Search for nonresonant Higgs boson pair production in the HH → bbγγ decay channel

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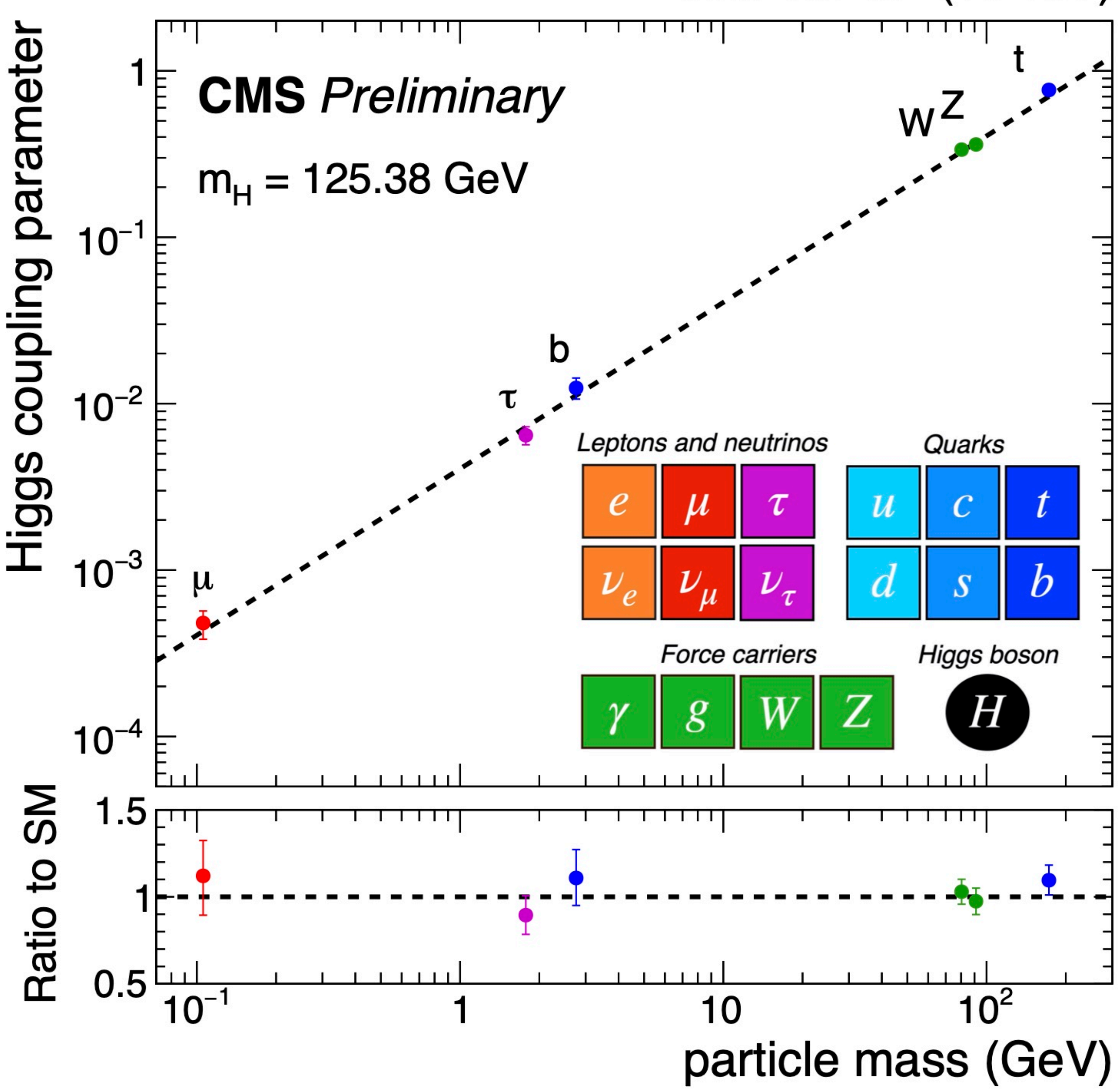
PhD advisor : *Günther Dissertori*

Higgs boson self-coupling

- mH = 125.38 ± 0.14 GeV
- Interactions with fermions and vector bosons established…

HIG-19-006



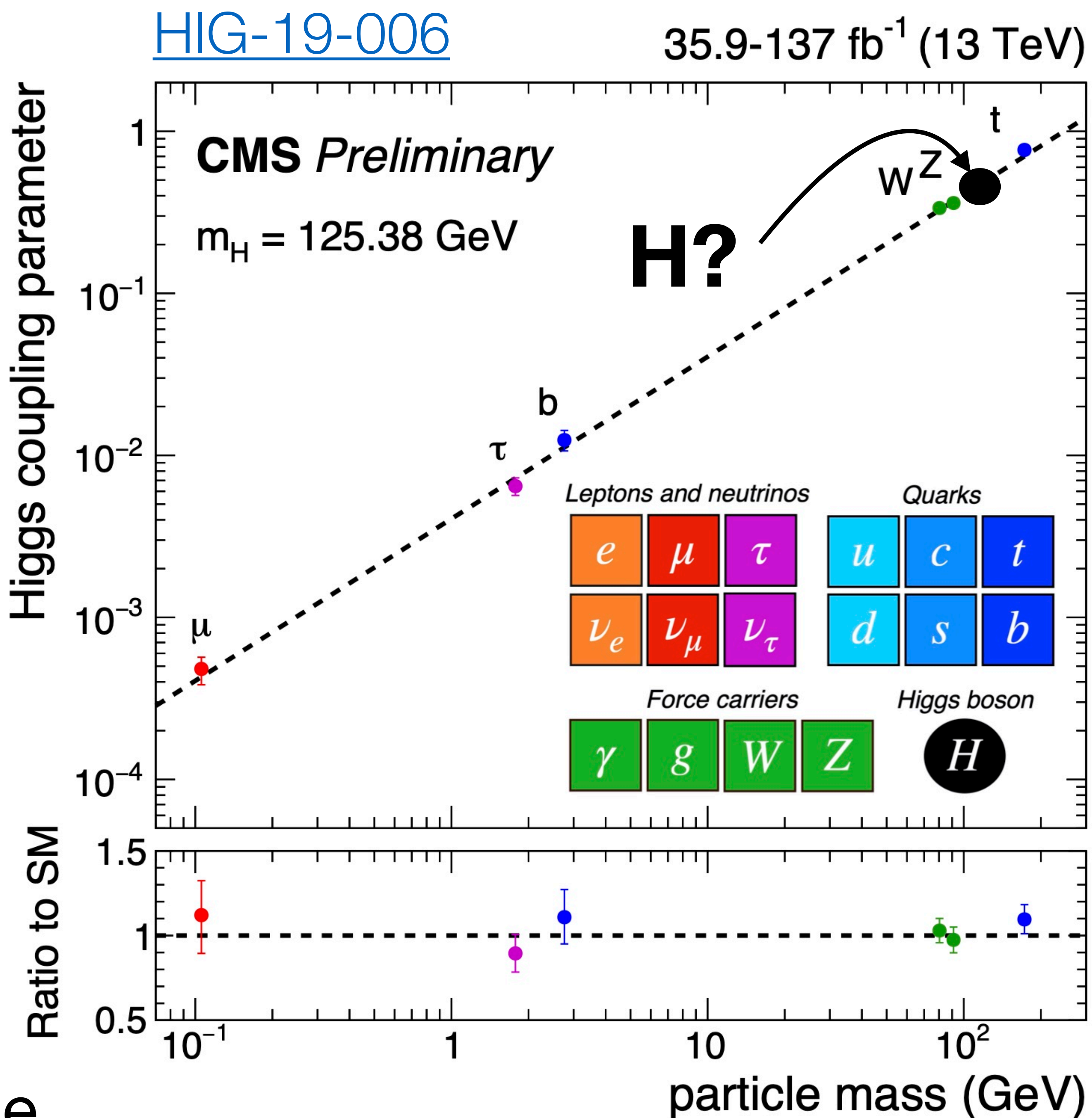
Higgs boson self-coupling

- mH = 125.38 ± 0.14 GeV
- Interactions with fermions and vector bosons established…

- But Higgs boson self-interactions are not yet measured experimentally!

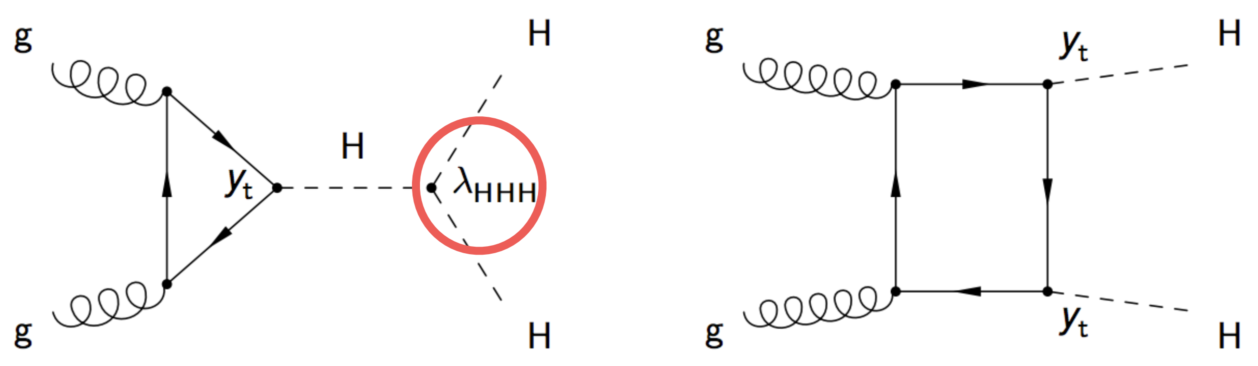
$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4 - \frac{\lambda}{4} v^4$$

$$\lambda_{HHH} = \lambda_{HHHH} = \lambda = \frac{m_H^2}{2v^2} \approx 0.13$$

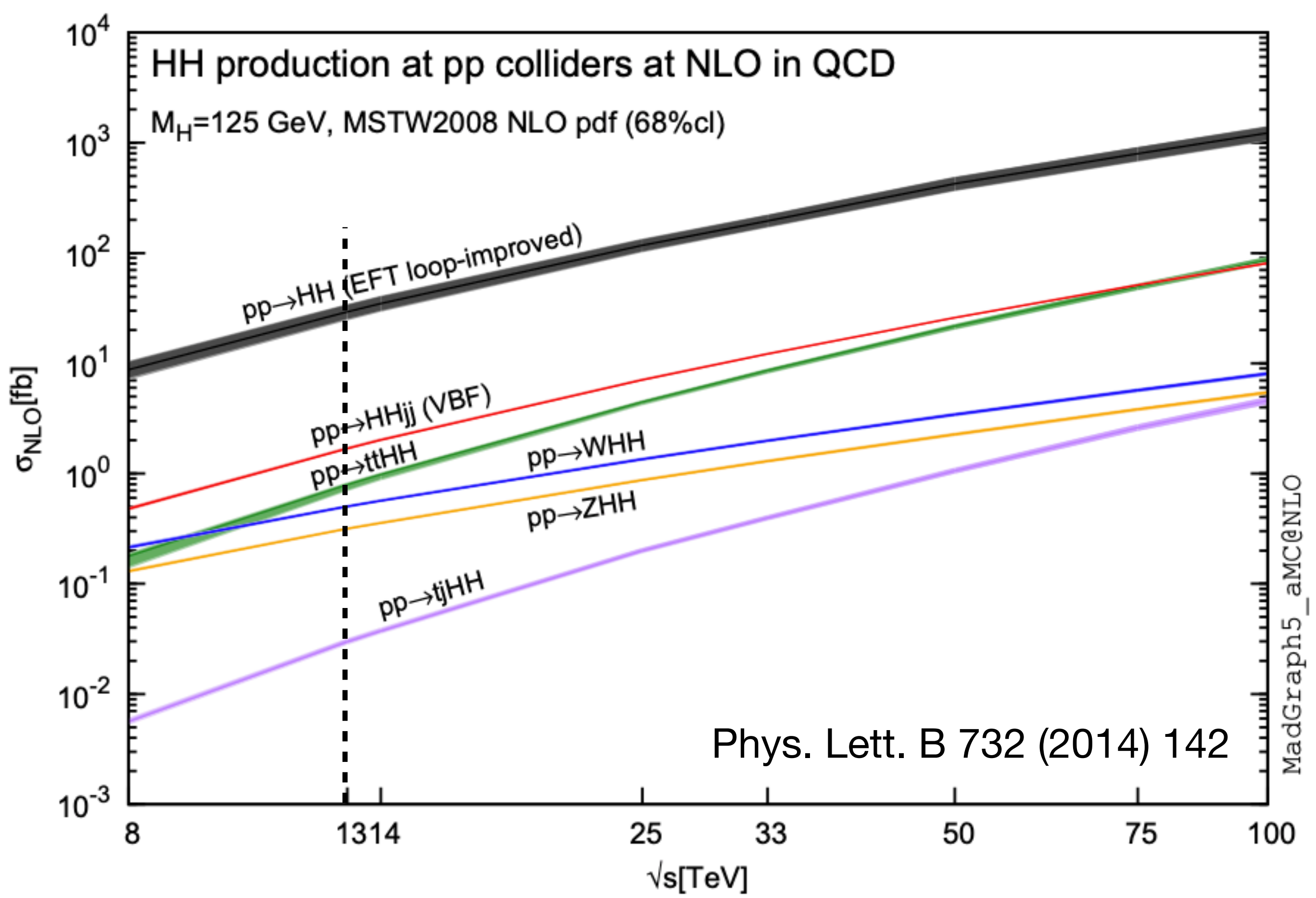


λHHH : direct access to the shape of the scalar potential

HH production in the SM : ggF



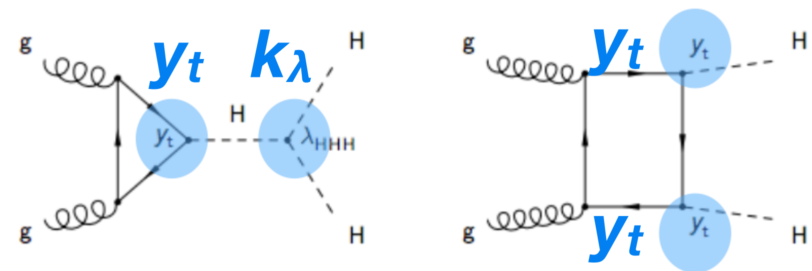
Gluon-gluon fusion (ggF) - dominant production mode : $\sigma^{SM}_{ggF\ HH} = 31.05$ fb



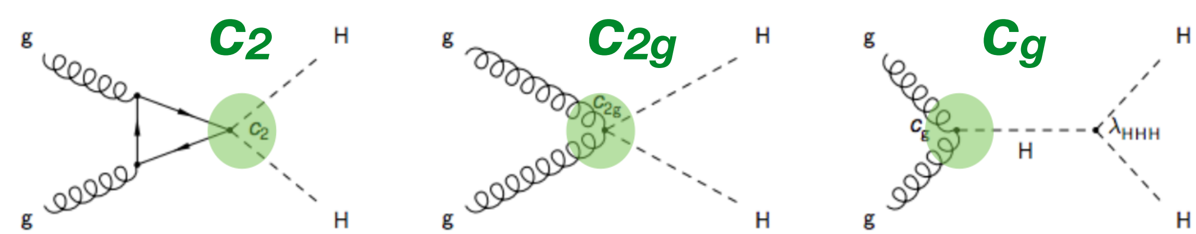
- Large destructive interference between the 2 diagrams and a **very small cross section**
- Not sensitive to SM prediction with current LHC data
- However **BSM effects** can significantly change kinematics and cross section

ggF HH : physics beyond SM

- Anomalous values of Higgs boson couplings have strong effect on kinematics and cross section

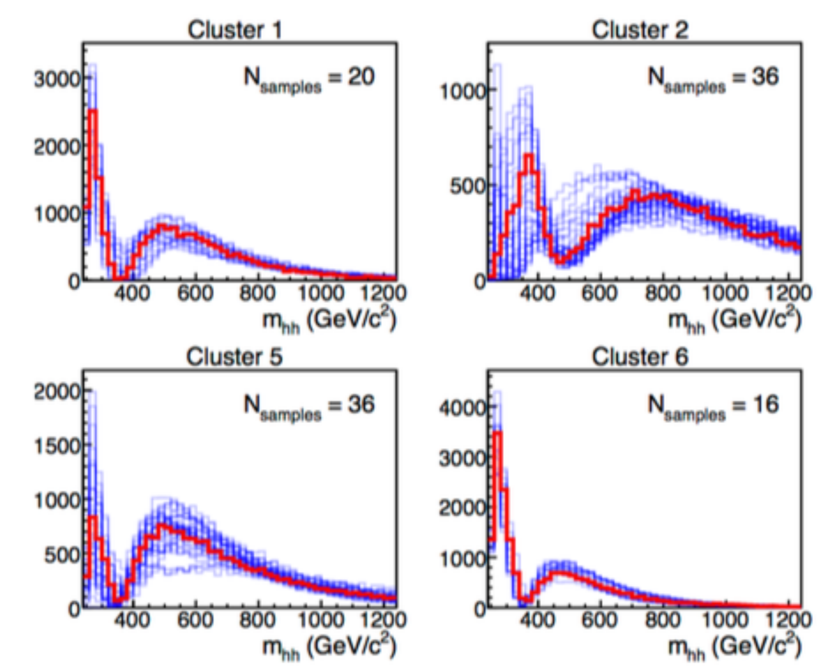


- In EFT approach ggF HH can be described by 5 parameters controlling tree-level interactions : k_λ, k_t, c_{2g}, c_g, c_2
- c_g, c_{2g}, c_2 are not predicted in SM but could arise through BSM

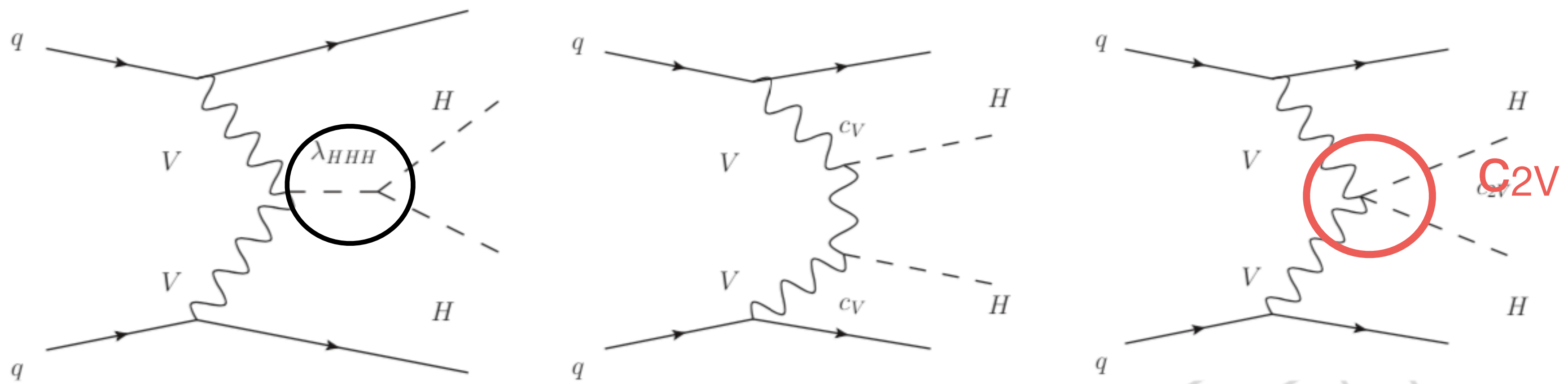


HH is a place to look for BSM physics with current LHC data

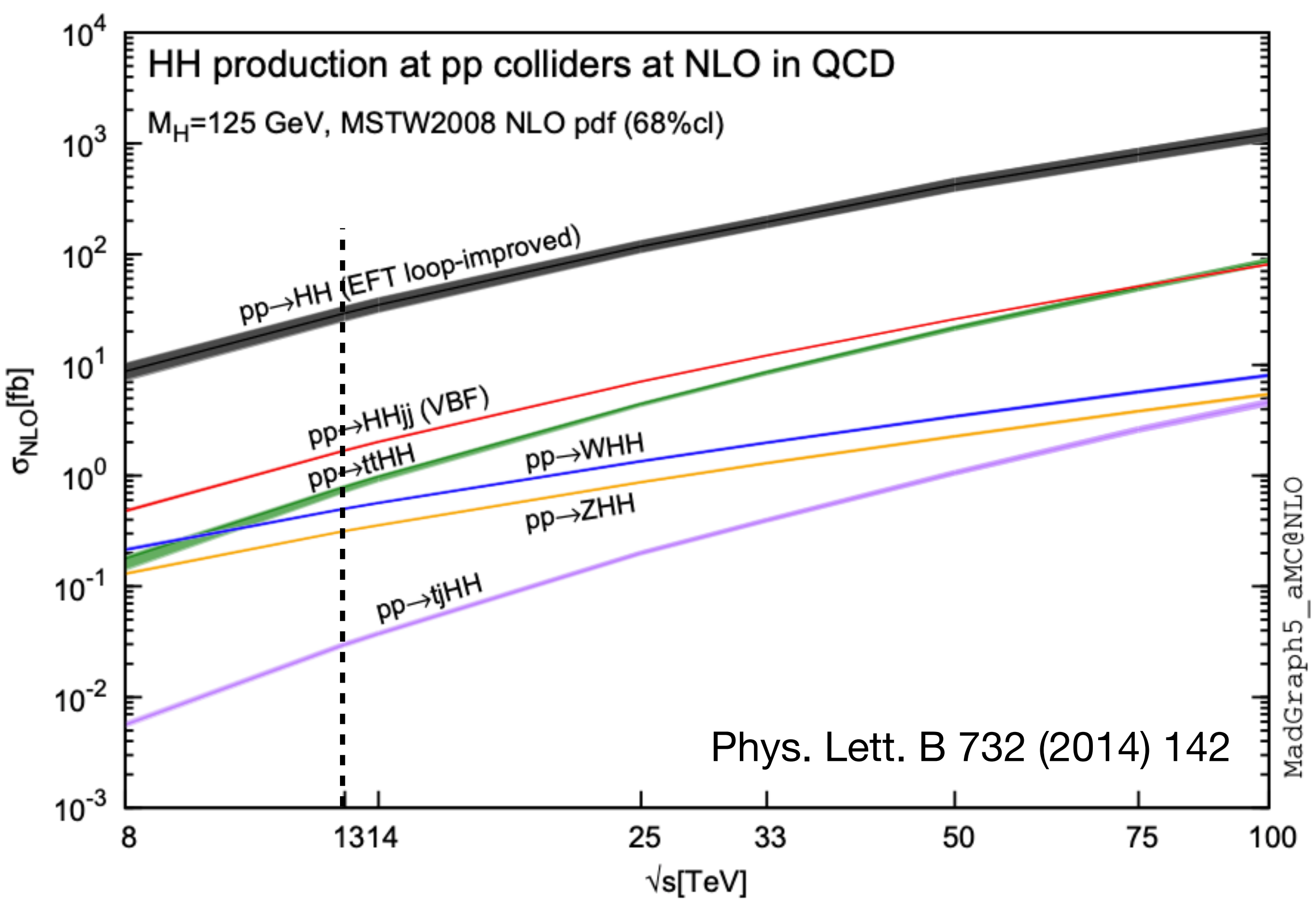
- Cluster points in 5D coupling space and create benchmarks with similar kinematics [Ref]
- Set limits on production of these benchmarks models and anomalous values of k_λ, k_t, c_{2g}, c_g, c_2



m(HH) for BSM benchmarks



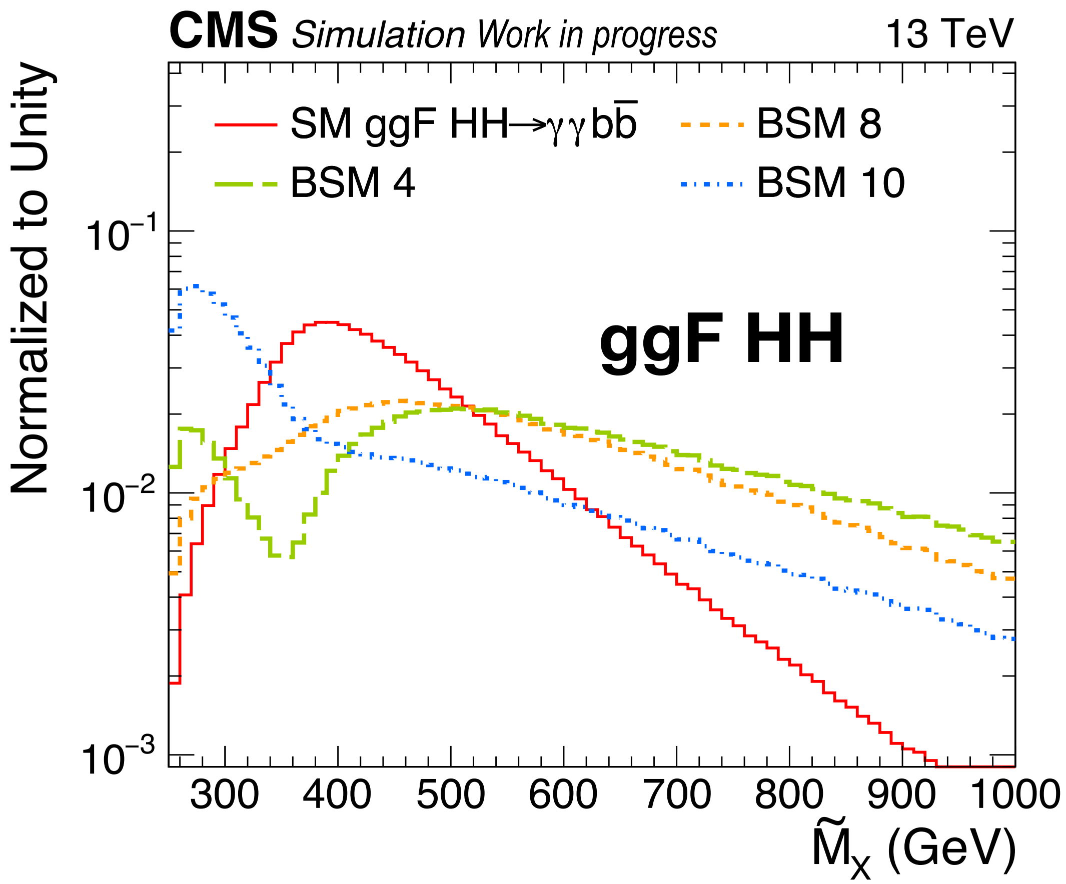
Vector boson fusion (VBF) - 2nd most important production mode : $\sigma^{SM}_{VBF\ HH} = 1.72$ fb

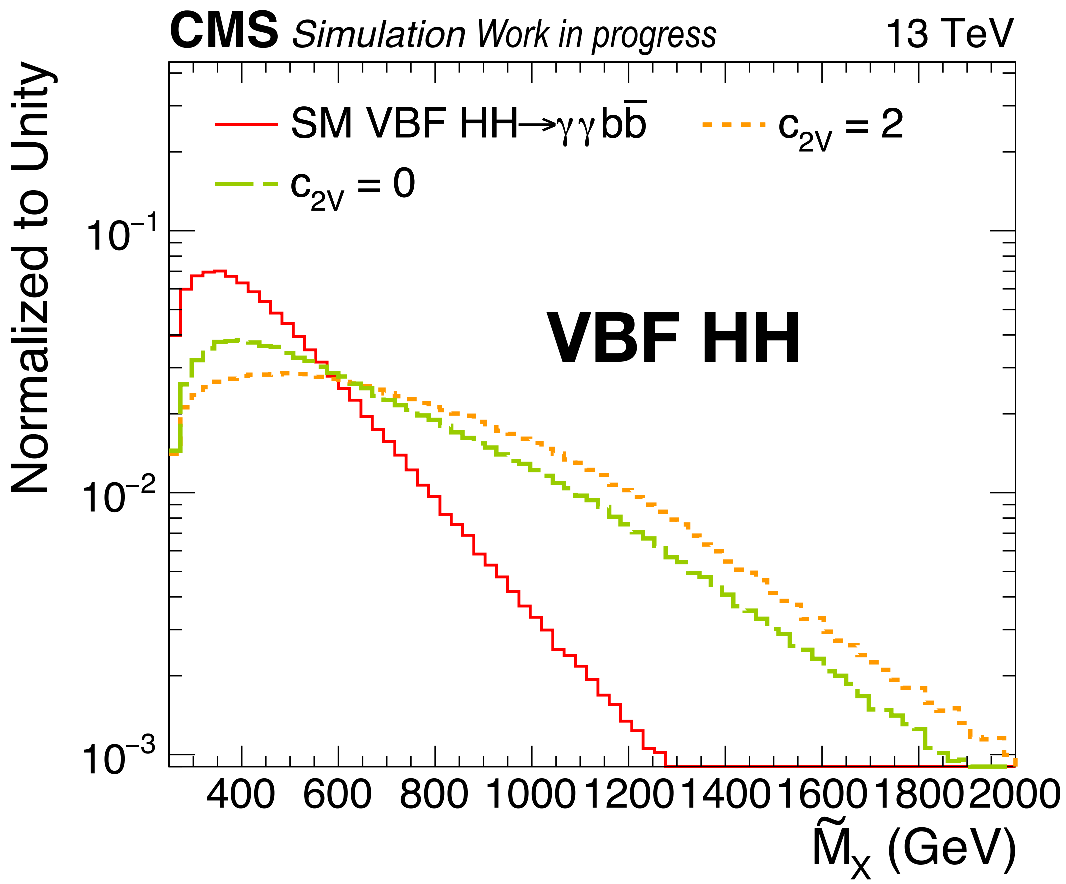


- Tiny cross section (~18x smaller than ggF) but very distinct topology
- The **only direct way to access C2V coupling** (VVHH)
- Anomalous values of C2V **dramatically change kinematic and cross section** and can be explored with the current LHC data

M(HH) for different couplings

- While the sensitivity to SM is very limited with the current LHC data, anomalous values of couplings can be explored already now





- M(HH) distribution is particularly sensitive to different values of the couplings
- In this analysis, a reconstructed variable M_X is used which is less dependent on dijet and diphoton energy resolutions

$$\tilde{M}_X = M(\gamma\gamma jj) - M(jj) - M(\gamma\gamma) + 2M_H$$

Final state and selections

HH(bbgg) final state

H(bb) - highest branching ratio $\mathcal{B}$

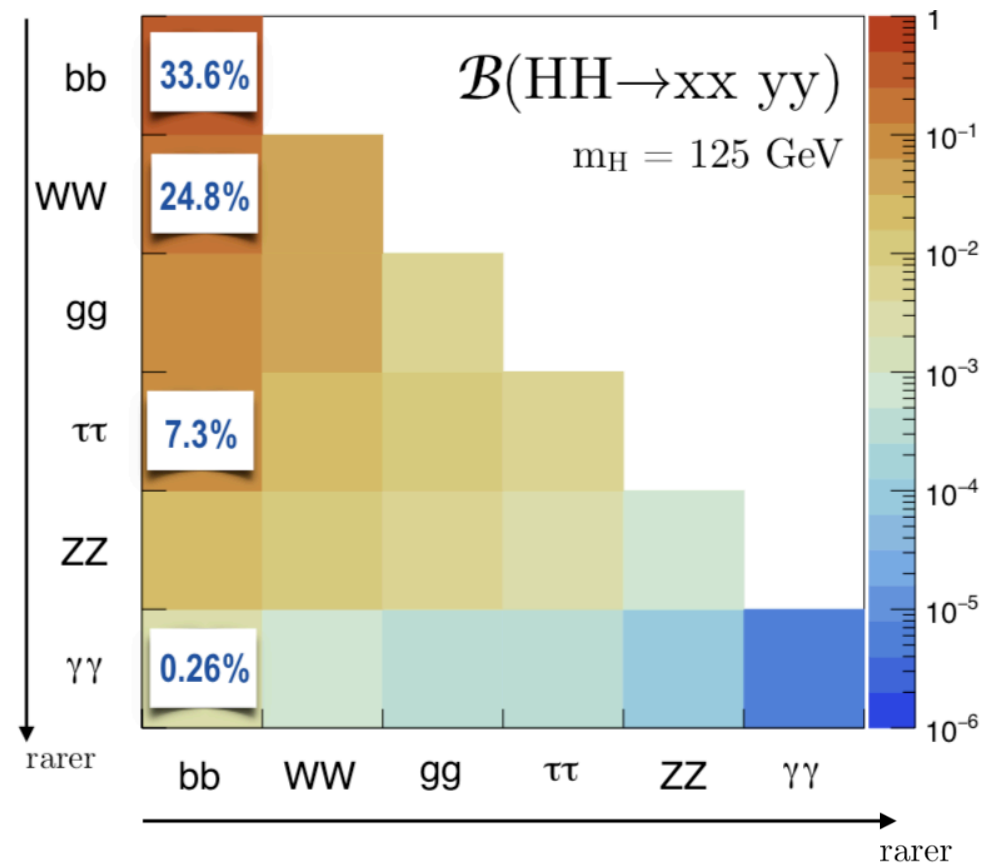
high b-tagging efficiency and low fake rate

H(γγ) - simple topology

Excellent mass resolution

But limited by small $\mathcal{B}$

Trade-off between $\mathcal{B}$ and purity

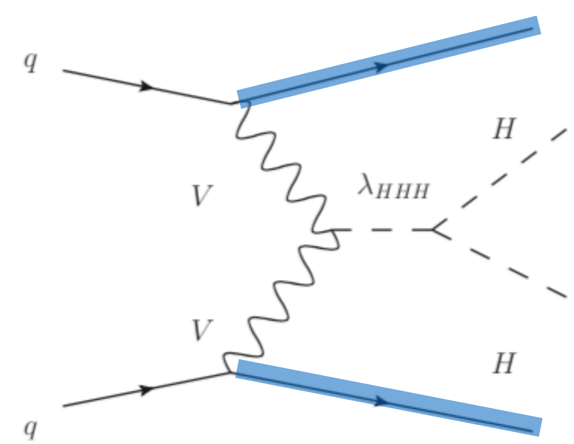


Use H→bb to keep $\mathcal{B}$ high

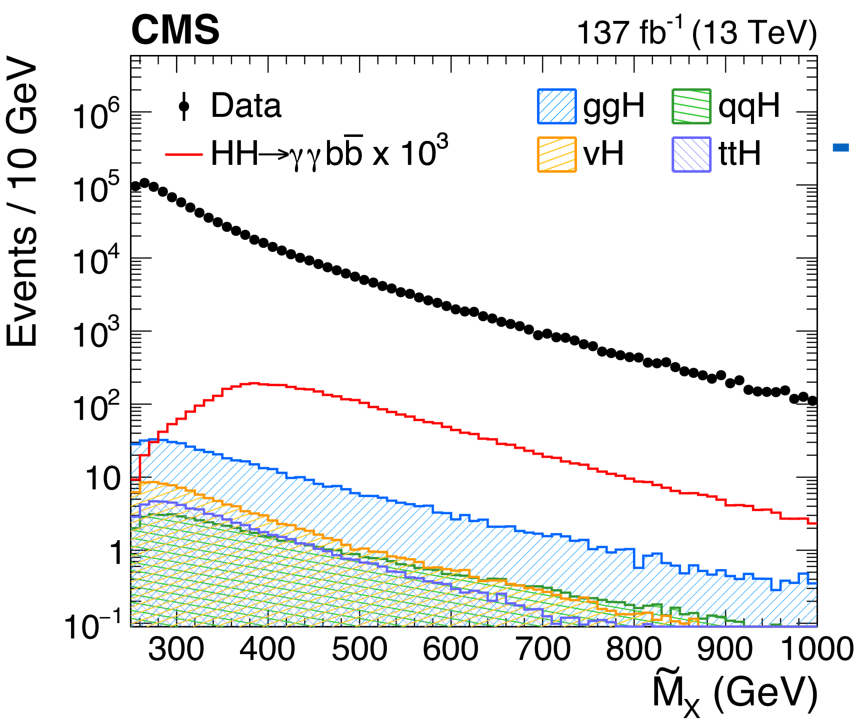
Select reconstructed objets : 2 γ and 2 b-jets

Distinctive topology of VBF signal helps to tag these events :

additionally require 2 light q-jets with largest m(jj)



Looking for a signal



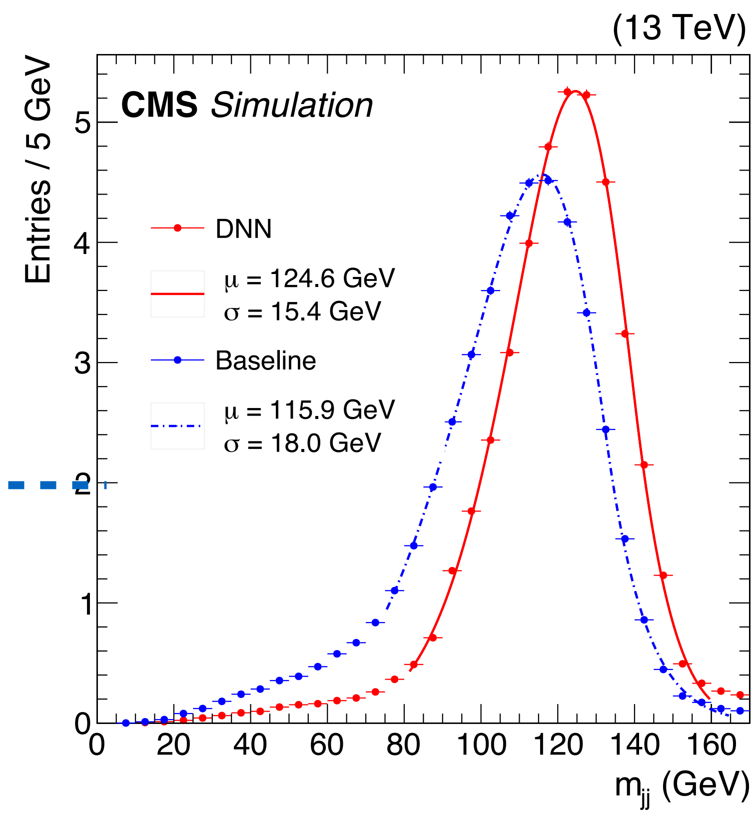
Select events compatible with HH signal

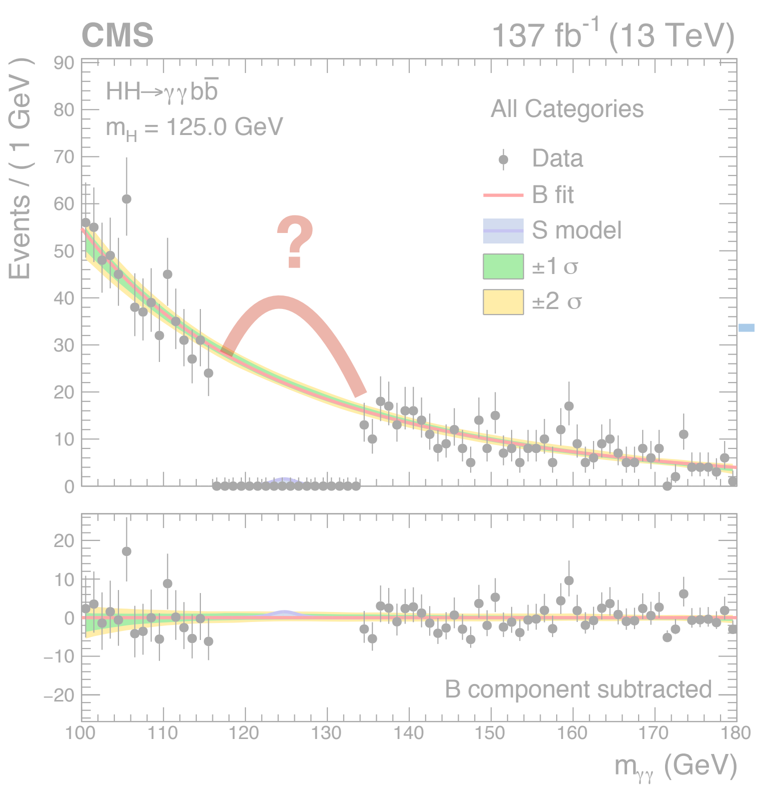
Improve object energy resolution

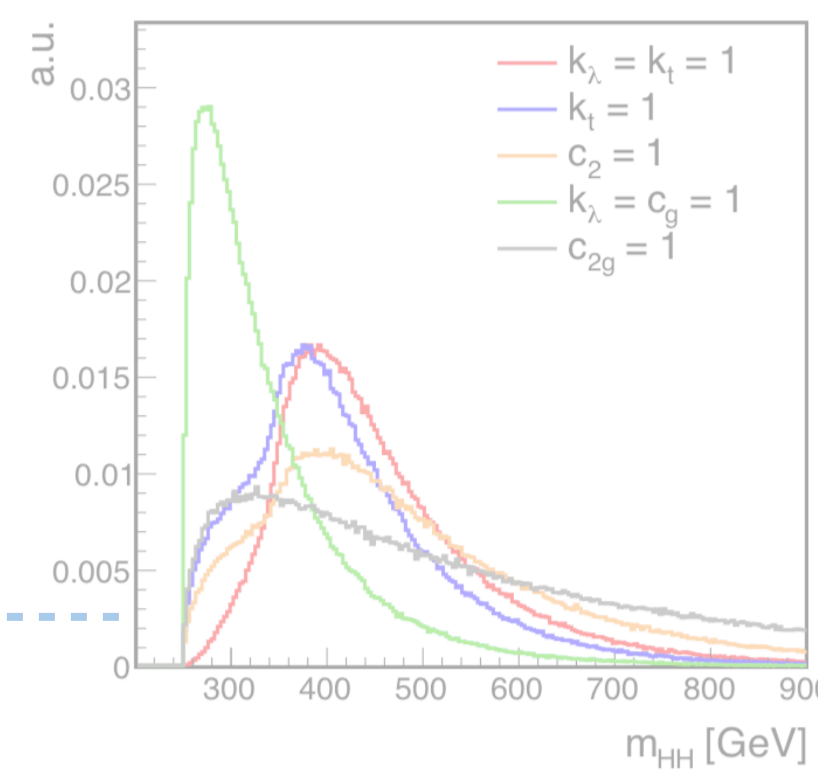
Reduce overwhelming BG

Look for a localized excess

Interpret results and set limits on BSM models







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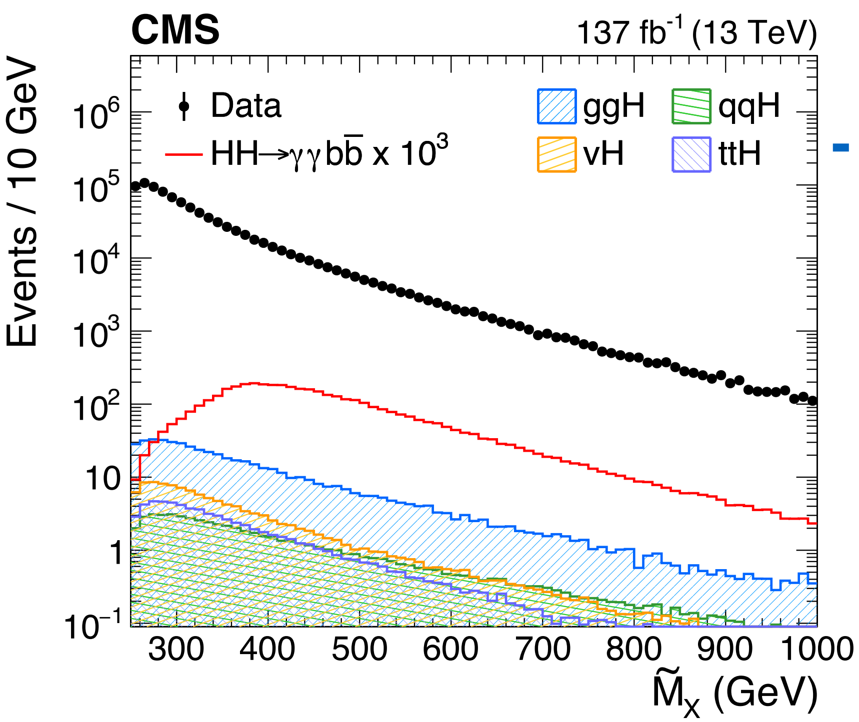

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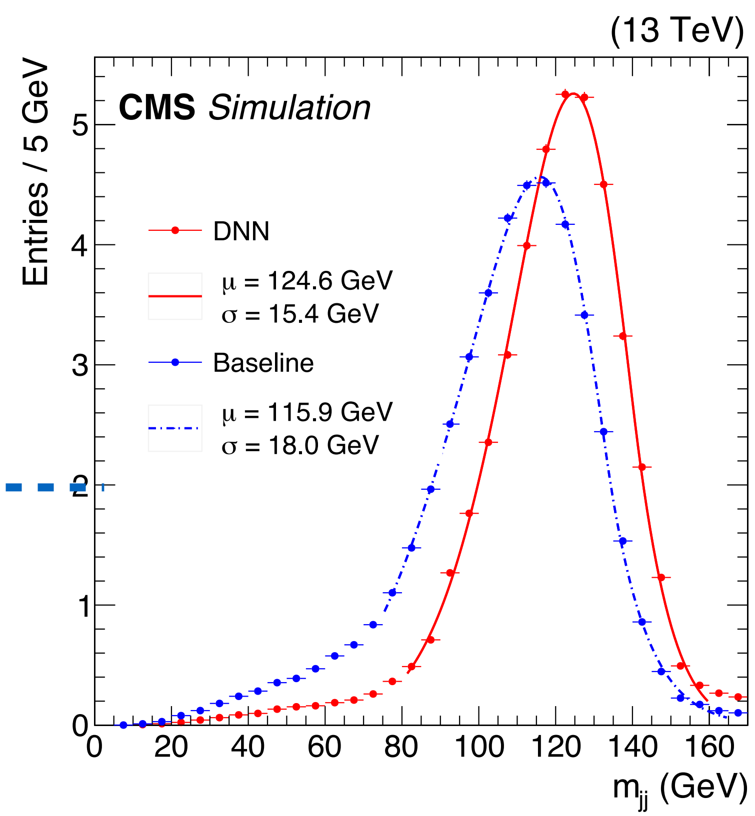

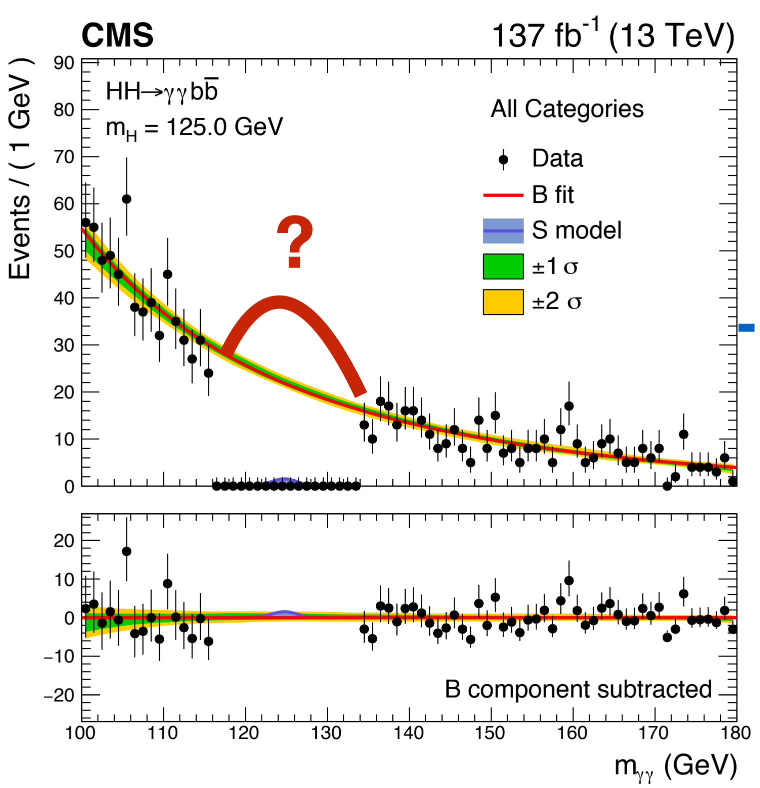

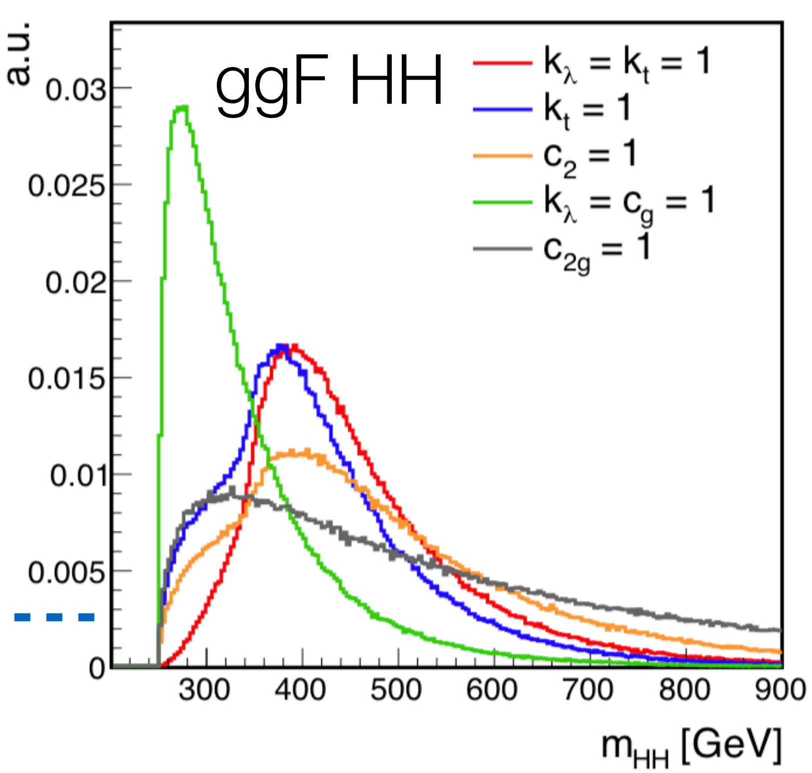

Looking for a signal

Select events compatible with HH signal

Improve object energy resolution

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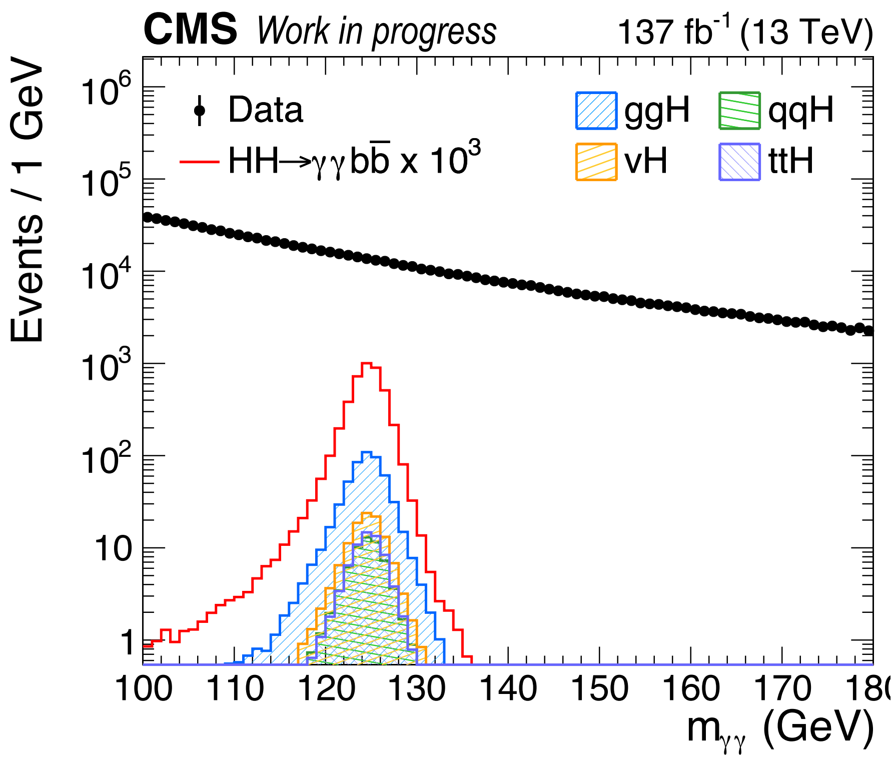
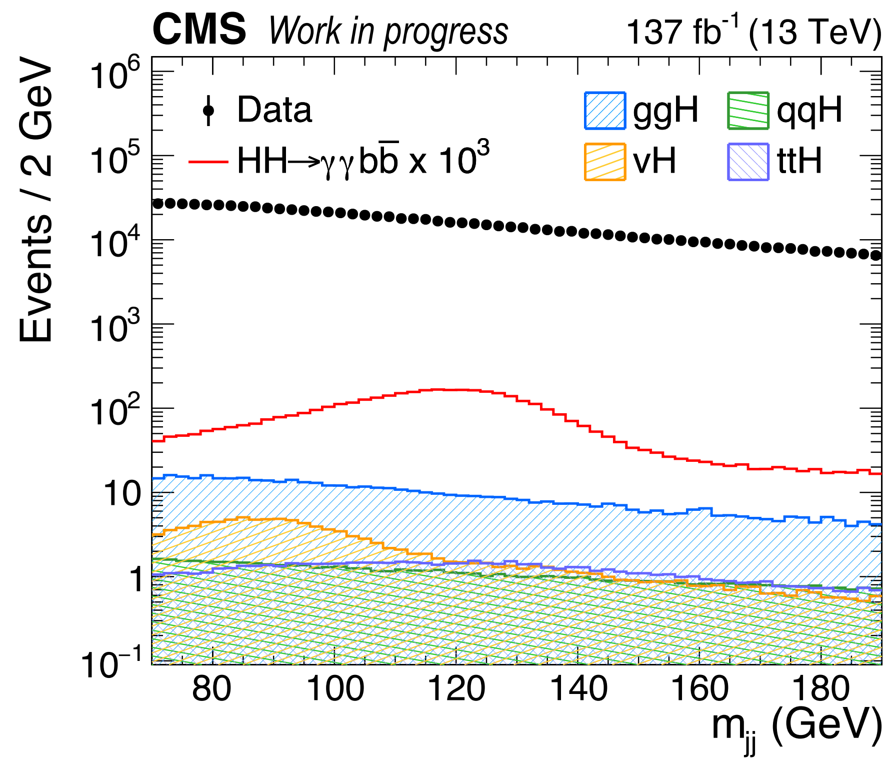
Interpret results and set limits on BSM models

Improving mass resolution

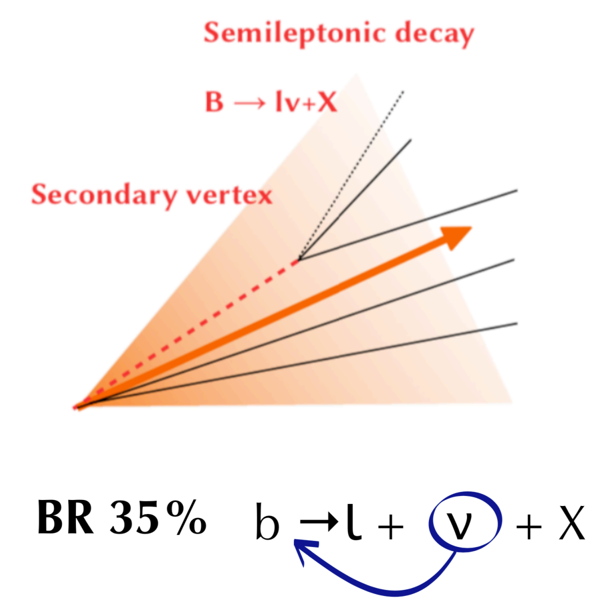
- Resonant signal : peaking distribution in M(gg) and M(jj)
- Excellent photon energy resolution, but b jet energy resolution is 10 times worse





- **Goal**: improve b-jet energy resolution
- b-jet fragmentation is different from light quarks and could benefit from a dedicated energy correction

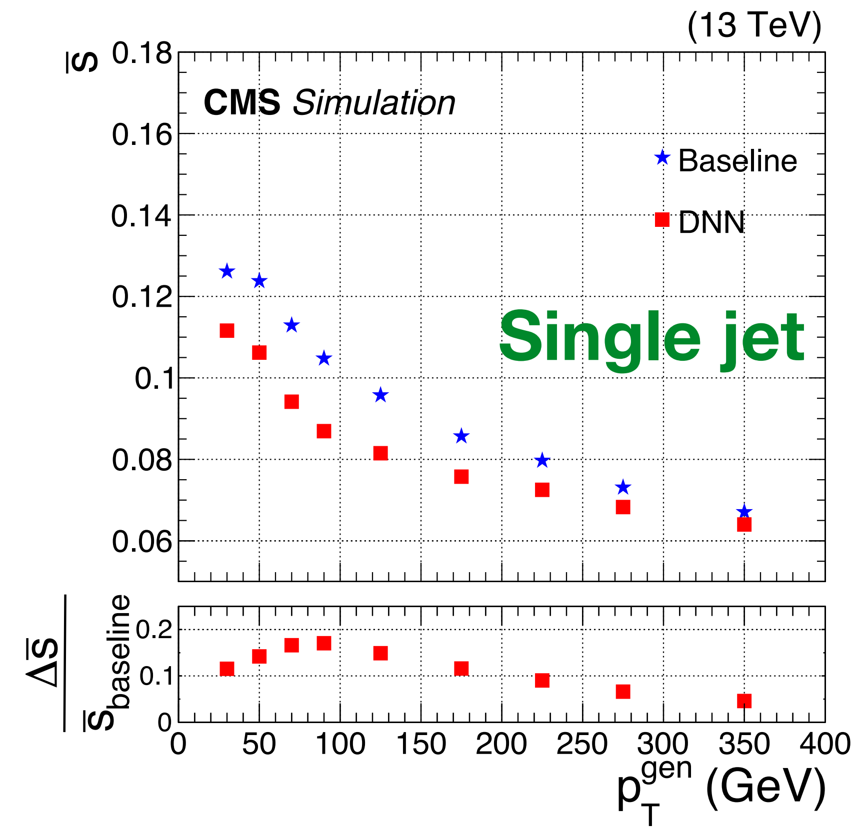
- **Task**: Develop a multidimensional b-jet energy regression based on jet composition and shape information

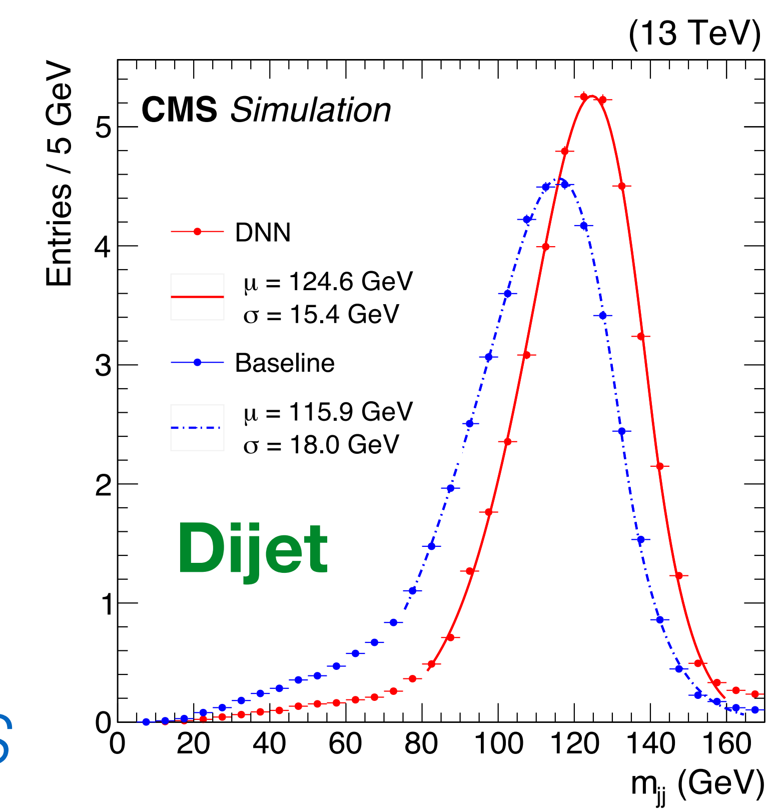


b-jet energy regression for CMS

New b-jet energy regression in CMS :
(part of my PhD thesis)

- Implemented in a Deep Neural Network (DNN) and trained per jet
- **Improves resolution of b jets regardless of the final state** of a process and already in use by multiple analyses in CMS
- Provides **jet energy correction and resolution estimator** on jet-by-jet basis
- Technique validated in data, and improves per jet energy resolution by ~ 13%, and djiet - 20-25%
- Improvement in dijet mass resolution brought by this regression **helped to reach** observation of H → bb





arXiv: 1912.06046, Accepted for publication in CSBS

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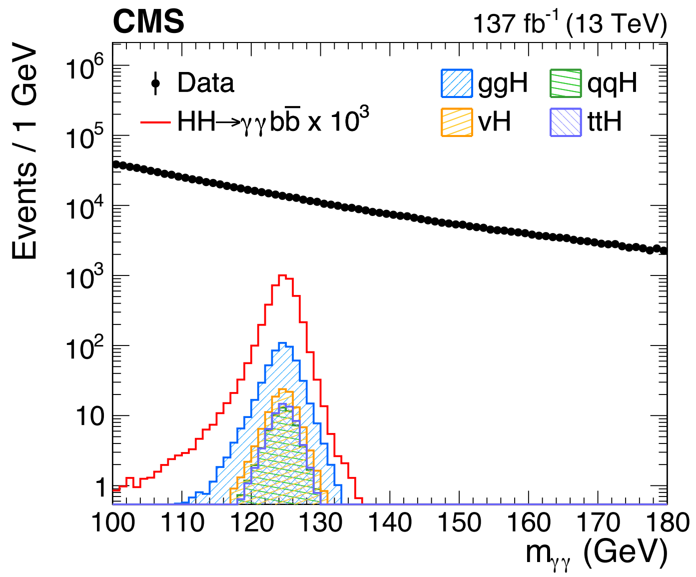
Reducing background

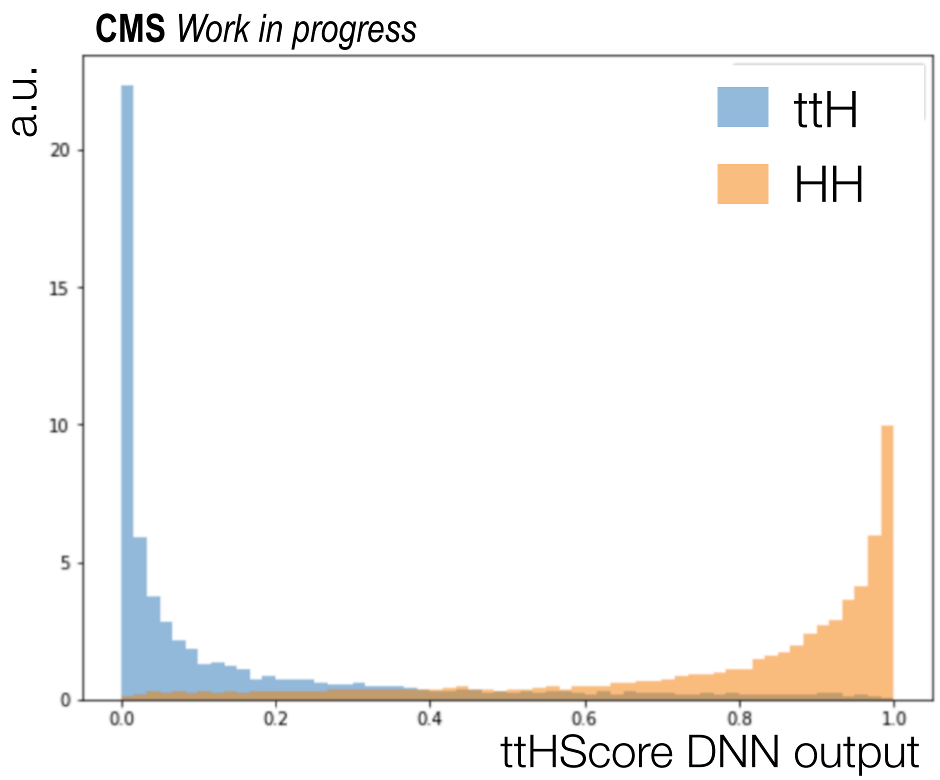
The **main background** can be split in **2 types** :

- Resonant (at m_H = 125 GeV) single Higgs production
- Dominant nonresonant γγbb :
  - irreducible prompt diphoton production (*γγ + jets)*
  - reducible *γ + jets* where jets are misindentified



Machine learning techniques are used to **reduce** the 2 types of background

- The dominant **resonant** background is ttH
- DNN is trained using high-level physics-motivated observables and low-level information (physics objects)
- Trained on MC HH signal versus ttH BG
- Optimized selection of the DNN output yields 80% background rejection at 95% signal efficiency



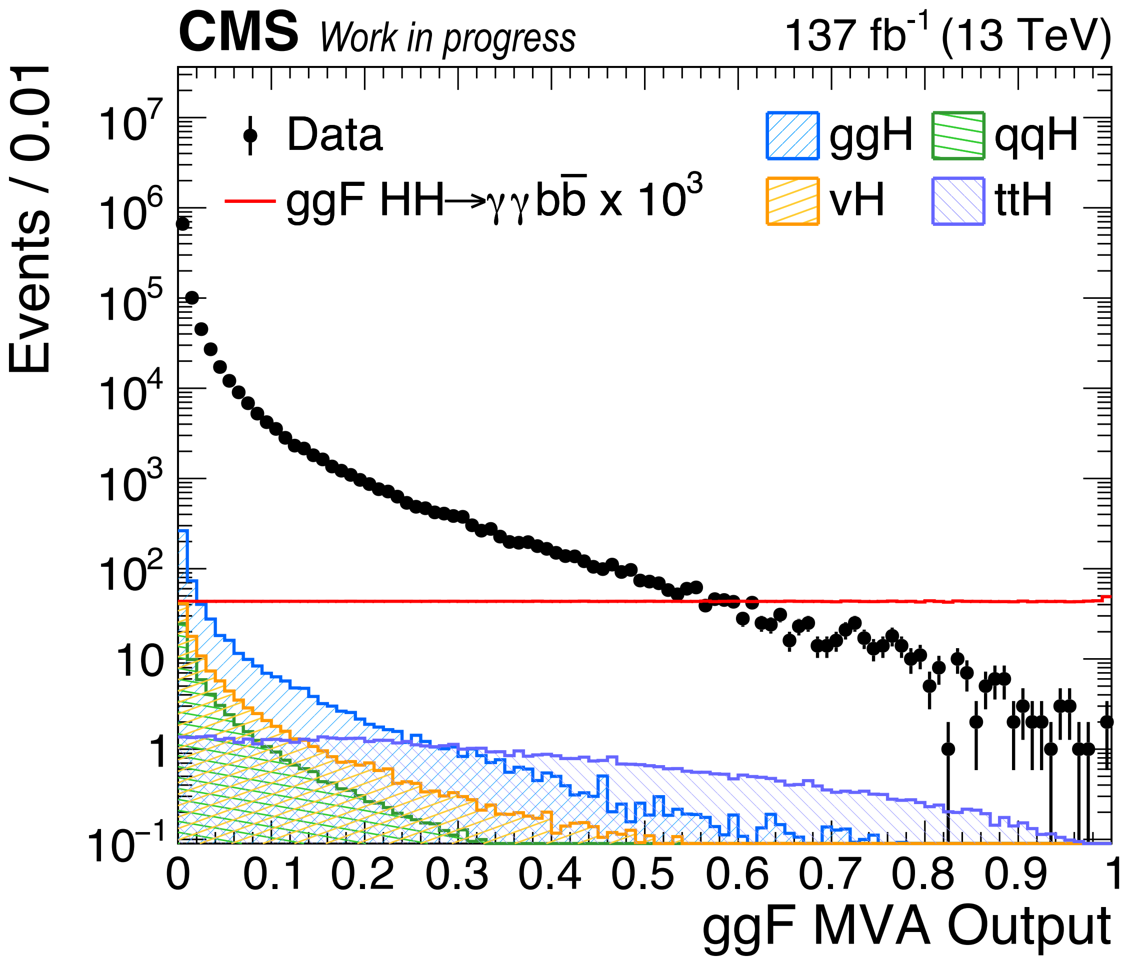
ggF HH : Reducing background

Dominant **nonresonant** background:

- Train BDT on MC events to differentiate HH signal from BG
- Train separate BDTs to discriminate ggF and VBF HH signals from BG

ggF HH signal BDT :

- As BG use *γγ + jets and γ + jets*
- As signal use a mixture of SM and 12 BSM benchmarks to be **sensitive to a broad spectrum of theoretical scenarios**
- Classification using Gradient Boosting algorithm and XGBoost
- Inputs variables include kinematic variables, object identification variables, and object resolution variables



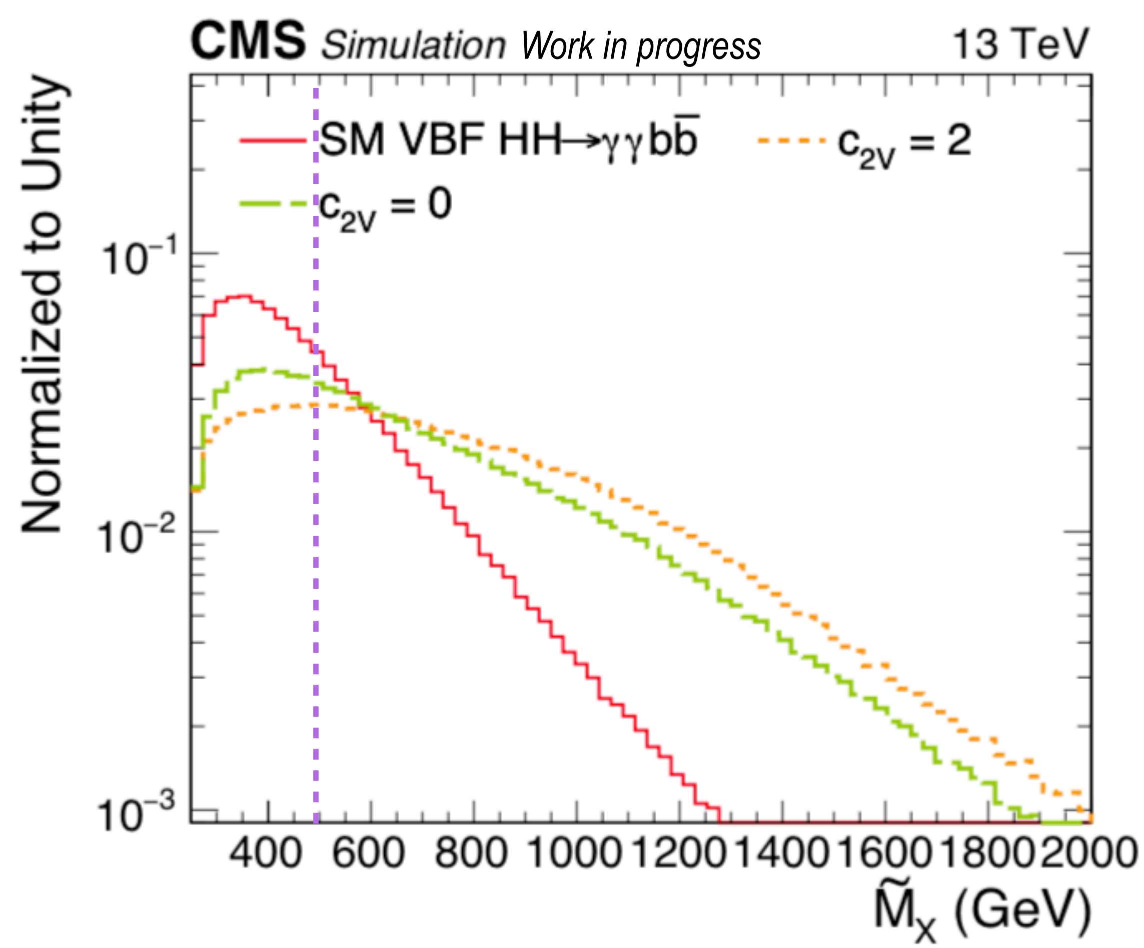
VBF HH : Reducing background

VBF HH signal BDT :

- *γγ + jets and γ + jets* - dominant source of BG
- In addition, ggF HH events are considered as BG
- Input variables are similar to the ggF HH BDT plus the VBF-topology features

2 M_X signal regions

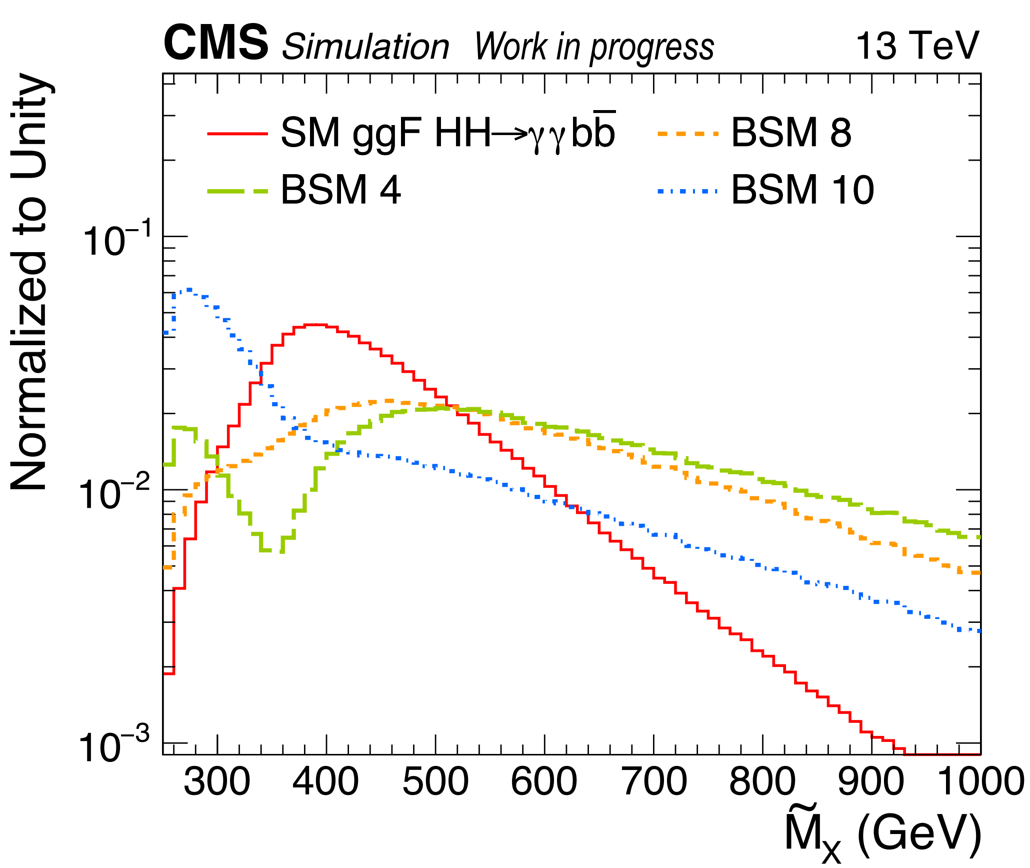
- VBFHH process is very sensitive to anomalous values of C2V coupling
- VBF phase space is split in 2 signal regions : M_X >/<500 GeV
- M_X >500 GeV is sensitive to anomalous values of C2V, M_X <500 GeV retains sensitivity to SM
- 2 BDTs are trained using a mixture of SM+C2V=0 MC samples as signal

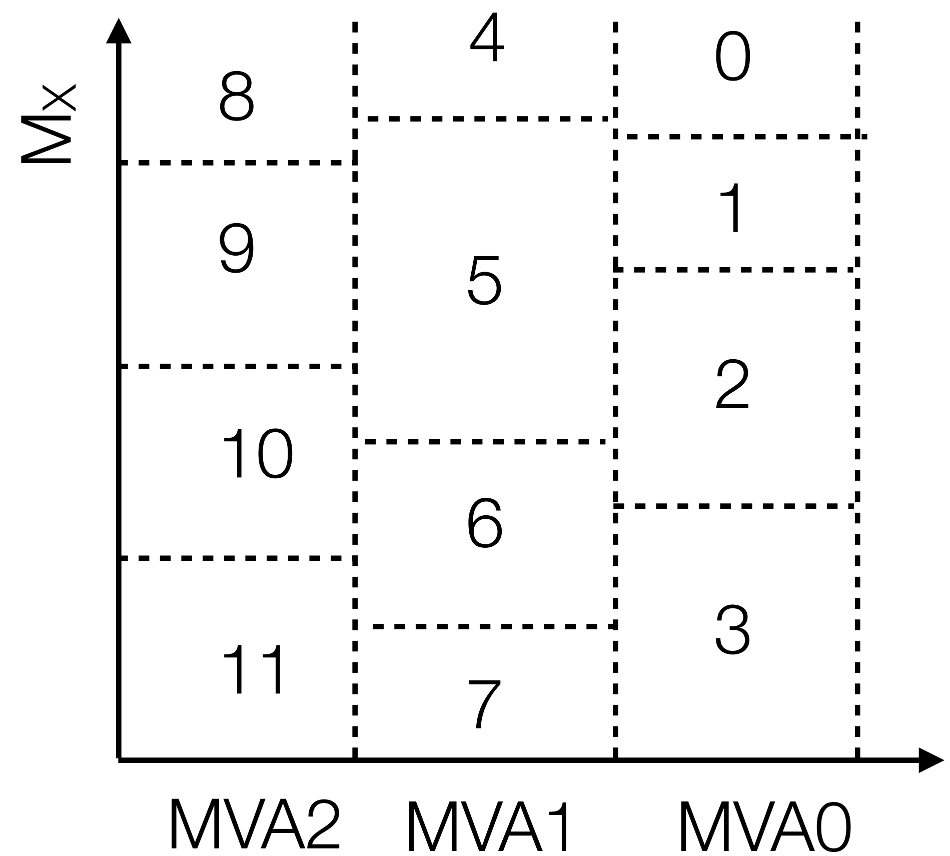


* $\tilde{M}_X = M(\gamma\gamma jj) - M(jj) - M(\gamma\gamma) + 2M_H$

Analysis signal regions

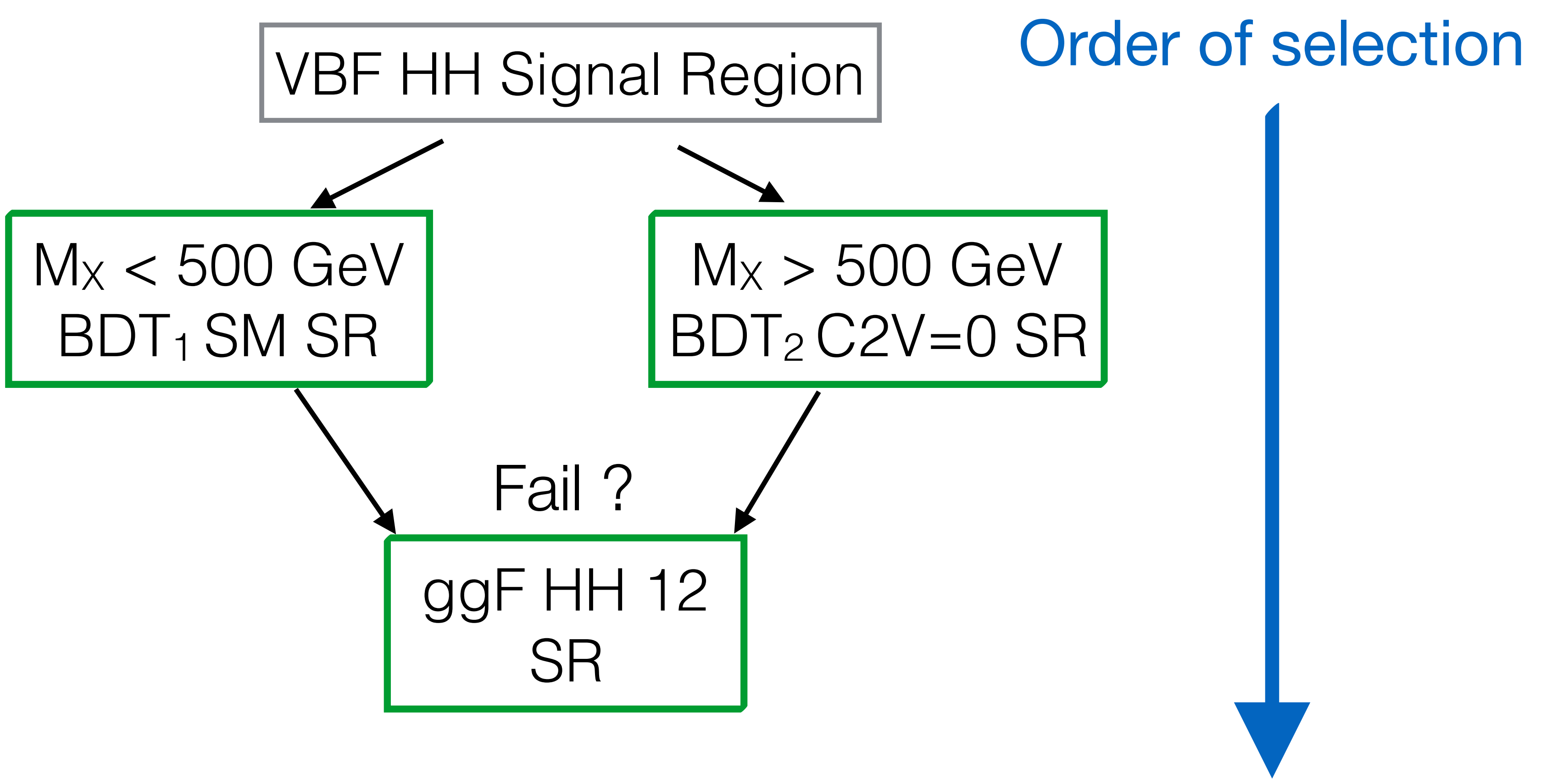
- In order to maximize sensitivity of the search, events are split into different categories based on BDT output and M_X
- Categorization is optimized by maximizing the expected significance over all categories
- 2 VBF HH and 12 ggF HH signal enriched categories are created
- Depending on the coupling values - low/high M_X categories are important





Analysis signal regions

- 2 VBF HH and 12 ggF HH signal enriched categories are created
- **VBF and ggF categories are mutually exclusive. Events are categorized, not rejected.**



14 HH categories in total

Looking for a signal

Select events compatible with HH signal

Improve object energy resolution

Reduce overwhelming BG

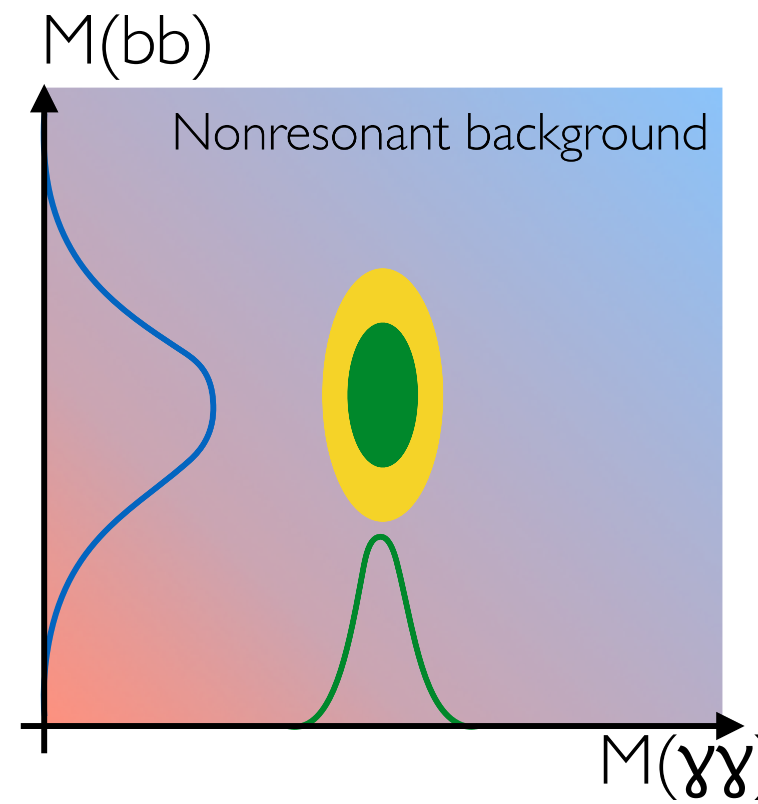
Look for a localized excess

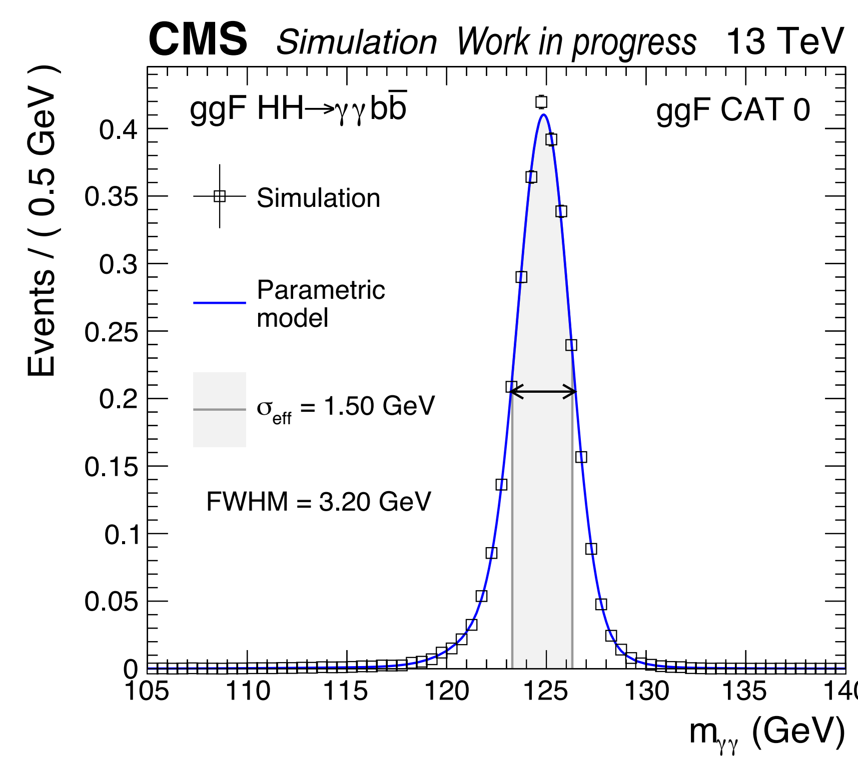
Interpret results and set limits on BSM models

Signal extraction

Signal extraction, 2D fit (M(ɣɣ) vs M(jj))

- Make use of resonant nature of HH signal and **fit simultaneously M(ɣɣ) x M(jj)** in all categories
- Shape templates of M(ɣɣ) and M(jj) are constructed from MC simulation for HH signal and single Higgs boson BG
- Model to describe nonresonant BG extracted from data using *discrete profiling method*
  - method treats model choices as discrete nuisance parameters in the likelihood
- Final 2D model is implemented as a product of independent models of M(ɣɣ) and M(jj)
  - Correlations between M(ɣɣ) and M(jj) were found to be negligible with present stat. precision





Systematic uncertainties

- **Statistically limited** search. Total impact of systematics is ~3%
- Mainly affect signal and single H models
- Systematic unc. can affect the overall normalization, or variation in category yields

- Theory uncertainties :
  - QCD scale, PDF choice, α_s unc., $\mathcal{B}(HH\rightarrow bbgg)$, cross-section predictions
- Experimental uncertainties :
  - Photon identification, energy scale and resolution
  - Jet energy scale and smearing
  - Jet b tagging
  - Trigger efficiencies
  - Photon preselection
  - Integrated luminosity
  - Pileup jet identification

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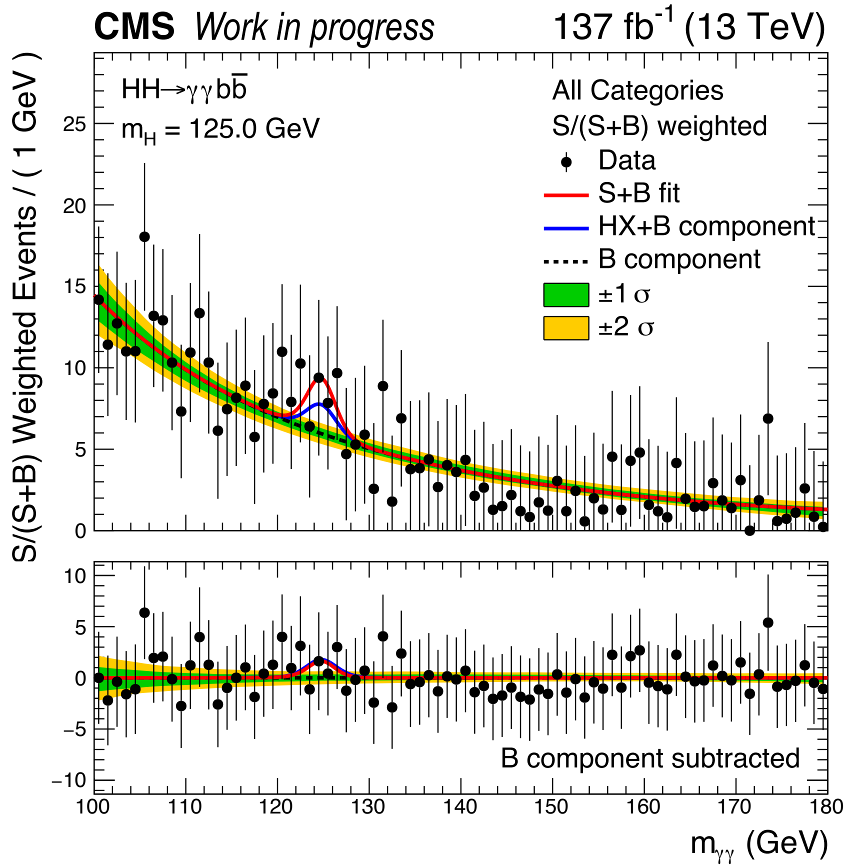
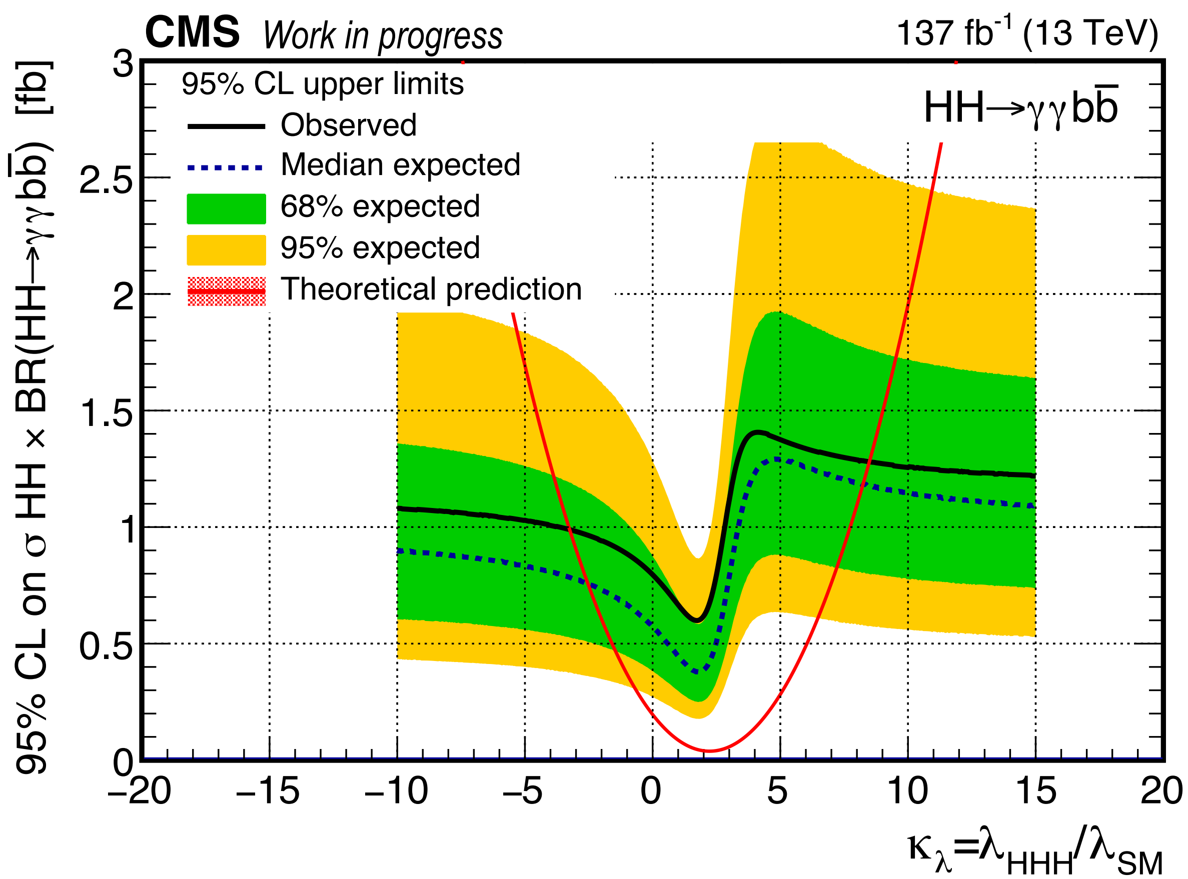
Results (CMS restricted)

- To extract HH signal a simultaneous unbinned maximum likelihood fit is performed in all categories
- **Full Run II, 136.8 fb^{-1}**

SM HH : σ(pp→HH) x ℬ(HH→bbγγ) = **0.76 (exp. 0.45) fb** which corresponds to **7.7 (5.2) times SM** prediction





95% CL upper limits on the cross-section as a function of k_λ

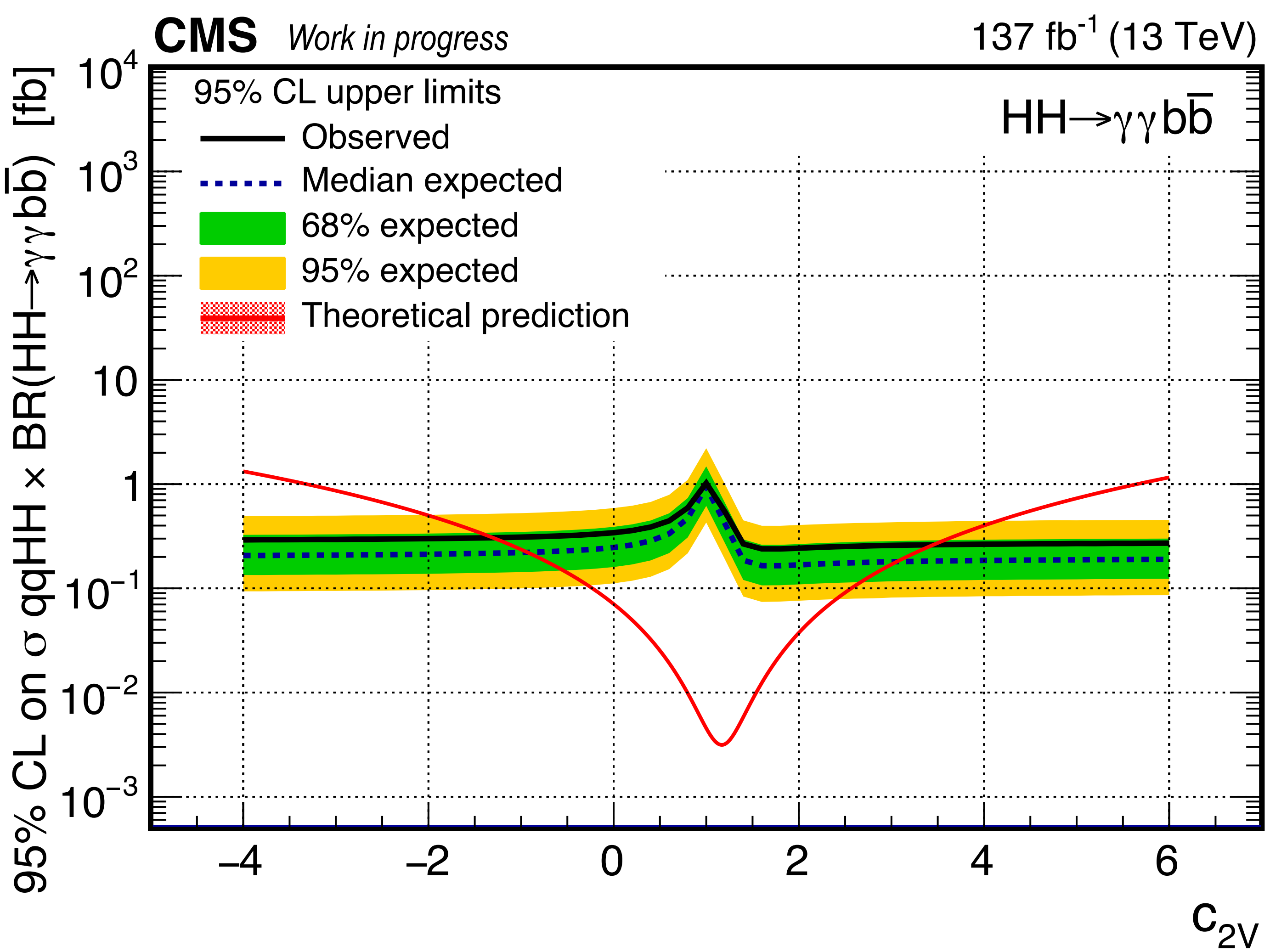
Obs. $k_\lambda \in$ [-3.3, 8.5]

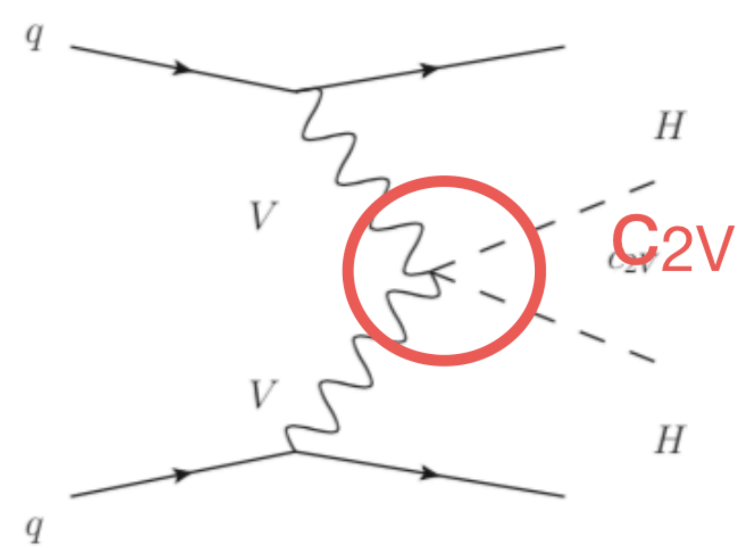
Exp. $k_\lambda \in$ [-2.5, 8.2]

Results (CMS restricted)

- Upper limits on **HH VBF** production

SM HH : σ(VBF HH) x $\mathcal{B}$(HH→bbγγ) = **1.02 (exp. 0.94) fb** which corresponds to **225 (208) times SM** prediction



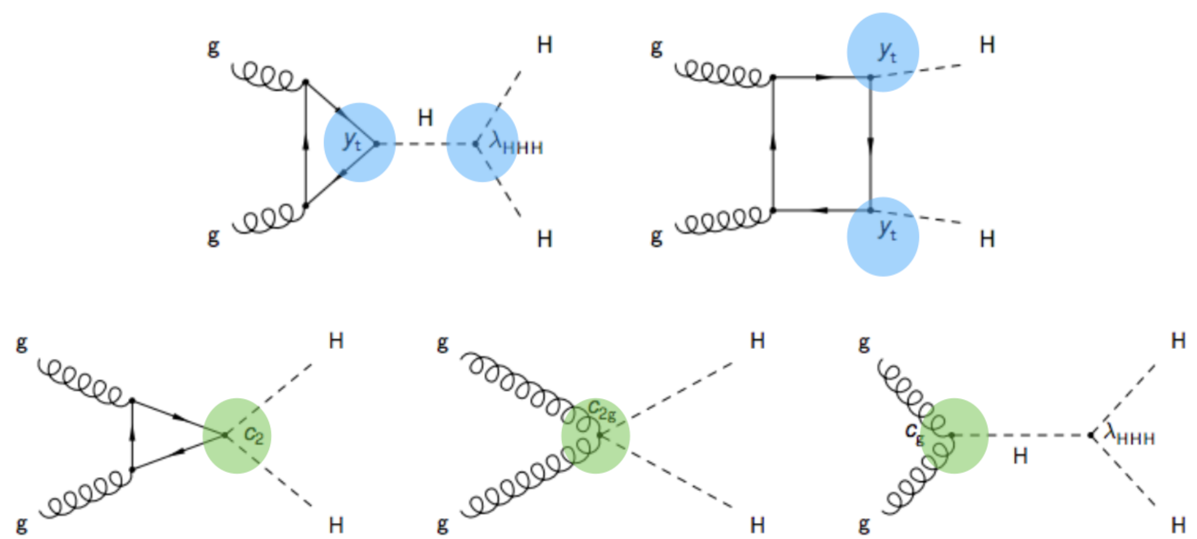


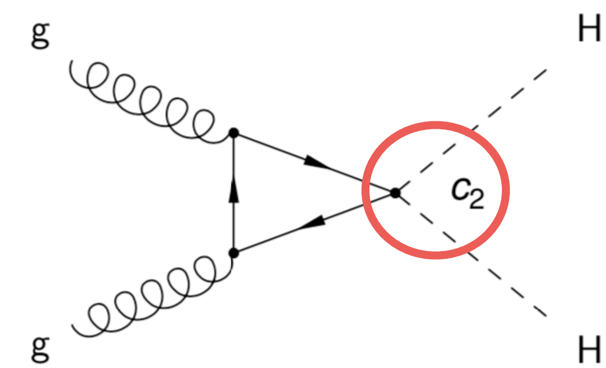
95% CL upper limits on the cross-section as a function of C_{2V}

Obs. $C_{2V} \in$ [-1.3, 3.5]

Exp. $C_{2V} \in$ [-0.9, 3.0]

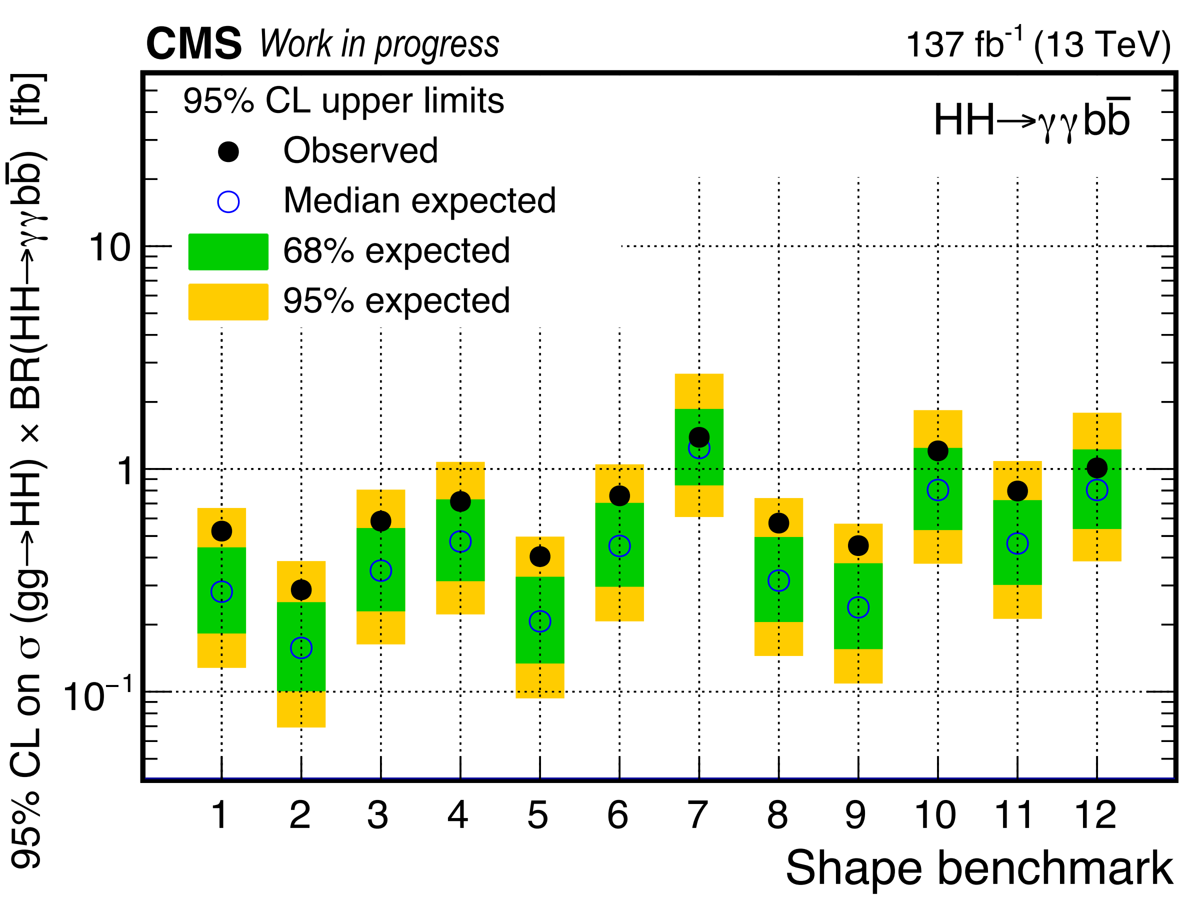
- Upper limits on **BSM ggF production**

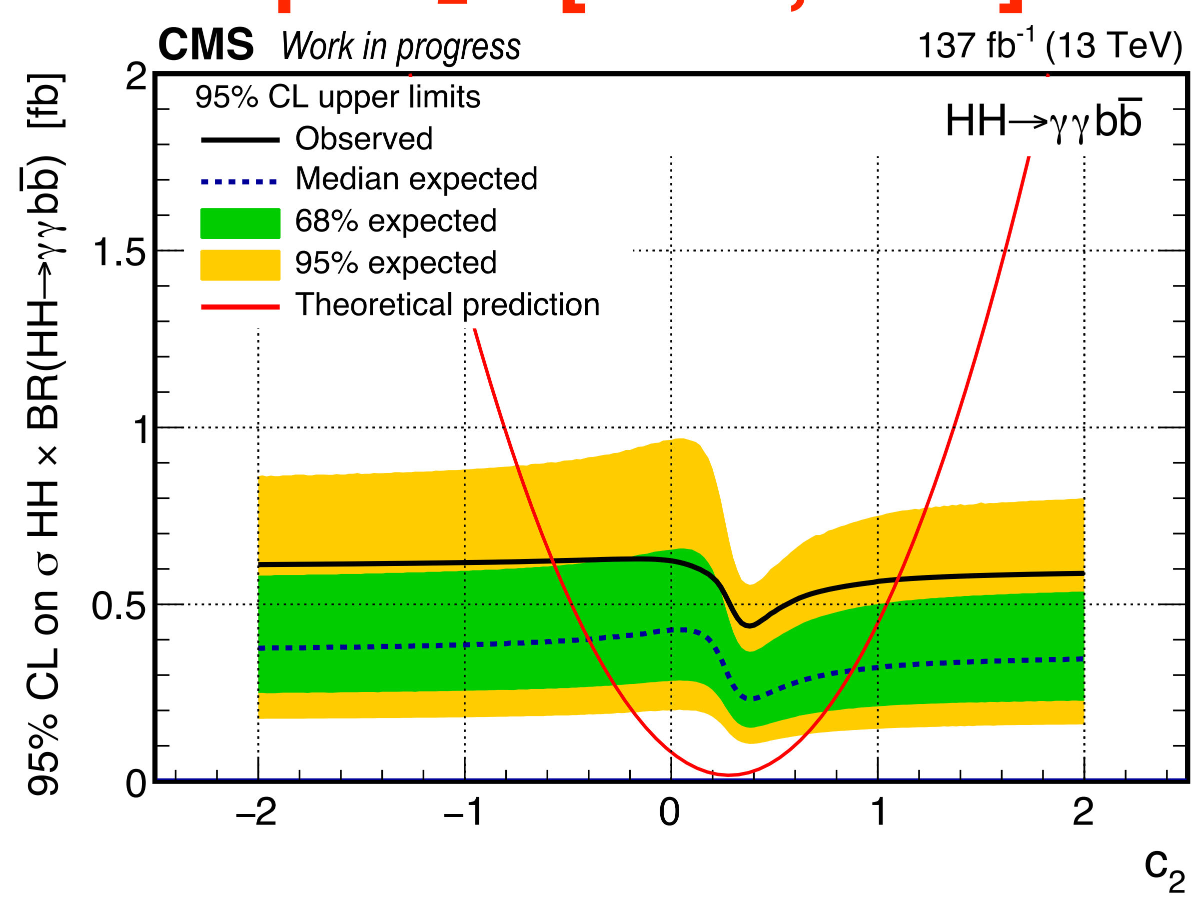




Obs. $C_2 \in [-0.58, 1.01]$

Exp. $C_2 \in [-0.40, 0.88]$





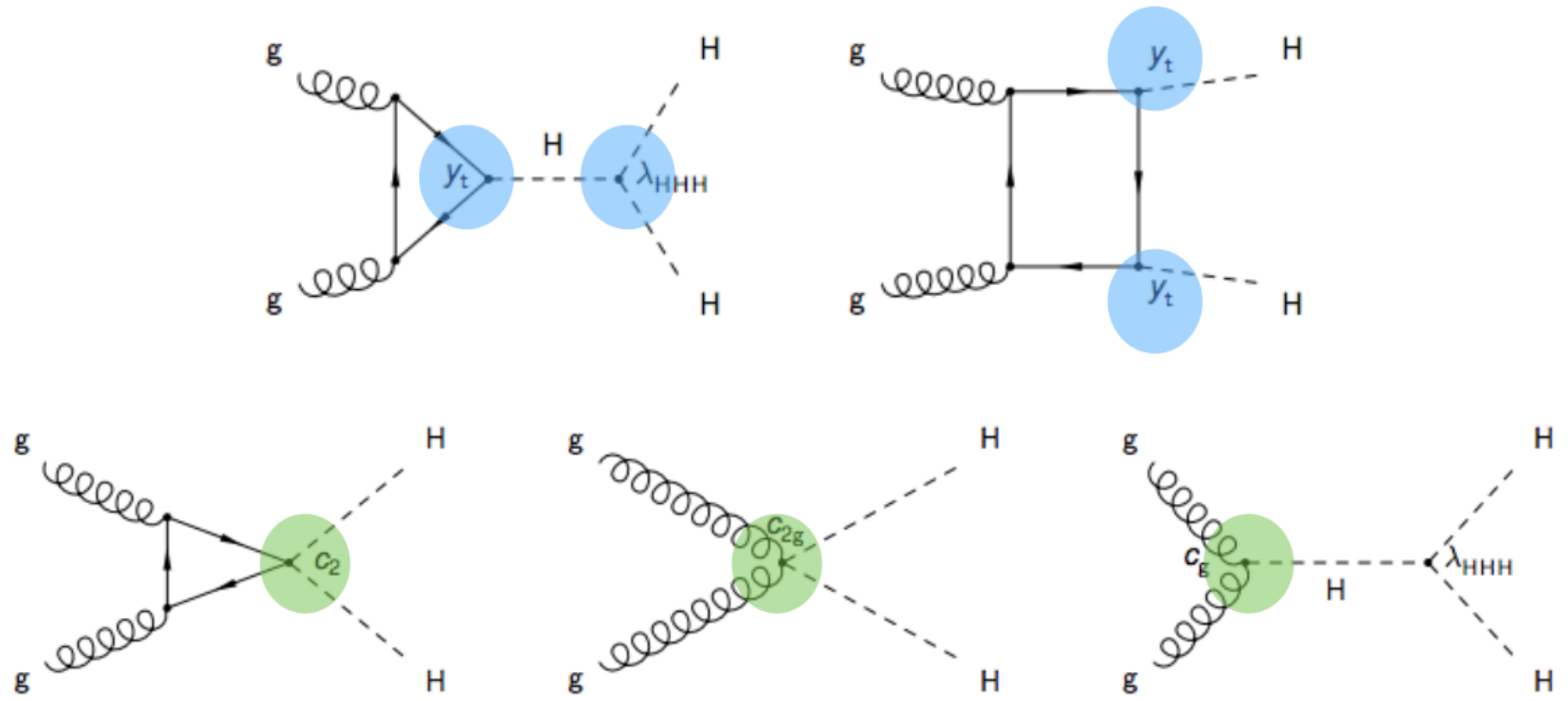
Summary

- **Search for HH → bbγγ** is performed with full Run II data collected by the CMS experiment 136.8 fb^{-1}
- Each step of the analysis was carefully optimized leading to 30% improvement with the respect to previously published CMS search
- Presented results are the **best DiHiggs results** to date
- We expected to release a preliminary PAS in September/October and a paper by Moriond 2021
- **b-jet energy regression** has already been public and **accepted for publication** in CSBS
- Graduation schedule - spring 2021

Additional Material

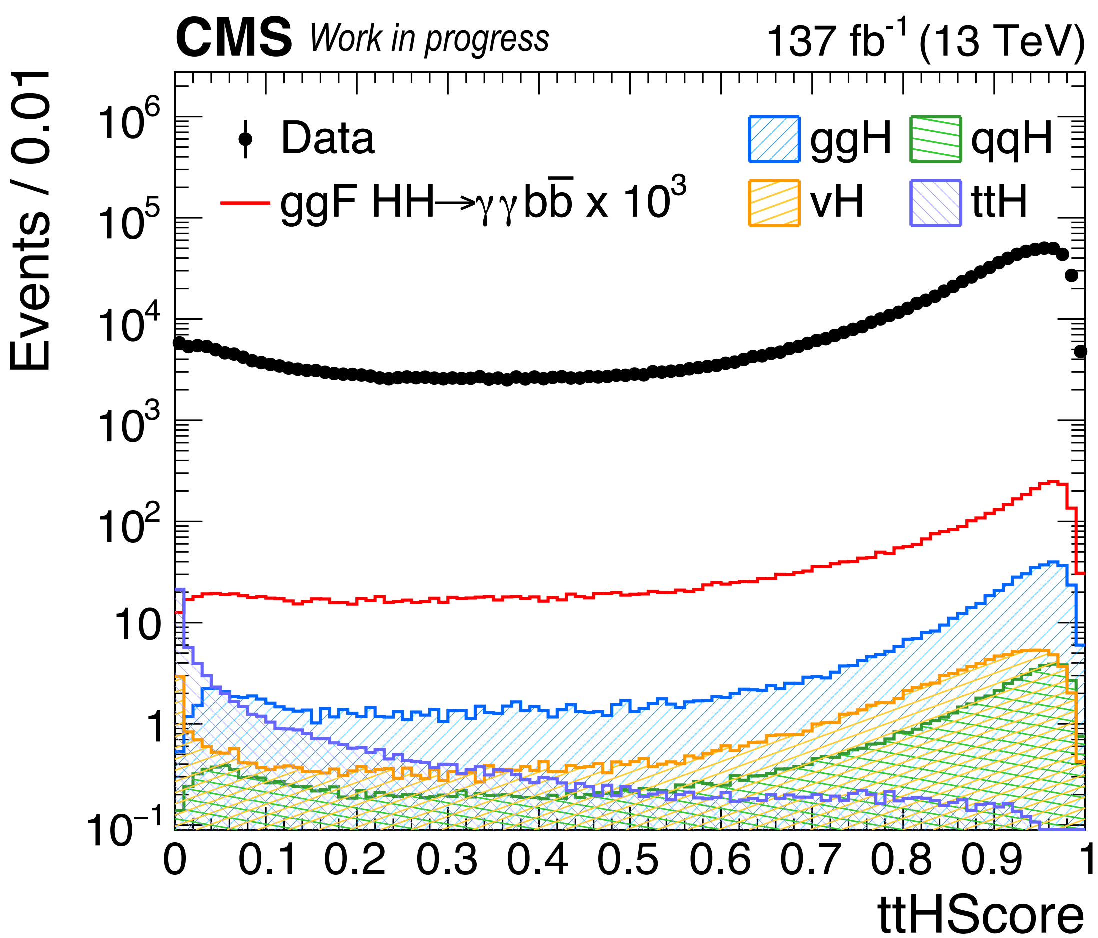
BSM benchmarks

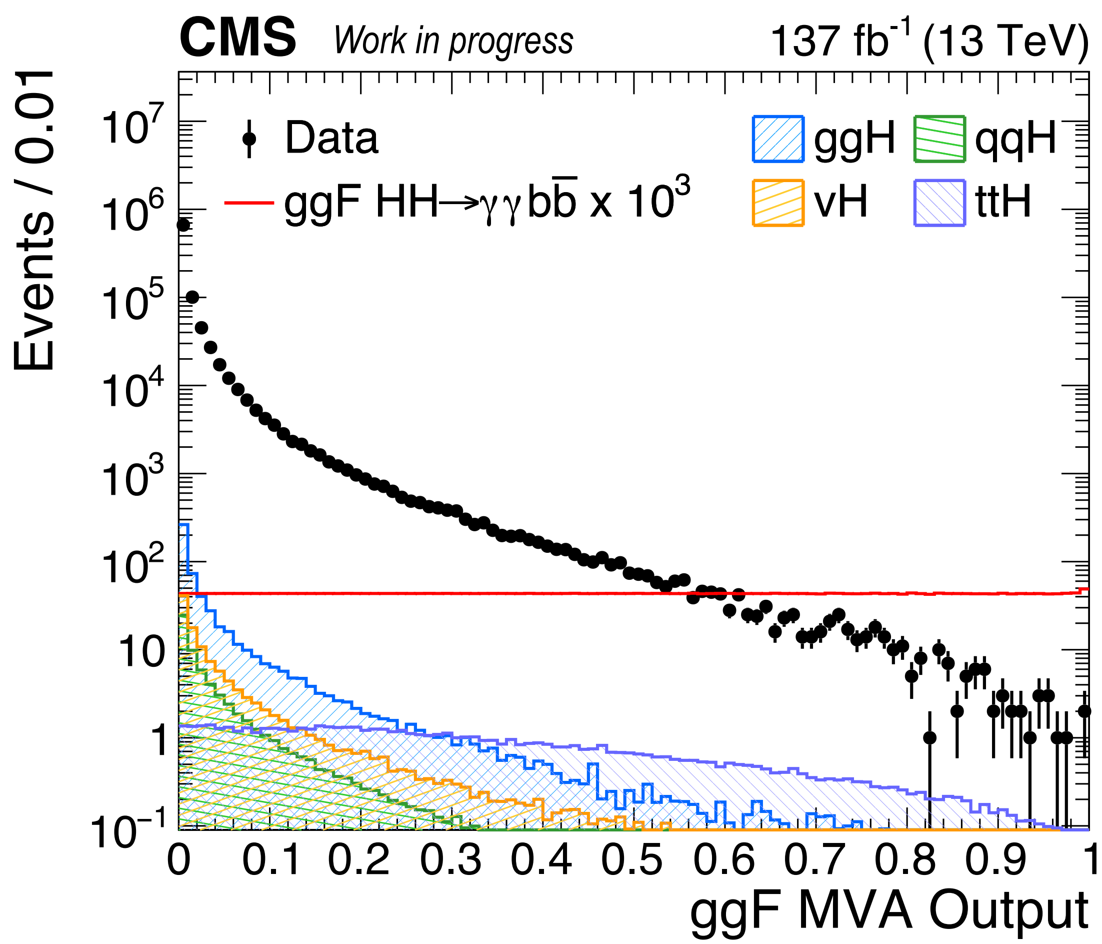
Cluster points in 5D coupling space and create benchmarks with similar kinematics [Ref]



	1	2	3	4	5	6	7	8	9	10	11	12	SM
κ_λ	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0	0.0
c_g	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0	0.0
c_{2g}	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0	0.0

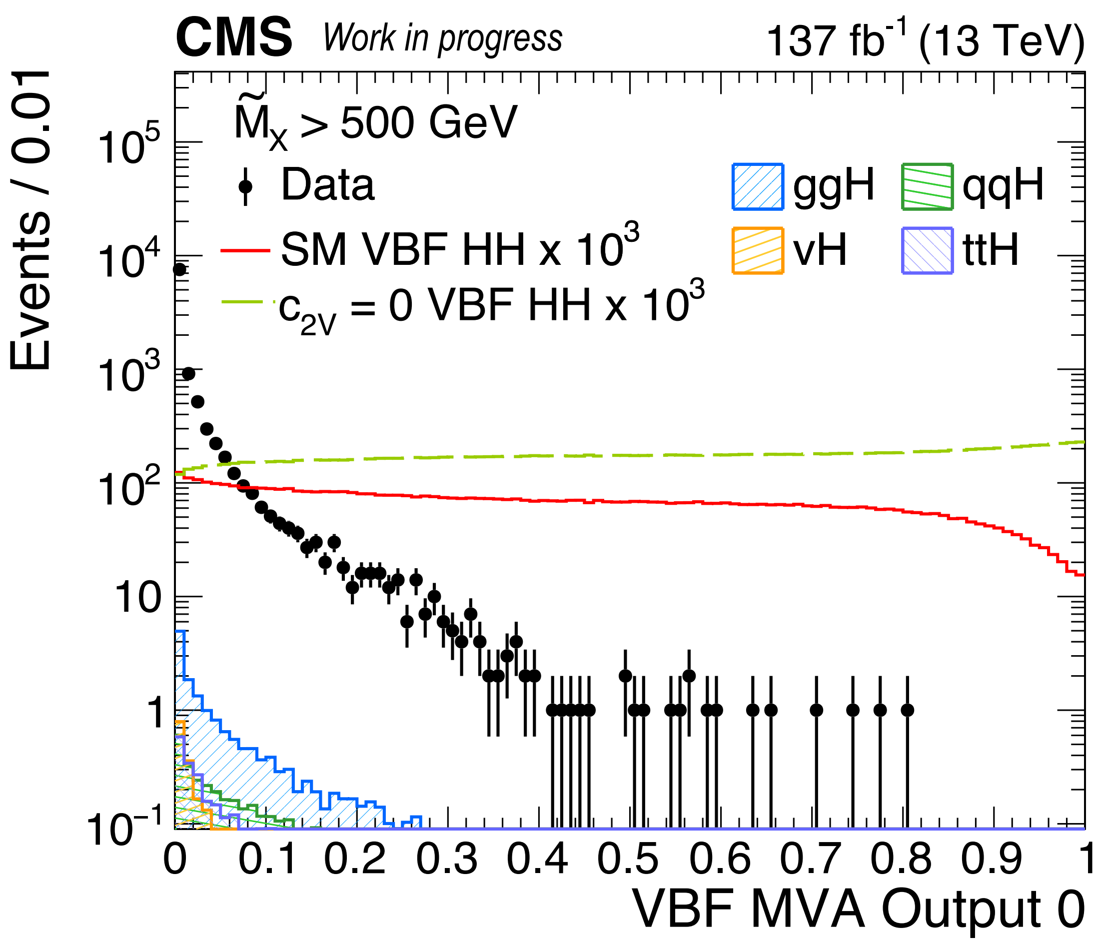
Output of MVA classifiers



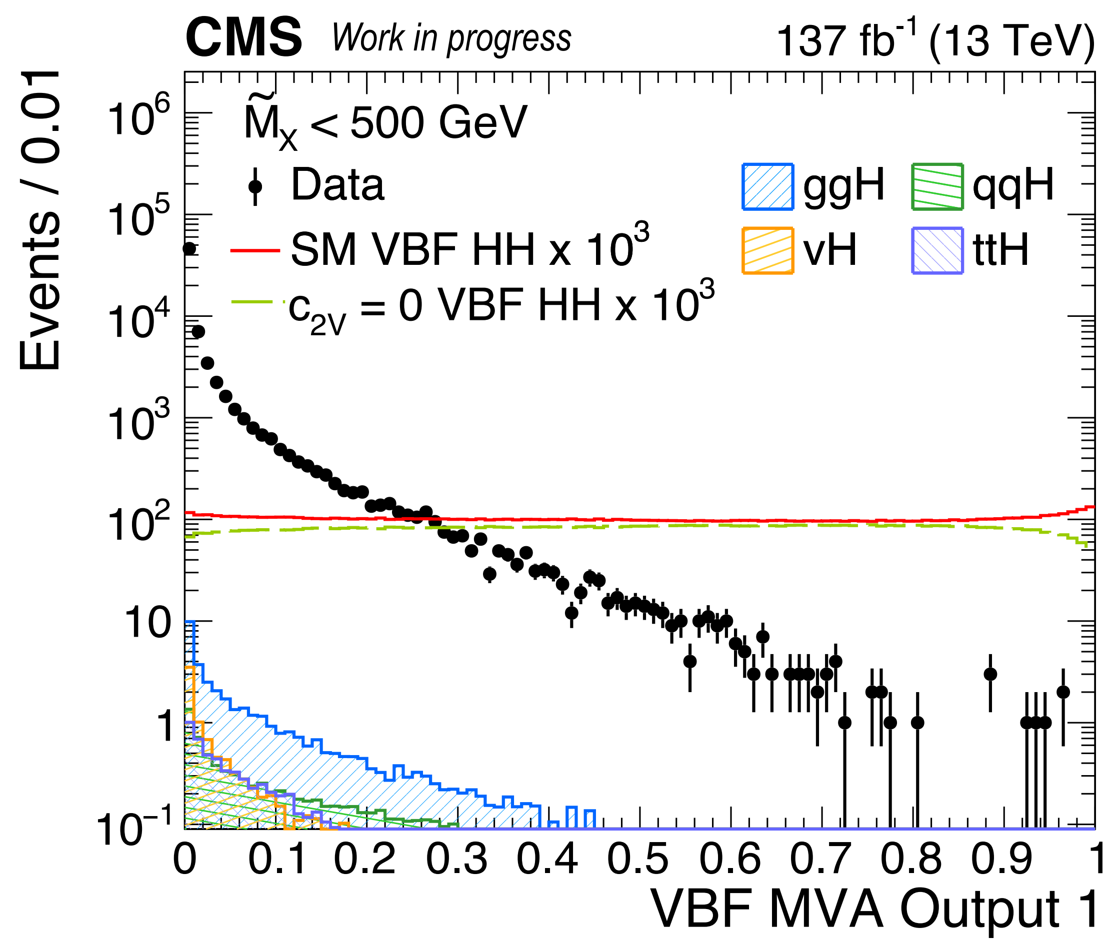


Output of MVA classifiers

$M_X > 500$ GeV



$M_X < 500$ GeV



BDT classifier : inputs variables

Input variables for ggF HH BDT classifier:

- b-tagging scores : leading, subleading jets
- $|\cos\theta^*_{CS}|$, $|\cos\theta^*_{bb}|$, $|\cos\theta^*_{\gamma\gamma}|$
- $p_T(\gamma\gamma)/m(HH)$, $p_T(bb)/m(HH)$
- $p_T(\gamma)/m(H)$, $p_T(b)/m(H)$ for leading, subleading photons and jets
- Photon ID MVA : leading, subleading Photons
- Photon resolution σ_E/E - leading, subleading photons; σ_M/M - diphoton resolution
- Jet resolution σ_j - leading, subleading jets; σ_{jj} - dijet resolution
- $\min\Delta R(jet,\gamma)$ and $\Delta R^{other}(jet,\gamma)$ for the other pair (sub)leading jet - (sub)leading photon not used in $\min\Delta R(jet,\gamma)$ calculation

BDT classifier : inputs variables

Additional variables for VBF HH BDT classifier:

- VBF-tagged jet kinematics : p_T^{VBF}/m^{VBF}_{jj}, η^{VBF}
- VBF-tagged jet invariant mass : m^{VBF}_{jj}
- Rapidity gap: product and difference of pseudorapidity between the VBF-tagged jets
- Quark-gluon likelihood of the two VBF-tagged jets. A likelihood discriminator used to distinguish between jets originating from quarks and from gluons
- HH system kinematics: M_x and the transverse momentum of the pair of the reconstructed Higgs bosons $p_T(HH)$
- Angular distance: minimum ΔR between a photon and a VBF-tagged jet, and between a b jet and a VBF-tagged jet
- Centrality variables for the reconstructed Higgs boson candidates

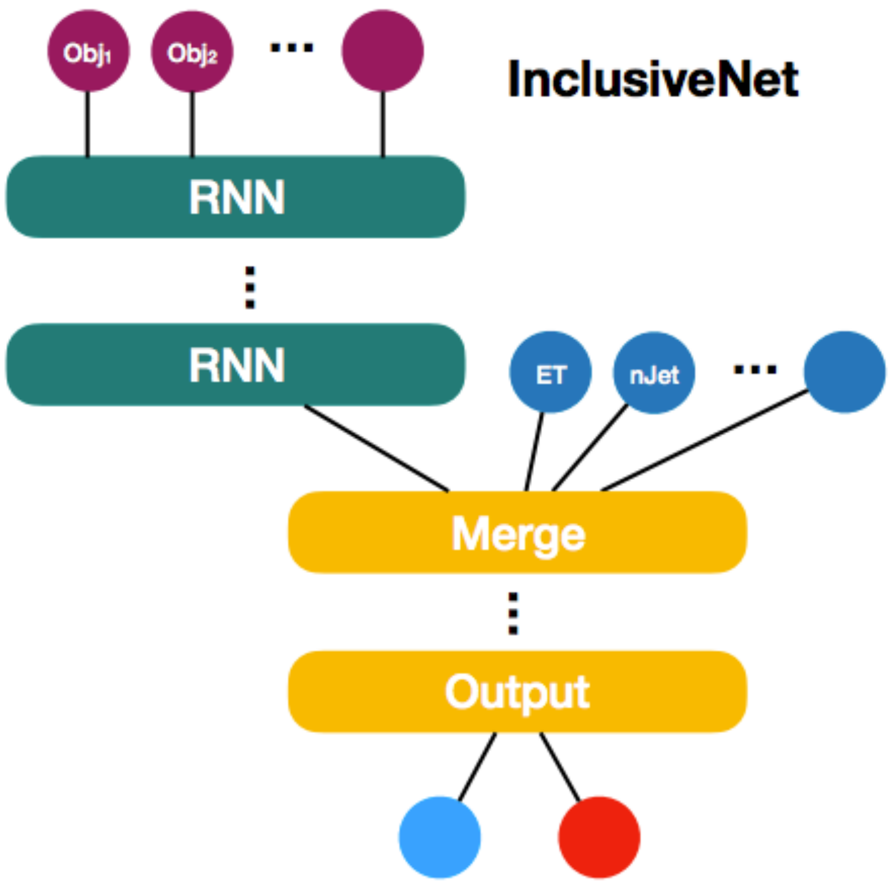
$$C_{xx} = exp\left(-\frac{4}{(\eta_1^{VBF} - \eta_2^{VBF})^2}\left(\eta^{xx} - \frac{\eta_1^{VBF} + \eta_2^{VBF}}{2}\right)^2\right),$$

where *xx* is Higgs boson candidate from diphoton or dijet pairs

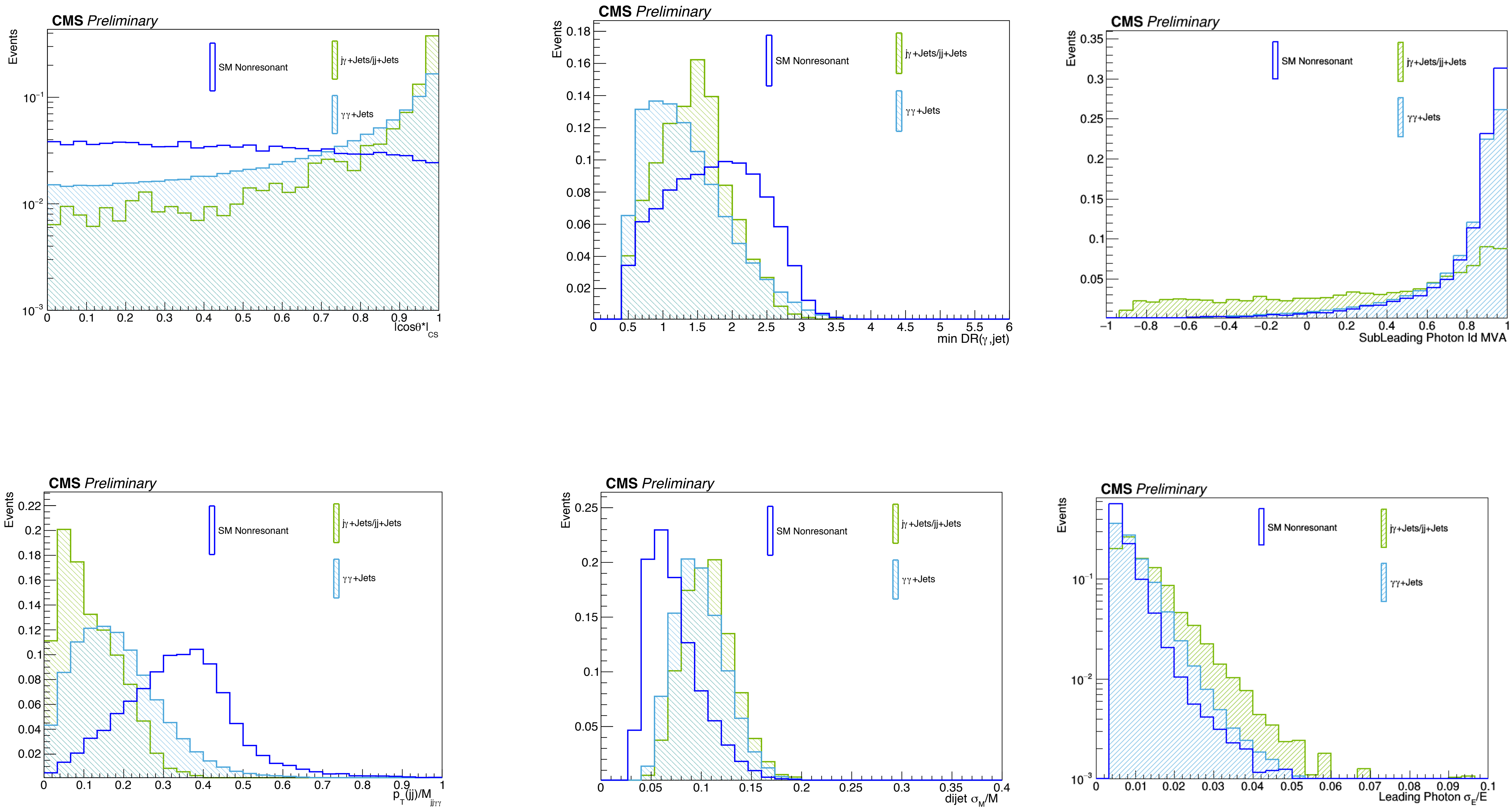
ttHScore : DNN to reduce ttH BG

- **ttH is a important background contribution**
- DNN was developed to kill this contribution with the following inputs :
  - global kinematic variables : sumE_T, MET, $\Delta\phi(j_1, MET)$, $\Delta\phi(j_2, MET)$, $\Delta R_{min}(\gamma, j)$, N_j, χ_{tt}, $|\cos\theta^*_{CS}|$, $|\cos\theta^*_{bb}|$
  - Reconstructed objects: (p_T, η, ϕ) of 2 leading electrons, 2 leading muons, selected b jets, diphoton, MET (η = 0)

- **Network architecture and hyper-parameters** optimized with Bayesian optimization:
  - 2 hidden dense layers with 500 dense nodes
  - 3 RNN (GRU) layers with size 180
  - dropout rate for dense layer: 0.11, GRU: 0.83
  - initial learning rate: 8e-4
  - batch_size: 316

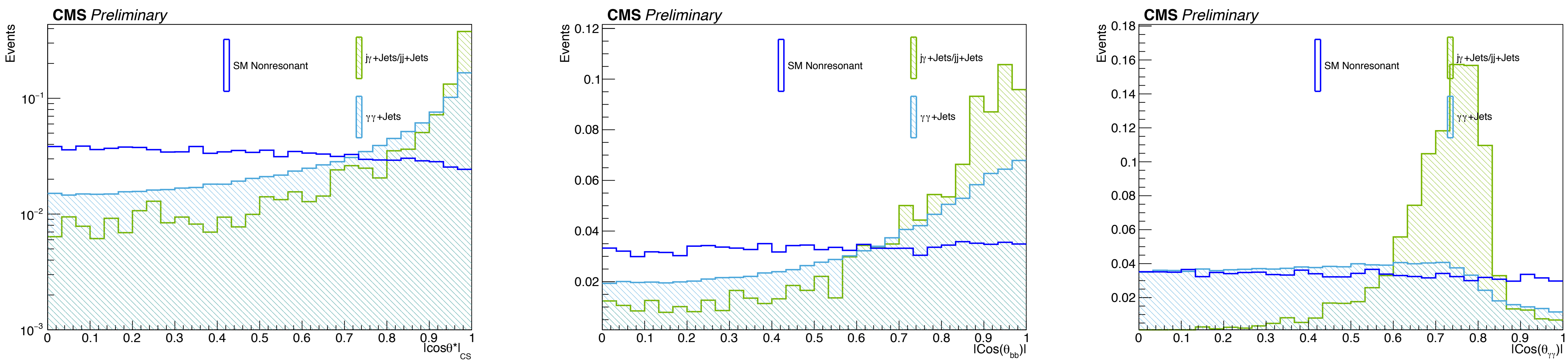


BDT classifier : inputs variables

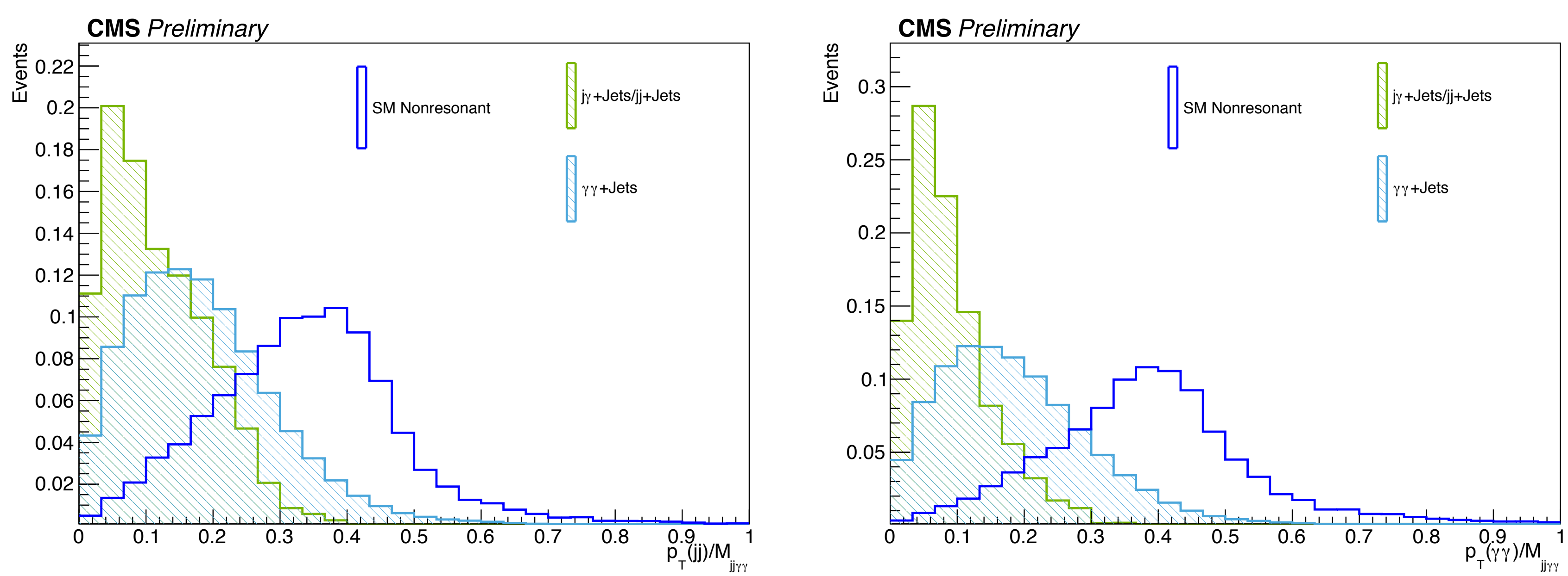


BDT classifier : inputs variables

Angles

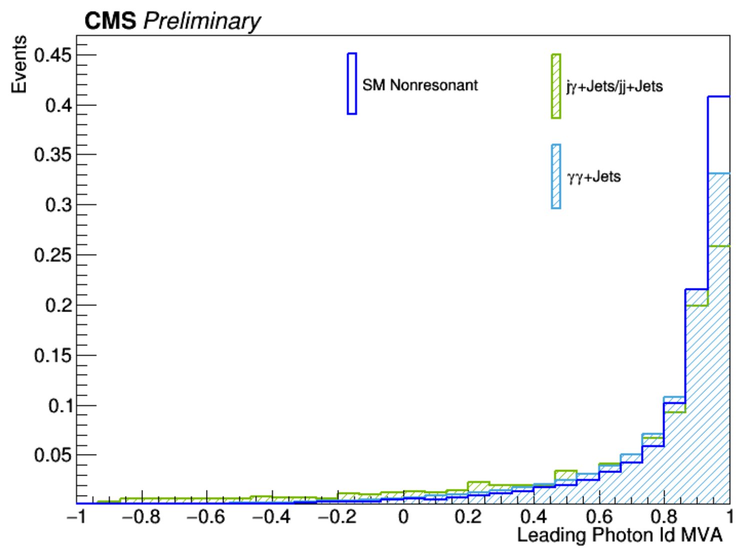


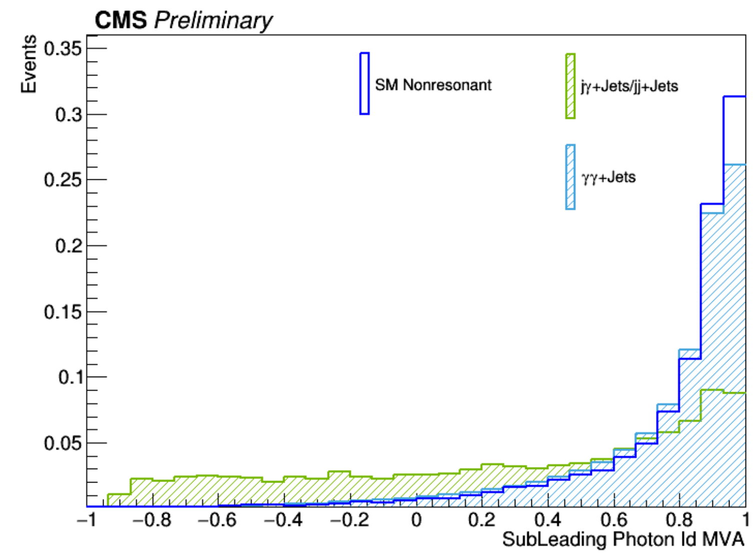
$p_T(H)/M(jj\gamma\gamma)$



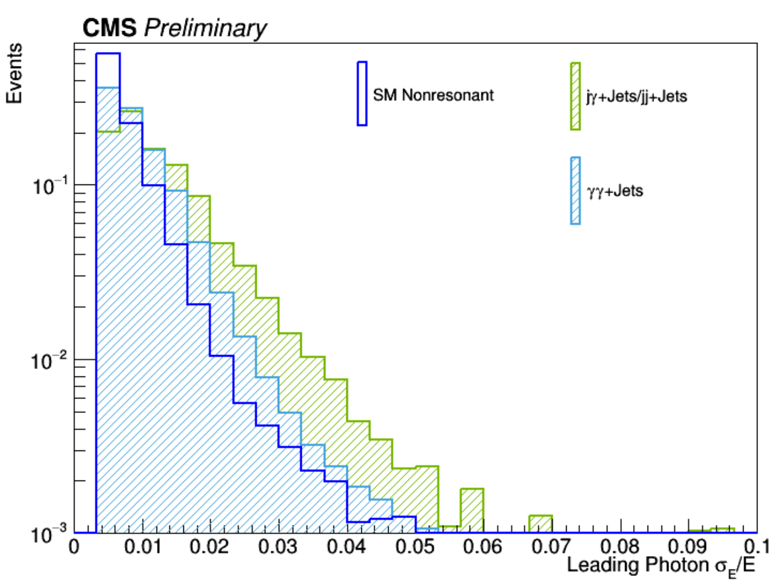
BDT classifier : inputs variables

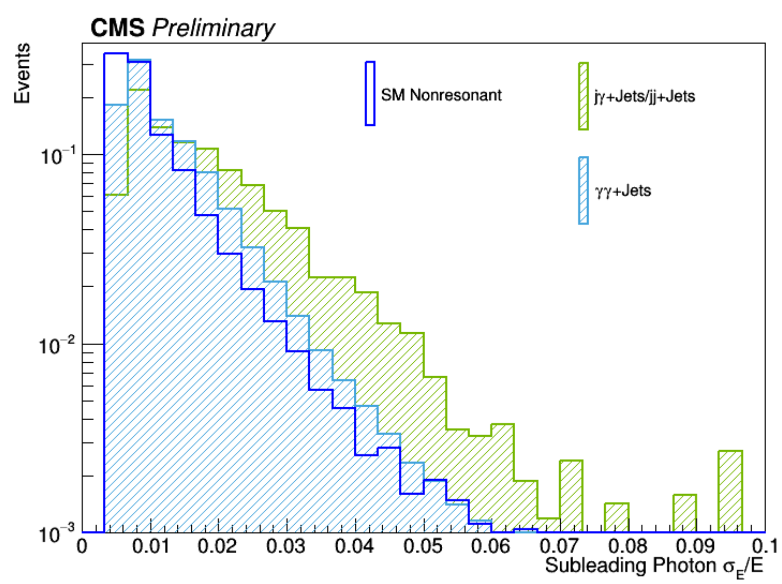
photonID leading & subleading



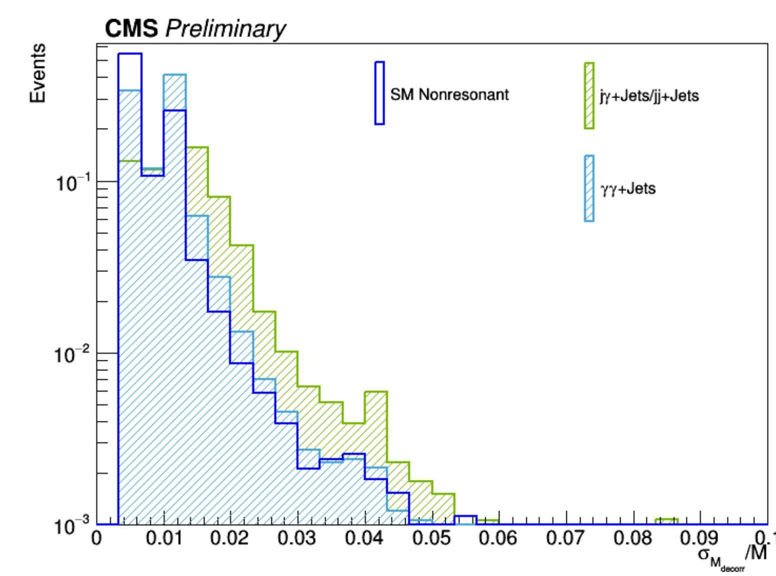


leading & subleading photon σ_E/E

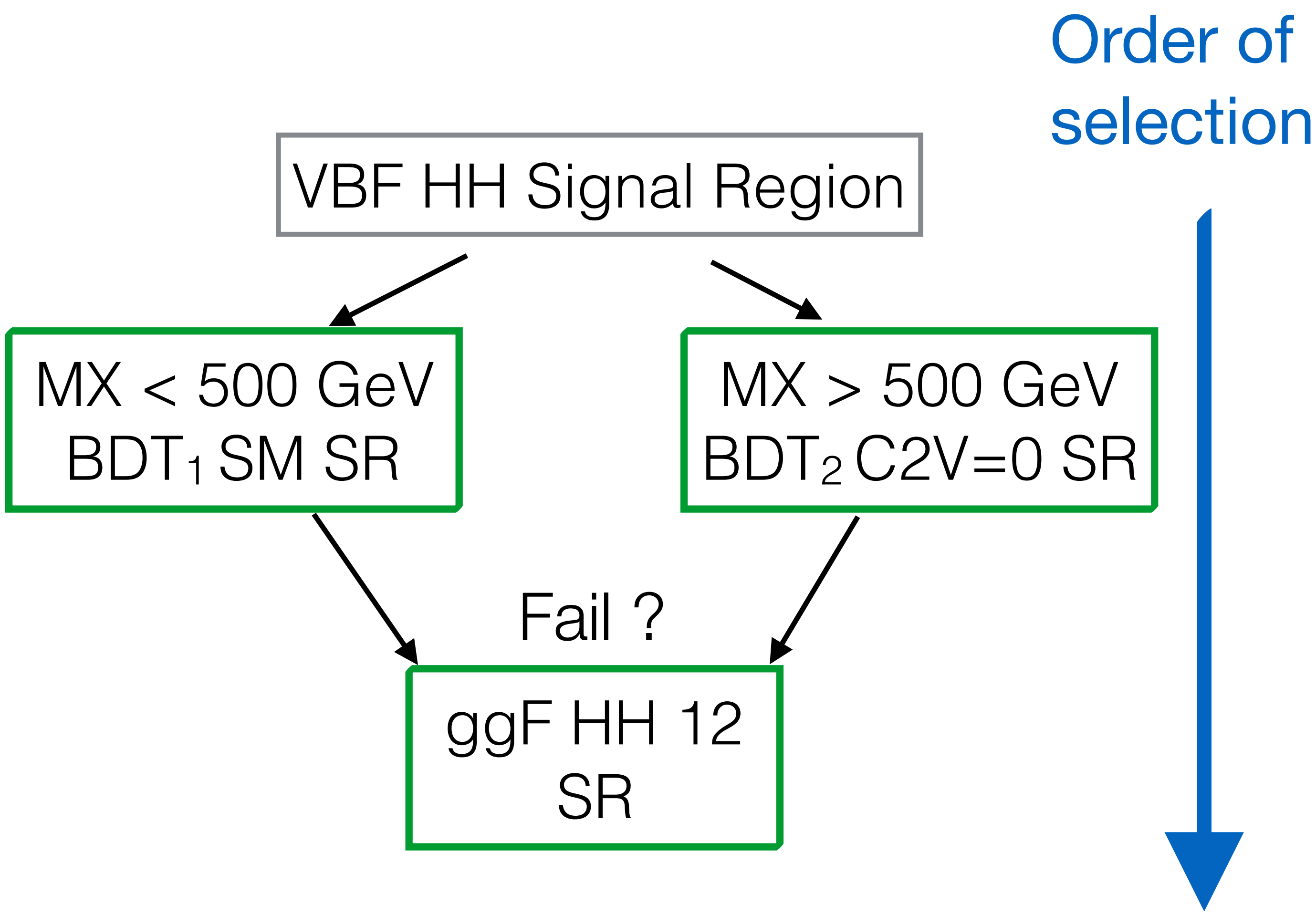




diphoton σ_M/M



Event categorization



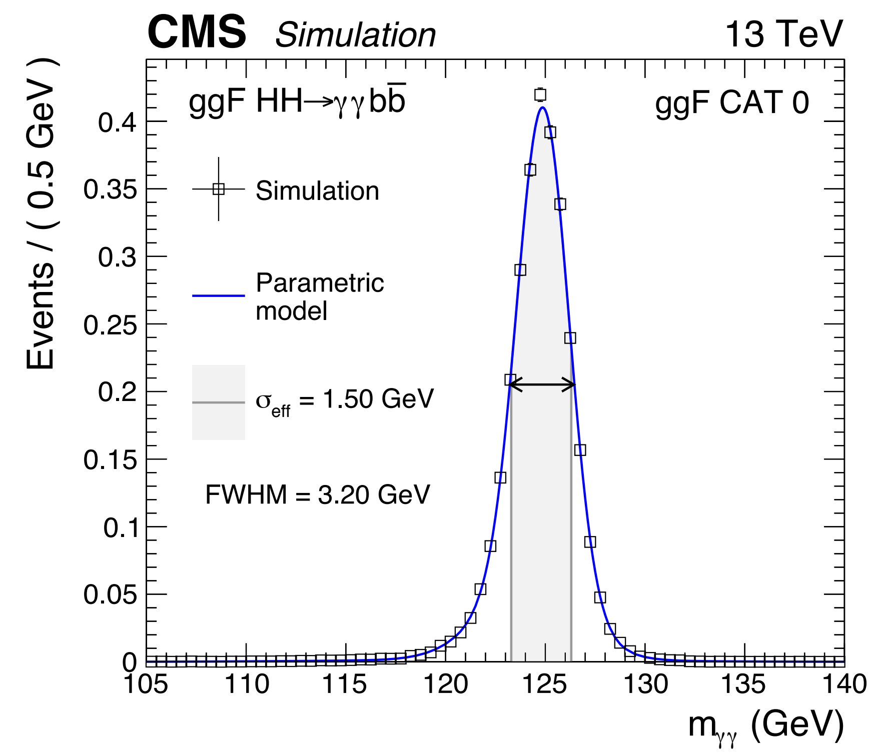
14 HH categories in total

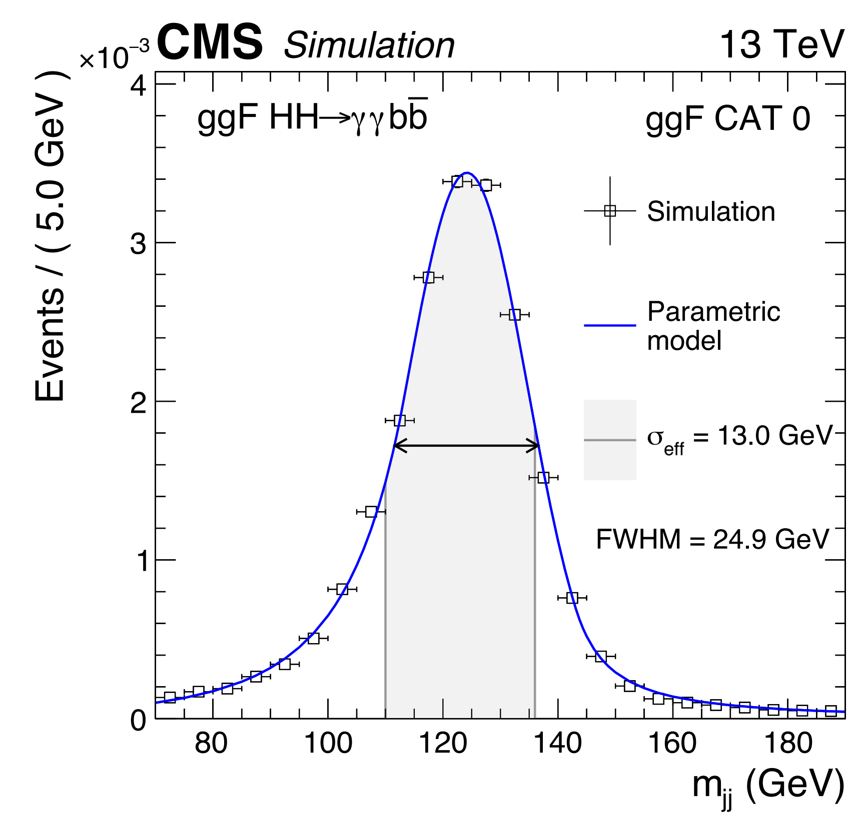
Category	MVA	$\widetilde{M}_X$ (GeV)
VBF CAT 0	0.52-1.00	>500
VBF CAT 1	0.86-1.00	250-500
ggF CAT 0	0.78-1.00	>600
ggF CAT 1		510-600
ggF CAT 2		385-510
ggF CAT 3		250-385
ggF CAT 4	0.62-0.78	>540
ggF CAT 5		360-540
ggF CAT 6		330-360
ggF CAT 7		250-315
ggF CAT 8	0.37-0.62	>585
ggF CAT 9		375-585
ggF CAT 10		330-375
ggF CAT 11		250-330

Signal and single H model

Signal model

- Signal and single Higgs (ttH,ggH,VBF,VH) parametric models are built from MC simulation
- M(γγ) model is built from a sum of up to 5 Gaussians
  - Determine how many Gaussians should be used to describe distribution with F-test
- M(jj) model depends on the process :
  - HH signal - double sided Crystal Ball
  - VH - Crystal Ball
  - ttH - Gaussian
  - ggH and VBF - Bernstein polynomial





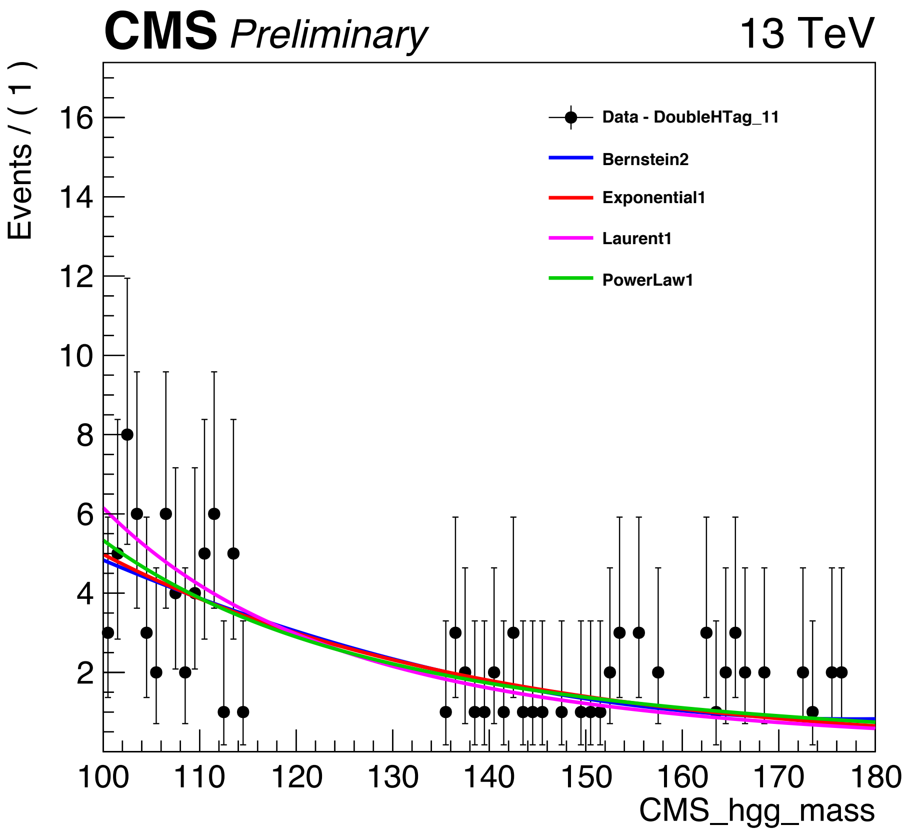
Nonresonant background model

Background model

- choice of BG model is done using **discrete profiling method**
- method treating model choices as discrete nuisance parameters
- **Profile** the choice and take the **envelope**
- Choice of which models to include open to user

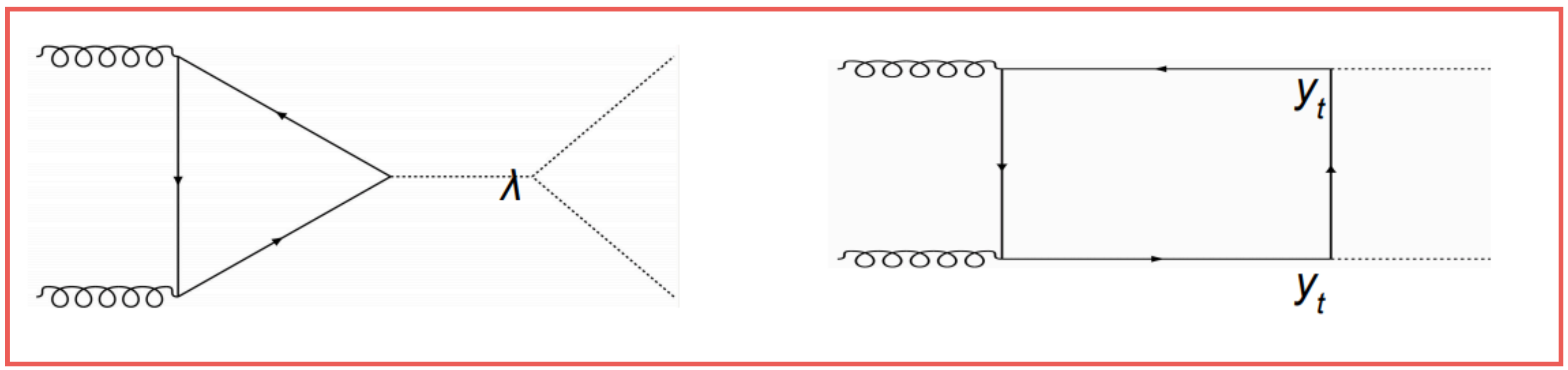
Implementation :

- First generate the background model to be used for the envelope method :
- pick a sensible subset of functions which could describe data using fTest. Functions considered :
  - Polynomial, Exp, Laurent, Power Law up to 7th order
- Treat the choice of function as discrete nuisance parameter in the final fit
-

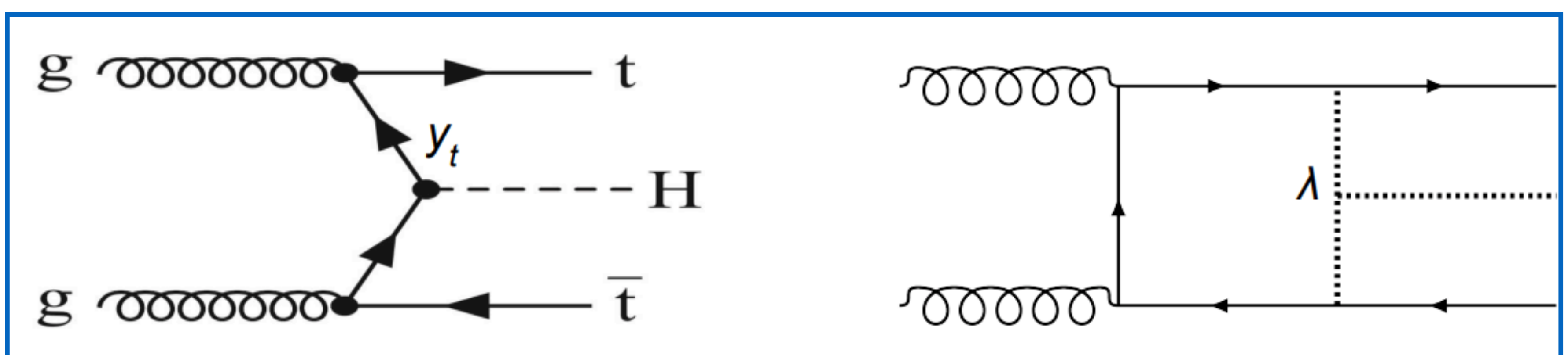


Combination of HH and ttH

- HH and ttH production are sensitive to the Higgs trilinear coupling λ and y_t
- **Fit σ_{HH} and σ_{ttH} simultaneously to extract λ and yt**
  - To provide constrain the k_λ and k_t , HH signal is combined with ttH ($H \to \gamma\gamma$)



Both ttH and HH depend on λ and y_t



Additional ttH categories

- Main HH analysis categories are designed to remove as much contamination from single Higgs background as possible
- Therefore additional categories are needed to select ttH events
- **Hgg tags** are used as additional categories targeting different single H production
  - tags are mutually exclusive and the order of tags was optimized to maximize HH signal efficiency with minimum contamination of other single H processes, and maximize ttH signal efficiency

Tag sequence

1. VBF HH
2. ggF HH
3. ttH