Search for non-resonant Higgs boson pair production in $b\bar{b}\gamma\gamma$ final states in p-p collisions at $\sqrt{E} = 13$ TeV

Sebastião Antunes nr 87355

Introduction

- Higgs potencial takes the form: $V(\phi) = \mu^2 |\phi|^2 + \lambda(|\phi|^2)^2$

- To expand around one of the minima, we first explicitly break electroweak symmetry. Result:

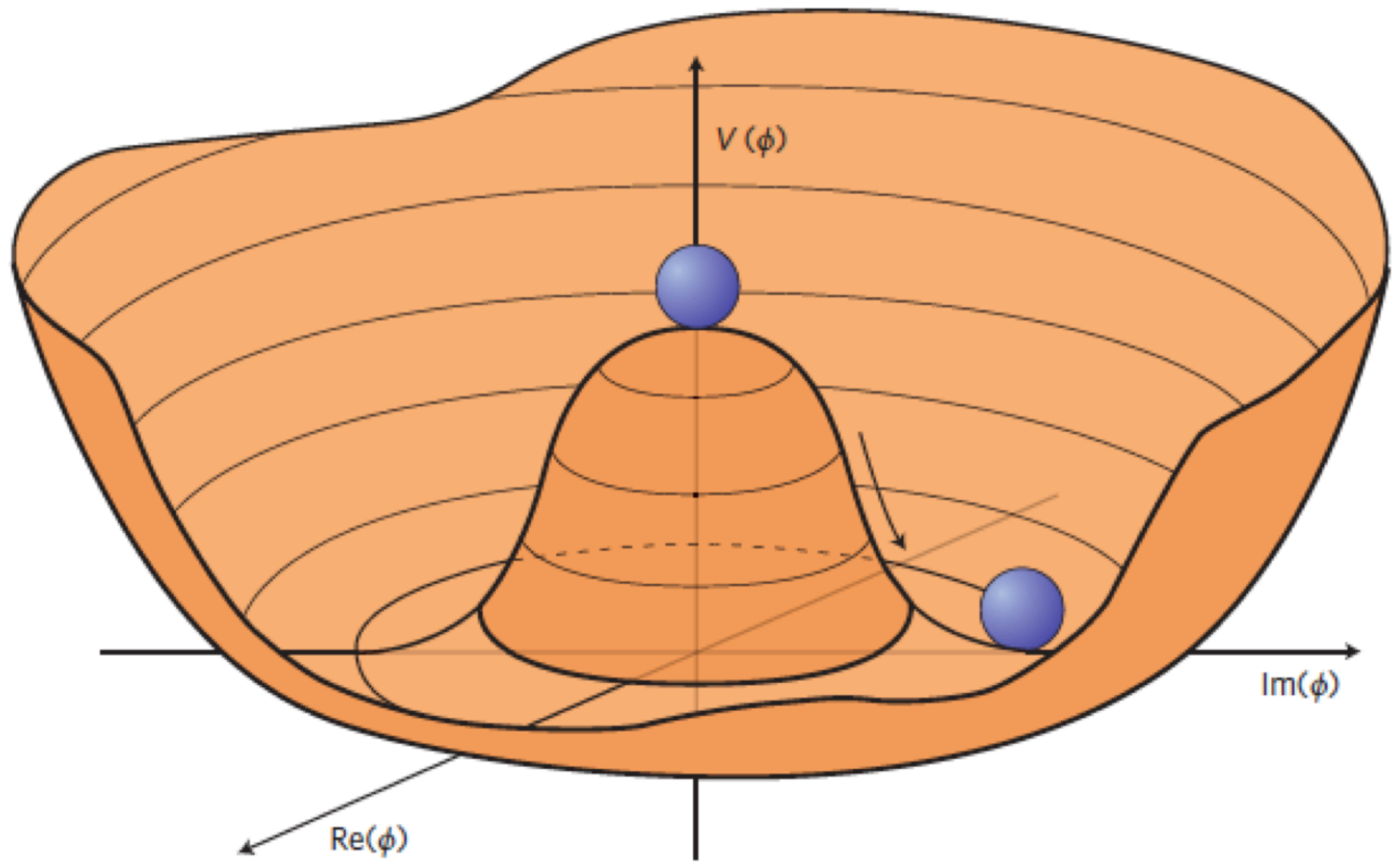
$$V(h) = \frac{1}{2} m_H^2 + \sqrt{\frac{\lambda}{2}} m_H h^3 + \frac{\lambda}{4} h^4$$

- To probe the structure of the potential we require information on the three Higgs coupling λ_{HHH}.

- κ_λ also confirms if symmetry breaking is SM-like.

- This and other couplings can only be directly studied in di-Higgs channel at LHC.

- Possibility of studying BSM interactions that might contribute to production



Symmetry breaking to the conventional $|\phi|^2 = -\mu^2/2\lambda$ minimum

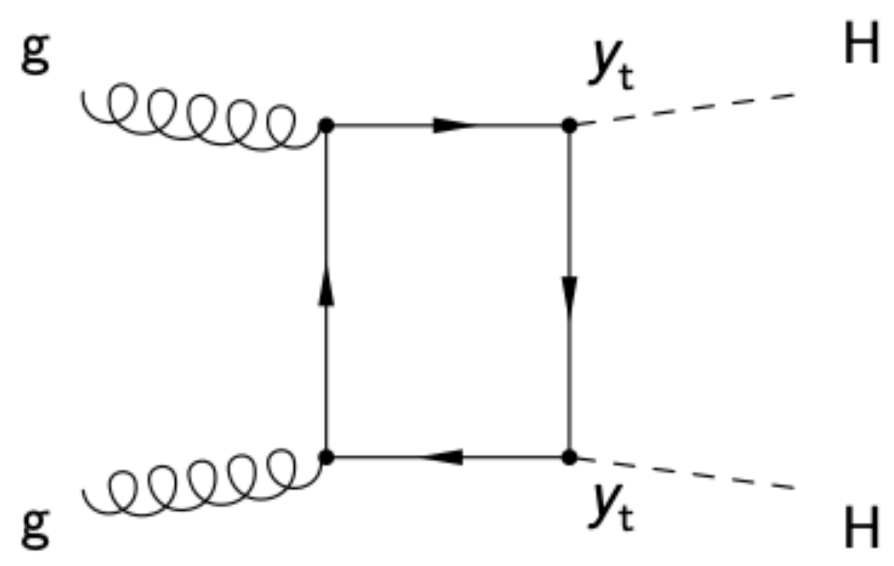
Di-Higgs production: SM

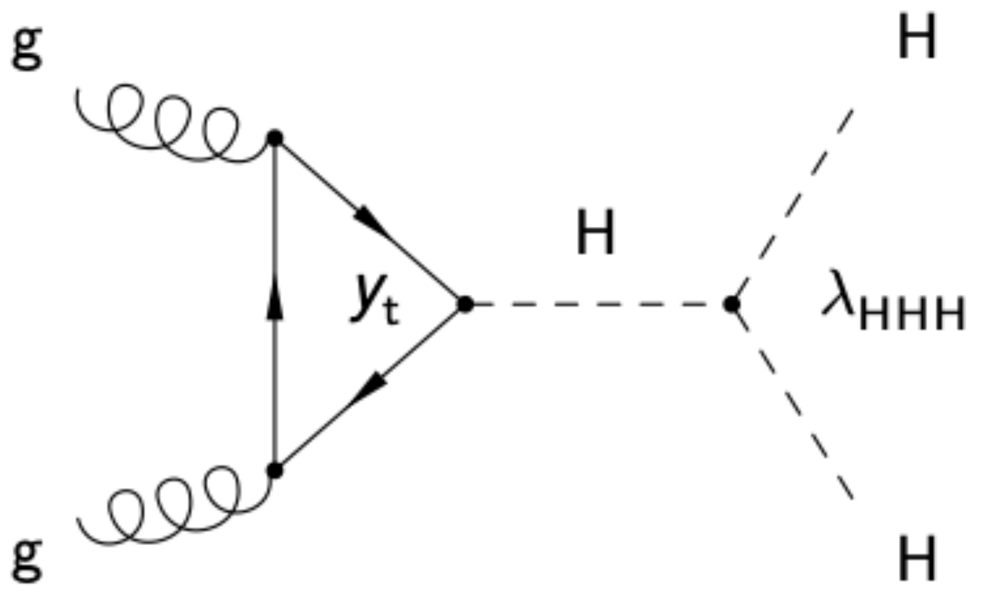
- **GGF:** as for single Higgs the main production mode in p-p collisions ($\sigma \approx 30$ fb).

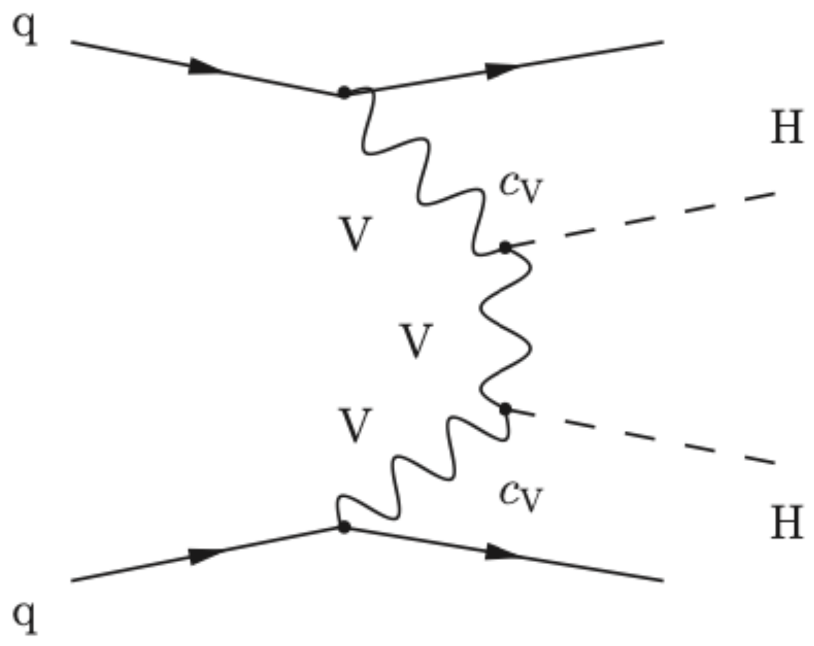
- **VBF:** second most dominant HH production mode ($\sigma \approx 2$ fb). Quarks scatter via the exchange of a virtual vector boson.

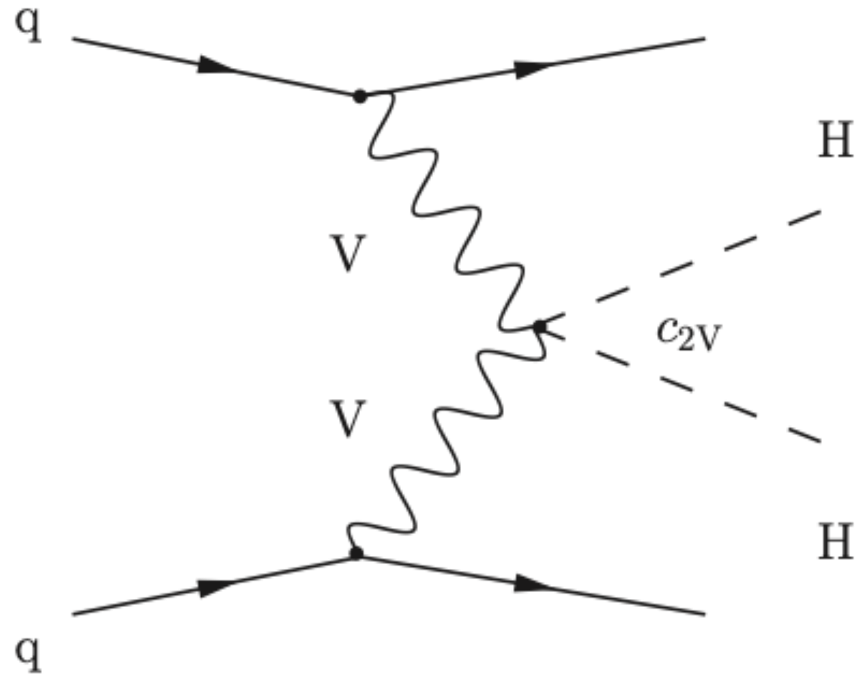
- Despite significantly lower σ the unique kinematics of the deflected quarks make this channel appealing $\rightarrow$ competitive sensitivity to trilinear coupling and unique handle on c_{2V}.

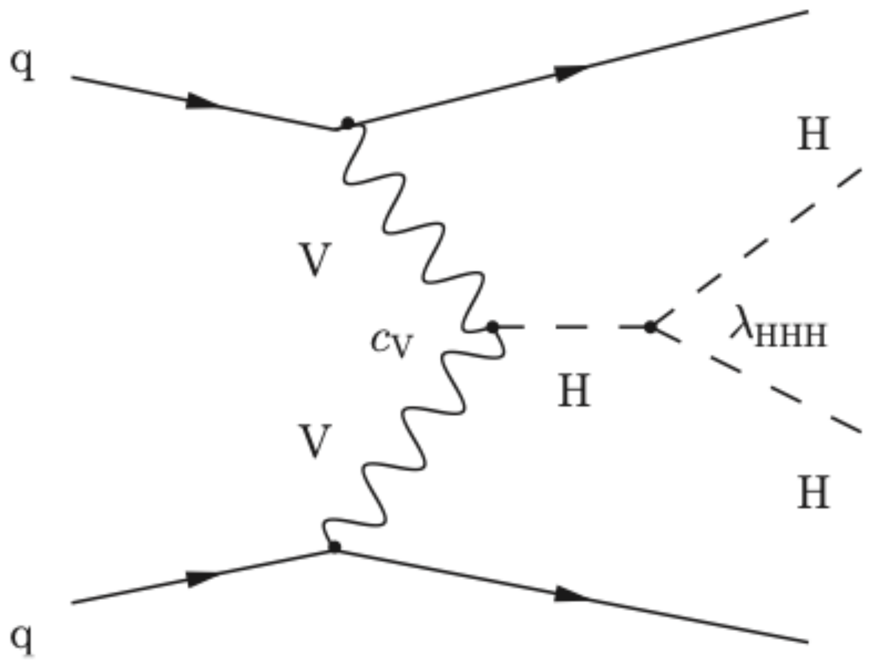
- c_V is also controlled by vector boson production of single Higgs and the decay of H to boson pairs.









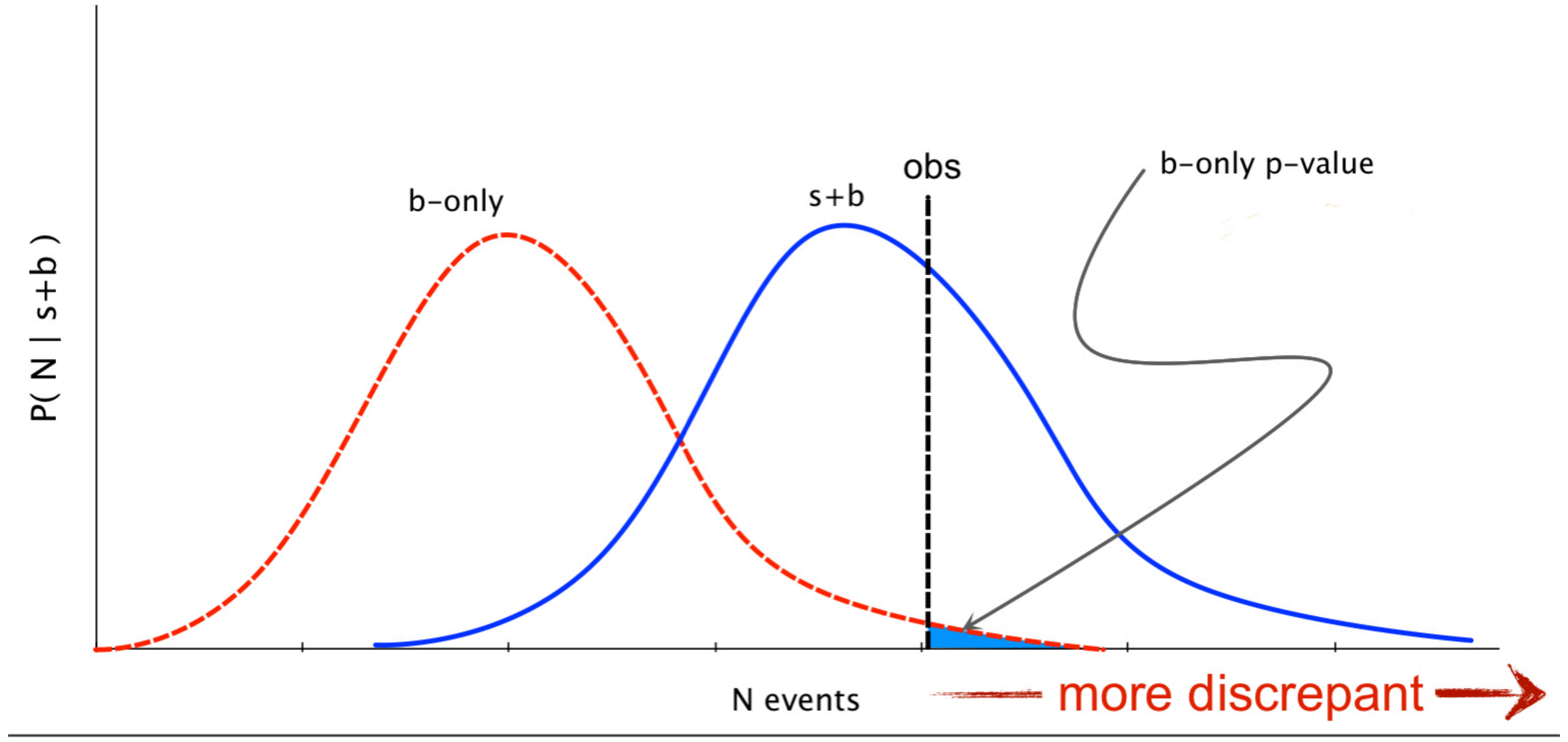


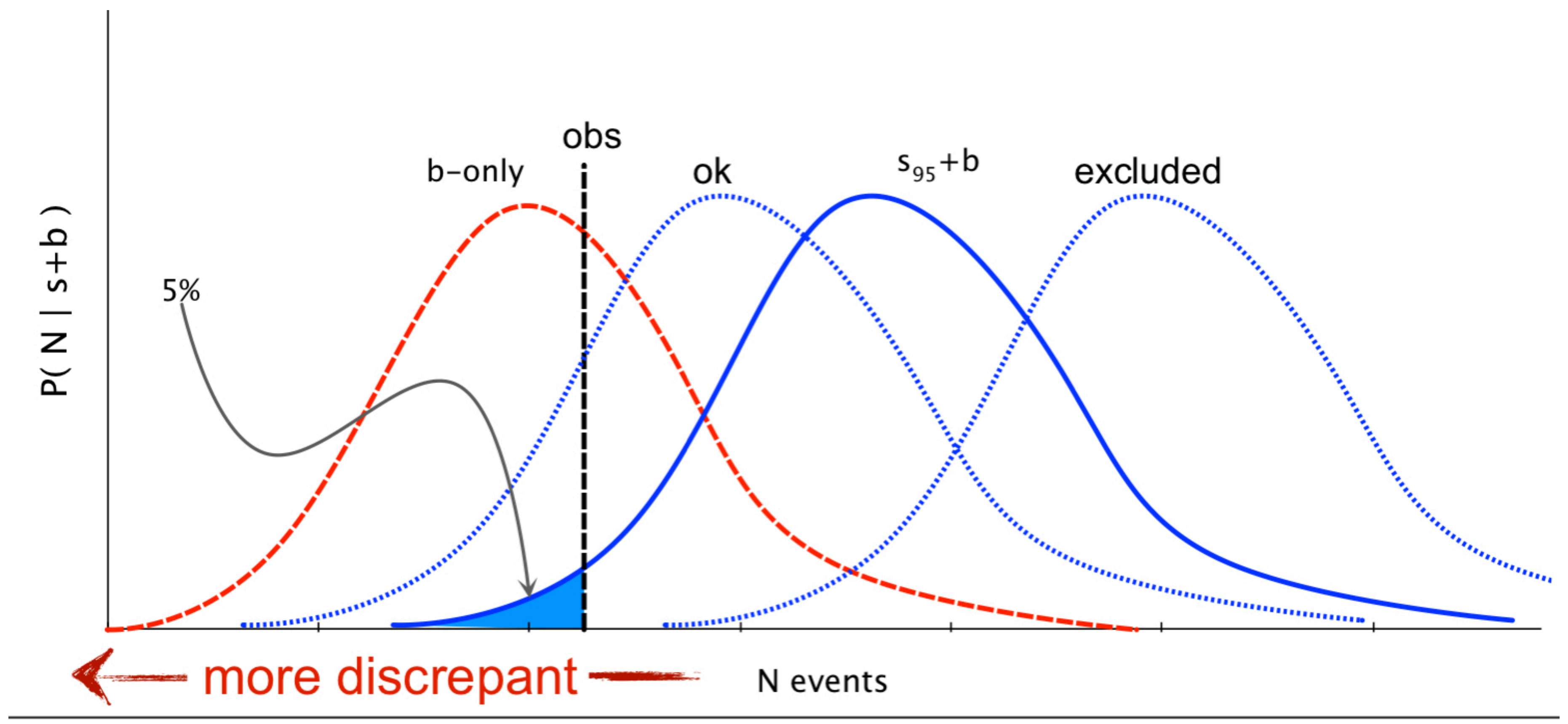
Di-Higgs production: Beyond SM

- Small HH cross section → current measurements have no sensitivity to SM production but we might discover/exclude enhancements by correct null + test statistics:

  1. Discovery: $H_0 = b - only$, downward fluctuations of b are not evidence against it.

  2. Exclusion: $H_0 = b + s$, upper limit → exclude by p-value.





- Enhancements can be resonant (new resonance couples to t quark or vector boson) or **non-resonant:**

  1. Variation of SM parameters

  2. Inclusion of couplings non-SM couplings through effective Lagrangian

Both parametrised with EFTs

Di-Higgs production: Beyond SM

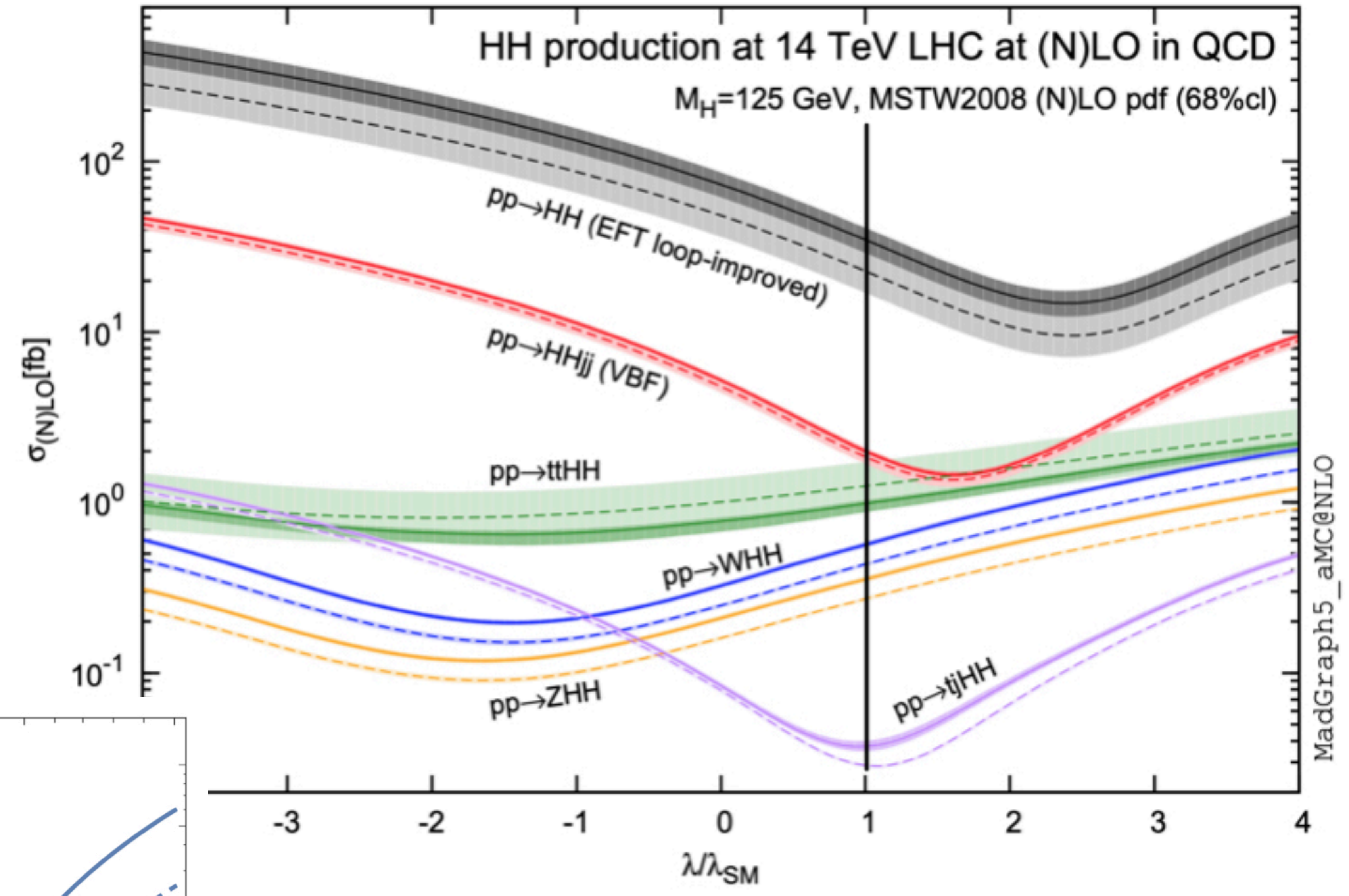
- κ_λ **deviations:**

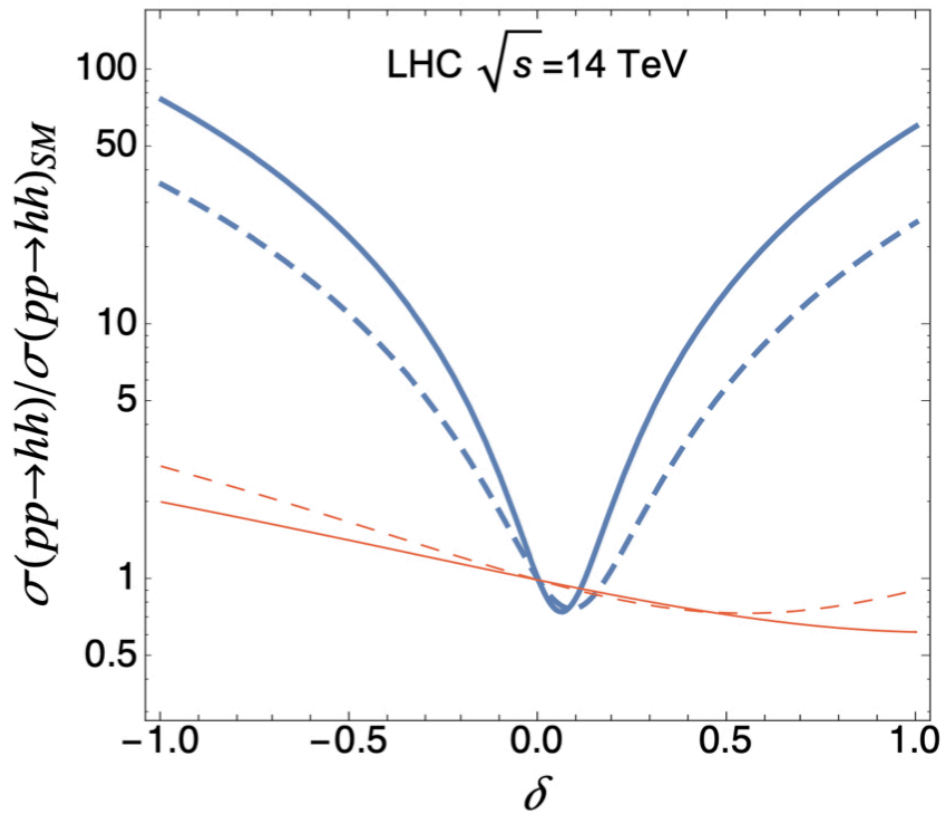
    1. enhancement to σ_{ggF} by ↓ destructive interference among box and triangle diagrams (maximal at 2.45 SM);

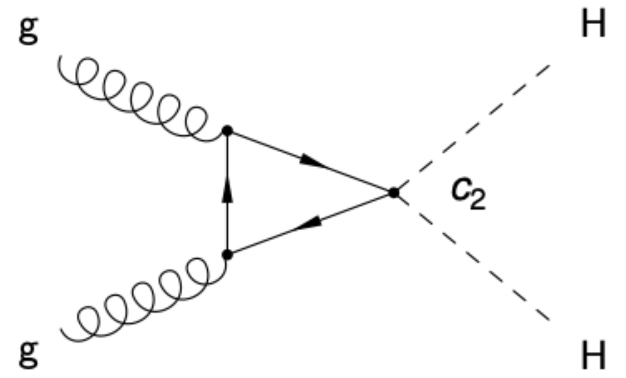
    2. enhancement to $\sigma_{VBF} \approx$ same % with min closer to SM value and << absolute ↓.

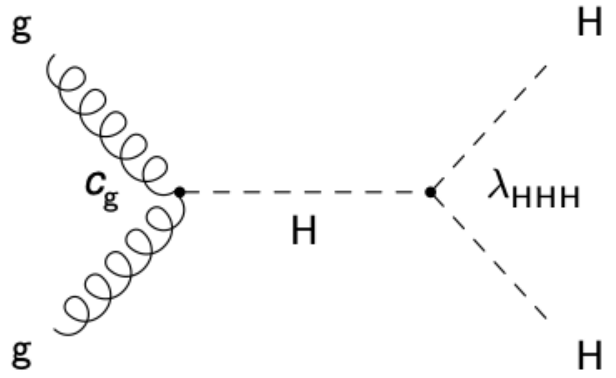
- $\kappa_{C_{2V}}$ **deviations:** any deviation from SM significantly↑ $\sigma_{VBF} \rightarrow$ high sensitivity.

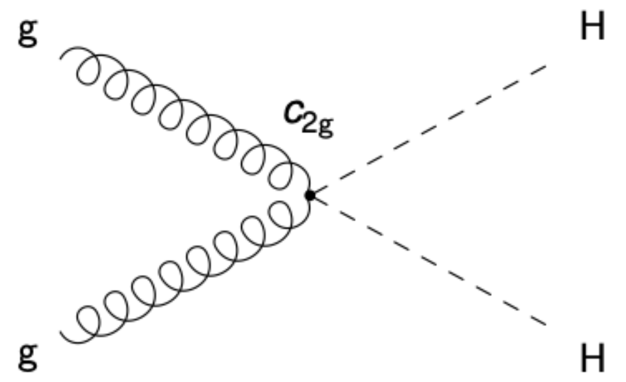
- **EFT for VBF:** only consider variations (c_V as well).











- **EFT for ggF:** operators up to 6D →3 new contact interactions + variations on κ_λ and κ_t.

- 12 benchmark H (≠ comb of parameters) shown to represent main kinematical observables dist over phase space.

Di-Higgs Decay: Why $b\bar{b}\gamma\gamma$ channel?

- Properties of both Higgs need to be considered.

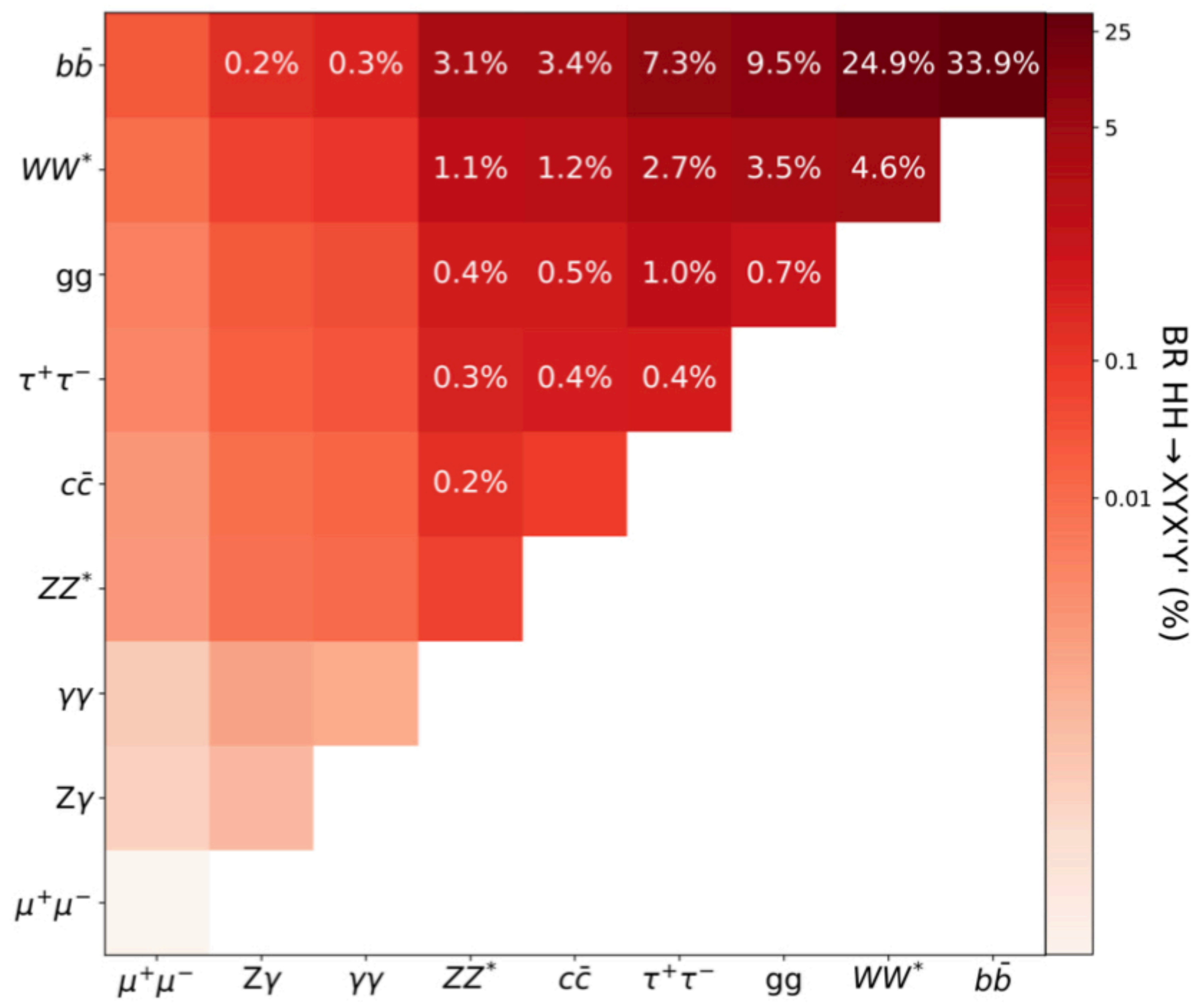
- The small σ_{HH} cross section motivates searches targeting higher branching ratio modes. However, event purity is also important.

1. $b\bar{b}b\bar{b}$: multiple triggers for 4 jets, high QCD multi-jet background;

2. $b\bar{b}WW*$: large irreducible $t\bar{t} \rightarrow b\bar{b}WW*$ background;

3. $b\bar{b}\tau\tau$: moderate $t\bar{t}$ decay + multi-jet background;

4. $b\bar{b}\gamma\gamma$: low background (as $b\bar{b}ZZ*$) + $H \rightarrow \gamma\gamma$ good mass resolution and clean di-photon trigger.



Events: Data Sample, Reconstruction + selection

- **CMS identifies** collisions vertices + particles by: track-finding, e/μ ID and reconstruction and jet clustering. **CMS records** interesting events (e.g. heavy jets, clean μ signals) after a 2 level trigger. It measures E, momentum and charge for participating particles.

- Analysed data comprises 2016 2017 2018 runs. To select ggF events:

  1. Identify photons: reconstructed E clusters not linked to charged tracks and use BDT to distinguish from jets (trained on isolation and shower shape criteria in $Z \to ee$ events)

  2. Require two photons for triggering with $100 < m_{\gamma\gamma} < 180$ GeV, $p_T^{\gamma 1} > m_{\gamma\gamma}/3$ and $p_T^{\gamma 2} > m_{\gamma\gamma}/4$ + geometry. For more than 2 γ choose pair of highest p_T .

  3. From photon candidates: identify primary pp vertex with BDT (trained on simulated ggF events for track recoiling against di-photon criteria). Double jet requirement allows 99.9% efficiency.

  4. Require your 2 jets to have $p_T > 25$ GeV, $\Delta R_{\gamma j} > 0.4$, geometry, not to be from calorimeter noise (associated b-tagging score from other vertex algorithm -DNN) and $70 < m_{jj} < 190$ GeV. For more than 2: b score.

- For VBF there are 2 additions jets from the scatter quarks → additional criteria based on well separated (from each other and photon + b candidates) and energetic “VBF-tagged” jets.

Events: Simulation

- For H testing we need a signal model → need signal simulation.
- **ggF events** are simulated at NLO, for samples with ≠ values of κ_λ. Samples for any point in (κ_λ, κ_t) from the LC of 3 simulations with $\neq \kappa_\lambda$. Full top quark mass dependence also modelled.
- Signal samples simulations are also performed for the benchmark H described by $(\kappa_\lambda, \kappa_t, c_2, c_g, c_{2g})$. These represent the distribution of kinematic variables over the hole parameter space →Add them (↑ N) and recover any point in the 5D spacey reweighing. Can only be done at LO.
- **VBF events** are generated at LO for different combinations of $(\kappa_\lambda, c_V, c_{2V})$.
- **Background events:** estimated by data-driven methods but we require simulations for MVA discriminants + optimisation of categories for analysis (later). The possible types are:

  1. $\gamma\gamma$+jets (irreducible) at LO: dominant!
  2. γ+jets (reducible) where jets are misidentified as isolated photon and b jets.
  3. $H \to \gamma\gamma$ (resonant, simulation-driven) at NLO for ggF H, VBF H, $t\bar{t}$H, V H.

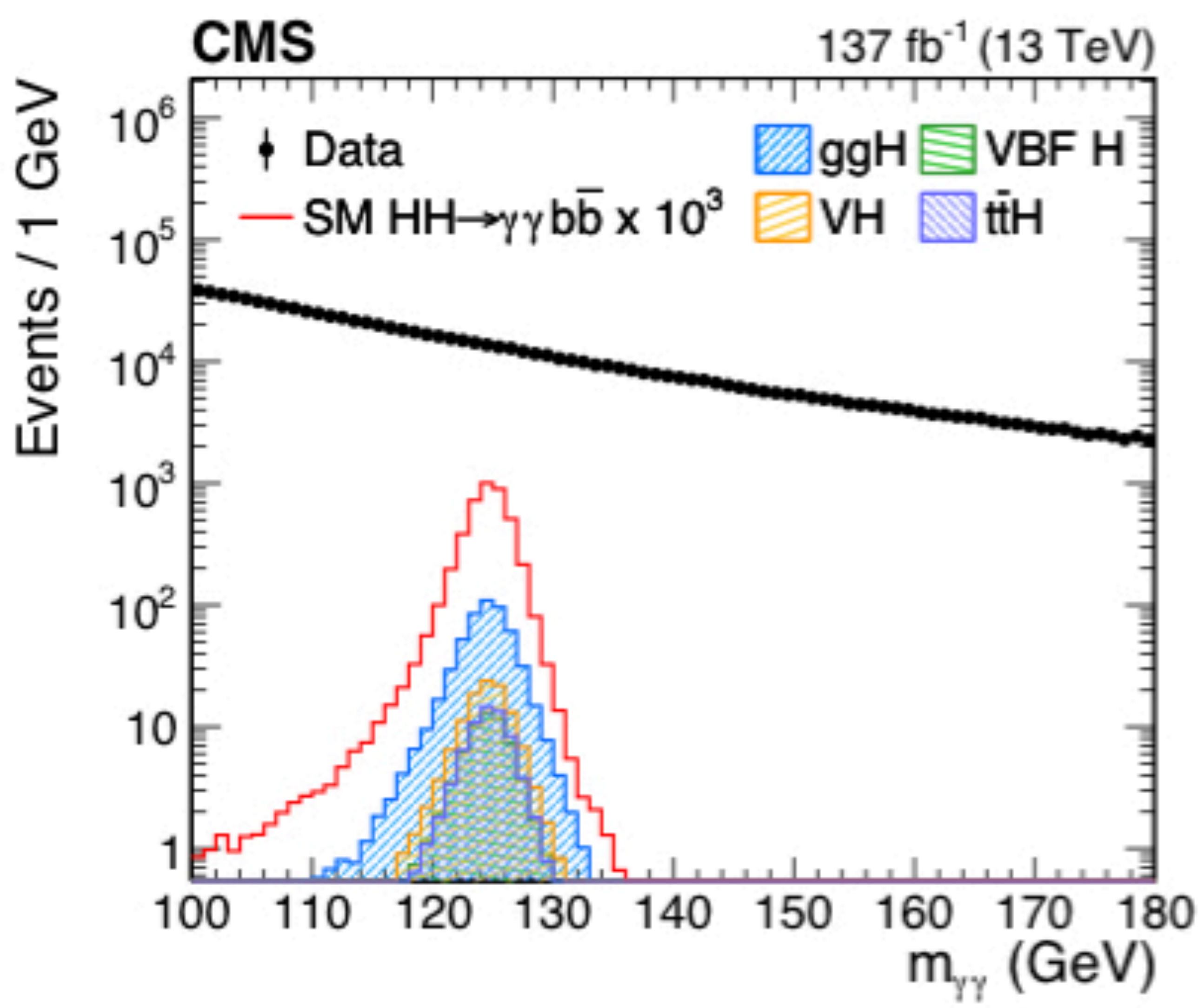
- All simulations use a Parton Shower scheme.

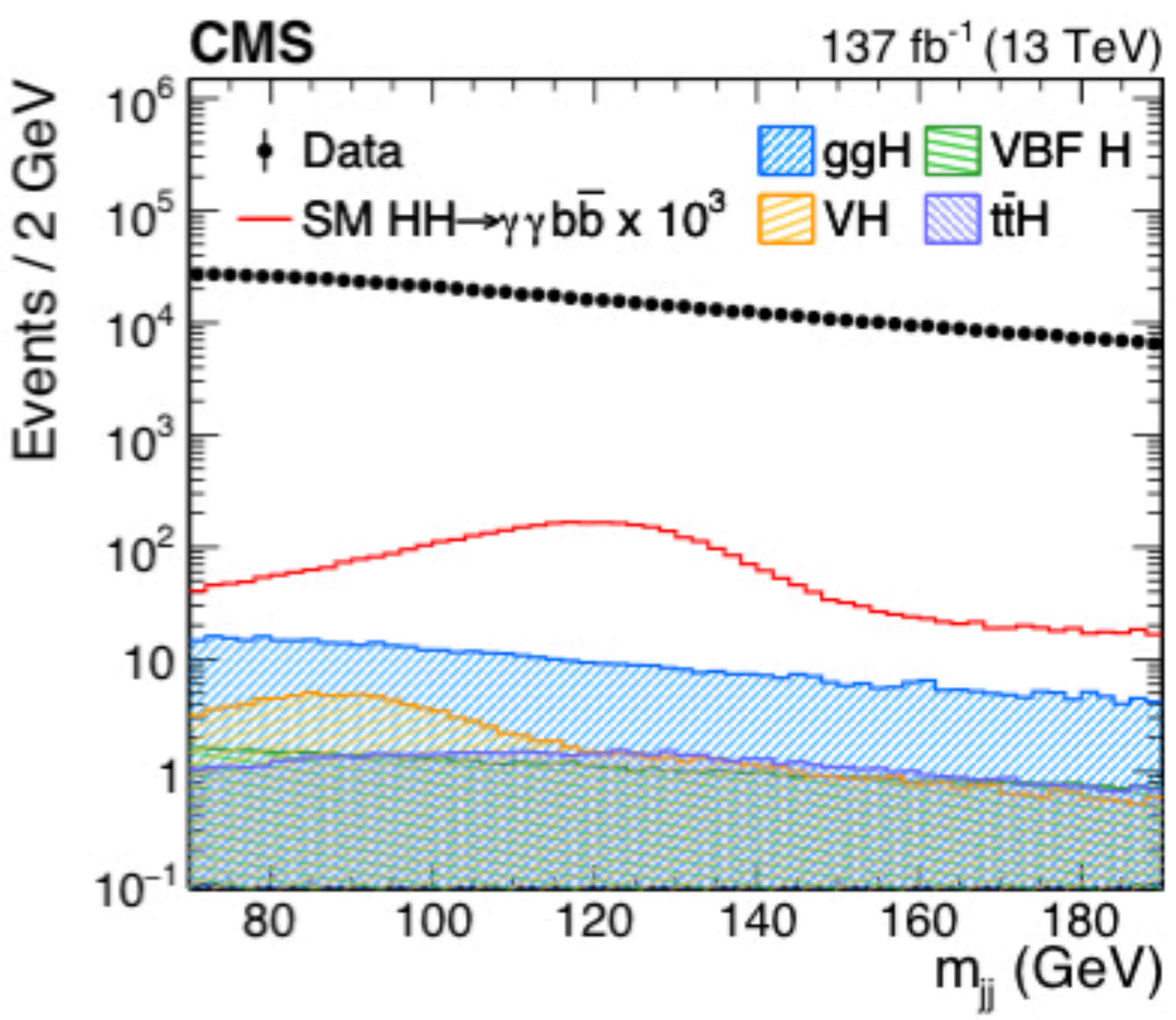
Analysis Strategy

- We expected: low sensitivity due to small BR → goal is to improve sensitivity while keeping a data driven narrative.

- **Strategy:** simulate resonant background and signal events → run them through selection → study $(m_{\gamma\gamma}, m_{jj})$ distribution of simulation vs data candidates → identify distinguishing characteristics for signal vs background .

- **Improvement:** train MVA classifier in MC samples signal+background and apply to actual data. Perform the fit in the mutually exclusive ggF and VBF categories we will obtain (already with less background), simultaneously.





- Background: falling spectrum (non-resonate) + Signal: peak → signal extraction = fit of candidates in $(m_{\gamma\gamma}, m_{jj})$ plane.

- $M_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$ particularly sensitive to ≠ values of the couplings.

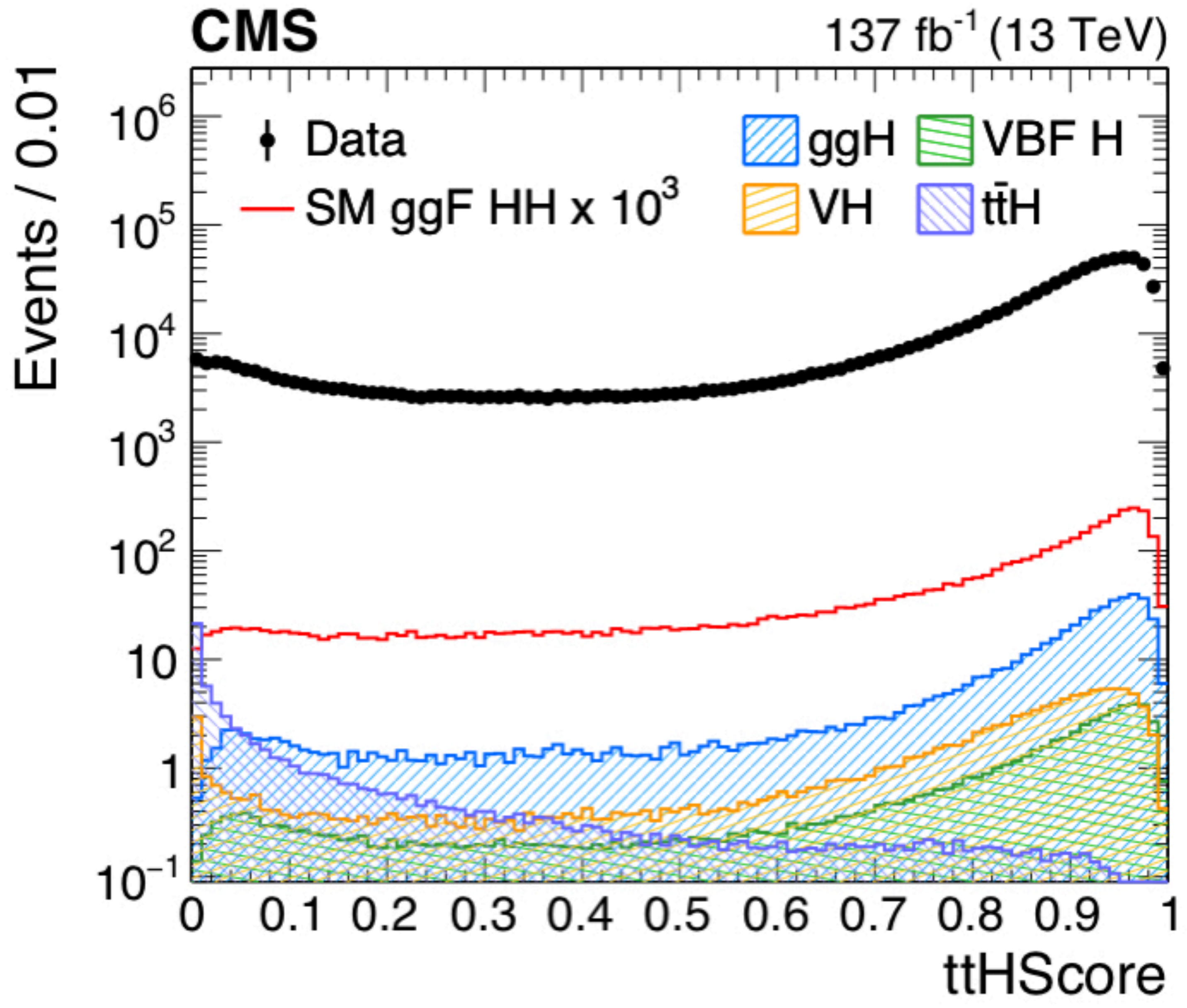
Background Rejection

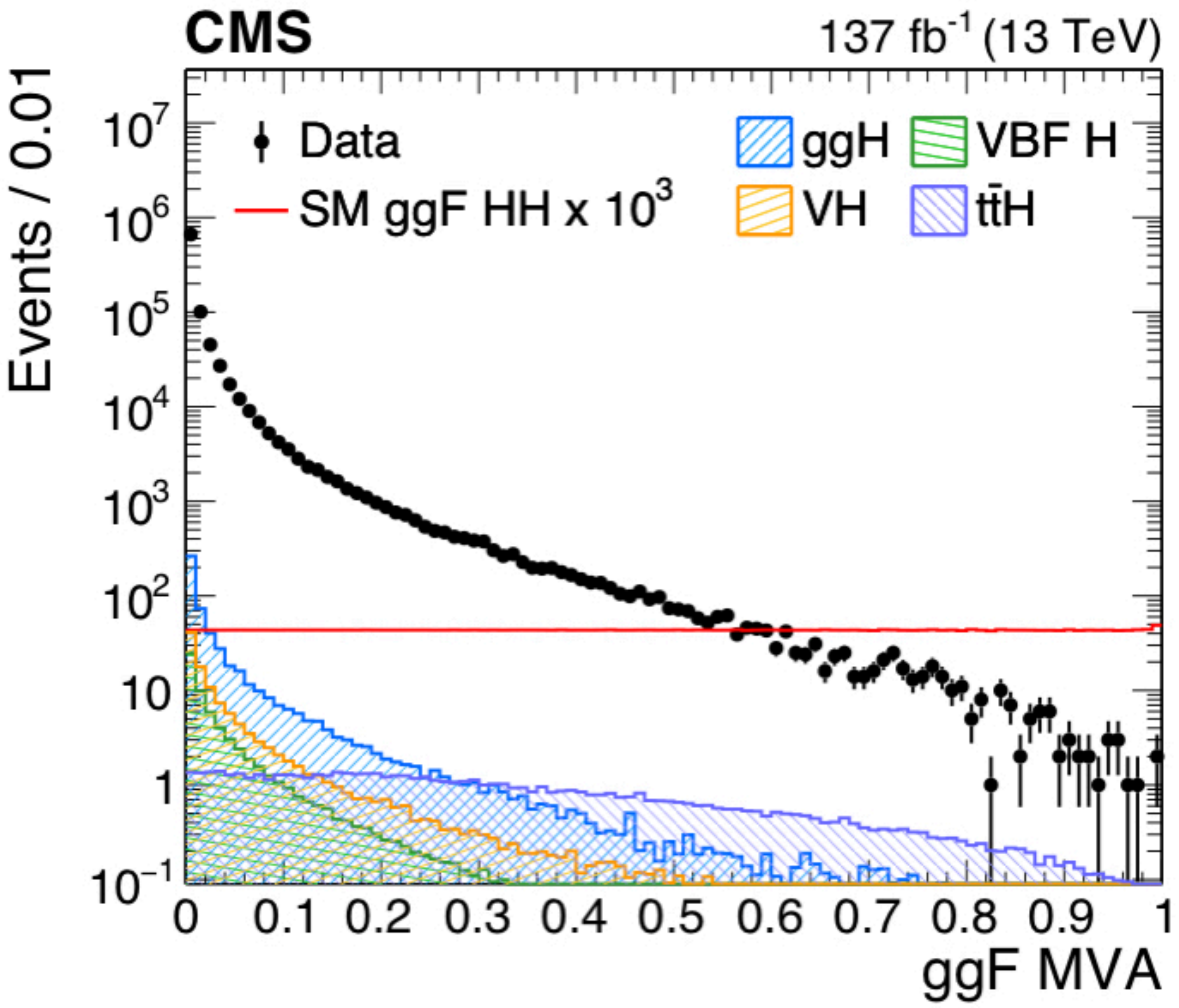
- Two types of backgrounds: resonant (similar shape to the signal → simulation driven rejection necessary) and non-resonate (falling spectrum → reduced by simulation rejection before data drive estimation).

- **Resonate rejection:** where signal is purest $t\bar{t}H$ production is dominant → dedicated classifier (ttH score). Trained on SM HH + 12 H (s) and $t\bar{t}H$ events (b). Uses low level and kinematic features (angular variables + variables do distinguish decays of W produced by top quark). Implemented with DRNN.

- **Non resonate rejection:** BDT tree to separate ggF events and background. Trained on $\gamma\gamma + jets$ and $\gamma + jets$ events (b) and SM ggF + 12 H (s) Uses kinematic variables (angular, single H and transverse HH), ID variables (photon ID + b tagging) for reducible background and energy resolution variables.

- Remark: BST output transformed for uniform signal.





VBF Background Rejection and Signal Categorisation

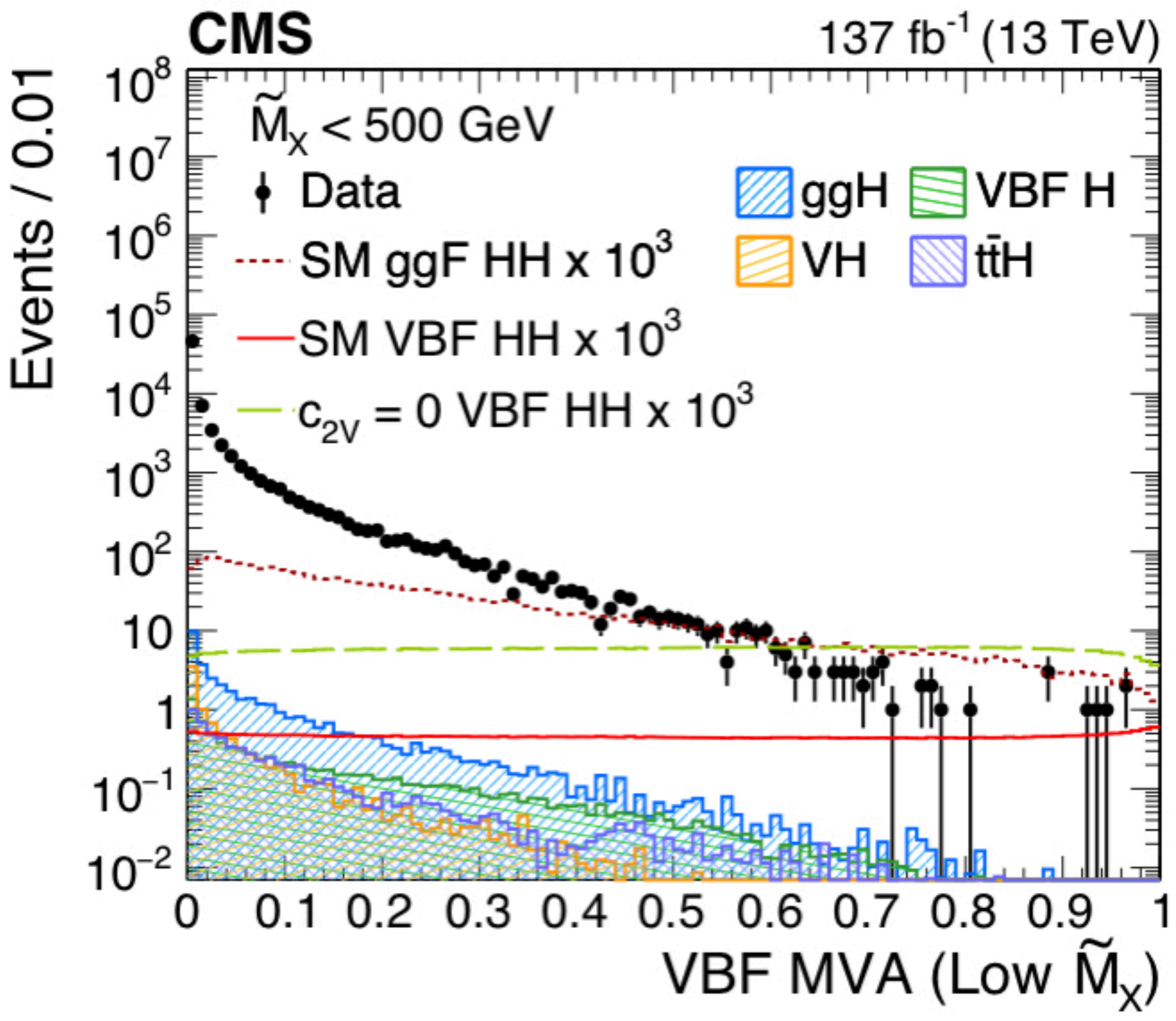
- 1/3 of ggF events passing selection criteria also pass dedicated VBF criteria → to separate them from resonant background and ggF need another BDT.

- Trained with MC non-resonant backgrounds and SM ggF simulated events (b) and a mix of SM VBF and $c_{2V} = 0$ (s). Uses same criteria as before + dedicated VBF-tagged jets criteria (kinematic variables, invariant mass, rapidity difference, quark-gluon likelihood, etc). Two ≠ regions are trained: low M_X sensible to SM and high M_X sensible to c_{2V} anomalous values.

- Events are further subcategorised taking into consideration MVA scores and M_X ranges and optimising for significance $S/\sqrt{B}$.

- MVA scores optimised simultaneously. For MVA VBF < 0.52 background contamination to ↑ for sensitivity to increase, same for MVA ggF < 0.37. Sub categories are optimised based on M_X for ggF.

- Events not passing selection for HH categories are tested for $t\bar{t}H$ for combined analysis of κ_λ and κ_t.



Category	MVA	$\tilde{M}_X$ (GeV)
VBF CAT 0	0.52–1.00	>500
VBF CAT 1	0.86–1.00	250–500
ggF CAT 0	0.78–1.00	>600
ggF CAT 1		510–600
ggF CAT 2		385–510
ggF CAT 3		250–385
ggF CAT 4	0.62–0.78	>540
ggF CAT 5		360–540
ggF CAT 6		330–360
ggF CAT 7		250–330
ggF CAT 8	0.37–0.62	>585
ggF CAT 9		375–585
ggF CAT 10		330–375
ggF CAT 11		250–330

Models + Systematics

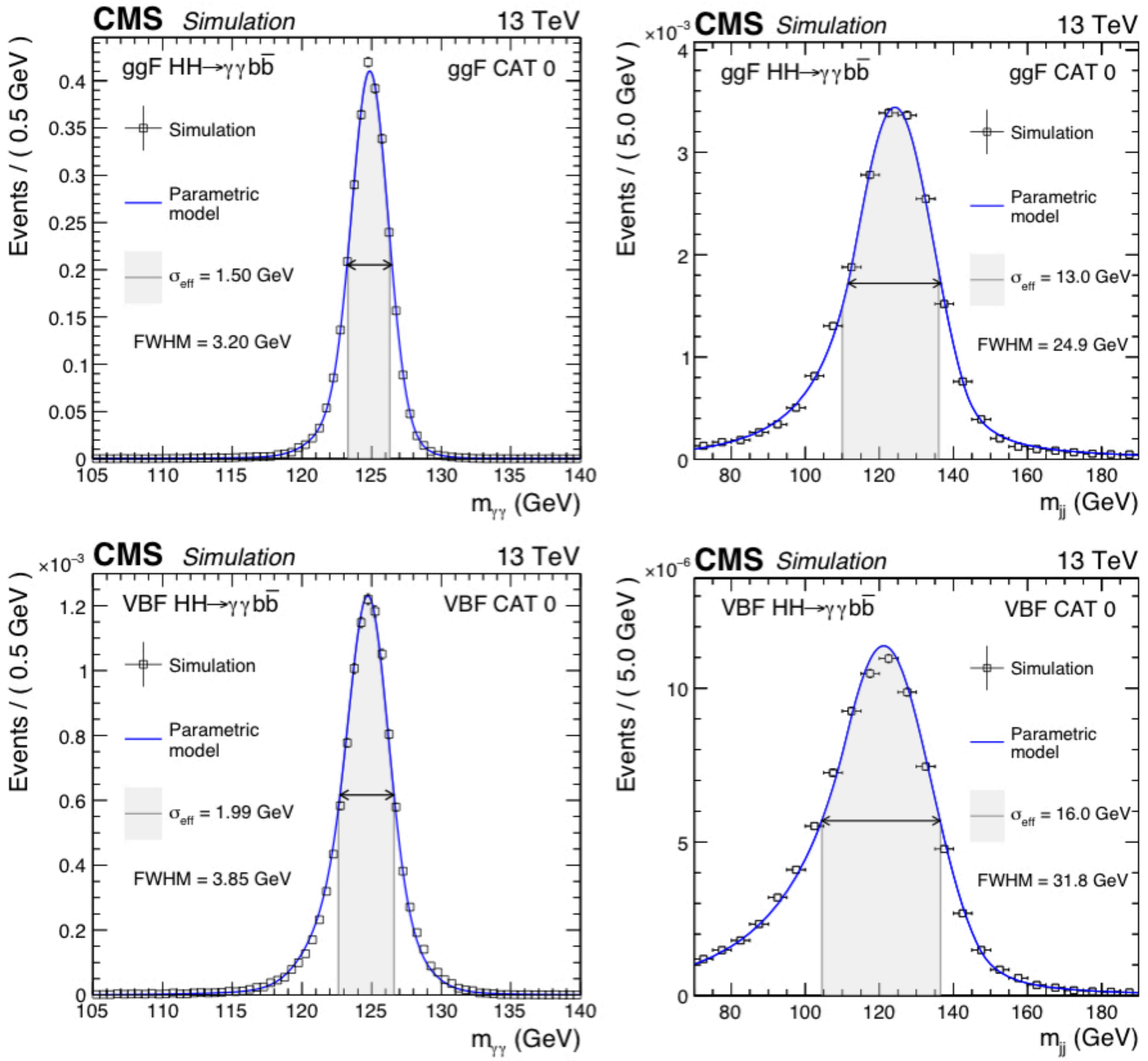
- To extract the signal, in each HH categories, we perform fits in $(m_{\gamma\gamma}, m_{tt}) \rightarrow$ need a shape template $\rightarrow$ simulation.

- Final 2D signal model is product of m_{jj} and $m_{\gamma\gamma}$. Correlations are not significant (by comparing simulated $m_{jj} - m_{\gamma\gamma}$ in signal samples with the built 2D one).

- Single Higgs background (resonant) shape is constructed from same methodology.

- Non-resonant background model extracted from data. Uses profiling method that consideres analytical function choice as nuisance, when profiling.

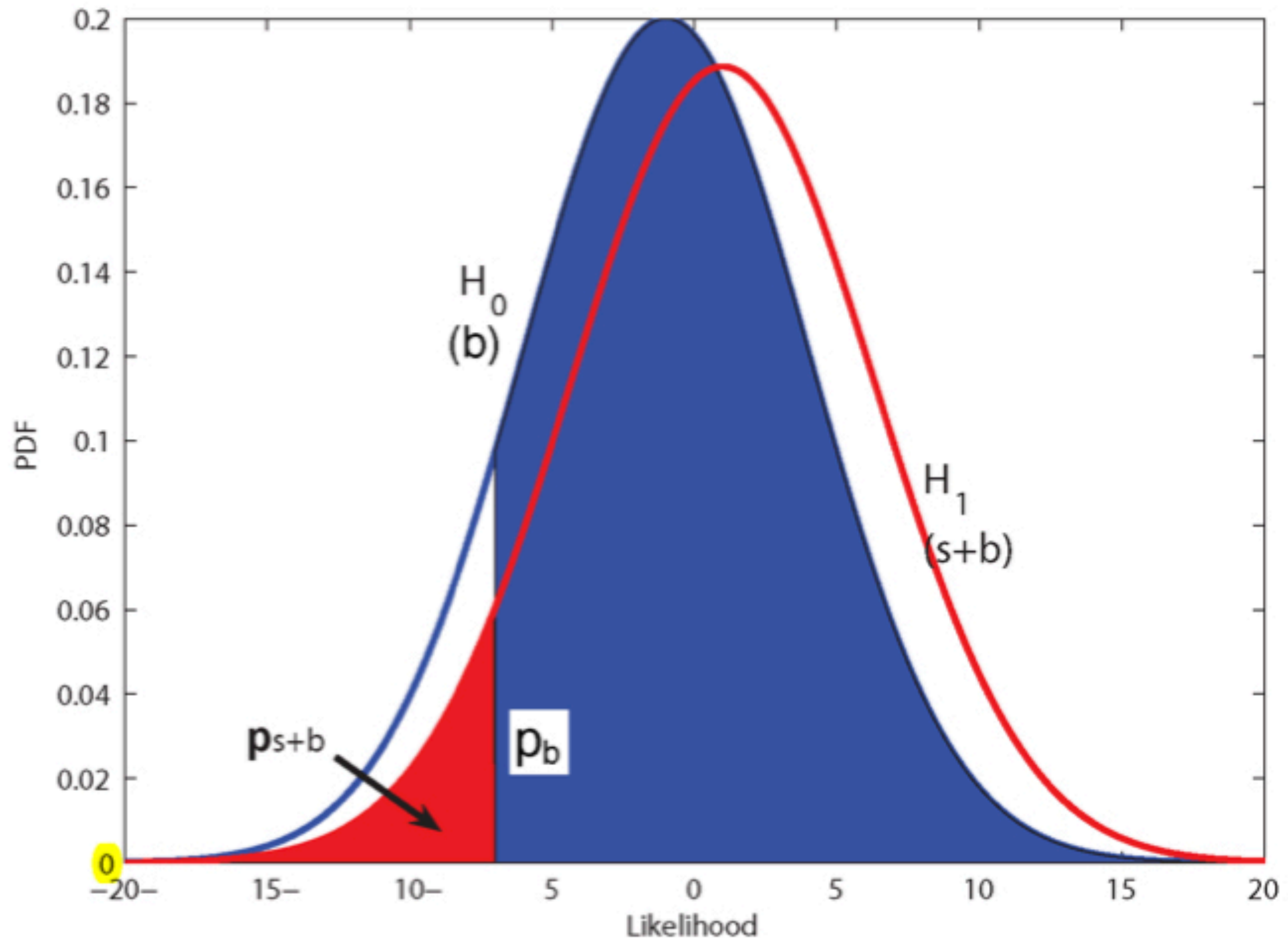
- **Systematics**: only affect 1st two models (data-driven method accounts for $\neq$ function choices). A study of main sources confirms statistical limitation of this search. (impact: 2%)

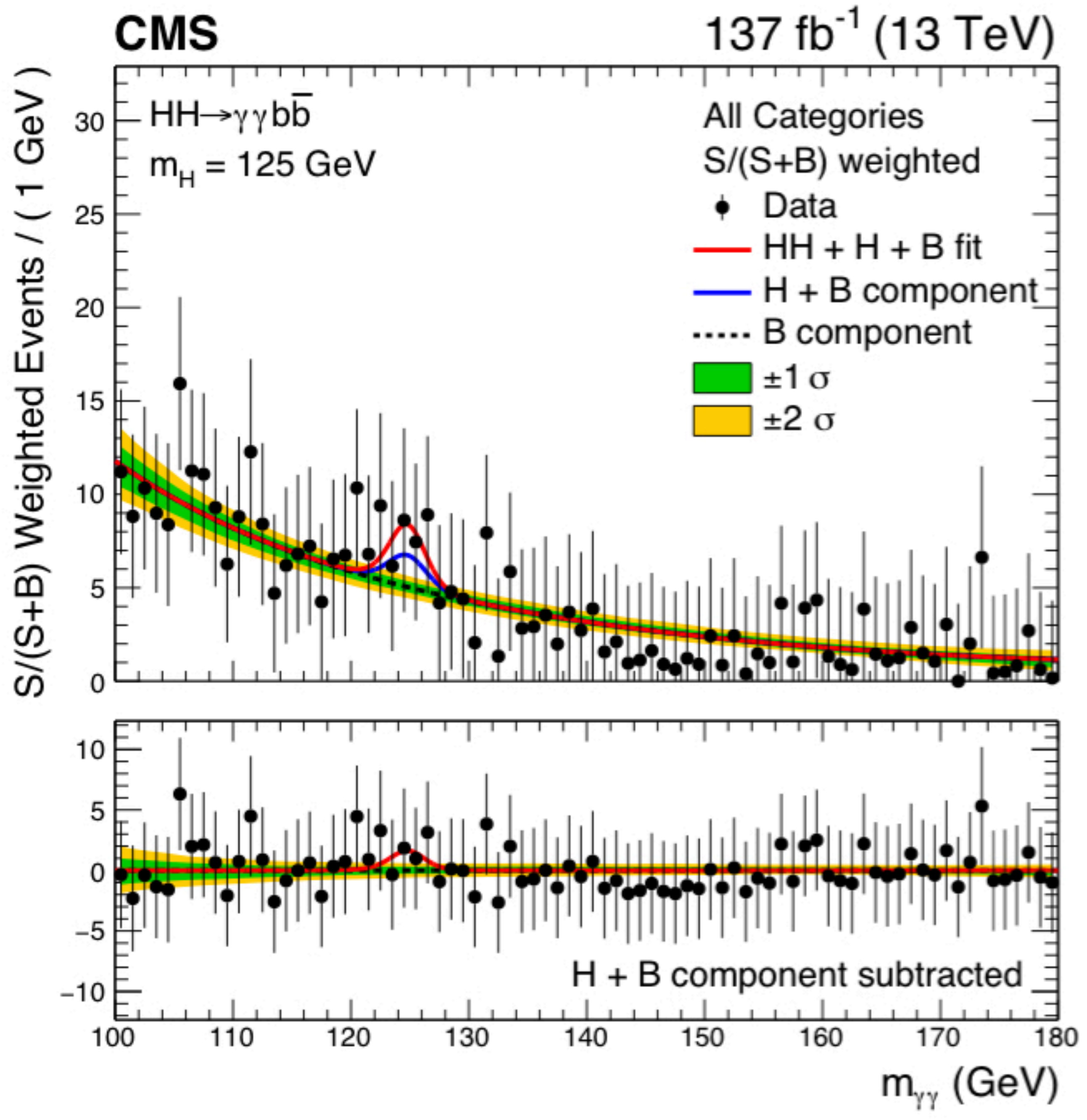


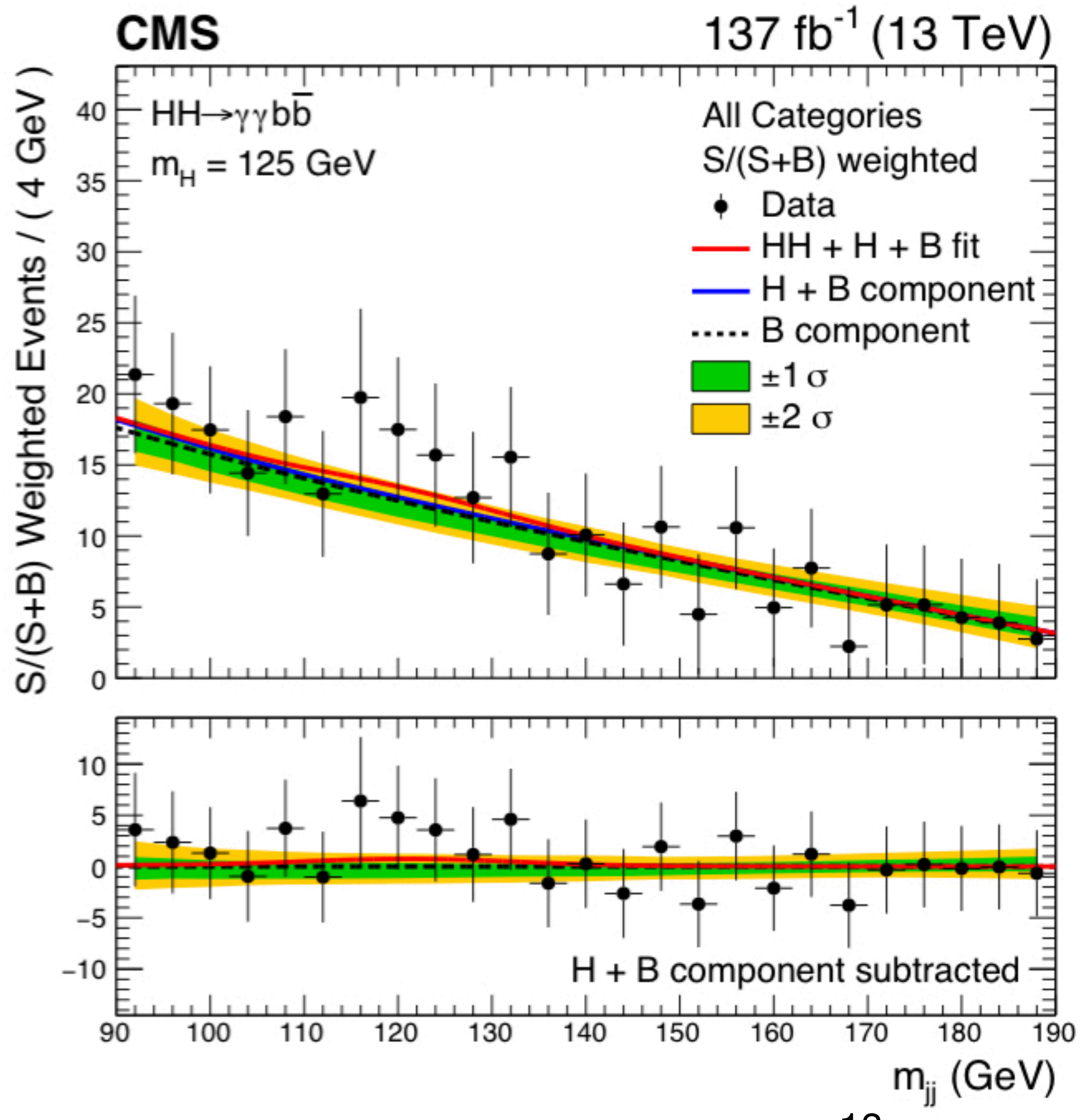
CL_S + Results

- **Sensitivity problem:** when sensitivity is ↓ we might reject the null when the alternate also deserves it (low power agains alternate).

- **Solution:** $p'_{s+b} = \dfrac{p_{s+b}}{1 - p_b} < 5\%$ for exclusion (prob of falsely rejecting s+b is ↓ + prob of correctly accepting b-only is ↑, protected agains downward b fluctuations setting arbitrarily small limits).







- To extract HH signal: fit to all 14 HH categories w/ L defined for each using s and b models + nuisance theoretical and experimental systematics.

- No significant deviation from b-only.

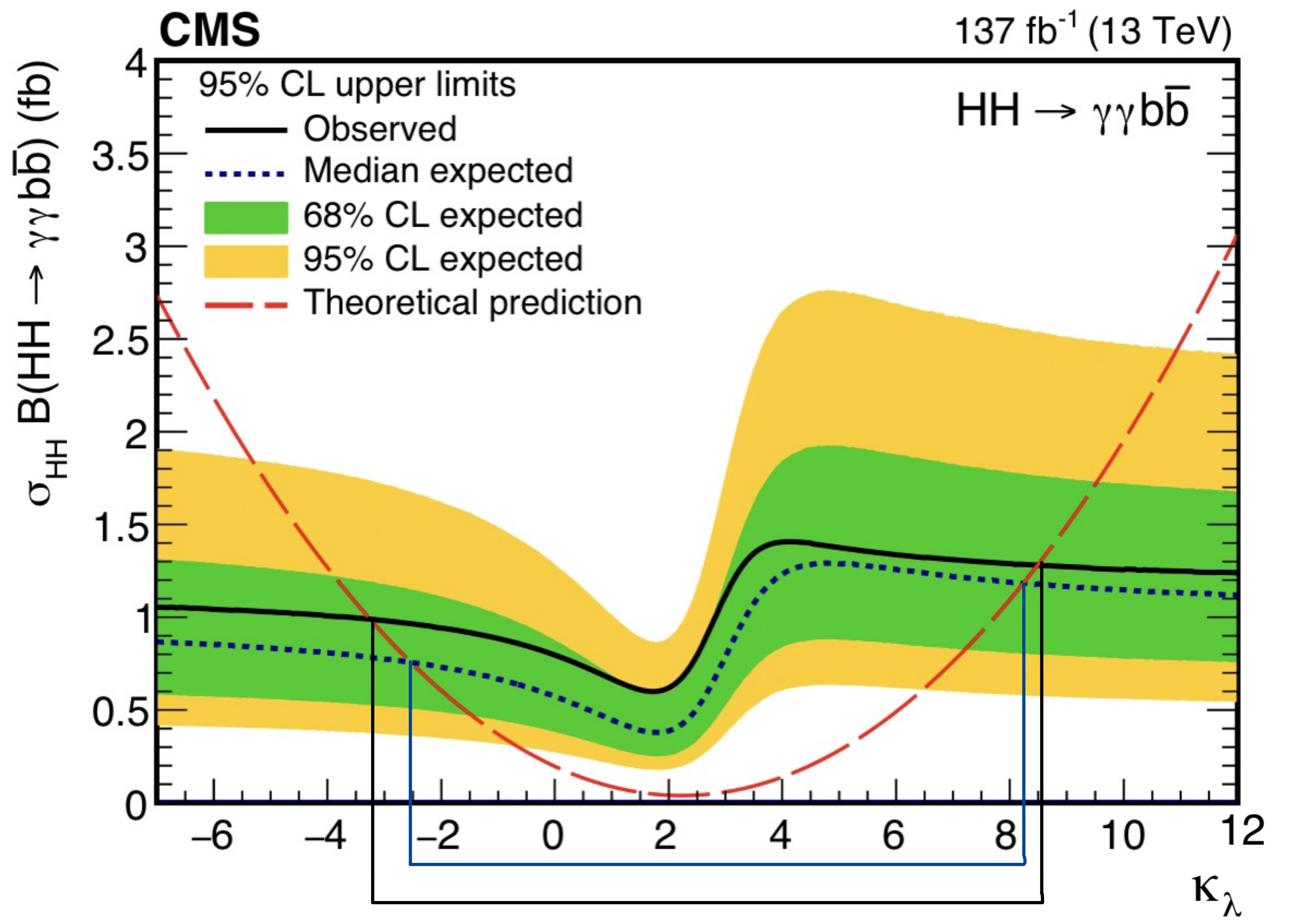
- 95% CL on $\mathscr{B}(HH \to \gamma\gamma b\bar{b}) = 0.67(0.45)$ fb 7.7 (5.2) × SM.

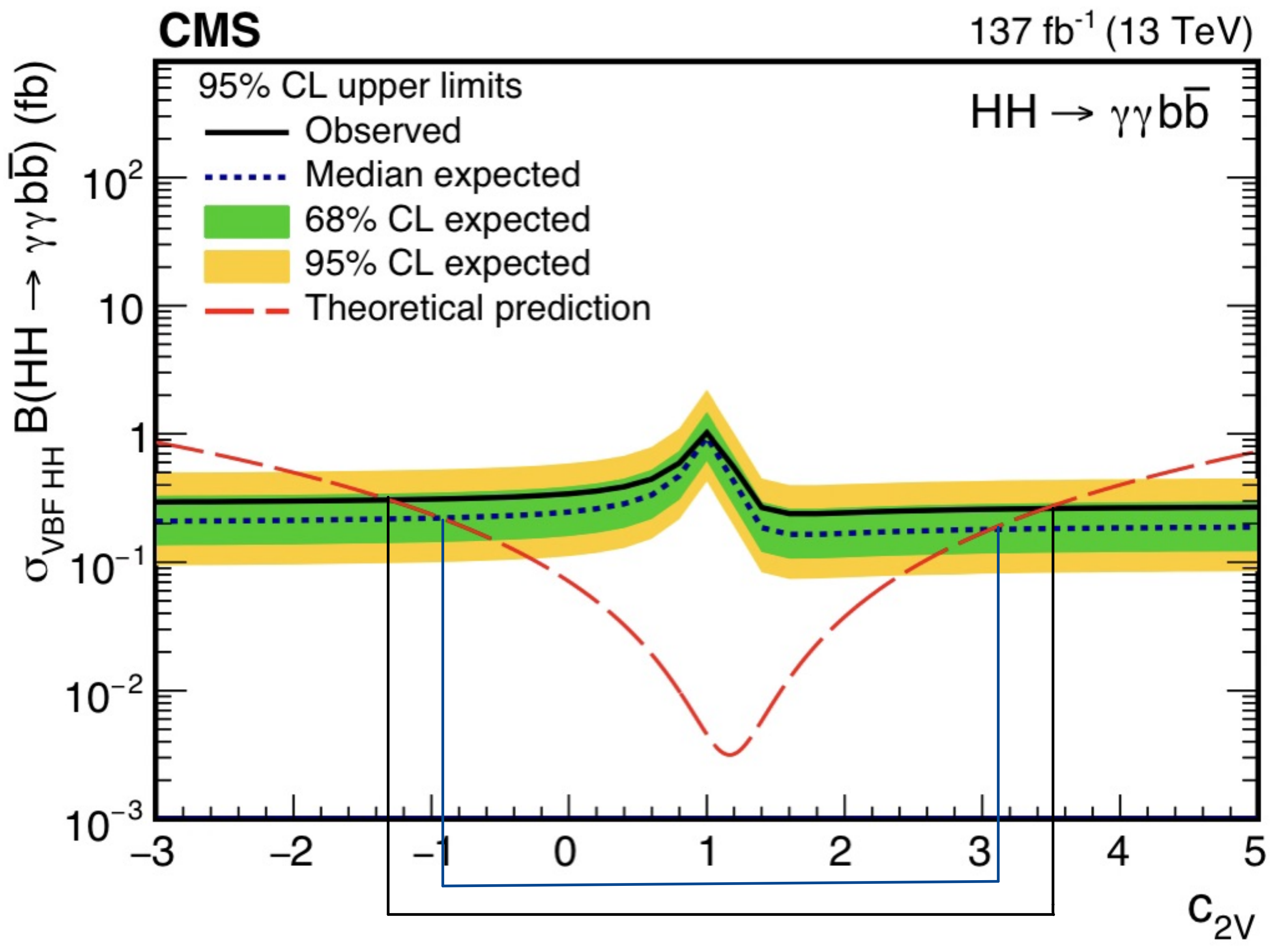
Results: Brasilian-flag plots

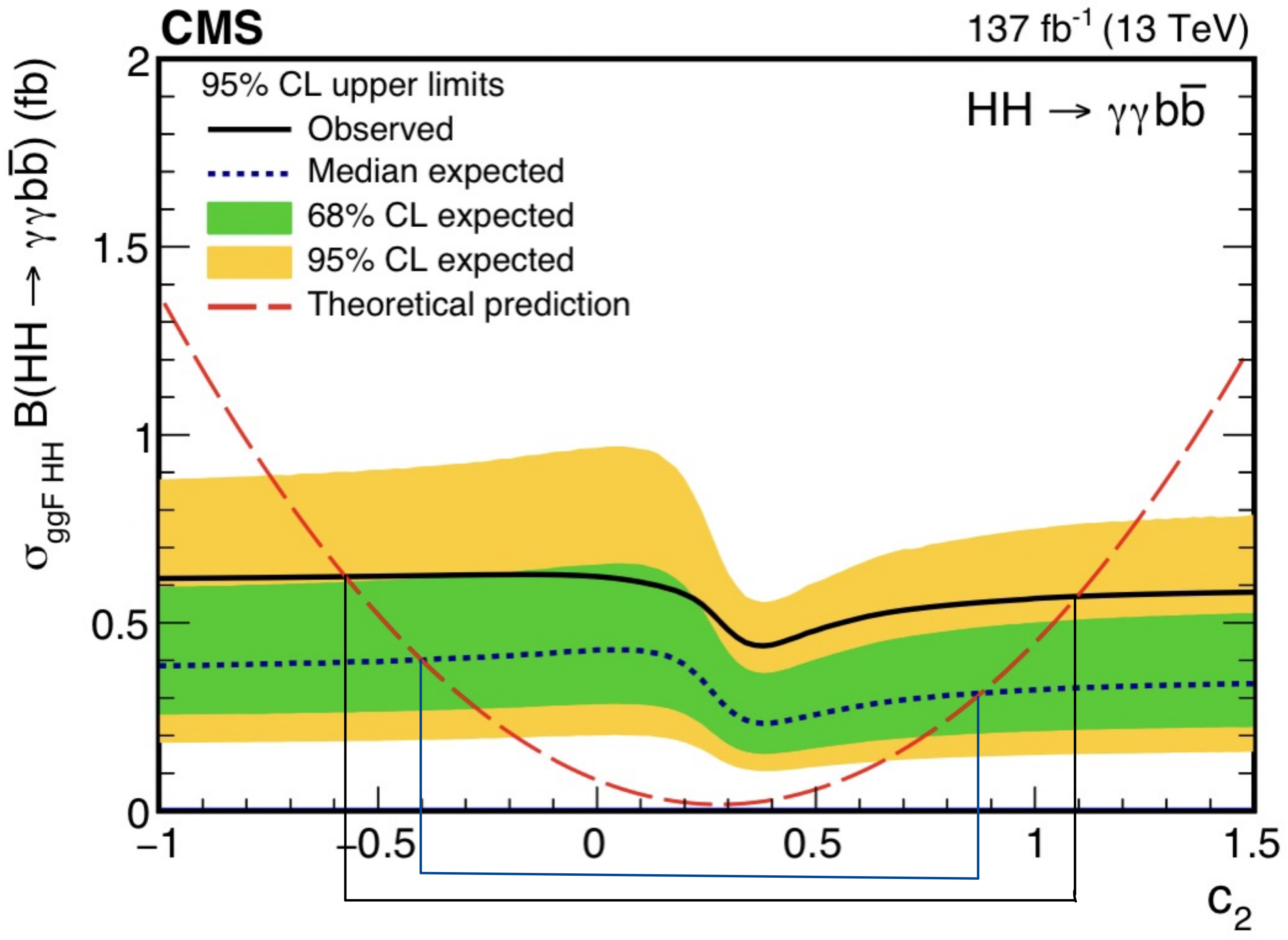
- Limits can be set (using all HH categories) as a function of κ_λ, assuming SM-like properties for other processes ($\kappa_t = 1$).

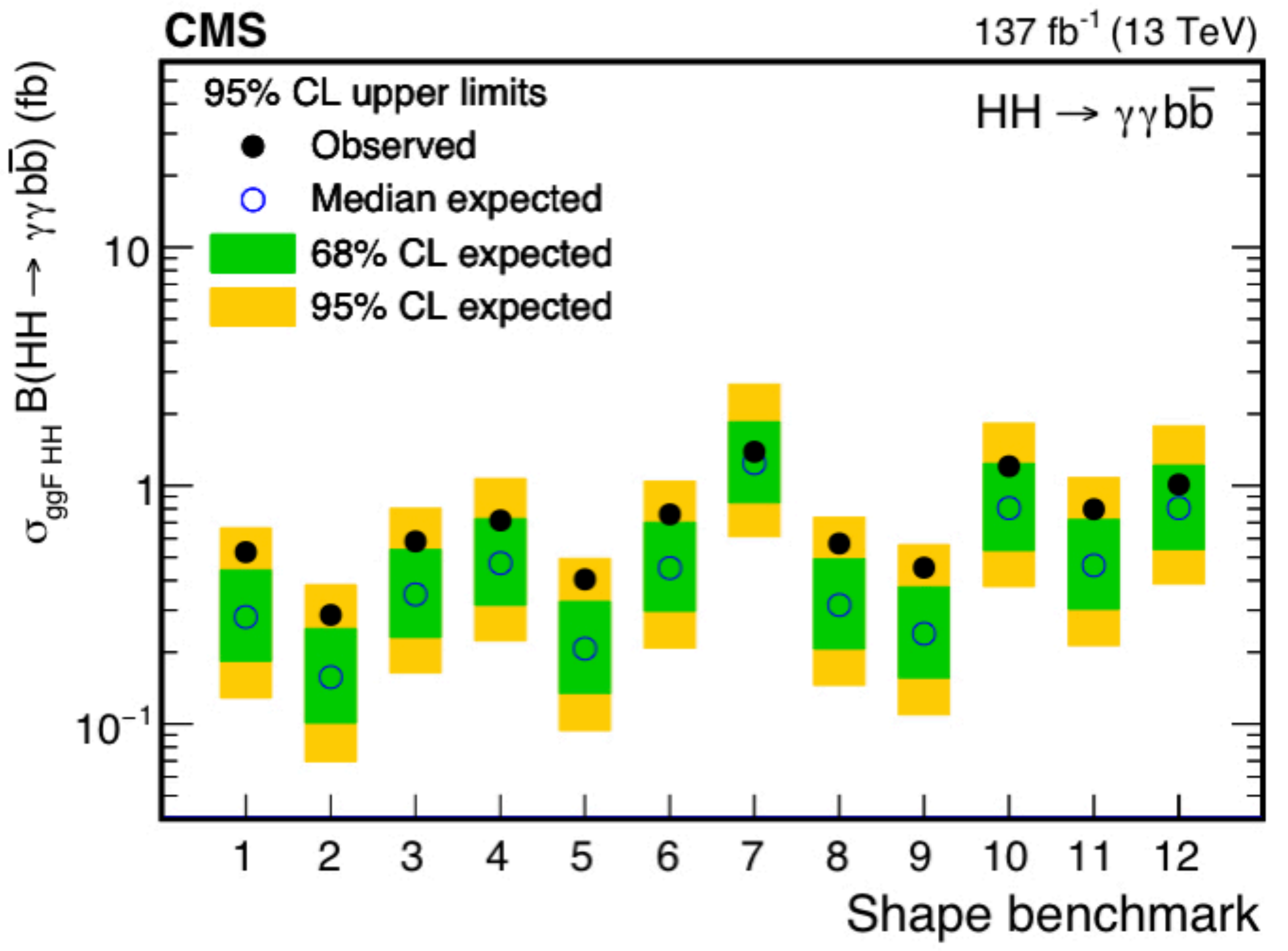
- Taking advantage of categorisation = focusing on one category and constraining yield of mutually exclusive ones to SM signals.

- Upper limits on $\sigma_{\text{VBF HH}}\mathscr{B}(HH \to \gamma\gamma b\bar{b} = 1.02(0.94)$ fb or 225(208) × SM (most stringent).



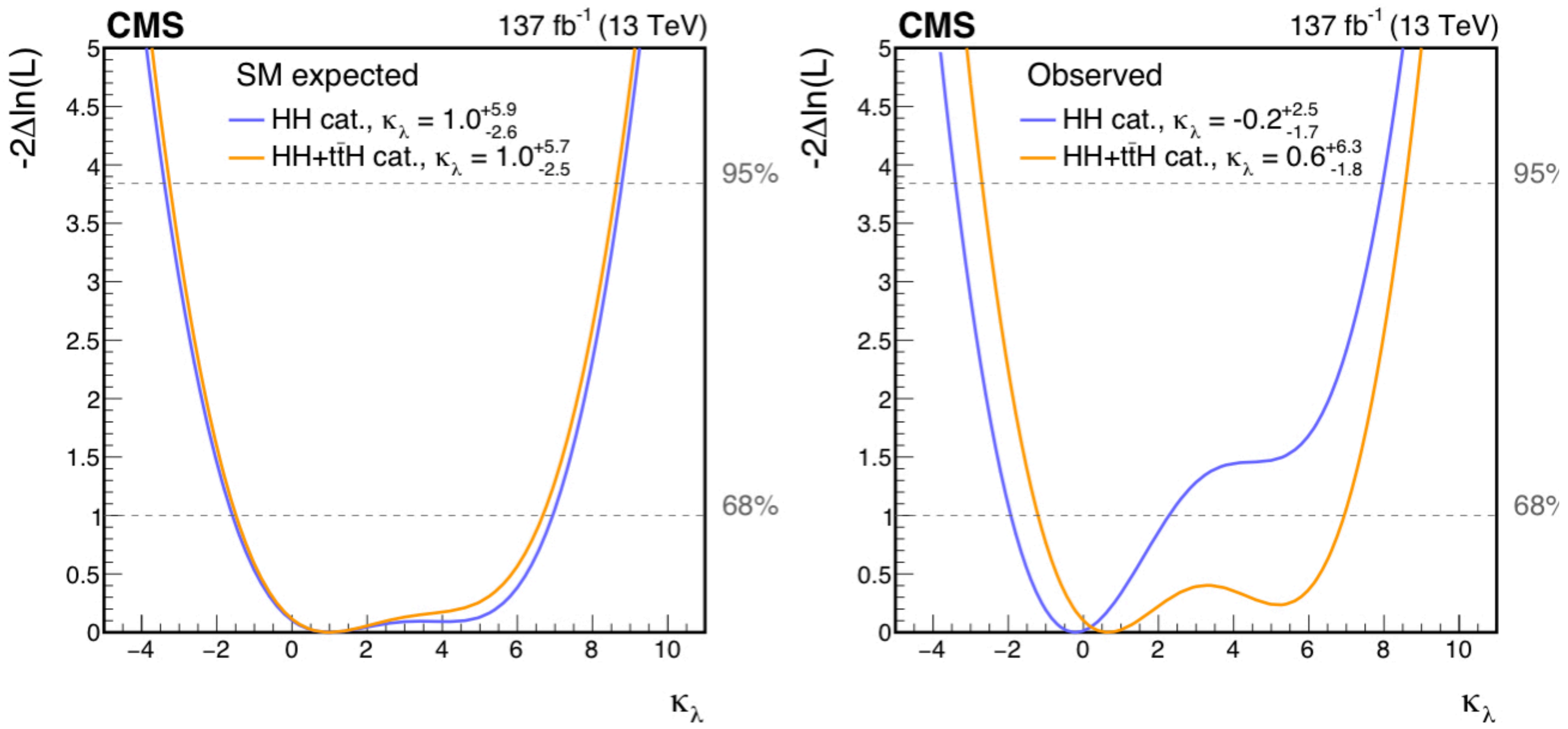


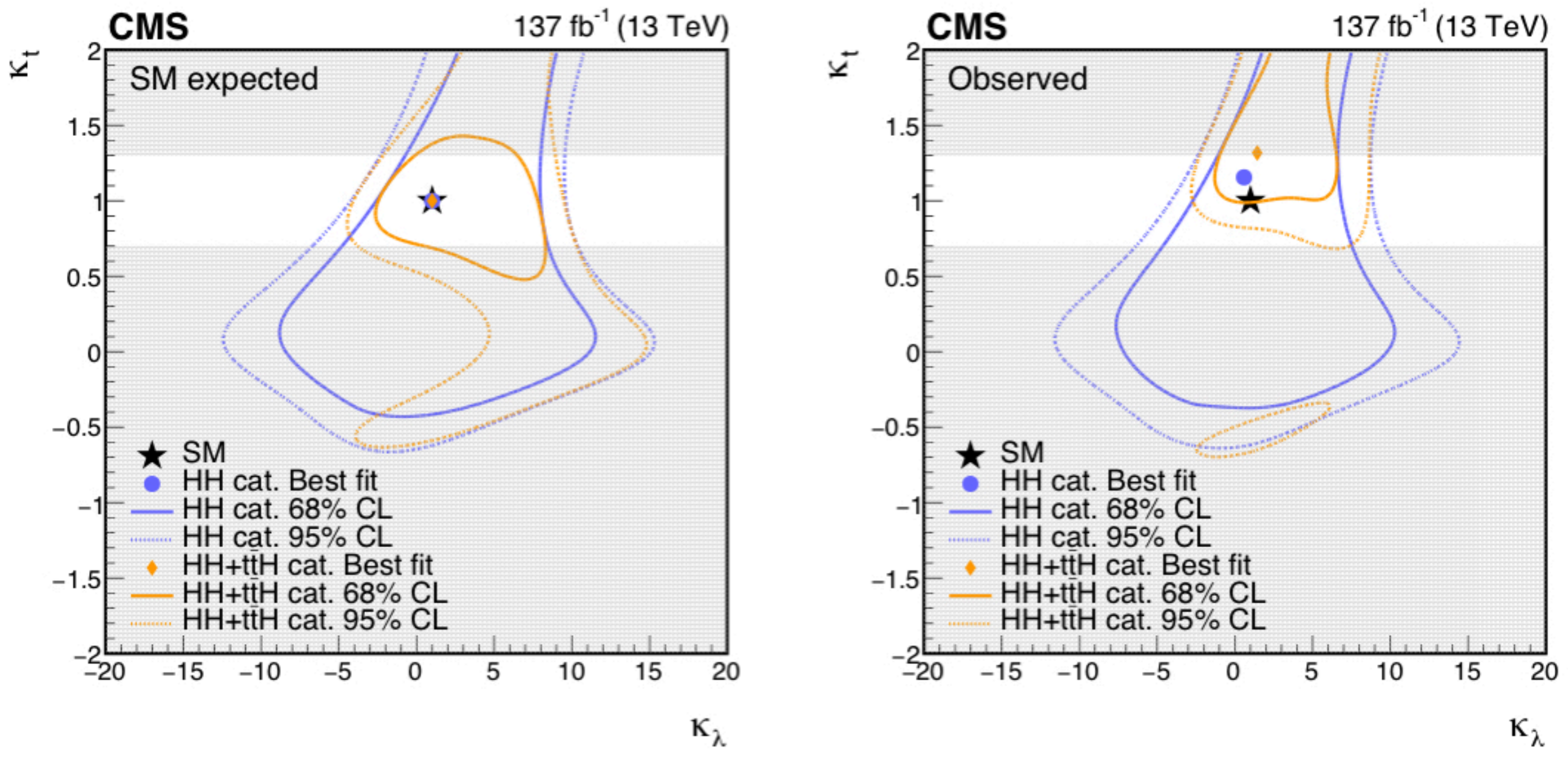


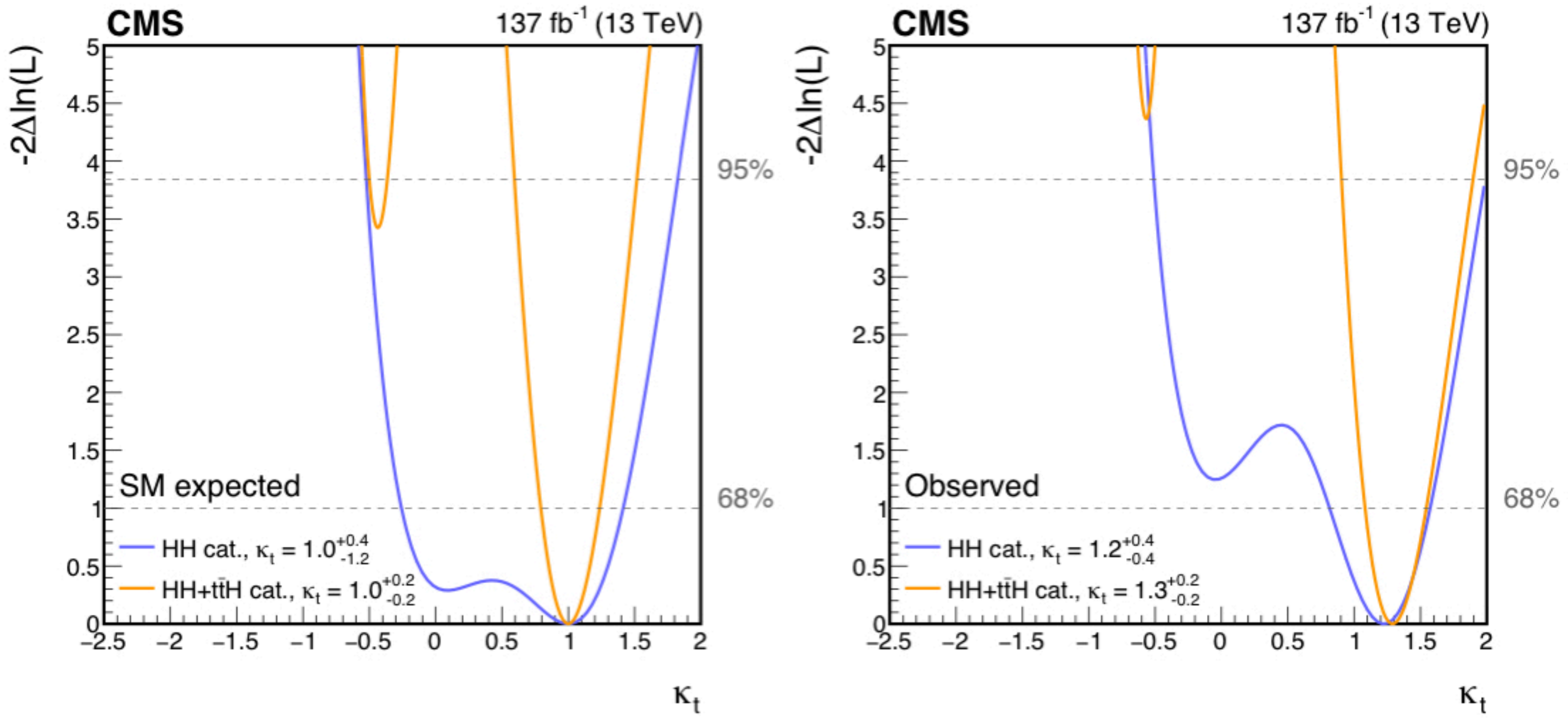


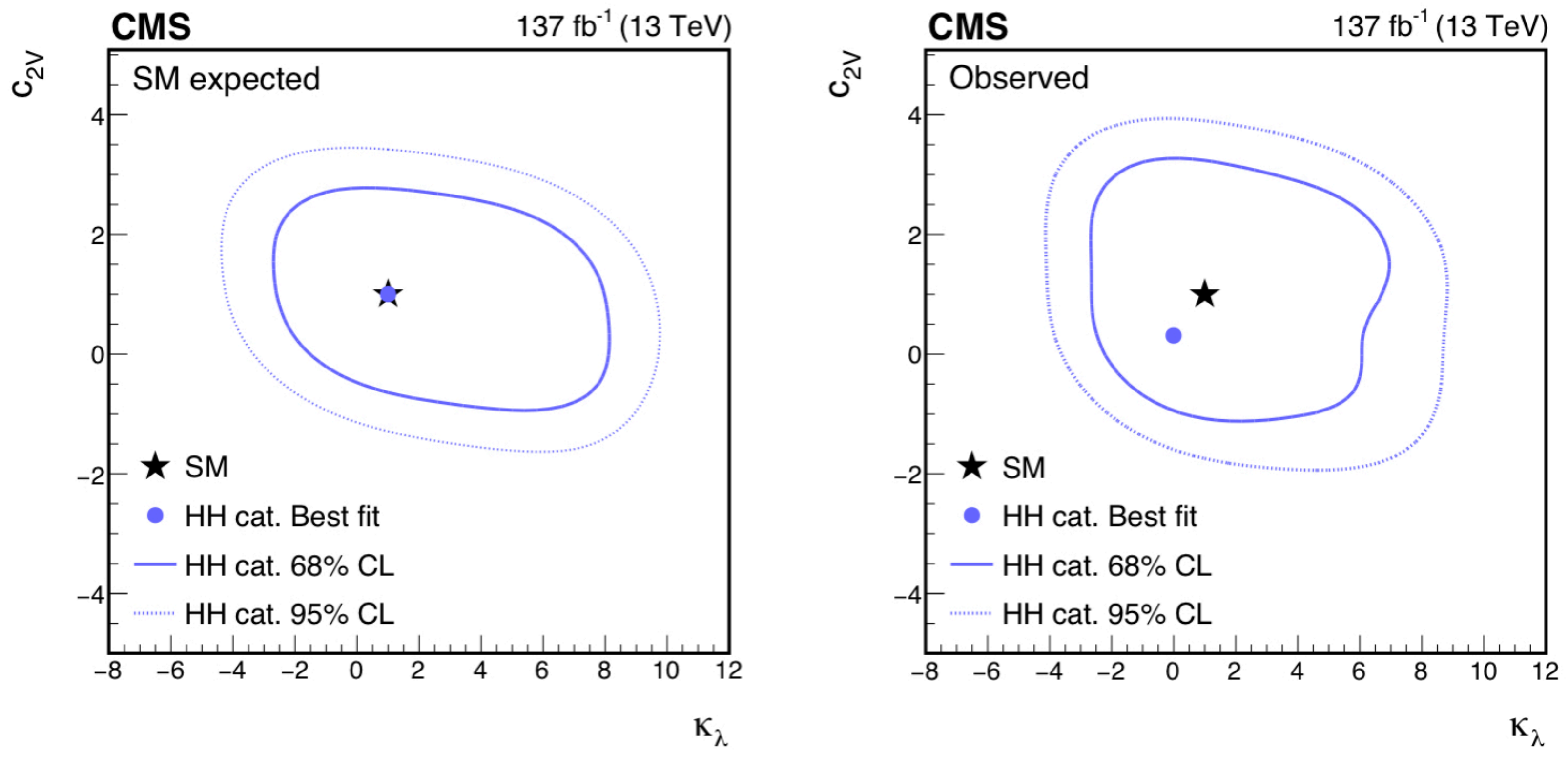
Results: Combined Searches

- If we assume a a HH signal with SM properties we can constrain κ_λ, κ_t, c_{2V}
- Combining HH categories with $t\bar{t}H$ one (signal extracted from $m_{\gamma\gamma}$ fit) we can perform further searches → evaluate likelihood on Asimov data set.



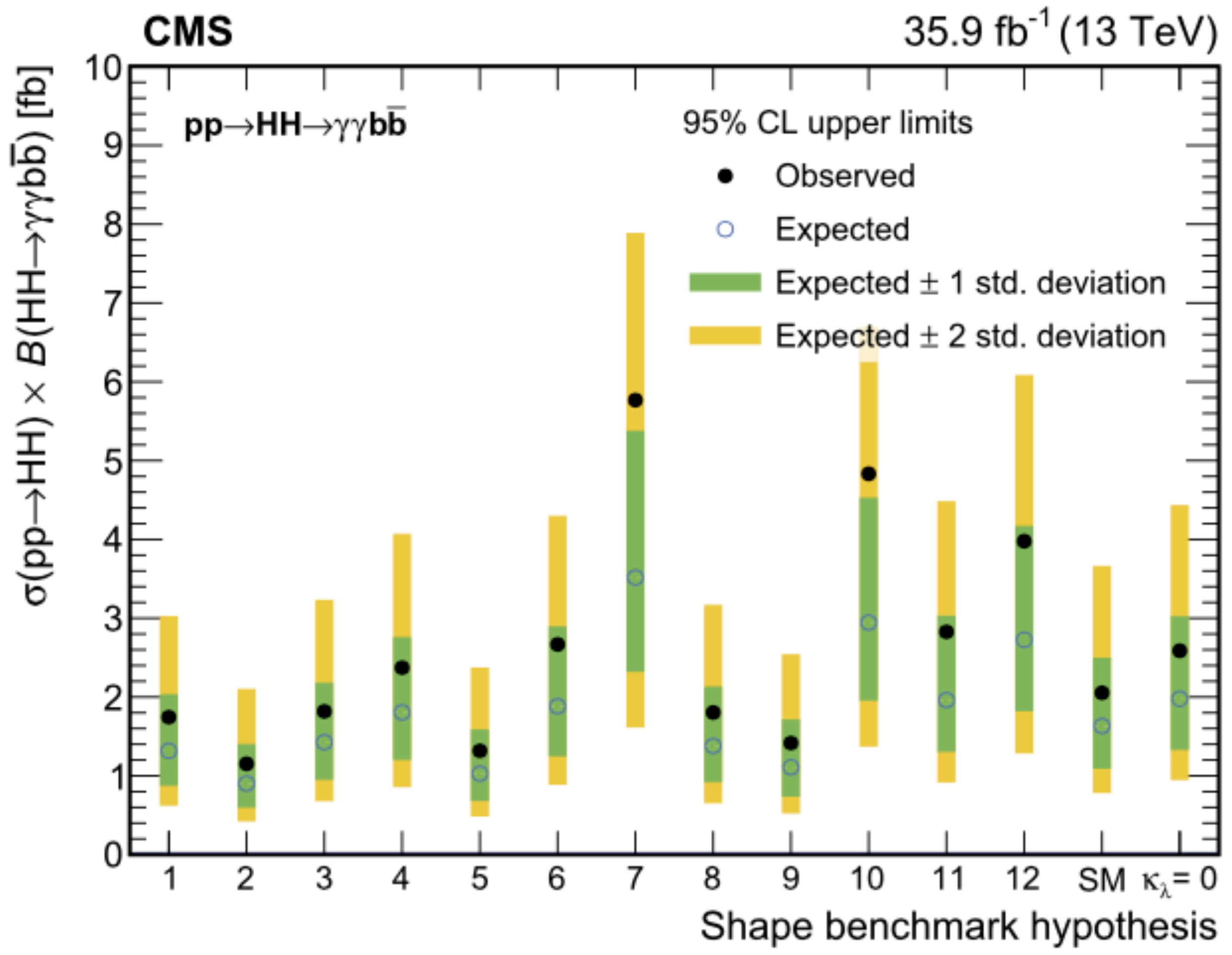


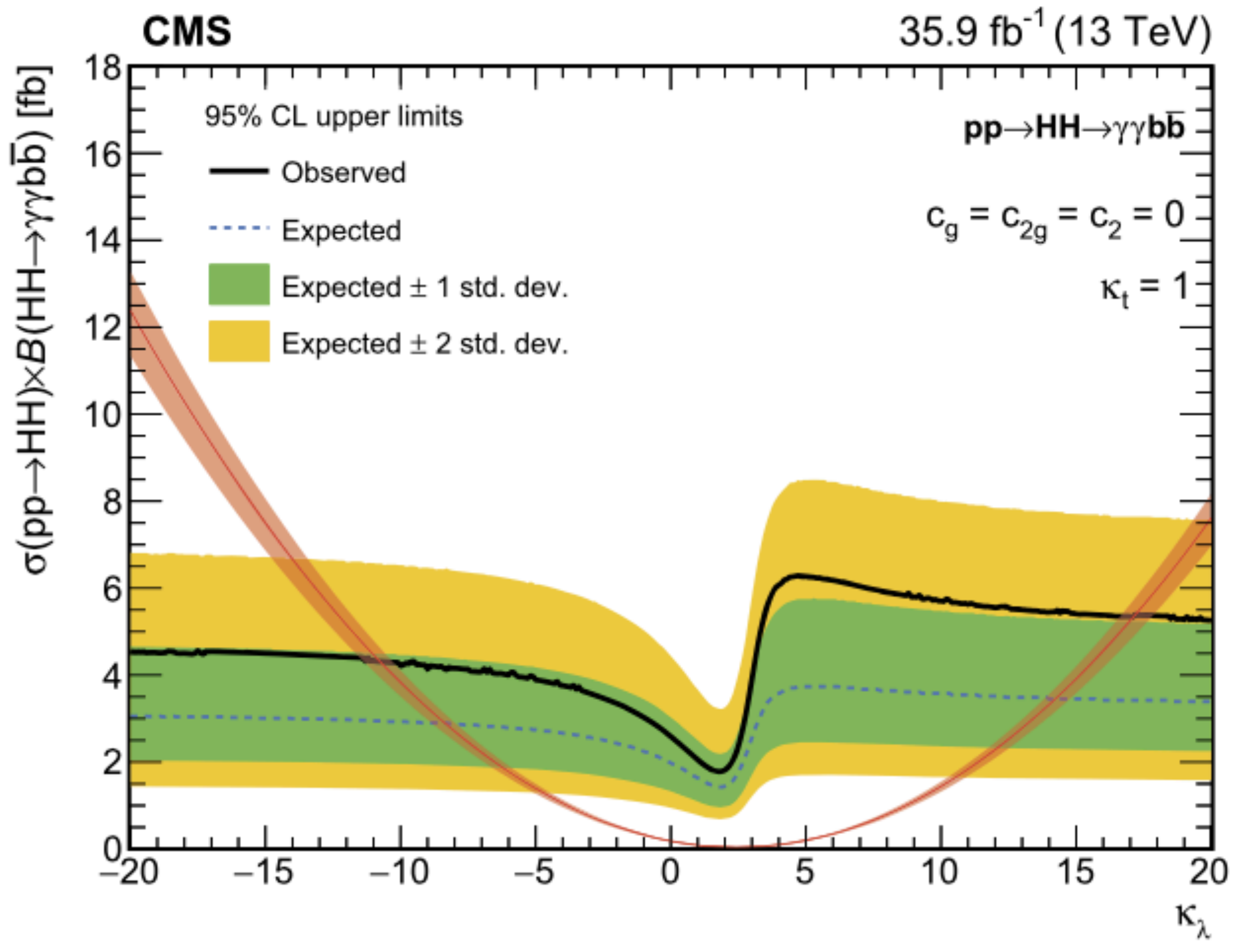




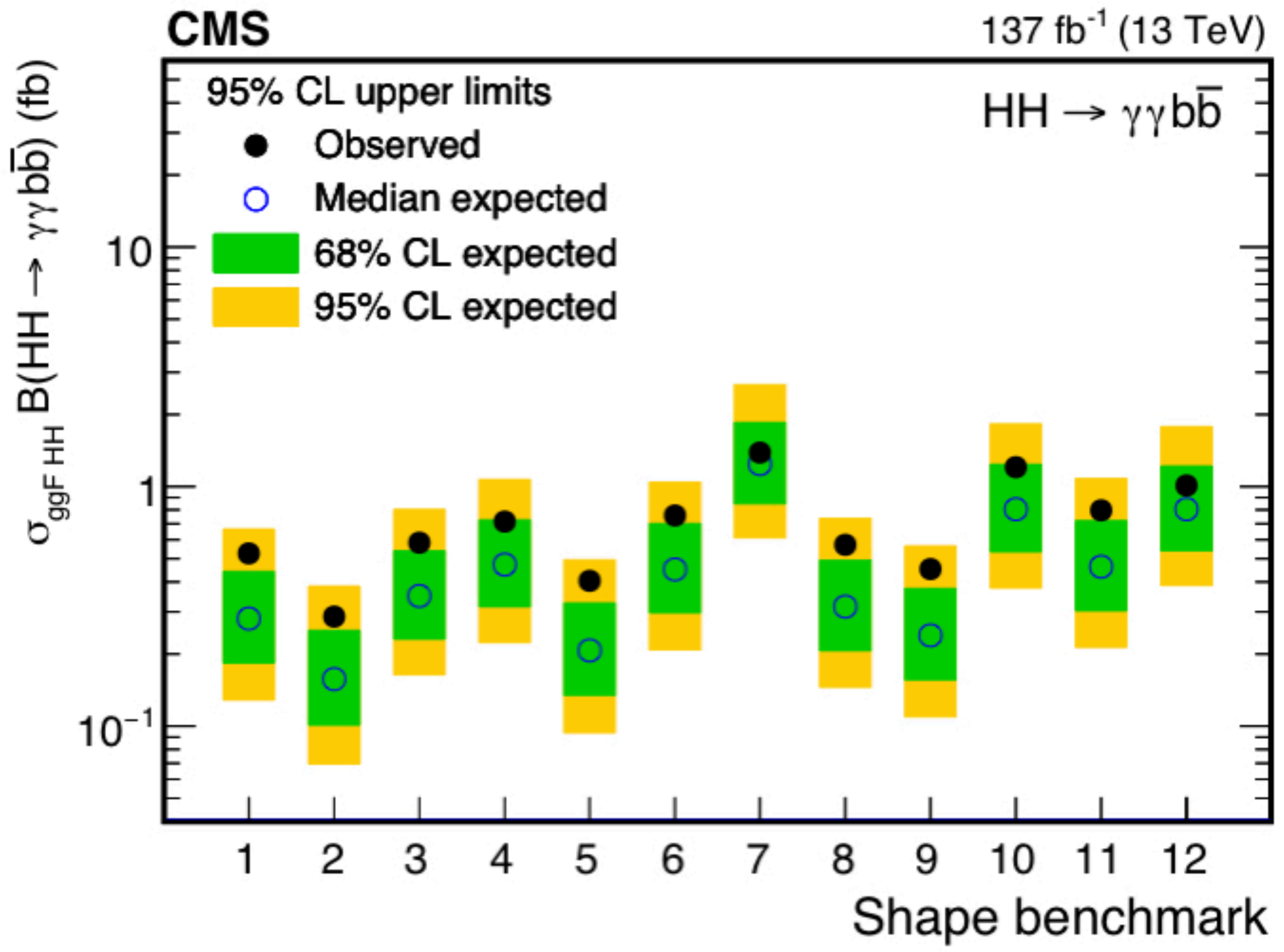
Previous best

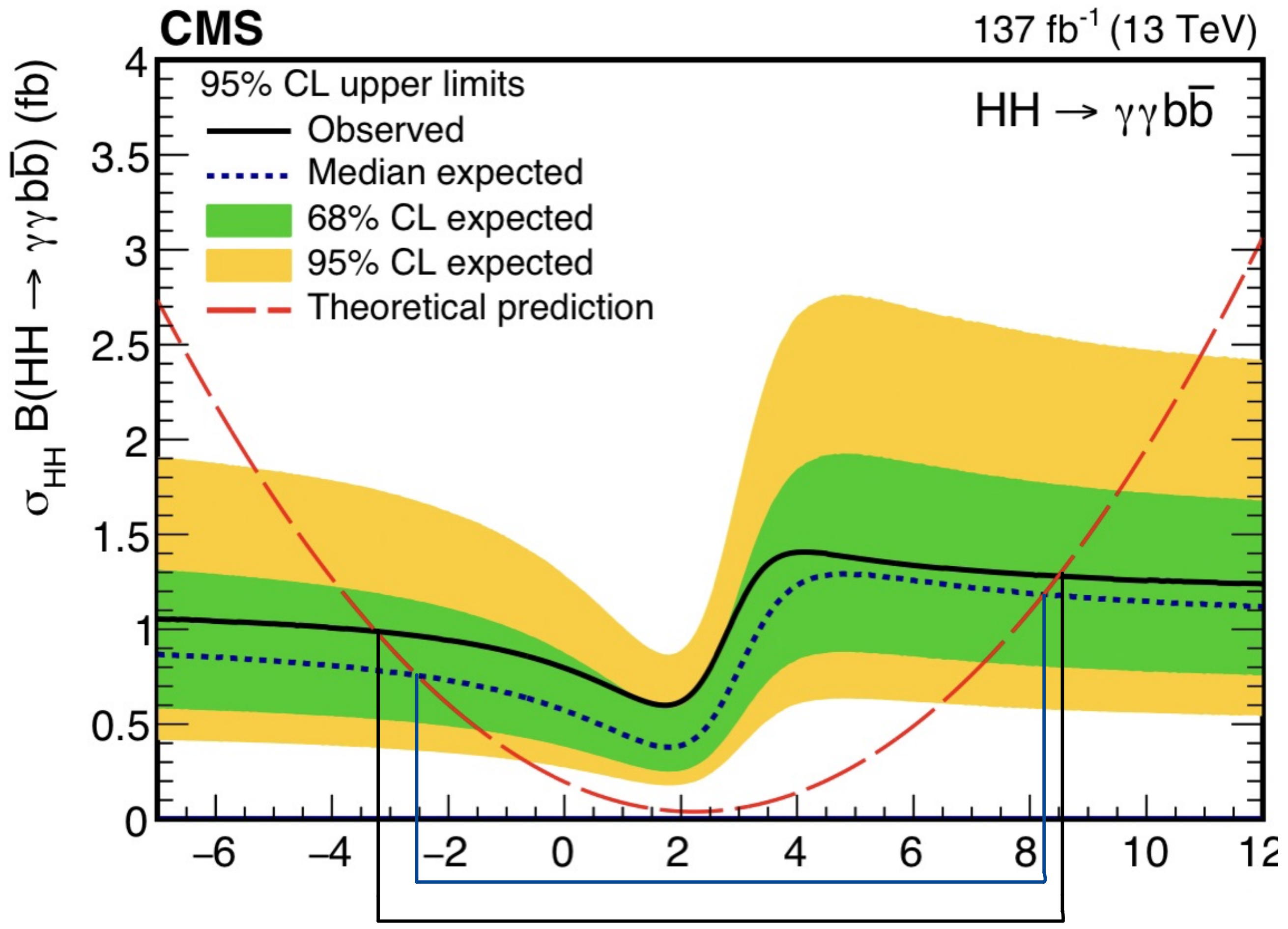
CMS 2018





CMS NOW





Atlas 2018