Search for low mass Higgs-boson like resonances at CMS

Junquan Tao (IHEP/CAS, Beijing) on behalf of the CMS collaboration

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中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Motivation

❖ Is the observed 125 GeV scalar at the LHC really the SM Higgs Boson ?

❖ Some BSM theories predict modified and extended Higgs sectors, possibly with additional low-mass (<125GeV)scalars/pseudoscalars.

➢ **General Two Higgs Doublet Model (2HDM):**
- **2 Higgs doublets → 5 Higgs bosons : h, H, a, $H^{\pm}$**
- **4 types of models**, main parameters : tanβ, α
- compatible with **a 125 GeV SM-like scalar (h or H) + a light Higgs Boson (a or h)** in the "alignment limit“

➢ **Next-to-Minimal Supersymmetric Standard Model (NMSSM):**
- **2 Higgs doublets + 1 singlet superfields → 7 Higgs bosons : h1, h2, h3, a1, a2, $H^{\pm}$**
- solves the known "**μ-problem**" of the simplest SUSY model MSSM
- compatible with **a 125 GeV SM-like scalar (h1 or h2) + a mostly "singlet-like" light Higgs Boson (a1 or h1)**

In this talk …

- Will present searches for a low-mass (pseudo-)scalar boson with a mass between 0.25 and 110 GeV, with the Run1 8 TeV dataset.
- Search for a direct production (+ possibly additional objects) or a pair production from the decay of h_{125}
- $\gamma\gamma$, $\tau\tau$, bb, $\mu\mu$ channels
- Scalar or pseudoscalar searches **experimentally equivalent**

Direct production

- $h \rightarrow \gamma\gamma$
- $a + bb \rightarrow \tau\tau + bb$
- $h + X \rightarrow bb + X$

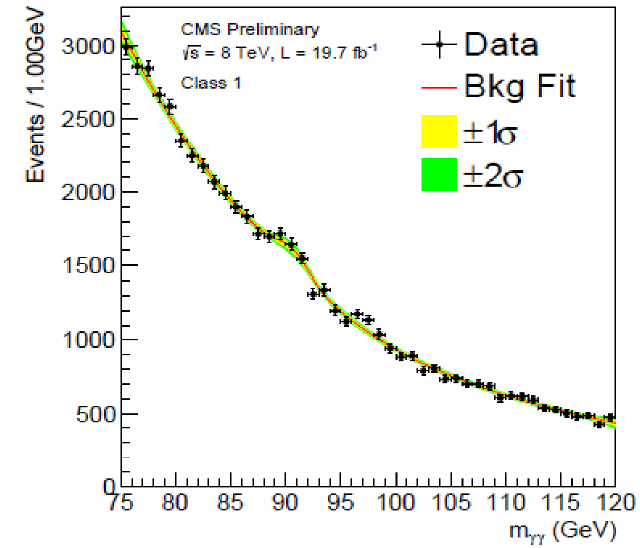
Pair production

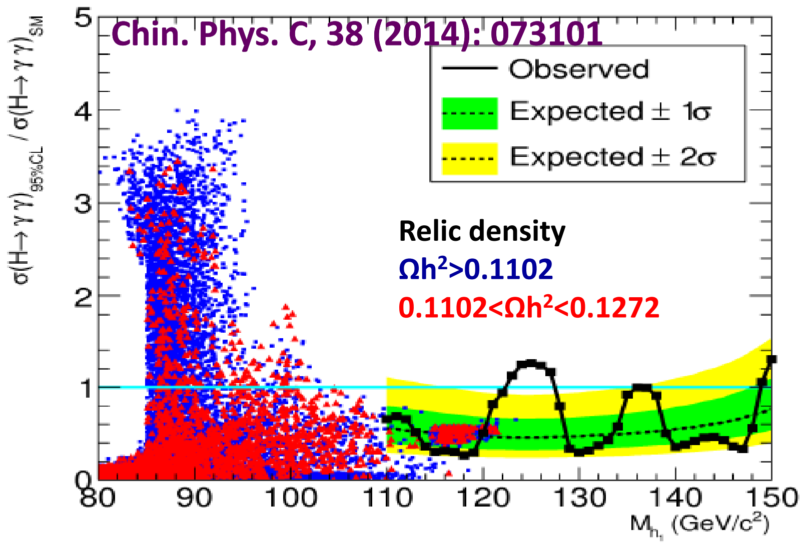
- $h_{125} \rightarrow aa/hh \rightarrow 4\tau$
- $h_{125} \rightarrow aa/\gamma_D\gamma_D \rightarrow 4\mu$
- $h_{125} \rightarrow aa \rightarrow \mu\mu bb$
- $h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$

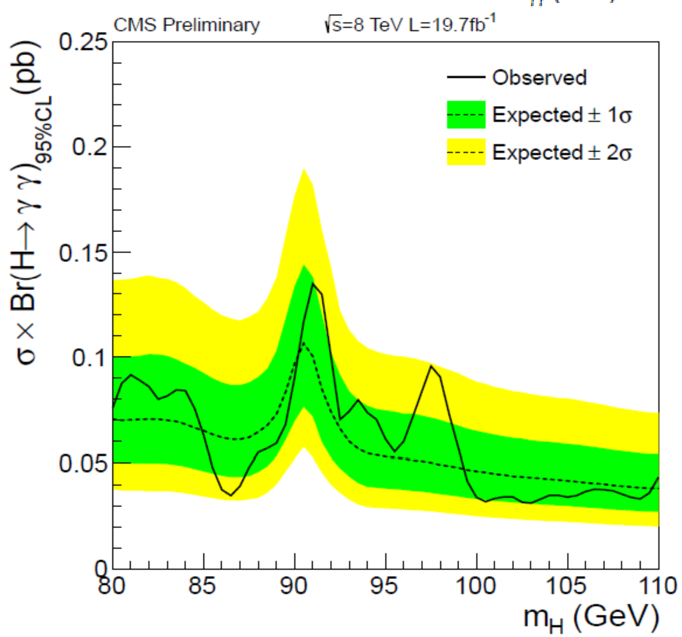
h→γγ

- NMSSM : σ × BR(h_1→γγ) up to ~3.5 higher compared to SM predictions
- Extension of the **standard h_{125} analysis** in the range **[80,110] GeV**
- Background model : diphoton continuum + Z peak contamination (electron veto to reduce it)
- **4 event categories** to increase the sensitivity (based on diphoton event MVA classifier)
- Exclude scalars with σ×BR from **0.8 - 3 times the SM**

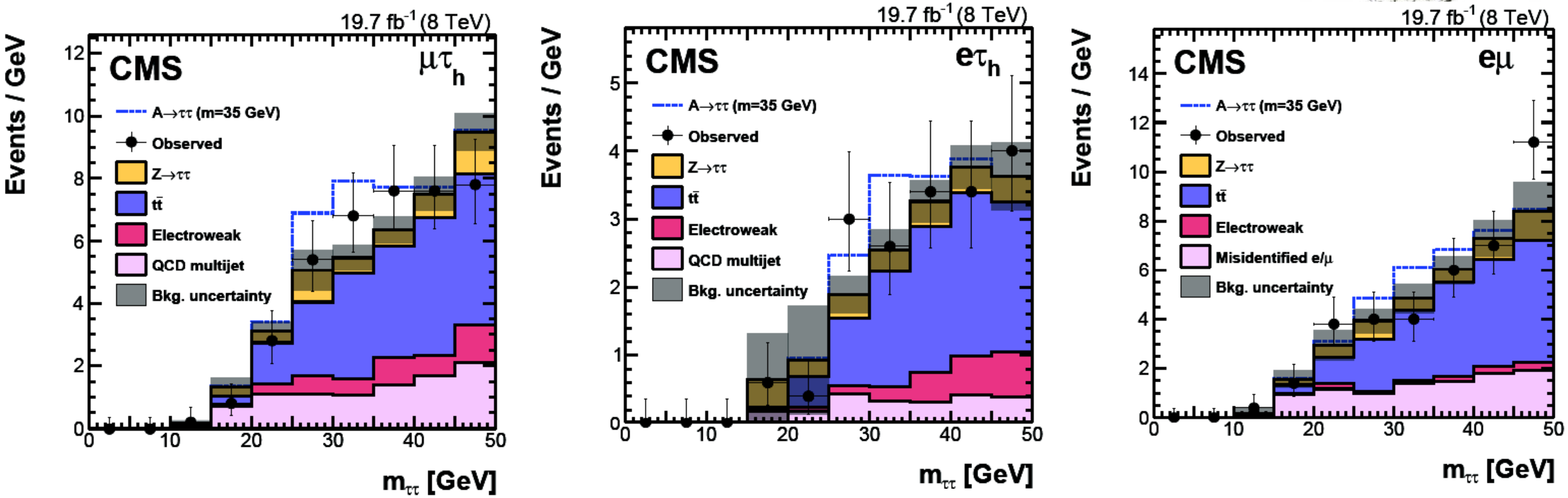
CMS-HIG-14-037



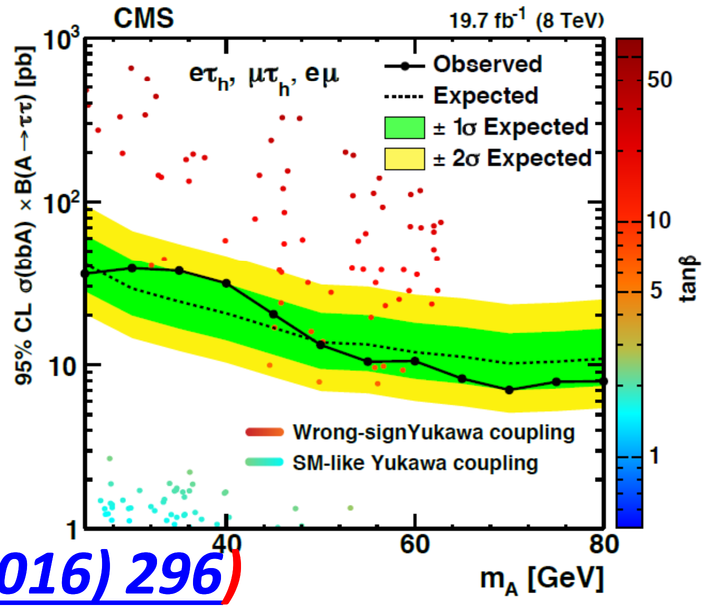




a + bb → ττ + bb

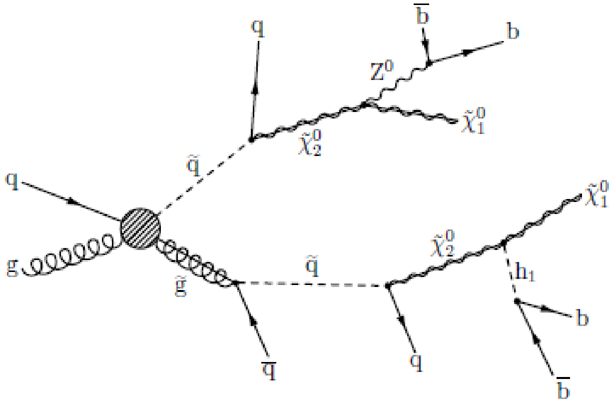


- ➢ Range : [25, 80] GeV
- ➢ $\mu\tau_h$, $e\tau_h$ and $e\mu$ channels
- ➢ Exclusion of 2HDM type II: exclude wrong-sign Yukawa coupling and large tanβ



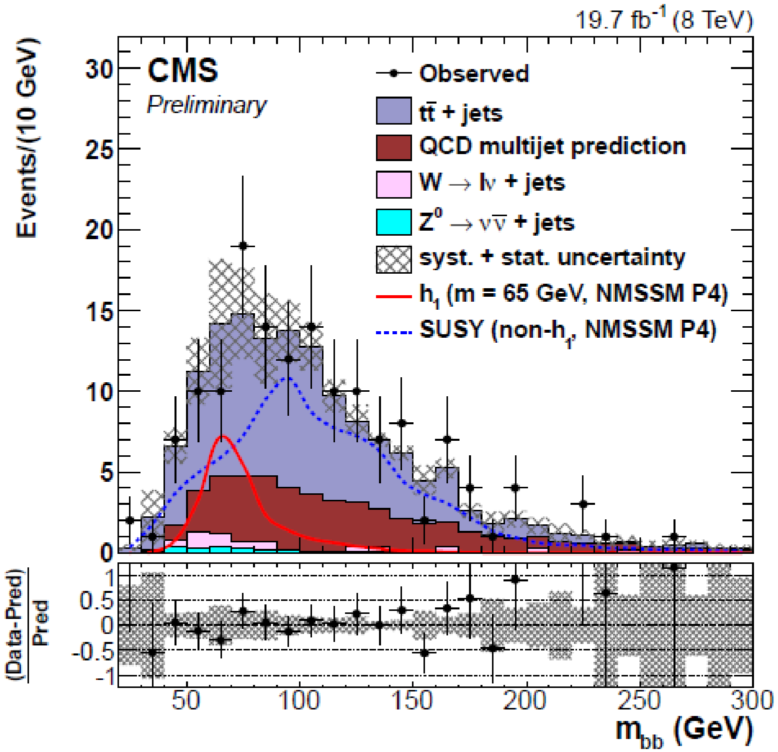
CMS-HIG-14-033 (*Phys. Lett. B 758 (2016) 296*)

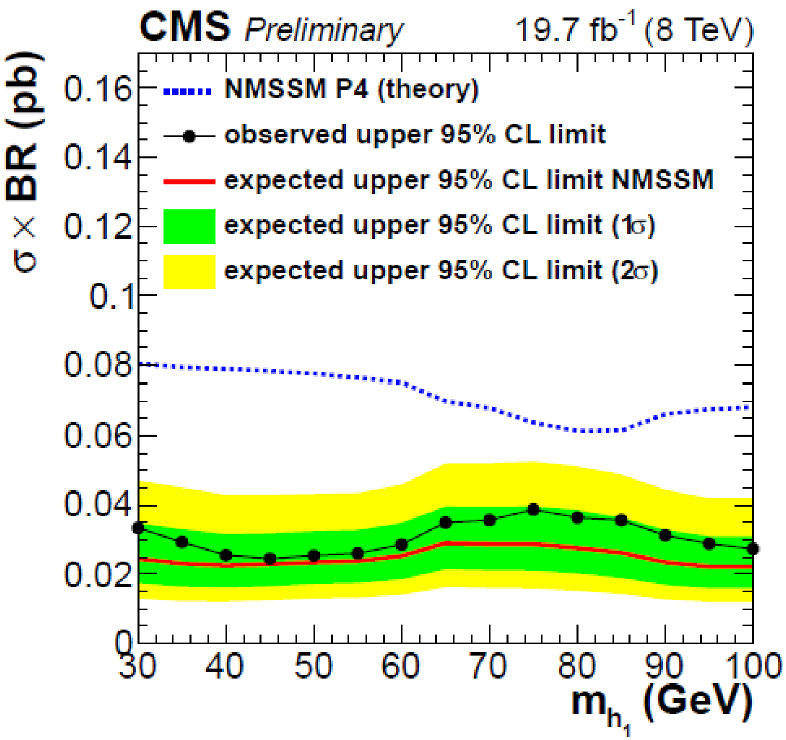
h + X → bb + X



- **NMSSM** ***modified P4 benchmark scenario***: h1 produced in supersymmetric cascades via neutralinos; masses of squark and gluino ~1 TeV
- **X : at least 2 vey energetic jets + large MET**
- **Range : [30,100] GeV**
- **Exclusion of P4**

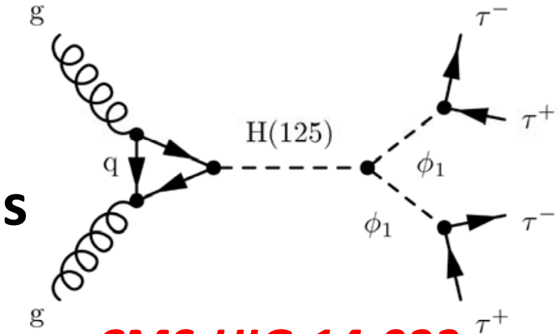
CMS-HIG-14-030

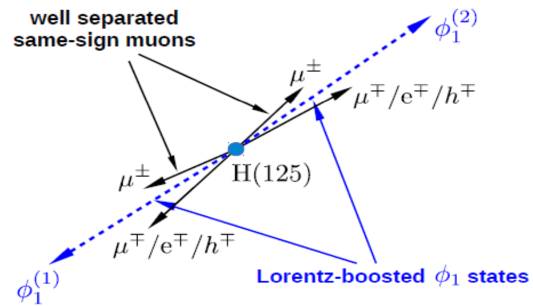




$h_{125} \rightarrow aa/hh \rightarrow 4\tau$

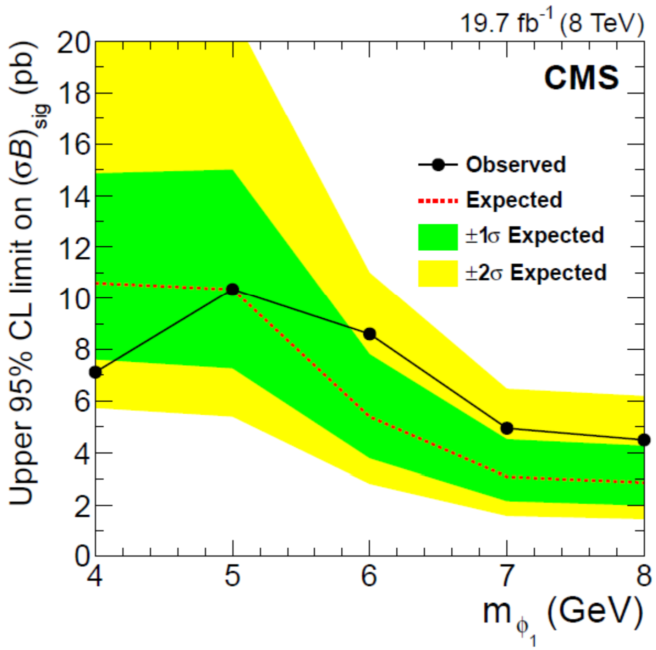
- **Highly-boosted pairs of τ**
- **Same-sign μ from τ**
- **2 complementary analyses**





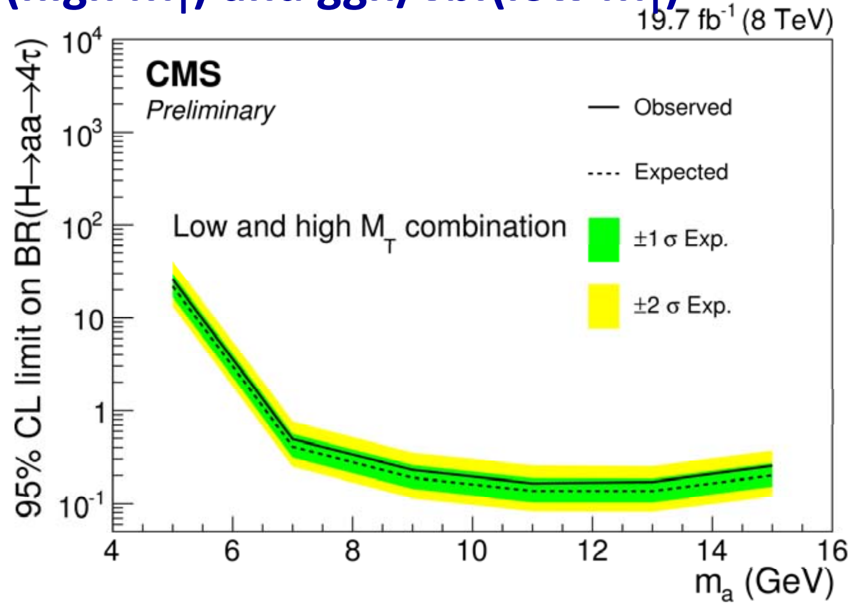
CMS-HIG-14-019
(JHEP 01 (2016) 079)

- **Range [4,8] GeV**
- **Pair of τ → 1μ + 1 track**

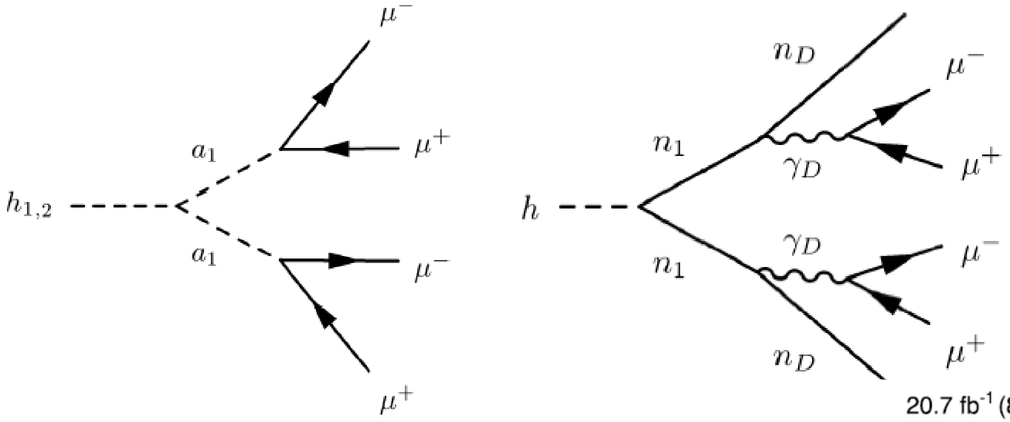


CMS-HIG-14-022

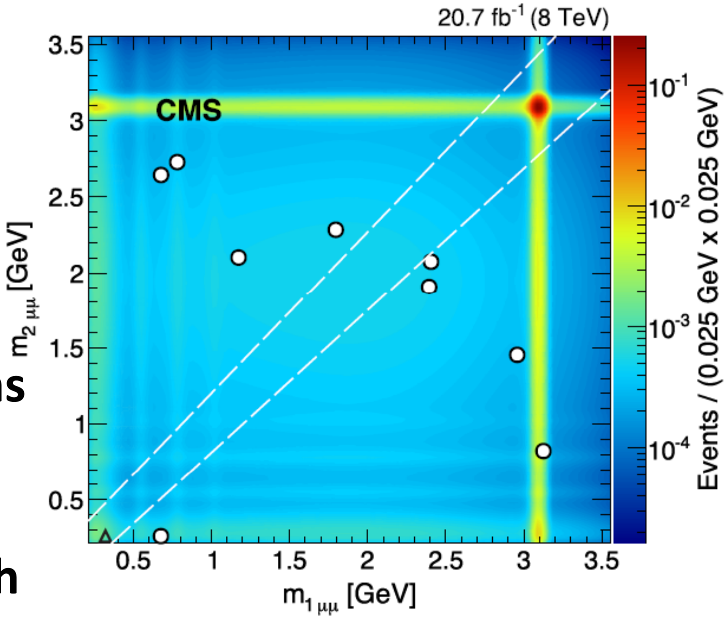
- **Range [5,15] GeV with pair of τ → 1μ + $1\tau_h$**
- **2 categories based on low/high M_T of a high pT muon and MET: to distinguish WH (high M_T) and ggh/vbf(low M_T)**

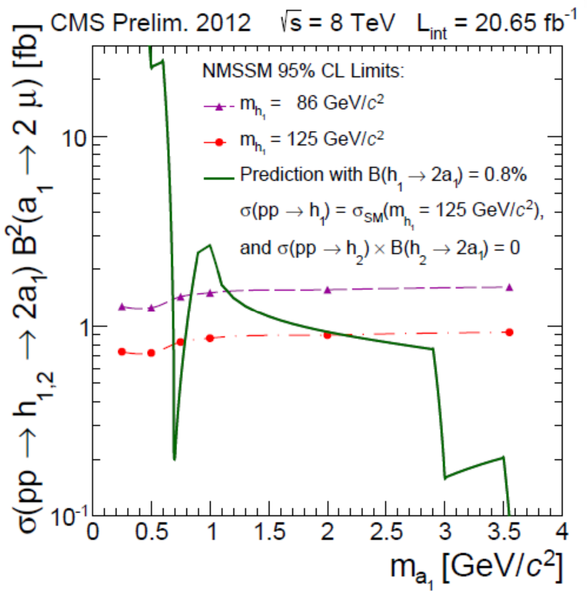


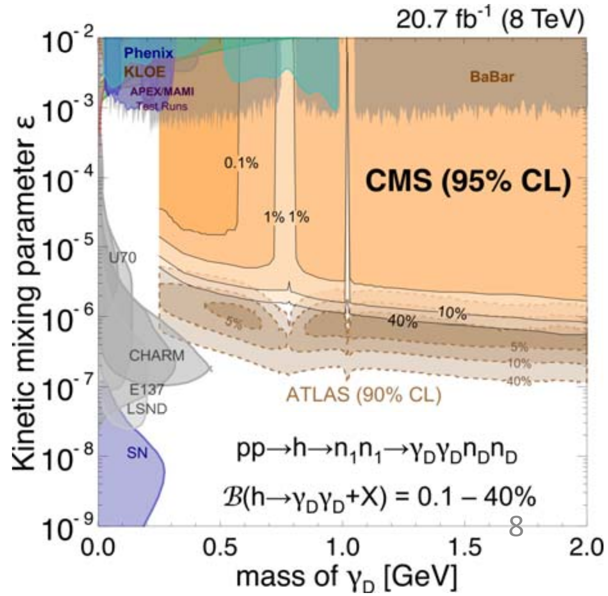
$h_{125} \to aa/\gamma_D\gamma_D \to 4\mu$



- **NMSSM and Dark SUSY scenarios**
- **Dark SUSY : Higgs boson decays to "dark“ neutralinos and photons**
- **Search for events in ($m_{1\mu\mu}$, $m_{2\mu\mu}$) space, with $0.25<m_{\mu\mu}<3.55$ GeV**







CMS-HIG-13-010

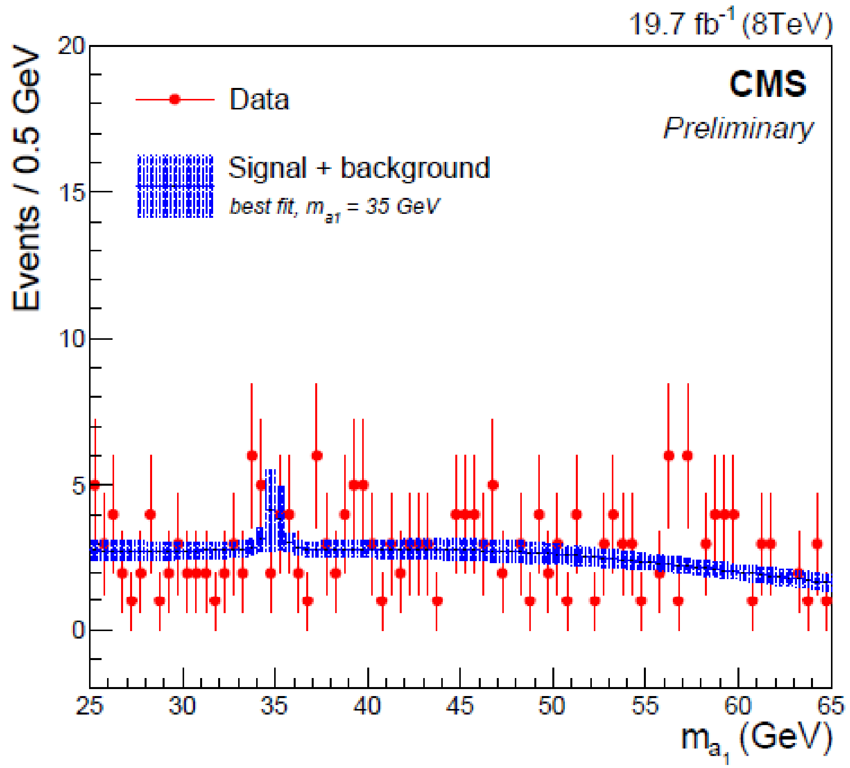
(PLB 752 (2016) 146)

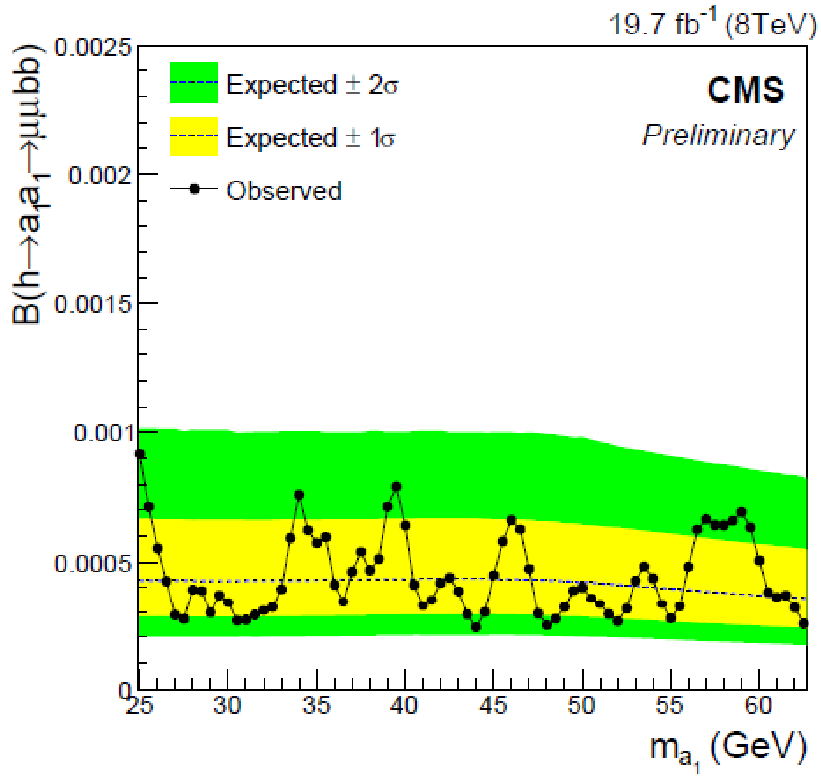
$$|m_1 - m_2| < 0.13\,\mathrm{GeV}/c^2 + 0.065 \times (m_1 + m_2)/2$$

$h_{125} \rightarrow aa \rightarrow \mu\mu bb$

- NMSSM : BR(h → a1a1 → μμ bb) up to ~2 × 10^{-3}
- **Range [25,65] GeV**
- Fit in $m_{\mu\mu}$ distribution
- Exclude pseudoscalars with BR(h1 → a1a1 → μμ bb) above 10^{-3}

CMS-HIG-14-041

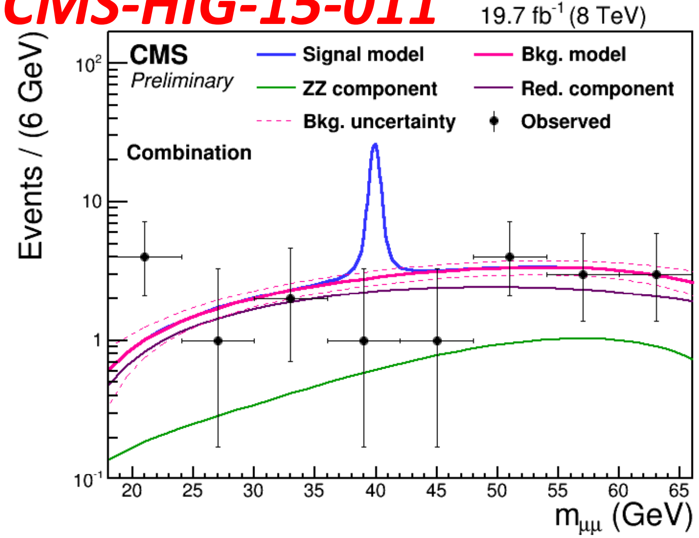


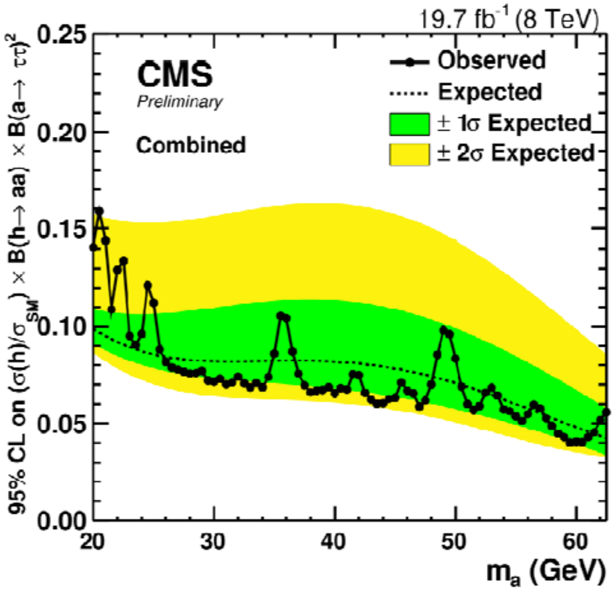


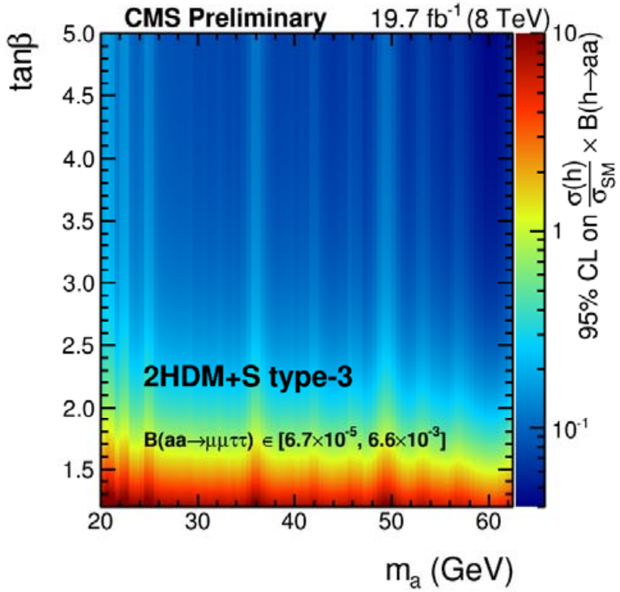
$h_{125} \to aa \to \mu\mu\tau\tau$

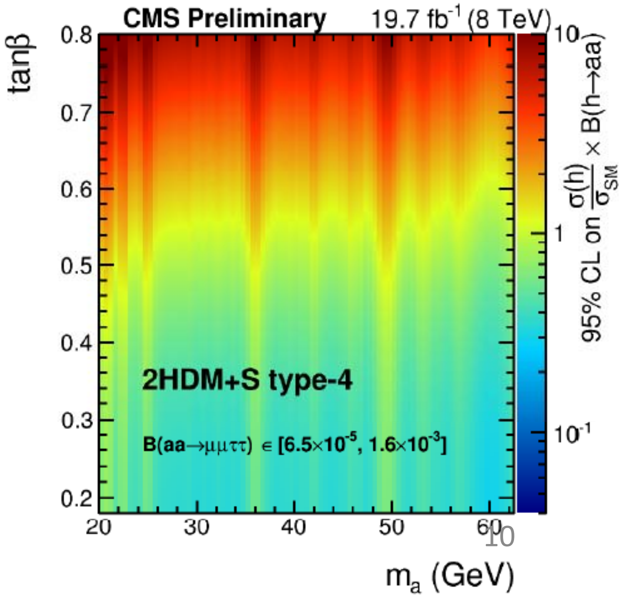
- General **2HDM+S scenarios** (type III at high tanβ and type IV at low tanβ)
- **Range [25,65] GeV**
- 5 ττ decay channels : **ee, $\mu\tau_h$, $e\tau_h$, eμ, $\tau_h\tau_h$**
- Fit in $m_{\mu\mu}$ distribution
- Limits set for general 2HDM+S, and for type III and IV (good sensitivity)

CMS-HIG-15-011





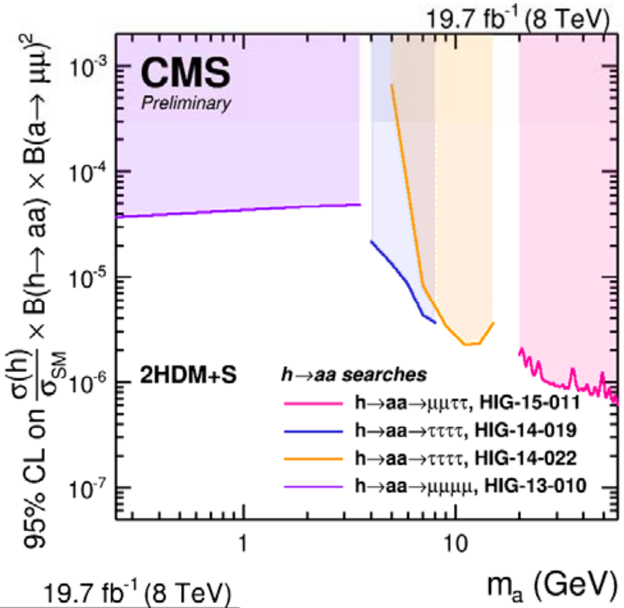




$h_{125} \to aa$ comparison

- **Comparison of 4μ, 4τ, μμττ channels**

- **General 2HDM+S, 2HDM+S type-3 and 2HDM+S type-4**



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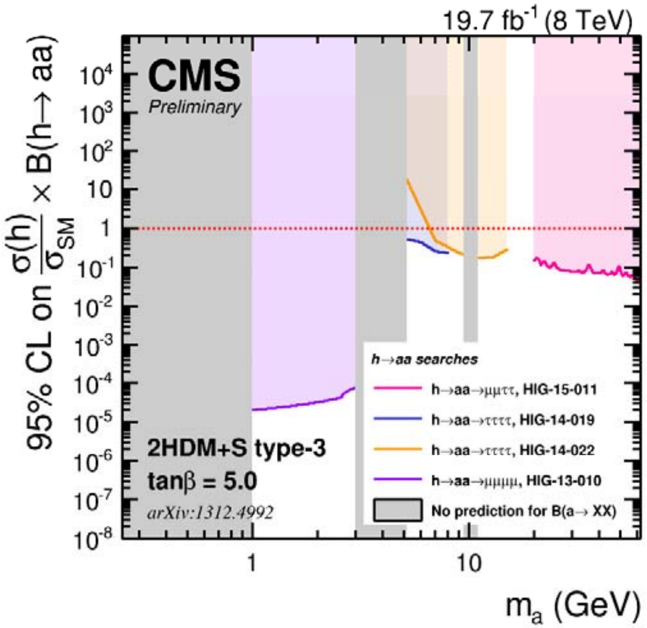
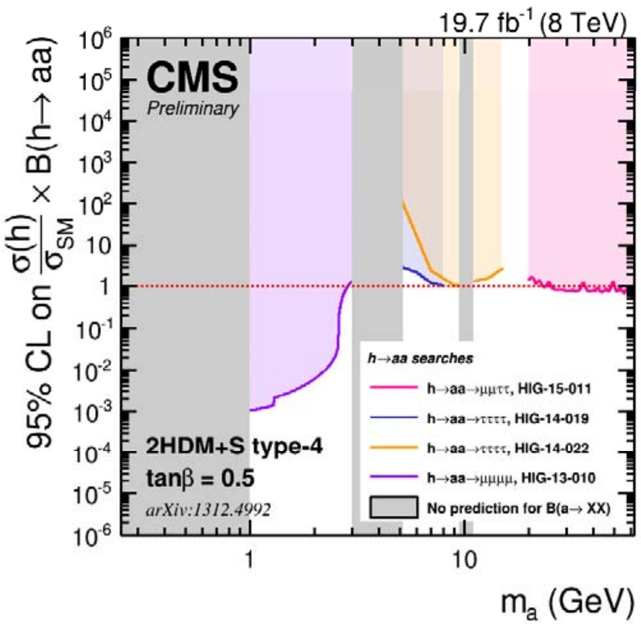




Conclusions

- Several **low-mass (pseudo) scalar searches** have been performed with **CMS Run-1 data** in the mass range **[0.25,110]** GeV, with both direct and pair production considered

- **No evidence for new particle production**

- **2HDM/NMSSM interpretations** : parameter space regions excluded, benchmark scenarios ruled out ...

- All analyses are **being continued in Run-2**. Sensitivity to BSM models will be increased.

- Looking forward for new results !

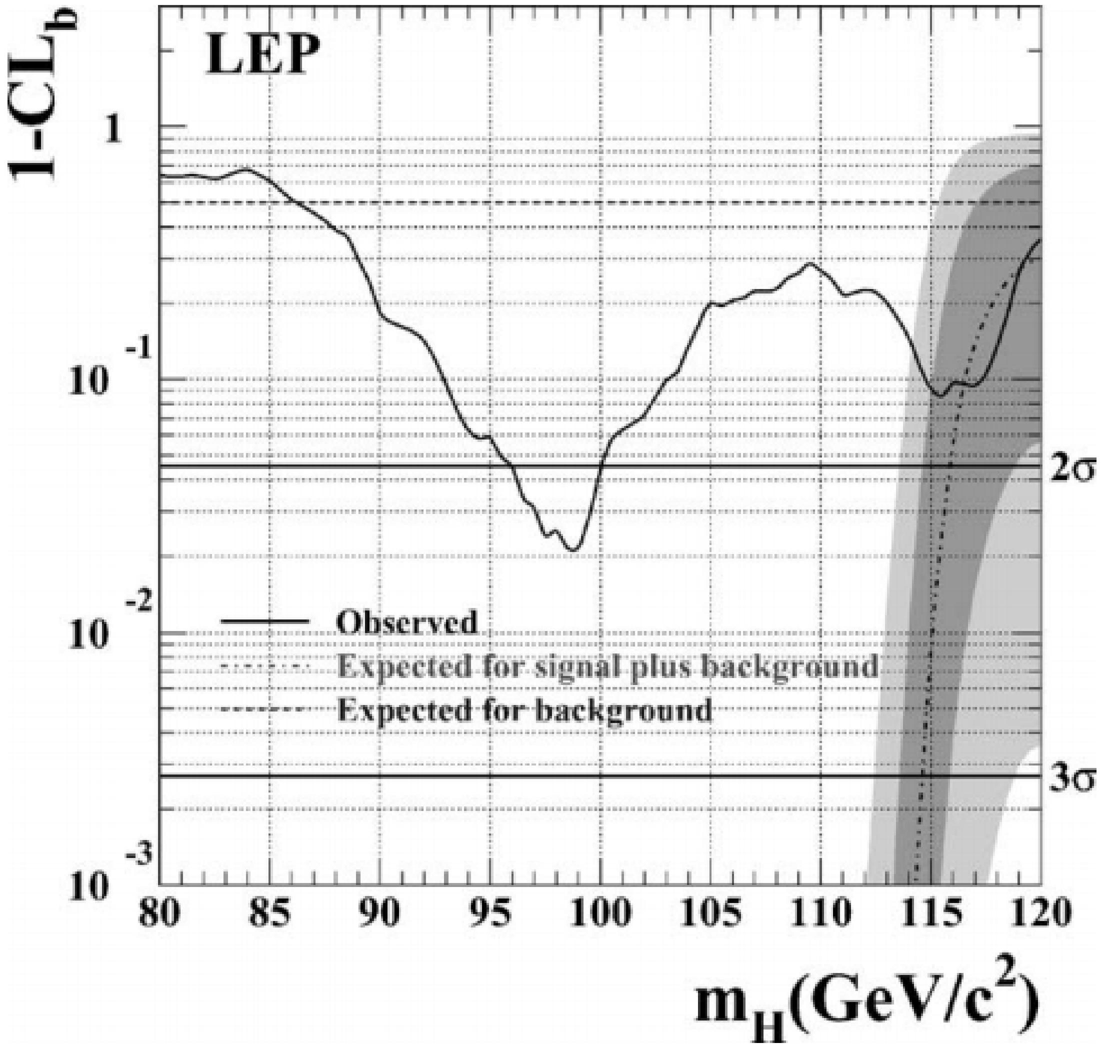
Thank you for your attention!

(only about 15% of us are in the photo!)

Back slides

LEP excess @ 98 GeV

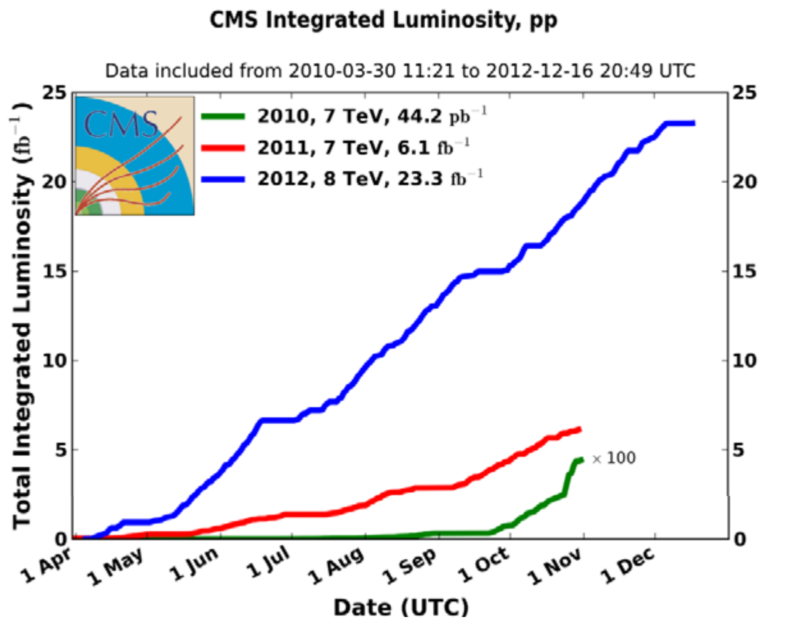
Phys. Lett. B, 565 (2003):61-75



LHC Run 1 dataset

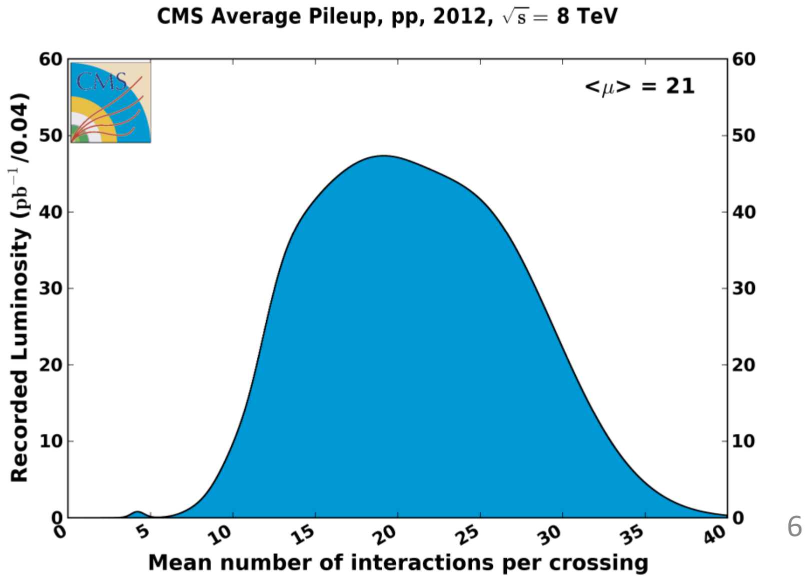
➢ **Excellent performance** of the **LHC** machine and **CMS** detector in **Run 1**:

- ~90% of the delivered data available for offline analysis.
- ~5fb^{-1} at 7TeV + ~20fb^{-1} at 8TeV



➢ **Challenging pile-up conditions**

Average PU ~10 events in 2011 and ~20 events in 2012



h→γγ

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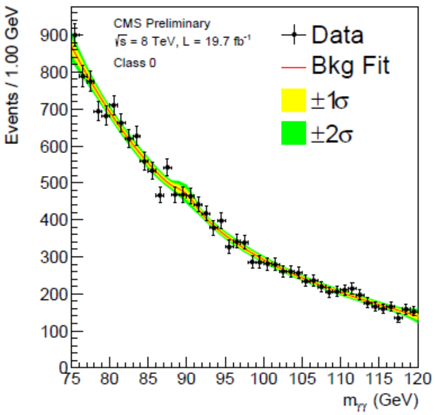
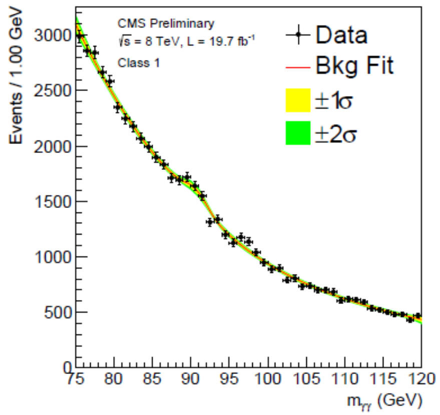
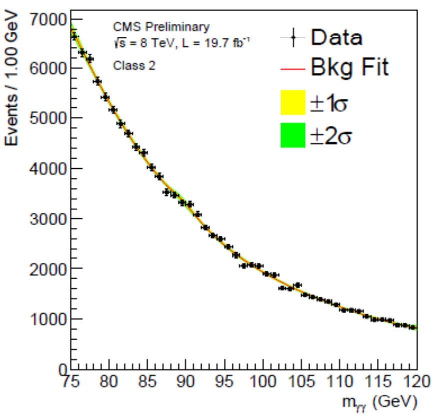


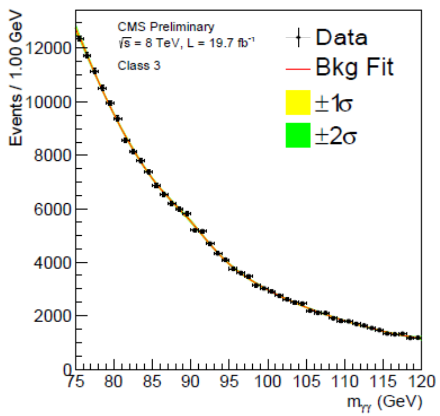
(a) Class 0



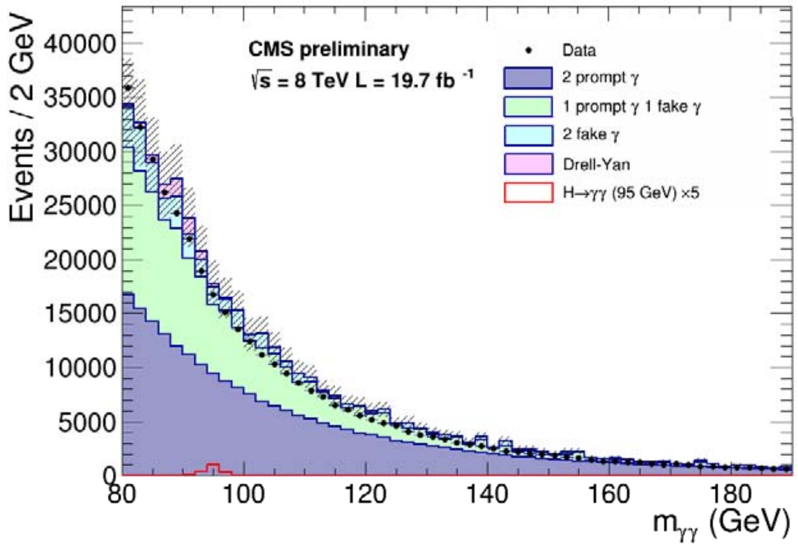
(b) Class 1



(c) Class 2



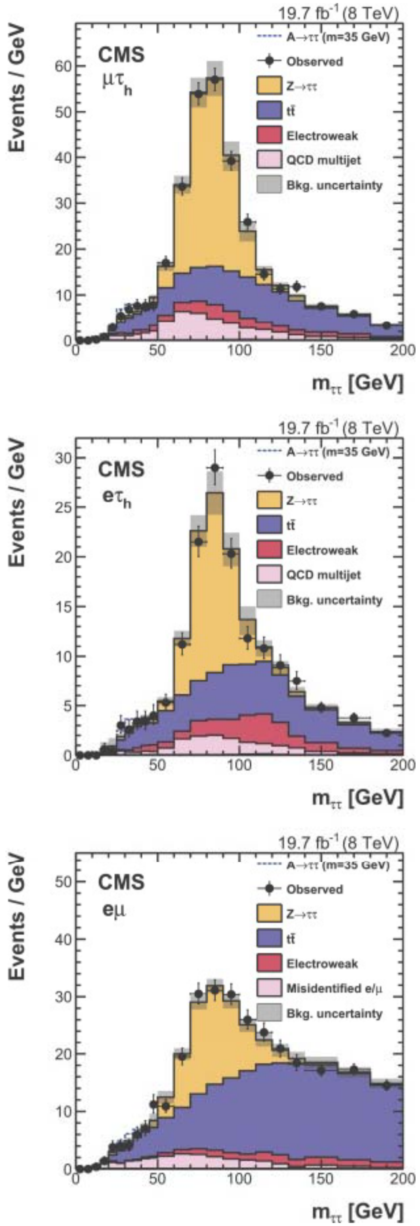
(d) Class 3

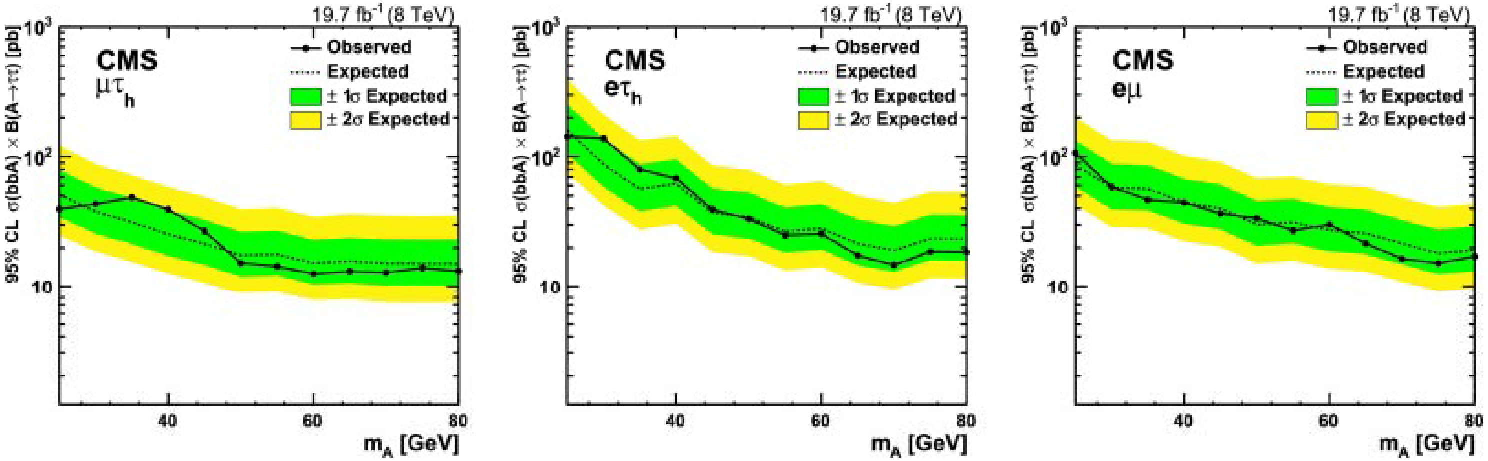


Sources of systematic uncertainty	Uncertainty	
	Barrel	Endcap
Photon preselection efficiency	1.0%	2.6%
Photon identification BDT distribution	±0.01 (shape shift)	
Photon energy resolution distribution	±10% (shape scaling)	

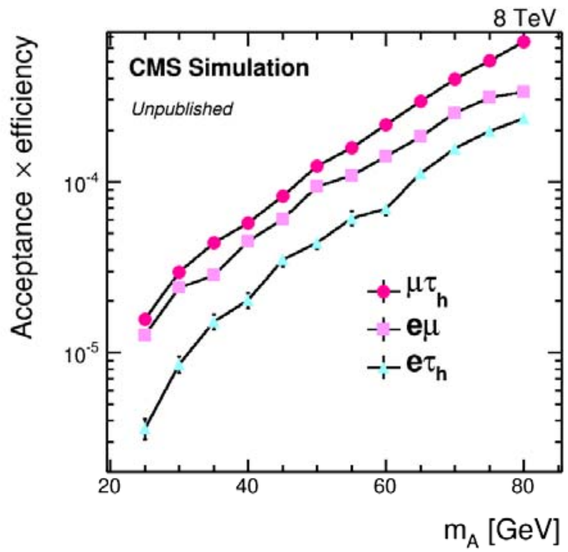
Sources of systematic uncertainty	Uncertainty
Integrated luminosity	2.6%
Vertex finding efficiency	1.02%
Trigger efficiency	1.0%

a + bb → ττ + bb



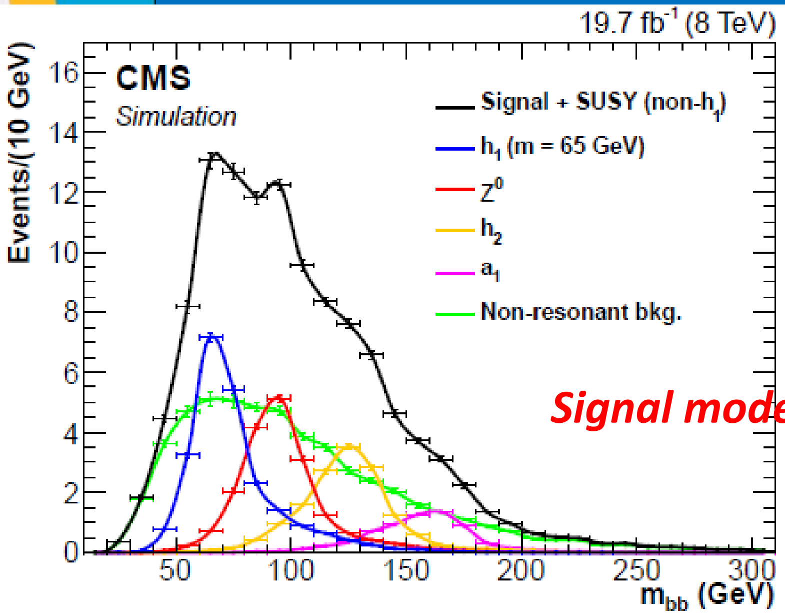


CMS-HIG-14-033 (Phys. Lett. B 758 (2016) 296)

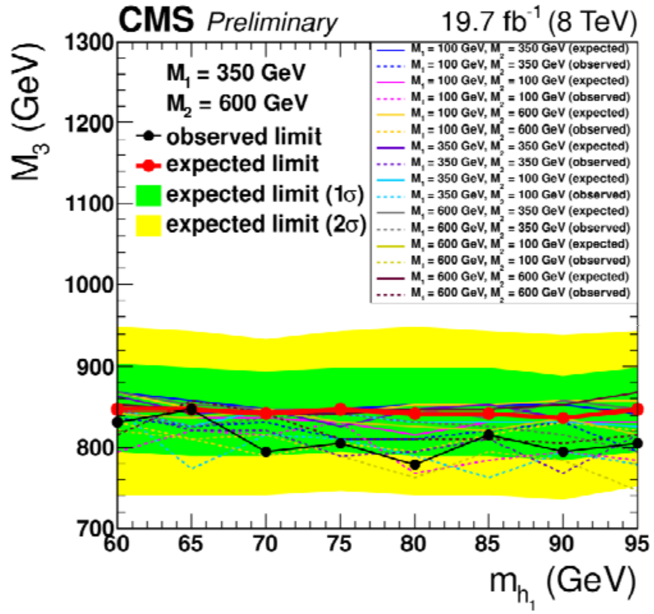


	Systematic source	Systematic uncertainty $\mu\tau_h$	$e\tau_h$	$e\mu$
Normalisation	Integrated luminosity	2.6%	2.6%	2.6%
	Muon ID/trigger	2%	—	2%
	Electron ID/trigger	—	2%	2%
	Tau ID/trigger	8%	8%	—
	Muon to tau misidentification rate	30%	—	—
	Electron to tau misidentification rate	—	30%	—
	b tagging efficiency	1–4%	1–4%	1–4%
	b mistag rate	1–9%	1–9%	1–9%
	E_T^{miss} scale	1–2%	1–2%	1–2%
	$Z/\gamma^* \to \tau\tau$ normalisation	3%	3%	3%
	$Z/\gamma^* \to \tau\tau$ low-mass normalisation	10%	10%	10%
	QCD multijet normalisation	20%	20%	—
	Reducible background normalisation	—	—	30%
	W+jets normalisation	30%	30%	—
	tt̄ cross section	10%	10%	10%
	Diboson cross section	15%	15%	15%
	$H \to \tau\tau$ signal strength	30%	30%	30%
Theory	Underlying event and parton shower	1–5%	1–5%	1–5%
	Scales for A boson production	10%	10%	10%
	PDF for generating signal	10%	10%	10%
	NLO vs. LO	20%	20%	20%

h + X → bb + X



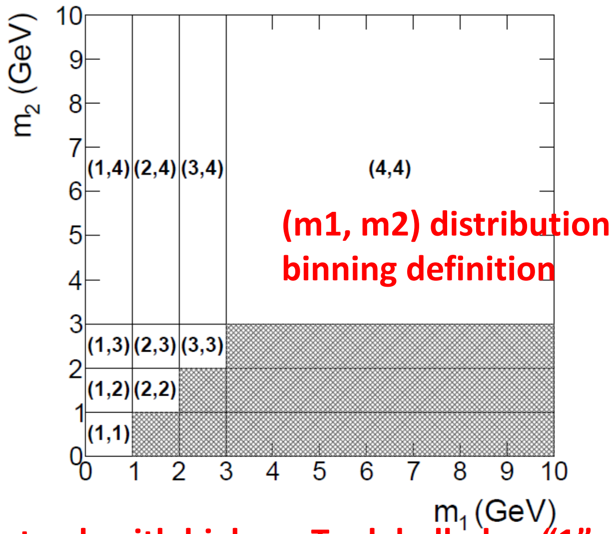
Signal model



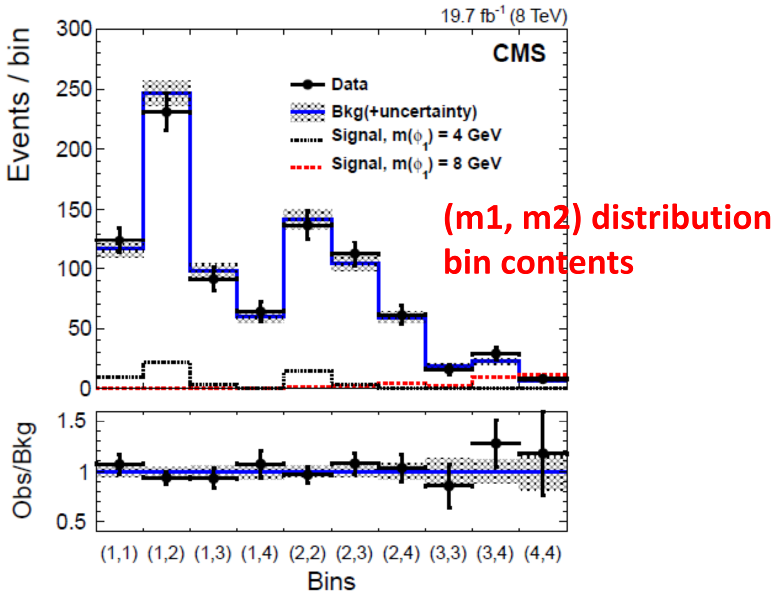
CMS-HIG-14-030

Systematics source	Event category	Type	Impact
Normalization of $t\bar{t}$	Background	rate	1.7 %
Normalization of QCD	Background	rate	2 %
Shape correction QCD	Background	shape + rate	3 %
QCD shape parameterization	Background	shape + rate	1 %
MC statistics $t\bar{t}$	Background	shape + rate	1.3 %
MC statistics $W \to \ell\nu$	Background	shape + rate	0.3 %
Luminosity	Signal + Background	rate	0.5 %
Trigger	Signal + Background	shape + rate	0.1 %
Pile-up	Signal + Background	shape + rate	0.1 %
PDF uncertainty	Signal	shape + rate	0.2 %
Offline b-tag (bc)	Signal + Background	shape + rate	1.0 %
Offline b-tag (udsg)	Signal + Background	shape + rate	0.05 %
JES	Signal + Background	shape + rate	1.3 %
JER	Signal + Background	shape + rate	0.1 %
τ energy scale	Signal + Background	shape + rate	0.6 %

$h_{125} \rightarrow aa/hh \rightarrow 4\tau$



μ-track with higher pT μ labelled as "1"



CMS-HIG-14-019
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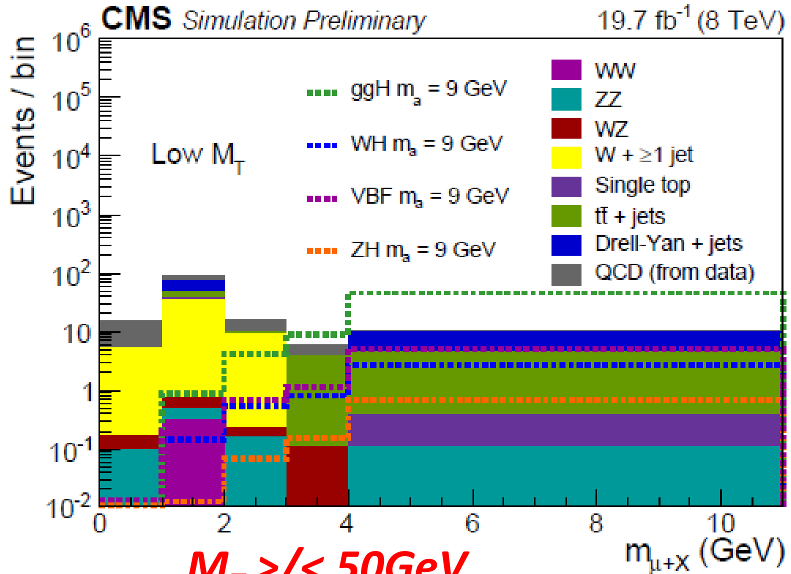
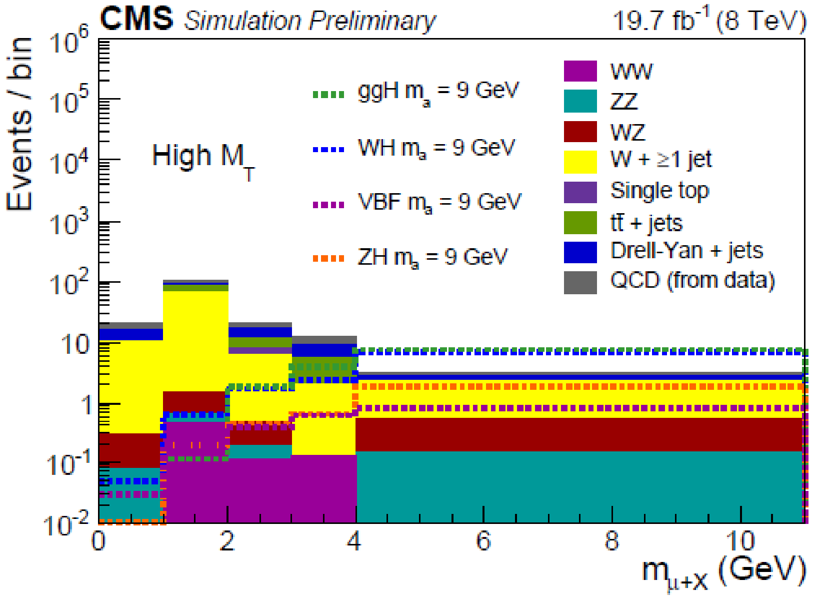
Source	Value	Affected sample	Type	Effect on the total yield
Statistical uncertainties in $C(i,j)$	2–14%	bkg.	bin-by-bin	—
Extrapolation uncertainties in $C(i,j)$	2–22%	bkg.	bin-by-bin	—
Integrated luminosity	2.6%	signal	norm.	2.6%
Muon ID and trigger efficiency	2% per muon	signal	norm.	4%
Track selection and isolation efficiency	5% per track	signal	norm.	10%
MC statistical uncertainties	7–100%	signal	bin-by-bin	4–6%
Theory uncertainties in the signal acceptance				
μ_r and μ_f variations	1%	signal	norm.	1%
PDF	1%	signal	norm.	1%
Effect of b quark loop contribution to $gg \rightarrow H(125)$	3%	signal	norm.	3%

$h_{125} \rightarrow aa/hh \rightarrow 4\tau$

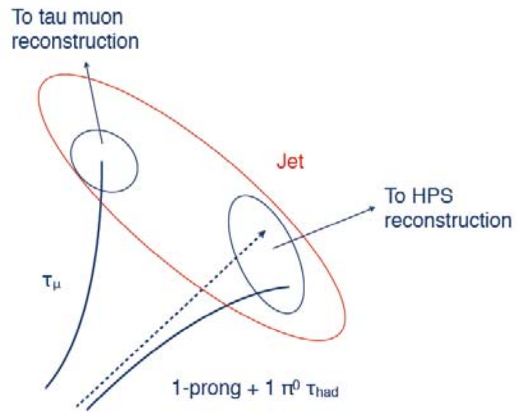


M_T >/< 50GeV



CMS-HIG-14-022

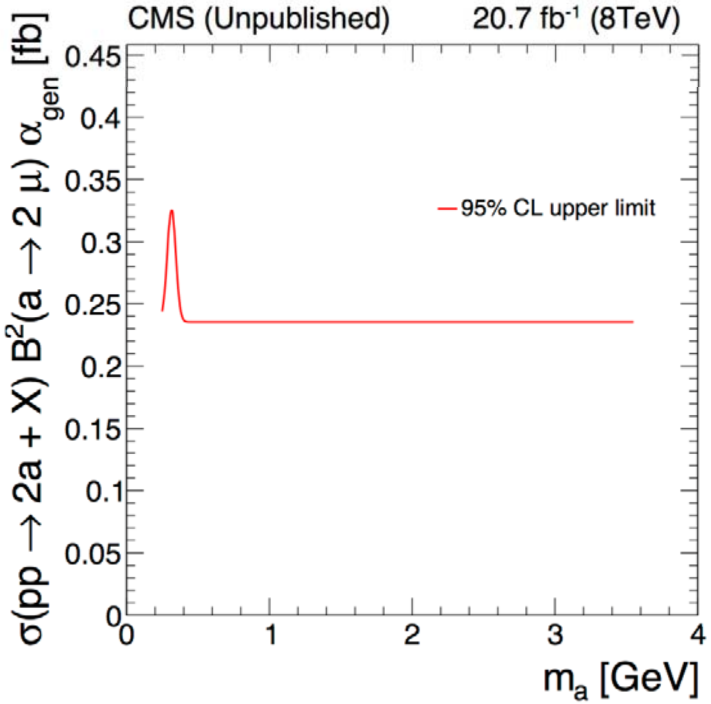
M_T is defined as $\sqrt{2 p_T^{\mu_{trg}} \not{E}_T (1 - \cos\Delta\phi(\mu_{trg}, \not{E}_T))}$

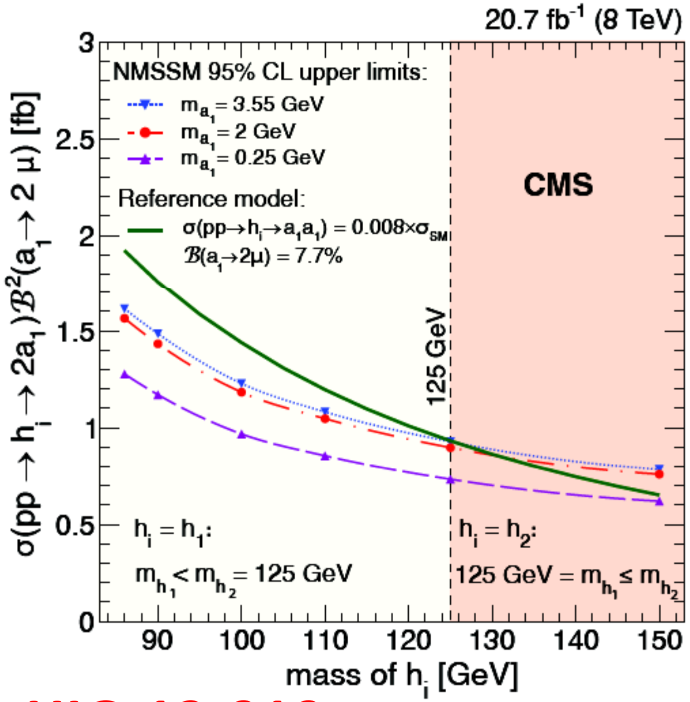


"tau muon" + one-prong/one-prong+one π^0/three-prong : ***1μ + 1/3 charged tracks + 0/more neutral hadrons***

Uncertainty	Magnitude	
	$M_T \leq 50$ GeV/c^2	$M_T > 50$ GeV/c^2
Luminosity	2.6%	2.6%
HLT	(0.2-4.2)%	(0.2-4.2)%
Trigger muon ID	0.5%	0.5%
Trigger muon isolation	(0.2-3.8)%	(0.2-3.8)%
Trigger muon lepton isolation	10%	10%
Tau muon ID	1.5%	1.5%
HPS tau ID	6%	6%
HPS tau charge mis-ID	-1%/+2%	-1%/+2%
Background model	-84%/+78%	-59/+61%
b veto	<9.4%	<8.5%
M_T scale	<4.2%	<9.3%
VBF extrapolation	23%	25%
ZH extrapolation	19%	24%

$h \to aa/\gamma_D\gamma_D \to 4\mu$





Only one event in the data (shown as empty circles) survive all selection requirements

$m_{1\mu\mu} = 0.33$ GeV and $m_{2\mu\mu} = 0.22$ GeV.

Expected bkg in the diagonal signal region:2.2 ± 0.7

CMS-HIG-13-010

(PLB 752 (2016) 146)

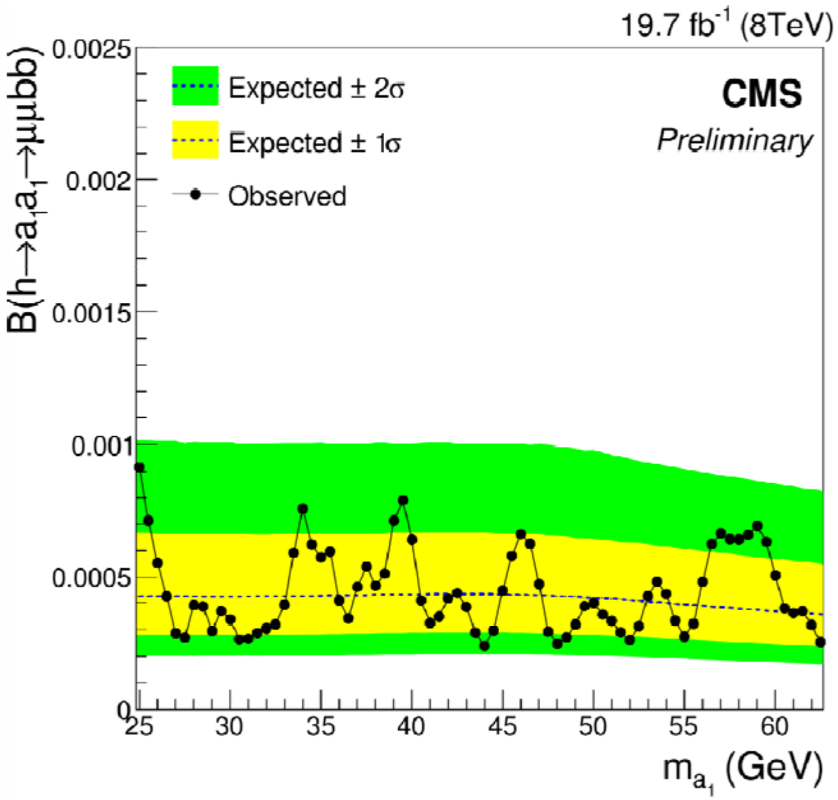
m_{h_1} [GeV]	90	125	125
m_{a_1} [GeV]	2	0.5	3.55
ϵ_{sim} [%]	11.0 ± 0.1	21.1 ± 0.1	17.3 ± 0.1
α_{gen} [%]	15.9 ± 0.1	32.0 ± 0.1	26.3 ± 0.1
$\epsilon_{sim}/\alpha_{gen}$	0.69 ± 0.01	0.66 ± 0.01	0.66 ± 0.01

m_{γ_D} [GeV]	0.25			1.0		
$c\tau_{\gamma_D}$ [mm]	0	0.5	2	0	0.5	2
ϵ_{sim} [%]	8.85 ± 0.12	1.76 ± 0.05	0.23 ± 0.03	6.13 ± 0.23	4.73 ± 0.07	1.15 ± 0.04
α_{gen} [%]	14.32 ± 0.14	2.7 ± 0.06	0.31 ± 0.03	8.89 ± 0.28	6.98 ± 0.09	1.68 ± 0.05
$\epsilon_{sim}/\alpha_{gen}$	0.62 ± 0.01	0.65 ± 0.02	0.74 ± 0.13	0.69 ± 0.03	0.68 ± 0.01	0.68 ± 0.03

$h_{125} \rightarrow aa \rightarrow \mu\mu bb$

CMS-HIG-14-041

	Z/γ^*+jets ($m_{\ell\ell} > 10\,\mathrm{GeV}$)		$t\bar{t}\,(\ell\ell)$	Other
Backgrounds	210 ± 35		22 ± 1	3 ± 1
Total	235 ± 35			
Data	252			
	$m_{a_1} = 30\,\mathrm{GeV}$	$m_{a_1} = 40\,\mathrm{GeV}$	$m_{a_1} = 50\,\mathrm{GeV}$	$m_{a_1} = 60\,\mathrm{GeV}$
Signal	1.18	0.972	1.11	1.49

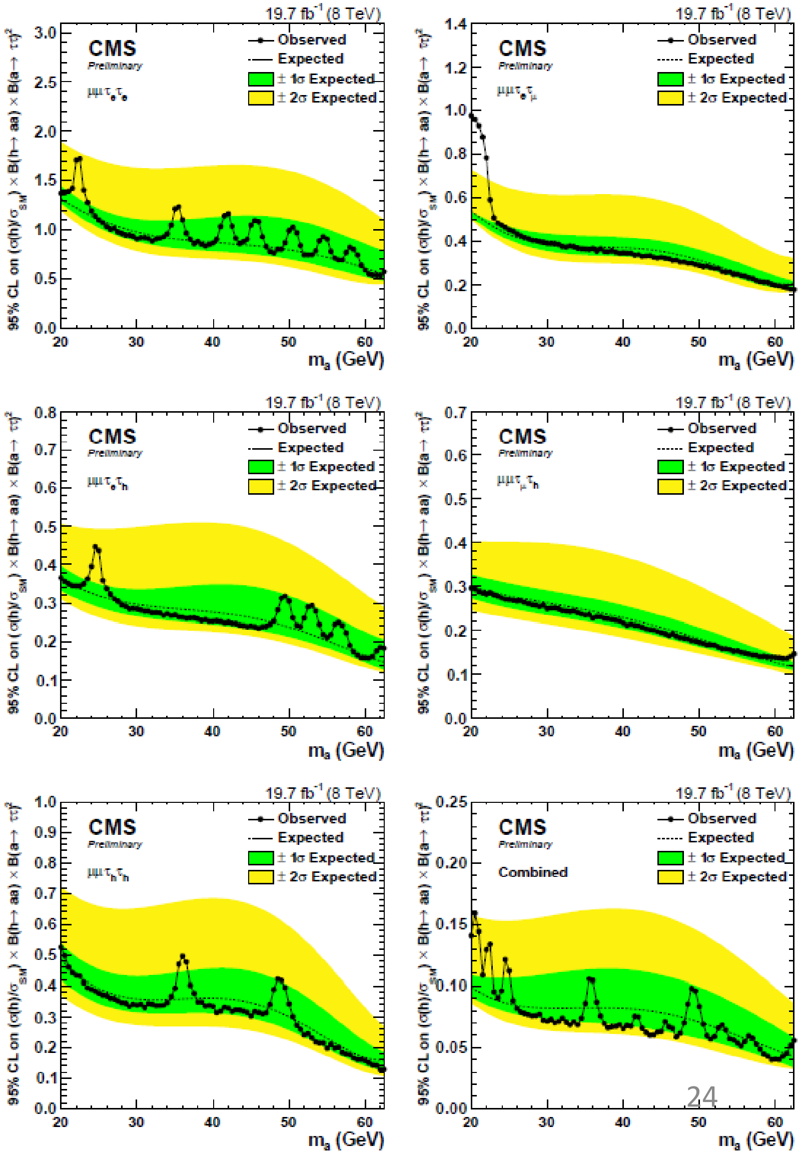


$h_{125} \to aa \to \mu\mu\tau\tau$

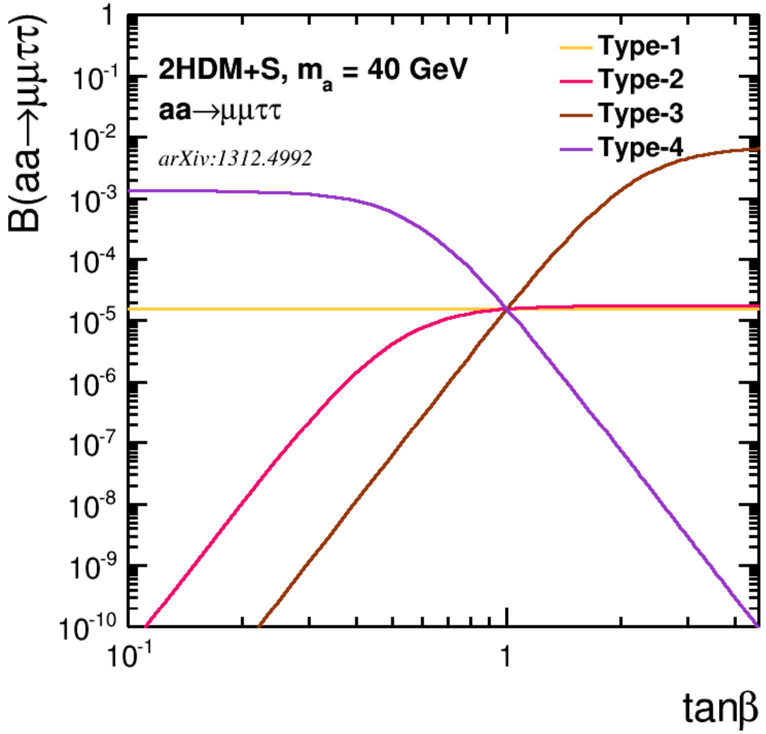
CMS-HIG-15-011

	$\mu\mu\tau_e\tau_e$	$\mu\mu\tau_e\tau_\mu$	$\mu\mu\tau_e\tau_h$	$\mu\mu\tau_\mu\tau_h$	$\mu\mu\tau_h\tau_h$
μ_1	$p_T > 18$ GeV, $\lvert\eta\rvert < 2.4$, $I_{rel} < 0.4$, Loose PF ID				
μ_2	$I_{rel} < 0.4$, Loose PF ID, $\lvert\eta\rvert < 2.4$				
	$p_T > 9$ GeV	$p_T > 5/9$ GeV	$p_T > 9$ GeV	$p_T > 5/9$ GeV	$p_T > 9$ GeV
τ_e	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.5$, MVA ID			-	-
	$I_{rel} < 0.4$	$I_{rel} < 0.4$	$I_{rel} < 0.2$		
τ_h	-	-	$p_T > 15$ GeV, $\lvert\eta\rvert < 2.3$, Loose anti-μ		
			Loose iso. Loose anti-e	Loose iso. vLoose anti-e	Medium iso. vLoose anti-e
τ_μ	-	$p_T > 9/5$ GeV $\lvert\eta\rvert < 2.4$ Loose PF ID $I_{rel} < 0.4$	-	$p_T > 9/5$ GeV $\lvert\eta\rvert < 2.4$ Tight PF ID $I_{rel} < 0.25$	-
b–Jet veto	No b–tagged jet in the event.				
Lepton veto	No additional identified and isolated electron or muon.				
$\lvert m_{\mu\mu\tau\tau} - 125\rvert$	< 25 GeV				
$\lvert m_{\mu\mu} - m_{\tau\tau}\rvert / m_{\mu\mu}$	< 0.8				
ΔR between leptons	> 0.4				
$\lvert m^{vis}_{\mu\mu ee} - 125\rvert$	> 15 GeV	-			

Systematic uncertainty	Relative change in yield		
	Signal	ZZ	Reducible backgrounds
Luminosity	2.6%	2.6%	-
Trigger	1%	1%	-
Tau identification	0-12%	0-12%	-
b-Jet veto	1%	1%	-
Tau energy scale	0-10%	0-10%	-
Electron identification	0-4%	0-4%	-
Muon identification	2-4%	2-4%	-
Signal prediction	10%	-	-
Signal efficiency	5-8%	-	-
PDF	-	5%	-
QCD scale VV	-	6%	-
ZZ statistics in MC	-	1-15%	-
Reducible background normalization	-	-	25-50%
Reducible background shape	-	-	shape only
Signal modeling	shape only	-	-
Muon energy scale	shape only	-	-



$h_{125} \to aa \to \mu\mu\tau\tau$



	Couplings	I	II (NMSSM-like)	III (Lepton specific)	IV (Flipped)
h	g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
	$g_{ht\bar{t}}$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
	$g_{hb\bar{b}}$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
	$g_{h\tau\bar{\tau}}$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
H^0	g_{H^0VV}	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
	$g_{H^0t\bar{t}}$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
	$g_{H^0b\bar{b}}$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
	$g_{H^0\tau\bar{\tau}}$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
A	g_{AVV}	0	0	0	0
	$g_{At\bar{t}}$	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
	$g_{Ab\bar{b}}$	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
	$g_{A\tau\bar{\tau}}$	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Table 2. Couplings of the mass eigenstates of the neutral CP-even scalars h and H^0, and CP-odd scalar A in the four types of 2HDM with a $\mathbb{Z}_2$ symmetry. The table follows the convention of [44]. All couplings are normalized to those of the SM Higgs, and only the coupling to the heaviest SM fermion with a particular set of quantum numbers is shown. Here $\tan\beta \equiv \langle H_2\rangle / \langle H_1\rangle$ and the mixing angle $\alpha \in (-\pi/2, \pi/2)$ defines the admixture of $H_{1,2}$ that make up the mass eigenstates h, H^0. In the 2HDM+S setup, the couplings of the singlet-like pseudoscalar a are identical to the couplings of A, up to an overall mixing angle. The couplings of the singlet-like scalar s can be obtained (again up to an overall mixing angle) from the h-couplings by replacing $\alpha \to \alpha'$, where the free parameter α' defines the mixture of $H_{1,2}$ that mixes with s (see [3] for details). The couplings listed here can be used for the calculation of the singlet branching ratios in the 2HDM+S, as additional mixing angles drop out.

CMS-HIG-15-011

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The branching fractions of the pseudoscalar a to SM particles depend on the model. In 2HDM+S type-1, the couplings of the pseudoscalar to fermions are SM-like; whereas in 2HDM+S type-2 (next-to-minimal-supersymmetric-SM-like), they are suppressed for down-type fermions for $\tan\beta < 1$ (and increased for $\tan\beta > 1$). In 2HDM+S type-3, the decays to leptons are enhanced with respect to the decays to quarks for $\tan\beta > 1$, and in 2HDM+S type-4, the decays to up-type quarks and leptons are enhanced for $\tan\beta < 1$.

ATLAS results