Search for Additional Scalar Bosons with CMS

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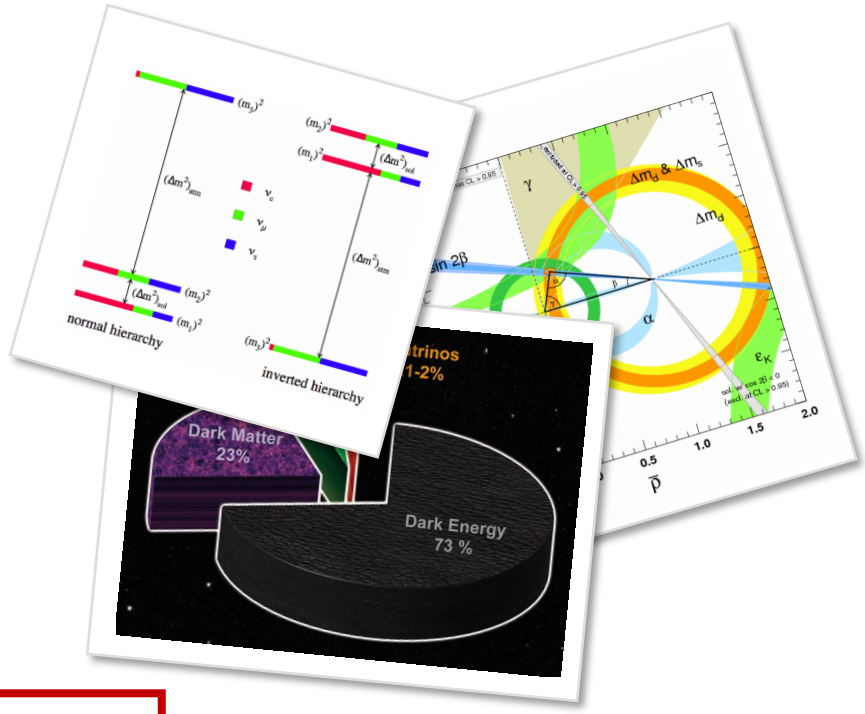
Theoretical Motivations

- The **discovery of a new boson** consistent with the SM Higgs boson has **completed the SM theory**

- Nevertheless, this theory **cannot address** several **crucial issues**

Direct evidence from observation:
- existence of neutrino masses
- existence of dark matter and dark energy
- matter-antimatter asymmetry

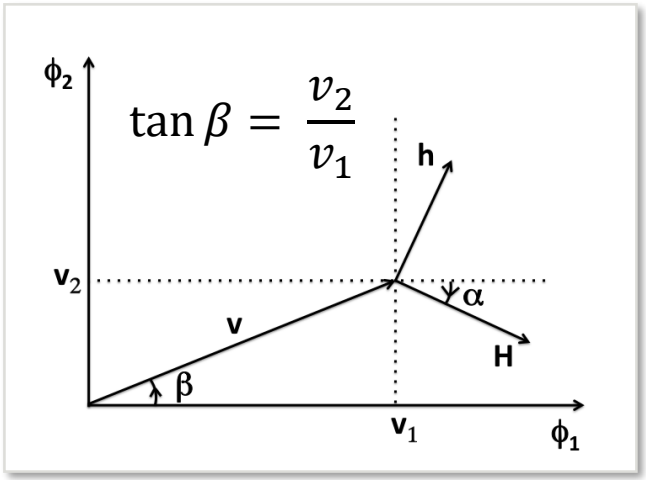
Conceptual problems in the SM:
- the large number of free parameters
- the "hierarchy problem“
- the coupling unification

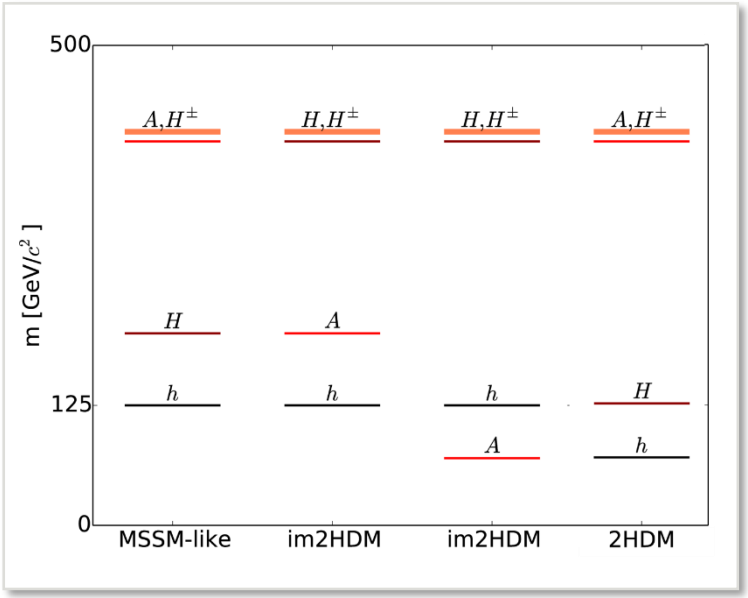


Strong indications that the SM is only a low-energy expression of a more global theory

Two Higgs Doublet Models

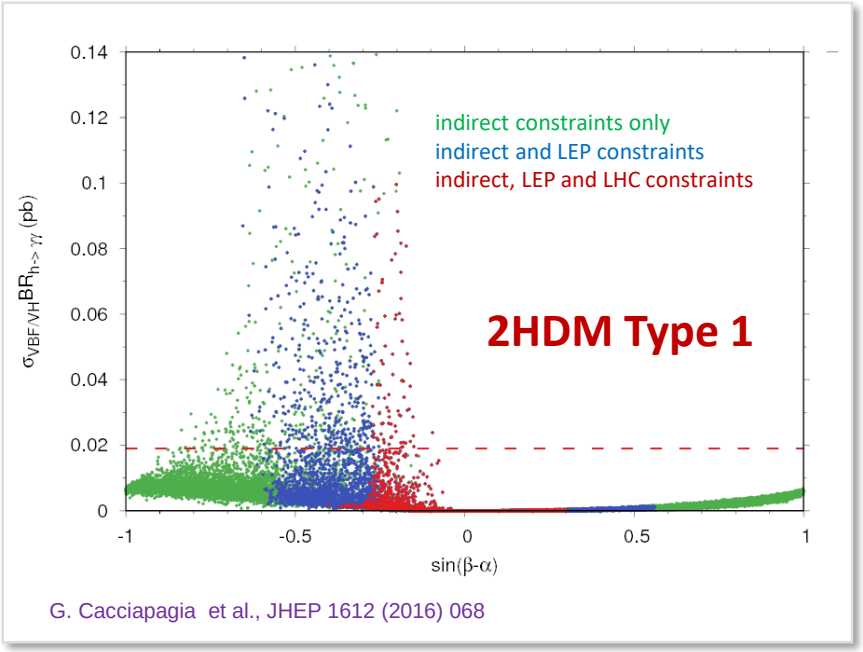
- Two-Higgs-doublet models are simple **extensions of the SM**
- They introduce **two doublets** of scalar fields, ϕ_1 and ϕ_2, in the SM Lagrangian of the scalar sector
- After symmetry breaking, **five physical states are left**: two CP-even ($\boldsymbol{h}$ and $\boldsymbol{H}$), one CP-odd ($\boldsymbol{A}$), and two charged ($\boldsymbol{H^{\pm}}$) bosons
- **Four types**, according to different patterns of **quark and lepton couplings**: most commonly considered are Type 1 and Type 2 (**MSSM**-like)
- **Different possibilities** of **mass** hierarchy





Search for BSM Physics at the LHC

LHC data could be **sensitive** to the presence of **additional scalars** corresponding to some combinations of **2HDM parameters**



G. Cacciapagia et al., JHEP 1612 (2016) 068

How can new physics be discovered?

- **Precision measurements** of the properties of the h(125 GeV) scalar boson
- Observation of BSM physics in **indirect searches** involving **scalar bosons**
- Discovery of **BSM decays** of the h(125 GeV) scalar boson
- Direct **discovery** of new **scalar particles**

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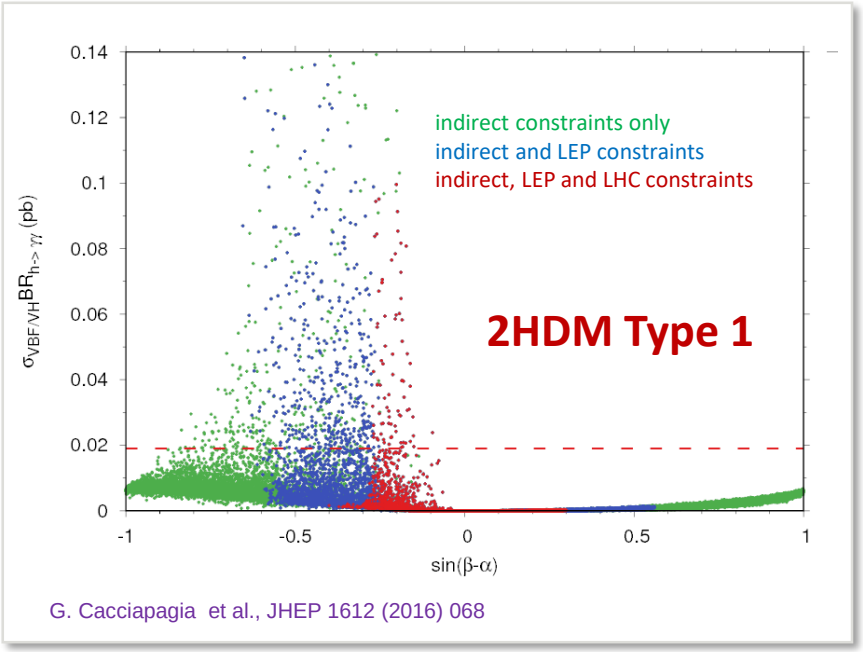

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S. Taroni's talk

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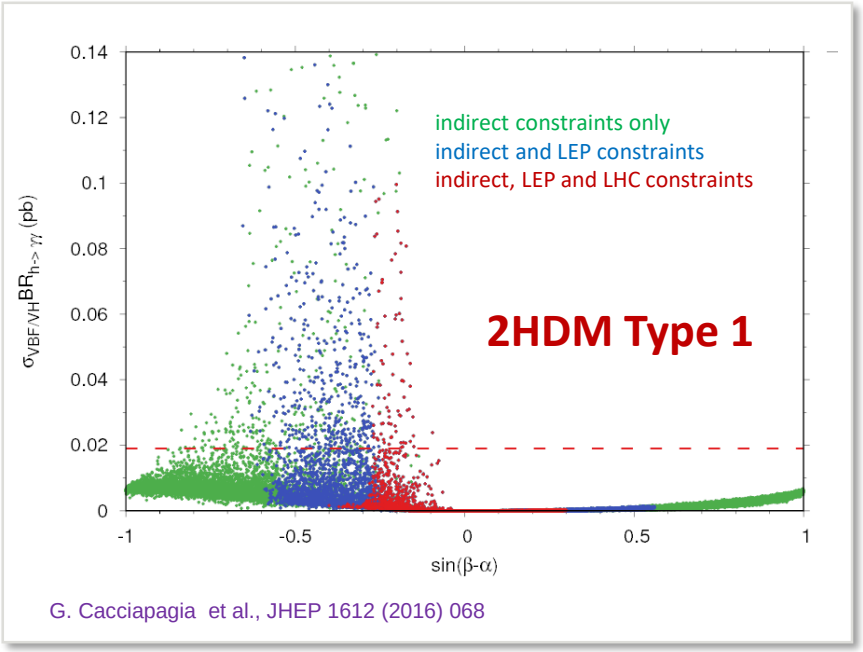

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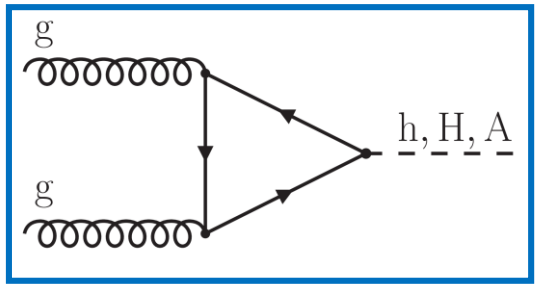
{ Direct **discovery** of new **scalar particles** } **THIS TALK**

MSSM H/A → $\tau\tau$

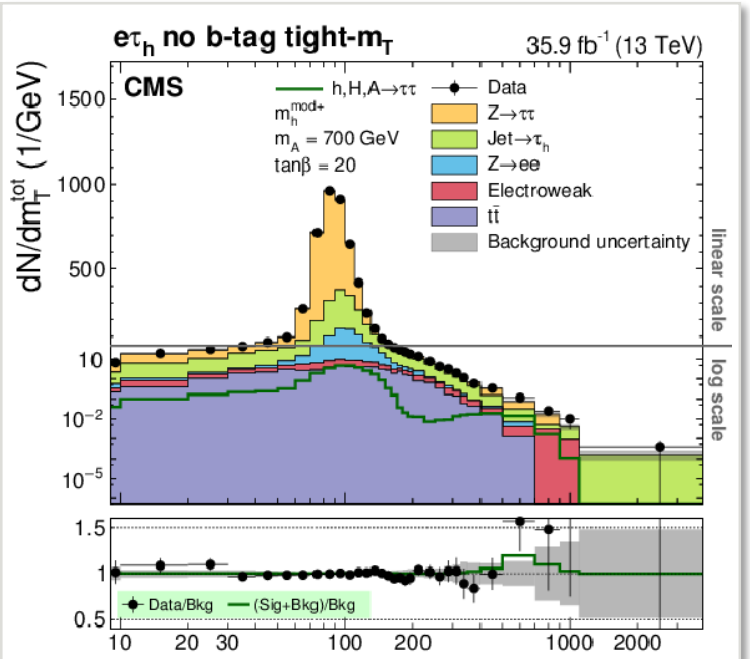
CMS-PAS-HIG-17-020 (SUB. TO JHEP)

- Search for $\phi(H/A) \rightarrow \tau\tau$:
  - Large BR
  - Clean final state
  - Manageable backgrounds
- **Production mechanisms**:
  - **Gluon fusion** (dominant at low $\tan\beta$)
  - **Associated with b-quarks** (dominant at large $\tan\beta$)
- $e\mu$, $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$ final states
- **16 categories** for sensitivity optimization
- **Background** estimated mainly by **data-driven** techniques
- **Signal extracted** as a function of the total transverse mass m_T^{tot}

$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_1}, p_{\mathrm{T}}^{\tau_2}) + m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_1}, p_{\mathrm{T}}^{\mathrm{miss}}) + m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_2}, p_{\mathrm{T}}^{\mathrm{miss}})}$$



CMS PAS HIG-17-020

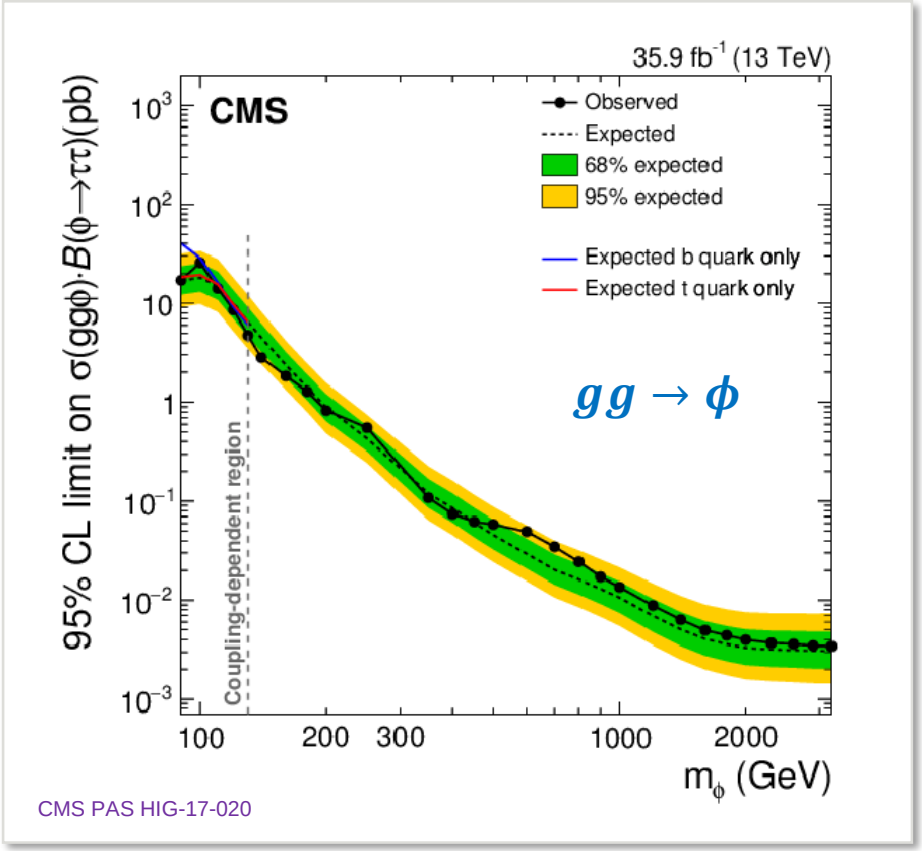


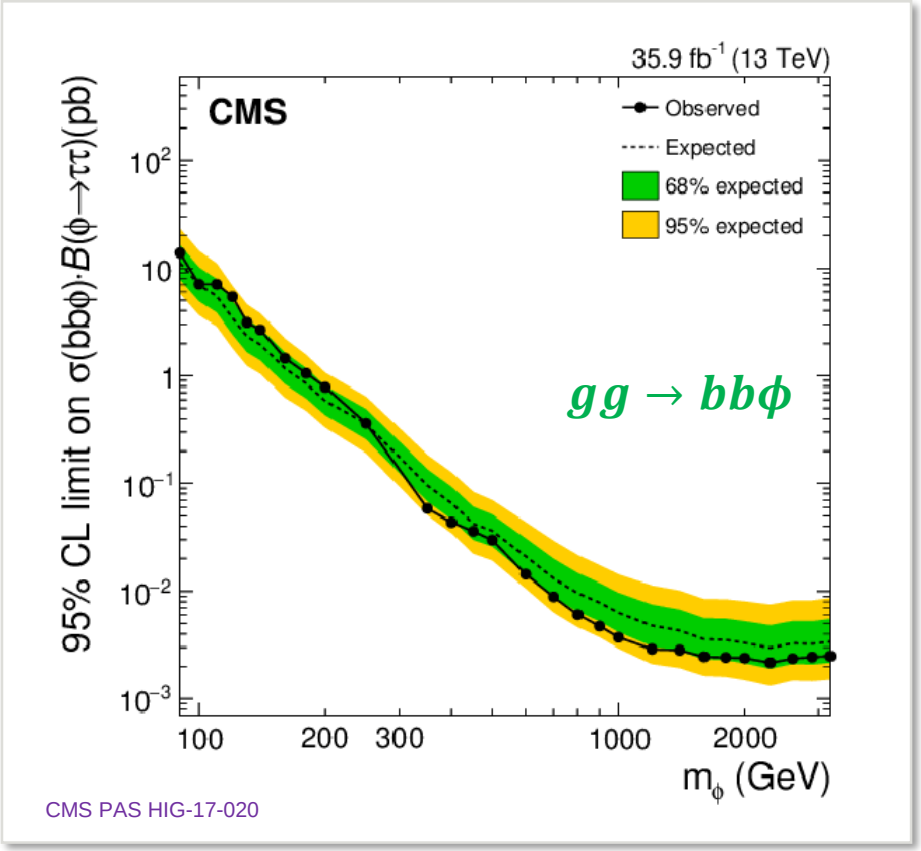
CMS PAS HIG-17-020

MSSM H/A → $\tau\tau$

CMS-PAS-HIG-17-020 (SUB. TO JHEP)

- **Model-independent** exclusion limits for $gg \to \phi$ and $gg \to bb\phi$:
  - All categories and final states combined together
  - Limits cover a **large range** of m_ϕ
  - **No significant excess** with respect to background expectations

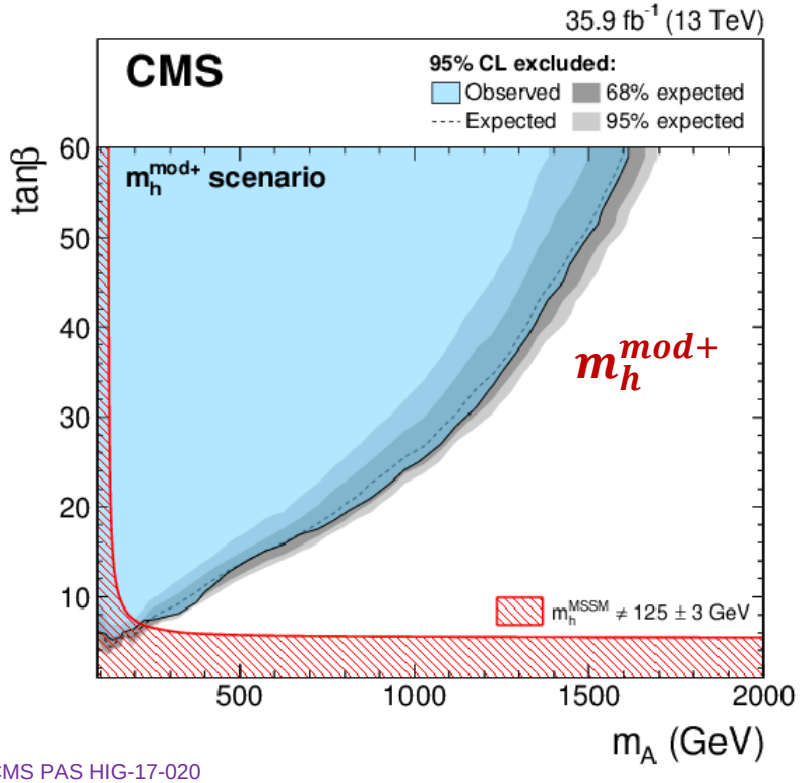




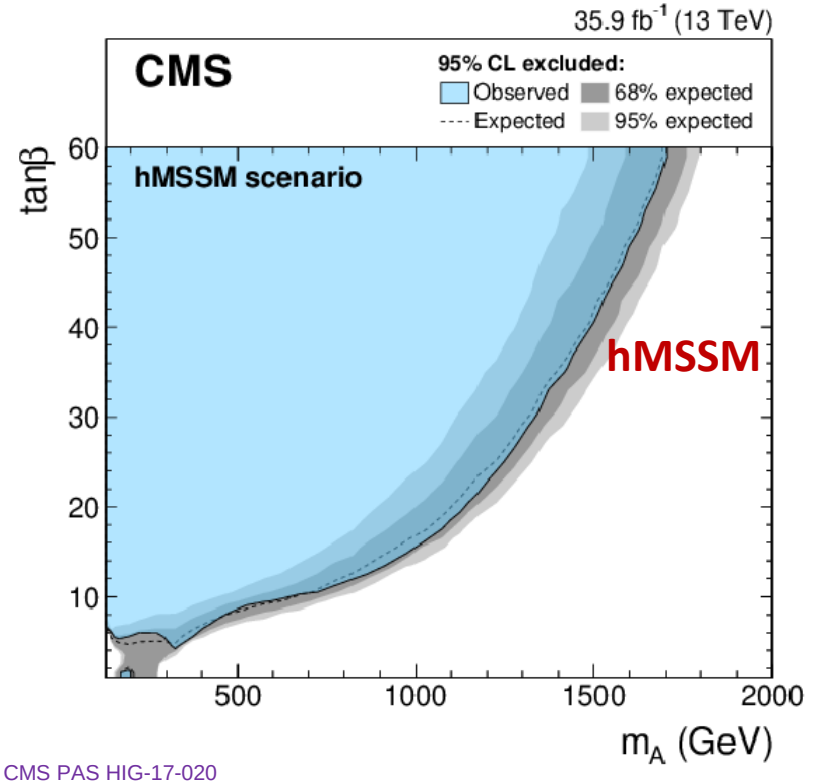
MSSM H/A → $\tau\tau$

CMS-PAS-HIG-17-020 (SUB. TO JHEP)

- **Results interpreted** for two benchmark scenarios of the MSSM (m_h^{mod+} and **hMSSM**)
- **Excluded regions** down to $\tan\beta \approx 6$ for $m_A \lesssim 250$ GeV
- Comparison with 8 TeV results in backup slides



CMS PAS HIG-17-020

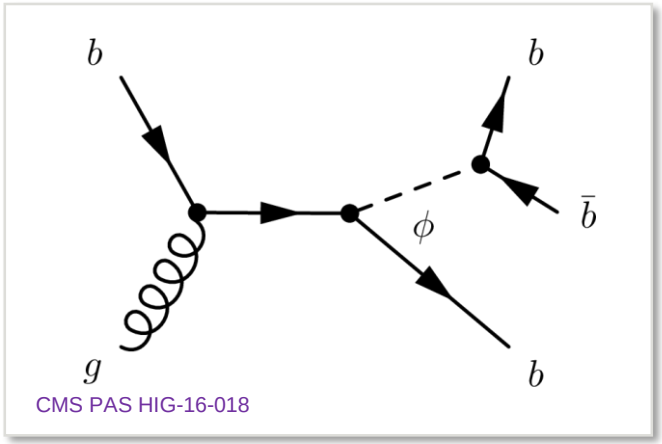


CMS PAS HIG-17-020

High Mass H/A → bb

CMS-PAS-HIG-16-018 (SUB. TO JHEP)

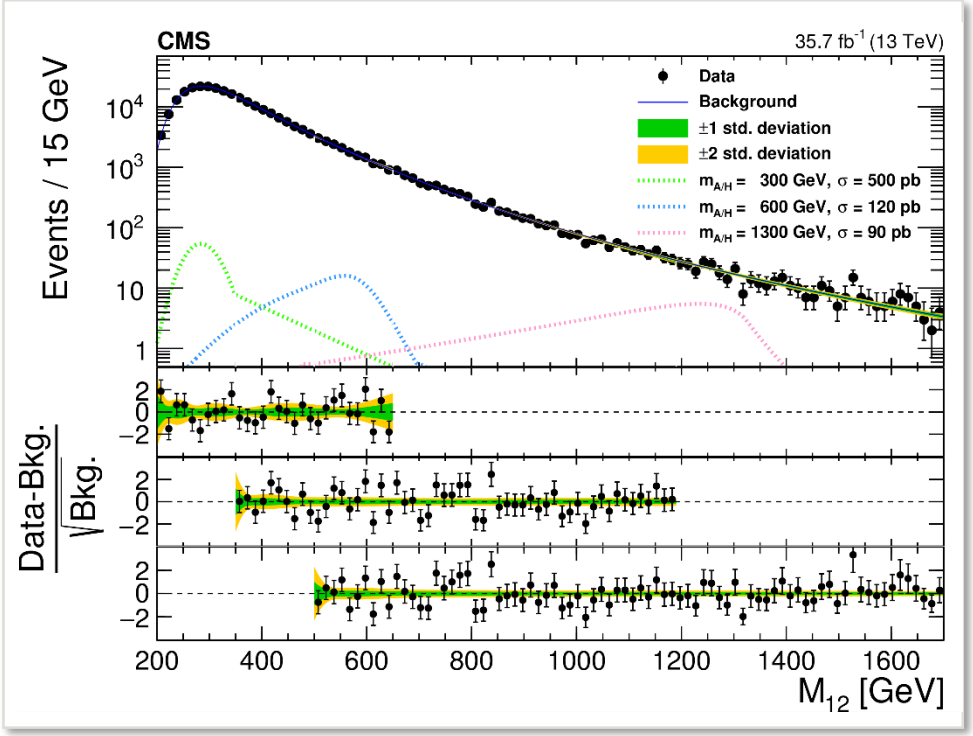
- Search for $\mathbf{H/A \rightarrow bb}$ associated with **b quark(s)** with $\boldsymbol{m_A = m_H}$:
  - **Enhanced cross-section** by up to $\sim 2\tan^2\beta$
  - **Large BR** in many 2HDM and MSSM scenarios



CMS PAS HIG-16-018

- At least **3 b-jets** in the **final state**:
  - Huge **QCD multi-jet** background modelled using **data-driven techniques**

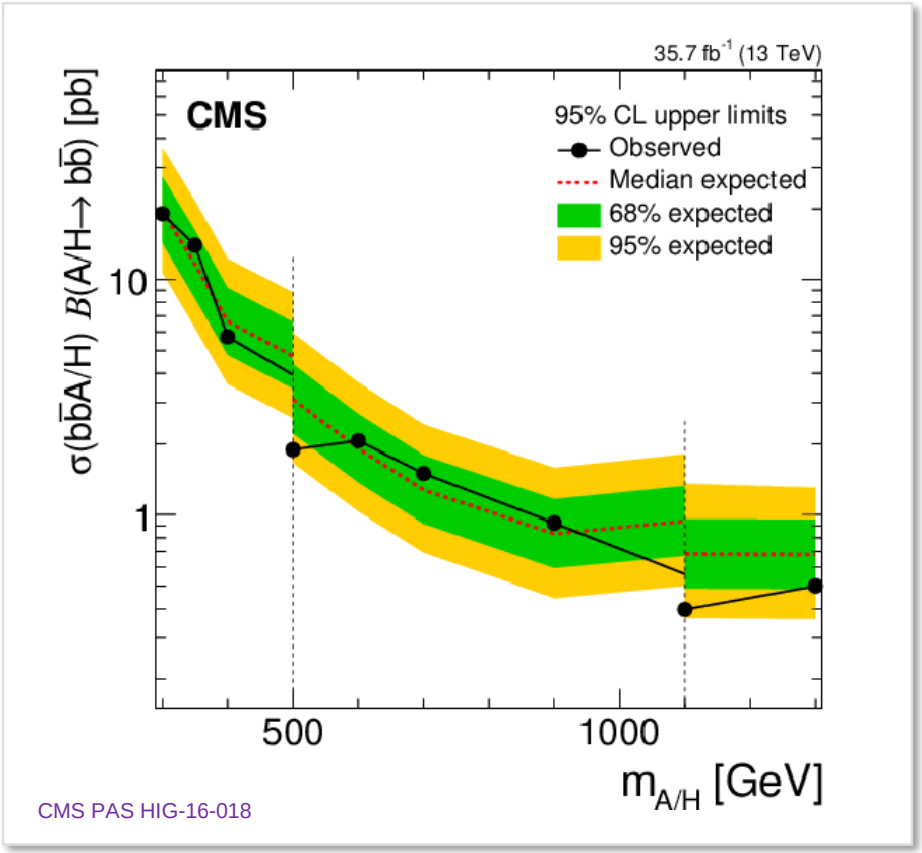
- **Fit** performed in a **large mass range**:
  - M_{12} (mass of the 2 b jets with highest p_T) distribution divided into **overlapping subranges** to **improve the fit** and **reduce the bias**
  - Background functions **validated** in **CRs**



High Mass H/A → bb

CMS-PAS-HIG-16-018 (SUB. TO JHEP)

- **Model independent** exclusion limits for $\mathbf{bbH/}A(\rightarrow bb)$:
  - **No significant excess** with respect to background expectations
- Limits cover a **large range** of $m_{H/A}$
- Translate into **exclusion limits on MSSM** parameters $\tan\beta$ and $m_{H/A}$



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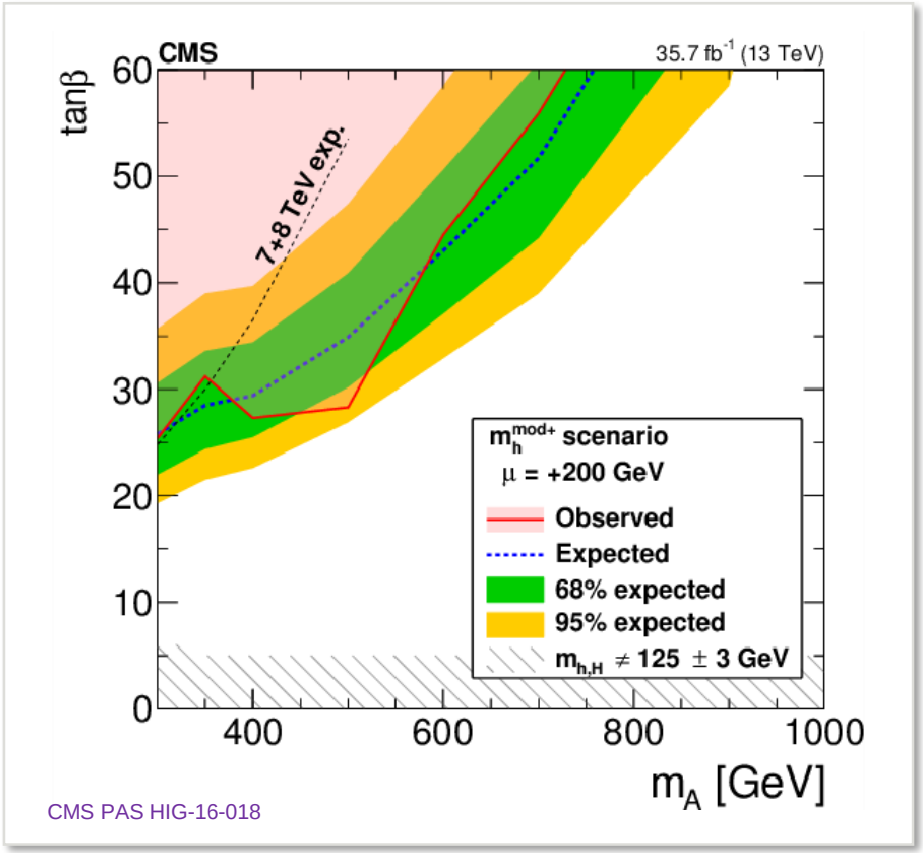


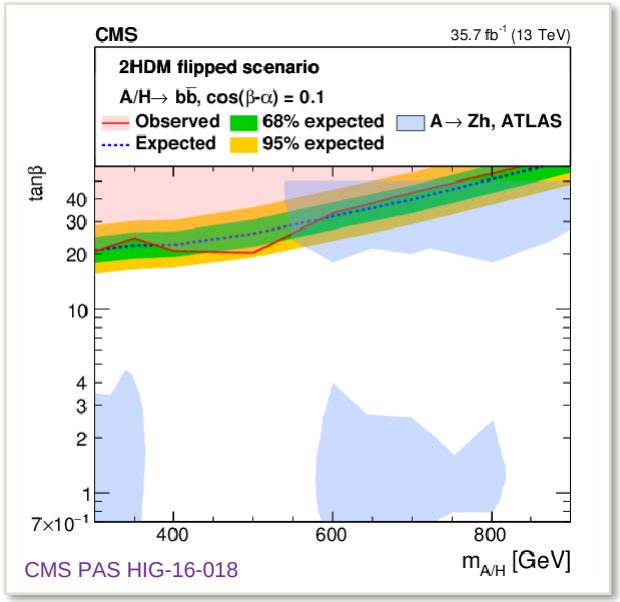
CMS PAS HIG-16-018

High Mass H/A → bb

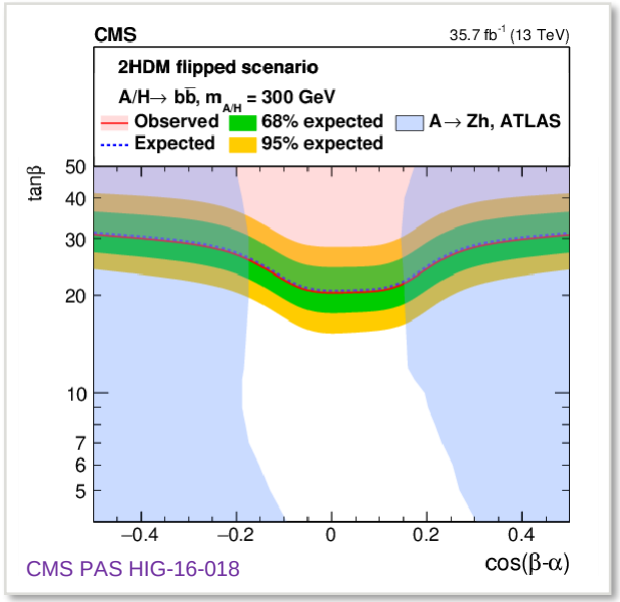
CMS-PAS-HIG-16-018 (SUB. TO JHEP)

- **Exclusion limits** on $\tan\beta$ vs $m_{H/A}$ and $|\cos(\beta-\alpha)|$ for **2HDM** type II and flipped scenarios
- For $|\cos(\beta-\alpha)| \to 0$, the light CP-even *h* state is indistinguishable from the SM Higgs boson
  - Measurements allow only small $|\cos(\beta-\alpha)|$ values (alignment limit)
  - Competitive upper limits and strong unique constraints on $\tan\beta$

$|\cos(\beta-\alpha)|$= 0.1



$m_{H/A}$ = 300 GeV



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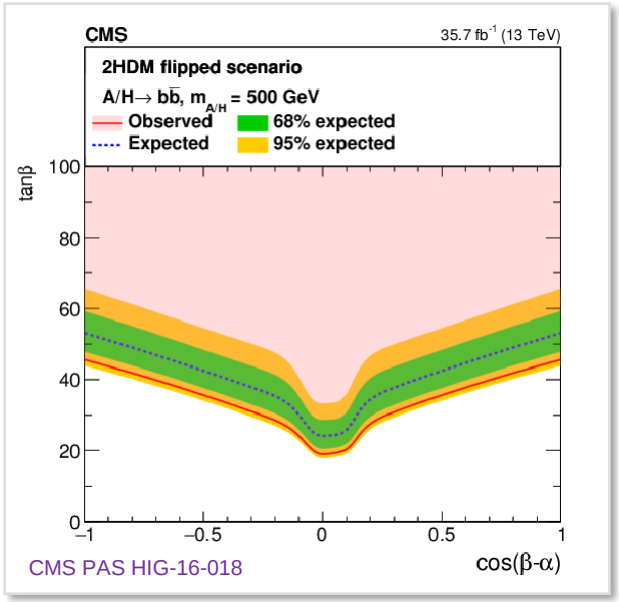
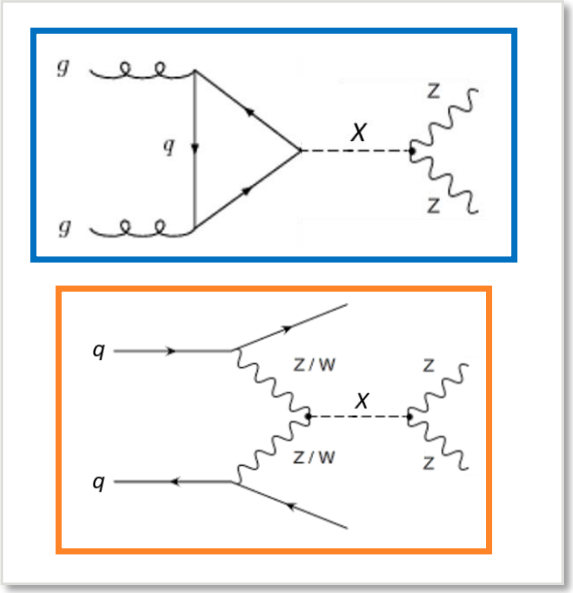
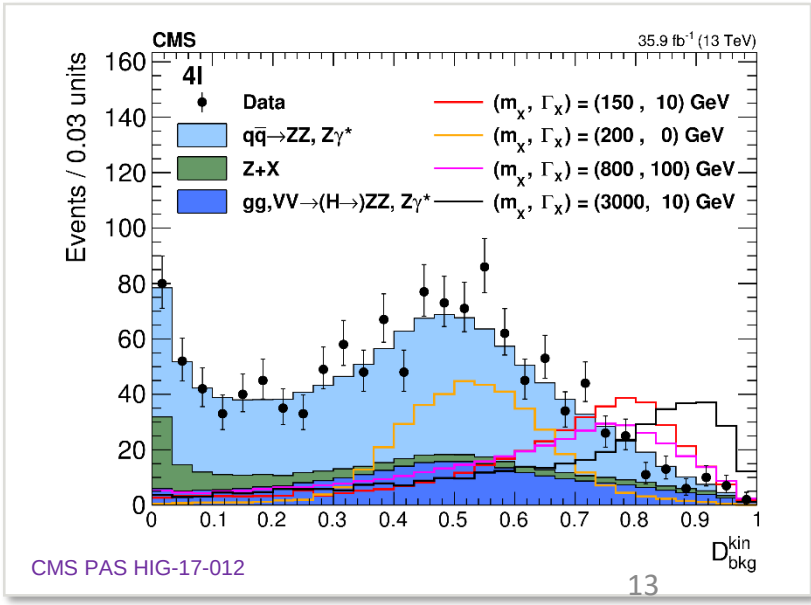


High Mass X → ZZ

CMS-PAS-HIG-17-012 (SUB. TO JHEP)

- Search for scalar ***X → ZZ***:
  - Clean final state
  - Manageable backgrounds
  - Strategy based on SM *h(125) → ZZ*
- **Production mechanisms**:
  - **Gluon fusion**
  - **Electroweak production** (dominated by VBF)
- **4ℓ**, **$2\ell 2q$** and **$2\ell 2\nu$** final states
- **3 parameters** scanned over a **large range**:
  - f_{VBF}, fraction of the EW production cross section
  - m_X, resonance mass
  - Γ_X, resonance width



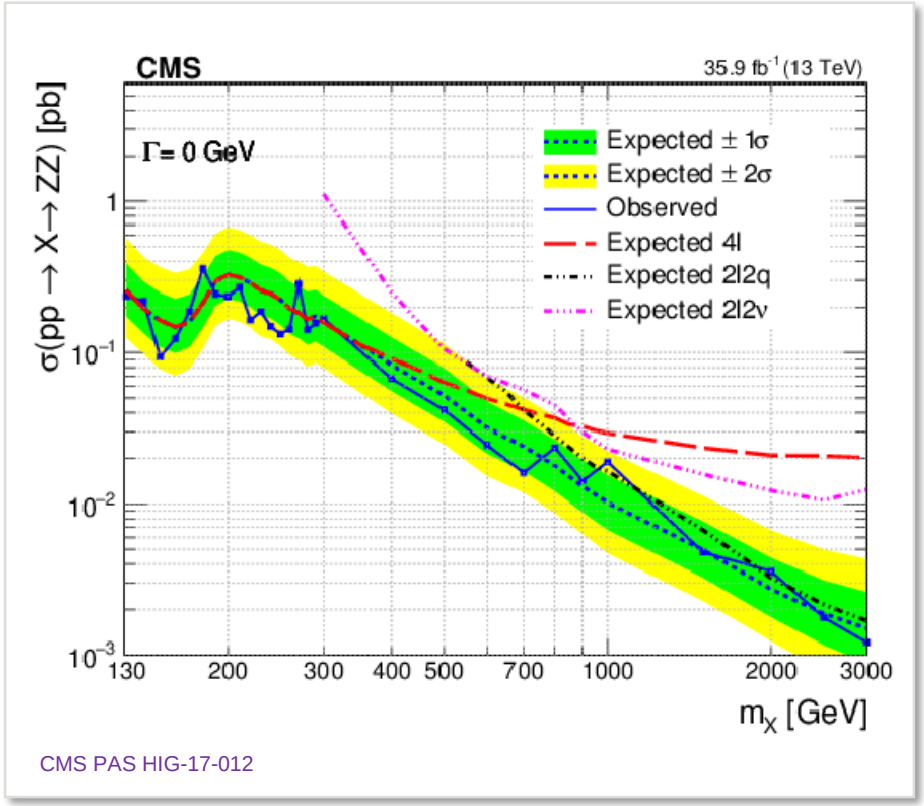


High Mass X → ZZ

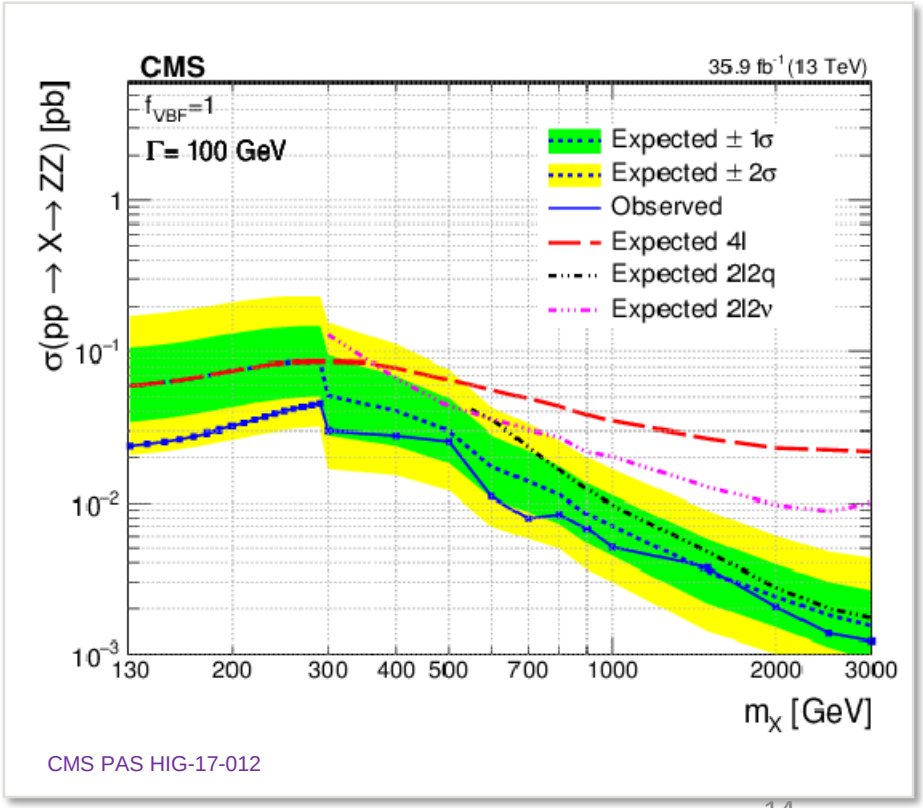
CMS-PAS-HIG-17-012 (SUB. TO JHEP)

- **Exclusion limits** as a function of m_X for several values of Γ_X and f_{VBF}
- Better limits for **VBF production** (smaller background) and **narrow Γ_X** (higher S/B)
- For $m_X \leq$ **300 GeV** complicated **interference effects with background**

f_{VBF} free parameter, **Γ_X = 0**



f_{VBF} = 1, Γ_X = 100 GeV

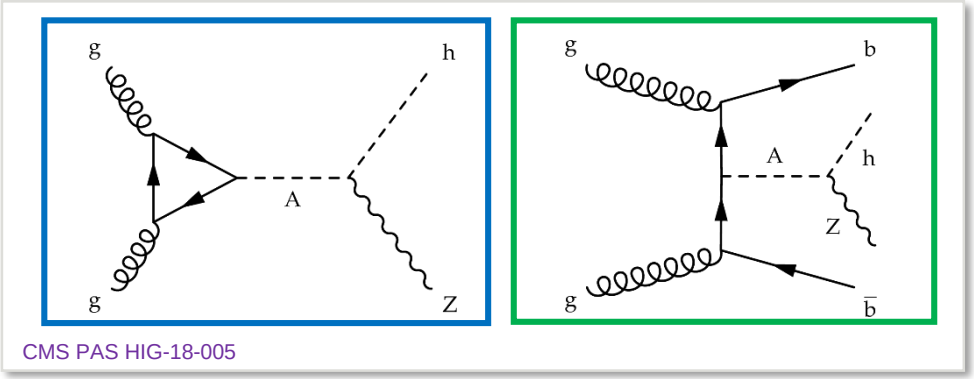


Heavy A → hZ

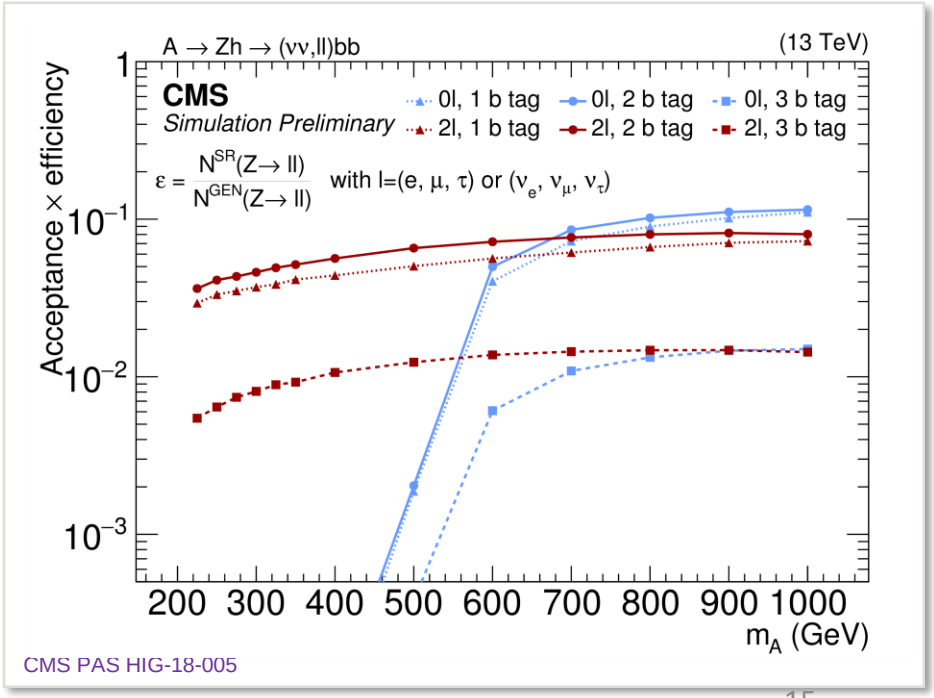
CMS-PAS-HIG-18-005

NEW

- Search for $A \to hZ$:
  - $h \to bb$, $Z \to \mu\mu$, ee and $\nu\nu$
  - **Large BR** in case of $m_A < 2m_t$ and for small $\tan\beta$ values
- **Production mechanisms**:
  - **Gluon fusion**
  - **Associated with b-quarks**
- **A boson** reconstructed **entirely** from m_{Zh}, if $Z \to \ell\ell$, and **partially** using m_{Zh}^{T}, if $Z \to \nu\nu$
- **Categories** defined according to the **number** of **leptons** and **b-jets**
- **Background** estimated mainly in **CRs**
- **Discriminators** based on angular and kinematical observables



CMS PAS HIG-18-005



CMS PAS HIG-18-005

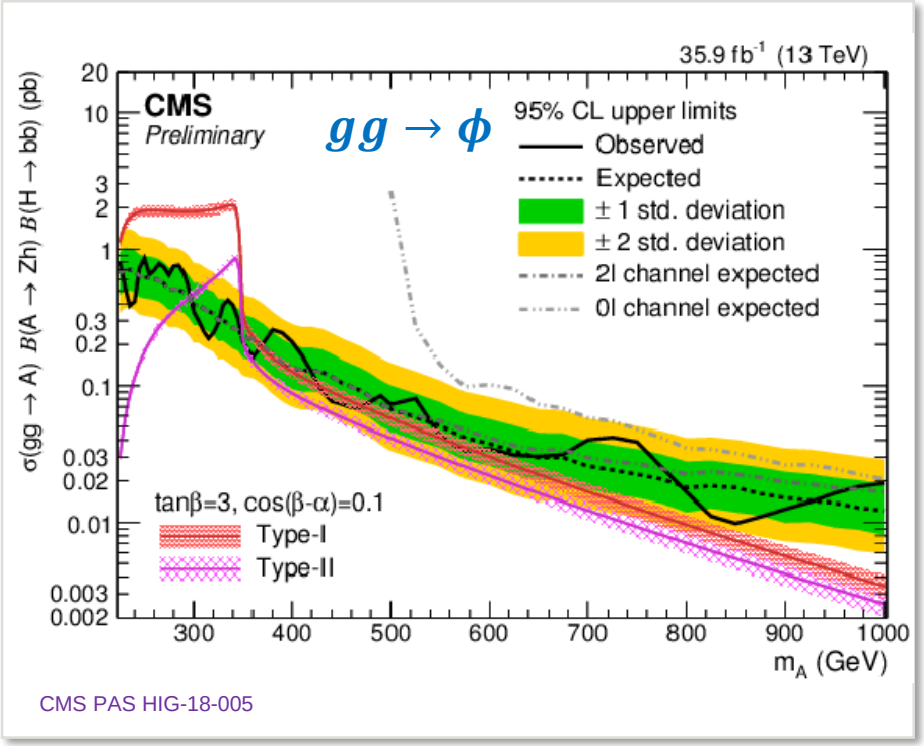
Heavy A → hZ

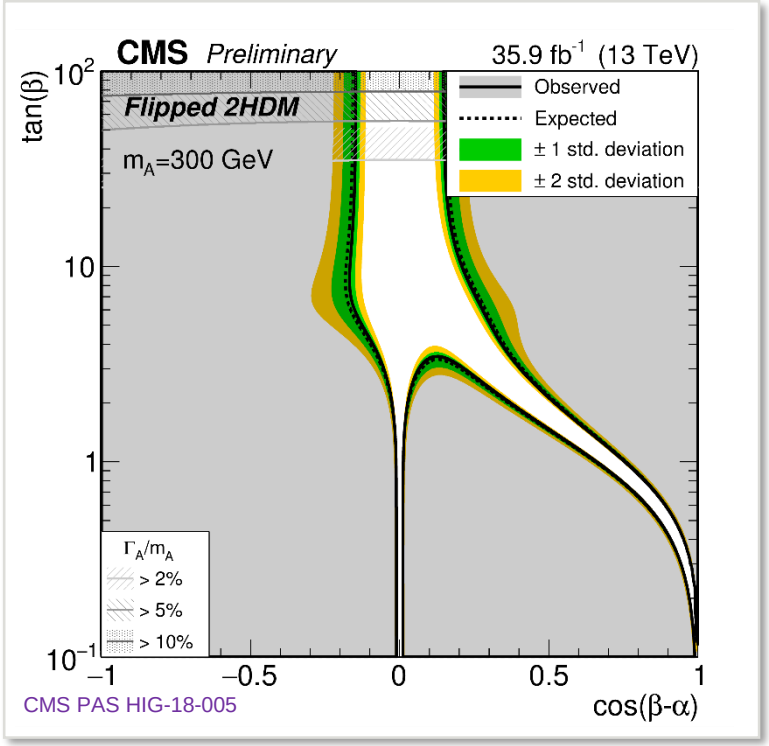
CMS-PAS-HIG-18-005

NEW

- **Model independent** exclusion limits for $gg \rightarrow \phi$ and $gg \rightarrow bb\phi$:
  - All categories and final states combined together
  - **No significant excess** with respect to background expectations
- Results **interpreted** for several **2HDMs** (more in backup)

m_A = 300 GeV – flipped 2HDM

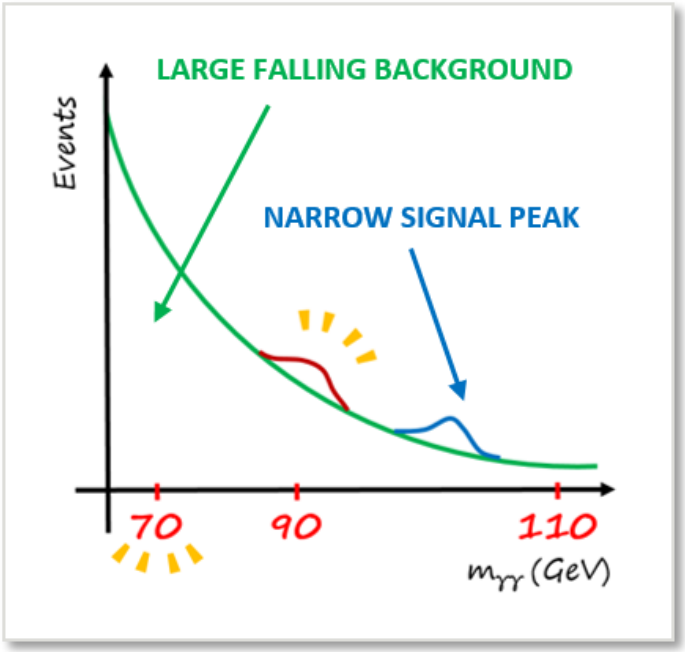


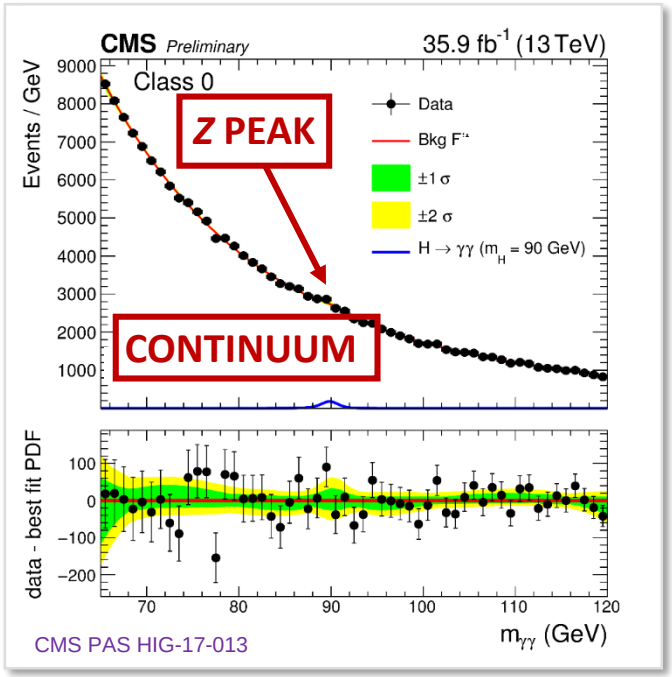


Low Mass $h \to \gamma\gamma$

CMS-PAS-HIG-17-013

- The **Higgs boson at 125 GeV** can be identified as the **heavier scalar H**, allowing to envisage a possible **lighter particle h**
- **Event categorization** defined to maximize S/B
- Signal extracted from background by **fitting the observed diphoton mass distributions** in each category



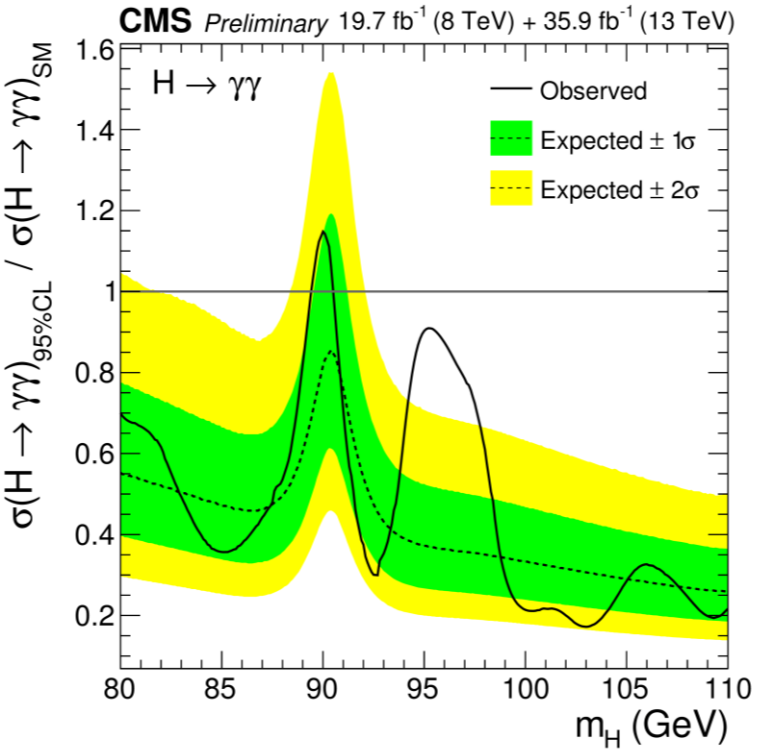


- The **signal shape** corresponds to a **standard Higgs boson**
- **Continuum background** modeled with a **sum of polynomials**
- **Drell-Yan contribution** modeled with a double-sided Crystal Ball distribution
- **Final background model** is fitted to data

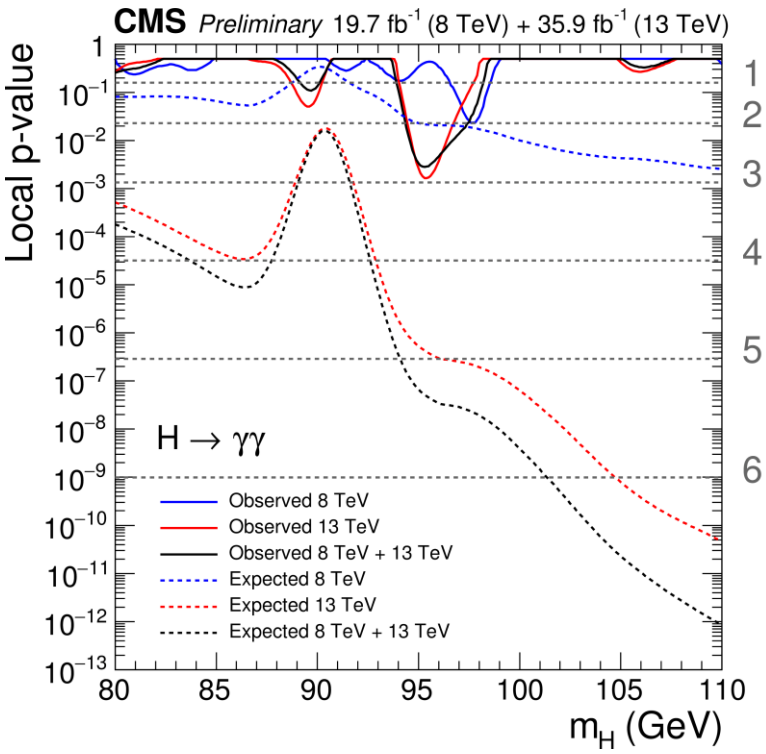
Low Mass $h \to \gamma\gamma$

CMS-PAS-HIG-17-013

- **Combined 8 TeV + 13 TeV** σ×BR limit normalized to SM expectation:
  - Production processes assumed in SM proportions
  - **No significant excess** with respect to background expectations
- Expected and observed local p-values for **8 TeV**, **13 TeV** and their **combination**



CMS PAS HIG-17-013



CMS PAS HIG-17-013

Conclusions

- The **Scalar Sector of the SM** is a favored place to look for **new physics effects**
- **LHC data** are **sensitive** to some theoretical models (2HDM, NMSSM…)
- We have **just started** to extract the physics **potential of the 13 TeV** dataset
- We have a **comprehensive view** of the potential of the main channels from the **Run1 experience**
- Many more BSM Higgs physics **results still to come**
- **Feedback** with **theory community** fundamental to keep interest in exploring these signatures

Backup

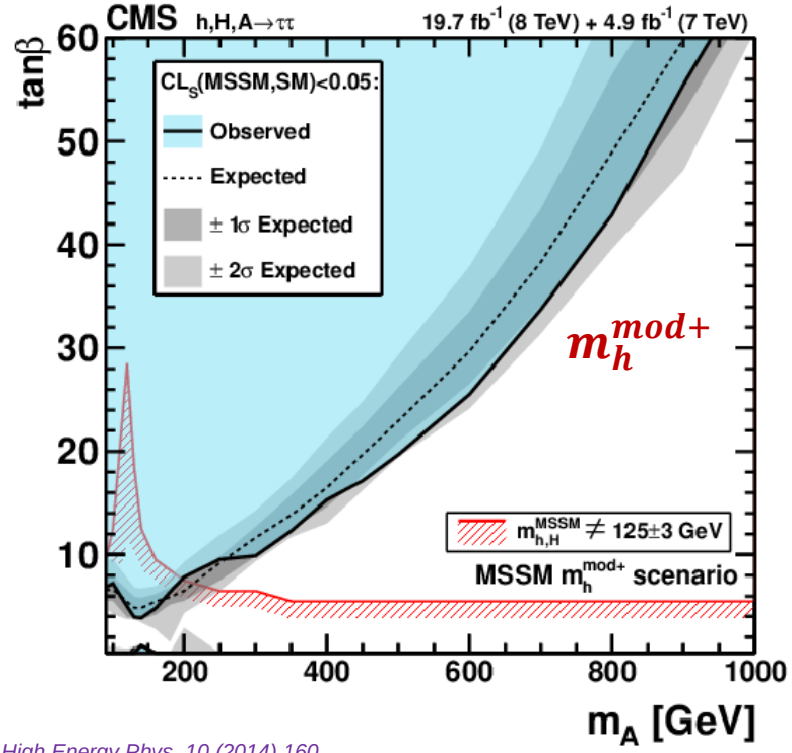
2HDM Types

	Type I	Type II	Flipped (Type Y)	Lepton Specific (Type X)
Up-type quark	ϕ_2	ϕ_2	ϕ_2	ϕ_2
Down-type quark	ϕ_2	ϕ_1	ϕ_1	ϕ_2
Leptons	ϕ_2	ϕ_1	ϕ_2	ϕ_1

MSSM H/A → $\tau\tau$

J. High Energy Phys. 10 (2014) 160

- **Comparison** with results **at 8 TeV**
  - The **13 TeV** analysis **extends the excluded mass range** by a factor of **2**
  - **Similar sensitivity** in the **low-mass region**: higher **trigger p_T thresholds**, **change of discriminating variable**, **softer p_T spectrum** at NLO



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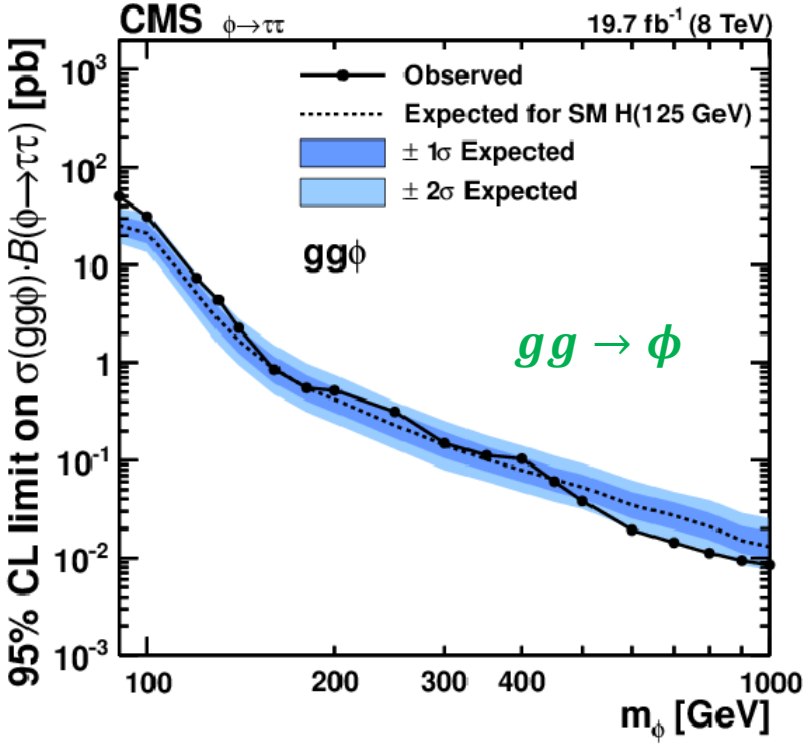

J. High Energy Phys. 10 (2014) 160

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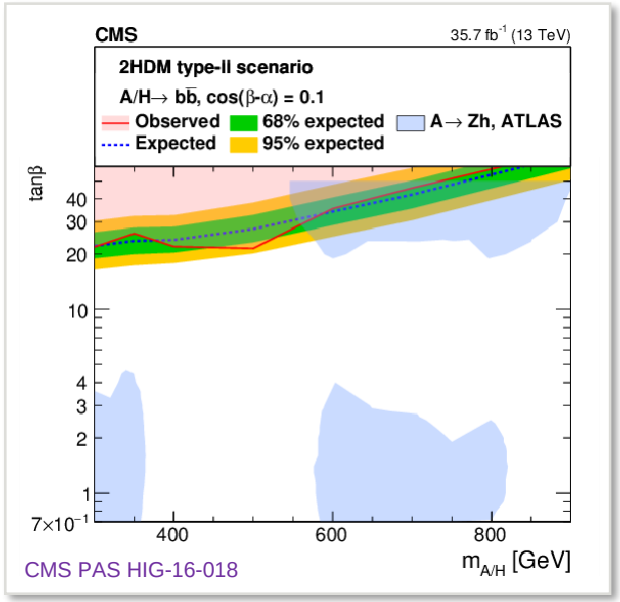

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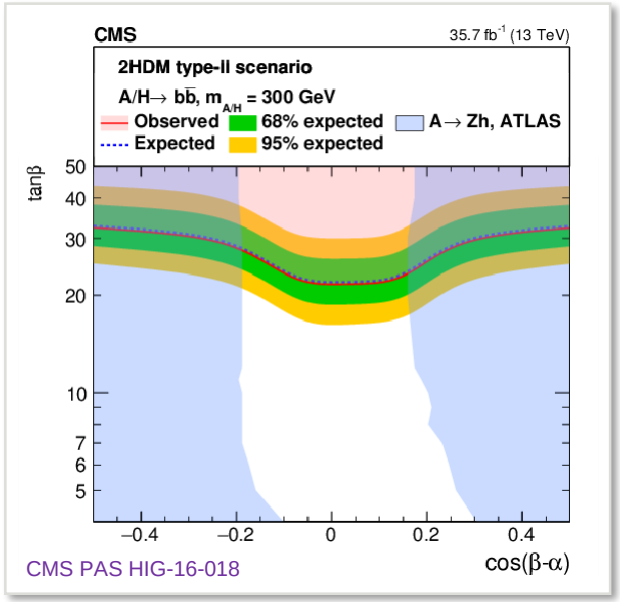

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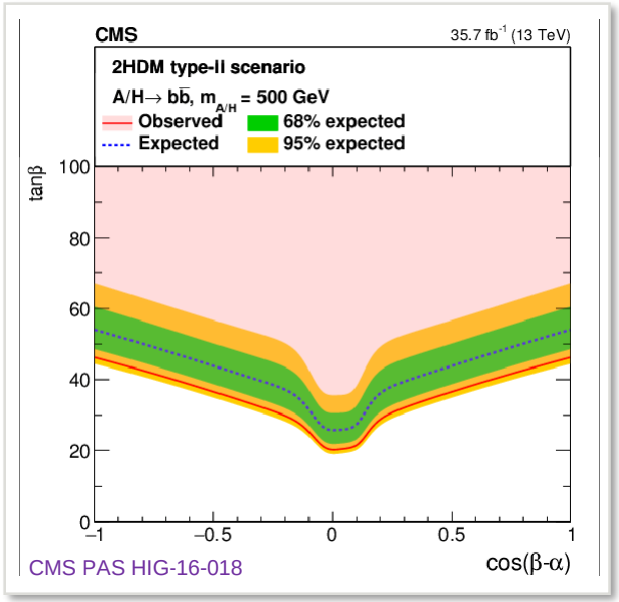

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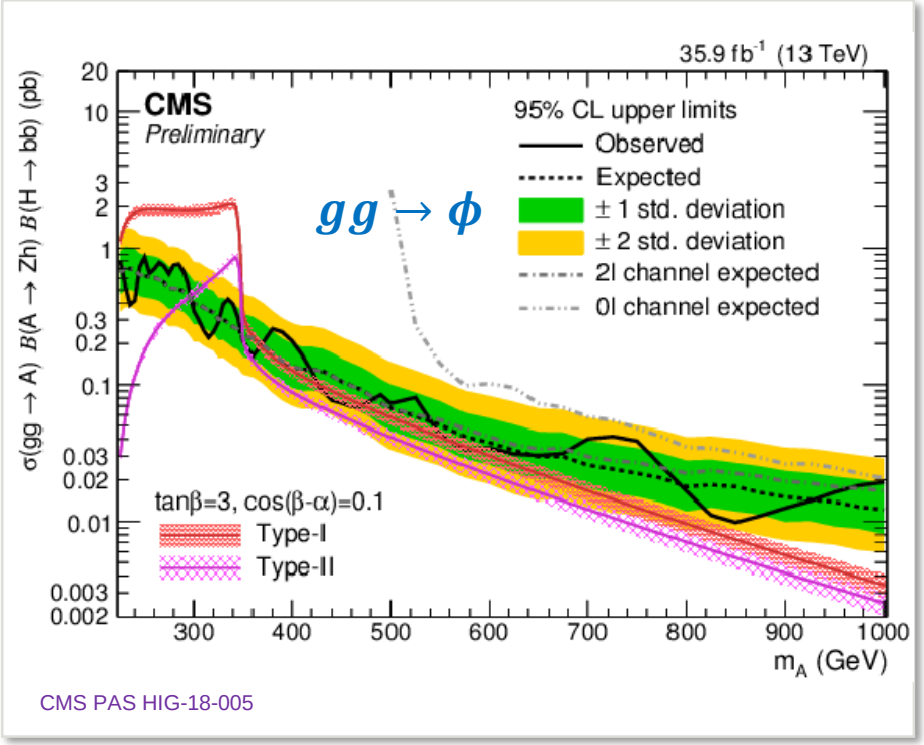
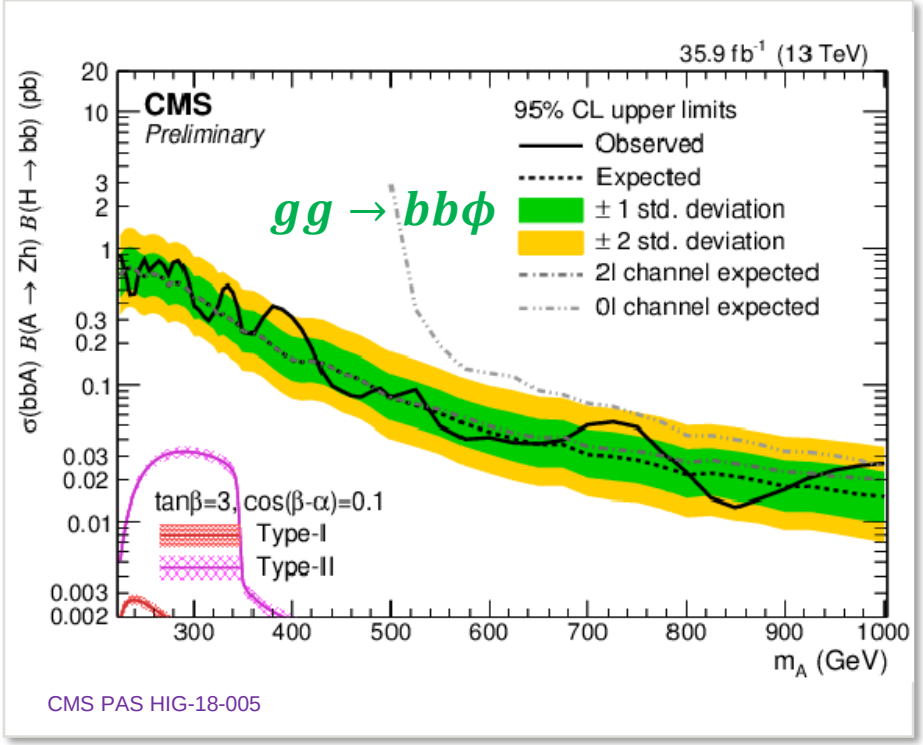
  - **No significant excess** with respect to background expectations
- Results **interpreted** for several **2HDMs** (more in backup)



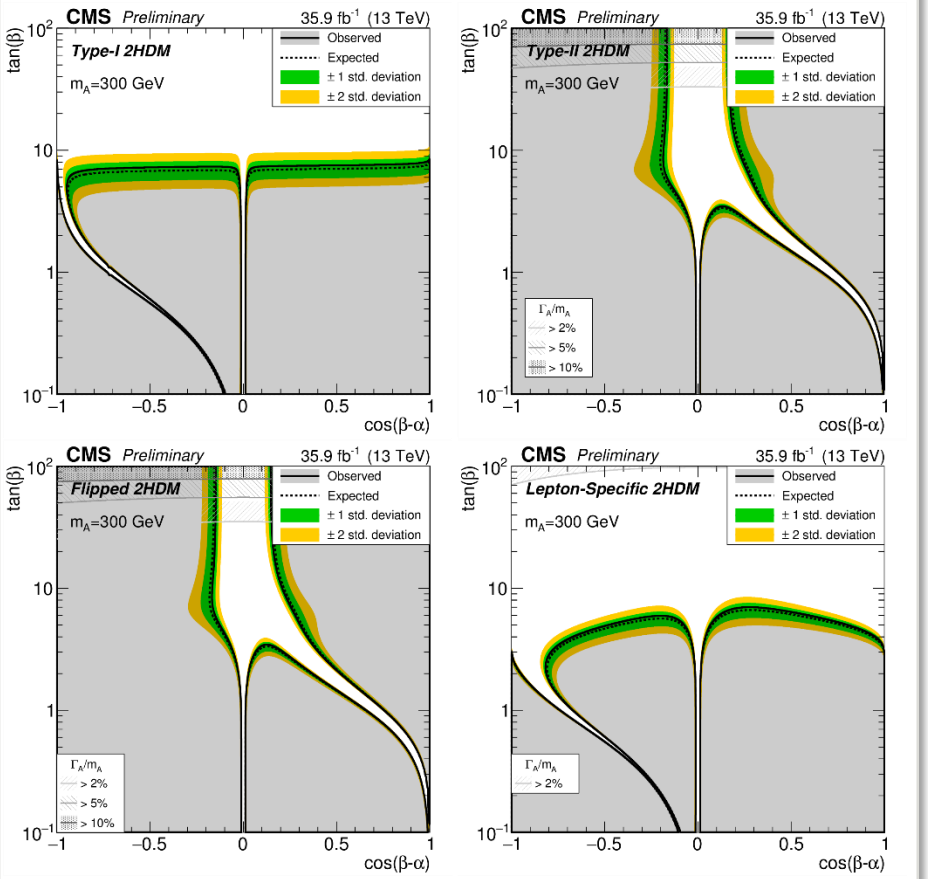
CMS PAS HIG-18-005



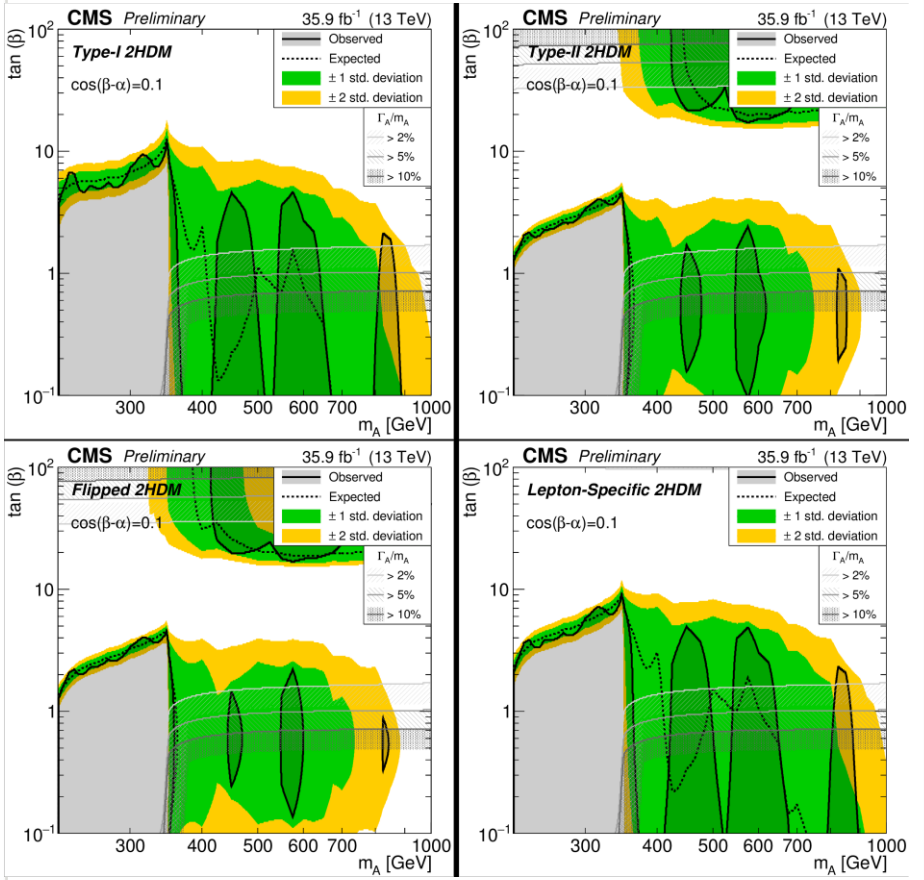
CMS PAS HIG-18-005

Heavy A → hZ

CMS-PAS-HIG-18-005



CMS PAS HIG-18-005

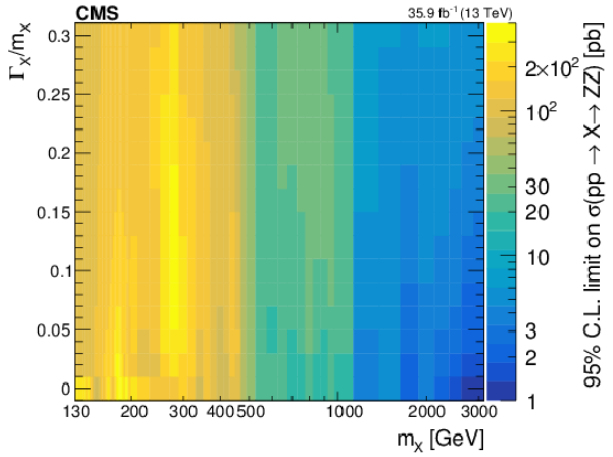


CMS PAS HIG-18-005

Results **interpreted** for several **2HDMs**, reducing the parameter space for SM extensions

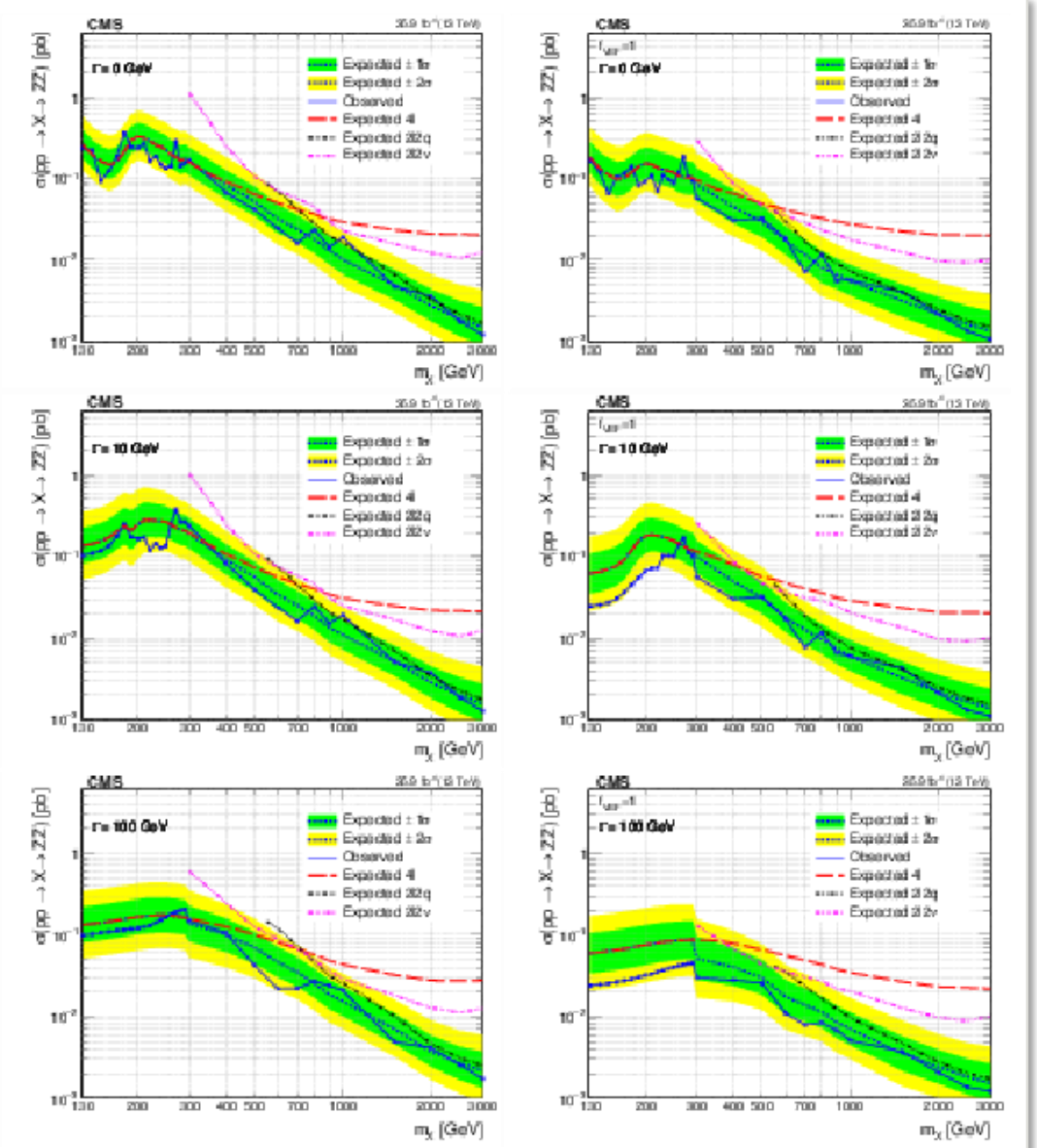
High Mass X → ZZ

CMS-PAS-HIG-17-012 (SUB. TO JHEP)



CMS PAS HIG-17-012

Cross section as a **function of** m_X and for **several** Γ_X **values** with f_{VBF} as a **free parameter** and **fixed to 1**

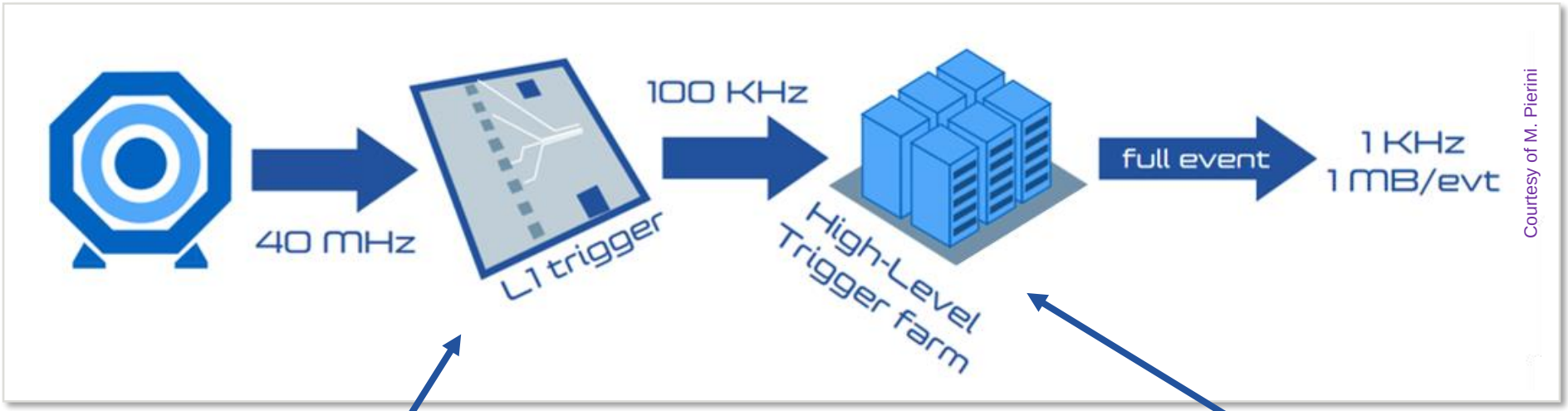


CMS PAS HIG-17-012

Challenges at Low-Mass

Low-mass searches are among the most **difficult** analyses at LHC:

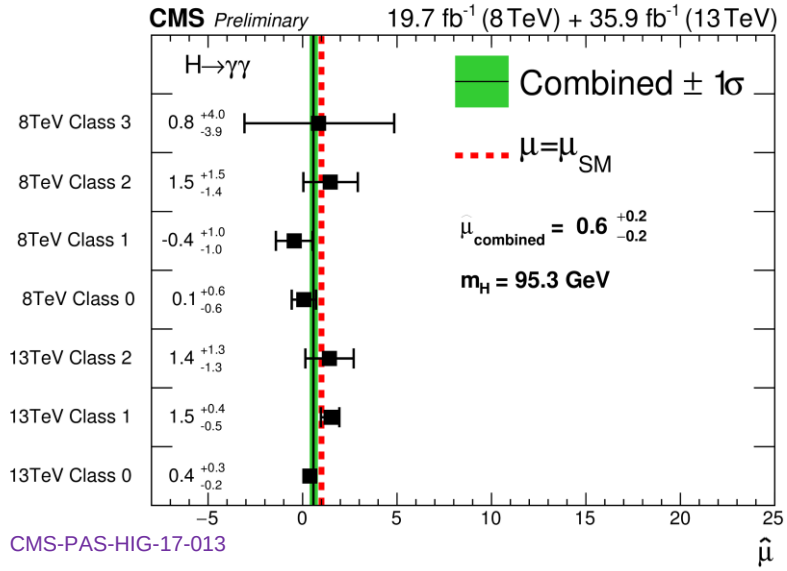
- **Theoretical guidance** sometimes **limited**
- **Special tuning** of selection tools
- **Trigger** issues: because of the **limited bandwidth**, low energy events are generally discarded (high thresholds for single and double objects)



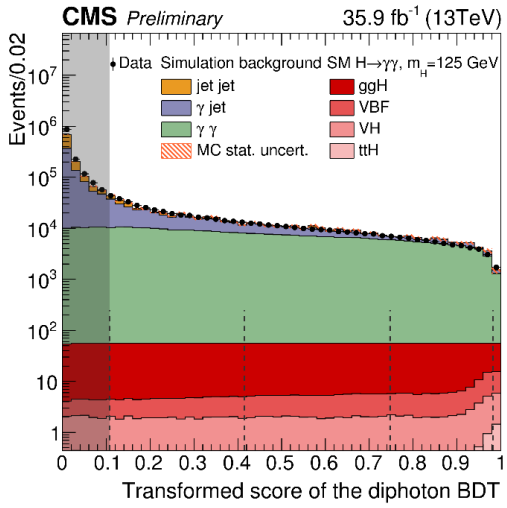
- Only calorimeters and muons
- High thresholds for one and two objects

- Can use the tracker
- Need to develop dedicated algorithms

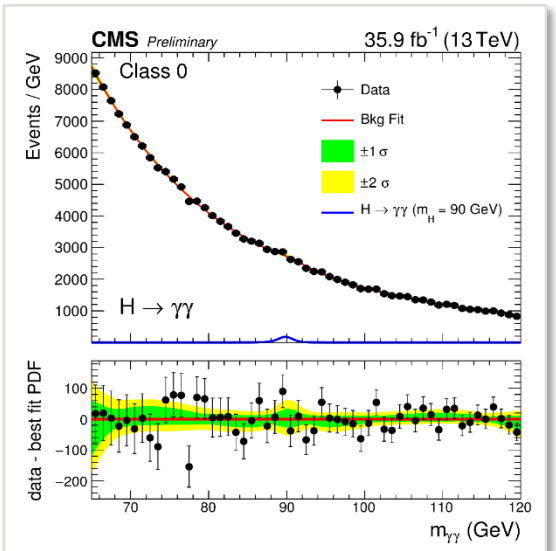
Low Mass $h \to \gamma\gamma$



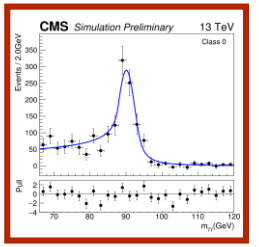
CMS-PAS-HIG-17-013

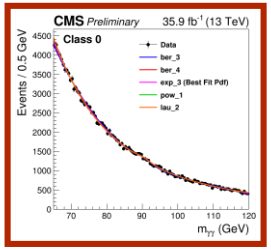


CMS-PAS-HIG-16-040



CMS PAS HIG-17-013



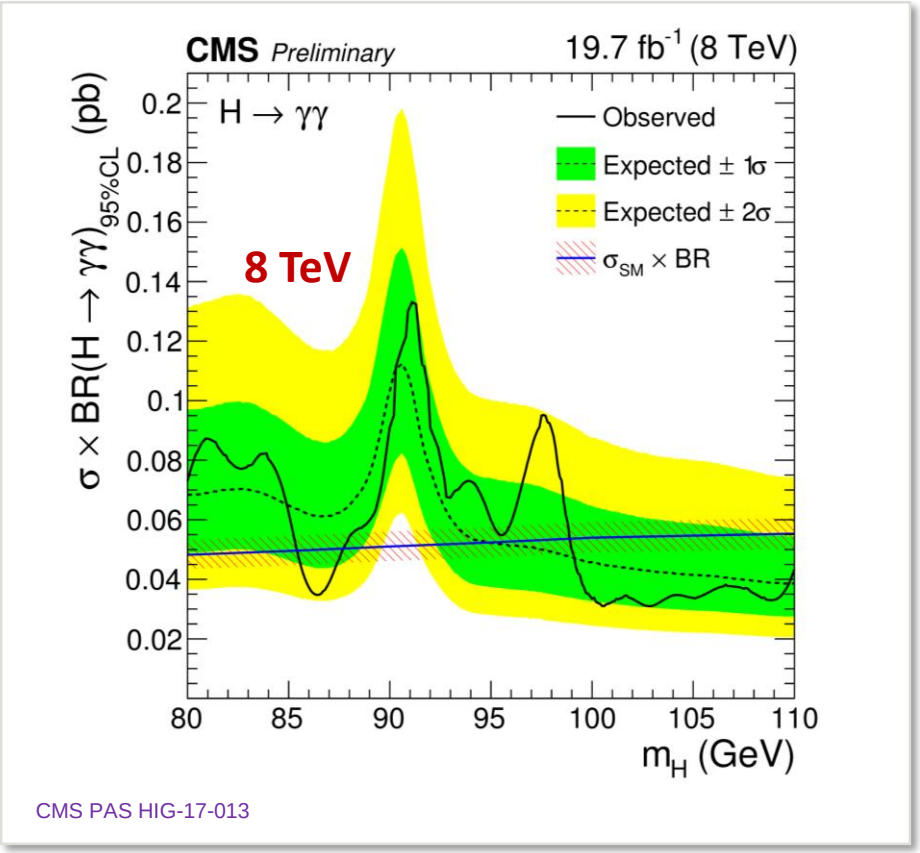


Low Mass $h \to \gamma\gamma$

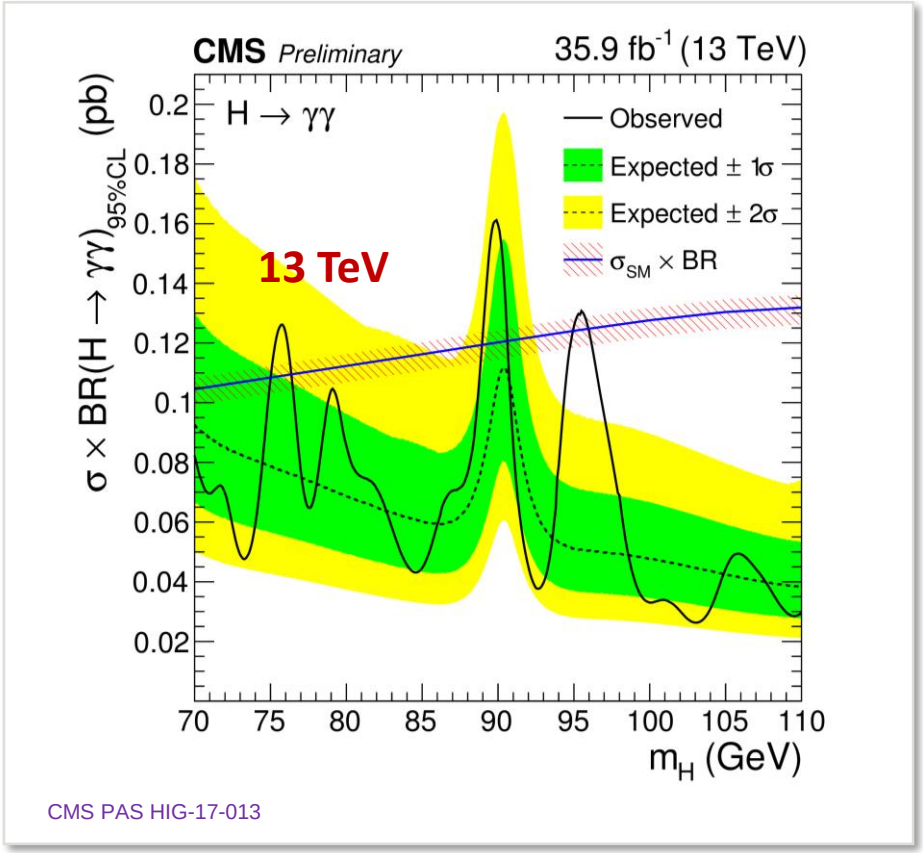
CMS-PAS-HIG-17-013

- **8 TeV limits** on σ×BR **redone** with 0.1 GeV step
- **No significant excess** with respect to background expectations

Production processes assumed in **SM proportions**

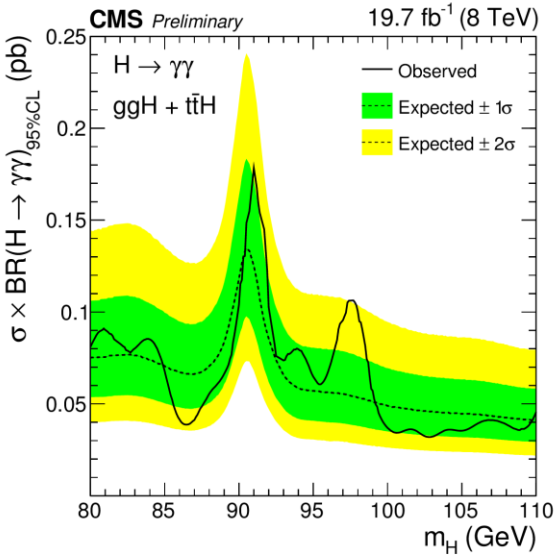


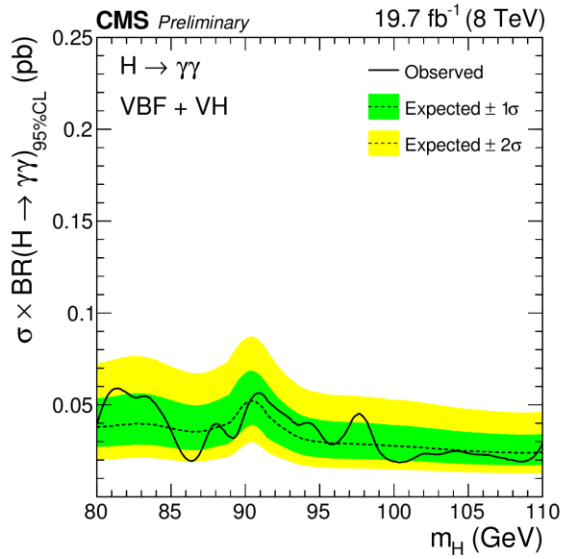
CMS PAS HIG-17-013

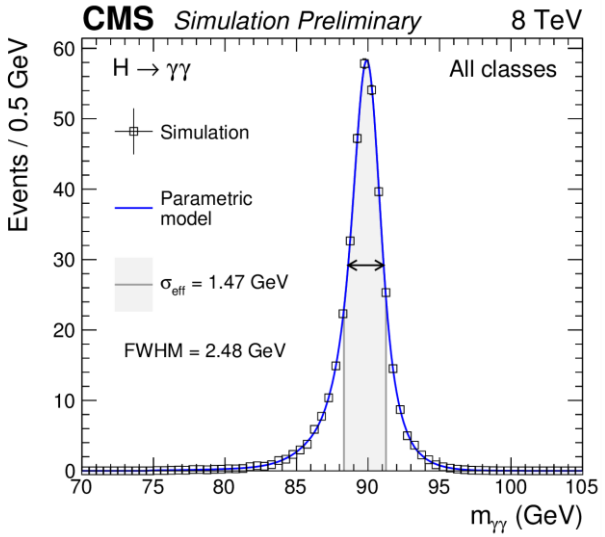


CMS PAS HIG-17-013

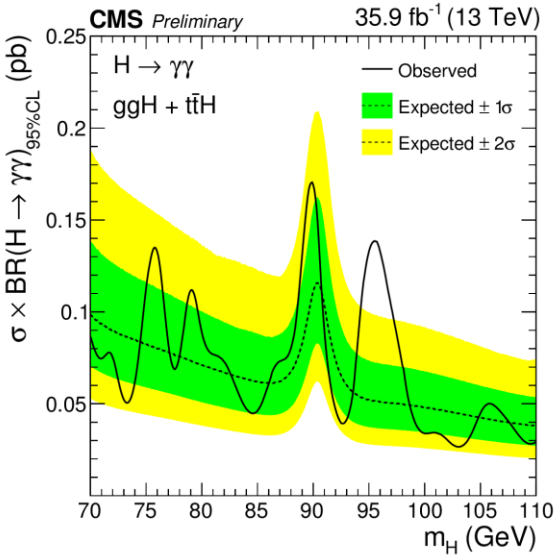
Low Mass $h \to \gamma\gamma$

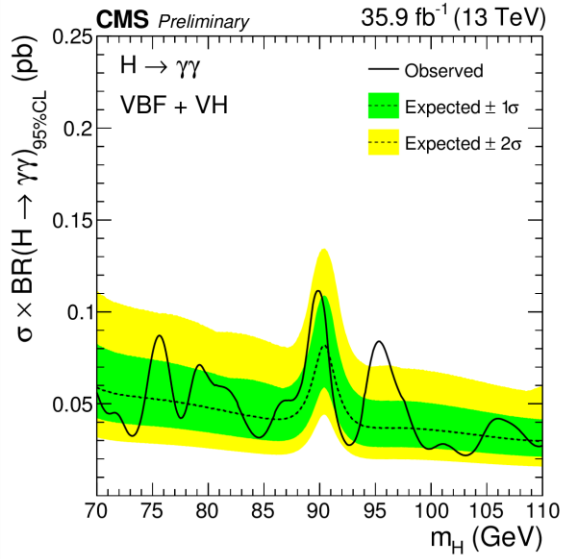


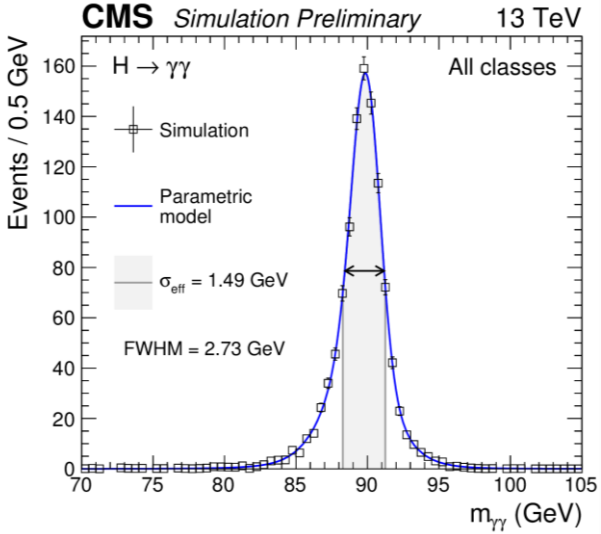




CMS-PAS-HIG-17-013

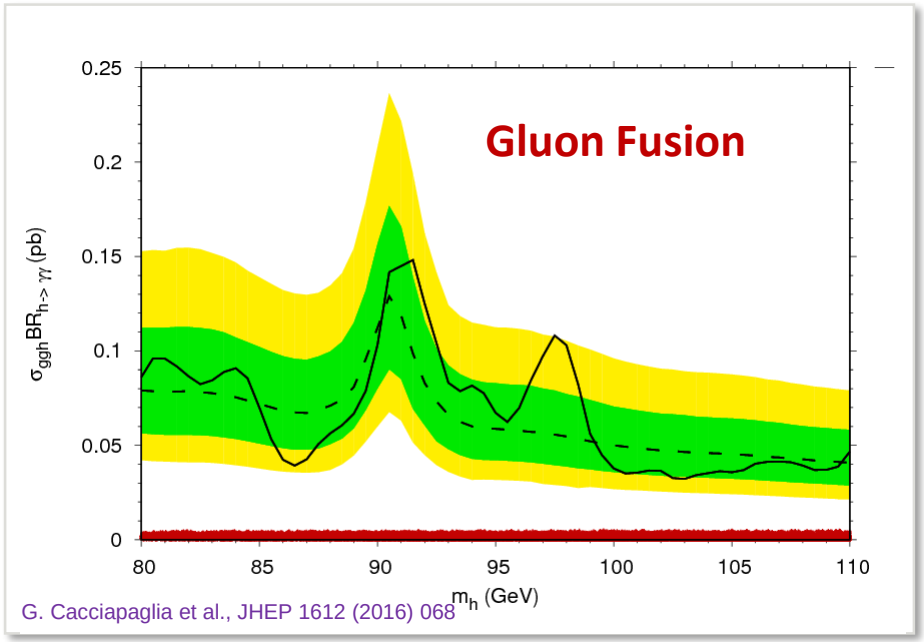




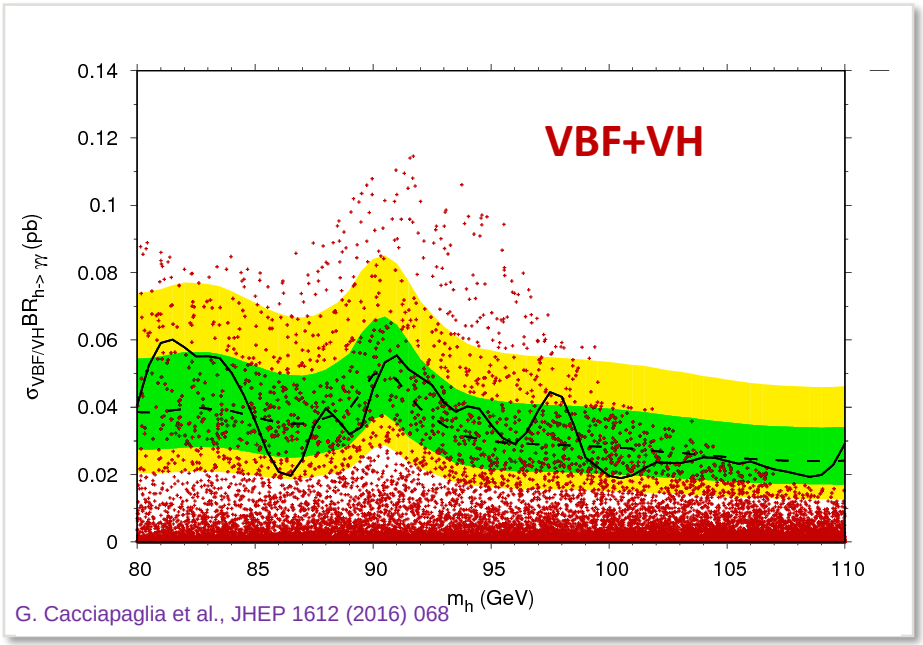


Phenomenological Interpretations

- CMS **Run I results interpreted** in the contest of **2HDM**
- Points generated in the **2HDM Type I** passing **indirect**, **LEP** and **LHC constraints**
- Some **exclusion** possible with **VBF + VH**, m_h ~< 105 GeV



G. Cacciapaglia et al., JHEP 1612 (2016) 068



G. Cacciapaglia et al., JHEP 1612 (2016) 068

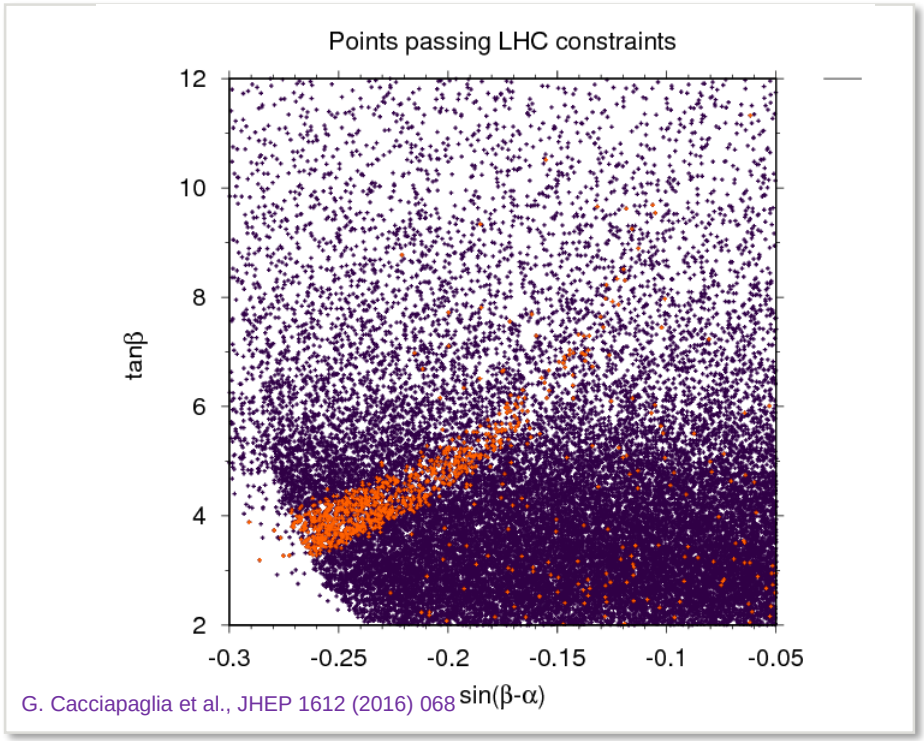
m_h (GeV)	m_H (GeV)	m_A (GeV)	$m_{H\pm}$ (GeV)	$\sin(\beta-\alpha)$	$\tan\beta$	$m12^2$
[80;110]	125	[60;650]	[80;630]	[-0.3;-0.05]	[2;12]	$[-(100)^2;+(100)^2]$

JHEP 1612 (2016) 068

Phenomenological Interpretations

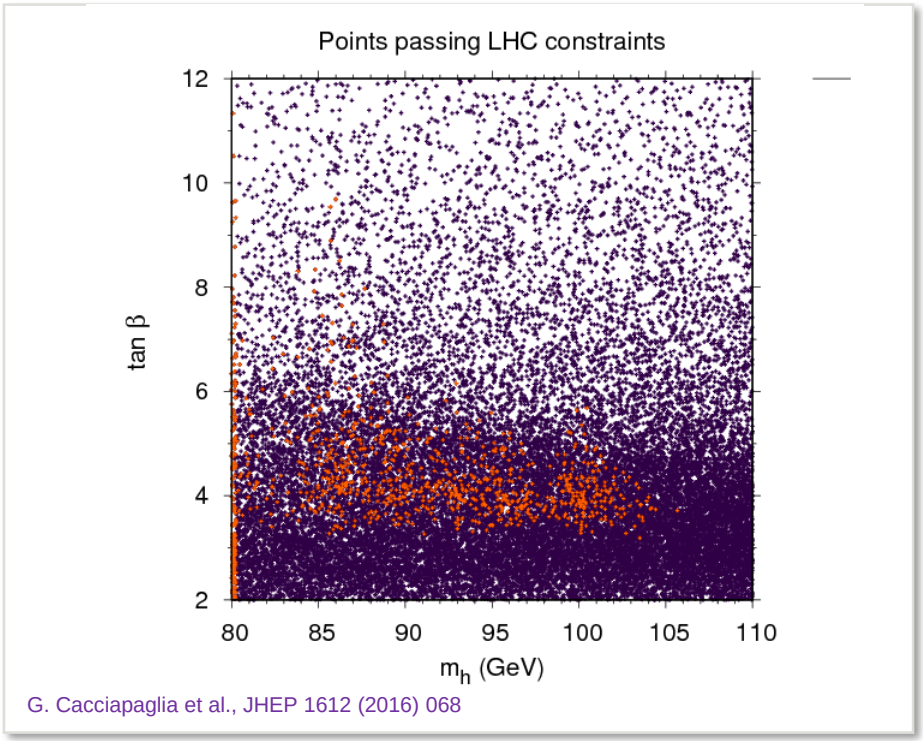
- Projections of **red** points on previous slide:
  - **orange** if $\sigma \times \mathcal{B}$ > CMS observed limit (excluded)
  - **violet** if $\sigma \times \mathcal{B}$ < CMS observed limit (still permitted)

$\tan\beta$ *vs* $\sin(\beta - \alpha)$



G. Cacciapaglia et al., JHEP 1612 (2016) 068

$\tan\beta$ *vs* m_h



G. Cacciapaglia et al., JHEP 1612 (2016) 068

JHEP 1612 (2016) 068

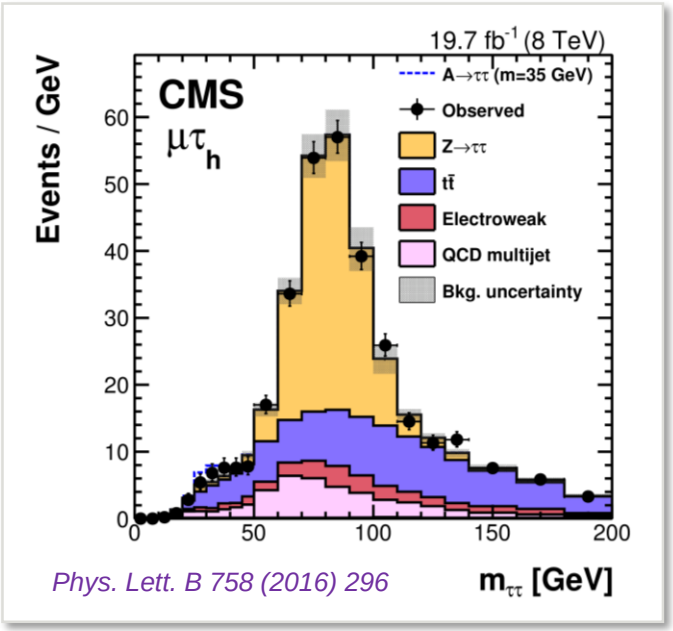
Search for Low Mass A

- The 2HDM includes a **CP-odd Higgs boson**, A, that could be lighter than h(125)
- At the LHC A could be produced in **association with bottom quarks**

  ➡ In some schemes, $\sigma(pp \to bbA) \times \mathcal{B}(A \to \ell\ell)$ could be very large for m_A < 60 GeV

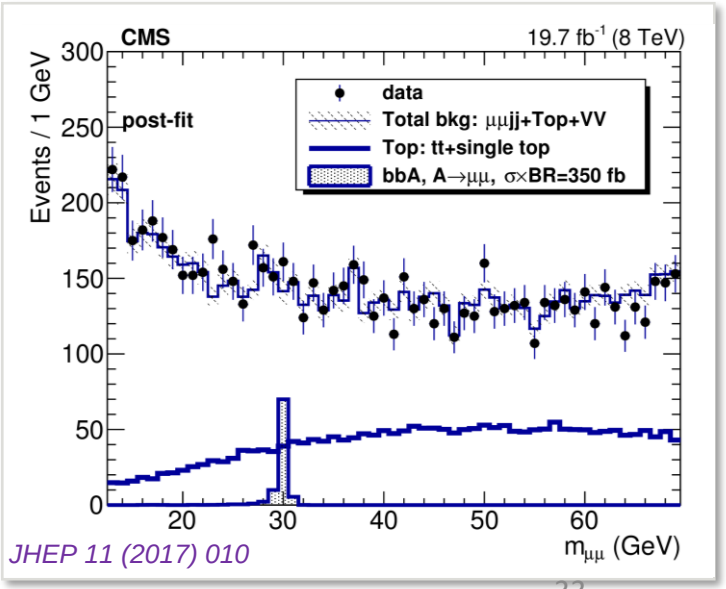
$bbA \to bb\tau\tau$ *Phys. Lett. B 758 (2016) 296*

- $e\tau_h$, $\mu\tau_h$ and $e\mu$ final states
- Trigger seeded by single muon or electron
- At least **1 b-tagged jet** with p_T > 20 GeV
- Simultaneous fit to the $m_{\tau\tau}$ distributions of the 3 final states



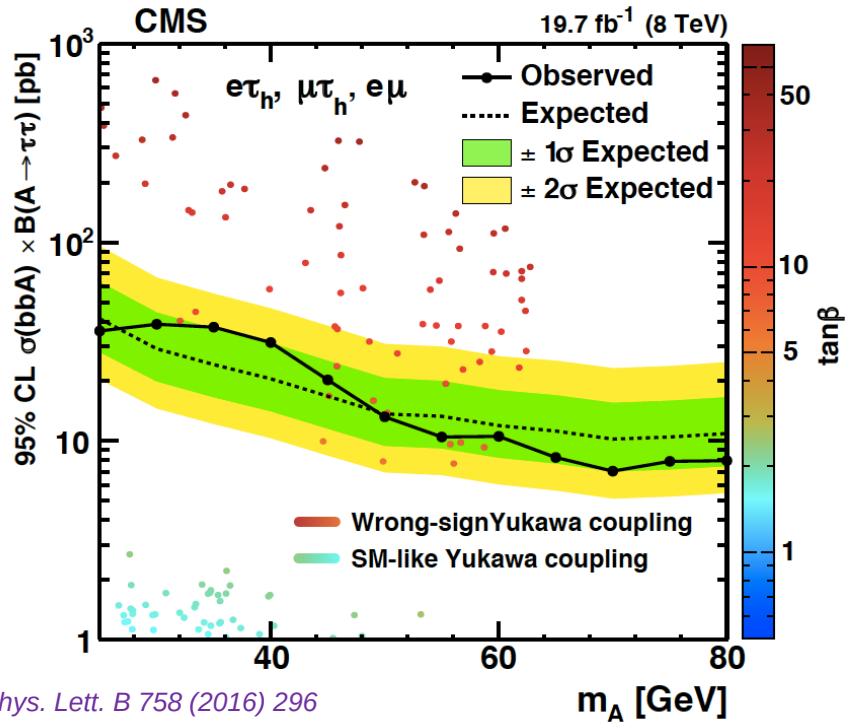
$bbA \to bb\mu\mu$ *JHEP 11 (2017) 010*

- Trigger seeded by single muon
- At least **1 b-tagged jet** with p_T > 20 GeV
- Fit to the $m_{\mu\mu}$ distribution with signal and background template from simulation



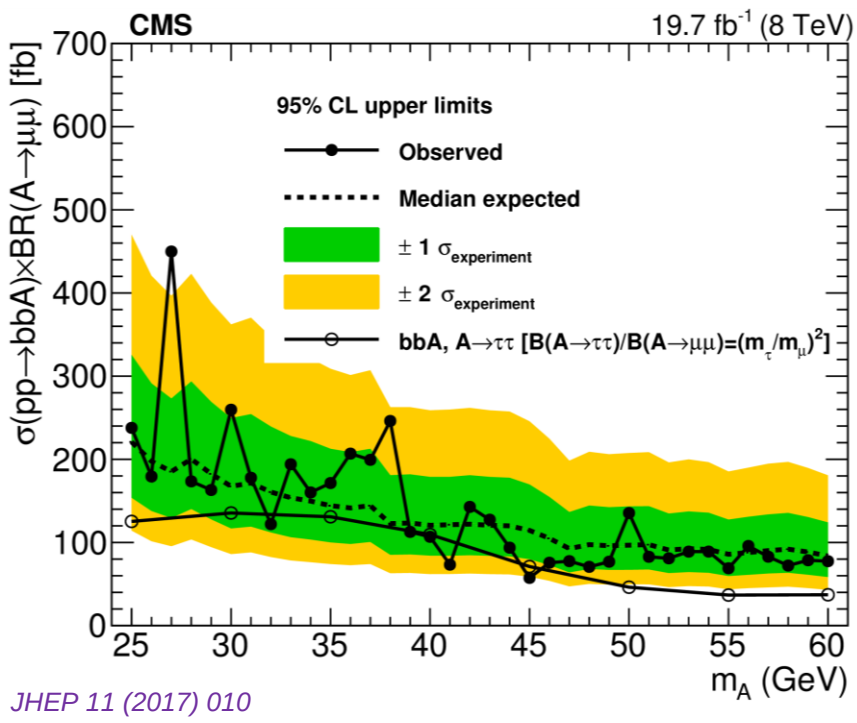
Search for Low Mass A

$bbA \rightarrow bb\tau\tau$



Phys. Lett. B 758 (2016) 296

$bbA \rightarrow bb\mu\mu$



JHEP 11 (2017) 010

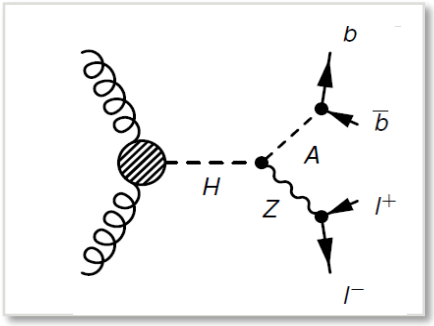
A 2HDM, type II, with SM-like Higgs boson negative couplings to down-type fermions is excluded

limits comparable to $A \rightarrow \tau\tau$ can be translated to $A \rightarrow \mu\mu$

$$\frac{\mathcal{B}(A \rightarrow \tau\tau)}{\mathcal{B}(A \rightarrow \mu\mu)} = \left(\frac{m_\tau}{m_\mu}\right)^2$$

Search for H and A in pp → H → ZA

- In 2HDMs **several mass hierarchies** of the 5 Higgs bosons are possible
- Inverted mass hierarchy with a **heavy H** and a **light pseudoscalar A** is well motivated
- If **$\tan\beta$** ranges between **0.5 and 1.5**, the decay mode **$H \to ZA$** is **dominant** and the decay mode **$A \to bb$** is **large**



$H \to ZA \to \ell\ell bb$

- Use of **dilepton trigger**
- Three **choices of m_H** and for each of them, between three and five **hypotheses of m_A**
- Search for excess in **$(m_{bb}, m_{\ell\ell bb})$ plane**

CMS-PAS-HIG-16-010