Stato e prospettive per ttH e HH

Giacomo Ortona (LLR)

Outline

ttH production

HH: motivations and theory

HH: What are we doing and what are we bringing to Moriond

- The main 4 channels: bbbb, bbWW, bb$\tau\tau$, bb$\gamma\gamma$
- The 2 new guys in town: bbZZ, $\gamma\gamma\gamma\gamma$

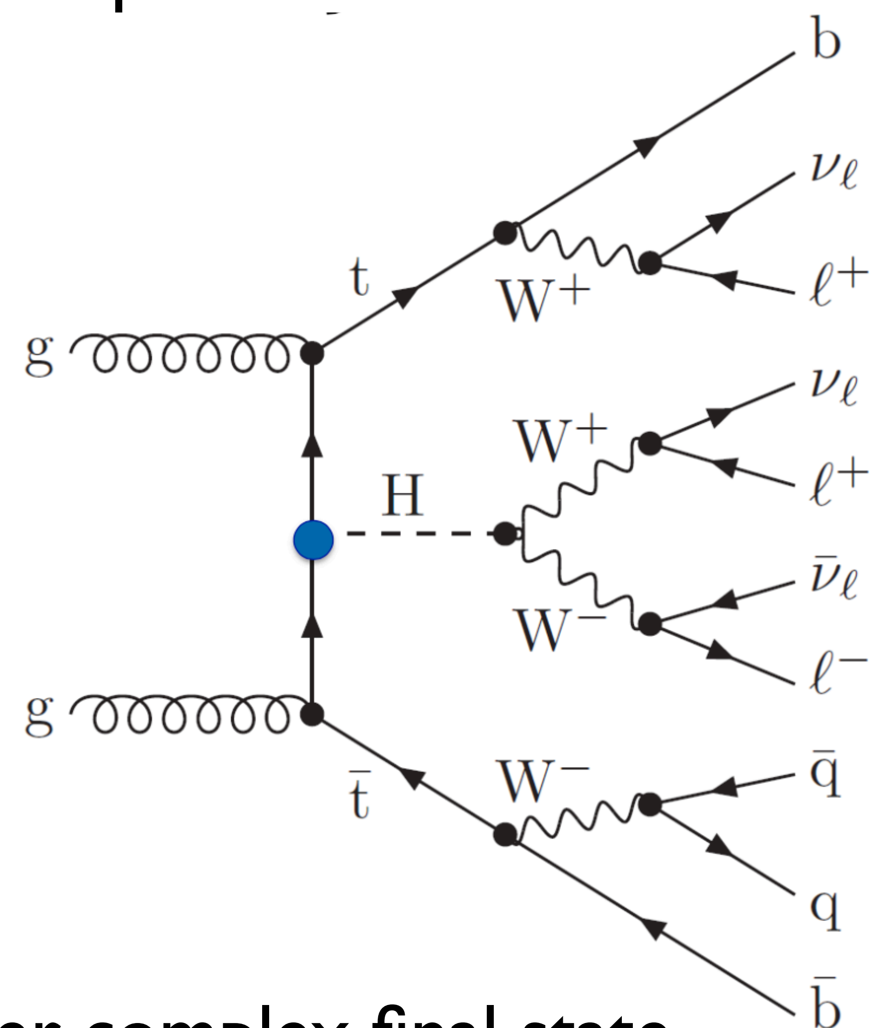
HH: what is coming soon…

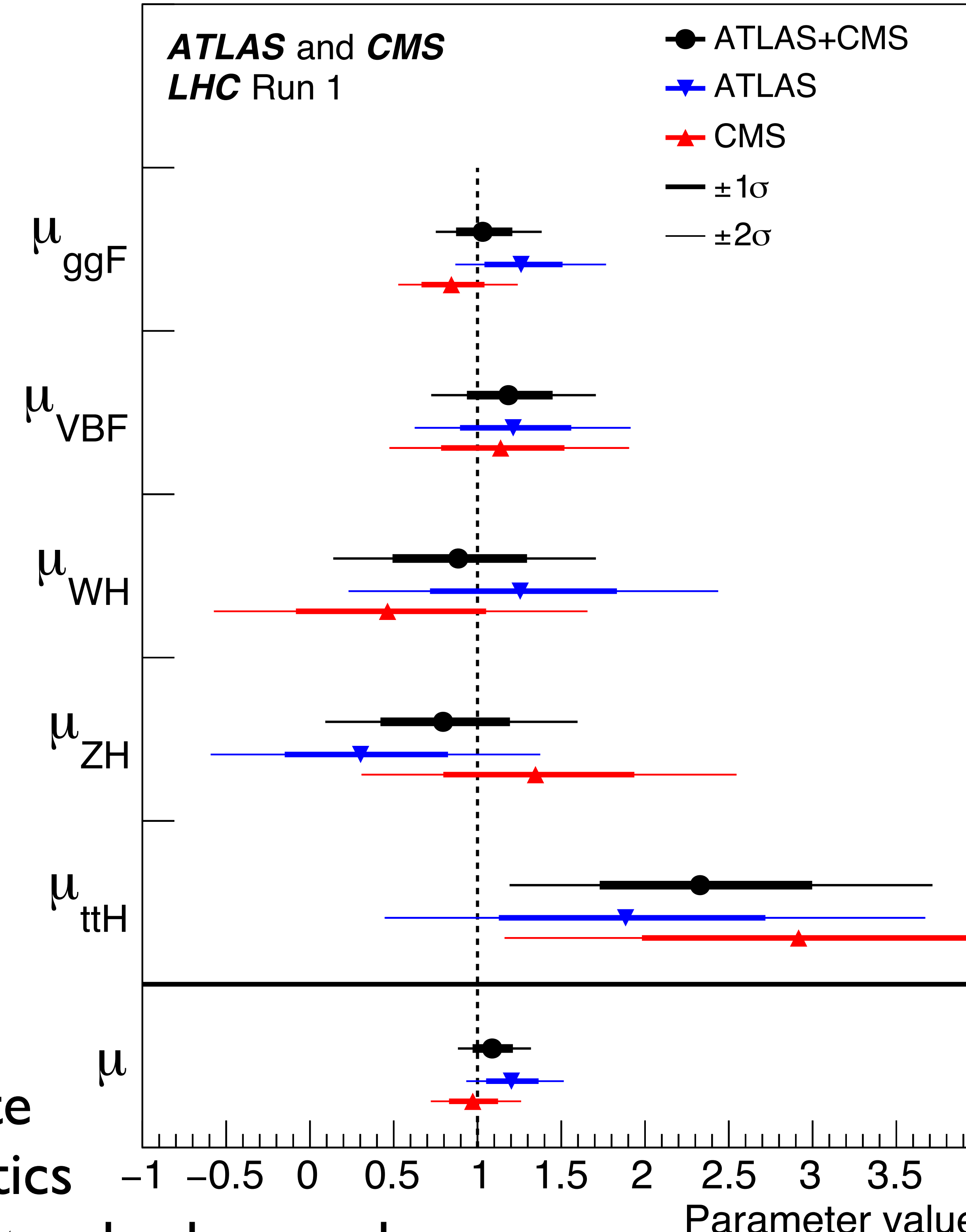
…and what to expect for the future

Conclusions and open points

ttH production

Why the interest in ttH production?
- Is dominated by the top-Yukawa
- 2-σ upward fluctuation in Run1

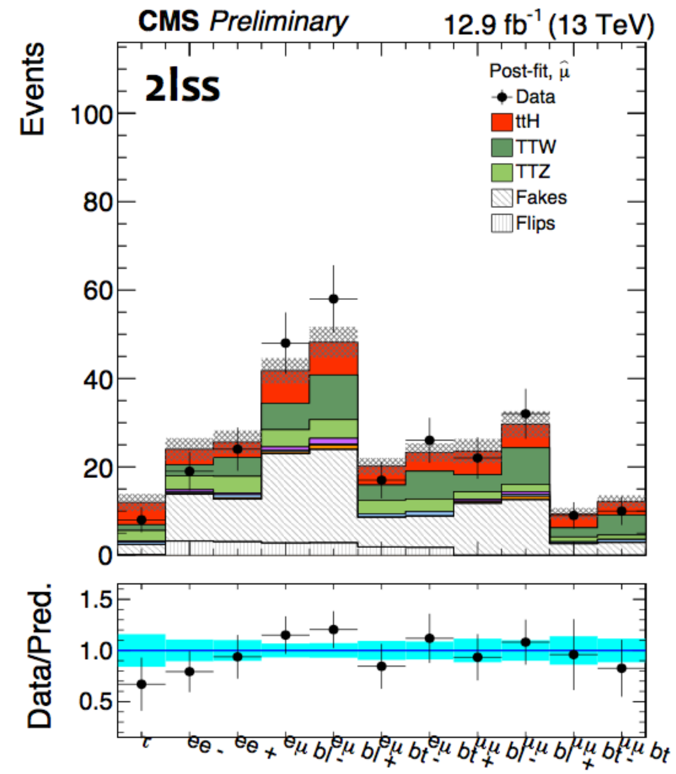


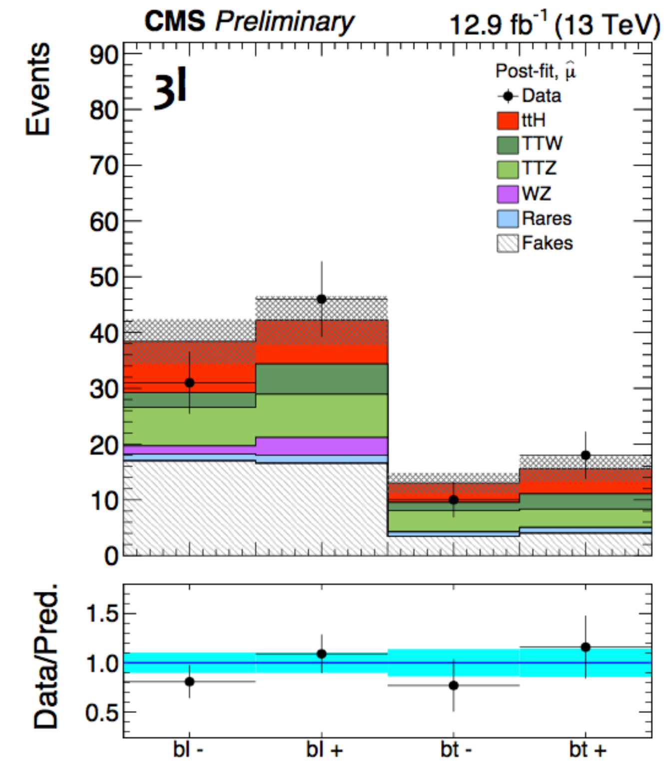


rather complex final state
- ttH→bb, high σxBR, lots of jets in final state
- ttH→γγ, small BR, very clean, low systematics
- ttH→WW*/ZZ*/ττ, low rate, low multilepton background

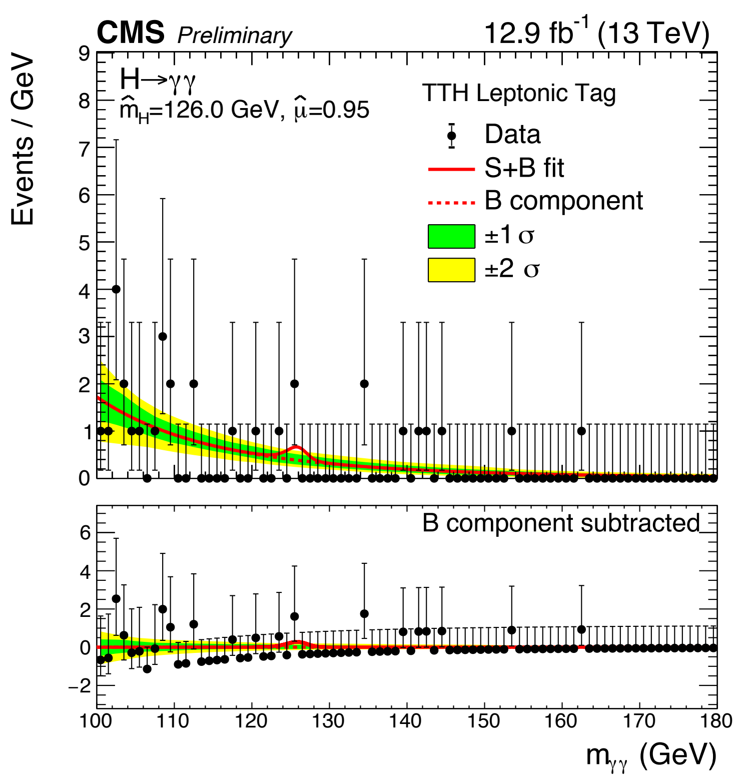
ttH, brief resume

multilepton: fit on BDT distributions in 2 categories: SS dilepton and 3-leptons, events categorised for b-tag, lepton flavour, τ decay, lepton charge

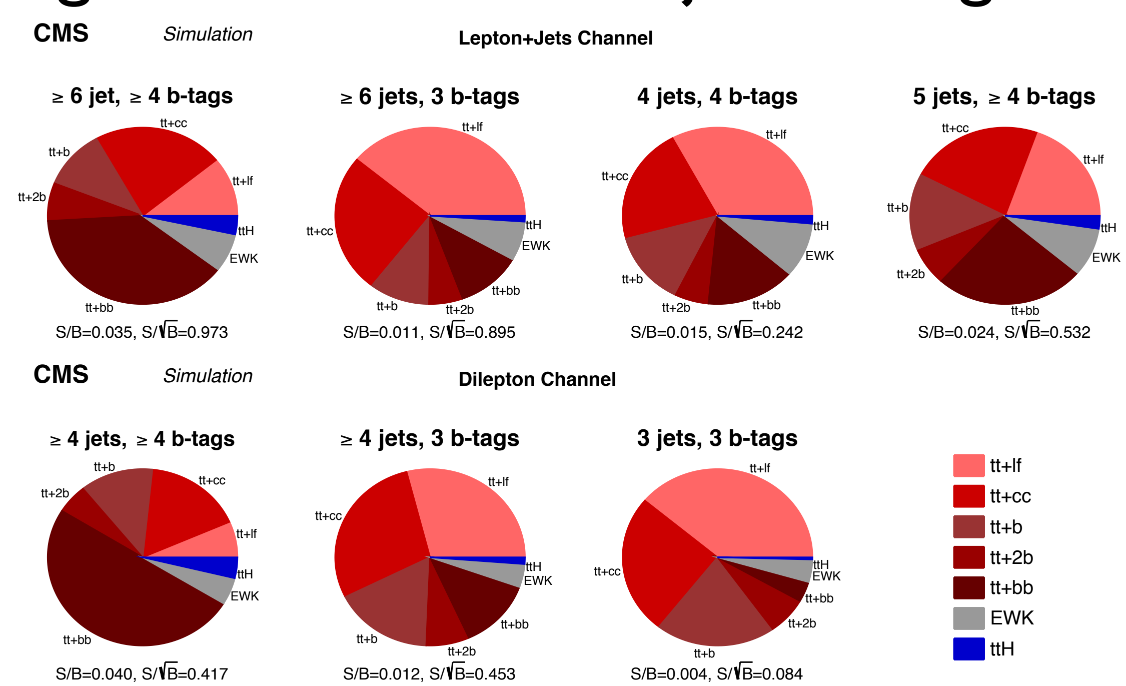




bb: dilepton/l+jets tt events + b-tags, categorise events according to njets+b-tag, BDT+MEMs to reject background

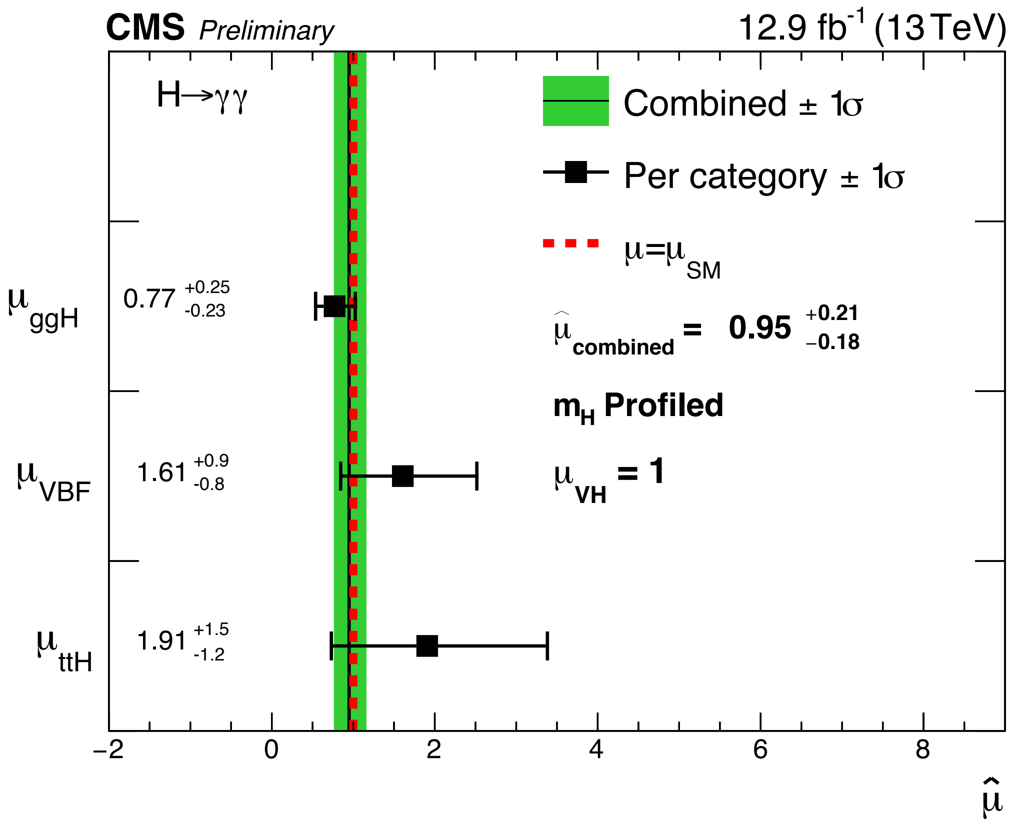


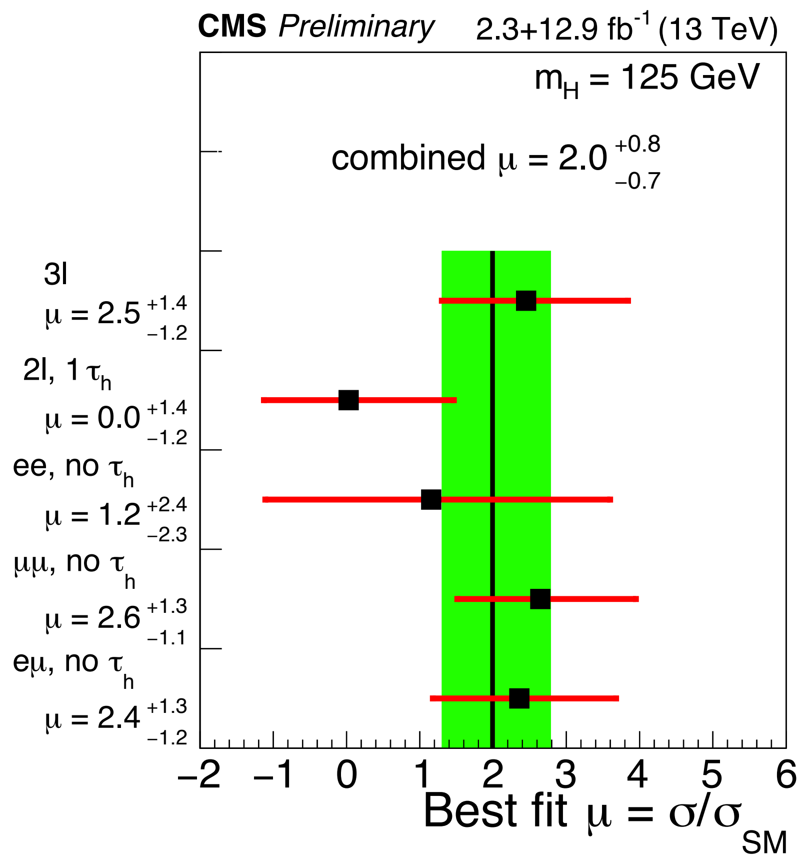
γγ: tagged H→γγ  categories



ttH: status and results

Quite excitingly, preliminary results from multi-lepton and $\gamma\gamma$ analyses seems to confirm the excess of run 1

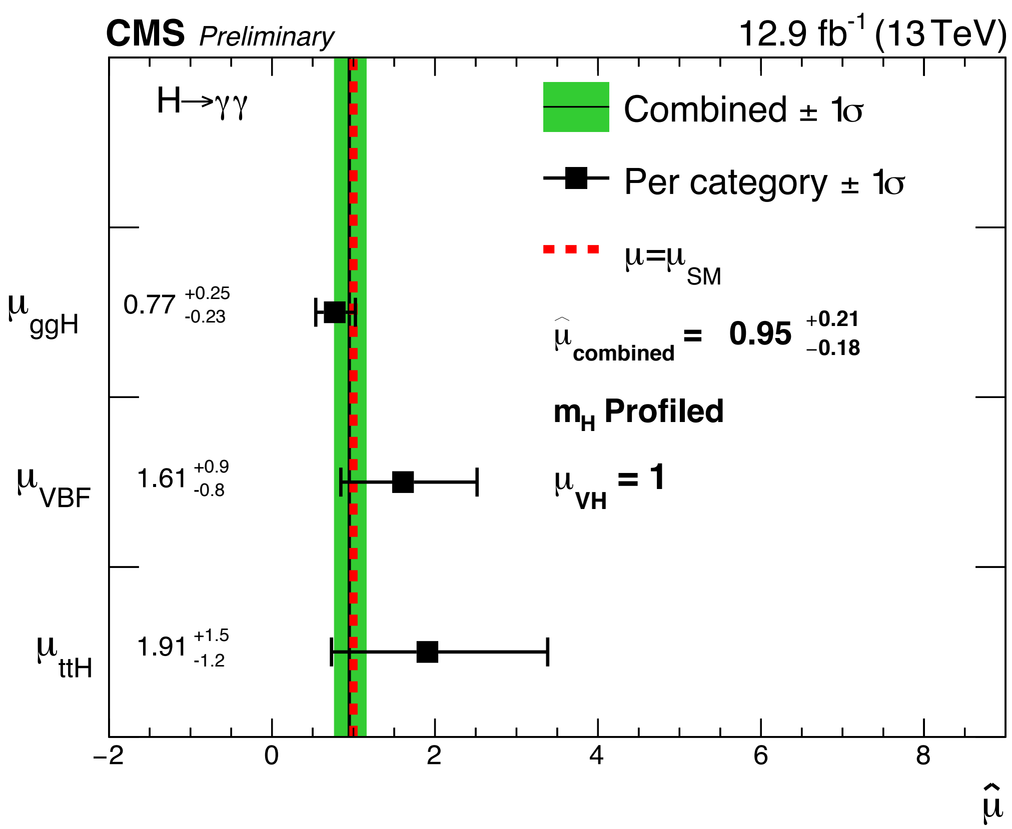


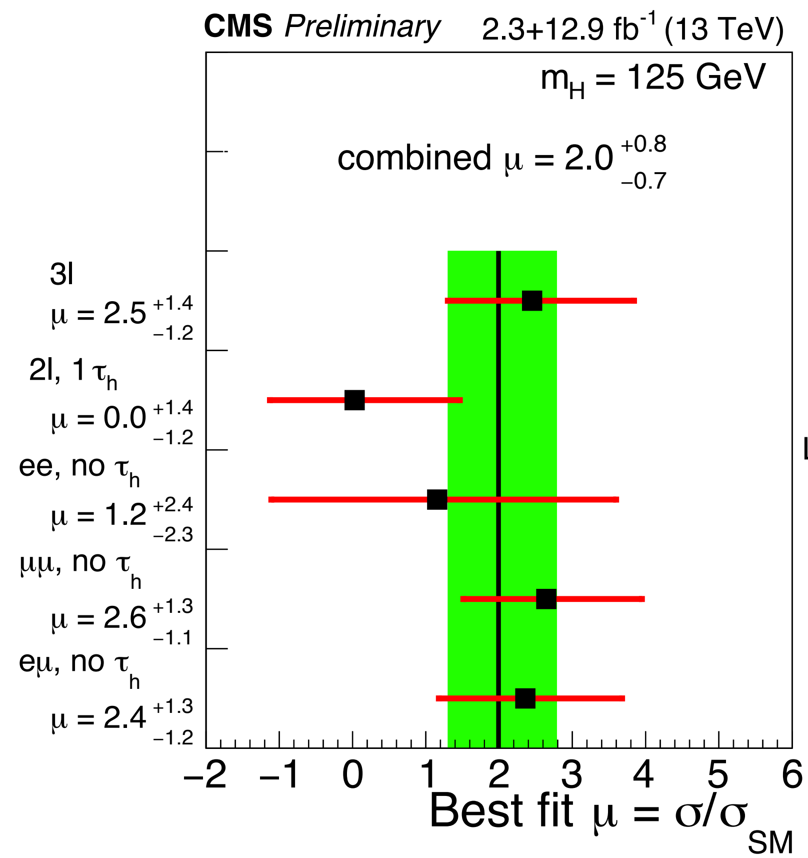


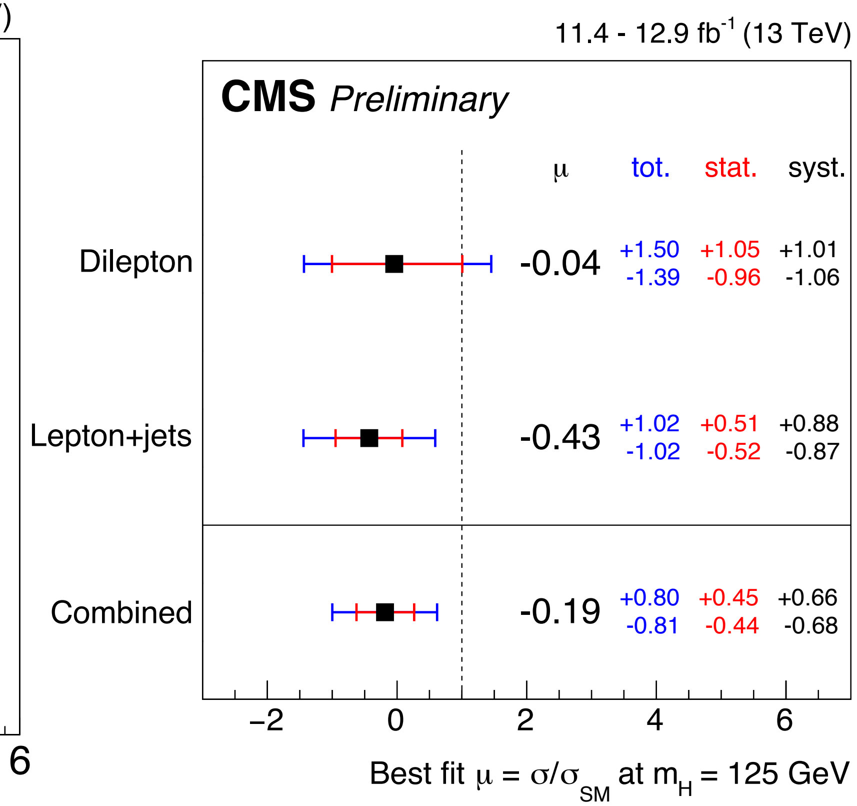
- Discussion on the handling of systematic uncertainties already started
- Planning towards CMS+ATLAS combination
- MEMs developments for multi leptons
- Let's see with the new 2016 statistics!

ttH: status and results

Quite excitingly, preliminary results from multi-lepton and $\gamma\gamma$ analyses seems to confirm the excess of run 1 But let's not get excited too early







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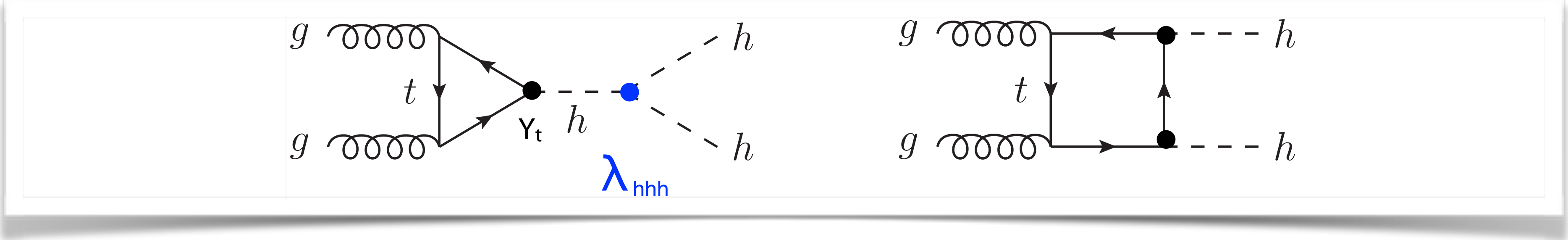
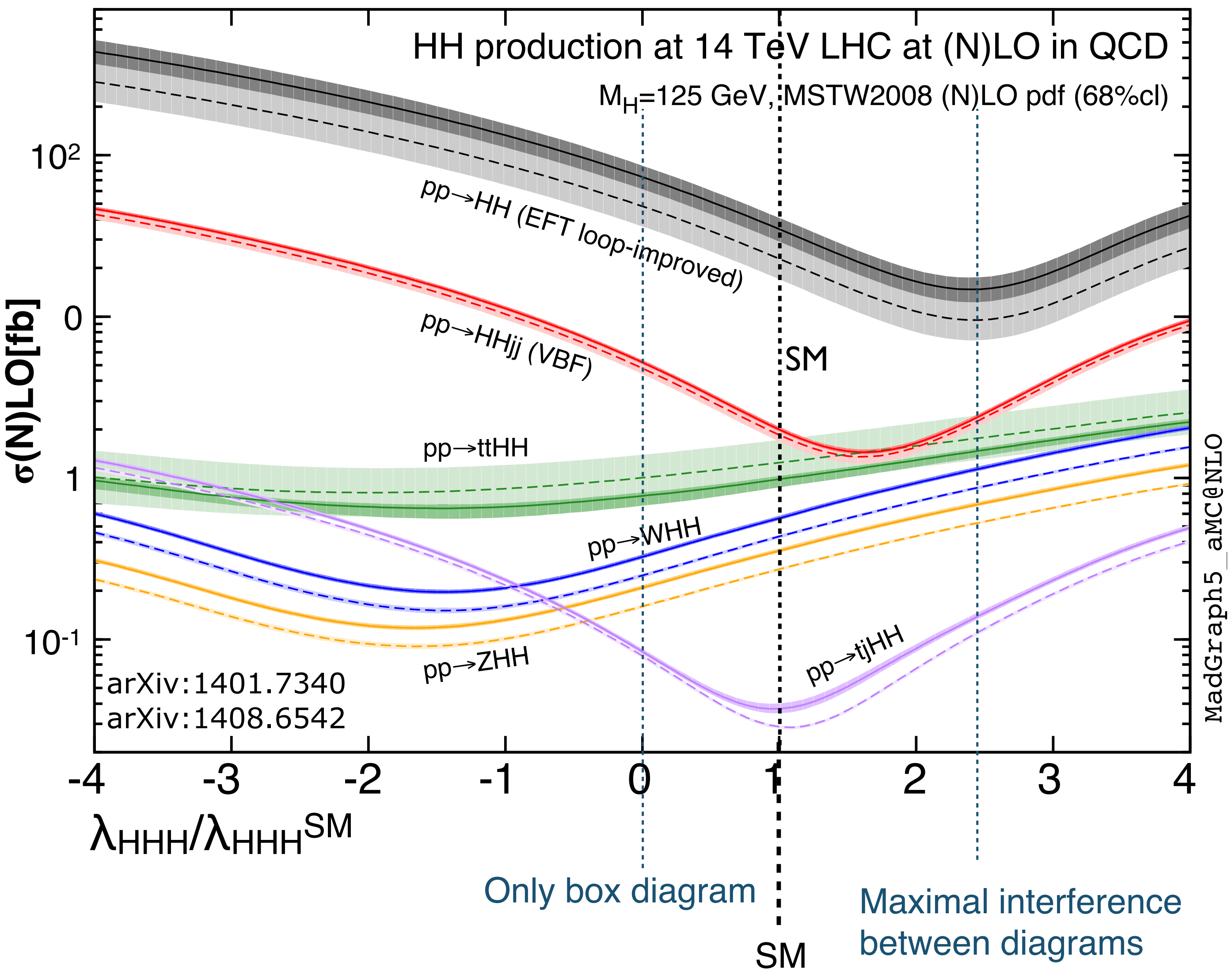
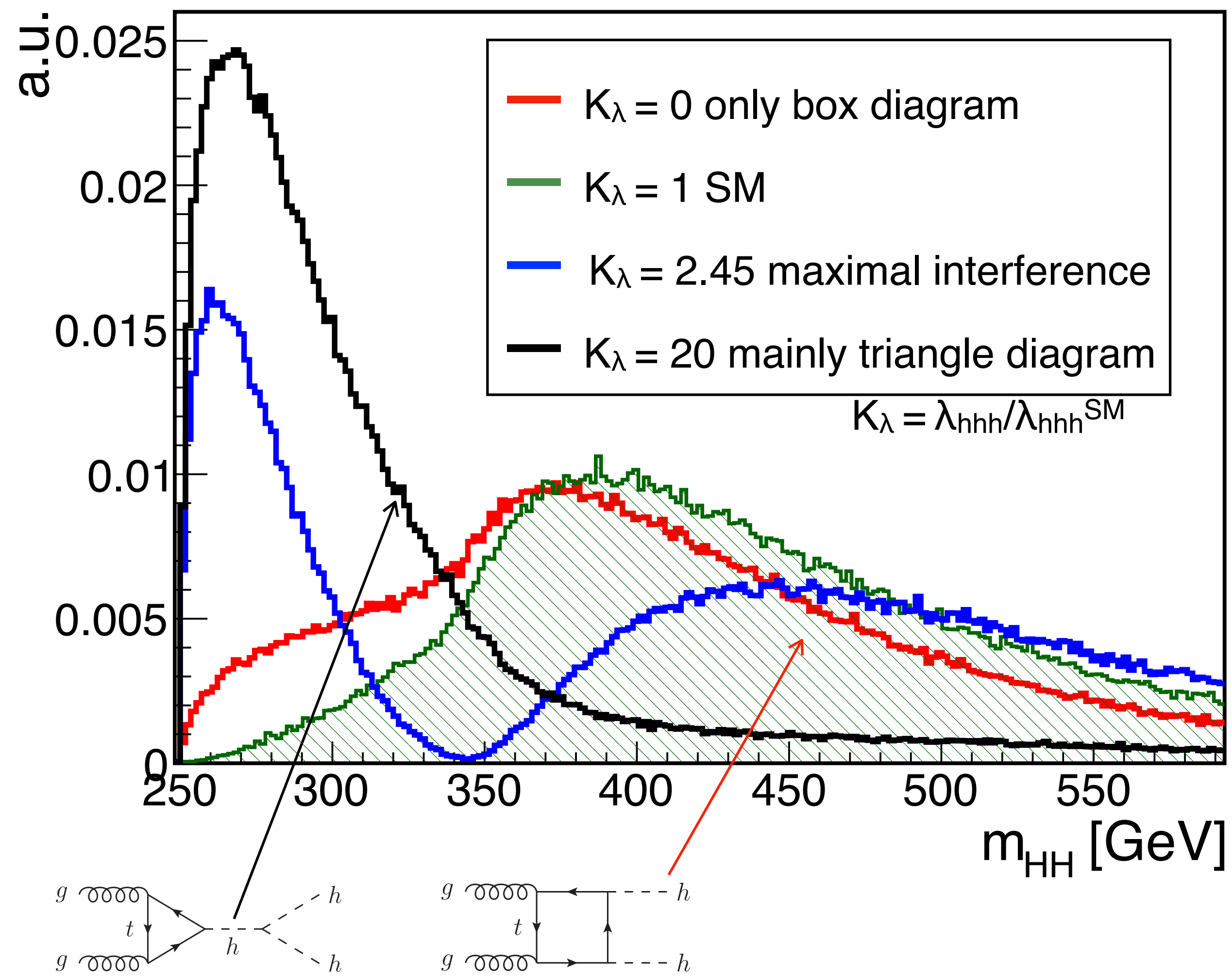
HH Motivations: anomalous λ_{hhh}



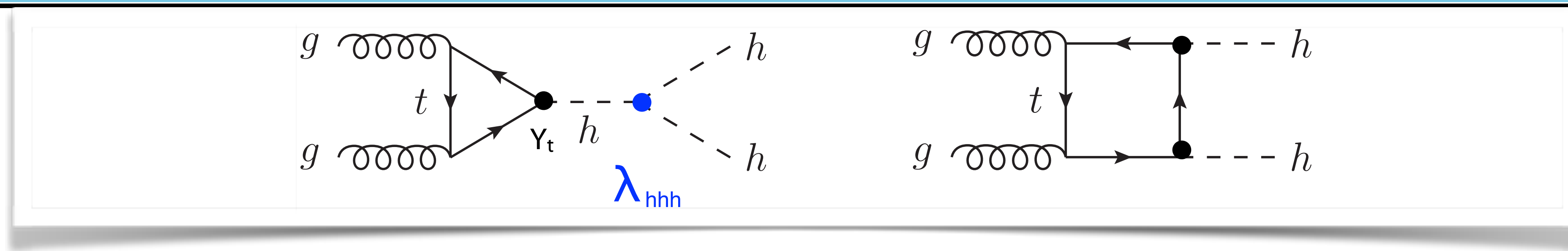




The value of λ_{hhh} affects both the production cross-section and the hh kinematical variables

~3.7 times increase in the production xsection going from 8 to 13TeV

HH Motivations: BSM

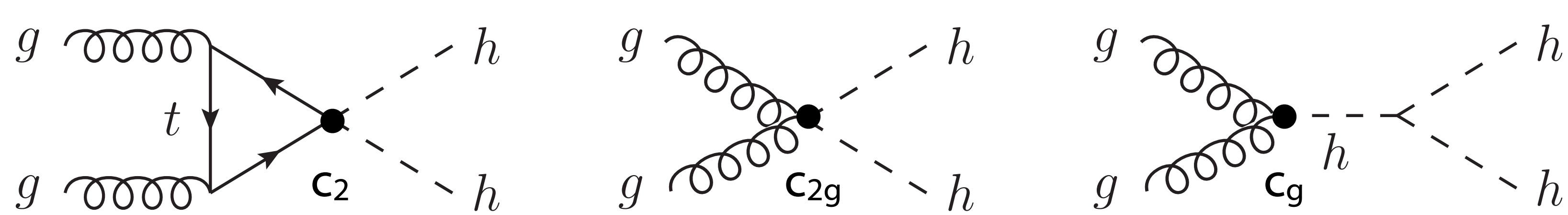


$\sigma^{SM}_{hh}(13TeV) = 33.45fb^{+4.3\%}_{-6.0\%}$(scale unc.) $\pm 3.1\%$(PDF+α_S unc)[1]

The non-resonant double Higgs production is the principal way to extract the Higgs trilinear coupling (λ_{hhh}). Even if in Run2 we will not have full sensitivity to "measure" λ_{hhh}

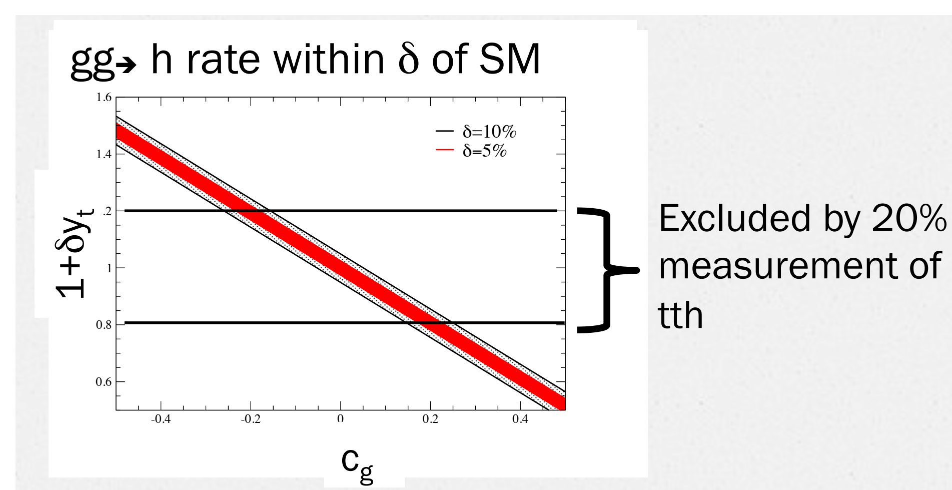
→ The BSM physics can be modelled in EFT adding dim-6 operators[2] to the SM Lagrangian, and the physics can be described with 5 parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g

- Non SM Yukawa and λ_{hhh} couplings
- New diagrams and couplings in the game



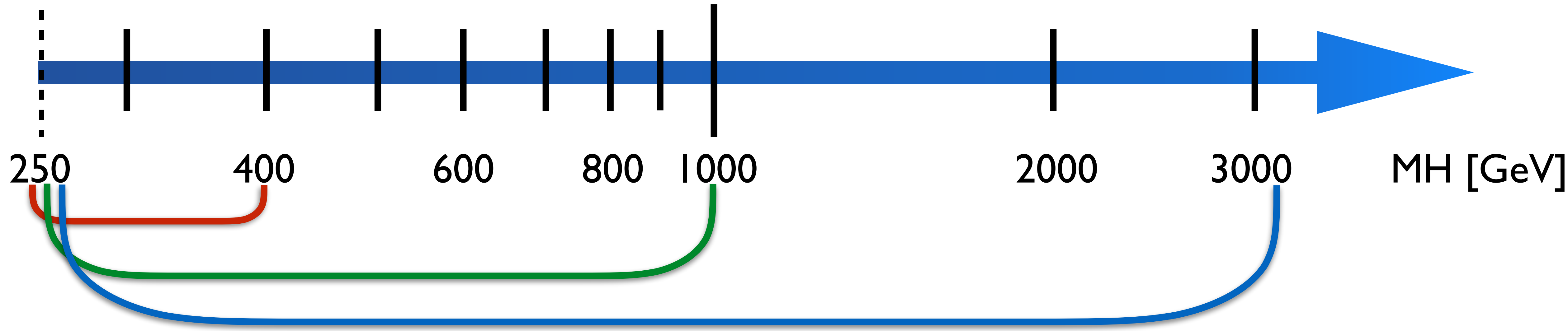
To be noted :

in a linear EFT $\quad c_g = c_{2g}$ and $c_2 = -(3m_t/2v)y_t$



[1] LHCHSWG Yellow Report 4
[2] *Phys. Rev.* **D91** (2015), no. 11, 115008

HH Motivations: Resonant



MSSM/2HDM: Additional Higgs doublet → CP-even scalar H.

- We can probe the low m_A/low $\tan\beta$ region where BR(H → h(125)h(125)) is sizeable.

Singlet model: Additional Higgs singlet with an extra scalar H.

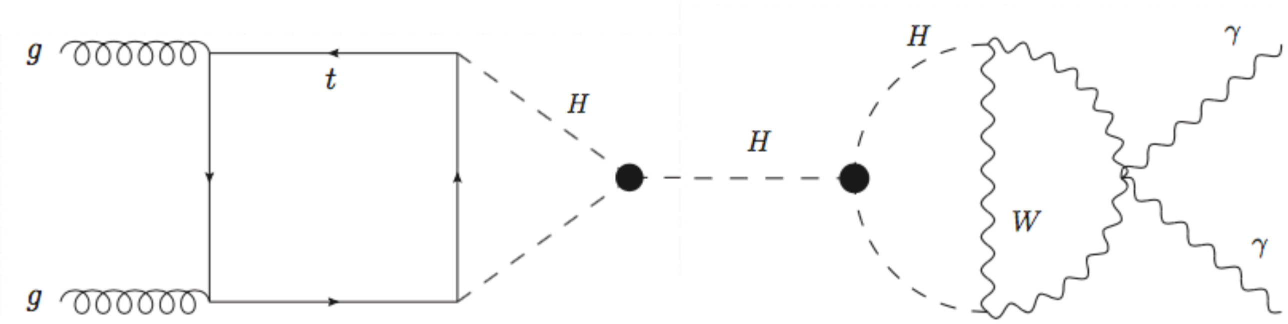
- Sizeable BR beyond $2xm_{top}$, non negligible width at high m_H.

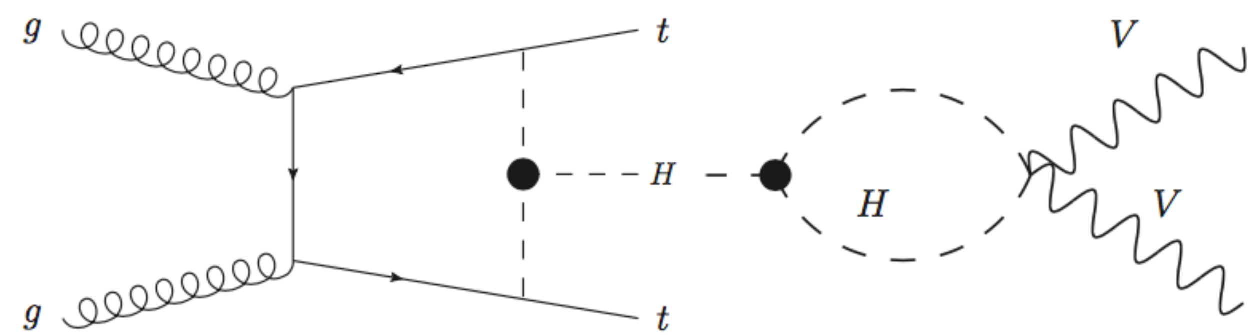
Warped Extra Dimensions:

spin-2 (KK-graviton) and spin-0 (radion) resonances.

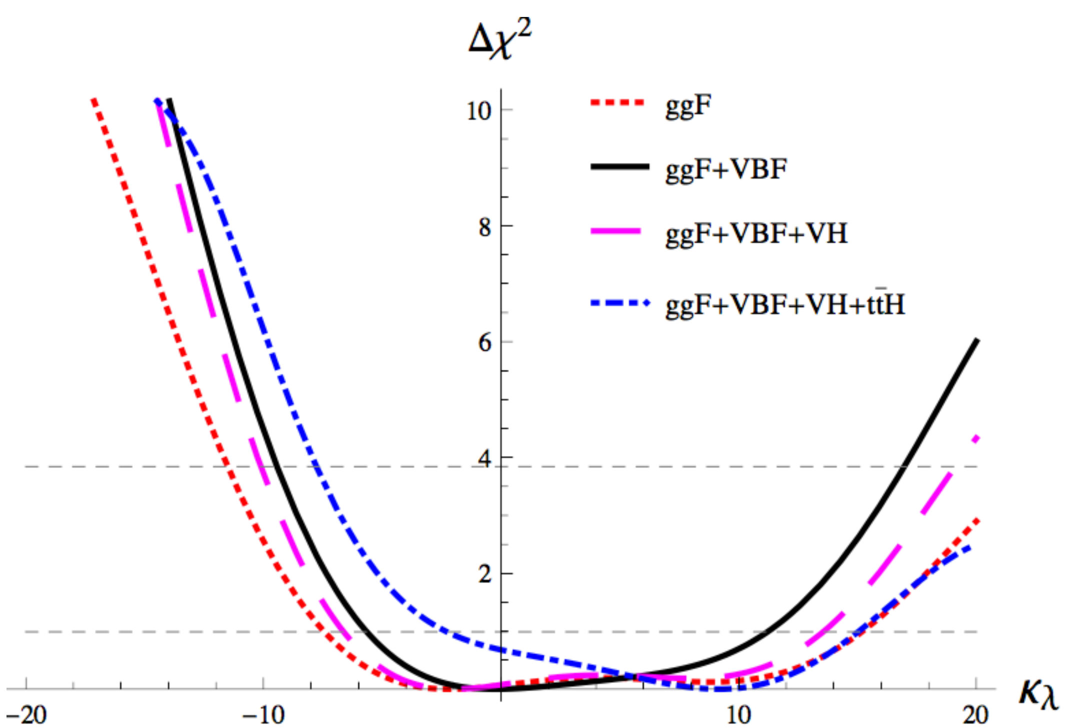
- Different phenomenology if SM particles are allowed (bulk RS) or not (RS1 model) in the extra dimensional bulk

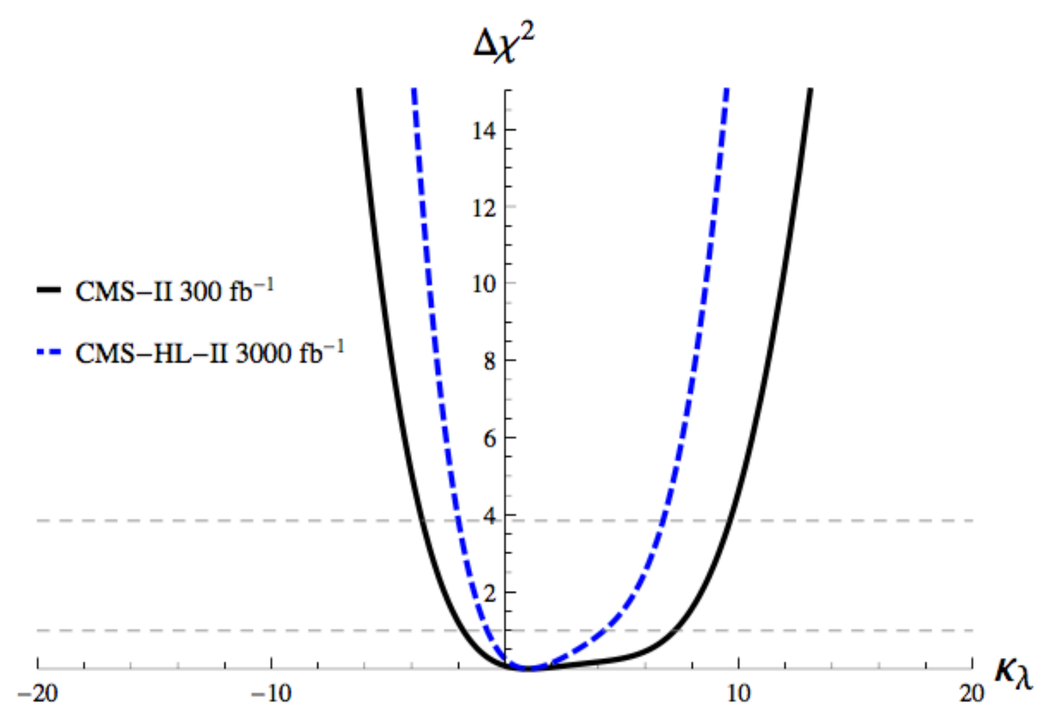
Trilinear coupling from single Higgs





Assumption: NP only manifest itself via an anomalous trilinear coupling, while all other couplings are unchanged (or modifications are negligible)
Several discussions are ongoing to decide if it is a reasonable assumption, requires Λ_{NP} to be not too high





Quick projection: results are competitive with what is obtained from double Higgs production.

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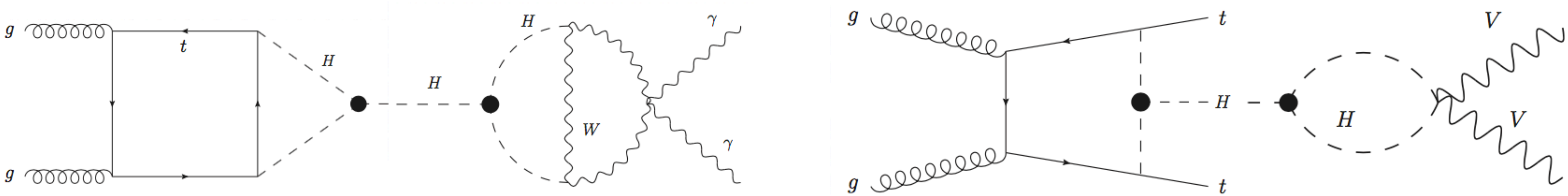

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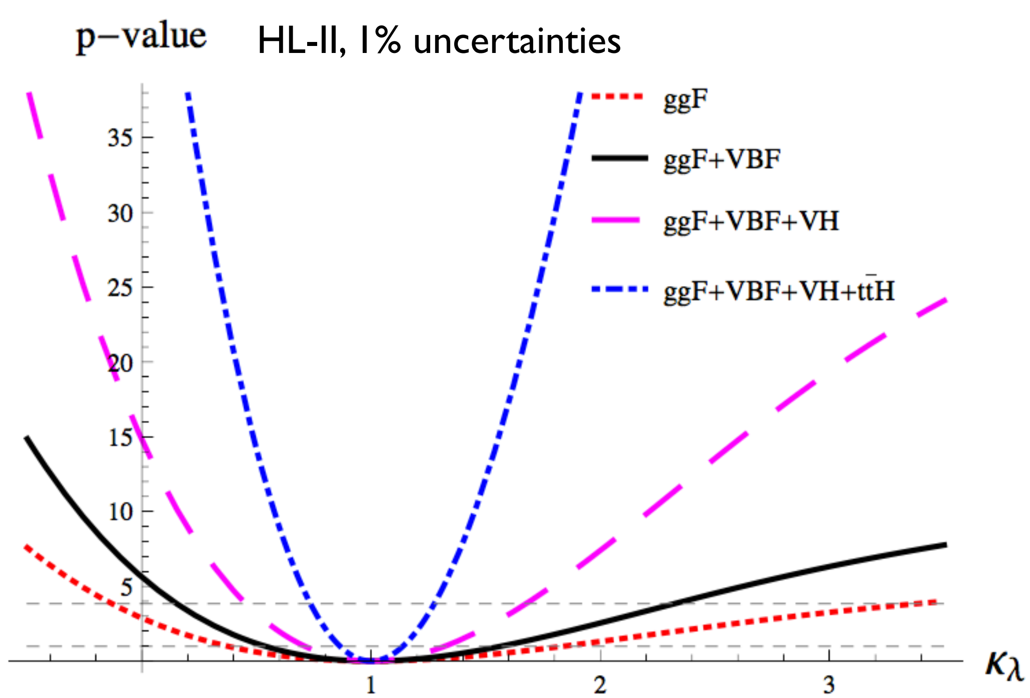
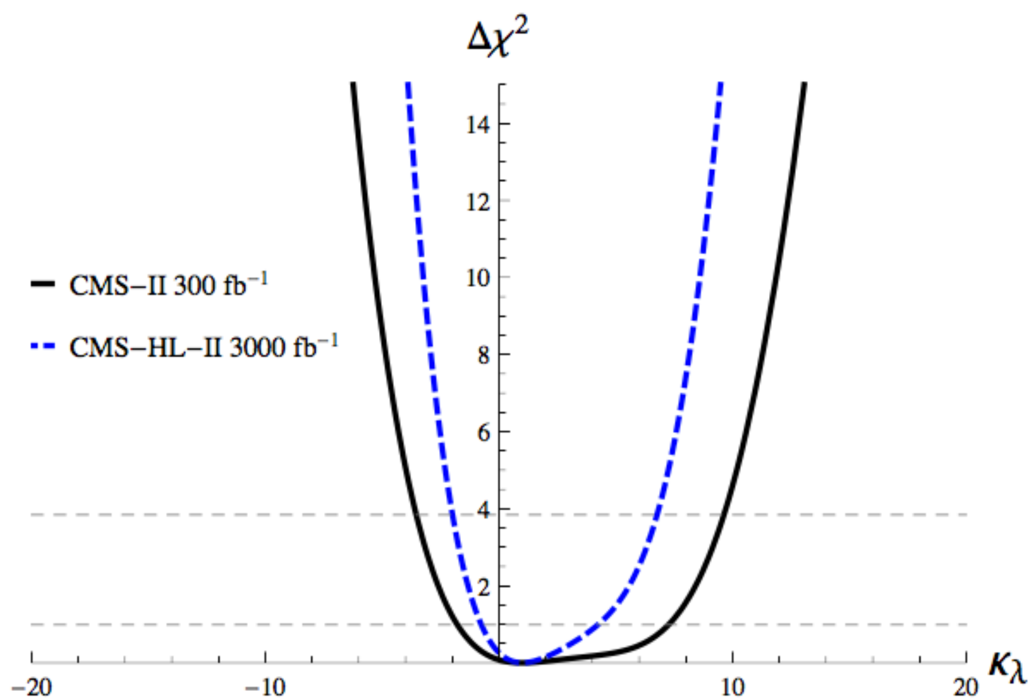




Quick projection: results are competitive with what is obtained from double Higgs production. ttH production is the main driver of the sensitivity

CMS searches

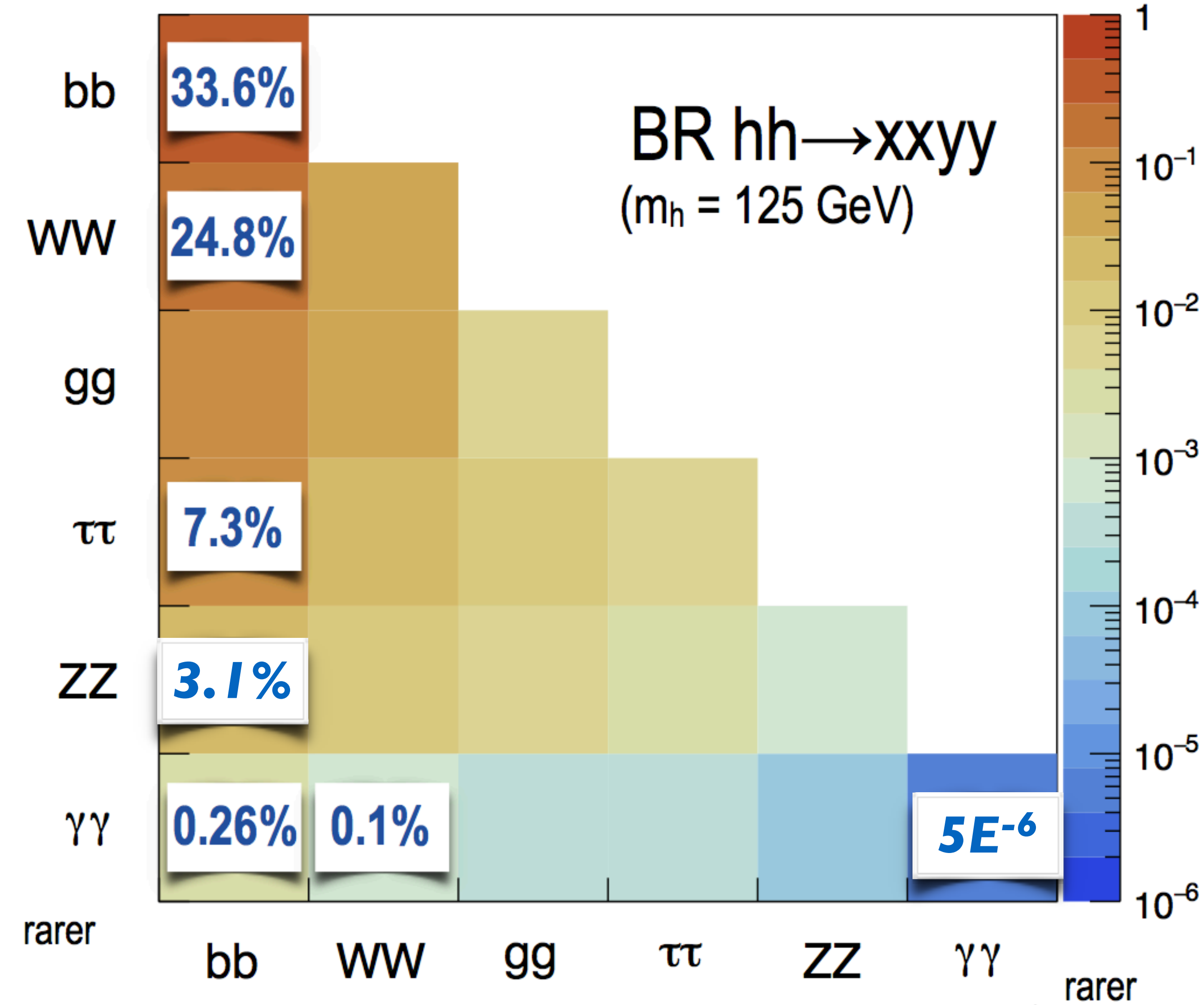
6 different searches at CMS

- bbbb, bbWW, bb$\tau\tau$, bb$\gamma\gamma$, bbZZ, $\gamma\gamma\gamma\gamma$

Rare processes, low σxBR, complex environment

channel		
bbbb	13.3	2.3/2.7
bbWW	2017	2.3
bb$\tau\tau$	-	12.9
bb$\gamma\gamma$	3.2	2.7
WW$\gamma\gamma$	13.3	-
bbZZ	-	2017
$\gamma\gamma\gamma\gamma$	-	2017

lumi analysed @ 13TeV



Complementarity among searches

- bbbb: high BR, large QCD, tt backgrounds
- bb$\gamma\gamma$: high purity, low BR
- bb$\tau\tau$: tradeoff between purity/BR
- bbWW: large BR, large tt background

different sensitivities to different m_H ranges

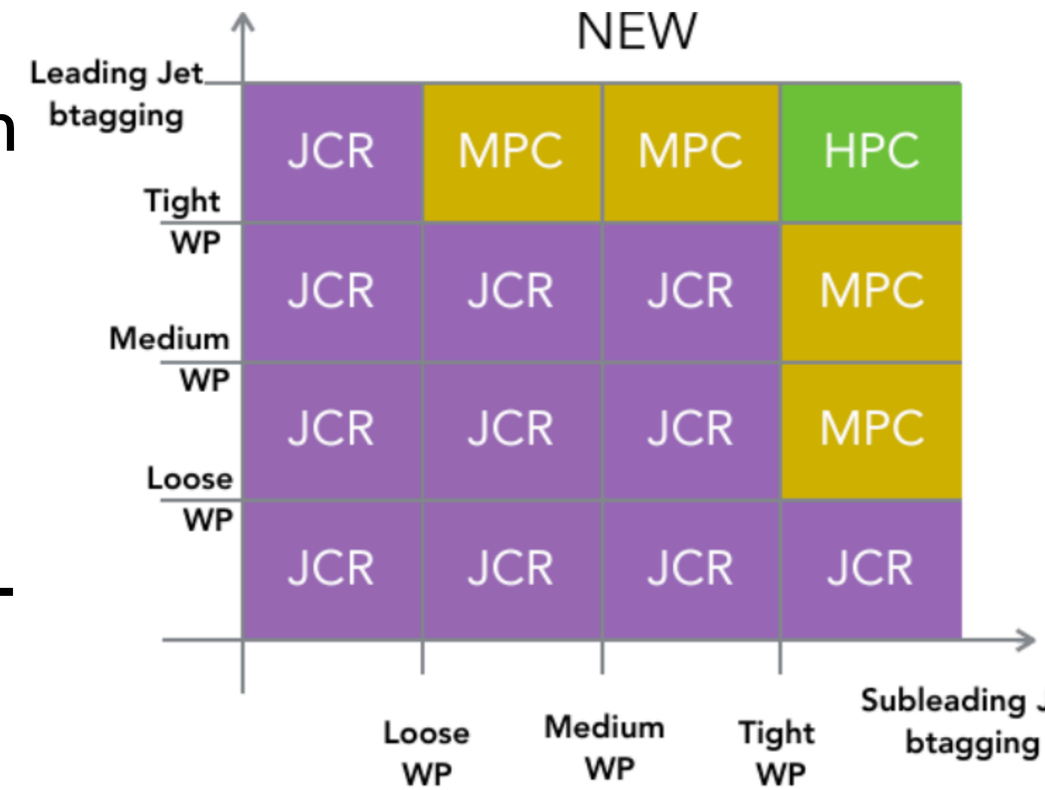
$hh \to bb\gamma\gamma$

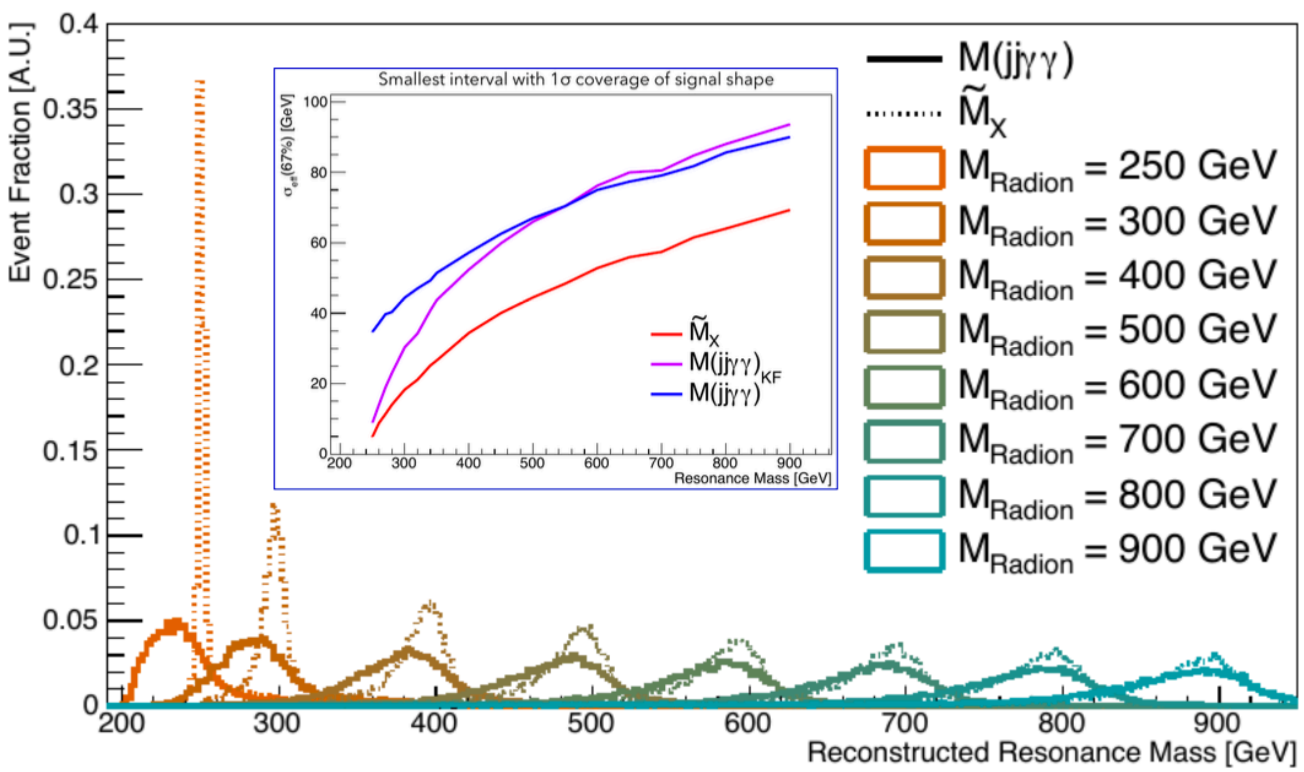
Most sensitive channel for non-resonant production

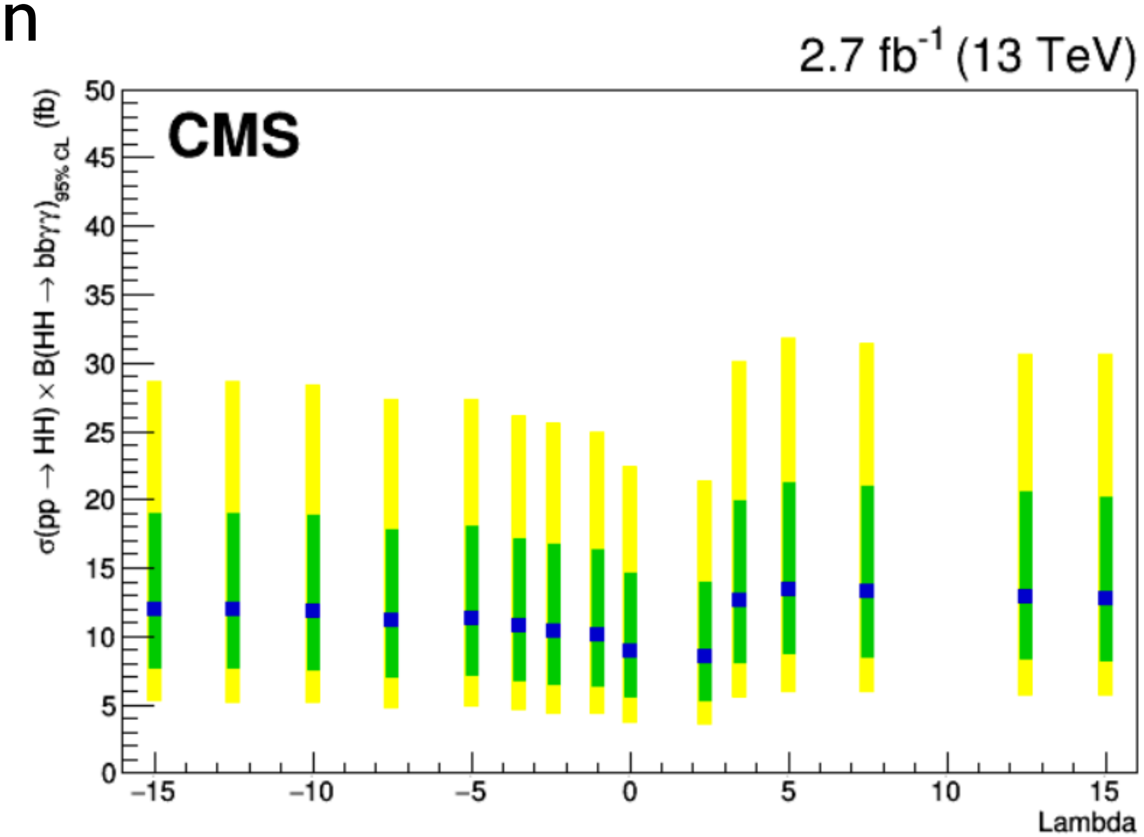
- 2 b-tag categories (low/high purity)
- background from fit to the data
- 2D fit on the reconstructed H masses
- Effective mass $M_X = M_{jj\gamma\gamma} - M_{jj} + 125$ GeV to remove background (resonant) or categorise events (non-resonant)

Still working on:

- B-jet regression, helicity angles, VBF production







HH→bbWW

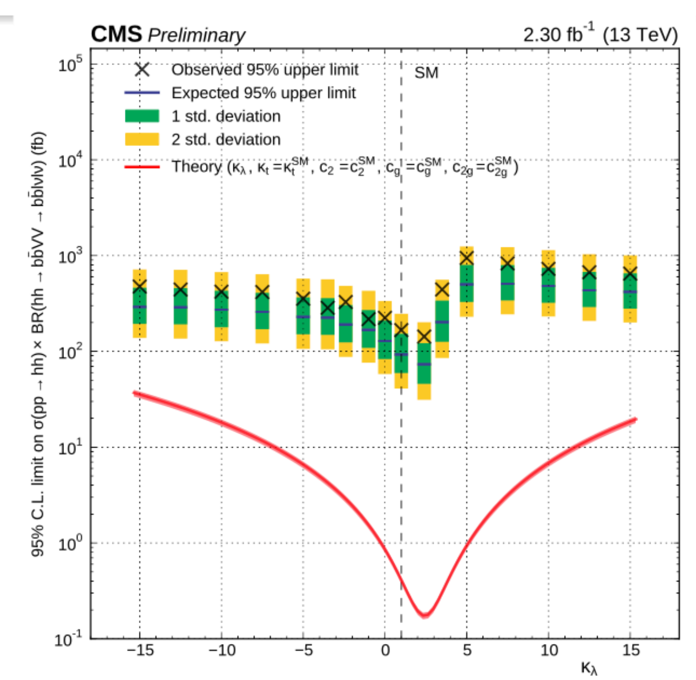
Search for hh→bbWW→bb2l2ν, BR=1.22%, huge irreducible tt background

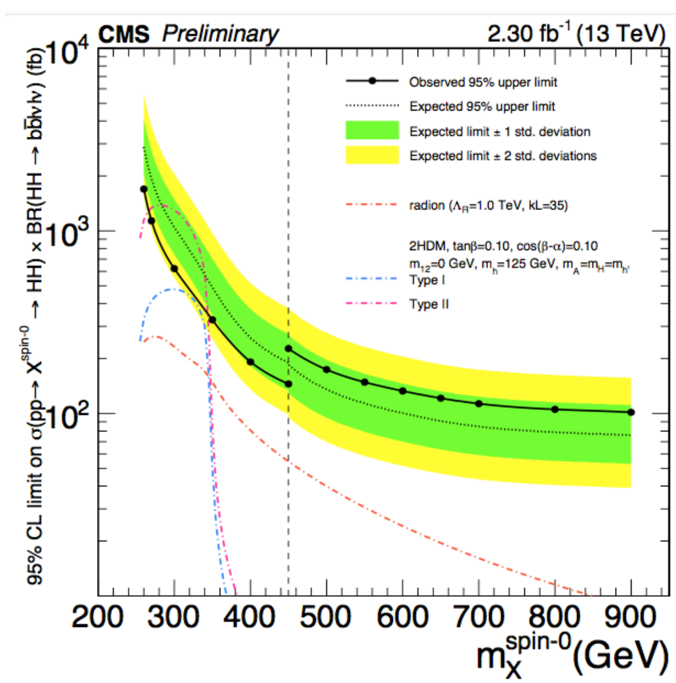
- ATLAS is planning the fully hadronic channel
- Select events with 2 OS leptons (HWW ID) +2 medium b-tag jets
- Reject pairs in the Z peakBDTs to reject the background
- Mjj side bands to check the background
- 2D fit in (M_{bb},BDT)

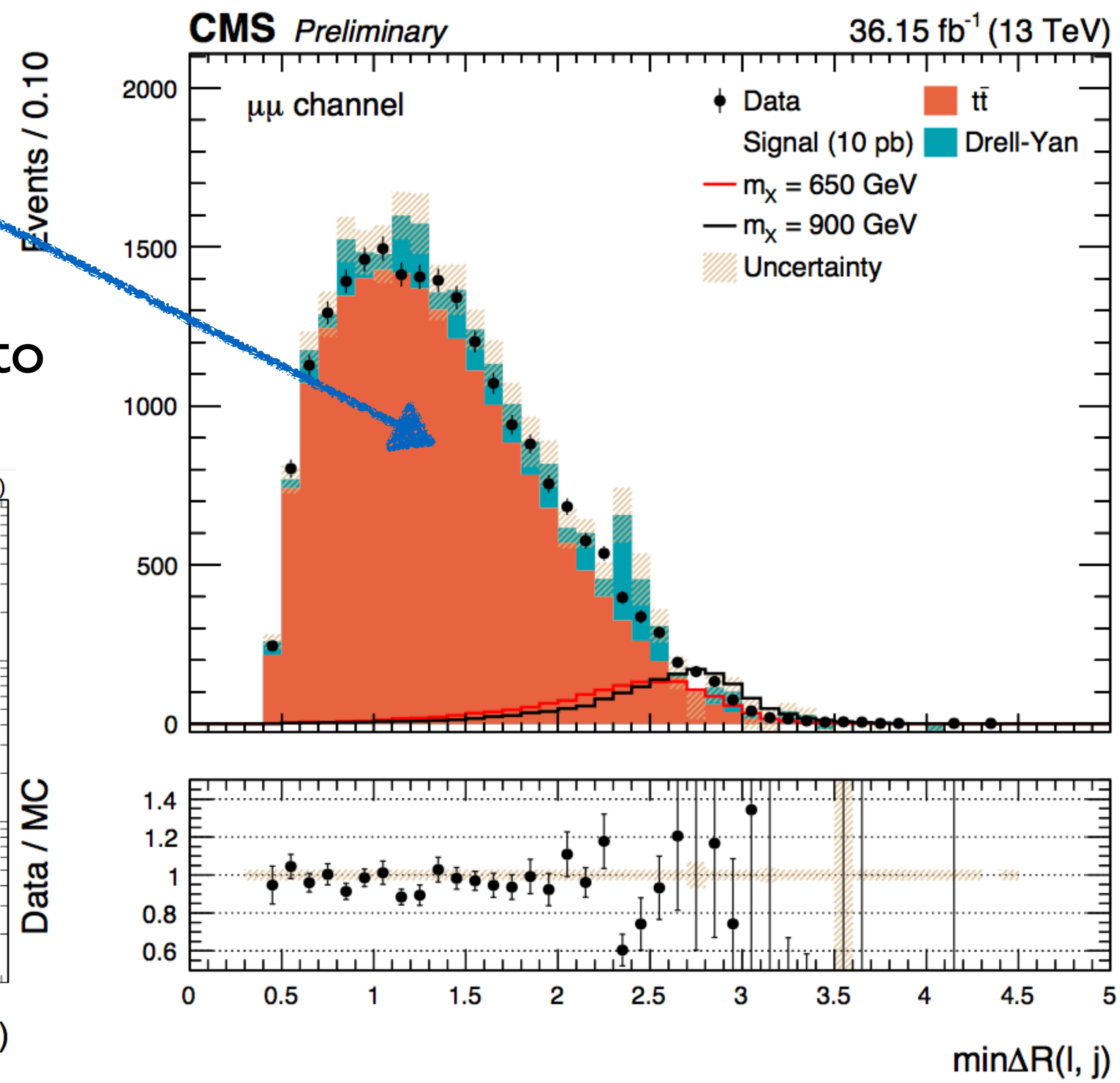
2016: already good agreement data/MC

Improvements for 2017: new MVA training, DY background estimation from data

At the moment not large sensitivity, mostly due to the small BR

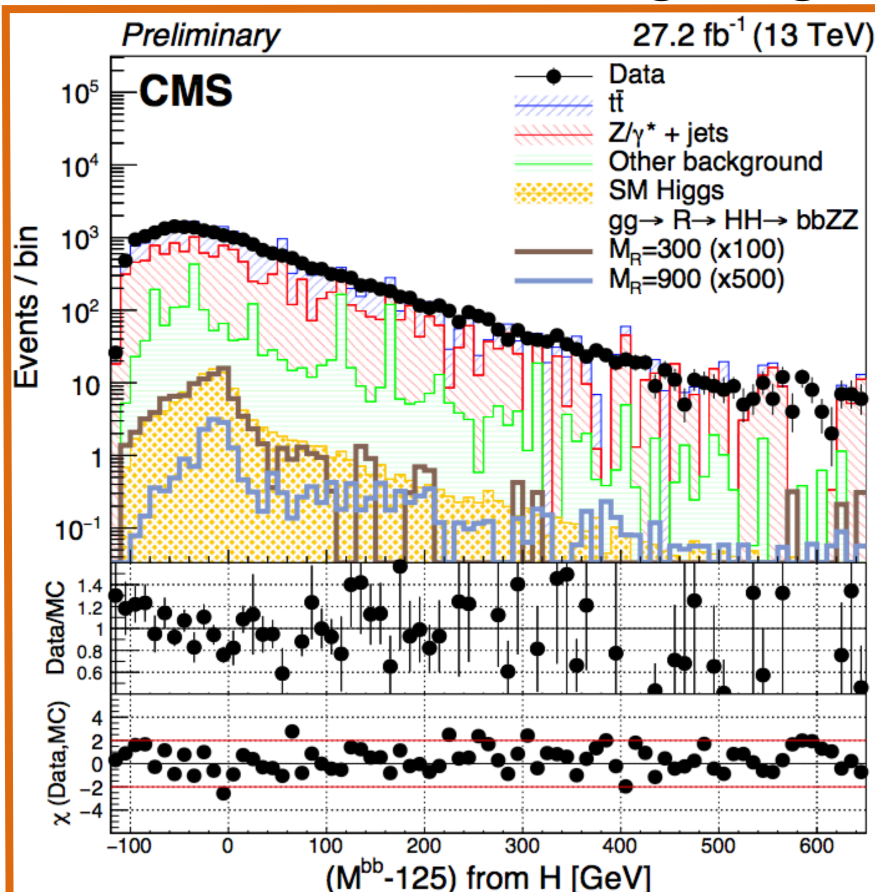


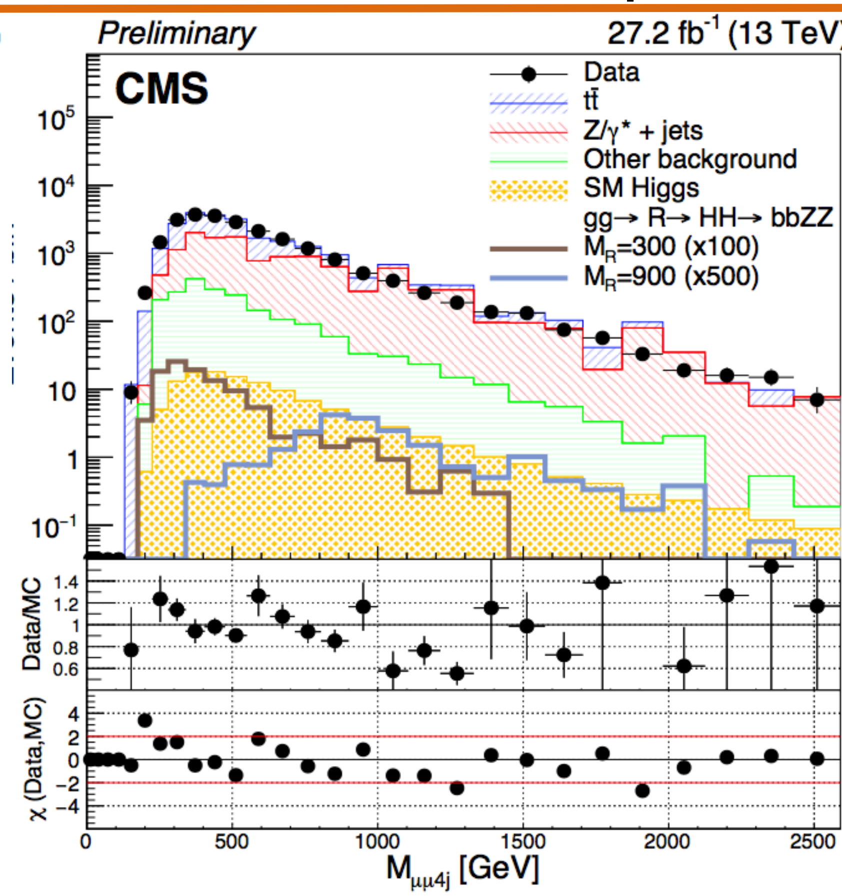




HH→bbZZ and γγγγ

- New entries in 2017! Only entering for resonant searches for now.
- Both targeting Moriond2017 for first public results



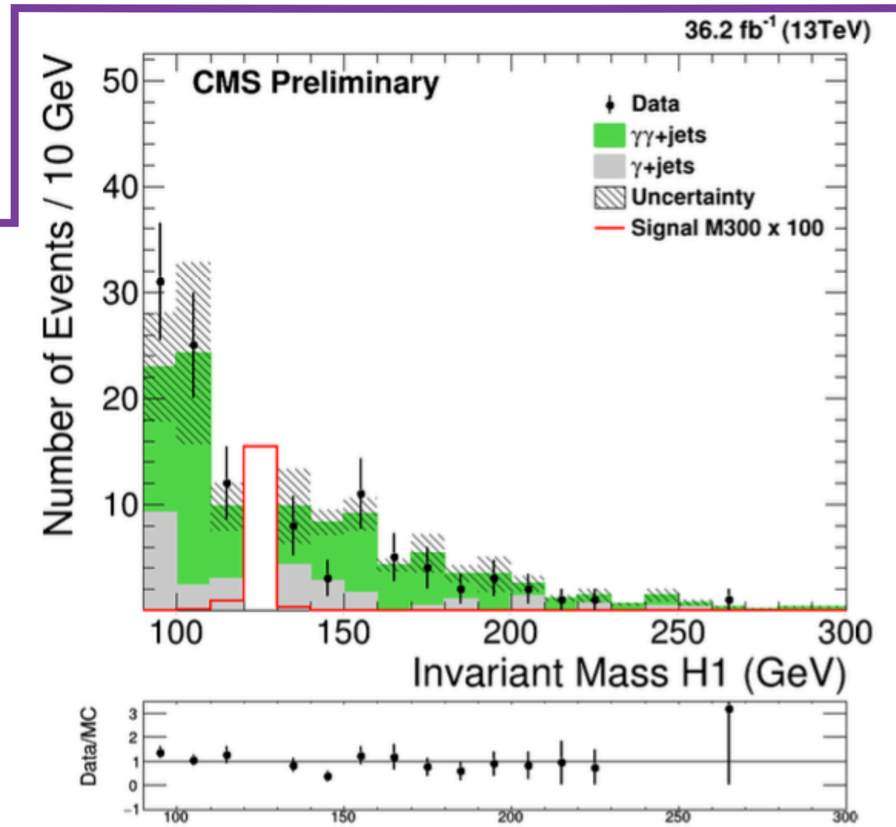


HH→bbZZ→bb2l2j BR=0.15%

- Can use a lot of kinematic handles/recoils
- but a lot of jet combinatorial as well
- Analysis not finalised yet
- Good data/(private)MC agreement

HH→γγγγ

- Inheriting from SM H→γγ, basically same strategy with loosen photon-ID
- Impressive resolution, almost 0 BR
- No estimate about sensitivity yet, but very few events in the signal region



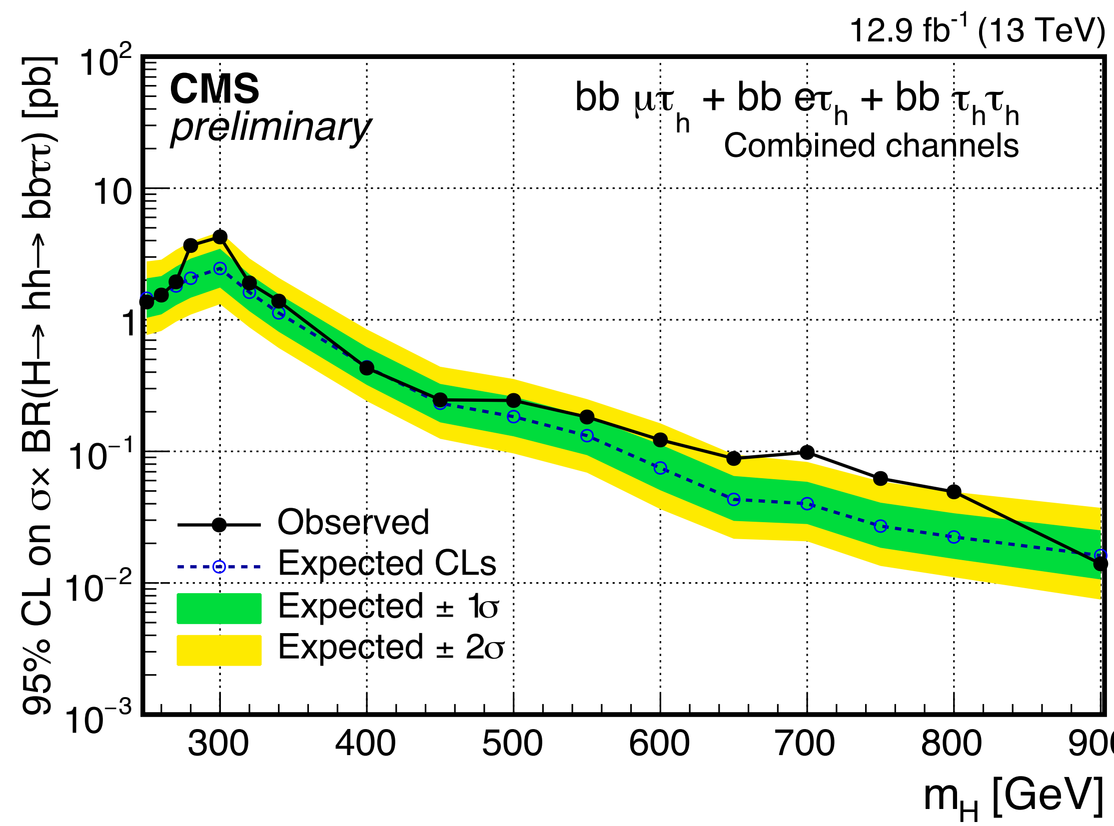
hh→bbττ

Bari-Pisa, Milano-Parigi (fully synchronised)

$1\tau_H$+1 isolated leptons (e, μ, τ_H)+2 b-jets

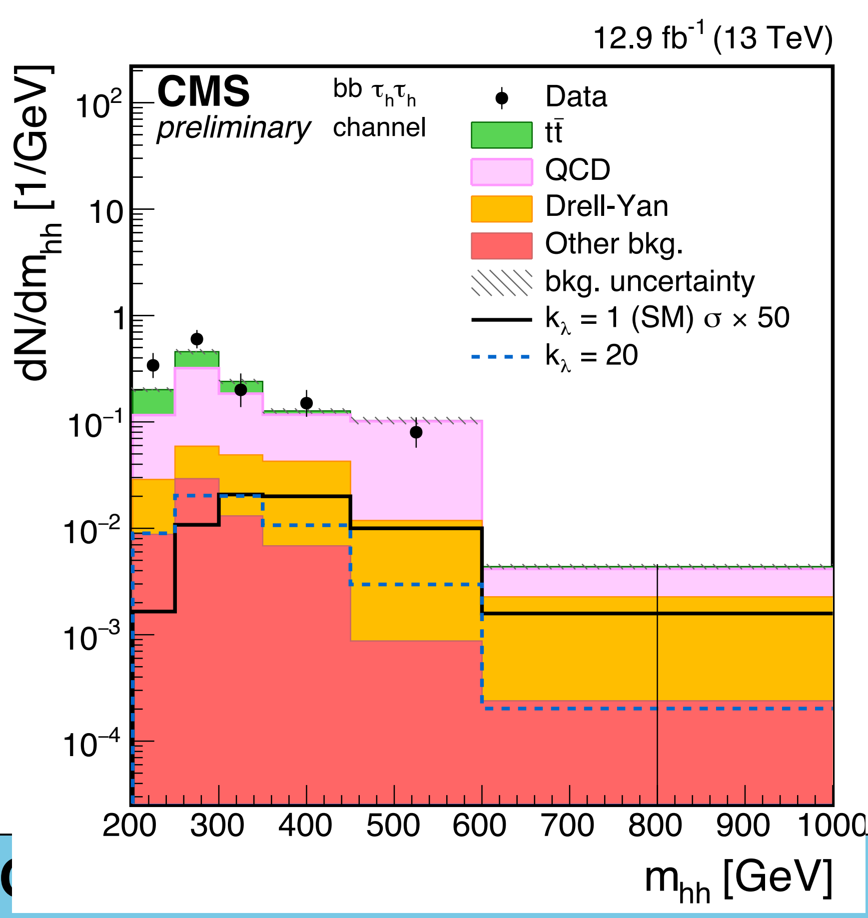
3 final states: $e\tau_H$, $\mu\tau_H$, $\tau_H\tau_H$

Main bkgs: $t\bar{t}$ (from MC), QCD multijet (from data in control regions)



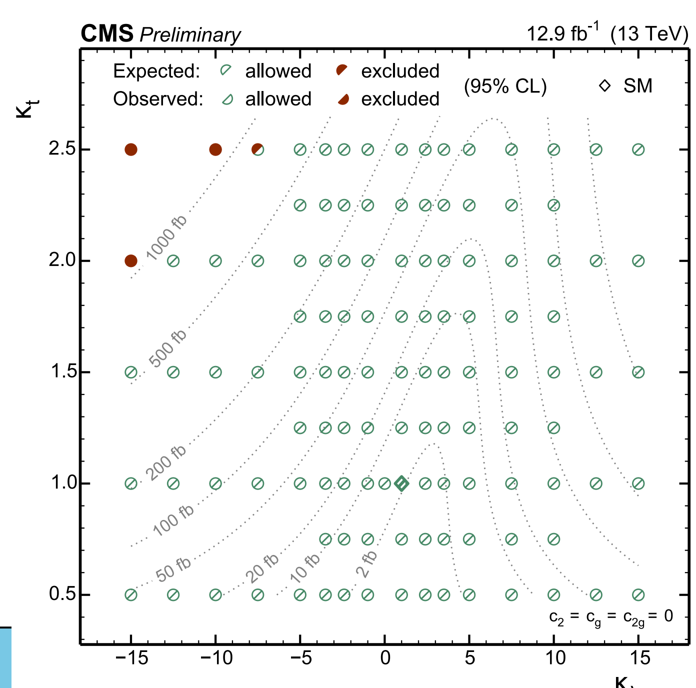
Resonant search:

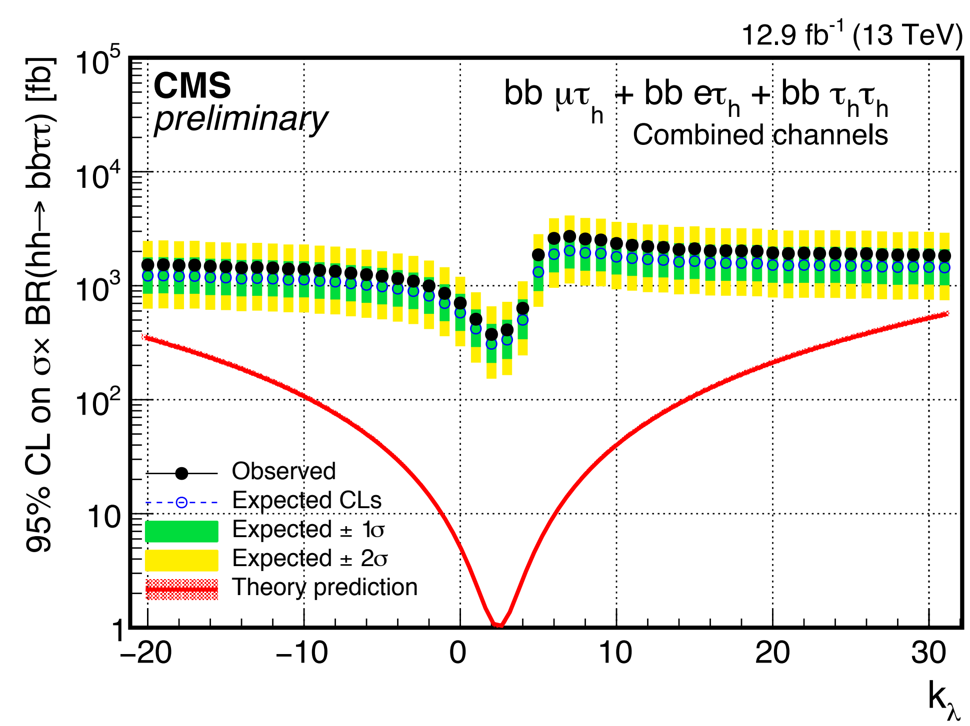
- Limit on kinematic fit of the 4-body invariant mass
- 3 categories: 1bjet, 2bjet, boosted b-jets category



Non-resonant analysis:

- kinematic BDT discriminant to reduce $t\bar{t}$
- visible/stransverse mass as final variable



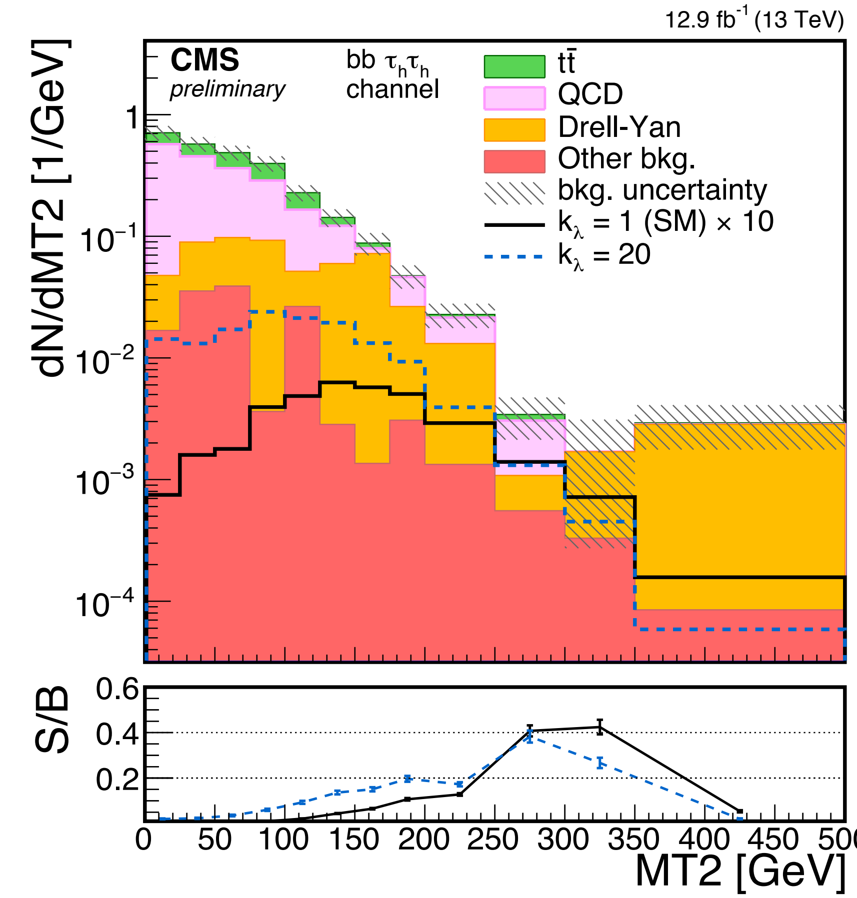


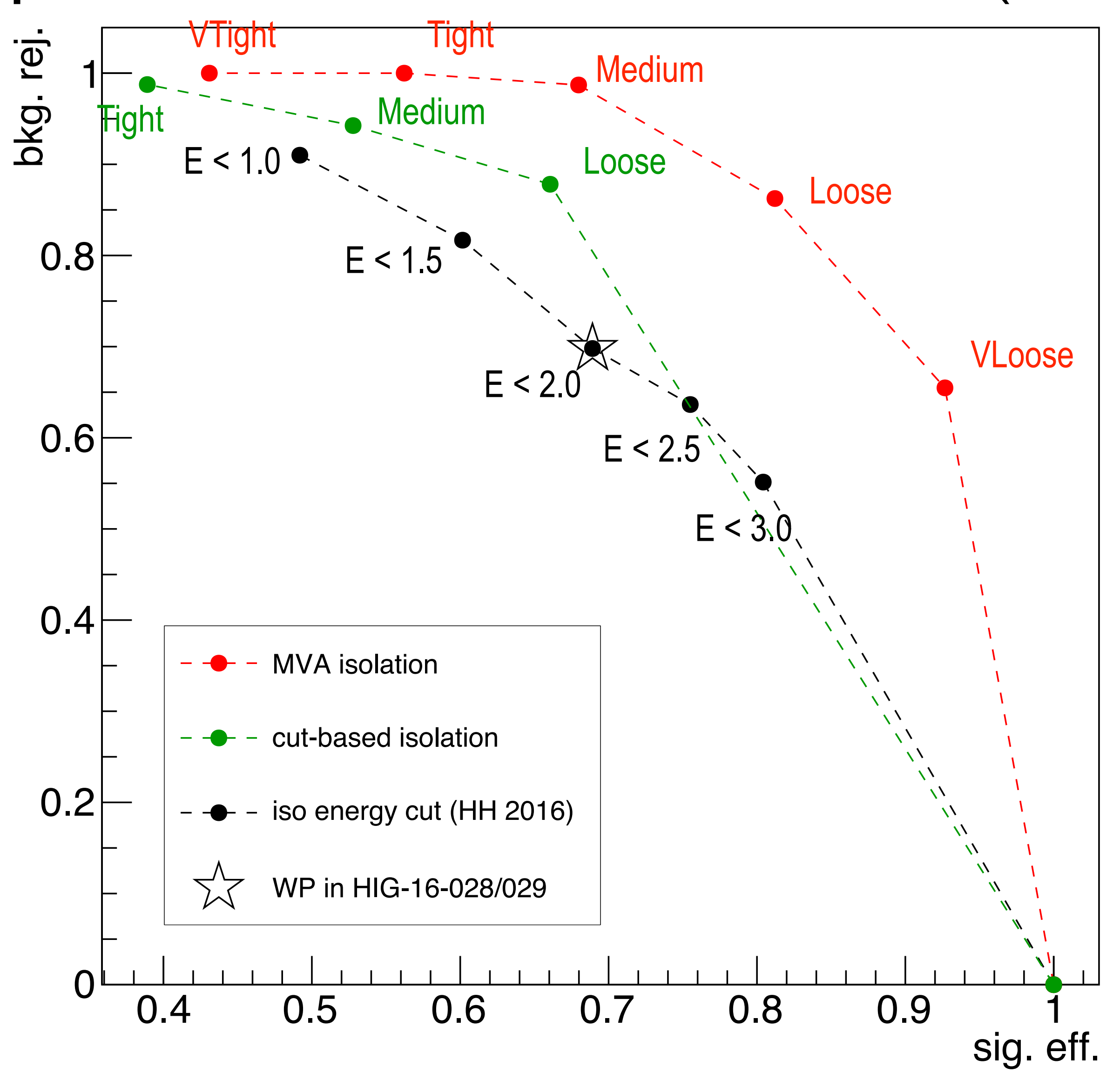
hh→bb$\tau\tau$: improvements

HIP mitigation alone will largely improve the sensitivity

Other improvements targeting bkg discrimination:

- MVA τ_H isolation to remove QCD
- Resonant: BDT to reject tt
- Non-res: Jet categorisation to remove DY+light jets production and stransverse mass (MT2) as final variable





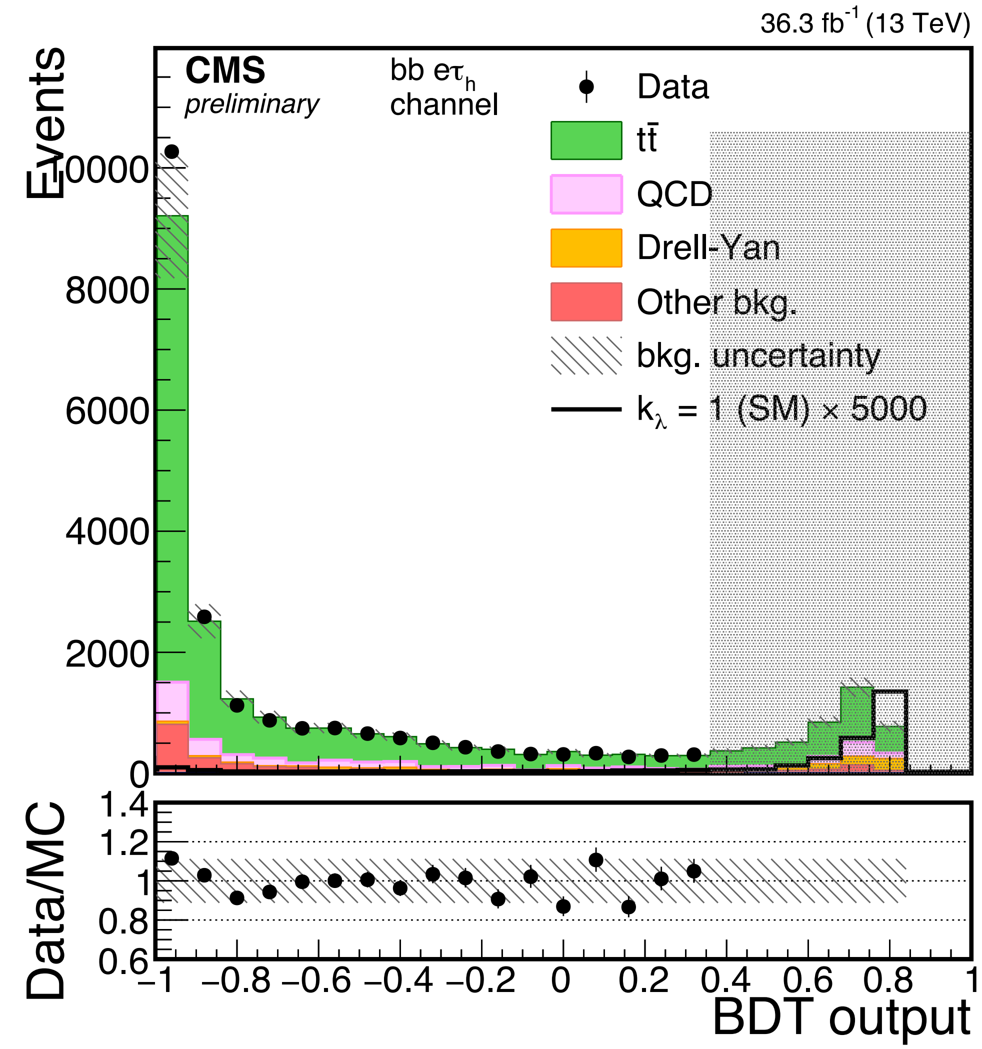
We expect large improvements once all the new features are included

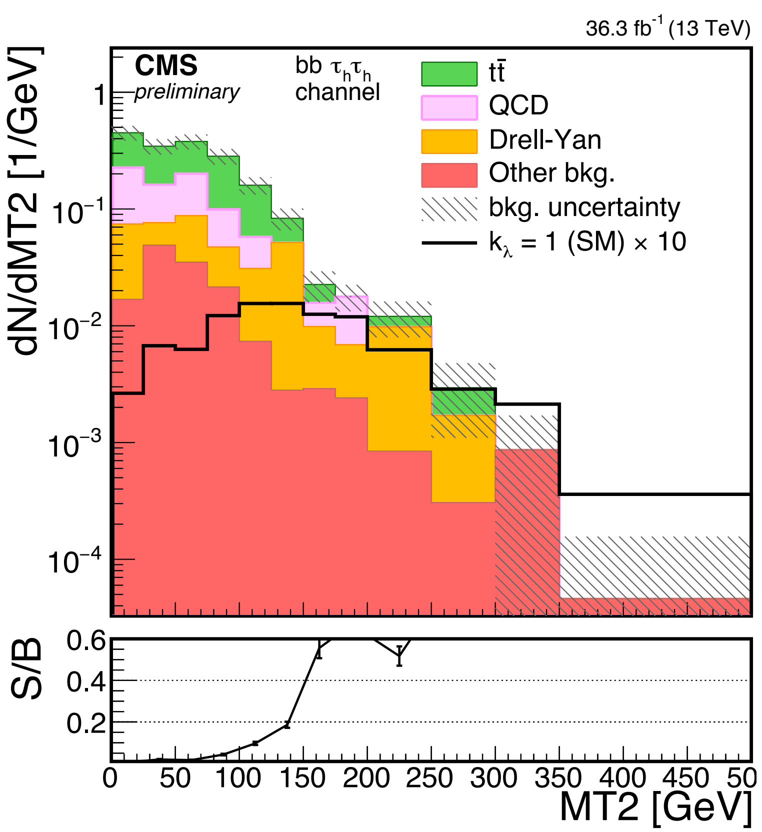
Signal	Exp. limit for gg→hh→bb$\tau\tau$ (fb)		
	HH mass	MT2	MT2+MVA iso
k_λ = 1 (SM)	436 (180xtheo)	279 (115 x theo)	204 (84 x theo)
k_λ = 20	1313 (6xtheo)	1097 (5 x theo)	709 (3 x theo)

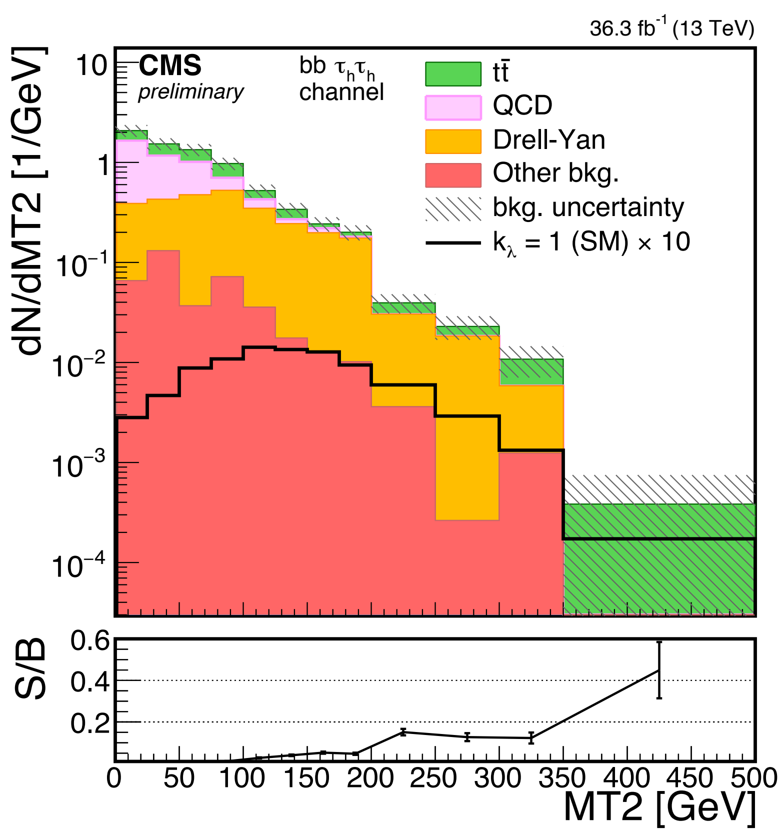
hh→bbττ: BDT and categorization

Resonant BDT goal: improve tt rejection while keeping performance stable against mass

- extension of the BDT training method used in the non-resonant analysis
- variables: angles (common to non-resonant BDT)+mT(1)+mT(2)
- Only for semi-leptonic channels







Current non resonant categorization: 2 b-tag loose. 68% of the DY bkg is $\tau h \tau h$ + 2 light jets

New: 2 b tag categories with 2b+1b1j

Good sig/bkg separation at high MT2 values

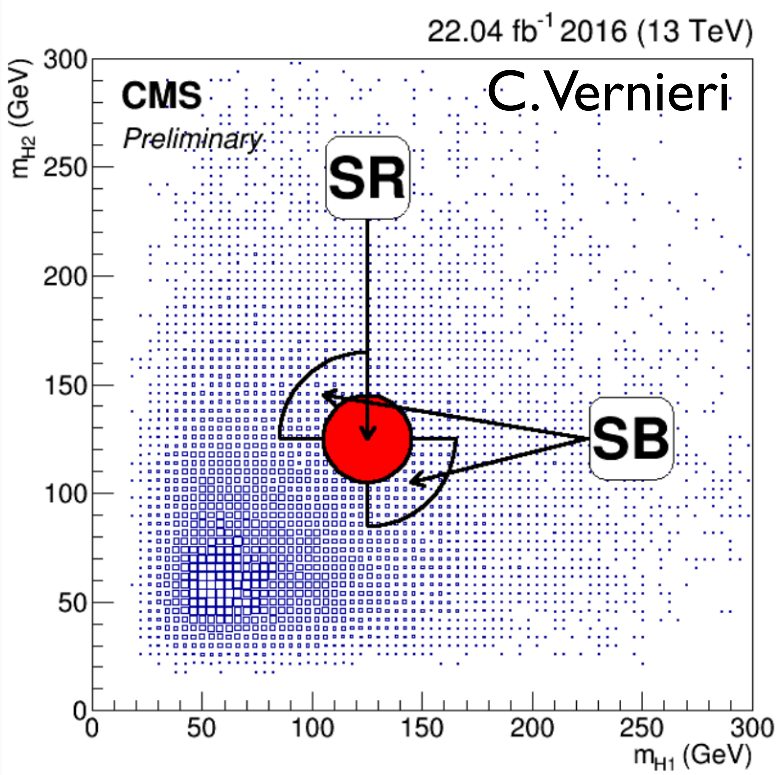
hh→bbbb

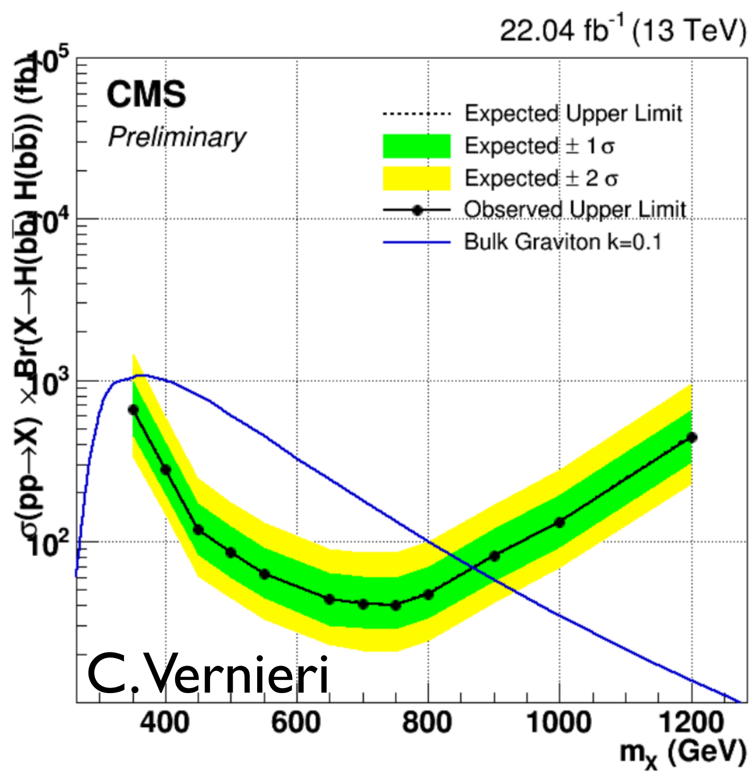
- Most sensitive channel (both for CMS and ATLAS)
- Different strategies for resonant/non-resonant (Bicocca)
- 3 b-tag online at trigger level, ≥4 b-tag offline
- ATLAS over performing CMS (for now)

Resonant analysis:

Low Mass (m_H<400) and High Mass (400<m_H<1200) studied separately

Background shape estimation from data





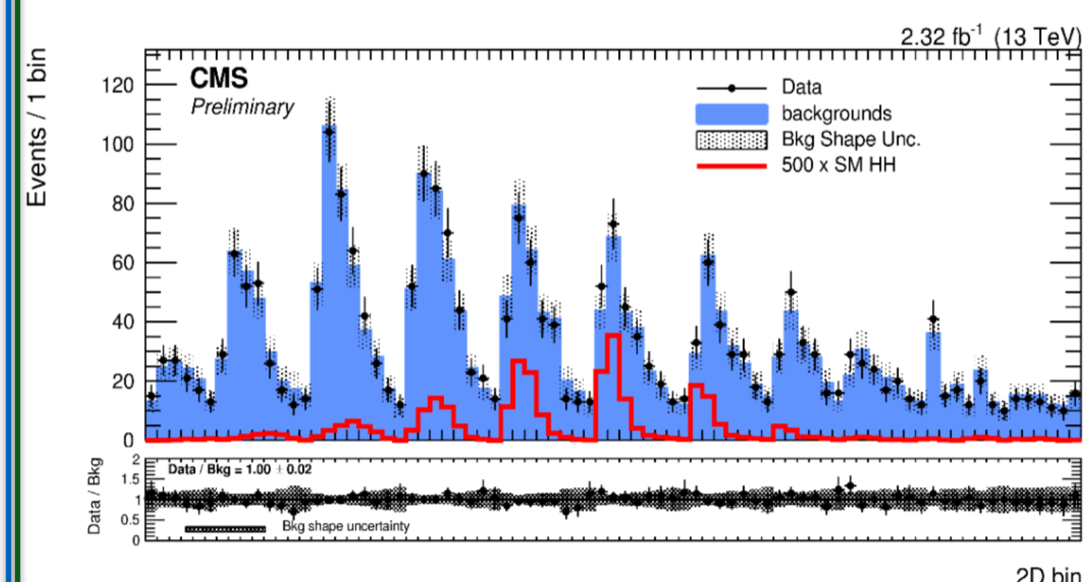
Non-Resonant analysis:

Background estimation from hemisphere mixing + BDT cut

2D fit on dijet masses

Final limit: 342xSM (308 exp)

ATLAS: 109xSM (with 3.2fb^{-1})
29xSM (with 13.3fb^{-1})



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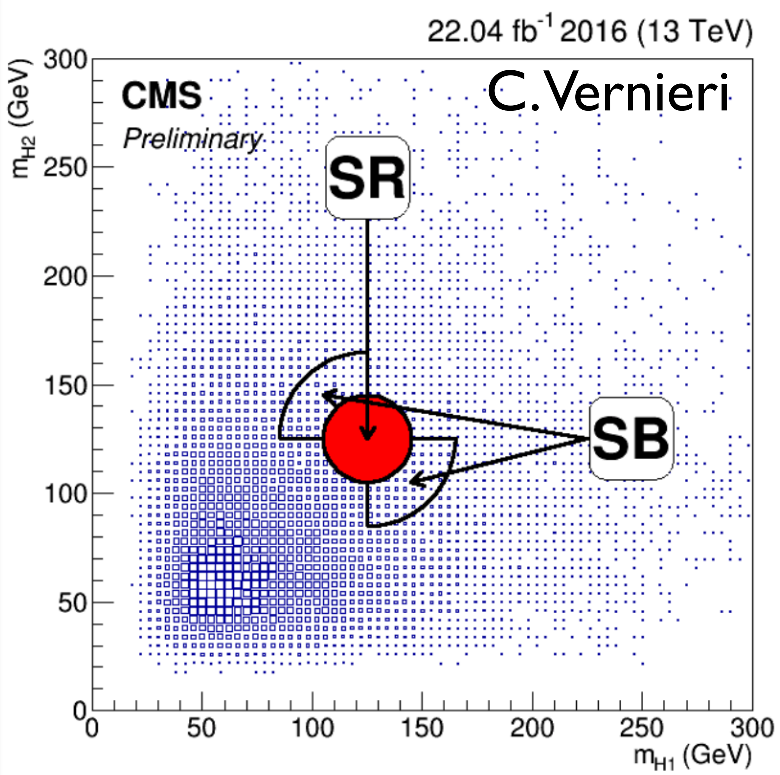

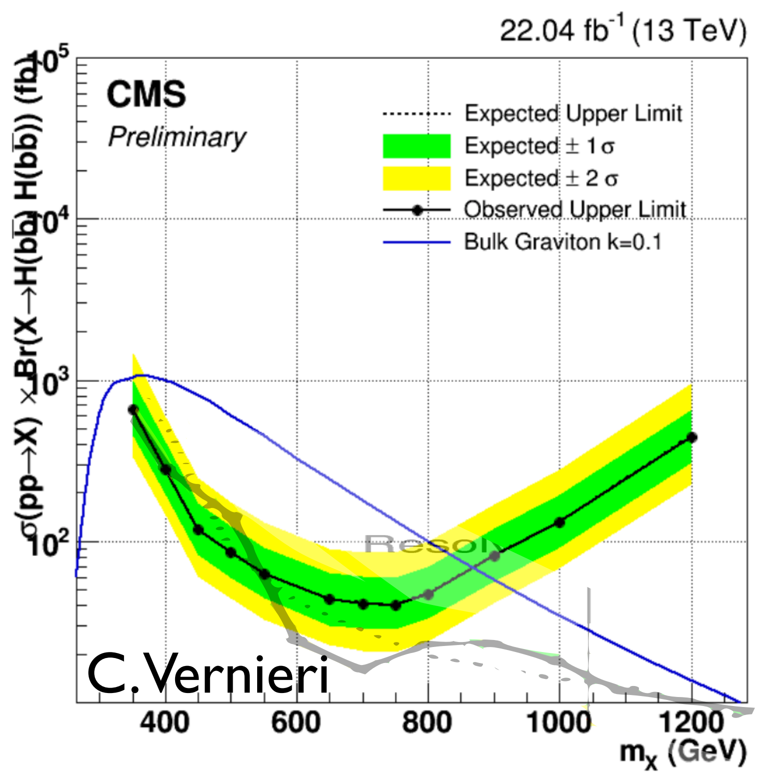

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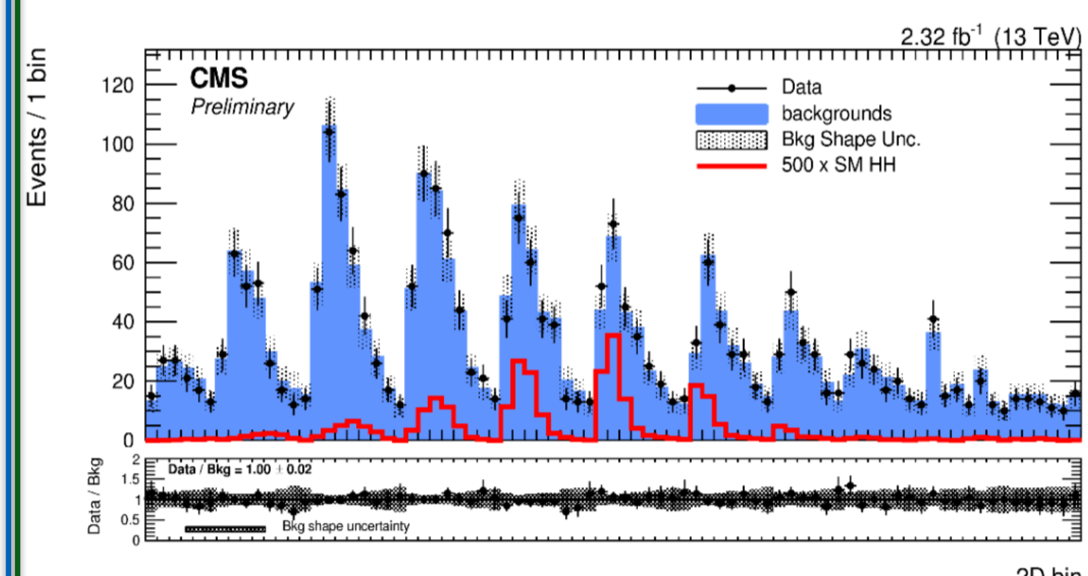


Room for improvements

Upgrades are being developed in the non-resonant analysis:

- BDT tuning and reduced mass $MX = M(4j) – M(jj_{H1}) – M(jj_{H2}) + 250$ GeV
- ATLAS can benefit from 2 b-tag online ev. selection, analysis optimised for several years

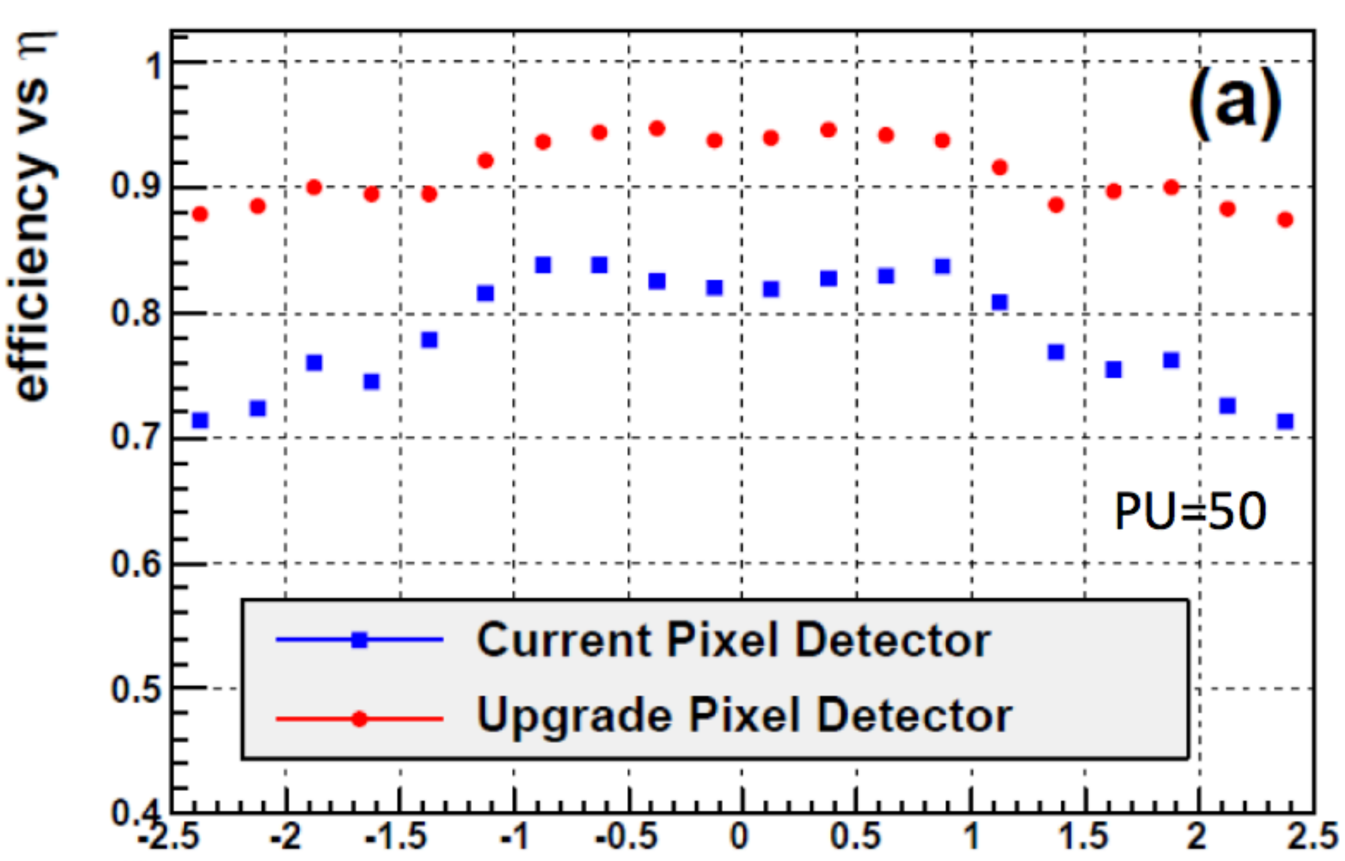
But the most important update to cover the gap will be the pixel upgrade: ATLAS got a factor 2-4 boost from their upgrade. We will get:

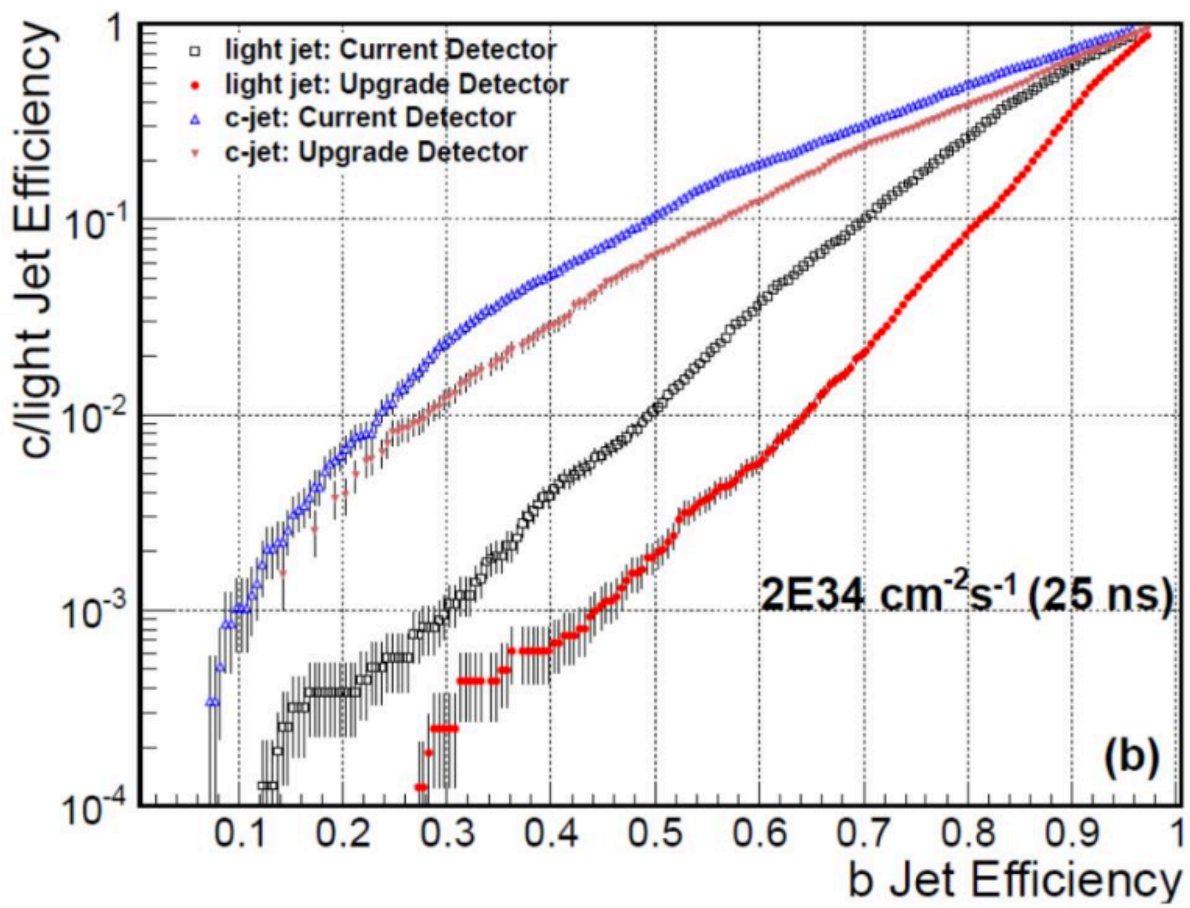
- Higher tracking efficiency
- >10% improvement in b-tagging (for each b-jets)

2017 trigger: general request is HT increase at L1, need to assess the impact on bbbb

After EYETS: How to fully exploit new pixels capabilities? Any contribution is welcome

Summary: we are confident we can cover the gap with ATLAS, but a lot of work to do!

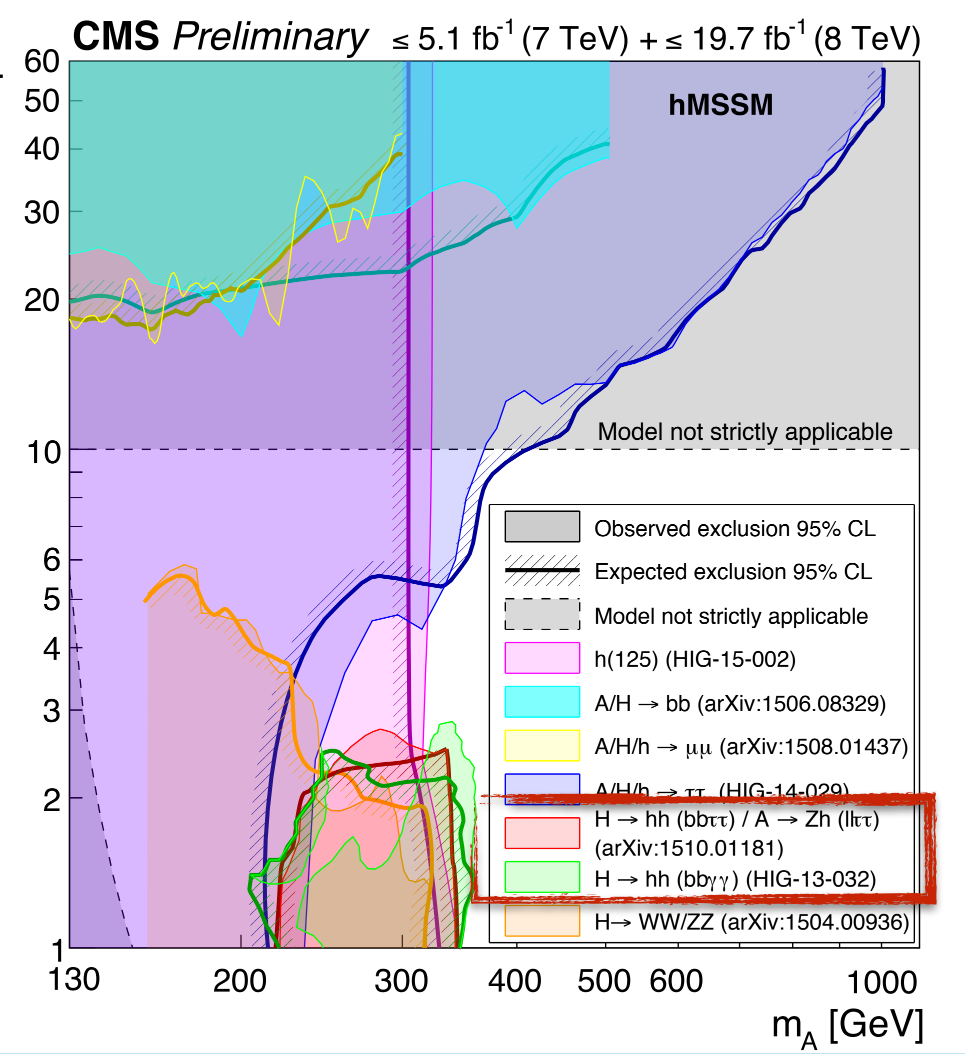


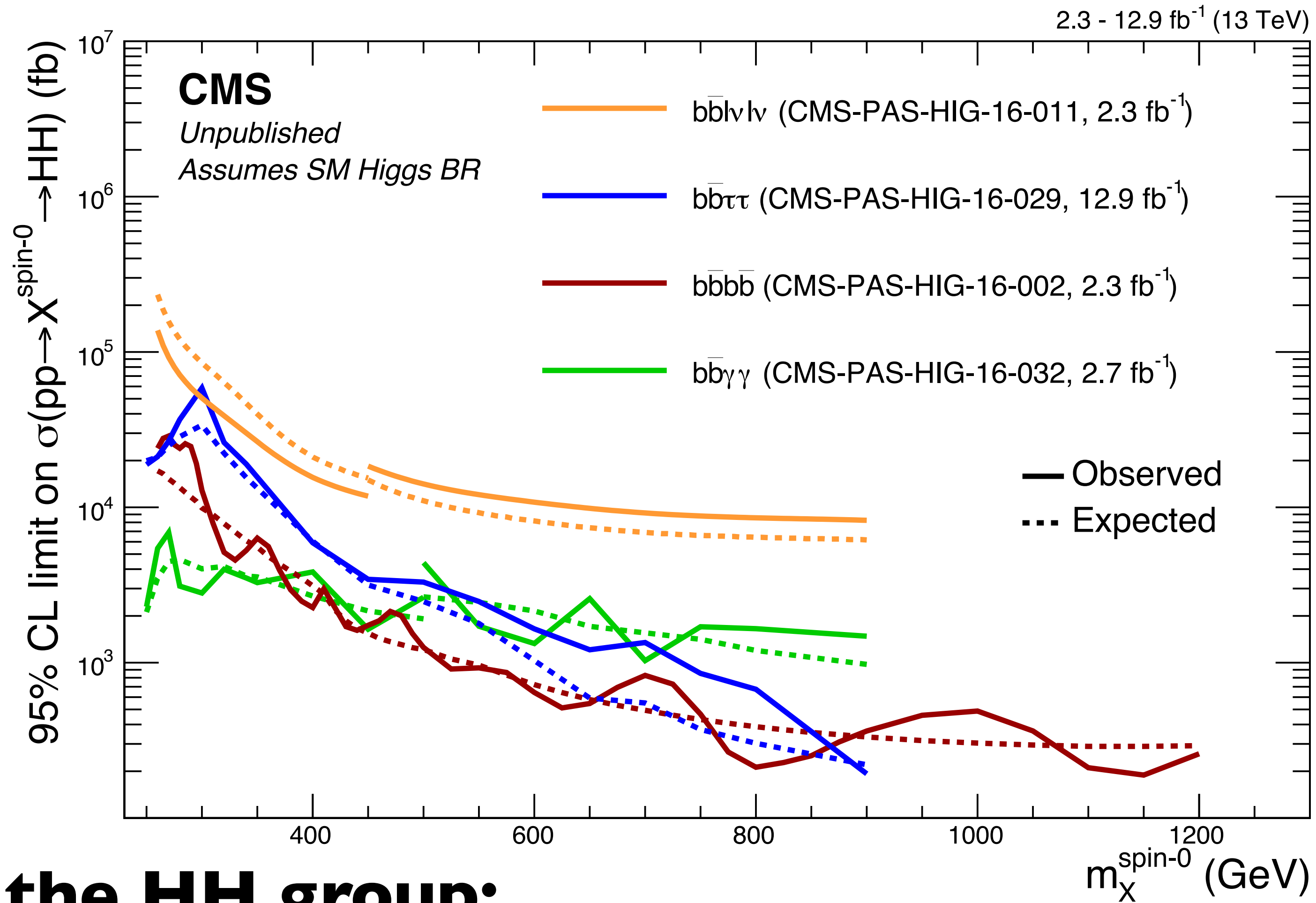


Coming soon: combination

channel		
bbbb	29 (38?)	342(308)
bbWW	-	410(227)
bb$\tau\tau$	-	208(172)
bb$\gamma\gamma$	117(161)	91(90)

lumi analysed @ 13TeV, obs(exp) non-resonant limitXSM





Plan in the HH group:

- All analyses are targeting Moriond 2017 for the update with the full 2016 dataset
- Needs coordination before Moriond (check overlapping signal/backgrounds, coordinate systematics, interpretation)
- Move to (CWR) right after the conference
- Use the time until EPS to prepare the combination of the channels
- After EPS start analyse extensions (VBF, finite width)

Future extrapolations

HH analyses are clearly a topic for HL-LHC

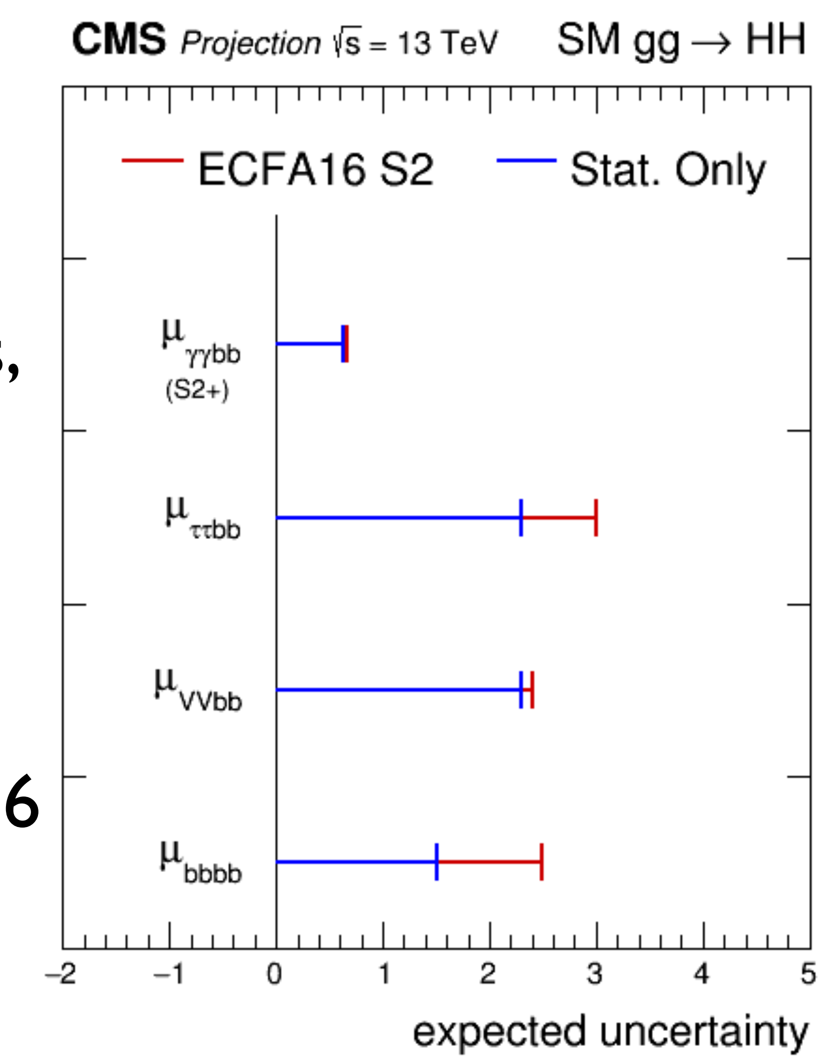
Studies have been prepared for ECFA, and are starting for the TDRs

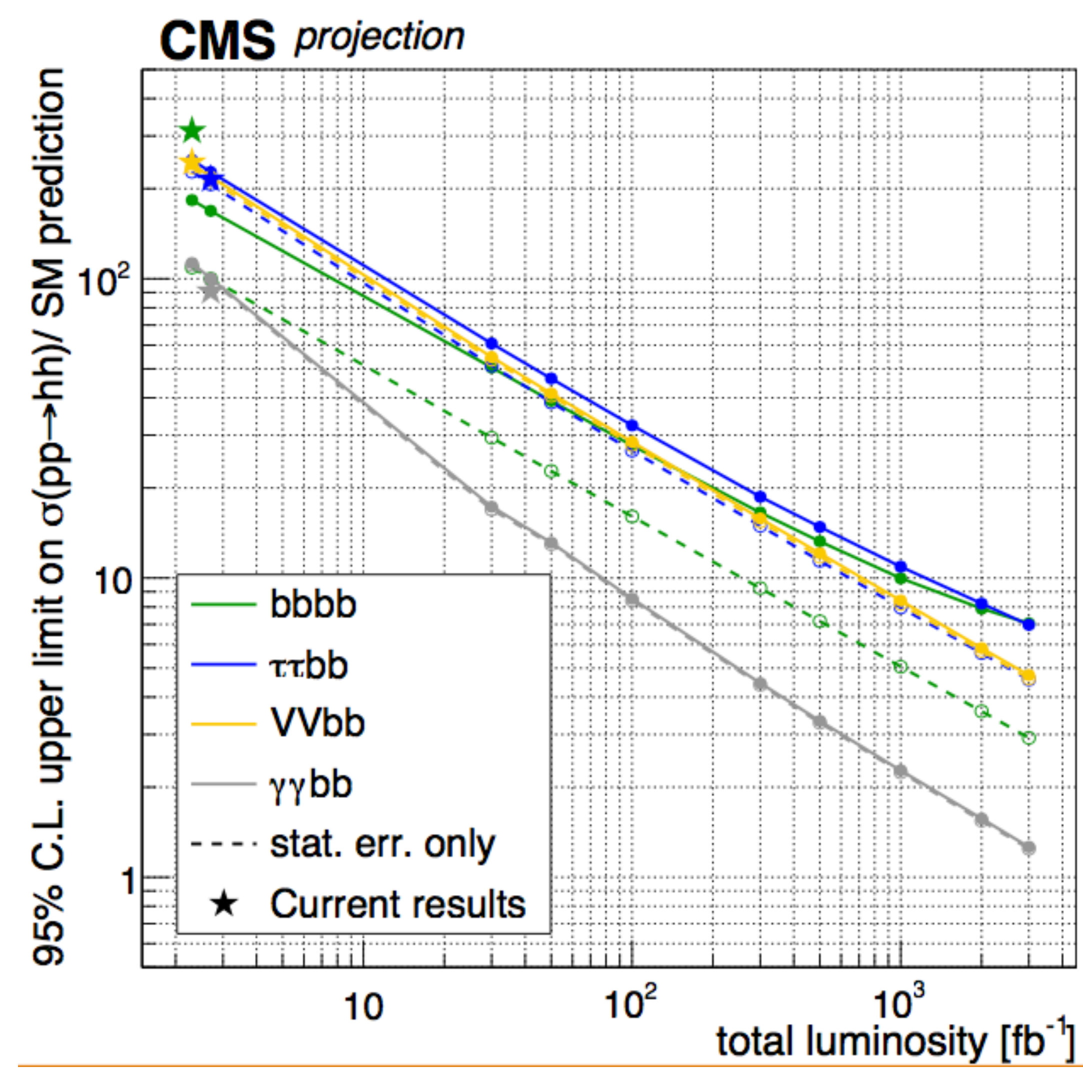
All HH analyses are involved in TDRs, main focus on hh→bbbb

	HH bbbb	HH bb$\gamma\gamma$	HH bb$\tau\tau$	HH bbWW
Tracker TDR	✓			
Muon TDR				
Barrel Cal TDR	✓	✓	✓	✓
Endcap Cal TDR				

ECFA exercise.

Underestimates the possible performances, mostly because larger statistics will improve the background estimation, and does not include all the 2016 improvements.





Open points

People are targeting certain channels mostly because of what PAG/POG they belong to or have expertise with.

- This left out a lot of interesting possibilities
- Interesting channels we are missing: WW$\tau\tau$, bbWW with hadronic final state, maybe WW$\gamma\gamma$

TDRs: we are preparing the MC, studies will start right afterwards

2017 preparation: HLT studies are starting, will need to study new thresholds and b-tag performances

A lot of extensions are planned, but not yet included, mostly due to lack of manpower

- (anomalous) VBF production (up to 15% final cross-section), finite width resonances, single Higgs combination…
- Theoreticians are coming up with suggestions at a faster pace then what we can implement

The HH is mostly **work in progress**. There's plenty of space for proposals! interpretation, channels, improvements, projections, MC…

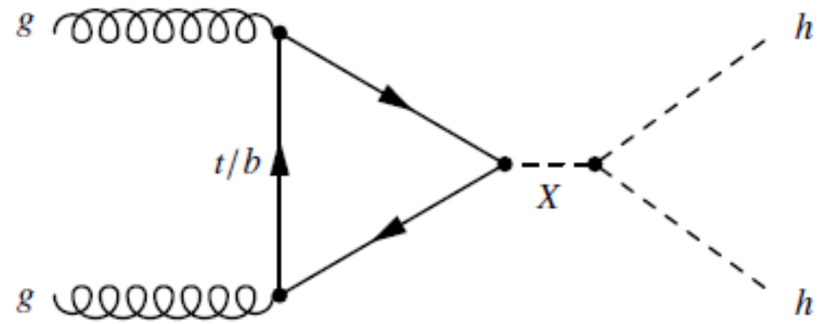
Conclusions

- The channels under study in CMS show a nice complementarity
- We are covering several channels ATLAS does not have.
  - Interest in HH is increasing more and more
  - If you are interested, this is a good moment to join
- Ideally, there are a lot of channels to cover
- The new pixels will have a big impact on HH analyses, especially 4b, and it is important in order to be competitive with ATLAS
- CMS is trying to coordinate the efforts under the Higgs-EXO
- Italy (Pisa, Bari, Milano Bicocca) is mostly active in bbbb and $bb\tau\tau$, but is also covering the combination, the trigger studies…

Still a long road before being able to directly probe the SM

BACKUP

Projections for resonant : bbbb



Typical BSM spin-0 production diagram

Projection of the sensitivity to the resonant HH production at 3 ab^{-1} expected to be collected during the HL-LHC program. The projections are based on 13 TeV analysis performed with data collected in 2015. The 95% CL expected limits are provided for different spin-0 resonances masses assuming: preliminary analysis from 2015; Scenario 2 - reduced systematic uncertainties taking advantage of a larger data sample and upgraded detector; no systematic uncertainties. For each resonant mass the value of the mass scale $\Lambda_R = \sqrt{6}\exp[-kl]\overline{M}_{Pl}$ excluded at 95% CL is also provided.

m_X(TeV)	Median expected limits on σ (fb)			$\sigma_R(\Lambda_R = 1\,\text{TeV})$ (fb)	Λ_R (TeV) excluded
	2.3 fb^{-1}	ECFA16 S2+	Stat. Only		
0.3	2990	46	41	7130	13
0.7	129.4	7.3	3.4	584	8.9
1.0	81.5	4.4	2.4	190	6.6

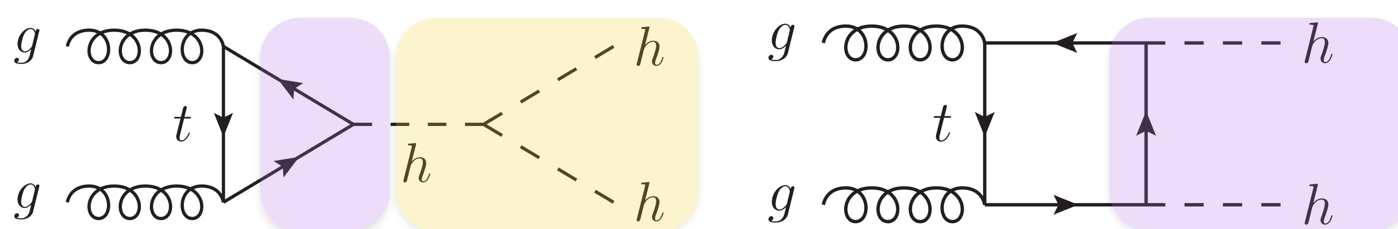
- **CMS-PAS-HIG-16-002**: gg → X → HH → bbbb

gg→hh parametrization

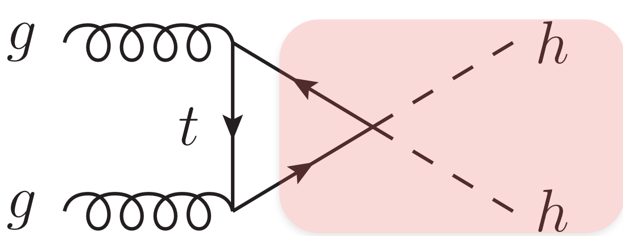
The relevant lagrangian terms of gg→HH production in D=6 EFT

$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1-\frac{3}{2}c_H + c_6\right)h^3 + \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a$$
$$- \left[\frac{m_t}{v}\left(1-\frac{c_H}{2}+c_t\right)\bar{t}_L t_R h + \text{h.c.}\right] - \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}-\frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \text{h.c.}\right]$$

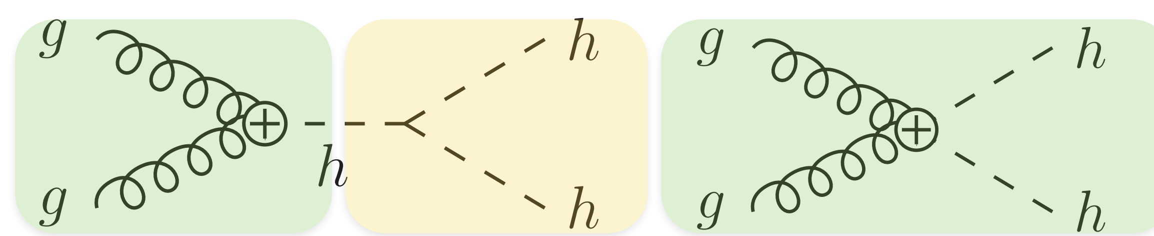
arXiv:1410.3471



SM diagrams



ttHH non-linear interaction



Higgs-gluon contact interactions

An EFT implementation for hh

The double Higgs production cross section can be written as a function of the 5 EFT parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g

$$R_{hh} \equiv \frac{\sigma_{hh}}{\sigma_{hh}^{SM}} \stackrel{LO}{=} A_1\kappa_t^4 + A_2 c_2^2 + (A_3\kappa_t^2 + A_4 c_g^2)\kappa_\lambda^2 + A_5 c_{2g}^2 + (A_6 c_2 + A_7\kappa_t\kappa_\lambda)\kappa_t^2$$
$$+(A_8\kappa_t\kappa_\lambda + A_9 c_g\kappa_\lambda)c_2 + A_{10}c_2c_{2g} + (A_{11}c_g\kappa_\lambda + A_{12}c_{2g})\kappa_t^2$$
$$+(A_{13}\kappa_\lambda c_g + A_{14}c_{2g})\kappa_t\kappa_\lambda + A_{15}c_g c_{2g}\kappa_\lambda\,.$$

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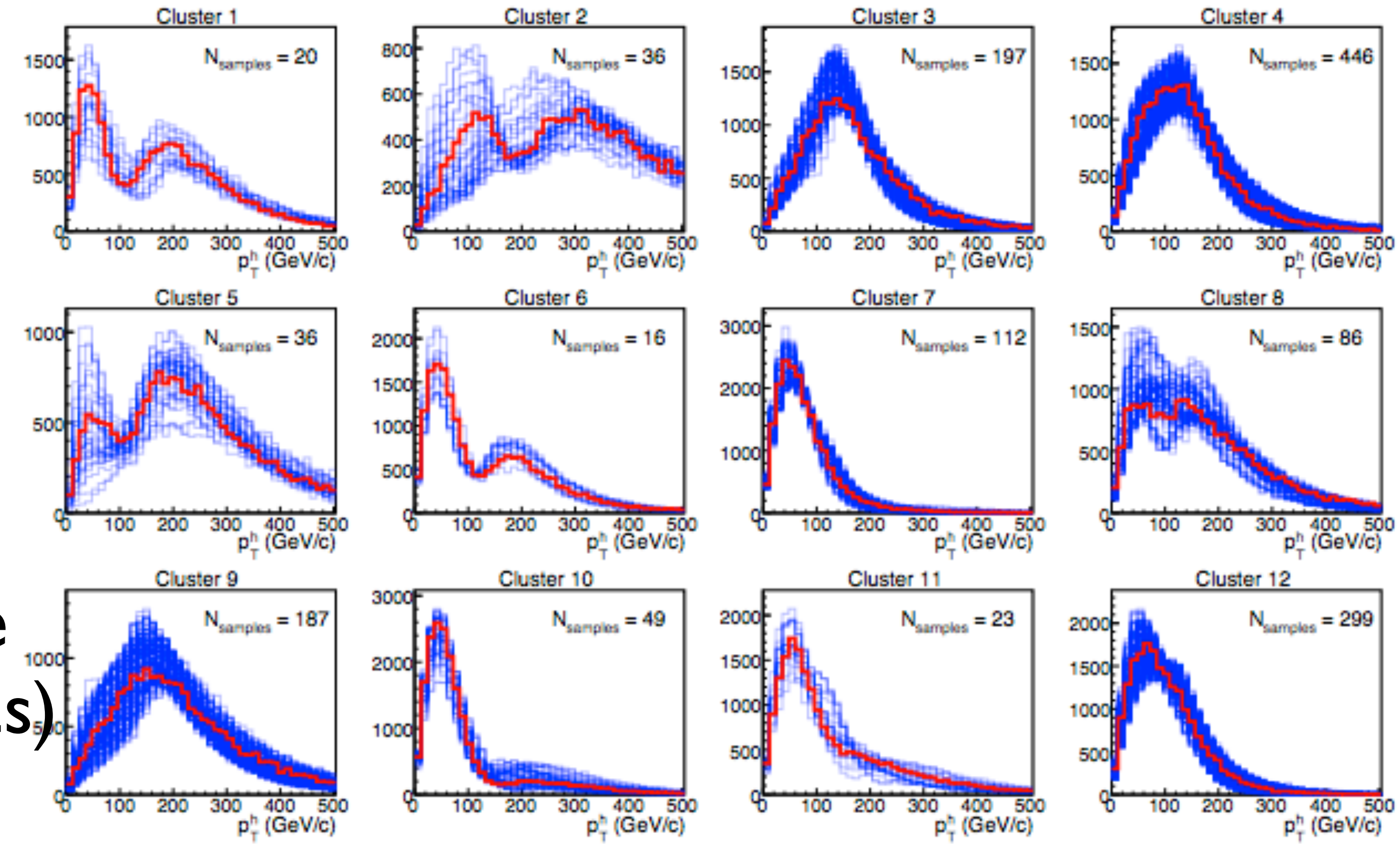
2D (M_{HH},cosϑ^*) signal shapes from different points in the 5D EFT phase space are clustered together.

12 clusters are identified according to there kinematical properties

Inside each cluster, a representative shape is identified, as the one with the minimum distance (in the test statistics) from all other shapes in the cluster



Each point of the phase space can be mapped by means of its cross-section and representative shape