DIS2018

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Search for rare and exotic Higgs boson decays with CMS

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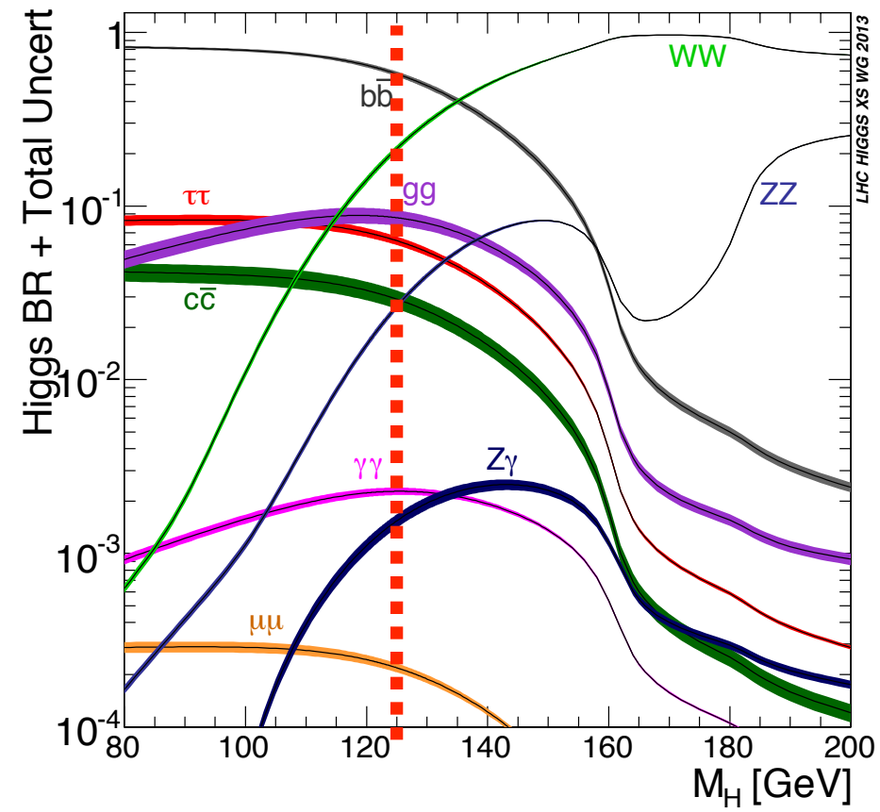
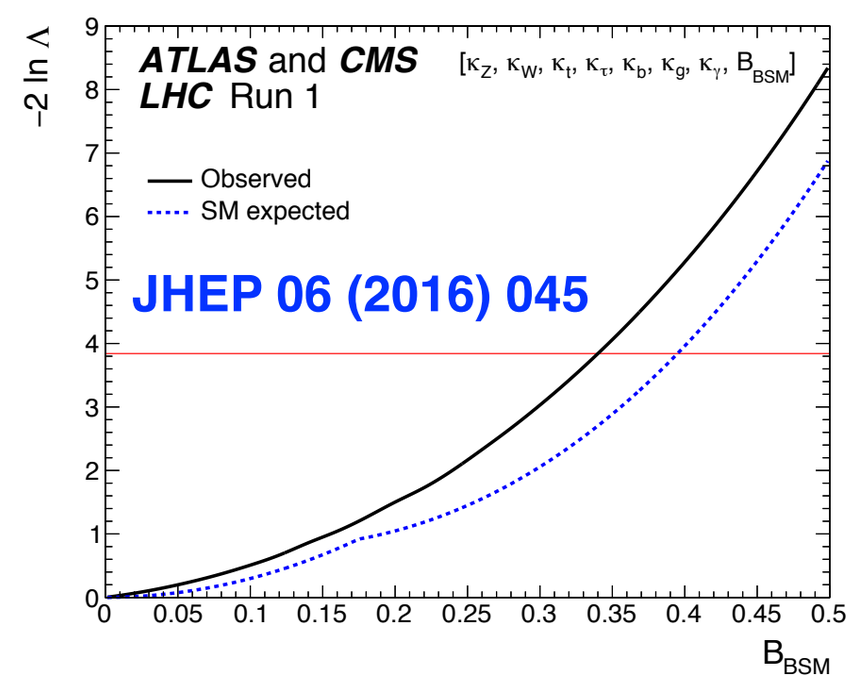
Motivation

- Higgs boson has been observed in several decay channels
  - current studies of its properties are consistent with the SM predictions
- Several rare decays have not been observed
  - an excess would be a clear indication of new physics
- Several BSM theories predict exotic decays
- potential invisible or undetectable $B_{BSM} < 34\%$ (39% exp.) @ 95% C.L. with Run-I data
  - still allow ample space to look for BSM Higgs decays
- provide an excellent opportunity to look for new physics !





Rare and exotic Higgs decays

Rare decays

Recently updated

$H \to ll + \gamma$

$H \to \mu\mu$

Recently updated

$H \to$ invisible

Exotic decays

LFV Higgs decays

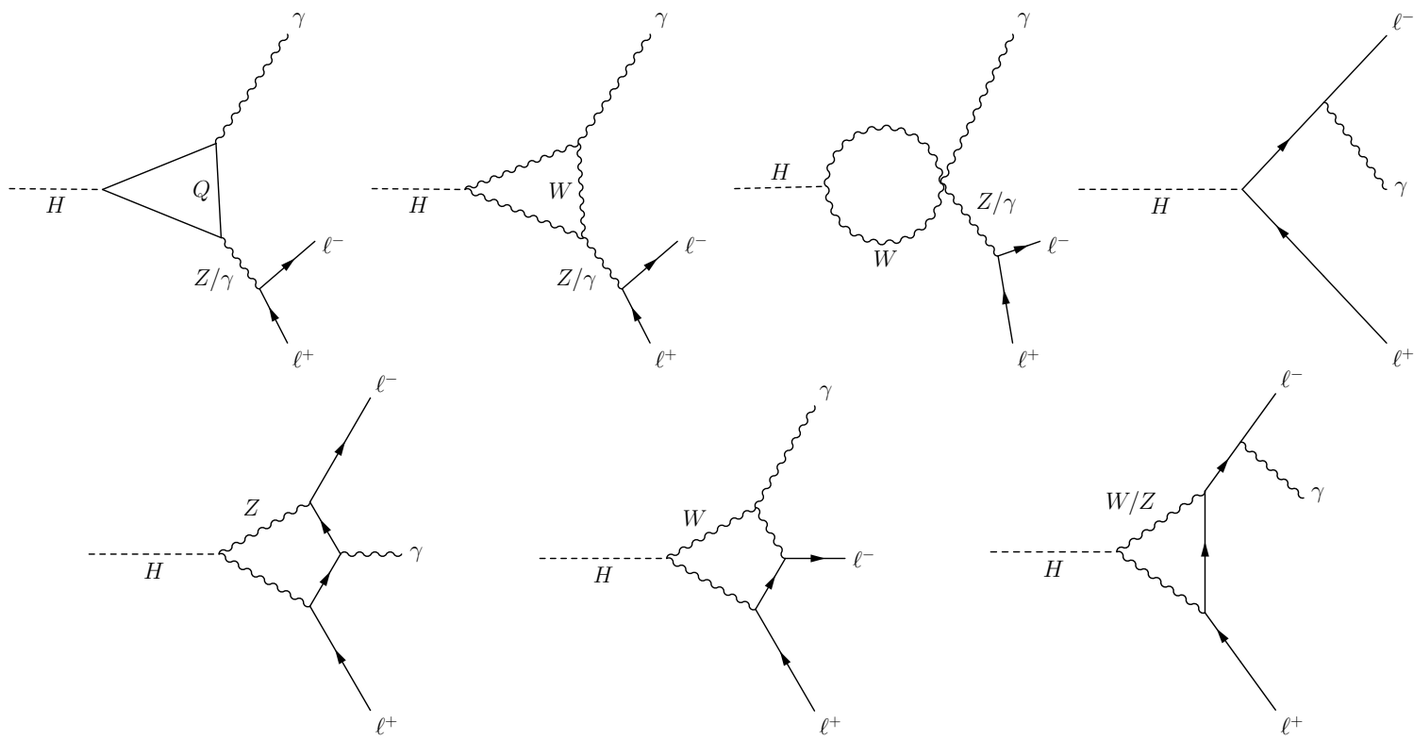
Recently updated

$H \to aa$

recently updated results are ~1 month old

$H \to Z/\gamma^* + \gamma \to ll\gamma$

CMS HIG-17-007



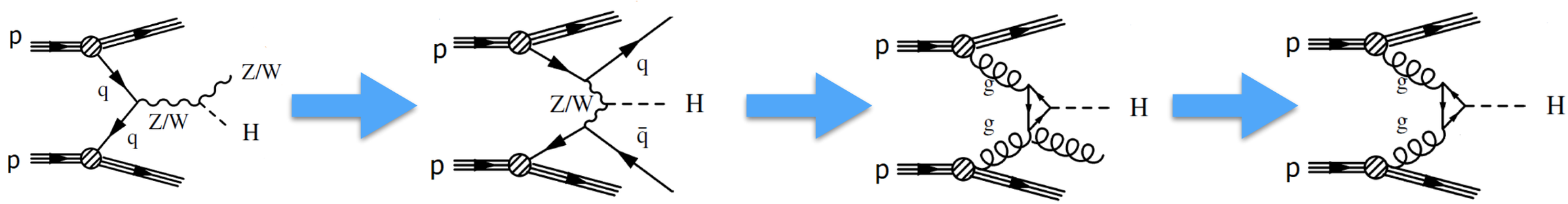
loop induced decay
→ sensitive to physics beyond SM

- Signature: an opposite-sign isolated lepton pair and an isolated photon
  - a clean final-state with good mass resolution
- the threshold, m_{ll} = 50 GeV, is used to separate $H \to Z\gamma$ and $H \to \gamma^*\gamma$
- In SM, $\frac{\Gamma(H \to \gamma^*\gamma \to \mu\mu\gamma)}{\Gamma(H \to \gamma\gamma)} = (1.69 \pm 0.10)\%$, $\frac{\Gamma(H \to Z\gamma \to \ell\ell\gamma)}{\Gamma(H \to \gamma\gamma)} = (2.27 \pm 0.14)\%$

$H \to Z\gamma \to ll\gamma$ (l = e, μ)

CMS HIG-17-007

- BR($H \to Z\gamma$) = 1.533×10^{-3}
- signal yield is similar to $H \to ZZ \to 4l$ but suffers from large background ($Z\gamma$, Z+jets)
- 7 mutually exclusive categories used to differentiate production modes, increase S/B, and enhance the peak resolution
  - sensitivity enhanced by 18%



lepton tag

electron p_T > 7 GeV
muon p_T > 5 GeV

di-jet tag

$\Delta\eta_{jj}$ > 3.5, m_{jj} >500 GeV
Zeppenfeld < 2.5
$\Delta\Phi(ll\gamma, jj)$ > 2.4

boosted tag

$p_T^{ll\gamma}$ > 60 GeV

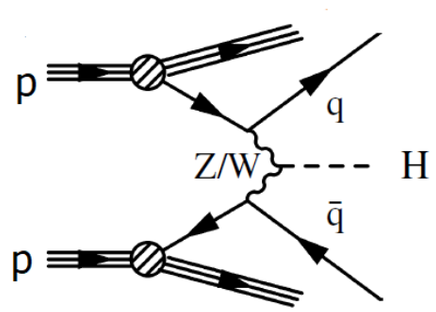
4 untagged categories

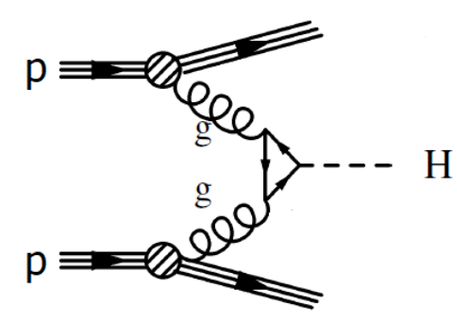
enhance $ll\gamma$ mass resolution and S/B

$H \to \gamma^* \gamma \to ll\gamma$ ($l = \mu$)

CMS HIG-17-007

- $BR(H \to \gamma^* \gamma \to \mu\mu\gamma) = 3.83 \times 10^{-5}$
- unique event topology → two collimated leptons from γ^* decay
  - challenge in trigger and identification
  - smaller signal yield but better sensitivity than $H \to Z\gamma$
- reject $J/\psi+\gamma$ and $\Upsilon+\gamma$ with $m_{\mu\mu}$
- 4 mutually exclusive categories used to differentiate production modes, increase S/B, and enhance the peak resolution
  - sensitivity enhanced by 11%





di-jet tag

$\Delta\eta_{jj} > 3.5$, $m_{jj} > 500$ GeV
Zeppenfeld < 2.5
$\Delta\Phi(ll\gamma, jj) > 2.4$

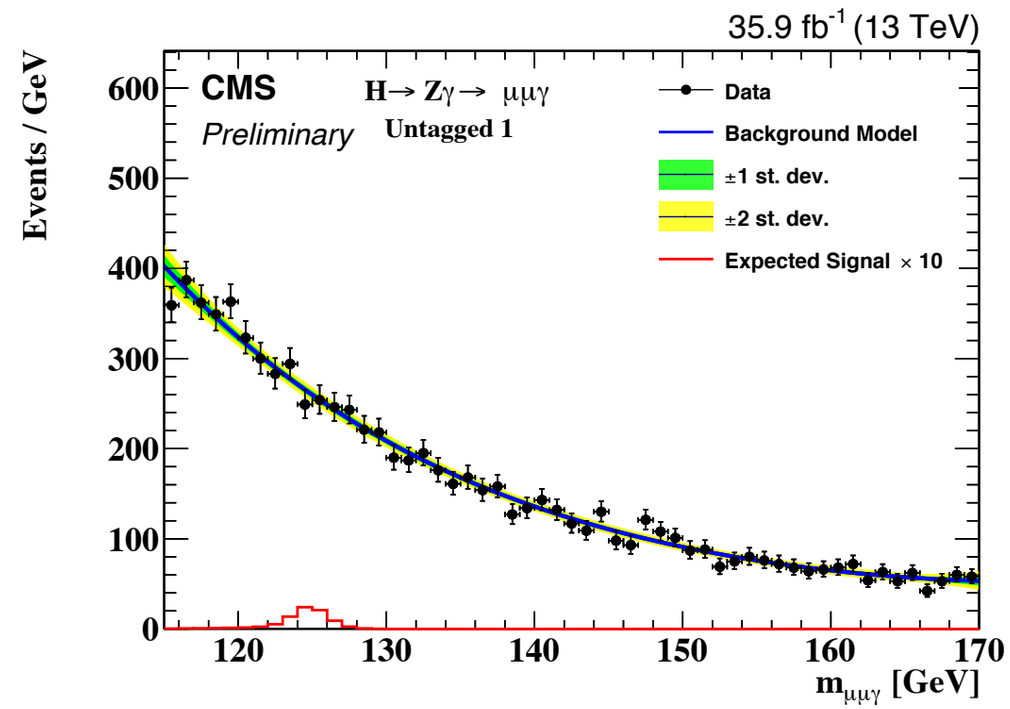
3 untagged categories

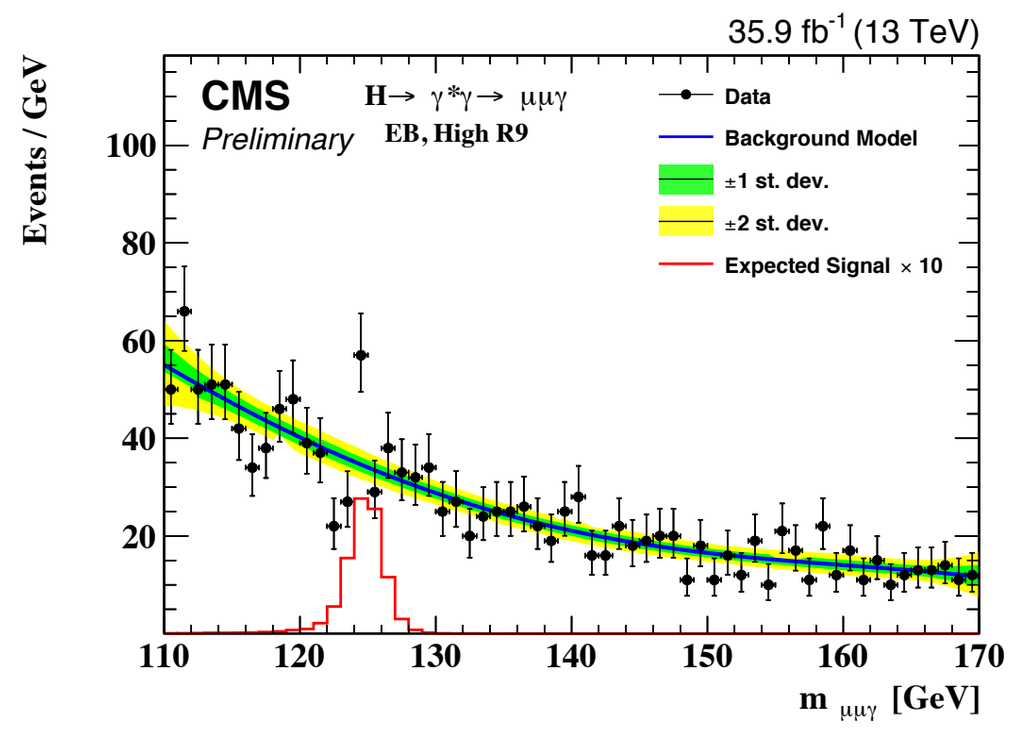
enhance $ll\gamma$ mass resolution and S/B

Signal extraction

CMS HIG-17-007

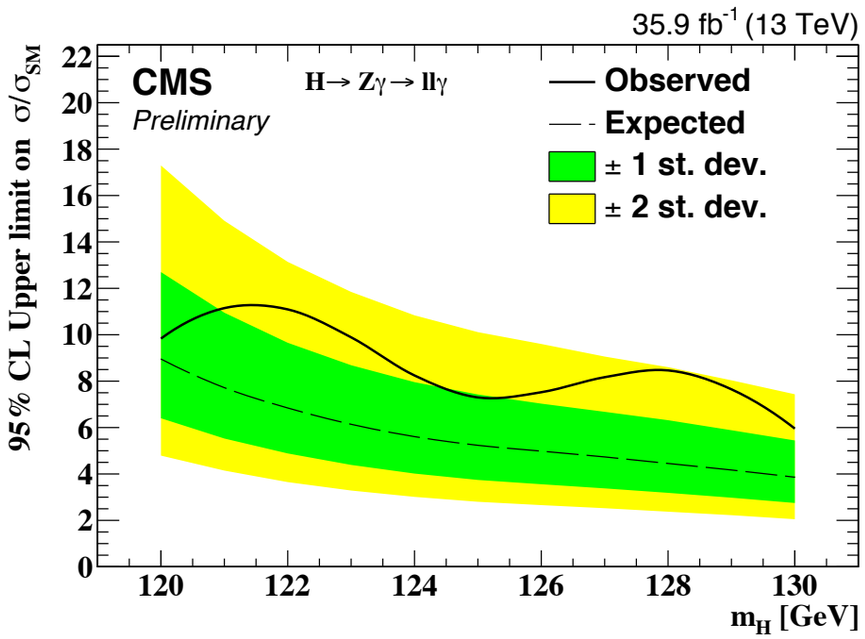
- background fit function minimizes the bias introduced by selected shape
- data are fitted by smoothly falling functions to determine the background
- signal is modeled with a double sided Crystal Ball function and a Crystal Ball function plus an additional Gaussian function for γ*γ and Zγ

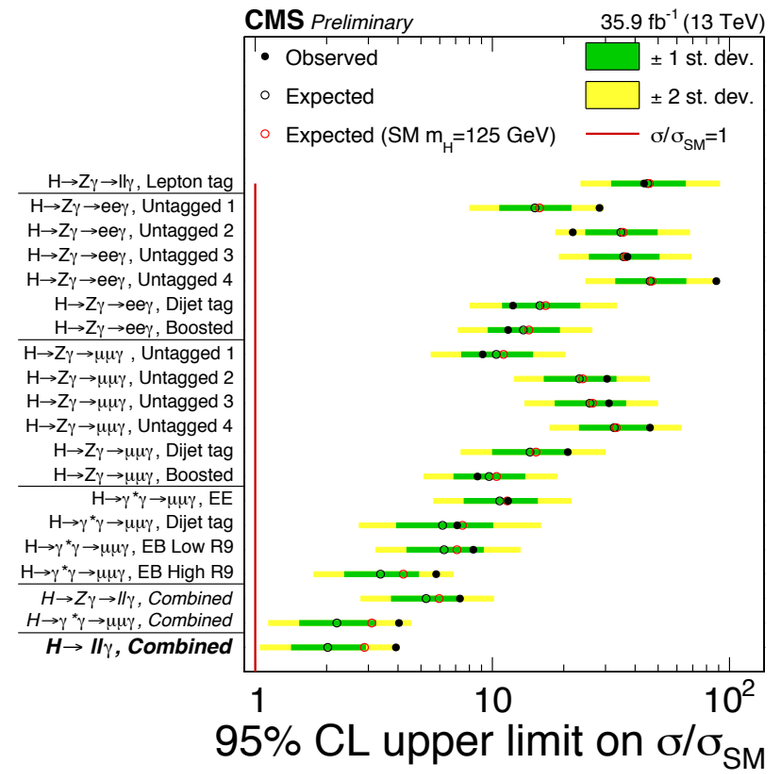


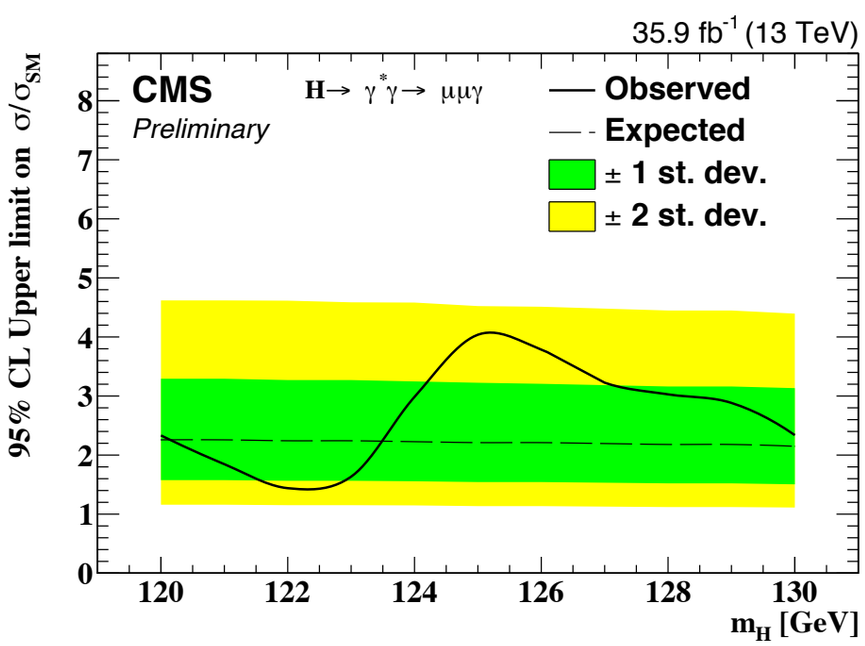


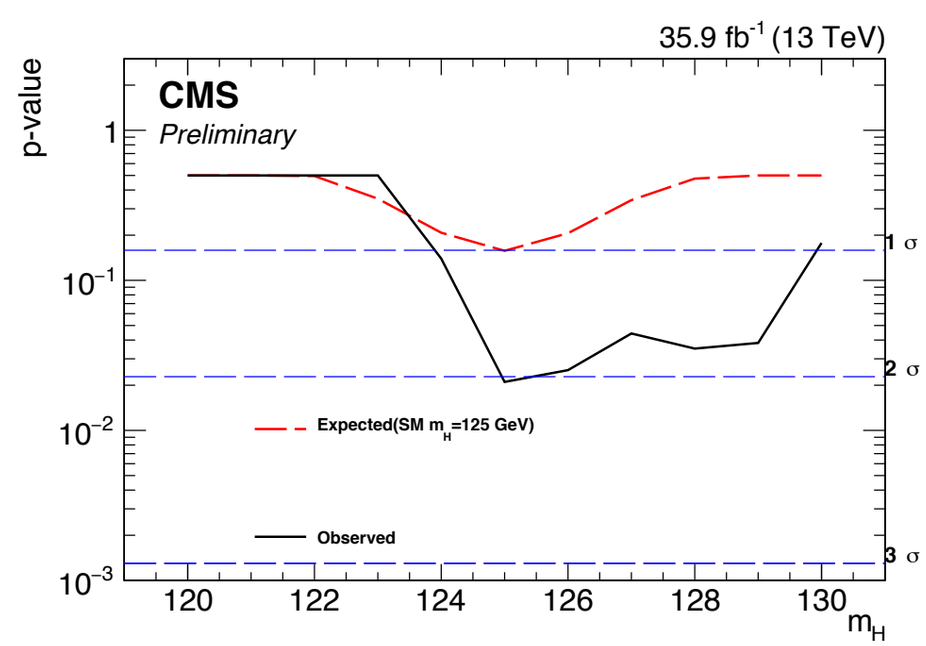
Results of $H \rightarrow ll\gamma$

CMS HIG-17-007







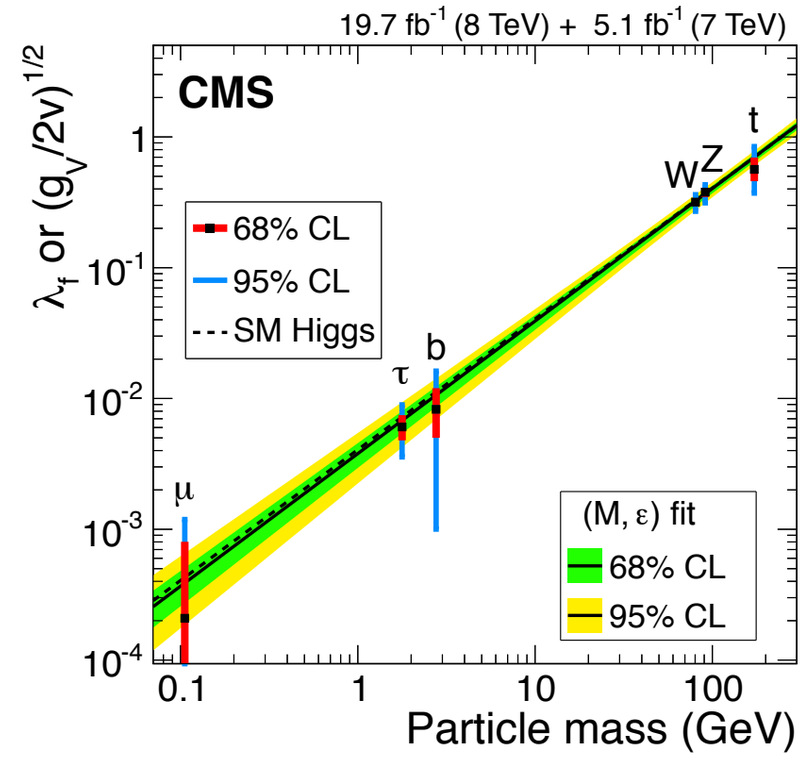


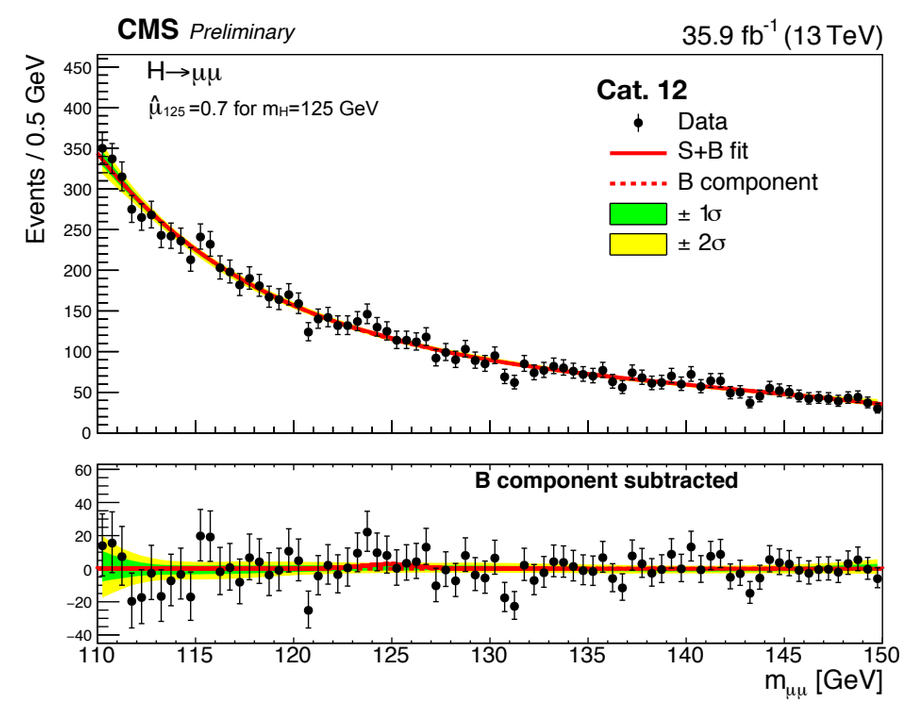
- **observed (expected) upper limit for σ/σ_{SM} is 3.9 (2.0)**
- **corresponding to an observed (expected) p-value of ~2σ (~1σ)**

$H \to \mu\mu$

CMS HIG-17-019

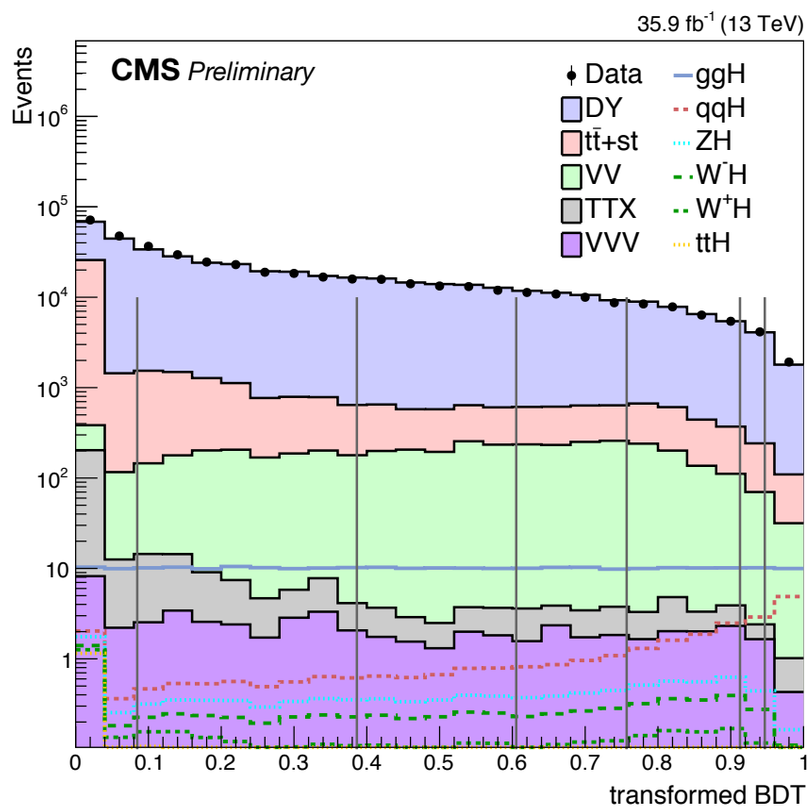
- BR($H \to \mu\mu$) = 2.18×10^{-4}
- only accessible channel to test Higgs couplings to second generation fermions at LHC
- clean fermionic decay
- search for a small peak over a large DY background
- several BSM scenarios predict a higher BR
  - deviation from SM could be a sign for new physics

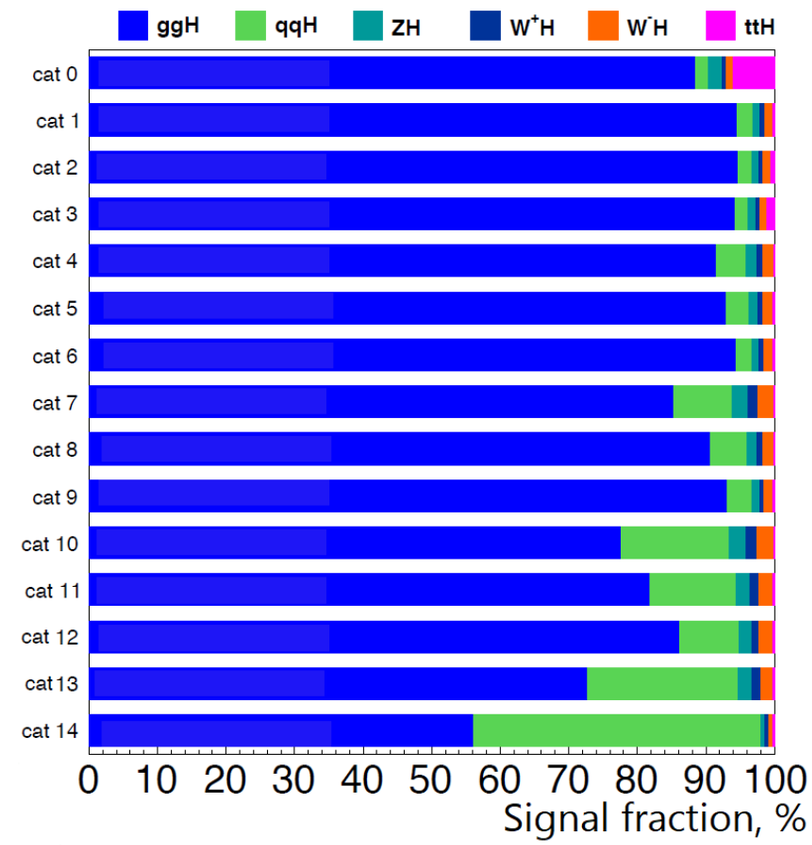




$H \rightarrow \mu\mu$ *analysis*

CMS HIG-17-019

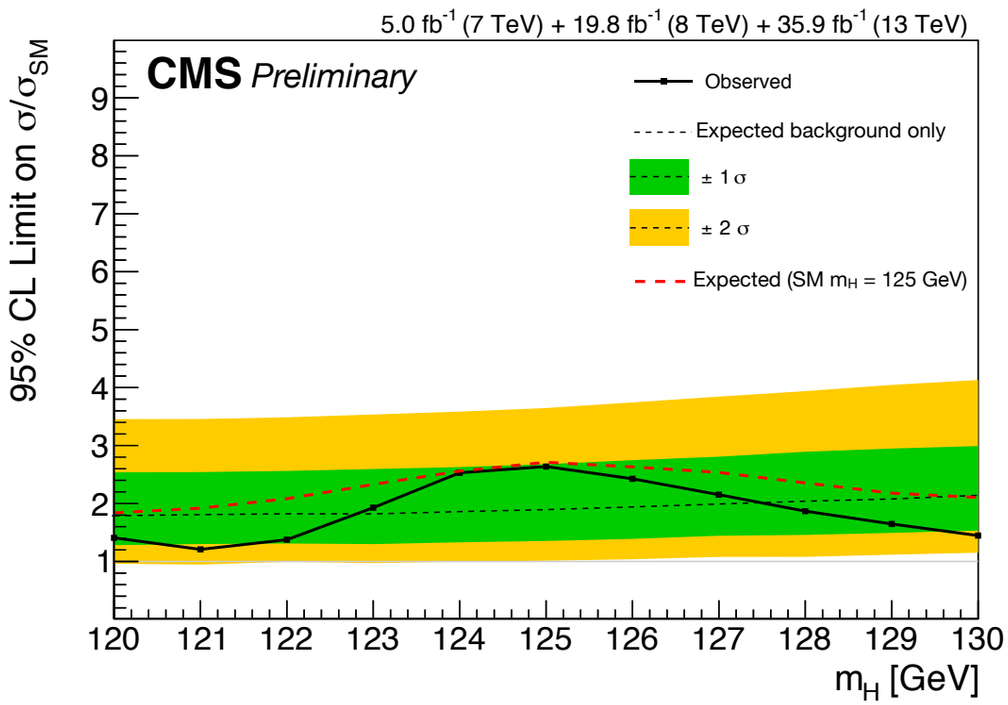


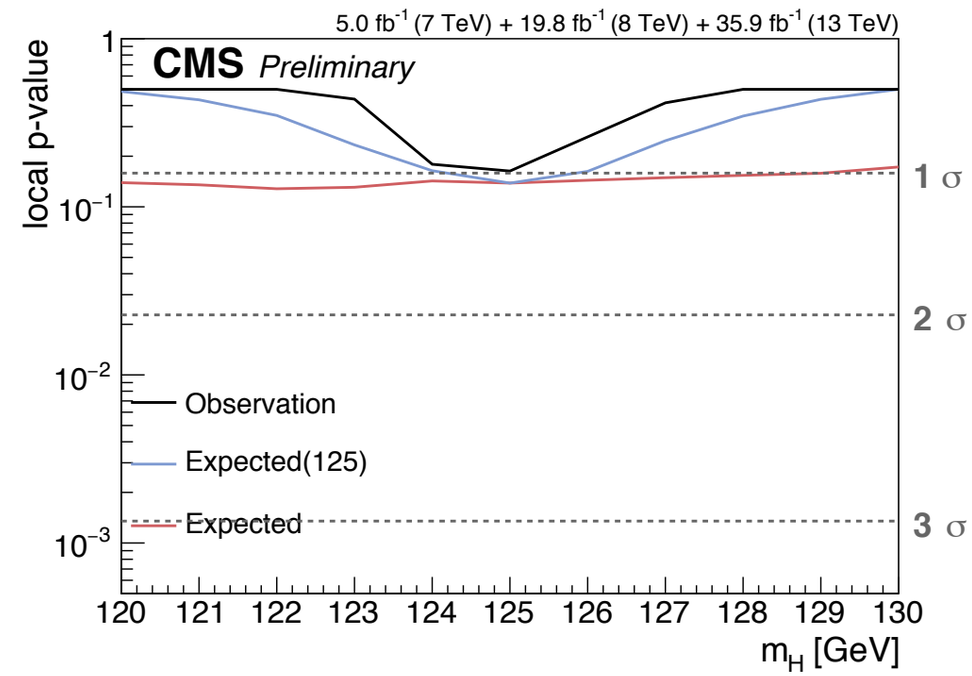


- BDT is used to improve the search sensitivity
- 15 categories are defined based on BDT score and μμ mass resolution
- BDT loosely correlated with VBF

Results of $H \rightarrow \mu\mu$

CMS HIG-17-019



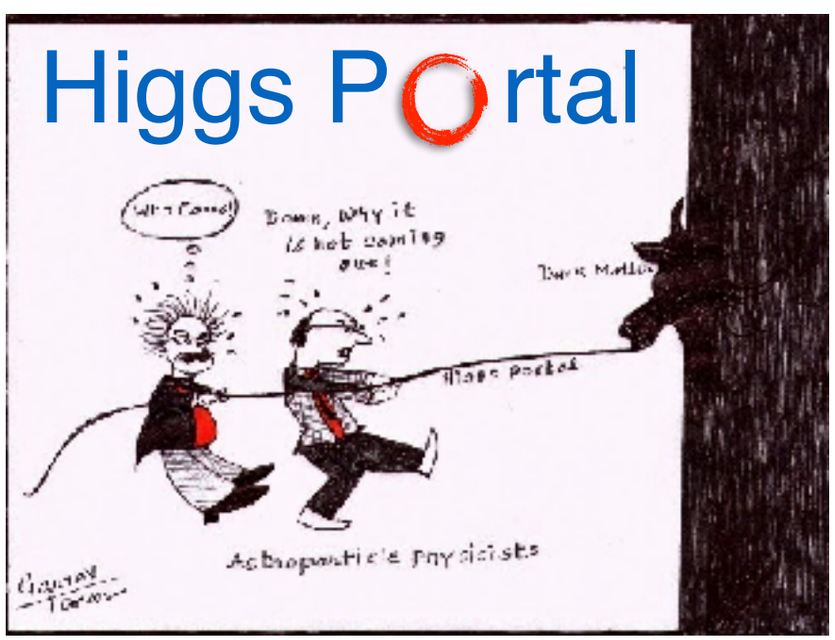


Dataset	95% CL limit on σ/σ_{SM} observed (expected)	Significance observed (expected)
13 TeV (35.9/fb)	2.64 (2.08)	0.74 (0.98)σ
7 TeV + 8 TeV+ 13 TeV	2.64 (1.89)	0.98 (1.09)σ

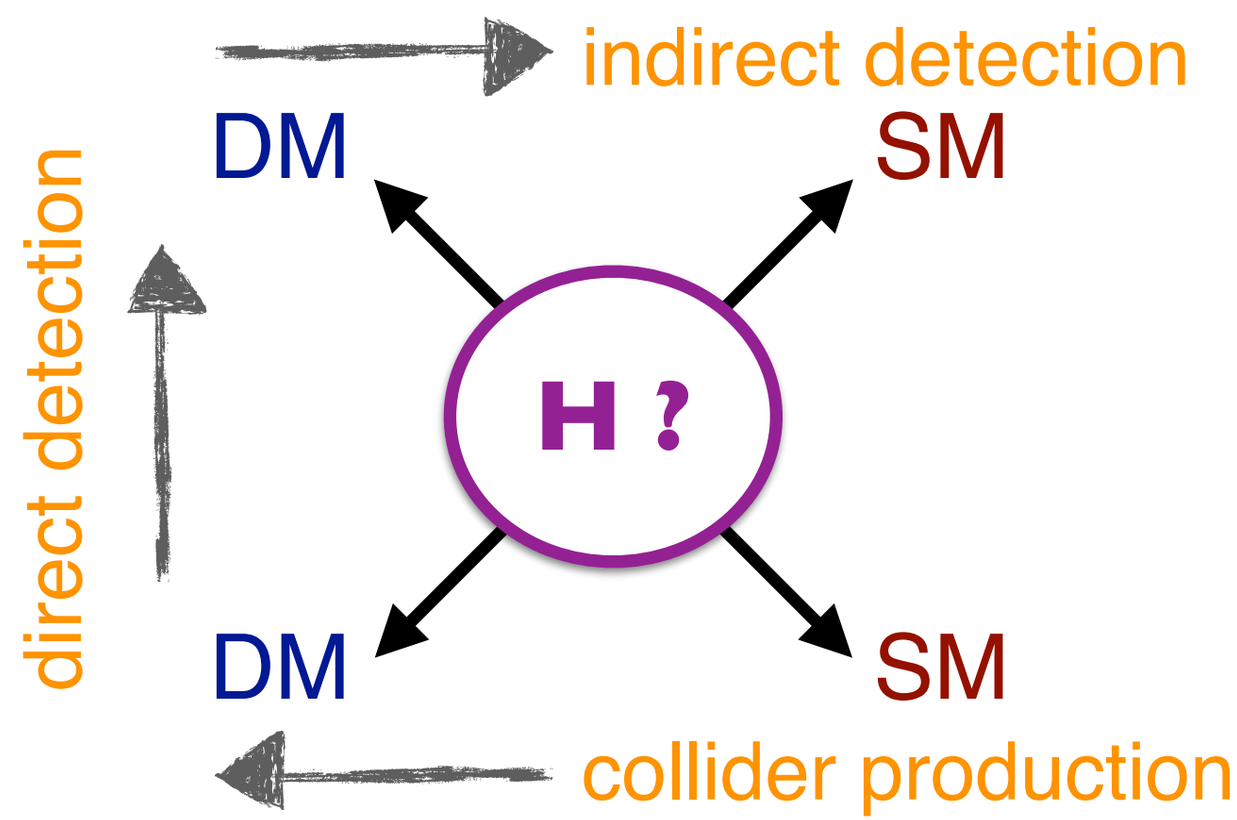
- **upper limit on BR($H \rightarrow \mu\mu$) is 5.7×10^{-4}**

$H \to invisible$

- BR($H \to ZZ \to 4\nu$) = 0.1% in SM
- a number of BSM models allow for this
  - interactions between the Higgs and dark matter
  - complementary to direct detection
    - dark matter mass < $m_H/2$; $H \to$ DM kinematically open

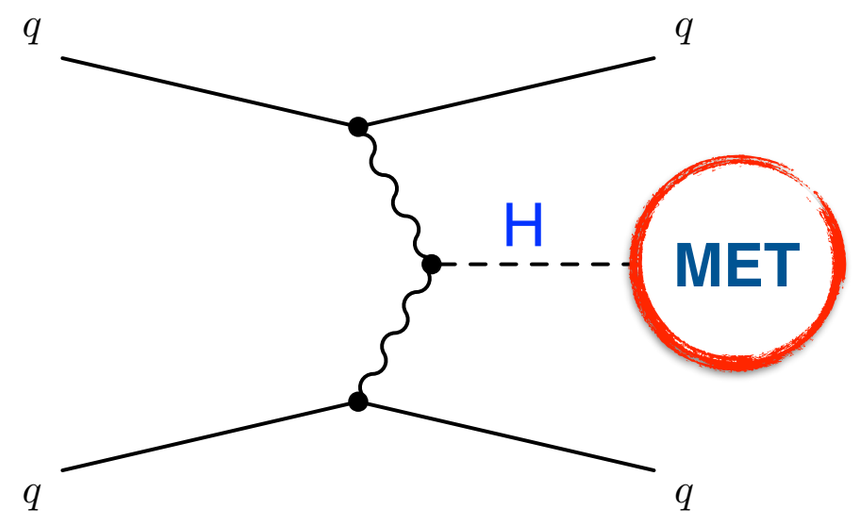


http://rejuvenatte.blogspot.tw

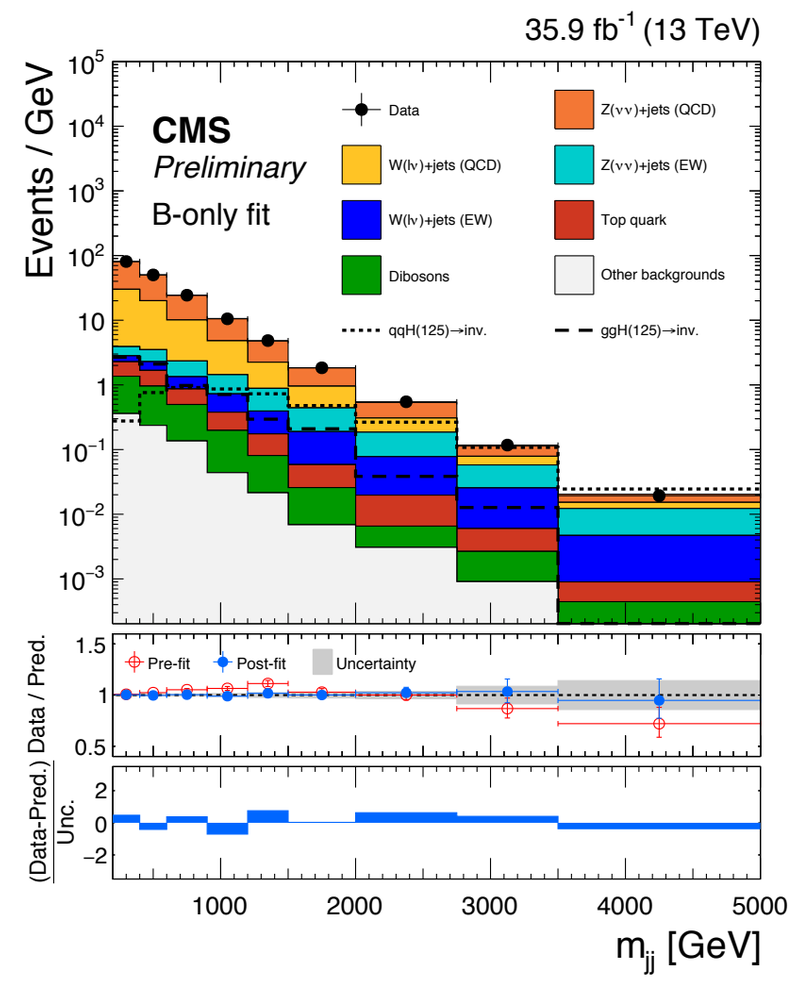


$H \rightarrow$ invisible : VBF tag

CMS HIG-17-023



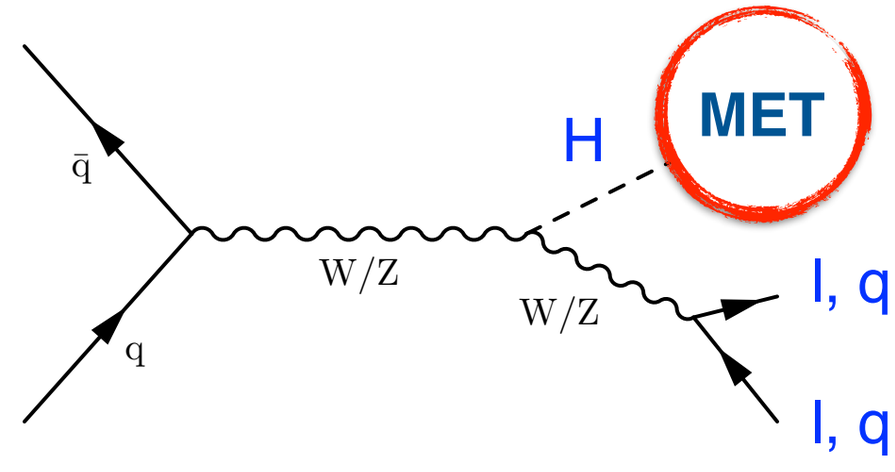
- most sensitive mode due to VBF topology
- reject extra leptons
- two strategies:
  - cut and count
  - shape analysis based on m_{jj}
    - use the full discrimination power of the invariant mass distribution
      - improve the search sensitivity

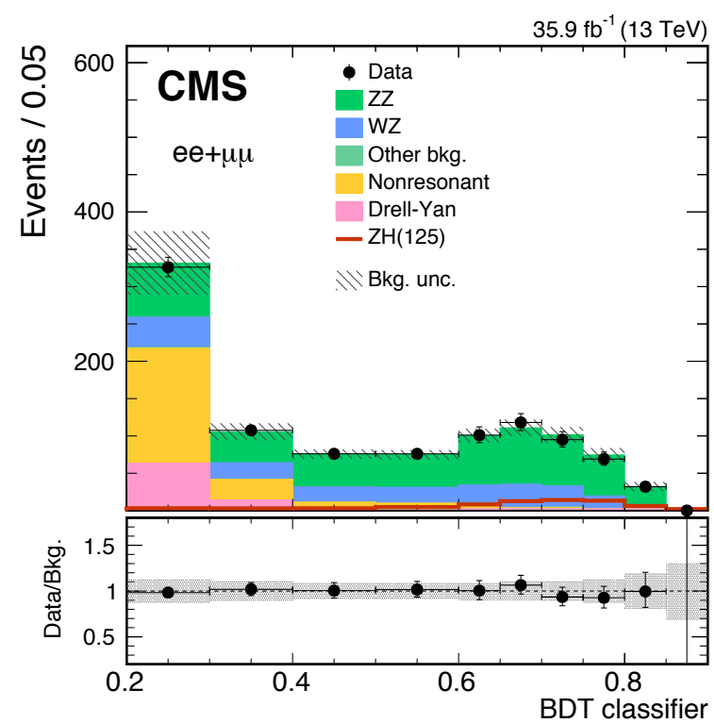


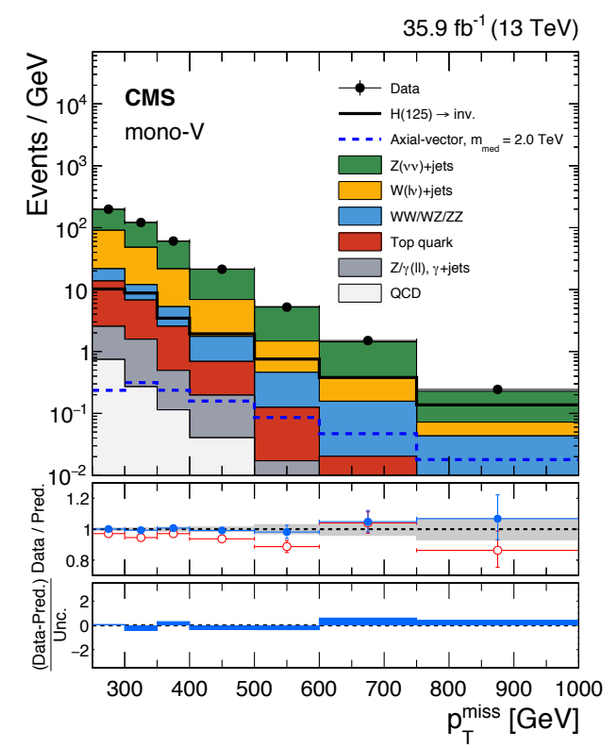
$H \rightarrow$ invisible : mono-V tag

arXiv:1711.00431
arVix:1712.02345

- **Z(→ll)+H**
  - smaller cross section than VBF
  - clean final state with low background
  - the multivariate BDT classifier is used to improve the search sensitivity by 10%
- **V(→qq)+H**
  - large background but relatively larger signal contribution
  - large radius jet (R = 0.8), p_T > 250 GeV
  - rely on jet substructure techniques

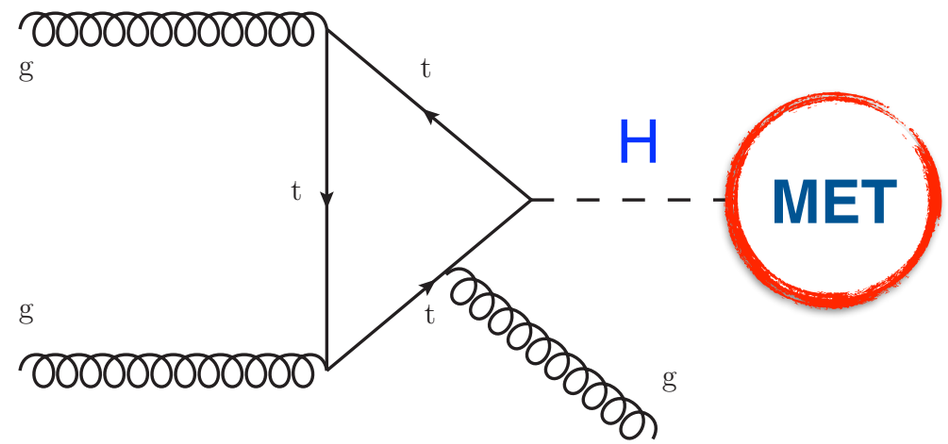




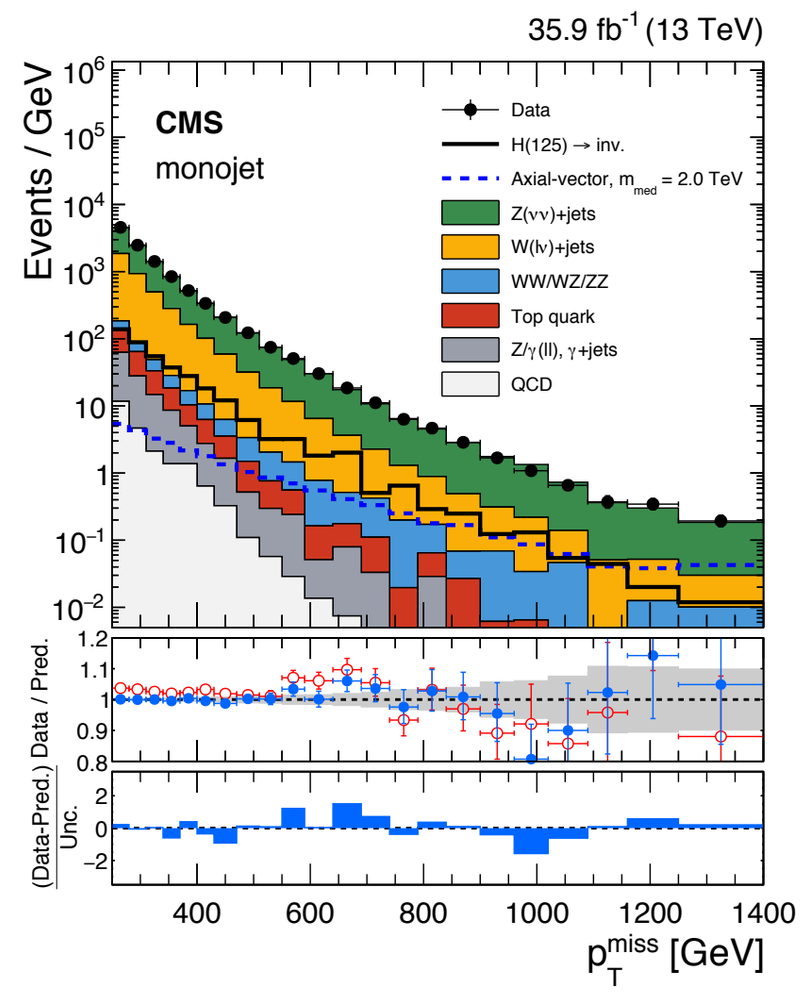


$H \rightarrow$ invisible : mono-jet tag

arVix:1712.02345

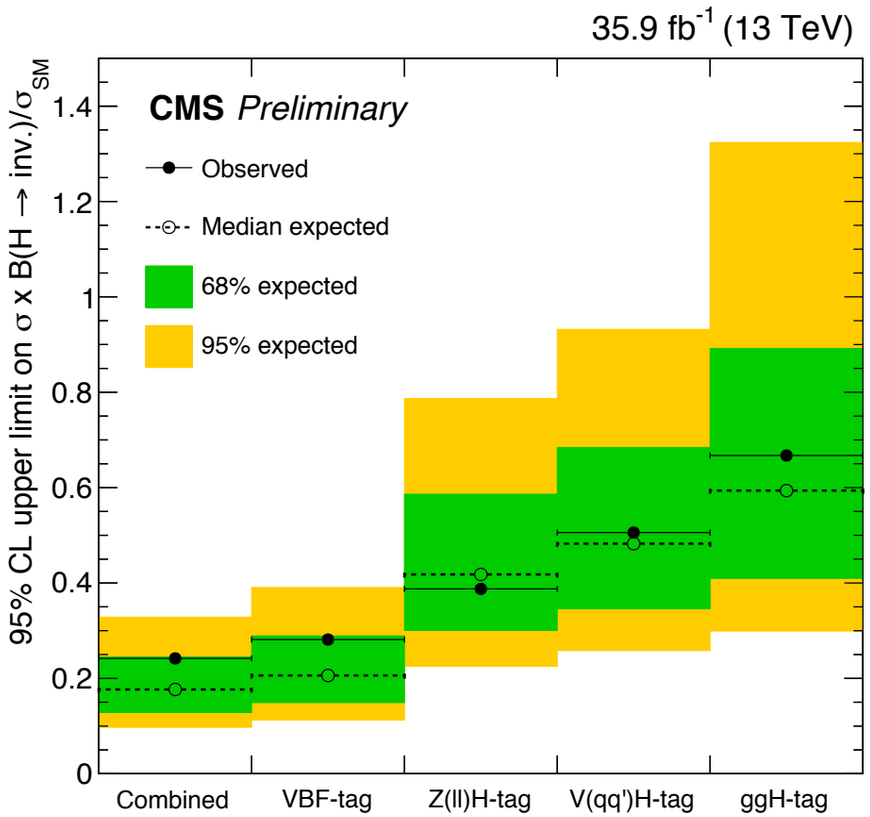


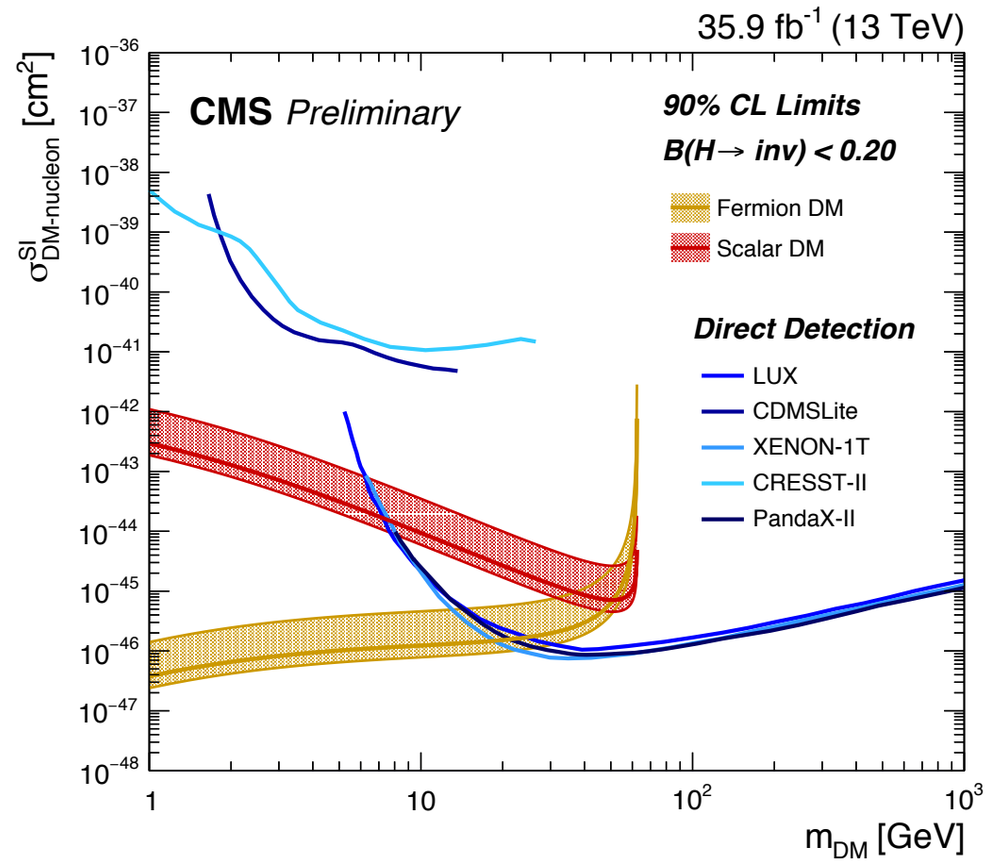
- measure ggH process where the Higgs system is boosted and recoils against a jet
- events failing mono-V tag but satisfying jet $p_T > 100$ GeV (R = 0.4) are included
- large background
- improve V(jj)H sensitivity by 12.5% after adding this mode



$H \rightarrow$ invisible : combination

CMS HIG-17-023





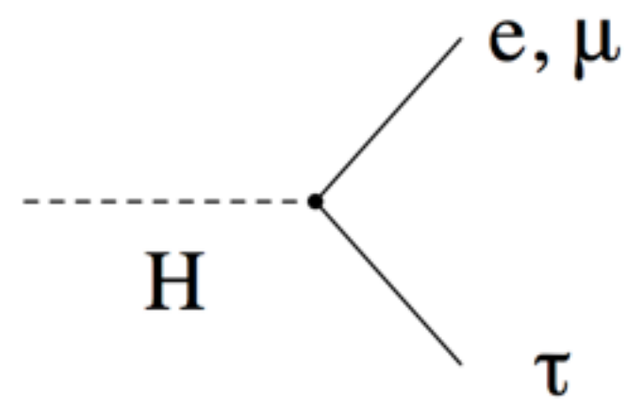
Analysis	Final state	Signal composition	Observed limit	Expected limit
qqH-tagged	VBF-jets + p_T^{miss}	52% qqH, 48% ggH	0.28	0.21
VH-tagged	$Z(\ell\ell) + p_T^{miss}$ [?]	79% qqZH, 21% ggZH	0.40	0.42
	$V(qq') + p_T^{miss}$ [?]	39% ggH, 6% qqH, 33% WH, 22% ZH	0.50	0.48
ggH-tagged	jets + p_T^{miss} [?]	80% ggH, 12% qqH, 5% WH, 3% ZH	0.66	0.59

- No significant deviations from SM expectation are observed in any search mode
- The observed (expected) 95% CL limit on BR(H→inv) assuming SM is 0.24 (0.18)
- The results have been interpreted in Higgs portal model assuming the scalar or fermion nature of the DM
  - excluding the very low DM masses below 20 (fermion) or 7 (scalar) GeV

Lepton flavor violating decays

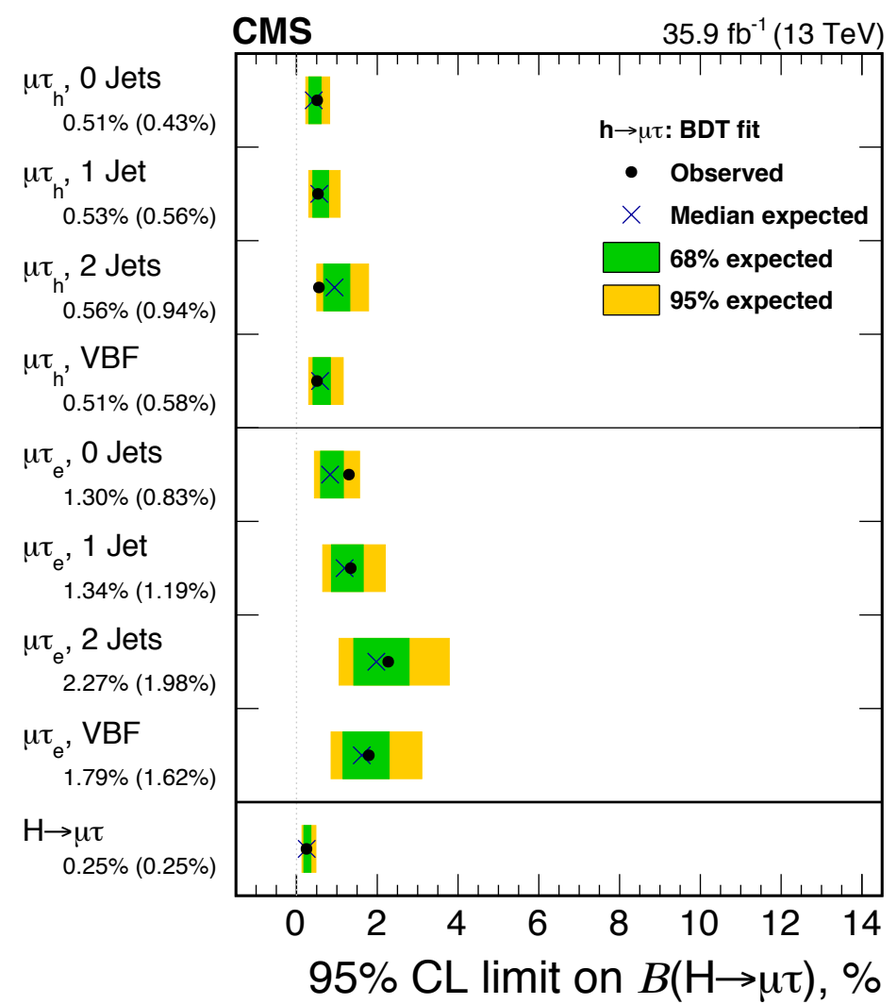
arVix:1712.07173

- a clear indication of BSM physics
- best sensitivity for H→eτ and H→μτ
  - look into multiple channels of the τ decay
- BDT is used to improve the search sensitivity
- no obvious excess observed
- set upper limits on branching ratios and non-diagonal elements of Yukawa coupling matrix



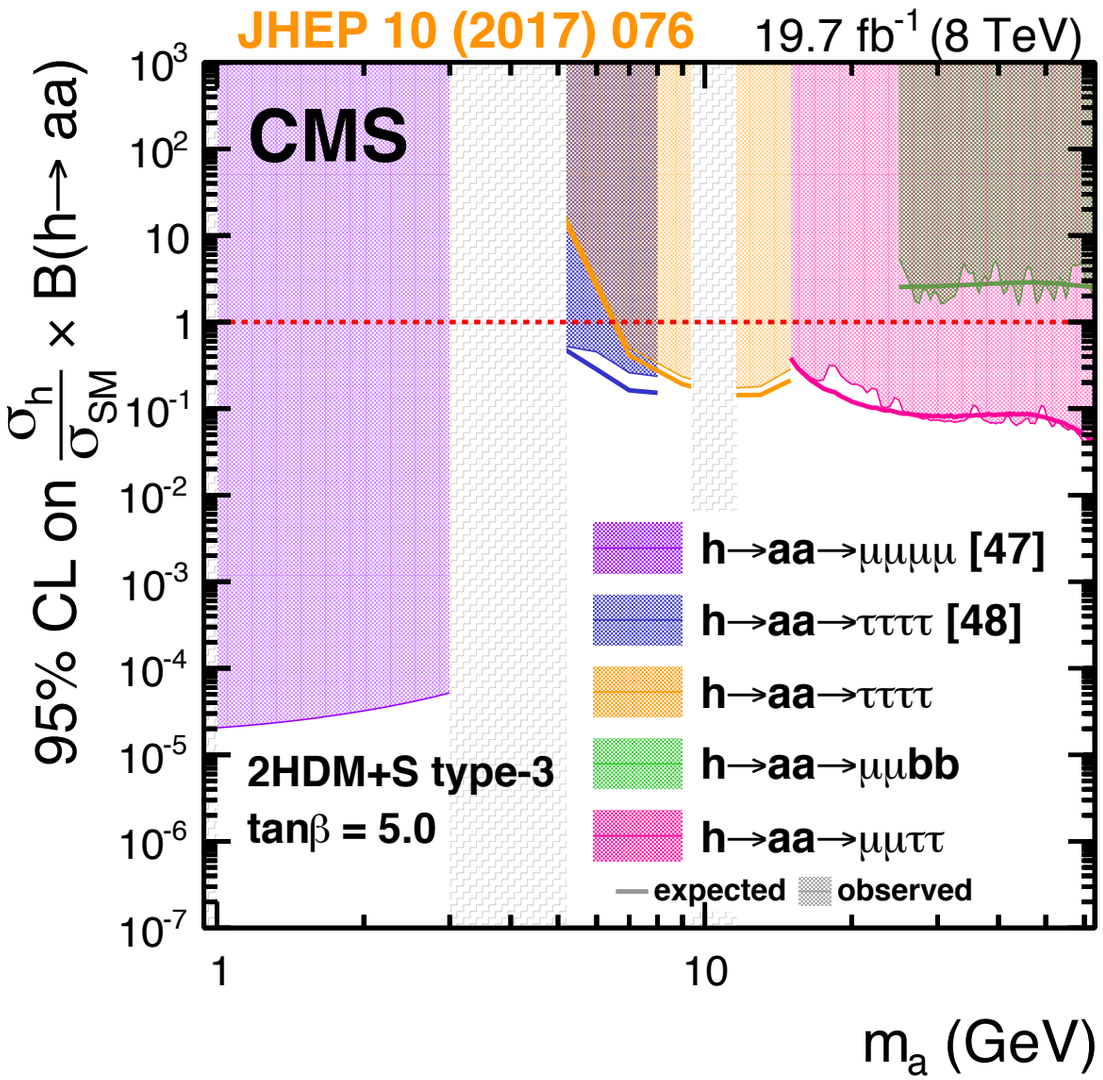
	Observed (expected) limits (%)		Best fit branching fraction (%)	
	BDT fit	M_{col} fit	BDT fit	M_{col} fit
$\mathrm{H} \to \mu\tau$	<0.25 (0.25)%	<0.51 (0.49) %	0.00 ± 0.12 %	0.02 ± 0.20 %
$\mathrm{H} \to \mathrm{e}\tau$	<0.61 (0.37) %	<0.72 (0.56) %	0.30 ± 0.18 %	0.23 ± 0.24 %

	BDT fit	M_{col} fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 1.43 \times 10^{-3}$	$< 2.05 \times 10^{-3}$
$\sqrt{\lvert Y_{\mathrm{e}\tau}\rvert^2 + \lvert Y_{\tau\mathrm{e}}\rvert^2}$	$< 2.26 \times 10^{-3}$	$< 2.45 \times 10^{-3}$



$h \rightarrow aa \rightarrow 2X2Y$

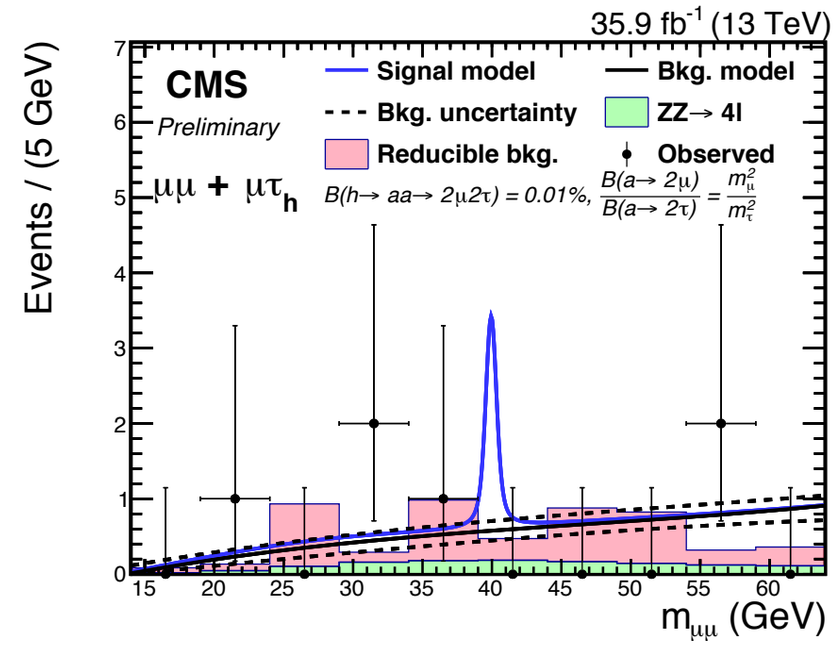
- well motivated by BSM theories such as 2HDM+S, …
- X and Y can be any types of fermions, gluon or photon
- BR of “a” boson to SM particles depends on
  - mass of the “a” boson
  - models (i.e. types of the 2HDM)
  - model parameters (i.e. tanβ)

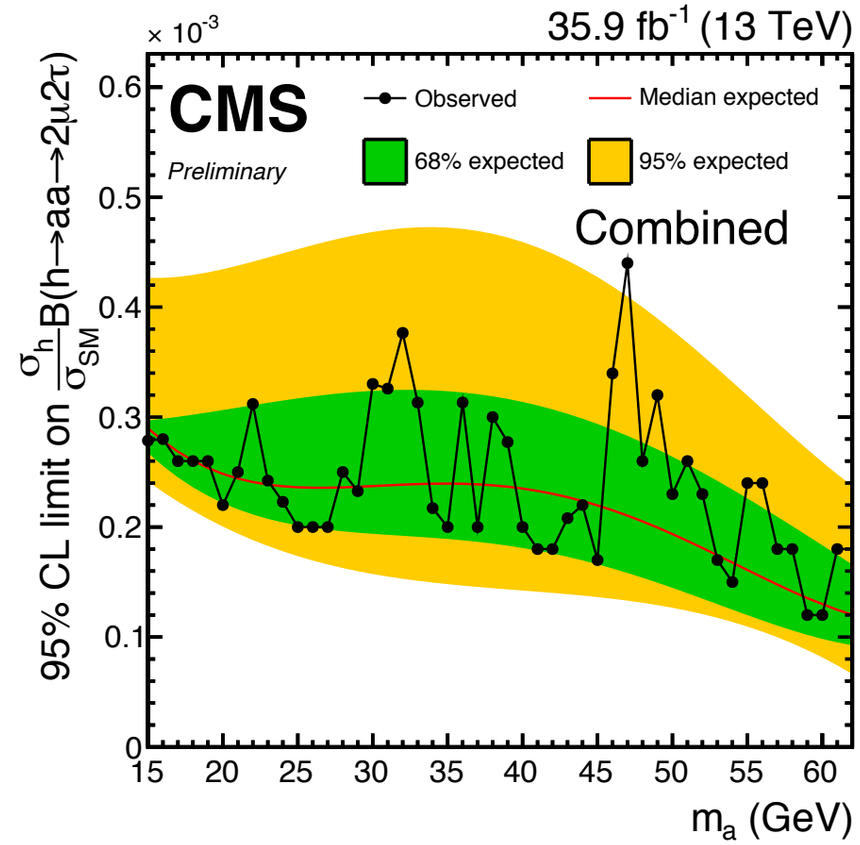


$h \to aa \to \mu\mu\tau\tau$

CMS HIG-17-029

- 4 final states: $\mu\mu \times (\tau_e\tau_\mu, \tau_e\tau_h, \tau_\mu\tau_h, \tau_h\tau_h)$
- targets on non-boosted τ pairs, and requires 4 well reconstructed and isolated leptons
- main backgrounds (fake leptons or taus) estimated from data
- final observable is the mass of $\mu\mu$
- no significant excess observed

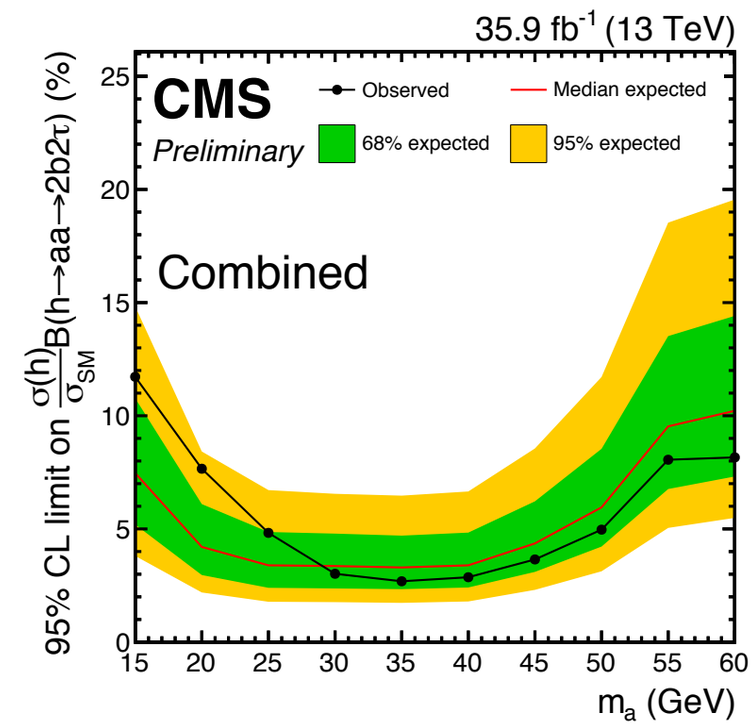


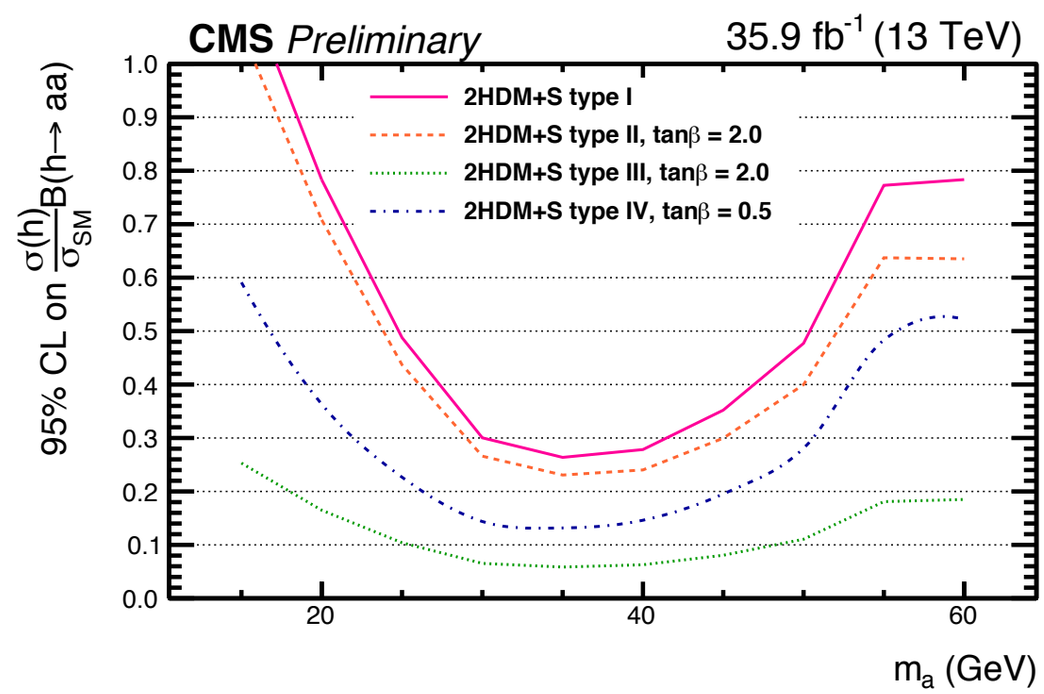


$h \to aa \to \tau\tau bb$

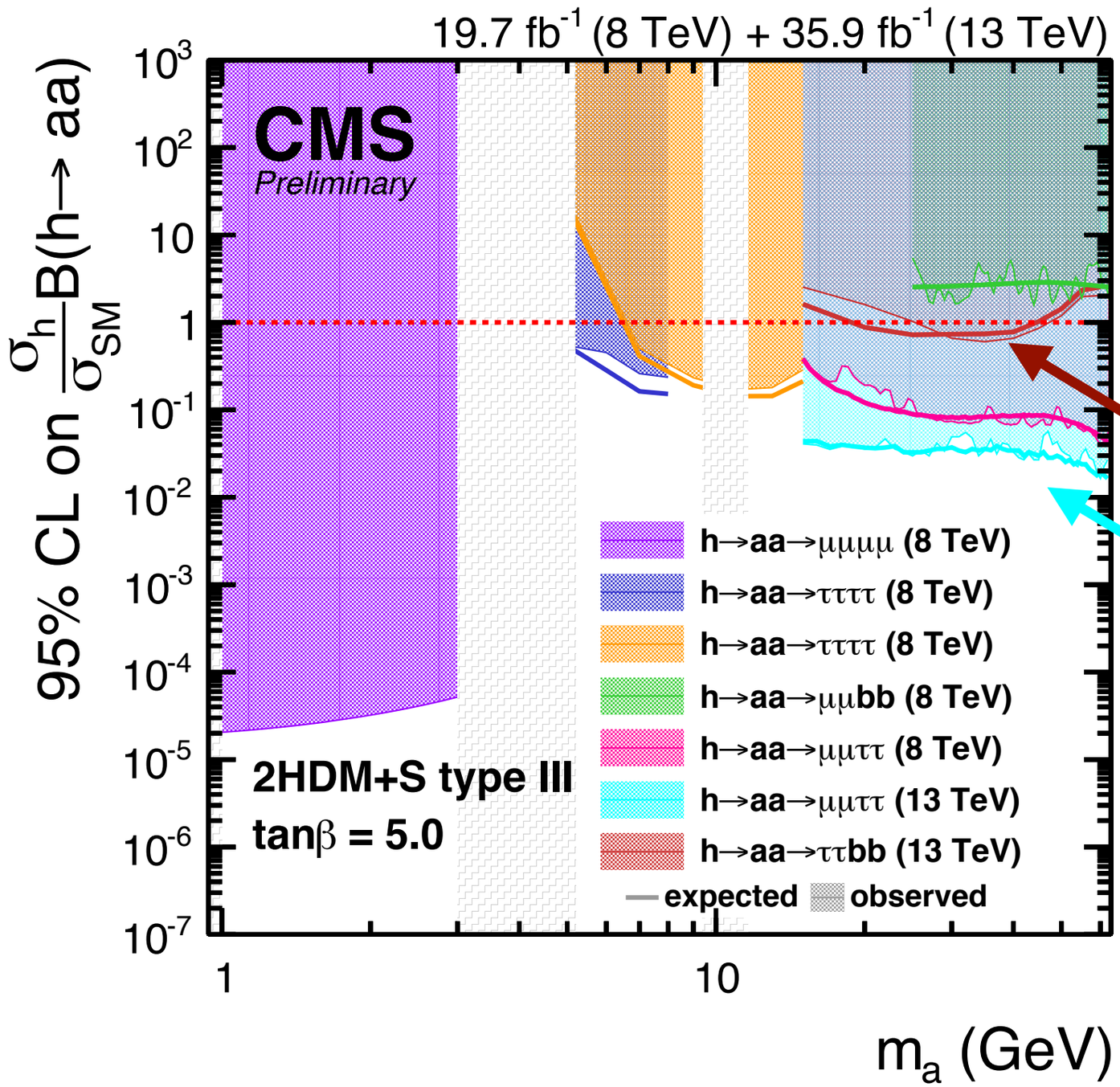
CMS HIG-17-024

- first probe of this final state
- large BRs in most models due to m_b and m_τ
- 3 ττ final states: $e\tau_h$, $\mu\tau_h$, $e\mu$
- at least 1 b-tagged jet ($p_T > 20$ GeV)
- backgrounds estimated from MC or data depending on whether taus are real or fake
- final observable is the visible mass of ττ
- the sensitivity at low(high) masses is reduced due to isolation inefficiencies of boosted "a" boson to ττ (higher backgrounds)
- the most stringent limits in 2HDM+S type II at the LHC so far





new summary plot of aa→2X2Y



CMS HIG-17-029

h→aa→ττbb

h→aa→μμττ

Summary

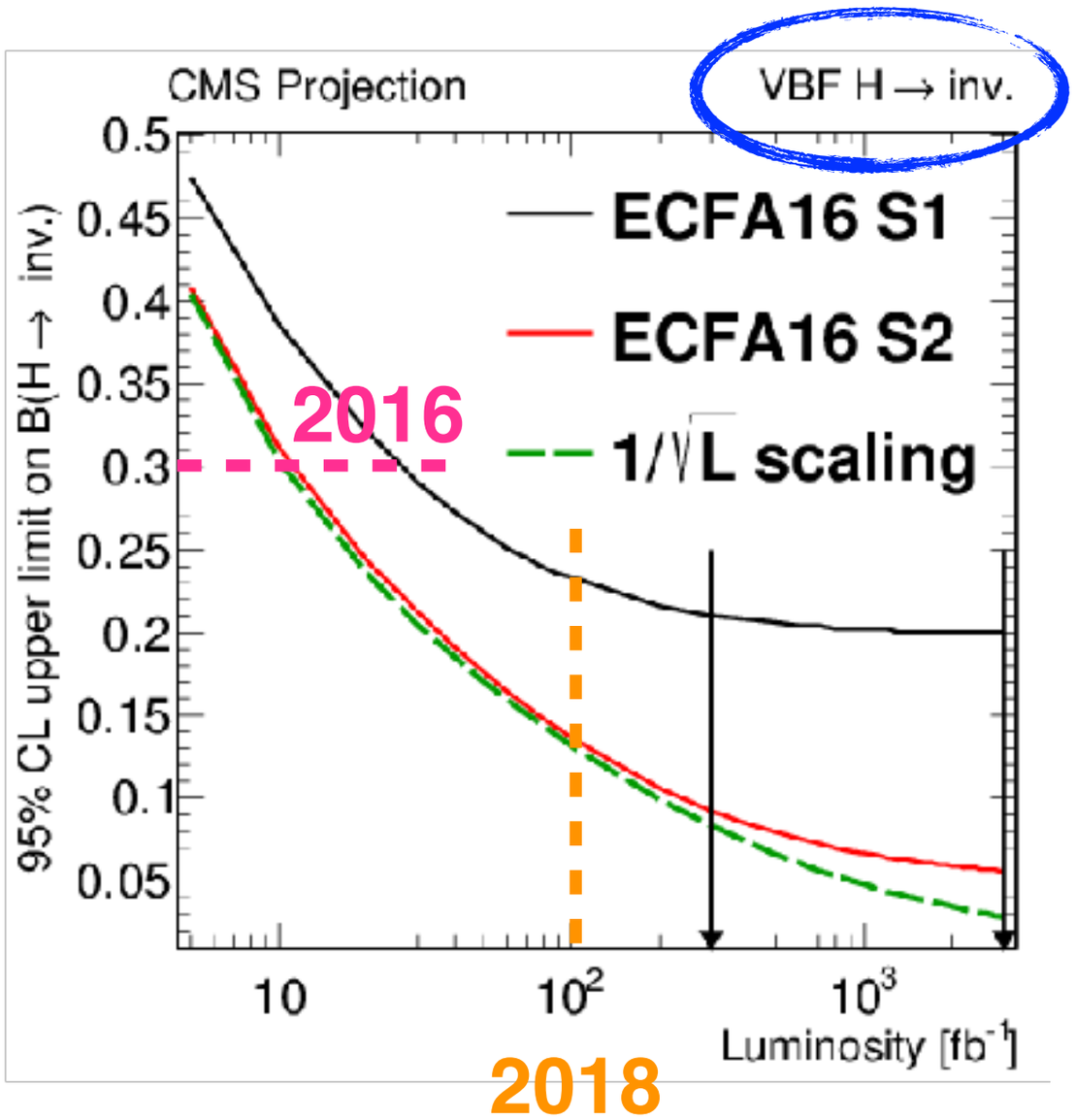
- the discovery of the Higgs boson opens a new opportunity to search for new physics via the rare or exotic decays!
- a broad program performed by CMS in this field
- observations are in agreement with SM
- still looking for it …

- Backup

Outlook of H→invisible

CMS DP-2016-064

- SM BR(H→inv.) = 0.001



S1 : all systematic uncertainties are fixed to 2015 values

S2 : experimental systematic uncertainties decrease with L and theoretical ones are scaled by 1/2
→ improved by a factor of 2 by the end of 2018 and 5 at HL-LHC

2HDM+S

- type I: all SM particles couple to the first doublet
- type II: leptons and down-type quarks couple to the second doublet and up-type quarks couple to the first doublet
- type III: leptons couple to the second doublet and quarks to the first one
- type IV: down-type quarks couple to the second doublet, while leptons and up-type quarks couple to the first doublet