Search for low-mass Higgs-boson-like resonances at CMS

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on behalf of the CMS collaboration

IPN Lyon

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Motivations

- Is the 125 GeV new scalar really the SM Higgs Boson ?
- 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 : $\tan\beta$, α
  - compatible with a 125 GeV SM-like scalar (h or H) + a light Higgs Boson (a or h) in the "alignment limit"
- 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)

Outline

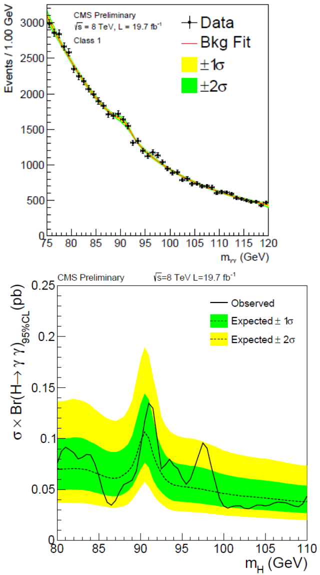
- I will present searches for a low-mass (pseudo) scalar boson with a mass between 0.25 and 110 GeV, with the 8 TeV dataset.
- Search for a direct production (+ possibly additionnal objects) or a pair production from the decay of h_{125}
- $\gamma\gamma$, $\tau\tau$, bb, $\mu\mu$ channels
- Scalar or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

1. Direct production
   - $h \to \gamma\gamma$
   - $a + bb \to \tau\tau + bb$
   - $h + X \to bb + X$
2. Pair production
   - $h_{125} \to aa/hh \to 4\tau$
   - $h_{125} \to aa/\gamma_D\gamma_D \to 4\mu$
   - $h_{125} \to aa \to \mu\mu bb$
   - $h_{125} \to aa \to \mu\mu\tau\tau$

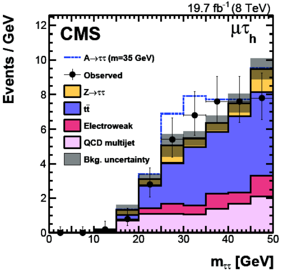
$h \to \gamma\gamma$

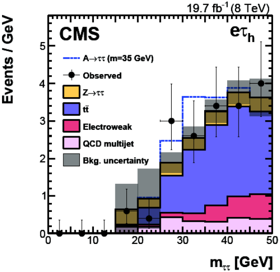
CMS-HIG-14-037

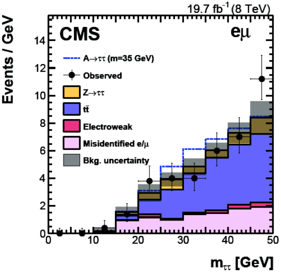
- NMSSM : $\sigma \times BR(h_1 \to \gamma\gamma)$ up to 3.5 higher compared to SM...
- Extension of the standard $h_{125} \to \gamma\gamma$ analysis in the range [80,110] GeV
- Background model : diphoton continuum + Z peak contamination (electron veto to reduce it)
- 4 event categories to increase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



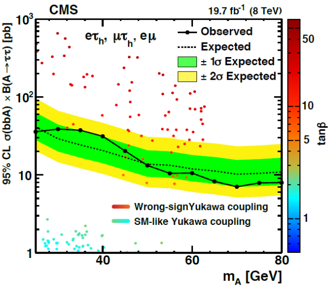
$a + bb \to \tau\tau + bb$ CMS-HIG-14-033



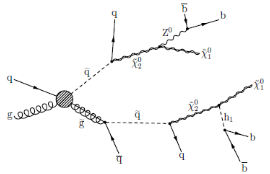




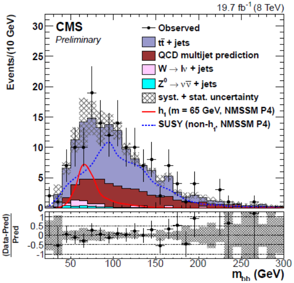
- Range : [25,80] GeV
- $\mu\tau_h$, $e\tau_h$ and $e\mu$ channels
- Exclusion of 2HDM type II, wrong-sign Yukawa coupling, high tan β

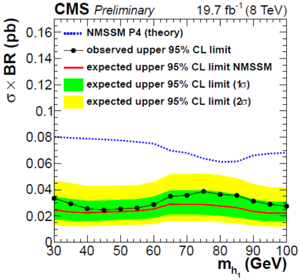


$h + X \to bb + X$ CMS-HIG-14-030



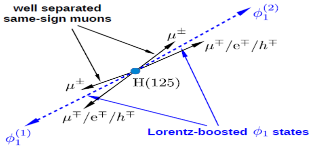
- NMSSM scenarios : "NMSSM P4" : high BR($h_1 \to bb$), $M_{\tilde{q},\tilde{g}} \sim 1$ TeV ; "decoupled squarks" : $M_1 < M_2 < M3 < 1$ TeV
- h_1 produced in supersymmetric coloured cascades
- X = high hadronic activity + high MET
- Range : [30,100] GeV
- Signal : h_1 resonance + non-resonant SUSY
- Exclusion of P4 scenario





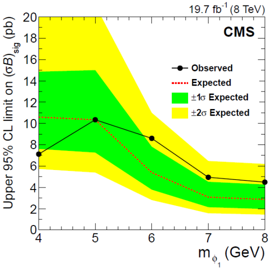
$h_{125} \to aa/hh \to 4\tau$

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



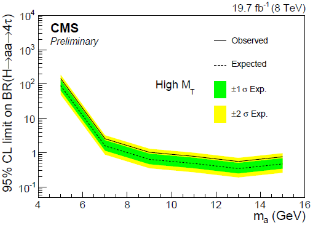
CMS-HIG-14-019

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

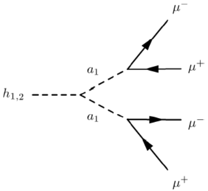


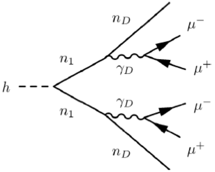
CMS-HIG-14-022

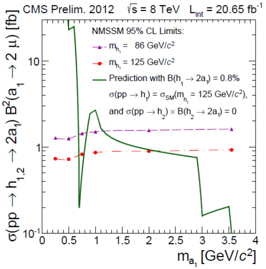
- Range [5,15] GeV
- Pair of $\tau \Rightarrow 1\ \mu + 1\ \tau_h$
- 2 categories based on the presence of MET : ggh/vbf and VH enriched



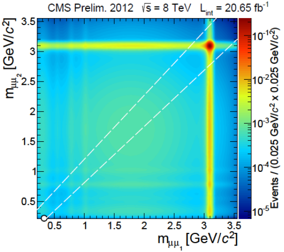
$h_{125} \to aa/\gamma_D\gamma_D \to 4\mu$ CMS-HIG-13-010

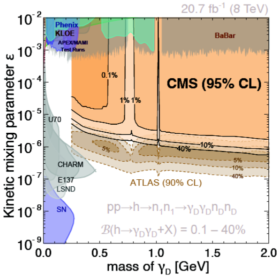






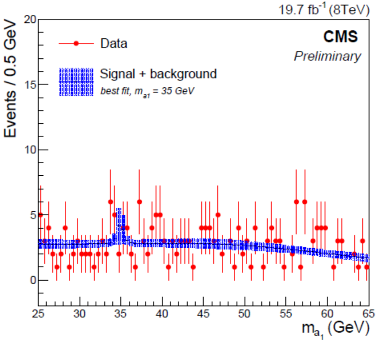
- NMSSM and Dark SUSY scenarios
- Dark SUSY : additional $U(1)_D$ symmetry, Higgs boson decays to "dark" neutralinos and photons
- Search for events in $(m_{\mu\mu 1}, m_{\mu\mu 2})$ space, with $0.25 < m_{\mu\mu} < 3.55$

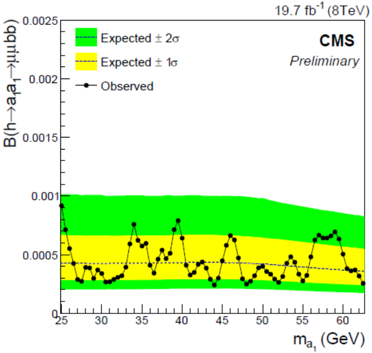




$h_{125} \to aa \to \mu\mu bb$ CMS-HIG-14-041

- NMSSM : BR($h_1 \to a_1 a_1 \to \mu\mu bb$) up to $\sim 2.10^{-3}$
- Range [25,65] GeV
- Fit in $m_{\mu\mu}$ distribution
- Exclude pseudoscalars with $BR(h \to a_1 a_1 \to \mu\mu bb)$ above 10^{-3}

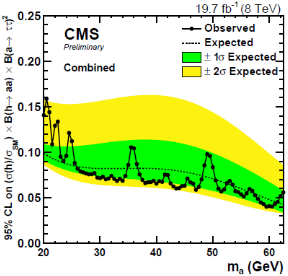


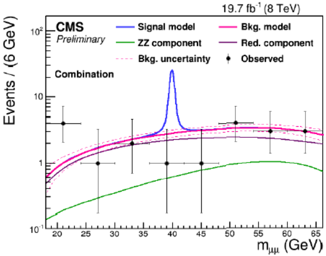


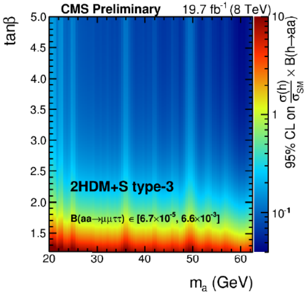
$h_{125} \to aa \to \mu\mu\tau\tau$

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)





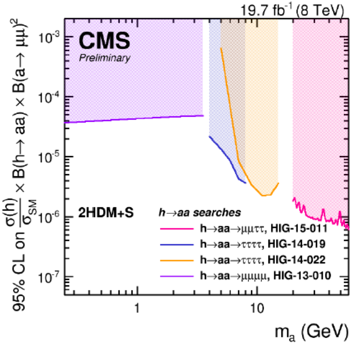


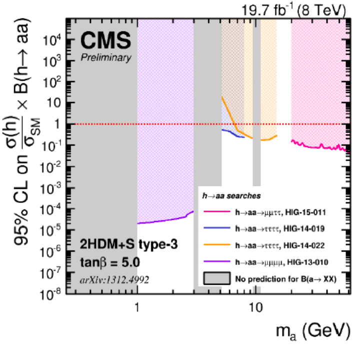
$h_{125} \to aa$ comparison

CMS-HIG-15-001

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

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



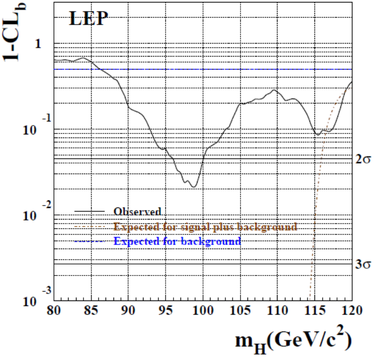


Conclusions

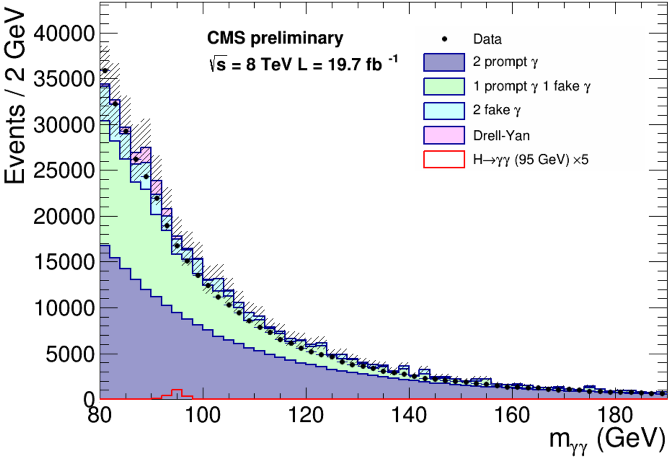
- Several low-mass (pseudo) scalar searches have been performed in CMS during run I in the range [0.25,110] GeV
- Both direct and pair production considered
- Low-p_T object reconstruction can be challenging
- No evidence for new particle production
- 2HDM, NMSSM interpretations : parameter space regions excluded, benchmark scenarios ruled out ...
- All analyses are being continued in run II, with several improvements : new triggers, final states, production modes ...
- Sensitivity to BSM models will be increased, looking forward for new results !

BACK-UP

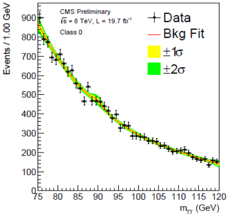
LEP excess @ 98 GeV



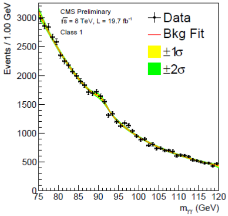
$h \to \gamma\gamma$: Data / MC comparison



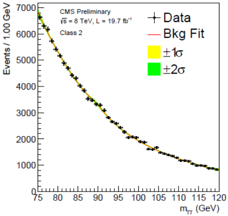
$h \rightarrow \gamma\gamma$: Background model



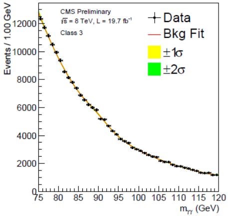
(a) Class 0



(b) Class 1



(c) Class 2



(d) Class 3

$h \rightarrow \gamma\gamma$: 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	±10% (shape scaling)	

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

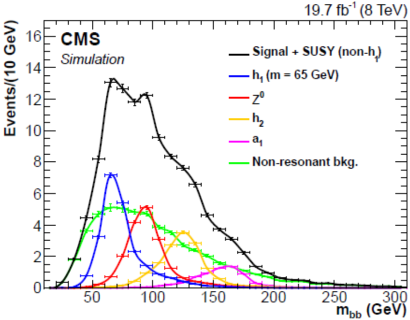
Event Class	μ (GeV)	$\Delta\mu_{stat}$ (GeV)	$\Delta\mu_{data-MC_{all}}$ (GeV)	$\Delta\mu_{MC_{all}-MC_{DY}}$ (GeV)	$\Delta\mu_{tot}$ (GeV)
0	89.9	0.3	0.64	0.40	0.81
1	90.6	0.2	0.64	0.40	0.78
2	89.6	0.1	0.64	0.40	0.76
3	89.24	0.08	0.64	0.40	0.76

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

$a + bb \to \tau\tau + bb$: Systematics

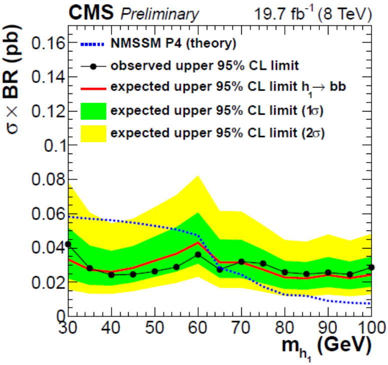
	Systematic source	Systematic uncertainty $\mu\tau_h$	$e\tau_h$	$e\mu$
Normalisation	Integrated luminosity	2.6%	2.6%	2.6%
	Muon ID/trigger	2%	—	2%
	Electron ID/trigger	—	2%	2%
	Tau ID/trigger	8%	8%	—
	Muon to tau misidentification rate	30%	—	—
	Electron to tau misidentification rate	—	30%	—
	b tagging 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%
	$Z/\gamma^* \to \tau\tau$ 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%	—
	$t\bar{t}$ 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%

$h + X \to bb + X$: Signal model

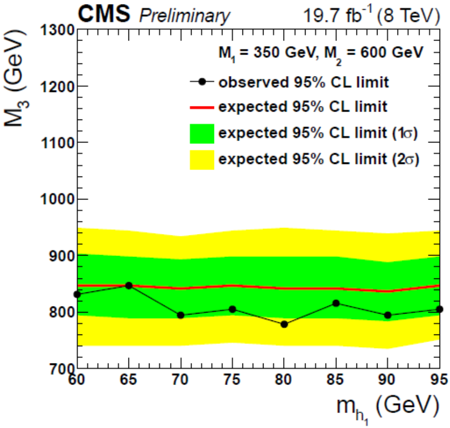


$h + X \rightarrow bb + X$: Exclusion limits (model independant)

- Signal Model : h_1 resonance only



$h + X \to bb + X$: Exclusion Limits (decoupled squarks)

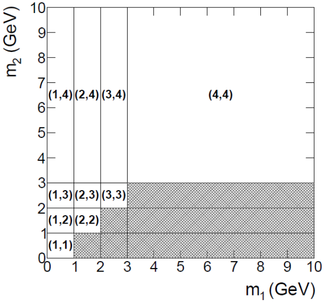


$h + X \to bb + X$: Systematics

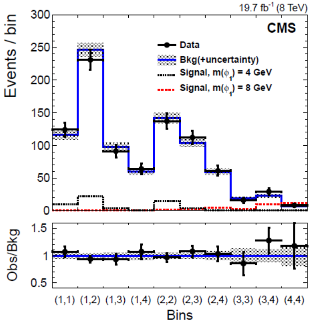
Systematics source	Event category	Type	Impact
Normalization of $t\bar{t}$	Background	rate	1.7 %
Normalization of QCD	Background	rate	2 %
Shape correction QCD	Background	shape + rate	3 %
QCD shape parameterization	Background	shape + rate	1 %
MC statistics $t\bar{t}$	Background	shape + rate	1.3 %
MC statistics $W \to \ell\nu$	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 %

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

- (m_1, m_2) distribution binning definition



- (m_1, m_2) distribution bins content

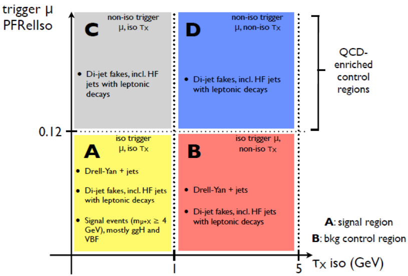


$h_{125} \to aa/hh \to 4\tau$ (HIG-14-019) : Systematics

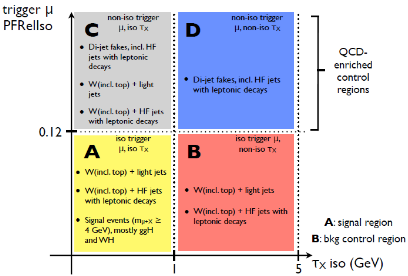
Source	Value	Affected sample	Type	Effect on the total yield
Statistical uncertainties in $C(i,j)$	2–14%	bkg.	bin-by-bin	—
Extrapolation uncertainties in $C(i,j)$	2–22%	bkg.	bin-by-bin	—
Integrated luminosity	2.6%	signal	norm.	2.6%
Muon ID and trigger efficiency	2% per muon	signal	norm.	4%
Track selection 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 $\to$ H(125)	3%	signal	norm.	3%

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

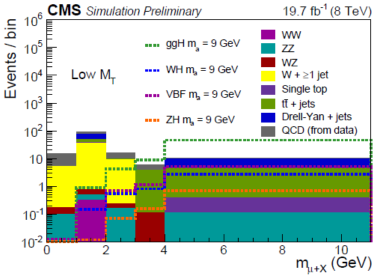
- Low MT



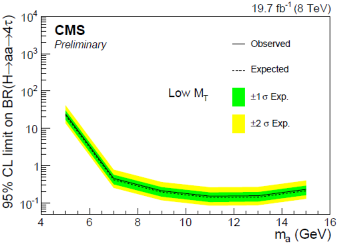
- High MT

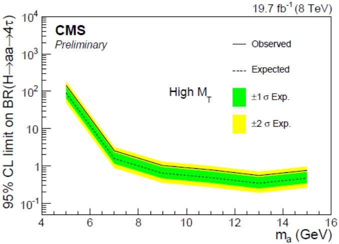


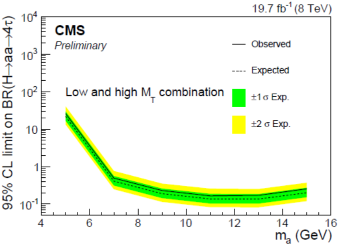
$h_{125} \rightarrow aa/hh \rightarrow 4\tau$ (HIG-14-022) : Signal vs background



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



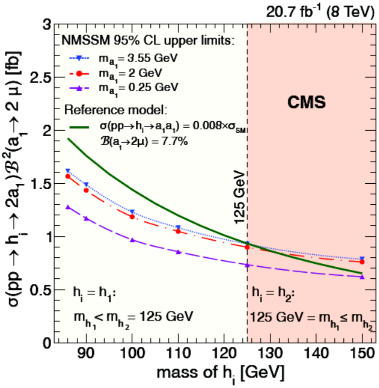


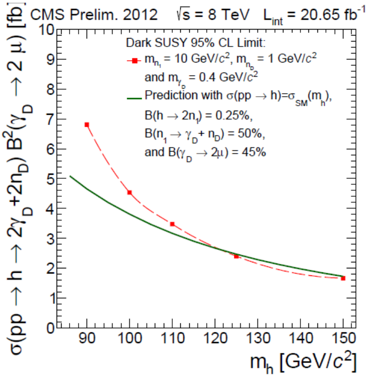


$h_{125} \to aa/hh \to 4\tau$ (HIG-14-022) : Systematics

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%

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

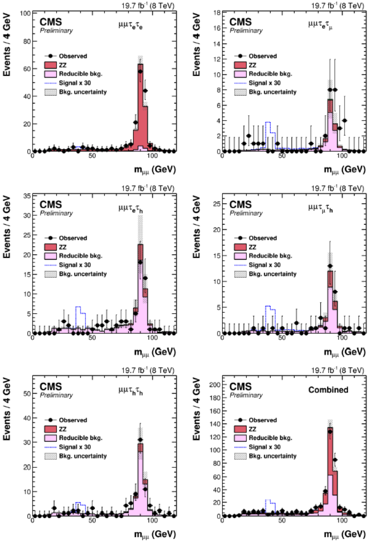




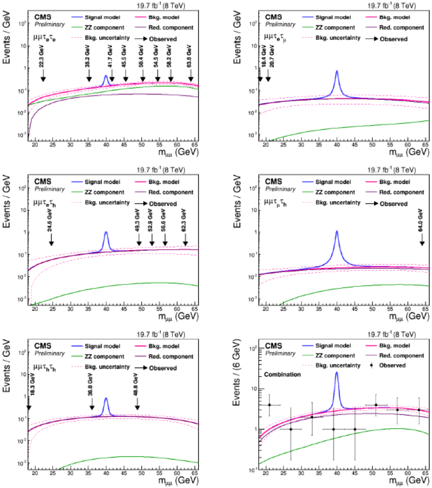
$h_{125} \to aa \to \mu\mu\tau\tau$: Event selection cuts

	$\mu\mu\tau_e\tau_e$	$\mu\mu\tau_e\tau_\mu$	$\mu\mu\tau_e\tau_h$	$\mu\mu\tau_\mu\tau_h$	$\mu\mu\tau_h\tau_h$
μ_1	p_T >18 GeV, $\|\eta\| < 2.4$, $I_{rel} < 0.4$, Loose PF ID				
μ_2	$I_{rel} < 0.4$, Loose PF ID, $\|\eta\| < 2.4$				
	$p_T > 9$ 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, $\|\eta\| < 2.5$, MVA ID			-	-
	$I_{rel} < 0.4$	$I_{rel} < 0.4$	$I_{rel} < 0.2$		
τ_h	-	-	$p_T > 15$ GeV, $\|\eta\| < 2.3$, 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 $\|\eta\| < 2.4$ Loose PF ID $I_{rel} < 0.4$	-	$p_T > 9/5$ 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 GeV				
$\|m_{\mu\mu} - m_{\tau\tau}\|/m_{\mu\mu}$	< 0.8				
ΔR between leptons	> 0.4				
$\|m^{vis}_{\mu\mu ee} - 125\|$	> 15 GeV	-			

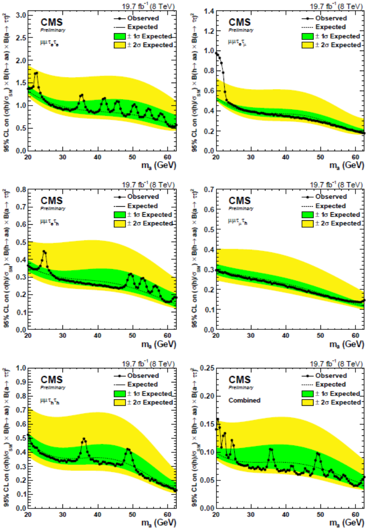
$h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$: Data vs MC



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



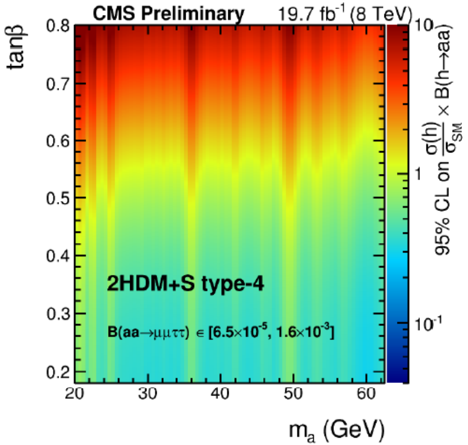
$h_{125} \to aa \to \mu\mu\tau\tau$: Exclusion limits



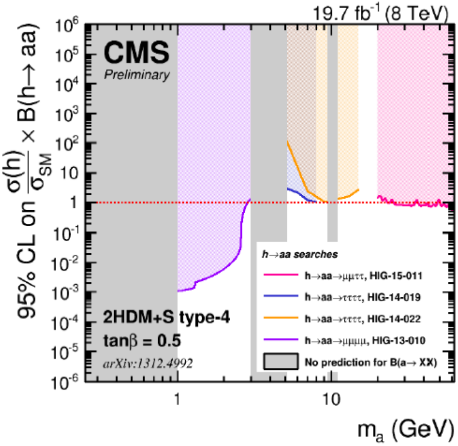
$h_{125} \to aa \to \mu\mu\tau\tau$: Systematics

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	-	-

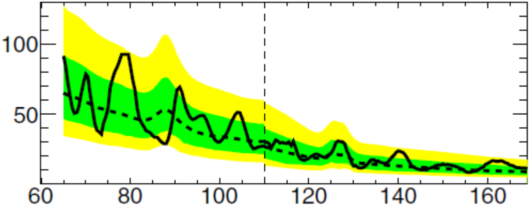
$h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$: 2HDM+S type 4 ("flipped") interpretation



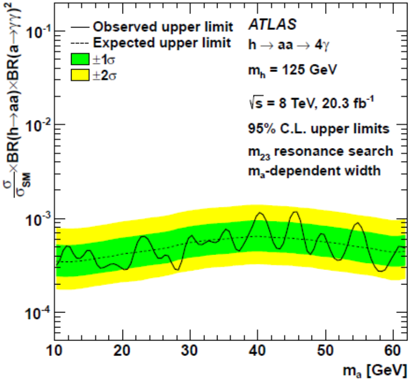
$h_{125} \to aa$ comparison : 2HDM+S type 4 ("flipped") interpretation



ATLAS results : $h \to \gamma\gamma$ Phys. Rev. Lett. 113, 171801



ATLAS results : $h_{125} \to aa \to 4\gamma$ arXiv :1509.05051



ATLAS results : $h_{125} \to \mu\mu\tau\tau$ Phys.Rev.D92 (2015) 052002