Recent HH results in CMS (resonant and non-resonant)

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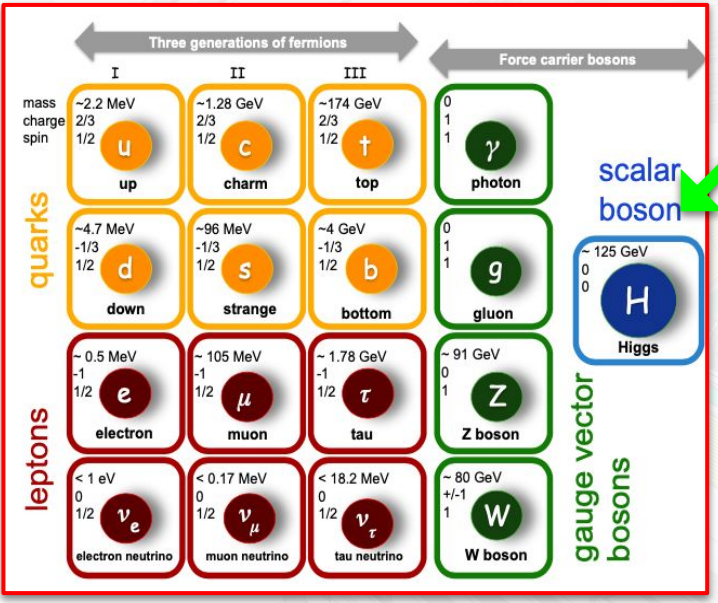
On behalf of the CMS Collaboration

THE HIGGS BOSON

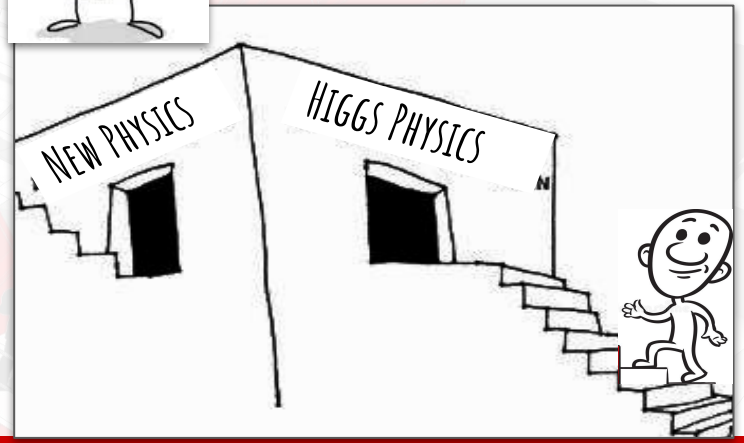


2012: discovery of Higgs completes SM

Still have open questions like Dark matter, gravity...

Need more physics

SM Higgs might be stairway for new physics

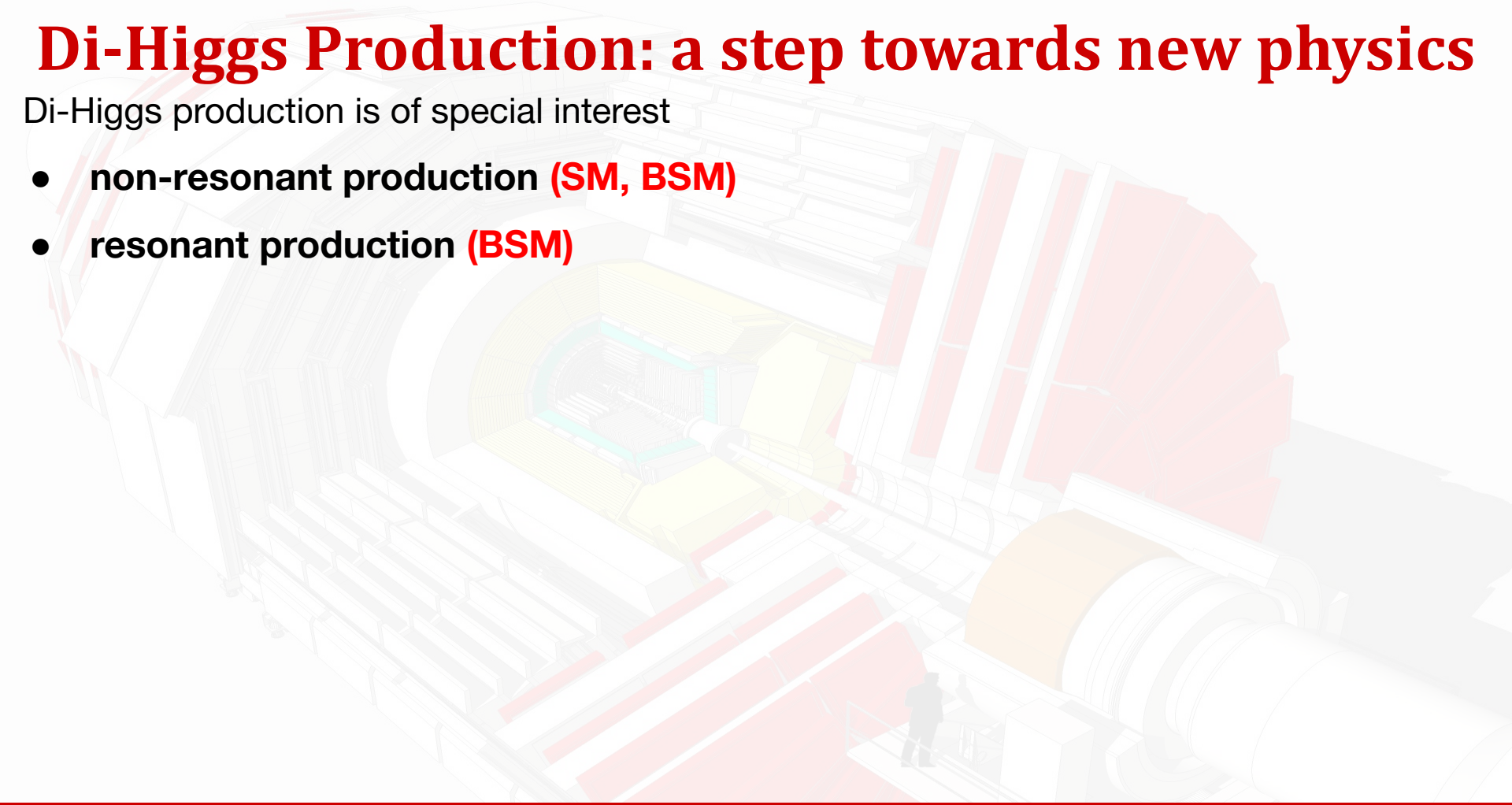


- Talk focuses on the Di-Higgs sector of Higgs physics where pp → HH at LHC with L= 137 fb^{-1} CMS Run2 data

Di-Higgs Production: a step towards new physics

Di-Higgs production is of special interest

- **non-resonant production (SM, BSM)**
- **resonant production (BSM)**



Di-Higgs Production: physics motivation

Di-Higgs production is of special interest

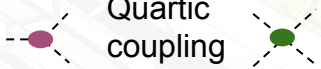
- **non-resonant production (SM)**
- resonant production

Only mode for SM HH-production

➢ Higgs potential term

$$V = \frac{m_H^2}{2}H^2 + \frac{m_H^2}{2v^2}vH^3 + \frac{1}{4}\frac{m_H^2}{2v^2}H^4$$

Mass term — Trilinear coupling — Quartic coupling

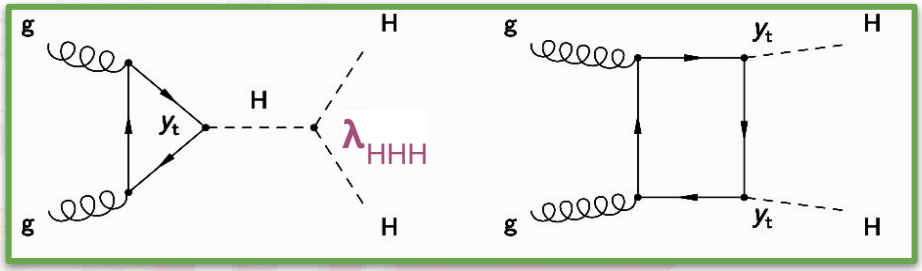


➢ Probe for Higgs trilinear self coupling λ_{HHH}

➢ $\lambda_{HHH,SM} = m_H^2/2v^2 = 0.13$ (for $v = 246$ GeV)

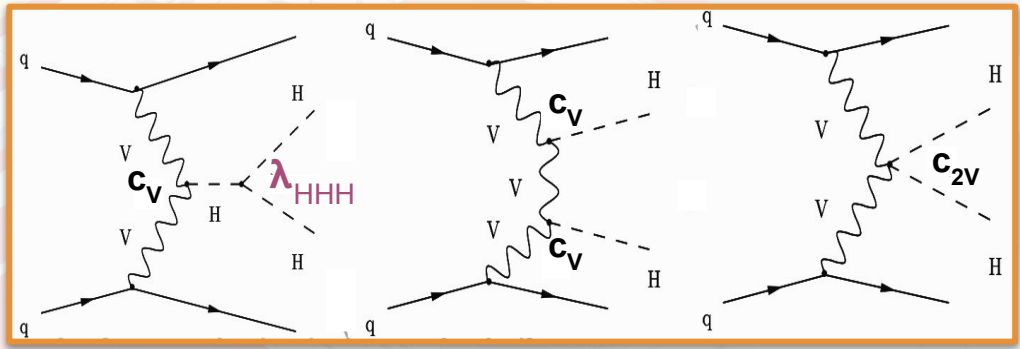
➢ Production modes: ggF HH, VBF HH, VHH, ttHH; ggF HH dominates

ggF HH LO



➢ Destructive interference diagrams makes the HH-production cross-section small (13 TeV ggF HH = 31.05 fb@NNLO; VBF HH = 1.73 fb@N^{3}LO)

VBF HH LO



Di-Higgs Production: physics motivation

Di-Higgs production is of special interest

- **non-resonant production (BSM)**
- resonant production

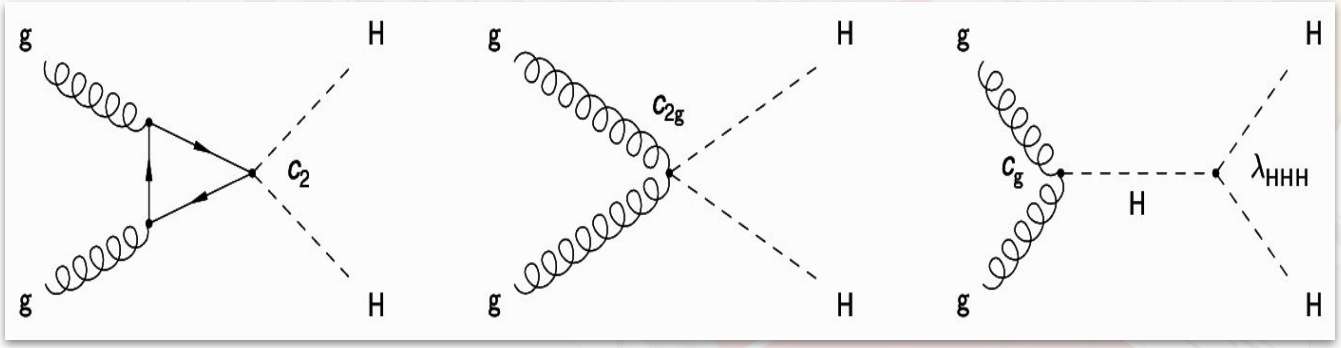
BSM EFT HH-production

➢ Approach to look for new physics existing at High scale by studying low energy signatures

➢ Anomalous values for SM predicted couplings can enhance the HH production cross-section

➢ CMS perform these searches for ggF HH only

- In five dimensional parameter space (k_t, k_λ, c_g, c_{2g}, c_2) which affects the kinematics and cross-section



$k_\lambda = \lambda_{HHH} / \lambda_{HHH,SM}$
$k_t = y_t / y_{t,SM}$
c_2 = ttHH contact interaction
c_g = gHH contact interaction
c_{2g} = gHH contact interaction

Di-Higgs Production: physics motivation

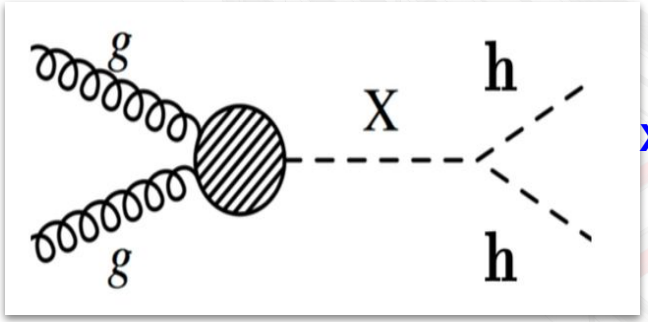
Di-Higgs production is of special interest

- non-resonant production
- **resonant production (BSM)**

➢ **Many BSM models predict resonances with higher cross-section which directly couple to Higgs**

➢ **Easier to observe with direct detection searches**

➢ **Dominant production via gluon-gluon fusion**



X mass up to 3 TeV

➢ **CMS explores BSM models such as**

Warped Extra dimension (WED)

Solution to SM hierarchy problem

Predicts Spin-0 and Spin-2 resonances

Minimal Supersymmetric Standard Model (MSSM)

Minimal supersymmetric extension to SM

Unify gauge couplings and cancels quadratic Higgs mass radiative corrections

Provide dark matter candidate

Extends Higgs sector with h, H, A, H^+, H^-

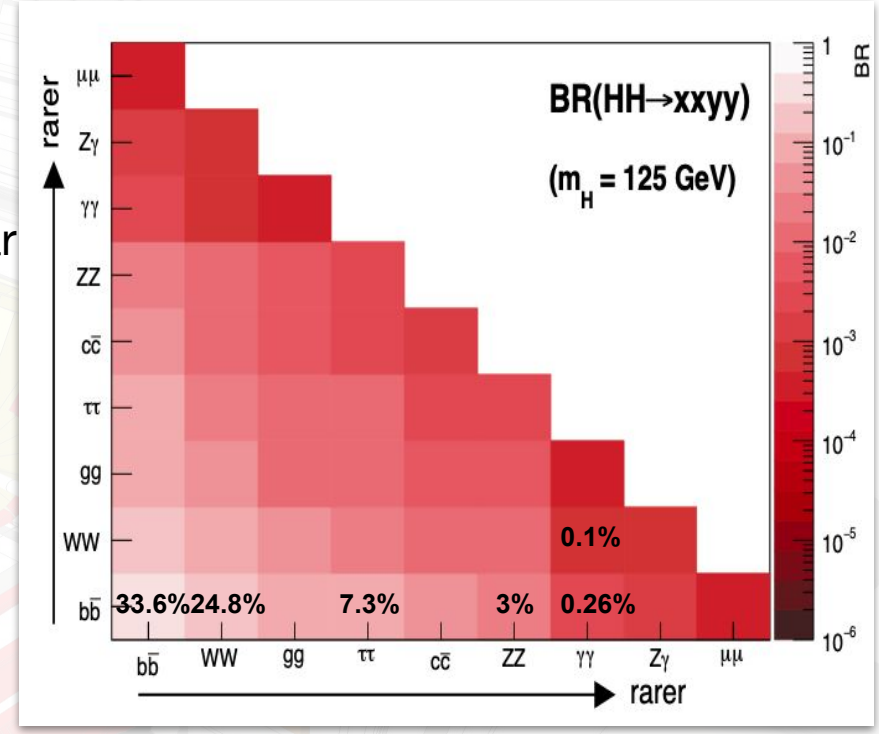
Next-to-Minimal Supersymmetric Standard Model (NMSSM)

MSSM with additional singlet, solves μ-problem

Enrich Higgs sector with h, H, h_S, A_1, A_2, H^+, H^-

Di-Higgs decay modes

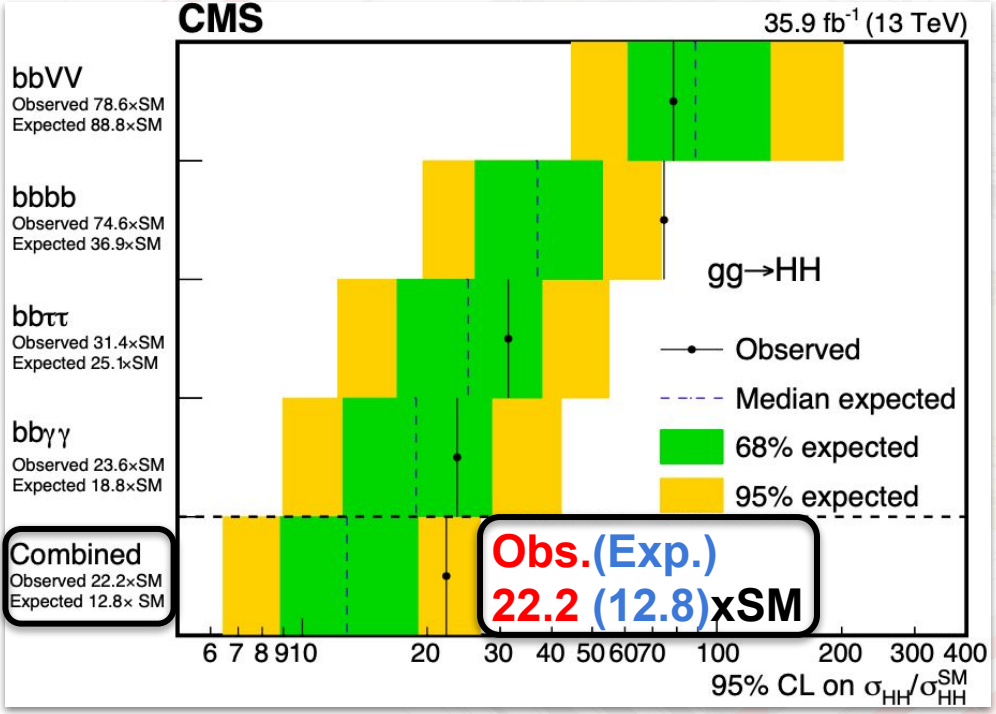
- Explore according to branching fraction (BR) and purity of the channel
  - **bbbb/bbWW**⇒ large BR, high QCD/ ttbar contamination
  - **bbττ** ⇒ relatively lower BR, tau-tagging increases S/√B
  - **bbɣɣ/bbZZ** ⇒ small BR, good selection efficiency

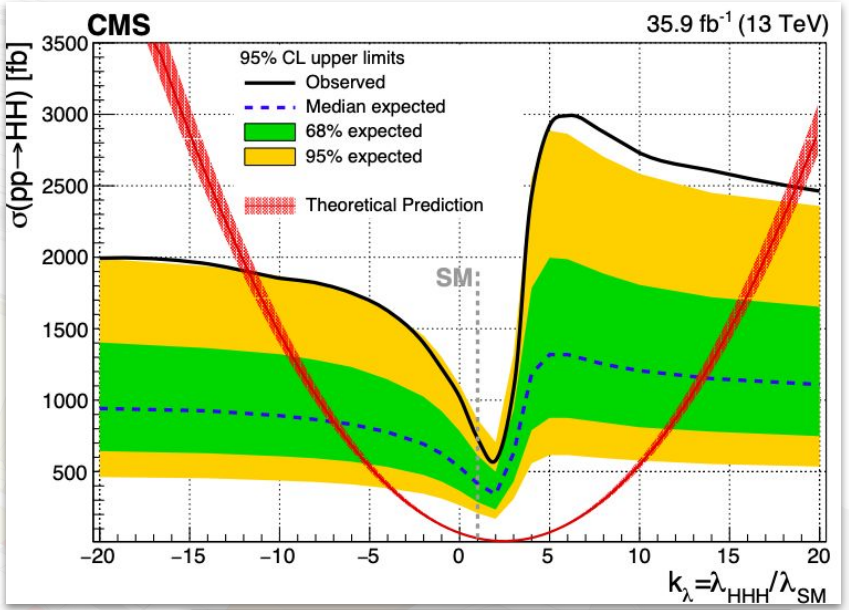


From next slide: brief overview of all HH searches at CMS with 2016 dataset (35.9 fb^{-1}) and status of recent searches with Run2 dataset (137 fb^{-1}) at 13 TeV

PRL 122 (2019)

Non-resonant HH Combination results





At 95% CL Obs. (Exp.)
-11.8 (-7.1) < k_λ < 18.8 (13.6)

- Results are from combination of bbbb, bbττ, bb$\gamma\gamma$, bbVV final states with 2016 data
- No deviation is observed from standard model background expectation
- **Upcoming slides focus on new full Run2 (2016+17+18) results for bb$\gamma\gamma$ and bbZZ channels**

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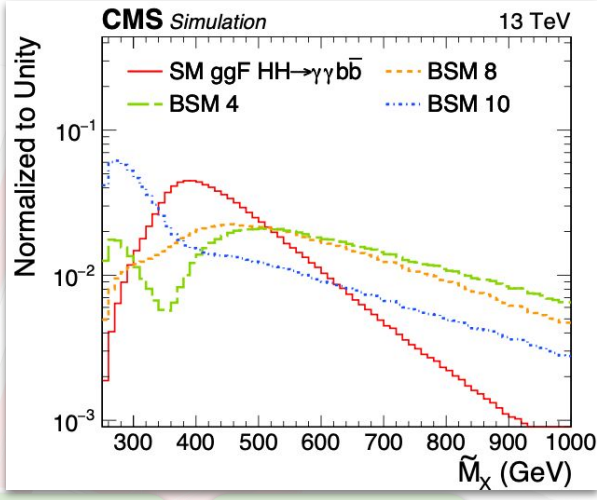
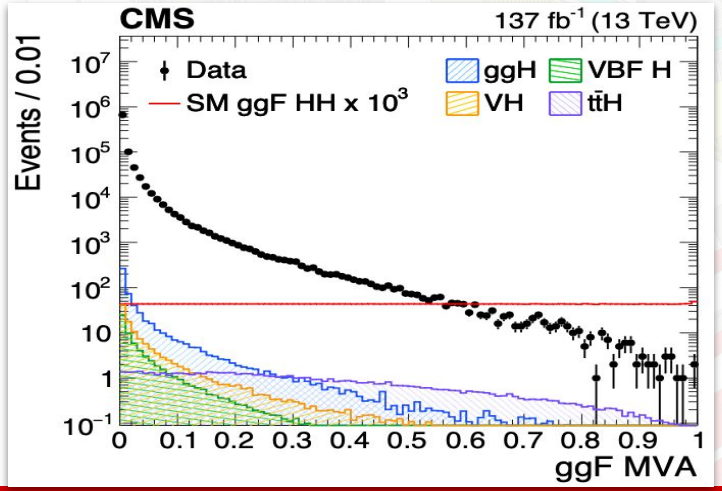
Non-resonant HH→ bbγγ

NEW

- High CMS ECAL resolution for H→ γγ provides good selection efficiency
- b-Tagging helps to suppress background for H→ bb with highest BR
- $\tilde{M}_X = m_{jj\gamma\gamma} - m_{jj} - m_{\gamma\gamma} + 250$ sensitive for BSM EFT shape benchmarks
- BDT trainings; MVA:$\tilde{M}_X$ based 2D categorization to enhance sensitivity
- Set 95% CL limits on non-resonant HH-production cross-section for SM and 13 EFT shape benchmarks and coupling scanes k_λ, k_t, c_{2V}, c_2





Loose selections on b-jets and γ → MVA training and categorisation → Signal extraction $m_{\gamma\gamma}$: m_{jj} 2D-fit

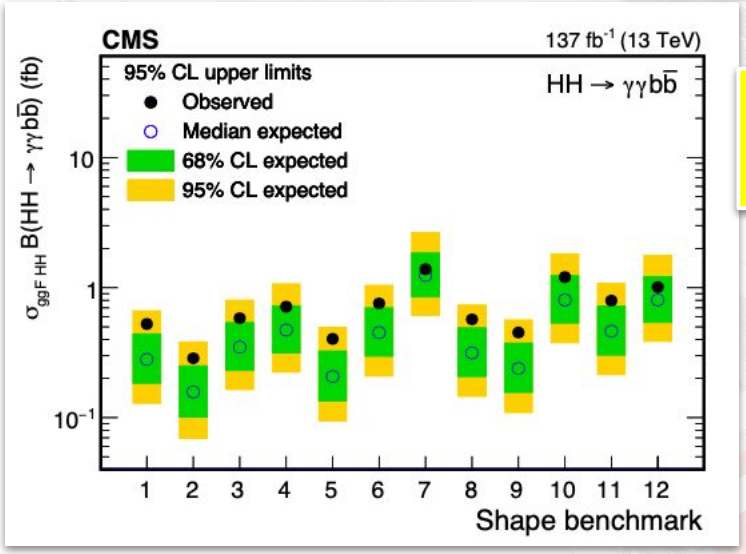
MVA training and categorisation → Yes → 14 HH categories (12 ggF + 2 VBF)

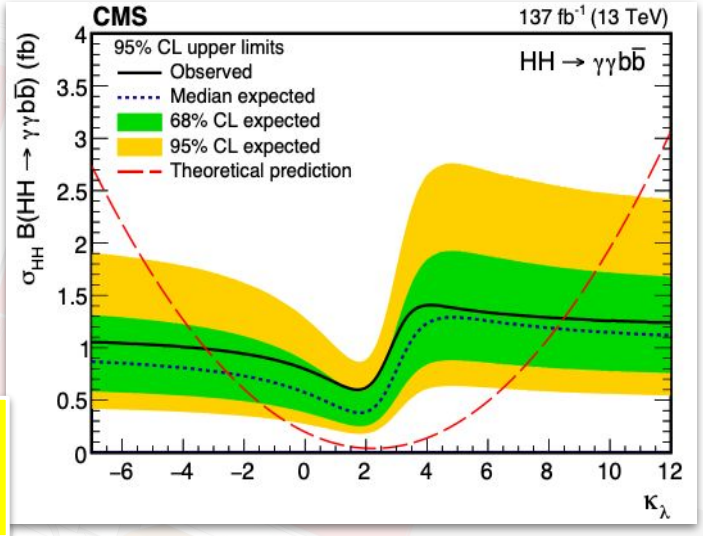
MVA training and categorisation → No → Events for ttH categories

Non-resonant HH→ bbγγ

NEW

- Backgrounds: non-resonant from data driven method and resonant from single Higgs simulations
- Background model: 2D discrete profiling method in $m_{\gamma\gamma}$ and m_{jj}
- Final signal extraction performed by fitting all categories
- **95% CL limits on cross-section Obs. (Exp.) = 7.7 (5.2) x SM**





Inclusive σ_{HH}*BR
60% impr. wrt 2016

Allowed ranges@95% CL

Obs.(Exp.)

-3.3 (-2.4) < k_λ < 8.5 (8.2)

Put Stringent limits on k_λ , best to date

-1.3 (-0.9) < c_{2V} < 3.5 (3.0)
-0.6 (-0.4) < c_2 < 1.0 (0.9)

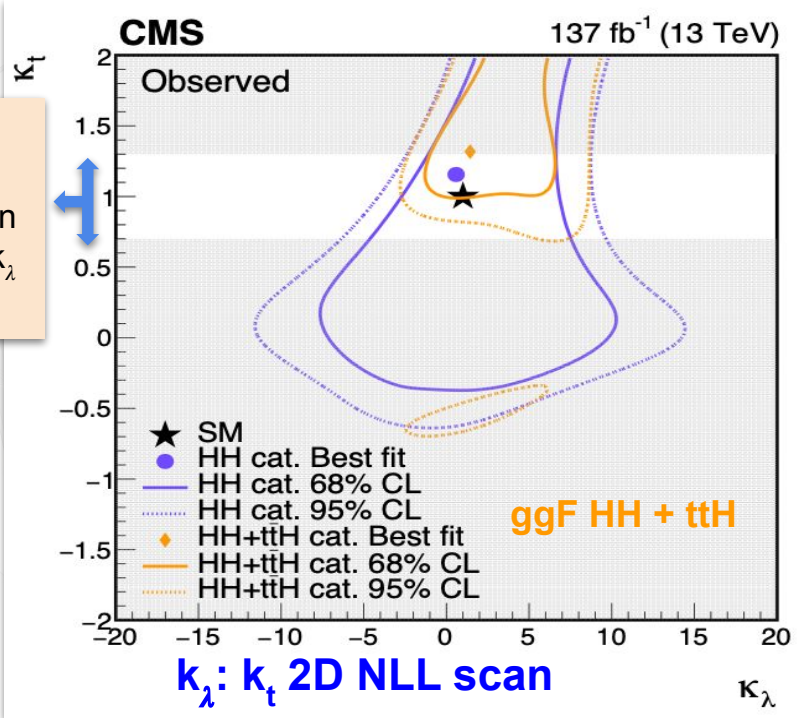
First from CMS constraints for c_{2V} & c_2

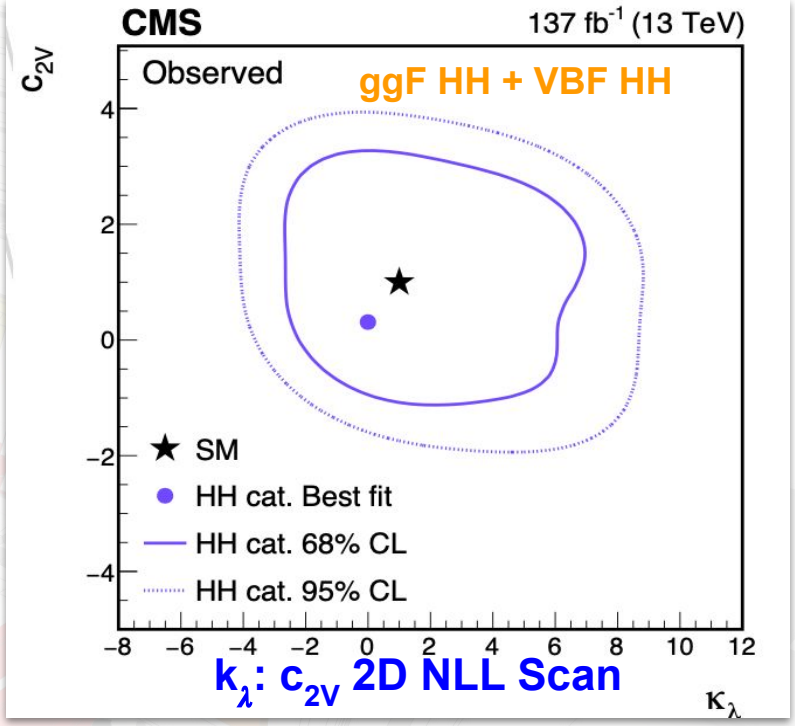
NOTE: Other 1D Coupling scan plots are in backup

Non-resonant HH→ bbγγ

NEW

Allowed region for k_t parameterisation for anomalous k_λ value (link)





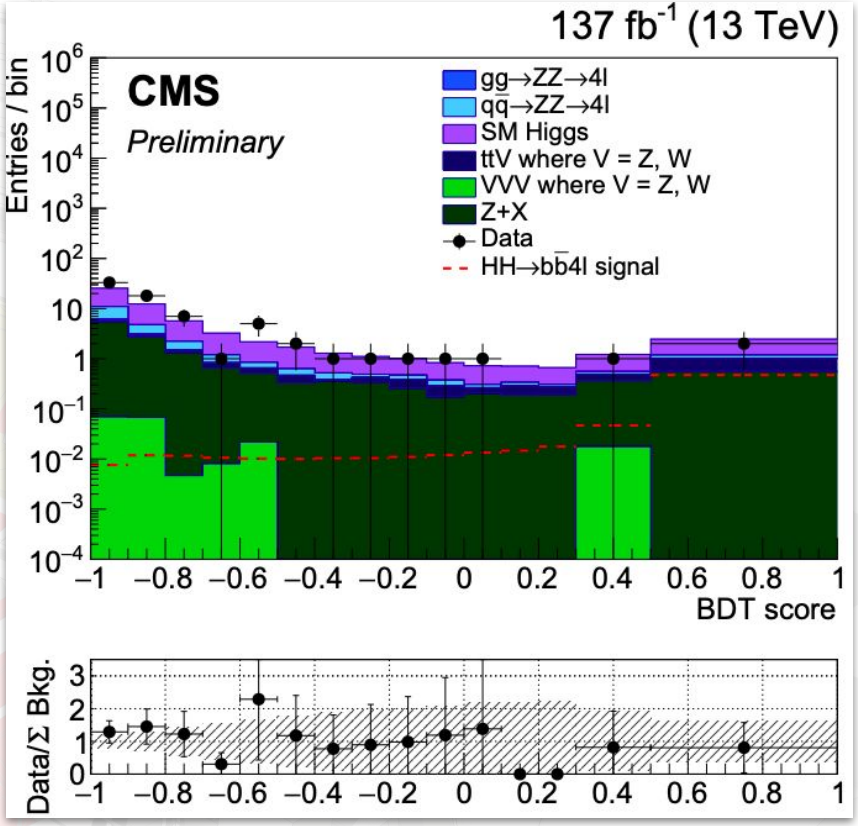
- Inclusion of ttH process provides better constraints k_λ and k_t
- Corresponding 1D scans are in backup which ruled out negative values of k_t with inclusion of ttH process

CMS-PAS-HIG-20-004

Non-resonant HH→ bbZZ (ZZ→ 4l)

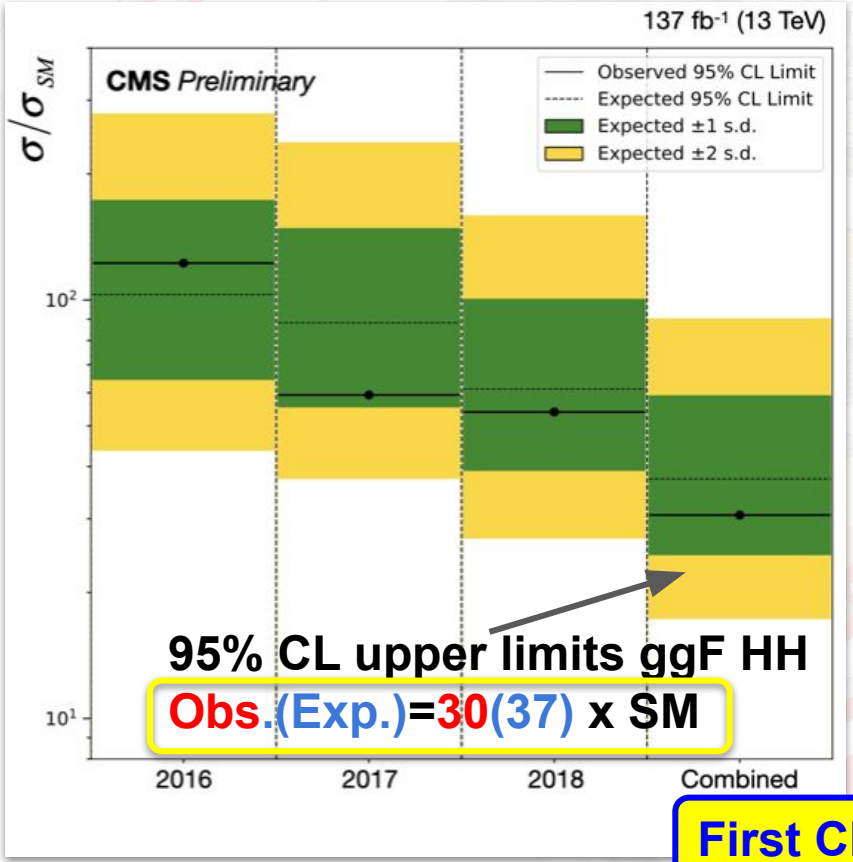
NEW

- **First time looking for bb4l decay mode for HH-searches** (combine bb4μ, bb4e, bb2e2μ channel)
- Select isolated 2 b-Tagged jets and set of 4 leptons with invariant mass close to Higgs mass
  - lepton pair with opposite charge, same flavor and close to Z mass
- BDT training to enhance the signal vs background discrimination
- Z+X Background from data-driven method, other background (Single H, ttW, ttZ, QCD) from simulations
- Signal extraction with maximum probability fit to merged BDT output distribution of all channels



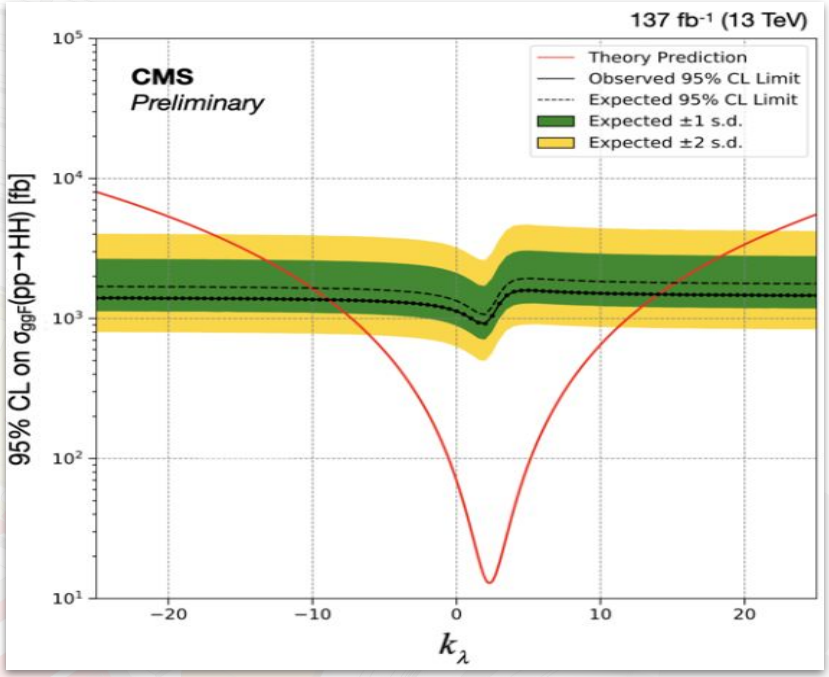
Non-resonant HH→ bbZZ (ZZ→ 4l)

NEW



95% CL upper limits ggF HH

Obs.(Exp.)=30(37) x SM



95% CL allowed k_λ ranges

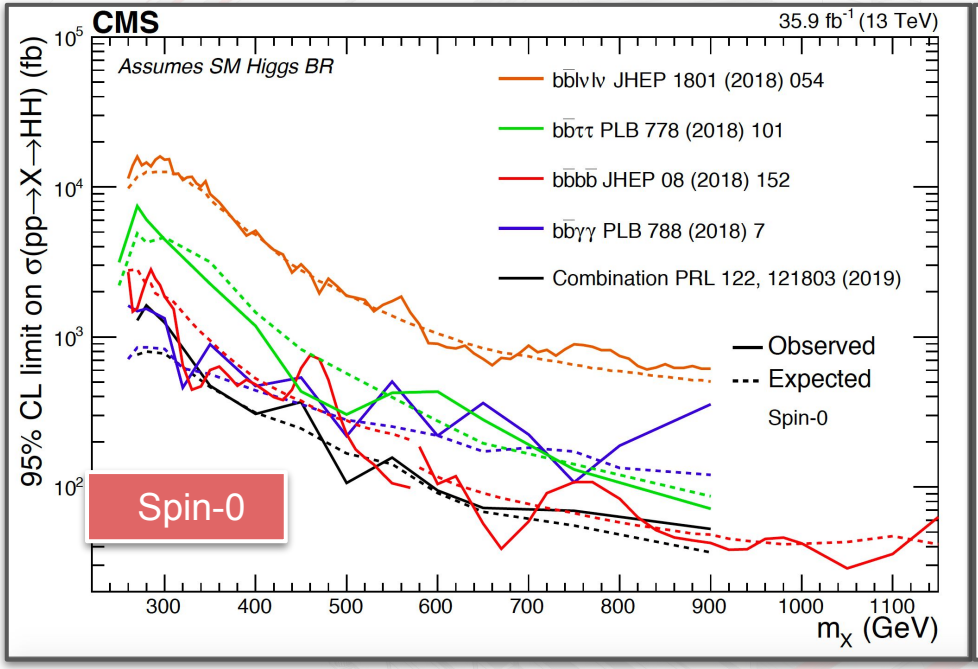
Obs.(Exp.)

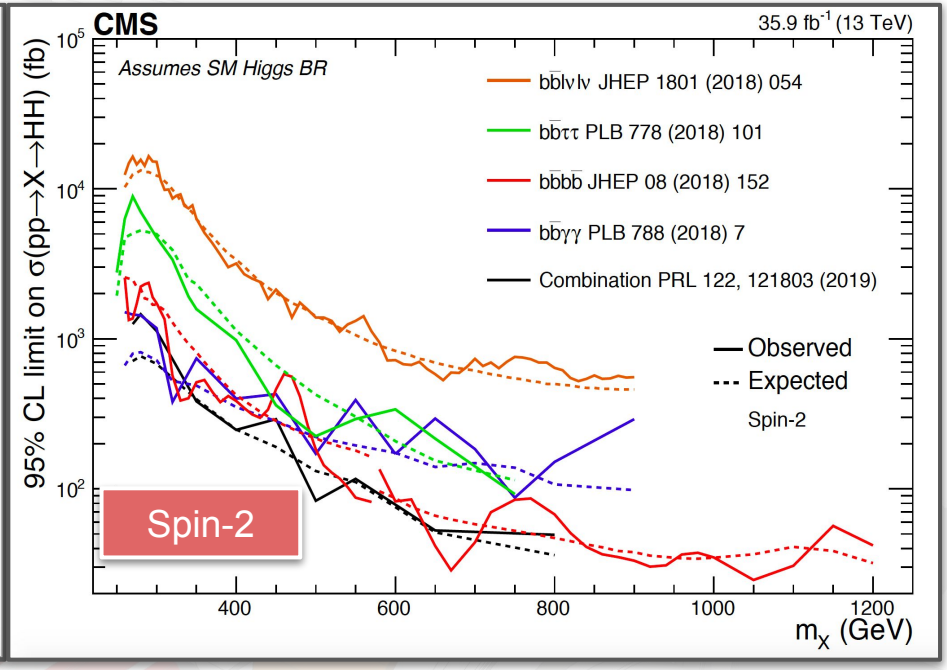
$-9\ (-10.5) < k_\lambda < 14\ (15.5)$

First CMS results

reference

Resonant→ X→ HH Combination results



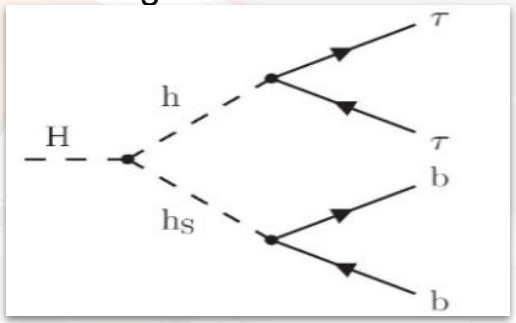


- 2016 Results are from combination of bbbb, bbll$\nu\nu$, bbττ, bb$\gamma\gamma$ final states; (other bblνqq', bbllqq)
  - No deviation is observed from standard model background expectation
- **Upcoming slide focus on new full Run2 (2016+2017+2018) results for bbττ channel**

NEW

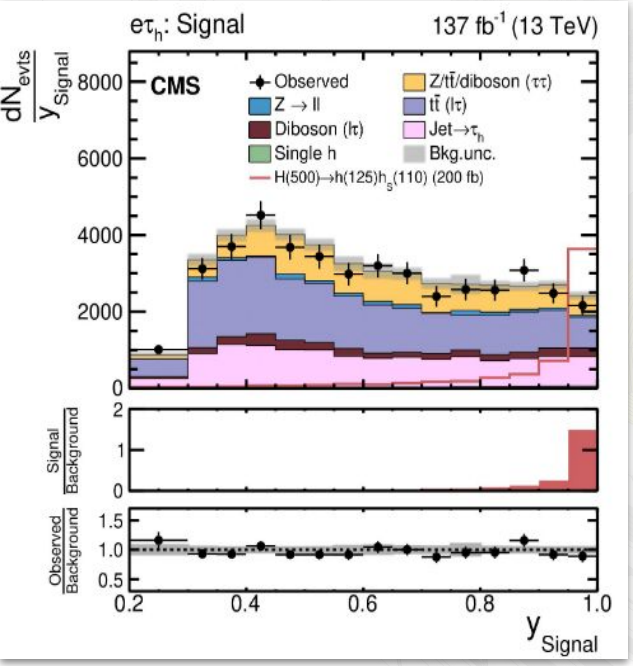
Resonant $H \rightarrow h_s h \rightarrow bb\tau\tau$

- **First time in CMS exploring NMSSM signatures with resonant di-Higgs searches**
  - Predicts 7 Higgs bosons with 3 CP-even Higgs H, h_s, h (SM Higgs)
  - Look for $H \rightarrow h_s h$ since dominant singlet component in h_s suppress its direct production at LHC
- Fix SM $h \rightarrow \tau\tau$ to have benefit of tau tagging to suppress background
- 3 τ-decay channels are combined: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Tag 2 b-jets and 2 tau's in an event
- Data driven method is used for background estimation, single H backgrounds from simulations
- Neural network (NN) based multi-classification training, NN-output based event categorisation
- Despite of NMSSM motivation, model independent limits are set
- analysis does not differentiate between scalar and pseudoscalar Higgs

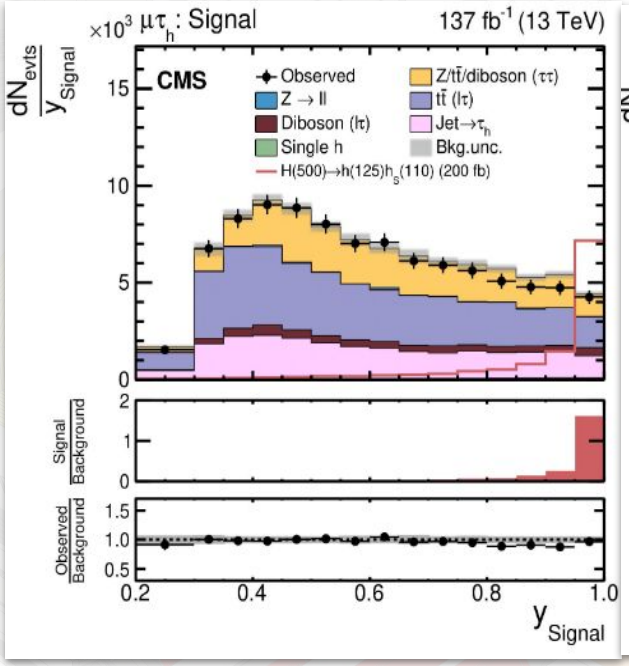


Resonant $H \to h_s h \to bb\tau\tau$

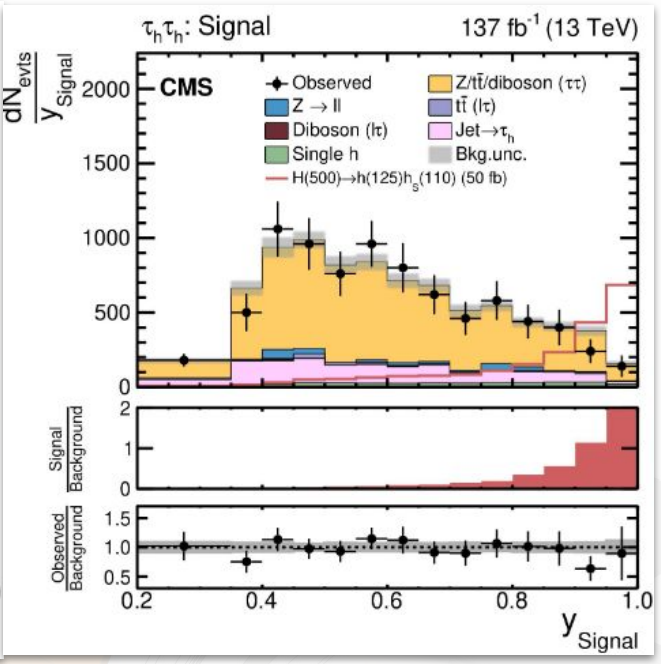
NEW



$e\tau_h$



$\mu\tau_h$

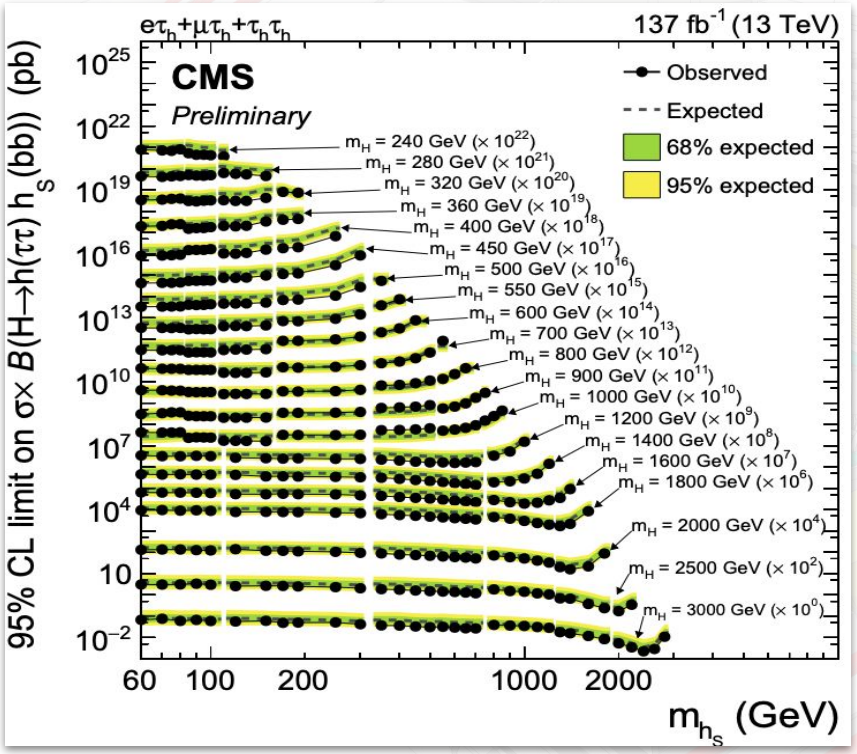


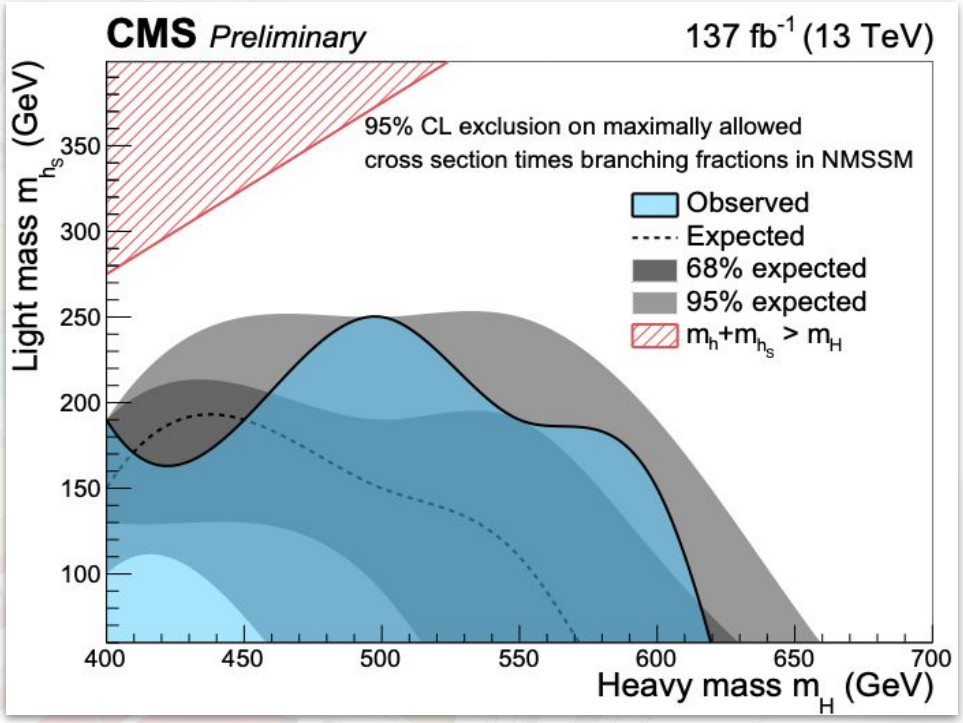
$\tau_h\tau_h$

- NN-output for signal category for all three channel

Resonant $H \to h_s h \to bb\tau\tau$

NEW





- Model-independent upper limit scaled by order of 10 for every H mass point
- No deviation from SM predictions

First CMS results

- Maximally allowed mass region for NMSSM scenario is constrained with m_H = [400,600] GeV

Summary and Conclusion

- Di-Higgs production is important to study Higgs potential and look for new physics
- At CMS, we study these signatures in various final states based upon its branching fraction and purity
- Non-resonant HH searches Run2 results are presented for bbγγ and bbZZ channels
  - (ggF+VBF HH) bbγγ results provide stringent bounds on Higgs self coupling parameter, first results for constraints on c_{2V} (VVHH) and c_2(ttHH) couplings
  - (ggF HH) bbZZ→ bb(4l) has first CMS results
  - No deviation from SM expectations
- Resonant searches have been extended to NMSSM model
  - first time looking for resonant NMSSM signatures with Run2 data,
  - Results are consistent with SM background predictions
- Other final state analyses with full Run2 data and final combined results are on the way. Stay tuned!

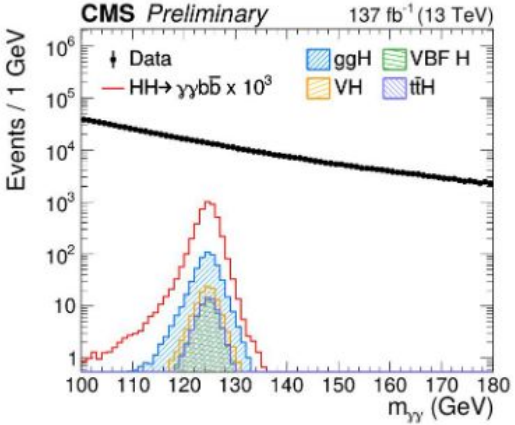
Thanks for your attention!

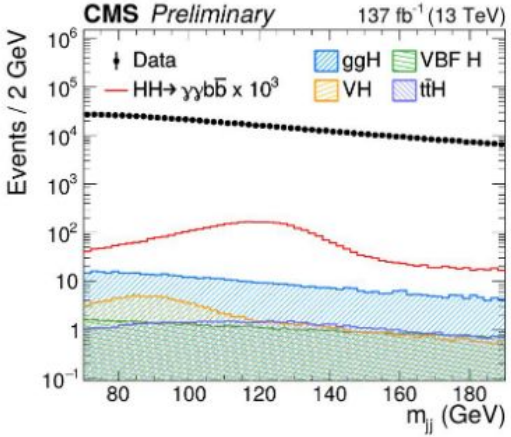
Backup

Non-resonant HH→ bbγγ

Benchmark points:

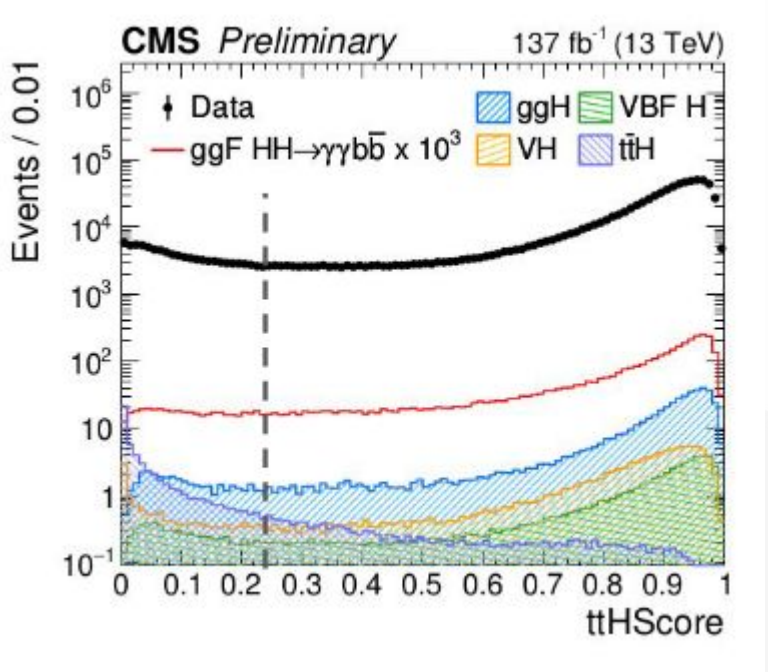
	1	2	3	4	5	6	7	8	9	10	11	12	SM
κ_λ	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0	0.0
c_g	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0	0.0
c_{2g}	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2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



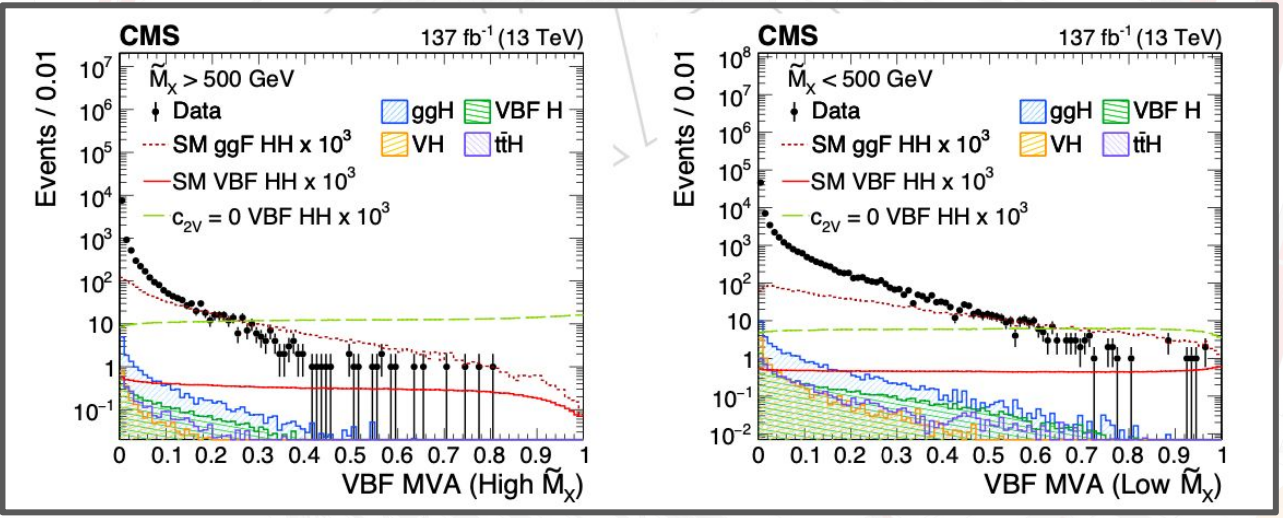


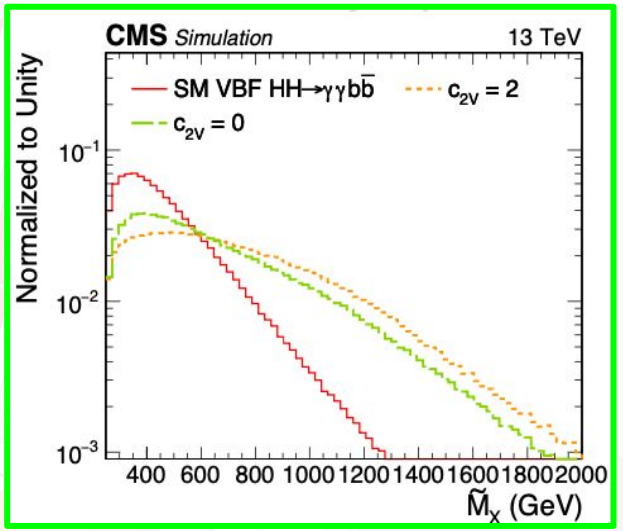
Non-resonant HH→ bbγγ

- DNN based tagger
- Trained on non-resonant SM and EFT benchmarks as signal and ttH as background
- Efficient discriminator to suppress dominating ttH background (with optimized cut 90% signal efficiency)

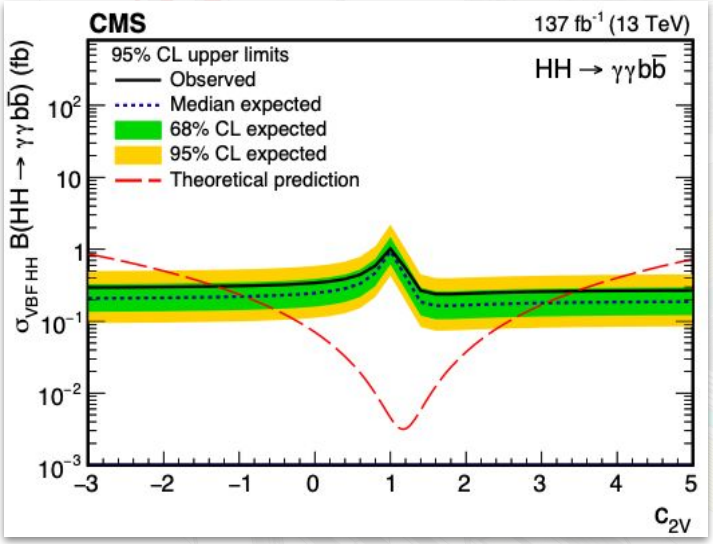


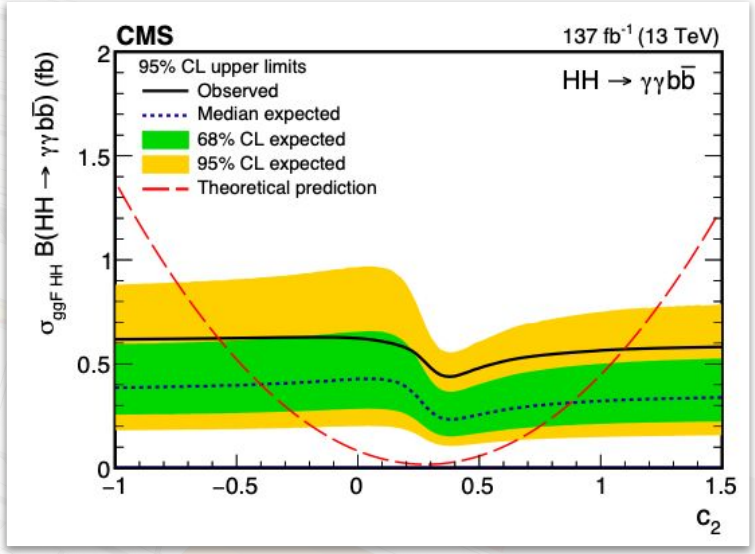
Non-resonant HH→ bbγγ

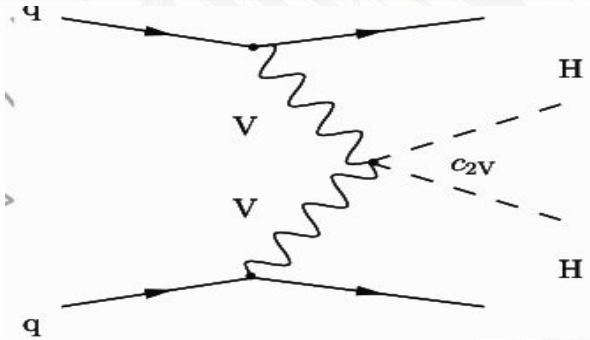


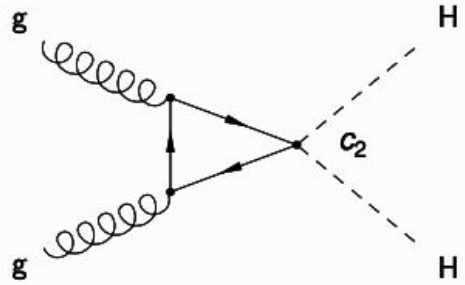


Non-resonant HH→ bbγγ

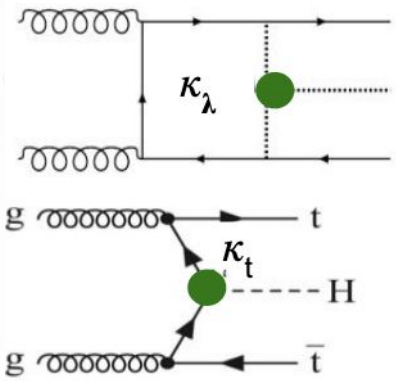


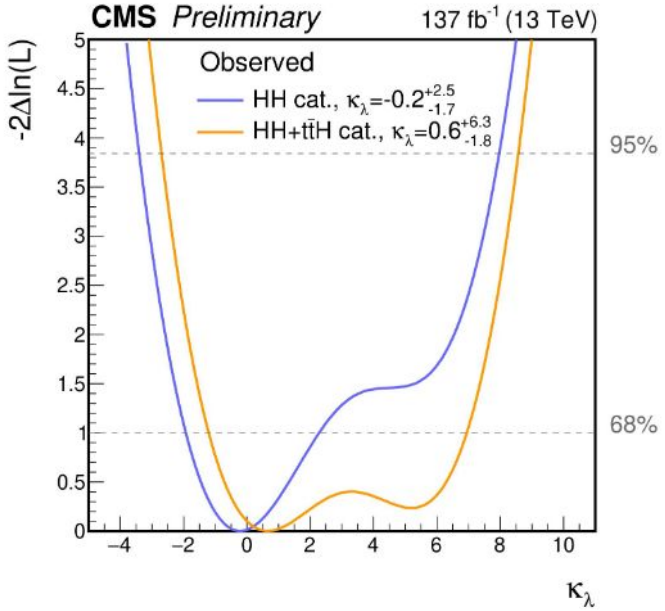


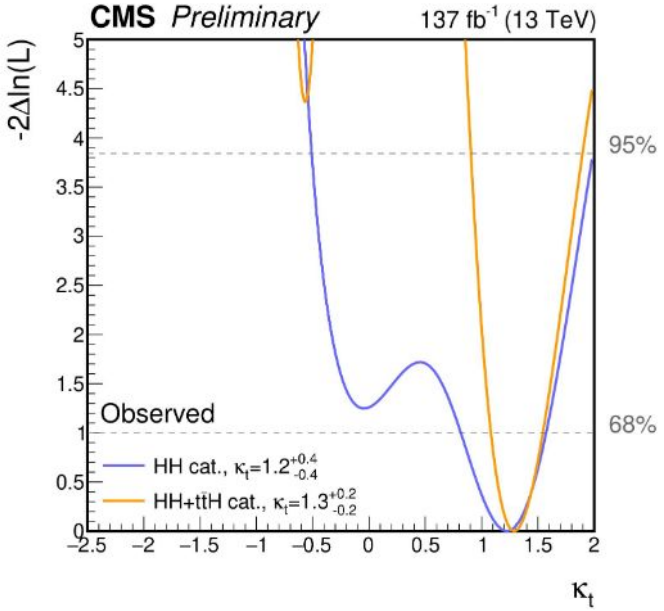




Non-resonant HH→ bbγγ







Non-resonant HH→ bbZZ (ZZ→ 4l)