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On behalf of CMS collaboration

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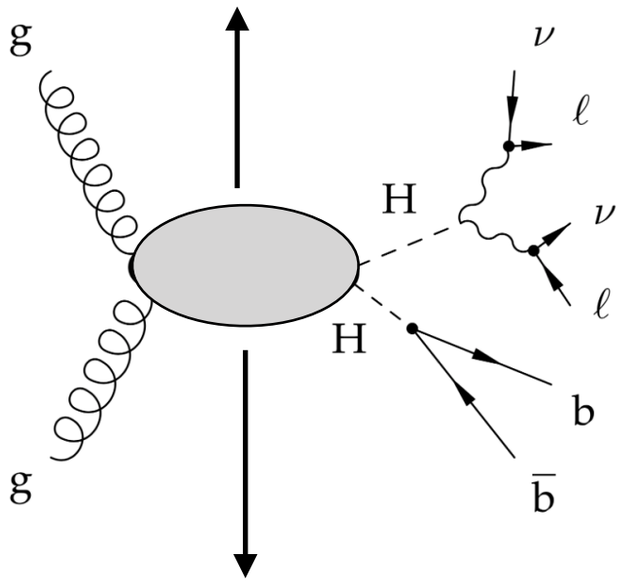
Outline

- Present searches at CMS
  - Main results and interpretations
  - More production modes
- Projections

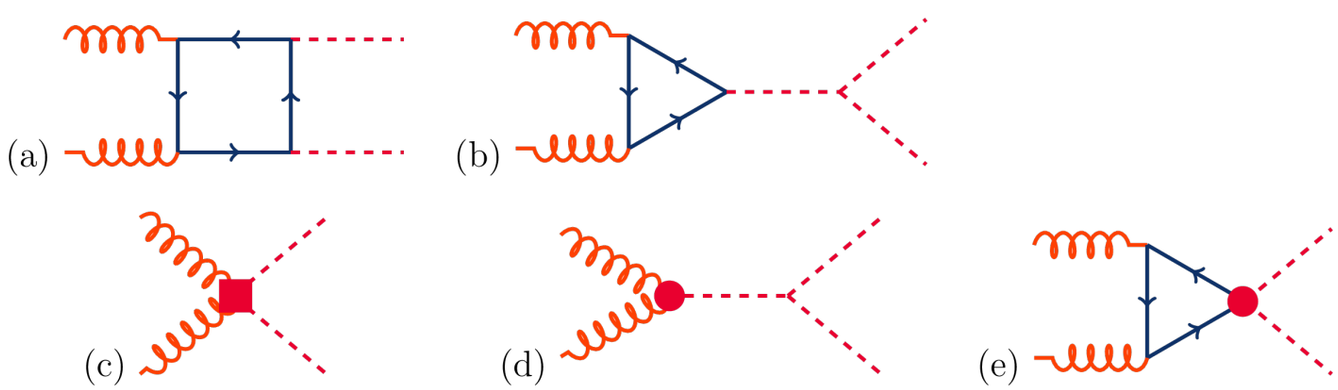
Present searches

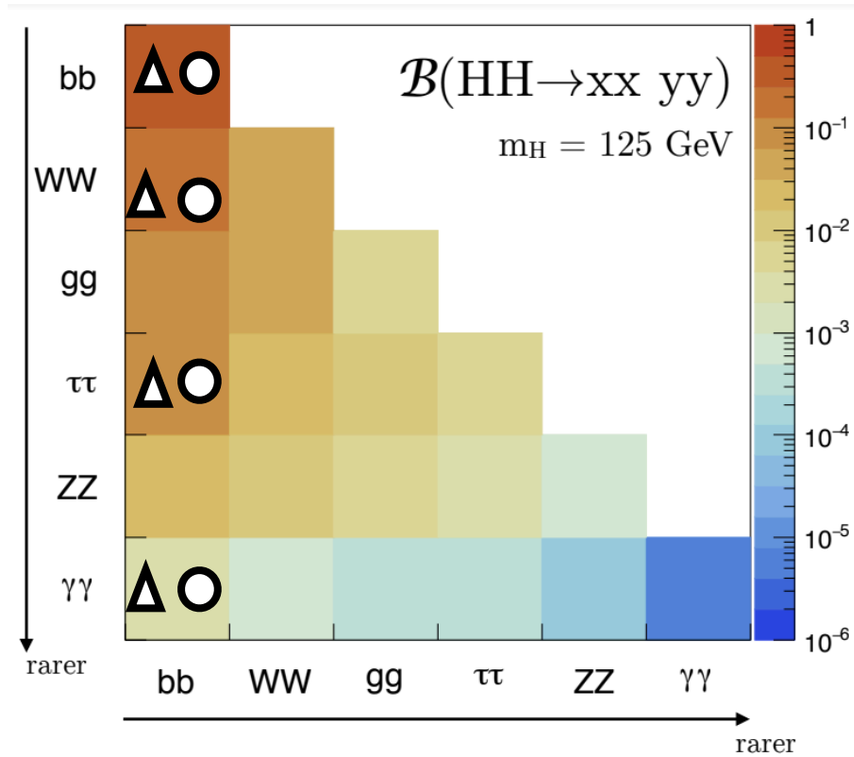
The dominant production mode for Higgs pairs is via gluon fusion***

Resonant search → Additional Higgs bosons (including SUSY and composite models), Extra Dimensions….



Non-resonant search: based in Higgs boson anomalous couplings





Motivations for variations/insertion of each one of those couplings can be found in extensive literature

E. N. Glover and J. van der Bij
S. Dawson, A. Ismail and I. Low
M. J. Dolan, C. Englert and M. Spannowsky
F. Goertz, A. Papaefstathiou, L. L. Yang and J Zurita
R. Grober, M. Muhlleitner, M. Spira and J. Streicher
B. Hespel, D. Lopez-Val and E. Vryonidou
... ... (I am sorry if you are missing from this list

Only information important for this talk:
Variation of Higgs couplings —> variation in HH signal topology

***See also Stephen Jones talk

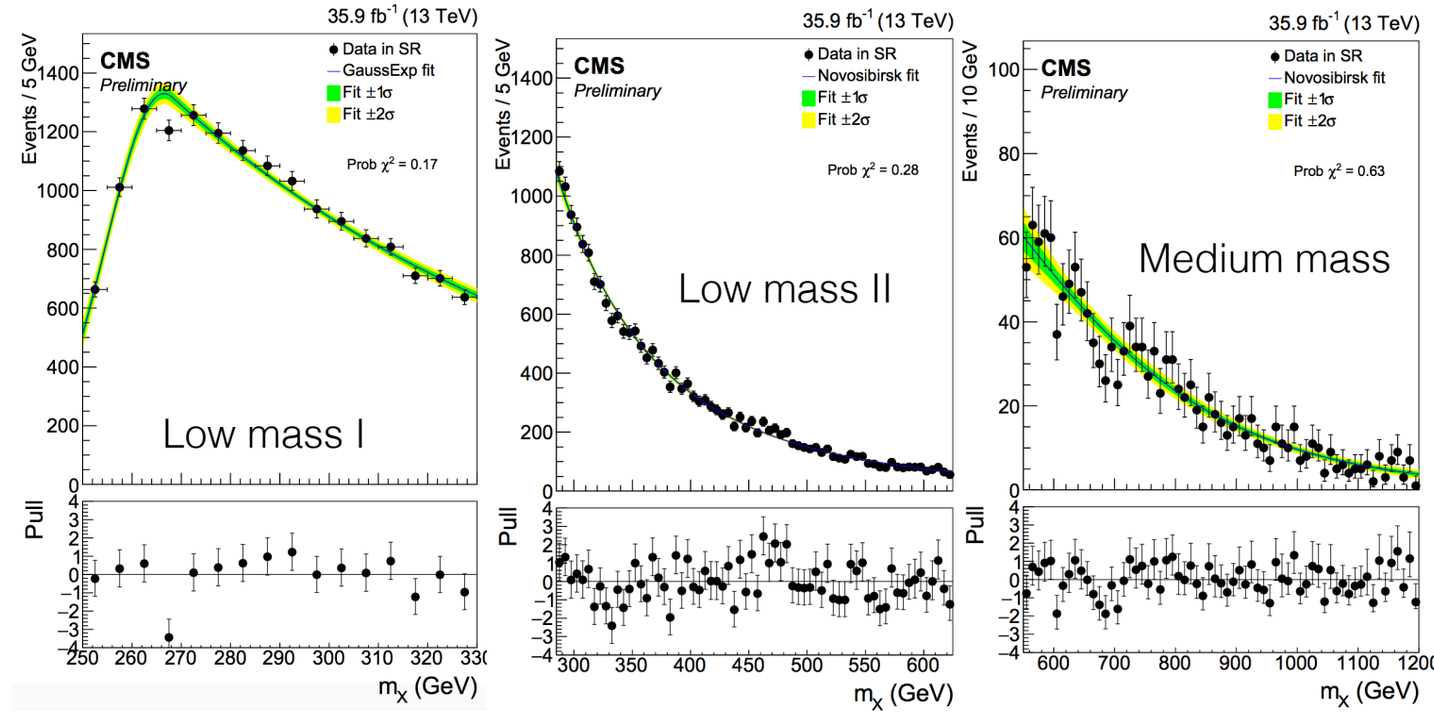
Highlights on bbbb

Three different approaches accordingly with the target of the search

Resonant case: pp > X (mX <~ 1 TeV) **HIG-17-009**

- Trigger: request 3/4 b-tags at trigger
- The BKG is dominated by QCD, followed by tt

- 4 b-tagged jets (new DeepCSV algorithm)
- B-jet energy regression (improve mh reconstruction)
- Low & Medium Mass regions <-> Different jet pairing
- Bkg. template from data:
  - Fit functional form taken from sidebands in the mbb X mbb plane
- Signal extraction from 4b spectrum (3 mass ranges ->different functional forms)



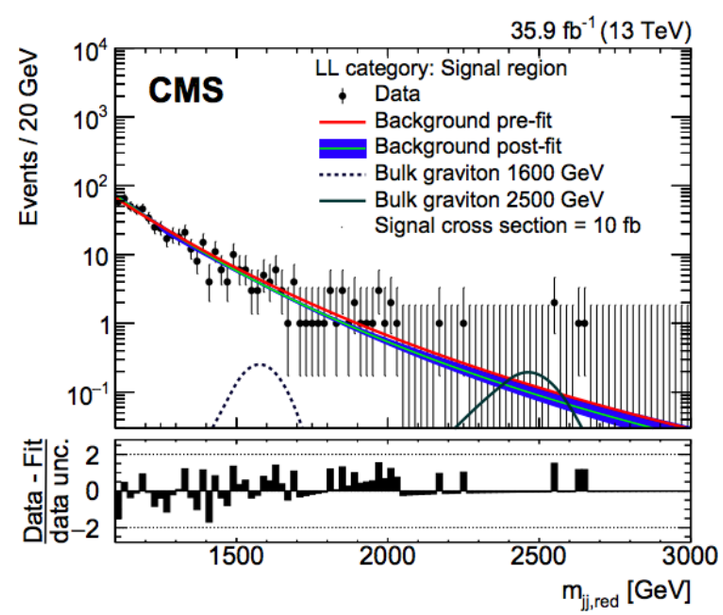
Resonant case: pp > X (mX > 800 GeV) **B2G-16-026** (submitted to PLB)

- Selections:
  - 2 jets, R=0.8 soft-dropped mass
    - Double-b tagger [1]
  - m(J),
  - N-subjettiness,
  - |Δη(J,J)|<1.3
  - Veto additional leptons

- Bkg. template from data:
  - Both normalization and functional form taken from data sidebands

- Signal extraction

Mred = m(JJ) – (m(J1) – mh) – (m(J2) - mh)



[1] BTV-16-002 submitted to JINST

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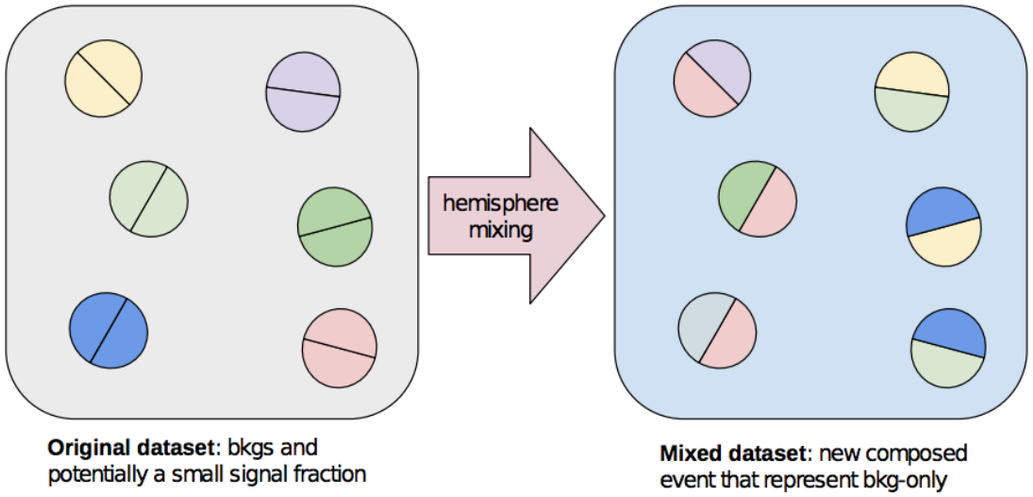
Highlights on bbbb

Three different approaches accordingly with the target of the search

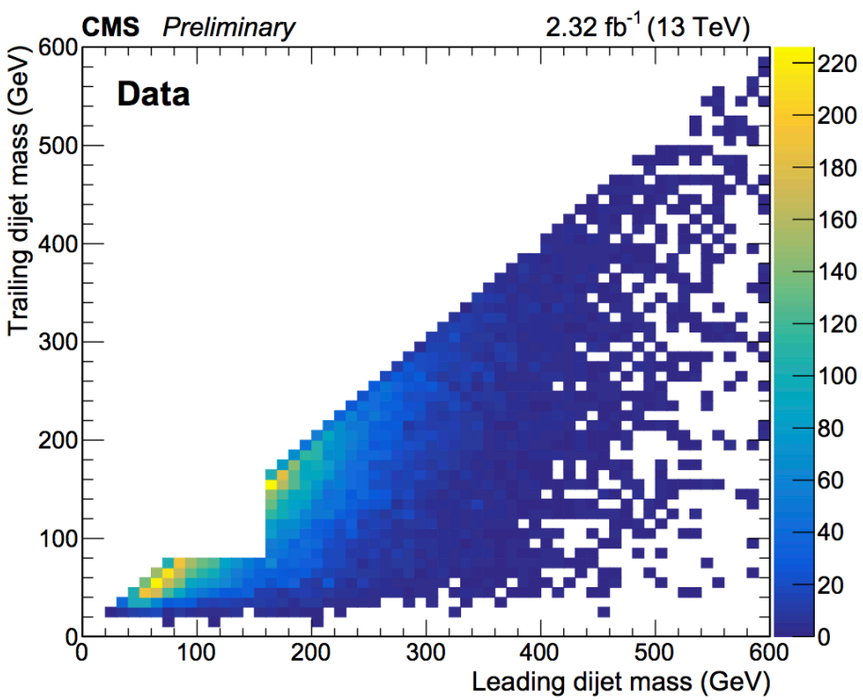
Non-resonant case **HIG-16-026**
(similar trigger of HIG-17-009, different BKG estimation strategy)

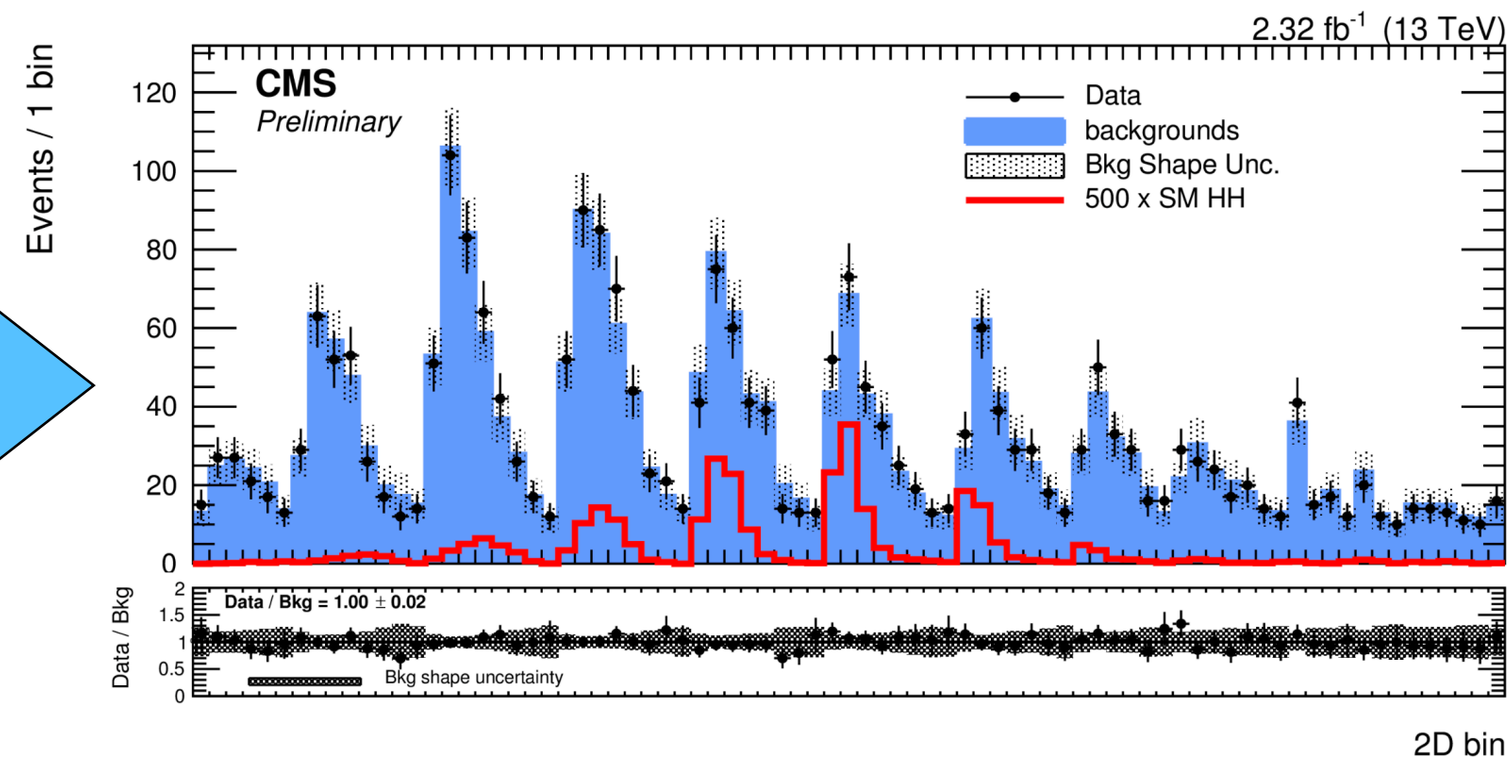
- 4 jets (R=0.4), 3/4 b-tagged
- Jet pairing: closest to mh
- A BDT trained on QCD+tt MC (used for selection)

- Bkg. template from data: hemisphere mixing
  Data events cut in 2 hemispheres: Cut ⊥ transverse thrust axis
  Hemisphere library recreate events pairing: nearest neighbor (based on kinematics)



- Signal extraction from leading vs. sub-leading m(jj)





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Highlights on $\tau\tau bb$ (HIG-17-002)

Final states: (e/μ/ hadronic tau+ hadronic tau)
+ 2 jets or 1 large-R jet

- For m_{hh} >1 TeV: dedicated boosted di-tau reconstruction [1]
- Categorize by 2/1 b-tags and boosted or resolved Hbb topology
- Main backgrounds: Top, Z→$\tau\tau$, Multijet

Selection:

- Likelihood fit to estimate $m_{\tau\tau}$ (despite the missing energy)
- m_{bb} and $m_{\tau\tau}$ in Higgses mass window
- BDT used to reduce top events in (e/μ + hadronic tau) channels

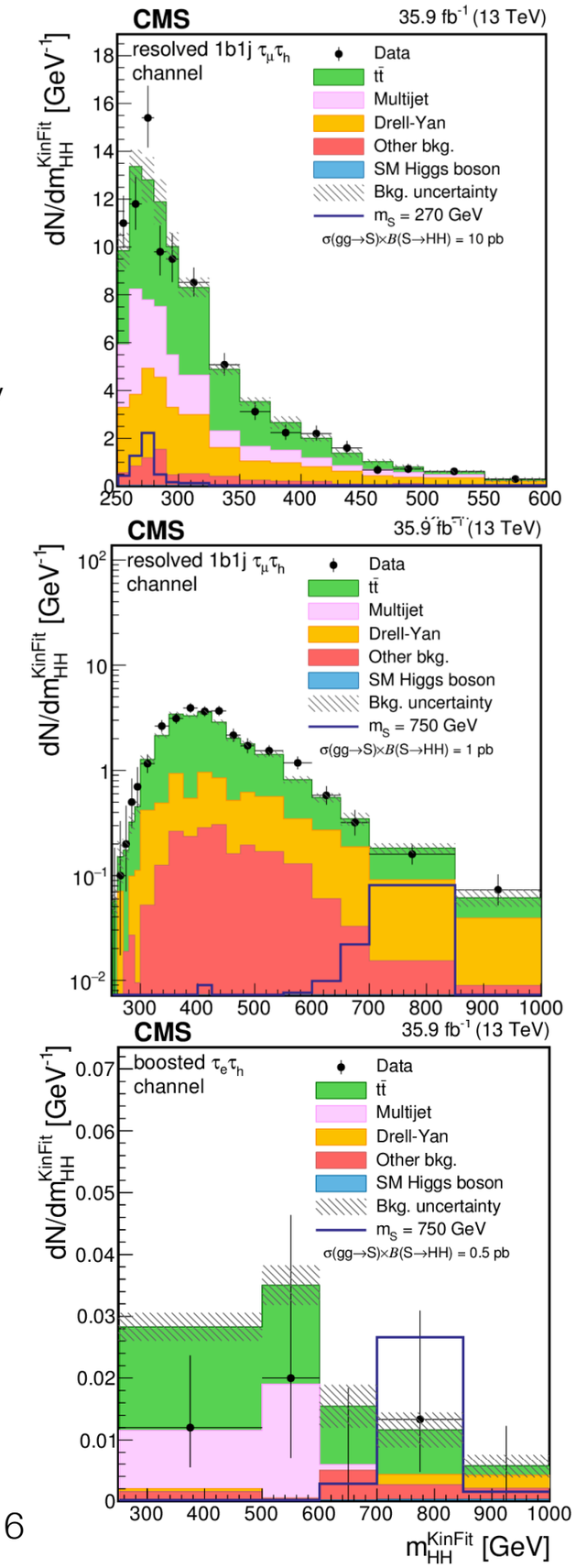
Signal extraction:

- Resonant: m_{HH}^{KinFit}
- Non-resonant: m_{T2}

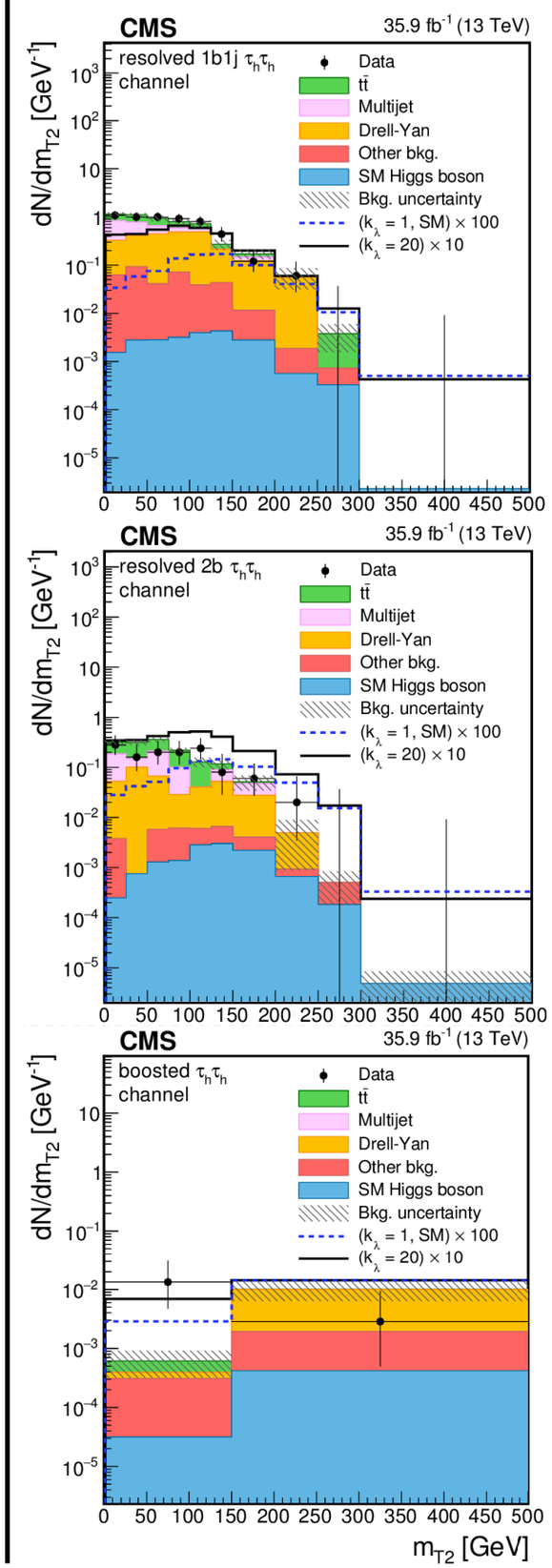
Published on Phys. Lett. B 778 (2018) 101

[1] B2G-17-006

Resonant (1b and 2b categories)



Non-Resonant



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Highlights on $VVbb$ (HIG-17-006)

2 opposite sign leptons 3 categories: ee, μμ and eμ+μe

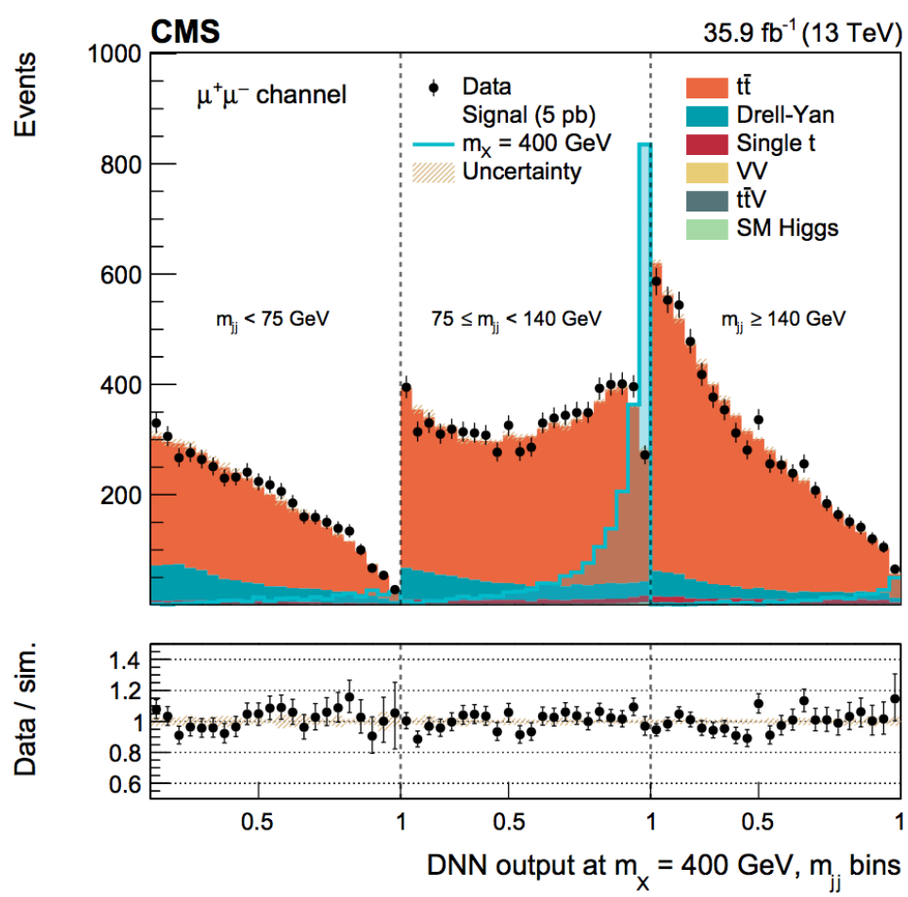
- Focus on WW* part – veto on Z(ll)
- 2 b-jets, ΔR(j, l) > 0.3
- dominant BKG: ttbar (irreducible)
- - Z+jets: from data, reweighed (≥0 b-jets)

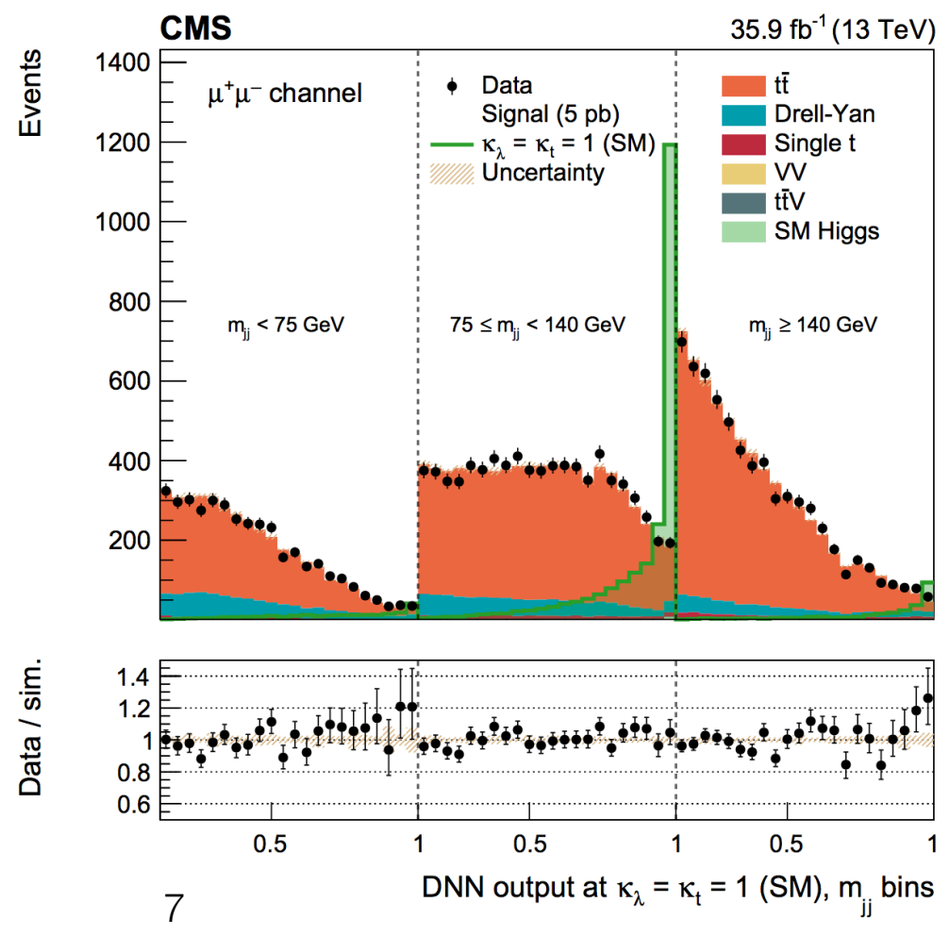
Signal extraction: parametrized DNNs with input

- 'isSameFlavor'
- mX for Resonant
- κt X κλ for Non-resonant

Published on JHEP 01 (2018) 054

- The final DNN discriminant is in the end used in three m_{jj} regions for background control / constraining purposes





[1] Phys.J.C 76:235 (2016)

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Highlights on $\gamma\gamma bb$ (HIG-17-008)

Event Selection:

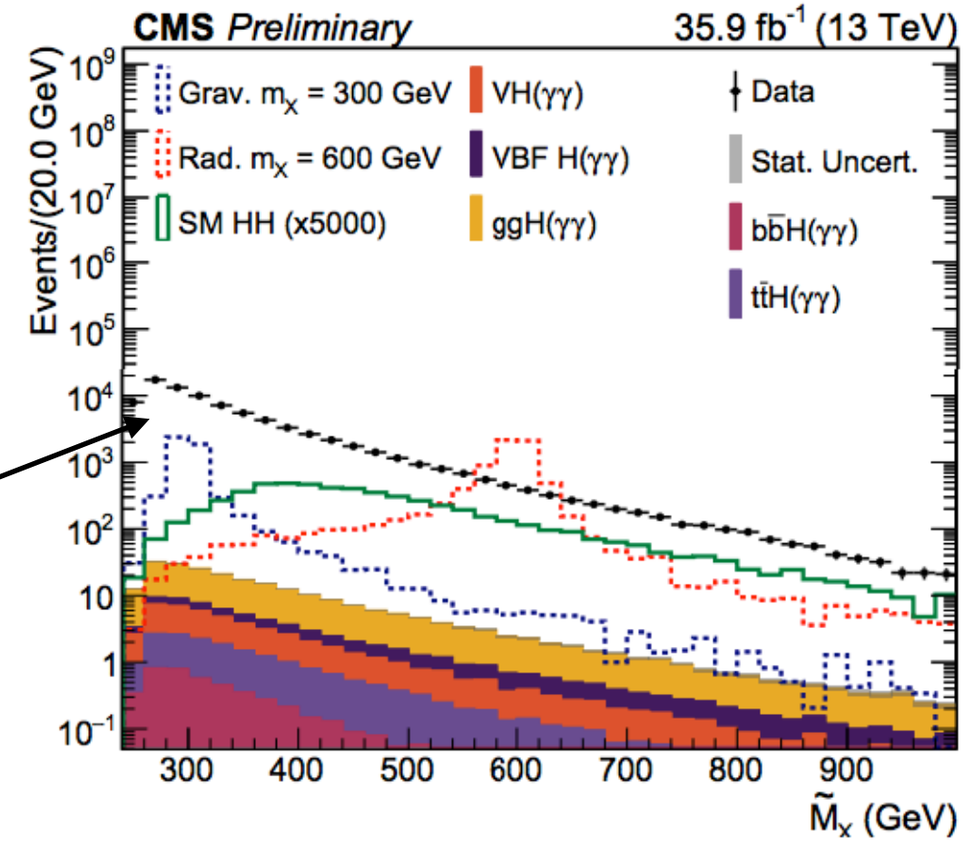
- Two γ's and two jets
- BDT classifier used to define high/medium signal-purity events
  This includes b-tag information, so there is no further need of categorize events in number of b-tags
  ==> The same BDT is used in resonant and non-resonant case

- Further classification "mass region", with corrected total mass:

$$\tilde{M}_X = M(jj\gamma\gamma) - M(jj) - M(\gamma\gamma) + 250\,\text{GeV}.$$

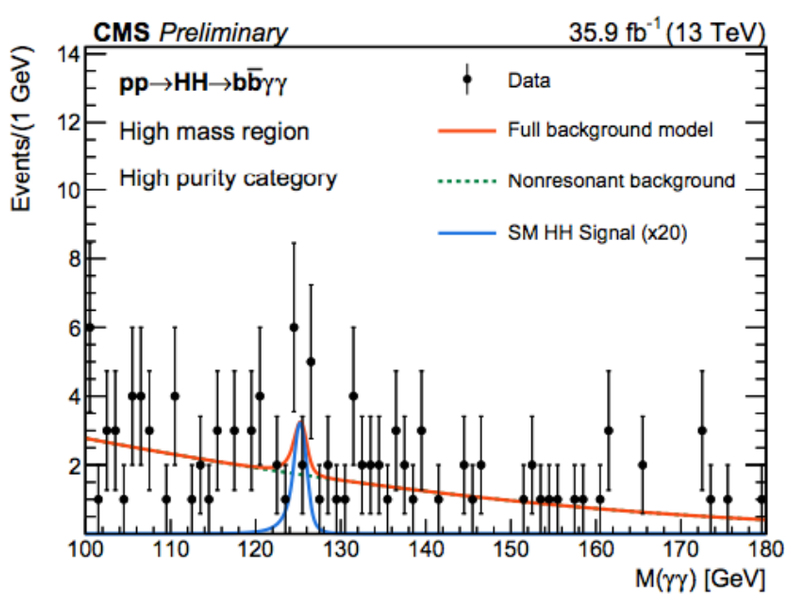
Main background from QCD (prompt and fake photons)

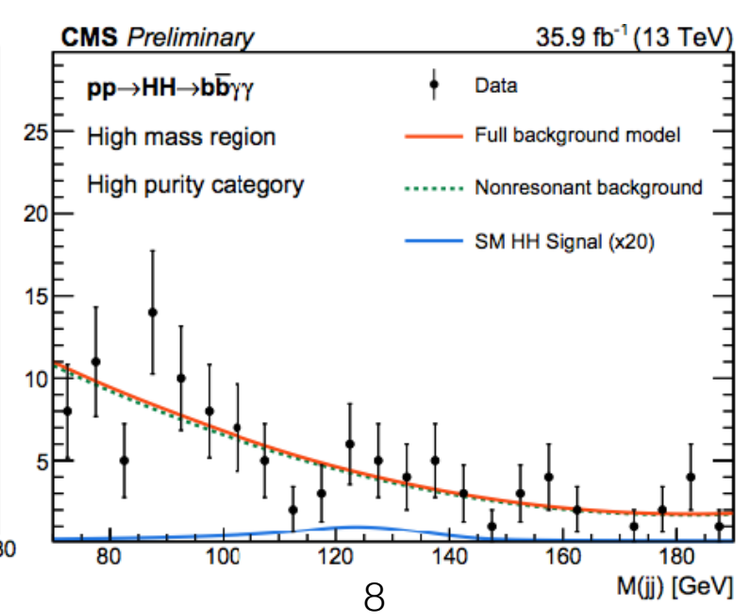
this white area



Signal extraction: Likelihood fits simultaneous to mbb and m$^{\gamma\gamma}$ with parametric functions

e.g. Non-Resonant in High Purity / High mass category





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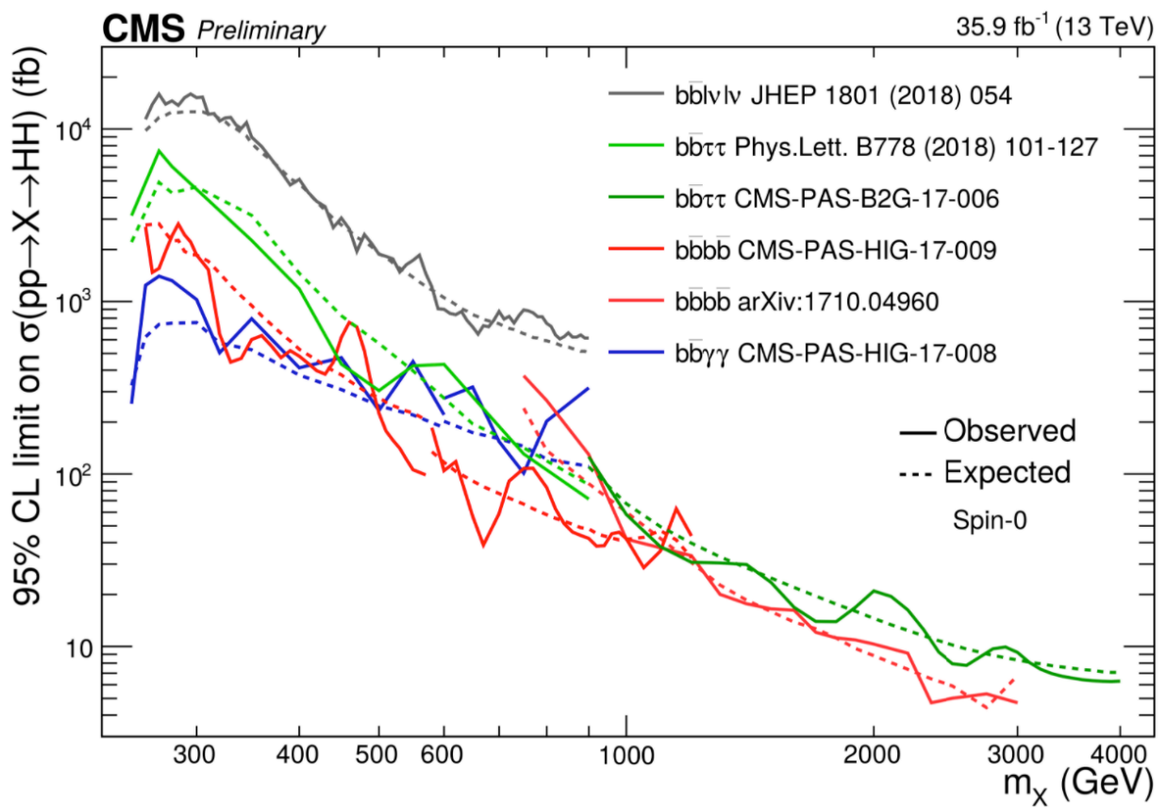
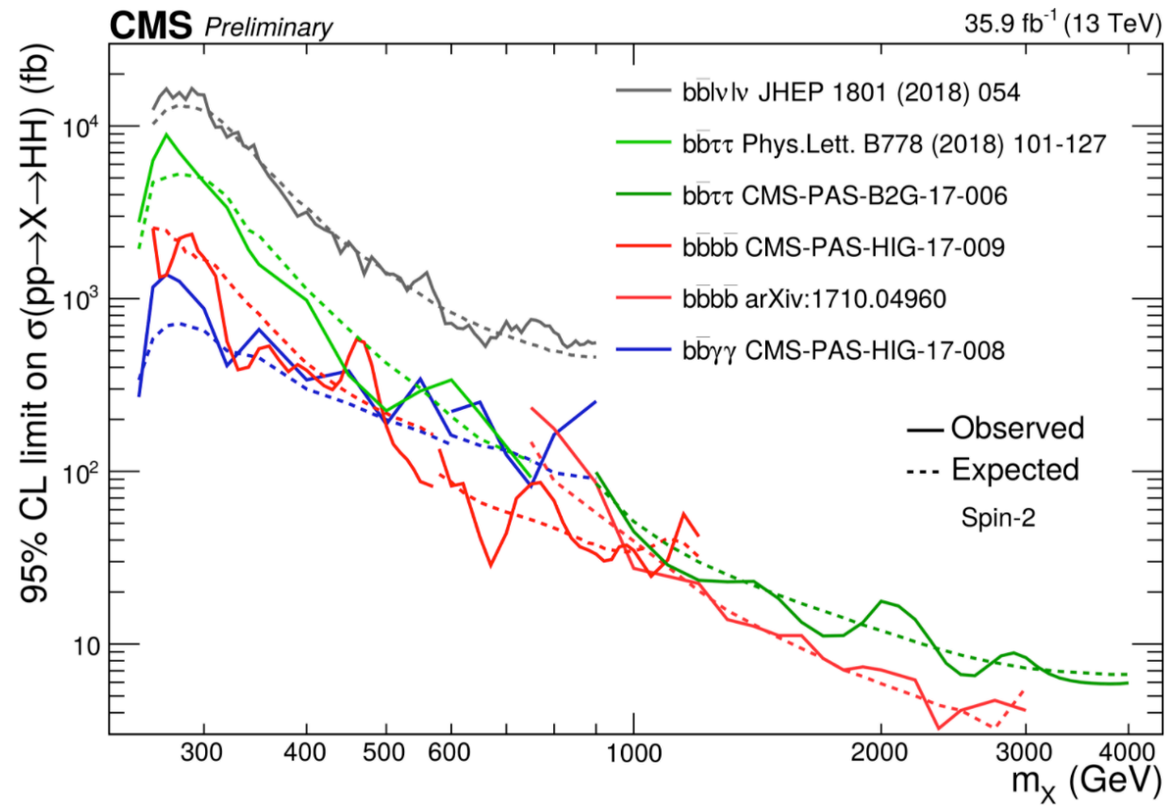
Summary resonant





The various final state sensitivities are in the same ballpark!

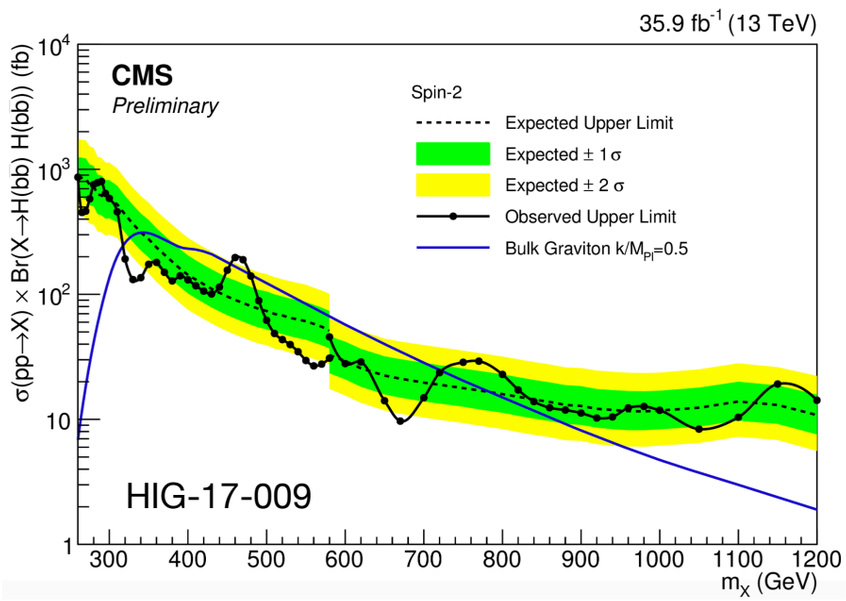
Almost smooth transition between resolved and boosted analyses

Our resonant interpretations (so far)

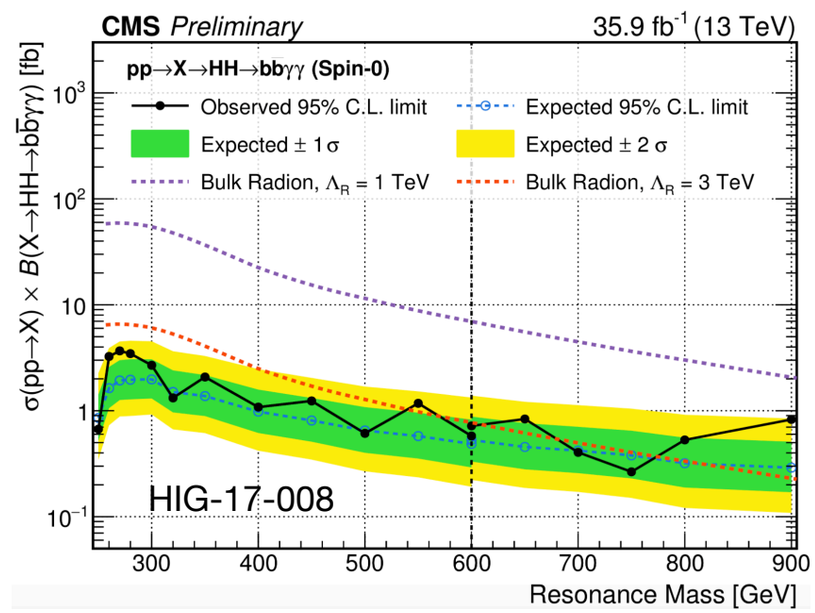
- We assume as signal a narrow-width resonance and expect our results to be 'model independent'
  - Spin 0 particle produced by gluon fusion
  - Spin 2 particle, with couplings compatible with a KK-graviton from Bulk Warped Extra dimension (WED) scenario

  - A model dependent interpretation is made on top of the results
    - making sure the Narrow Width Approximation regime is valid

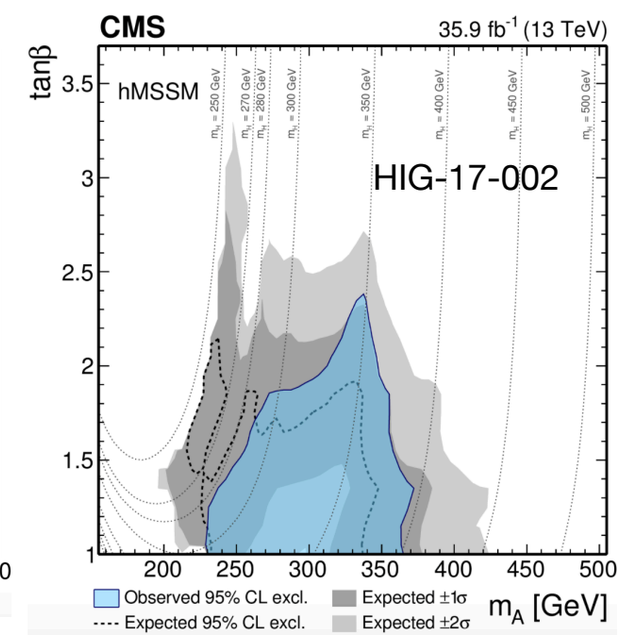
Bulk KK-graviton (WED)



Bulk Radion(WED)



MSSM



- The plan is to try consider the case of non-narrow resonances in signal assumption
  - If possible with scan on interference patterns with SM HH continuum
    - Need input from theory community!
    - It would be great for instance to have an idea of the parameter space of explicit models we are missing with the model-independent results (= by not scanning different resonance widths and signal interference with BKG)

- What about other products modes?

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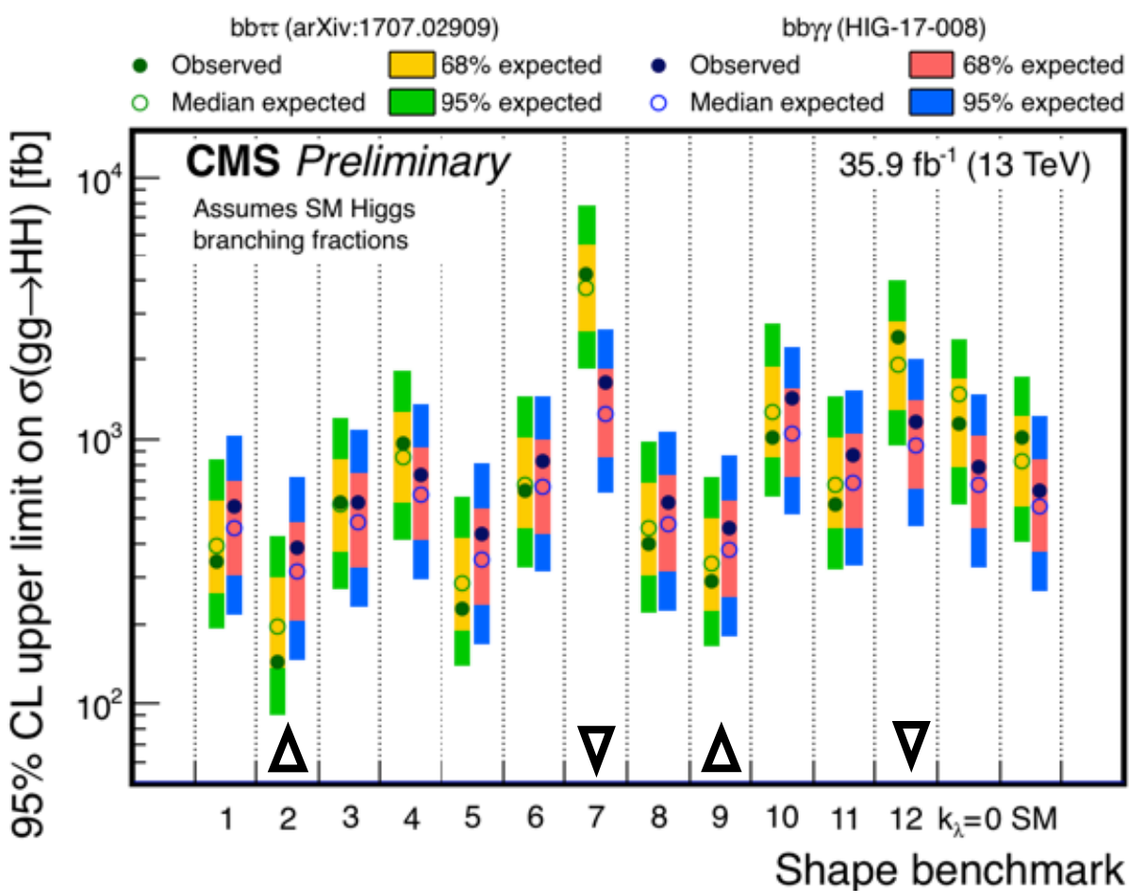
Our non-resonant interpretations (so far)

- None of the current searches is passible of recast from the phenomenology community,
  - it is our responsibility the devise results directly useful to the th/ph community
    - Not an easy task on the case of anomalous couplings

1) how sensitive each search is to the SM hypothesis

σ/σ_{SM}	95% CL (exp)	Lumi
bbbb	< 342 (308)	2.32/fb
$\tau\tau$bb	< 31 (25)	35.7/fb
$\gamma\gamma$bb	< 19 (17)	35.9/fb
VVbb	< 79 (89)	35.9/fb

2) how sensitive each search is to deviations of the SM signal shape (e.g. inspired by EFT)



Each one of these points correspond to a shape benchmark, derived in define the most different possible kinematics of the HH system when performing

∇ For parameter regions dominant contribution of the trilinear on the process the HH topology looks like the one of a low mass (~ 250 GeV) resonance: $\gamma\gamma$bb has better sensitivity

Δ When considering Higgs-gluon contact interactions or regions with strong interference effects we can expect final objects with higher energy: $\tau\tau$bb has better sensitivity

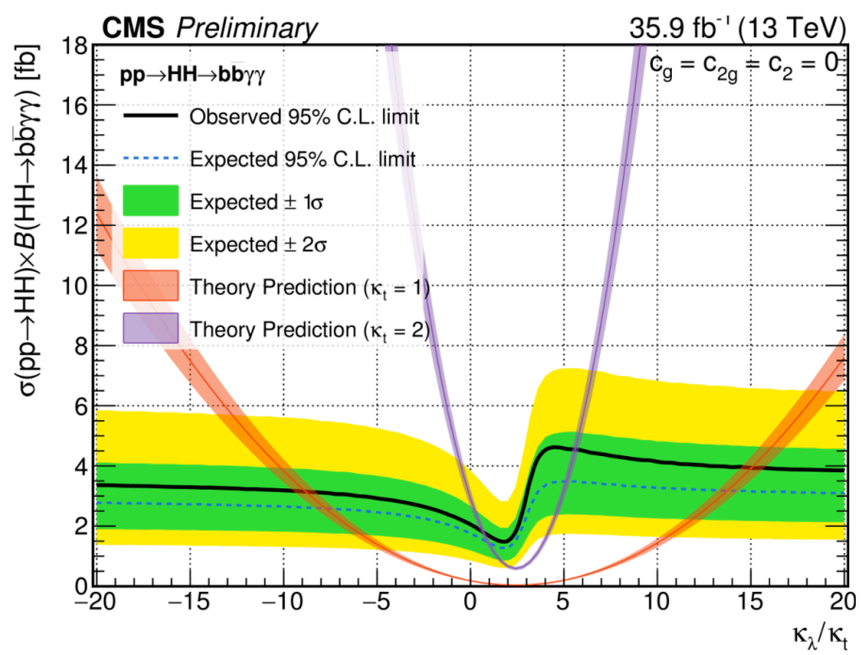
Lecon: The different final states are complementary in different regions of BSM topologies

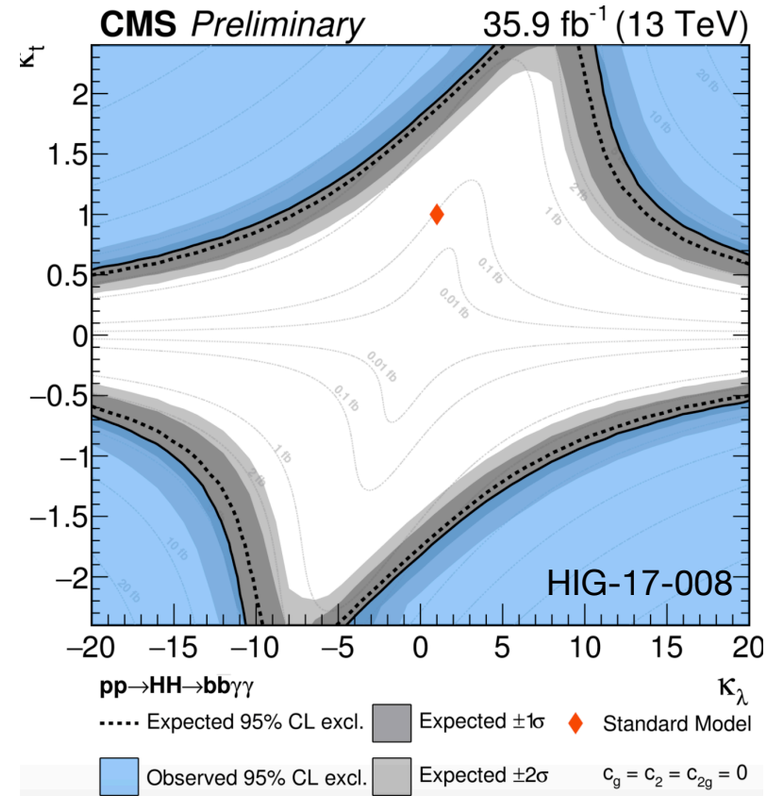
A more detailed description of the shape benchmarks is in backup and here JHEP04(2016)126

Our non-resonant interpretations (so far)

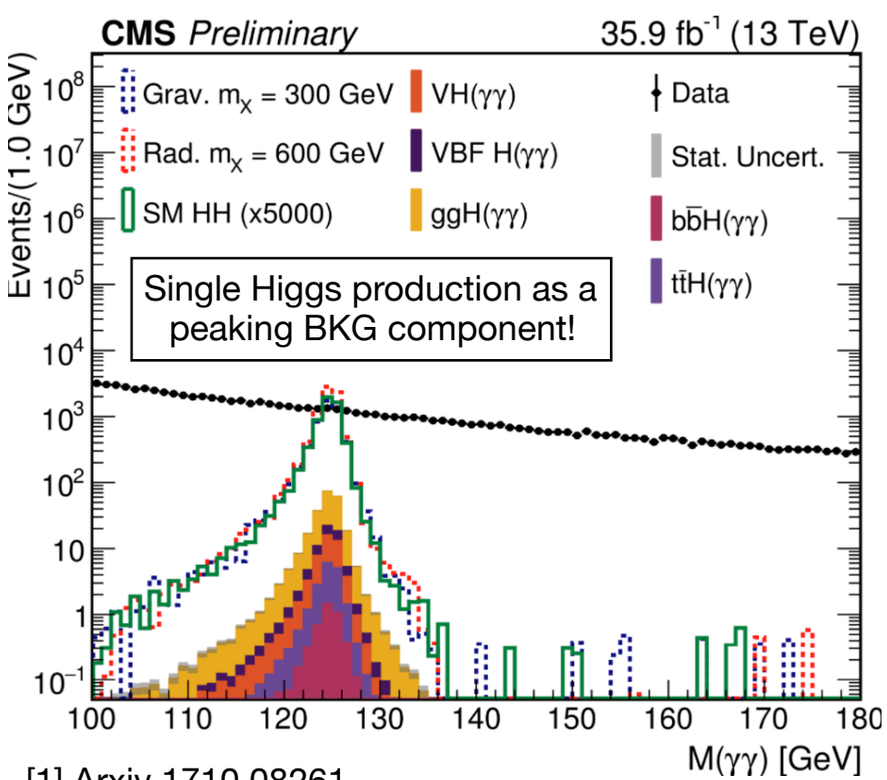
3) Extensive scans on Higgs anomalous couplings

- One of the practical challenges to make such interpretations is partially solved with a reweighing technique [1]





- We start to have a problem with those scans with the increasing luminosity:



In some channels the single Higgs component of BKG (specially ttH) starts to be non negligible

If one variate the Higgs top Yukawa coupling not only HH production is affected, but also single Higgs

Possible solutions

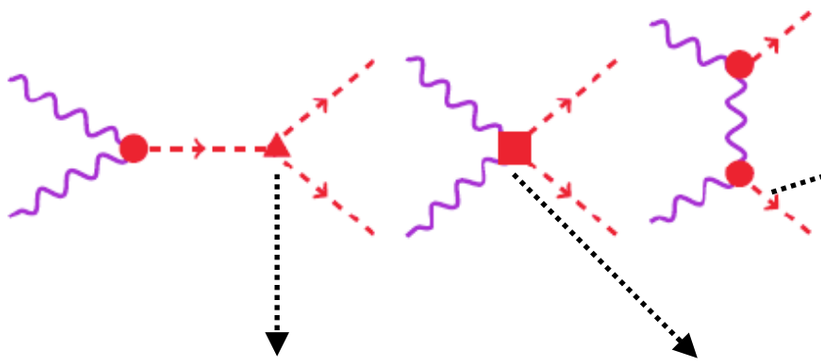
- Reduce to negligible the single Higgs component with smarter selections
- Perform HH scans including single Higgs contributions
  - Variating accordingly the Higgs anomalous couplings

- Would the inclusion of additional 2D scans (in the other variables) be desirable?
  - Which ones? With which parameter correlations
    - With the relations Dim. 6 operators we still have 4D / 3D
      - Ideas for additional scans in backup

[1] Arxiv 1710.08261

We want to learn more about HH!

- The second largest production mode of HH is the VBF mode
  - By consistence we could also consider it also using the anomalous couplings approach

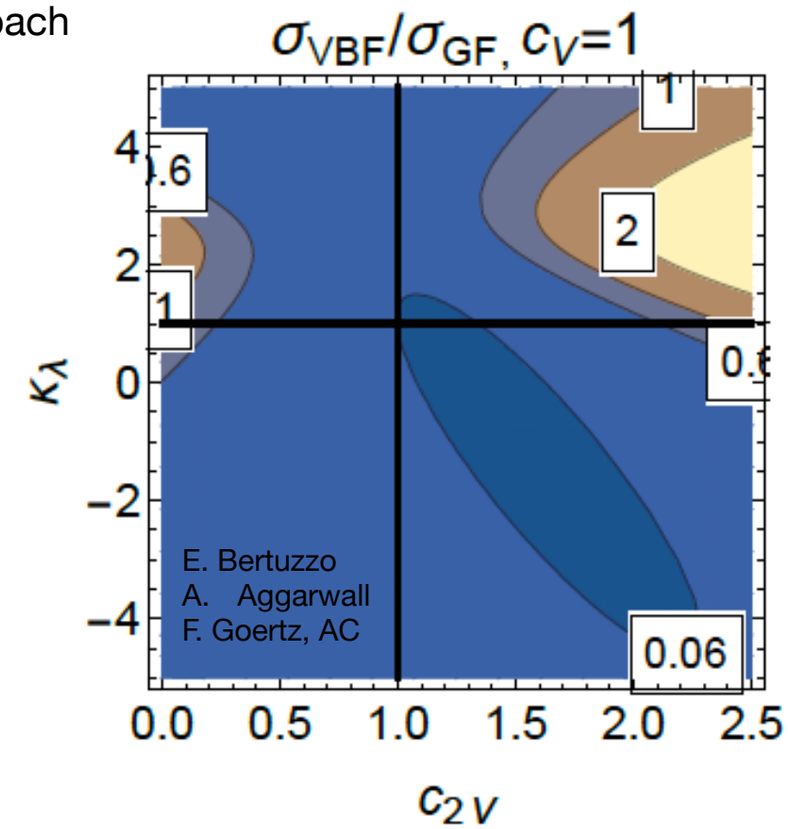


It appears in VBF case +
Is constrained by single H
~[0.8, 1.2]

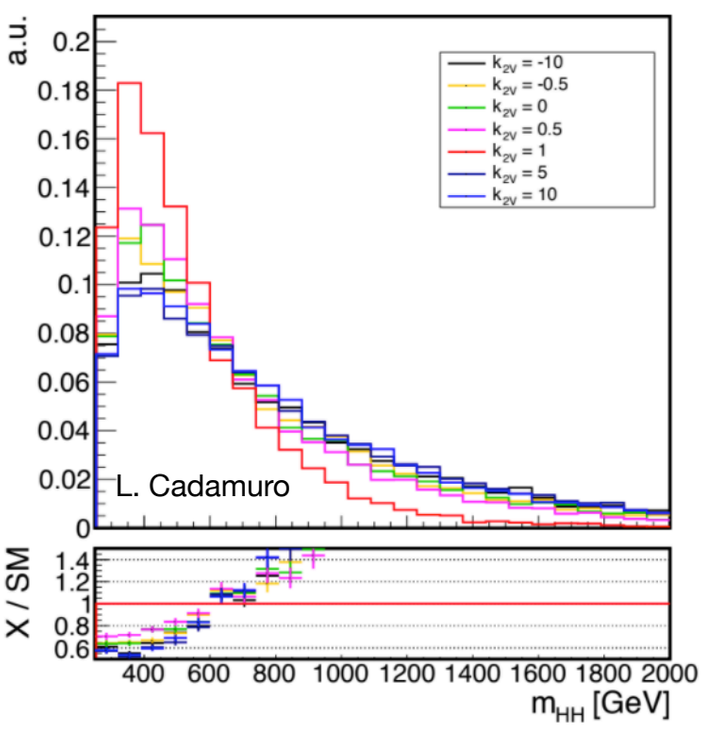
Correlated in many of real model cases (also in D6 EFT)

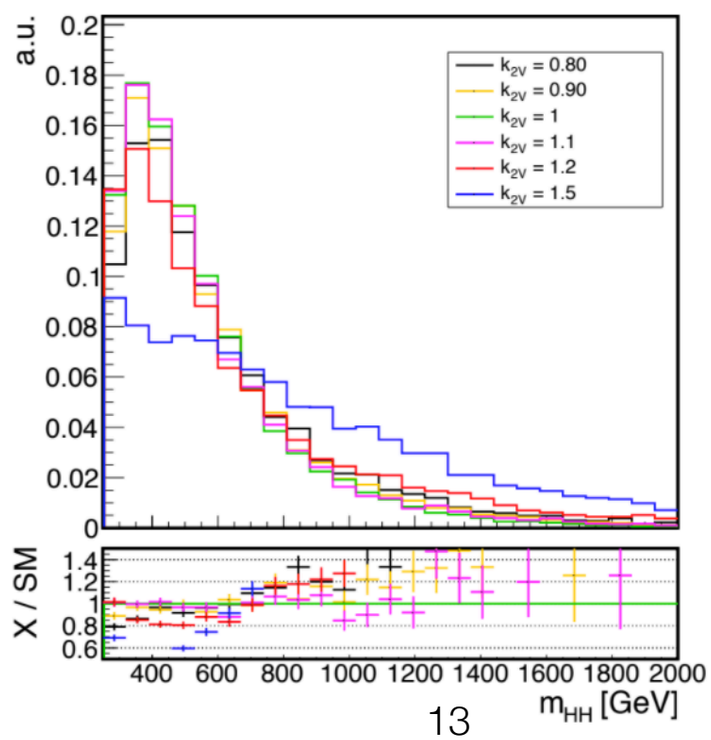
It also appears in gg>HH

It only appears in VBF case



Parton level studies:





The gluon fusion production contamination can be relevant in VBF topologies phase space

How to construct a HH signal composed of gluon fusion and VBF components on EFT on the most model independent way possible?

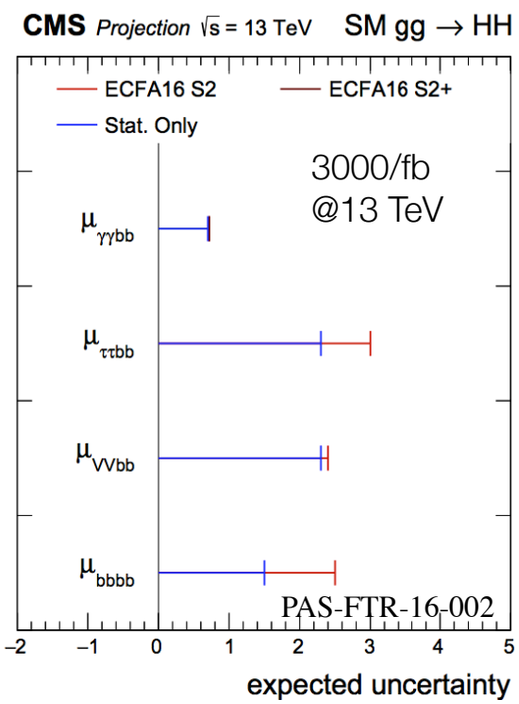
==> Up to now we just have the question…

What can we expect for LHC future?

LHC → $\sqrt{s}$ = 14 TeV → 18% increase in SM HH cross section
Ultimate integr. Lumi 3000 fb/1 (2025 – 2035)
Instantaneous lumi → 5e34/cm^2/s
average pileup 200

In the menu of detector improvements:

- New all-silicon tracker == |η|<4, track-trigger
- Barrel calorimeters: new electronics
- New endcap calorimeter (high granularity)
- Muon detectors to |η|<2.8
- Trigger: L1 @ 750 kHz, HLT @ 7.5 kHz



- Extrapolations based on searches for non-resonant HH final state which used 2015 data, ≈ 2.3-2.7 /fb

  Different scenarios:
  - No systematics ("stat. only")
  - ECFA16 S2(+) = reduced theory uncertainties & reduced systematics (≈ future detector performances)

- Those indicate a SM HH discovery is challenging

- Data analysis improvements are supposed to make the scenario more auspicious
  - extrapolations have already been shown ECFA results to be very conservative at least in $\tau\tau$bb
    - we achieved with 35.9 fb-1 the same sensitivity that we projected for 100 fb-1

- We are working on full analyses that use PhaseII Delphes+FullSim samples to produce a more accurate prediction for the Yellow Report

What physics results are certain to enter in the YR extrapolations (up to now):

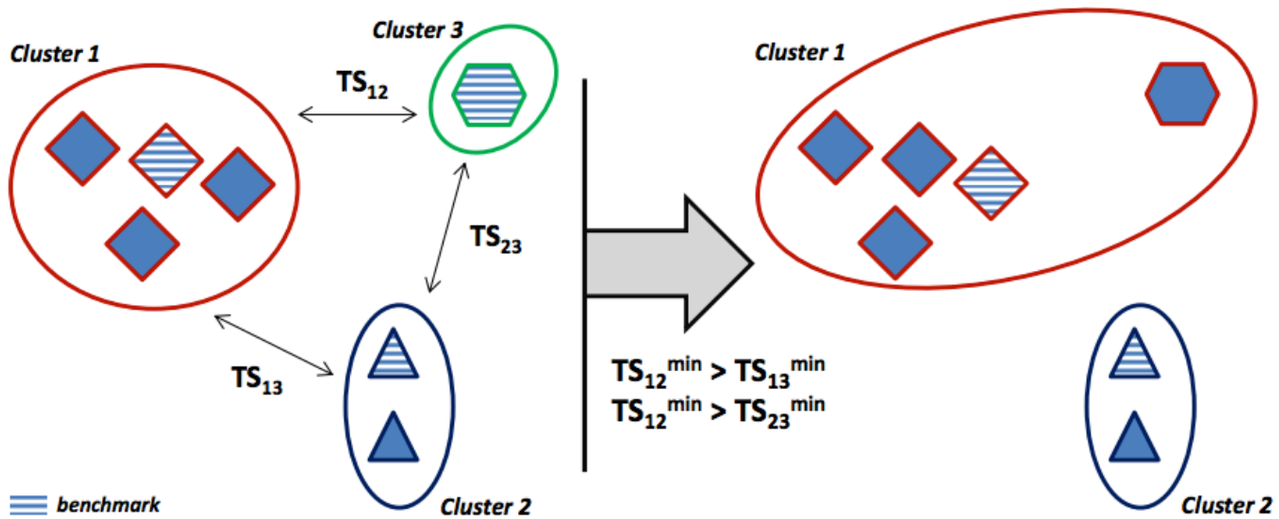
Non-resonant HH
- SM ggF + VBF (at least) in the four presented channels
- Higgs trilinear coupling scan
- shape benchmarks

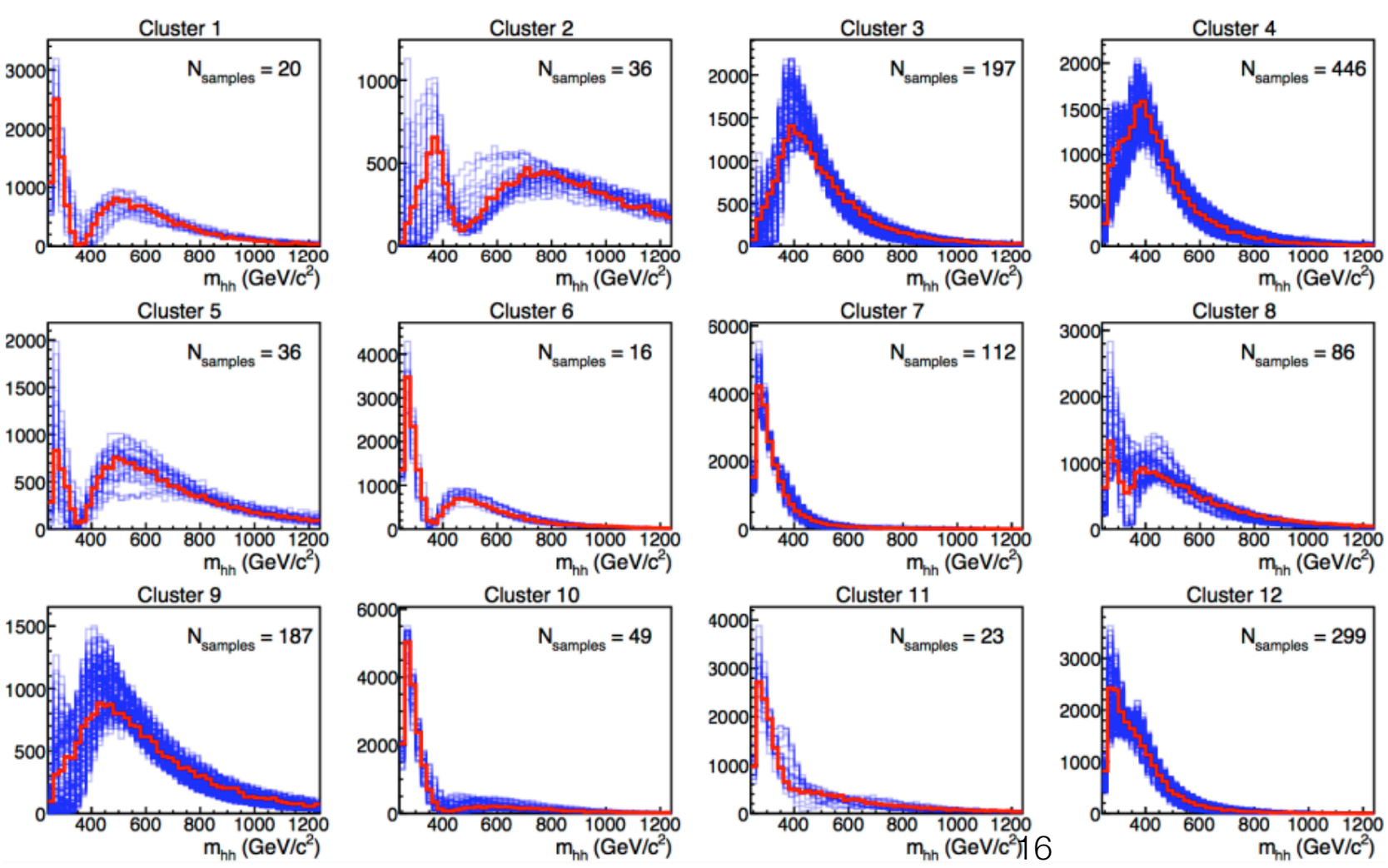
Anything else is a bonus
Suggestions are very welcome!

Conclusions

- Many people in CMS are working with the HH final state
  - Nice results on display ==> no discovery so far
- Many new results and possibly interpretations in the oven
- Keep posted!

Clusters and benchmarks





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

Ideas to scan Higgs anomalous couplings scans

1) Use EFT relations and/or fix as SM some constraints

Gluon-Fusion only
- klambda / kt (with c2 = 0)
- klambda / kt (with c2 = kt)

VBF only
- cV / c2V
- klambda / c2V (with cV = 1)

2) Using matching to UV completions

Examples for GF:

arxiv: 1710.08261

Model	NP integrated out	Ref.
1	real scalar singlet with explicit Z_2 breaking	[37, 38]
2	real scalar singlet with spontaneous Z_2 breaking	[37]
3	real scalar triplet	[37, 38]
4	complex scalar triplet	[37, 38]
5	quartet scalar with $Y = 1/2$	[37, 38]
6	quartet scalar with $Y = 3/2$	[37, 38]
7	2HDM (addtl. scalars heavy + Z_2)	[39]
8	vector-like quark: T (singlet top partner)	[40]
9	vector-like lepton: E (flavor universal singlet)	[41]
10	MCHM_5	[7, 8, 42, 43]
11	MCHM_4	[7, 8, 42, 43]

Model	Free Parameters	κ_λ	κ_t	c_2
1	κ_t, κ_λ	κ_λ	κ_t	$\kappa_t - 1$
2	κ_t	$3\kappa_t - 2$	κ_t	$\kappa_t - 1$
3	κ_λ, c_2	κ_λ	1	c_2
4	κ_t, κ_λ	κ_λ	κ_t	$2\kappa_t - 2$
5	κ_λ	κ_λ	1	0
6	κ_λ	κ_λ	1	0
7	κ_t, κ_λ	κ_λ	κ_t	$3/2(\kappa_t - 1)$
8	κ_t	1	κ_t	$3/2(\kappa_t - 1)$
9	κ_t	κ_t	κ_t	0
10	κ_t	κ_t	κ_t	$\kappa_t(\kappa_t + \sqrt{\kappa_t^2 + 8})/4 - 1$
11	κ_t	κ_t	κ_t	$(\kappa_t^2 - 1)/2$

[7] G. F. Giudice, C. Grojean, A. Pomarol, and R. Rattazzi. "The Strongly-Interacting Light Higgs". In: *JHEP* 06 (2007), p. 045. DOI: 10.1088/1126-6708/2007/06/045. arXiv: hep-ph/0703164 [hep-ph].

[8] R. Grober and M. Muhlleitner. "Composite Higgs Boson Pair Production at the LHC". In: *JHEP* 06 (2011), p. 020. DOI: 10.1007/JHEP06(2011)020. arXiv: 1012.1562 [hep-ph].

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Examples for VBF:

MCHM

$$c_{2V} = -1 + 2c_V^2, \quad \kappa_\lambda = \begin{cases} c_V & \text{(spinorial)}, \\ \dfrac{-1 + 2c_V}{c_V} & \text{(fundamental)} \end{cases}$$

Higgs portal

$$c_{2V} = -1 + 2c_V, \quad \kappa_\lambda = -2 + 3c_V$$

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