Search for low mass BSM particles using h(125)

Chayanit Asawatangtrakuldee — DESY

on behalf of the CMS Collaboration

DIS2017

University of Birmingham, UK (3-7 April 2017)

Introduction

- The discovered Higgs boson at 125 GeV play a central role in probing physics beyond the Standard Model (BSM)
- Many BSM theories predicted several BSM decay modes of h(125)

Two-Higgs Doublet Models (2HDM)

Additional Higgs doublets give rise to 5 Higgs bosons

H^+, H^-, A (CP-odd), H^0, h (CP-even)

Minimal Supersymmetric Standard Model (MSSM)
Type-II 2HDM

e.g. h→invisible, LFV decays

Composite Higgs
e.g. LFV Higgs decays

Hidden Valley Model
Higgs to dark sector
e.g. h→invisible

Observed h(125)

Higgs Triplet

An additional scalar triplet results in charged, doubly-charged, and neutral bosons

2HDM+S

Two Higgs Doublets with an additional complex singlet (e.g. NMSSM)

CP-even (h_1,h_2,h_3), *CP-odd* (a_1,a_2), H^+, H^-

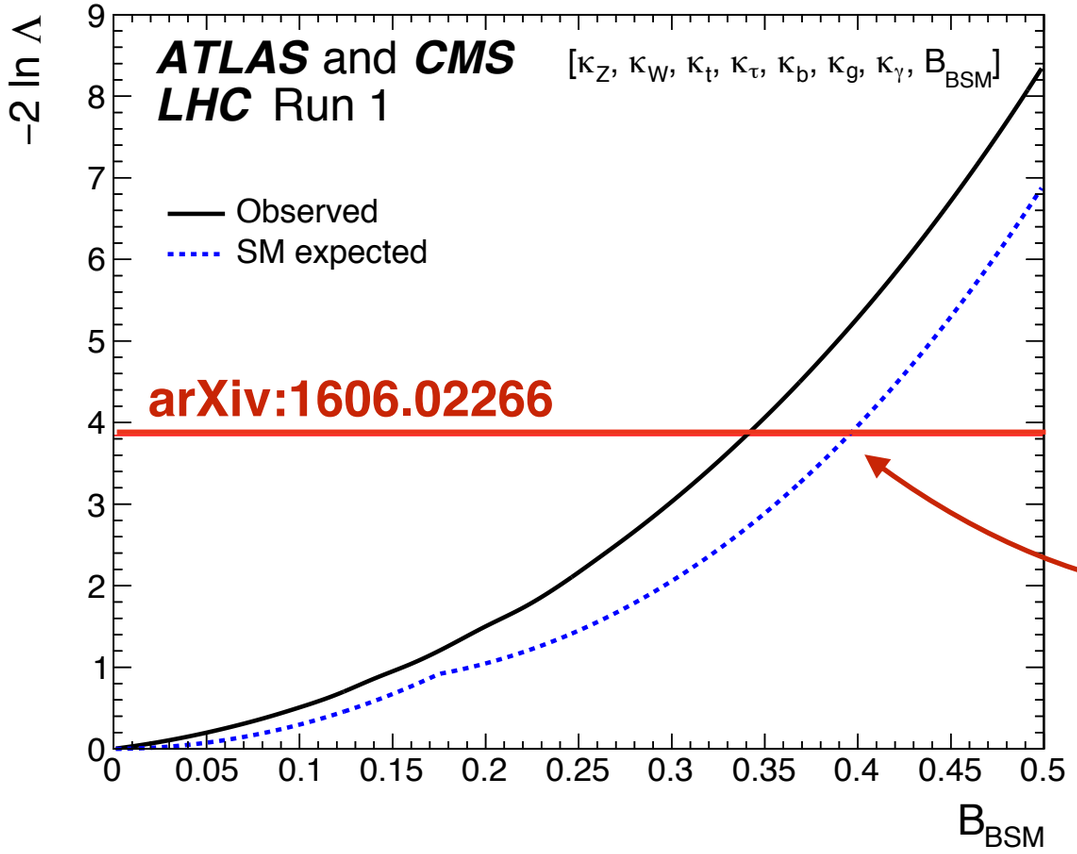
e.g. h→aa searches

Electroweak Singlet (EWS)

Additional singlet, resulting in 2 CP-even bosons *h,H*

h(125) → invisible

h(125)→invisible



- Indirect constraints from LHC couplings
  - no invisible channels included
  - assuming $|\kappa_V| \leq 1$, $B_{BSM} \geq 0$

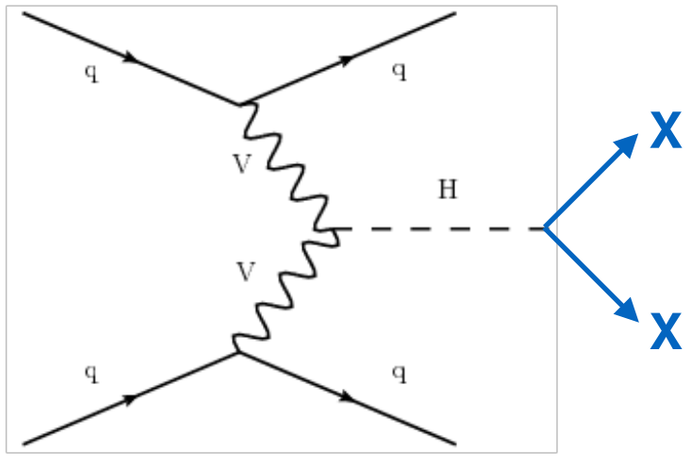
Br(h→BSM)
< **0.34 (0.39)** obs (exp)

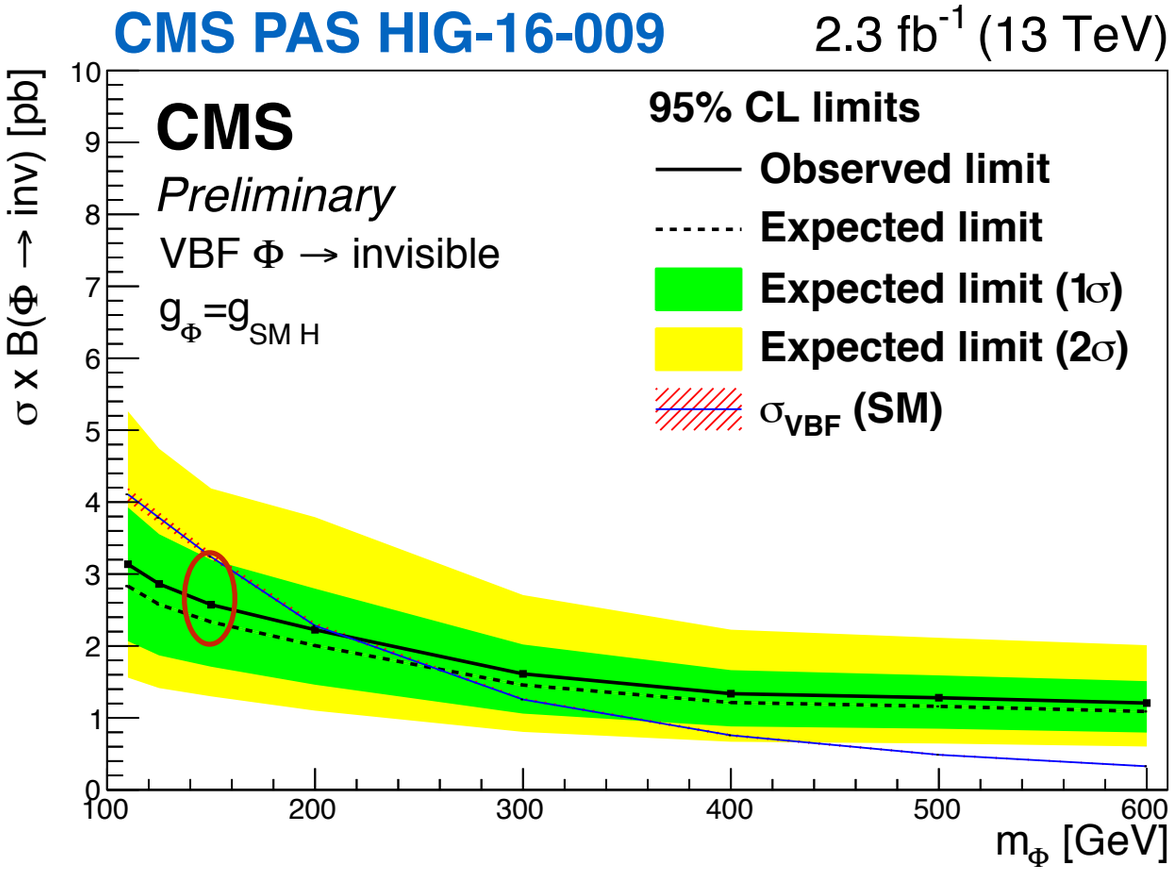
- Br(h→invisible) in the SM, Higgs can only decay via H→ZZ*→4ν (~0.1%)
  - a hint of new physics e.g. dark matter

- Direct searches must be performed in channels where the Higgs recoils against a visible system
  - vector boson fusion (VBF)
  - associated with vector bosons (VH)
  - gluon fusion (ggH)

VBF h→invisible

- Signal characteristics : **2 jets large $\triangle\eta_{jj}$, M_{jj}** + **large missing E_T**
- Dominant backgrounds from **SM Z($\nu\nu$)/W($l\nu$)+jets**
  - lepton control regions in data to normalize MC
- Signal extraction based on counting experiment
  - simultaneous fit in 5 control + signal regions





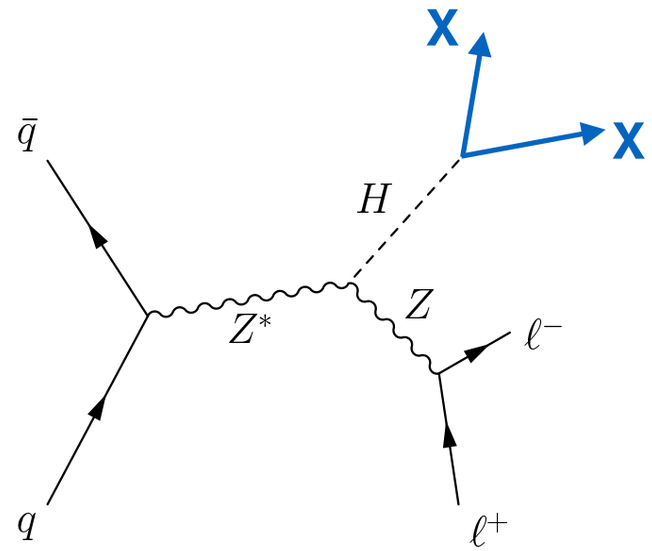
- Systematic uncertainties driven by **JES/JER**
- Limit on ***σ*×Br** as a function of mass
  - assuming SM Higgs cross-section

@125 GeV, Br(h→invisible)
< **0.69 (0.62)** obs (exp)*

* Br(h→invisible) < 0.65 (0.49) obs (exp) at 8 TeV

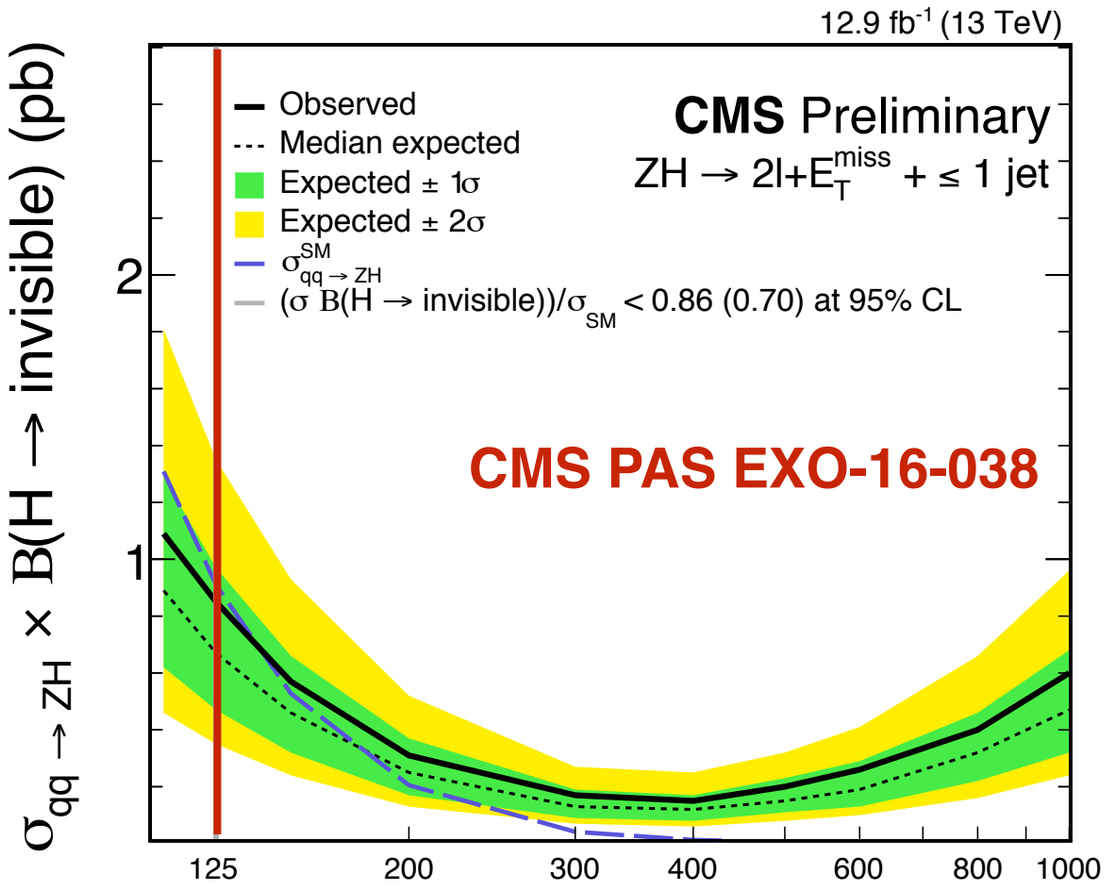
Z(*ll*)h→invisible

- Clean final state from leptonic Z decay
  - events with **missing E_T + 2 leptons ($e^+e^-/\mu^+\mu^-$)**
- Backgrounds dominated by **diboson processes**
  - ZZ(2*l*2**ν**) (70%), WZ(***lνll***) (25%) from MC
- Signal extraction by fitting **m_T distribution** in 0-, 1-jet categories



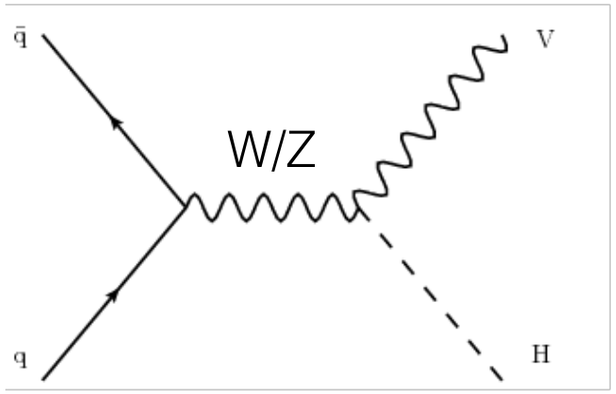
$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell\ell} E_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos\Delta\phi(\ell\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\right]}$$

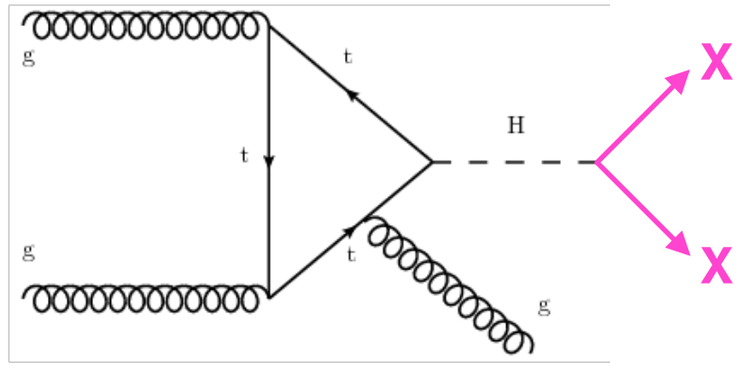
Assuming SM Higgs cross-section @125 GeV, Br(h→invisible) < **0.86 (0.70)** obs (exp)



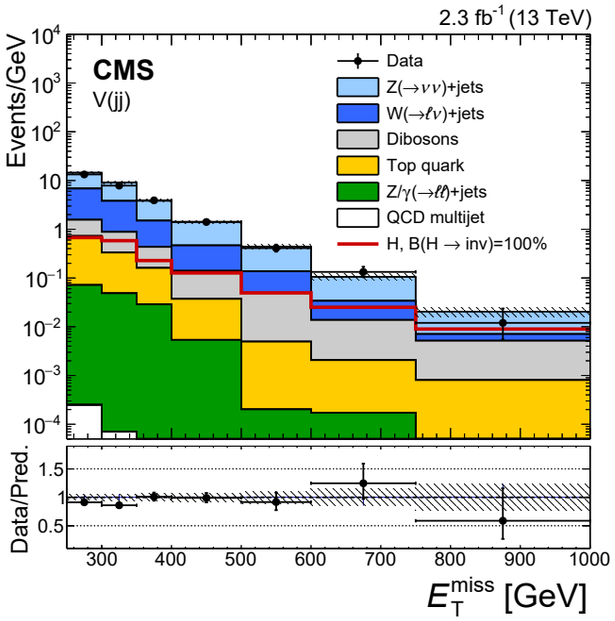
V(jj)h & ggh→invisible

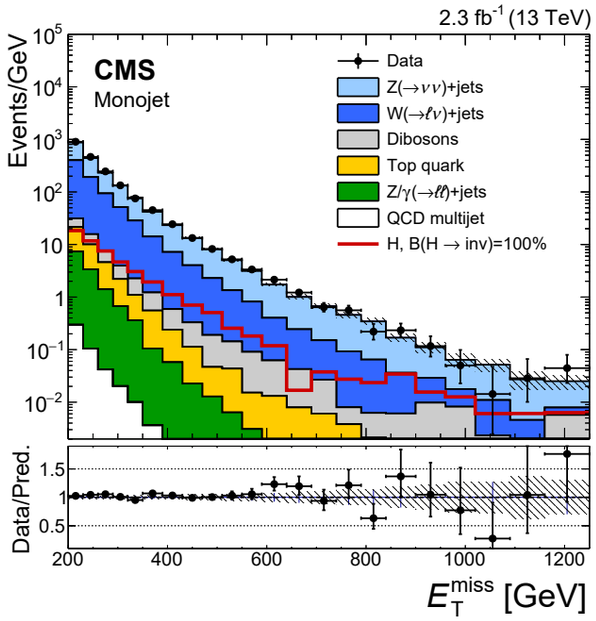
- Both look for events with **Jet+missing E_T** (VBF veto)
  - "fat" jet from W/Z decays hadronically
  - "central" jet from a gluon/quark ISR
- Dominant backgrounds arise from **W/Z(νν)+jets**





CMS PAS HIG-16-016





CMS PAS EXO-16-037

Limits with 12.9	Expect	Observed
V(jj)h→invisible	0.72	**1.17**
ggh→invisible	0.85	**0.48**
combined	0.56	**0.44**

- Signal extracted from fit to Missing E_T spectrum

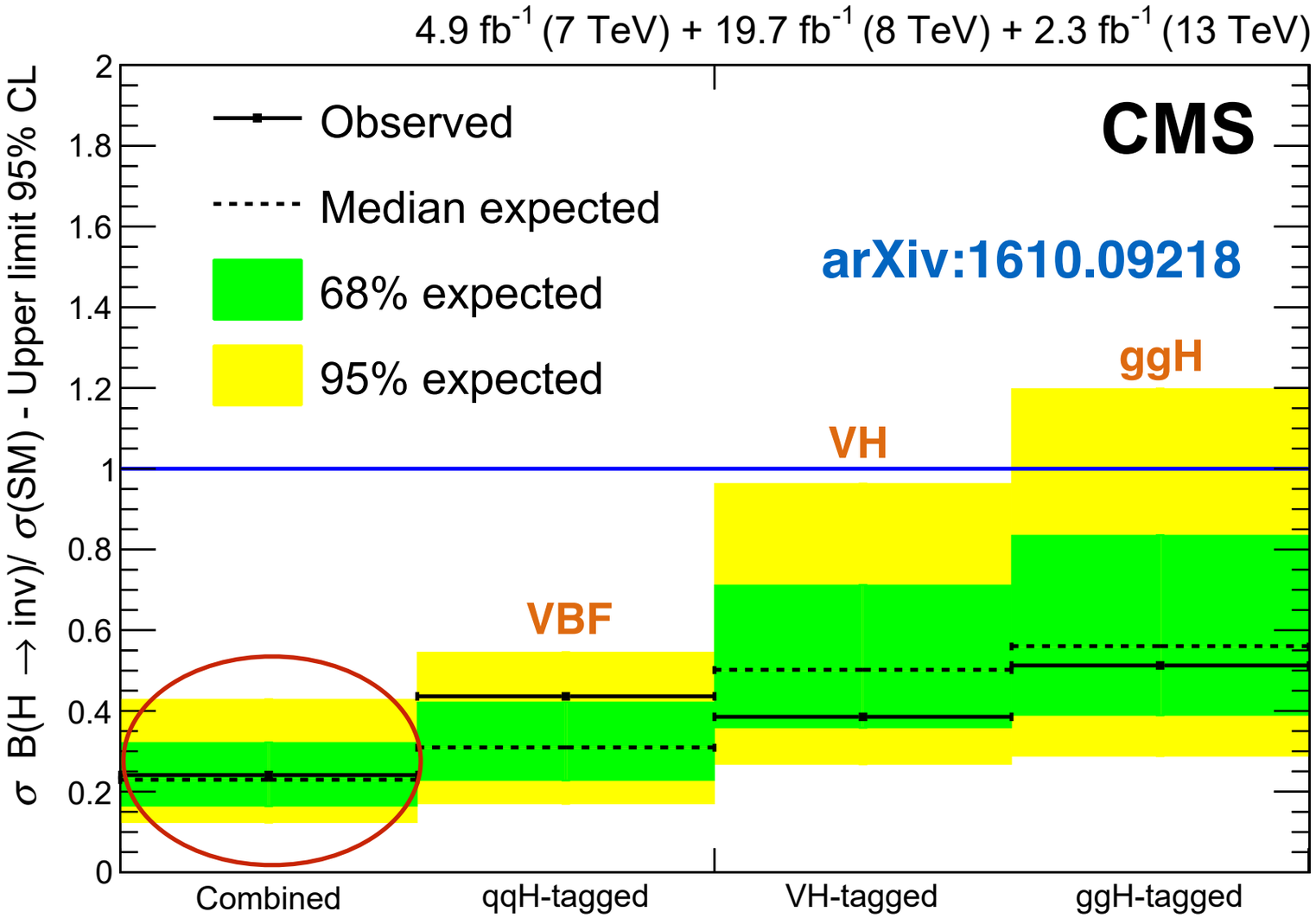
Upper limits on **σxBr/$σ_{SM}$** for Higgs decaying invisibly @125 GeV

Combination h→invisible

- No significant deviations from the SM expectations are observed
- Combination of h→invisible searches performed using **Run-1 dataset** and **2.3 fb^{-1} of 13 TeV (2015) data**
  - 95% CL upper limits on **σxBr** relative to SM production is estimated

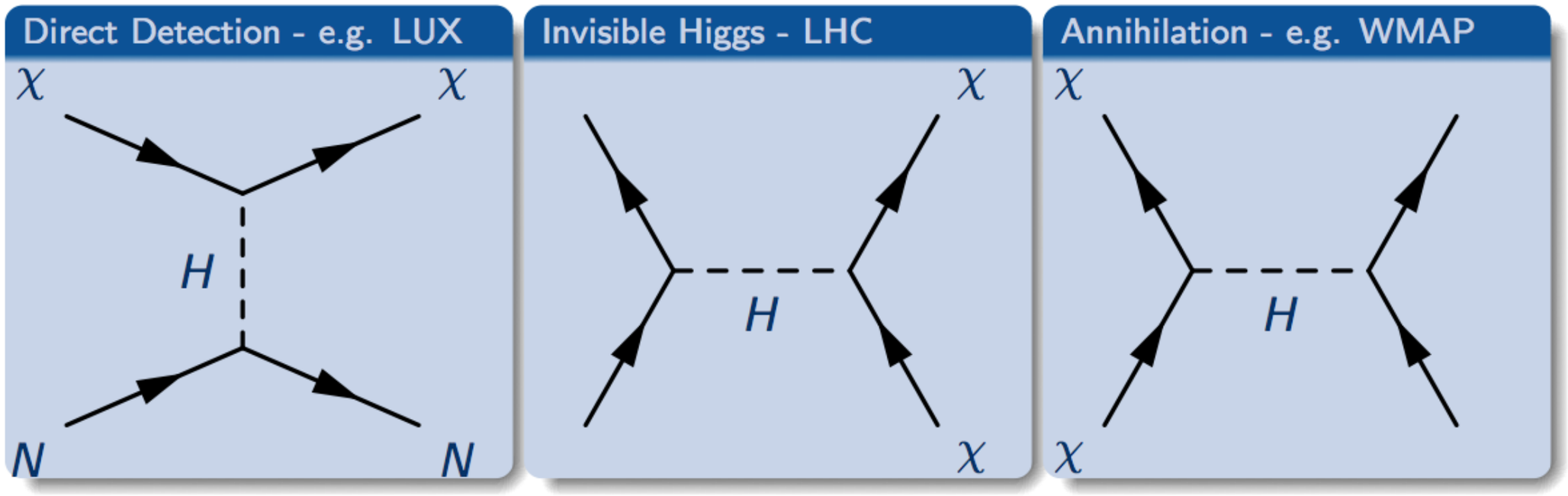
- VH includes Z(*ll*), Z(bb) and V(jj)H channels

Br(h→invisible) < 0.24 (0.23) obs (exp) @125 GeV 95% CL



Higgs-Portal Model

- If dark matter (DM) couples to the Higgs, the following diagrams are possible

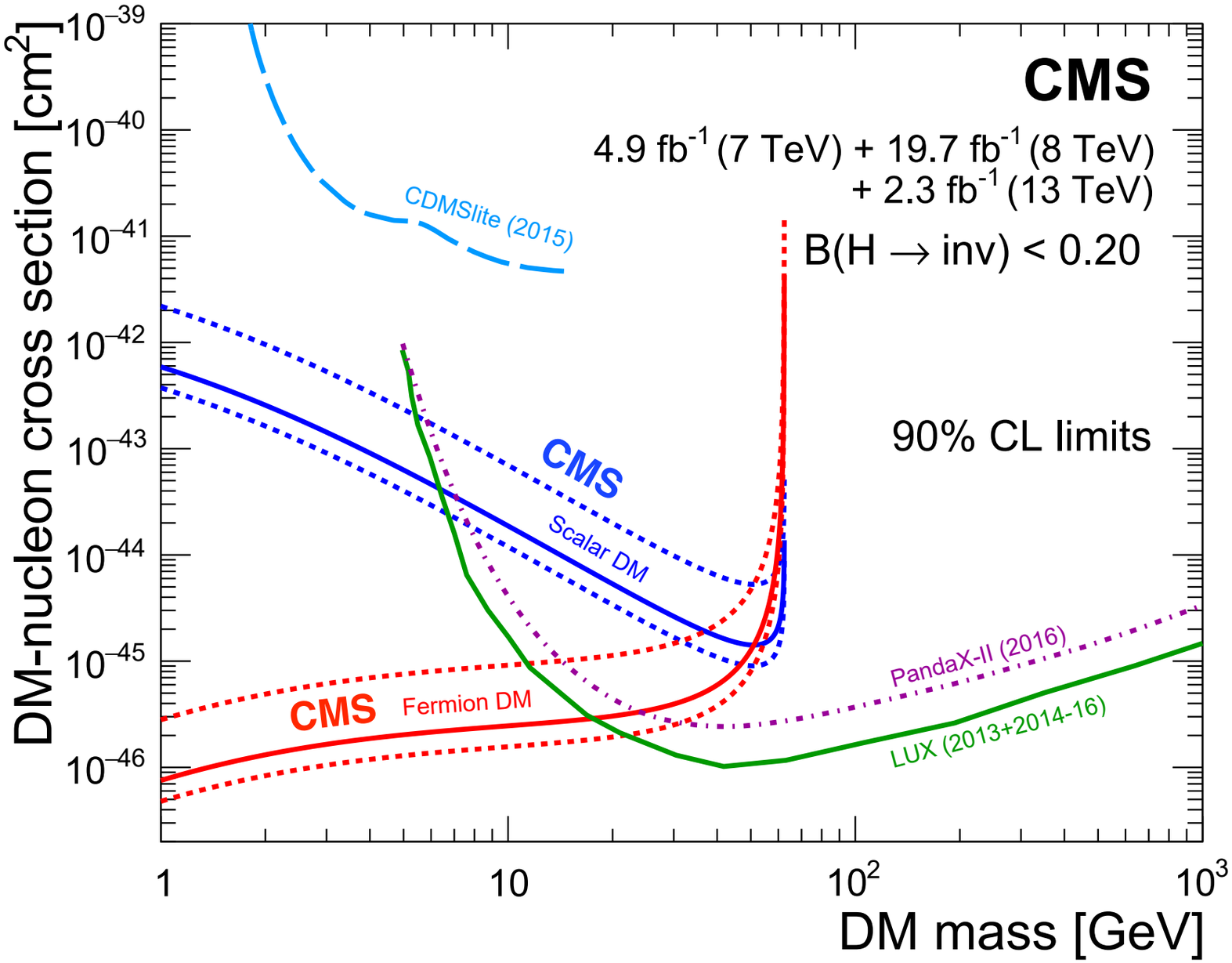


- **Br(h→invisible)** translated into **DM-nucleon spin-independent cross section** limits as a function of DM mass (if DM mass < $m_h/2$)*

*A. Djouadi et al, Phys. Lett. B 709 (2012)

Dark Matter Interpretation

CMS PAS HIG-16-016 **arXiv:1610.09218**



- Assuming **scalar,fermion** dark matters
- 90% CL to compare with direct detection experiments
  - **LUX, PandaX-II, CDMSlite**
- CMS limits more stringent for small DM masses

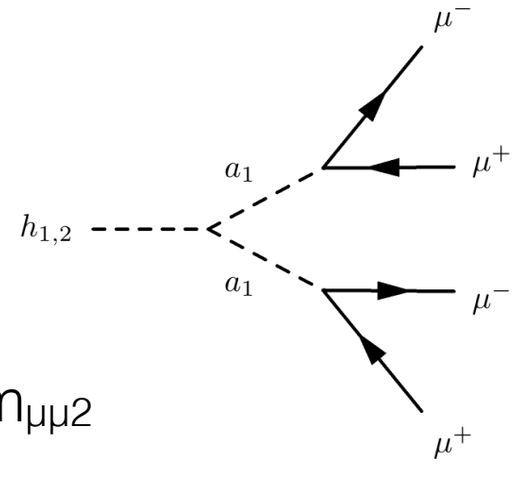
h(125) → aa

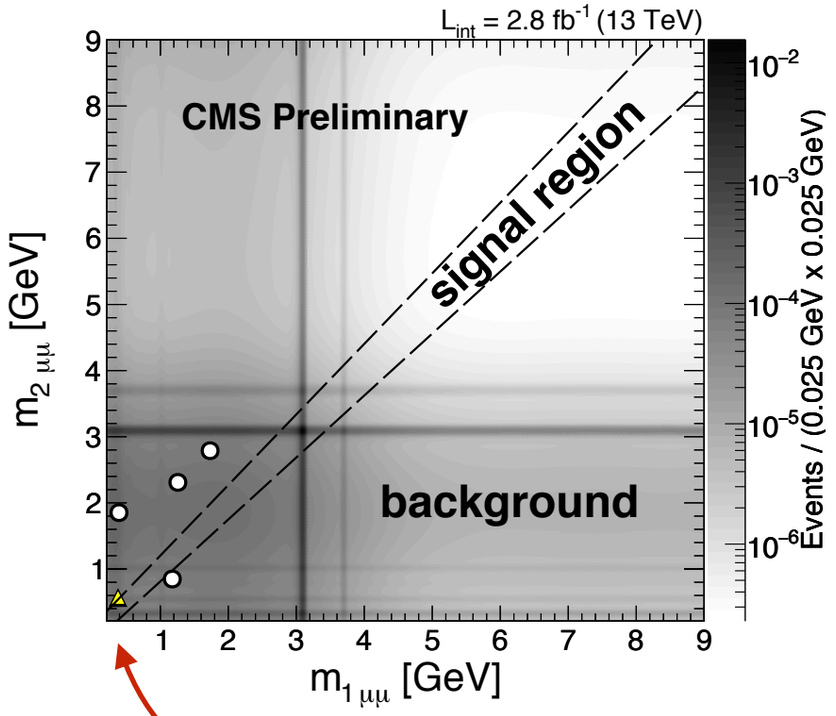
$h \rightarrow aa \rightarrow 4\mu$

new

CMS PAS HIG-16-035

- Two models interpretation
  - **NMSSM** : $h \rightarrow aa \rightarrow 4\mu$ ($2m_\mu \leq m_a \leq 2m_\tau$)
  - **Dark SUSY** : $h \rightarrow 2n_1 \rightarrow 2n_D + 2\gamma_D \rightarrow 4\mu$ ($m_h > m_{n1}$)
- Mass range of $m_a \in$ 0.25 to 3.55 (8.5) GeV
- Main backgrounds from bb, J/Ψ and EWK $pp \rightarrow 4\mu$
- **No excess data is observed :** diagonal signal region : $m_{\mu\mu 1} \simeq m_{\mu\mu 2}$

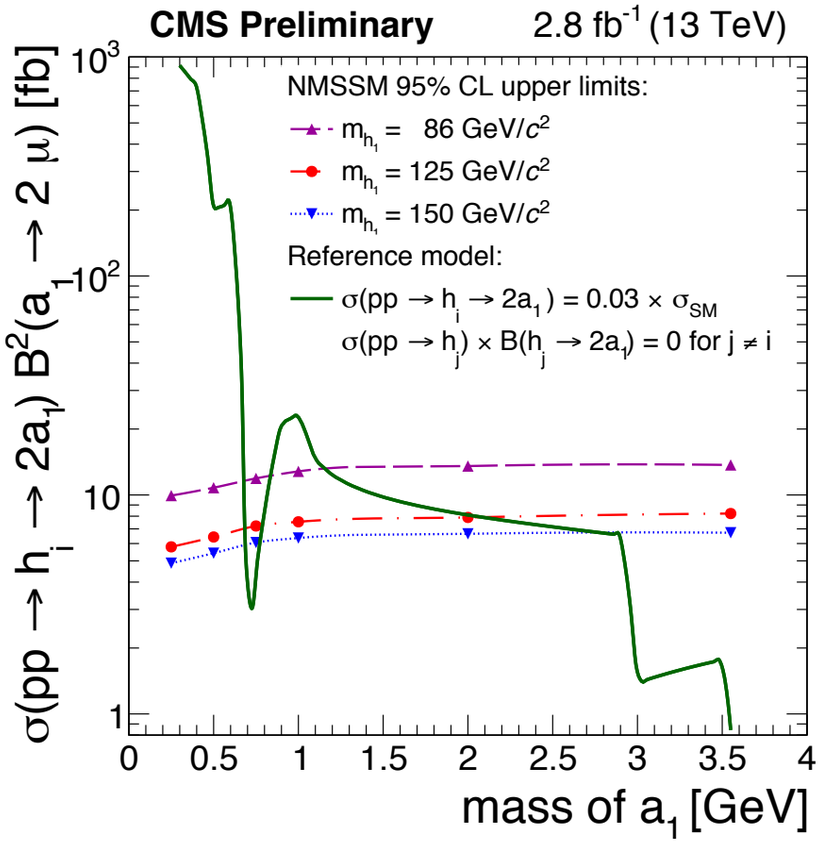




observed 1 event w.r.t
0.74 ± 0.34 (stat.) ±0.15 (syst.) SM background

NMSSM limits

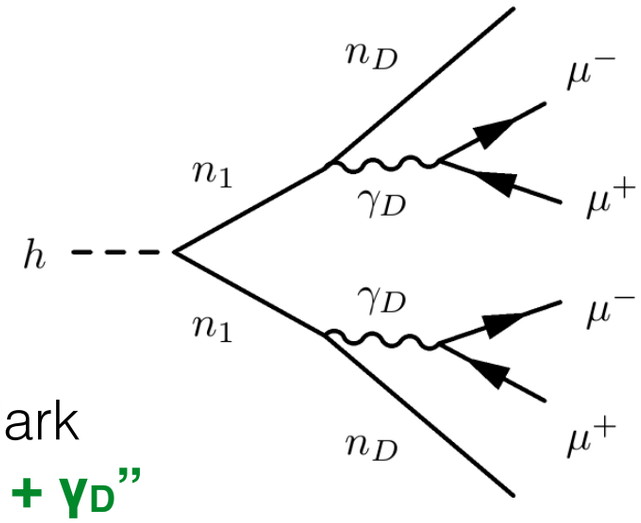
- 95% CL upper limits as functions of m_{a1} for m_{h1} = **86**,**125**,**150** GeV

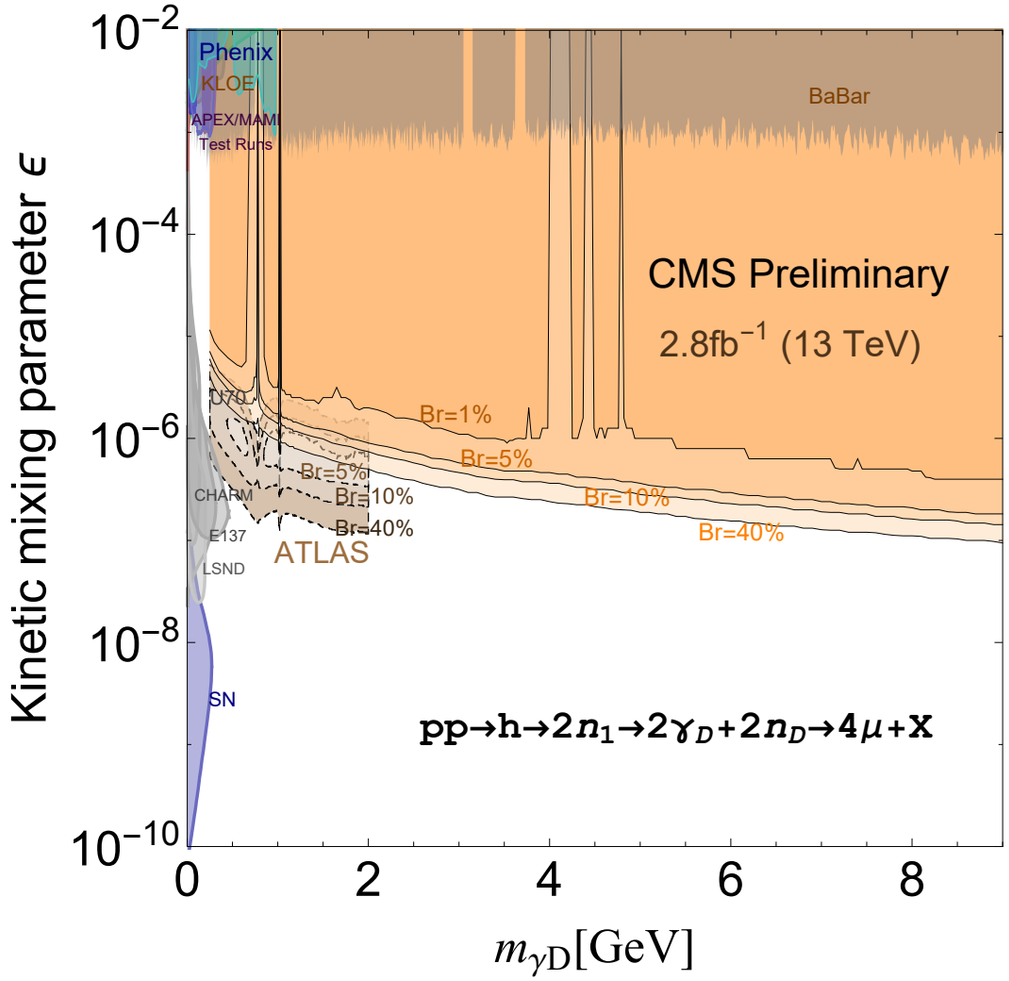


h→aa→4μ

new

- **Dark SUSY Interpretation :**
  - predict cold dark matter at ~1TeV scale
  - $U(1)_D$ is broken, giving rise to light dark photons (γ_D)
  - γ_D weakly couples to SM particles via small kinetic mixing (ε)
  - Lightest neutralino (n_1) is no longer stable and can decay to a dark neutralino (escape from detection) and a dark photon **"$n_1 \rightarrow n_D + \gamma_D$"**





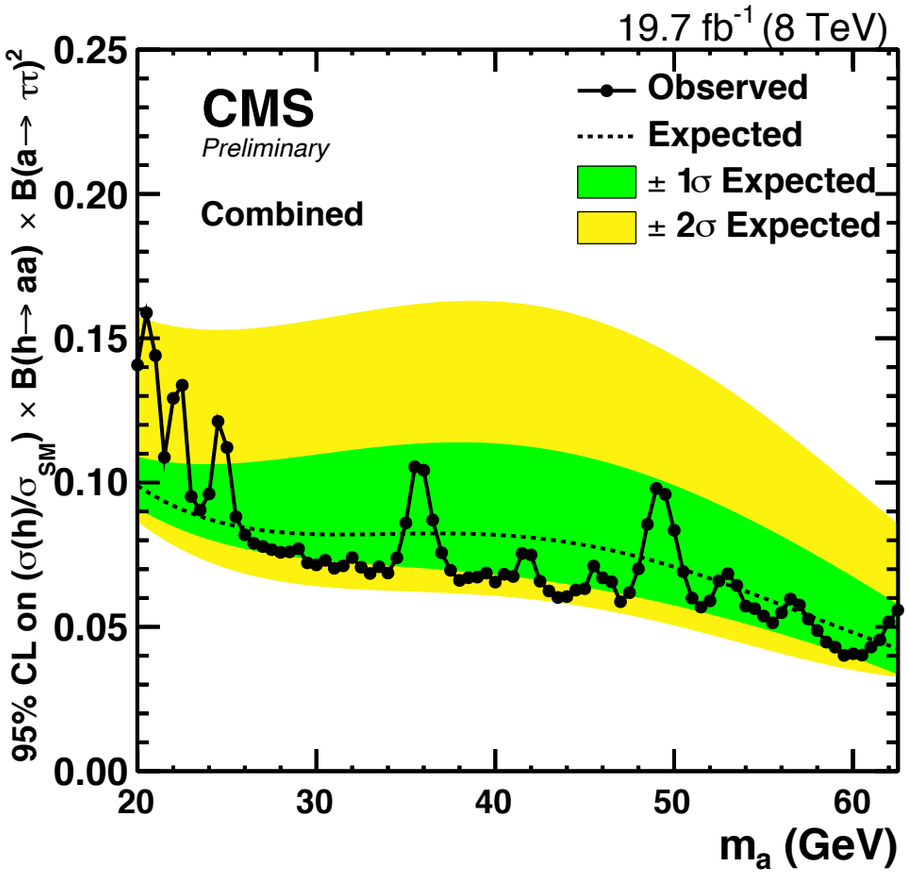
CMS PAS HIG-16-035

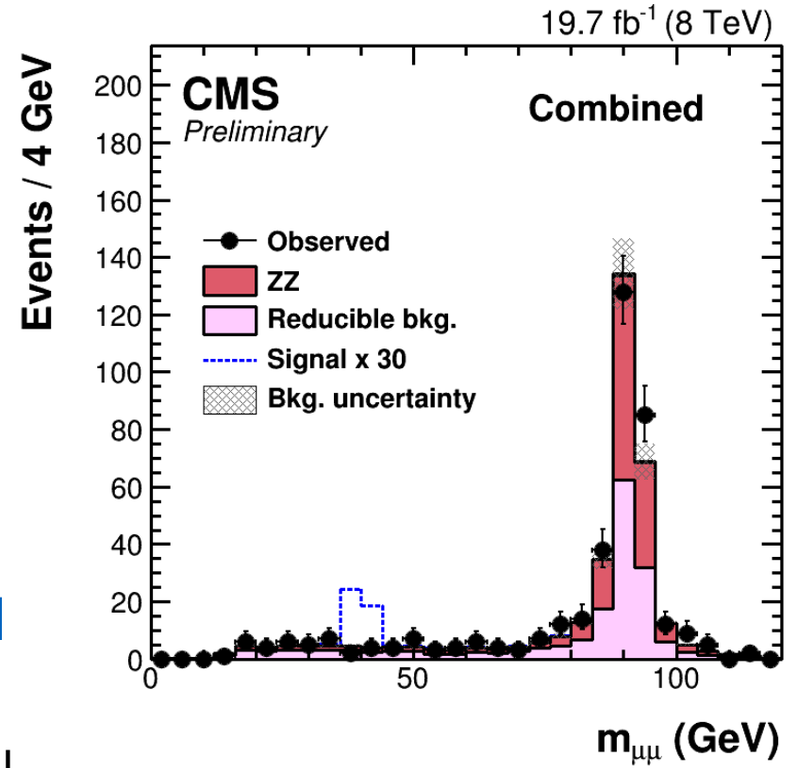
- 95% CL upper limits on
  $\sigma(pp \rightarrow h \rightarrow 2\gamma_D + X)Br(h \rightarrow 2\gamma_D + X)$
  - colored contours represent different values of $Br(h \rightarrow 2\gamma_D + X)$ in the range 1-40%
  - assumed m_{n1} = 10 GeV, m_{nD} = 1GeV

h→aa→2μ2τ

- Reconstructed events with 2μ (good resolution) plus 2τ
  - combined 5 final states → **μμτ$_e$τ$_e$, μμτ$_e$τ$_\mu$, μμτ$_e$τ$_h$, μμτ$_\mu$τ$_h$ and μμτ$_h$τ$_h$**
- Limits set on Br(h → aa) x Br(a → ττ)^2 from an unbinned fit of mμμ distributions with the following relation

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



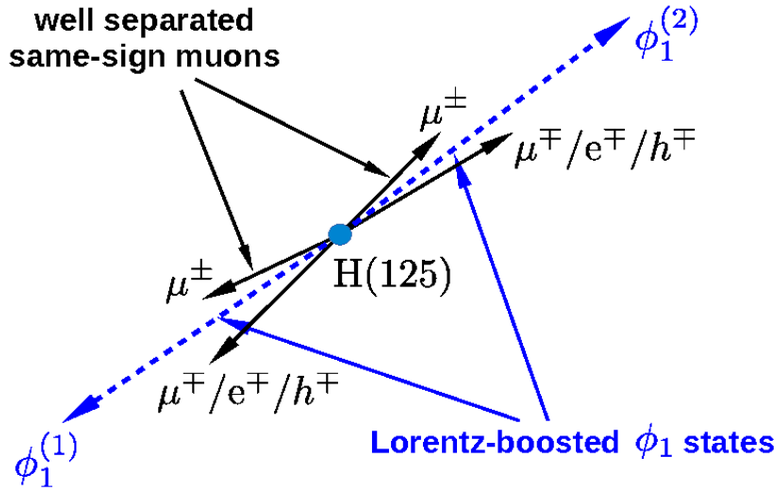


CMS PAS HIG-15-011

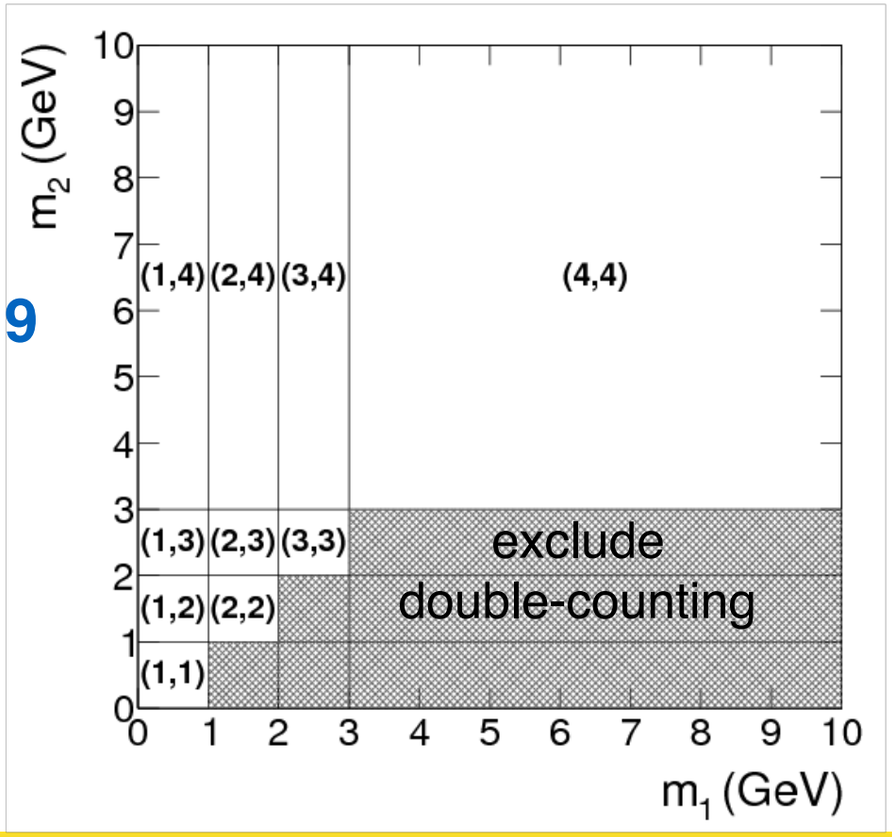
Upper limits at 95% CL on h → aa relative to the SM Higgs production, scaled by Br(a→ττ)^2 placed between **4-15% for m$_{\mu\mu}$ ∈ 20 to 62.5 GeV**

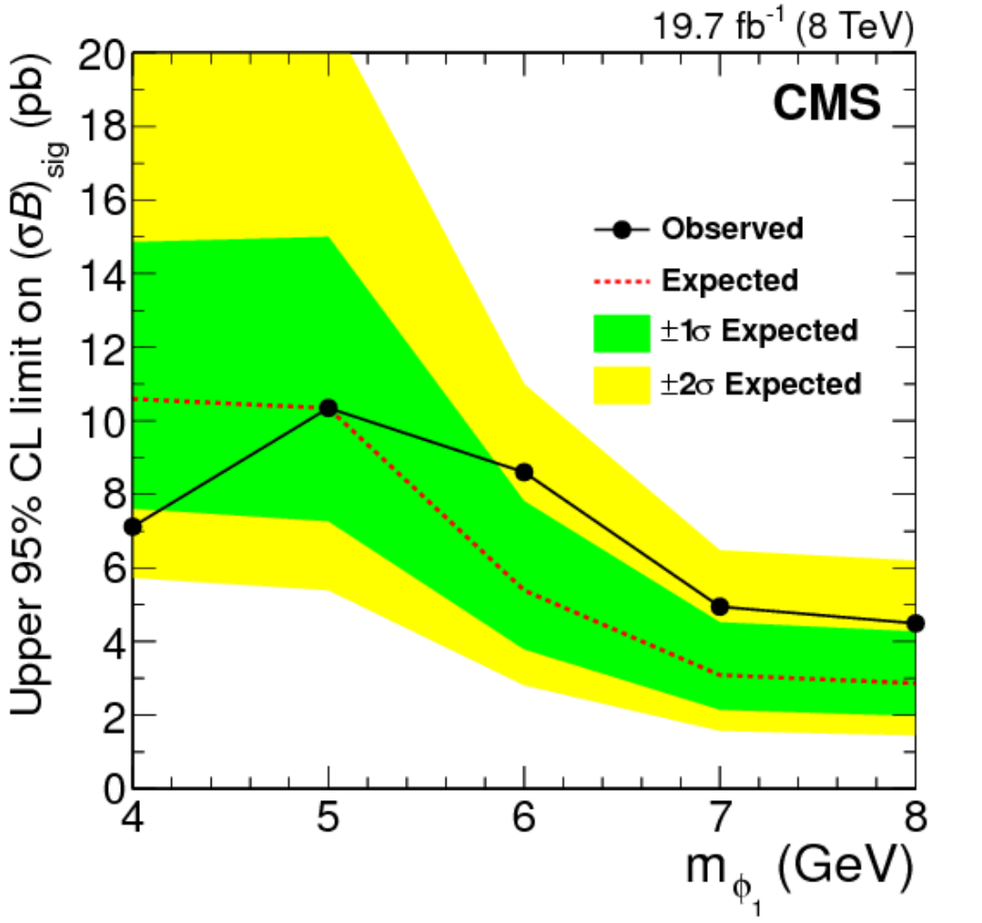
h→aa→4τ (1)

- Focus ggh → aa → 4τ
  - 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 is observed**
  - upper limits range from 4.5 pb at $m_{a1}(m_{h1})$ = 8 GeV to 10.3 pb at $m_{a1}(m_{h1})$ = 5 GeV



CMS PAS HIG-14-019

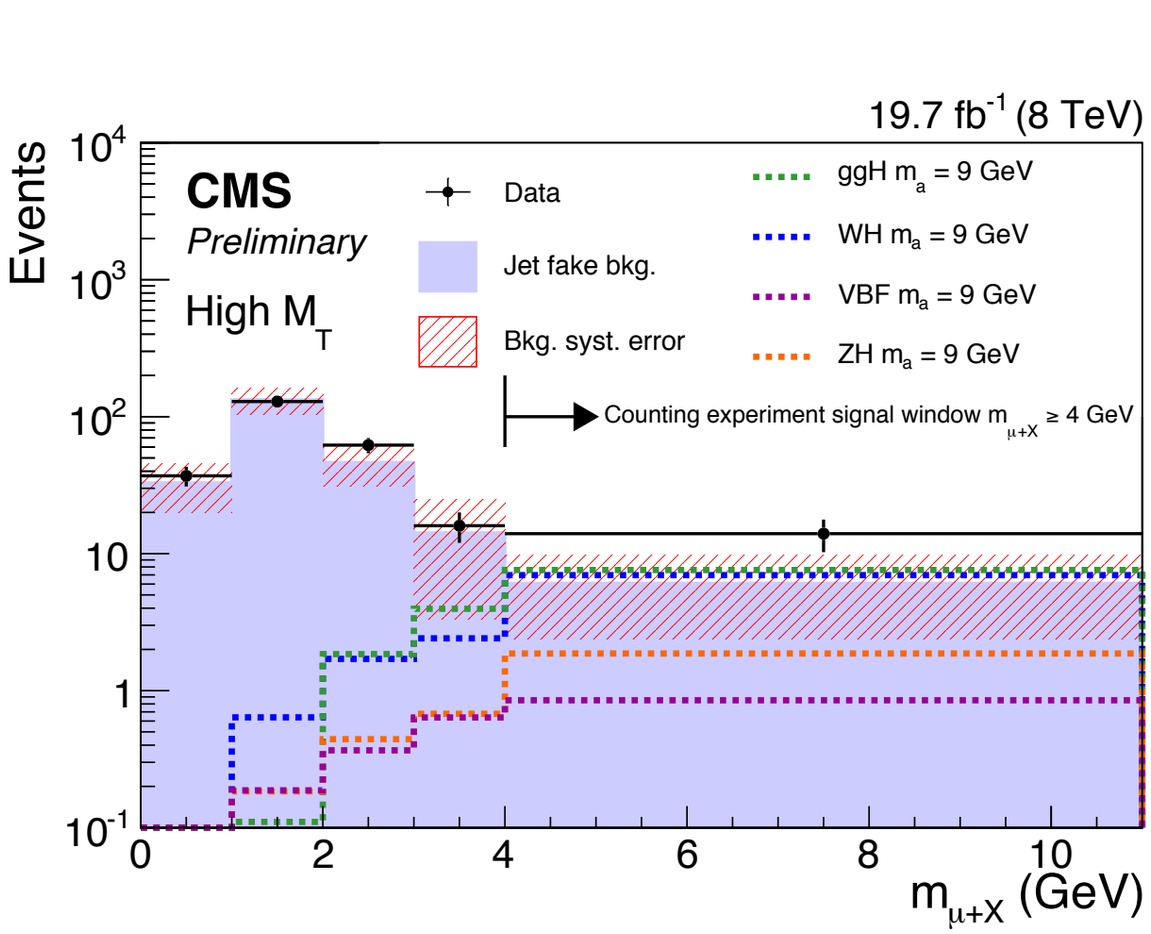


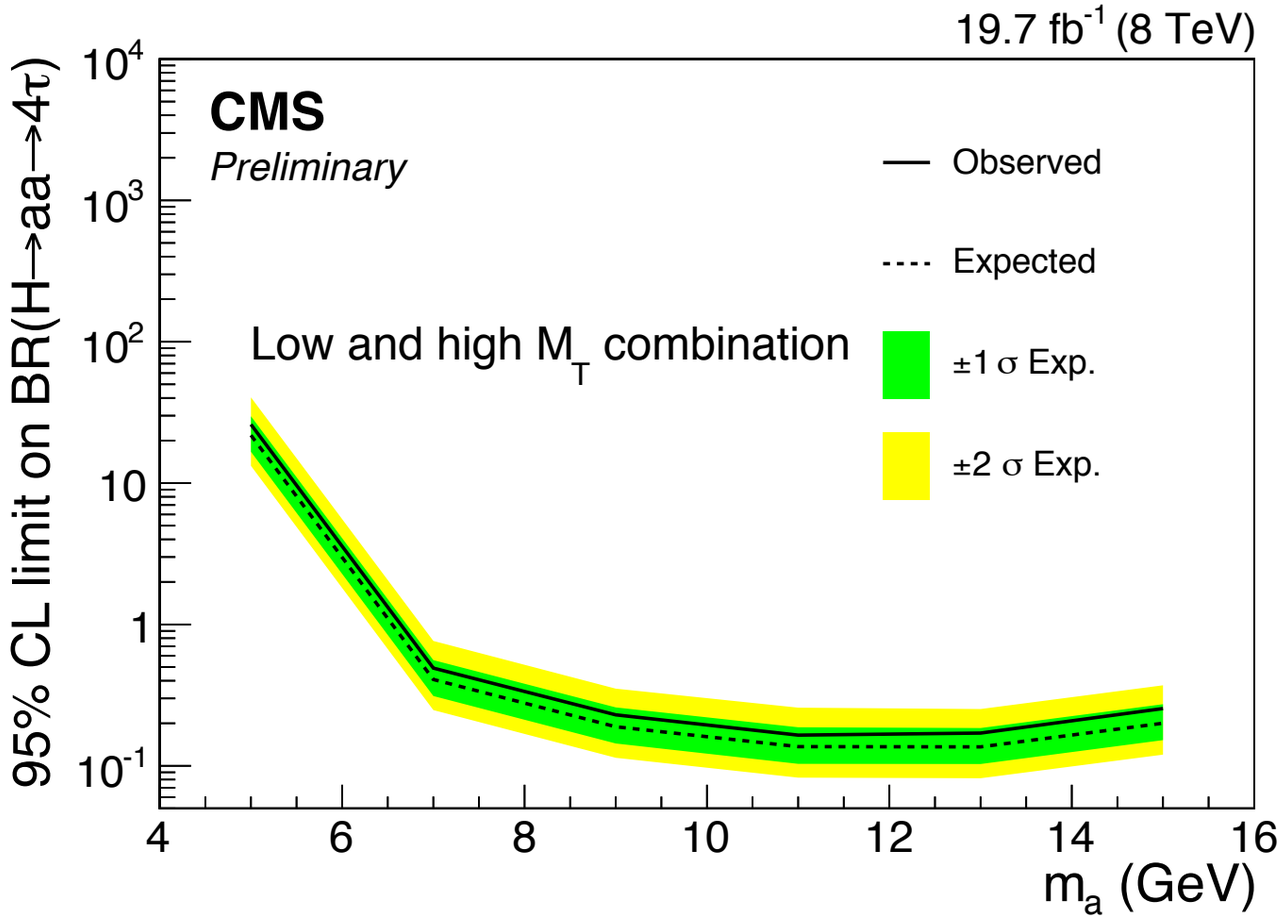


$h \rightarrow aa \rightarrow 4\tau$ (2)

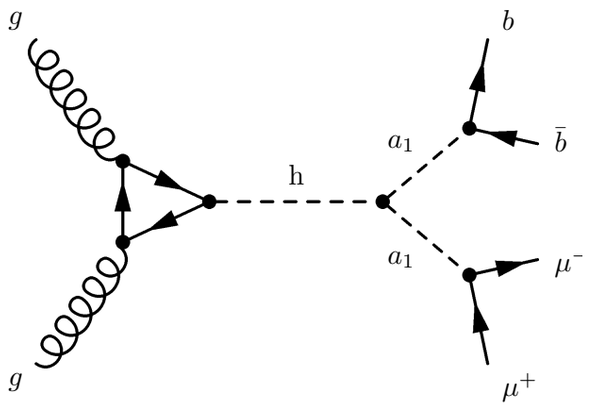
- Different analysis strategy ($\tau_\mu \tau_x$ using HPS algorithm for hadronic tau)
  - including ggH, WH, ZH and VBF production modes of h(125)
  - higher mass region covered $m_a \in$ 5-15 GeV
- No excess is found above the SM backgrounds
  - upper limits on **Br(h → aa)Br(a → ττ)²** are set assuming SM cross-sections for all Higgs production modes

CMS PAS HIG-14-022

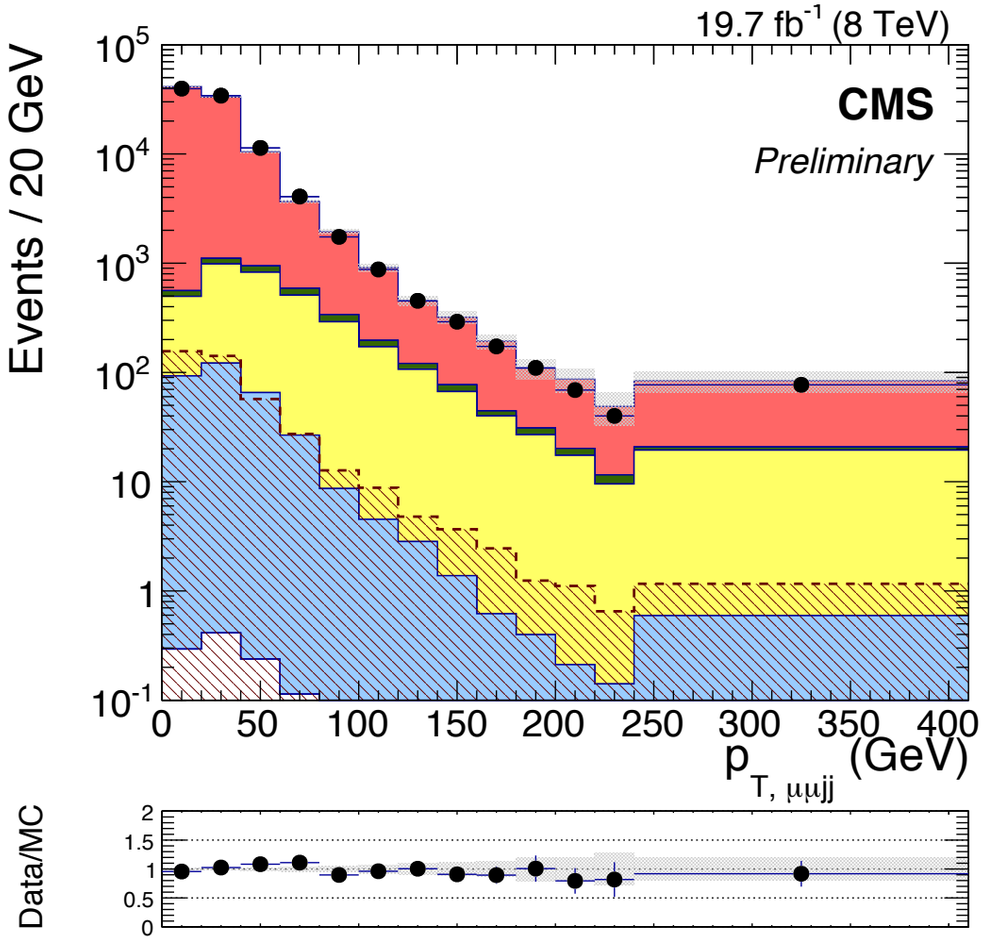


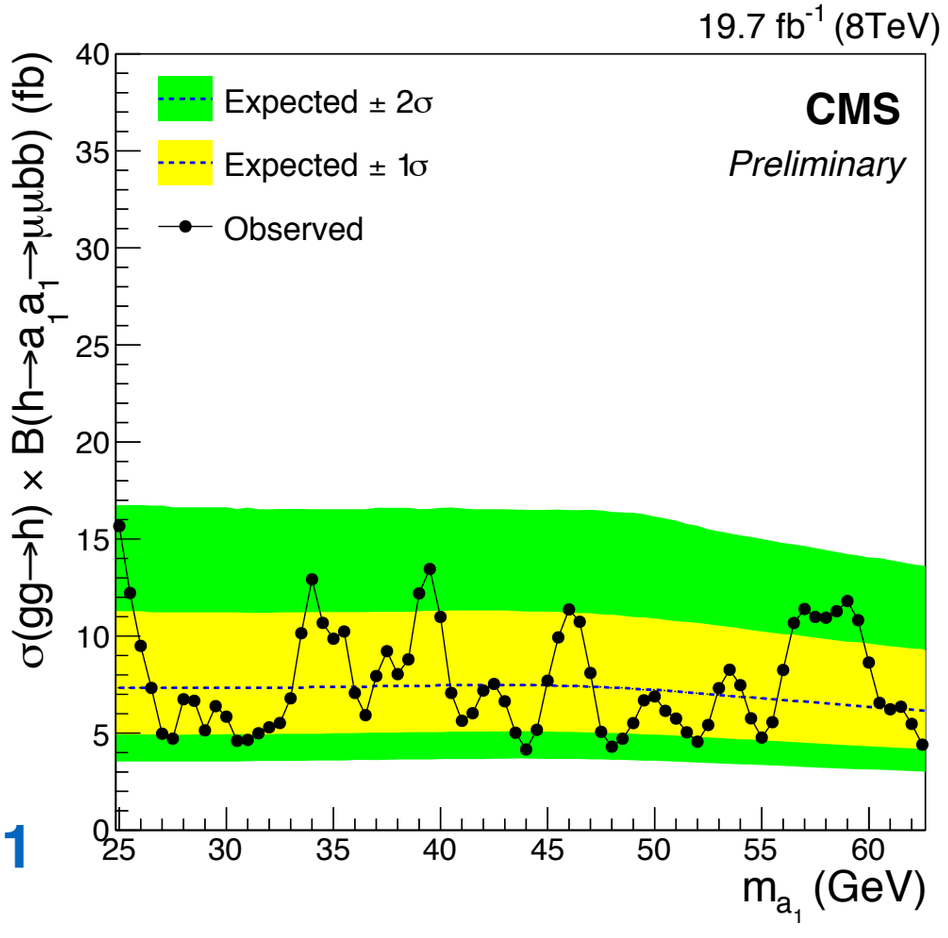


h→aa→2μ2b



- 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 $\sigma_{ggF} \times Br(h \rightarrow aa \rightarrow \mu\mu bb)$ with ranging between 4 to 12 fb for $m_{\mu\mu} \in$ 25 to 65 GeV



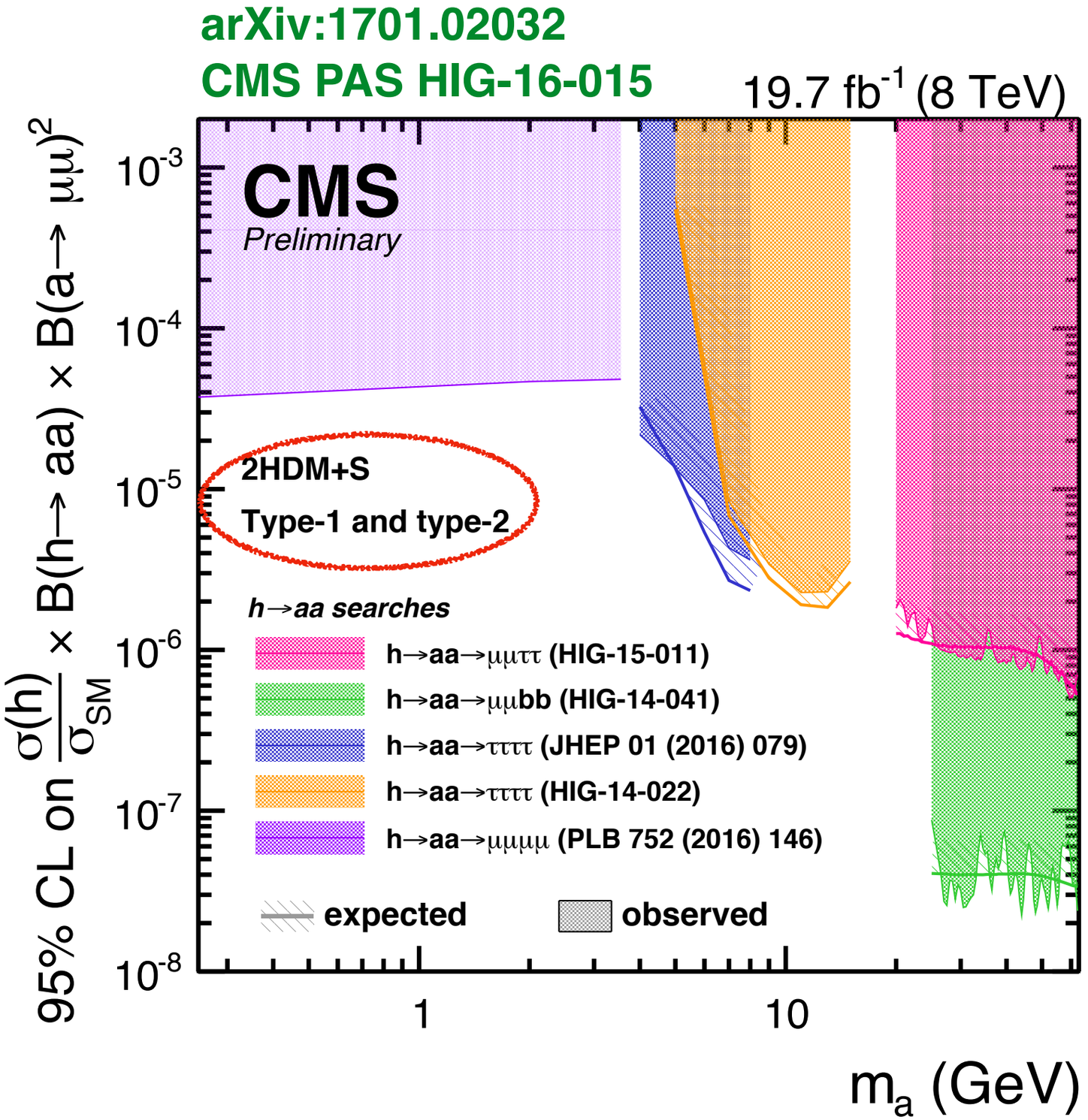


CMS PAS HIG-14-041

Overview of h→aa

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

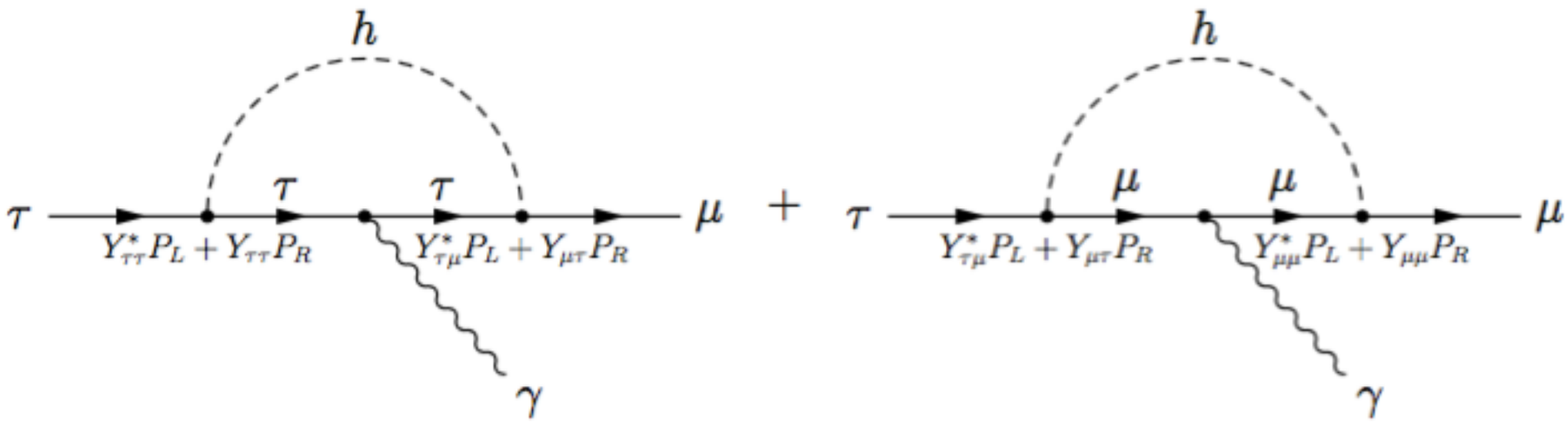
- Upper limits from different h→aa searches in the context of "2HDM+S"
  - Type-1 and Type-2
  - quarkonia decays at 3, 5, 9, 11 GeV
  - all results from 8 TeV data



Lepton Flavor Violation

LFV Higgs Decays

- Forbidden in the SM, described by **composite Higgs** or **2HDM** models
- 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 → e**τ**, h → μ**τ** (theoretical approach described in JHEP **03** (2013) 26)
  - stringent constraints from μ → eγ, 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 h→eμ,e/μτ

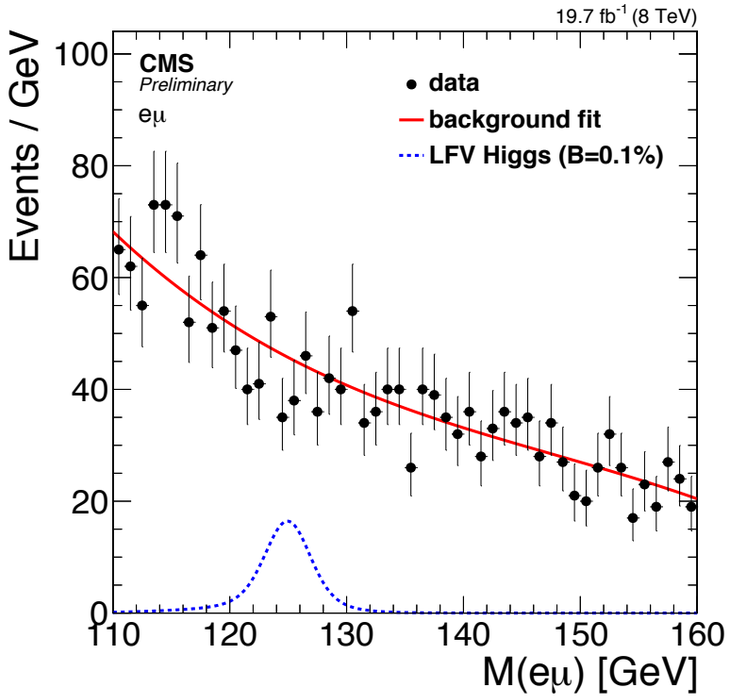
- Similar signature to the SM h→ττ and h→μμ searches but significant kinematic differences
- Provide direct constraints on the off-diagonal Higgs Yukawa couplings

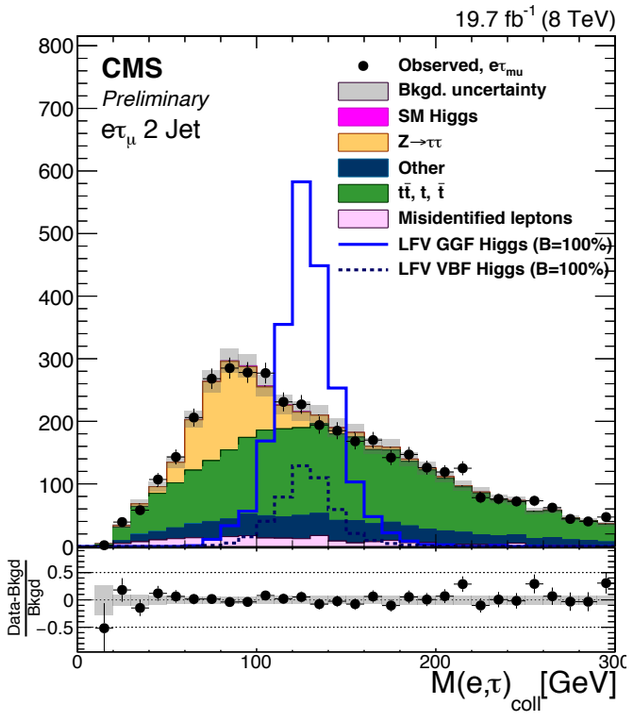
h→eμ

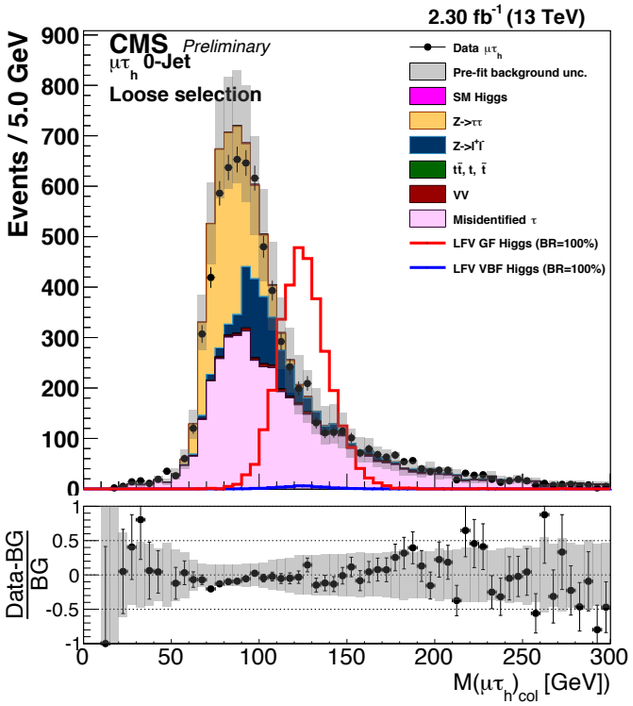
- Very clean but branching ratio strongly constrained!
- 10 channels (barrel/endcap leptons mix with 0-1-2 jets)
- unbinned likelihood fit to $M_{e\mu}$ distribution

h→eτ and μτ

- 3 categories (0,1,2 jets) from 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.)





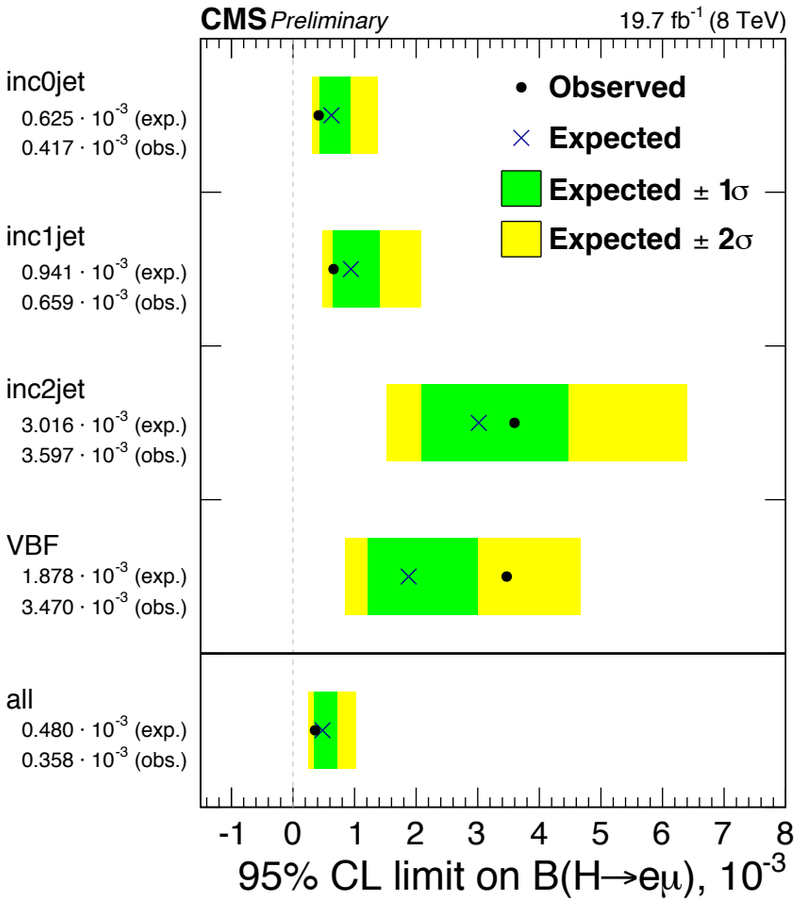


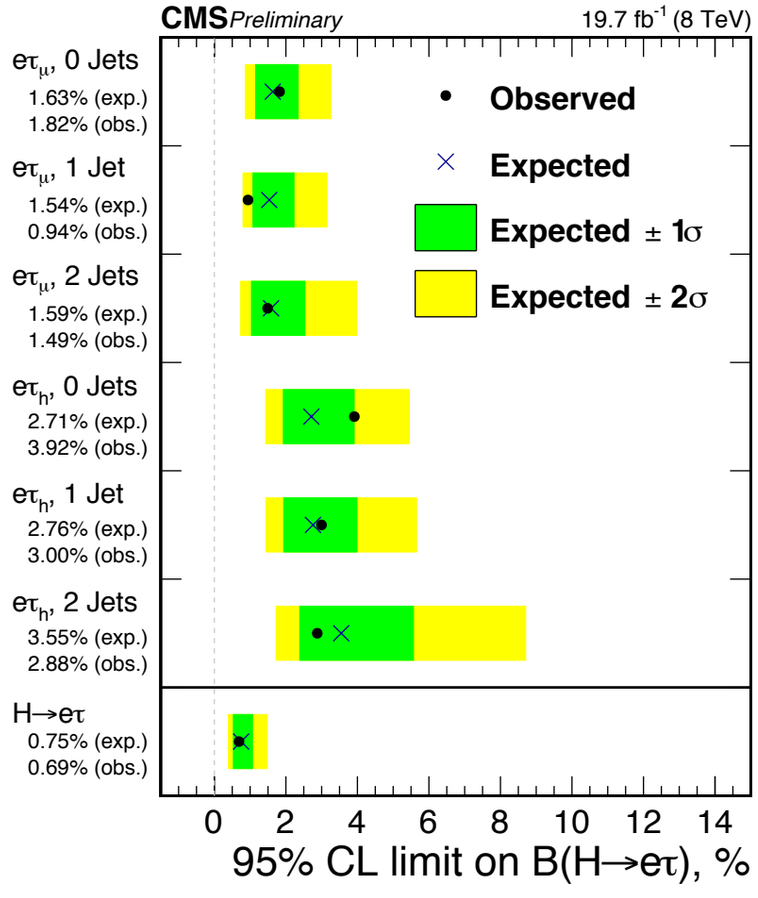
LFV h→eμ,e/μτ

8 TeV 20 fb^{-1}

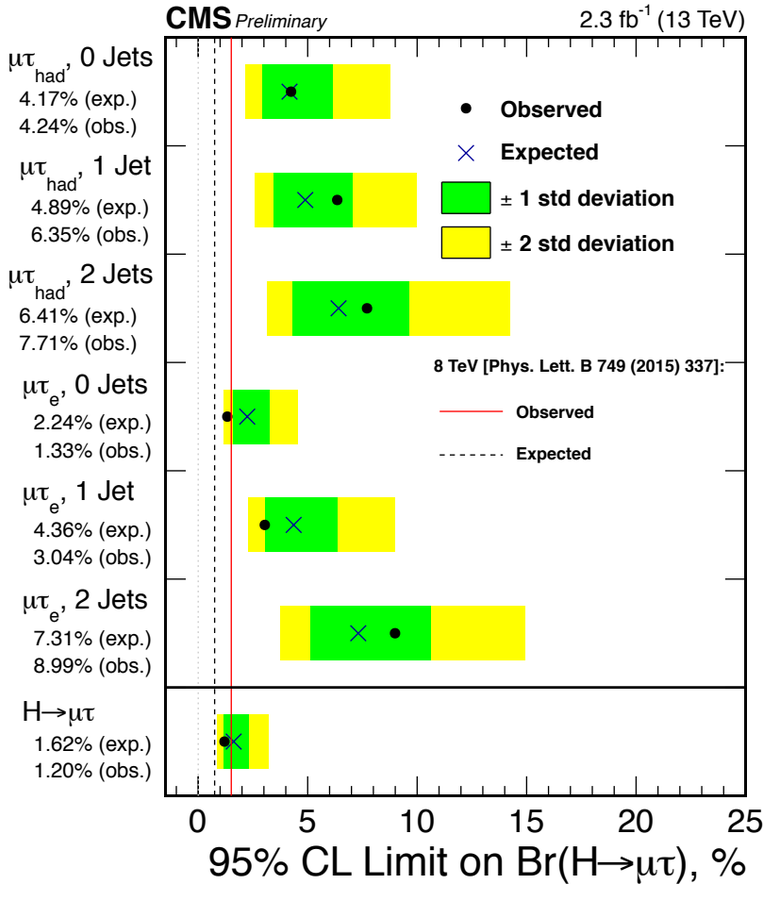
13 TeV 2.3 fb^{-1}

CMS PAS HIG-14-040





CMS PAS HIG-16-005



Br(h→eμ) < 0.035%
(0.048% expected)

Br(h→eτ) < 0.69%
(0.75% expected)

Br(h→μτ) < 1.20%
(1.62% expected)

No excess is observed
(2.4σ at 8 TeV from h→μτ not confirmed but comparable results)

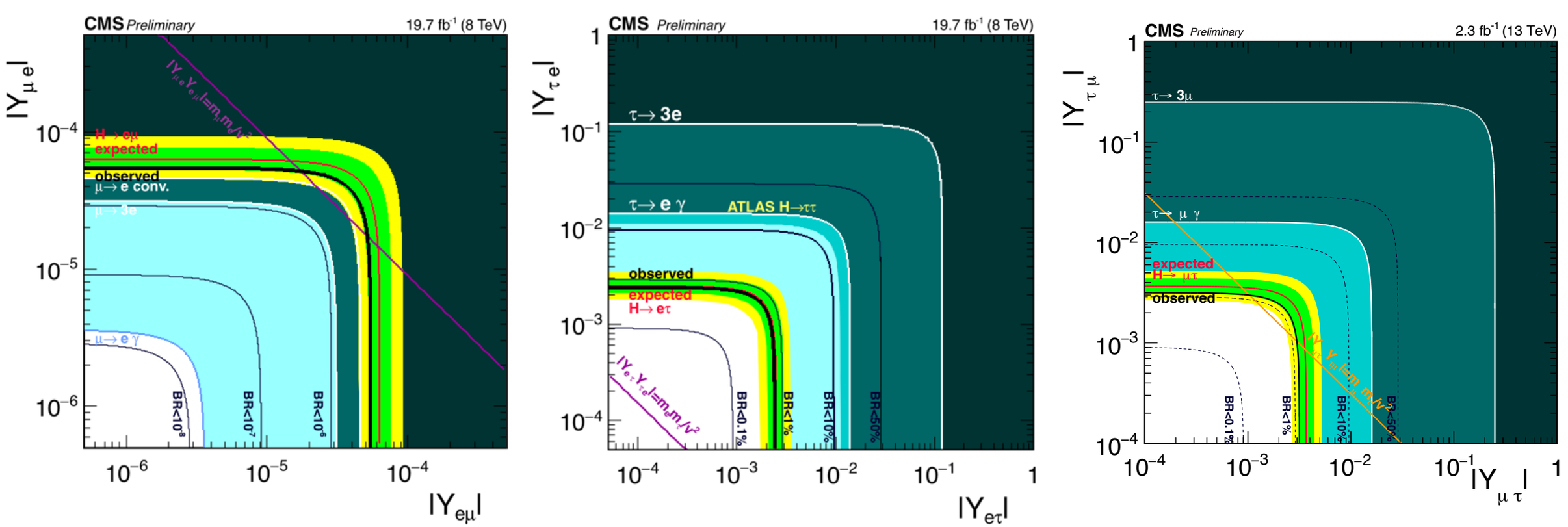
Higgs Yukawa Couplings

- The constraints on **Br(h→eμ), Br(h→eτ) and Br(h→μτ)** can be bounded on the Higgs Yukawa couplings comparing to theoretical numbers*

$$h\to e\mu : \sqrt{|Y_{e\mu}|^2+|Y_{\mu e}|^2} < 5.4 \times 10^{-4} \ (< 3.6 \times 10^{-6})$$

$$h\to e\tau : \sqrt{|Y_{e\tau}|^2+|Y_{\tau e}|^2} < 0.0024 \ (< 0.014)$$

$$h\to \mu\tau : \sqrt{|Y_{\mu\tau}|^2+|Y_{\tau\mu}|^2} < 0.0032 \ (< 0.016)$$



*R. Harnik, J. Kopp, and J. Zupan JHEP **03** (2013) 26

Summary

- The discovery of the SM-like Higgs boson opens an era of search for new physics
- h(125)→invisible searches at CMS shown the latest results from Run-2 at 13 TeV with 2.3 fb^{-1} and some new results with 12.9 fb^{-1} and their combinations
- h(125)→aa searches done in many channels and interpreted results in the context of 2HDM+S
- Direct searches for LFV h(125) decays can constrain Br(h→LFV) and set bounds on the off-diagonal Higgs Yukawa couplings
- Stay tuned! a lot more to come!
  - many more BSM results with full 2016 dataset (36 fb^{-1}) are on the way

Thanks for your attention!

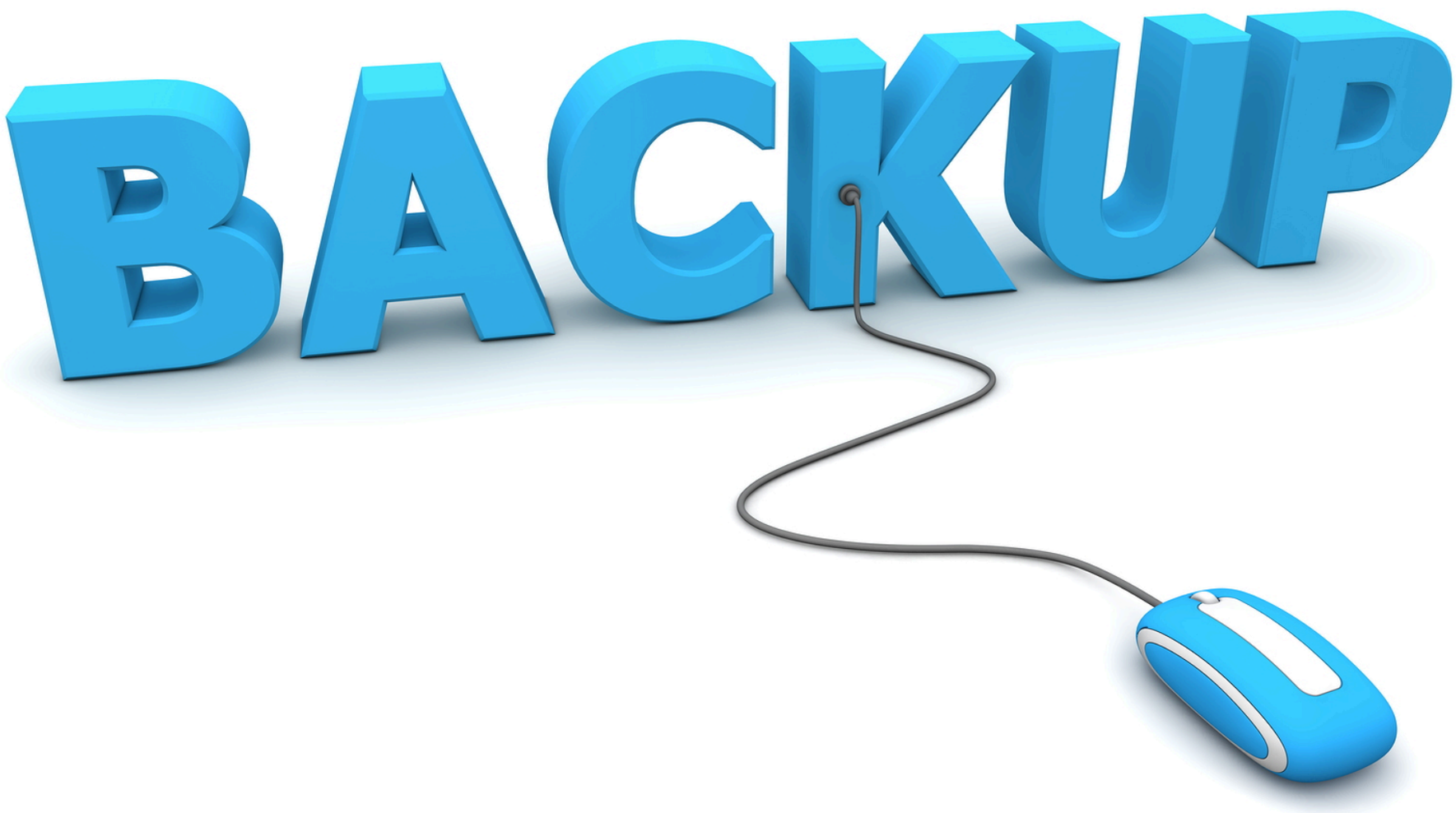
References

- CMS Public Results
  - http://cms.web.cern.ch/org/cms-papers-and-results
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html
  - https://cds.cern.ch/collection/CMS%20Physics%20Analysis%20Summaries?ln=en

CMS PAS ID

- **h(125)→invisible searches**
  - VBF channel : CMS PAS HIG-16-009
  - VH channel : CMS PAS HIG-16-008, CMS PAS EXO-16-013
  - ggH channel : CMS PAS EXO-12-055, CMS PAS EXO-16-037
  - combination : CMS PAS HIG-16-016
- **h(125)→aa searches**
  - h→aa→4**μ** : CMS PAS HIG-16-035
  - h→aa→2**μ**2**τ** : CMS PAS HIG-15-011
  - h→aa→2**μ**2b : CMS PAS HIG-14-041
  - h→aa→4**τ** : CMS PAS HIG-14-019, CMS PAS HIG-14-022
  - combination : CMS PAS HIG-16-015
- **LFV h(125) decays**
  - h→**μτ** : CMS PAS HIG-16-005
  - h→e**μ**,e**τ** : CMS PAS HIG-14-040

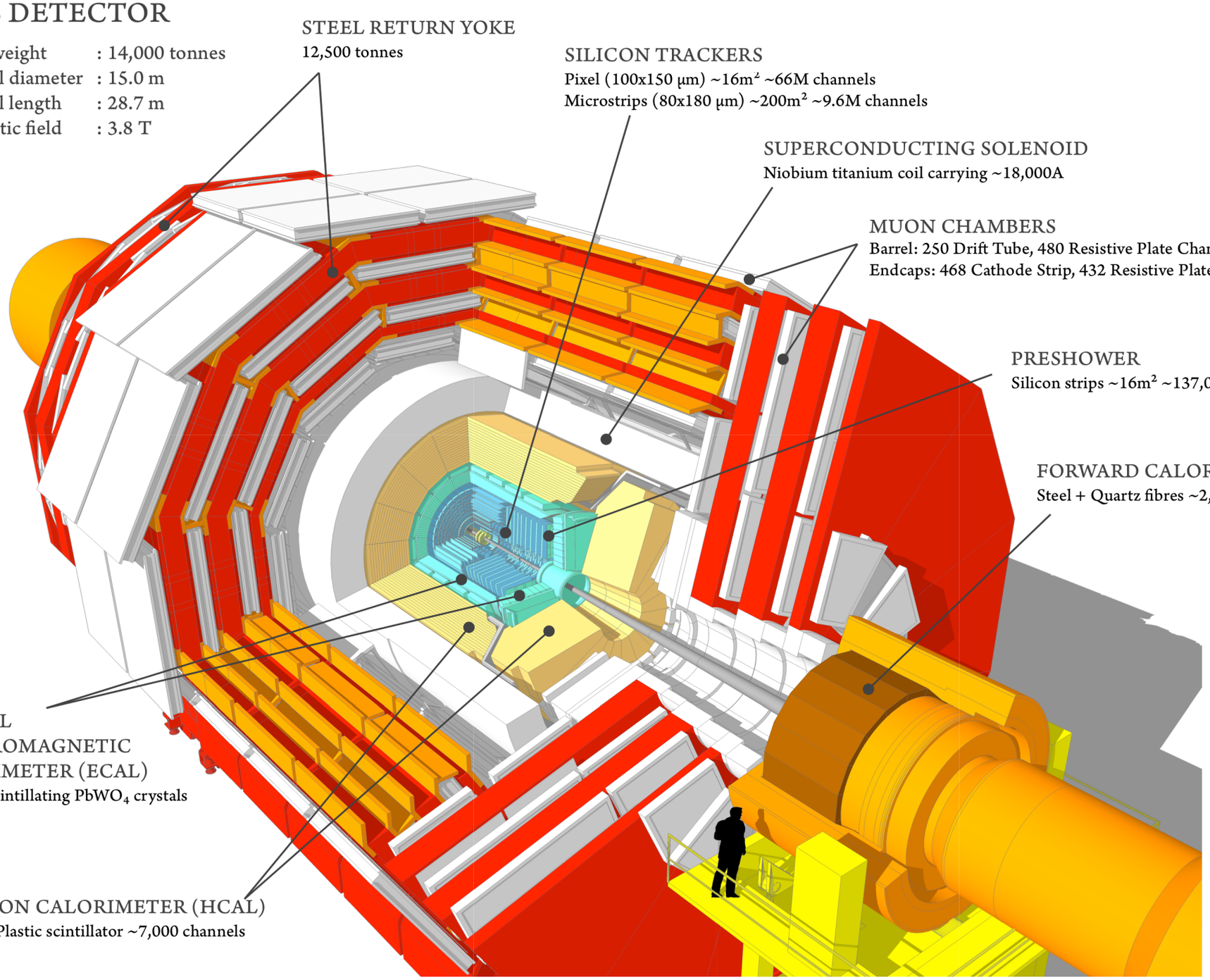
* http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/


BACKUP

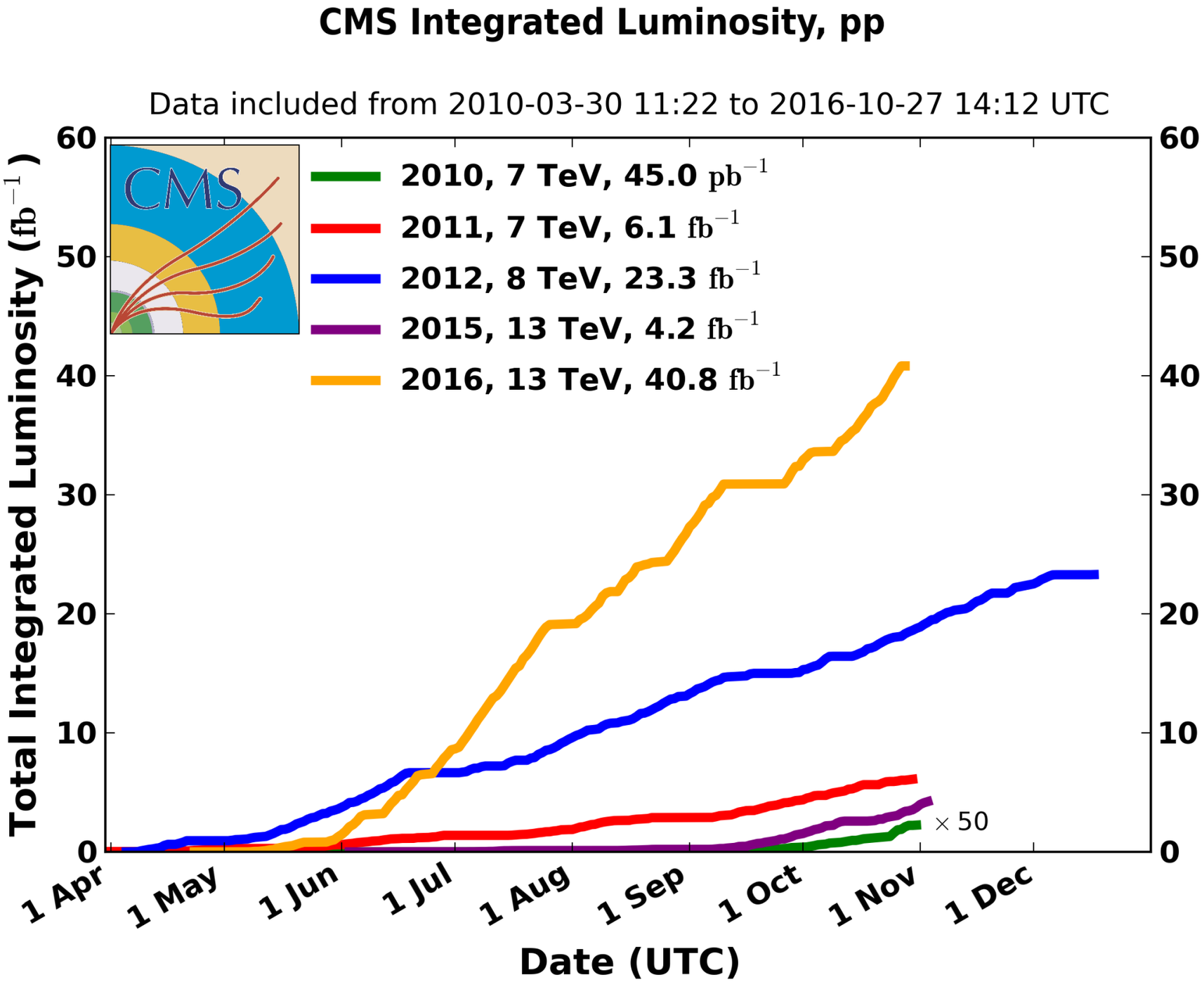
Compact Muon Solenoid (CMS)

CMS DETECTOR

Total weight	: 14,000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

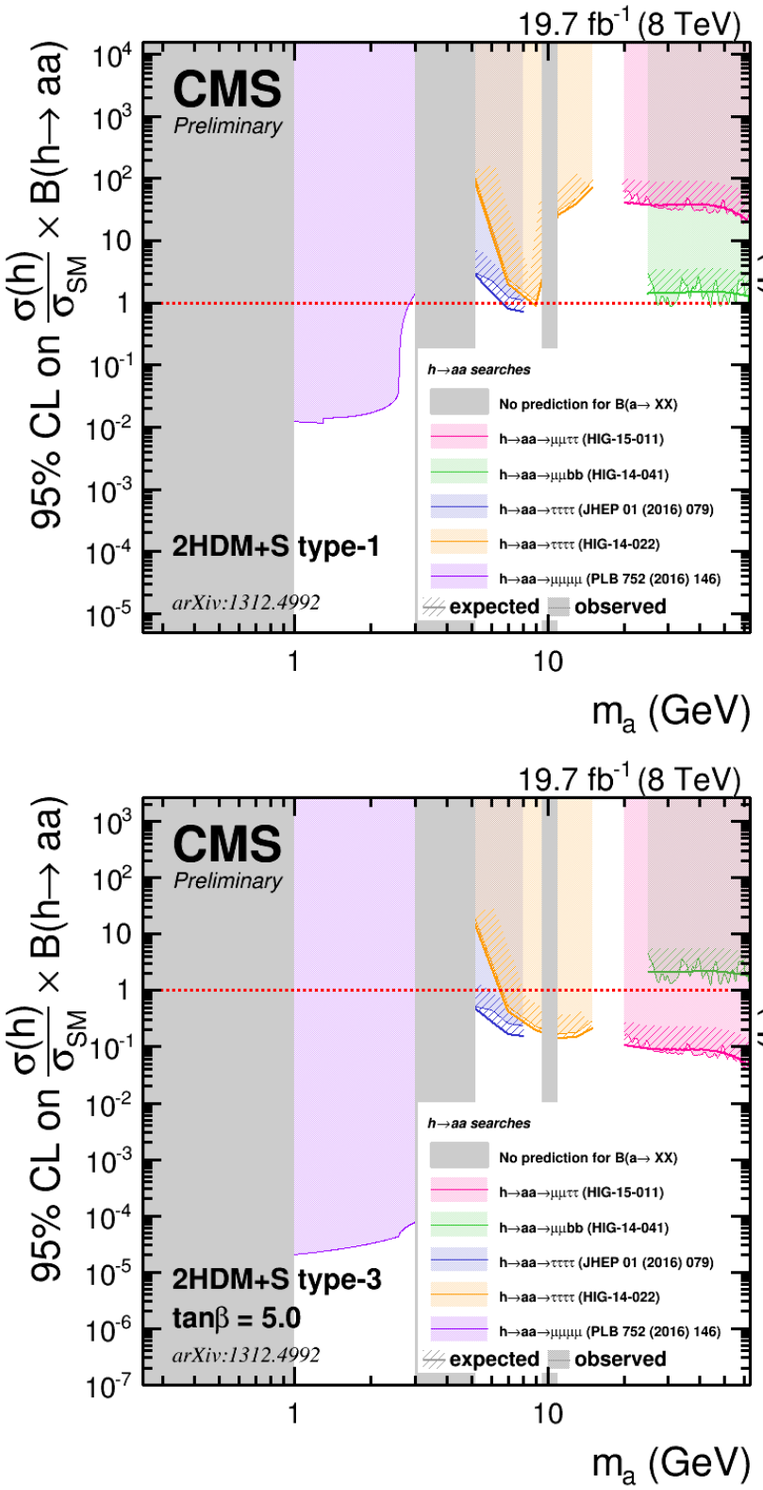


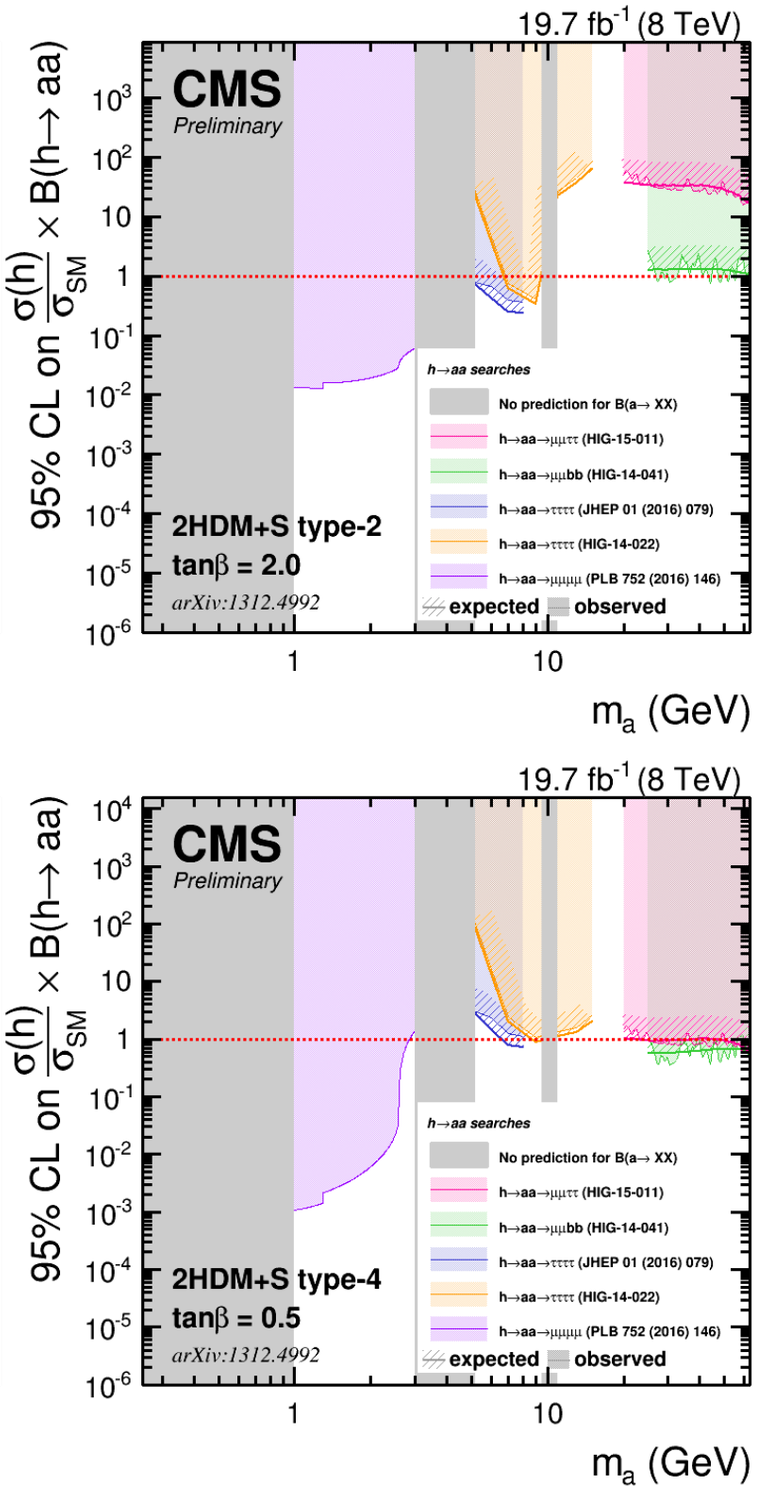
Luminosity 2011-2016



Overview of h→aa

CMS PAS HIG-16-015





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
$\tau \to 3\mu$	$\sqrt{\lvert Y^2_{\tau\mu} + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau}Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$\left(\lvert Y_{\tau\mu}Y_{e\tau}\rvert^2 + \lvert Y_{\mu\tau}Y_{\tau e}\rvert^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

JHEP 03 (2013) 026

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

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