Anomalies found in Higgs boson measurements and searches in Run I

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UK HEP Forum: Anomalies and Deviations

5-6 November 2015,

The Cosener's House

BSM Physics with Higgs bosons

- Precise measurements for h(125)
- Searches for additional Higgs bosons
- Searches for non-SM decays of h(125)

will be discussed

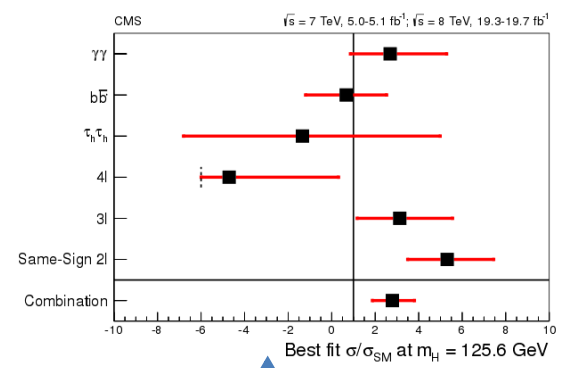
- Recent ATLAS+CMS combination for h(125)
- Curiosities in the searches for additional Higgs bosons
- h(125)->$\mu\tau$

Testing the compatibility of h(125) with SM:
ATLAS+CMS combination

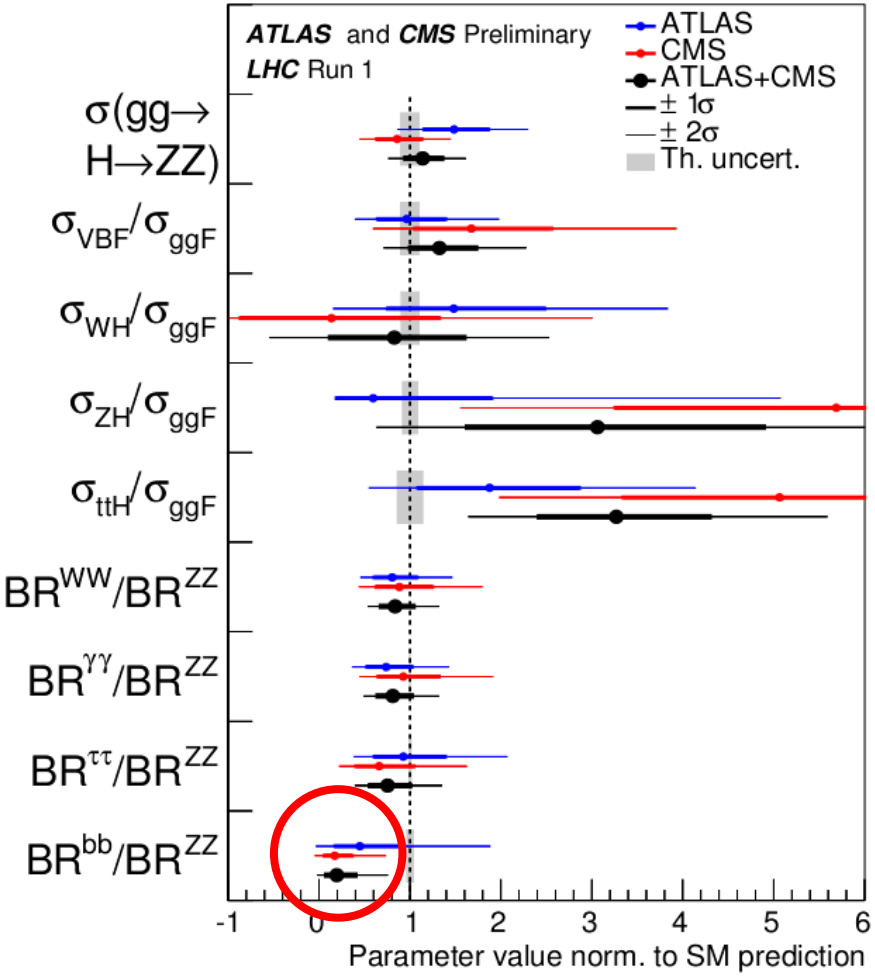
- **ATLAS and CMS input:**
  - **analyses of $\gamma\gamma$, ZZ->4ℓ, WW, $\tau\tau$, bb decays and ttH**

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]	$1.15^{+0.27}_{-0.25}$ $(^{+0.26}_{-0.24})$	$1.12^{+0.25}_{-0.23}$ $(^{+0.24}_{-0.22})$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ \to 4\ell$	[53]	[54]	$1.51^{+0.39}_{-0.34}$ $(^{+0.33}_{-0.27})$	$1.05^{+0.32}_{-0.27}$ $(^{+0.31}_{-0.26})$	6.6 (5.5)	7.0 (6.8)
$H \to WW$	[55,56]	[57]	$1.23^{+0.23}_{-0.21}$ $(^{+0.21}_{-0.20})$	$0.91^{+0.24}_{-0.21}$ $(^{+0.23}_{-0.20})$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[58]	[59]	$1.41^{+0.40}_{-0.35}$ $(^{+0.37}_{-0.33})$	$0.89^{+0.31}_{-0.28}$ $(^{+0.31}_{-0.29})$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[38]	[39]	$0.62^{+0.37}_{-0.36}$ $(^{+0.39}_{-0.37})$	$0.81^{+0.45}_{-0.42}$ $(^{+0.45}_{-0.43})$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[60]	[61]	-0.7 ± 3.6 (± 3.6)	0.8 ± 3.5 (± 3.5)		
$tt\,H$ production	[28,62,63]	[65]	$1.9^{+0.8}_{-0.7}$ $(^{+0.72}_{-0.66})$	$2.9^{+1.0}_{-0.9}$ $(^{+0.88}_{-0.80})$	2.7 (1.6)	3.6 (1.3)

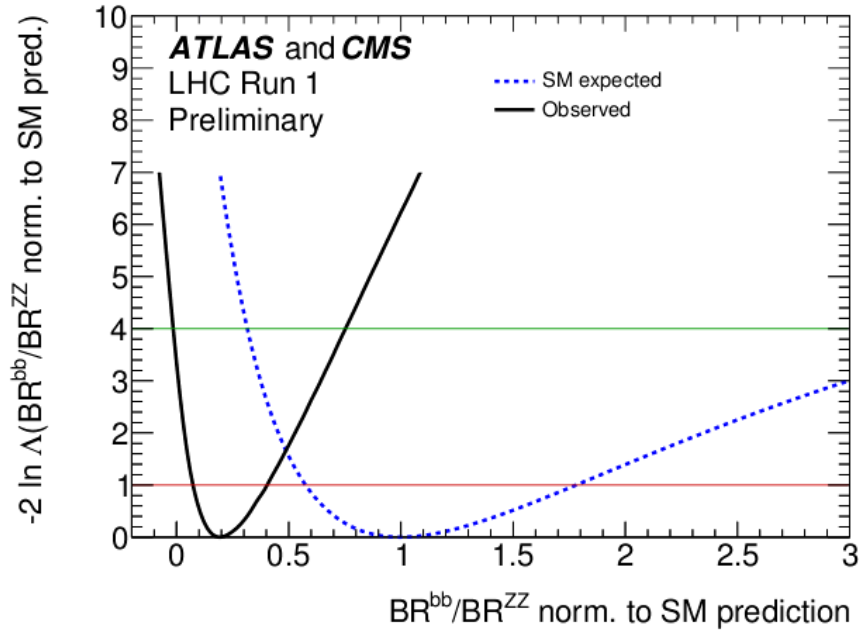
ATLAS-CONF-2015-044
CMS-PAS-HIG-002



- **Generic parameterisation of results with ratios**
  - **most model-independent**



BR^{bb}/BR^{ZZ}
deviation more than 2 σ from SM

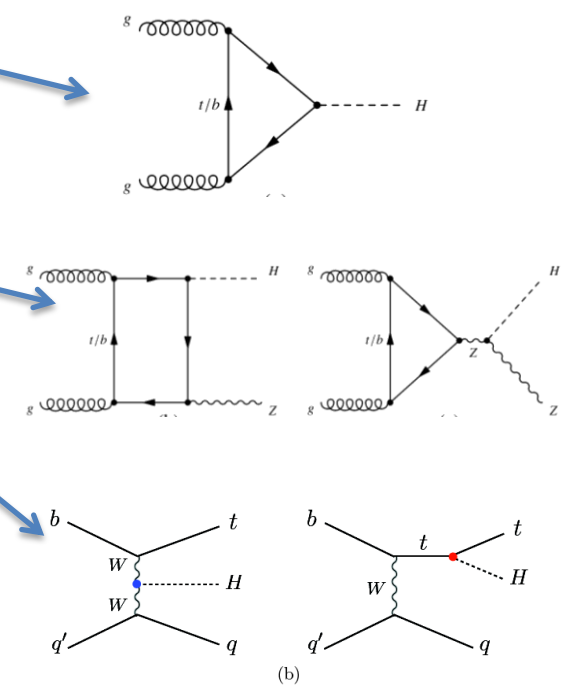


κ Framework (in LHCHXSWG YR4, CERN-2013-004)

- **SM σ and BR's with Yukawa couplings modifiers, κ's**

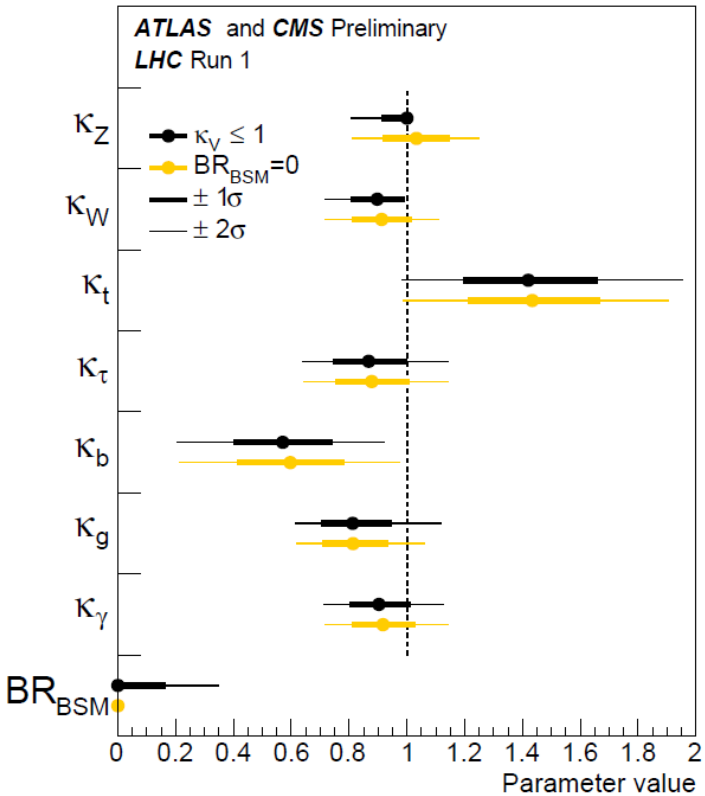
Including higher orders QCD and EWK and EWK, m_h=125.09 GeV

Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $BR_{BSM} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$



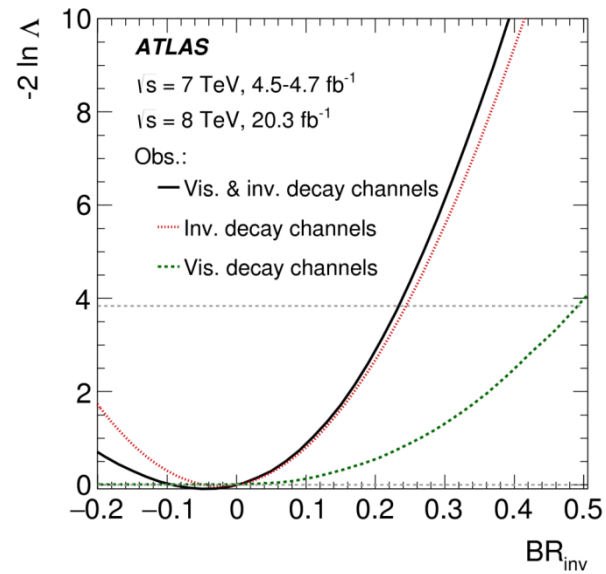
This framework allows to measure compatibility with SM

- **κ parameterisation assuming BSM in loops and in decays**



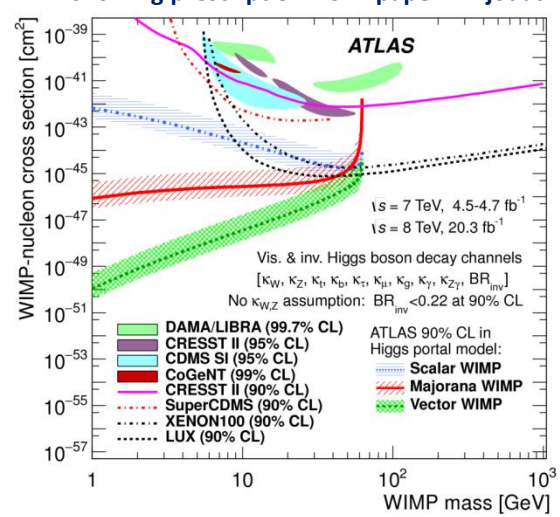
BR_{BSM} < 0.34 at 95% CL (ATLAS+CMS)

- **h(125)->invisible**

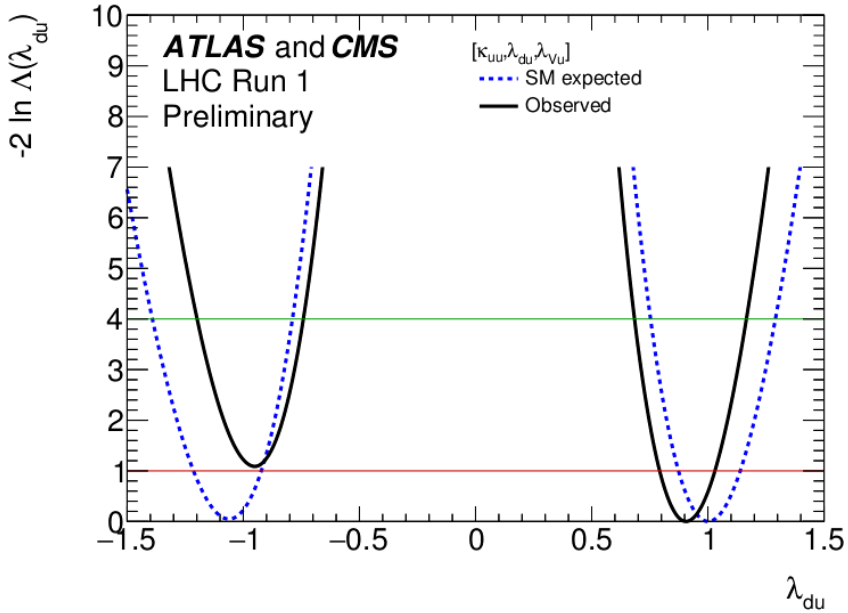


Interpretation in Higgs-portal Dark Matter model

- **following prescription from paper A.Djouadi at al, arXiv:1112.3299**



- **Parameterisation with Yukawa coupling ratios κ_d/κ_u**

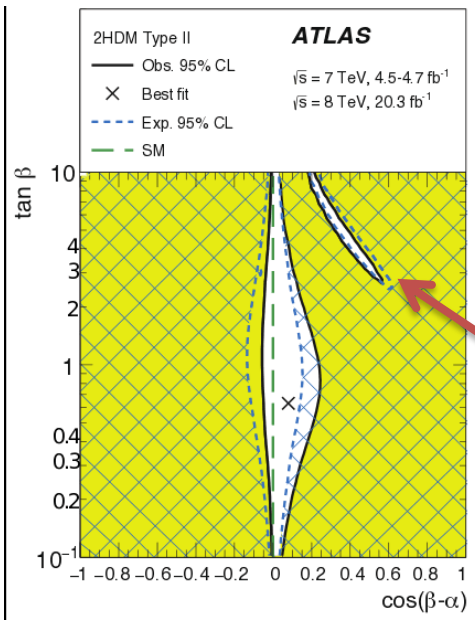


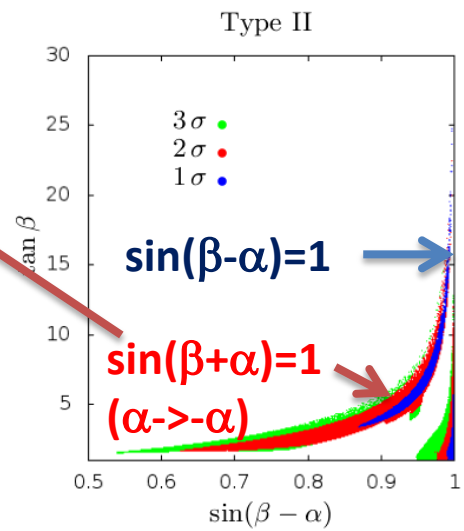
Higgs boson couplings to fermions and bosons in 2HDM

	$h\overline{U}U$	$h\overline{D}D$	$h\overline{E}E$	$H\overline{U}U$	$H\overline{D}D$	$H\overline{E}E$	$iA\overline{U}\gamma_5 U$	$iA\overline{D}\gamma_5 D$	$iA\overline{E}\gamma_5 E$
Type I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$-\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type X	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$-\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-\cot\beta$	$-\tan\beta$	$\cot\beta$

Wrong sign Yukawa Y_{hDD} coupling scenario in 2HDM

- **from h(125) measurements:**





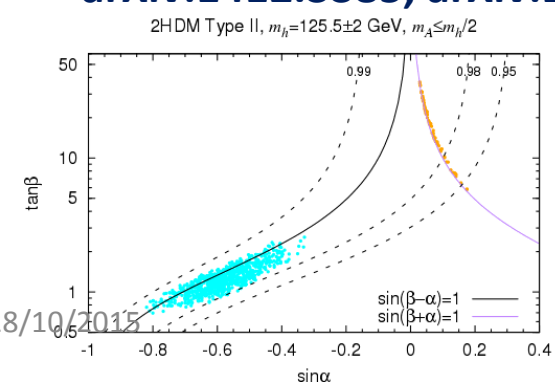
Ferreira et al, arXiv:1410.1926

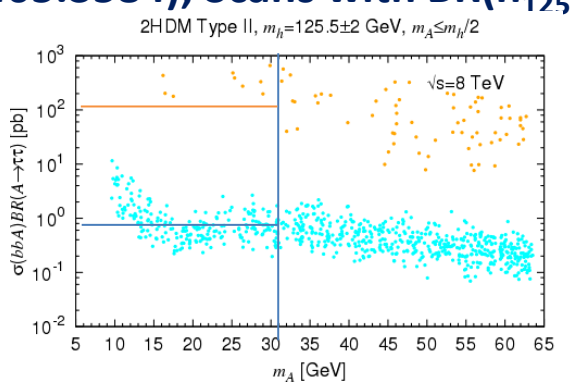
Y_{hDD} = -sinα/cosβ in Type II

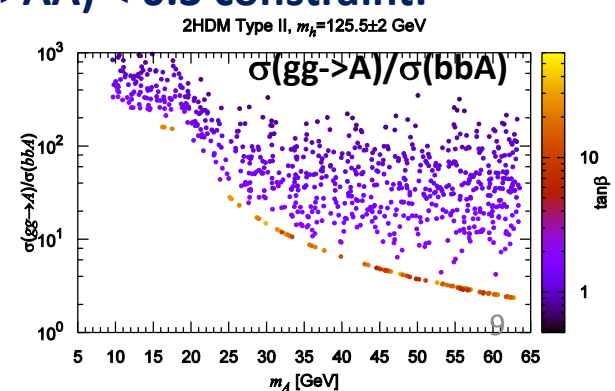
sin(β-α)=1 => SM like limit (alignment): $k_F=k_V=1$

sin(β+α)=1 => k_D=-1 ($k_U=k_V=1$) "wrong sign Y_b limit; can be excluded with ~ 5 % accuracy of h->γγ measurement"

- **bbA, A->ττ (and gg->A, A->ττ) cross-section can be very large in the "wrong sign Yukawa coupling (Y_{hbb}) scenario for the ligh pseudoscalar boson, A (Gunion et al. arXiv:1412.3385, arXiv:1405.3584); Scans with BR(h_{125}->AA) < 0.3 constraint:**



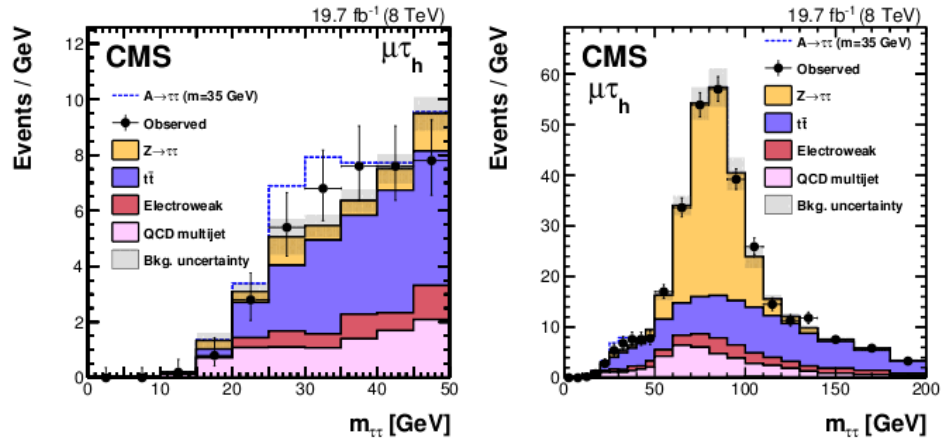


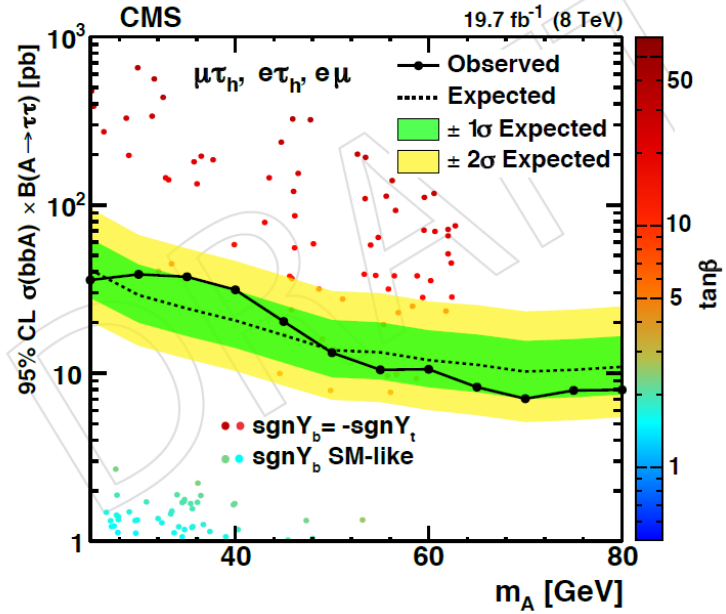


2HDM specific analyses: bbA->ττ

m_h=125 GeV; 24 GeV < m_A < 80 GeV

- **First 8 TeV analysis looking at low mass ττ+b data**
- **Low mass μμ+b analysis at 8 TeV is on the way**
- ***Observation of light A will exclude MSSM***



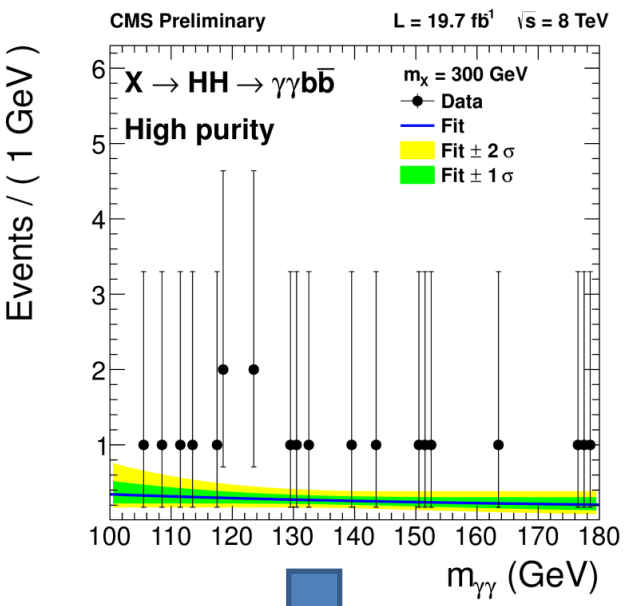


- **wrong sign Yukawa coupling, Y_b scenario is almost excluded for m_A=[24-80] GeV**
- **at Run II low mA analyses, gg->A and H->ZA will be complementary at low tanβ**

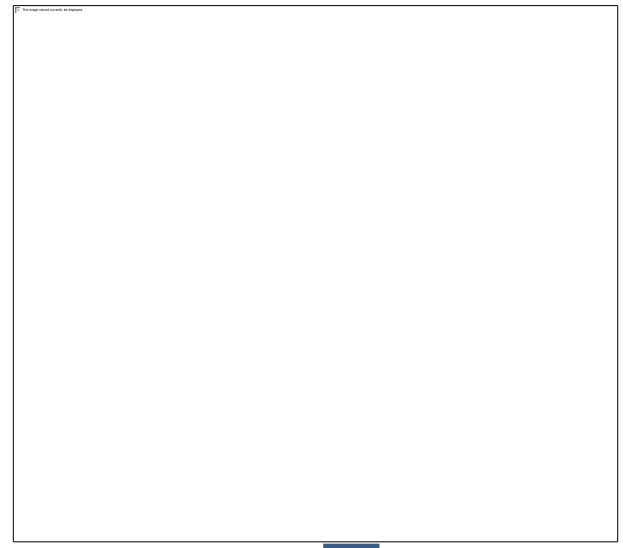
Curiosities in the searches for additional Higgs bosons

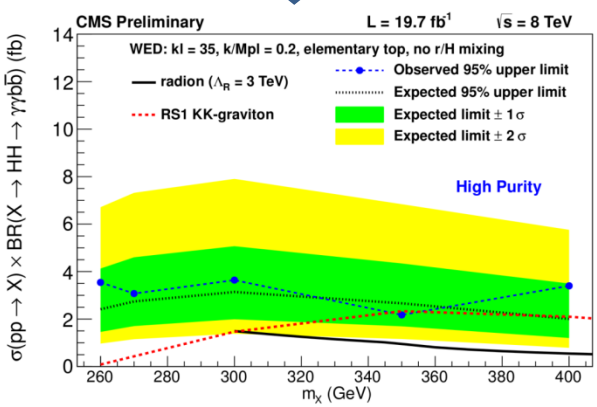
$H \rightarrow hh \rightarrow \gamma\gamma bb$

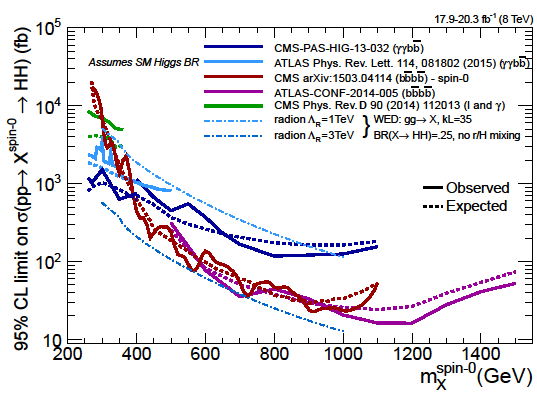
- **CMS search strategy:**
  - looking for signal in $m_{\gamma\gamma}$ distribution for $\gamma\gamma bb$ events selected within m_{bb} and $m_{\gamma\gamma bb}$ mass windows
- **ATLAS search strategy**
  - looking for signal in $\gamma\gamma bb$ mass window for $\gamma\gamma bb$ events selected with $m_{\gamma\gamma}$ and m_{bb} mass windows

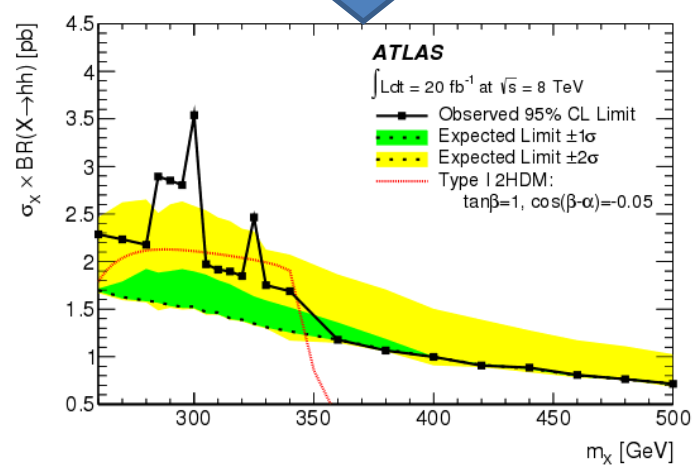


ATLAS:
excess at m_H ~ 300 GeV
Local significance 3.0
with LEE 2.1
CMS:
does not see the excess



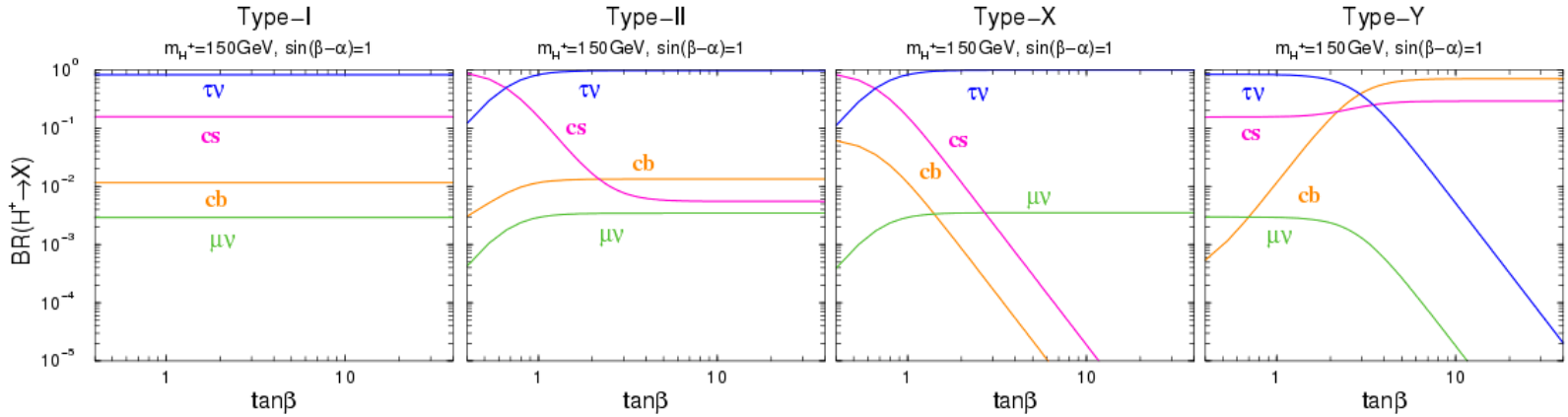


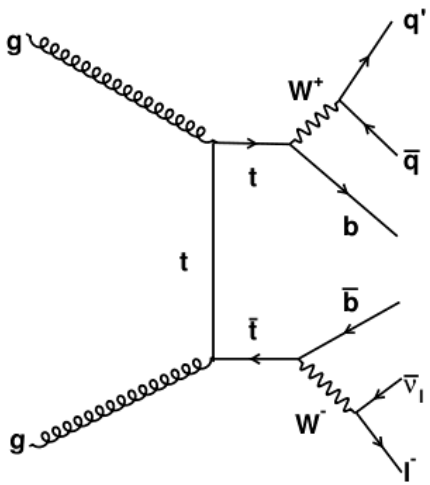


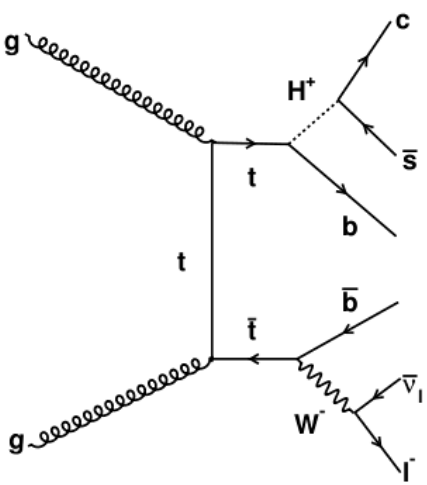


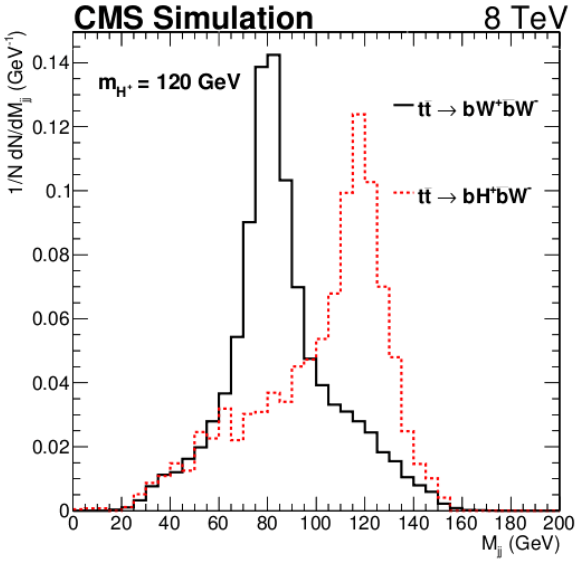
Light charged Higgs boson from top decay, t->H$^+$b with H$^+$->cs decay

BR(H$^+$->cs) in 2HDM, Mayumi Aoki et al, Phys.Rec.D80:015017,2009, arXiv:0902.4665

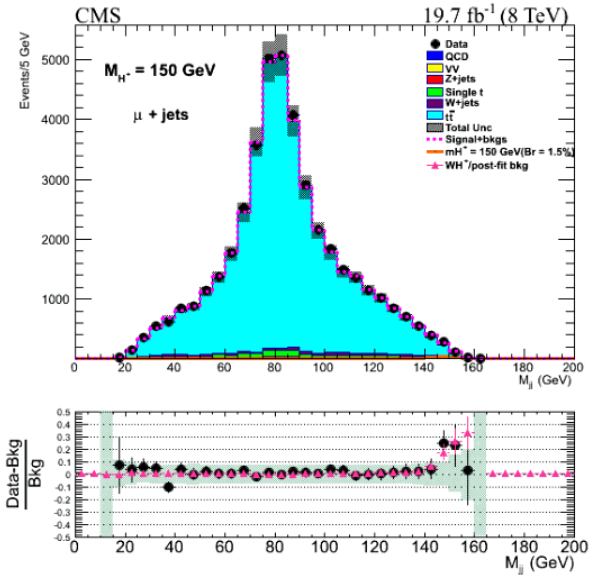




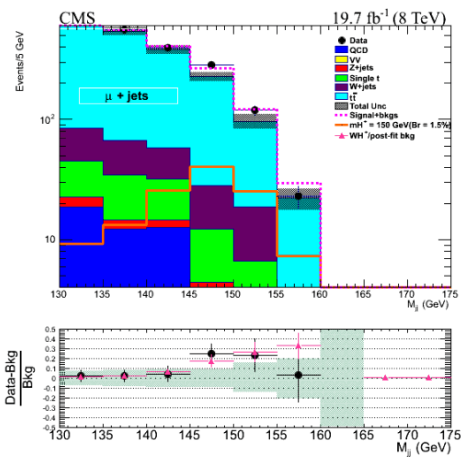


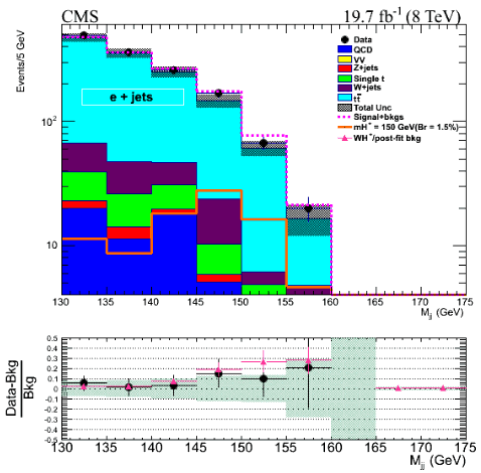


- **No Top mass uncertainty**

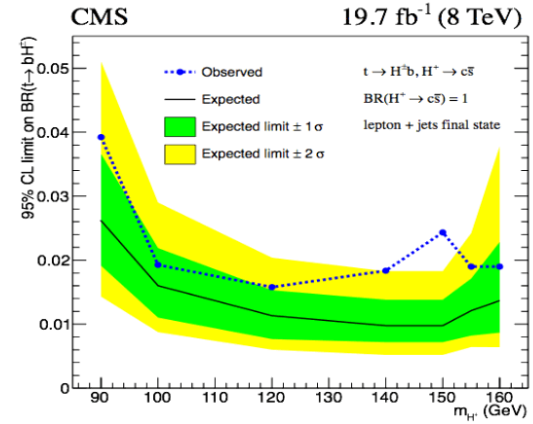


Best fit BR: 0.0153201 -0.00516482/+0.00453616 (68% CL)



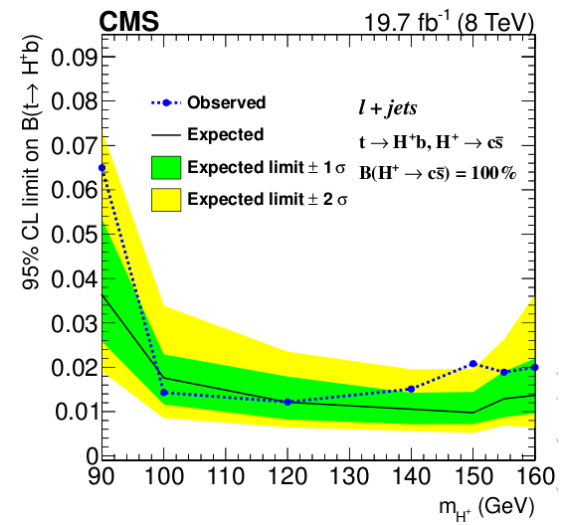


- **No Top mass uncertainty**



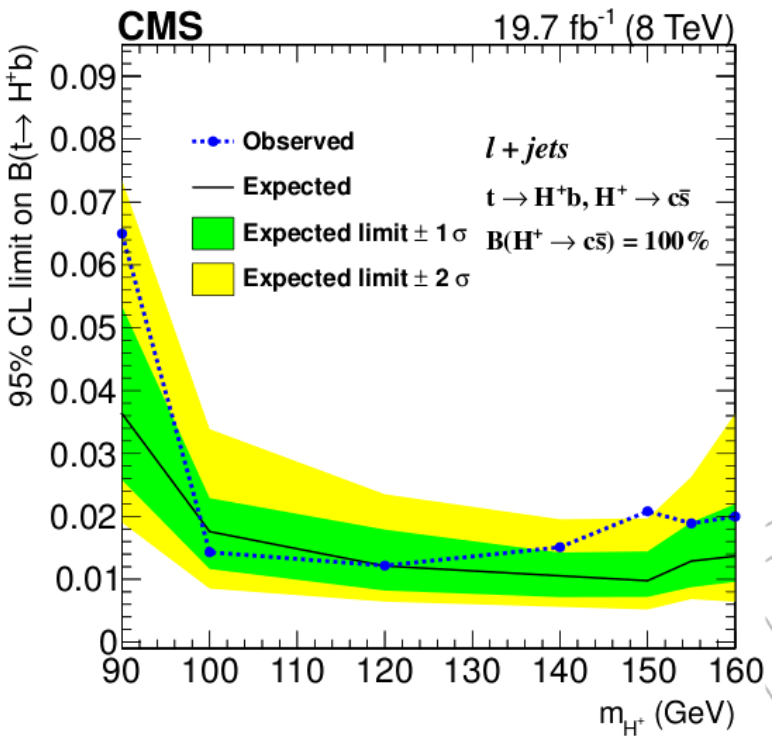
Local significance 2.9; with LEE 2.4

- **with Top mass uncertainty 1 GeV**

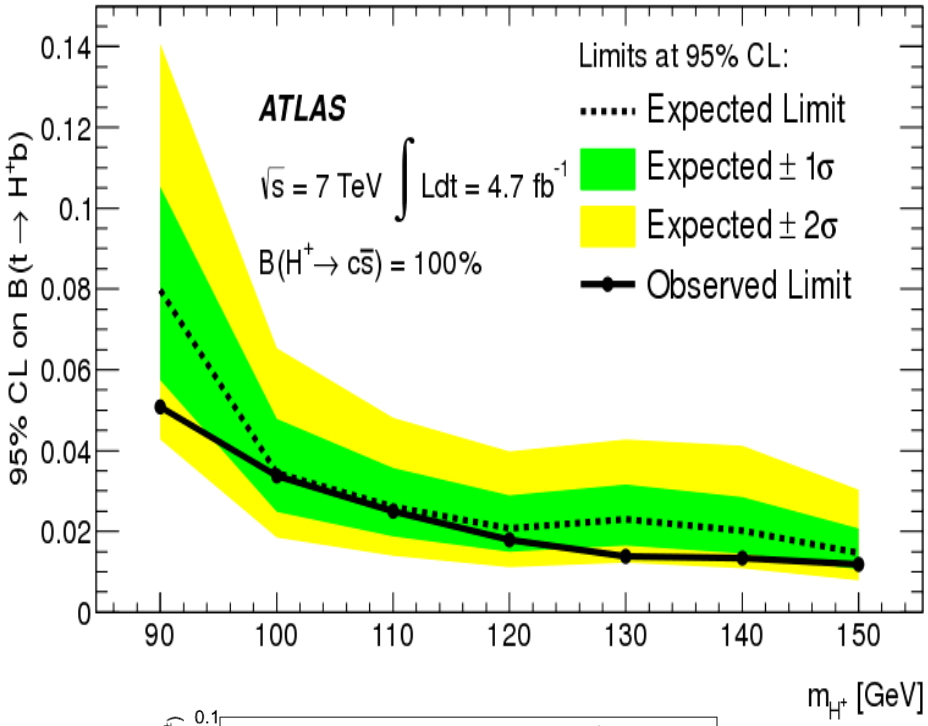


Local significance 2.1; with LEE 1.5
Best fit BR (t->H⁺b)=1.2 %

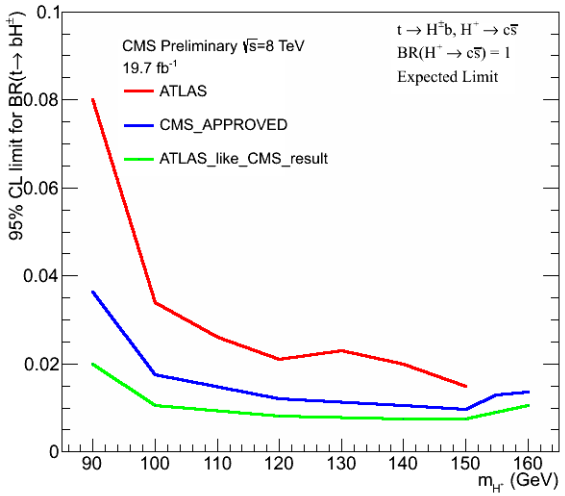
- **CMS result**



- **ATLAS result**



CMS and ATLAS expected limits on one plot

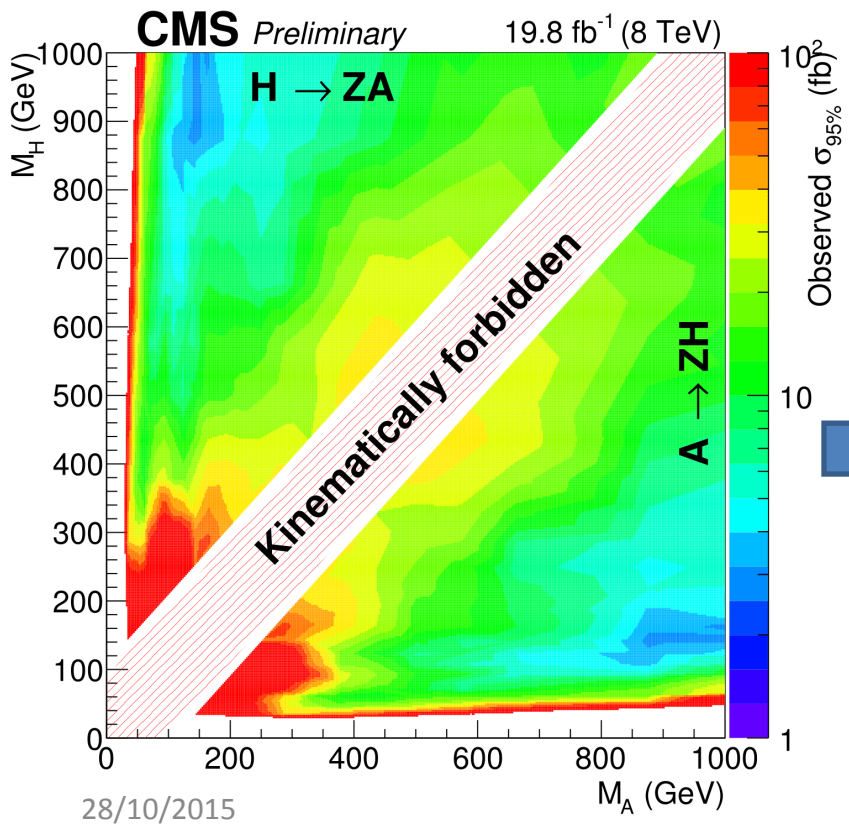


2HDM specific analysis: H->ZA, A->ZH

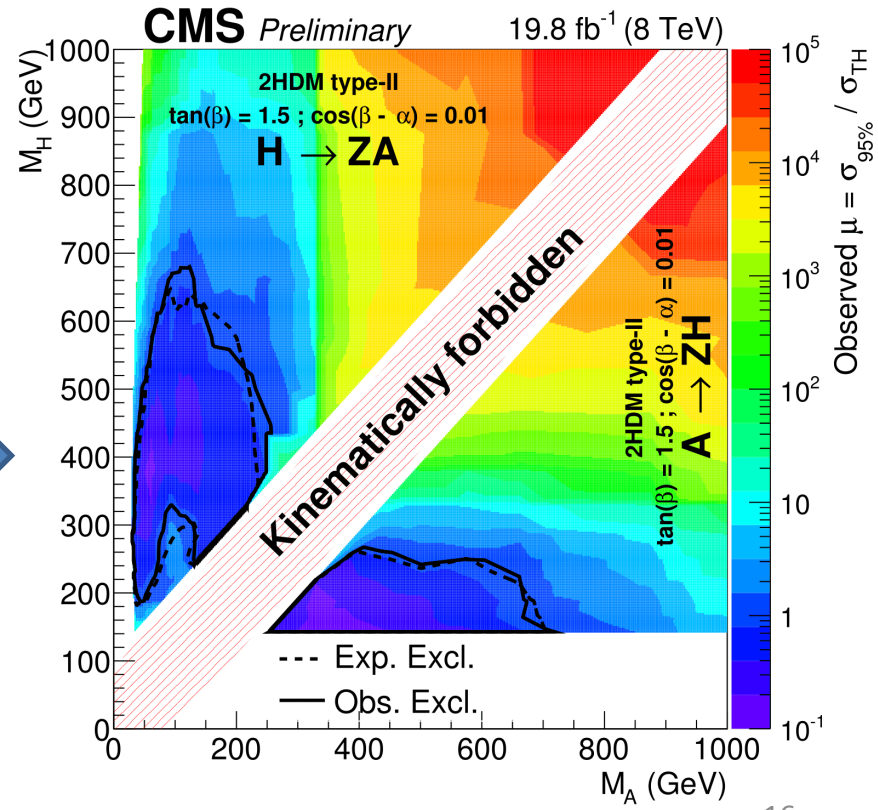
m_h=125 GeV; $m_h < m_H < 1$ TeV, 50 GeV < m_A < 1 TeV

- **Recent CMS H->ZA, A->ZH analysis with $\ell\ell$bb, $\ell\ell\tau\tau$ final states**
- **Limits are shown for $\ell\ell$bb analysis and interpretation in 2HDM assumes m_h=125 GeV ($m_H > m_h$)**

σ x BR observed limit



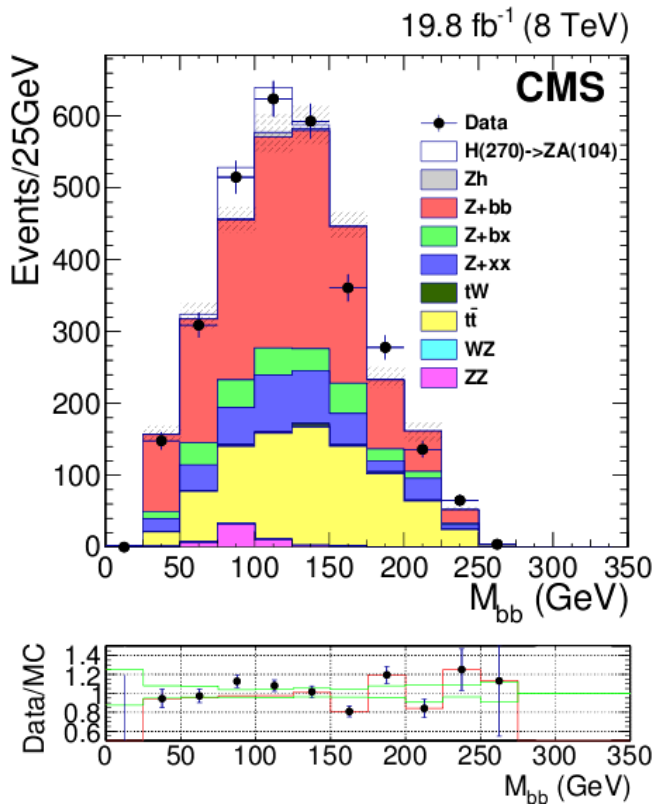
interpretation in 2HDM



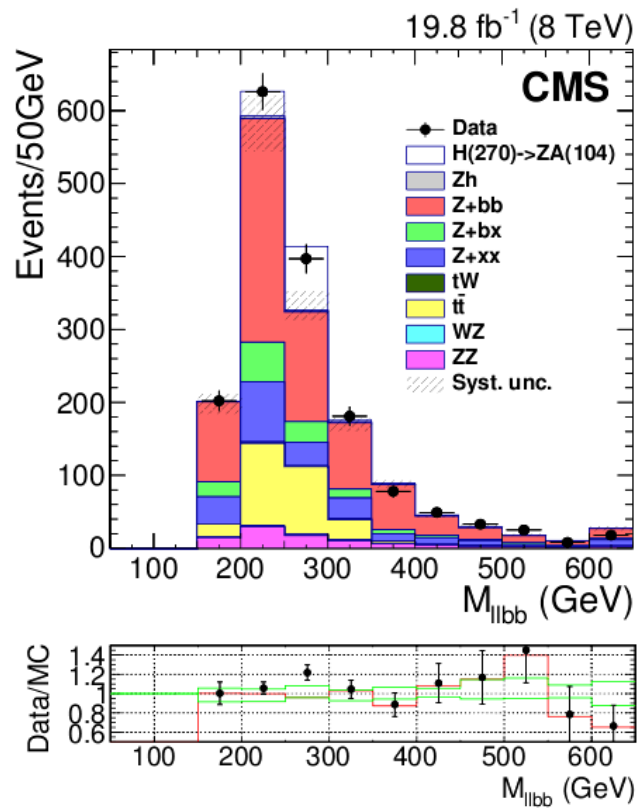
7 Results

Two moderate excesses are observed for the $\ell\ell$bb channel in the region around $(M_{bb}, M_{\ell\ell bb}) = (93, 286)$ GeV and $(M_{bb}, M_{\ell\ell bb}) = (575, 662)$ GeV. They have local significances of 2.6 and 2.85 σ respectively, which become globally 1.6 and 1.9 σ once accounting for the Look Elsewhere Effect [51]. The reconstructed invariant mass distributions for the bb and $\ell\ell$bb final states,

$222 < m_{\ell\ell bb} < 350$ GeV



$72 < m_{bb} < 114$ GeV



h(125)->μτ

arXiv:1202.5704

Flavour-Changing Decays of a 125 GeV Higgs-like Particle

Gianluca Blankenburg[a,b], John Ellis[c,b], Gino Isidori[d,b]

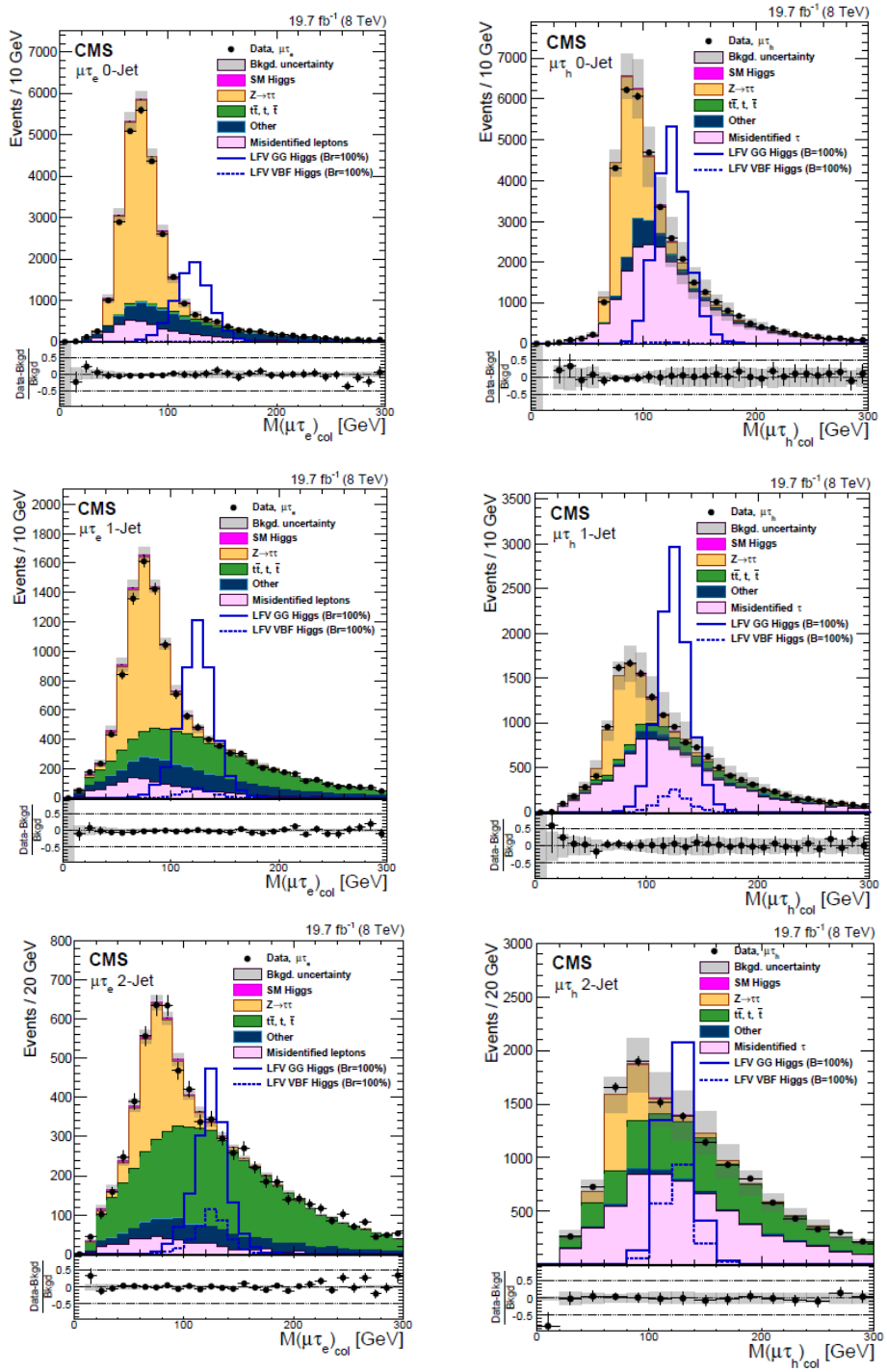
observable at the LHC. On the other hand, the upper limits on lepton-flavour-changing decays are weaker, and the experimental signatures less challenging. In particular, we find that either $\mathcal{B}(h \to \tau\bar{\mu} + \bar{\mu}\tau)$ or $\mathcal{B}(h \to \tau\bar{e} + \bar{e}\tau)$ could be $\mathcal{O}(10)\%$, i.e., comparable to $\mathcal{B}(h \to \tau^+\tau^-)$ and potentially observable at the LHC.

h(125)->$\mu\tau$

CMS analysis: $\mu\tau_e$, $\mu\tau_h$

Event pre-selections

- **Loose event selections**
  - $\mu\tau_e$
    - $p_{T\mu} > 25$ GeV, $|\eta|<2.1$
    - $p_T^e > 10$ GeV, $|\eta|<2.3$
  - $\mu\tau_h$
    - $p_T^\mu > 30$ GeV, $|\eta|<2.1$
    - $p_T^{\tau h} > 30$ GeV, $|\eta|<2.3$
  - Jets, $p_T > 30$ GeV, $|\eta|<4.7$
    - 0, 1, 2 jet bins



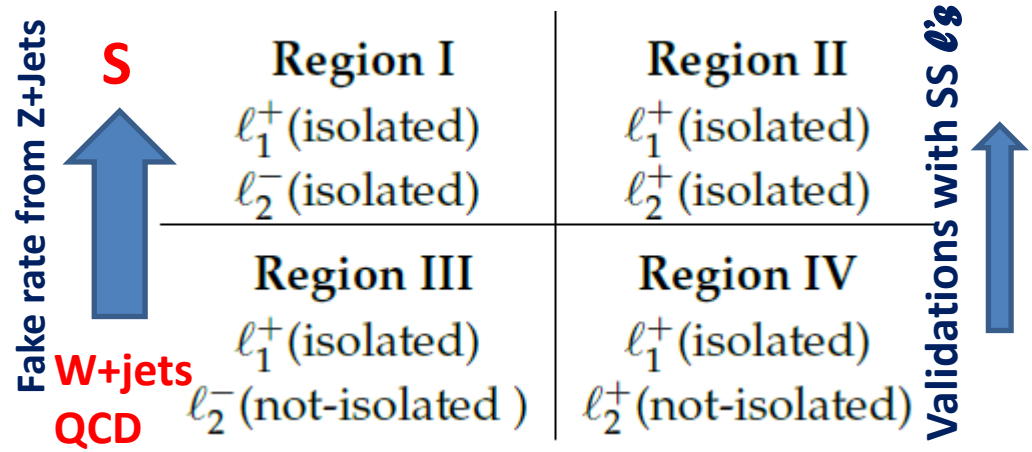
- **Final event selections**
  - **optimized with S/sqrt(S+B)**

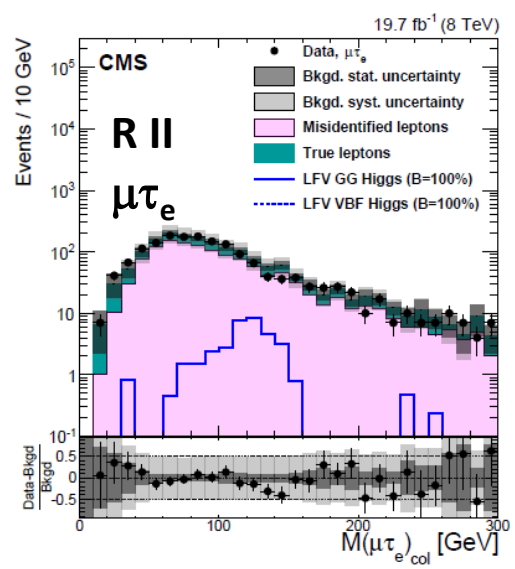
Variable [GeV]	$H \to \mu\tau_e$ 0-jet	1-jet	2-jet	$H \to \mu\tau_h$ 0-jet	1-jet	2-jet
$p_T^\mu >$	50	45	25	45	35	30
$p_T^e >$	10	10	10	—	—	—
$p_T^{\tau_h} >$	—	—	—	35	40	40
$M_T^e <$	65	65	25	—	—	—
$M_T^\mu >$	50	40	15	—	—	—
$M_T^{\tau_h} <$	—	—	—	50	35	35
[radians]						
$\Delta\phi_{\vec{p}_T^\mu - \vec{p}_T^{\tau_h}} >$	—	—	—	2.7	—	—
$\Delta\phi_{\vec{p}_T^e - \vec{E}_T^{miss}} <$	0.5	0.5	0.3	—	—	—
$\Delta\phi_{\vec{p}_T^e - \vec{p}_T^\mu} >$	2.7	1.0	—	—	—	—

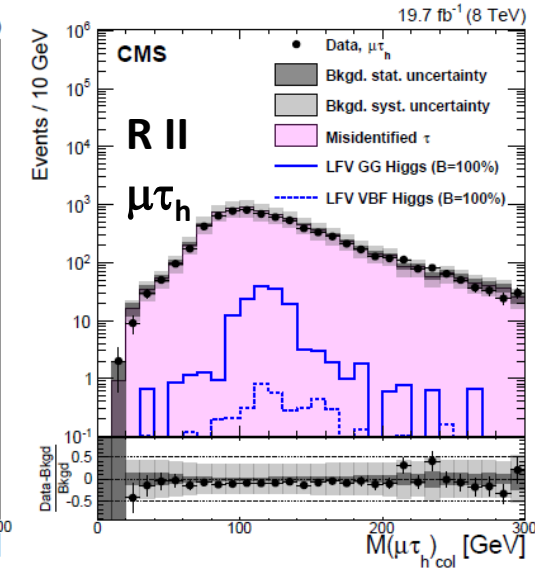
$$M_T^\ell = \sqrt{2 p_T^\ell E_T^{miss} (1 - \cos\Delta\phi_{\vec{p}_T^\ell - \vec{E}_T^{miss}})}.$$

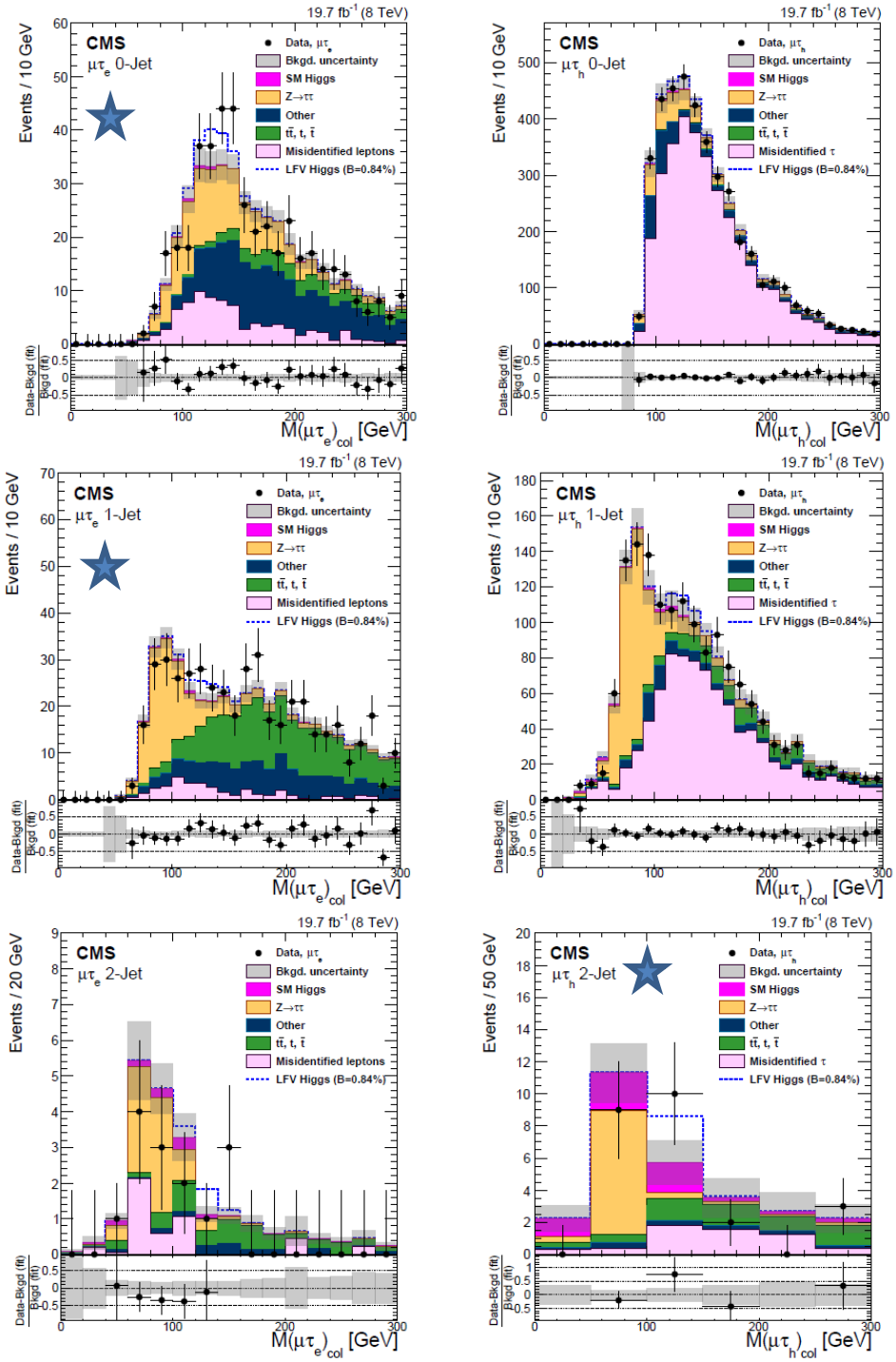
- for 2 jet category:
  $m_{jj} > 550$ GeV, $\Delta\eta_{jj} > 3.5$
  no b-jets in $\mu\tau_e$ channel

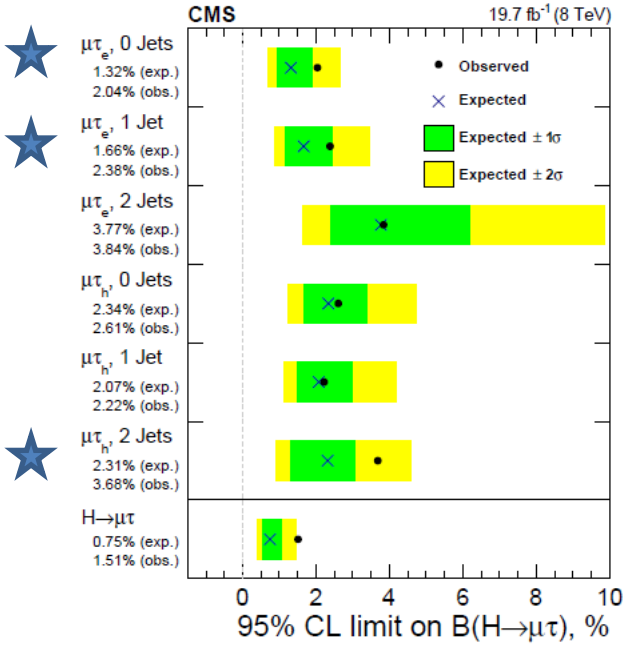
- **Background from miss identified leptons**
  - **W+jets, multijets**

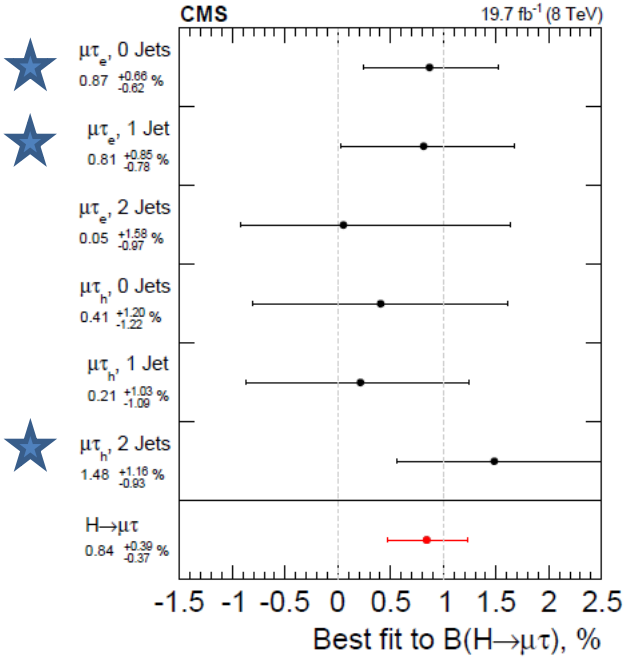






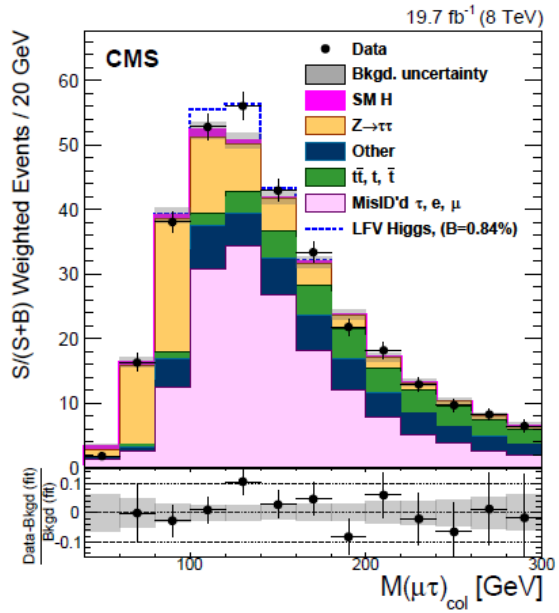

19.7 fb^{-1} (8 TeV)
CMS
$\mu\tau_e$ 0-Jet
$\mu\tau_h$ 0-Jet
$\mu\tau_e$ 1-Jet
$\mu\tau_h$ 1-Jet
$\mu\tau_e$ 2-Jet
$\mu\tau_h$ 2-Jet
Data, $\mu\tau_e$
Data, $\mu\tau_h$
Bkgd. uncertainty
SM Higgs
$Z\to\tau\tau$
Other
$t\bar{t}$, t, $\bar{t}$
Misidentified leptons
Misidentified τ
LFV Higgs (B=0.84%)
Events / 10 GeV
Events / 20 GeV
Events / 50 GeV
Data-Bkgd (fit) / Bkgd (fit)
$M(\mu\tau_e)_{col}$ [GeV]
$M(\mu\tau_h)_{col}$ [GeV]

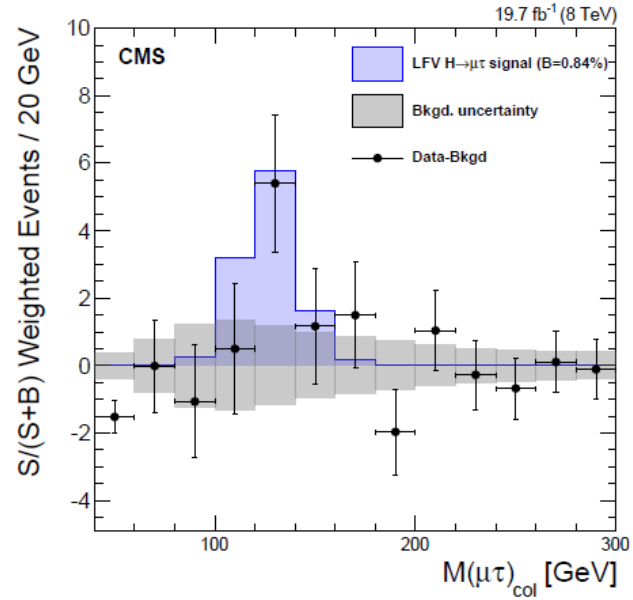

CMS
19.7 fb^{-1} (8 TeV)
$\mu\tau_e$, 0 Jets
1.32% (exp.)
2.04% (obs.)
$\mu\tau_e$, 1 Jet
1.66% (exp.)
2.38% (obs.)
$\mu\tau_e$, 2 Jets
3.77% (exp.)
3.84% (obs.)
$\mu\tau_h$, 0 Jets
2.34% (exp.)
2.61% (obs.)
$\mu\tau_h$, 1 Jet
2.07% (exp.)
2.22% (obs.)
$\mu\tau_h$, 2 Jets
2.31% (exp.)
3.68% (obs.)
$H\to\mu\tau$
0.75% (exp.)
1.51% (obs.)
Observed
Expected
Expected $\pm 1\sigma$
Expected $\pm 2\sigma$
95% CL limit on $B(H\to\mu\tau)$, %


CMS
19.7 fb^{-1} (8 TeV)
$\mu\tau_e$, 0 Jets
0.87 $^{+0.66}_{-0.62}$ %
$\mu\tau_e$, 1 Jet
0.81 $^{+0.85}_{-0.78}$ %
$\mu\tau_e$, 2 Jets
0.05 $^{+1.58}_{-0.97}$ %
$\mu\tau_h$, 0 Jets
0.41 $^{+1.20}_{-1.22}$ %
$\mu\tau_h$, 1 Jet
0.21 $^{+1.03}_{-1.09}$ %
$\mu\tau_h$, 2 Jets
1.48 $^{+1.16}_{-0.93}$ %
$H\to\mu\tau$
0.84 $^{+0.39}_{-0.37}$ %
Best fit to $B(H\to\mu\tau)$, %

CMS result on h(125)->μτ search

Excess significance
2.4
(p=0.010)



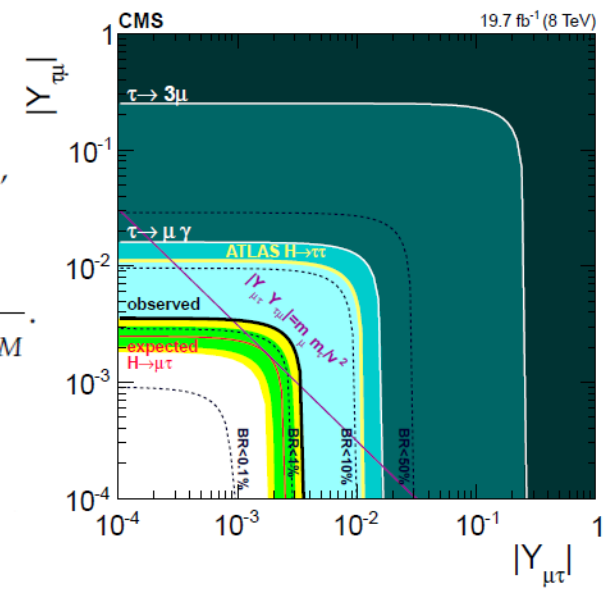


	Expected Limits		
	0-Jet (%)	1-Jet (%)	2-Jets (%)
$\mu\tau_e$	<1.32 (±0.67)	<1.66 (±0.85)	<3.77 (±1.92)
$\mu\tau_h$	<2.34 (±1.19)	<2.07 (±1.06)	<2.31 (±1.18)
$\mu\tau$	<0.75 (±0.38)		
	Observed Limits		
$\mu\tau_e$	<2.04	<2.38	<3.84
$\mu\tau_h$	<2.61	<2.22	<3.68
$\mu\tau$	<1.51		
	Best Fit Branching Fractions		
$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_h$	$0.41^{+1.20}_{-1.22}$	$0.21^{+1.03}_{-1.09}$	$1.48^{+1.16}_{-0.93}$
$\mu\tau$	$0.84^{+0.39}_{-0.37}$		

$$\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{m_\mathrm{H}}{8\pi}\left(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2\right),$$

$$B(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta)}{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) + \Gamma_{SM}}.$$

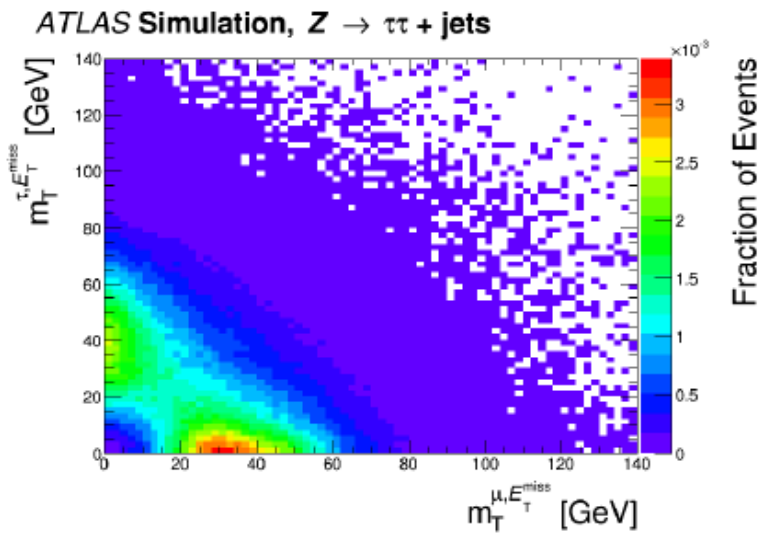
$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}.$$

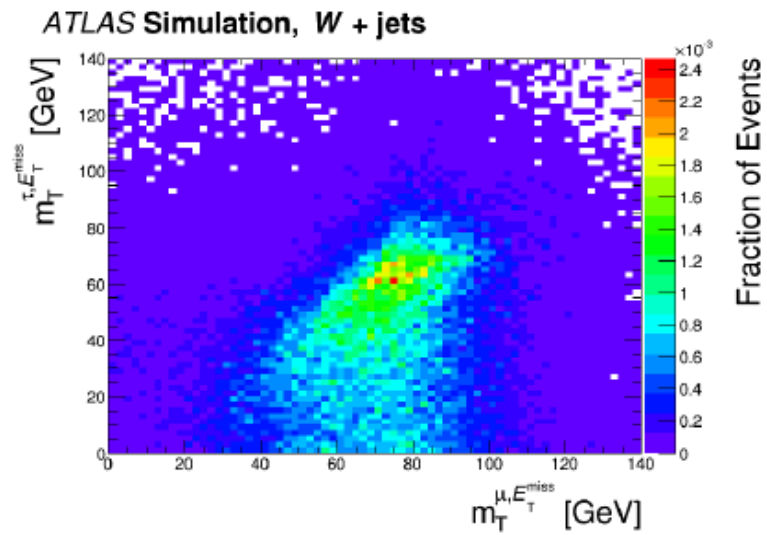


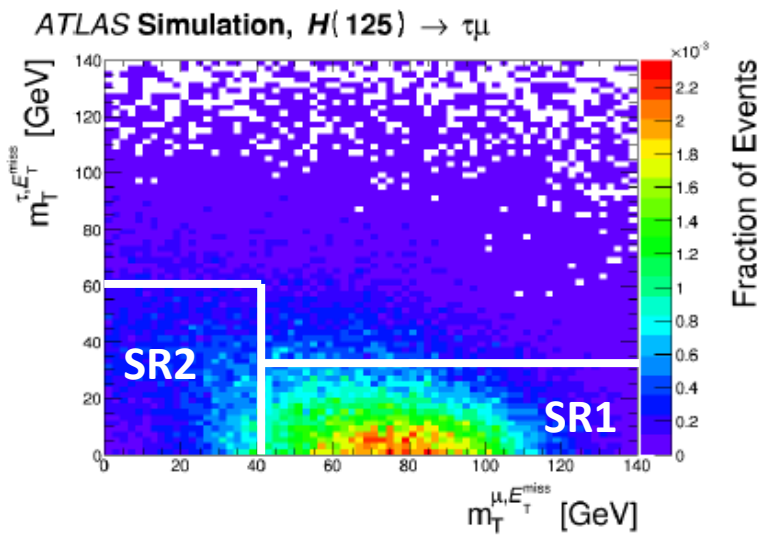
h(125)->$\mu\tau$

ATLAS analysis: $\mu\tau_h$

Signal and control regions







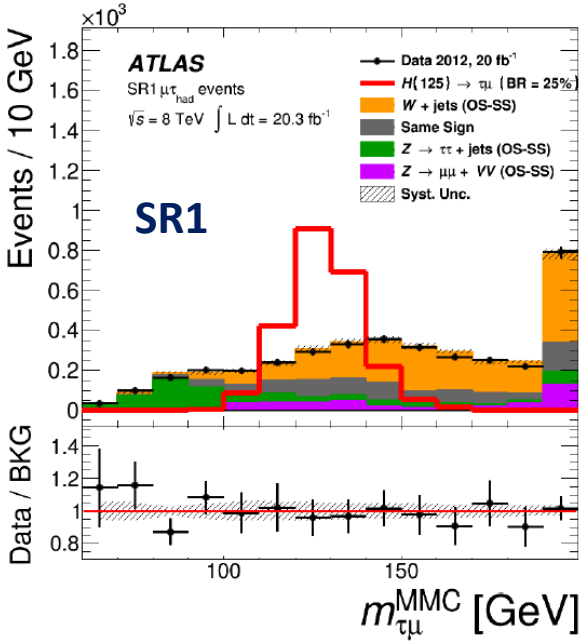
			W	Top
Cut	SR1	SR2	WCR	TCR
$p_T(\mu)$	>26 GeV	>26 GeV	>26 GeV	>26 GeV
$p_T(\tau_{had})$	>45 GeV	>45 GeV	>45 GeV	>45 GeV
$m_T(\mu, E_T^{miss})$	>40 GeV	<40 GeV	>60 GeV	–
$m_T(\tau_{had}, E_T^{miss})$	<30 GeV	<60 GeV	>40 GeV	–
$\lvert\eta(\mu) - \eta(\tau_{had})\rvert$	<2	<2	<2	<2
N_{jet}	–	–	–	>1
N_{b-jet}	0	0	0	>0

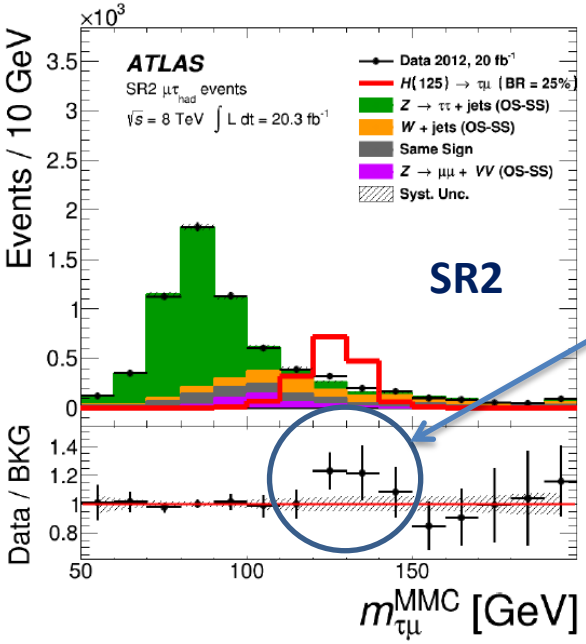
- **multijet background estimation with Same Sign data**

$$N_{\mathrm{OS}}^{\mathrm{bkg}} = r_{\mathrm{QCD}} \cdot N_{\mathrm{SS}}^{\mathrm{data}} + N_{\mathrm{OS-SS}}^{Z\to\tau\tau} + N_{\mathrm{OS-SS}}^{Z\to\mu\mu} + N_{\mathrm{OS-SS}}^{W+\mathrm{jets}} + N_{\mathrm{OS-SS}}^{\mathrm{top}} + N_{\mathrm{OS-SS}}^{VV} + N_{\mathrm{OS-SS}}^{H\to\tau\tau},$$

$$N_{\mathrm{OS-SS}}^{\mathrm{bkg}-i} = N_{\mathrm{OS}}^{\mathrm{bkg}-i} - r_{\mathrm{QCD}} \cdot N_{\mathrm{SS}}^{\mathrm{bkg}-i} \qquad r_{\mathrm{QCD}} = N_{\mathrm{OS}}^{\mathrm{multi-jet}} / N_{\mathrm{SS}}^{\mathrm{multi-jet}} \qquad r_{\mathrm{QCD}} = 1.10 \pm 0.14$$

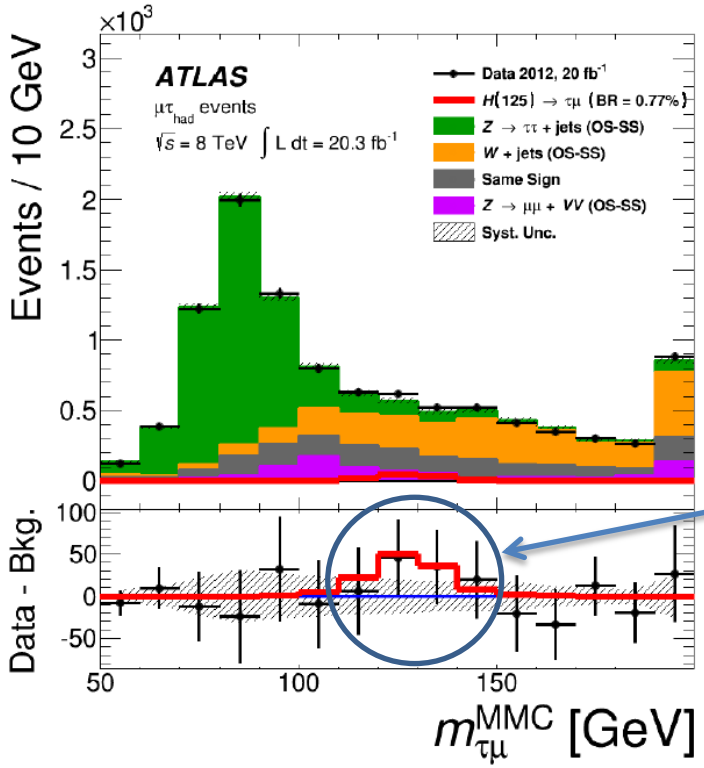
- **$\mu\tau_h$ mass in Signal Region 1 and 2**





Local significance 2.2 standard deviations

ATLAS result on h(125)->μτ search



Local significance 2.2 standard deviations

	SR1	SR2	Combined
Expected limit on Br($H \to \mu\tau$) [%]	$1.60^{+0.64}_{-0.45}$	$1.75^{+0.71}_{-0.49}$	$1.24^{+0.50}_{-0.35}$
Observed limit on Br($H \to \mu\tau$) [%]	1.55	3.51	1.85
Best fit Br($H \to \mu\tau$) [%]	$-0.07^{+0.81}_{-0.86}$	$1.94^{+0.92}_{-0.89}$	0.77 ± 0.62

Conclusions

- **Not everything is "compatible with SM" in the h(125) measurements**
  - **$BR_{bb/}BR_{ZZ}$ is outside of two σ**
- **Excited excesses in the searches for**
  - **H^+->cs, H->ZA, h->$\tau\mu$**
- **Will be carefully looked at it again with Run II analyses**

THE END