



Experimental Overview Of Flavor-changing And Non-standard Flavor-diagonal Higgs Boson Decays

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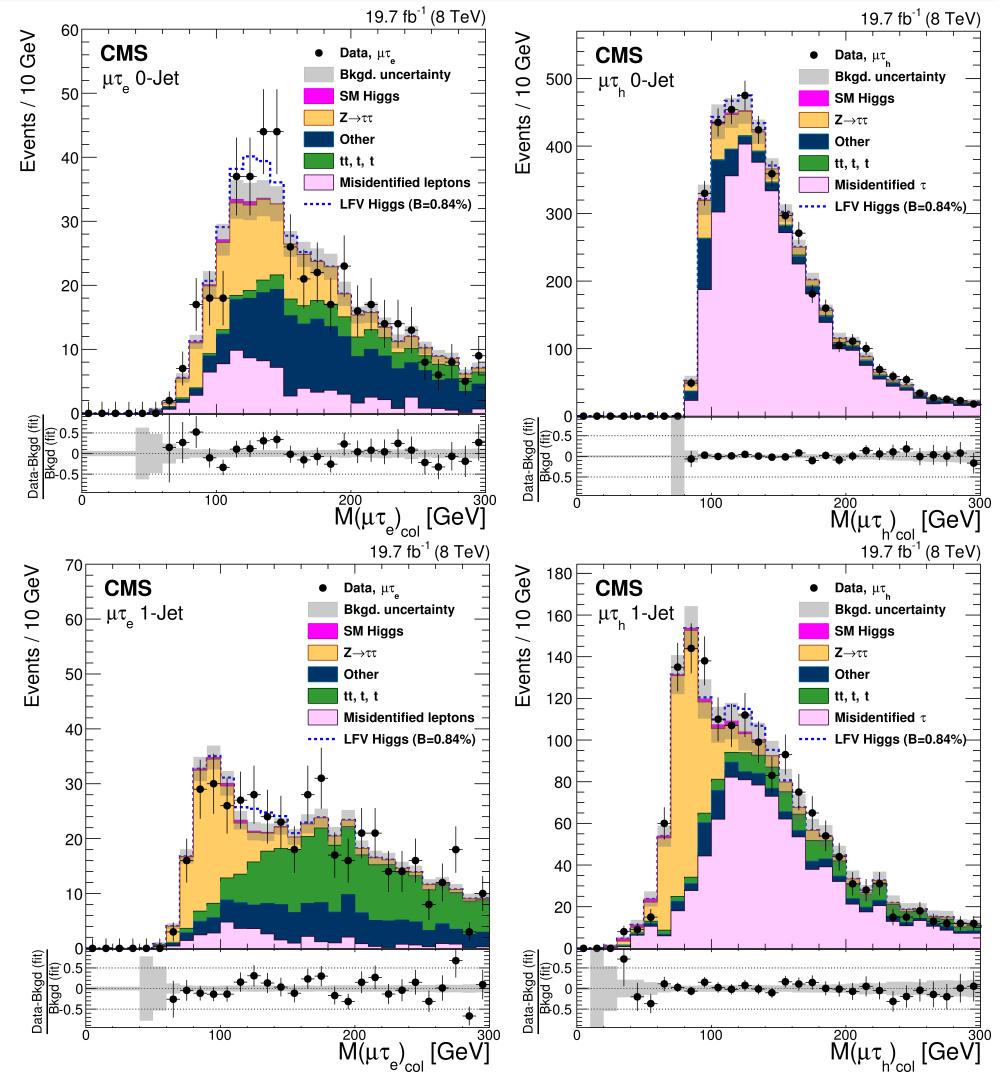
Lepton Flavor Violation (LFV)

- Lepton and baryon numbers are conserved symmetries in SM, but SM is only an effective theory which describes physics at EWK scale
- (Neutral) Lepton flavor violation exists in Nature: neutrino oscillations
- A number of models beyond SM predict LFV in charged sector at levels observable at LHC
 - RPV SUSY
 - Models with more than one Higgs doublet
 - Composite Higgs models
 - Randall-Sundrum models
 - Models with warped extra dimensions
 - Models with Majorana neutrinos
 - Theories with Grand Unification

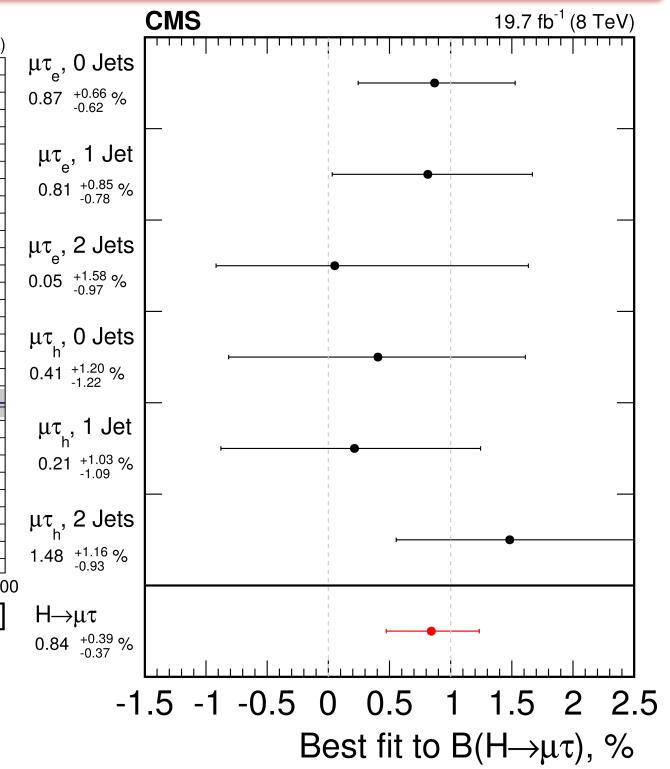
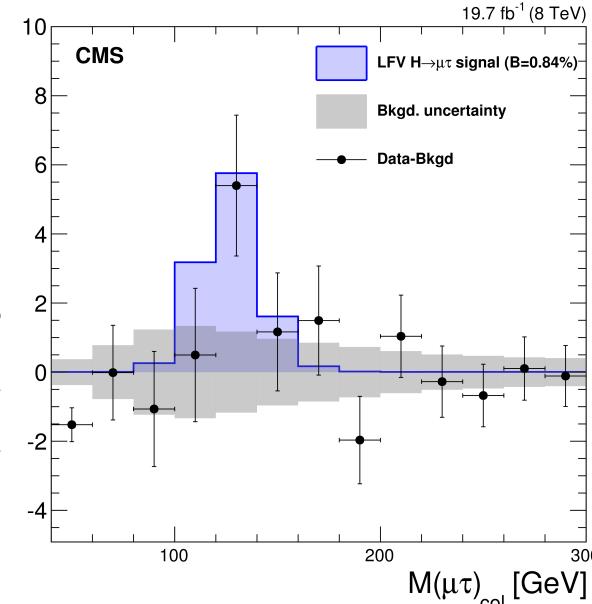
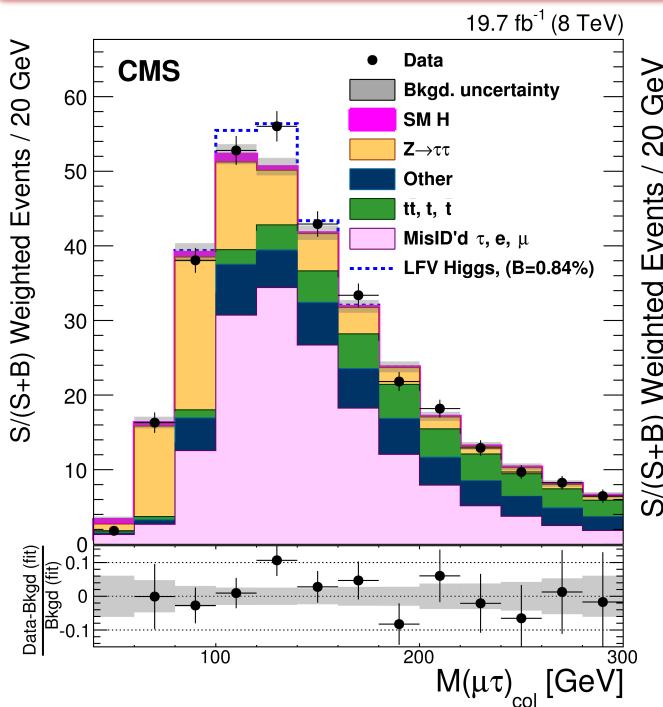
CMS Search For LFV $H \rightarrow \mu\tau$: Analysis Overview

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

- Two channels: $H \rightarrow \mu\tau(\rightarrow e)$ and $H \rightarrow \mu\tau(\rightarrow \text{hadrons})$
- 3 categories per channel
 - 0-jet, 1-jet, VBF-like 2-jet
- Dominant backgrounds
 - $Z \rightarrow \tau\tau$, VV, ttbar, events with fake τ_{had}
- Leading systematics: modeling of backgrounds with fakes (30-40%)



CMS Search For LFV $H \rightarrow \mu\tau$: Results



arXiv: 1502.07400

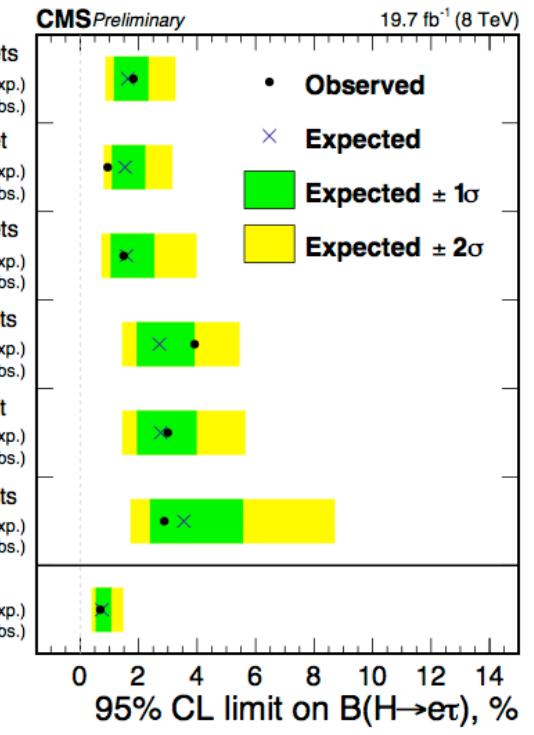
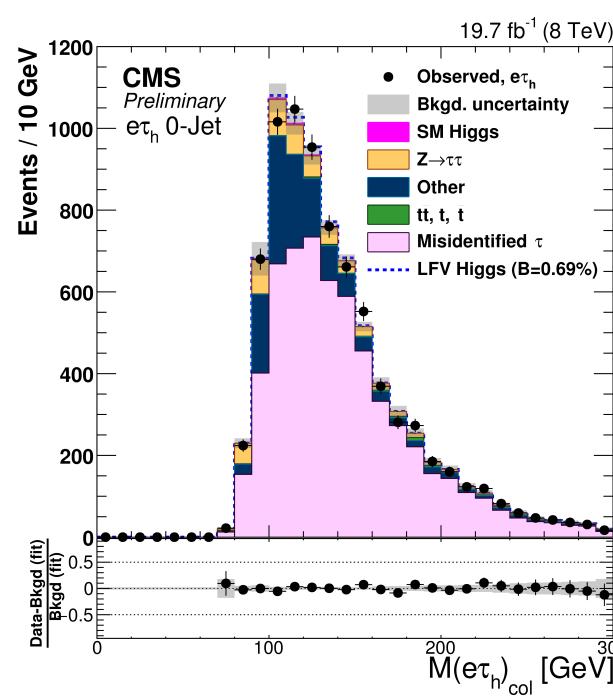
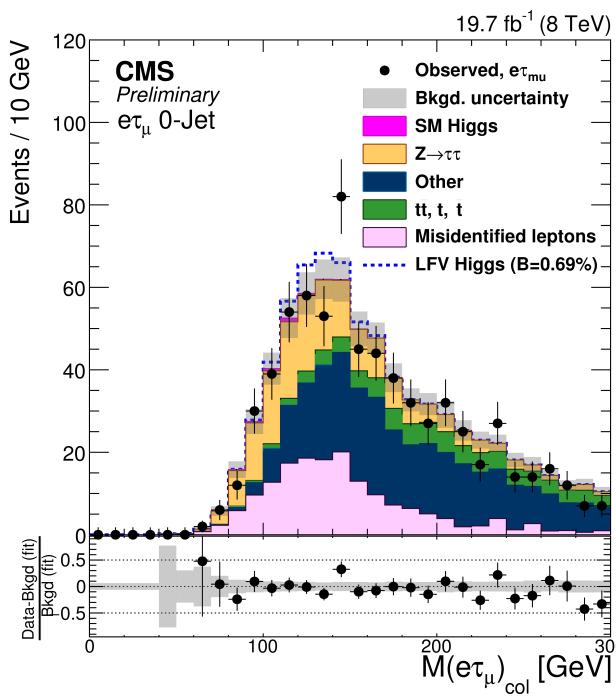
PLB749, 337

- **Observe 2.4σ excess**
 - Excesses ($\sim 1\sigma$) are observed in 3 out of 6 categories
 - Best fit $\text{Br}(H \rightarrow \mu\tau) = (0.84^{+0.39}_{-0.37})\%$
 - Observed (expected) 95% CL limit is $\text{Br}(H \rightarrow \mu\tau) < 1.51\%$ ($< 0.75\% \pm 0.38\%$)

CMS Search For LFV $H \rightarrow e\tau$

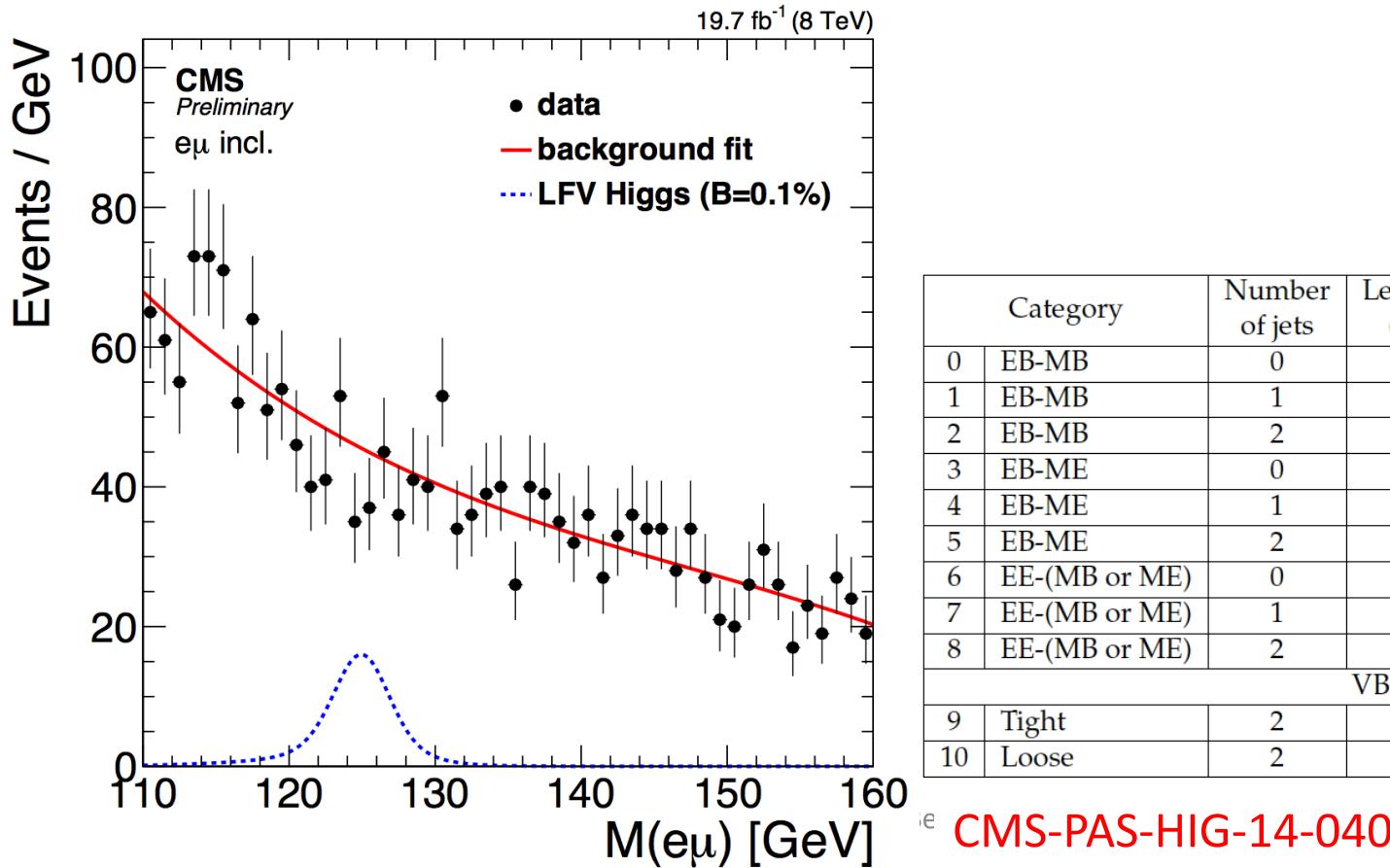
- Two channels: $H \rightarrow e\tau(\rightarrow \mu)$ and $H \rightarrow e\tau(\rightarrow \text{hadrons})$
- Event selection, analysis categories and techniques are almost the same as in the $H \rightarrow \mu\tau$ search
- Major backgrounds: fake leptons/ τ_{had} , $Z \rightarrow \tau\tau/\text{ee}/\mu\mu$
- **No excess observed: 95% CL limit is $\text{Br}(H \rightarrow e\tau) < 0.69\%$**
 - Expected limit: $\text{Br}(H \rightarrow e\tau) < (0.75^{+0.32}_{-0.22})\%$

CMS-PAS-HIG-14-040



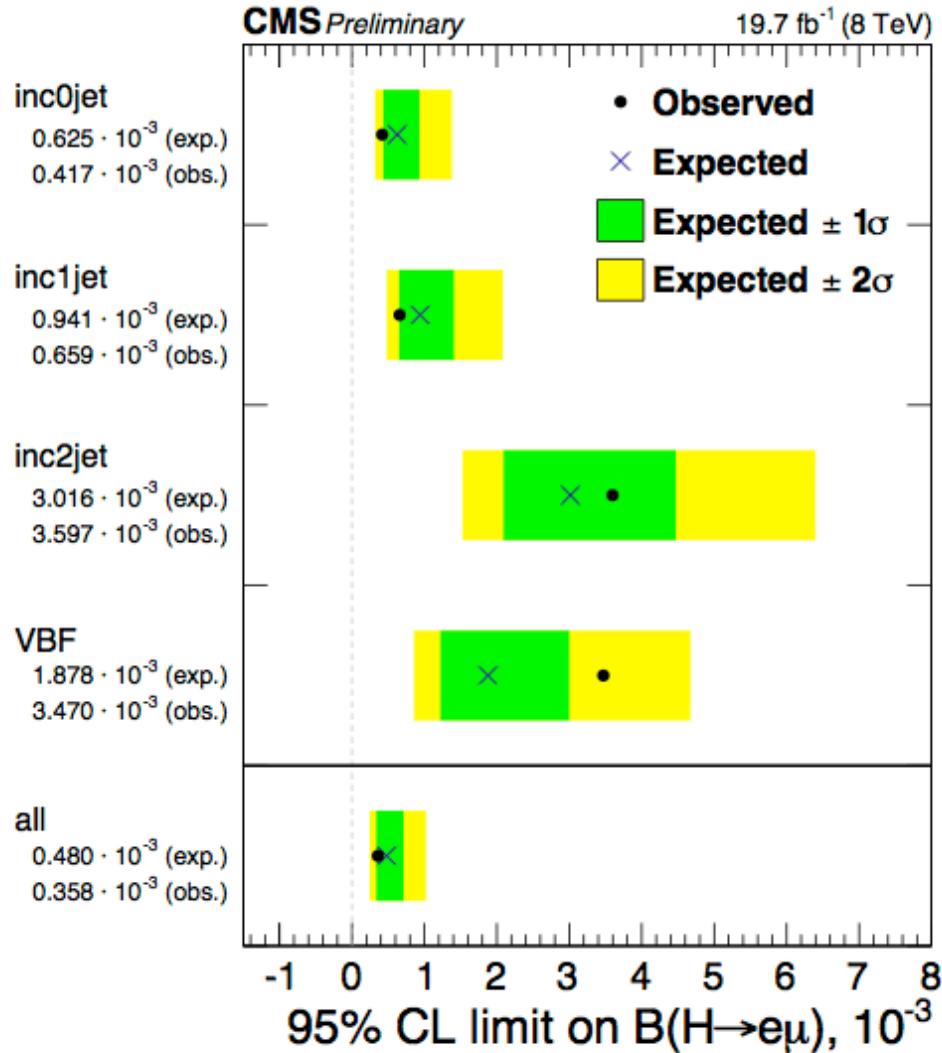
CMS Search For LFV $H \rightarrow e\mu$: Analysis Overview

- 11 analysis categories (including 2 VBF categories)
 - Approach similar to $H \rightarrow \gamma\gamma$ analysis
- Fit $M_{e\mu}$ distribution is fitted with analytic function
 - Background: polynomial, power law, exponential (depending on category)
 - Signal: sum of two Gaussians



Category		Number of jets	Lepton p_T (GeV)	E_T^{miss} (GeV)	B-tag
0	EB-MB	0	> 25	< 30	-
1	EB-MB	1	> 22	< 30	< 0.38
2	EB-MB	2	> 25	< 25	$< 0.38, < 0.48$
3	EB-ME	0	> 20	< 30	-
4	EB-ME	1	> 22	< 20	< 0.48
5	EB-ME	2	> 20	< 30	$< 0.51, < 0.57$
6	EE-(MB or ME)	0	> 20	< 30	-
7	EE-(MB or ME)	1	> 22	< 20	< 0.48
8	EE-(MB or ME)	2	> 20	< 30	$< 0.51, < 0.57$
VBF					
9	Tight	2	> 22	< 30	$< 0.58, < 0.244$
10	Loose	2	> 22	< 25	$< 0.62, < 0.30$

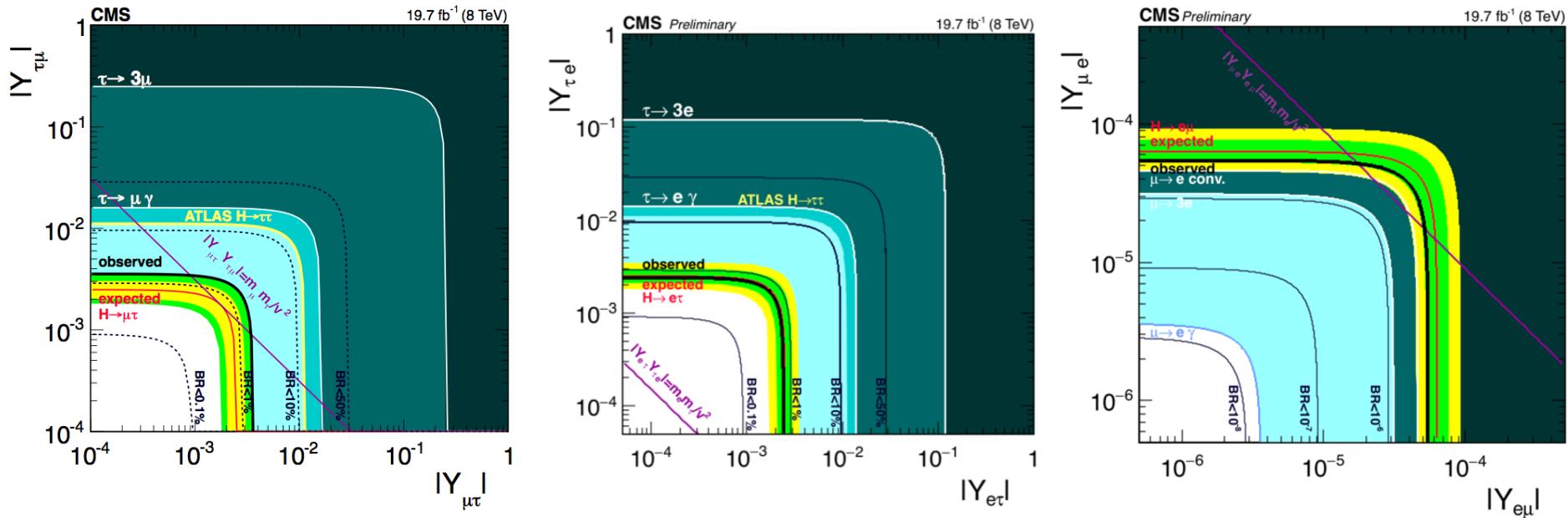
CMS Search For LFV $H \rightarrow e\mu$: Results



- 0-jet categories have largest sensitivity, followed by events with 1-jet
- **No excess observed: 95% CL limit is $\text{Br}(H \rightarrow e\mu) < 0.358 \times 10^{-3}$**
 - Indirect constraint based on experimental bounds on $\mu \rightarrow e\gamma$: $\text{Br}(H \rightarrow e\mu) < O(10^{-8})$

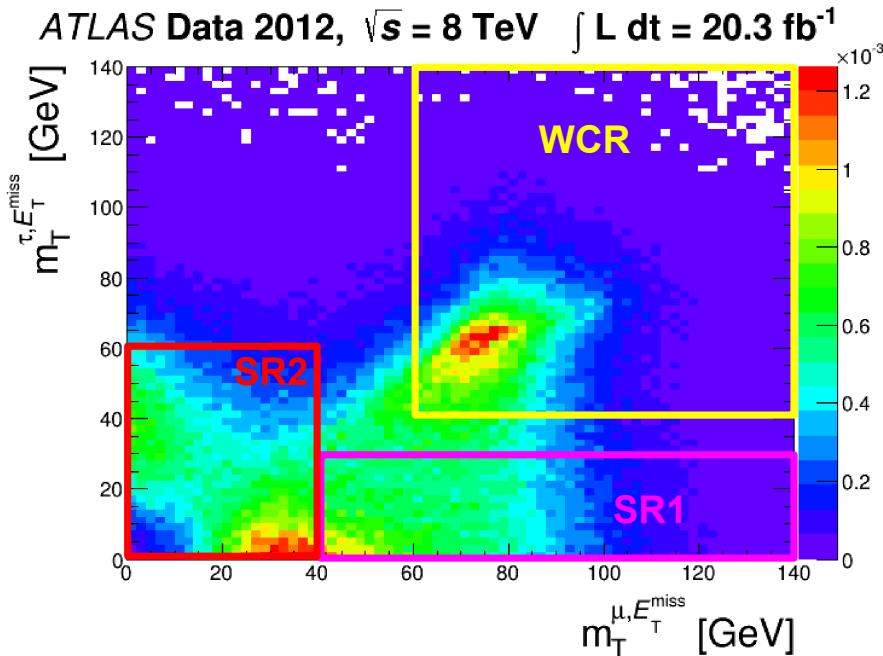
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CMS Search For LFV Higgs Boson Decays

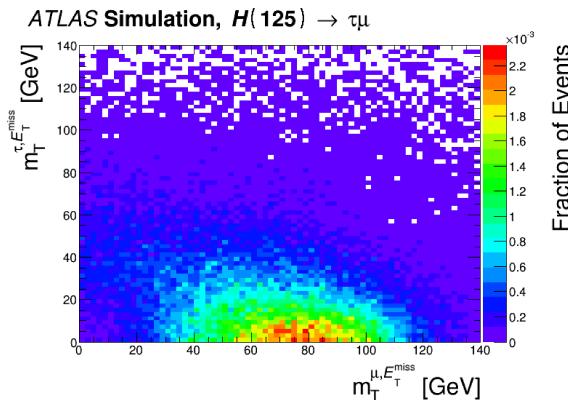


- **Limits on lepton-flavor-violating Yukawa couplings**
 - Naturalness limit $|Y_{ij} Y_{ji}| < m_i m_j / v^2$
 - Direct $H \rightarrow \mu\tau$ and $H \rightarrow e\tau$ searches provide most stringent constraints
 - Searches for $H \rightarrow \mu\tau$ decays already probe phenomenologically interesting region
 - Experimental results in $\mu \rightarrow e\gamma$ searches provides most stringent indirect constraint on $|Y_{e\mu} Y_{\mu e}|$

ATLAS Search For LFV $H \rightarrow \mu\tau$: Analysis Overview



- Events with $P_T(\mu) > 26 \text{ GeV}$ and $P_T(\tau_{\text{had}}) > 45 \text{ GeV}$
 - Two signal regions based on $M_T(\text{MET}, \mu)$ and $M_T(\text{MET}, \tau_{\text{had}})$
- Major backgrounds: $W + \text{jets}$ and $Z \rightarrow \tau\tau$
- Major uncertainty: normalization of $W + \text{jets}$ and $Z \rightarrow \tau\tau$ and modeling of $W + \text{jets}$

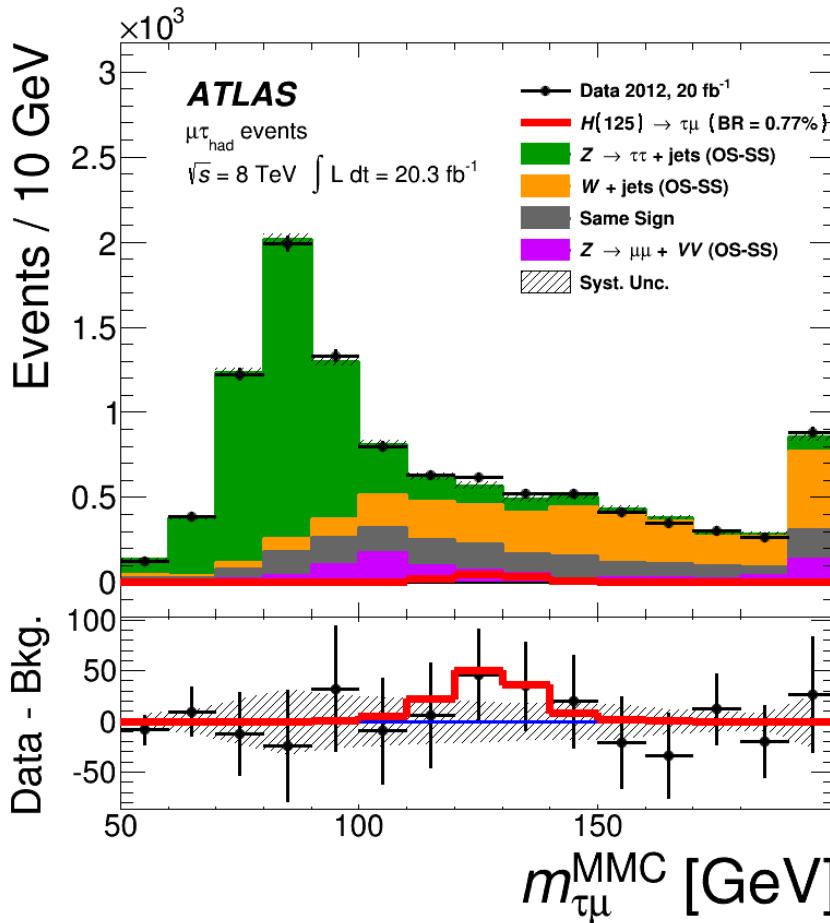


Signal regions Control regions

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

ATLAS Search For LFV $H \rightarrow \mu\tau$: Results

- Observe small 1.3σ excess
 - Fitted $\text{Br}(H \rightarrow \mu\tau) = (0.77 \pm 0.62)\%$
- Observed 95% CL limit $\text{Br}(H \rightarrow \mu\tau) < 1.85\%$
 - Expected 95% CL limit: $\text{Br}(H \rightarrow \mu\tau) < (1.24^{+0.50}_{-0.35})\%$



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

arXiv: 1508.03372

Rare Decays

- $H \rightarrow Q\gamma$ ($Q = J/\psi, \Upsilon$) decays
 - $H \rightarrow J/\psi\gamma$ probes Hcc coupling, which can be enhanced by new physics
 - SM expectation for $\text{Br}(H \rightarrow J/\psi\gamma) = (2.8 \pm 0.2) \times 10^{-6}$
 - SM expectation for $\text{Br}(H \rightarrow \Upsilon(nS)\gamma) = O(10^{-10})$
- $H \rightarrow \gamma\gamma^* \rightarrow ll\gamma$ decays
 - Probes new couplings predicted by some new physics models
 - Non-trivial angular distributions and forward-backward asymmetry variables reconstructed from the $ll\gamma$ final state have potential to investigate Higgs boson properties beyond what can be learned from $H \rightarrow \gamma\gamma$

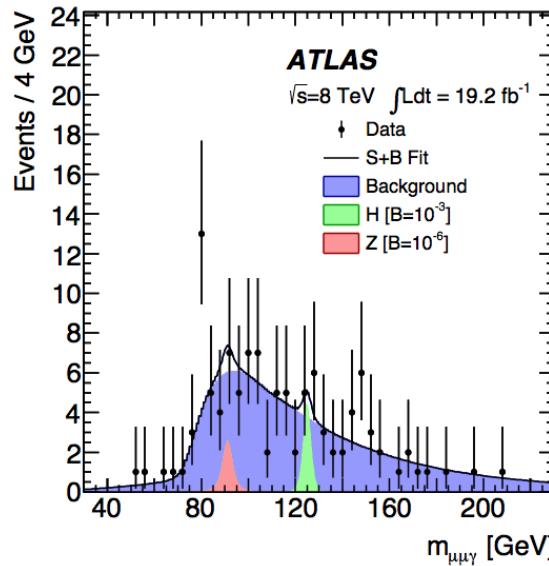
$$\frac{\Gamma(H \rightarrow \gamma^*\gamma \rightarrow ee\gamma)}{\Gamma(H \rightarrow \gamma\gamma)} \sim 2.9\%, \quad \frac{\Gamma(H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma)}{\Gamma(H \rightarrow \gamma\gamma)} \sim 1.1\%, \quad \frac{\Gamma(H \rightarrow Z\gamma \rightarrow ll\gamma)}{\Gamma(H \rightarrow \gamma\gamma)} \sim 2.2\%.$$

- $H \rightarrow \mu\mu$ and $H \rightarrow ee$ decays
 - $H \rightarrow \mu\mu$ probes coupling to 2nd generation of leptons
 - Probes mass dependence of Hff couplings
 - Unlike Z or Z' bosons, Higgs boson does not couple universally to leptons
 - Sensitive to new physics

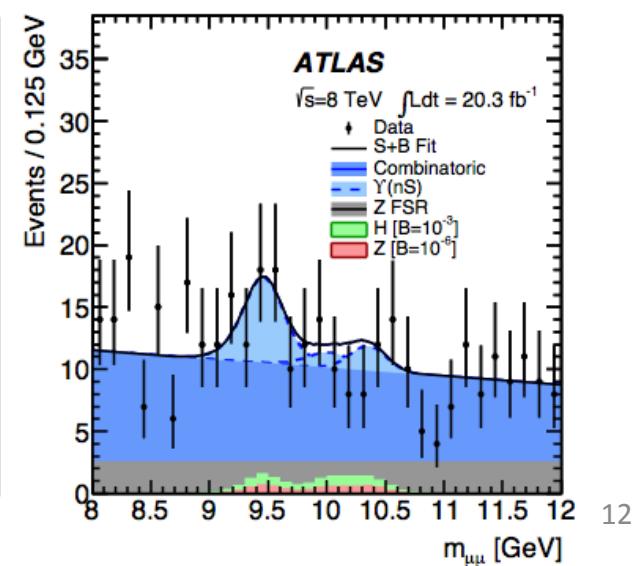
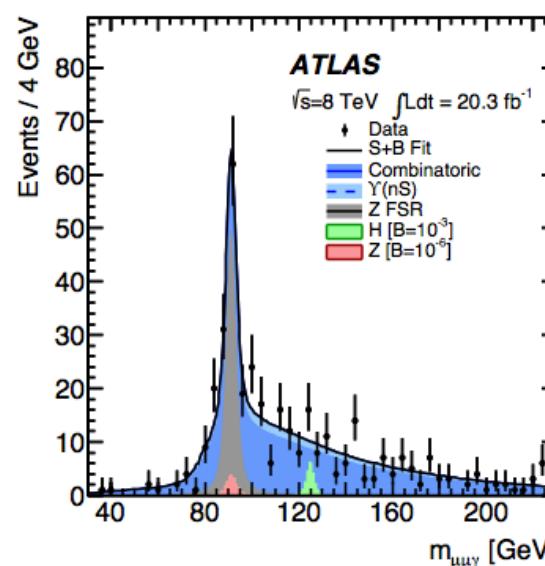
ATLAS Search For $H \rightarrow Q\gamma$ ($Q=J/\psi, \Upsilon$): Analysis Overview

- Search is performed in $J/\psi \rightarrow \mu\mu$ and $\Upsilon(nS) \rightarrow \mu\mu$ decay modes
- Analysis assumes SM Higgs boson production and dynamics
 - NP affecting Hcc coupling can also modify Higgs boson production and dynamics
- Event selection:
 - Two OS muons with $P_T(\mu 1) > 20$ GeV, $P_T(\mu 2) > 3$ GeV, $P_T(\mu\mu) > 36$ GeV
 - Isolated photon with $P_T(\gamma) > 36$ GeV, $\Delta\phi(\mu\mu, \gamma) > 0.5$
- 4 analysis categories based on location of muon pairs and photon type (converted/unconverted)
- Main background: inclusive quarkonium production in association with jet $\rightarrow \gamma_{\text{fake}}$
- Background is modeled by loosely selected data

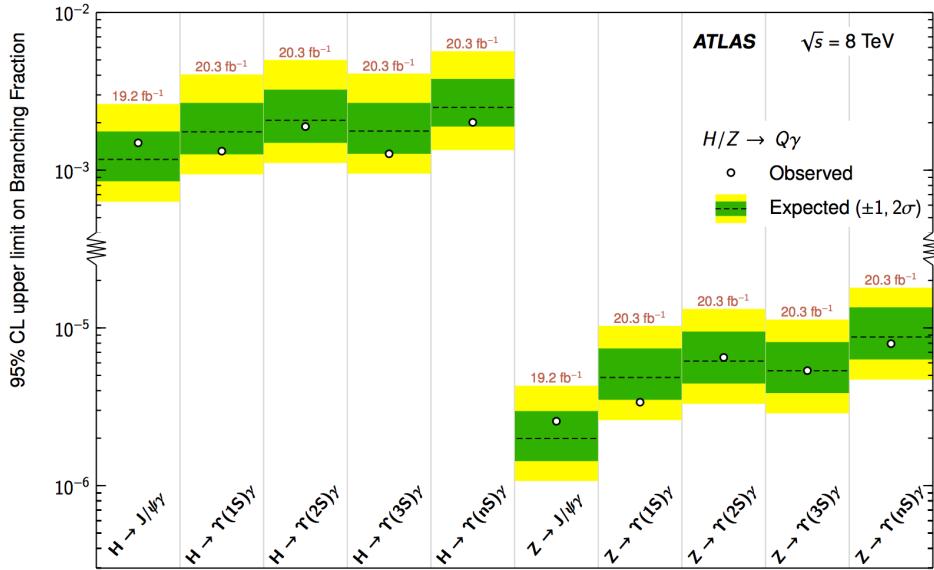
$H \rightarrow J/\psi\gamma$ search



$H \rightarrow \Upsilon(nS)\gamma$ search



ATLAS Search For $H \rightarrow Q\gamma$ ($Q=J/\psi, \Upsilon$): Results



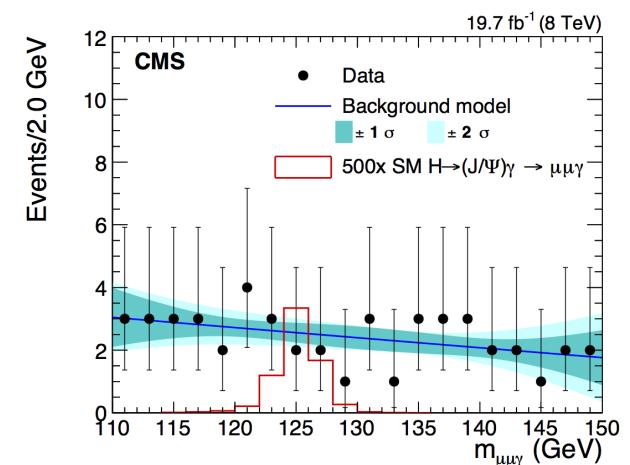
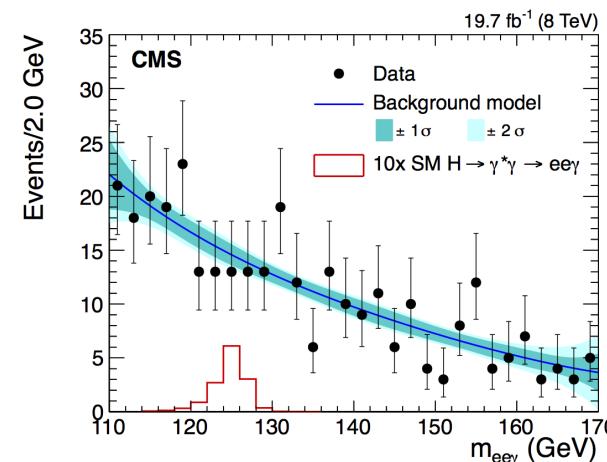
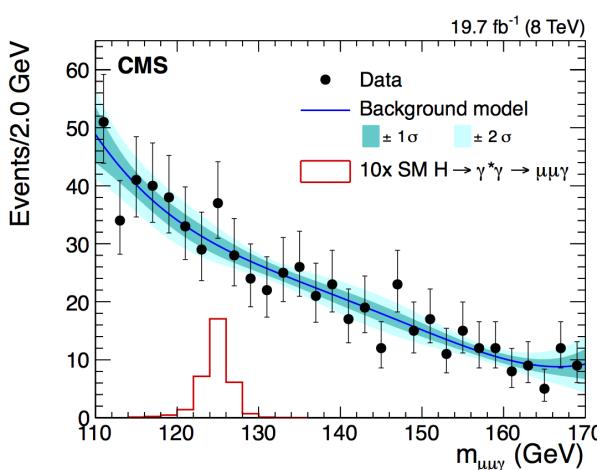
		95% CL_s Upper Limits				
		J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum^n \Upsilon(nS)$
$\mathcal{B}(Z \rightarrow Q\gamma) [10^{-6}]$						
Expected		$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed		2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H \rightarrow Q\gamma) [10^{-3}]$						
Expected		$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed		1.5	1.3	1.9	1.3	2.0
$\sigma(pp \rightarrow H) \times \mathcal{B}(H \rightarrow Q\gamma) [\text{fb}]$						
Expected		26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed		33	29	41	28	44

PRL 114 (2015) 121801

- No signs of $H \rightarrow Q\gamma$ or $Z \rightarrow Q\gamma$ ($Q=J/\psi, \Upsilon$) are observed
- 95% CL limits on branching ratio are set
 - $\text{Br}(H \rightarrow J/\psi\gamma) < 1.5 \times 10^{-3}$, ~ 540 time the expected SM value
 - $\text{Br}(H \rightarrow \Upsilon(nS)\gamma) < (1.3, 1.9, 1.3) \times 10^{-3}$ for $(1S, 2S, 3S)$

CMS Search For $H \rightarrow \gamma\gamma^* \rightarrow ll\gamma$: Analysis Overview

- Search for Dalitz $H \rightarrow \gamma\gamma^* \rightarrow ee\gamma/\mu\mu\gamma$ decays and for $H \rightarrow J/\psi\gamma \rightarrow \mu\mu\gamma$ decays
 - Contribution from $H \rightarrow Z\gamma$ and $H \rightarrow \mu\mu \rightarrow \mu\mu\gamma^{\text{brem}}$ are removed by $M_{ll} < 20$ GeV and isolation cuts
- Event selection
 - Leptons: $|\eta(\mu)| < 2.4$, $|\eta(e)| < 1.44$, $p_T(l) > 0.3M_{ll\gamma}$, $p_T(\mu_1/\mu_2) > 23/4$ GeV, $p_T(e_1) + p_T(e_2) > 44$ GeV
 - Photons: $|\eta| < 1.44$, $p_T > 0.3M_{ll\gamma}$
 - $110 \text{ GeV} < M_{ll\gamma} < 170 \text{ GeV}$
 - $H \rightarrow \gamma\gamma^*$ search: $M_{\mu\mu} < 20$ GeV (veto J/ψ , Υ decays), $M_{ee} < 1.5$ GeV
 - $H \rightarrow J/\psi\gamma \rightarrow \mu\mu\gamma$ search: $2.9 \text{ GeV} < M_{\mu\mu} < 3.3 \text{ GeV}$, $p_T(\mu\mu/\gamma) > 40$ GeV

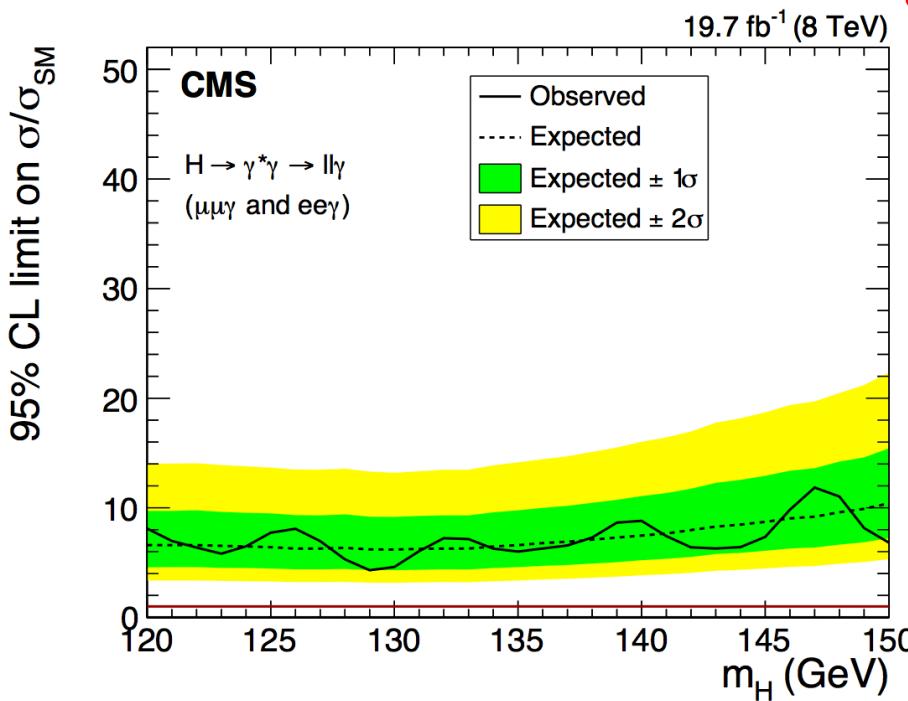


Background model: polynomial function (4th or 2nd degree)

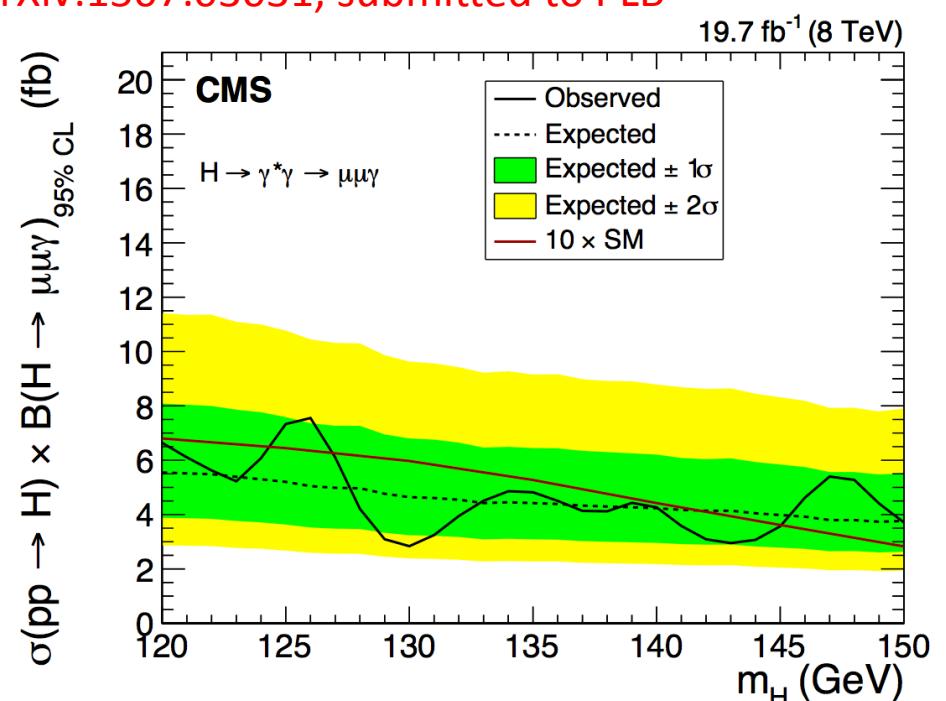
Signal model: Crystal Ball + Gaussian

CMS Search For $H \rightarrow \gamma\gamma^* \rightarrow ll\gamma$: Results

- No signs of signal are observed
- Limits on $H \rightarrow \gamma\gamma^* \rightarrow ll\gamma$ for $M_H = 125$ GeV: $\sigma/\sigma_{SM} < 7.7$ ($6.4^{+3.1}_{-2.0}$)
 - Results are statistically limited
 - Need ~ 30 more data (~ 600 fb^{-1}) to have sensitivity for SM $H \rightarrow \gamma\gamma^* \rightarrow ll\gamma$ decays
- Limit on $\text{Br}(H \rightarrow J/\psi\gamma) < 1.5 \times 10^{-3}$, ~ 540 time the expected SM value
 - No hope to observe at LHC

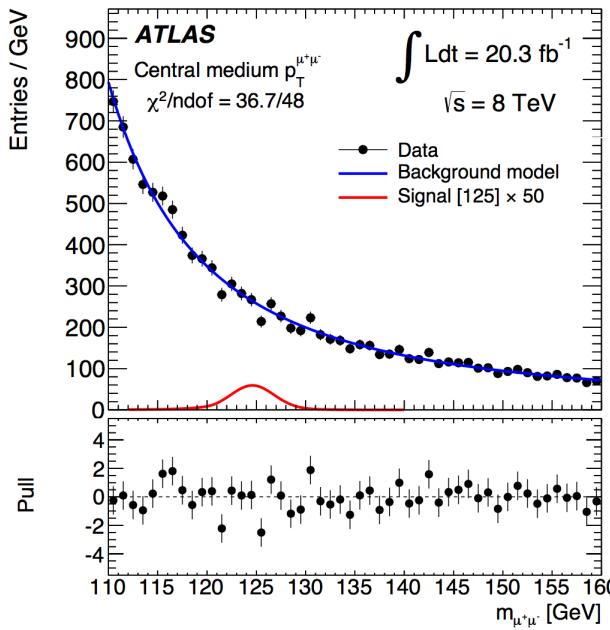


arXiv:1507.03031, submitted to PLB

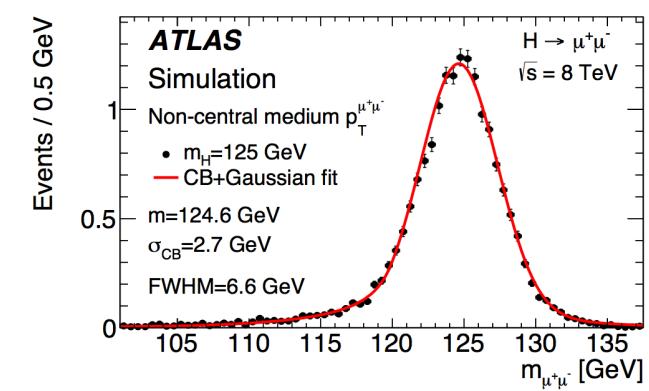
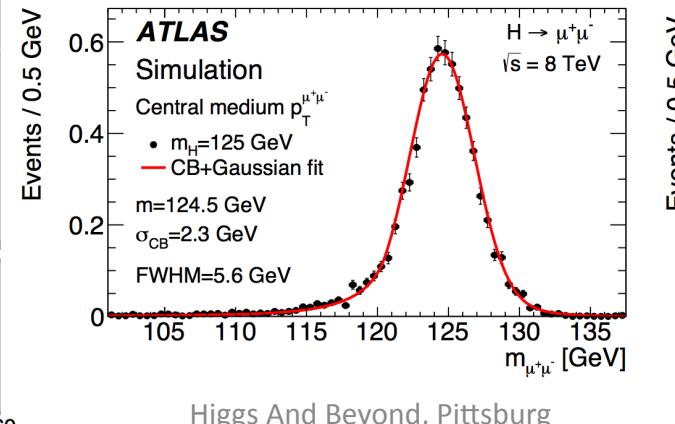


ATLAS Search For $H \rightarrow \mu\mu$: Analysis Overview

- Event selection
 - $p_T(\mu 1) > 25 \text{ GeV}$, $p_T(\mu 2) > 15 \text{ GeV}$, $\text{MET} < 80 \text{ GeV}$, $120 \text{ GeV} < M_{\mu\mu} < 150 \text{ GeV}$
- Event categories
 - 6 analysis categories based on $|\eta(\mu)|$ and $p_T(\mu\mu)$
 - VBF category: $M_{jj} > 500 \text{ GeV}$, $|\Delta\eta_{jj}| > 3$, $\eta_{j1}\eta_{j2} > 0$
- Background model: $f^* \text{BW}(x)^* \text{GS}(x) + (1-f)^* \text{Exp}(x)/x^3$
 - Background model in VBF category: $\text{BW}(x)^* \text{Exp}(x)$
- Signal model: $f_{\text{CB}}^* \text{CB}(x) + (1-f_{\text{CB}})^* \text{GS}(x)$



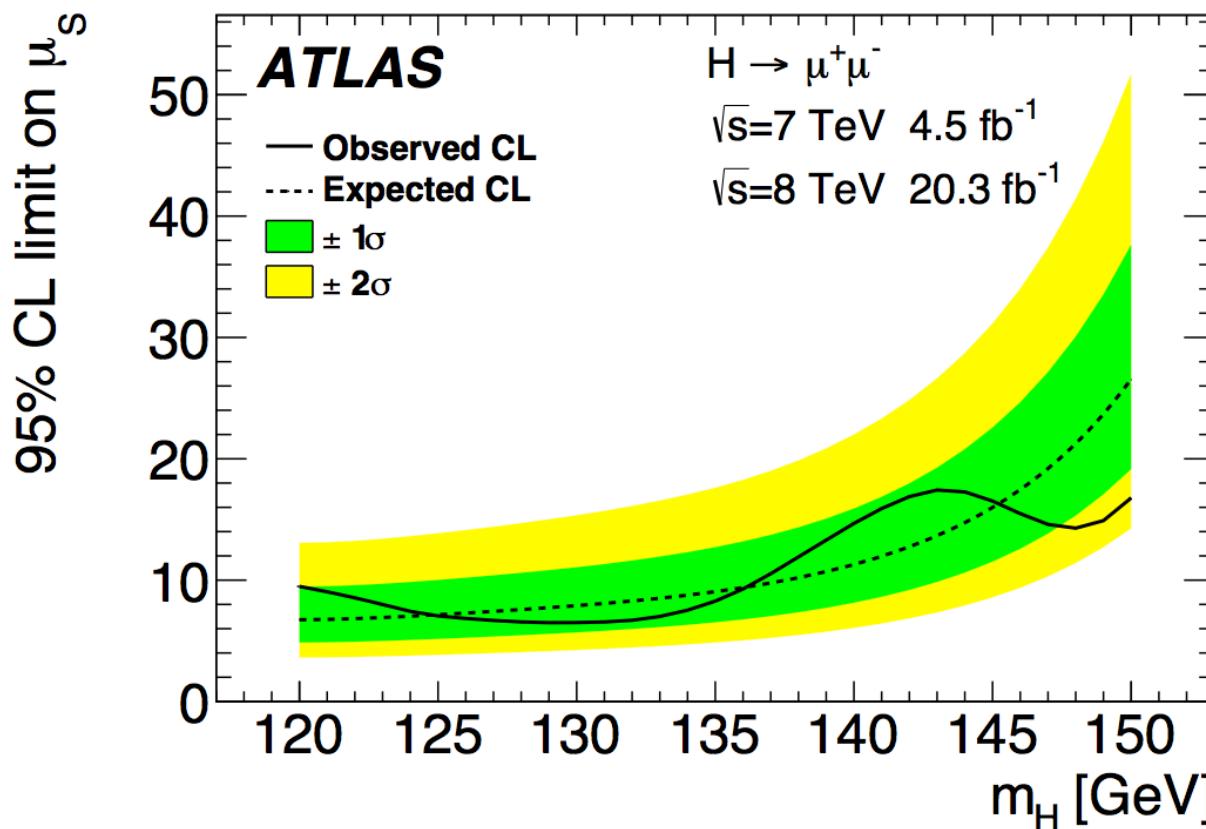
Major background: $Z/\gamma^* \rightarrow \mu\mu$



Higgs And Beyond, Pittsburg

ATLAS Search For $H \rightarrow \mu\mu$: Results

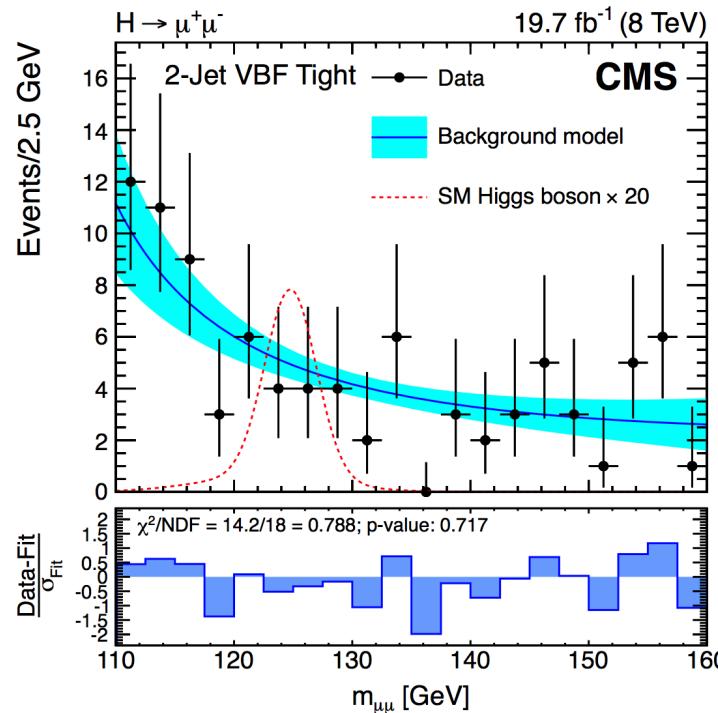
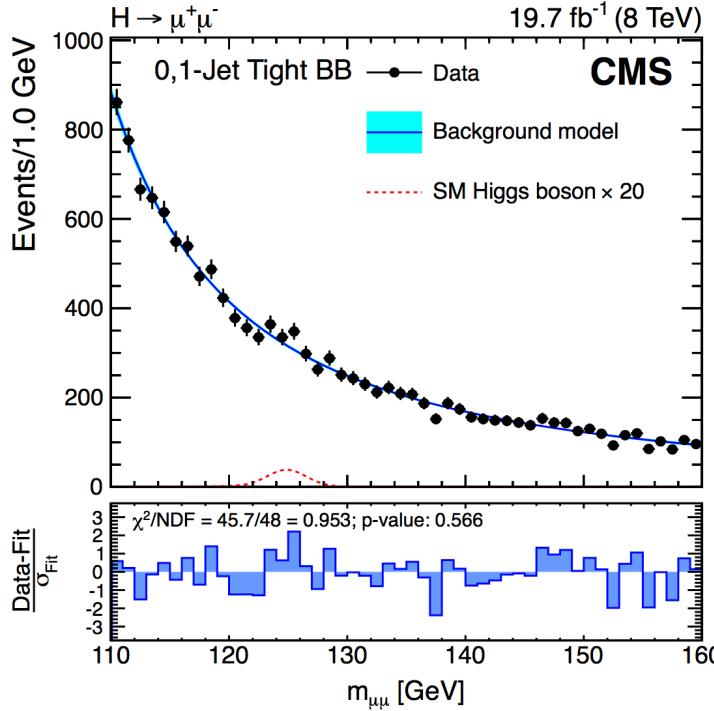
- No sign of signal
- Limits on $\mu_s = (\sigma^* BR) / (\sigma^* BR)_{SM}$ for $M_H = 125$ GeV: observed (expected) $\mu_s < 7.1$ (7.2)
- Limit on $Br(H \rightarrow \mu\mu) < 1.5 \cdot 10^{-3}$
- Statistically limited analysis; sensitivity to SM $H \rightarrow \mu\mu$ decays with ~ 40 more data
 - Should be able to see this decay with 1000 fb^{-1} of data



CMS Search For $H \rightarrow \mu\mu$: Analysis Overview

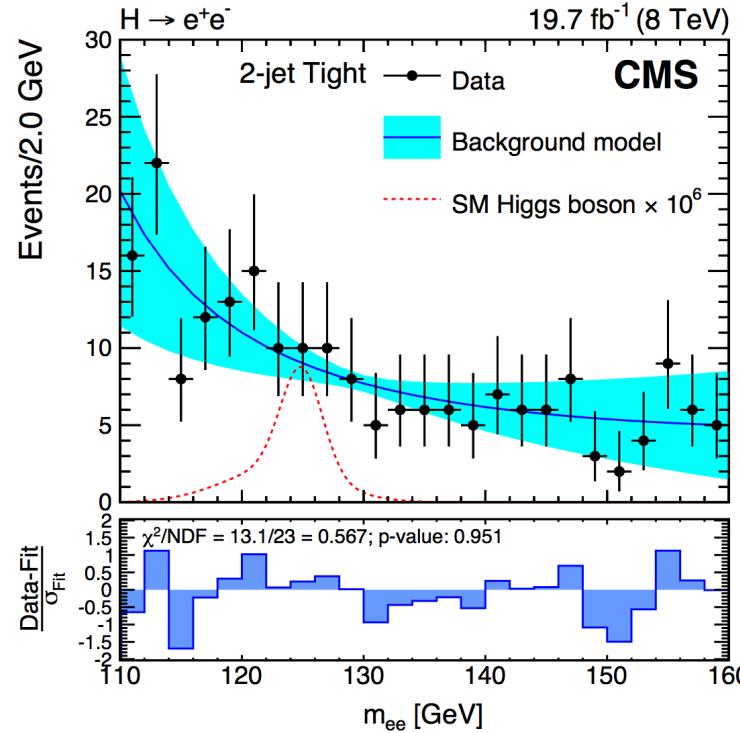
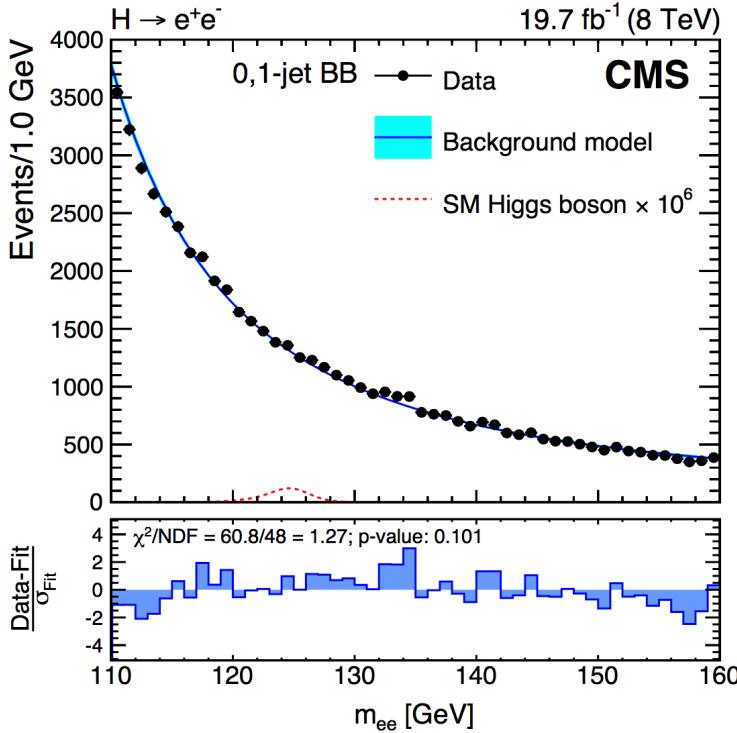
- $H \rightarrow \mu\mu$ event selection & categorization
 - $p_T(\mu 1) > 25 \text{ GeV}$, $p_T(\mu 2) > 15 \text{ GeV}$, $|\eta(\mu)| < 2.1$, $M_{T} < 40 \text{ GeV}$ (2-jet events only)
 - 15 analysis categories based on number of jets, $|\eta(\mu)|$ and $p_T(\mu\mu)$
 - VBF Tight category: $M_{jj} > 650 \text{ GeV}$, $|\Delta\eta_{jj}| > 3.5$
 - GF Tight category: $M_{jj} > 250 \text{ GeV}$, $p_T(\mu\mu) > 50 \text{ GeV}$
 - Search window: $120 \text{ GeV} < M_{\mu\mu} < 150 \text{ GeV}$
- Signal model: double-Gaussian
- Background model:

$$f(m_{\mu\mu}) = \beta C_1 e^{-\lambda m_{\mu\mu}} \frac{1}{(m_{\mu\mu} - m_Z)^2 + \frac{\Gamma^2}{4}} + (1 - \beta) C_2 e^{-\lambda m_{\mu\mu}} \frac{1}{m_{\mu\mu}^2}$$



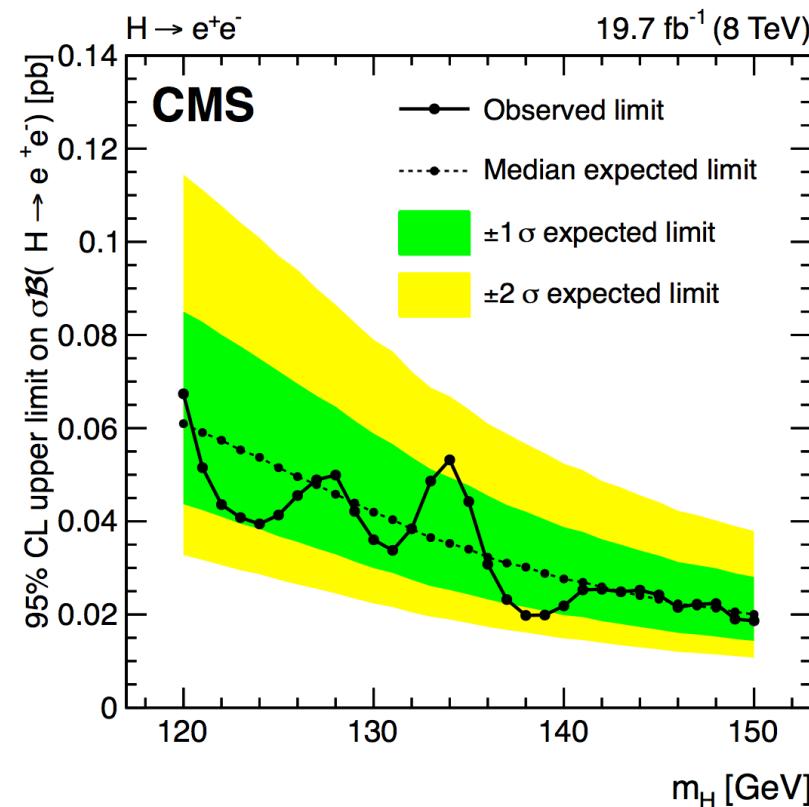
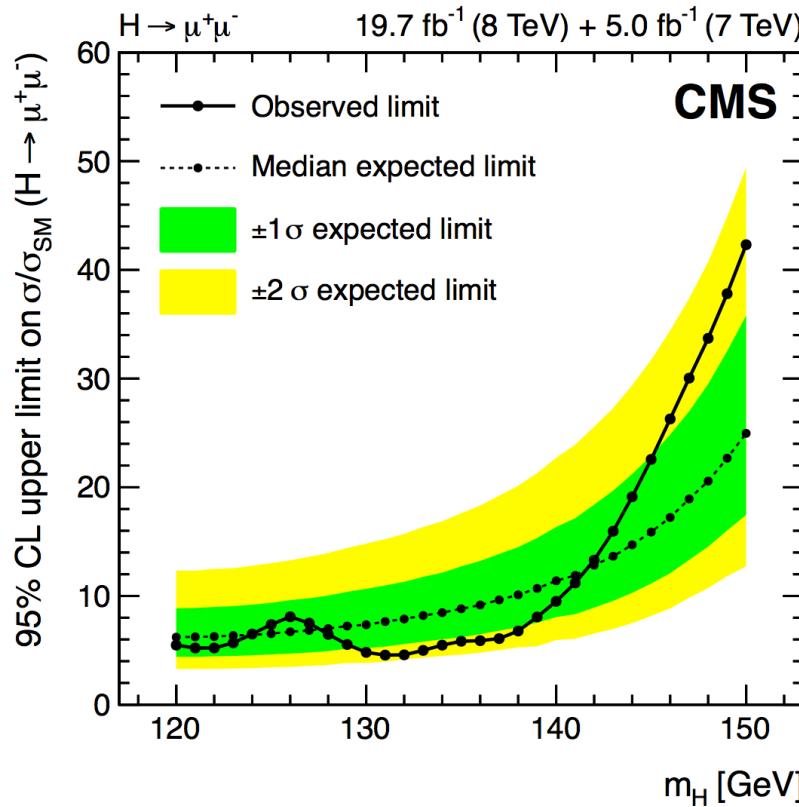
CMS Search For $H \rightarrow ee$: Analysis Overview

- $H \rightarrow ee$ event selection & categorization
 - $p_T(e) > 25 \text{ GeV}$, $|\eta(e)| < 2.5$
 - 4 analysis categories based on number of jets and $|\eta(e)|$
 - Tight (Loose) 2-jet category: $M_{jj} > 500$ (250) GeV , $p_T(\text{jets}) > 30$ (20) GeV ,
 - $|\eta(ee) + 0.5 * [\eta(j1) + \eta(j2)]| < 2.5$, $|\Delta\phi(jj, ee)| > 2.6$
 - Search window: $120 \text{ GeV} < M_{ee} < 150 \text{ GeV}$
- Signal and background models are the same as in $H \rightarrow \mu\mu$ search



CMS Search For $H \rightarrow \mu\mu$ and $H \rightarrow ee$: Results

- $H \rightarrow \mu\mu$ search, results for $M_H = 125$ GeV:
 - Limits on $\mu_S = (\sigma^* BR) / (\sigma^* BR)_{SM}$: observed (expected) $\mu_S < 7.4$ ($6.5^{+2.8}_{-1.9}$)
 - Limit on $Br(H \rightarrow \mu\mu) < 1.6 \cdot 10^{-3}$
- $H \rightarrow ee$ search, results for $M_H = 125$ GeV:
 - Limit on $Br(H \rightarrow ee) < 1.9 \cdot 10^{-3}$, which is 3.7×10^5 times the SM prediction



Summary

- Searches for LFV $H \rightarrow \mu\tau/\ell\tau/\ell\mu$ decays
 - $H \rightarrow \mu\tau$: **CMS & ATLAS observe 2.4σ and 1.3σ excesses, respectively**
 - results already probe phenomenologically interesting phase-space
 - $H \rightarrow \ell\tau$ & $H \rightarrow \ell\mu$: no significant excess, $\text{Br}(H \rightarrow \ell\tau) < 0.69\%$, $\text{Br}(H \rightarrow \ell\mu) < 0.358 \times 10^{-3}$
 - Much tighter indirect limits on $\text{Br}(H \rightarrow \ell\mu)$ based on $\mu \rightarrow e\gamma$ searches
- Searches for $H \rightarrow Q\gamma$ ($Q = J/\psi, \Upsilon$) and $H \rightarrow \gamma\gamma^*$
 - CMS/ATLAS limits on $\text{Br}(H \rightarrow J/\psi\gamma) < 1.5 \times 10^{-3}$ or ~ 540 times SM value
 - no hope to observe this decays at LHC
 - ATLAS limits on $\text{Br}(H \rightarrow \Upsilon(nS)\gamma) < (1.3, 1.9, 1.3) \times 10^{-3}$ for (1S, 2S, 3S)
 - CMS limits on $H \rightarrow \gamma\gamma^*$: $\sigma/\sigma_{\text{SM}} < 7.7$ ($6.4^{+3.1}_{-2.0}$)
 - Need $\sim 600 \text{ fb}^{-1}$ to have sensitivity for SM $H \rightarrow \gamma\gamma^* \rightarrow ll\gamma$ decays
- Searches for $H \rightarrow \mu\mu$ and $H \rightarrow ee$:
 - Higgs boson does not couple to leptons universally
 - ATLAS/CMS limit on $\text{Br}(H \rightarrow \mu\mu) < 1.5/1.6 \times 10^{-3}$ or 7.1/7.4 times SM value
 - Should be able to see this decay with 1000 fb^{-1} of data
 - CMS limit on $\text{Br}(H \rightarrow ee) < 1.9 \times 10^{-3}$, which is 3.7×10^5 times the SM prediction