Higgs boson rare and exotic decays at CMS

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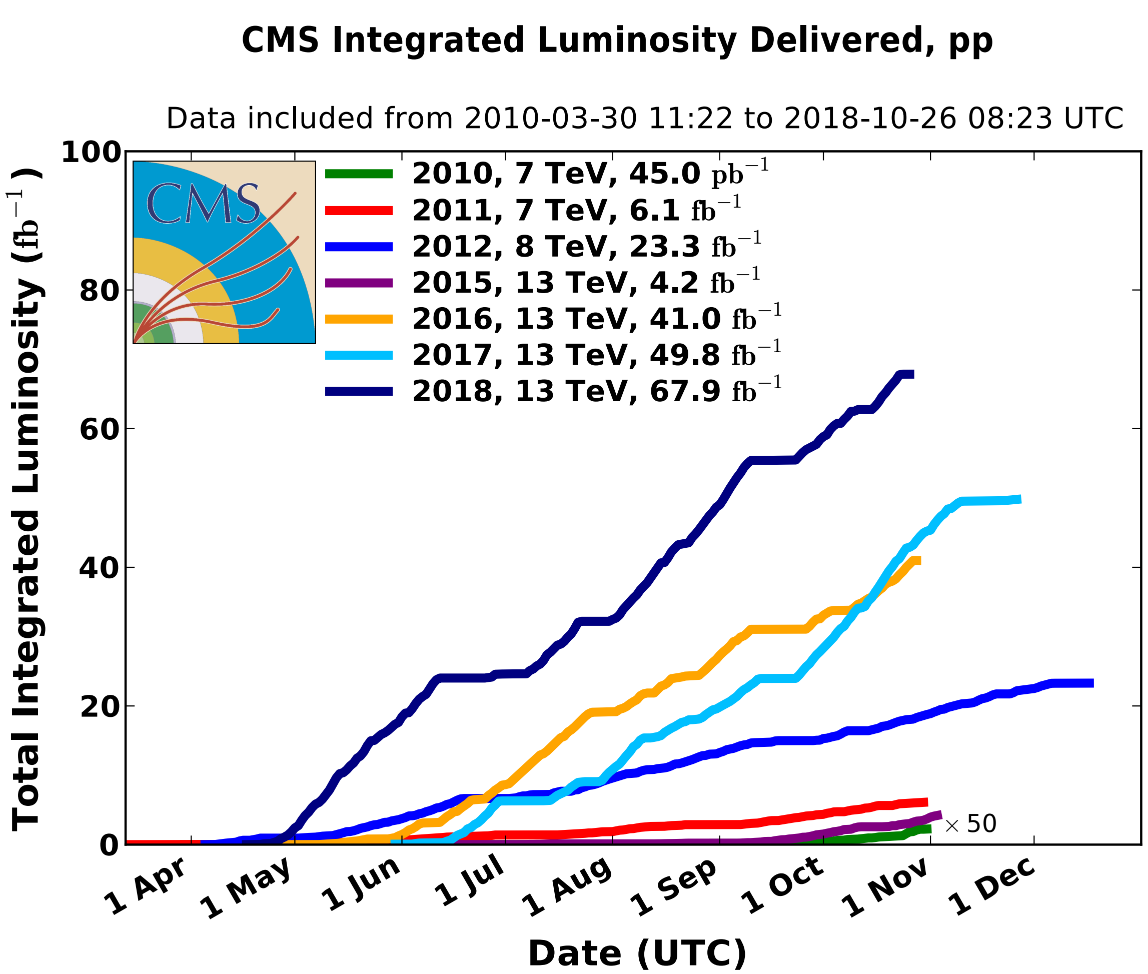
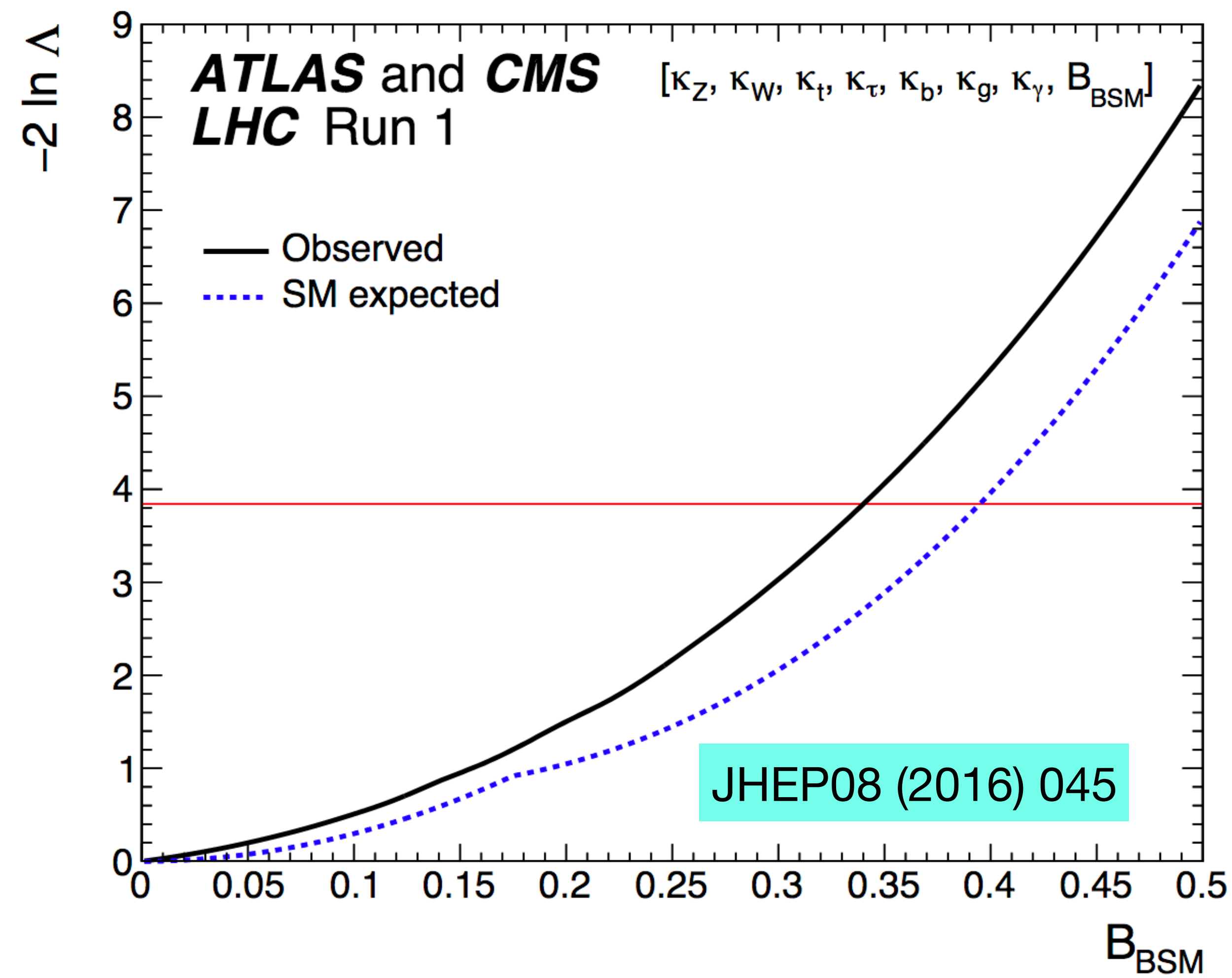
On behalf of CMS Collaboration

Motivation

- Higgs boson (125 GeV — scalar sector):
  - Discovery in 2012 completed the Standard Model (SM) theory
  - Measurements of Higgs coupling to SM particles consistent with predictions for the moment
  - Beyond Standard Model decays (BSM) not completely excluded by current physics limits
    - Branching ratio of H—> BSM less than 34% with LHC RunI results
    - Deviations from the SM predictions might give a hint of BSM



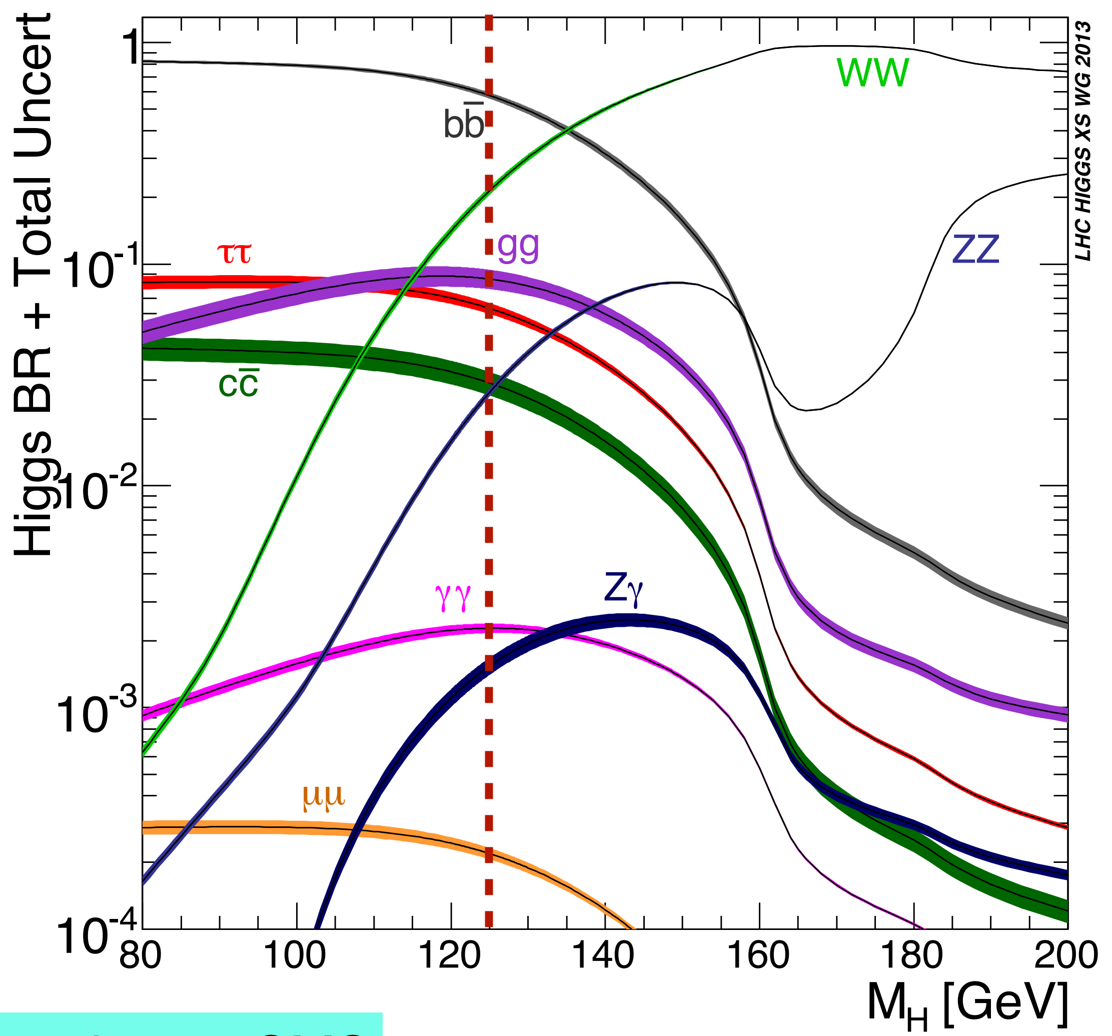


Exotic & rare decays of Higgs boson

- **Class 1: Decays to SM particles:**
  - Very small branching ratio increases difficulty of observation (eg: H—> $\mu\mu$)
  - Invisible decays with neutrinos in the final states
  - An excess on SM prediction (decay rates & cross section) might be a sign of BSM

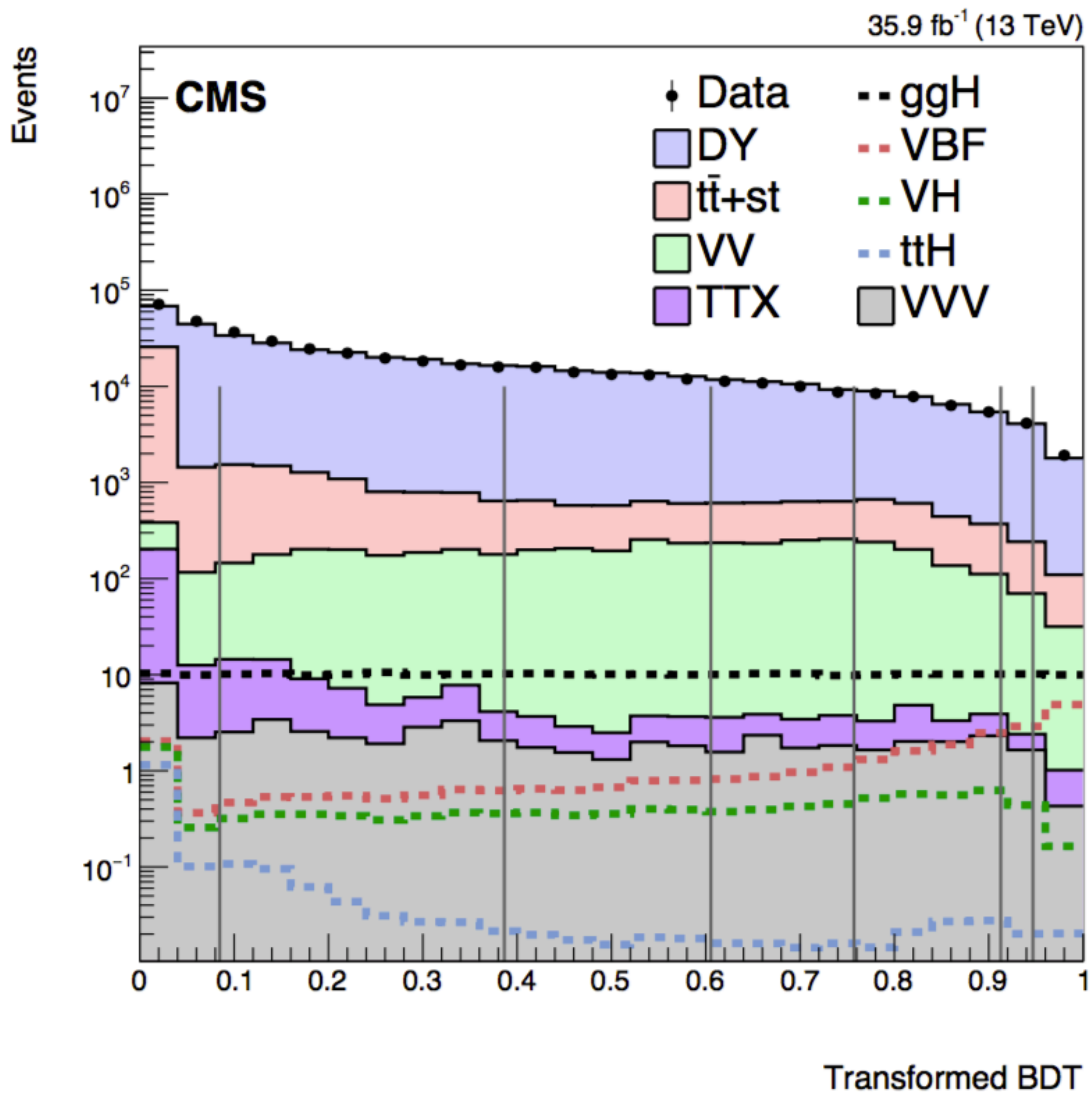
- **Class 2: Decays in BSM modes:**
  - Decays to light pseudo-scalar bosons (eg: H—> aa)
  - Invisible decays with large missing transverse energy (eg: H—> dark photon)
  - Decays with lepton favor violation (LFV) (eg: H—> $\mu\tau$)

Process	SM Branching ratio	Class
H —> μμ	~ 2×10^{-4}	1
H—> J/ψ J/ψ	~ 1.5×10^{-10}	1
H—> YY	~ 2×10^{-9}	1
H—> aa —> μμττ	-	2
H —> aa —> 4τ	-	2
H —> invisible	~ 1×10^{-3}	1/2
LFV	-	2

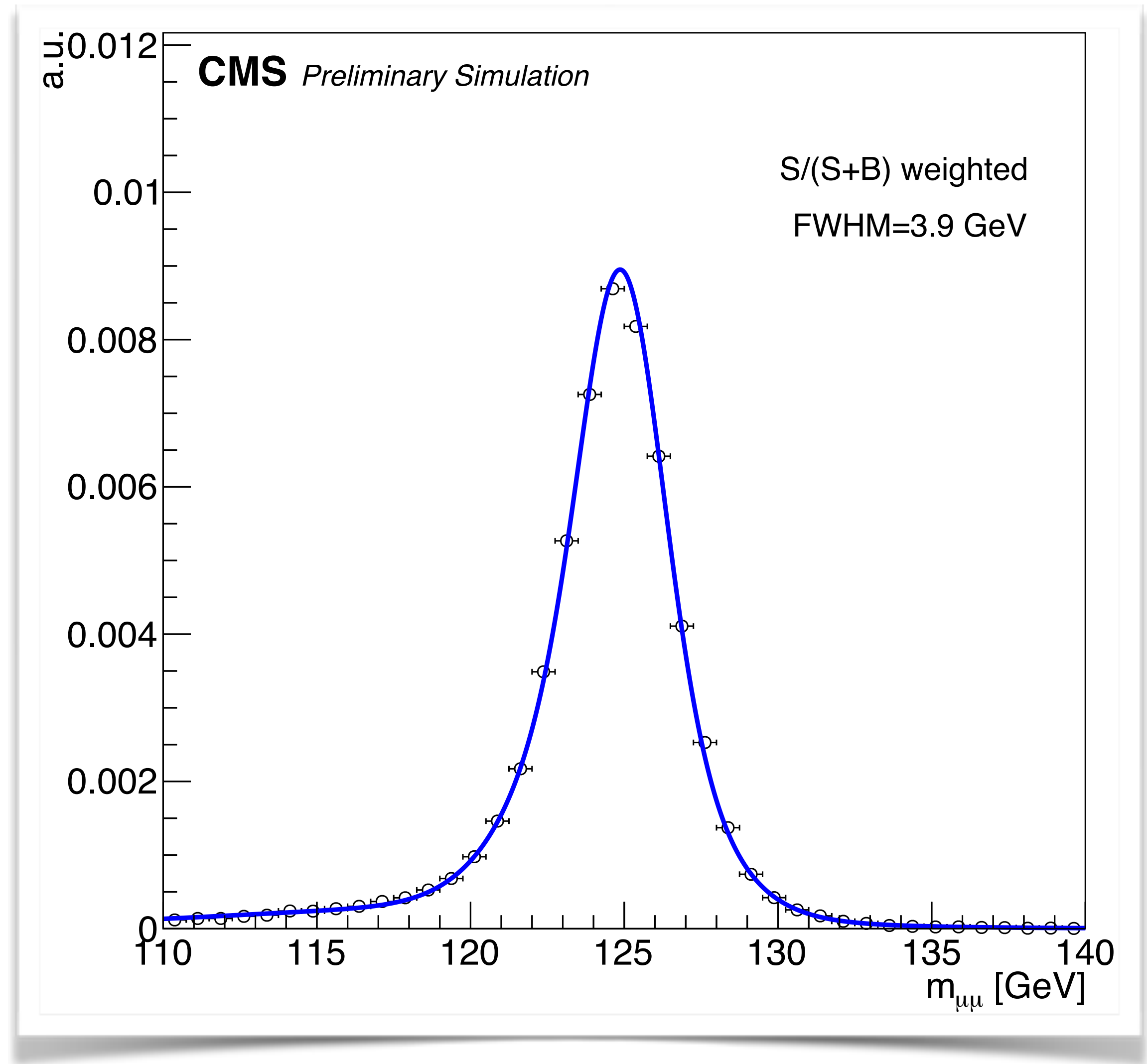


- LFV results in backup page & Dermot's talk
- This talk presents two recent examples of many H —> aa searches at CMS

Higgs decays to $\mu^+\mu^-$ pair

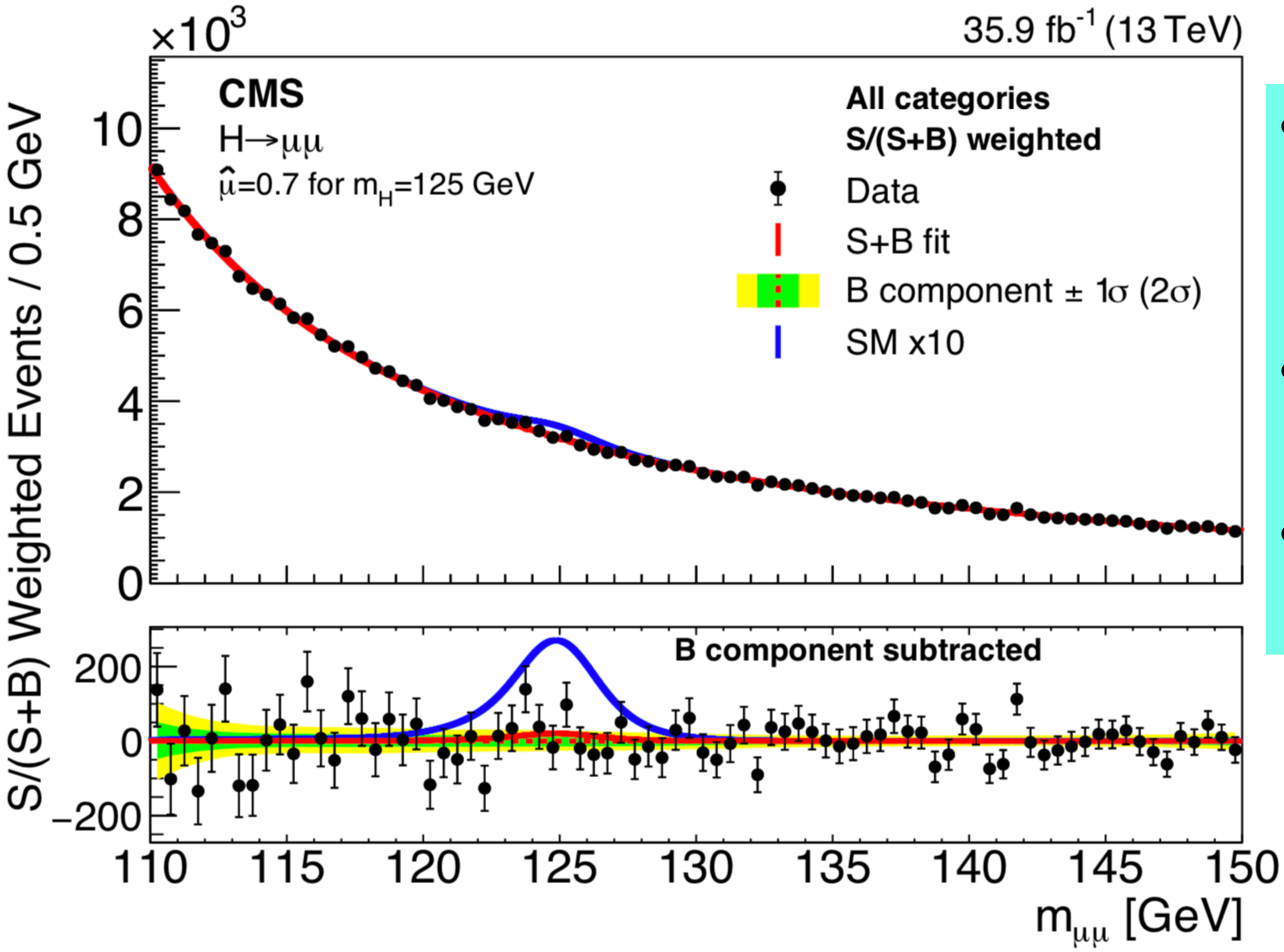


Phys. Rev. Lett. 122, 021801



- **Generated Next-to-leading order (NLO)** for mass ranges: **120, 125, 130 GeV**
- Background estimated from data
- **Boost decision tree (BDT)** method applied for distinguishing signal & background shapes
- **Dimuon mass resolution** is incorporated for optimizing the signal sensitivity

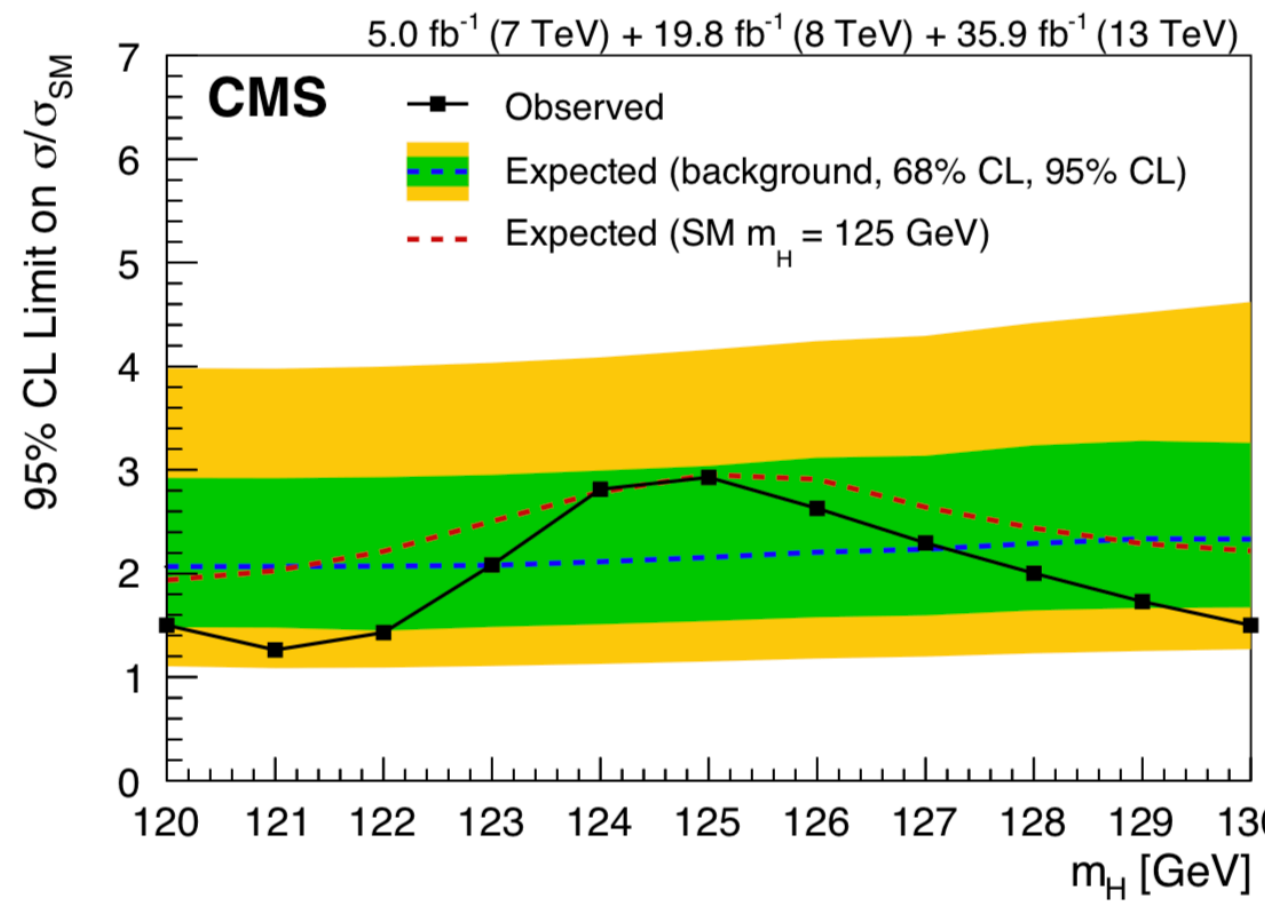
Higgs decays to $\mu^+\mu^-$ pair



Phys. Rev. Lett. 122, 021801

- To measure the signal strength:
  - Maximum likelihood fit to **dimuon invariant mass** spectrum:
- Main experimental uncertainties:
  - Jet energy scale & resolution: 6%
- Main theoretical uncertainty:
  - Factorization & renormalization scales: 6%

Combined RunI and RunII data

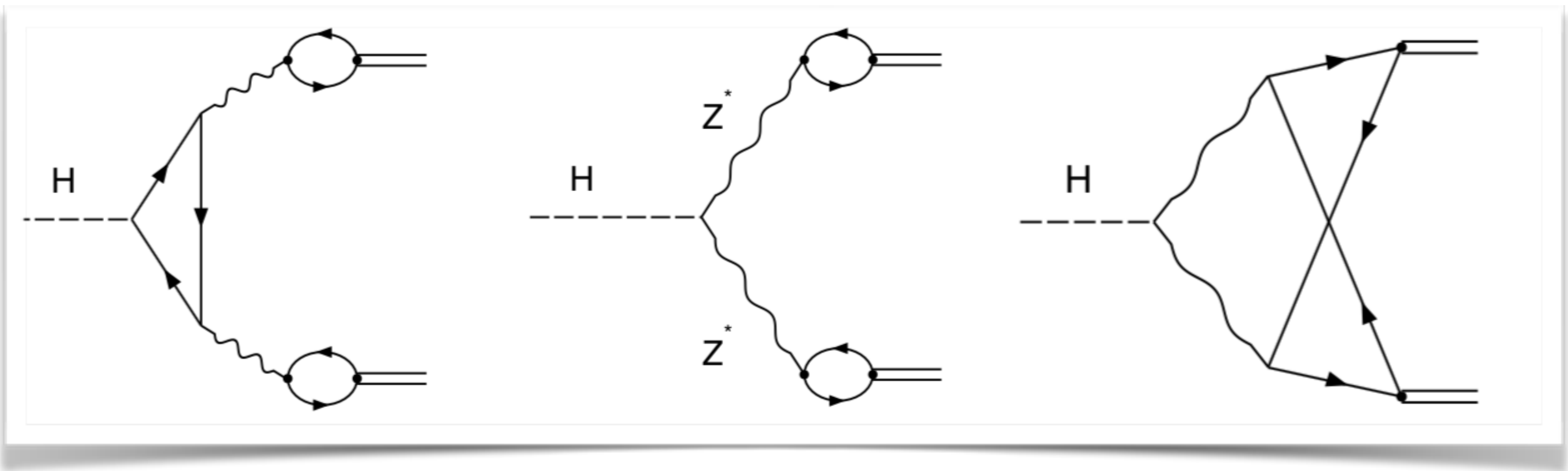


- SM branching ratio: 2.17×10^{-4}
- Observed branching ratio upper limits: 6.4×10^{-4}

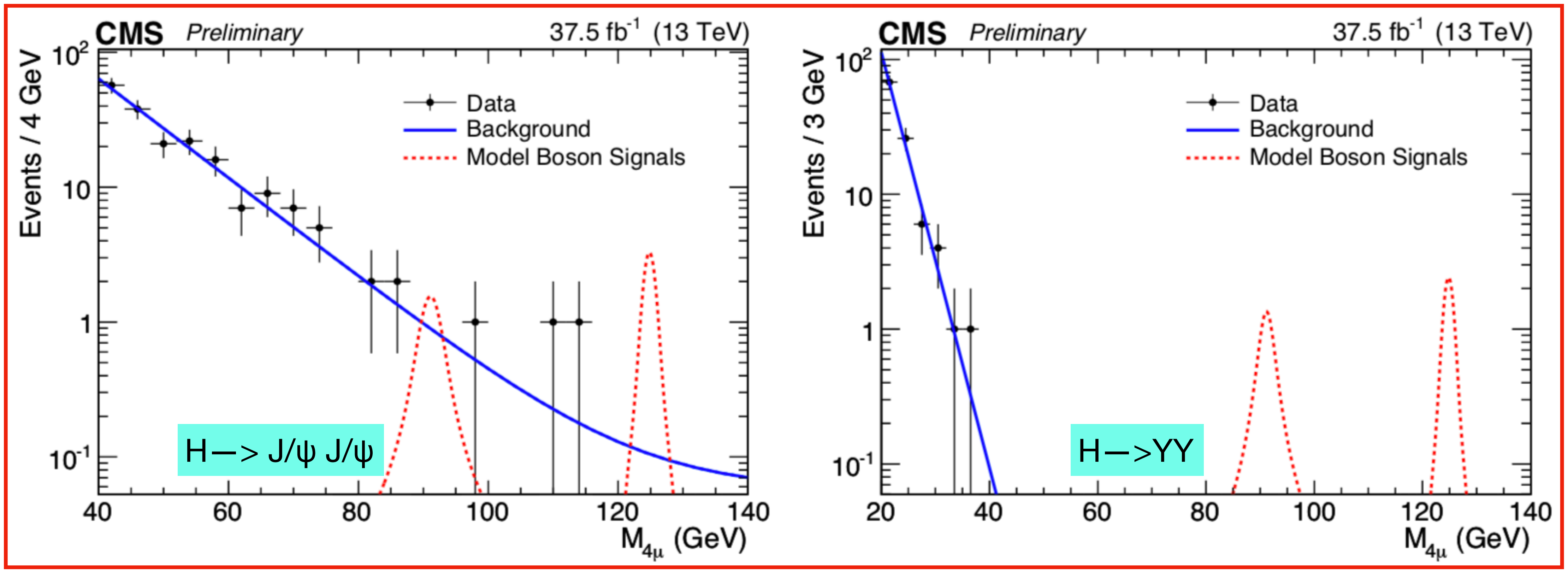
- Expected upper limits: 2.2 σ
- Observed upper limits: 2.9 σ

- Expected signal significance: 0.9
- Observed signal strength: 1.0 ± 1.0 (stat.) ± 0.1 (syst.)

H —> J/ψ J/ψ - YY



Channel	Branching ratio
H —> J/ψ J/ψ	1.5×10^{-10}
H —> YY	2×10^{-9}



arXiv:1905.10408

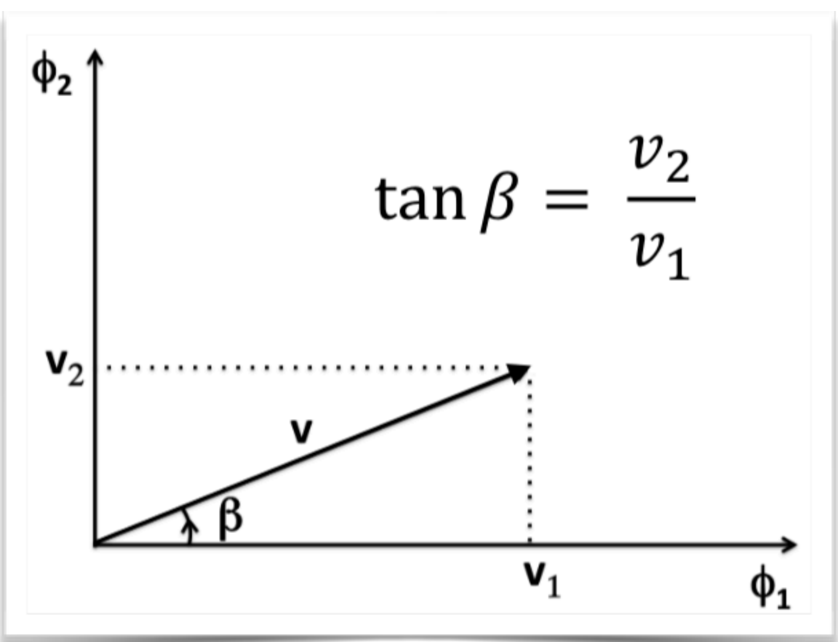
- Rare exclusive decays of Higgs to mesons
  - Promising lab to study **Yukawa couplings & BSM**
- 4μ final state offers a clean signature
- Observed upper limits set for H—> unpolarized mesons

Exclusion limits 95% C.L.	Observed	Expected
H —> J/ψ J/ψ	1.8×10^{-3}	$1.8\ (+0.2/-0.1) \times 10^{-3}$
H —> YY	1.4×10^{-3}	$1.4\ (\pm 0.1) \times 10^{-3}$

Exotic decays in 2HDM + S

- **Two-Higgs-Doublet Model (2HDM)**: two doublets of scalar fields (ϕ_1,ϕ_2) in the SM Lagrangian
  - Type-2 : **minimal supersymmetry model (MSSM)**
- Further extension: **a scalar singlet (2HDM + S)**
  - Type-2 : **Next-to-minimal-supersymmetry-model (NMSSM)**
- Symmetry breaking —> five physical states are predicted:
  - Neutral scalars: h_1, h_2, h_3
  - Neutral pseudo-scalars: a_1, a_2
  - Charged scalars: $H^\pm$
- Four types of 2HDM (doublets couplings to fermions):

	Type-1	Type-2	Type-3 (lepton-specific)	Type-4 (flipped)
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1
Charged leptons	Φ_2	Φ_1	Φ_1	Φ_2



$$\tan\beta = \frac{v_2}{v_1}$$

- Type-2: MSSM-like
- Type-3: enhanced couplings to leptons at large tanβ

H —> aa —> μμττ

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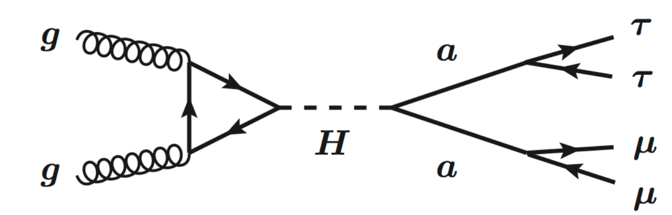
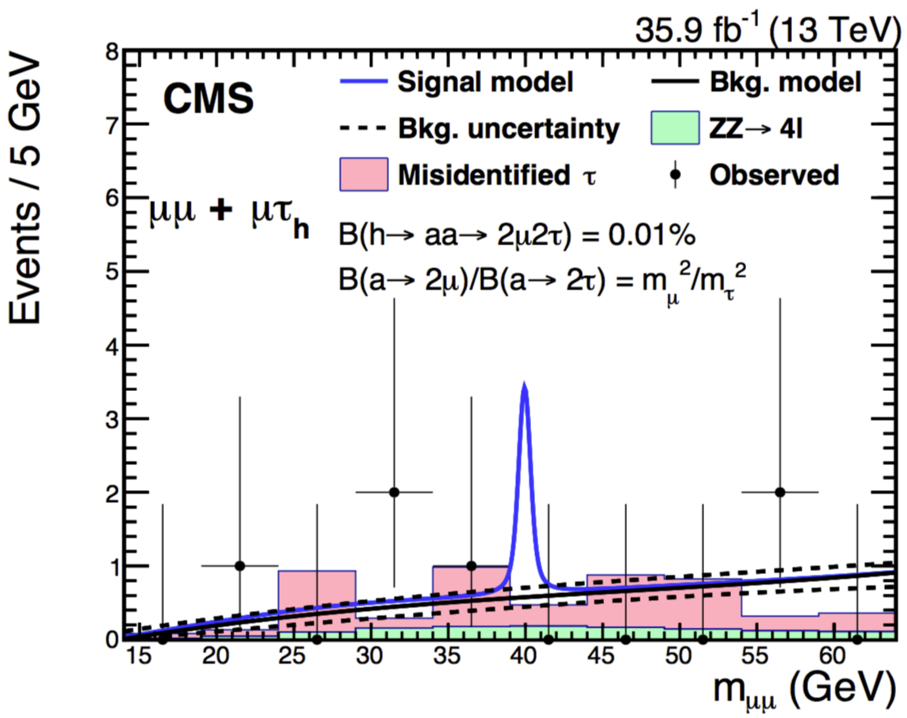


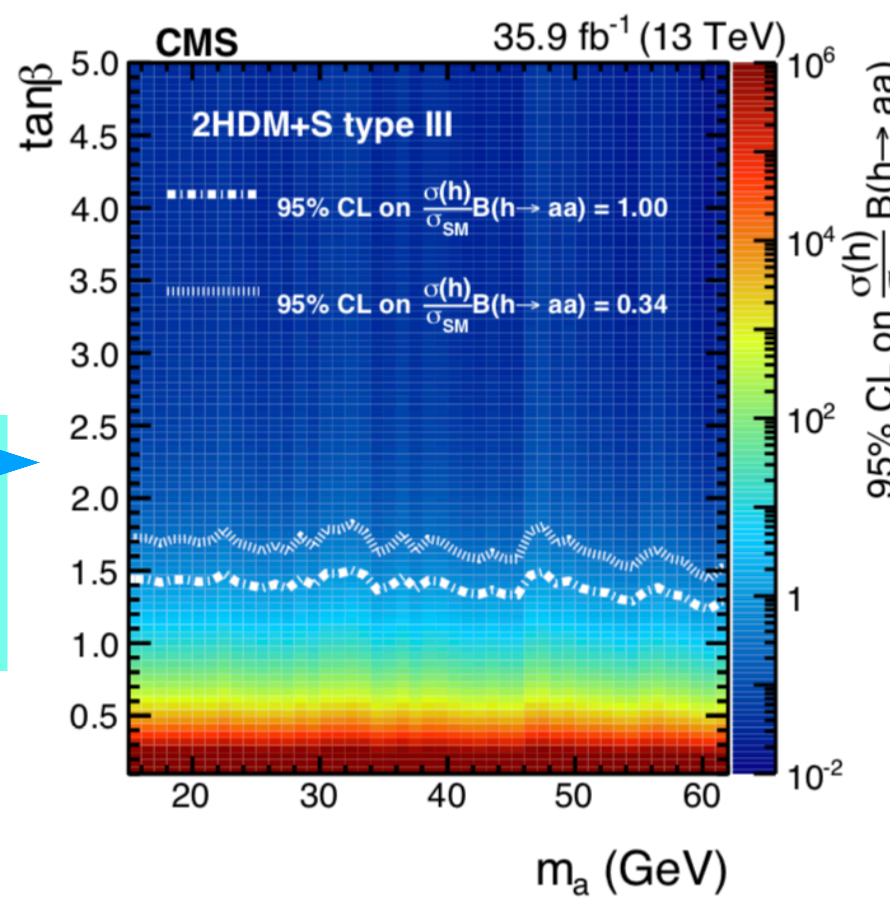
$$\frac{\Gamma(a \to \mu^+\mu^-)}{\Gamma(a \to \tau^+\tau^-)} = \frac{m_\mu^2\sqrt{1-(2m_\mu/m_a)^2}}{m_\tau^2\sqrt{1-(2m_\tau/m_a)^2}}$$

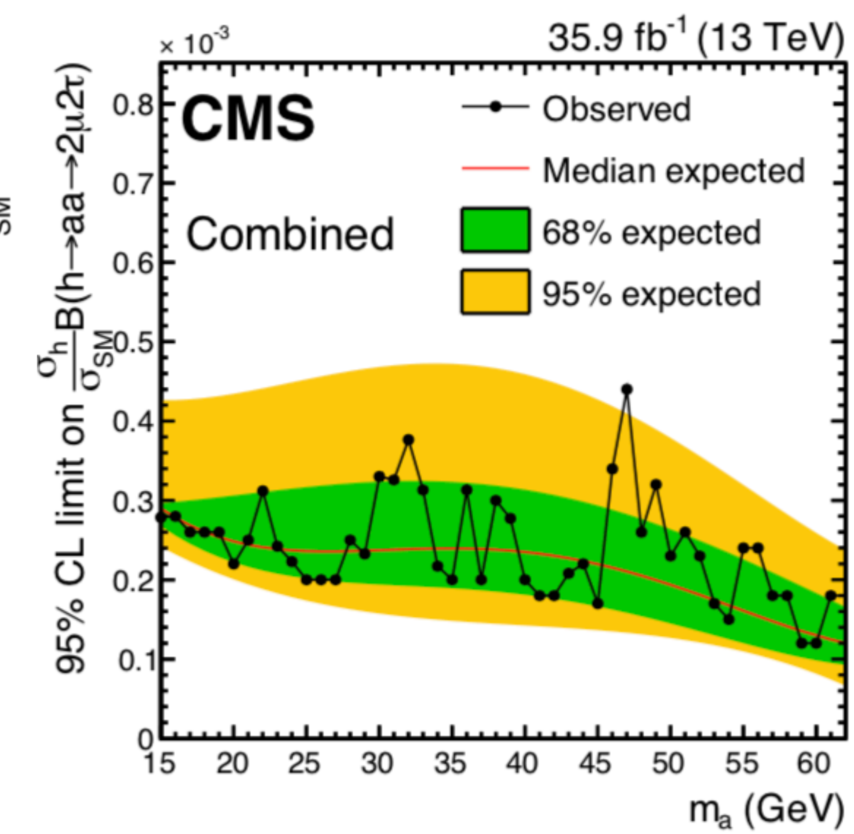
- Scan the reconstructed **dimuon mass spectrum**:
  - For a characteristic resonance structure
- Invariant mass of four objects in the final state is below **100-130 GeV**:
  - Compatibility with a **Higgs boson decay**
- Parametrized signal & background distribution:
  - Perform an **unbinned maximum likelihood fit**
- Final states with different **tau decay modes**:
  - **μμ + eμ**
  - **μμ + eτh**
  - **μμ + μτh**
  - **μμ + τhτh**

- Pseudo-scalar boson mass range: [15, 60] GeV
  - **Isolated muons and taus**



- In the scenario of type-3:
  - Results provide the **tightest constraints** in this mass range

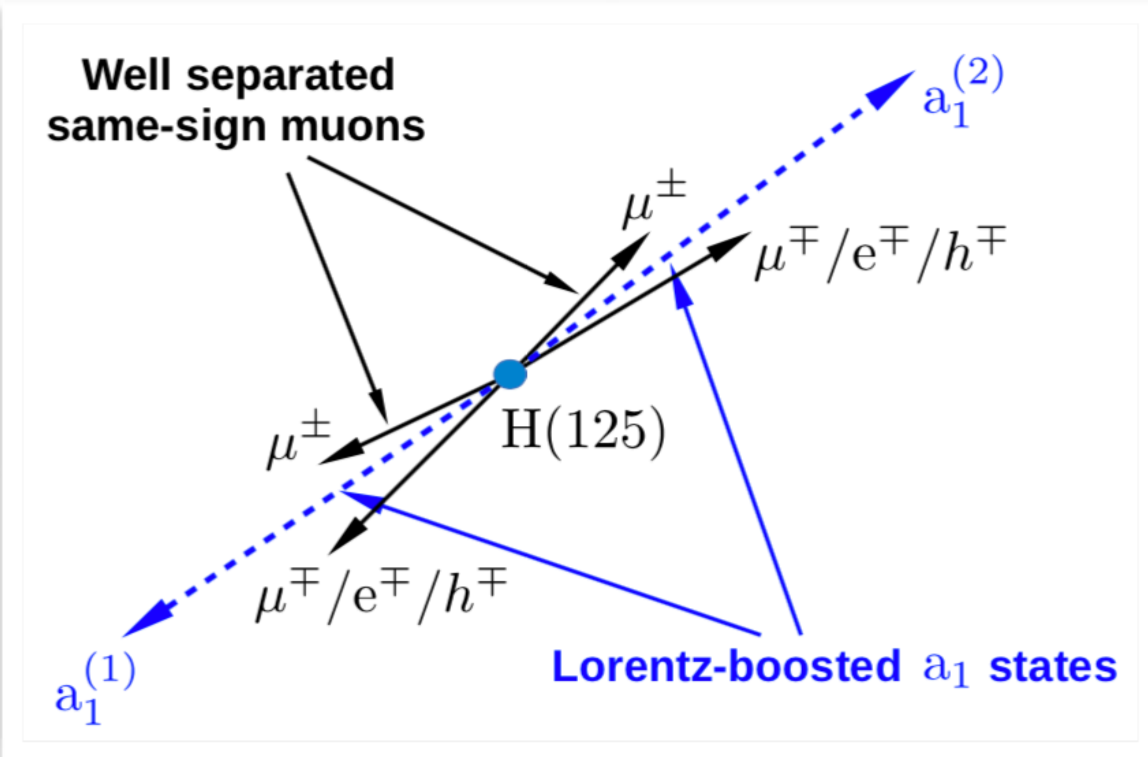




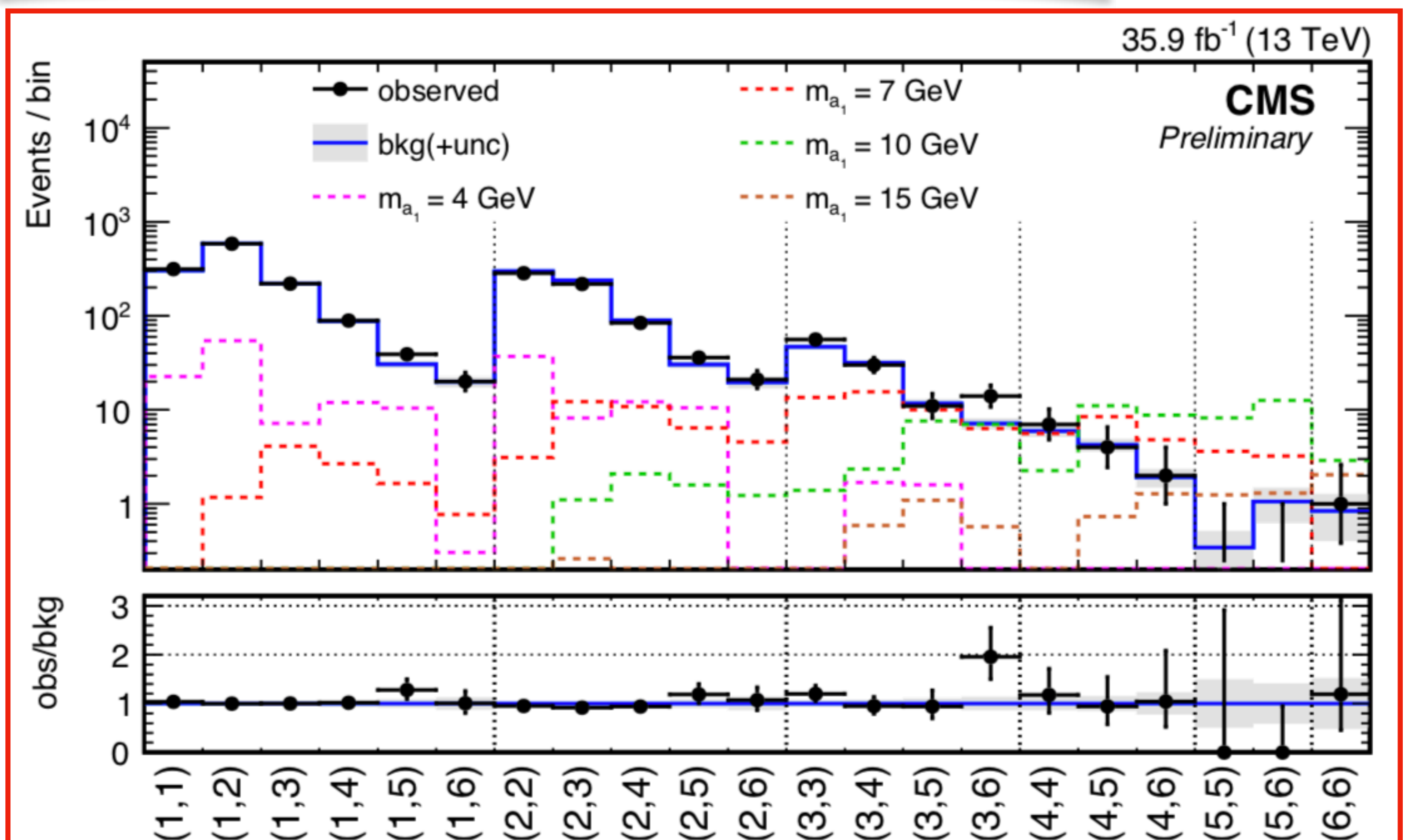
CMS-HIG-18-006

H —> aa —> 4τ

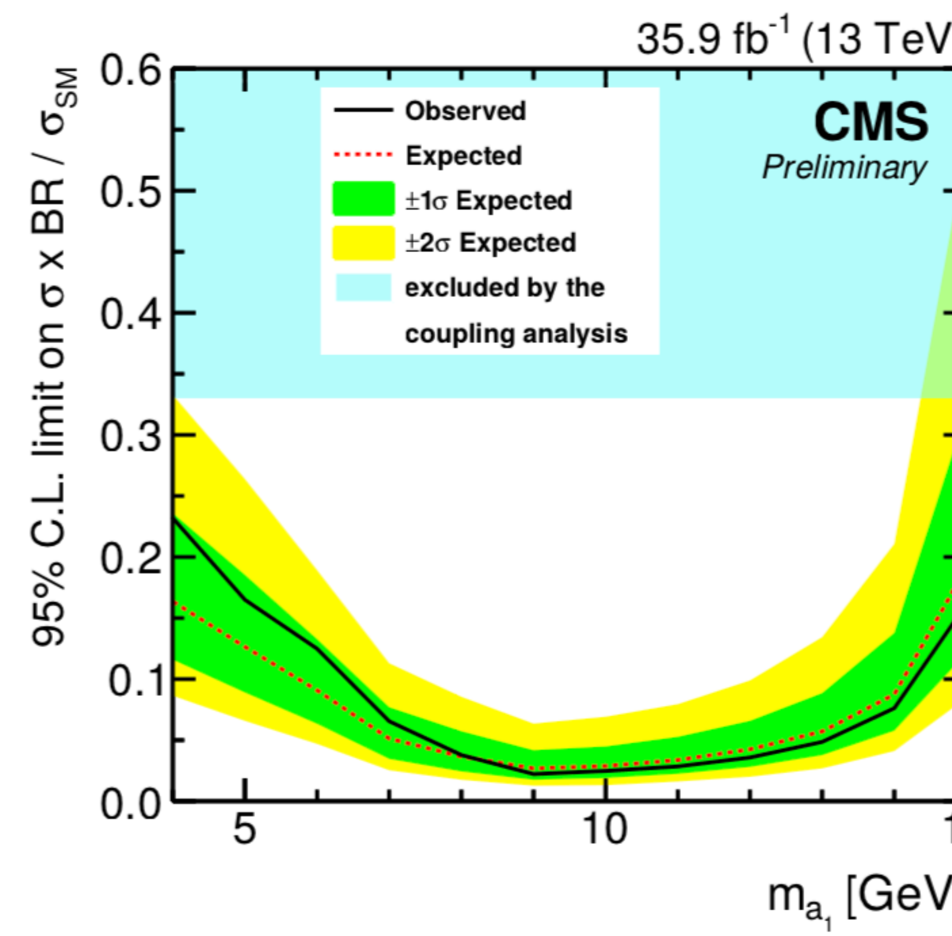
- Pseudo-scalar boson mass range: [4, 15] GeV
- **Lorentz-boosted taus** with overlapping decay products
- Objects in the final states: **$3\tau_{\mu}$ + τ_{h} (one prong)**



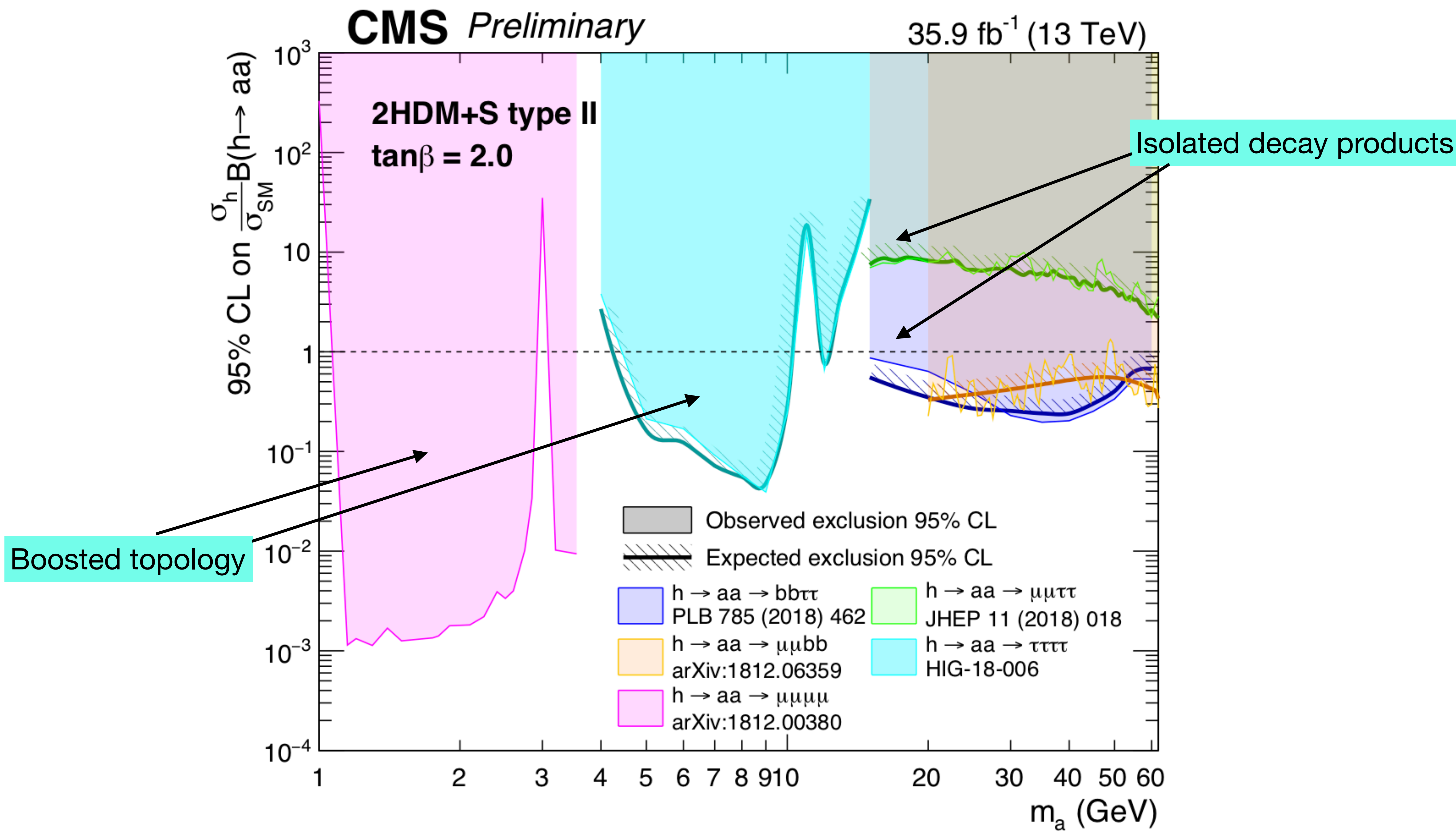
- Signal event signature:
  - **Two same sign muons** with large angular separation
  - Each muon accompanied by a nearby **opposite-sign particle (track)**
- Compared to RunI, significantly **improved upper limits**:
  - 30% for low masses
  - ~ 80% for intermediate masses



2D pseudo-scalar boson mass [GeV]



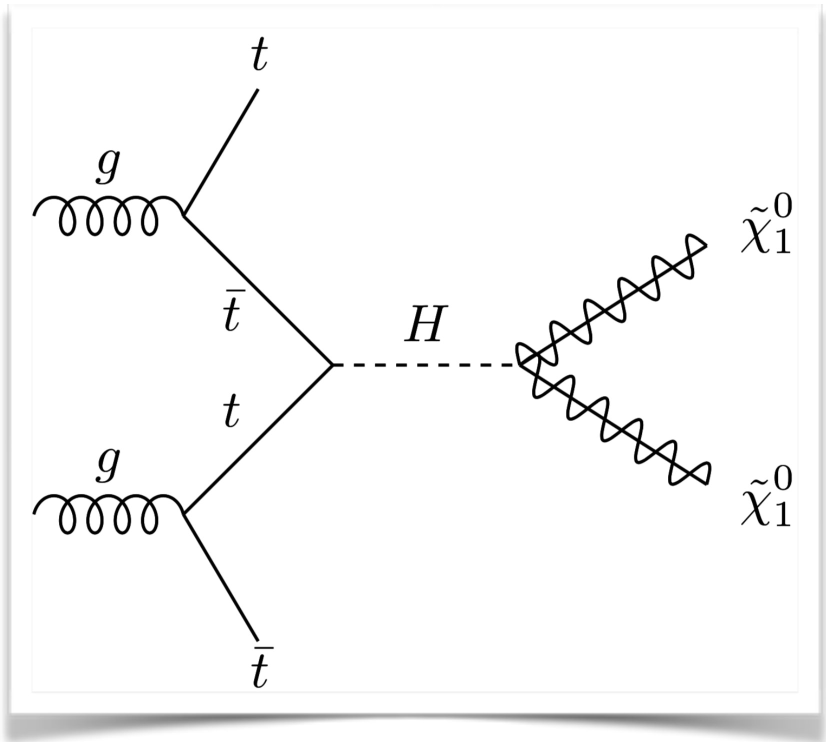
2HDM + S type II Summary

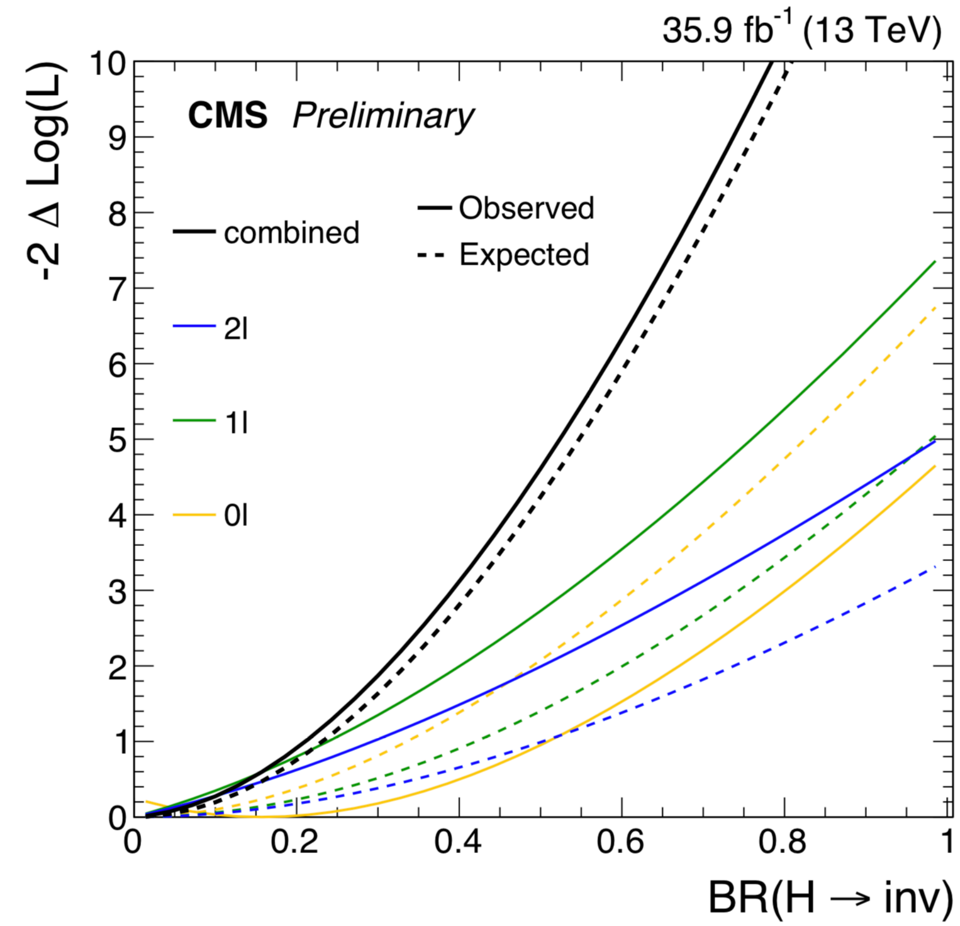


https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

H —> invisible (association with top-quark pair)

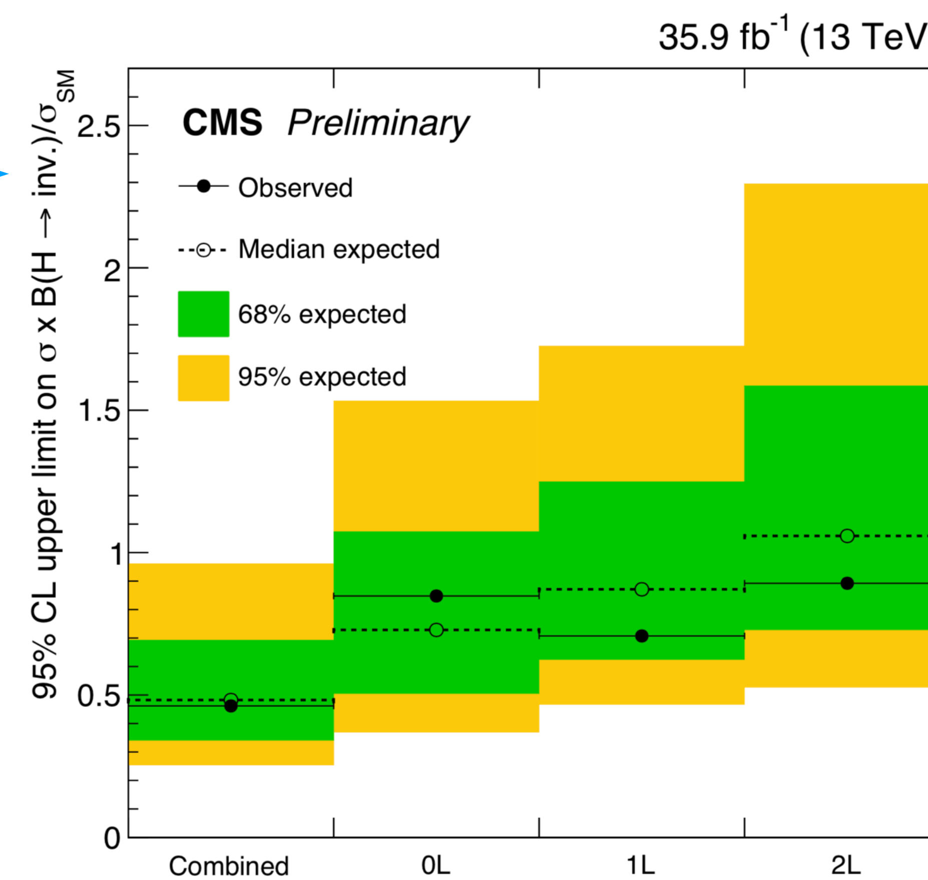
CMS-HIG-18-008





- Reinterpretation of an analysis designed for:
  - **top squarks—> top quarks + neutrinos**

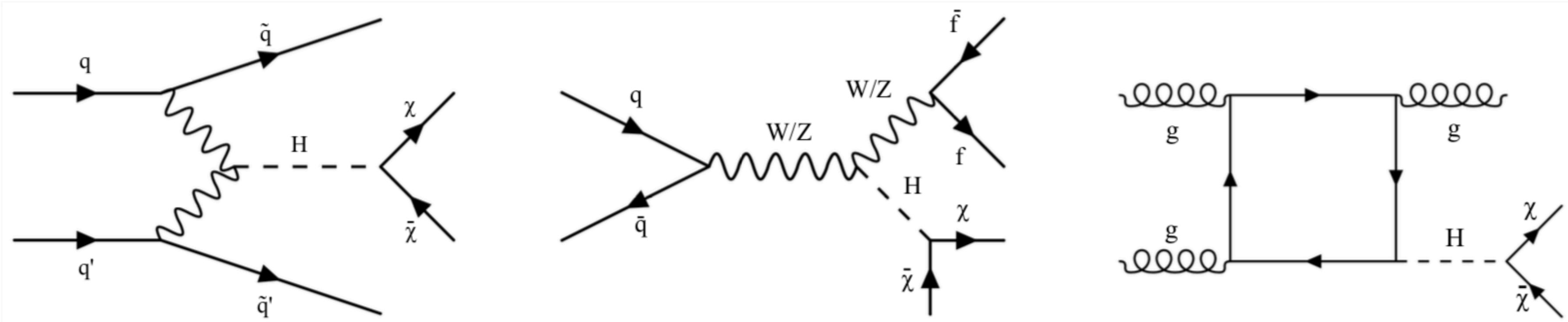
First constraints on the branching fraction of this channel



- Allow to significantly suppress and constrain SM backgrounds
- Provide **higher sensitivity** for BSM with **enhanced top quark Yukawa coupling** than other Higgs production modes
- Constraint:
  - **Weaker** than limits using **VBF** topology
  - **Comparable** with limits from **VH**
  - **Stronger** than limits from **ggH**

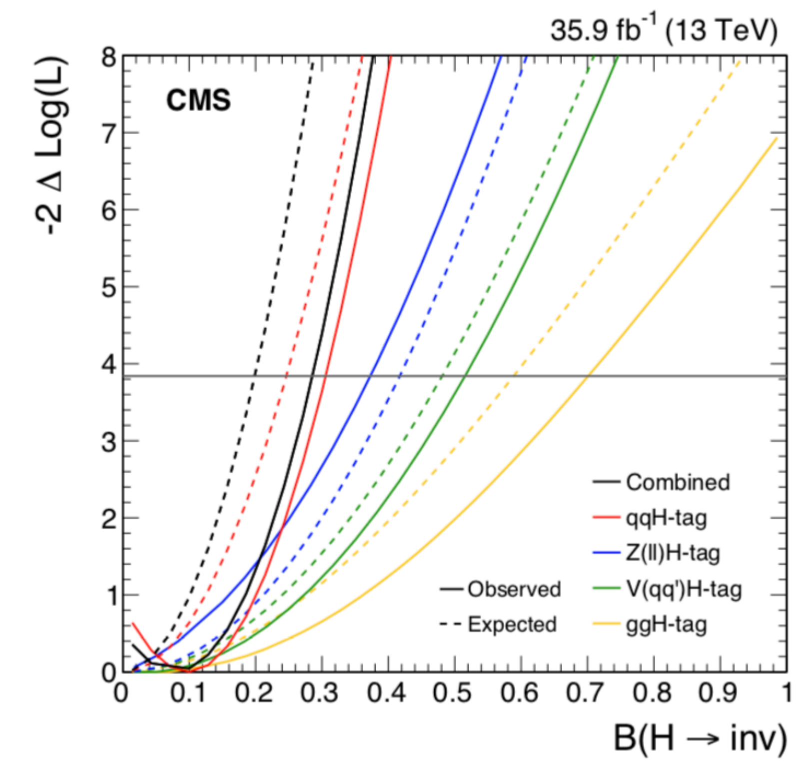
H —> invisible (VBF & VH & ggH)

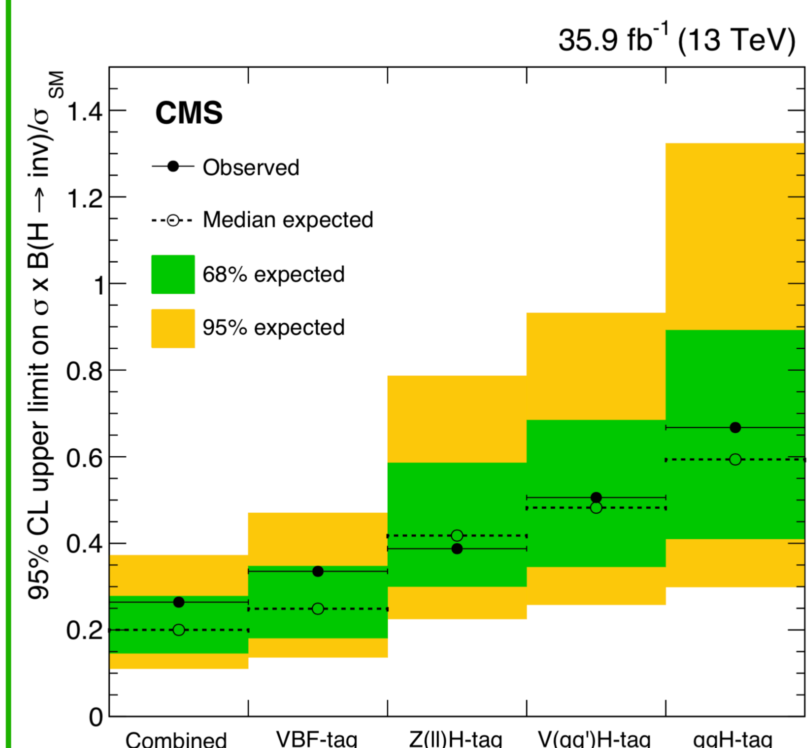
arXiv:1809.05937



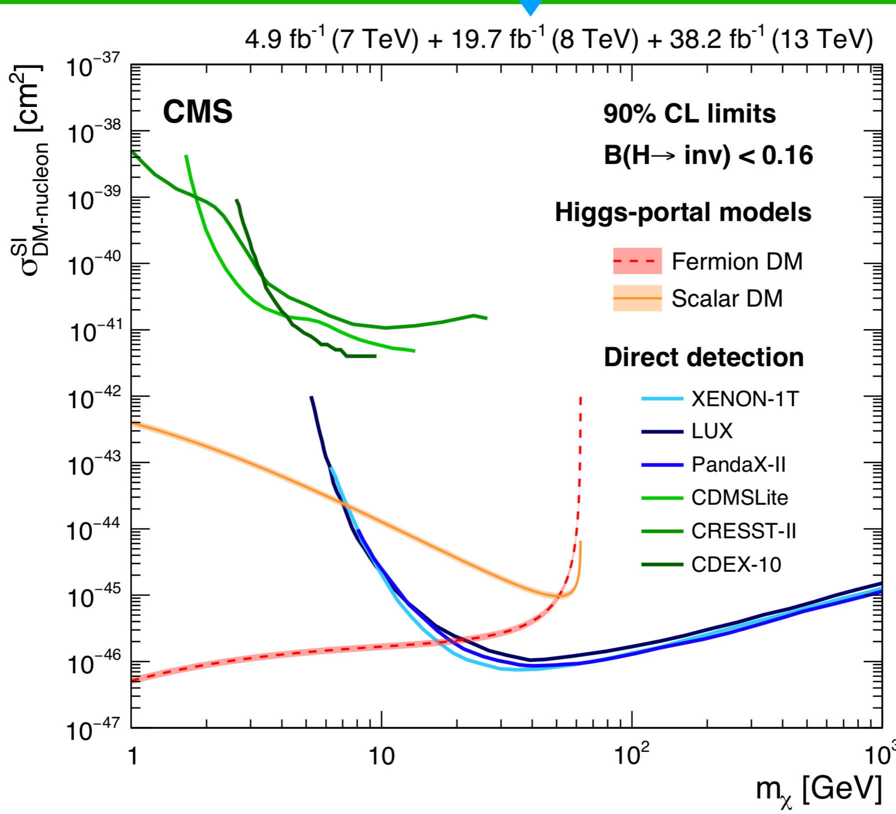
- Consistent with backgrounds from SM prediction
- Most sensitive channel in the combination: **VBF**
- **Strongest constraints on fermion (scalar) dark-matter** particles with masses smaller than **18 (7) GeV**

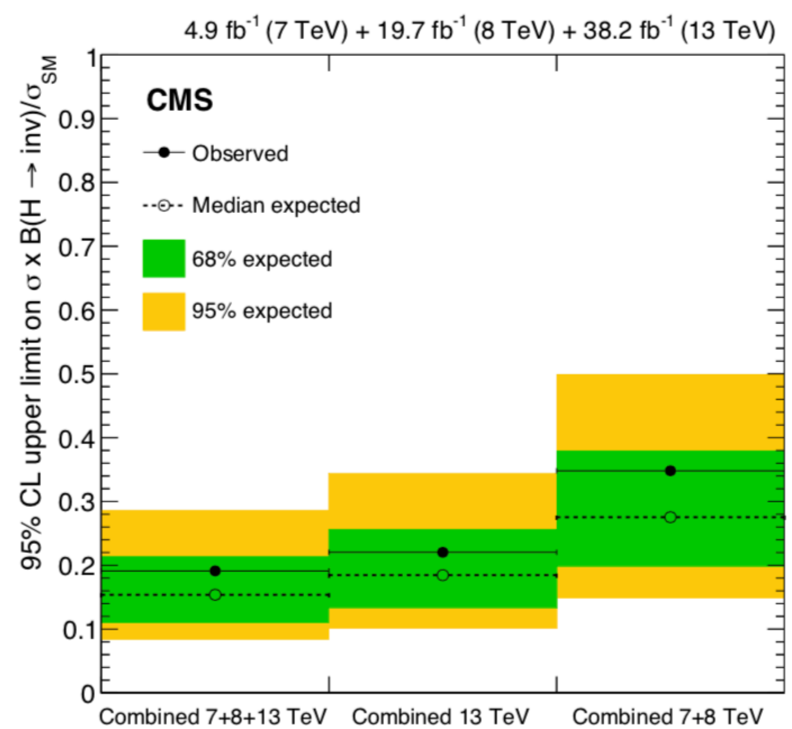
Channel combination:



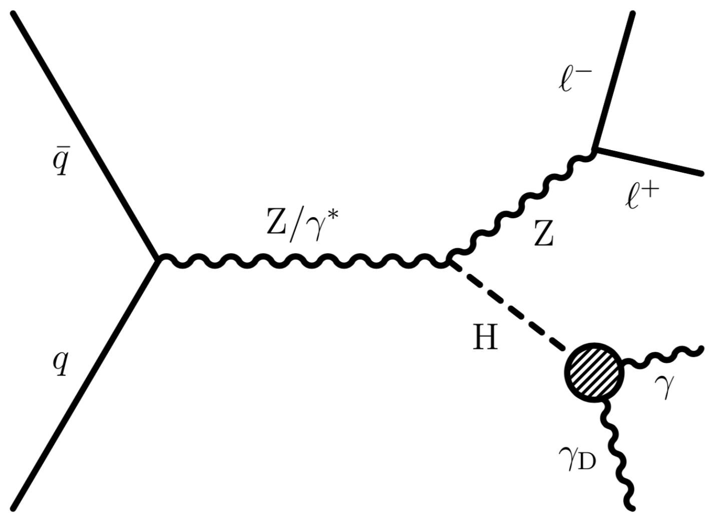


Run I + RunII combination:





Search for dark photons in ZH decays

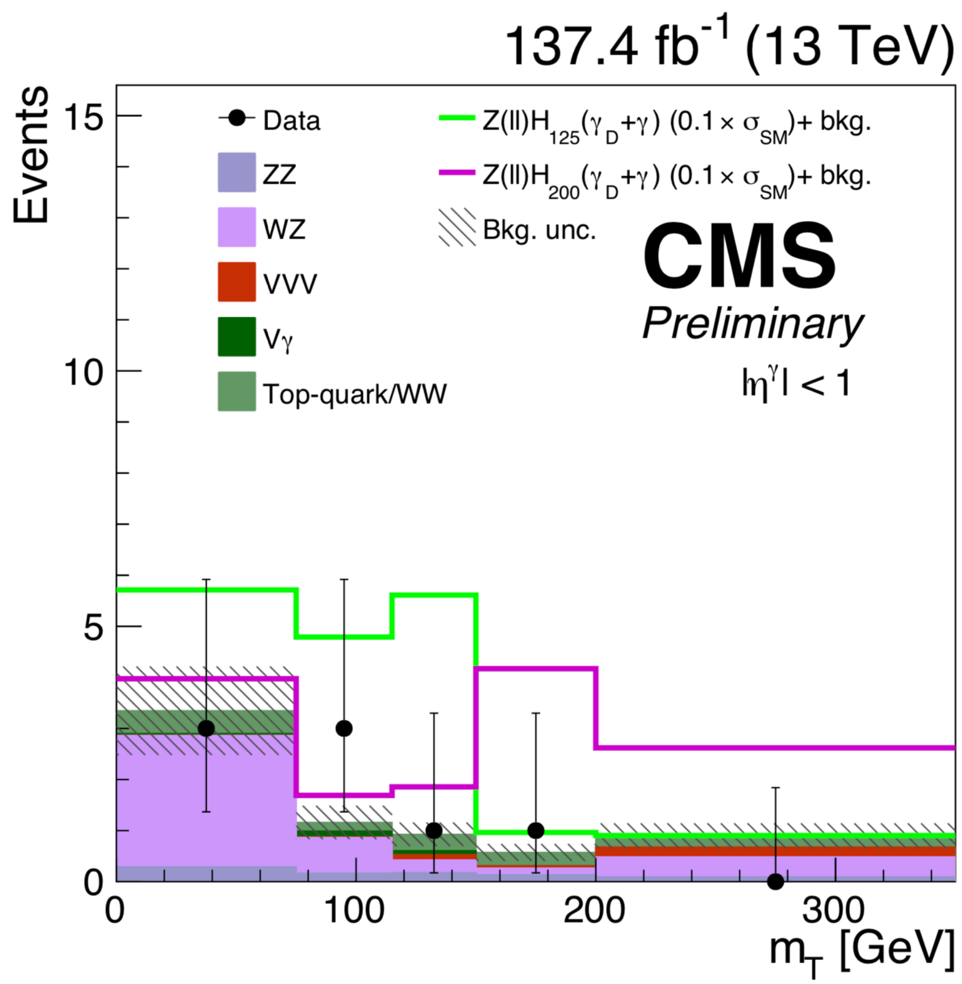


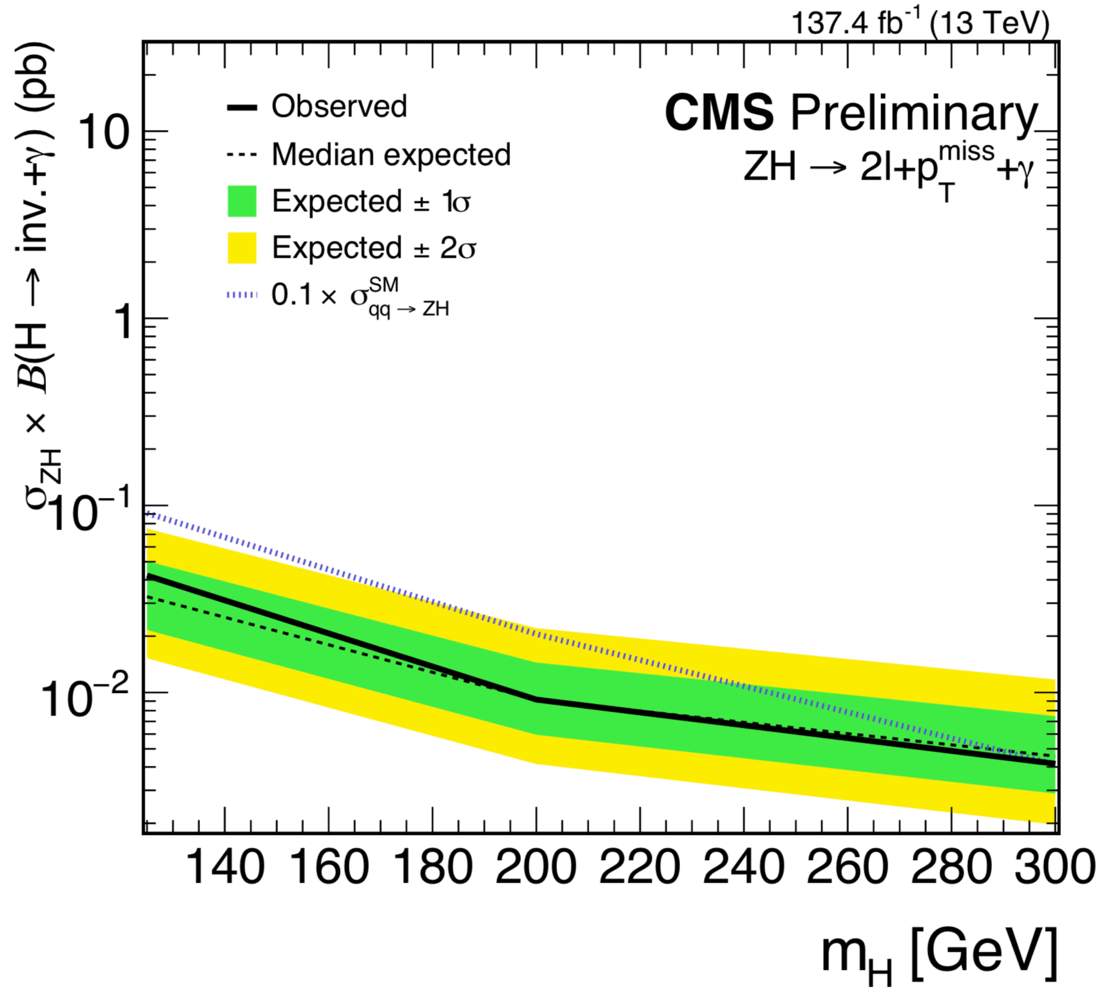
CMS-EXO-19-007

Reference: Phys. Rev. D. 93. 093011

- γ_D: a massless dark photon coupling to Higgs boson through a dark charged sector
- No significant excess of events is found
- **First time to set upper limits based on the full RunII data**

Also see Varun's talk





Summary & Conclusion

- CMS collaboration has made many progresses in Higgs rare & exotic decays
  - **No significant excess** above SM prediction has been found
  - In general, **more stringent constraints** were set using partial **RunII** data than RunI
- More data are needed for some decay channels to **reach the sensitivity**
- **First limit setting based on full RunII data analysis:**
  - **H —> photon + dark photon (in association with a Z boson)**
- More interesting results are coming out

Stay tuned!

Backup

Higgs decays to $\mu^+\mu^-$ pair

Phys. Rev. Lett. 122, 021801

Table 1: The optimized event categories, the product of acceptance and selection efficiency in % for the different production processes, the total expected number of SM signal events ($m_H = 125$ GeV), the estimated number of background events per GeV at 125 GeV, the FWHM of the signal peak, the background functional fit form, and the $S/\sqrt{B}$ ratio within the FWHM of the expected signal distribution.

BDT response quantile [%]	Maximum muon $\|\eta\|$	ggH [%]	VBF [%]	WH [%]	ZH [%]	$t\bar{t}$H [%]	Signal	Bkg/GeV @125 GeV	FWHM [GeV]	Bkg fit function	$S/\sqrt{B}$ @ FWHM
0 – 8	$\|\eta\| < 2.4$	4.9	1.3	3.3	6.3	32	21.2	3.13×10^3	4.2	mBW $B_{\deg 4}$	0.12
8 – 39	$1.9 < \|\eta\| < 2.4$	5.6	1.7	3.9	3.5	1.3	22.3	1.34×10^3	7.2	mBW $B_{\deg 4}$	0.16
8 – 39	$0.9 < \|\eta\| < 1.9$	10	2.8	6.5	6.4	5.2	41.1	2.24×10^3	4.1	mBW $B_{\deg 4}$	0.29
8 – 39	$\|\eta\| < 0.9$	3.2	0.8	1.9	2.1	3.5	12.7	7.83×10^2	2.9	mBW $B_{\deg 4}$	0.18
39 – 61	$1.9 < \|\eta\| < 2.4$	2.9	1.7	2.7	2.7	0.3	11.8	4.37×10^2	7.0	mBW $B_{\deg 4}$	0.14
39 – 61	$0.9 < \|\eta\| < 1.9$	7.2	3.3	6.1	5.2	1.3	29.2	9.70×10^2	4.0	mBW $B_{\deg 4}$	0.31
39 – 61	$\|\eta\| < 0.9$	3.6	1.1	2.6	2.2	0.9	14.5	4.81×10^2	2.8	mBW	0.26
61 – 76	$1.9 < \|\eta\| < 2.4$	1.2	1.5	1.8	1.7	0.2	5.2	1.48×10^2	7.6	mBW $B_{\deg 4}$	0.11
61 – 76	$0.9 < \|\eta\| < 1.9$	4.8	3.6	4.5	4.4	0.7	20.3	5.12×10^2	4.2	mBW $B_{\deg 4}$	0.29
61 – 76	$\|\eta\| < 0.9$	3.2	1.6	2.3	2.1	0.6	13.1	3.22×10^2	3.0	mBW	0.28
76 – 91	$1.9 < \|\eta\| < 2.4$	1.2	3.1	2.2	2.1	0.2	5.8	1.04×10^2	7.1	mBW $B_{\deg 4}$	0.14
76 – 91	$0.9 < \|\eta\| < 1.9$	4.4	8.7	6.2	6.0	1.1	20.3	3.60×10^2	4.2	mBW $B_{\deg 4}$	0.35
76 – 91	$\|\eta\| < 0.9$	3.1	4.0	3.8	3.6	0.9	13.7	2.36×10^2	3.2	mBW	0.34
91 – 95	$\|\eta\| < 2.4$	1.7	6.4	2.5	2.6	0.5	8.6	96.0	4.0	mBW	0.28
95 – 100	$\|\eta\| < 2.4$	2.0	19	1.5	1.4	0.7	13.7	83.4	4.1	mBW	0.48
Total	$\|\eta\| < 2.4$	59	61	51	52	49	253	1.30×10^4	3.9		

FWHM: Full Width at Half Maximum of the expected signal distribution

H —> aa —> 2μ2τ/4τ

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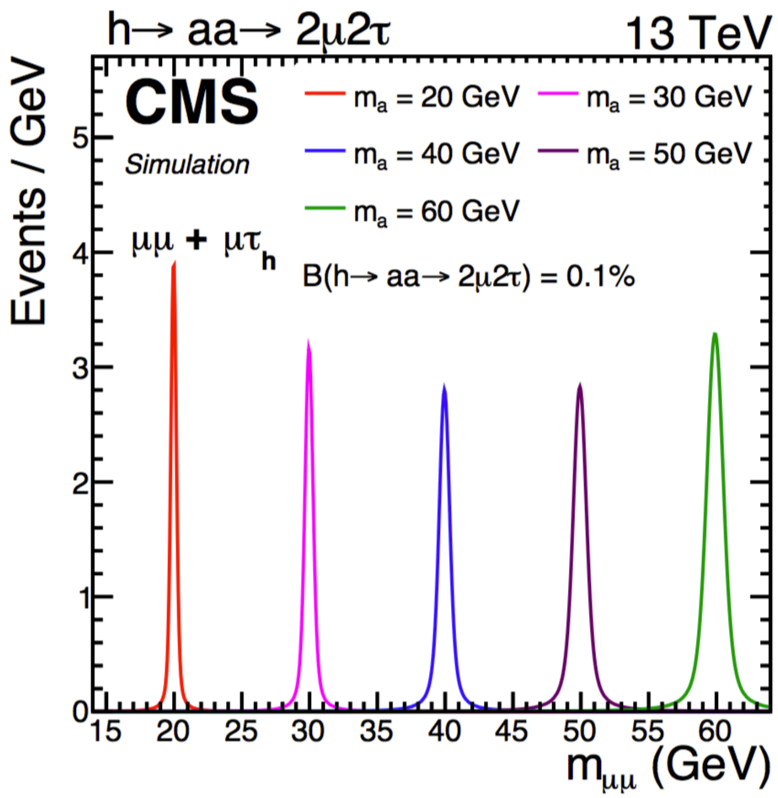
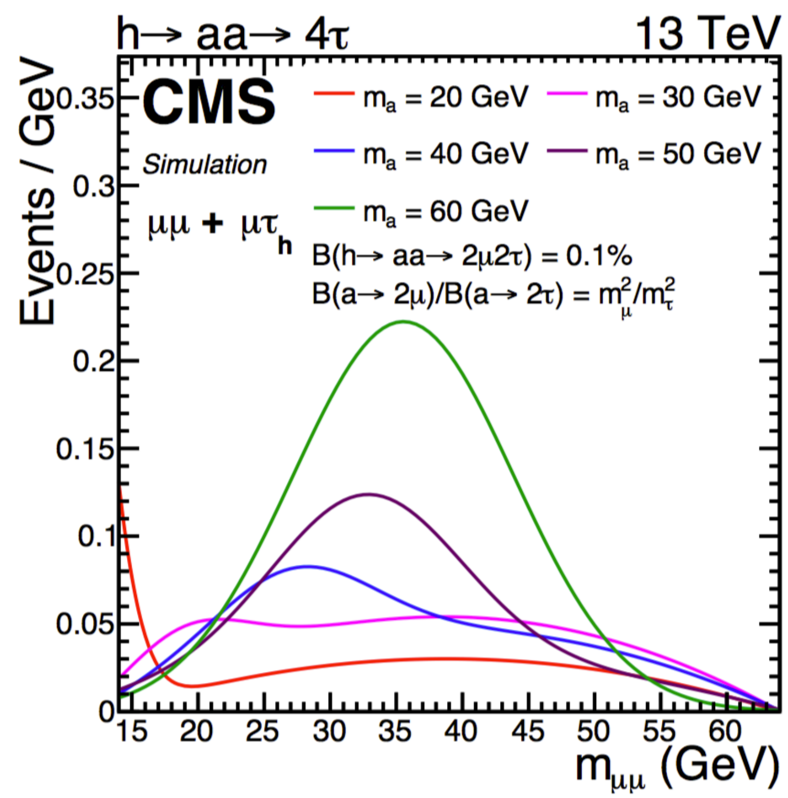
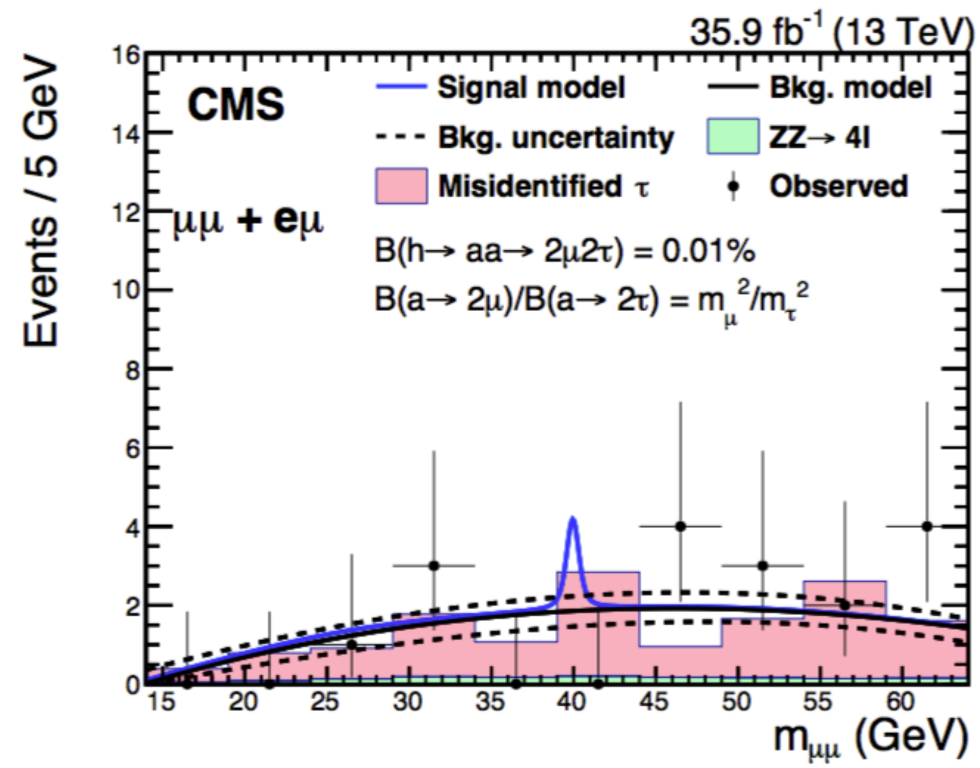
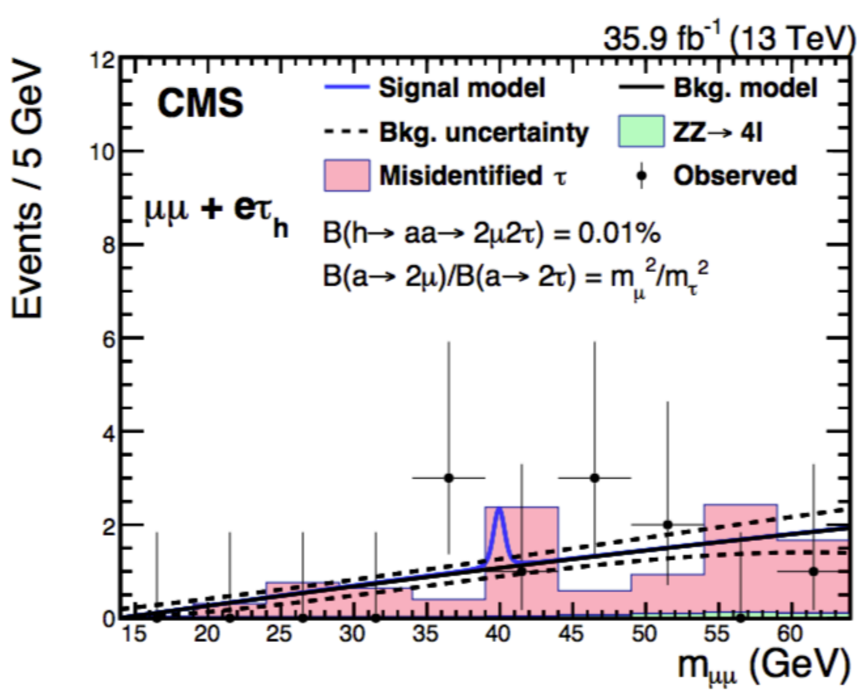
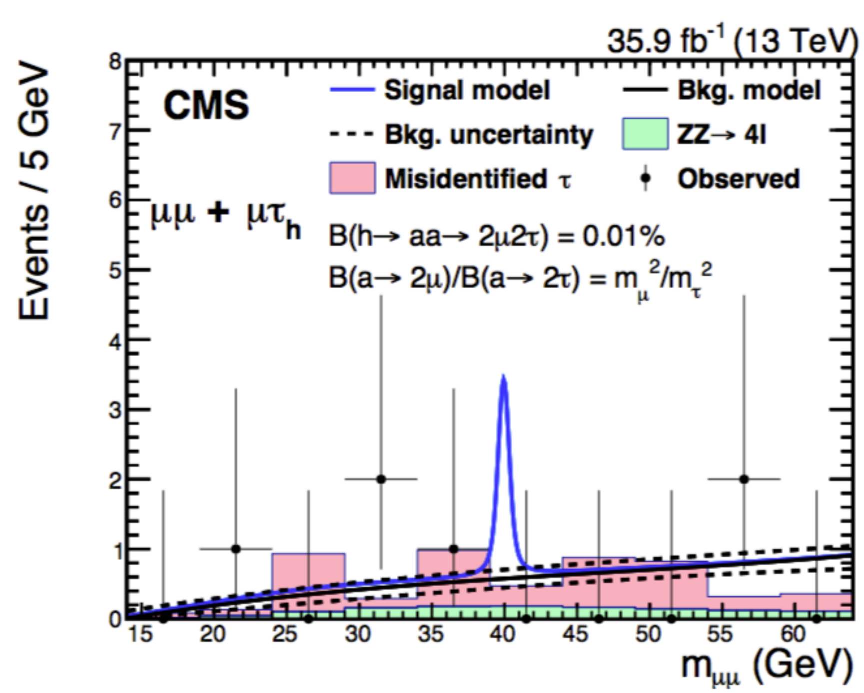
Pseudo-scalar boson mass range: [15, 60] GeV

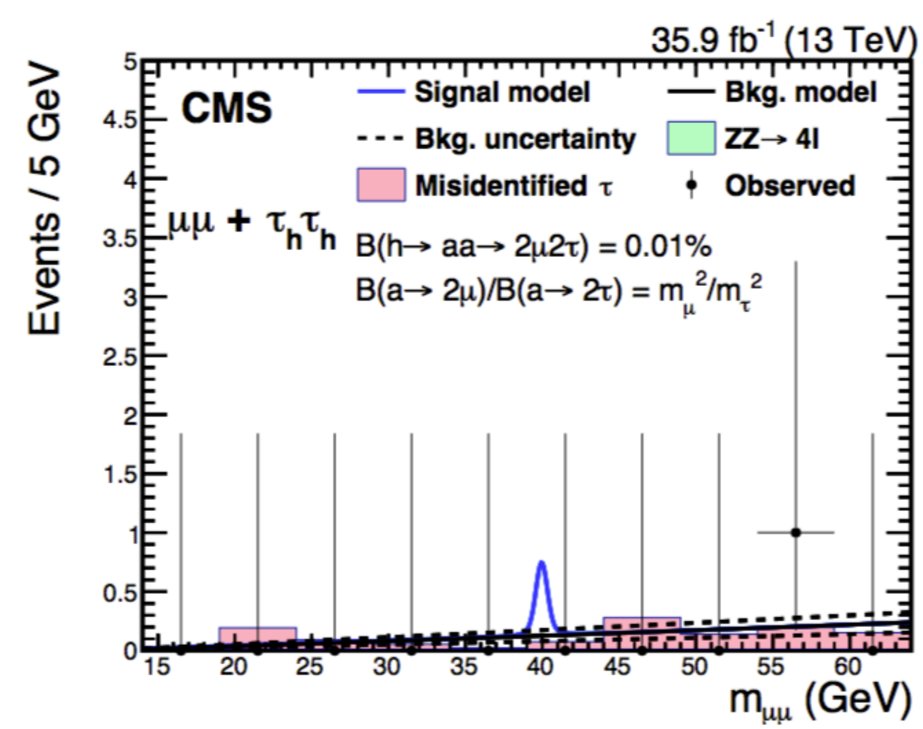






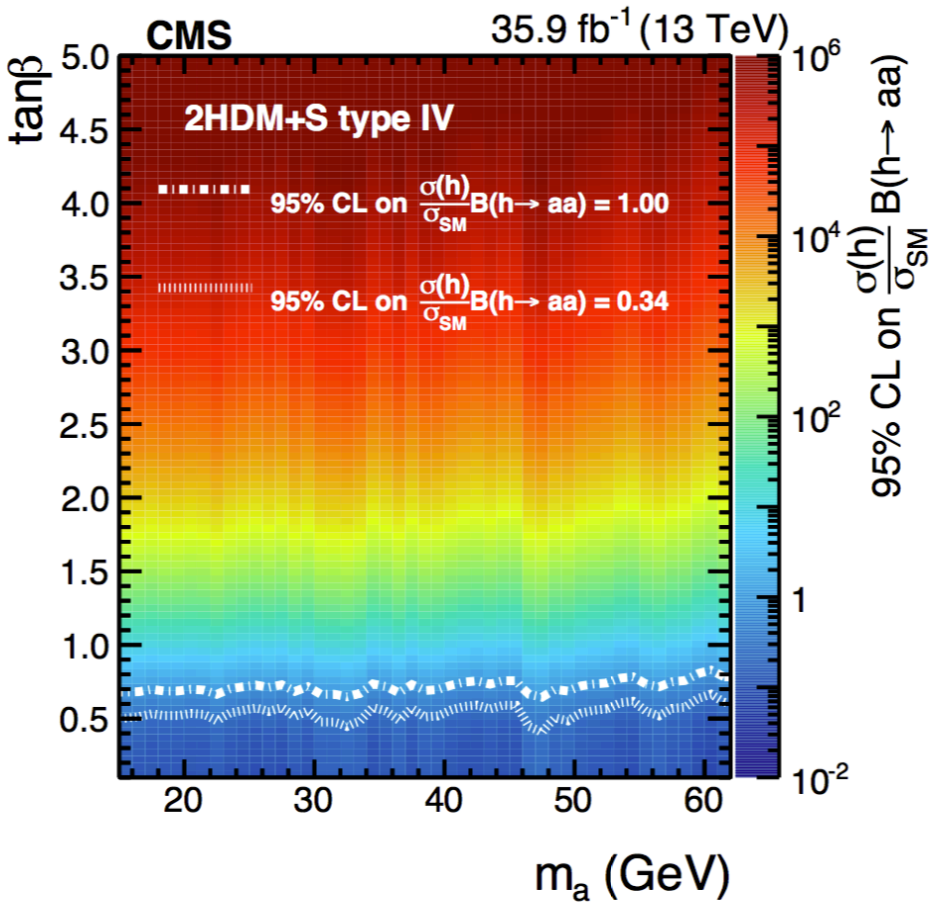


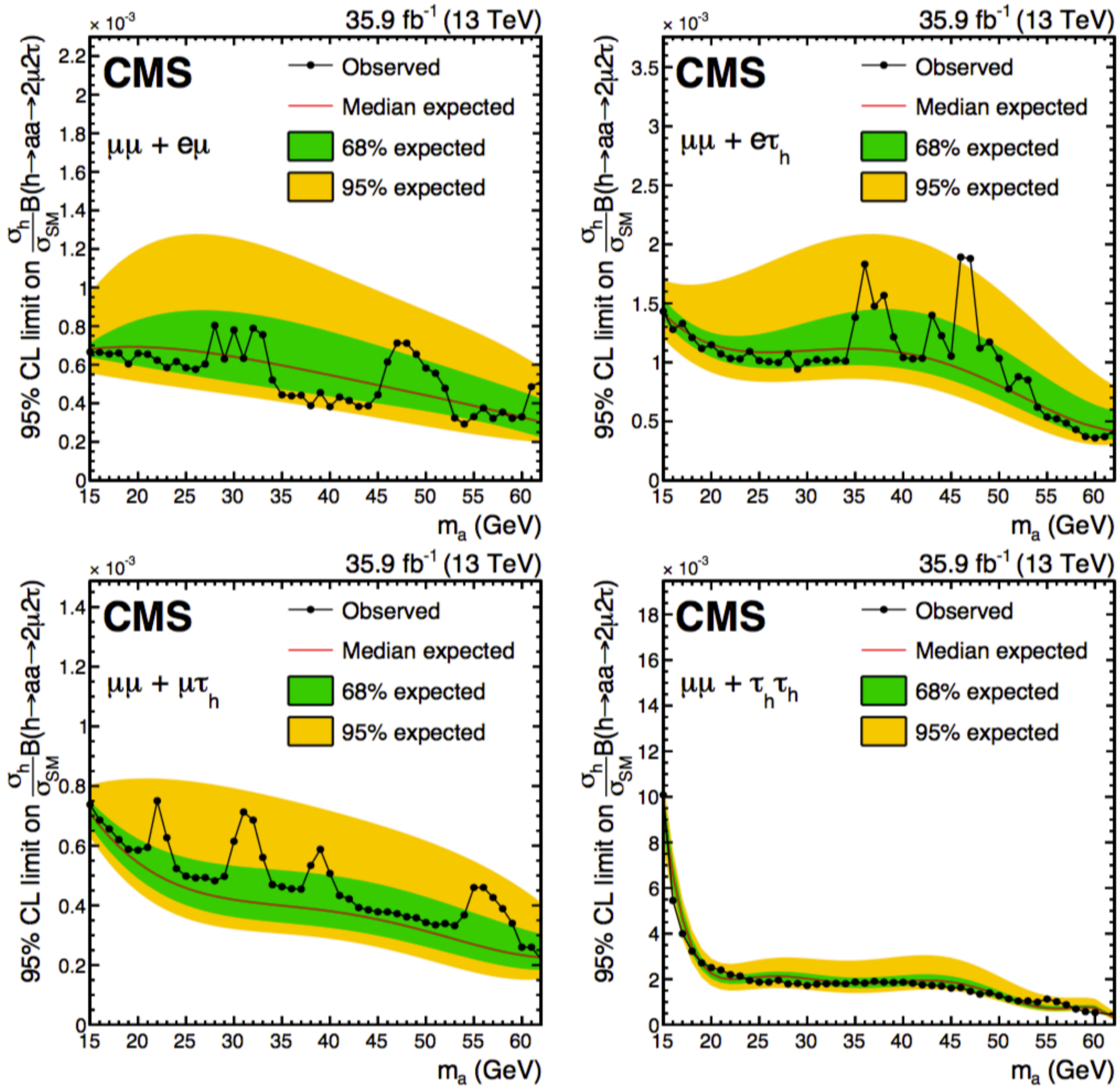




H —> aa —> 2μ2τ/4τ

Pseudo-scalar boson mass range: [15, 60] GeV





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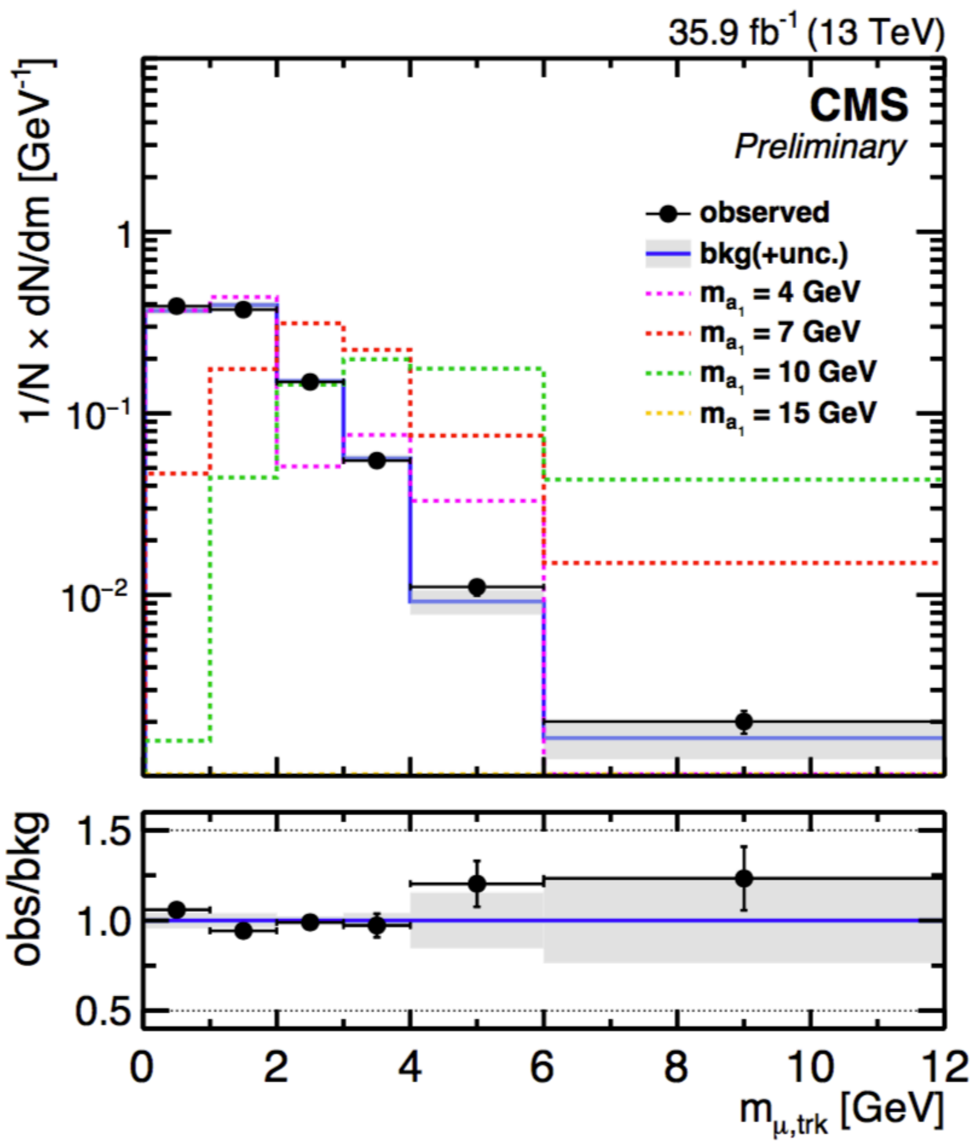
H —> aa —> 4τ

CMS-HIG-18-006

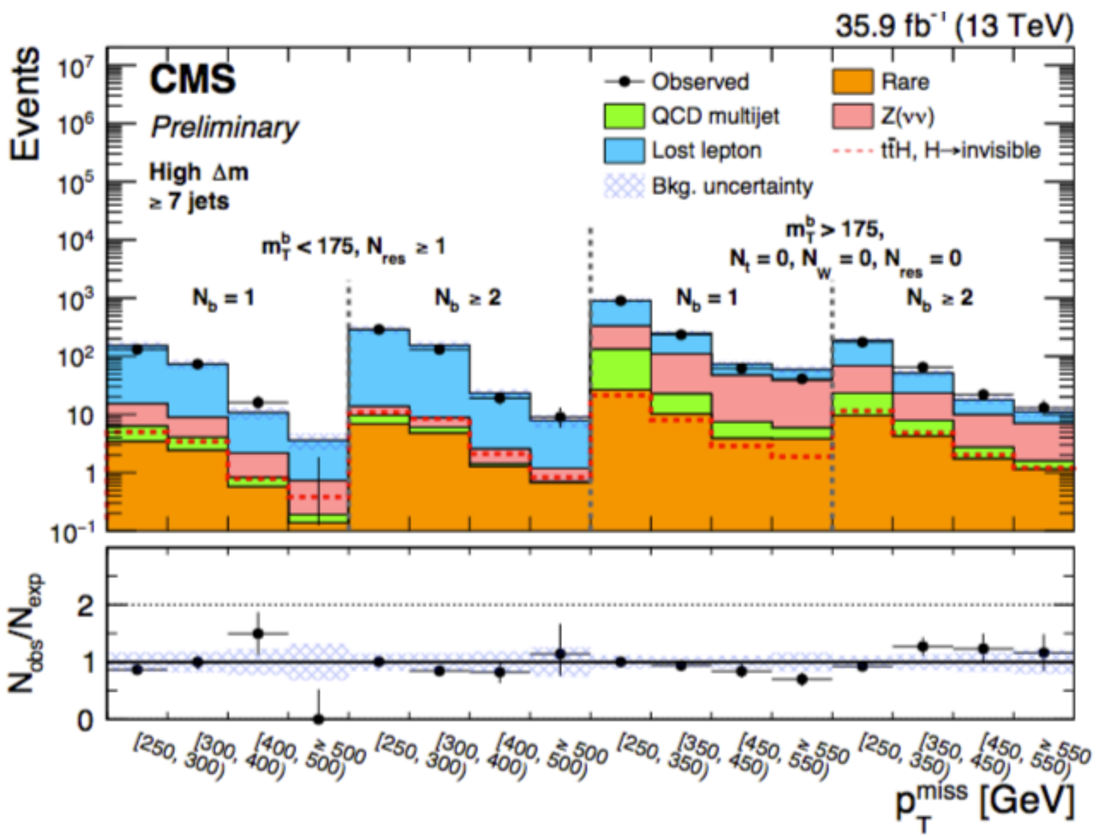
Pseudo-scalar boson mass range: [4, 15] GeV

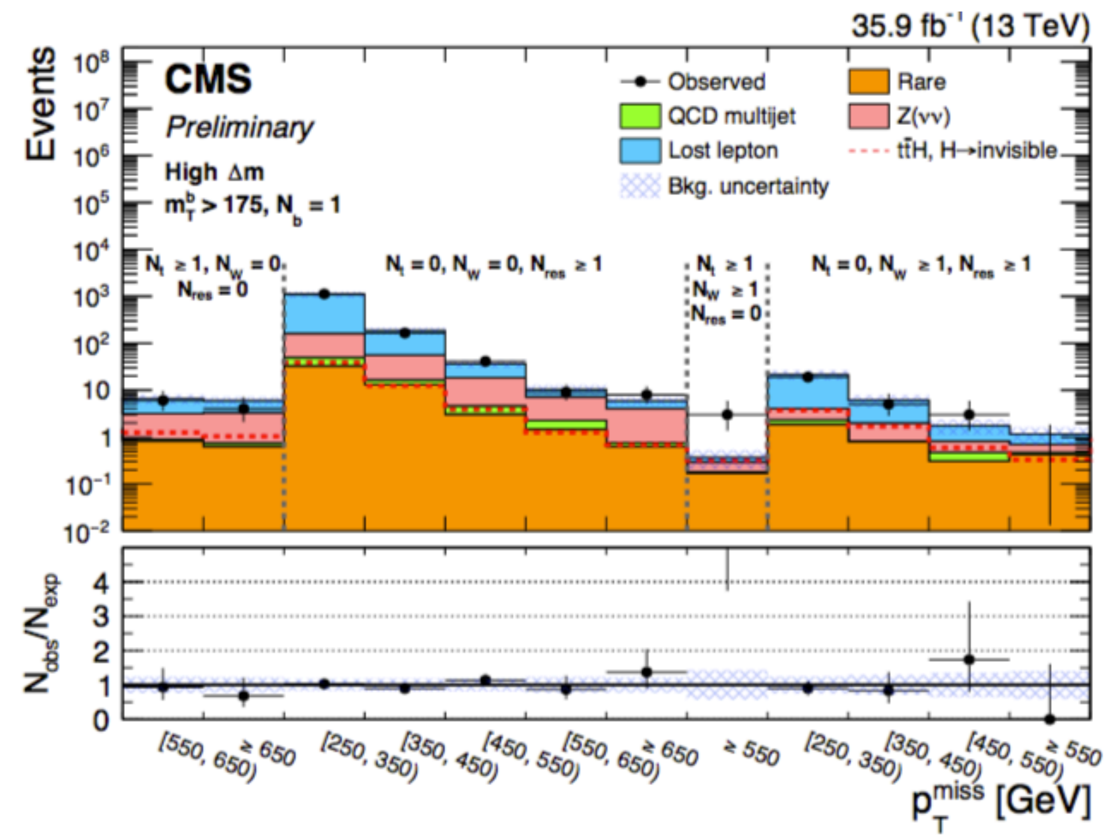


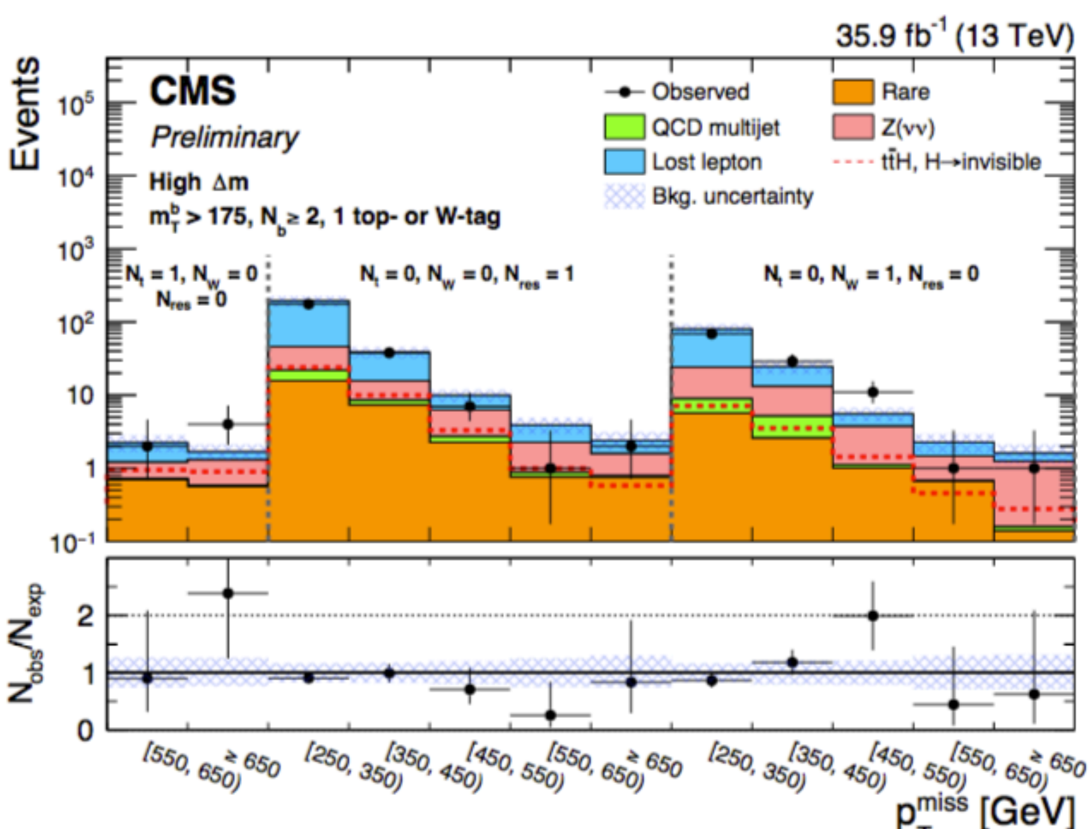
Source	Value	Affected sample	Type	Effect on the total yield
Statistical uncertainties in $C(i,j)$	3–60%	bkg.	bin-by-bin	–
Extrapolation uncertainties in $C(i,j)$	–	bkg.	shape	–
Uncertainty in the 1D template $f_{1D}(i)$	–	bkg.	shape	–
Integrated luminosity	2.5%	signal	norm.	2.5%
Muon identification and trigger efficiency	2% per muon	signal	norm.	4%
Track selection and isolation efficiency	4–12% per track	signal	shape	10–18%
MC stat. uncertainties in signal yields	8–100%	signal	bin-by-bin	5–20%
Theory uncertainties in the signal acceptance				
μ_R and μ_F variations		signal	norm.	$< 2\%$
PDF (VBF, VH, $t\bar{t}$H)		signal	norm.	2%
Theory uncertainties in the signal cross sections				
μ_R and μ_F variations (gg $\rightarrow$ H(125))			norm.	$^{+4.6\%}_{-6.7\%}$
μ_R and μ_F variations (VBF)			norm.	$^{+0.4\%}_{-0.3\%}$
μ_R and μ_F variations (VH)			norm.	$^{+1.8\%}_{-1.6\%}$
μ_R and μ_F variations ($t\bar{t}$H)			norm.	$^{+5.8\%}_{-9.2\%}$
PDF (ggF $\rightarrow$ H(125))			norm.	3.1%
PDF (VBF)			norm.	2.1%
PDF (VH)			norm.	1.8%
PDF ($t\bar{t}$H)			norm.	3.6%

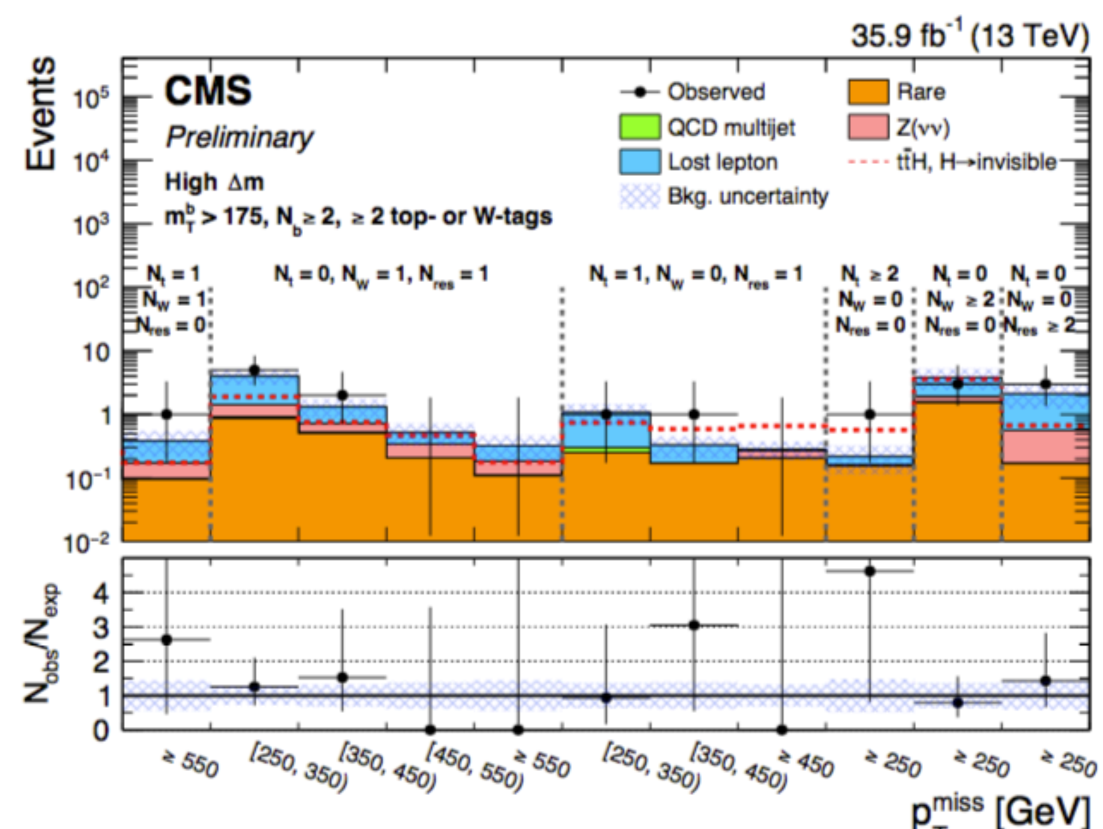
H —> invisible (association with top-quark pair)

CMS-HIG-18-008

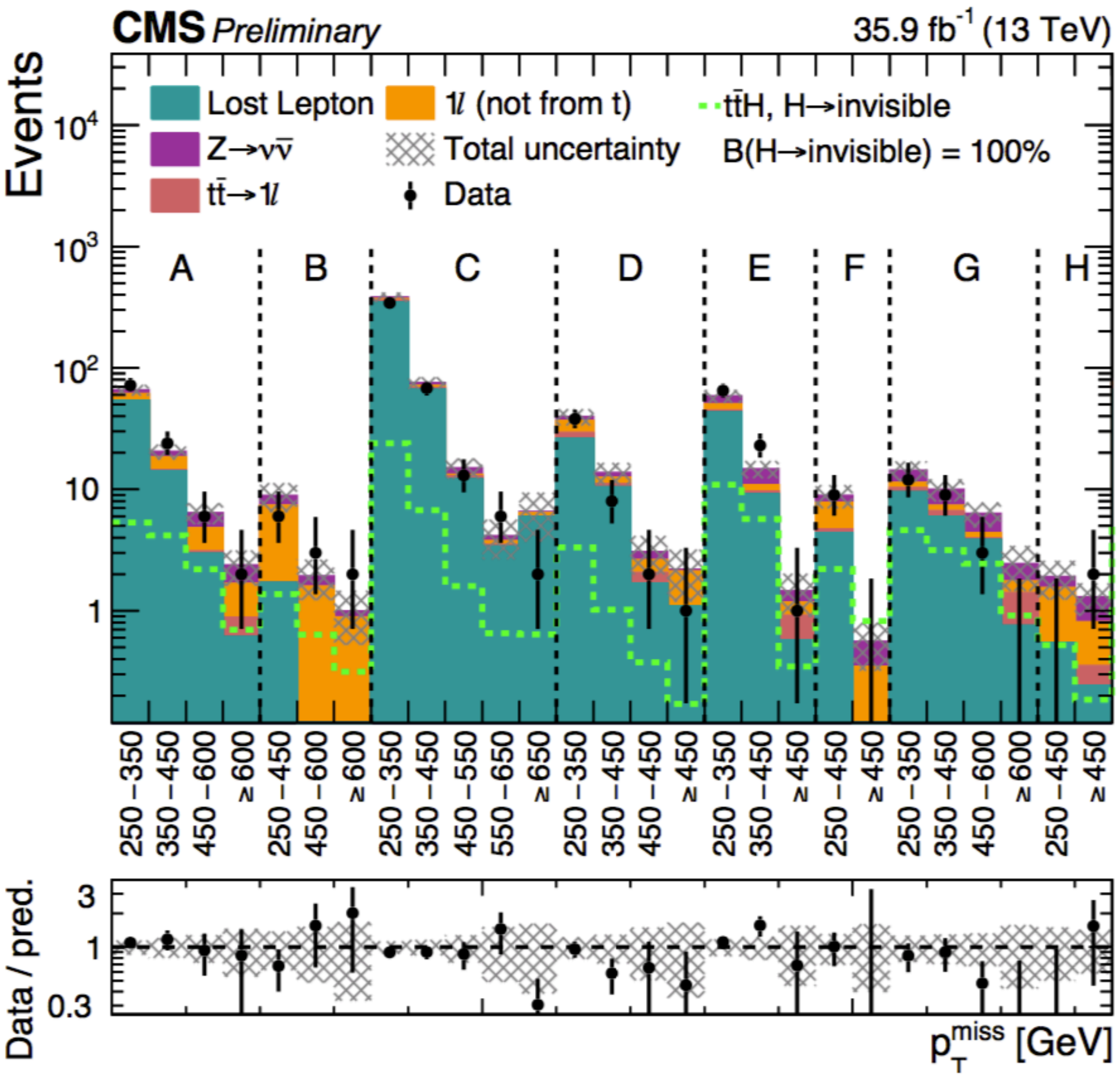








H —> invisible (association with top-quark pair)



A: $N_J \leq 3$, $t_{mod} > 10$, $M_{lb} \leq 175$ GeV

B: $N_J \leq 3$, $t_{mod} > 10$, $M_{lb} > 175$ GeV

C: $N_J \geq 4$, $t_{mod} \leq 0$, $M_{lb} \leq 175$ GeV

D: $N_J \geq 4$, $t_{mod} \leq 0$, $M_{lb} > 175$ GeV

E: $N_J \geq 4$, $0 < t_{mod} \leq 10$, $M_{lb} \leq 175$ GeV

F: $N_J \geq 4$, $0 < t_{mod} \leq 10$, $M_{lb} > 175$ GeV

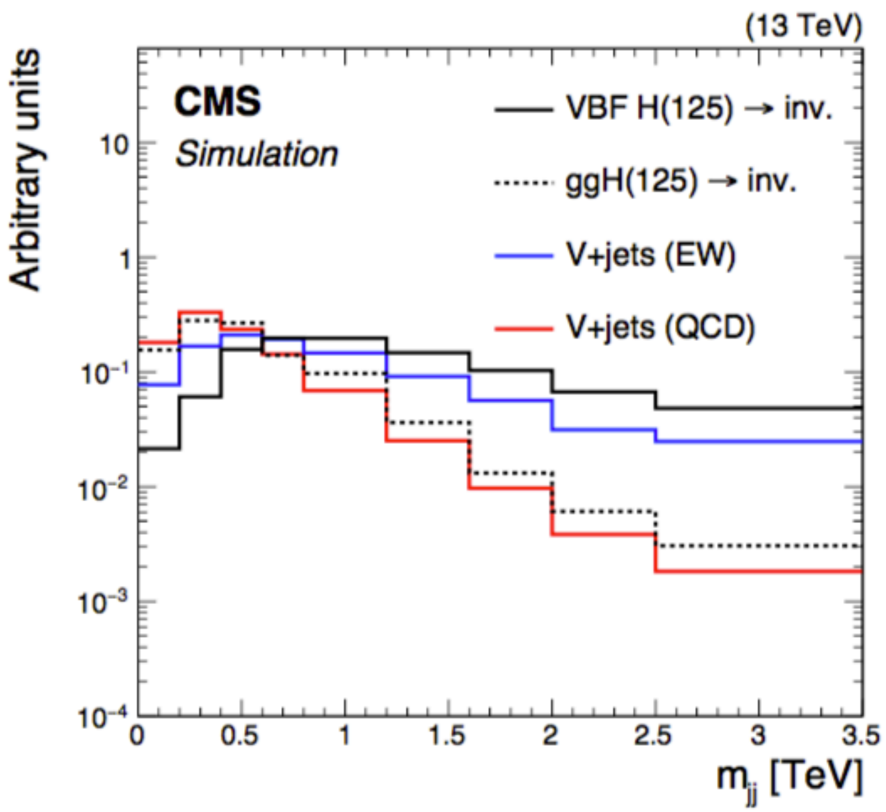
G: $N_J \geq 4$, $t_{mod} > 10$, $M_{lb} \leq 175$ GeV

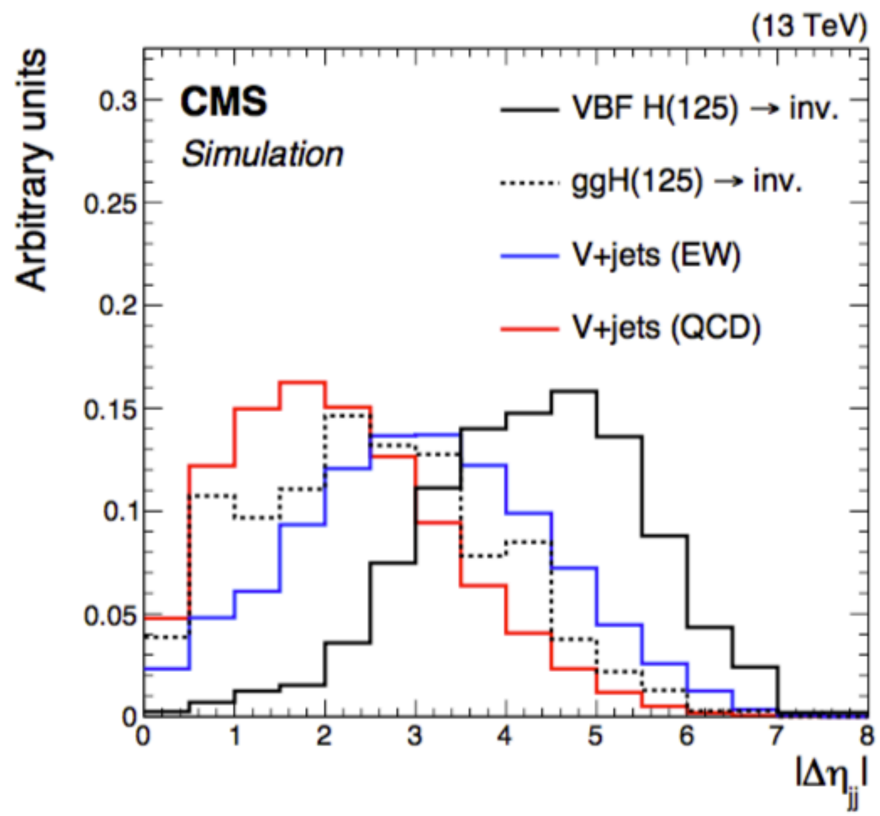
H: $N_J \geq 4$, $t_{mod} > 10$, $M_{lb} > 175$ GeV

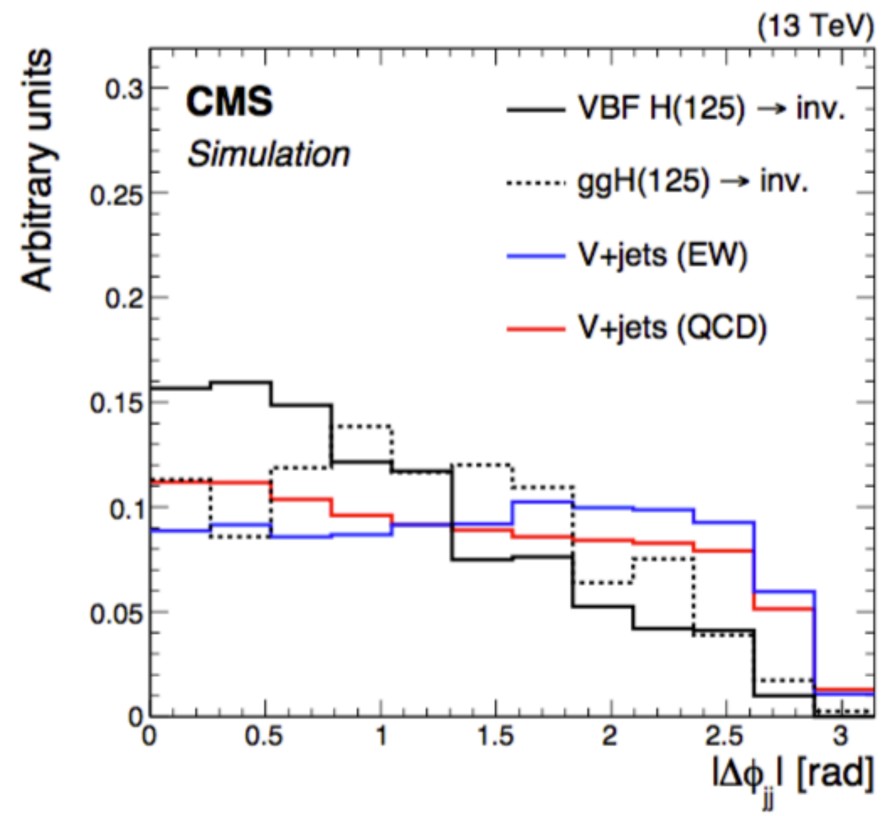
CMS-HIG-18-008

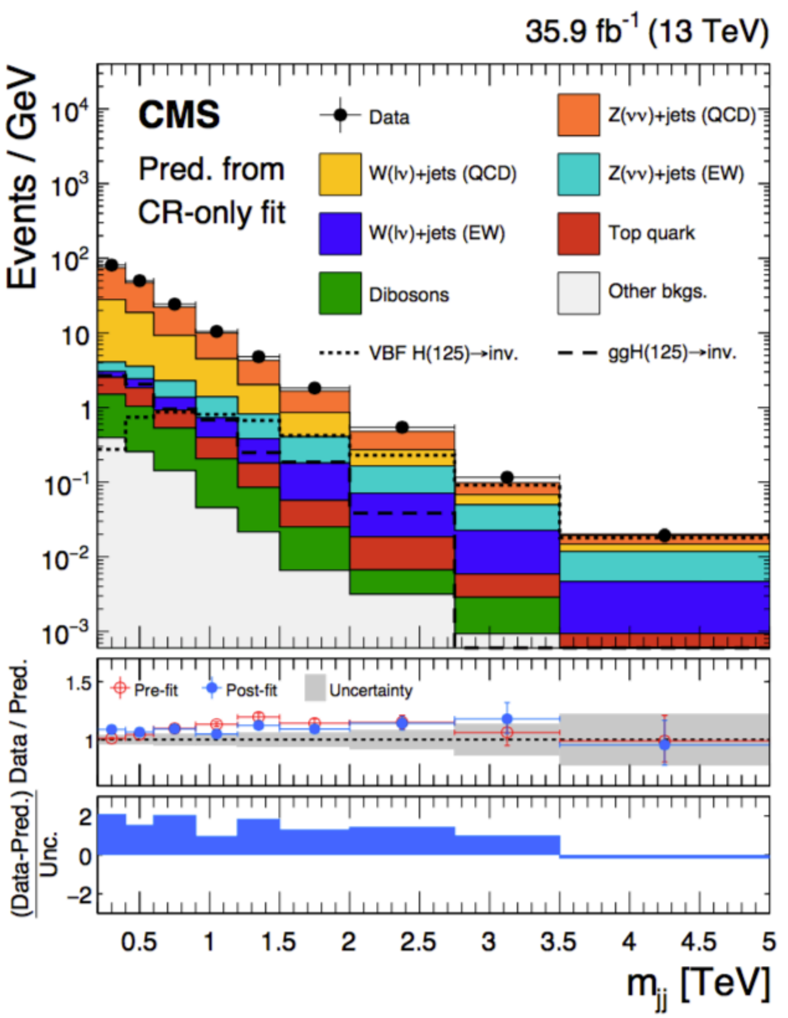
Source	All-hadronic	Semi-leptonic	Di-leptonic
QCD scale cross section	+5.8/−9.2%	+5.8/−9.2%	+5.8/−9.2%
QCD scale acceptance	0.7–14.0%	0.8–30.0%	1.0–7.0%
PDF cross section	3.6%	3.6%	3.6%
PDF acceptance	0.6–3.7%	0.5–4.0%	1.0–1.9%
Sample statistics	1.0–10.0%	1.6–11.2%	3.3–26.4%
Luminosity	2.5%	2.5%	2.5%
Trigger	2.0 %	2.0%	0.2–0.5%
Pileup	0.2–2.0%	0.1–2.5%	0.0–3.0%
Jet energy scale	2.8–7.6%	2.8–9.7%	0.0–9.0 %
B-tagging scale factor	0.3–3.3%	1.2–1.6%	0.1–1.3%
Lepton efficiency	0.0–0.7 %	3.0–3.1%	3.8–5.5%
Unclustered p_T^{miss}	0.2–1.8 %	–	0.1 –12.3 %
Top/W tagging	1.0 – 20 %	–	–

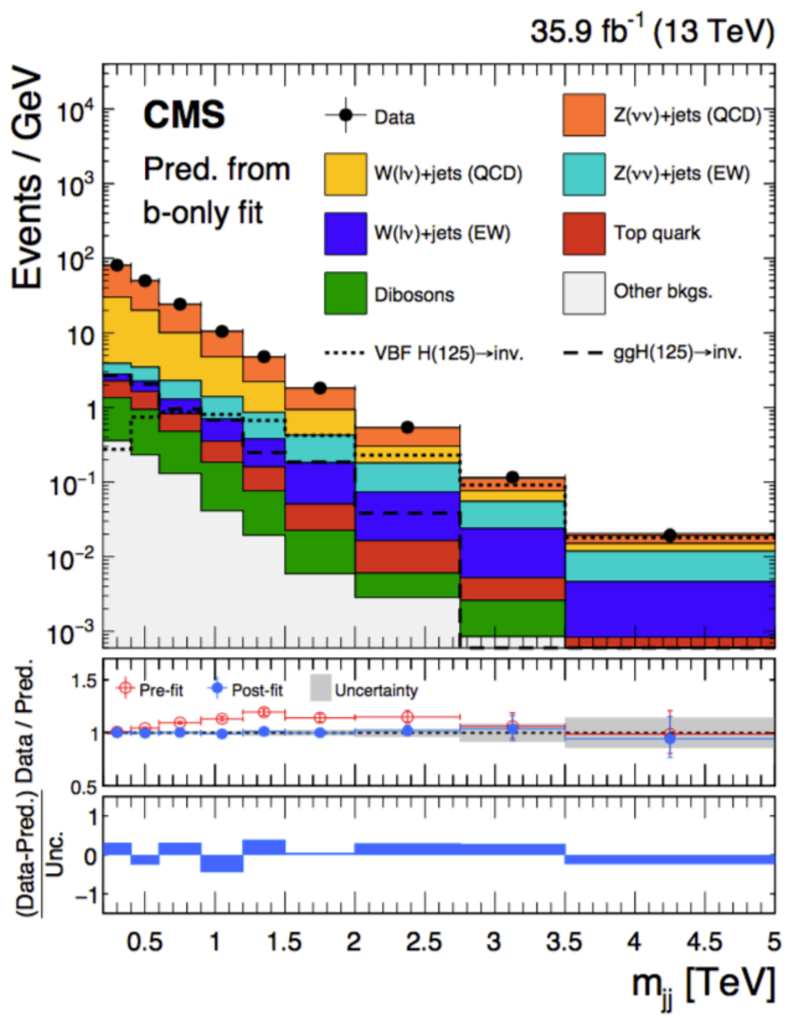
H —> invisible (VBF & VH & ggH)





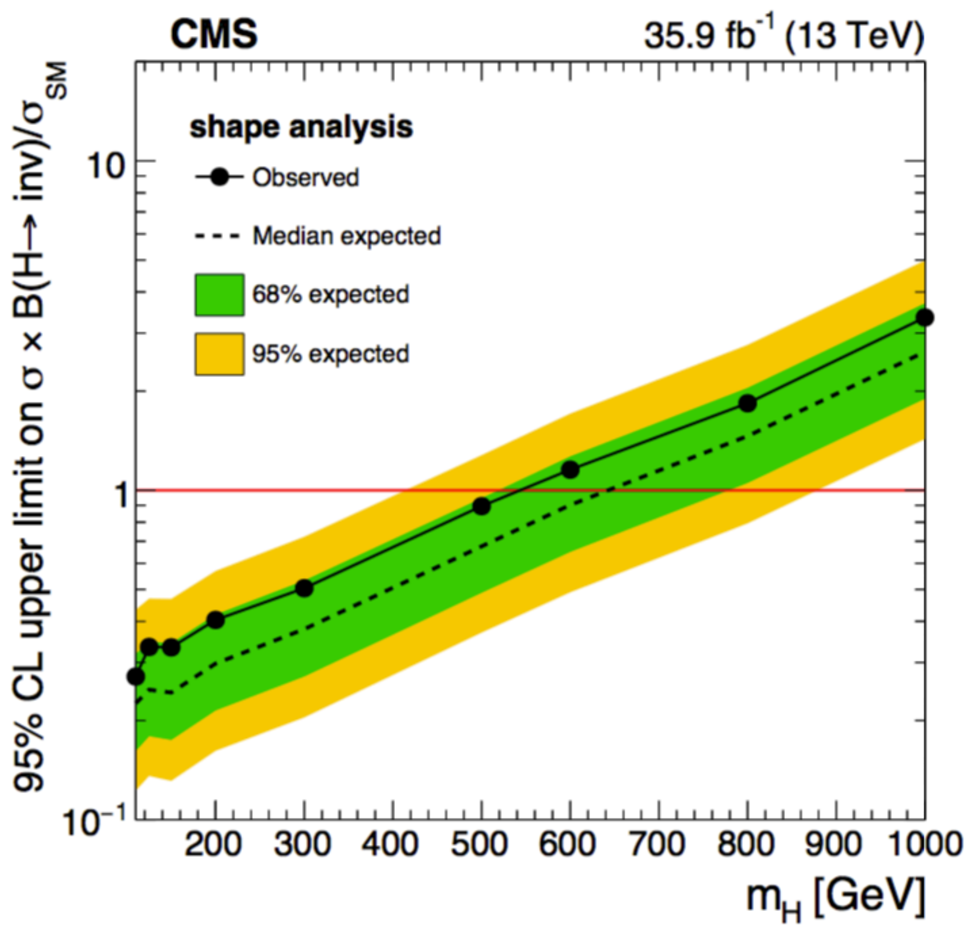


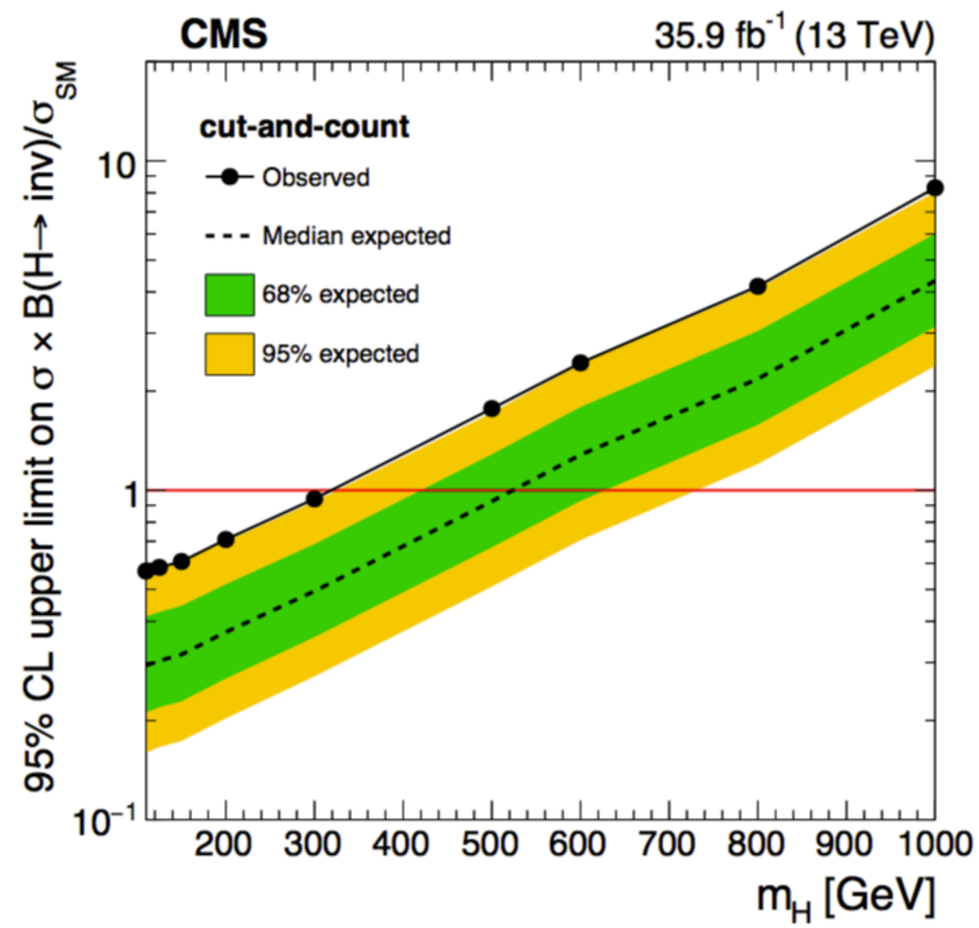




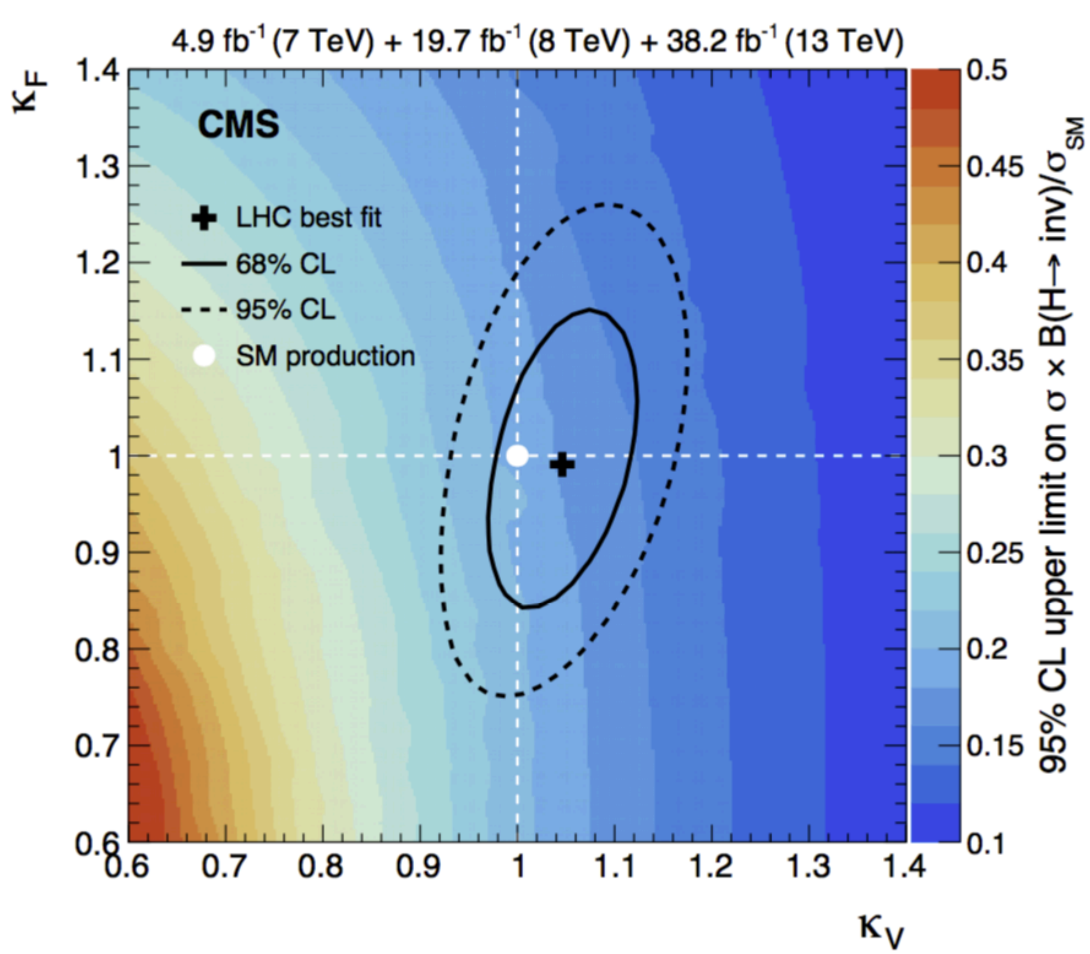
arXiv:1809.05937

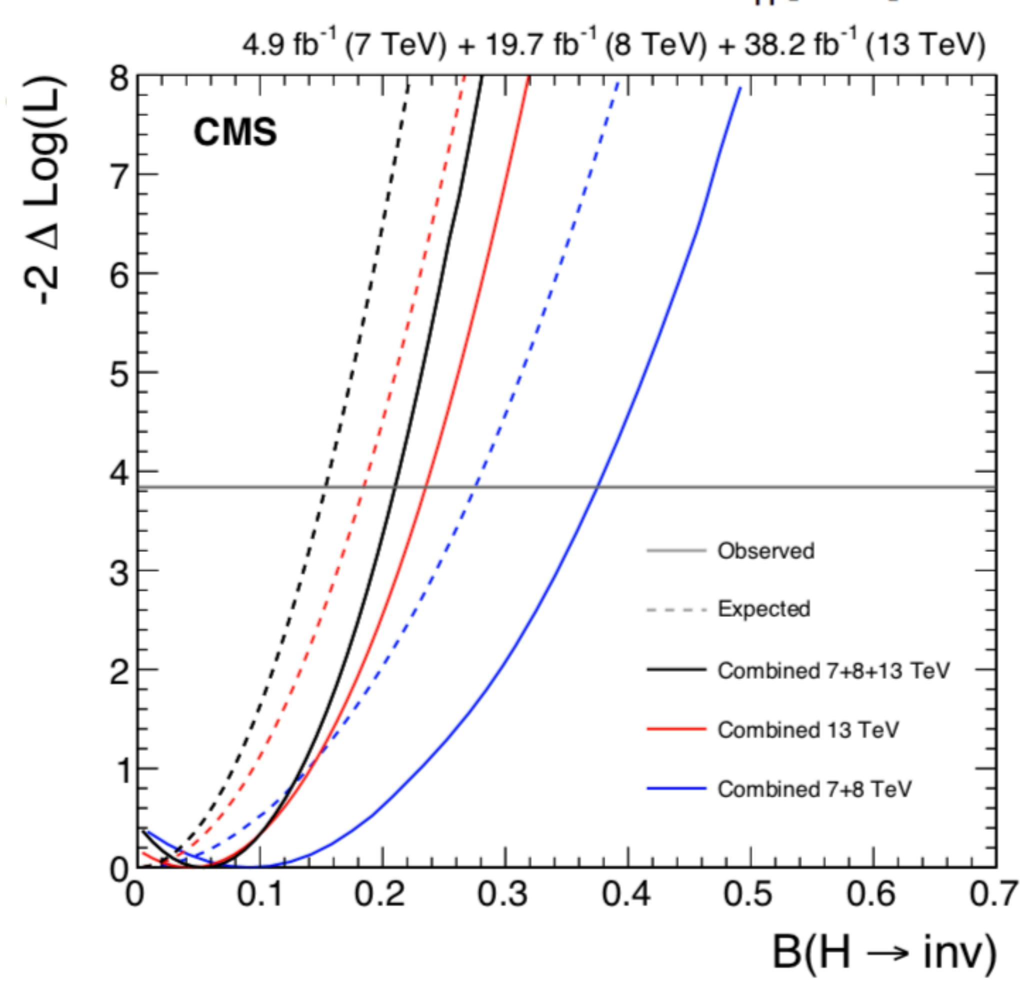
H —> invisible (VBF & VH & ggH)





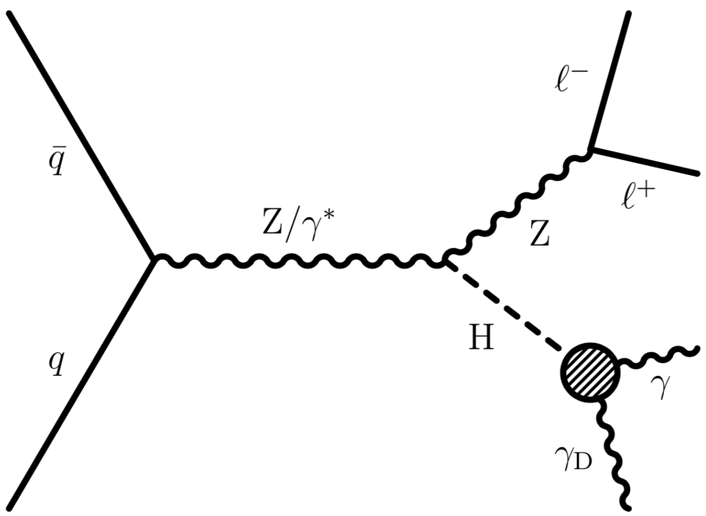
arXiv:1809.05937



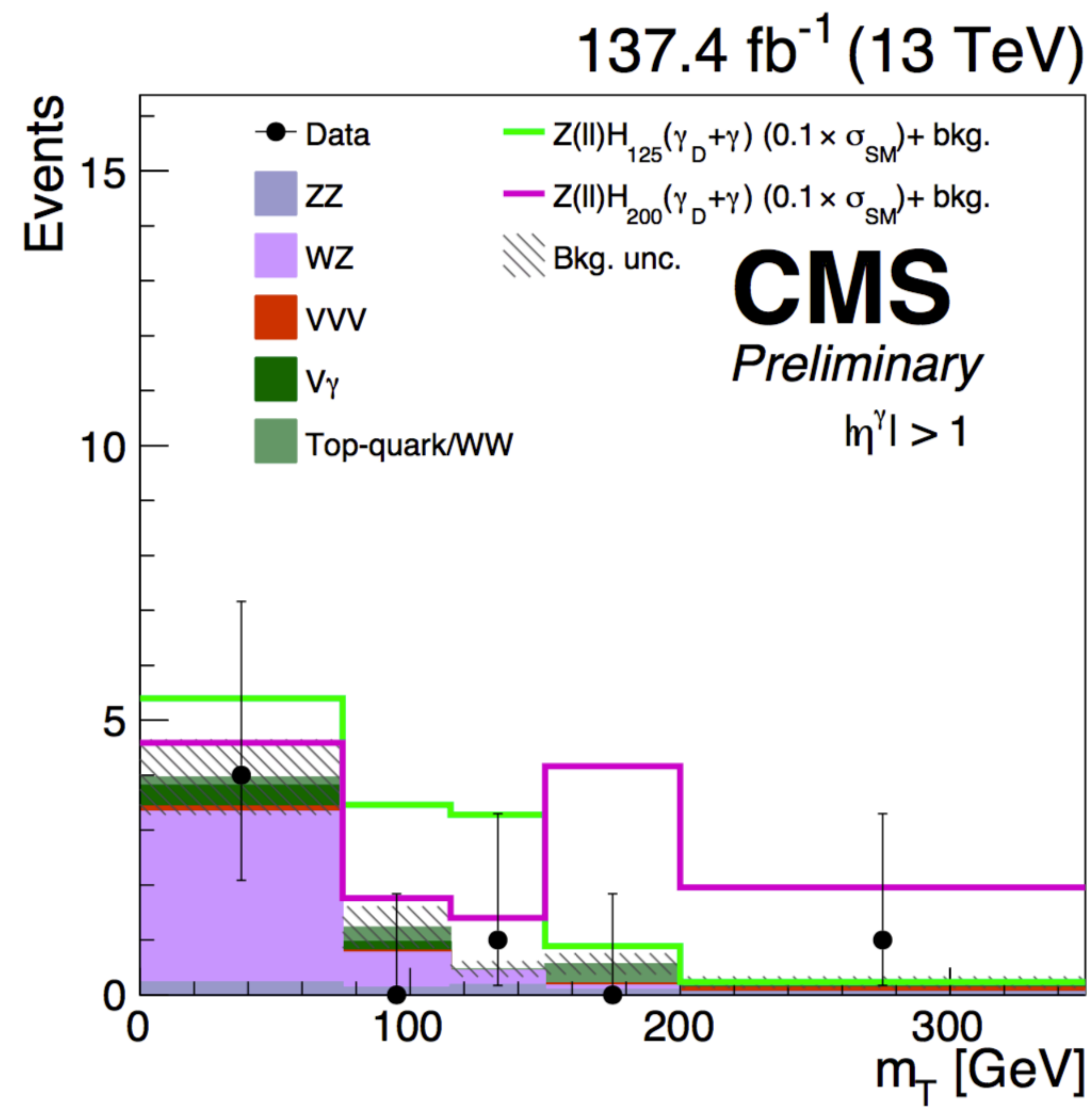


Search for dark photons in ZH decays

CMS-EXO-19-007



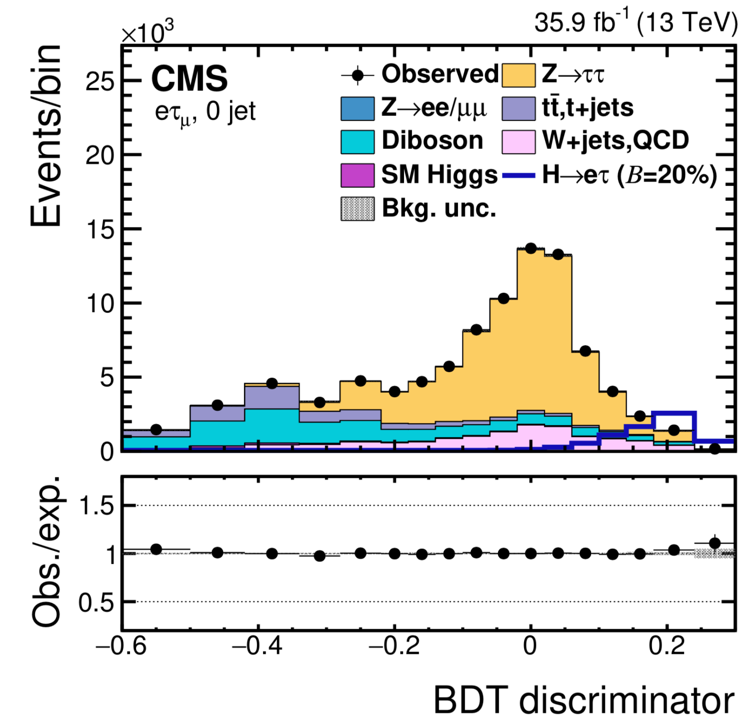
Process	Yields
Data	14
Nonresonant bkg.	2.4 ± 1.1
WZ	8.1 ± 2.0
ZZ	1.5 ± 0.3
$Z\gamma$	0.7 ± 0.7
Other bkg.	0.6 ± 0.3
Total bkg.	13.3 ± 3.8
ZH_{125} (BR=10%)	17.9 ± 1.2 (1.42 ± 0.09 %)
ZH_{200} (BR=10%)	12.3 ± 0.8 (4.32 ± 0.28 %)
ZH_{300} (BR=10%)	3.9 ± 0.2 (6.80 ± 0.34 %)



Reference: Phys. Rev. D. 93. 093011

Lepton flavor violation of Higgs decaying to μτ and eτ

- Use boost decision tree approach to distinguish signal and background
- Misidentified lepton background estimated from data
- Final states with different Higgs decay modes:
  - $\mu\tau_h$
  - $\mu\tau_e$
  - $e\tau_h$
  - $e\tau_\mu$



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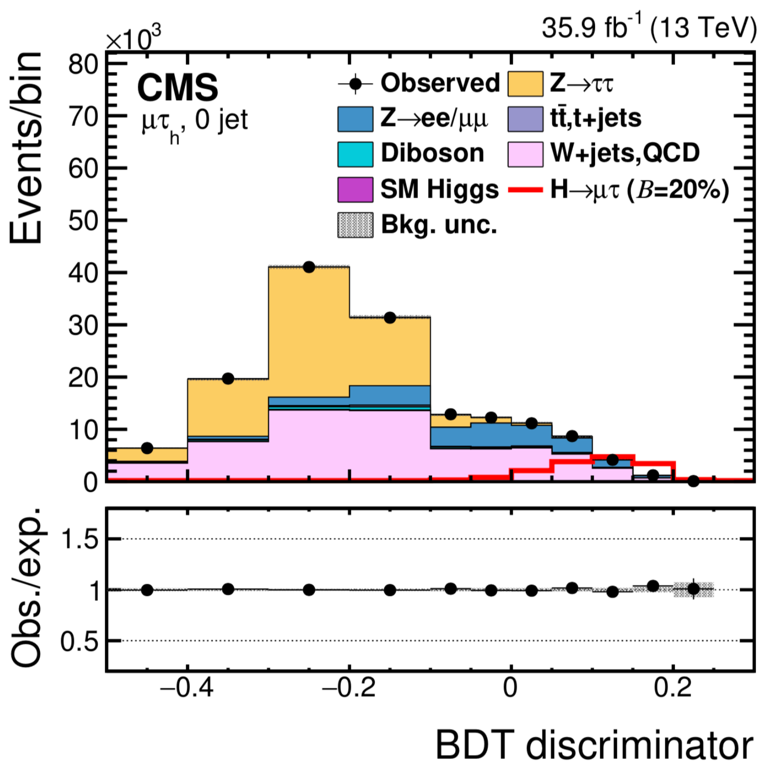
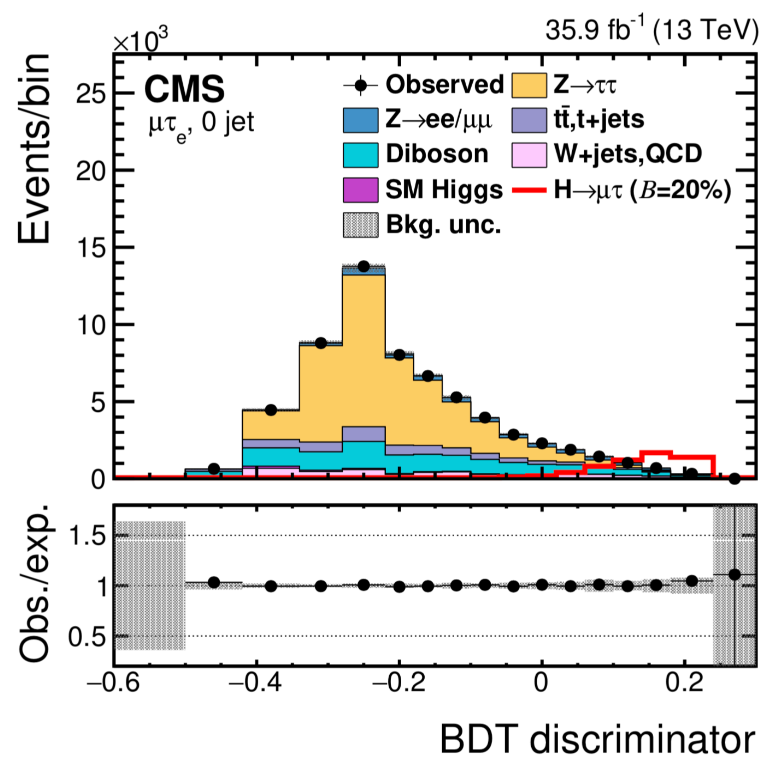
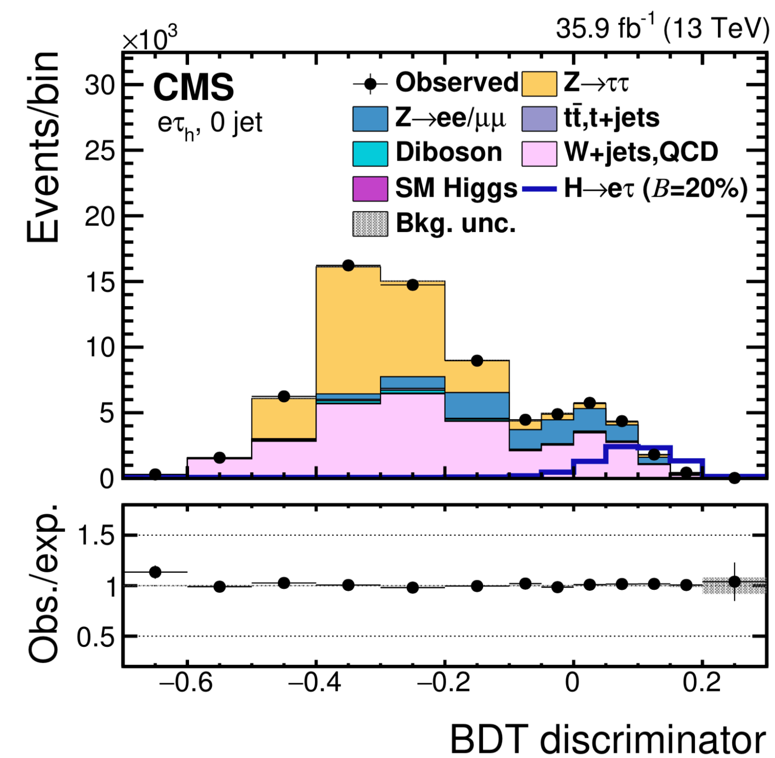
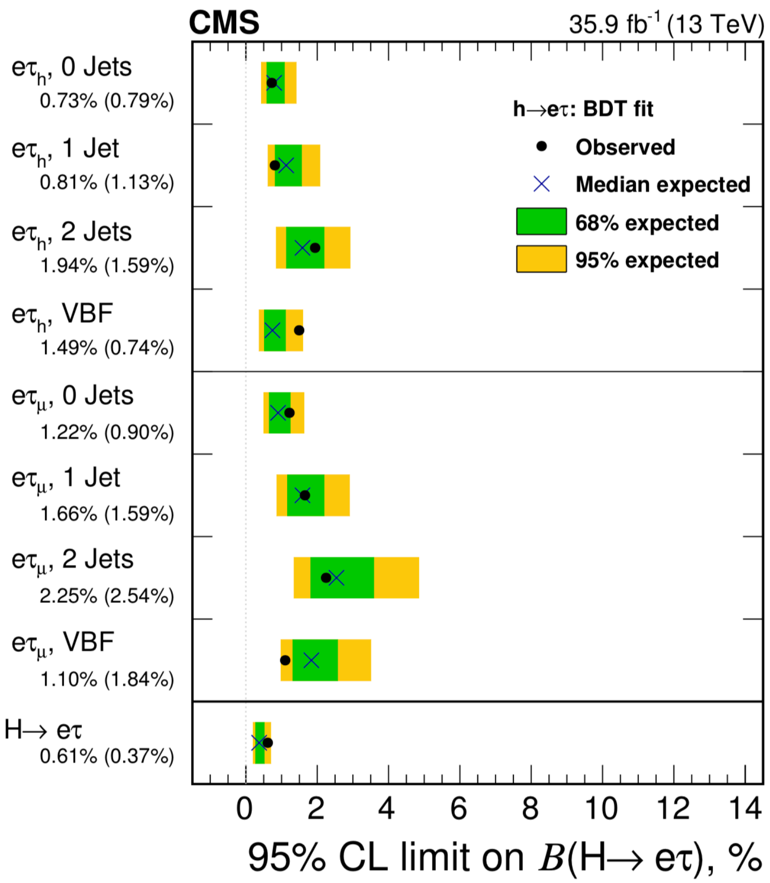


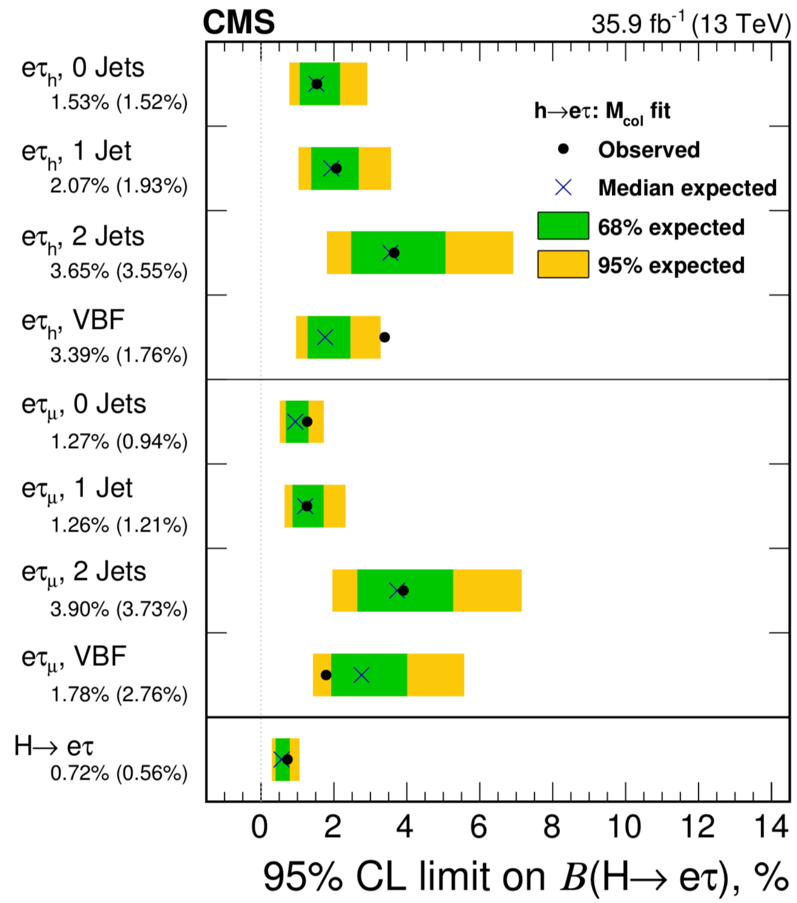




- Presence of LFV Higgs boson couplings would allow τ —> *μ* or τ —> e through a virtual Higgs boson
- LFV Higgs boson decay to *μ*e is strongly constrained by the *μ*—> eγ limit

Lepton flavor violation of Higgs decaying to μτ and eτ





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- Upper limits on the off-diagonal $\mu\tau$ and eτ Yukawa couplings at 95% confidence level

	BDT fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 1.43 \times 10^{-3}$
$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.26 \times 10^{-3}$