Exotic Decays of h(125)

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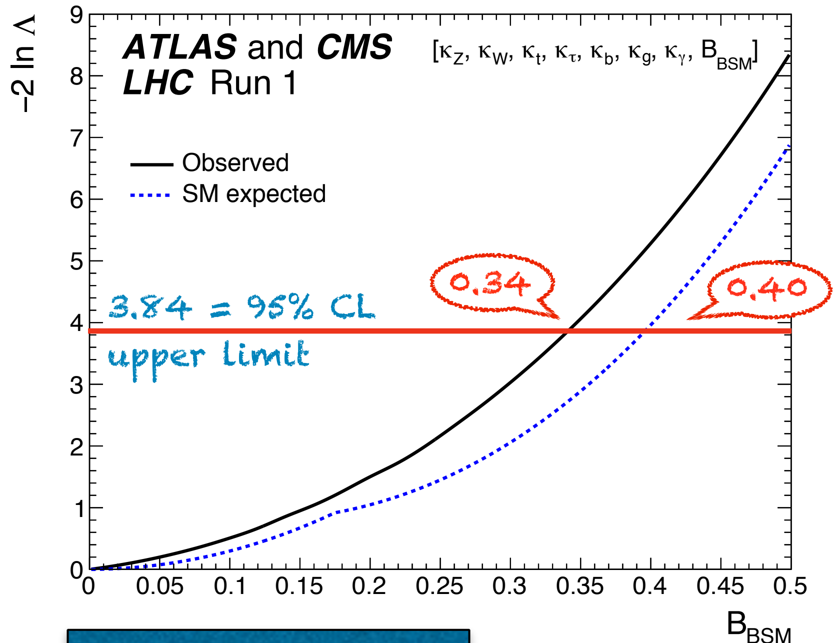
on behalf of the CMS and ATLAS Collaborations

Precision theory for precise measurements at LHC and future colliders
Quy Nhon, Vietnam (25 Sep to 1 Oct 2016)

HELMHOLTZ ASSOCIATION | DESY | CMS Compact Muon Solenoid | ATLAS EXPERIMENT

Exotic decay modes : Why?

- Standard Model (SM) successfully describe particles and interactions but doesn't address the hierarchy problem, fine tuning, dark matter … ➜ **need to go beyond the SM**
  - The discovered Higgs at 125 GeV can play a crucial role in probing BSM physics
- Combined ATLAS and CMS couplings measurements constrains **BR(H → BSM) < 0.34 (0.4)** at 95% CL from Run-1 data (7 and 8 TeV)
  - **Still room for "New Physics"!**



JHEP 08 (2016) 045

- Many BSM theories such as SUSY, 2HDM, EWS (etc.) predict such decays, e.g.
  - Higgs → invisible particles
  - Higgs → light (pseudo-)scalars
  - LFV Higgs
- CMS and ATLAS experiments are actively working on the full Run-2 data to cover large number of BSM Higgs searches
- **Is it the time for BSM era?**

Exotic decay modes : Which?

Theoretical models include :

more details given by W. Jiawei

- **Two Higgs Doublet Models (2HDM)** extend beyond the SM Higgs sector by including two complex Higgs doublets, which, after symmetry breaking, lead to five physical states

  $$H^+, H^-, A \text{ (CP-odd)}, H^0, h \text{ (CP-even)}$$

  - e.g. $h \to AA$, $H^0 \to hh/AA$, LFV of the Higgs
  - an additional scalar singlet (**2HDM+S**) — CP-even (h_1,h_2,h_3), CP-odd (a_1,a_2), H^+, H^-
- **Minimal Supersymmetric Standard Model (MSSM)** describes solution to hierarchy problem and dark matter (DM) candidates
  - e.g. $h \to \chi_i \chi_j$ (i.e. Higgs to invisible searches)
- **Next-to-MSSM (NMSSM)** provides larger possibilities for the Higgs decays to other (pseudo-) scalars as well as the neutralinos sectors
- Other models such as **Little Higgs model**, include Higgs as a composite particle, or Higgs decays to valley particles which in turn decay to SM particles in **Hidden Valley models**
  - e.g. LFV of the Higgs, $h \to$ dark sector

Exotic decay modes : Which?

Experimental results so far...

h(125) → (pseudo)scalars

- CMS results currently cover **h → aa → μμμμ, μμbb, μμττ, ττττ**
- ATLAS results currently cover **h → aa → γγγγ, μμττ and Wh → aa → bbbb**

Lepton Flavor Violating (LFV) of h(125)

- CMS and ATLAS results both cover **LFV h → eτ, μτ and eμ**

not covered here

h(125) → dark sector (invisible, dark photons, …)

- gluon-gluon fusion (ggF) : events with ISR jet (Monojet search)
- vector boson fusion (VBF) : events with two tagged jets
- associated production with W/Z (VH) : events with leptons/hadrons from W/Z
  - Z → ll, Z → bb, V → jj

see talk given by L. Truong

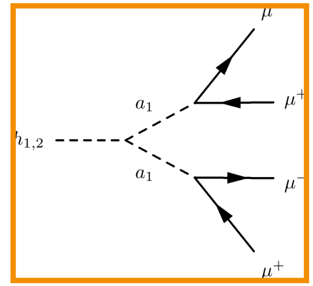
$h(125) \rightarrow aa$

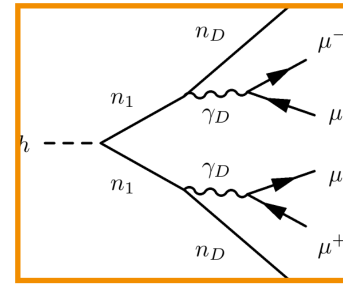
h → aa → 4μ

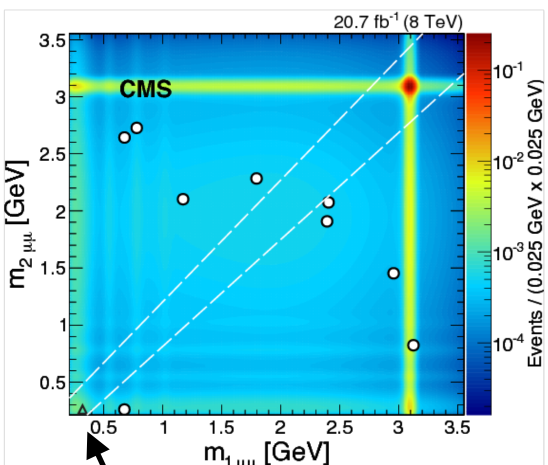
8 TeV 20 fb^{-1}

Phys.Lett.B 752(2016)146-168

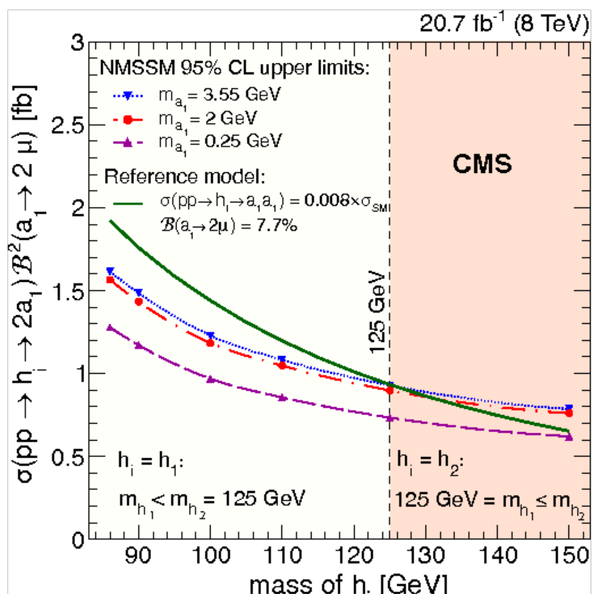
- Two models interpretation
  - NMSSM benchmark $h \to aa \to 4\mu$ ($2m_\mu \le m_a \le 2m_\tau$)
  - Dark SUSY benchmark $h \to 2n_1 \to 2n_D + 2\gamma_D \to 4\mu$
- Very small mass range $m_a \in 0.25$ to 3.55 GeV
- Main backgrounds from bb, J/Ψ and $pp \to 4\mu$
- No excess data is observed
  - diagonal signal region : $m_{\mu\mu 1} \simeq m_{\mu\mu 2}$

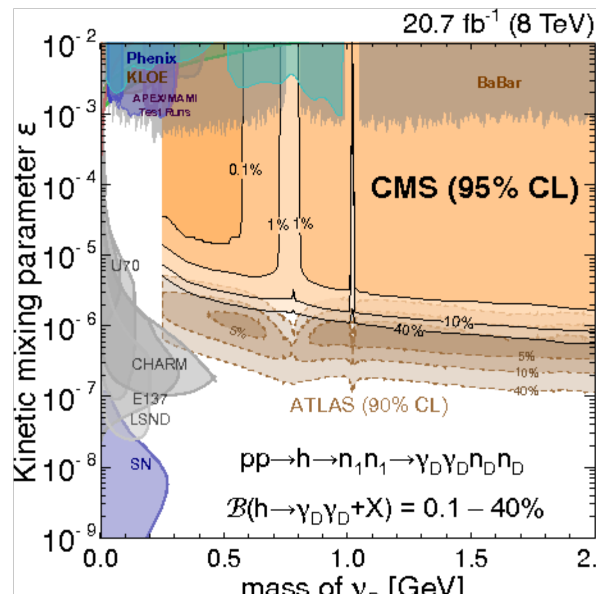






observed 1 event w.r.t
2.2 ± 0.7 SM background



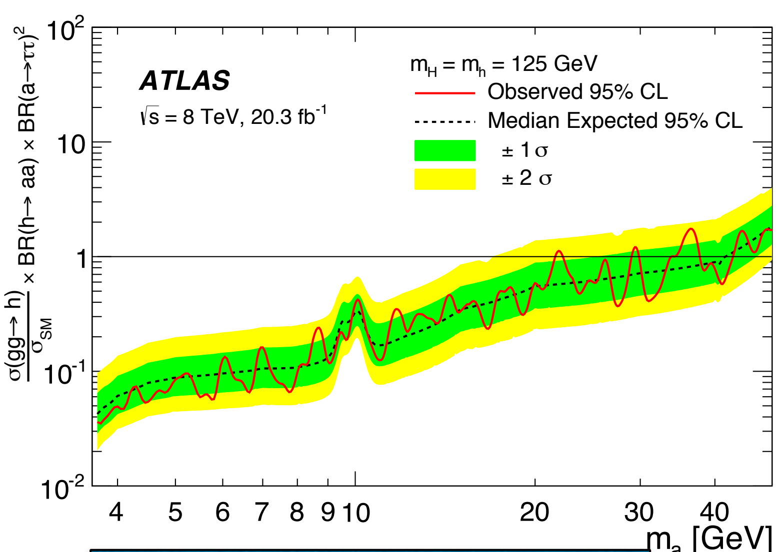


h → aa → μμττ

8 TeV 20 fb^{-1}

- Well-motivated by **2HDM+S,** especially type-3 at large tan**β** and type-4 at small tan**β**
- Reconstructed events with 2 muons (good resolution) plus 2 taus
  - CMS combined 5 final states → $\mu\mu\tau_e\tau_e$, $\mu\mu\tau_e\tau_\mu$, $\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$ and $\mu\mu\tau_h\tau_h$
  - ATLAS considered two μ + one lepton (e,μ) and tracks
- Limits are set on Br(h → aa) x Br(a → ττ)^2 from an unbinned fit of $m_{\mu\mu}$ distributions
  - CMS placed upper limits between 4-15% for $m_{\mu\mu} \in$ 20 to 62.5 GeV
  - ATLAS provided the most stringent limit at 3.5% for $m_{\mu\mu}$ 3.75 GeV over 3.7 to 50 GeV

- No significant excess of data over SM backgrounds



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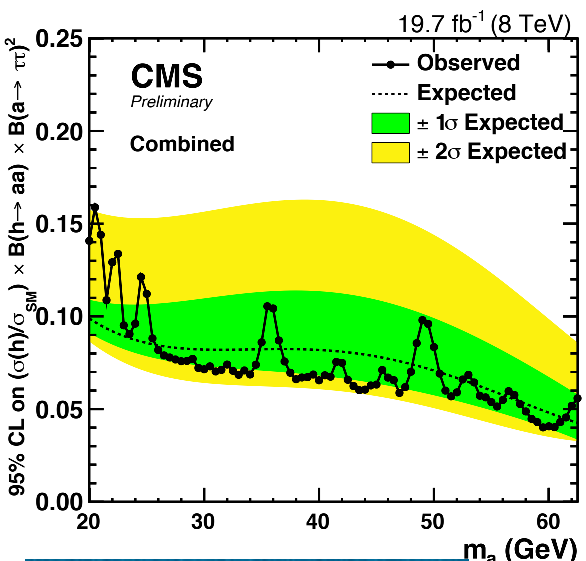
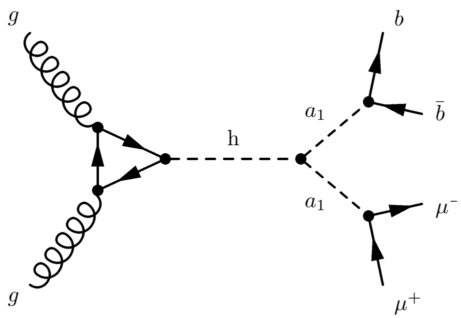


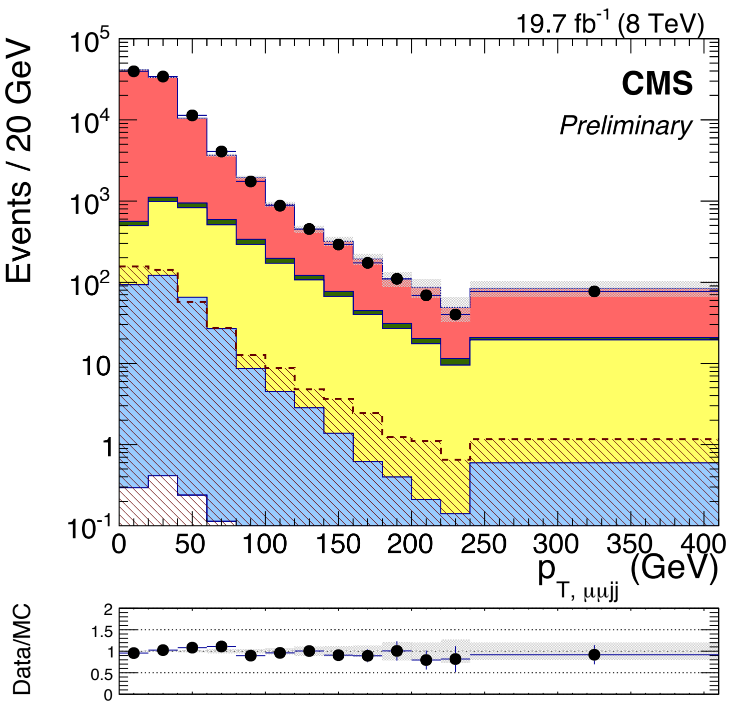
CMS PAS HIG-15-011

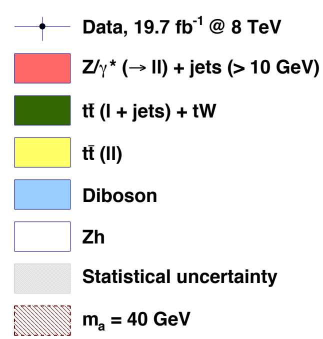
h → aa → μμbb

8 TeV 20 fb-1

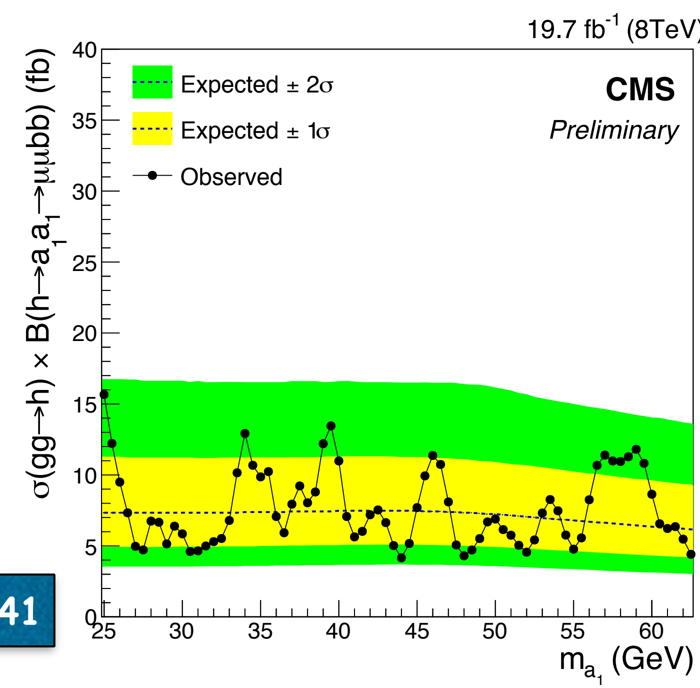


- Interpretation of **NMSSM** and even more generic **2HDM+S**
- Advantage of the higher rate and lower background contamination in comparison with the 4μ and 4b final states
- No significant excess is observed
  - upper limits are set on $\sigma_{ggF} \times Br(h \to aa \to \mu^+\mu^- bb)$ with ranging between 4 to 12 fb for $m_{\mu\mu} \in$ 25 to 65 GeV





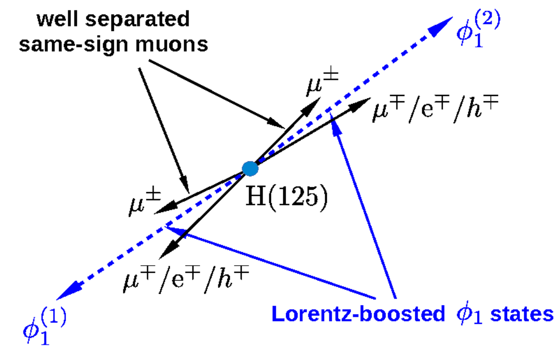
CMS PAS HIG-14-041



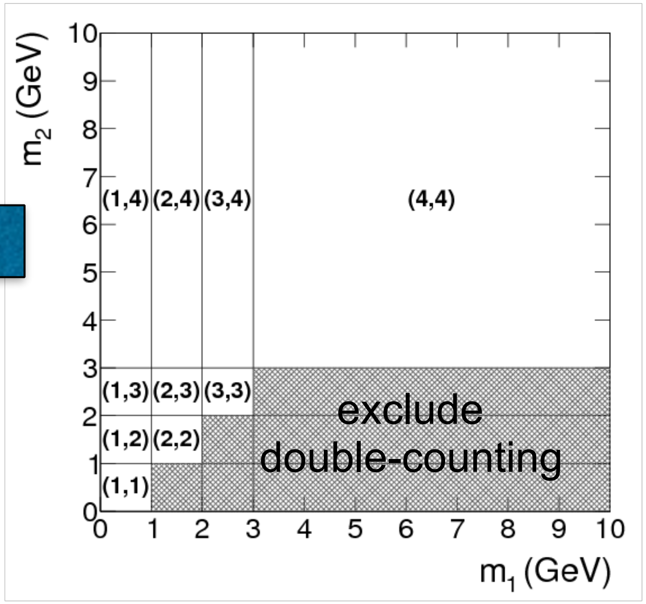
h → aa → 4τ (1)

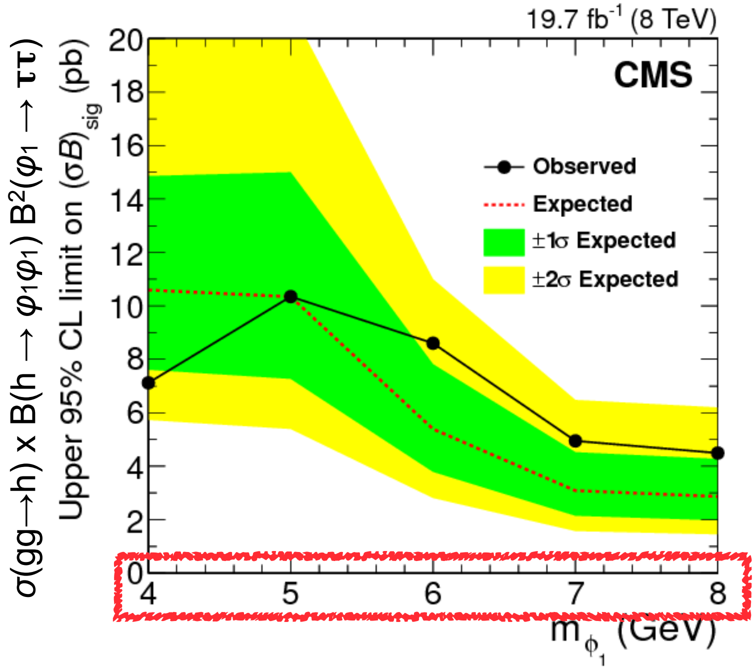
8 TeV 20 fb^{-1}

- Focus ggh → aa → 4τ within the framework of **NMSSM**
  - same-sign di-muon events with large angular separation plus one nearby opposite-sign track (μ+track)
- Signal extracted with binned maximum likelihood fit to the 2D distribution of ($m_{\mu track1}$,$m_{\mu track2}$)
- No excess data is observed
  - upper limits range from 4.5 pb at $m_{a_1}(m_{h_1})$ = 8GeV to 10.3 pb at $m_{a_1}(m_{h_1})$ = 5GeV



JHEP 01(2016)079



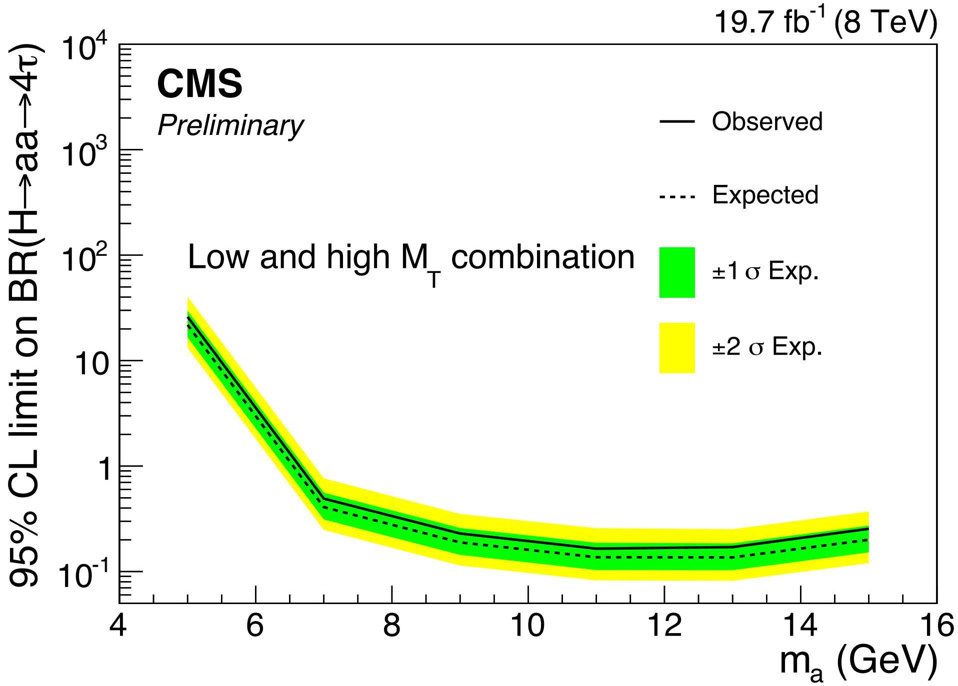


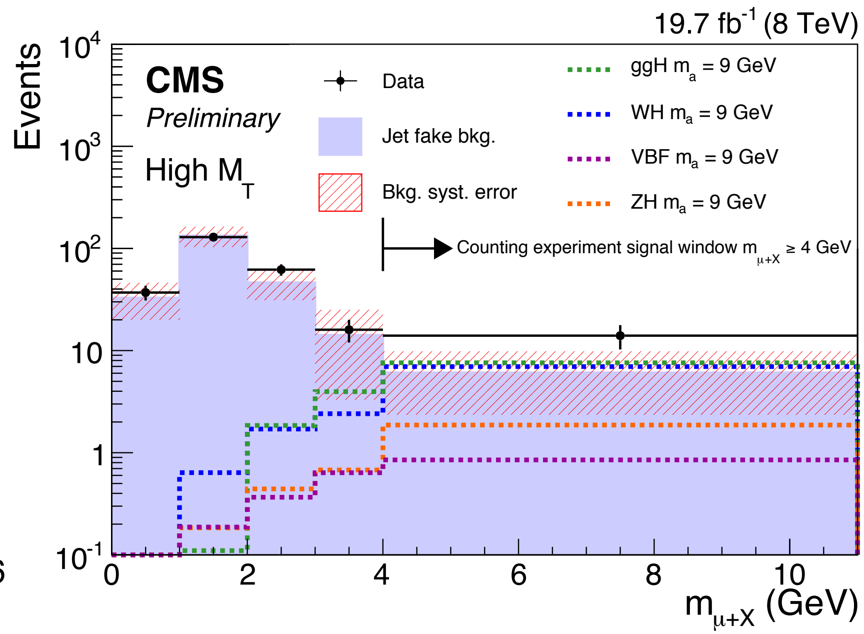
$h \rightarrow aa \rightarrow 4\tau$ (2)

8 TeV 20 fb^{-1}

- Different approach (μ+jet) within the context of **NMSSM and 2HDM+S**
  - including ggH, WH, ZH and VBF production modes of h(125)
  - higher mass region covered $m_a \in$ 5-15 GeV
- Simple counting experiment
- No excess of events above the SM backgrounds is found
  - upper limits on $BR(H \rightarrow aa/hh)BR^2(a/h \rightarrow \tau\tau)$ are set assuming SM cross-sections for all Higgs production modes

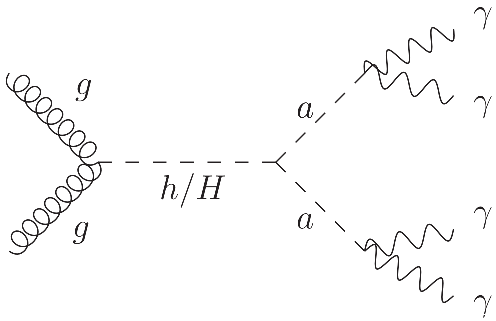
CMS PAS HIG-14-022





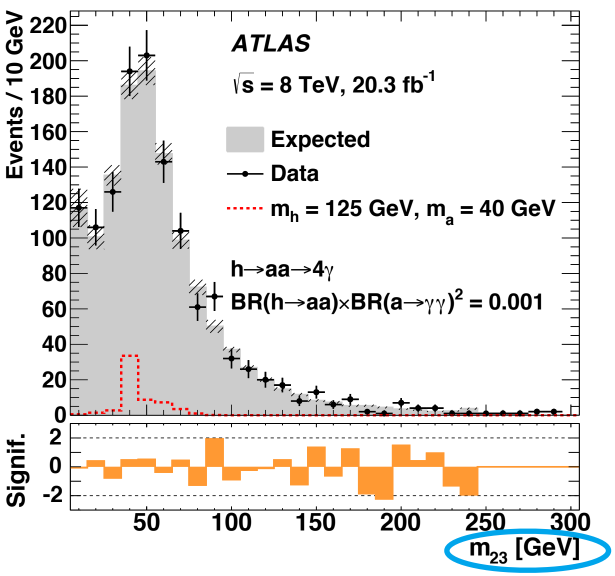
$h \rightarrow aa \rightarrow 4\gamma$

8 TeV 20 fb^{-1}

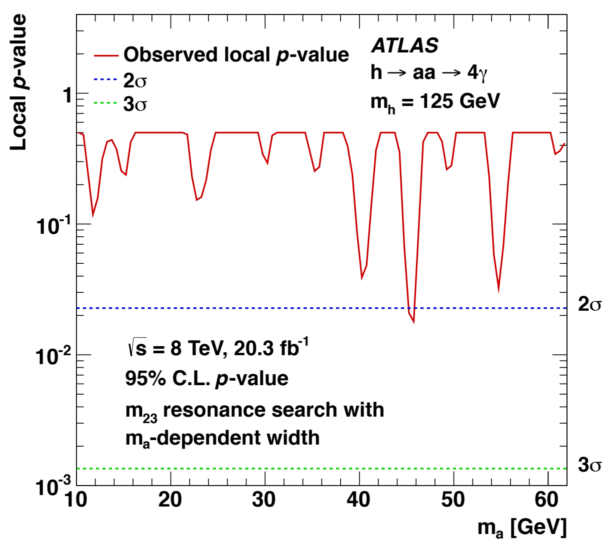


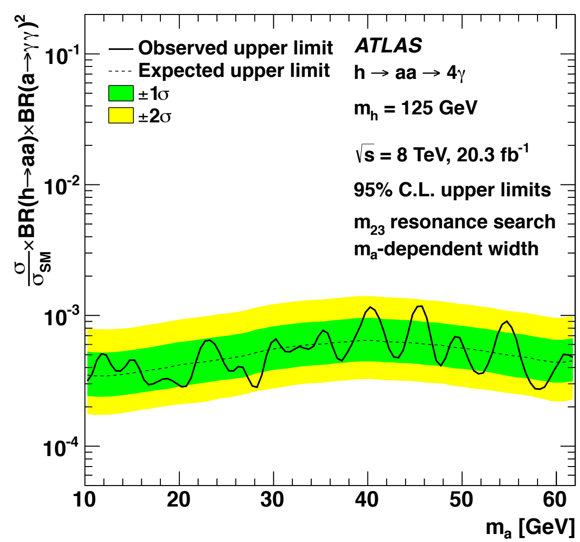
EPJC 76(4)1-26(2016)

- Inclusive three photons search interpreted in **NMSSM** context
  - select events have ≥ 3γ with p_T > 22,22,17 GeV
- Main backgrounds estimated from MC and data
  - irreducible multi-photon processes by MC
  - photons+jet (jet fakes) from data
- No excess above SM backgrounds is detected
  - Limits are found to be $\sigma \times BR(h \rightarrow aa) \times BR(a \rightarrow \gamma\gamma)^2 < 10^{-3}\sigma_{SM}$ for $m_a \in$ 10-62 GeV



2nd+3rd leading p_T photon



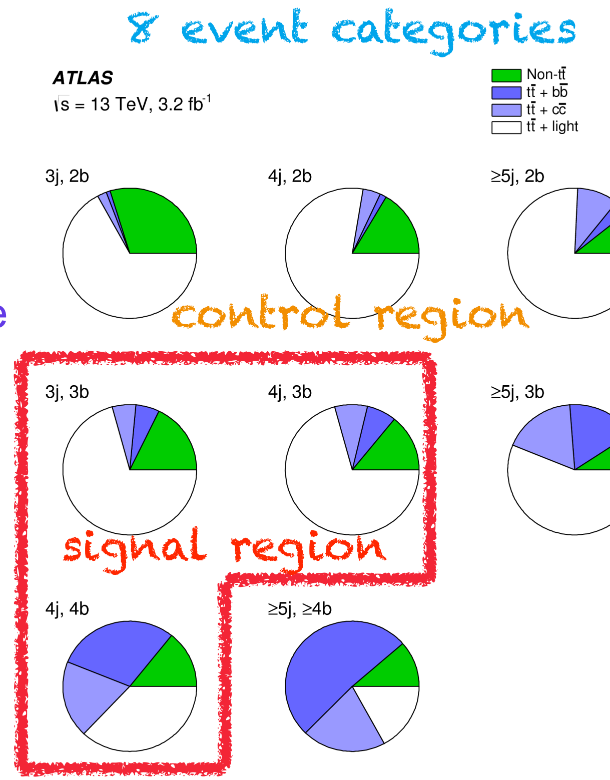


$Wh \to aa \to 4b$

13 TeV 3.2 fb^{-1}

arXiv:1606.08391

- First published result from 13 TeV data at the LHC
- Associated production of h(125) with W boson
  - charged lepton from W provides efficient trigger and background reduction
  - final states contain e/μ + $E_{T,miss}$ + multi-jets (≥ 2 b-tagged)
- In the framework of **NMSSM** covered $m_a \in$ 20-60 GeV
- 8 categories from N_{jets} (3,4,≥5) mixed with $N_{b\text{-tagged}}$ (2,3,≥4)
  - 3 signal regions (3j,3b), (4j,3b), (4j,4b)
  - 5 control regions — tt background constraint
- The Boosted Decision Tree (**BDT**) is trained to discriminate between signal events with an m_a of 60 GeV and tt events



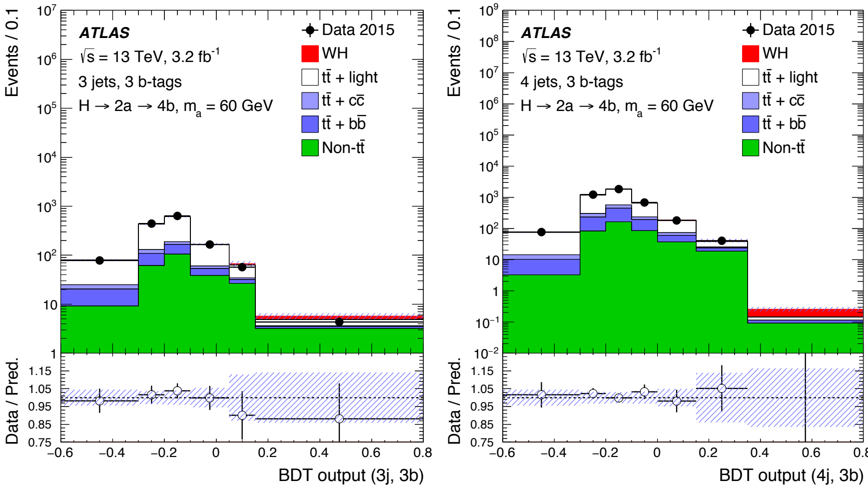
kinematic variables for BDT

Region		m_{bbb}	m_{bbbb}	Δm^{bb}_{min}	H_T	p^W_T	ΔR^{bb}_{av}	$\Delta R^{\ell b}_{min}$	m_{bbj}	m_{T2}
	(3j, 3b)	✓			✓	✓	✓	✓		
Signal	(4j, 3b)	✓			✓	✓	✓		✓	
	(4j, 4b)		✓	✓	✓		✓			✓
Control					✓					

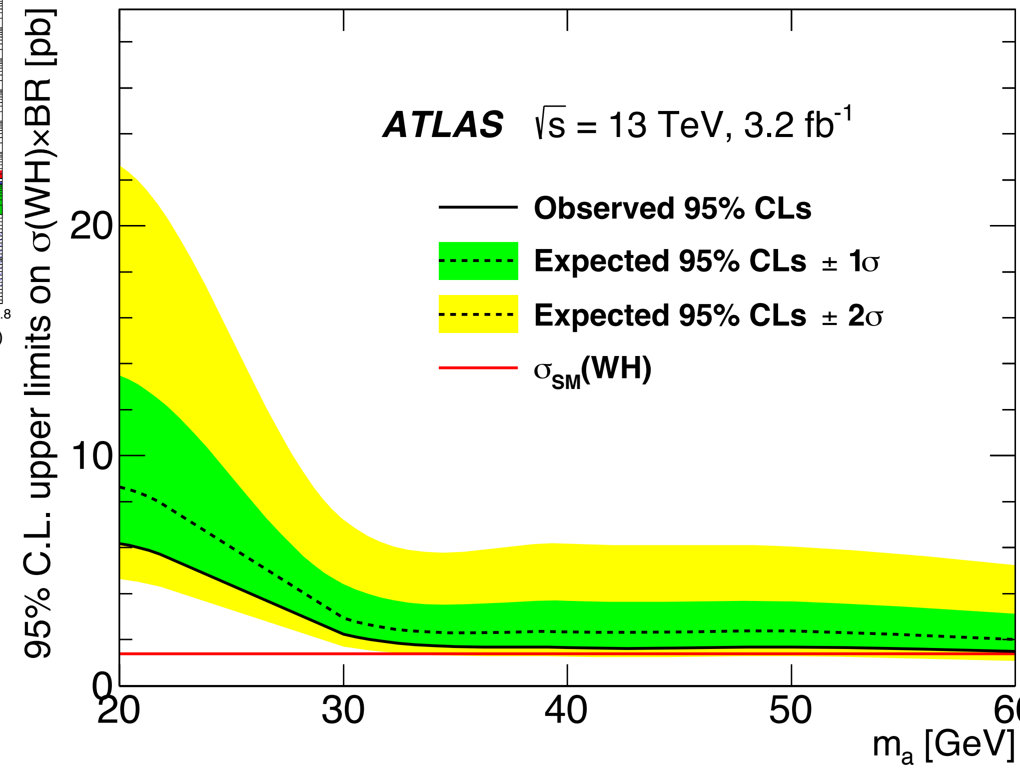
Wh → aa → 4b

13 TeV 3.2 fb^{-1}

arXiv:1606.08391



Process	(3j, 3b)	(4j, 3b)	(4j, 4b)
$t\bar{t}$ + light	1089 ± 76	2940 ± 180	53 ± 16
$t\bar{t} + c\bar{c}$	70 ± 28	280 ± 110	21 ± 11
$t\bar{t} + b\bar{b}$	172 ± 55	610 ± 160	74 ± 15
$t\bar{t} + \gamma/W/Z$	0.8 ± 0.1	4 ± 1	0.4 ± 0.1
W + jets	93 ± 31	129 ± 40	2 ± 1
Z + jets	18 ± 12	14 ± 10	–
Single-top-quark	135 ± 13	208 ± 17	8 ± 1
Multijet	48 ± 20	67 ± 28	4 ± 2
Dibosons	4 ± 1	9 ± 1	0.6 ± 0.4
$t\bar{t} + H$	0.7 ± 0.1	4 ± 1	0.8 ± 0.2
Total	1640 ± 58	4270 ± 130	165 ± 15
Data	1646	4302	166
WH, $H \to 2a \to 4b$			
m_a = 60 GeV	10 ± 2	9 ± 1	3 ± 1
m_a = 40 GeV	11 ± 2	10 ± 2	2 ± 1
m_a = 20 GeV	6 ± 1	5 ± 1	0.7 ± 0.2



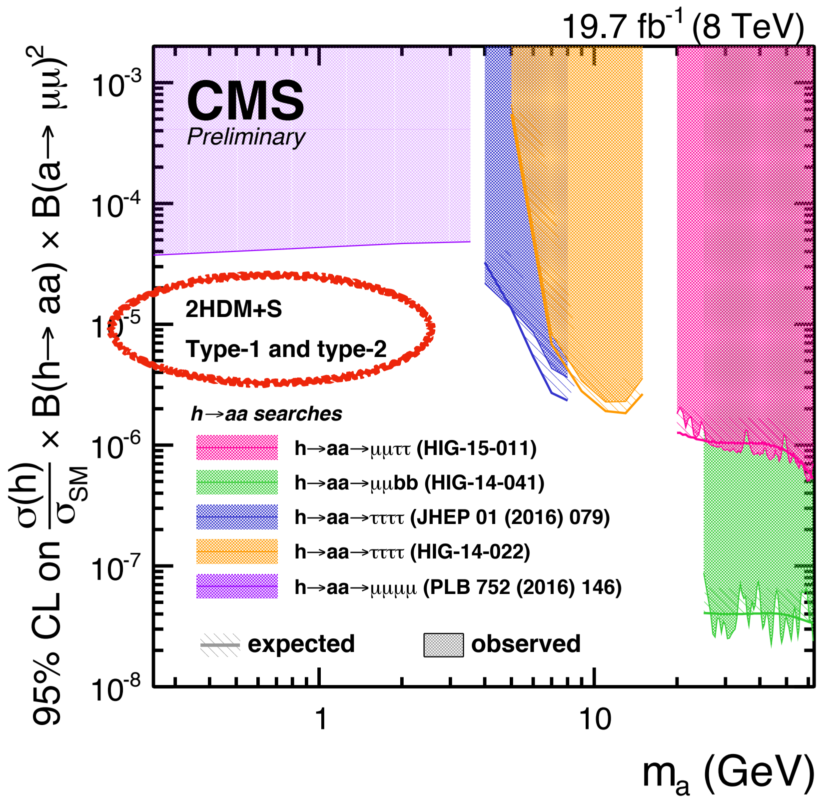
> **The observed (expected) 95% CL upper limits range from 6.2 (8.6) pb for m_a = 20 GeV, to 1.5 (2.0) pb for m_a = 60 GeV**

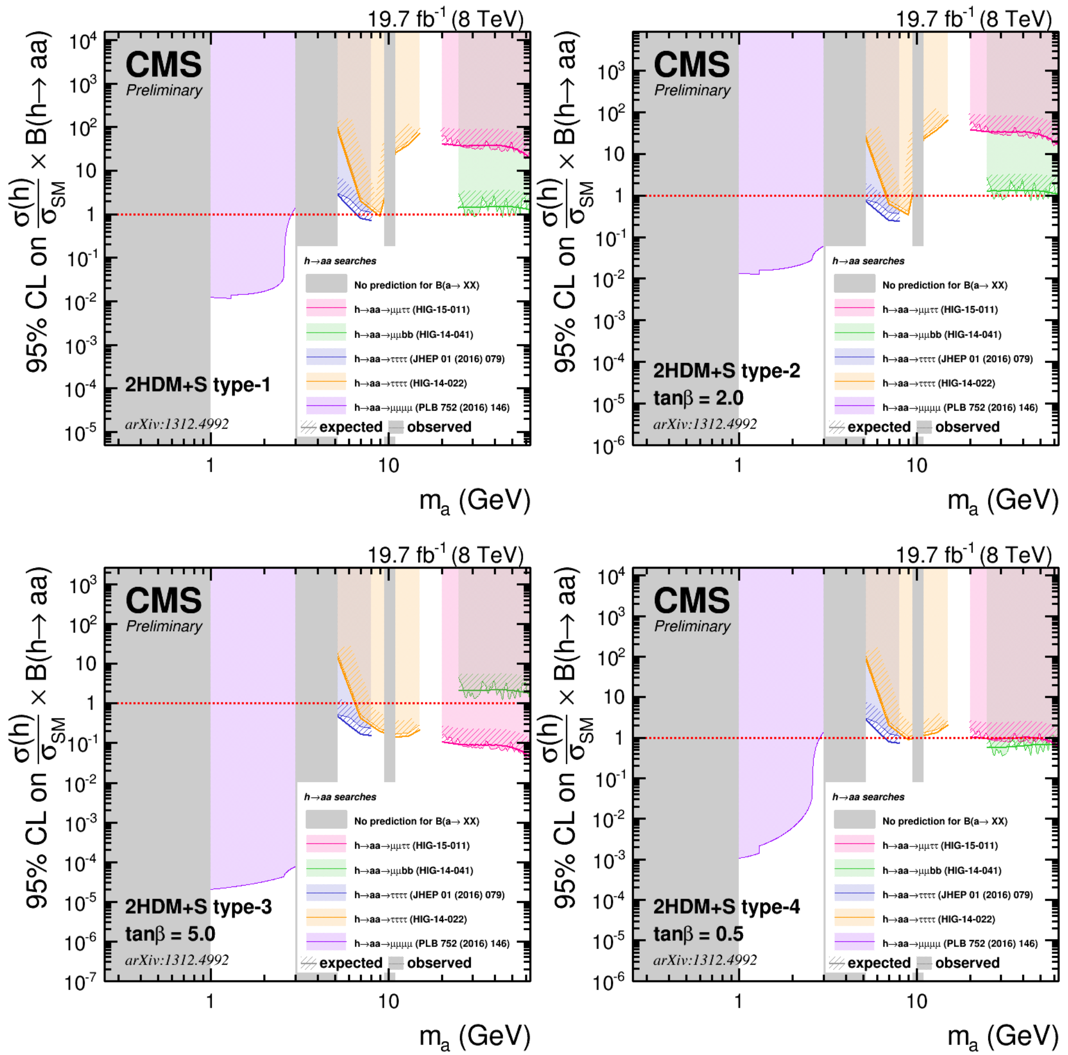
h → aa in 2HDM+S

8 TeV 20 fb^{-1}

CMS PAS HIG-16-015

Combined upper limits from different h→aa searches in the context of "2HDM+S"



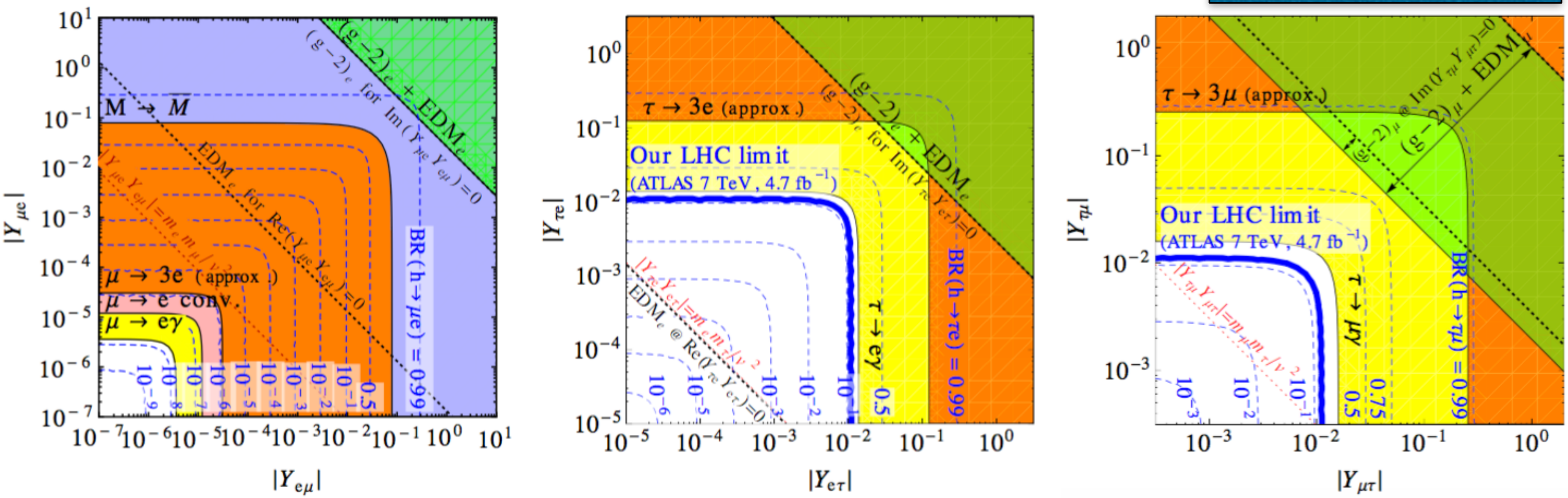


Lepton-Flavor-Violating decays of h(125)

LFV Higgs decays

- LFV Higgs couplings allow μ → e, τ → μ, τ → e to proceed via a virtual Higgs boson
- **Indirect constraints** to branching ratios of H → eμ, H → eτ, H → μτ (theoretical approach by re-interpretation ATLAS 7 TeV results)

JHEP 03 (2013) 026



Stringent constraints from μ → eγ
Indirect upper limit at 95% CL
Br(H→ μe) < O(10^{-8})

Bounds from τ → μγ and τ → eγ indirectly provide upper limit at 95% CL
Br(H → μτ) and Br(H → eτ) < O(10%)

LFV Higgs (Run-1)

8 TeV 20 fb^{-1}

CMS results :

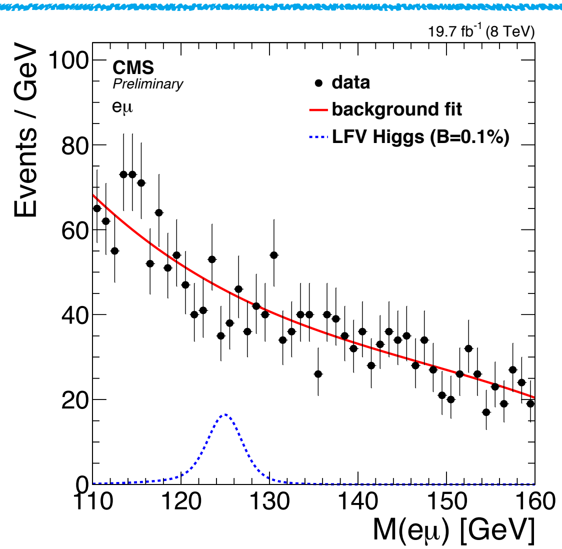
- Similar signature to the SM H → ττ and μμ searches but significant kinematic differences
- Provide direct constraints on the off-diagonal Higgs Yukawa couplings

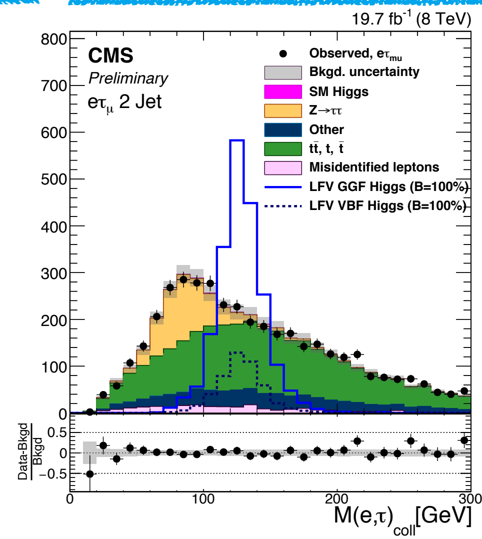
H→eμ

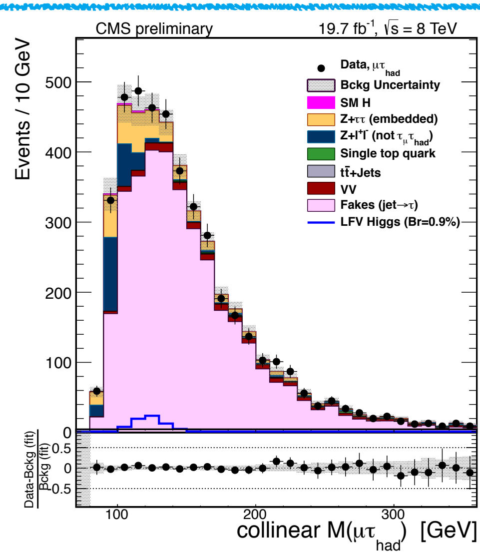
- Very clean but branching ratio strongly constrained!
- 10 channels (barrel/endcap leptons mix with 0-1-2 jets)
- unbinned likelihood fit to $M_{e\mu}$ distribution

H→eτ and μτ

- 3 categories (0,1,2 jets) from both τ_{had} and τ_{lep}
- large background leads to high systematic uncertainties
- binned likelihood fit to the distributions of M_{col} (m_H estimated with collinear approx.)



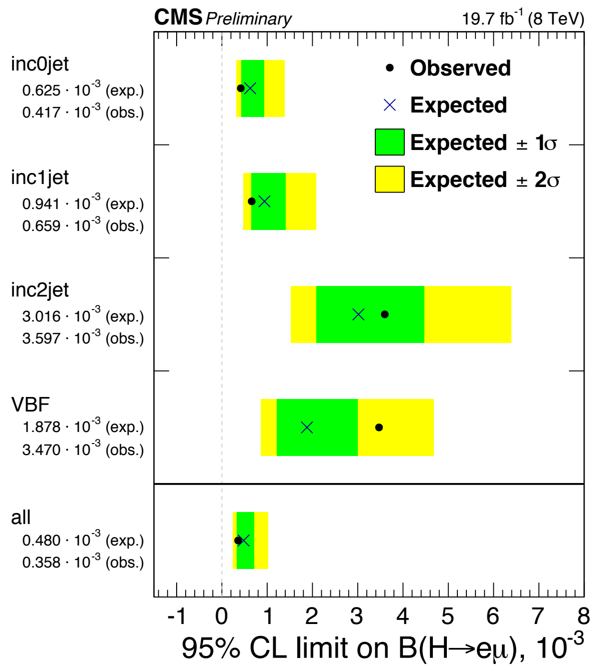


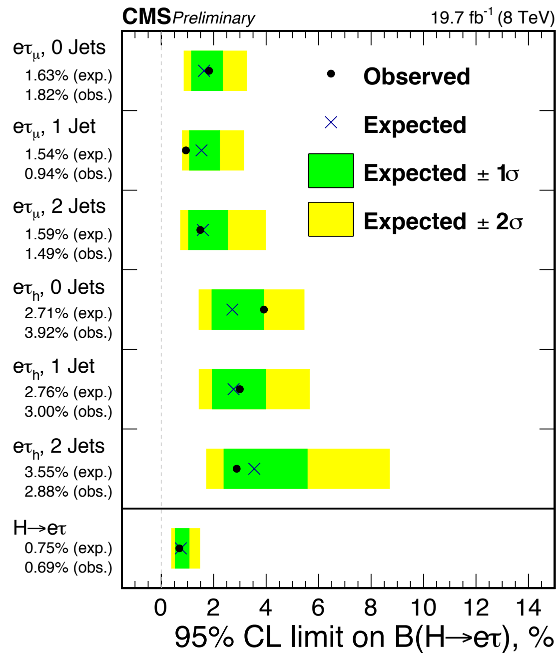


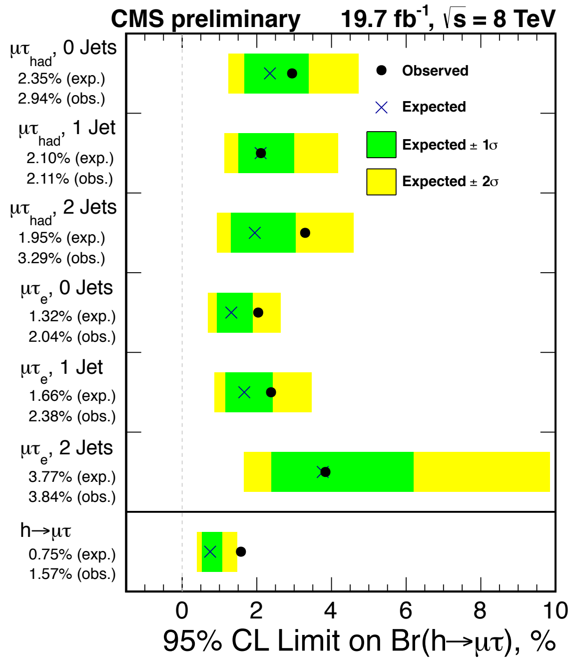
LFV Higgs (Run-1)

8 TeV 20 fb^{-1}

CMS results :







BR(H→eμ) < 0.035%
(0.048% expected)

BR(H→eτ) < 0.69%
(0.75% expected)

BR(H→μτ) < 1.51%
(0.75% expected)

CMS PAS HIG-14-040
arXiv:1607.03561

CMS PAS HIG-14-040
arXiv:1607.03561

CMS PAS HIG-14-005
arXiv:1502.07400

LFV Higgs (Run-1)

8 TeV 20 fb^{-1}

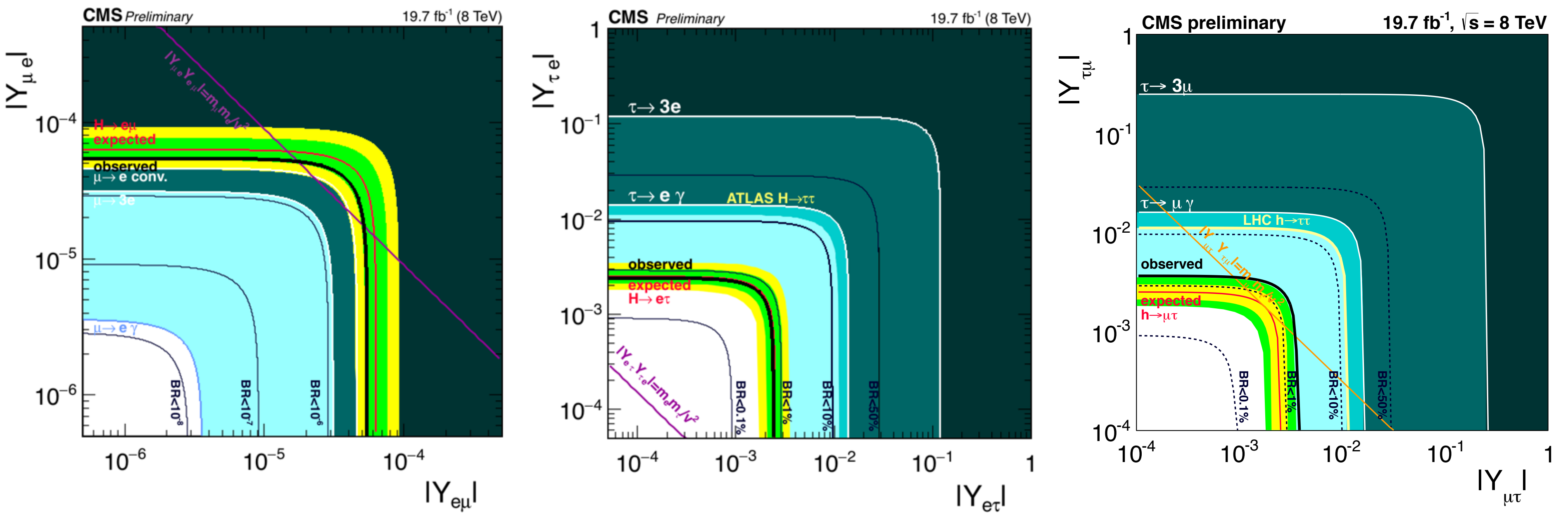
CMS results :

Bounds on the Higgs Yukawa couplings (theoretical no.)

H→eμ : $\sqrt{|Y_{e\mu}|^2+|Y_{\mu e}|^2}$ < 5.4 x 10^{-4} (< 3.6 x 10^{-6})

H→eτ : $\sqrt{|Y_{e\tau}|^2+|Y_{\tau e}|^2}$ < 0.0024 (< 0.014)

H→μτ : $\sqrt{|Y_{\mu\tau}|^2+|Y_{\tau\mu}|^2}$ < 0.0026 (< 0.016)



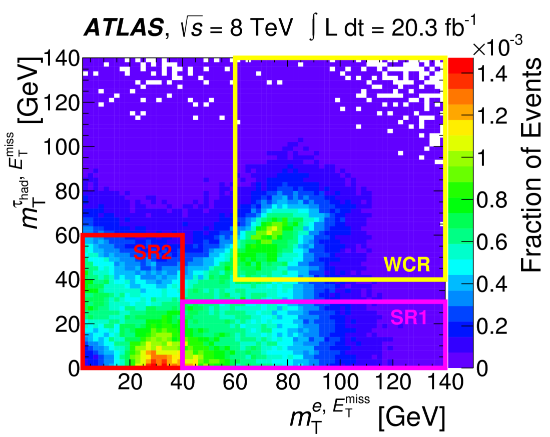
LFV Higgs (Run-1)

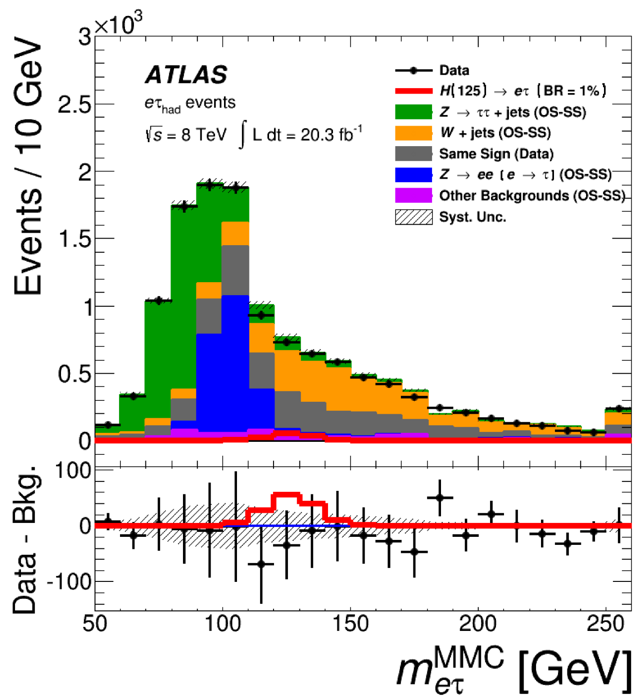
8 TeV 20 fb^{-1}

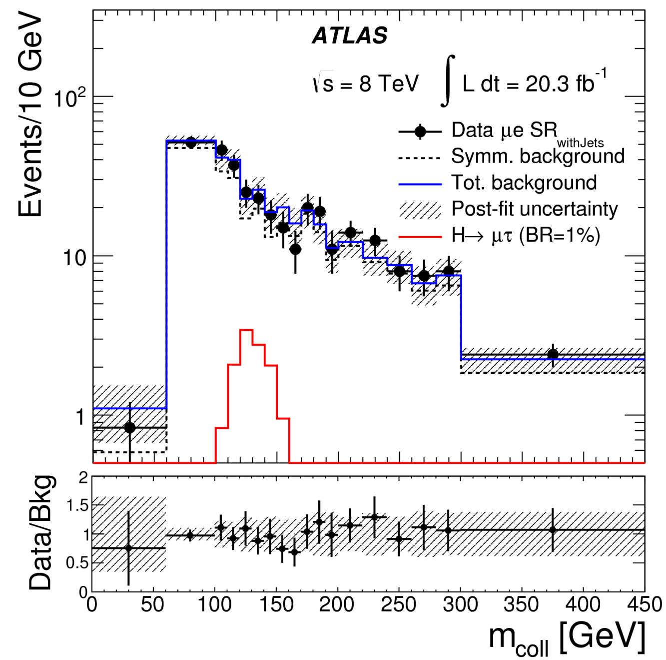
ATLAS results :

- Analyses performed for **H→eτ, H→μτ** but slightly different for **τ_{had}** and **τ_{lep}**
  - **$e\tau_{had}+\mu\tau_{had}$** : opposite-sign, well-separated e/μ with τ_{had} plus $E_{T,miss}$; two signal regions to fit missing mass calculator (MMC), reconstructed from e/μ, τ_{had} and $E_{T,miss}$
  - **$e\tau_{\mu}+\mu\tau_{e}$** : opposite charge e+μ with final discriminant of collinear mass (M_{col})
- Binned likelihood fit on the distributions of MMC (τ_{had}) and M_{col} (τ_{lep})

JHEP 1511(2015)211
arXiv:1604.07730





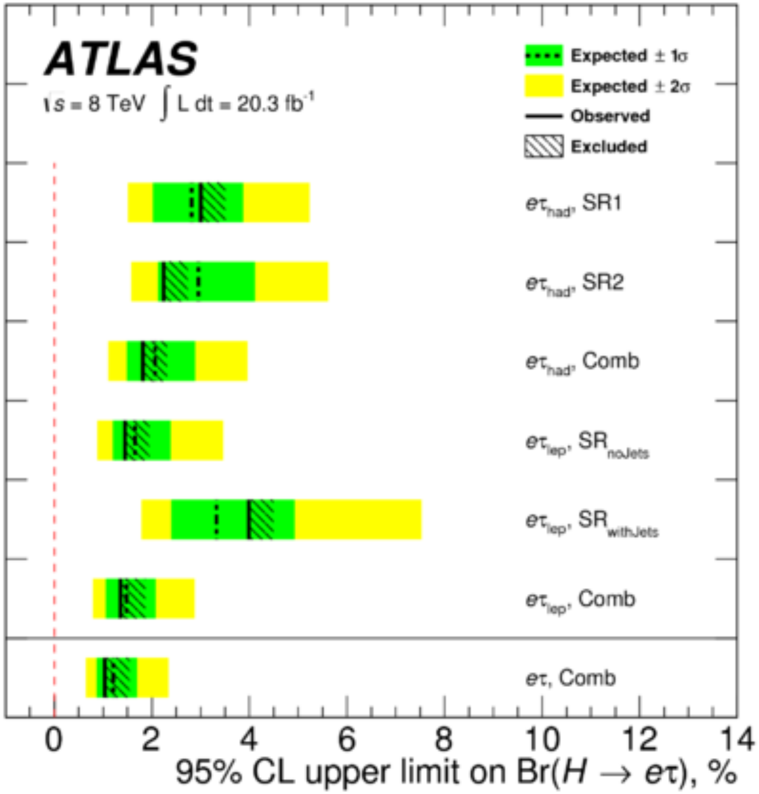


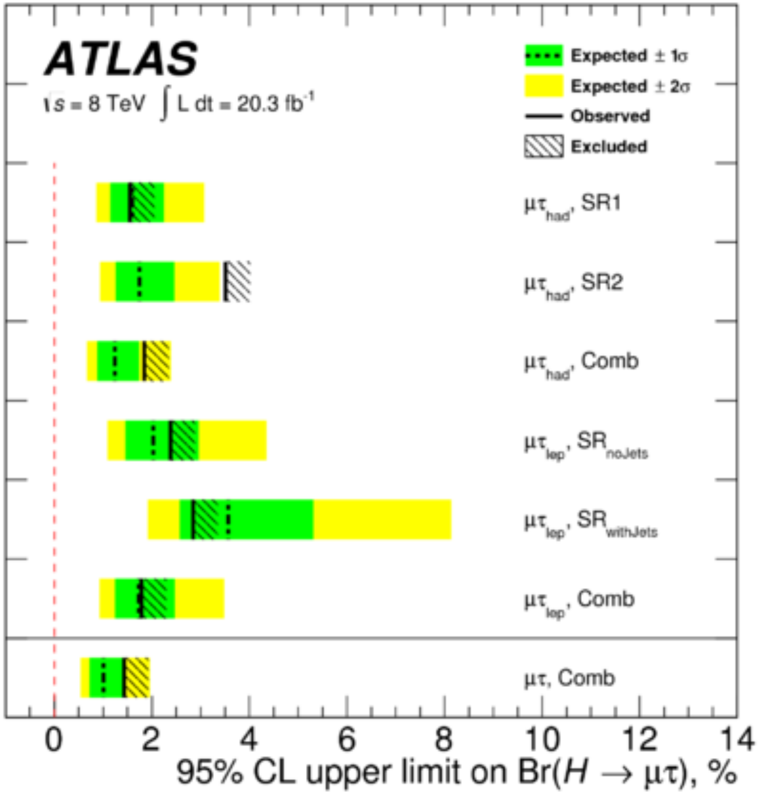
LFV Higgs (Run-1)

8 TeV 20 fb^{-1}

ATLAS results :

arXiv:1604.07730





Observed 95% CL upper limit
BR(H→eτ) < 1.04%
(1.21% expected)

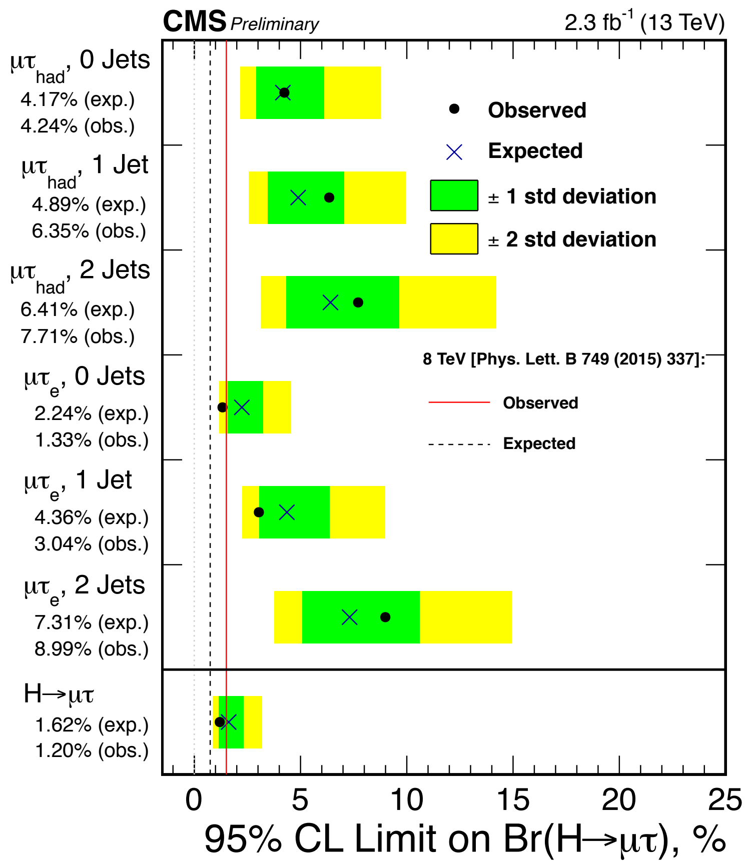
Observed 95% CL upper limit
BR(H→μτ) < 1.43%
(1.01% expected)

LFV Higgs (Run-2)

13 TeV 2.3 fb^{-1}

CMS results :

CMS PAS HIG-16-005



	0-jet (%)	1-jet (%)	2-jets (%)	Combined (%)
Expected limits				
$\mu\tau_h$	<4.17	<4.89	<6.41	<2.98
$\mu\tau_e$	<2.24	<4.36	<7.31	<1.96
$\mu\tau$	<1.62 %			
Observed limits				
$\mu\tau_h$	<4.24	<6.35	<7.71	<3.81
$\mu\tau_e$	<1.33	<3.04	<8.99	<1.15
$\mu\tau$	<1.20 %			
Best-fit branching fractions				
$\mu\tau_h$	$0.12^{+2.02}_{-1.91}$	$1.70^{+2.41}_{-2.52}$	$1.54^{+3.12}_{-2.71}$	$1.12^{+1.45}_{-1.40}$
$\mu\tau_e$	$-2.11^{+1.30}_{-1.89}$	$-2.18^{+1.99}_{-2.05}$	$2.04^{+2.96}_{-3.31}$	$-1.81^{+1.07}_{-1.32}$
$\mu\tau$	$-0.76^{+0.81}_{-0.84}$%			

BR(H→μτ) < 1.20% (1.62% expected)

$\sqrt{|Y_{\mu\tau}|^2+|Y_{\tau\mu}|^2} < 0.0032$

No excess is observed

(2.4σ at 8 TeV not confirmed but not excluded)

What next?

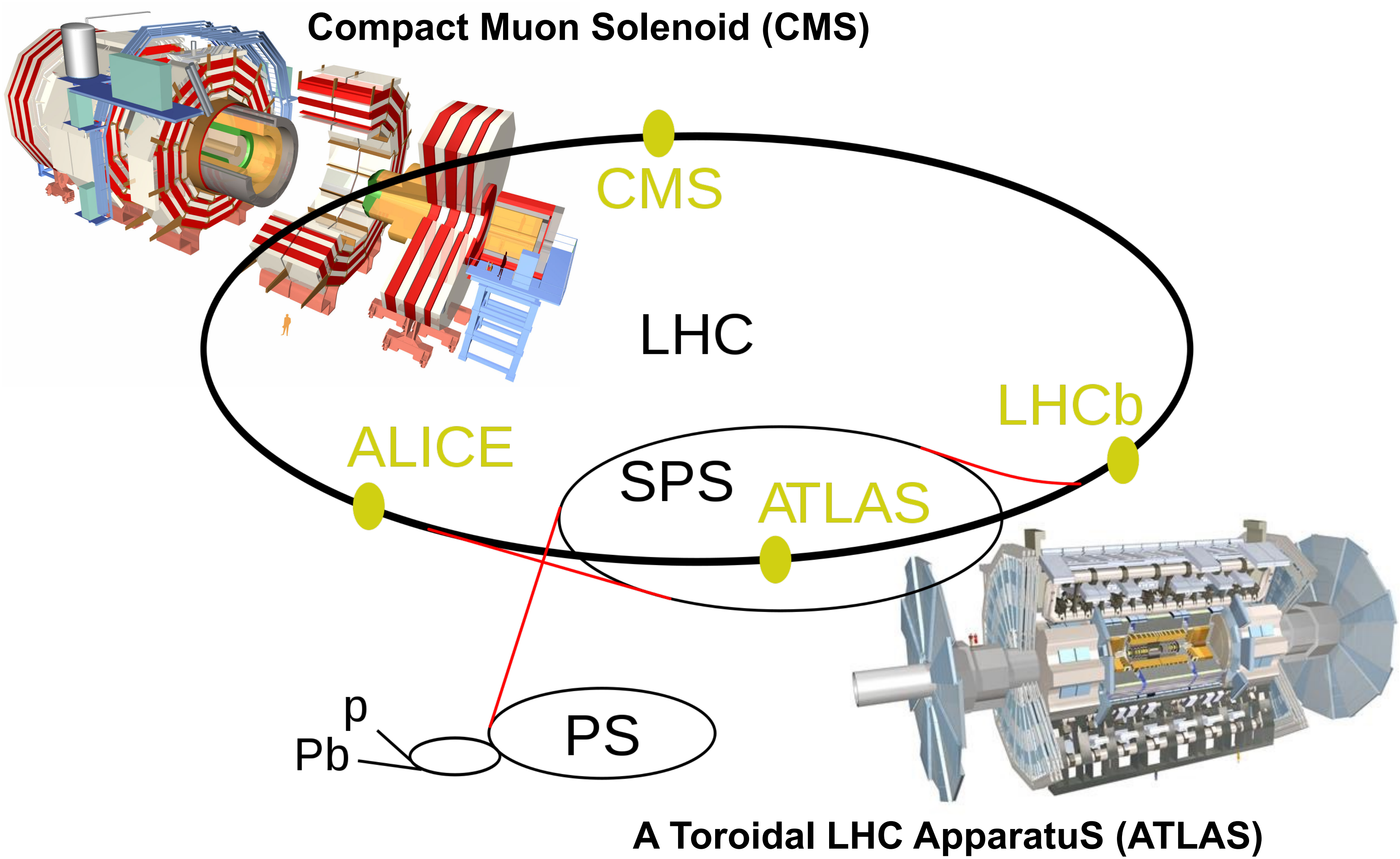
- The discovery of the SM-like Higgs opens an era of **Precision Physics**
  - Exotic decays would be a strong sign of BSM physics
  - No excess is observed so far but significant results are found/provided
- CMS and ATLAS enthusiastically broaden BSM Higgs searches to cover as many topics as possible using all 7, 8 and 13 TeV data
- Keep your eyes peeled!
  - Stay tuned, many more physics results with Run-2 2016 full dataset (> 30 fb^{-1}) are on their ways ;-)
- Enjoy the conference under sunny sky and nice beach :-)

References

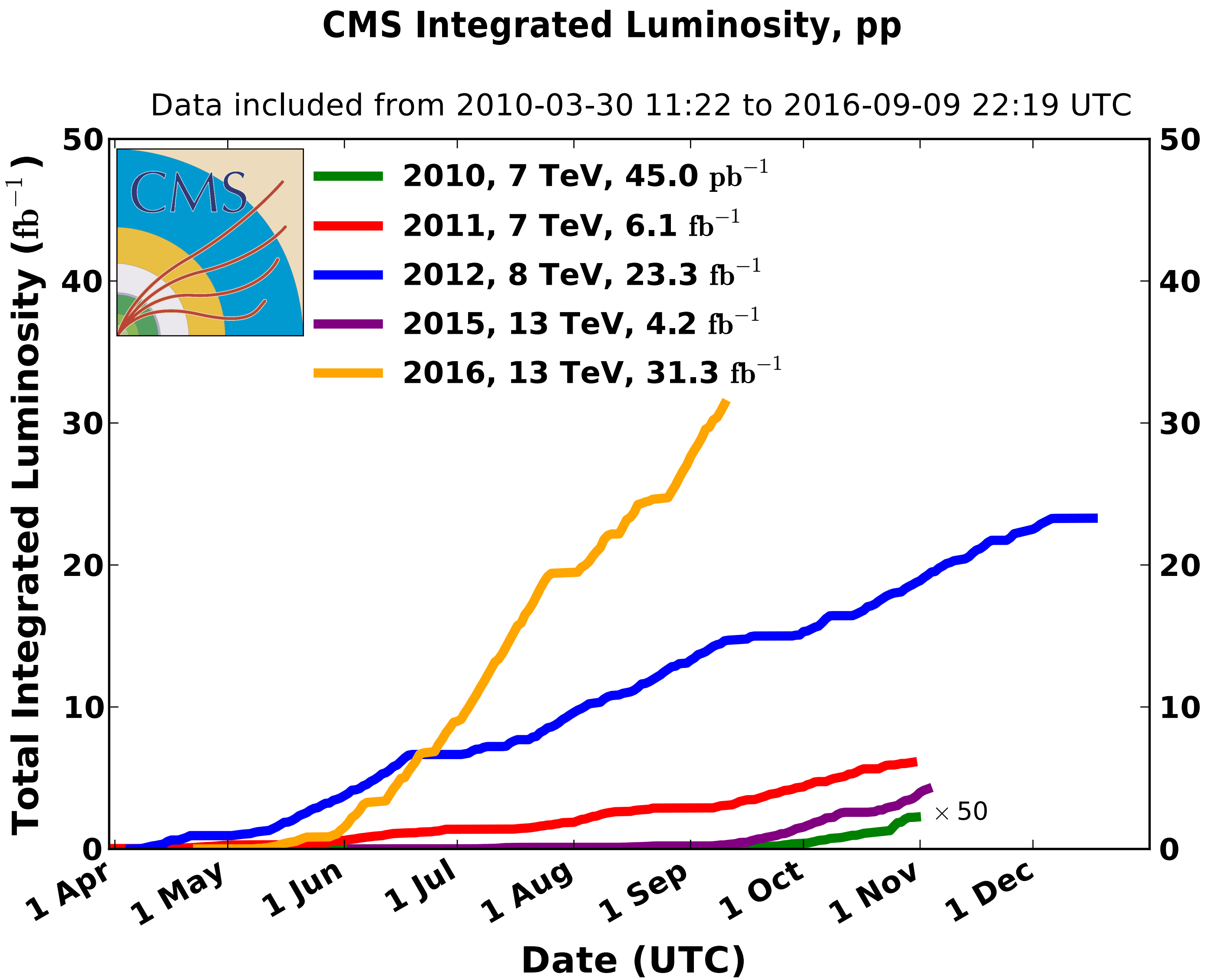
- CMS Public Results
  - http://cms.web.cern.ch/org/cms-papers-and-results
  - https://cds.cern.ch/collection/CMS%20Physics%20Analysis%20Summaries?ln=en
- ATLAS Public Results
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CONFnotes

Backup

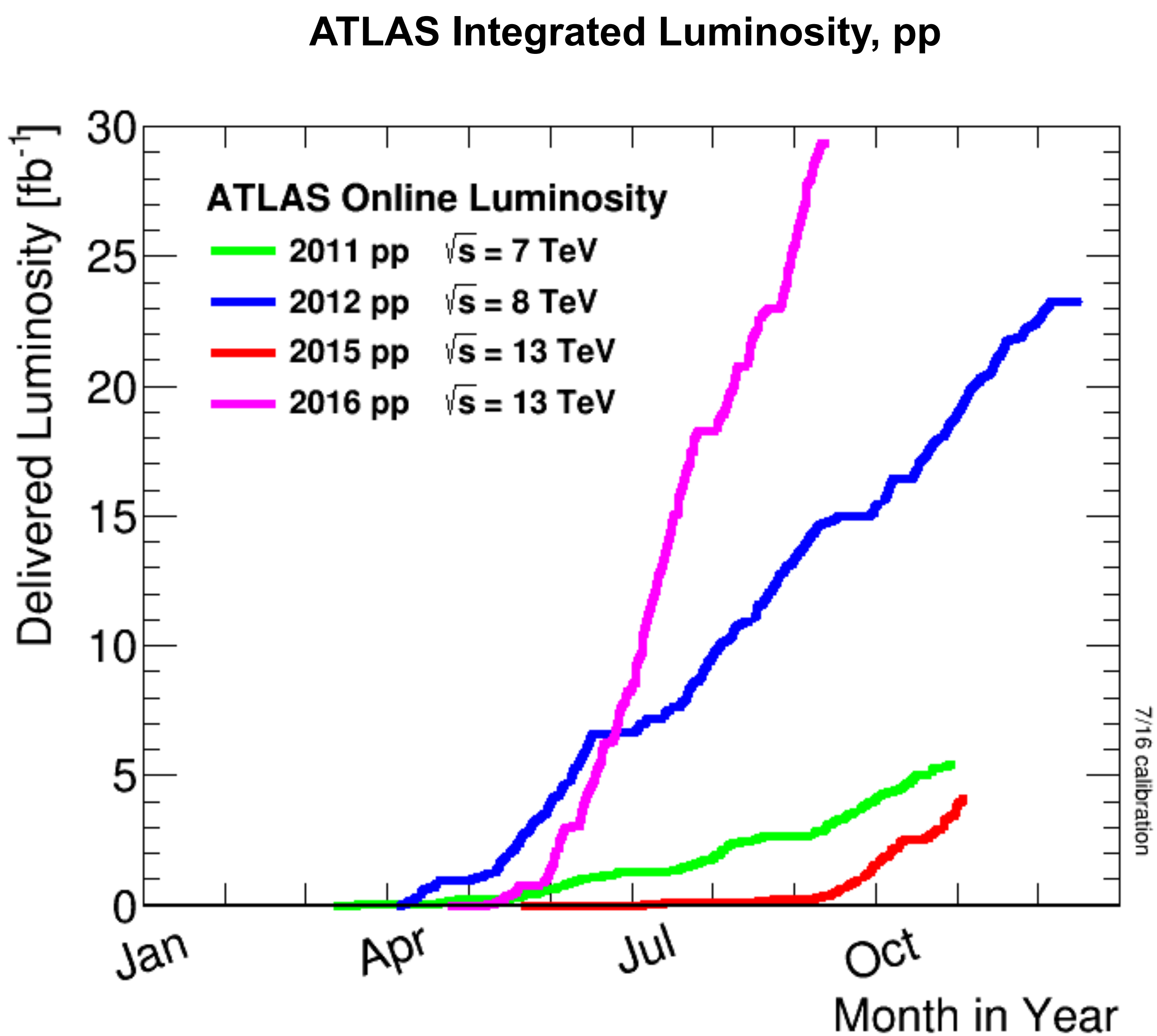
Experiments at the LHC



Luminosity 2011-2016



Luminosity 2011-2016



LFV indirect constraints

- Constraints on flavor violating Higgs couplings to e, μ, τ for a Higgs mass m_h = 125 GeV and assuming that the flavor diagonal Yukawa couplings equal the SM values

Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu}Y_{\mu e})$	$-0.019 \ldots 0.026$
electron EDM	$\lvert\mathrm{Im}(Y_{e\mu}Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 1.2 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y_{e\mu}^*\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
electron $g-2$	$\mathrm{Re}(Y_{e\tau}Y_{\tau e})$	$[-2.1 \ldots 2.9] \times 10^{-3}$
electron EDM	$\lvert\mathrm{Im}(Y_{e\tau}Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y_{\tau\mu}^2 + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau}Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$(\lvert Y_{\tau\mu}Y_{e\tau}\rvert^2 + \lvert Y_{\mu\tau}Y_{\tau e}\rvert^2)^{1/4}$	$< 3.4 \times 10^{-4}$

JHEP 03 (2013) 026

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

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