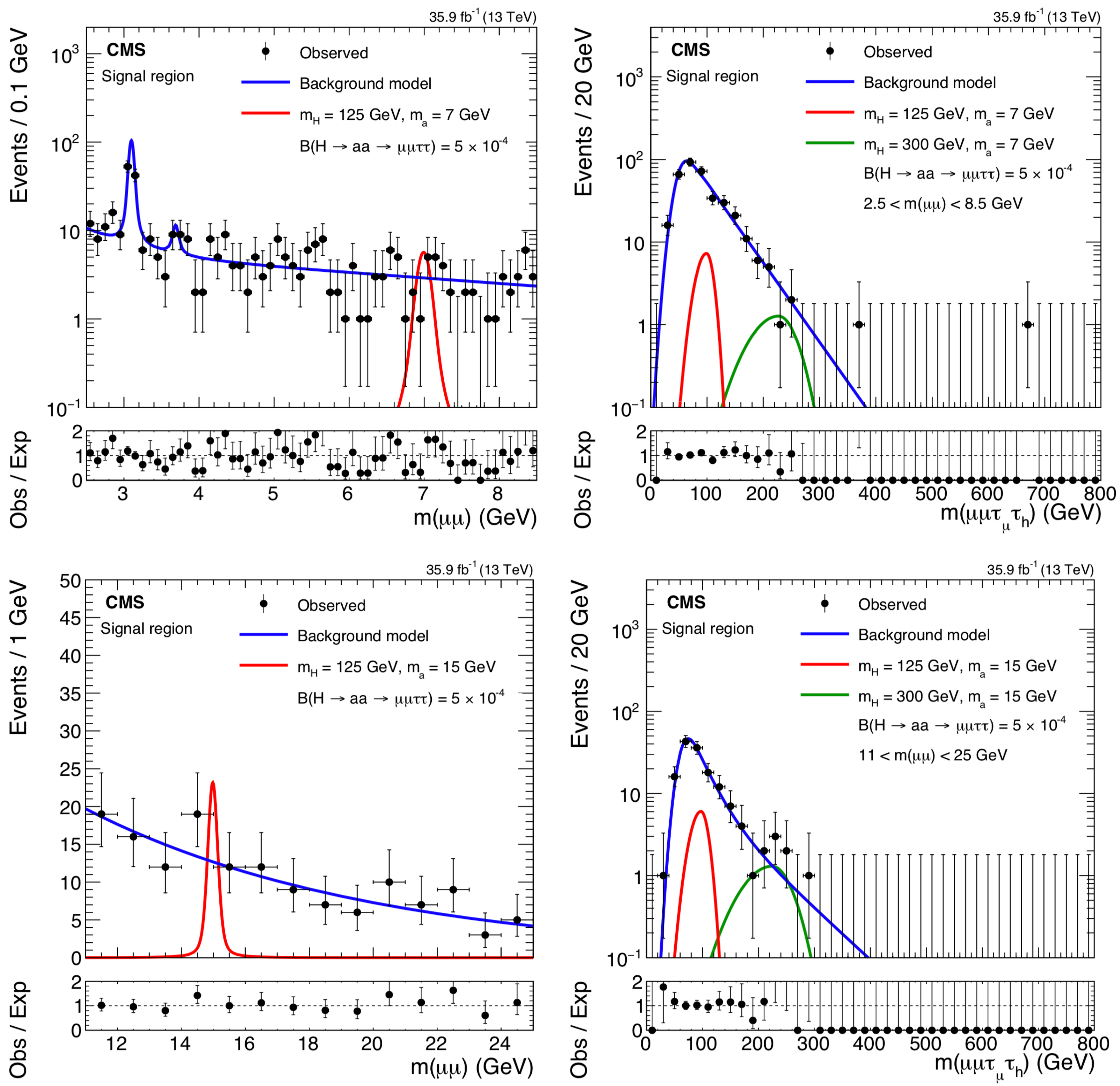
arXiv:2005.08694



- The control region is fitted with voigtian profiles with an exponential continuum

H → aa → μμττ signal region 2D fit

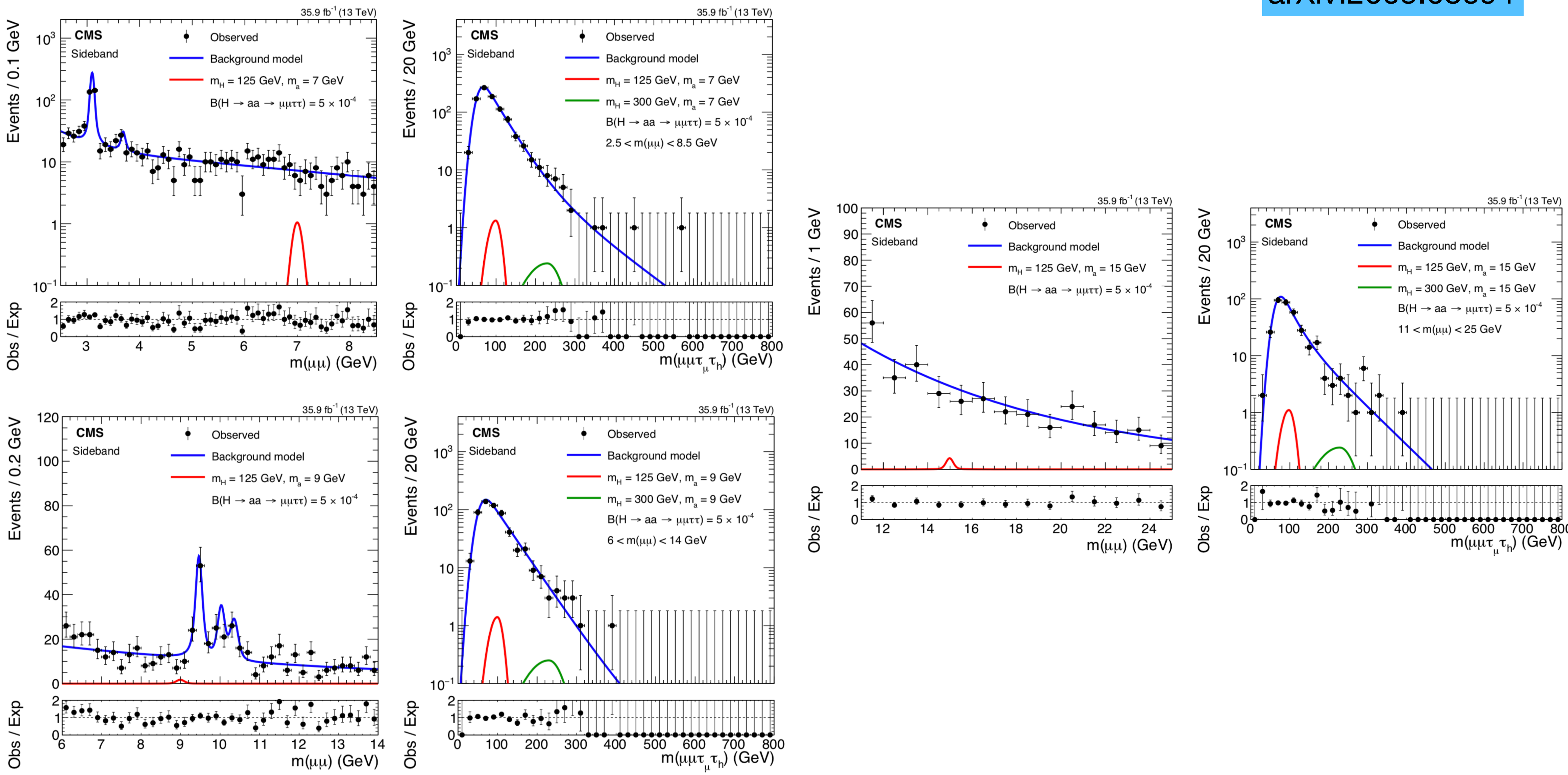
arXiv:2005.08694



- The signal region is fitted with 2D unbinned likelihood approach:
  - M(μμ) : voigtian profiles with an exponential continuum
  - M(μμττ) visible: convolution of 2 error function * exponential profiles

H → aa → μμττ sideband 2D fit

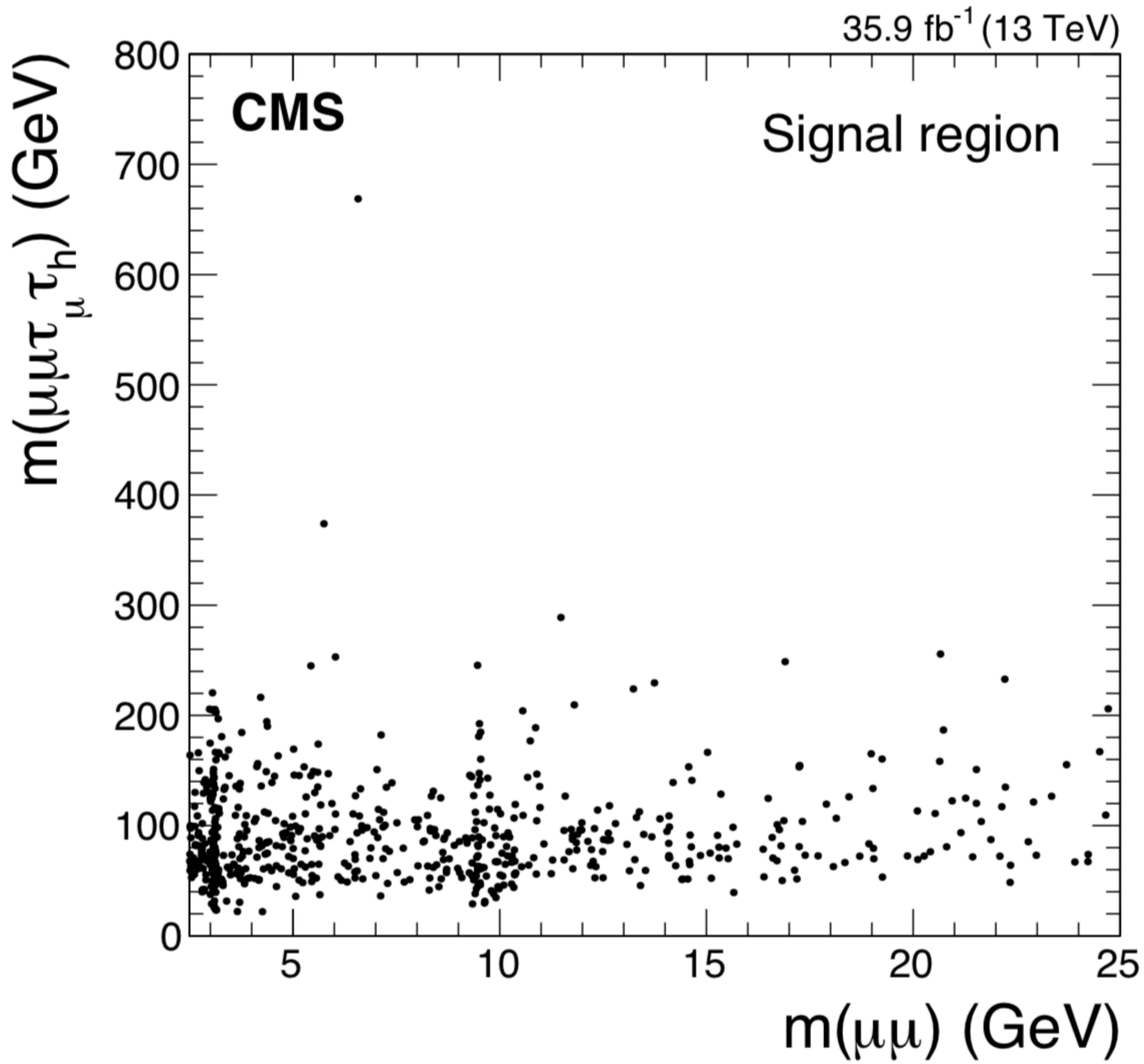
arXiv:2005.08694



- The sideband is fitted with 2D unbinned likelihood approach:
  - M(μμ) : voigtian profiles with an exponential continuum
  - M(μμττ) visible: convolution of 2 error function * exponential profiles

$H \to aa \to \mu\mu\tau\tau$ data

arXiv:2005.08694



- 614 events are observed in the signal region

H → aa → μμττ

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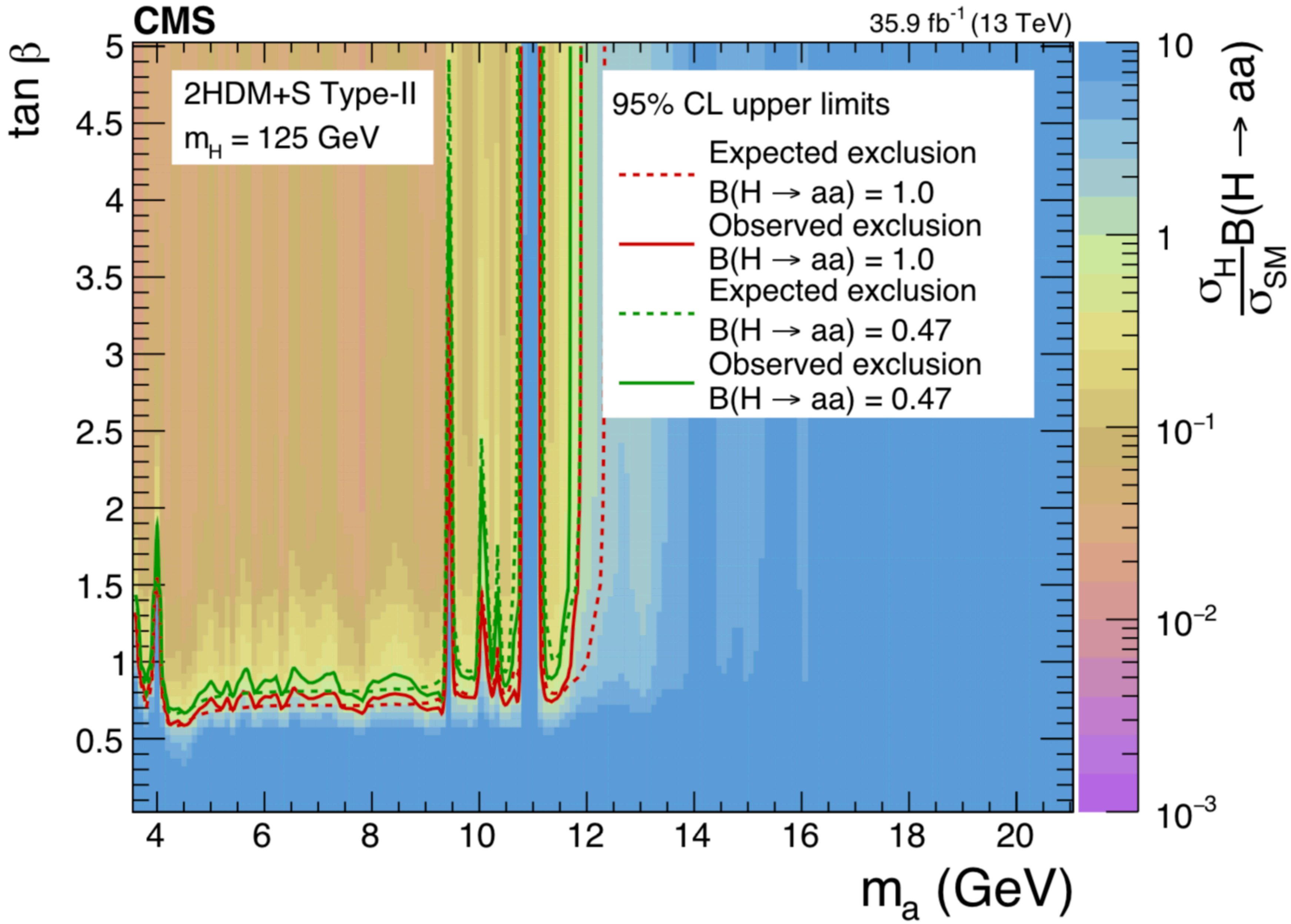
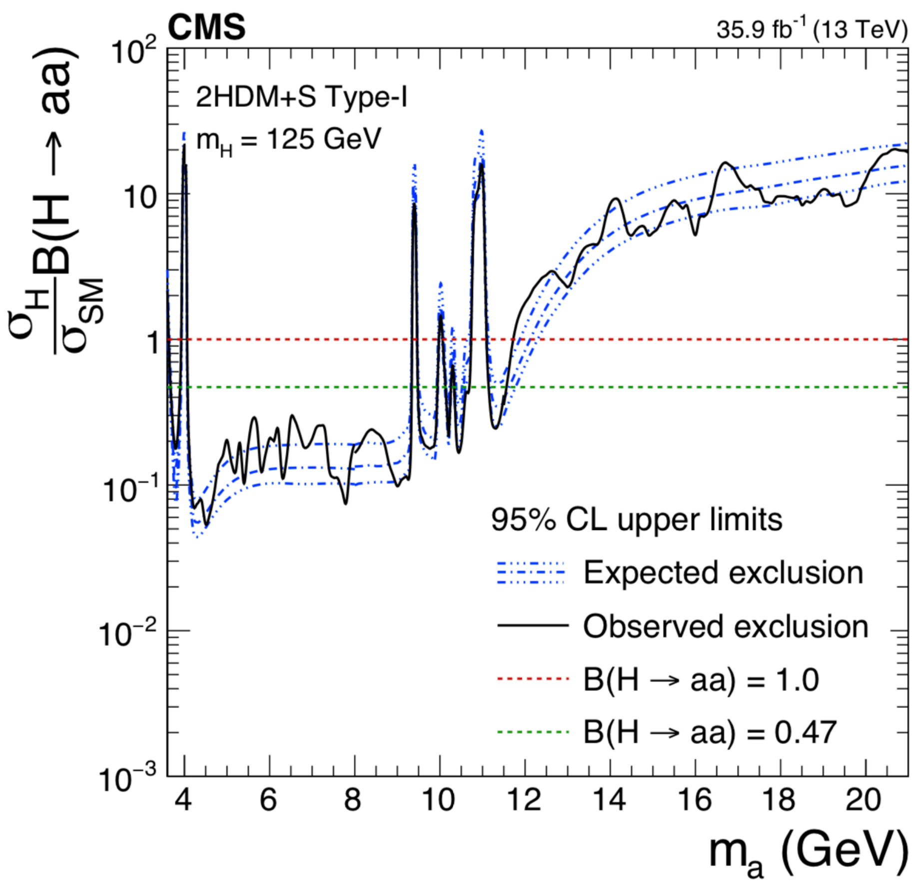


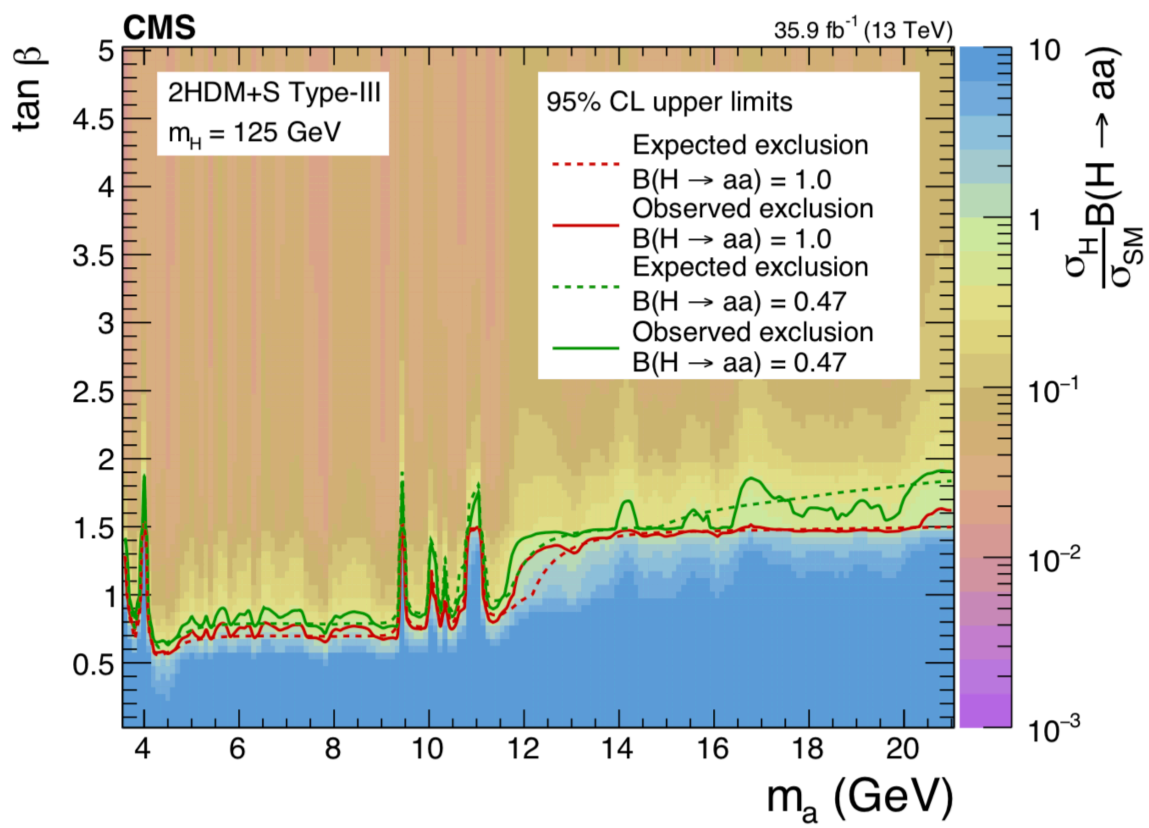
- When the a mass is below the bb(bar) threshold:
    - Upper limits on B(H → aa) are stronger than the 0.47 inferred from combined measurements of SM Higgs couplings for tan $\beta \geq$ 0.8-0.9 (Eur. Phys. J. C 79 (2019) 421)
    - Upper limits become as strong as 10% for tan $\beta \geq$ 1.5

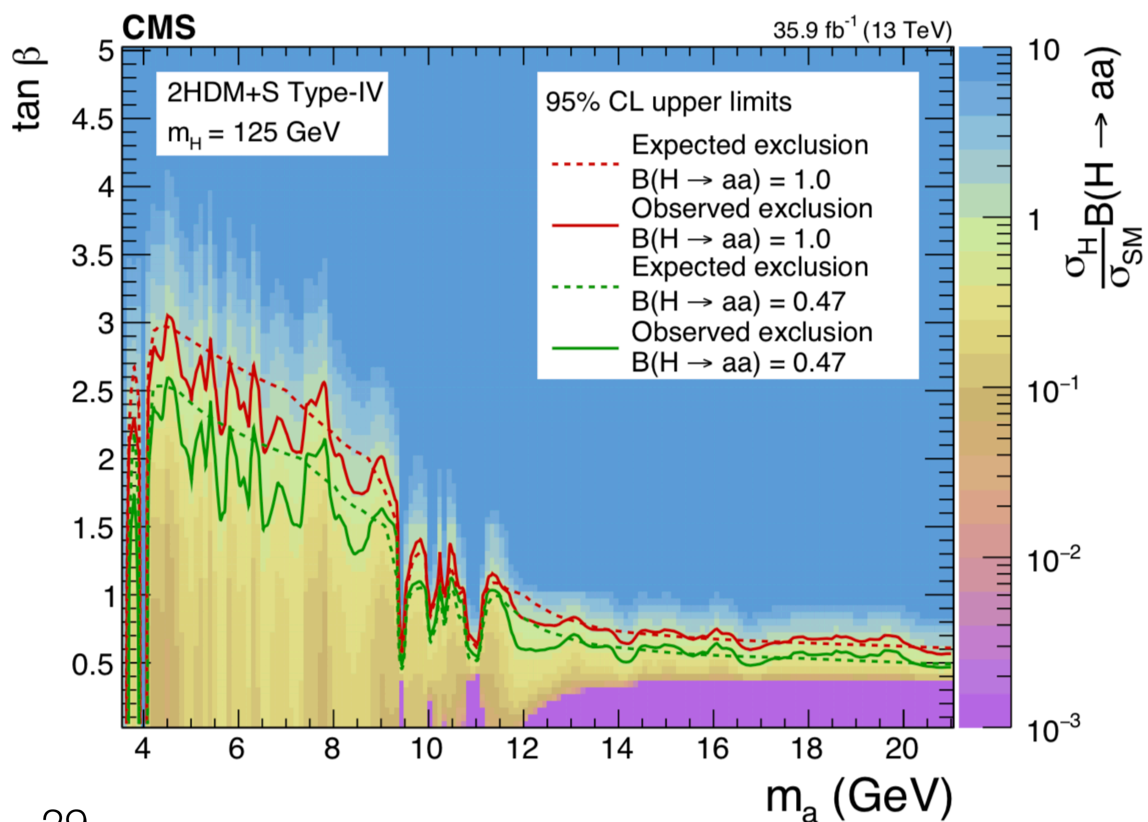
H → aa → μμττ 2D limits

arXiv:2005.08694

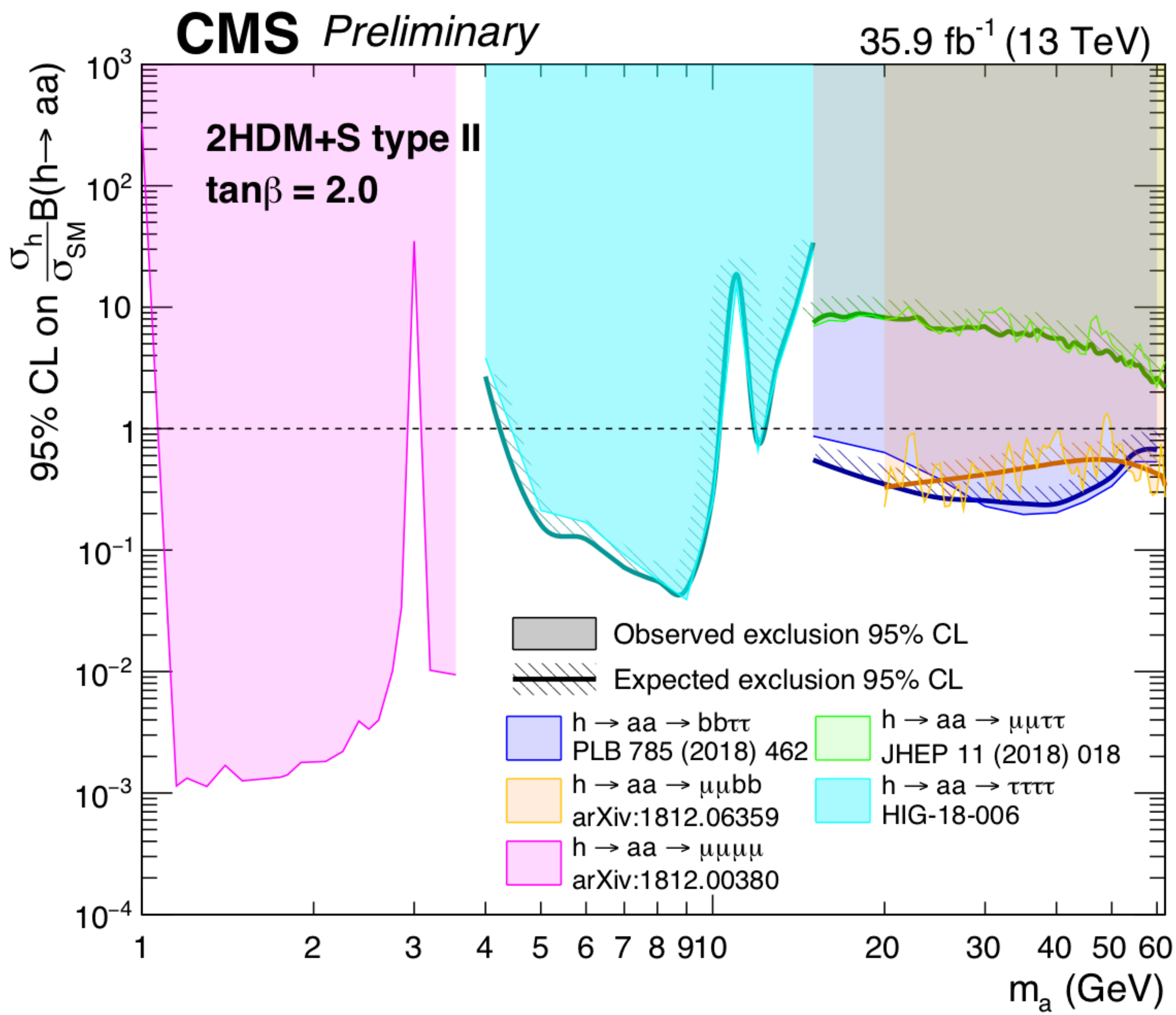


- In the Type-III models, the predicted branching fraction to leptons increases with tan β, leading to strong upper limits for all pseudoscalar boson masses tested when tan $\beta \geq 1.5$
- The strongest upper limits for Type-IV models are set when tan $\beta < 1$





2HDM + S type II Summary



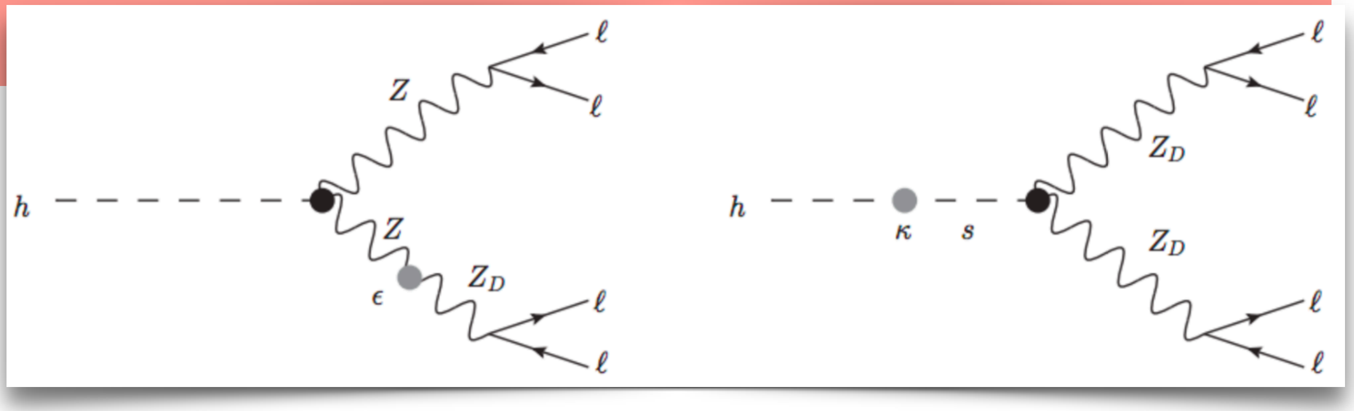
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

H→ZX && H→XX

CMS-PAS-HIG-19-007

- Large signal-to-background ratio: pp→H→4l
  - Allows complete reconstruction of the kinematics of the Higgs boson based on final-state decay particles
  - Reveals hints to exotic Higgs decays from beyond Standard Model

- Dark photon model:
  - Z_D: mediates a dark $U(1)_D$ gauge symmetry, simultaneously broken by dark Higgs mechanism
  - Interaction type:
    - Hypercharge portal via kinematical mixing coupling
    - Higgs portal via Higgs mixing coupling

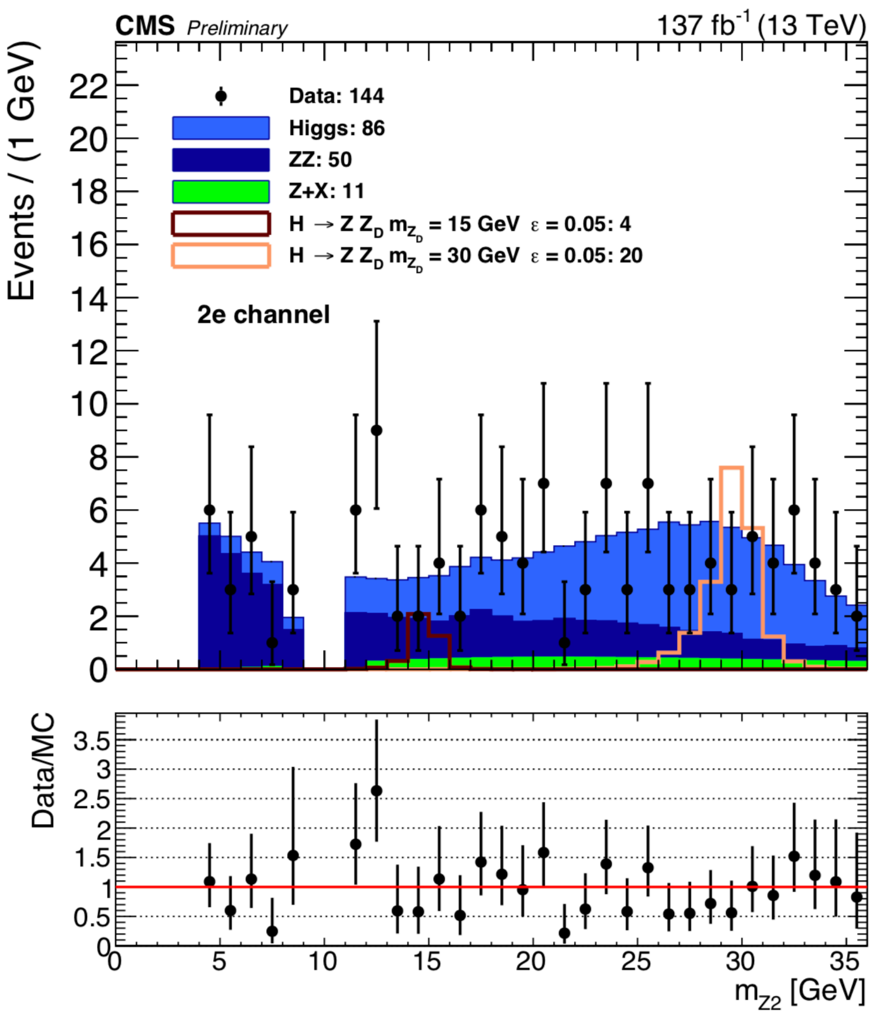


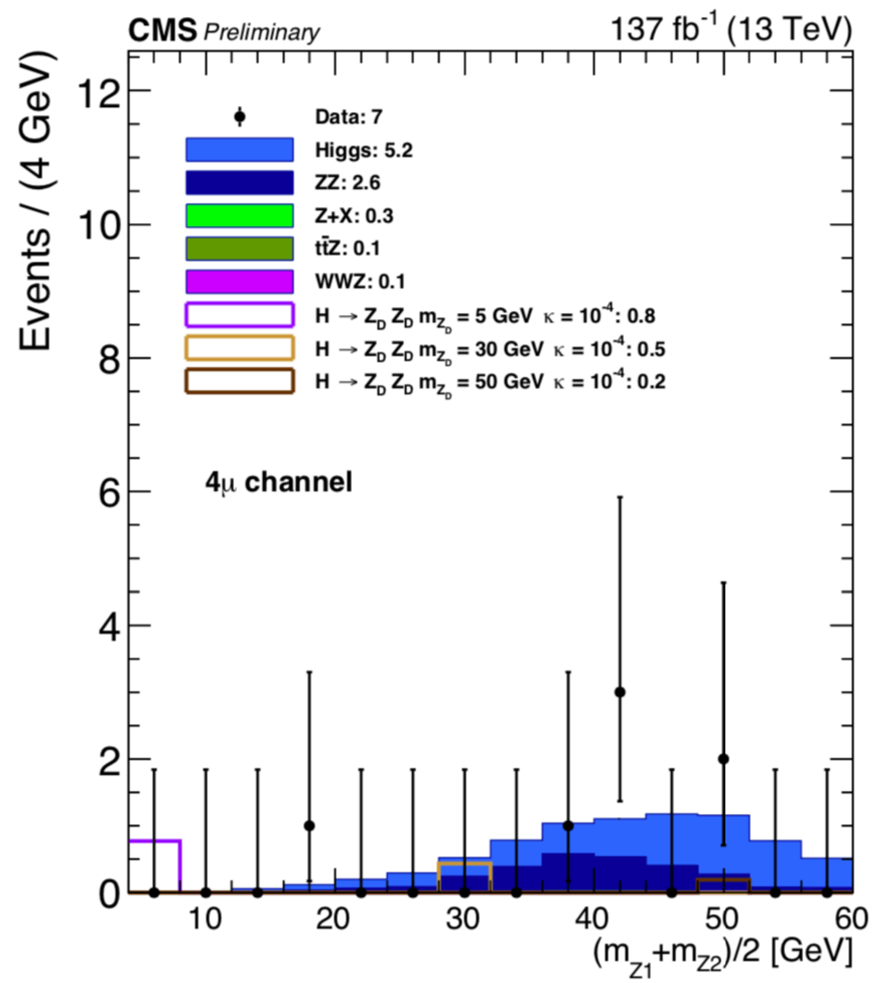
- Axion-like particle model:
  - X: gauge singlet pseudo-scalar (a)
  - The coupling mechanism represented by two Wilson coefficients: $C^{\text{eff}}_{\text{ZH}}/\Lambda$ && $C^{\text{eff}}_{\text{aH}}/\Lambda^2$

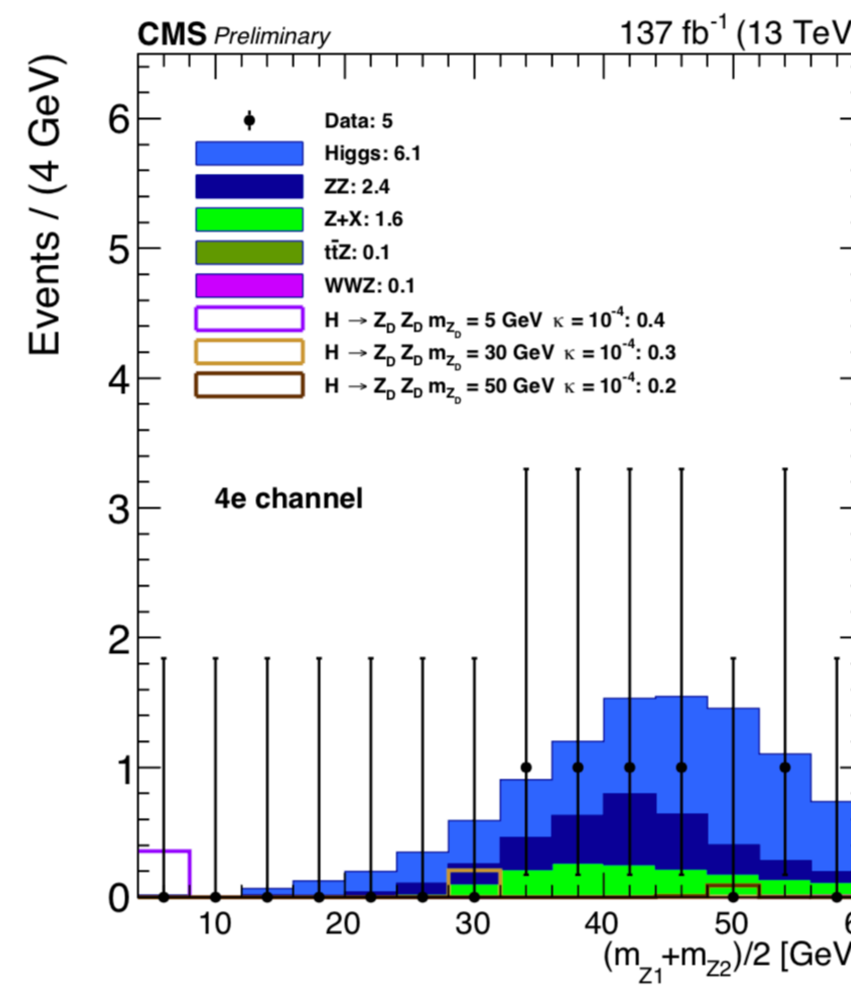
H→ZX && H→XX

CMS-PAS-HIG-19-007

- **Generated Next-to-leading order (NLO)** for the signal process
- Four final-state lepton categories: ***4μ, 2μ2e, 2e2μ, 4e***
- The main background (Z + jets) estimated from data



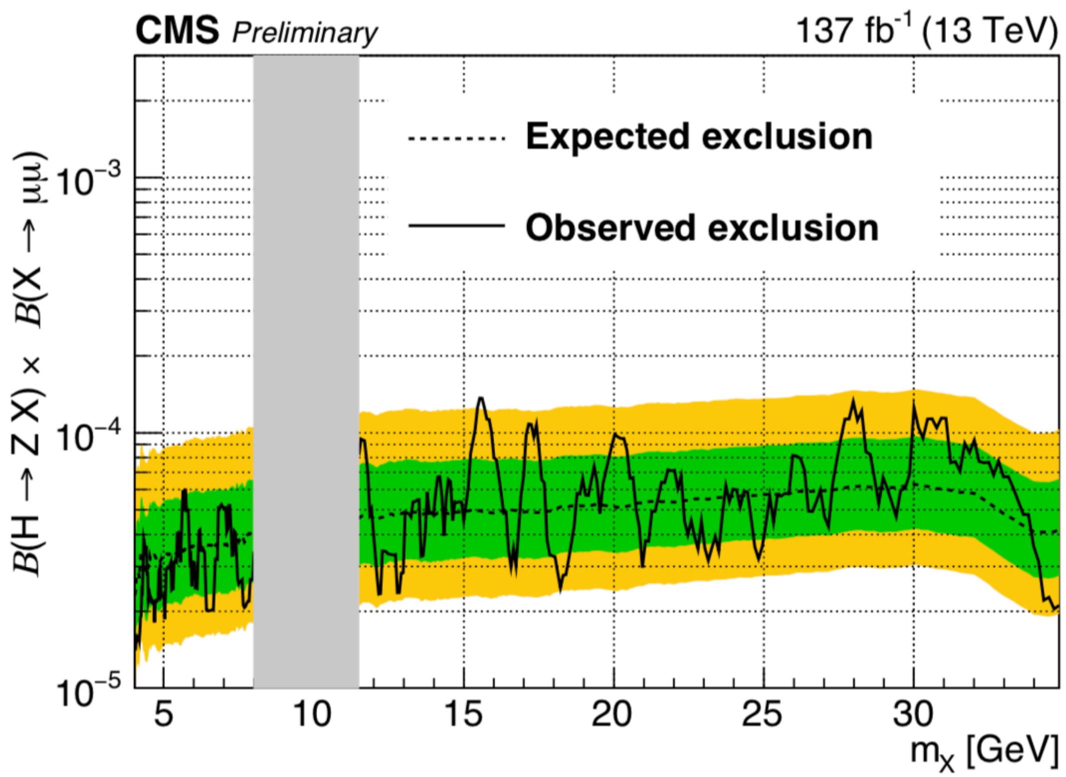


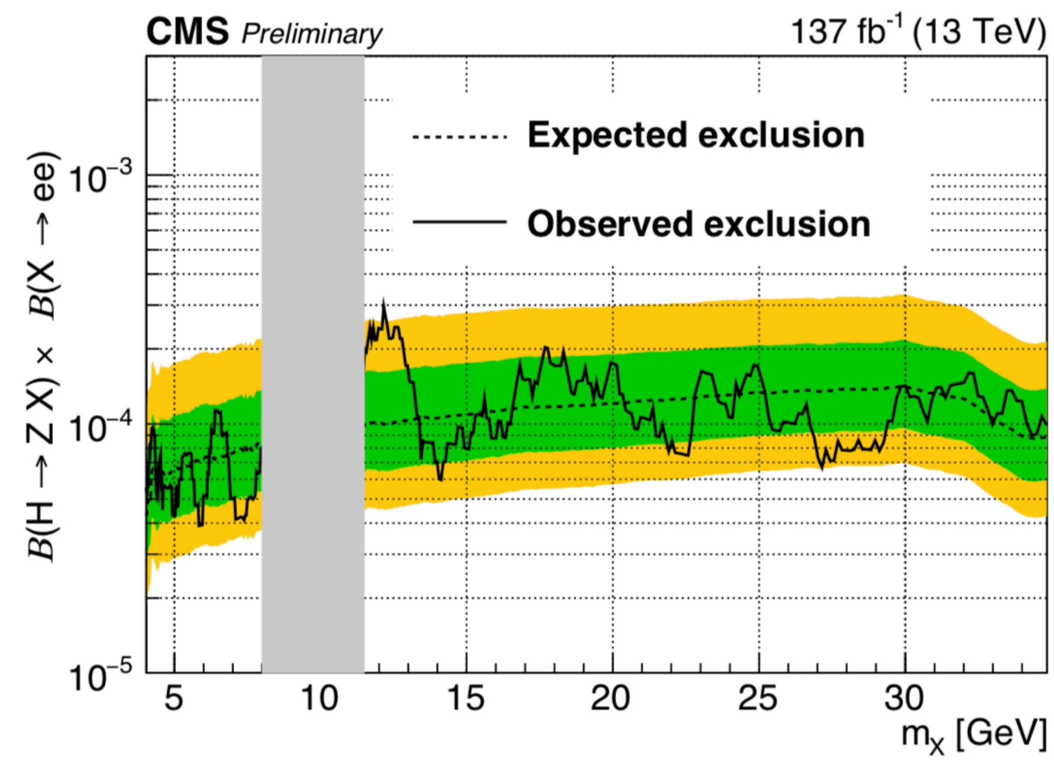


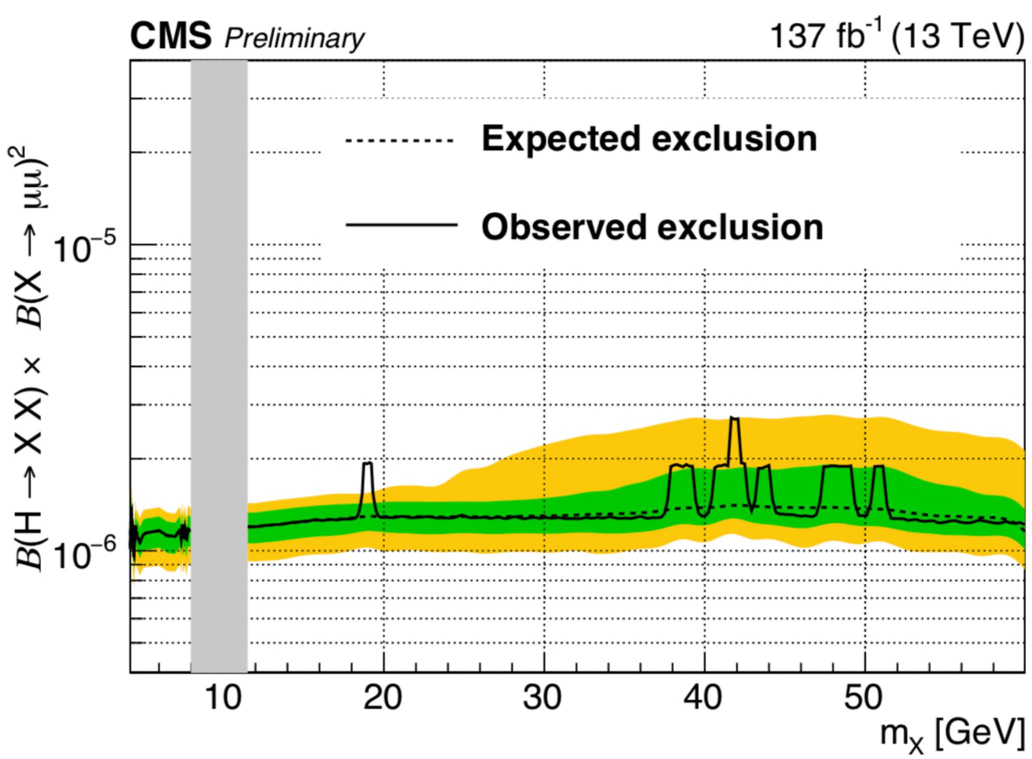
- **No significant deviation from SM background prediction**

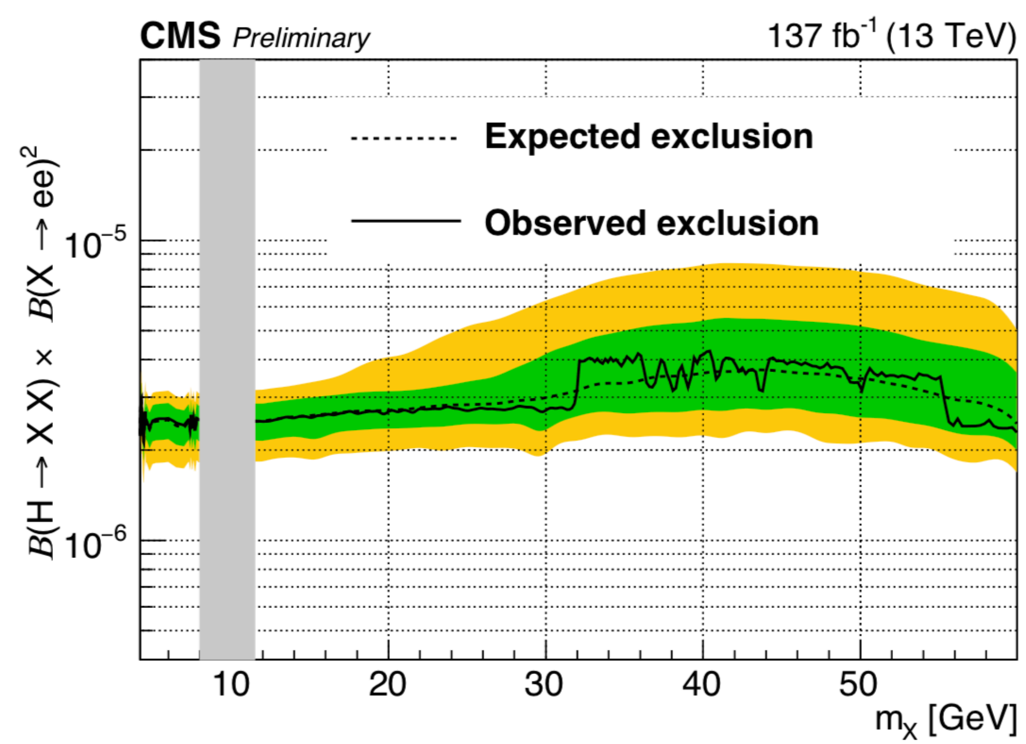
H→ZX && H→XX

CMS-PAS-HIG-19-007





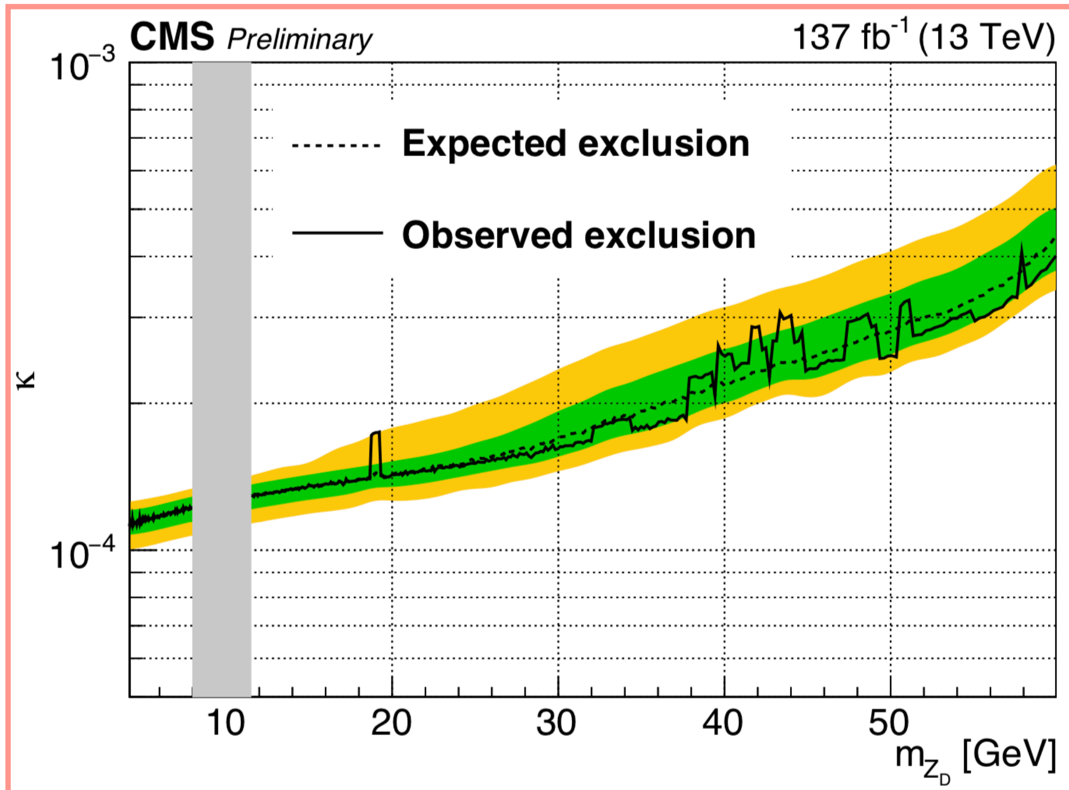




- **The mass range of upsilon meson states is excluded**
- **The normalization of Higgs background is allowed to float freely in the likelihood fit**
- **The largest uncertainty is Z + jets background estimation (48 -100 %)**

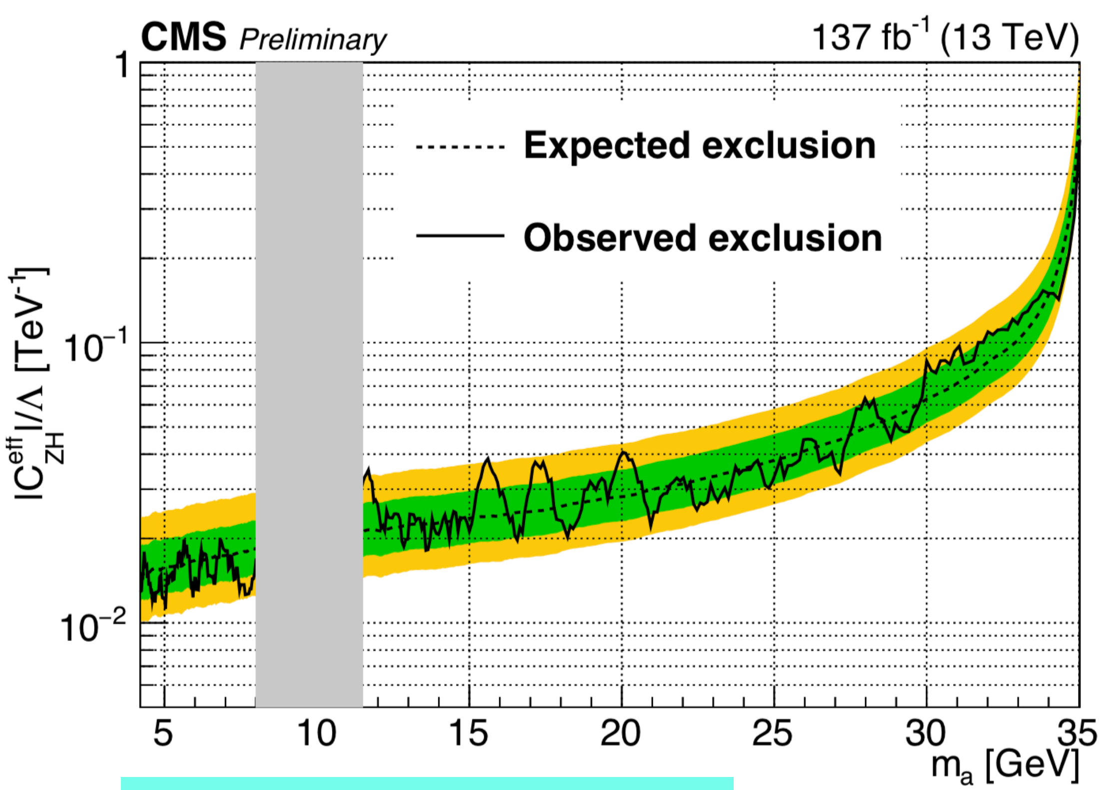
H→ZX && H→XX

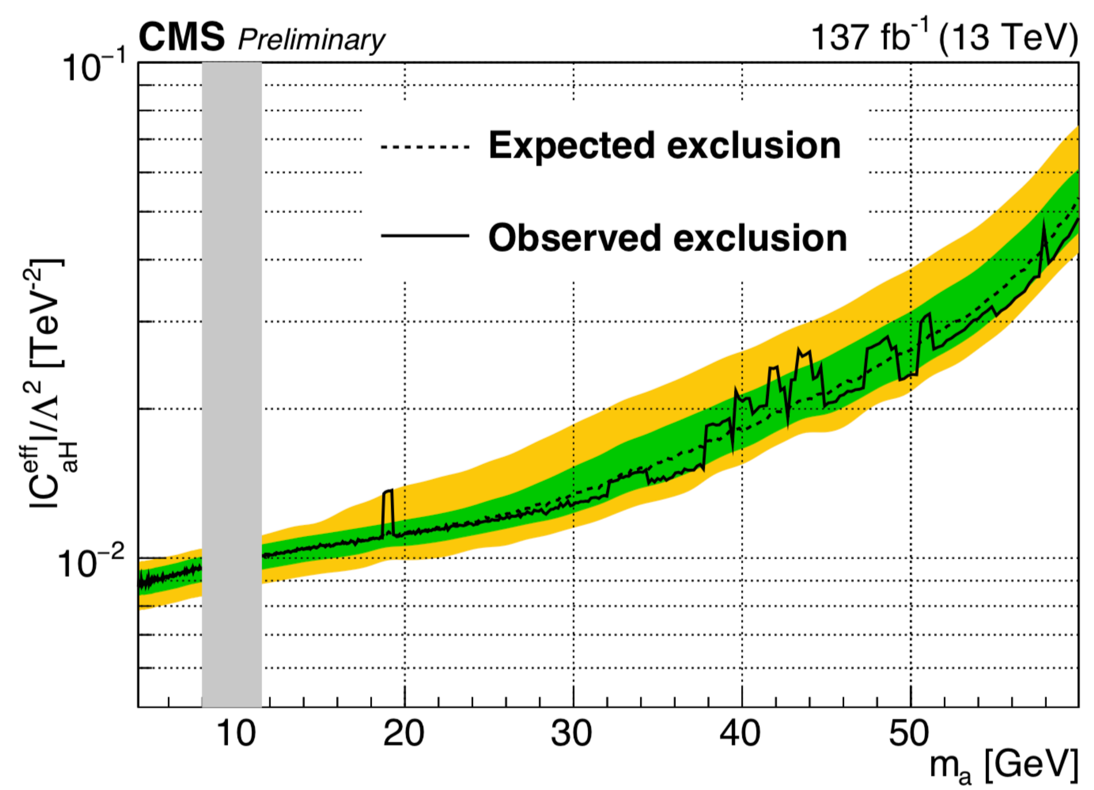
CMS-PAS-HIG-19-007



Dark photon model

- **Upper limits of Higgs mixing parameter set in 95% confidence level**





Axion-like particle model

- **Upper limits on Wilson coefficients set at 95% confidence level**