Searches for rare Higgs decays at CMS

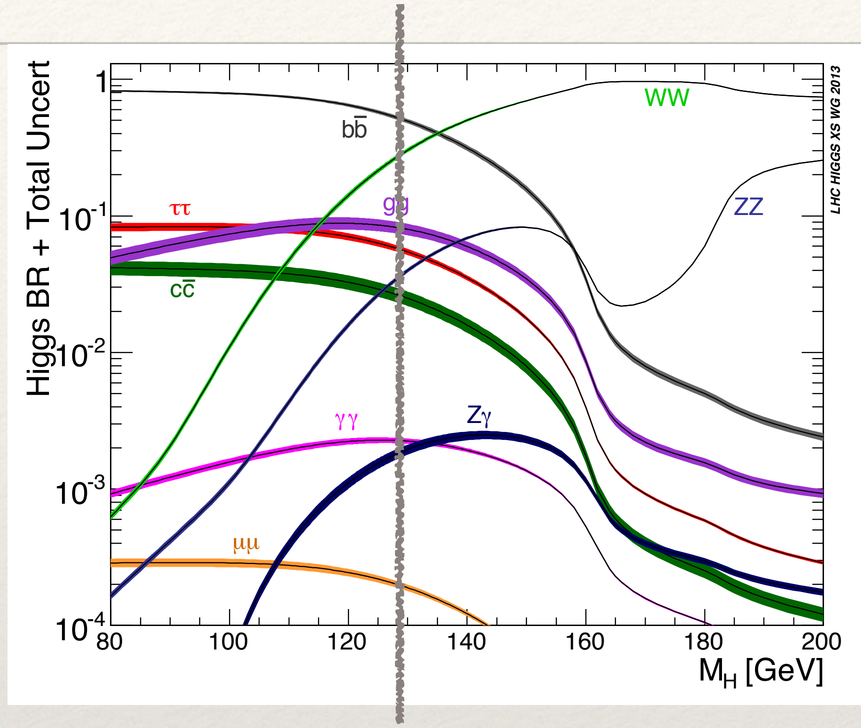
Shilpi Jain (National Central University, Taiwan)

On behalf of the CMS collaboration

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + \ h.c..$$

$$\Delta\mathcal{L}_Y = -\frac{\lambda'_{ij}}{\Lambda^2} \bar{F}_L^i F_R^j H(H^\dagger H) + \ h.c$$

Current status of Higgs boson decays



Channel	BR[%]	Results from CMS(Run II)	References
bb	58	~3.8σ	CMS-HIG-16-044
WW	22	~4.7σ	CMS-PAS-HIG-16-021
gg	8.6	-	
ττ	6.3	~5.9σ	CMS-HIG-16-043
cc	2.9	-	
ZZ	2.6	~7σ	CMS-HIG-16-041
γγ	0.23	~5.6σ	CMS-HIG-16-040
Zγ	0.15	95% CL UL	Rare decays
μμ	0.022	95% CL UL	
γ*γ—>llγ	3.2×10^{-5}	95% CL UL	
J/ψ γ	2.8×10^{-6}	95% CL UL	

- SM-like Higgs observed in many standard decay channels
- For the rest, 95% CL upper limit on σ/σ_{SM} has been set
- From Run I, BR(H—>BSM) < 34% at 95% CL **[arXiv: 1606.02266]**
- Allows significant contribution from exotic decays
- Room for H—> invisible, H —> lepton flavour violation (LFV)
- Many BSM scenarios also allow SM-like Higgs to decay to two light scalars

- In summary, following decays fall under rare decays of Higgs:
  - **H—>LFV (35.9 fb-1 at 13 TeV)**
  - **H—>aa—>μμ (2.5 fb-1 at 13 TeV)**
  - **H—>Zγ (8TeV)**
  - **H—>J/ψγ (8TeV)**
  - **H—>γ*γ (8TeV)**

  covered in this talk

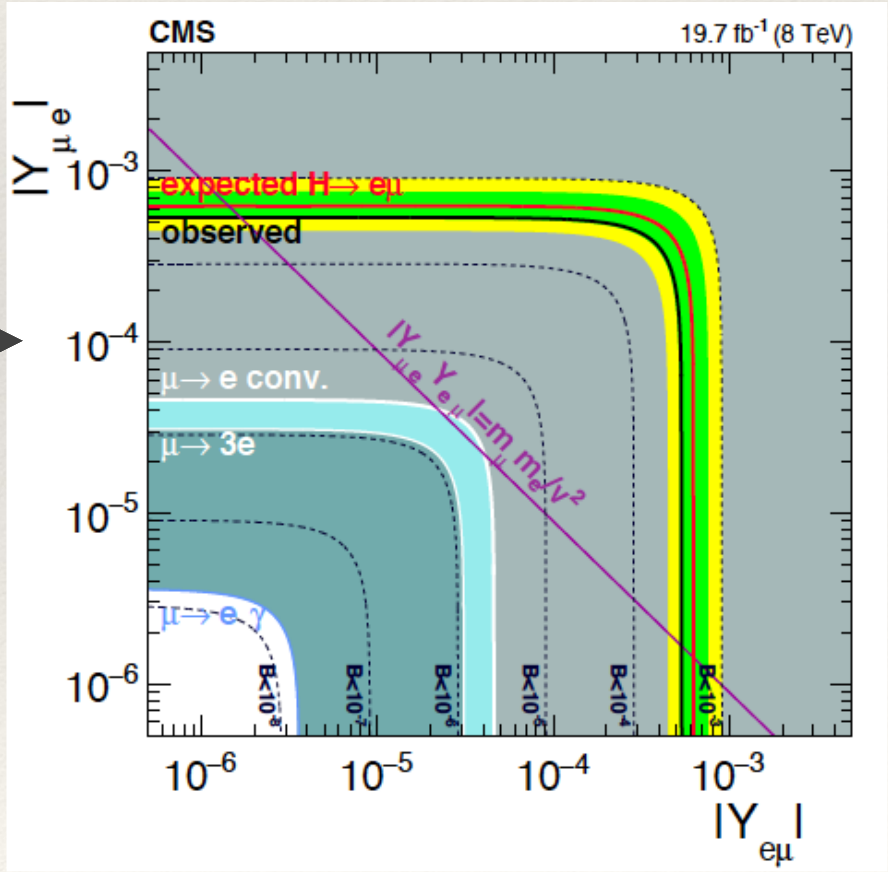
  - H—>μμ —-> covered in Adrian Perieanu's talk
  - H—>invisible —> covered in Kajari Mazumdar's talk

13 TeV 35.9 fb^{-1}

Lepton flavour violation

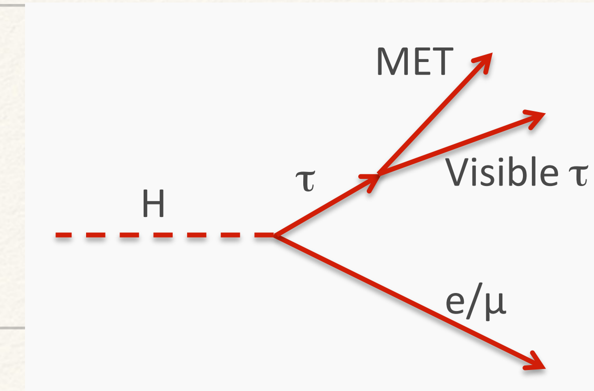
PAS: HIG-17-001

- LFV decays forbidden in SM but occur in many new physics scenarios (e.g. some effective field theories (EFT), certain two Higgs doublet models, composite Higgs models, Randall-Sundrum models)
  - Searches for H—>μτ and H—>eτ provide unique ways to probe off-diagonal Yukawa couplings
- LHC can provide stronger constraints than any other current precision measurements on H—>μτ and H—>eτ
- Tight bounds on BR(H—>μe) < O(10^{-9}) from μ—>eγ decays
  - Stringent bounds till date
  - LHC cannot perform better
- CMS results from Run I
  - H—>μτ: 2.4σ excess
  - H—>eτ: No excess

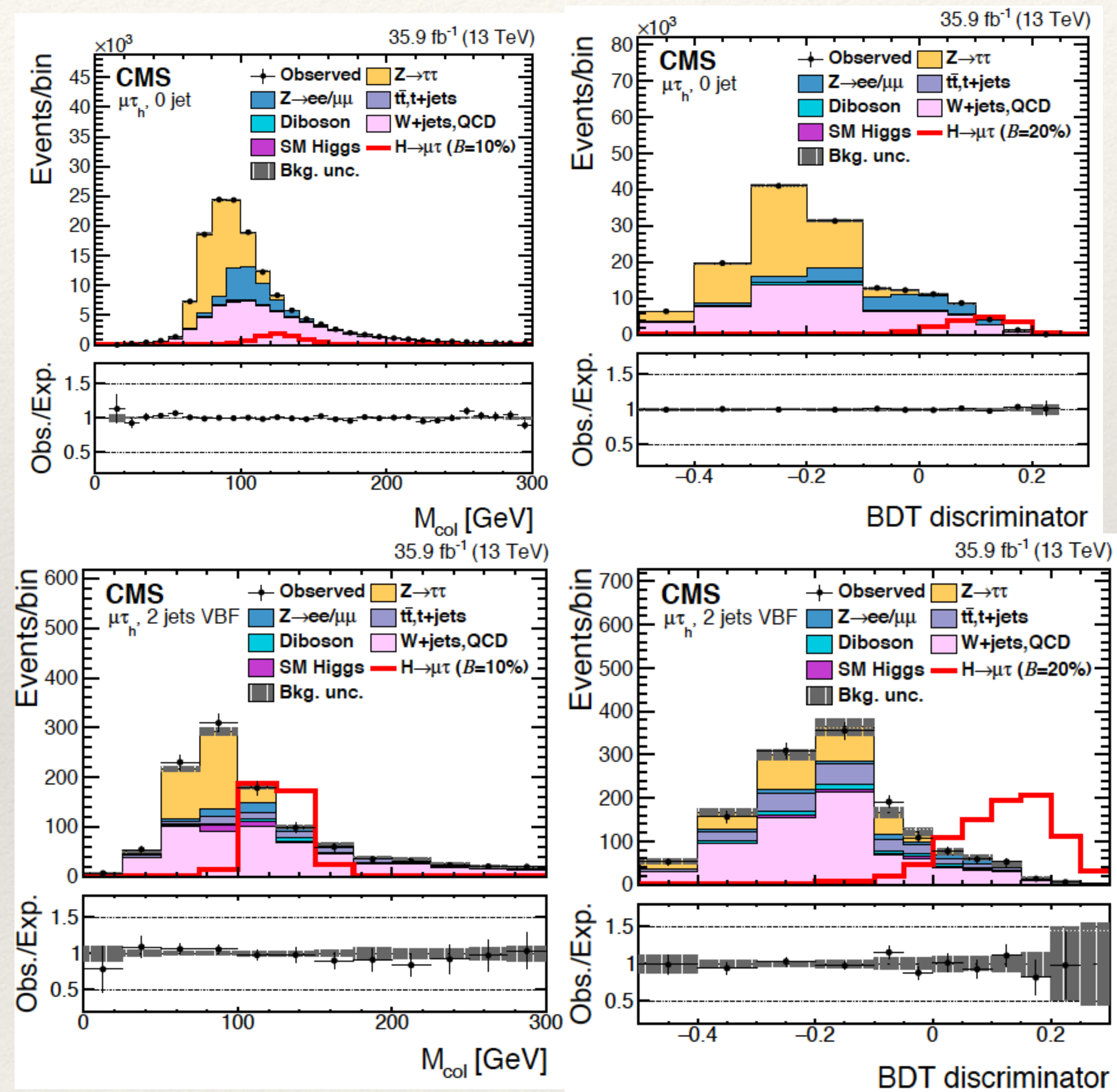


Bounds on BR(H—>μe) from Run I

Analysis strategy

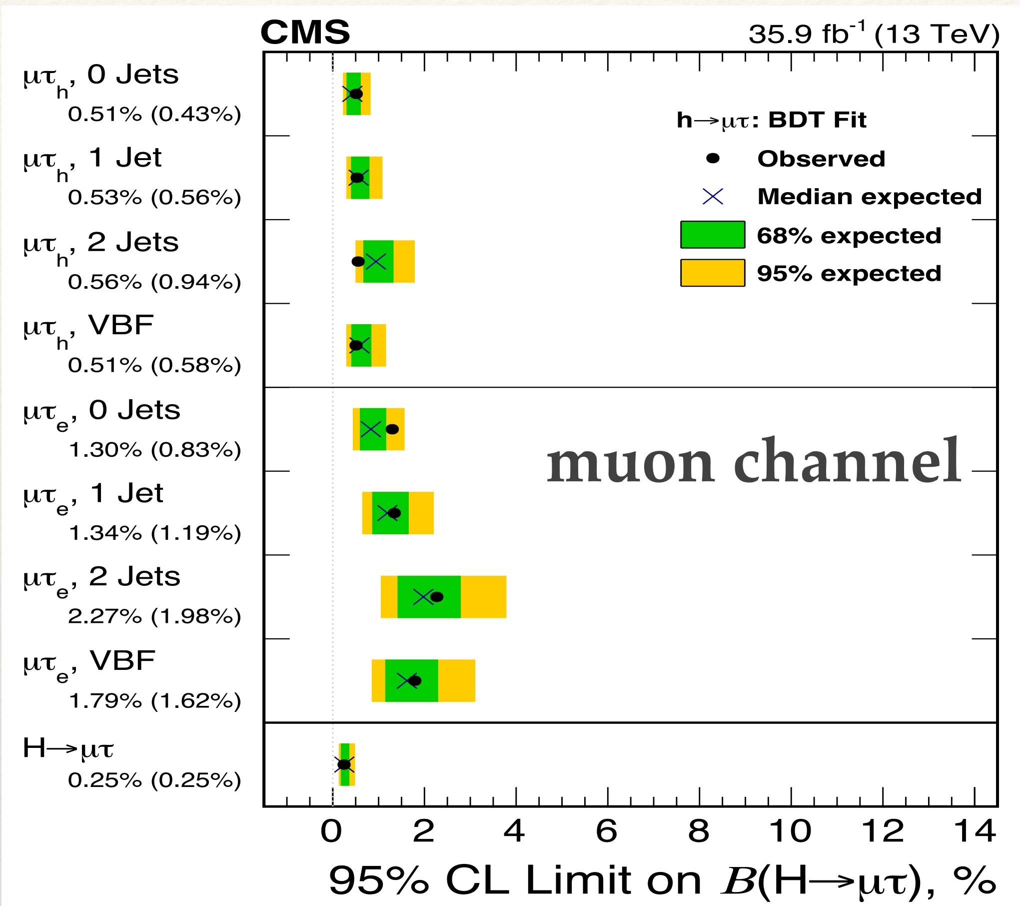


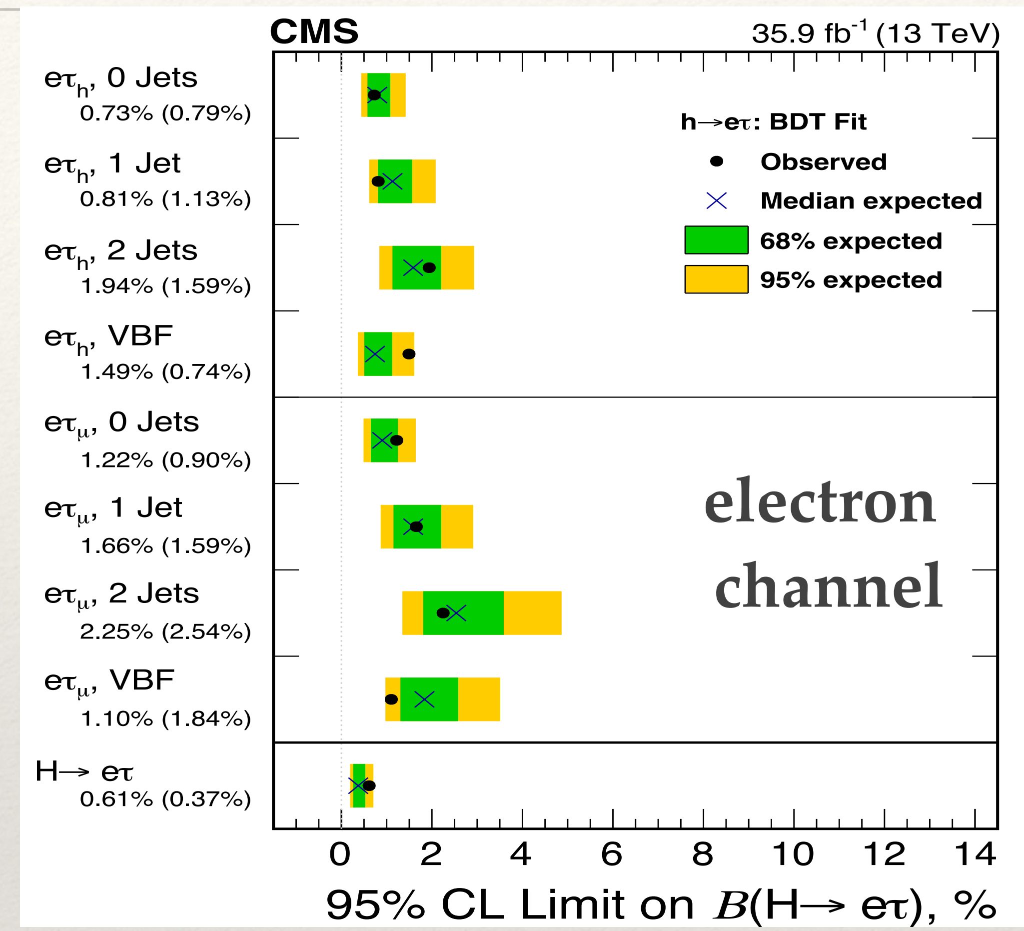
- Channels and final states looked at with 35.9 fb^{-1} of data:
  - $H \to e\tau_h$, $H \to e\tau_\mu$, $H \to \mu\tau_h$, $H \to \mu\tau_e$
- Categories with 0, 1, and 2 jets plus exclusive 2-jets VBF category
- Backgrounds modeled using MC and data sidebands (jets mis-identified as leptons from data driven)
  - Dominant contributions from $Z \to \tau\tau$, W+jets
- Signal extraction:
  - A BDT is trained in each category with various kinematic discriminants (pT, mT, collinear mass(m_{col}) , $\Delta\phi/\eta$ of $e/\mu/\tau$)
  - BDT is then fitted with signal and background models
  - Cross-check measurement by performing a fit to m_{col}



m_{col} provides an estimate of m_H, reconstructed using all visible particles

Limits on Branching ratio





Best fit branching fractions (%)

	0-jet	1-jet	2-jets	VBF	Combined
$\mu\tau_e$	0.61 ± 0.36	0.22 ± 0.46	0.39 ± 0.83	0.10 ± 1.37	0.35 ± 0.26
$\mu\tau_h$	0.12 ± 0.20	-0.05 ± 0.25	-0.72 ± 0.43	-0.22 ± 0.31	-0.04 ± 0.14
$\mu\tau$			0.00 ± 0.12		

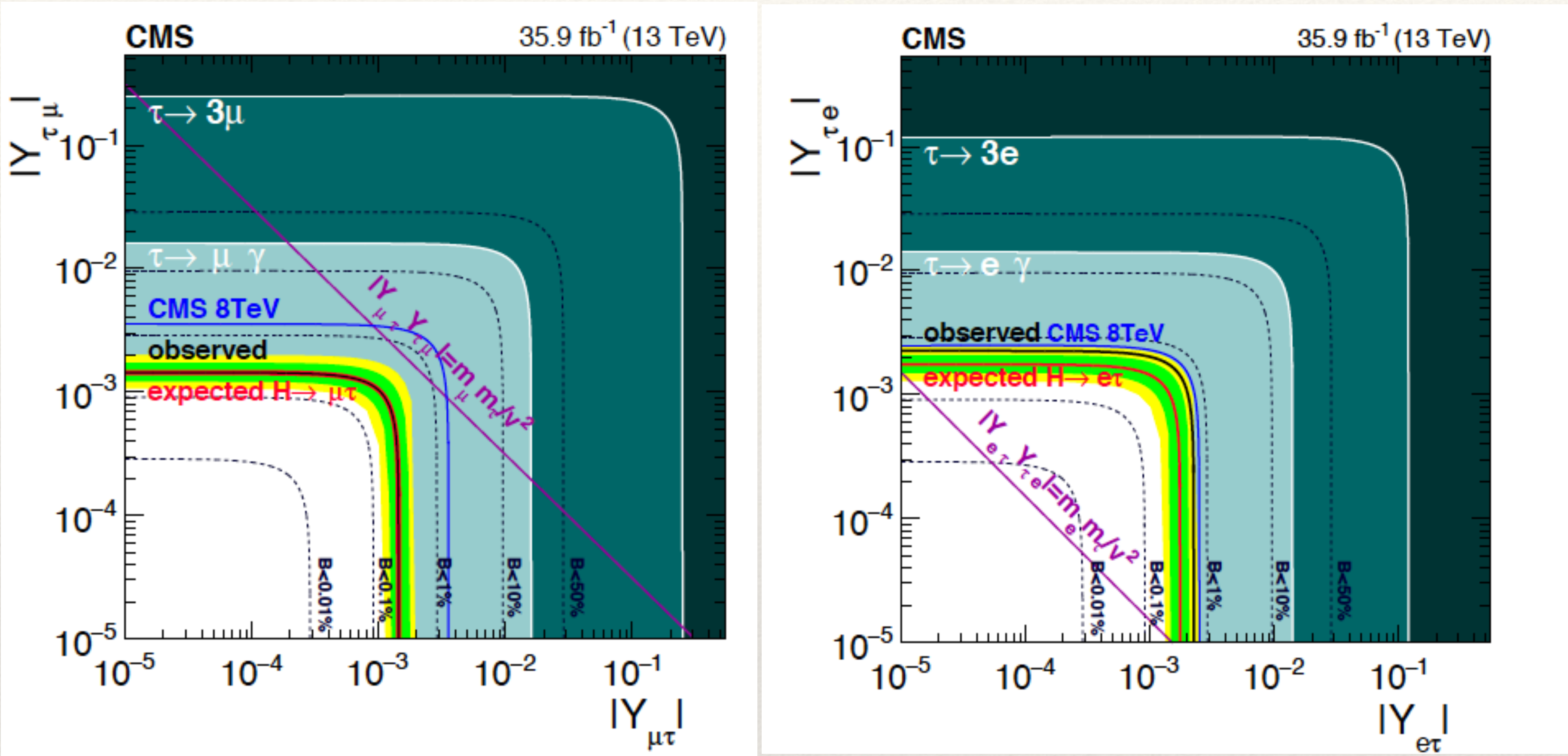
No excess

Best fit branching fractions (%)

	0-jet	1-jet	2-jets	VBF	Combined
$e\tau_\mu$	0.47 ± 0.42	0.17 ± 0.79	-0.42 ± 1.01	-1.54 ± 0.44	0.18 ± 0.32
$e\tau_h$	-0.13 ± 0.39	-0.63 ± 0.40	0.54 ± 0.53	0.70 ± 0.38	0.33 ± 0.24
$e\tau$			0.30 ± 0.18		

	95% CL(obs/exp) on BR	Best-fit BR
H—>μτ(Run I)	<1.51/0.75%	0.84 +/- 0.38%
H—>μτ(Run II)	<0.25/0.25%	0.00 +/- 0.12%
H—>eτ(Run I)	<0.69/0.75%	-0.10+/-0.36%
H—>eτ(Run II)	<0.61/0.37%	0.30+/-0.18%

Limits on Yukawa couplings



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

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

- 95% CL upper limit on BR(H—>μτ) and BR(H—>eτ) can be interpreted in terms of LVF Yukawa couplings:

Run II

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \times 10^{-3}$$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \times 10^{-3}$$

Run I: 3.6×10^{-3}

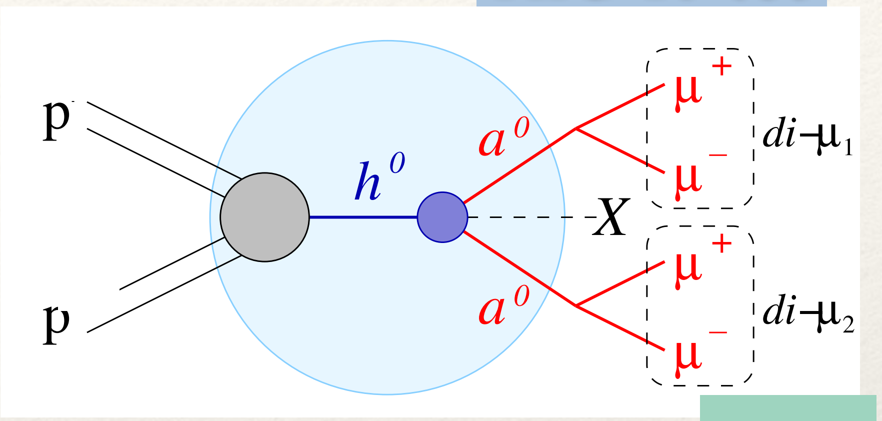
Run I: 2.4×10^{-3}

13 TeV 2.8 fb^{-1}

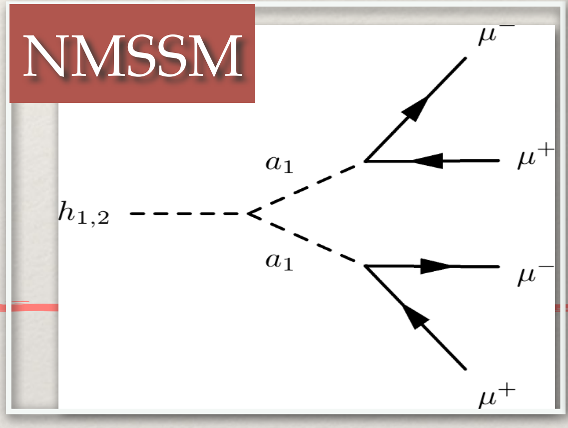
Decay to light scalar searches

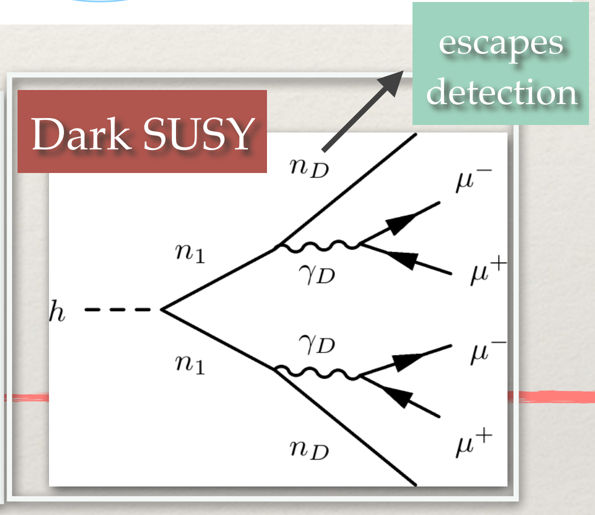
HIG-16-035

- Distinguishing between an SM Higgs boson from a non-SM Higgs boson with slightly different couplings can be a challenge
    - Looking at some exotic non-SM decay modes of Higgs can shed some light



- Some of the possible exotic non-SM decay modes:
    - **H—>2a —>4μ — New result from CMS at 13 TeV, focus for this talk**
    - H—>aa—>4τ
    - H—>aa—>2μ2τ
    - H—>aa—>2μ2b



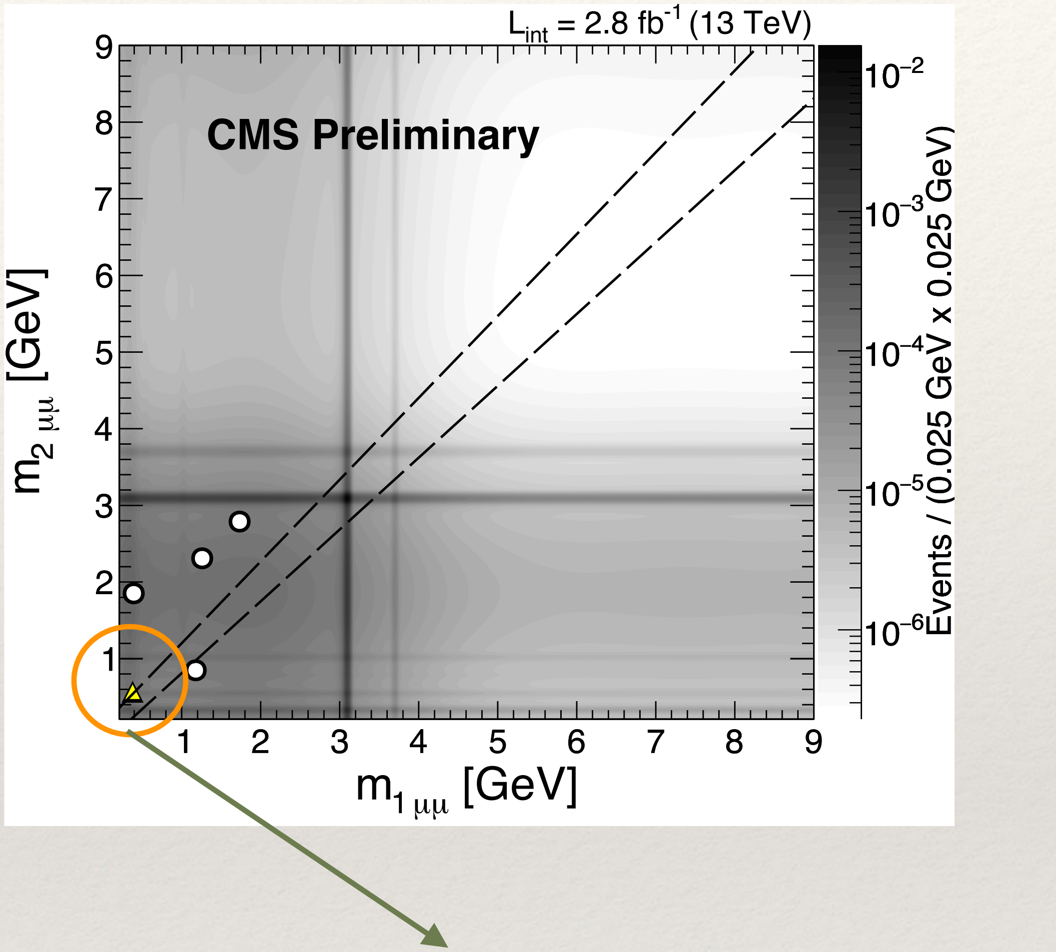


- Model independent search
- Two specific scenarios studied:
    - Next-to-minimal supersymmetric model (NMSSM):
        - Higgs sector contains 3 CP-even Higgs boson $h_{1,2,3}$ and 2 CP-odd Higgs boson $a_{1,2}$
    - SUSY models with "dark" sectors (dark SUSY)
        - Coupling of Higgs boson to lightest neutralino (n1) which decays: n1—>n_D + γ_D [n_D is the dark neutralino]
        - γ_D (dark photon) can be long-lived

Mass range of light scalars(a/γ_D): 0.25 < M < 8.5 GeV

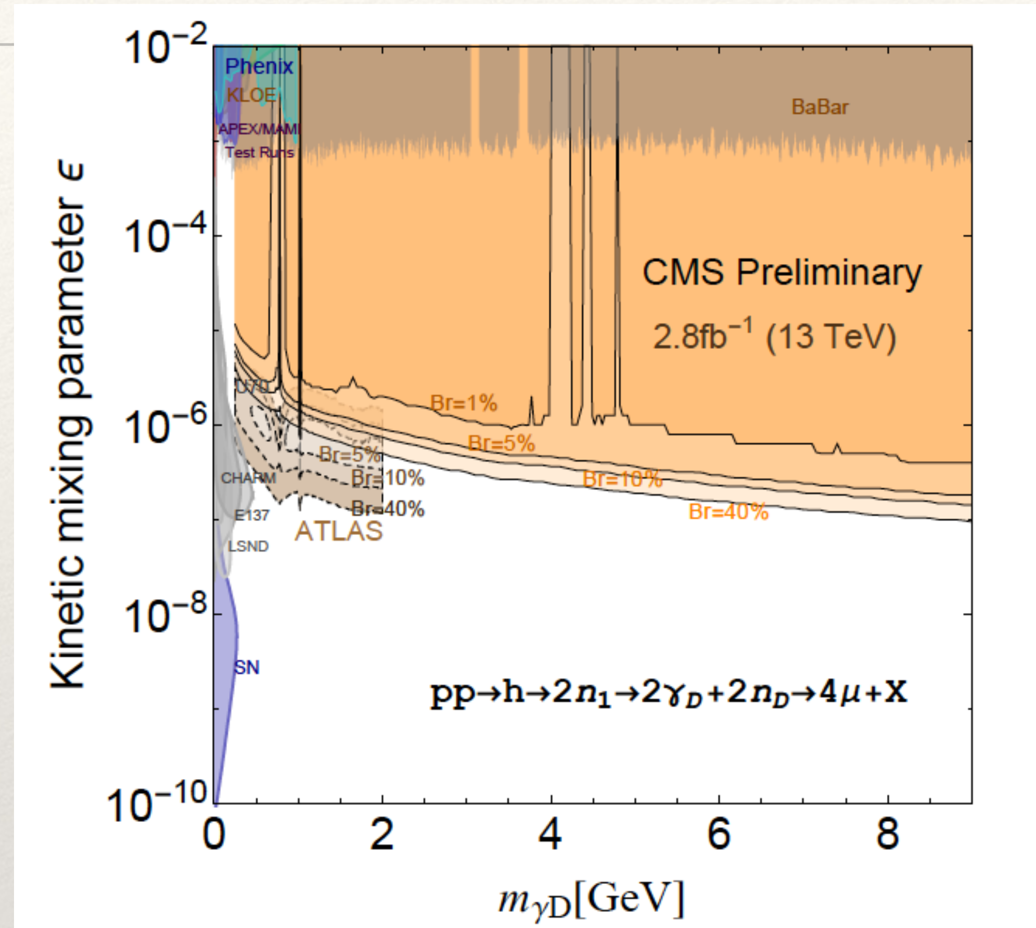
Analysis strategy

- Either cut on probability of common vertex fit OR cut on $\Delta R(\mu+\mu-)$ for forming a di-muon system
- Compatibility of reconstructed di-muon mass:
  - $|m1-m2| < 0.13 + 0.065(m1+m2)/2$; last term corresponds to the dimuon mass resolution
- No constraint on $M_{4\mu}$ to maintain the model independence
- Background estimation:
  - Events containing bb in the final state (Leading background)
    - Modeled as a 2D template in the plane of invariant mass of 2 di-muon systems(m1,m2)
    - Background di-muon mass templates - derived from a control region in data
  - Minor backgrounds: pp —> 4 muons (EWK) and Prompt J/ψ estimated from MC and data respectively



1 candidate event observed in the signal region consistent with the background prediction (=0.74 +/- 0.34 +/- 0.15)

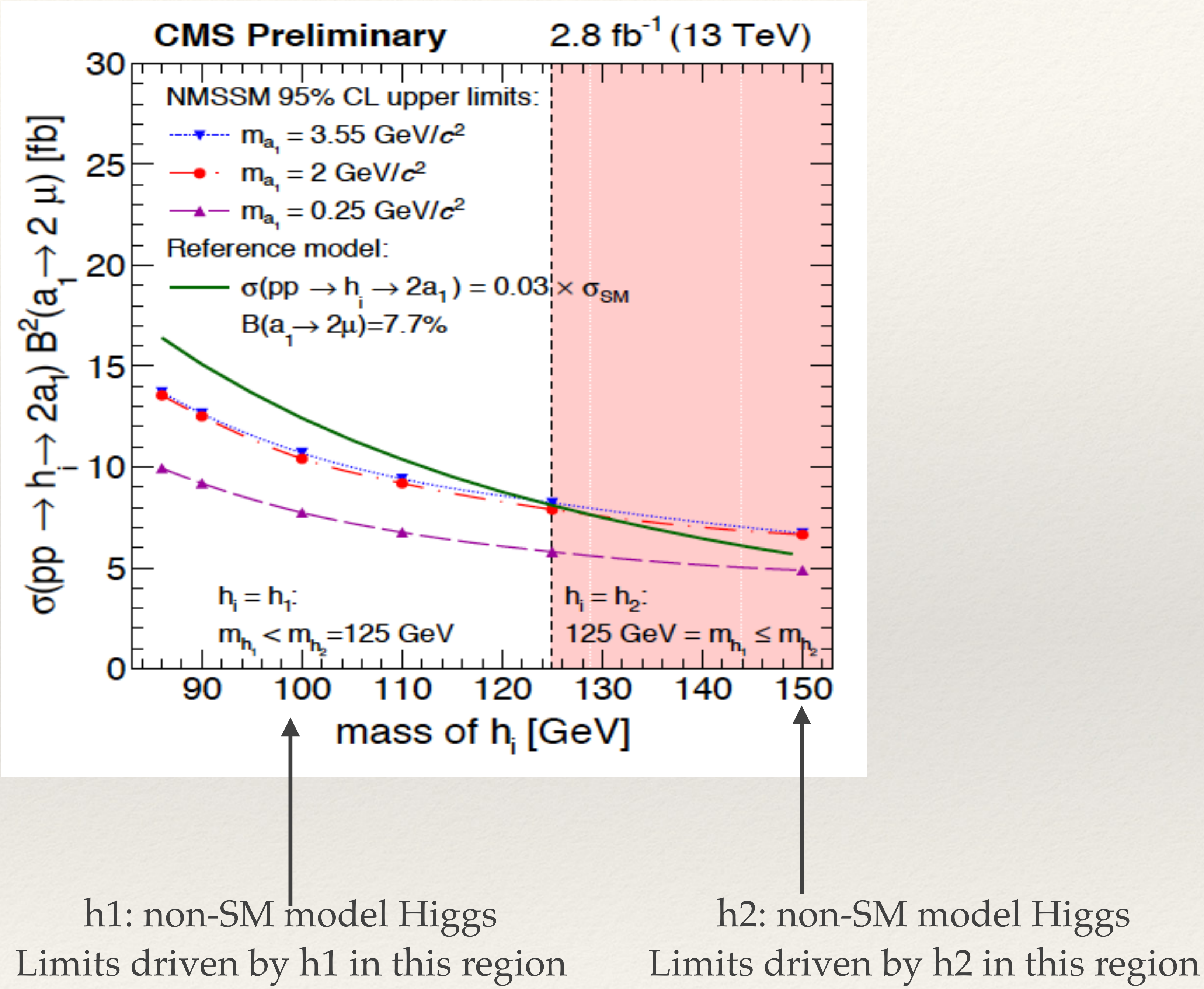
Limits on Dark SUSY



$m_{n1} = 10$ GeV
$m_{nD} = 1$ GeV

- Model independent limits on
  - $\sigma(pp \longrightarrow 2a) \times BR^2(a \longrightarrow 2\mu) \times \alpha_{gen}$ are derived, where α_{gen} is the generator level kinematic and geometric acceptance
  - 95% CL UL on $\sigma(pp \longrightarrow 2a) \times BR^2(a \longrightarrow 2\mu) \times \alpha_{gen} = 1.7$ fb
- Limits ($\sigma(pp \longrightarrow 2a) \times BR^2(a \longrightarrow 2\mu)$) on any model can now be set using the above by knowing the α_{gen}
- Model independent limits used to put limits on Dark SUSY
- Life-time of γ_D is related to mass by kinetic mixing parameter ε

Limits on NMSSM

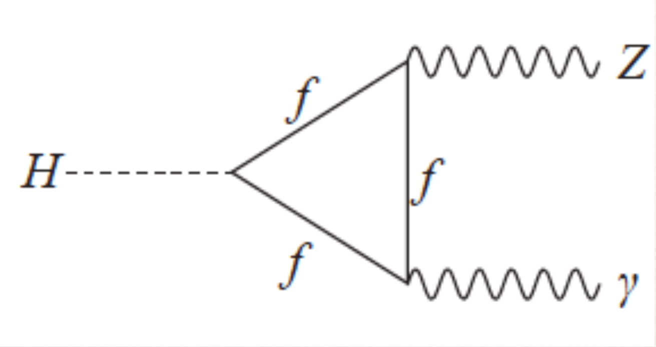


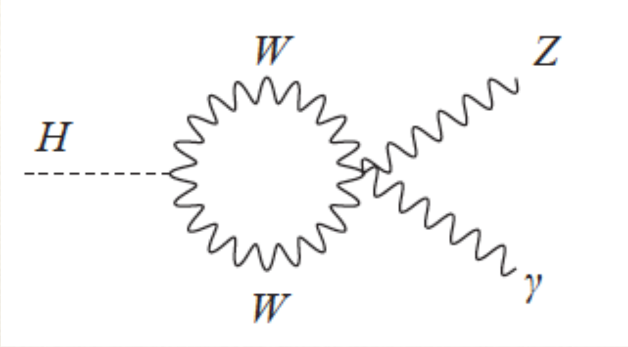
- Model independent limits used to put limits on NMSSM

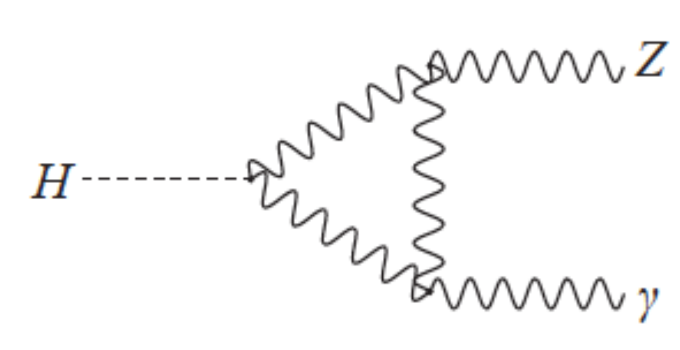
(7+8) TeV (5+19.6) fb^{-1}

$H \rightarrow Z\gamma$

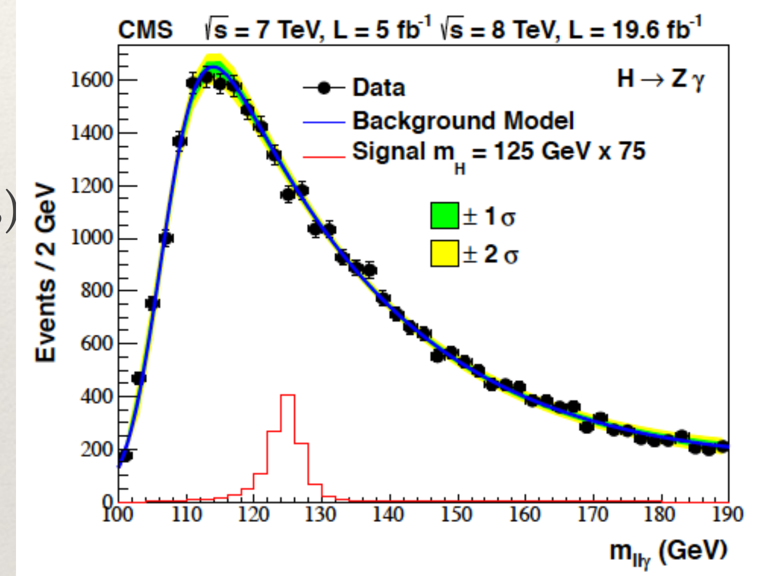
Phys. Lett. B 726 (2013) 587

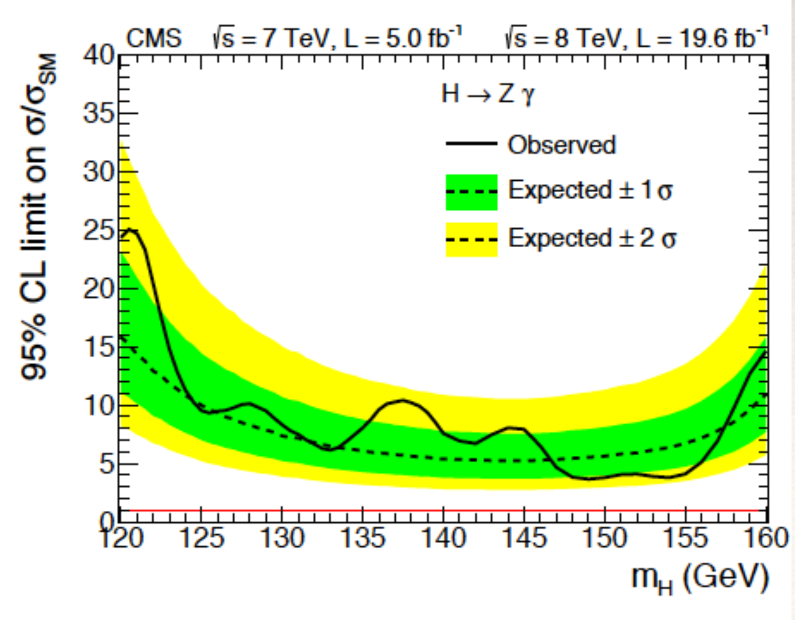






- Loop-induced decay—> can be sensitive to BSM particles
- Could be enhanced w.r.t SM while $\mu(H \rightarrow \gamma\gamma) \sim 1$ (e.g. in composite models)
- Signature: 2 same flavour isolated leptons and 1 isolated photon
- $BR(H \rightarrow Z\gamma \rightarrow ll\gamma) \sim 0.009\%$ at 125 GeV [l=e,μ]
- Large background from SM $Z\gamma$ and Z+jets (S/B ~0.3)
- Analysis strategy: Shape based analysis
  - Signal shape: fit MC $m_{ll\gamma}$ with a function
  - Background: estimated from data by fitting with a suitable function
  - 5 categories:
    - Di-jet: VBF production mode
    - 4 untag classes based on pT, η and R9 of the final objects
- 95% CL UL on $\sigma/\sigma_{SM} \sim 10$





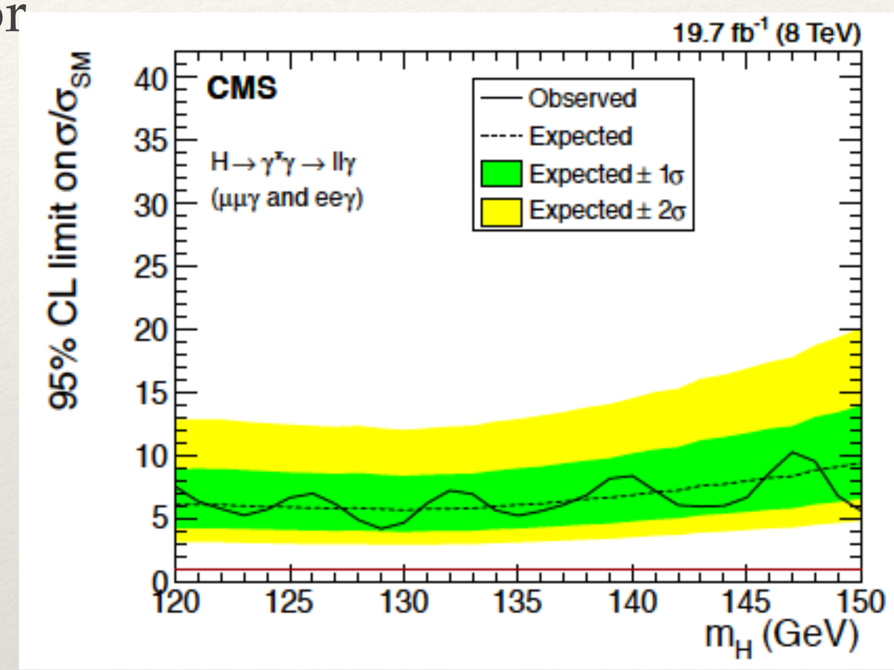
Run II results expected soon

8 TeV 19.6 fb^{-1}

H→γ*γ and H→J/ψγ

Phys. Lett. B 573 (2015) 341

- H—> γ* γ: Internal conversion of γ* to μμ/ee
  - different from H—>γγ (γ—>ee): since that happens in the detector region
  - Can probe novel couplings
  - BR(H—>γ* γ—>llγ) ~ 3.22 (7.36)x10^{-5} for μμγ (eeγ) for m_H = 125 GeV
  - 95% CL UL on σ/σ_{SM} ~6.7



- H—>J/ψ γ:
  - probes H—>cc coupling: another test of coupling to 2nd generation
  - SM BR(H—>J/ψ γ) ~2.8x10^{-6} with BR(J/ψ γ—>μμγ) ~ 0.059
  - 95% CL UL on BR(H—>J/ψ γ) ~ 1.5x10^{-3} (~540 times of the SM) at 125 GeV
  - Very challenging to probe even at HL-LHC!

Run II results expected soon

Conclusions

- Rare decays of Higgs are being widely looked for at CMS in various channels
- No significant hints so far
- In LFV, the H—>$\mu\tau$ excess is excluded with 2016 data and no significant excess in H—>$e\tau$
- 'Model independent' limits put on BR(H—>aa)
- H—>Zγ, H—>J/ψ γ and H—> $\gamma^*\gamma$ analysis with 13 TeV data ongoing
    - expected early next year - stay tuned!

Thank you

Backup

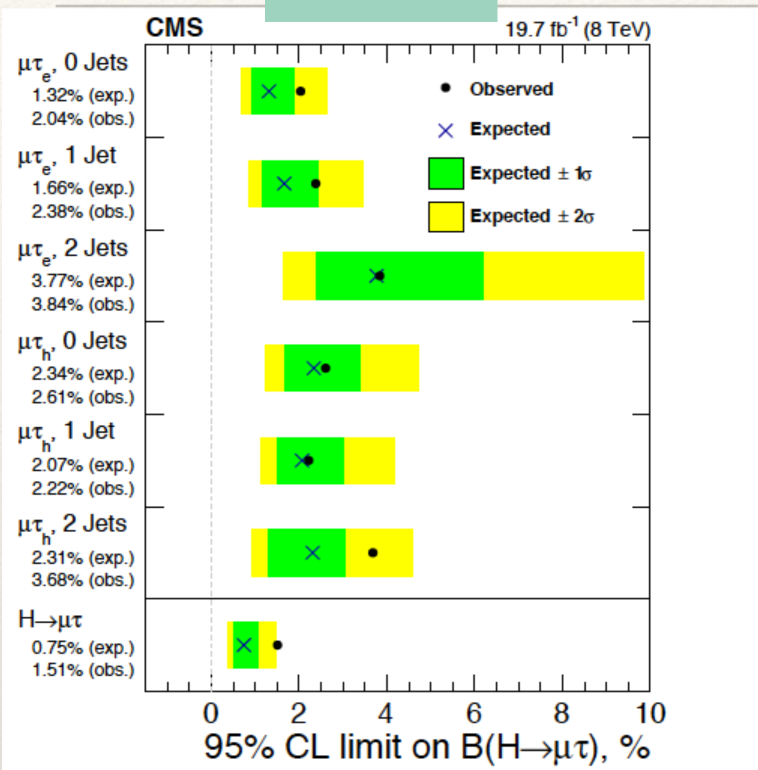
Constraints on LVF decays

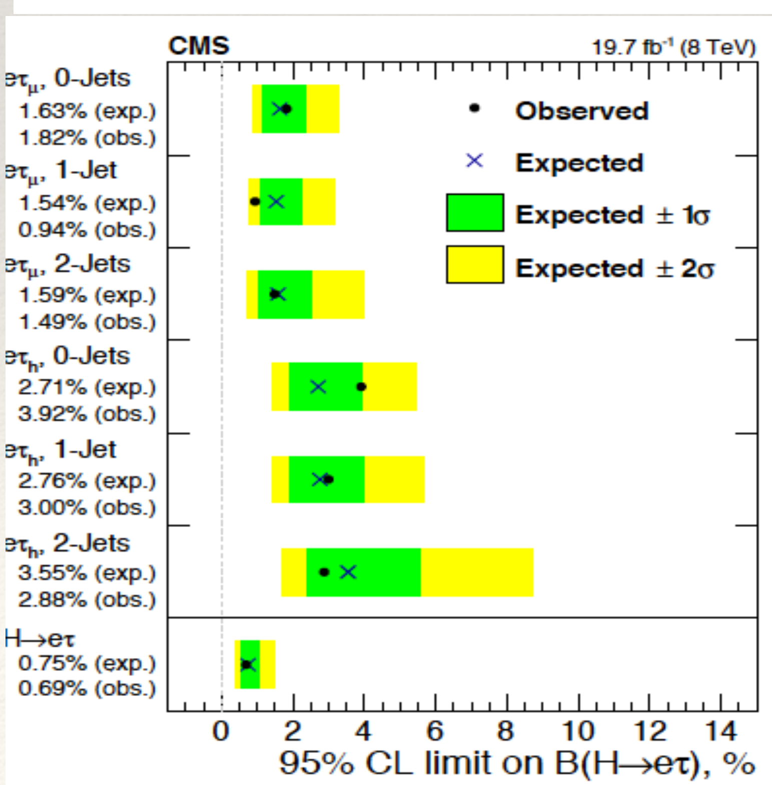
Searches	Experimental limit on branching ratios	Limits on Yukawas
$\tau \to \mu\gamma$	4.4×10^{-8} [70, 71]	$Y_{\mu\tau} < 0.011$
$\tau \to 3\mu$	2.1×10^{-8} [70, 71]	$Y_{\mu\tau} < 0.176$
Muon EDM	$-10 \times 10^{-20} e$ cm $<$ $\lvert d_\mu \rvert$ $< 8 \times 10^{-20} e$ cm [73]	$-0.8 \lesssim$ $\lvert \mathrm{Im}(Y_{\mu\tau} Y_{\tau\mu}) \rvert \lesssim 1.0$
Muon $g-2$	–	$\mathrm{Re}(Y_{\mu\tau} Y_{\tau\mu}) < (2.7 \pm 0.75) \times 10^{-3}$
$\tau \to \mu\gamma$ (f) (Belle-II/super KEKB)	10^{-9} [85]	$Y_{\mu\tau}$ <0.0017
$\tau \to e\gamma$	3.3×10^{-8} [70, 71]	$Y_{e\tau}$ <0.0099
$\tau \to 3e$	2.7×10^{-8} [70, 71]	$Y_{e\tau} < 0.085$
Electron $g-2$	–	$\mathrm{Re}(Y_{e\tau} Y_{\tau e}) < [-2.1, 2.9] \times 10^{-3}$
Electron EDM	$\lvert d_e \rvert \leq 0.105 \times 10^{-26}$ e cm	$\lvert \mathrm{Im}(Y_{e\tau} Y_{\tau e}) \rvert < 1.1 \times 10^{-8}$
$\tau \to e\gamma$ (f) (Belle-II/super KEKB)	10^{-9} [85]	$Y_{e\tau}$ <0.00172
$\mu \to e\gamma$	5.7×10^{-13} [70, 71]	$Y_{\mu e} < 1.24 \times 10^{-6}$
$\mu \to 3e$	1.0×10^{-12} [70, 71]	$Y_{\mu e} < 2.19 \times 10^{-5}$
Electron $g-2$	–	$\mathrm{Re}(Y_{e\mu} Y_{\mu e}) < [-0.019, 0.026]$
Electron EDM	$\lvert d_e \rvert \leq 0.105 \times 10^{-26}$ e cm	$\lvert \mathrm{Im}(Y_{e\mu} Y_{\mu e}) \rvert < 9.8 \times 10^{-8}$
$\mu \to e$ conversion	–	$Y_{\mu e} < 8.49 \times 10^{-6}$
$M - \bar{M}$ oscillations	–	$\lvert Y_{\mu e} + Y^*_{e\mu} \rvert < 0.079$
$\mu \to e\gamma$ (f) (MEG-II)	4×10^{-14} [84]	$Y_{\mu e}$ $<3.28 \times 10^{-7}$
$\mu \to e\gamma$	5.7×10^{-13}	$Y_{\mu\tau} Y_{e\tau}$ $<3.98 \times 10^{-8}$
$h \to \tau\mu$ (CMS)	1.51% [22]	$Y_{\mu\tau} < 2.55 \times 10^{-3}$
	0.84%	$Y_{\mu\tau} = 1.87 \times 10^{-3}$
$h \to \tau\mu$ (ATLAS)	1.43% [24]	$Y_{\mu\tau} < 2.45 \times 10^{-3}$
	0.77% [25]	$Y_{\mu\tau} = 1.79 \times 10^{-3}$
$h \to \tau\mu$ (CMS)+ $\mu \to e\gamma$	0.84%, 5.7×10^{-13}	$Y_{e\tau} < 2.13 \times 10^{-5}$
$h \to \tau\mu$ (ATLAS)+ $\mu \to e\gamma$	0.77%, 5.7×10^{-13}	$Y_{e\tau} < 2.23 \times 10^{-5}$
$h \to \tau e$ (CMS)	0.69% [23]	$Y_{e\tau} < 1.69 \times 10^{-3}$
$h \to \tau e$ (ATLAS)	1.04% [24]	$Y_{e\tau} < 2.08 \times 10^{-3}$
$h \to e\mu$ (CMS)	3.6×10^{-2}% [23]	$Y_{\mu e} < 3.85 \times 10^{-4}$

S.Banerjee, B. Bhattacharjee, M. Mitra, M. Spannowsky
arXiv: 1603.05952

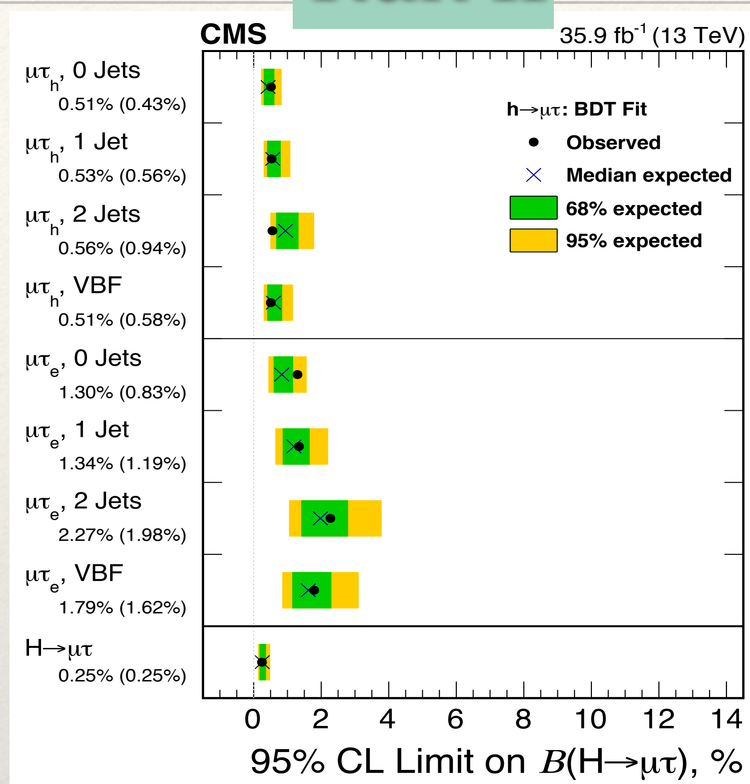
Limits on Branching ratio

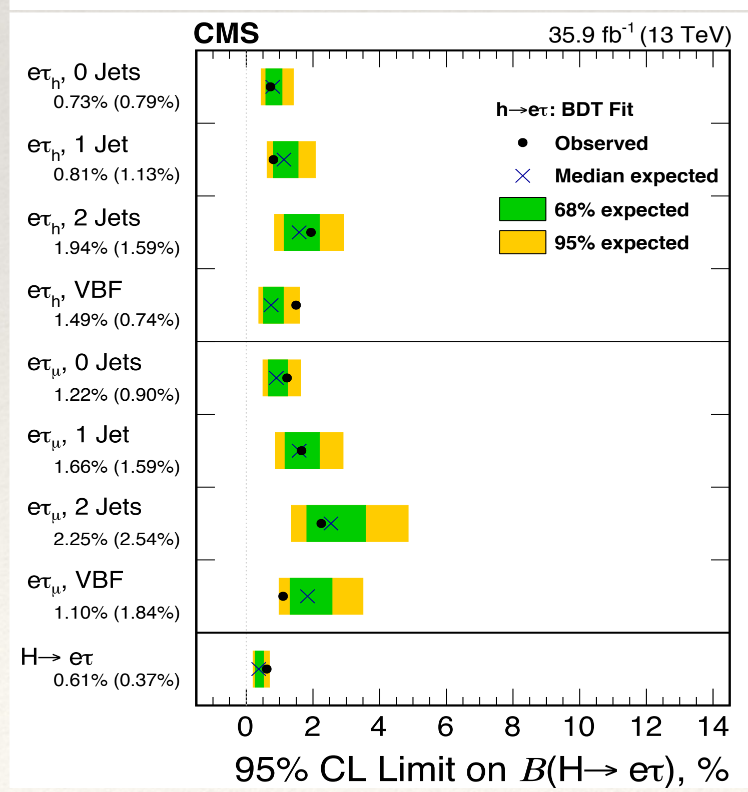
Run I





Run II



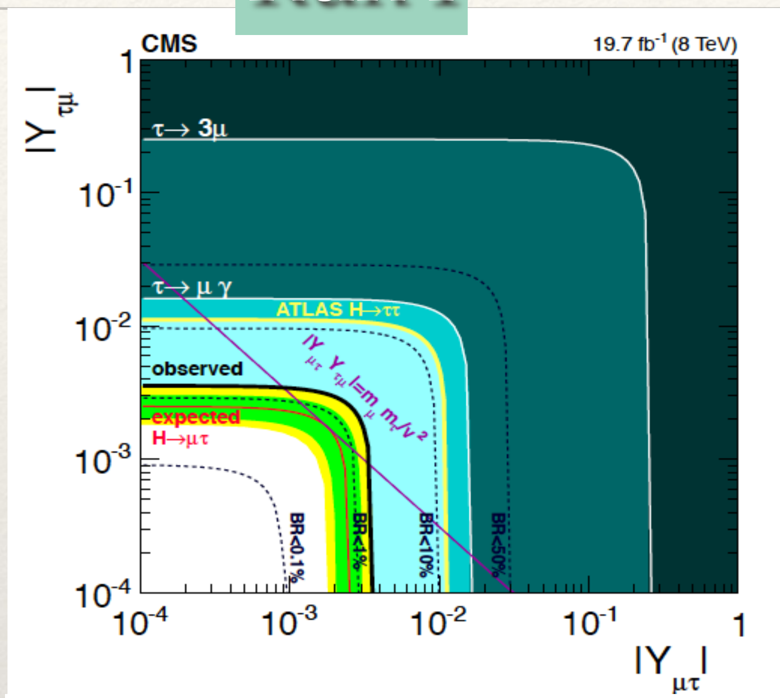


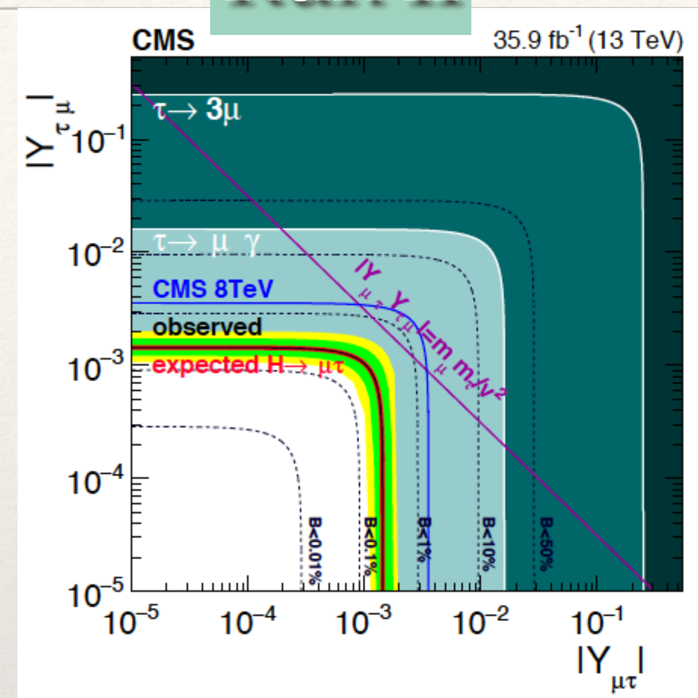
	95% CL(obs/exp) on BR	Best-fit BR
H—>μτ(Run I)	<1.51/0.75%	0.84 +/- 0.38%
H—>μτ(Run II)	<0.25/0.25%	-0.005 +/- 0.121%
H—>eτ(Run I)	<0.69/0.75%	-0.10+/-0.36%
H—>eτ(Run II)	<0.61/0.37%	-0.30+/-0.18%

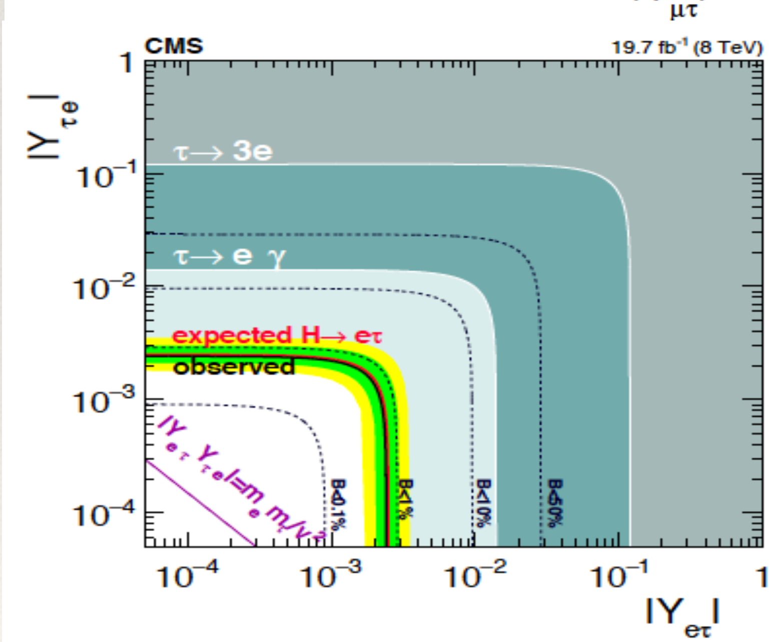
Limits on Yukawa couplings

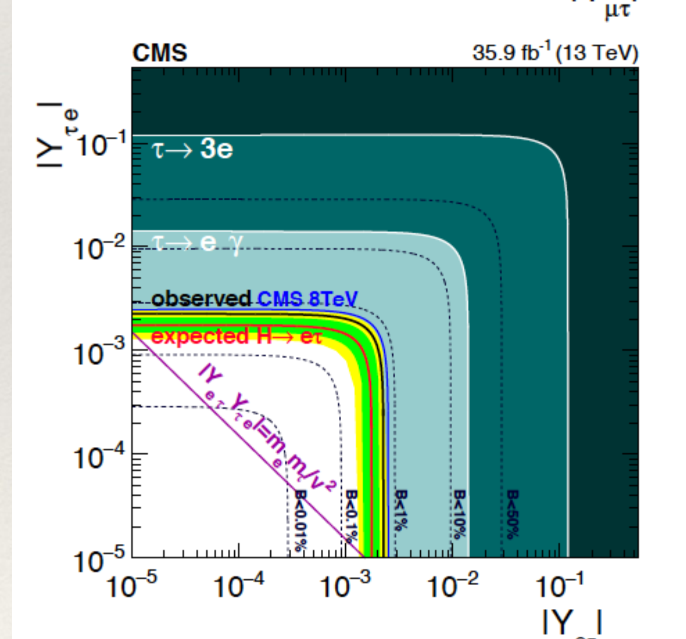
Run I

Run II









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

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

- 95% CL upper limit on BR(H—>μτ) and BR(H—>eτ) can be interpreted in terms of LVF Yukawa couplings from Run II

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \times 10^{-3}$$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \times 10^{-3}$$

Run I: 3.6 x 10^{-3}

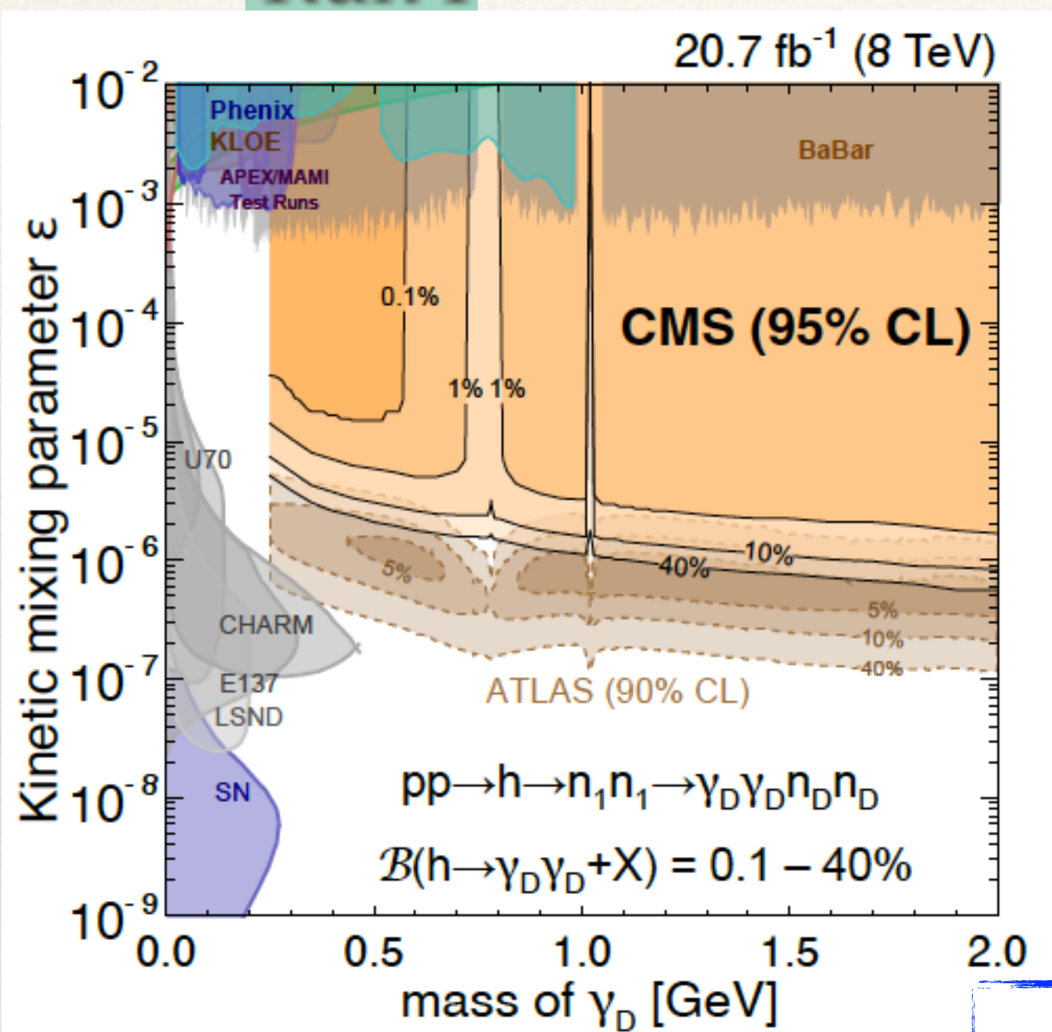
Run I: 2.4 x 10^{-3}

Systematics in LVF decays

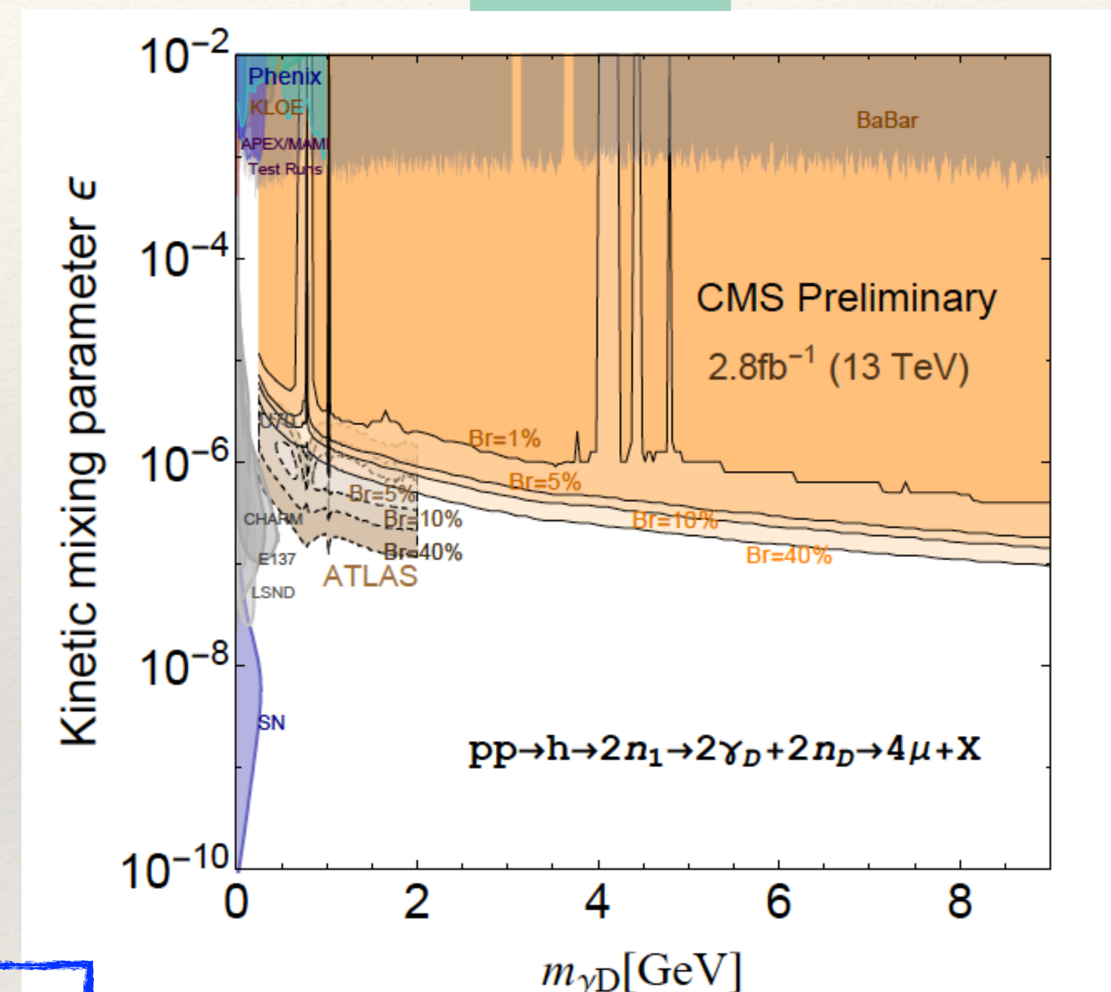
Systematic uncertainty	$H \to \mu\tau_h$	$H \to \mu\tau_e$	$H \to e\tau_h$	$H \to e\tau_\mu$
Muon trigger/identification/isolation	2%	2%	-	2%
Electron trigger/identification/isolation	-	2%	2%	2%
Hadronic tau lepton efficiency	5%	-	5%	-
b tagging veto	2.0–4.5%	2.0–4.5%	-	2.0–4.5%
$Z \to \mu\mu, ee$ + jets background	-	$10\%\oplus5\%$	-	$10\%\oplus5\%$
$Z \to \tau\tau$ + jets background	$10\%\oplus5\%$	$10\%\oplus5\%$	$10\%\oplus5\%$	$10\%\oplus5\%$
W + jets background	-	10%	-	10%
QCD multijet background	-	30%	-	30%
WW, ZZ background	$5\%\oplus5\%$	$5\%\oplus5\%$	$5\%\oplus5\%$	$5\%\oplus5\%$
$t\bar{t}$ background	$10\%\oplus5\%$	$10\%\oplus5\%$	$10\%\oplus5\%$	$10\%\oplus5\%$
$W\gamma$ background	-	$10\%\oplus5\%$	-	$10\%\oplus5\%$
Single top quark background	$5\%\oplus5\%$	$5\%\oplus5\%$	$5\%\oplus5\%$	$5\%\oplus5\%$
$\mu \to \tau_h$ background	25%	-	-	-
$e \to \tau_h$ background	-	-	12%	-
Jet $\to \tau_h, \mu, e$ background	$30\%\oplus10\%$	-	$30\%\oplus10\%$	-
Jet energy scale	3–20%	3–20%	3–20%	3–20%
τ_h energy scale	1.2%	-	1.2%	-
$\mu, e \to \tau_h$ energy scale	1.5%	-	3%	-
e energy scale	-	0.1 – 0.5%	0.1 – 0.5%	0.1 – 0.5%
μ energy scale	0.2%	0.2%	-	0.2%
Unclustered energy scale	$\pm1\sigma$	$\pm1\sigma$	$\pm1\sigma$	$\pm1\sigma$
Renorm./fact. acceptance (ggH)	-3.0% – +2.0%			
Renorm./fact. acceptance (VBF and VH)	-0.3% – +1.0%			
Renorm./fact. scales (ggH) [84]	3.9%			
Renorm./fact. scales (VBF and VH) [84]	0.4%			
PDF + α_s acceptance (ggH)	-1.5% – +0.5%			
PDF + α_s acceptance (VBF and VH)	-1.5% – +1.0%			
PDF + α_s (ggH) [84]	3.2%			
PDF + α_s (VBF and VH) [84]	2.1%			
Integrated luminosity	2.5%			

Limits on Dark SUSY

Run I



Run II

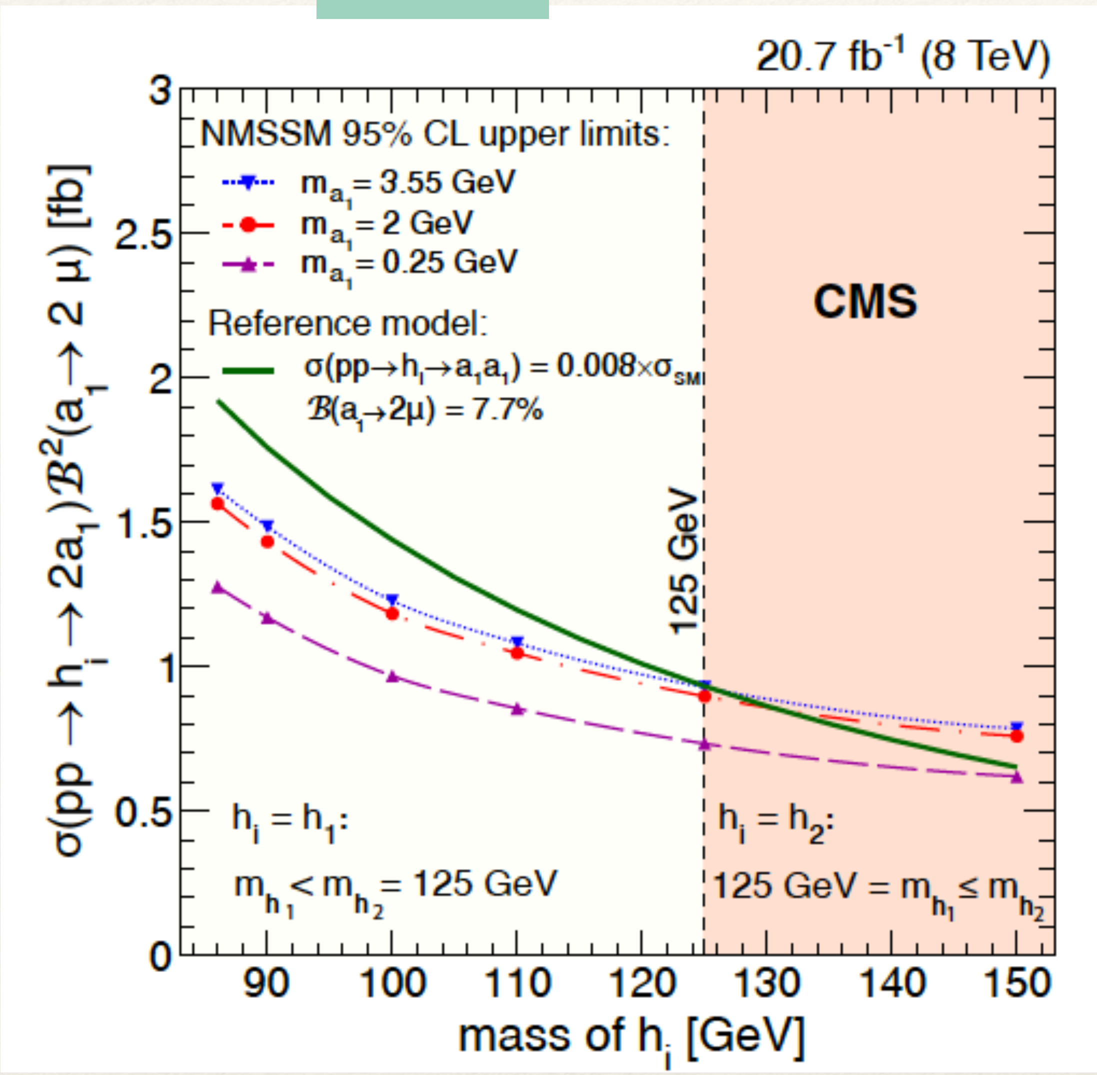


$m_{n1} = 10$ GeV
$m_{nD} = 1$ GeV

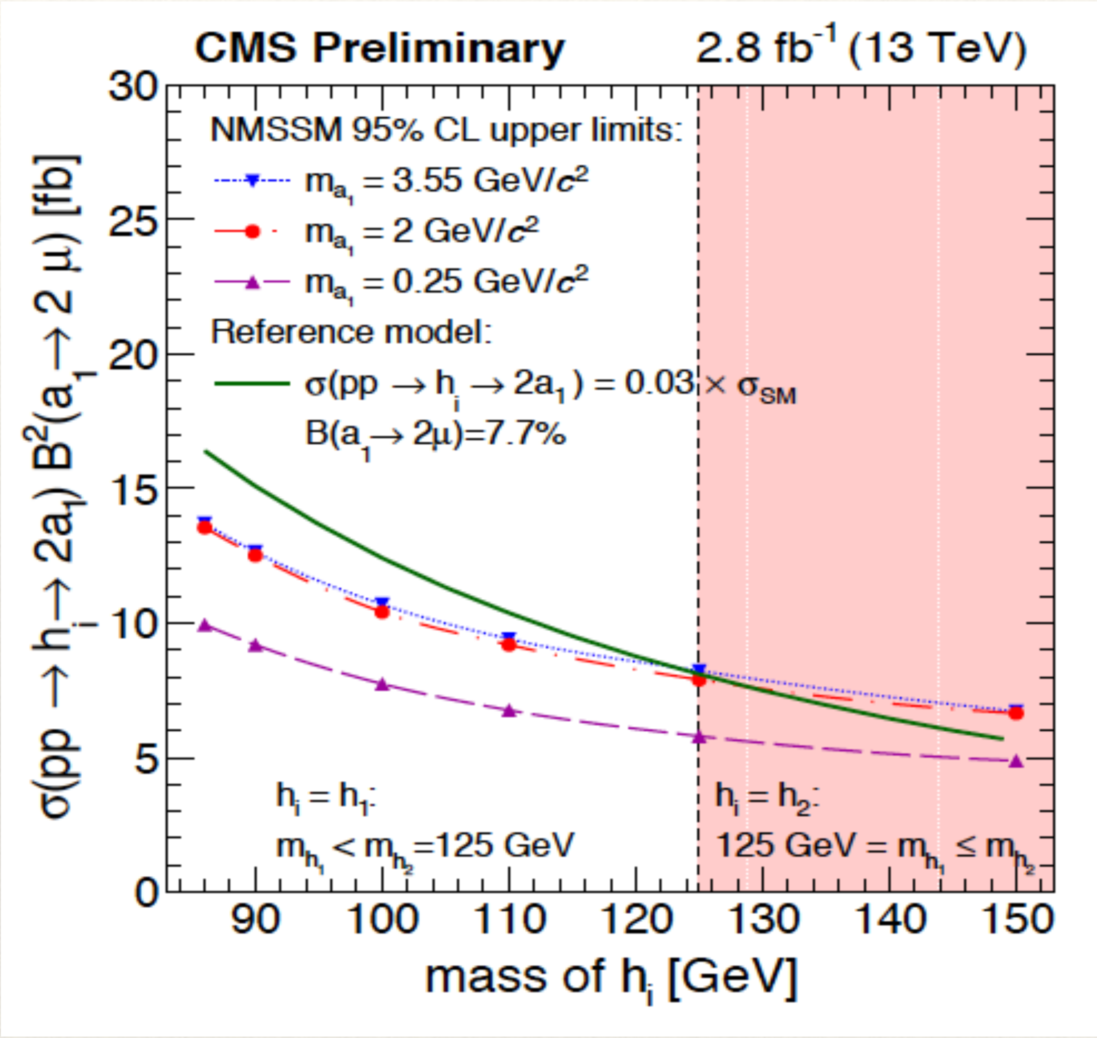
- Model independent limits used to put limits on Dark SUSY

Limits on NMSSM

Run I

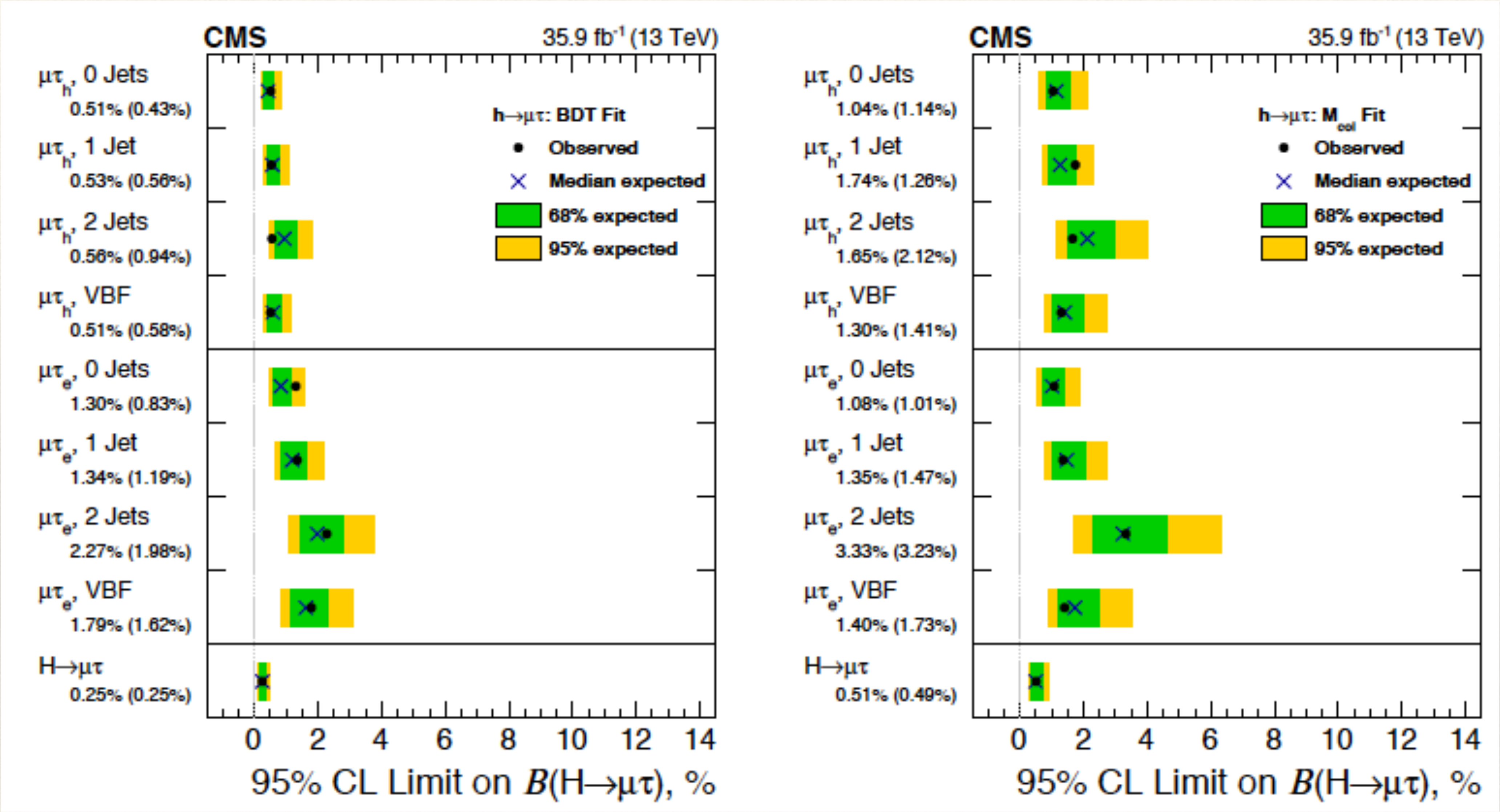


Run II



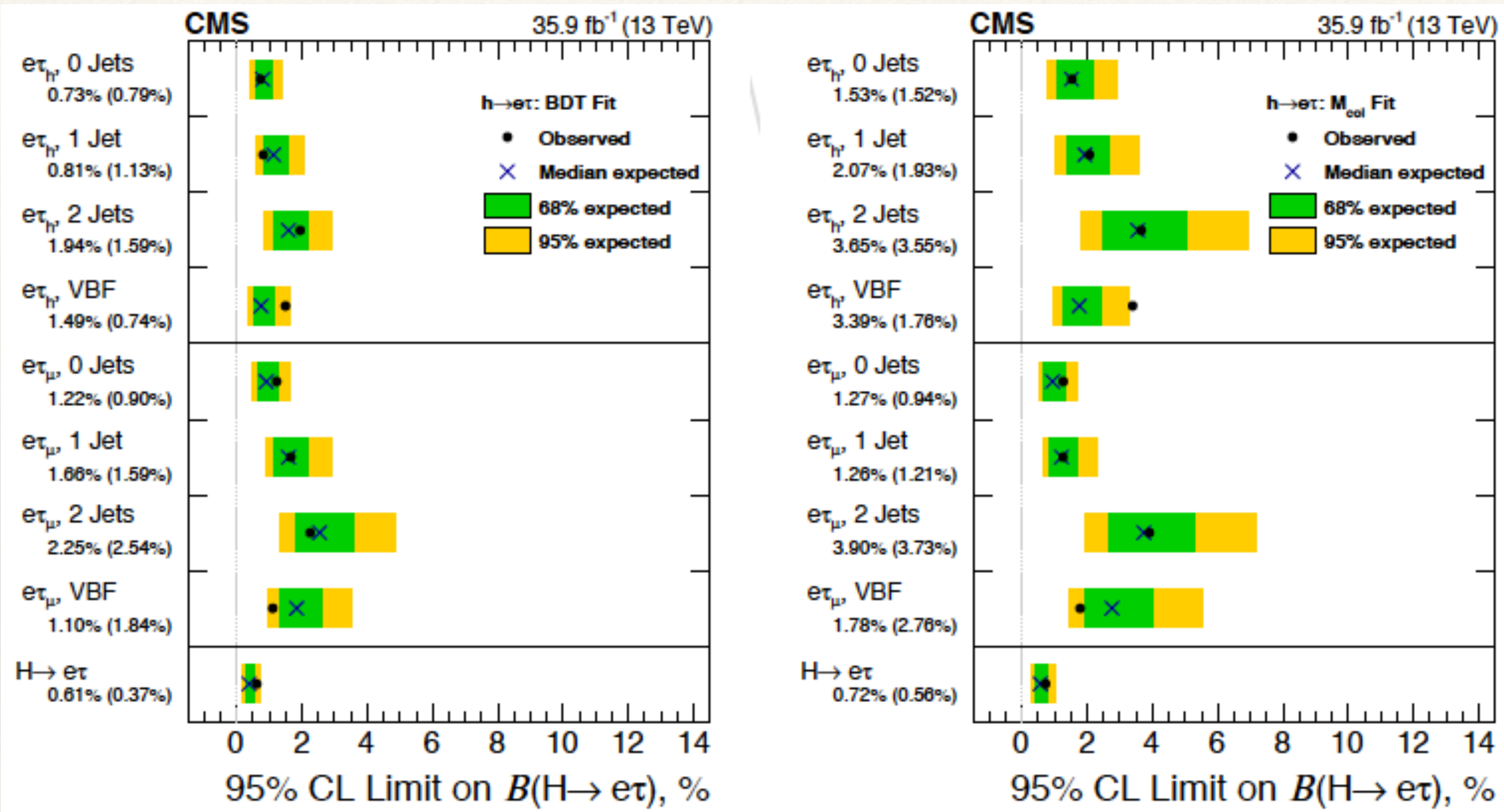
- Model independent limits used to put limits on NMSSM

LFV

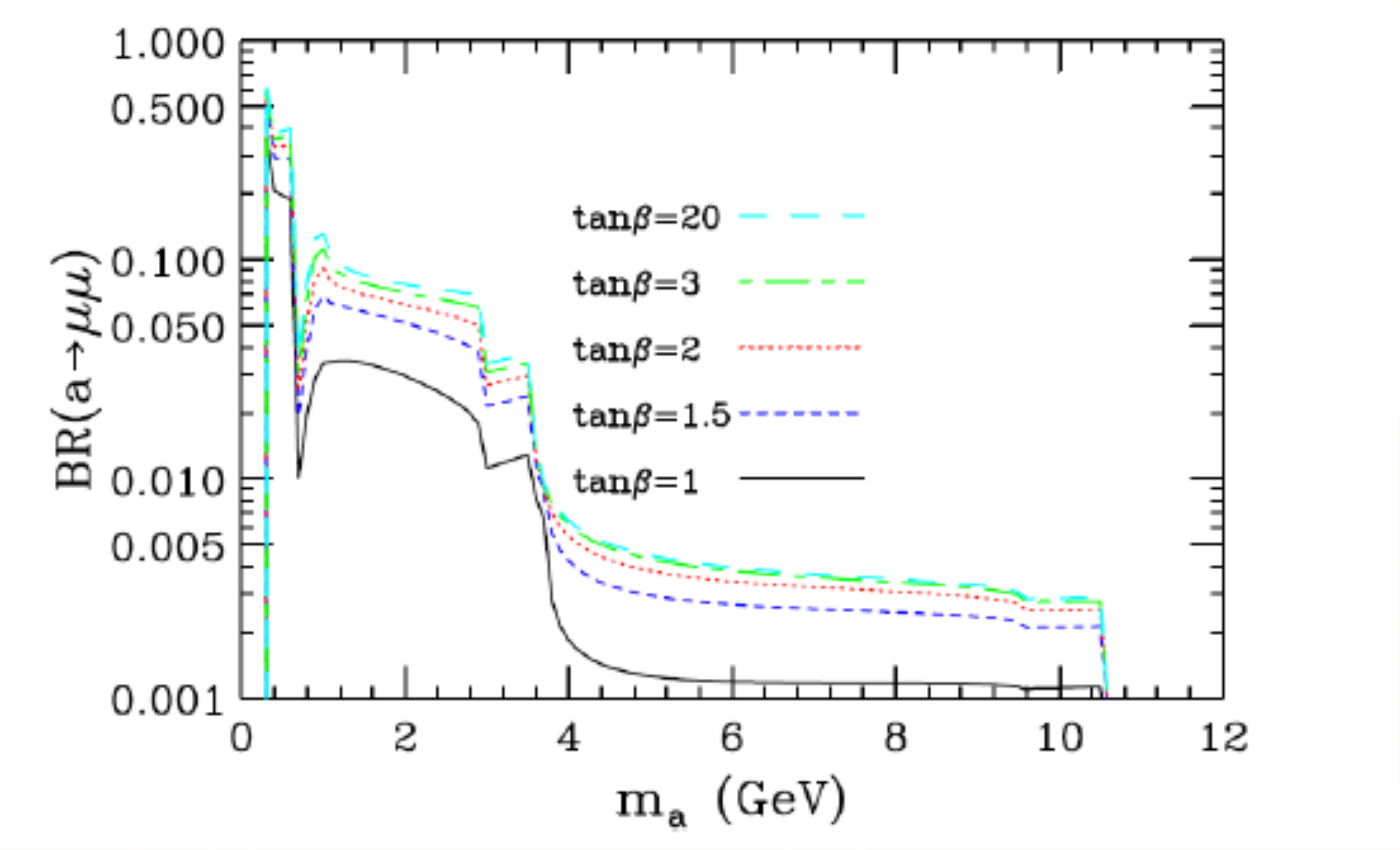


CMS
35.9 fb^{-1} (13 TeV)
$\mu\tau_h$, 0 Jets
0.51% (0.43%)
$\mu\tau_h$, 1 Jet
0.53% (0.56%)
$\mu\tau_h$, 2 Jets
0.56% (0.94%)
$\mu\tau_h$, VBF
0.51% (0.58%)
$\mu\tau_e$, 0 Jets
1.30% (0.83%)
$\mu\tau_e$, 1 Jet
1.34% (1.19%)
$\mu\tau_e$, 2 Jets
2.27% (1.98%)
$\mu\tau_e$, VBF
1.79% (1.62%)
$H\rightarrow\mu\tau$
0.25% (0.25%)
$h\rightarrow\mu\tau$: BDT Fit
Observed
Median expected
68% expected
95% expected
0 2 4 6 8 10 12 14
95% CL Limit on $B(H\rightarrow\mu\tau)$, %
CMS
35.9 fb^{-1} (13 TeV)
$\mu\tau_h$, 0 Jets
1.04% (1.14%)
$\mu\tau_h$, 1 Jet
1.74% (1.26%)
$\mu\tau_h$, 2 Jets
1.65% (2.12%)
$\mu\tau_h$, VBF
1.30% (1.41%)
$\mu\tau_e$, 0 Jets
1.08% (1.01%)
$\mu\tau_e$, 1 Jet
1.35% (1.47%)
$\mu\tau_e$, 2 Jets
3.33% (3.23%)
$\mu\tau_e$, VBF
1.40% (1.73%)
$H\rightarrow\mu\tau$
0.51% (0.49%)
$h\rightarrow\mu\tau$: M_{col} Fit
Observed
Median expected
68% expected
95% expected
0 2 4 6 8 10 12 14
95% CL Limit on $B(H\rightarrow\mu\tau)$, %

LFV


CMS
35.9 fb^{-1} (13 TeV)
$e\tau_h$, 0 Jets
0.73% (0.79%)
$e\tau_h$, 1 Jet
0.81% (1.13%)
$e\tau_h$, 2 Jets
1.94% (1.59%)
$e\tau_h$, VBF
1.49% (0.74%)
$e\tau_\mu$, 0 Jets
1.22% (0.90%)
$e\tau_\mu$, 1 Jet
1.66% (1.59%)
$e\tau_\mu$, 2 Jets
2.25% (2.54%)
$e\tau_\mu$, VBF
1.10% (1.84%)
H→ eτ
0.61% (0.37%)
h→eτ: BDT Fit
Observed
Median expected
68% expected
95% expected
0 2 4 6 8 10 12 14
95% CL Limit on B(H→ eτ), %
CMS
35.9 fb^{-1} (13 TeV)
$e\tau_h$, 0 Jets
1.53% (1.52%)
$e\tau_h$, 1 Jet
2.07% (1.93%)
$e\tau_h$, 2 Jets
3.65% (3.55%)
$e\tau_h$, VBF
3.39% (1.76%)
$e\tau_\mu$, 0 Jets
1.27% (0.94%)
$e\tau_\mu$, 1 Jet
1.26% (1.21%)
$e\tau_\mu$, 2 Jets
3.90% (3.73%)
$e\tau_\mu$, VBF
1.78% (2.76%)
H→ eτ
0.72% (0.56%)
h→eτ: M_{col} Fit
Observed
Median expected
68% expected
95% expected
0 2 4 6 8 10 12 14
95% CL Limit on B(H→ eτ), %

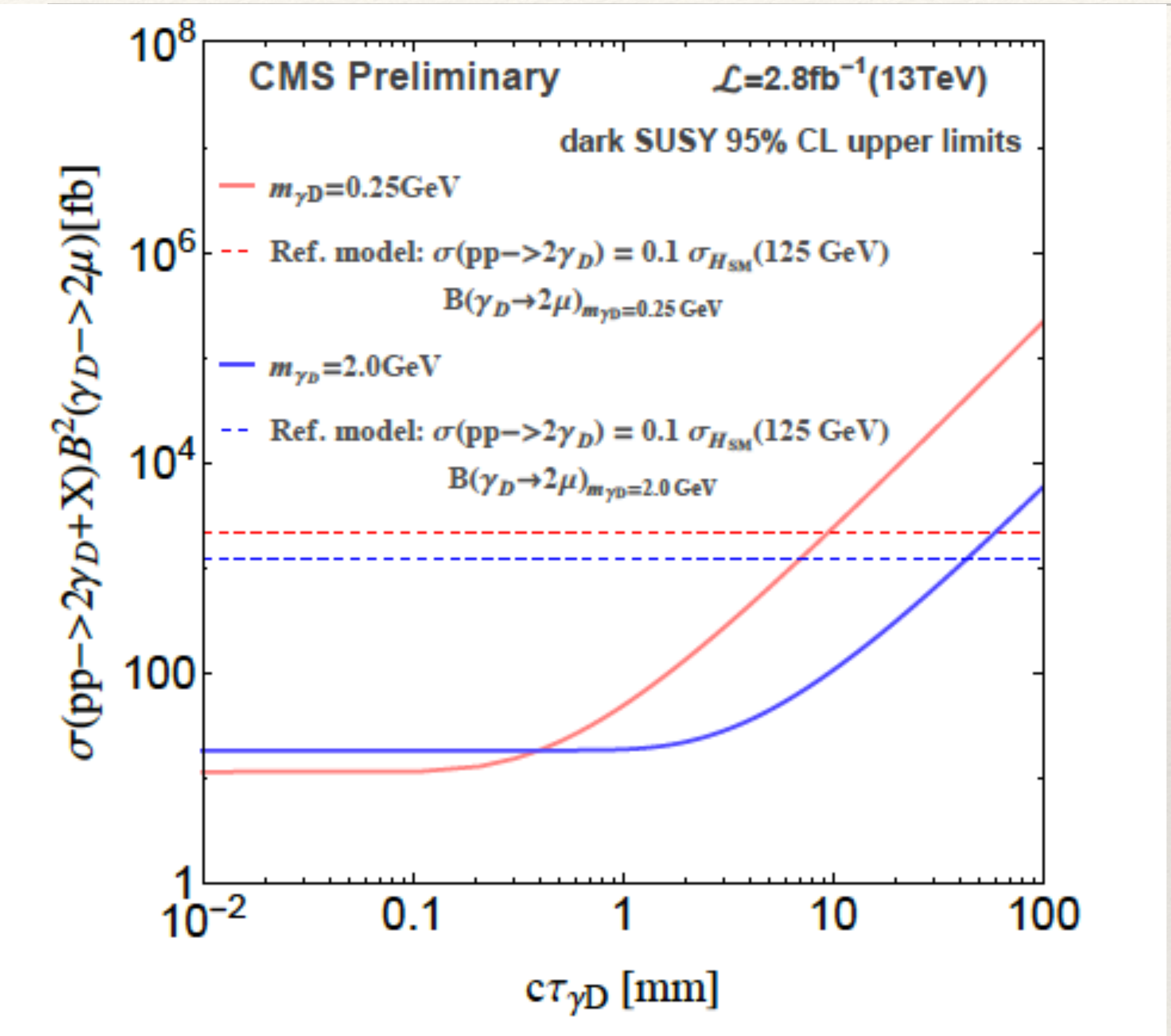
Branching fraction of CP odd Higgs



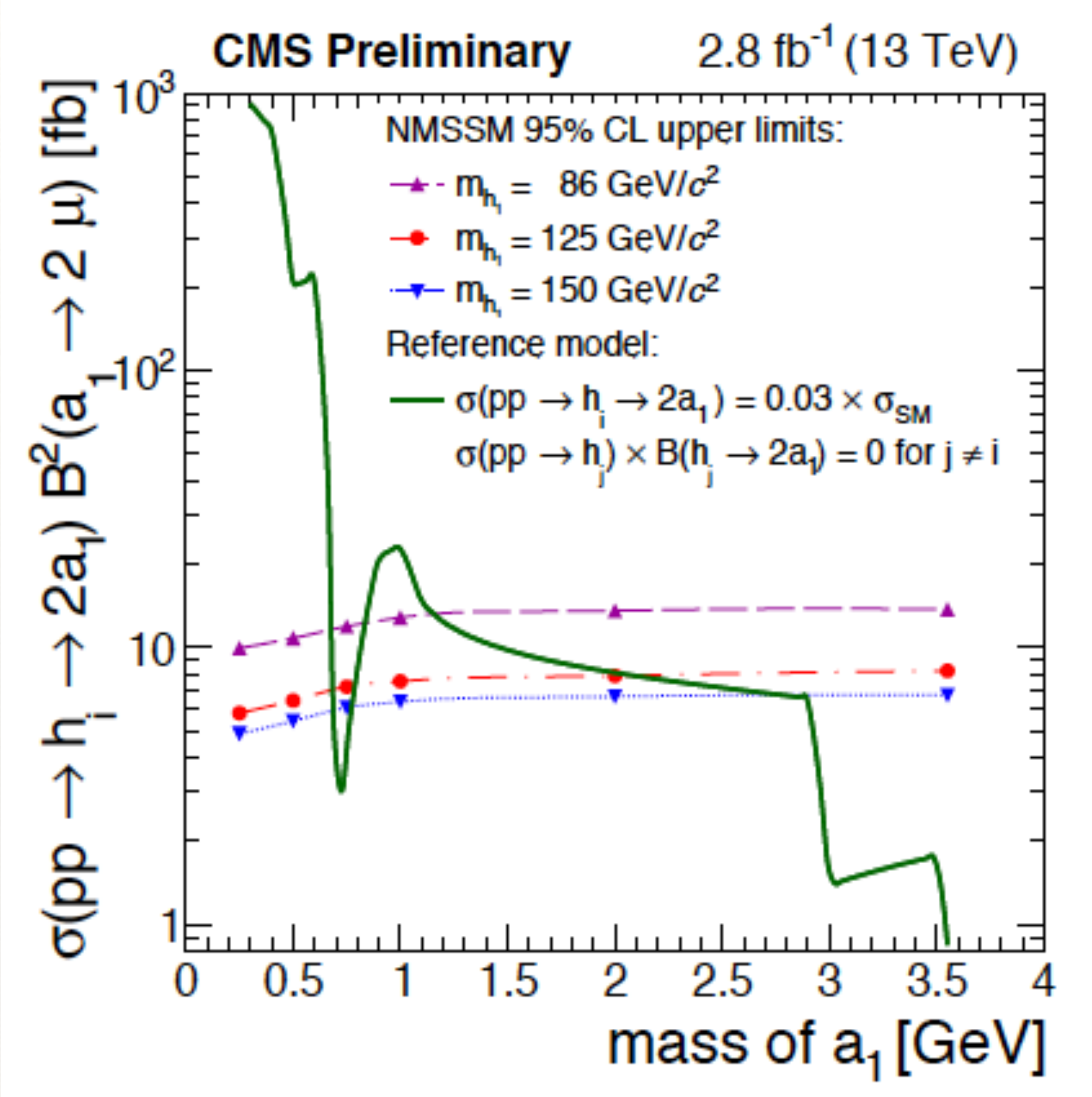
Systematics in light scalar decays of Higgs

Source of uncertainties	Uncertainty [%]
Integrated luminosity	2.7
Muon trigger	3
Muon ID	1 (per μ) $\times$ 4
Muon tracking	0.2 (per μ) $\times$ 4
Di-muon isolation	1 (per di-μ) $\times$ 2
Overlapping in Tracker	1.2 (per di-μ) $\times$ 2
Overlapping in Muon System	1.3 (per di-μ) $\times$ 2
Pile-up	1.6
Dimuons mass consistency	1.5
NNLO Higgs p_T re-weighting	2.0
PDF+α_s	3.0
Total	11.1

H—>aa—>4μ



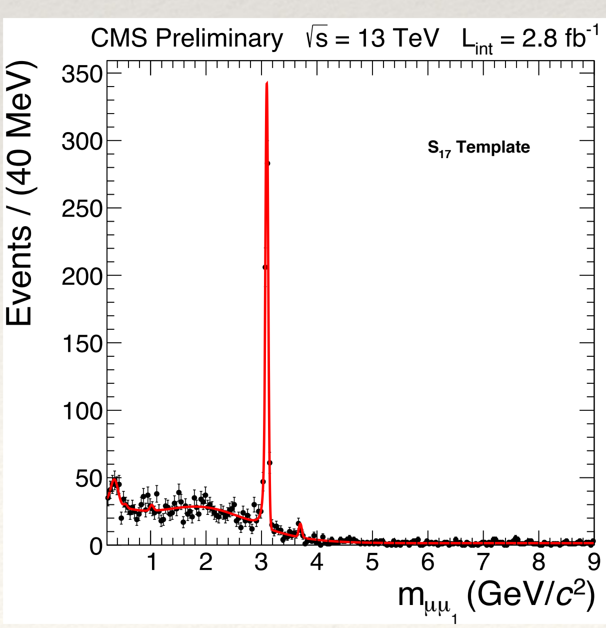
Dark SUSY



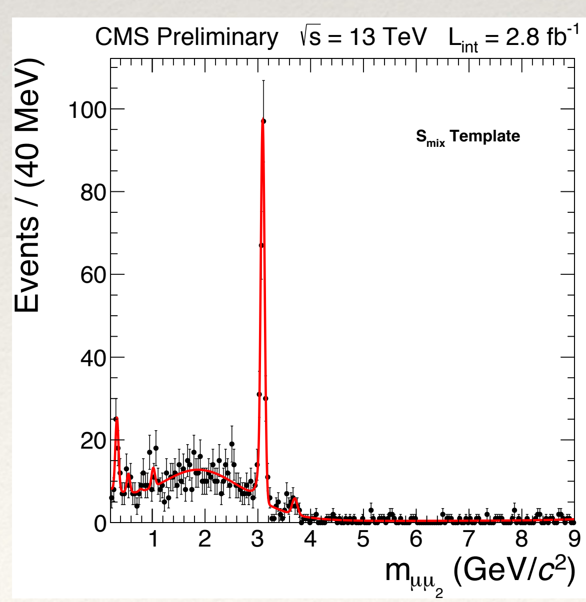
NMSSM

Background estimation

- EWK to 4 muons (minor contribution): pp—>4μ: contribution is estimated using MC simulation
- Prompt J/ψ(minor contribution): estimated with a combination of data and MC simulation
- Events containing bb in the final state (Leading background)
  - Leading contribution from b-quark decays to pairs of muons via double semileptonic decays or resonances, i.e. ω, ϱ, ϕ, J/ψ
  - Estimated from data:
    - Modeled as a 2D template in the plane of invariant mass of 2 di-muons: B_{bb}(m1,m2), m1 refers to the dimuon system with muon pT > 17 GeV
    - Templates: S_{17} (both muon pairs contain a high pT muon); S_{mix} (just one contains a high pT muon), constructing from bb enriched egion



X



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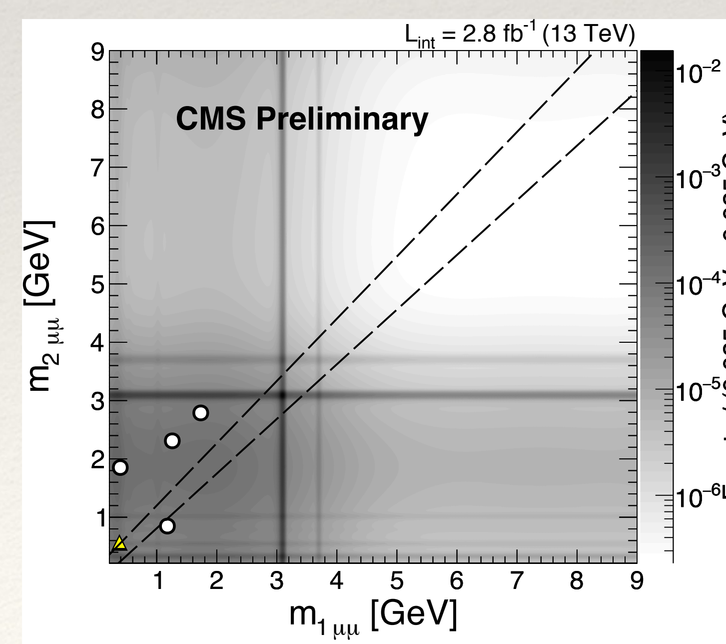

Event yield in H –> γ*γ and H –> J/ψγ

Sample	Signal events before selection $m_H = 125\,GeV$	Signal events after selection $m_H = 125\,GeV$	Number of events in data $120 < m_{\ell\ell\gamma} < 130\,GeV$
$\mu\mu\gamma$	13.9	3.3	151
$ee\gamma$	25.8	1.9	65
$(J/\psi \rightarrow \mu\mu)\gamma$	$0.065(J/\psi) + 0.32$ (non-res.)	$0.014(J/\psi) + 0.078$ (non-res.)	12

Event yield in H –> Zγ

Table 1: Observed and expected event yields for a 125 GeV SM Higgs boson.

Sample	Integrated luminosity (fb^{-1})	Observed event yield for $100 < m_{\ell\ell\gamma} < 190$ GeV	Expected number of signal events for $m_H = 125$ GeV
2011 ee	5.0	2353	1.2
2011 $\mu\mu$	5.1	2848	1.4
2012 ee	19.6	12899	6.3
2012 $\mu\mu$	19.6	13860	7.0