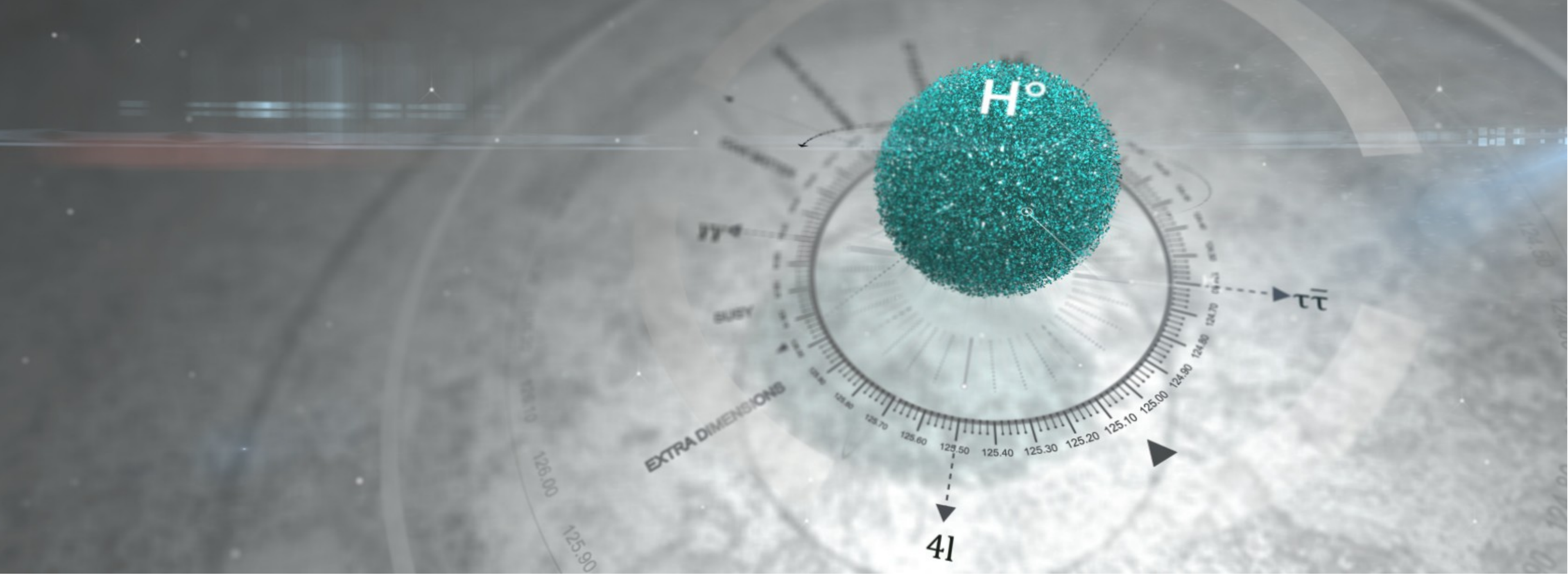

Search for the exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two muons and two τ leptons $\sqrt{s}$=13 TeV

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2HDM + S

- Contains 2 higgs doublets H_1 and H_2 and one additional singlet S
- Predicts 7 physical states:

  3 CP – even (scalar)

  2 CP – odd (pseudoscalar)

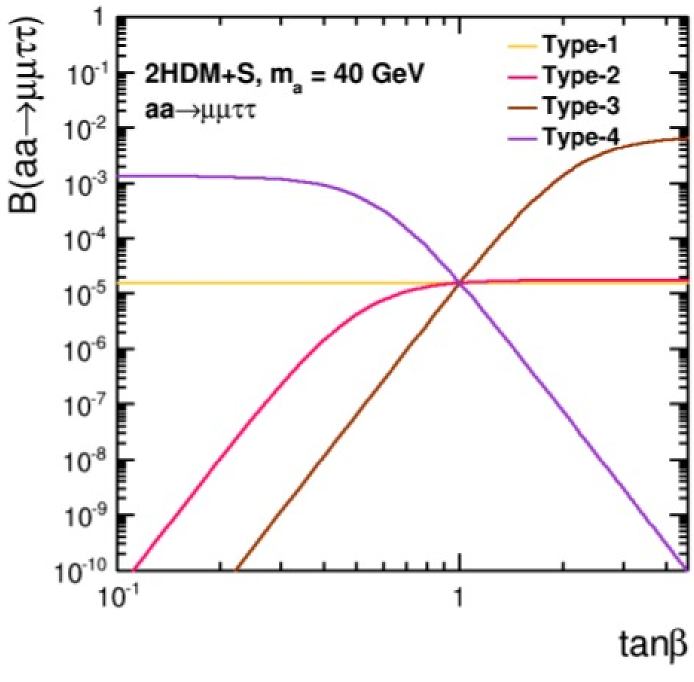
  2 Charged
- Four types of 2HDM+S forbid FCNC at tree level
- Decay **$h(125GeV) \longrightarrow 2\alpha \longrightarrow 2\mu 2\tau$** is favored in 2HDM+S Type-3

	Type-1	Type-2	Type-3	Type-4
u	H_1	H_1	H_1	H_1
d	H_1	H_2	H_1	H_2
e	H_1	H_2	H_2	H_1

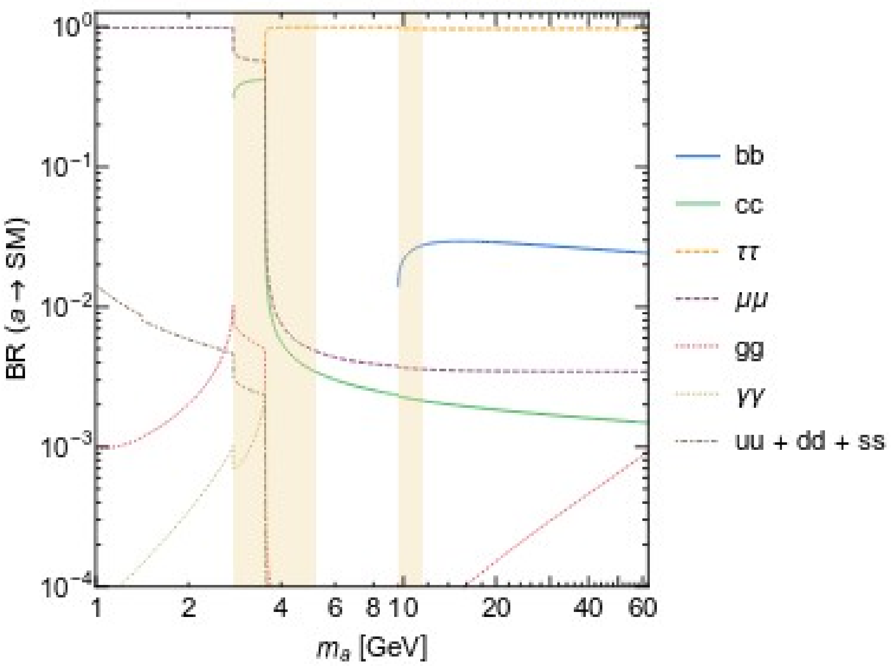
2HDM + S

- For the decay h(125GeV)⟶ 2α ⟶ 2μ2τ the largest branching fraction is obtained in Type 3 for large values of tanβ

- Largest branching fraction for Type-3 (0.6%) : For tanβ>1 decays to leptons are enhanced over the decays to quarks



Type-3 tanβ=5



$h(125\text{GeV}) \to \alpha\alpha \to 2\mu 2\tau$

- Di-muon pair has excellent mass resolution, di-tau pair has reasonable mass resolution backgrounds are low
- Four ditau final states are studied $e\tau_h$, $\mu\tau_h$, $e\mu$,τ_h τ_h
- Ditau final states with two muons or two electrons are not studied because of the low branching fraction and of the large contribution of $ZZ \to 4l$ background events
- LHC 7 & LHC 8 allows Br of the 125 GeV higgs boson into BSM states to be O(20%-50%)

Simulated Signal Samples

Signal Samples

- Signal: h(125GeV)⟶ 2α ⟶ 2μ2τ generated with AMC@NLO
- 9 MC Samples 15,20,25,30,35,40,45,50,55,60 GeV

Signal MC simulations	Nb of gen. events
SUSYGluGluToHToAA_AToMuMu_AToTauTau_M-15_TuneCUETP8M1_13TeV_madgraph_pythia8	250 000
SUSYGluGluToHToAA_AToMuMu_AToTauTau_M-20_TuneCUETP8M1_13TeV_madgraph_pythia8	250 000
SUSYGluGluToHToAA_AToMuMu_AToTauTau_M-25_TuneCUETP8M1_13TeV_madgraph_pythia8	250 000
SUSYGluGluToHToAA_AToMuMu_AToTauTau_M-30_TuneCUETP8M1_13TeV_madgraph_pythia8	250 000
SUSYGluGluToHToAA_AToMuMu_AToTauTau_M-35_TuneCUETP8M1_13TeV_madgraph_pythia8	250 000
SUSYGluGluToHToAA_AToMuMu_AToTauTau_M-40_TuneCUETP8M1_13TeV_madgraph_pythia8	250 000
SUSYGluGluToHToAA_AToMuMu_AToTauTau_M-45_TuneCUETP8M1_13TeV_madgraph_pythia8	250 000
SUSYGluGluToHToAA_AToMuMu_AToTauTau_M-50_TuneCUETP8M1_13TeV_madgraph_pythia8	250 000
SUSYGluGluToHToAA_AToMuMu_AToTauTau_M-55_TuneCUETP8M1_13TeV_madgraph_pythia8	250 000
SUSYGluGluToHToAA_AToMuMu_AToTauTau_M-60_TuneCUETP8M1_13TeV_madgraph_pythia8	250 000

Via VBF

SUSYVBFHToAA_AtoMuMu_AtoTauTau_M40_4F_TuneCUETP8M1_13TeV_madgraph_pythia8/MINIAODSIM/PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6-v3/70000	250000
SUSYVBFHToAA_AtoMuMu_AtoTauTau_M20_4F_TuneCUETP8M1_13TeV_madgraph_pythia8/MINIAODSIM/PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6-v3/70000	250000
SUSYVBFHToAA_AtoMuMu_AtoTauTau_M60_4F_TuneCUETP8M1_13TeV_madgraph_pythia8/MINIAODSIM/PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6-v3/70000	250000

Simulated Signal Samples

Additional Signal Process: h(125GeV)⟶ 2α ⟶ 4τ

$$\frac{\mathcal{B}(a \to \tau\tau)}{\mathcal{B}(a \to \mu\mu)} \simeq \frac{m_\tau^2}{m_\mu^2}$$

- The probability of having at least 2 muons in the final state with four taus is 13.6%
- 20 times more h(125GeV)⟶ 2α ⟶ 4τ than h(125GeV)⟶ 2α ⟶ 2μ2τ
- Additional filter at generated level selects at least two muons with P_T>5 Gev and P_T>15GeV

Signal MC simulations	Gen. events	Filter eff.
SUSYGluGluToHToAA_AToTauTau_AToTauTau_FilterMu5Mu15_M-20_TuneCUETP8M1_13TeV	30M	2.73%
SUSYGluGluToHToAA_AToTauTau_AToTauTau_FilterMu5Mu15_M-30_TuneCUETP8M1_13TeV	30M	2.81%
SUSYGluGluToHToAA_AToTauTau_AToTauTau_FilterMu5Mu15_M-40_TuneCUETP8M1_13TeV	30M	2.92%
SUSYGluGluToHToAA_AToTauTau_AToTauTau_FilterMu5Mu15_M-50_TuneCUETP8M1_13TeV	30M	3.10%
SUSYGluGluToHToAA_AToTauTau_AToTauTau_FilterMu5Mu15_M-60_TuneCUETP8M1_13TeV	30M	3.39%

Corrections to simulated samples

- τ_h energy scale : the energy of τ_h in simulations is corrected based on the reconstructed decay mode (Z-⟶ττ TauPOG)

-1.8%	1 prong
0.4 %	3 prong

- τ_h Identification Efficiency : Data/MC scale factor corresponding to the loose working point of the MVA τ_h isolation is 0.99% (TauPOG with a tag-and-probe method in Drell-Yan events)
- Energy Scale of e/mu faking τ_h : depend on the reconstructed decay mode with largest correction to 9.5% in 1-prong decays for electrons faking τ_h candidates
- PileUp Reweighting: Reweighed using a minimum bias cross section of 69.2mb
- Electron and Muon Identification efficiency: Muon Scale Factor HTT group, Electron SF from Egamma POG

MC and Data Samples

Data Samples

Dataset	Run range	Integrated Luminosity
/DoubleMuon/Run2016B-03Feb2017-ver2-v2/MINIAOD	272007–275376	5.788 /fb
/DoubleMuon/Run2016C-03Feb2017-v1/MINIAOD	275657–276283	2.573 /fb
/DoubleMuon/Run2016D-03Feb2017-v1/MINIAOD	276315–276811	4.248 /fb
/DoubleMuon/Run2016E-03Feb2017-v1/MINIAOD	276831–277420	4.009 /fb
/DoubleMuon/Run2016F-03Feb2017-v1/MINIAOD	277772–278808	3.102 /fb
/DoubleMuon/Run2016G-03Feb2017-v1/MINIAOD	278820–280385	7.540 /fb
/DoubleMuon/Run2016H-03Feb2017-ver2-v1/MINIAOD	280919–284044	8.606 /fb
/DoubleMuon/Run2016H-03Feb2017-ver3-v1/MINIAOD	280919–284044	see above

- The analysis is based on 2016 data with a corresponding integrated luminosity of 35.9 fb^{-1} in double muon datasets at $\sqrt{s}$=13 TeV

Background MC Samples

Background MC simulations	Cross section
ZZTo4L_13TeV_powheg_pythia8	1.256 pb
GluGluToContinToZZTo2mu2tau_13TeV_MCFM701_pythia8	2*0.00319 pb
GluGluToContinToZZTo2e2tau_13TeV_MCFM701_pythia8	2*0.00319 pb
GluGluToContinToZZTo2e2mu_13TeV_MCFM701_pythia8	2*0.00319 pb
GluGluToContinToZZTo4e_13TeV_MCFM701_pythia8	2*0.00159 pb
GluGluToContinToZZTo4mu_13TeV_MCFM701_pythia8	2*0.00159 pb
GluGluToContinToZZTo4tau_13TeV_MCFM701_pythia8	2*0.00159 pb

- Scaled to NLO cross section

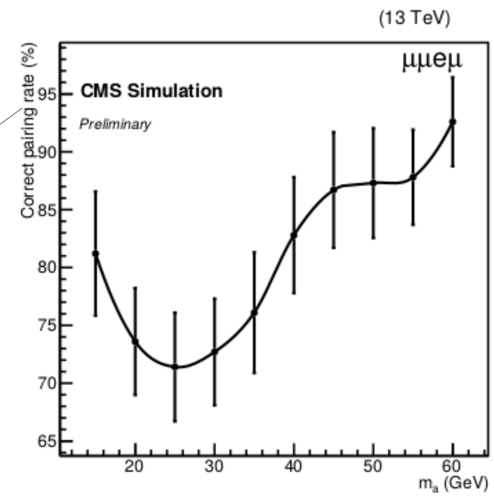
Event Selection

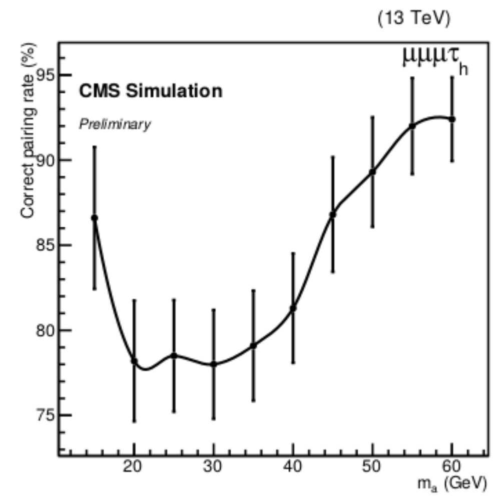
μμeμ	μμeτ	μμμτ	μμττ
Leading muon P_T>18 GeV Subleading muon P_T>9 GeV ΔR<0.5 |eta|<2.4 , Muon ID Medium Iso<0.20			
e	e	μ	τ
P_T>7 GeV |eta|<2.5 MVA 80%	P_T>7 GeV |eta|<2.5 MVA 80%	P_T>5 GeV |eta|<2.4 Muon ID Medium Iso<0.20	P_T>18.5 GeV |eta|<2.3 Loose MVA iso Loose anti-mu VL anti-e
μ	τ	τ	τ
P_T>5 GeV |eta|<2.4 Muon ID Medium Iso<0.20	P_T>18.5 GeV |eta|<2.3 Loose MVA iso, Loose anti-mu VL anti-e	P_T>18.5 GeV |eta|<2.3 Loose MVA iso Loose anti-mu VL anti-e	P_T>18.5 GeV |eta|<2.3 Loose MVA iso Loose anti-mu VL anti-e

Event Selection

- If more than two muons in the final state mass $m_\alpha \rightarrow \mu\mu$ is formed from the leading muon and the highest P_T opposite sign muon among the remaining muons

Success rate 70 to 95%





- Opposite Sign in each pair
- Trigger: **Double Muon Trigger** with online thresholds of 8 and 17 GeV

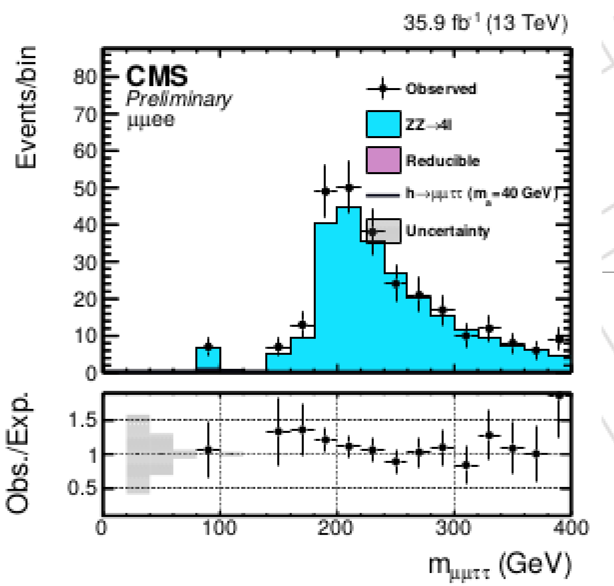
- bjet vetoes:

  Events with at least one jet with P_T>20GeV , |eta|<2.4, Medium working point on CSV

  Reduce the contribution of the reducible background tt and of the irreducible ttZ

Irreducible Background Estimation

- Estimated from MC simulations ⟶ Scaled to NLO cross sections
- qq⟶ZZ⟶ 4l : largest
- gg⟶ZZ⟶4l : 10%
- ttZ, WZZ, ZZZ ,SM Higgs Boson: Estimated from MC ⟶ Negligible and become zero after optimization selection

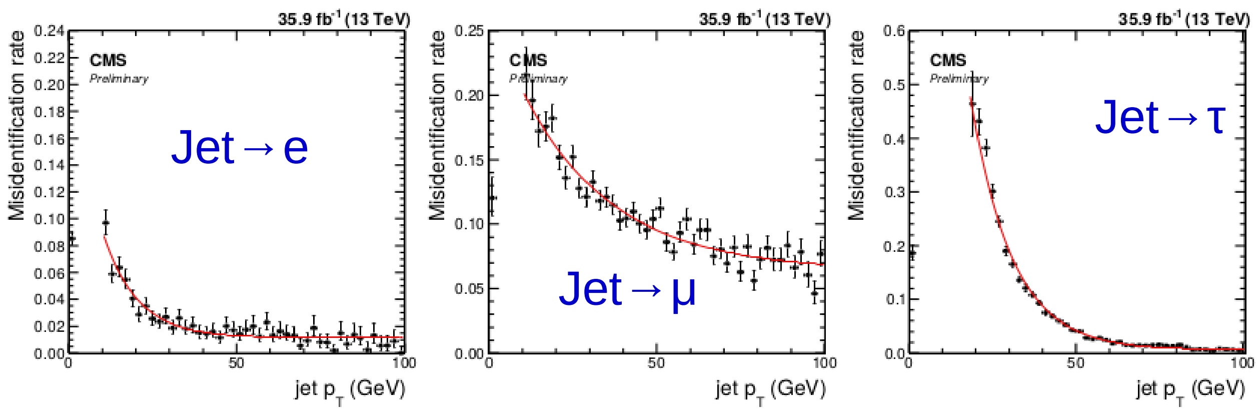


ZZ⟶ 4l is well described in mmee final state

Reducible Background

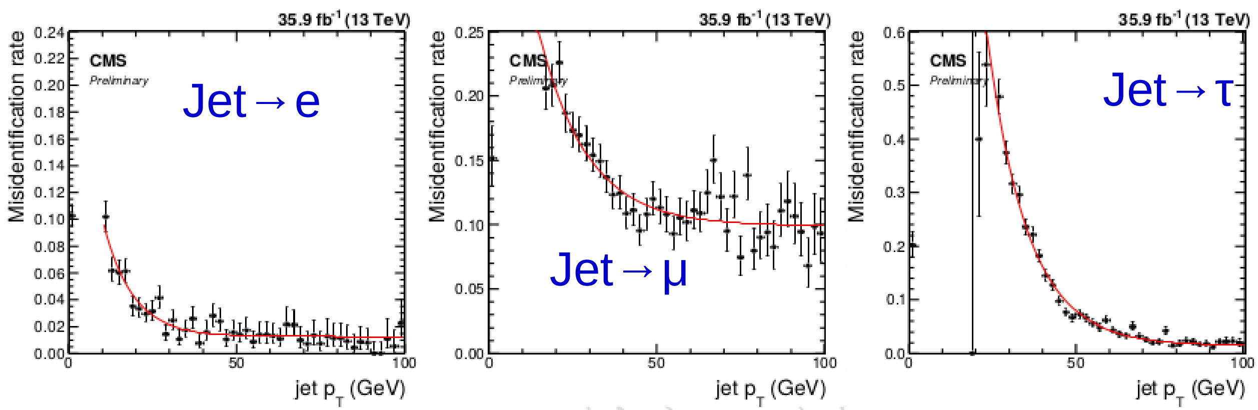
- Events where at least one jet is misidentified as a lepton
- Z+jets, WZ+jets, ZZ⟶2l2q, tt QCD multijet
- Fake rate = Events passing id+iso/ Events with loosened id+iso
- Parametrized with an exponential + constant as a function of the P_T of the jet closest to lepton

Barrel



(a) jet→ μ, barrel (b) jet→ e, barrel (c) jet→ τ_h, barrel

Endcap



(d) jet→ μ, endcaps (e) jet→ e, endcaps (f) jet→ τ_h,endcaps

Reducible Background - Yield

- Events passing all selection criteria for the signal region except that one or two tau candidates fail iso + id are reweighed as a function of fake rate $f(P_T)$

  $+f1(P_T)/(1-f1(P_T)$: 1st fake lepton , $+f2(P_T)/(1-f2(P_T)$: 2nd fake lepton

  $-f1(P_T)f2(P_T)/(1-f1(P_T)(1-f2(P_T)$: both leptons as fake

High invariant mass

	FF	PF	FP	PP estimate
$\mu\mu e\mu$	3.675 ± 0.072	5.664 ± 0.344	8.772 ± 0.740	10.67 ± 0.85
$\mu\mu e\tau_h$	21.483 ± 0.303	31.372 ± 2.231	23.431 ± 0.715	33.32 ± 2.40
$\mu\mu\mu\tau_h$	27.715 ± 0.691	46.256 ± 3.121	31.175 ± 1.490	49.72 ± 3.90
$\mu\mu\tau_h\tau_h$	88.551 ± 2.031	114.480 ± 5.453	69.758 ± 3.351	95.69 ± 6.23

Low Invariant mass

	FF	PF	FP	PP estimate
$\mu\mu e\mu$	0.155 ± 0.015	0.334 ± 0.067	0.477 ± 0.136	0.66 ± 0.18
$\mu\mu e\tau_h$	0.393 ± 0.034	0.859 ± 0.283	0.653 ± 0.111	1.12 ± 0.33
$\mu\mu\mu\tau_h$	0.834 ± 0.105	0.557 ± 0.168	0.865 ± 0.243	0.59 ± 0.32
$\mu\mu\tau_h\tau_h$	1.073 ± 0.247	—	—	1.073 ± 0.247

Shape of the reducible background

- Tau candidates have the same electric charge, while the dimuon pair is selected as previously
- To increase the statistical precision the iso criteria on the tau candidates are loosened

Final State	Loosened cuts
$e\mu$	Iso <2.0, no e-id, Loose PF Muon ID
$e\tau_h$	e ID 90%, tauMVAraw>-0.9
$u\tau_h$	Loose PF muon ID, iso<1.0, taurawMVA iso >-0.9
$\tau_h\tau_h$	TauMVAraw>-0.9

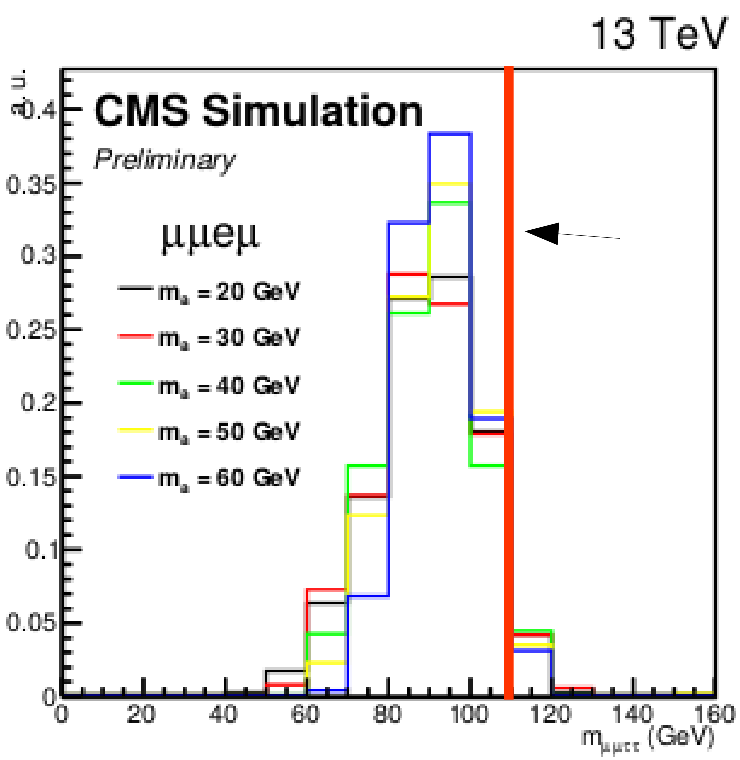
Optimization Cuts

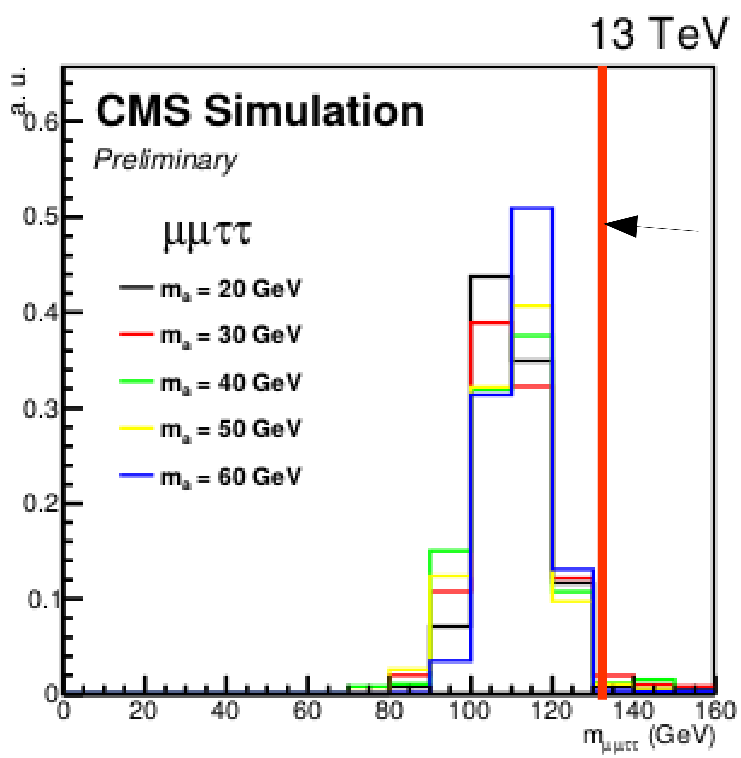
Final State	Invariant mass of four leptons (GeV)
eμ	< 110
$e\tau_{h}$, $\mu\tau_{h}$	< 120
$\tau_{h}\tau_{h}$	< 130

- Signal Efficiency ~**100%**

Because the visible invariant mass is expected to peak below the Higgs boson mass due to the presence of neutrinos

- Fake background reduction ~**90%**

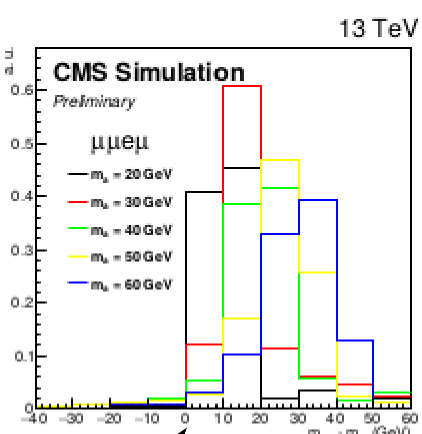




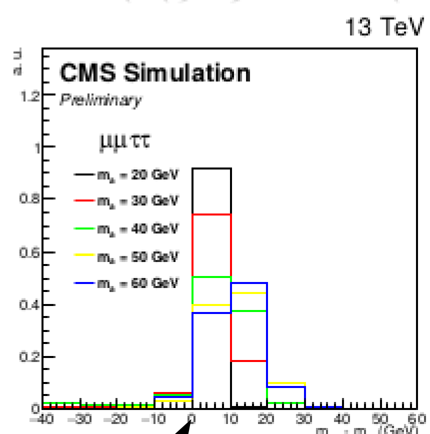
Event Selection – Optimization Cuts

$$\boxed{m_{\mu\mu} > m_{\tau\tau}}$$

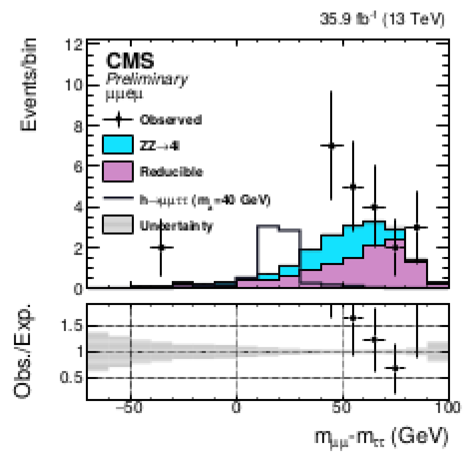
- High Signal Efficiency⟶ energy lost by neutrinos in tau decays whereas the reducible background is reduced by a factor 2 in all final states
- The mass difference between the two pairs increases with mass α



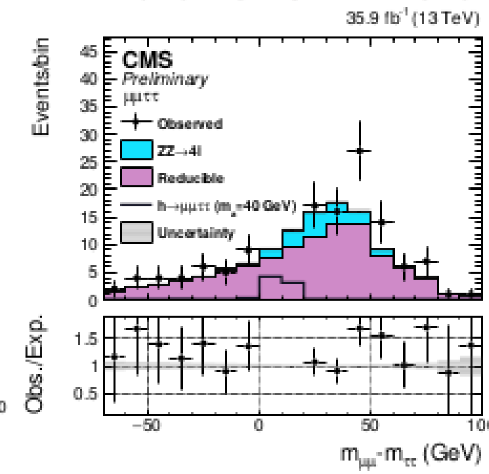
(a) $\mu\mu e\mu$



(d) $\mu\mu\tau_h\tau_h$



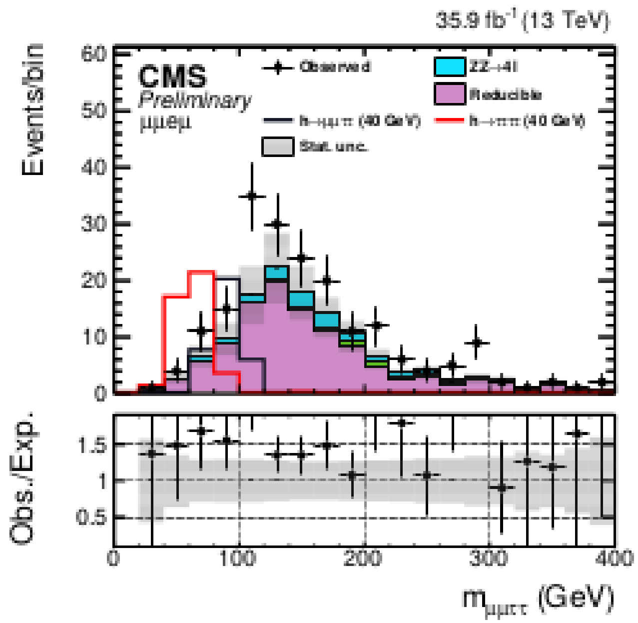
(a) $\mu\mu e\mu$



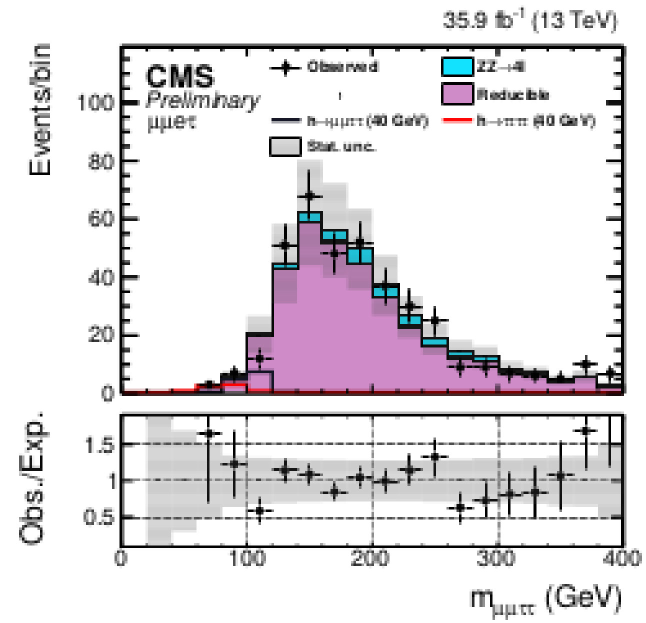
(d) $\mu\mu\tau_h\tau_h$

Peak above 0 because the mass of dimuon is greater than the of ditau

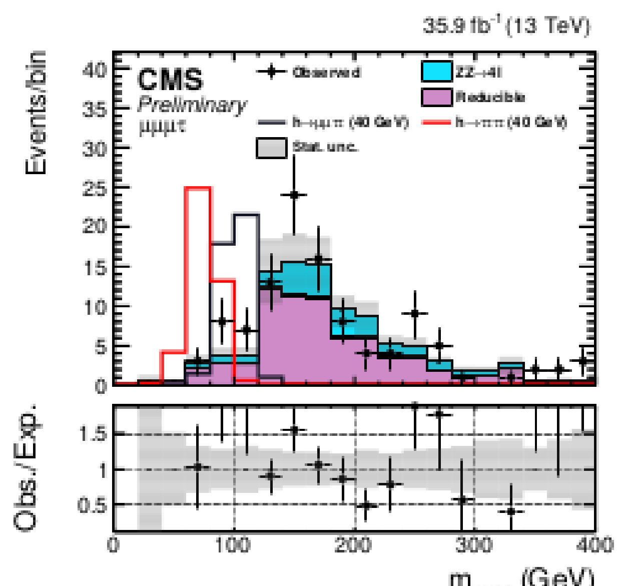
Control Plots of invariant mass (μμττ)



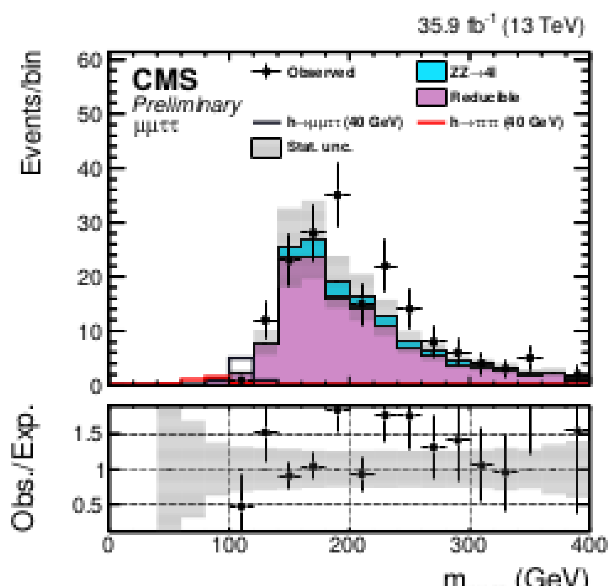
(a) $\mu\mu e\mu$



(b) $\mu\mu e\tau_h$



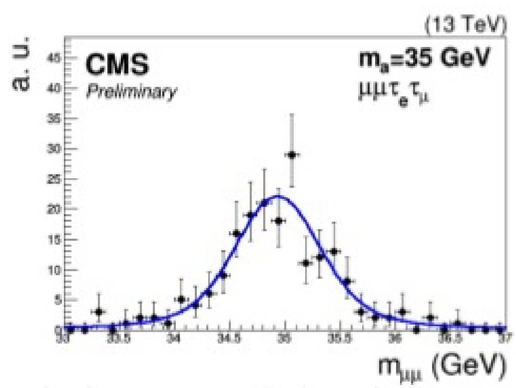
(c) $\mu\mu\mu\tau_h$



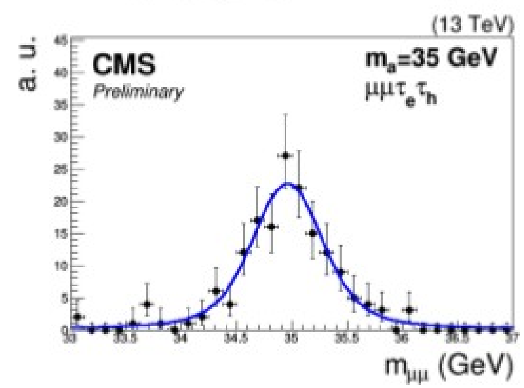
(d) $\mu\mu\tau_h\tau_h$

Signal Model for h→ αα→ 2μ2τ

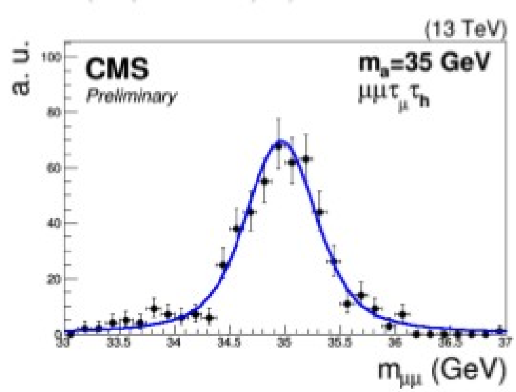
- Voigt profiles (3 parameters: mean, α (Lorentzian) and σ(Gaussian))
- Dimuon mass resolution 2%



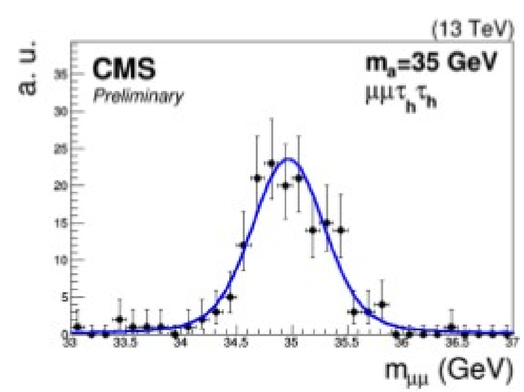
(a) $\mu\mu e\mu$



(b) $\mu\mu e\tau_h$



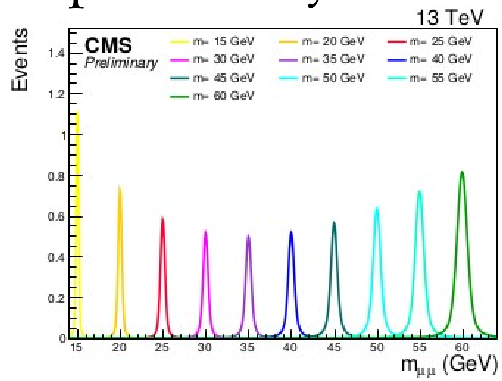
(c) $\mu\mu\mu\tau_h$

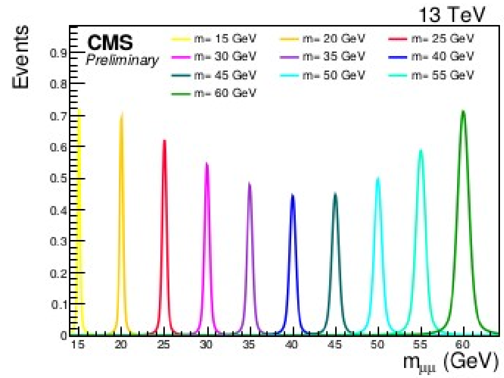


(d) $\mu\mu\tau_h\tau_h$

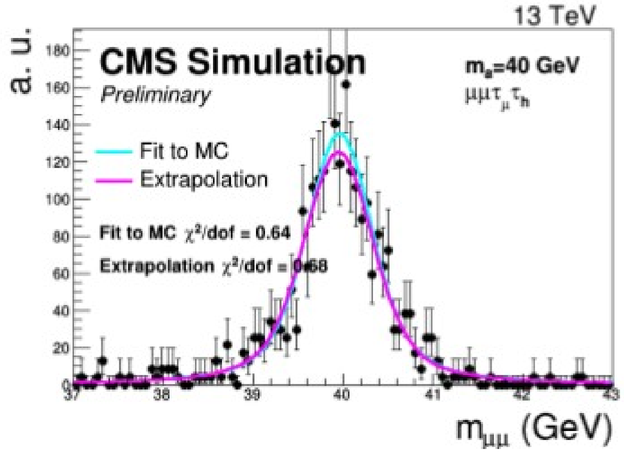
Signal Model for h⟶ αα⟶ 2μ2τ

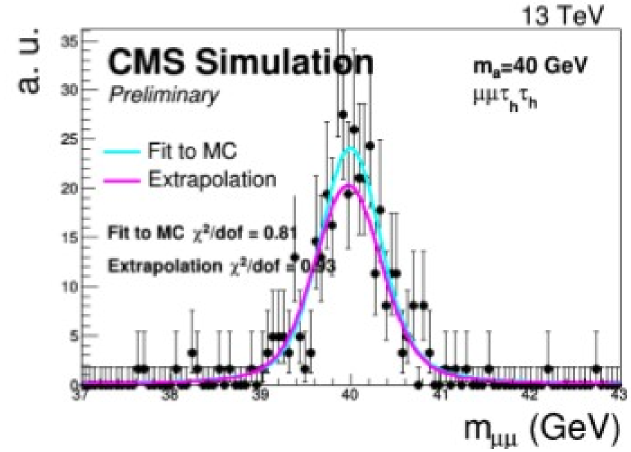
- Signal Shape for any mass of m_α





- Remove a signal sample from the parametrization and compare the functions obtained from the extrapolated parametrization with those obtained from the direct fit





Signal Model for $h \longrightarrow \alpha\alpha \longrightarrow 4\tau$

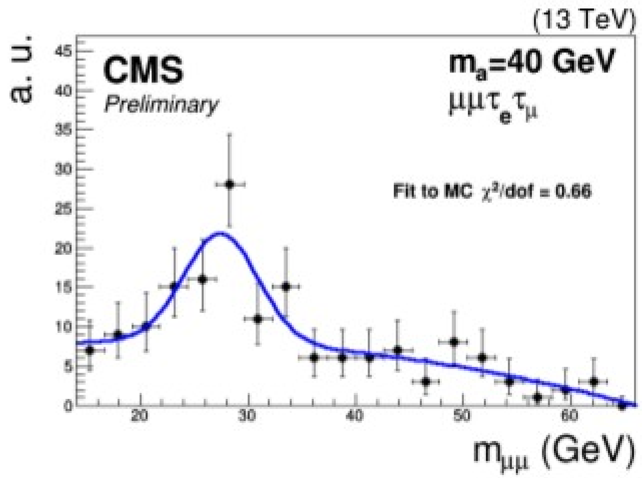
- The two reconstructed muons that form the dimuon mass distrubution come from:

  1) same pseudoscalar boson $\longrightarrow$ wide peak distribution below m_α

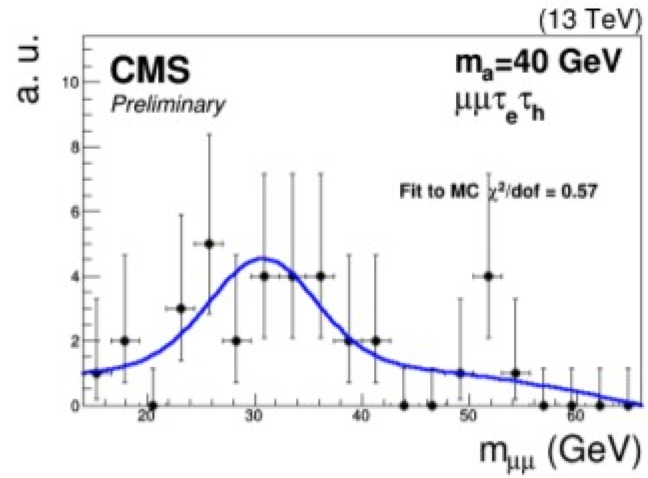
  2) from two different pseudoscalar bosons$\longrightarrow$ do not form a resonance and their distribution is rather flat.

- Distributions are parametrized by the sum of a low mass Gaussian and a flatter Bernstein polynomial for the non-resonant combinations.
- Six free parameters: the mean and width of the low mass Gaussian, 3 parameters of Bernstein polynomial, and the ratio between the normalization of the Gaussian and Bernstein components.

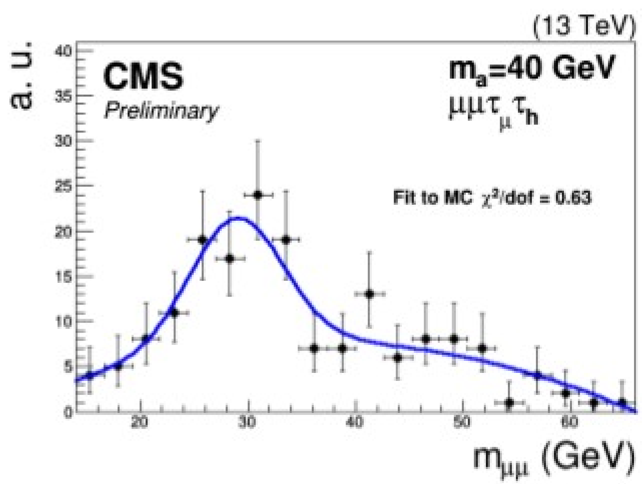
Signal Model $h \rightarrow \alpha\alpha \rightarrow 4\tau$

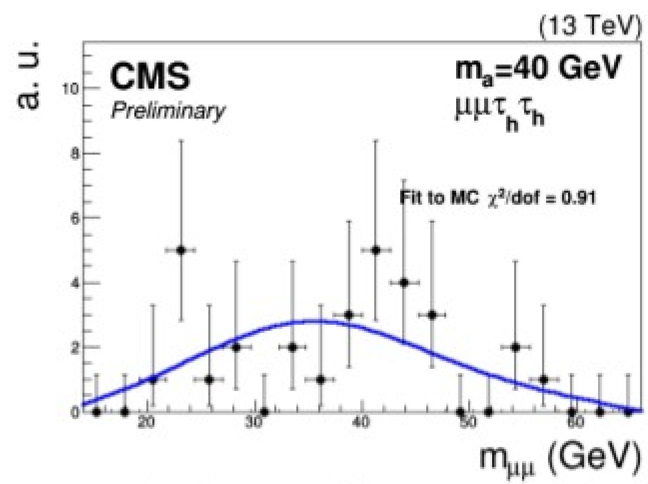


(a) $\mu\mu e\mu$



(b) $\mu\mu e\tau_h$





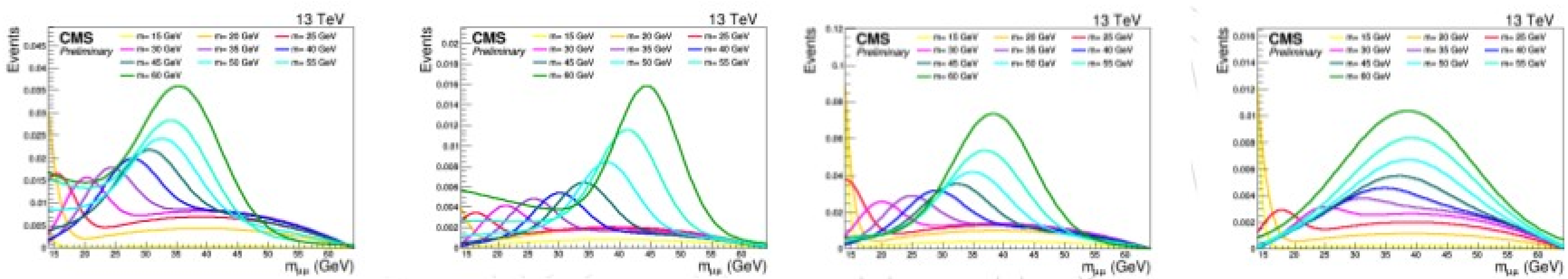
Signal Model for h→ αα→ 4τ

After selection, the yield of h→αα→4τ is about 30% of the yield of h→ αα→ 2μ2τ

The reduction of the ratio after selection is explained by the following:

- Muons are not necessarily of opposite sign→ lower efficiency
- Muons are softer as they come from tau decays leading to a lower efficiency for the cuts on the P_T of the leptons
- Dimuon mass is not necessarily larger than ditau mass because muons come also from hadronic taus leading to a lower efficiency for the cut on $m_{\mu\mu} > m_{\tau\tau}$
- Dimuon mass is not necessarily less than 62.5 GeV

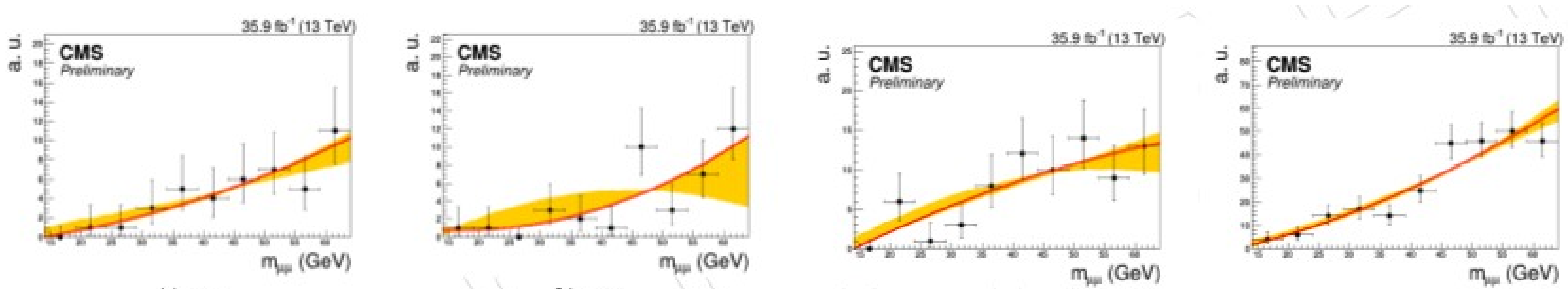
Signal Shape for every m_α sample



Background Parametrization

Reducible

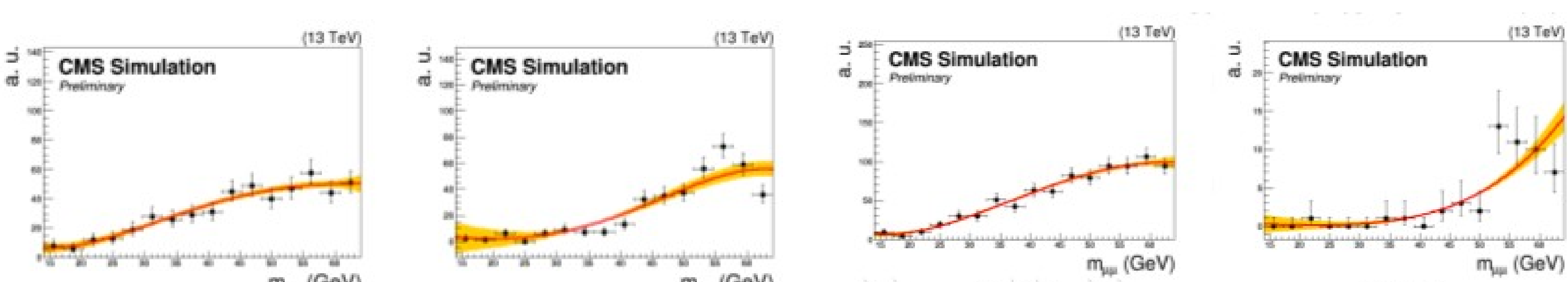
- 3rd degree Bernstein polynomials⟶ Good fit quality in all the final states



(a) $\mu\mu e\mu$ (b) $\mu\mu e\tau_h$ (c) $\mu\mu\mu\tau_h$ (d) $\mu\mu\tau_h\tau_h$

Irreducible

- 5th degree Bernstein polynomials⟶ Good fit quality in all the final states



(a) $\mu\mu e\mu$ (b) $\mu\mu e\tau_h$ (c) $\mu\mu\mu\tau_h$ (d) $\mu\mu\tau_h\tau_h$

Estimation of uncertainties Physics Objects

- Tracking and Identification of Muons, per single muon: 2%
- 2% is assigned to the yield of MC processes with real electrons in the final state, to account for the uncertainty in the electron isolation and identification efficiency
- Electron isolation and identification efficiency : 2%
- Tau Efficiency ID : 5 % (TauPOG)
- Tau energy scale : 1.2%
- B jet veto is 0.5 % yield uncertainty for signal and irreducible background events

Estimation of uncertainties Background

- zz⟶4l : 10% (CMS Measurement)
- Fitting motel for irreducible background is negligible

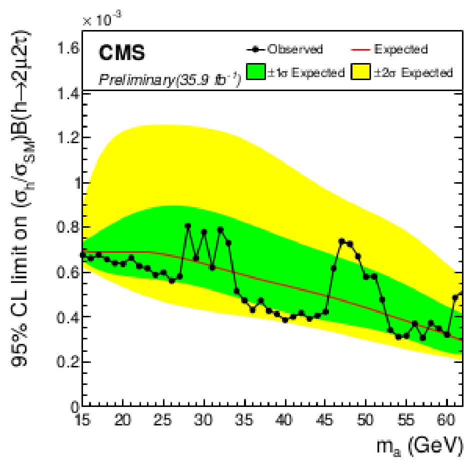
  ⟶ Irreducible background is generally sub-dominant

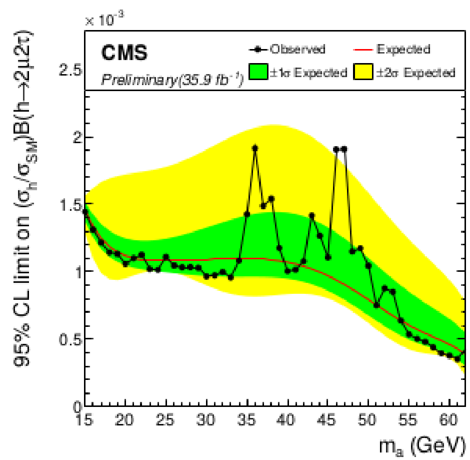
  ⟶ MC simulations populated enough leading to precise shape description
- Yield uncertainty in reducible background:

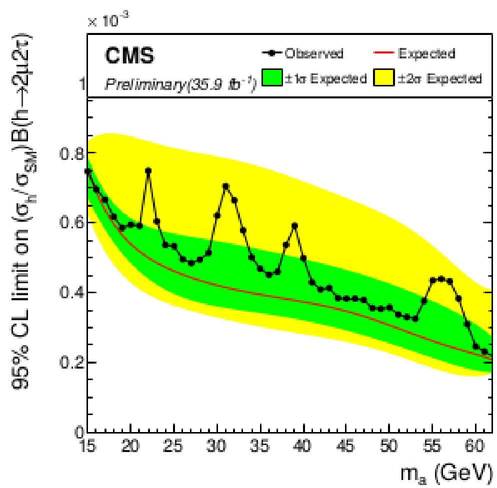
  Statistical uncertainty in the yield predicted by fake rate method in the signal region

- Shape Uncertainty for reducible: Three parameters of the Bernstein functions considered as parametric uncertainties in the fit model ⟶ limited impact on the analysis because the statistical uncertainties on the data and background predictions dominate

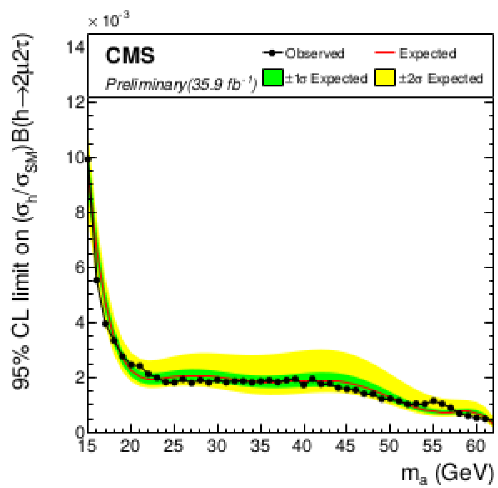
Expected Limits on σ_H/σ_{SM} x $B(H\rightarrow\alpha\alpha\rightarrow 2\mu 2\tau)$



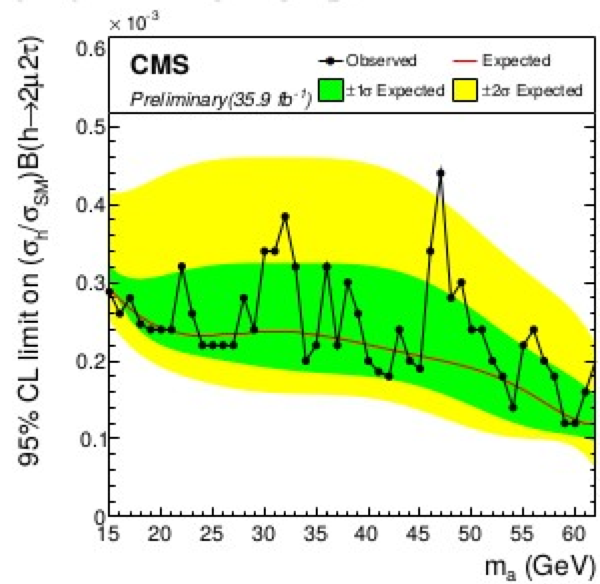




(c) $\mu\mu\mu\tau_h$



(d) $\mu\mu\tau_h\tau_h$

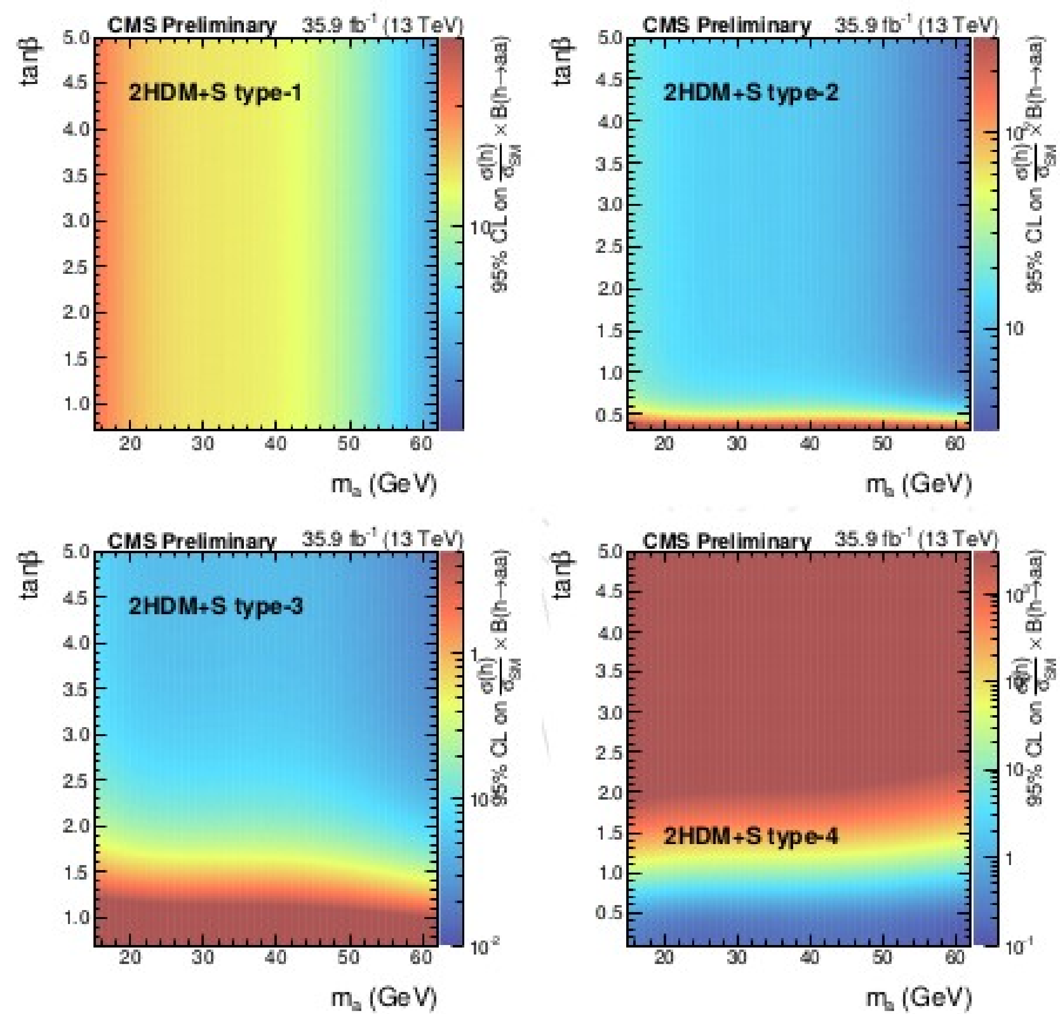


(e) Combined

$\mu\mu\mu\tau_h$ best limits because the lepton P_T thresholds are lower than $\mu\mu\tau_h\tau_h$ and $e\tau_h$ final states, and because BR is larger than in the mmeμ final state

Results

- The results are interpreted as limits on B(H⟶αα) in the different types of 2HDM+S as a function of tanβ



HDM+S type-3 is the most sensitive scenario at large tanβ

Conclusion

- A search for the decay of $h \rightarrow \alpha\alpha \rightarrow 2\mu 2\tau$ has been presented
- The reducible background is estimated from the data with the fake rate method and irreducible background is estimated from MC
- Lowest limit on m_{α}=60 GeV at 1.2 x 10^{-4}
- 2HDM+S type 3 is the most sensitive scenario with large $\tan\beta$ where the couplings to leptons are enhanced over the decays to quarks with $BR(h \rightarrow \alpha\alpha \rightarrow 2\mu 2\tau) \sim 0.08\%$
- The analysis current status is APP (HIG 17-0-29)
- Targeting JHEP publication