

ICHEP 2016

**Searches for low-mass neutral Higgs bosons
using the CMS detector**

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Agenda

1 Introduction

- Why low mass?

2 Direct production

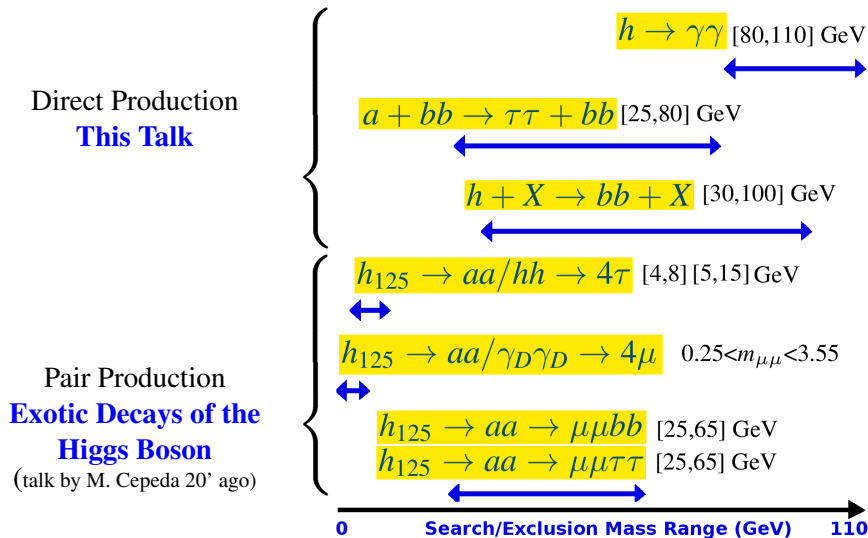
- $h \rightarrow \gamma\gamma$
- bbA with $A \rightarrow \tau\tau$
- $h + X \rightarrow b\bar{b} + X$

3 Conclusions

Why low mass? / Motivation

- Is the 125 GeV new scalar really the SM Higgs Boson? Is it the lightest?
- Some BSM theories predict modified and extended Higgs sectors, possibly with additional low-mass (<125 GeV) scalars / pseudoscalars.
 - General 2HDM :
 - 2 Higgs doublets \rightarrow 5 Higgs bosons : h, H, a, H^\pm
 - 4 types, main parameters : $\tan \beta, \alpha$
 - compatible with a 125 GeV SM-like scalar (h or H) + a light Higgs Boson (a or h)
 - MSSM :
 - simplest supersymmetric model (2HDM type II)
 - low-mass (pseudo) scalars disfavoured within this model
 - NMSSM :
 - 2 Higgs doublets + 1 singlet \rightarrow 7 Higgs bosons : $h_1, h_2, h_3, a_1, a_2, H^\pm$
 - solves the " μ -problem" of the MSSM
 - compatible with a 125 GeV SM-like scalar (h_1 or h_2) + a mostly "singlet-like" light Higgs Boson (a_1 or h_1)

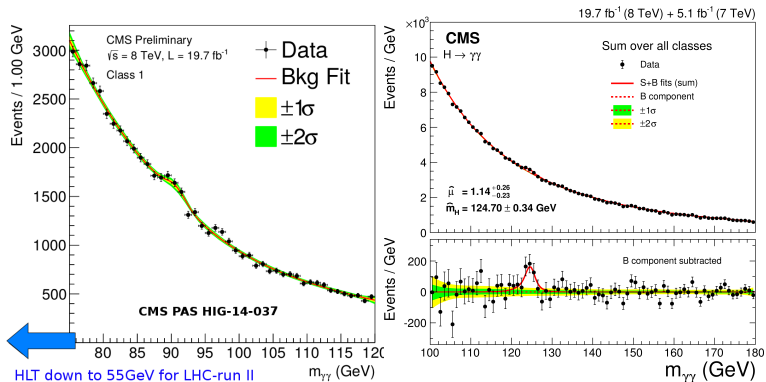
CMS Searches for low-mass neutral Higgs bosons



$h \rightarrow \gamma\gamma$

CMS-HIG-14-037

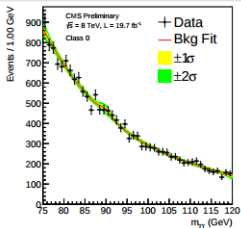
- NMSSM : $\sigma \times BR(h_1 \rightarrow \gamma\gamma)$ up to 3.5 higher compared to the SM prediction for this mass range.
- Extension of the standard $h_{125} \rightarrow \gamma\gamma$ analysis to the low invariant mass region.



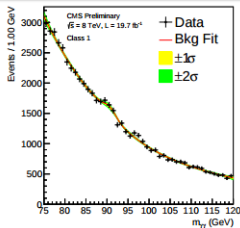
- Same object identification as the $h_{125\text{GeV}}$ analysis: **(PhotonID, DiphotonID, VertexID)**
- The modeling of the **Z background** (misidentified electrons) is an important feature of this search.

$h \rightarrow \gamma\gamma$

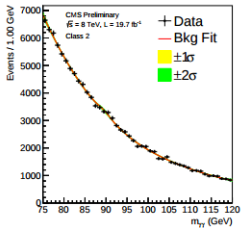
CMS-HIG-14-037



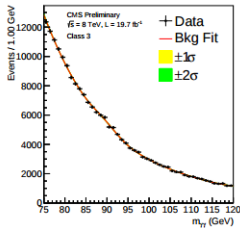
(a) Class 0



(b) Class 1



(c) Class 2

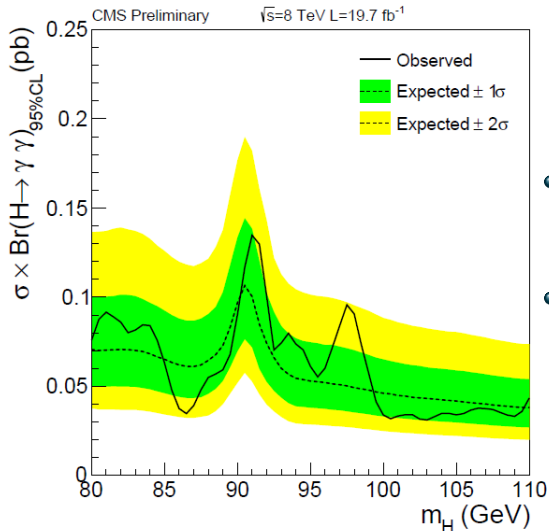


(d) Class 3

- The **same multivariate event classifier as in the h_{125} analysis** is built to discriminate signal from background.
- It incorporates the kinematic properties of the diphoton system, a per-event estimate of the diphoton mass resolution, and the photon identification BDT output value.
- In this analysis, events are separated into **4 classes based on the classifier score**; events having a score below a minimum value are rejected.
- Background model : diphoton continuum + Z peak contamination (electron veto to reduce it)

$h \rightarrow \gamma\gamma$

CMS-HIG-14-037

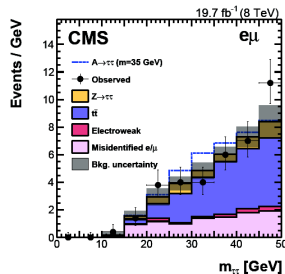
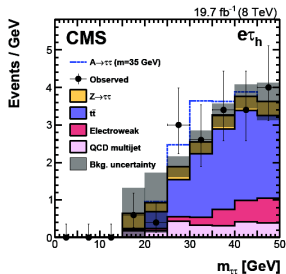
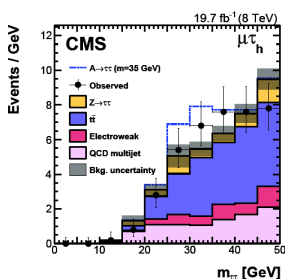
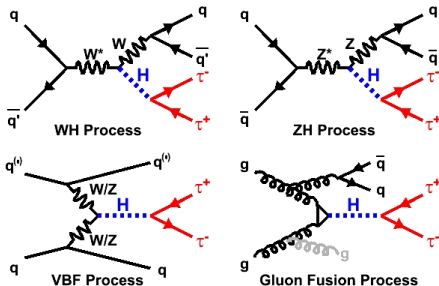


- Exclude scalars with $\sigma \times BR(h \rightarrow \gamma\gamma)$ from 0.8 - 3 times the SM.
- New trigger dedicated to this analysis in **run-II** down to $m_{\gamma\gamma} = 55$ GeV.

bbA with $A \rightarrow \tau\tau$

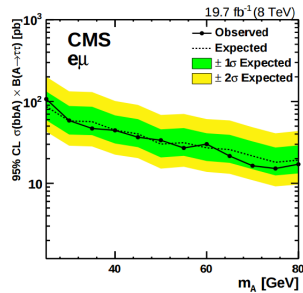
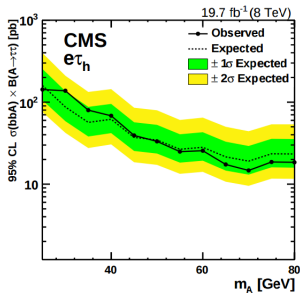
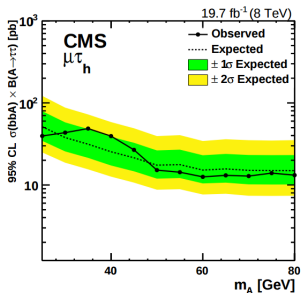
CMS-HIG-14-033

- Search for a light pseudoscalar Higgs boson decaying to a pair of τ leptons produced in association with a $b\bar{b}$ pair.
- Three final states: $\mu\tau_h$, $e\tau_h$ and $e\mu$ are used (τ_h represent the hadronic τ decay).
- The $\mu\mu$ and ee final states are discarded \rightarrow small branching fractions and large backgrounds. $\tau_h \tau_h$ not considered because of inefficiencies due to the trigger threshold.
- Pseudoscalar boson masses between 25 and 80 GeV are probed.

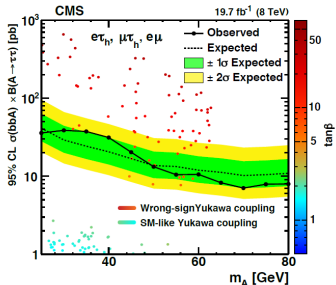


bbA with $A \rightarrow \tau\tau$

CMS-HIG-14-033

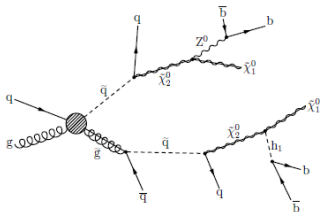


- This analysis is similar to the MSSM analysis (Drell-Yan background).
- Range : [25,80] GeV
- $\mu\tau_h$, $e\tau_h$ and $e\mu$ channels
- Exclusion of 2HDM type II, wrong-sign Yukawa coupling, high $\tan\beta$

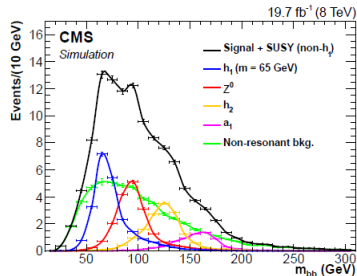
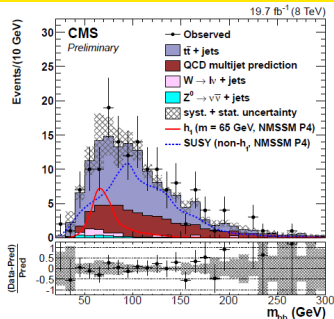


$$h + X \rightarrow b\bar{b} + X$$

CMS-HIG-14-030



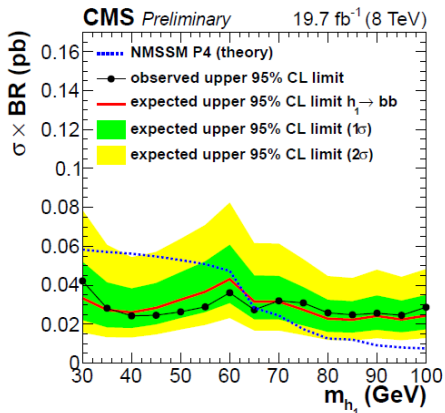
- NMSSM scenarios : "NMSSM (P4)" : high $BR(h_1 \rightarrow b\bar{b})$, $M_{\tilde{q}, g} \sim 1$ TeV ; "decoupled squarks" : $M_1 < M_2 < M_3 < 1$ TeV
- h_1 produced in supersymmetric colored cascades
- $X =$ high hadronic activity + high MET
- Range : [30,100] GeV
- Signal : h_1 resonance + non-resonant SUSY. We look for a 'bump' or a 'normalization' excess.
- Large contribution from SUSY decays in this search.



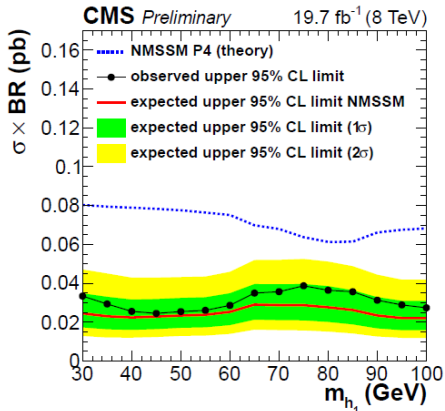
$h + X \rightarrow b\bar{b} + X$: Exclusion limits

CMS-HIG-14-030

Model independent, resonance only

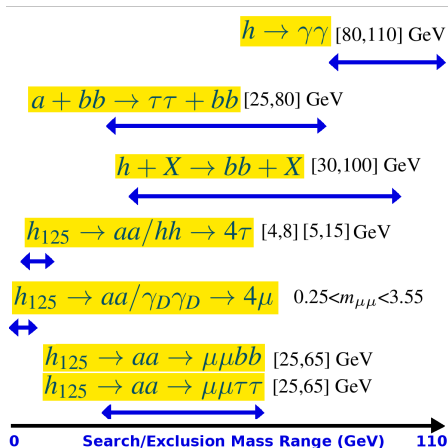


Normalization excess



Conclusions

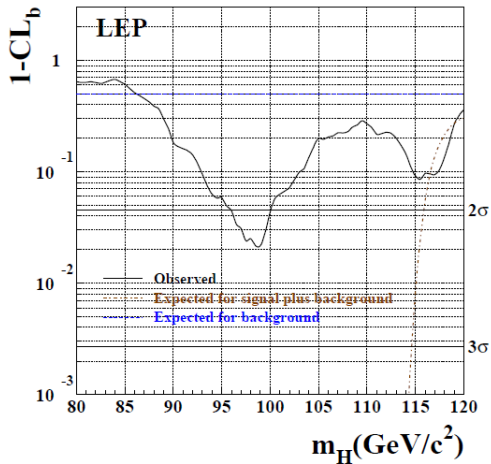
- Comprehensive low-mass higgs searches have been performed in CMS with the LHC run I data.
- Low- p_T object trigger and reconstruction are challenging.
- Both direct (this talk) and pair production have been considered.
- **No evidence for new particle production has been found**
- 2HDM and NMSSM interpretations \rightarrow parameter space regions excluded and benchmark scenarios ruled out.
- Improvements like new triggers, final states, and production modes are under development.
- The run-II data will complete the overall picture of these low mass analysis. Stay tuned.



BACKUP



LEP excess @ 98 GeV



<https://arxiv.org/pdf/hep-ex/0306033v1.pdf>

$h \rightarrow \gamma\gamma$: Systematics

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	$\pm 10\%$ (shape scaling)	

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

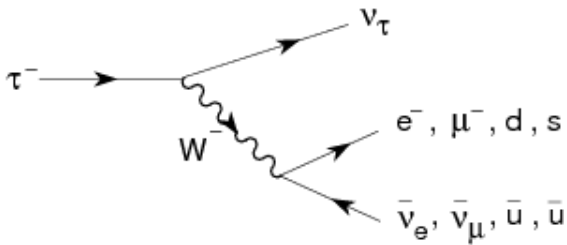
Event Class	μ (GeV)	$\Delta\mu_{stat}$ (GeV)	$\Delta\mu_{data-MC_{all}}$ (GeV)	$\Delta\mu_{MC_{all}-MC_{DY}}$ (GeV)	$\Delta\mu_{tot}$ (GeV)
0	89.9	0.3	0.64	0.40	0.81
1	90.6	0.2	0.64	0.40	0.78
2	89.6	0.1	0.64	0.40	0.76
3	89.24	0.08	0.64	0.40	0.76

Event Class	σ (GeV)	$\Delta\sigma_{stat}$ (GeV)	$\Delta\sigma_{data-MC_{all}}$ (GeV)	$\Delta\sigma_{MC_{all}-MC_{DY}}$ (GeV)	$\Delta\sigma_{tot}$ (GeV)
0	1.5	0.3	1.46	1.70	2.26
1	1.8	0.2	1.46	1.70	2.25
2	1.8	0.2	1.46	1.70	2.25
3	3.22	0.08	1.46	1.70	2.24

bbA with $A \rightarrow \tau\tau$, $a + b\bar{b} \rightarrow \tau\tau + b\bar{b}$: Systematics

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%
	$Z/\gamma^* \rightarrow \tau\tau$ normalisation	3%	3%	3%
	$Z/\gamma^* \rightarrow \tau\tau$ low-mass normalisation	10%	10%	10%
	QCD multijet normalisation	20%	20%	—
	Reducible background normalisation	—	—	30%
	W+jets normalisation	30%	30%	—
	$t\bar{t}$ cross section	10%	10%	10%
Diboson cross section	15%	15%	15%	
$H \rightarrow \tau\tau$ 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%

τ decay

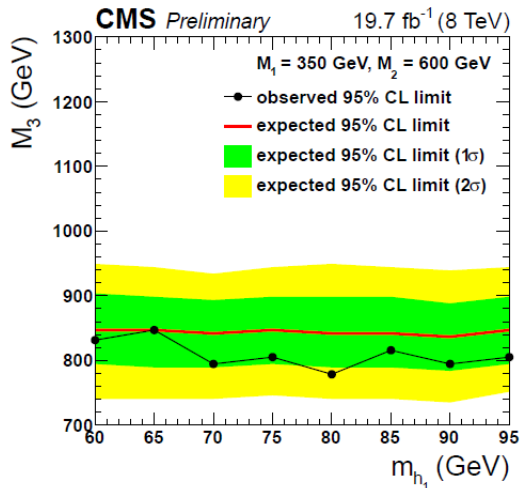


$h + X \rightarrow b\bar{b} + X$: Systematics

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 $W \rightarrow \ell\nu$	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%

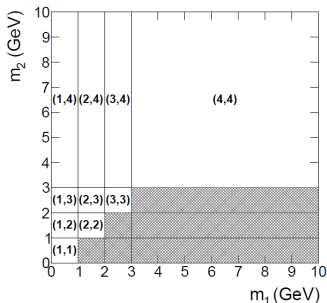
$h + X \rightarrow b\bar{b} + X$: Exclusion limits

Exclusion Limits (decoupled squarks)

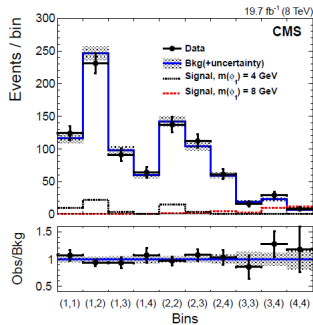


$h_{125} \rightarrow aa/hh \rightarrow 4\tau$ (CMS-HIG-14-019) : (m_1, m_2) distribution

- (m_1, m_2) distribution binning definition



- (m_1, m_2) distribution bins content

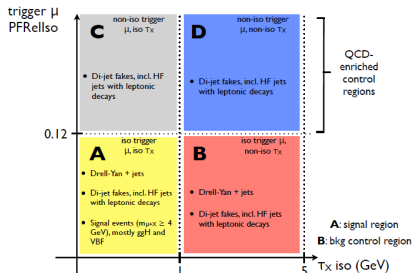


$h_{125} \rightarrow aa/hh \rightarrow 4\tau$ (CMS-HIG-14-019) : Systematics

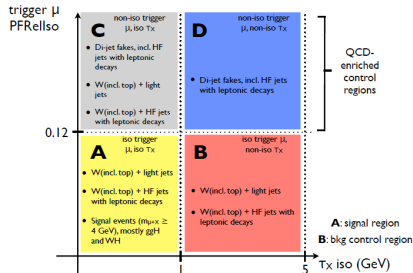
Source	Value	Affected sample	Type	Effect on the total yield
Statistical uncertainties in $C(i,j)$	2–14%	bkg.	bin-by-bin	—
Extrapolation uncertainties in $C(i,j)$	2–22%	bkg.	bin-by-bin	—
Integrated luminosity	2.6%	signal	norm.	2.6%
Muon ID and trigger efficiency	2% per muon	signal	norm.	4%
Track selection 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%

$h_{125} \rightarrow aa/hh \rightarrow 4\tau$ (CMS-HIG-14-022) : Background control regions

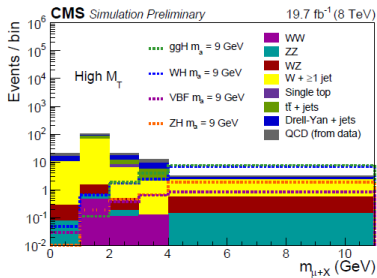
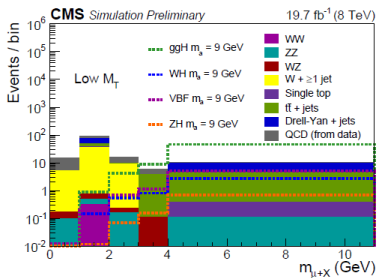
● Low MT



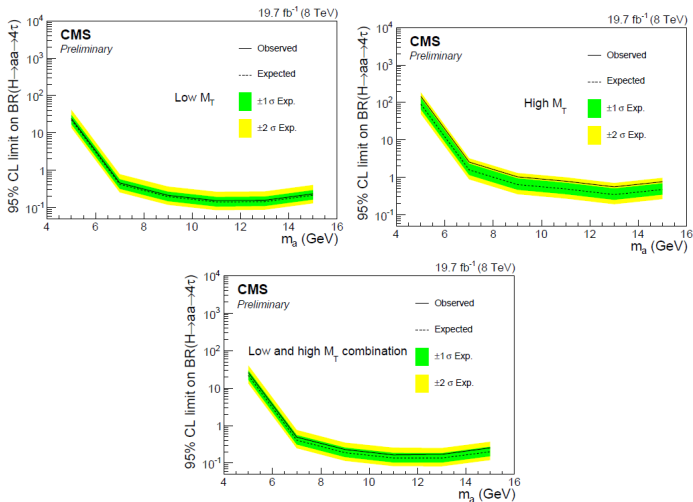
● High MT



$h_{125} \rightarrow aa/hh \rightarrow 4\tau$ (CMS-HIG-14-022) : Signal vs background



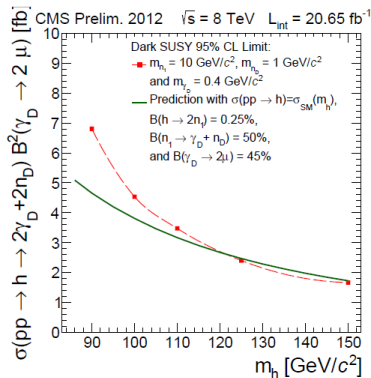
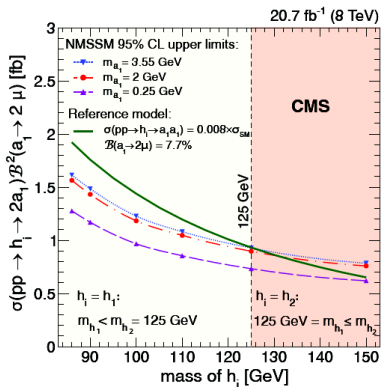
$h_{125} \rightarrow aa/hh \rightarrow 4\tau$ (CMS-HIG-14-022) : Exclusion limits



$h_{125} \rightarrow aa/hh \rightarrow 4\tau$ (CMS-HIG-14-022) : Systematics

Uncertainty	Magnitude	
	$M_T \leq 50 \text{ GeV}/c^2$	$M_T > 50 \text{ GeV}/c^2$
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%

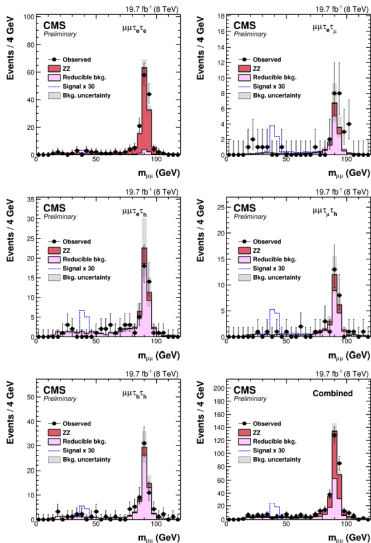
$h_{125} \rightarrow aa/\gamma_D\gamma_D \rightarrow 4\mu$: Exclusion limits



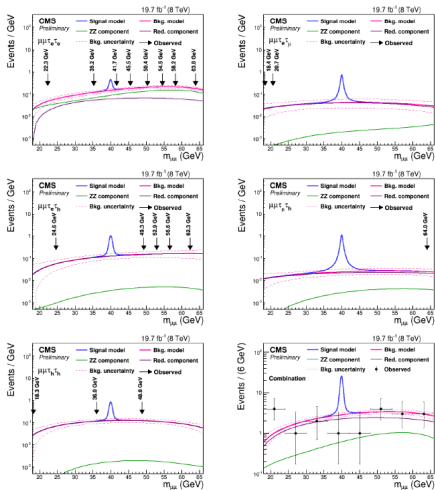
$h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$: Event selection cuts

	$\mu\mu\tau_e\tau_e$	$\mu\mu\tau_e\tau_\mu$	$\mu\mu\tau_e\tau_h$	$\mu\mu\tau_\mu\tau_h$	$\mu\mu\tau_h\tau_h$
μ_1	$p_T > 18 \text{ GeV}, \eta < 2.4, I_{rel} < 0.4, \text{Loose PF ID}$				
μ_2	$I_{rel} < 0.4, \text{Loose PF ID}, \eta < 2.4$				
	$p_T > 9 \text{ GeV}$	$p_T > 5/9 \text{ GeV}$	$p_T > 9 \text{ GeV}$	$p_T > 5/9 \text{ GeV}$	$p_T > 9 \text{ GeV}$
τ_e	$p_T > 7 \text{ GeV}, \eta < 2.5, \text{MVA ID}$			-	-
	$I_{rel} < 0.4$	$I_{rel} < 0.4$	$I_{rel} < 0.2$		
τ_h	-	-	$p_T > 15 \text{ GeV}, \eta < 2.3, \text{Loose anti-}\mu$		
			Loose iso. Loose anti-e	Loose iso. vLoose anti-e	Medium iso. vLoose anti-e
τ_μ	-	$p_T > 9/5 \text{ GeV}$ $ \eta < 2.4$ Loose PF ID $I_{rel} < 0.4$	-	$p_T > 9/5 \text{ GeV}$ $ \eta < 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.				
$ m_{\mu\mu\tau\tau} - 125 $	$< 25 \text{ GeV}$				
$ m_{\mu\mu} - m_{\tau\tau} /m_{\mu\mu}$	< 0.8				
ΔR between leptons	> 0.4				
$ m_{\mu\mu ee}^{vis} - 125 $	$> 15 \text{ GeV}$	-			

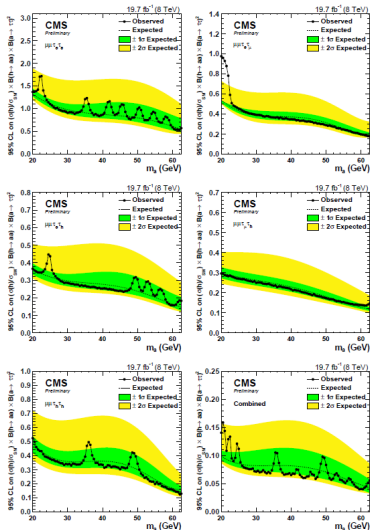
$h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$: Data vs MC



$h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$: Signal and background model



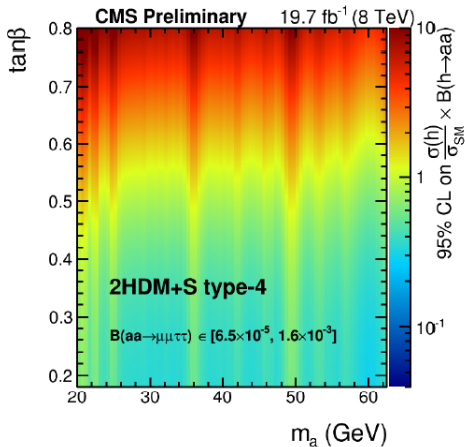
$h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$: Exclusion limits



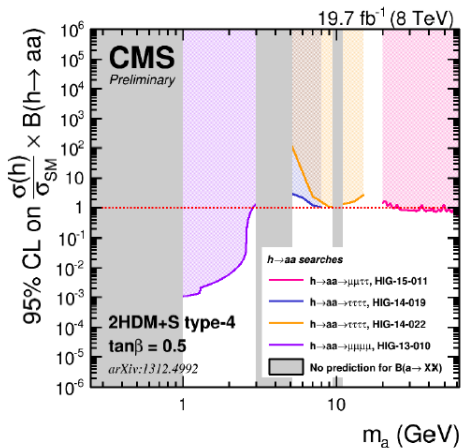
$h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$: Systematics

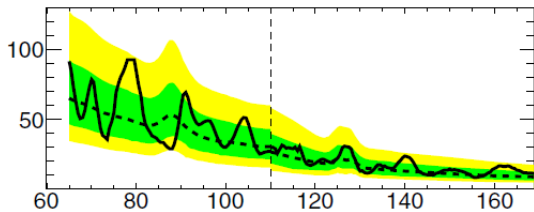
Systematic uncertainty	Relative change in yield		
	Signal	ZZ	Reducible backgrounds
Luminosity	2.6%	2.6%	-
Trigger	1%	1%	-
Tau identification	0-12%	0-12%	-
b-Jet veto	1%	1%	-
Tau energy scale	0-10%	0-10%	-
Electron identification	0-4%	0-4%	-
Muon identification	2-4%	2-4%	-
Signal prediction	10%	-	-
Signal 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	-	-

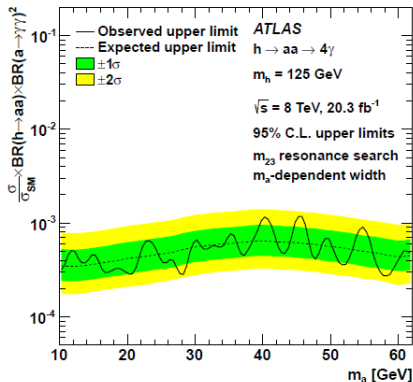
$h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$: 2HDM+S type 4 ("flipped") interpretation

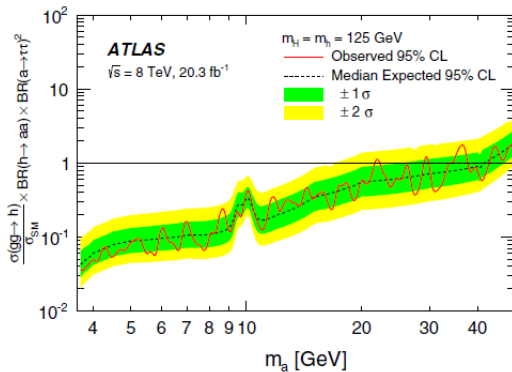


$h_{125} \rightarrow aa$ comparison : 2HDM+S type 4 ("flipped") interpretation



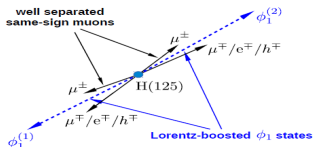






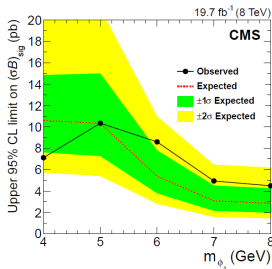
$h_{125} \rightarrow aa/hh \rightarrow 4\tau$

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



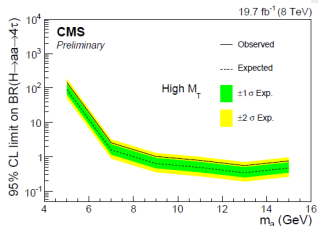
CMS-HIG-14-019

- Range [4,8] GeV
- Pair of $\tau \Rightarrow 1 \mu + 1$ track



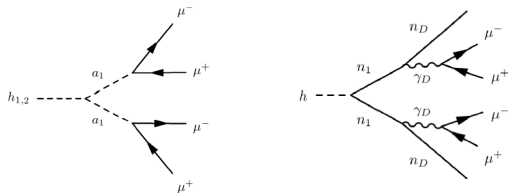
CMS-HIG-14-022

- Range [5,15] GeV
- Pair of $\tau \Rightarrow 1 \mu + 1 \tau_h$
- 2 categories based on the presence of MET : ggh/vbf and VH enriched

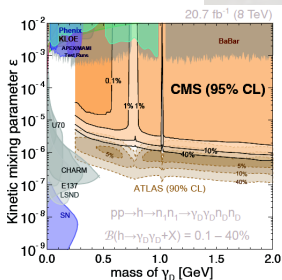
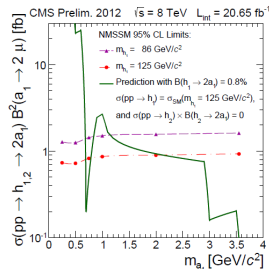
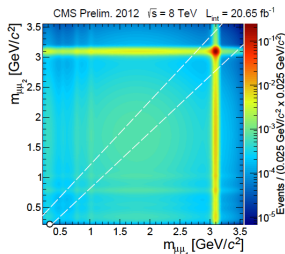


$h_{125} \rightarrow aa/\gamma_D \gamma_D \rightarrow 4\mu$

CMS-HIG-13-010



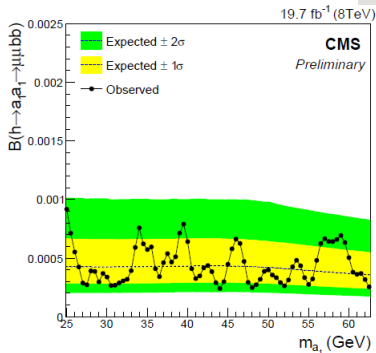
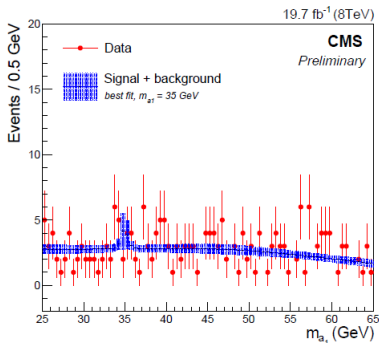
- NMSSM and Dark SUSY scenarios
- Dark SUSY : additional $U(1)_D$ symmetry, Higgs boson decays to "dark" neutralinos and photons
- Search for events in $(m_{\mu\mu 1}, m_{\mu\mu 2})$ space, with $0.25 < m_{\mu\mu} < 3.55$



$h_{125} \rightarrow aa \rightarrow \mu\mu b\bar{b}$

CMS-HIG-14-041

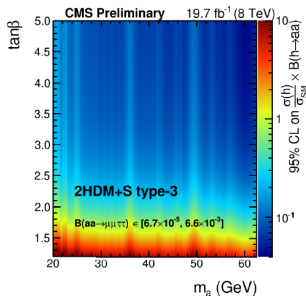
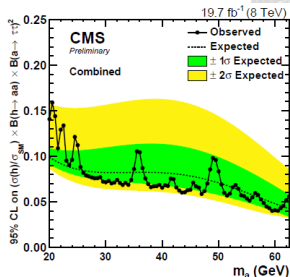
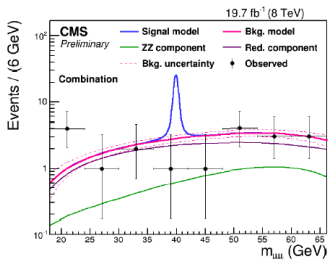
- NMSSM : $BR(h_1 \rightarrow a_1 a_1 \rightarrow \mu\mu b\bar{b})$ up to $\sim 2 \cdot 10^{-3}$
- Range [25,65] GeV
- Fit in $m_{\mu\mu}$ distribution
- Exclude pseudoscalars with $BR(h \rightarrow a_1 a_1 \rightarrow \mu\mu b\bar{b})$ above 10^{-3}



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

CMS-HIG-15-001

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



$h_{125} \rightarrow aa$ comparison

CMS-HIG-15-001

- Comparison of $4\tau, 4\mu, \mu\mu\tau\tau$ channels
- General 2HDM+S framework \Rightarrow , using

$$\frac{\Gamma(a \rightarrow \mu\mu)}{\Gamma(a \rightarrow \tau\tau)} = \frac{m_\mu^2 \sqrt{1 - (2m_\mu/m_a)^2}}{m_\tau^2 \sqrt{1 - (2m_\tau/m_a)^2}}$$

- Very little background in this search.

