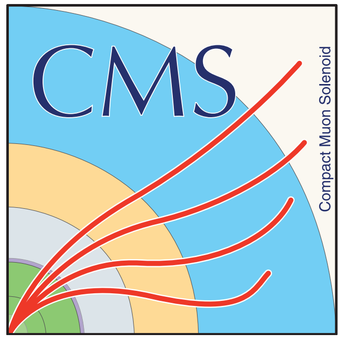
Combination of HH searches with the CMS experiment



UF | UNIVERSITY of FLORIDA

Fermilab

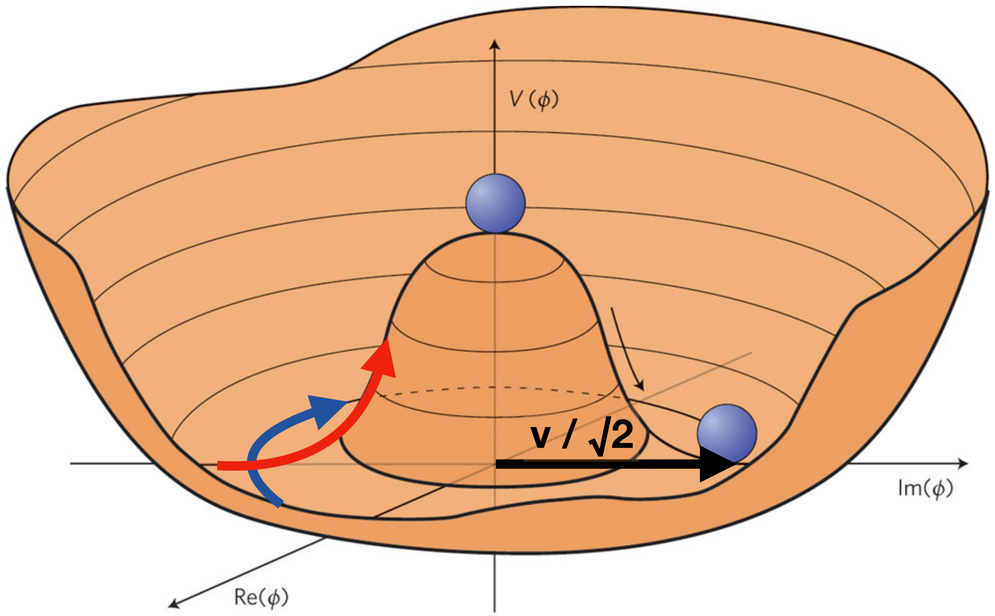
Luca Cadamuro

on behalf of the CMS Collaboration

Double Higgs Production at Colliders workshop

Fermilab, September 4th, 2018

HH and the Higgs boson trilinear coupling



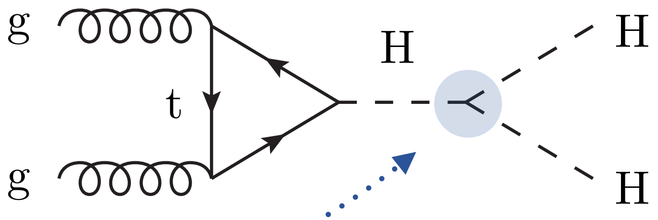
Higgs boson pair production — **A milestone in the exploration of the scalar sector**

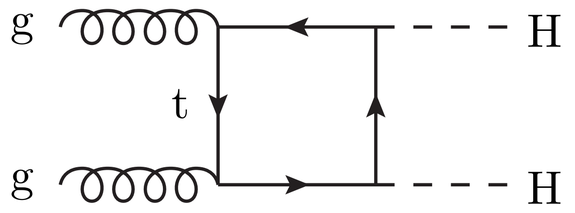
- Experimentally difficult because of the **tiny cross section** ⟹ improve the sensitivity by **combining several decay channels**

$$\sigma_{\mathrm{HH}}^{\mathrm{SM}} = 33.49^{+7.3\%}_{-8.4\%}\ \mathrm{fb}\,(\mathrm{scale} \oplus \mathrm{PDF} \oplus \alpha_{\mathrm{S}} \oplus m_{\mathrm{t}})$$

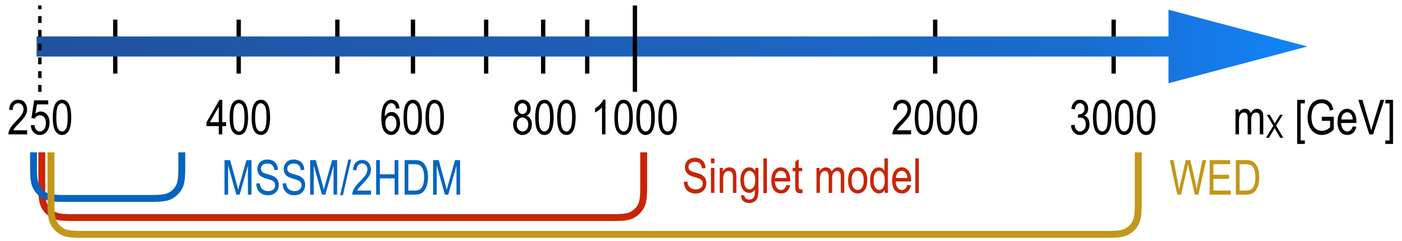
$$V(\Phi^\dagger\Phi) = -\mu^2\Phi^\dagger\Phi + \boldsymbol{\lambda}(\Phi^\dagger\Phi)^2$$

Direct determination of the shape of the scalar potential λ





HH beyond the SM

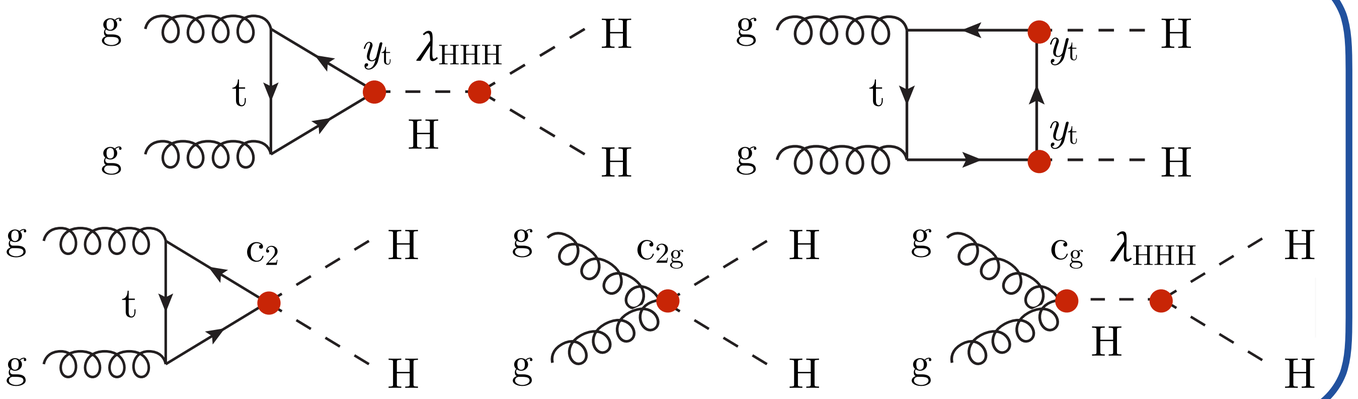


Resonant production

- Broad class of models predicting new scalars that can decay to HH
- Broad mass range to explore

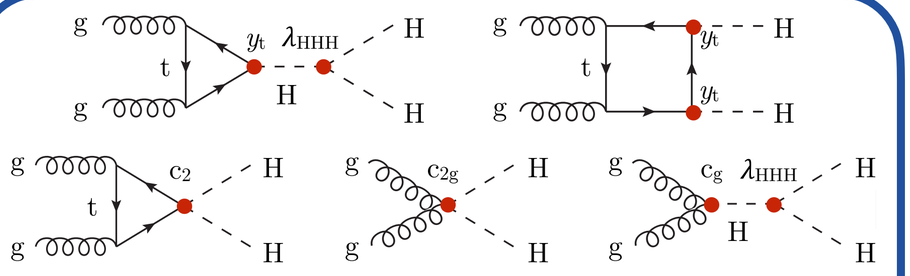
Nonresonant production

- Extension of SM Lagrangian with dim-6 operators introduces 5 anomalous couplings
- Changes in HH total and differential xs



HH is the ideal place to look for new physics
Combination of decay channels ensures optimal coverage of BSM topologies

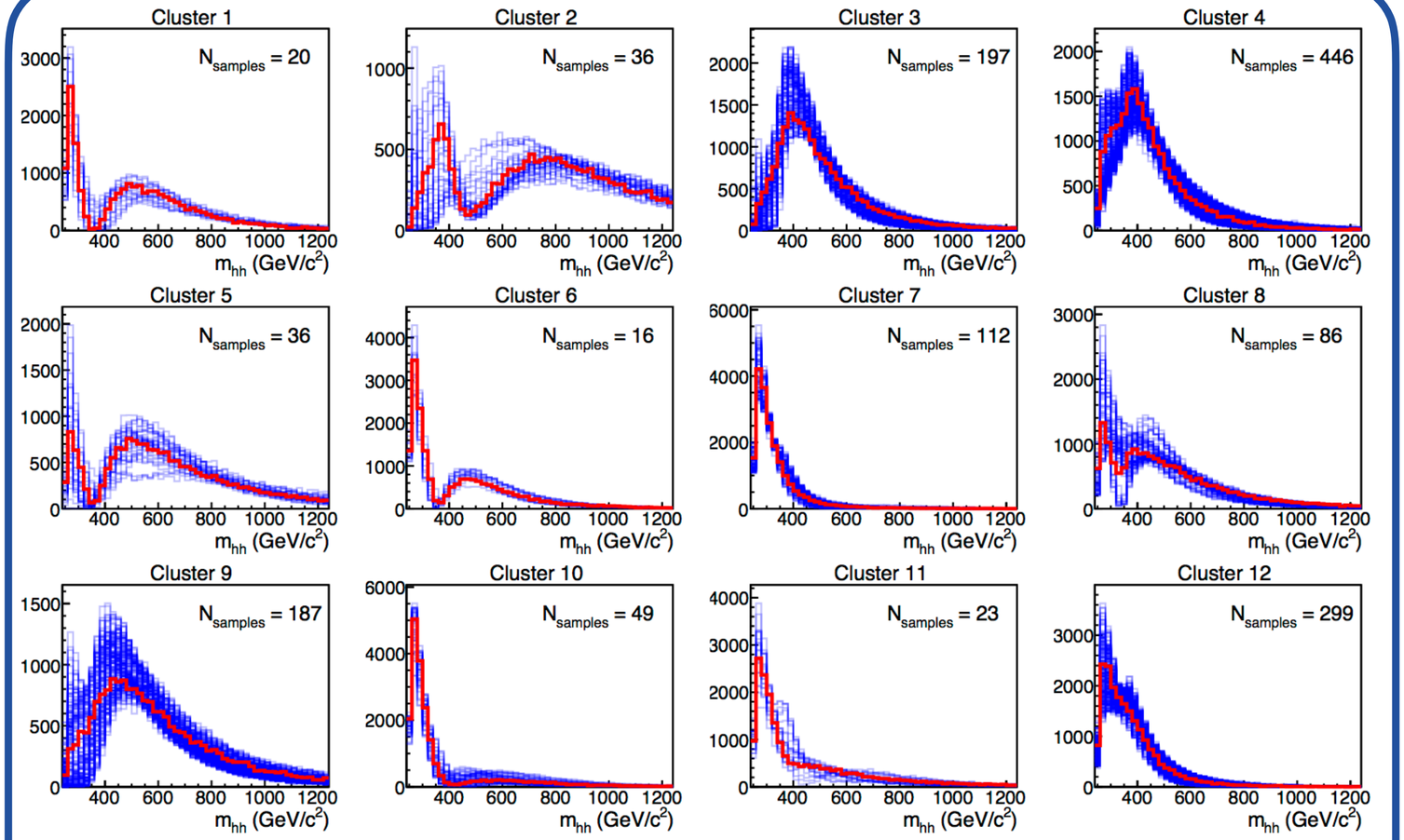
Benchmark signal shapes



5-dimensional parameter space

in a linear EFT $c_g = c_{2g}$

- Coupling space sampled to identify 12 groups of “similar” shapes
- One **shape benchmark** signal per group representing a **typical EFT signal**
  - ⟹ arbitrary coupling choice
  - does not indicate a special theory point
- A point in EFT can be mapped with its shape and cross-section

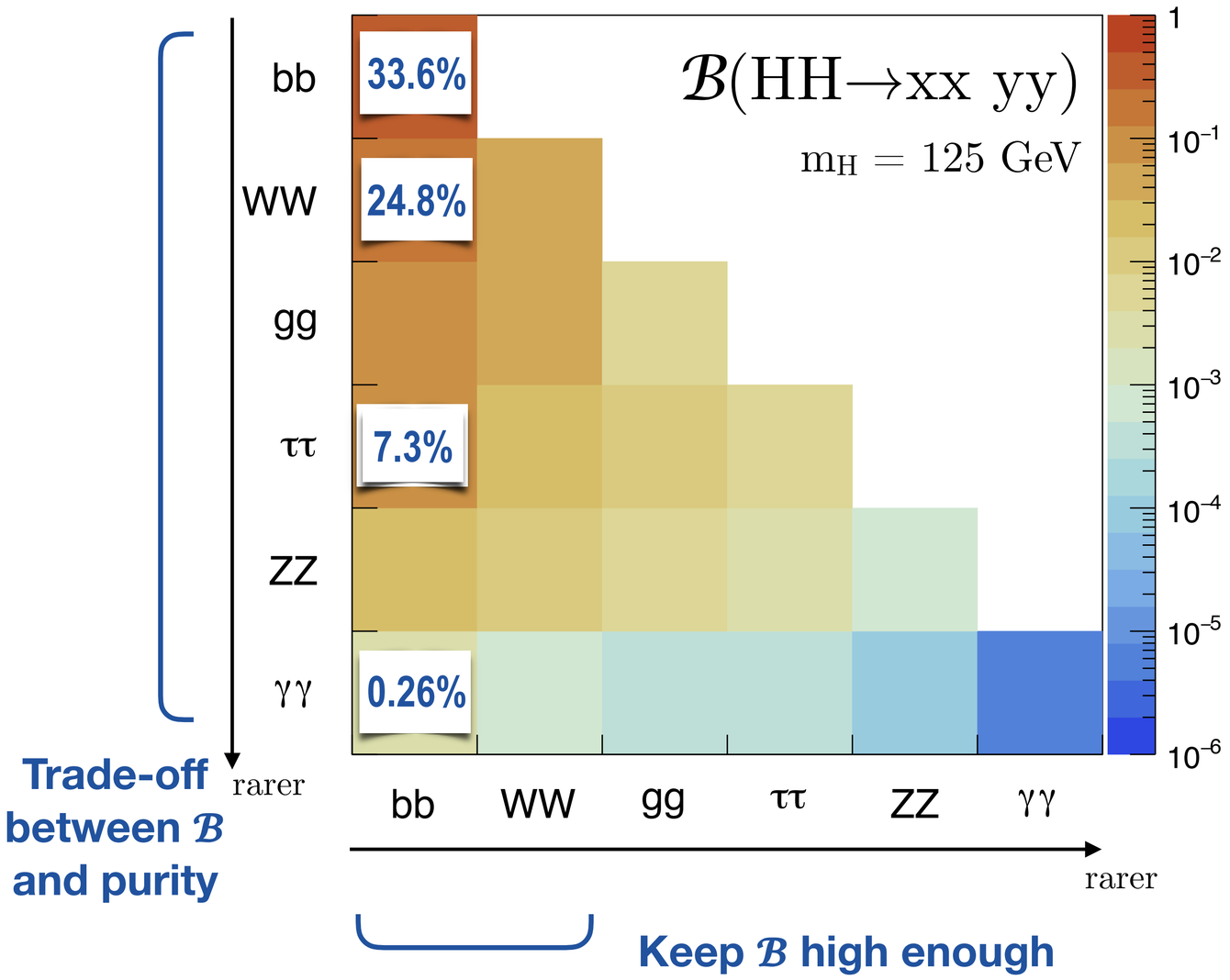


sampled signals

shape benchmark point

more details in Alexandra’s talk

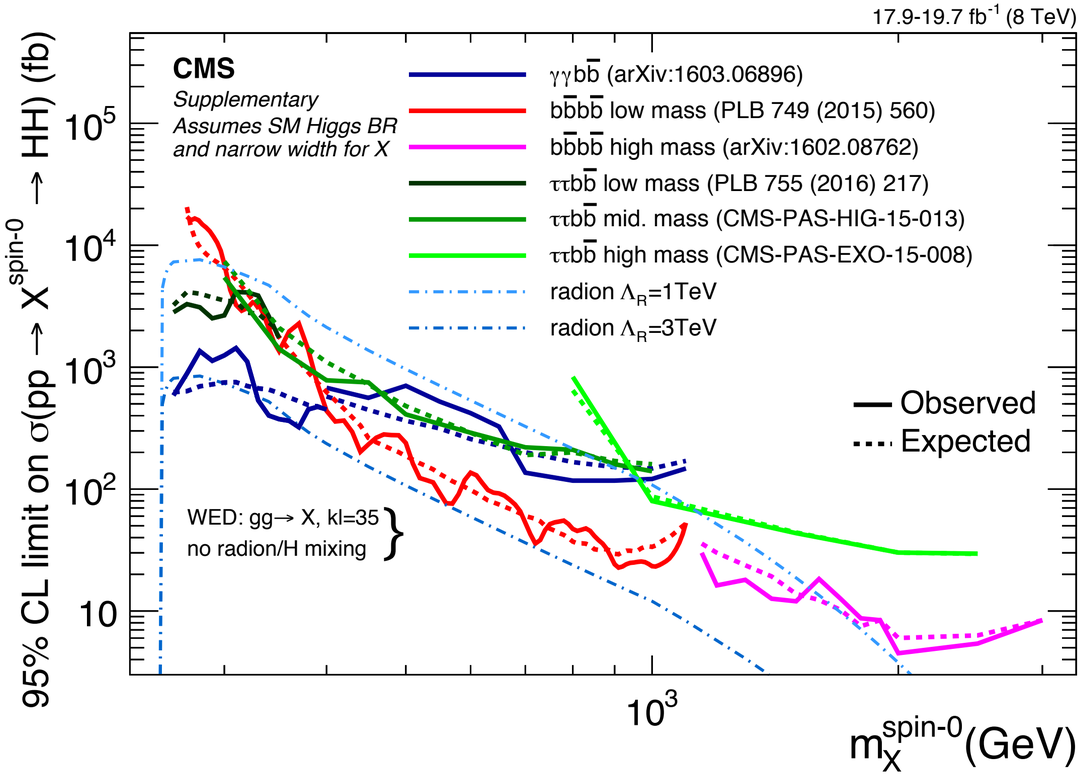
Exploring HH production

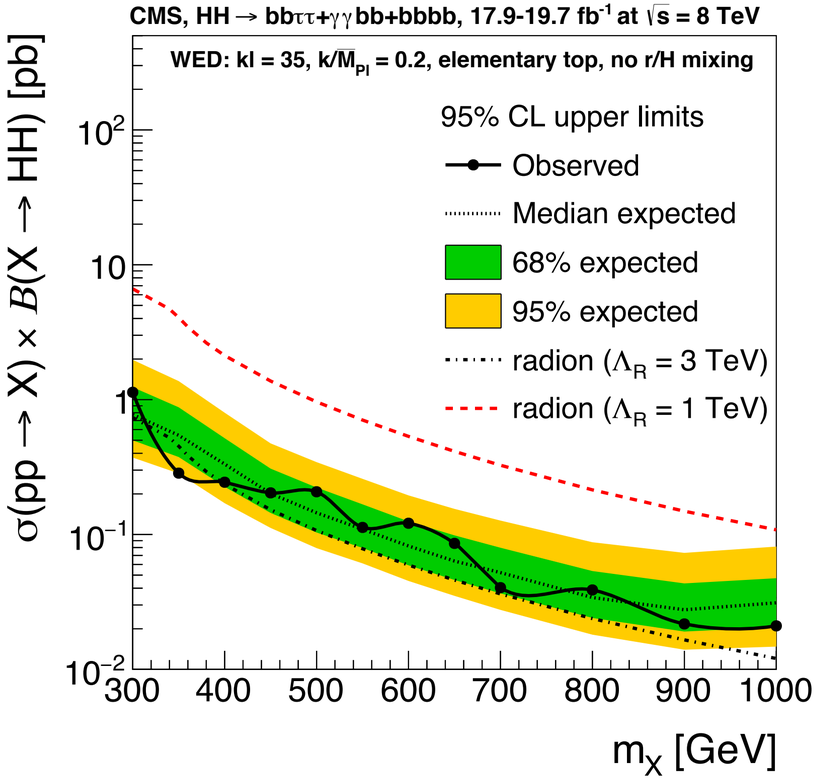


- Run II: an opportunity for HH because of the increase in the cross section
- Rich phenomenology with many final states accessible at the LHC
- Four final states explored by CMS at 13 TeV in a variety of topologies
  - similar sensitivity to SM production
  - complementary sensitivity to different BSM models

PRD 96 (2017) 072004

Run I CMS combination





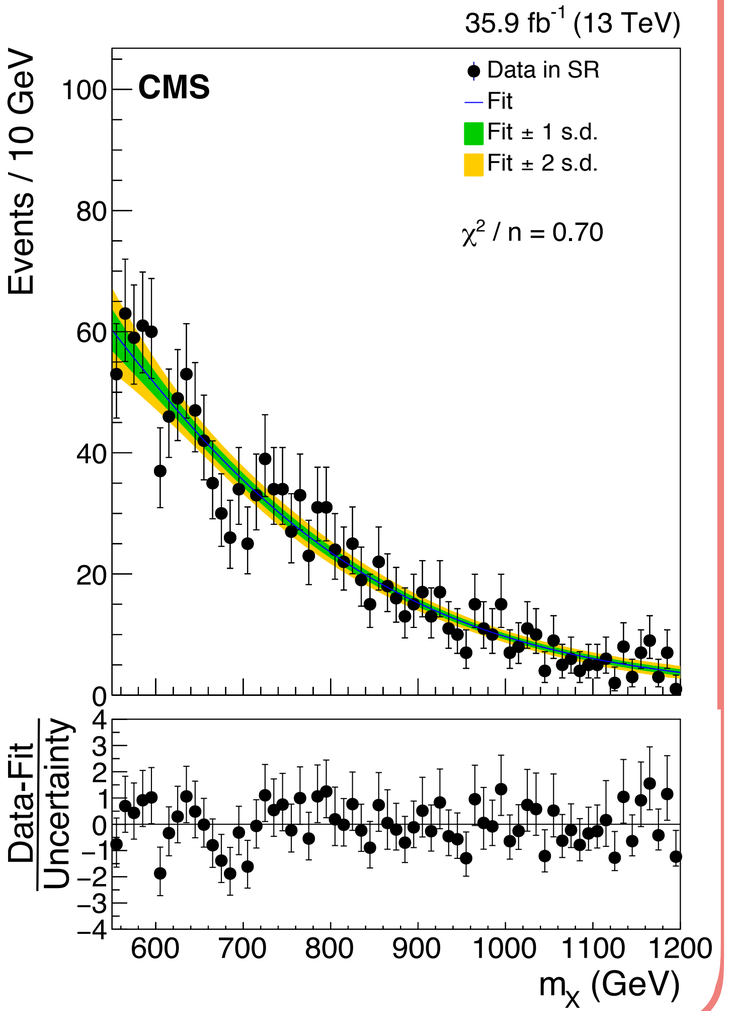
- bbbb + bb$\tau\tau$ + bb$\gamma\gamma$
- Resonant and nonresonant production studied
  - complementarity of final states to cover the 250 GeV - 1 TeV mass range
  - improvement in SM limit from combination

Channel	95% CL limit on σ / σ_{SM}	
	Observed	Expected
bb$\gamma\gamma$	74	62
bb$\tau\tau$	59	94
Combined	43	47

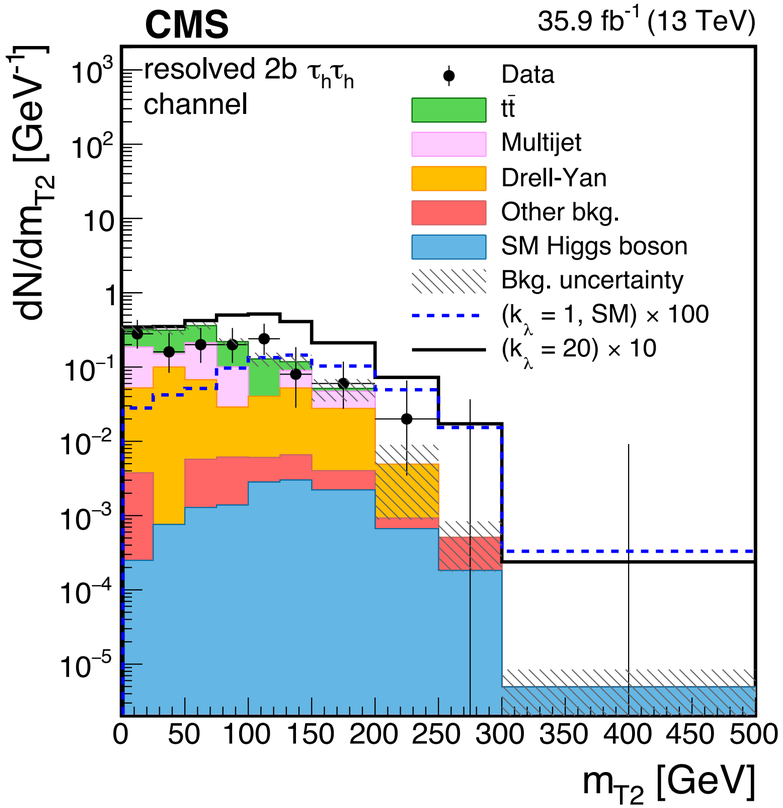
Run II analyses - 1/2

bbbb — talk by Andres

- 4 analyses covering resonant and nonresonant production in resolved, semiboosted and boosted topologies
- Different trigger, background estimation, and signal extraction techniques, phase space overlap



bb$\tau\tau$ — talk by L. C.

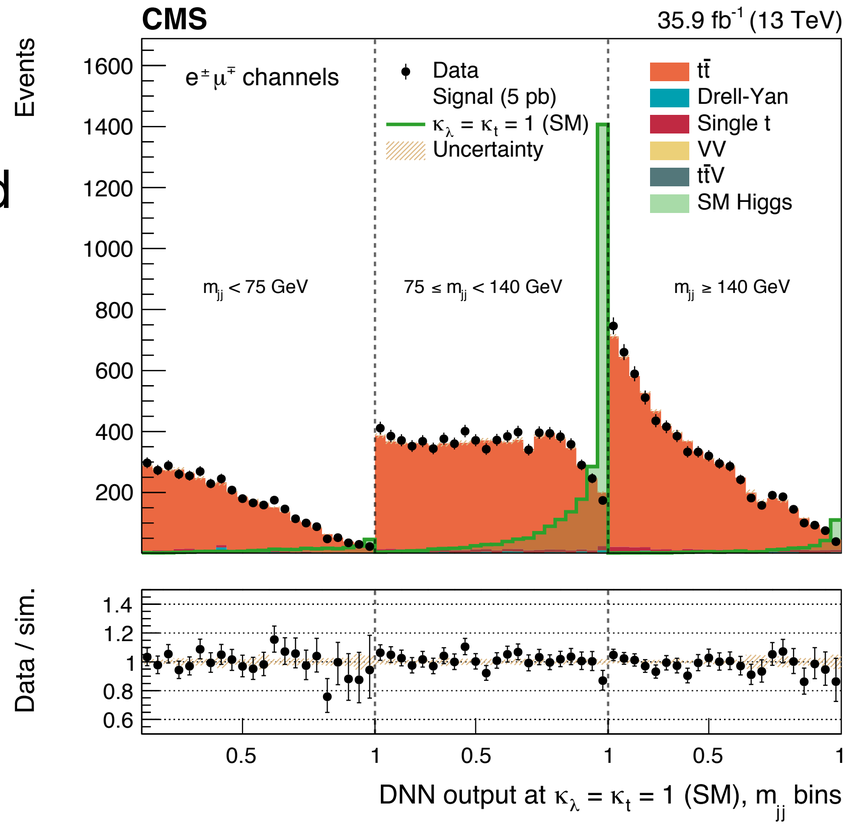


- 2 analyses covering resolved (resonant and nonresonant) and boosted τ topologies
- Analysis strategies tailored to final state topology

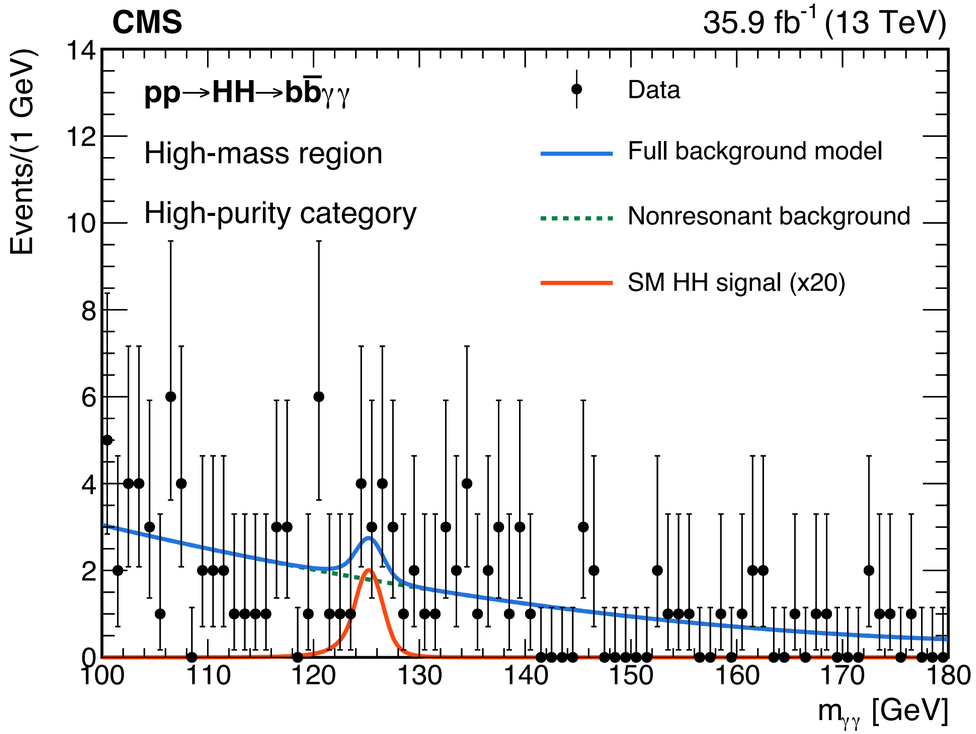
Run II analyses - 2/2

bbWW — talk by Tao

- Single analysis for resonant and nonresonant production
- Based on MVA methods for signal extraction



bbγγ — talk by Maxime



- Single analysis for resonant and nonresonant production
- Signal extraction on $m_{bb}/m_{\gamma\gamma}$

Exclusive phase spaces

Tight photon selections reject all events from the other analyses → X → bb$\gamma\gamma$

Only analysis to use 2 leptons, no overlap with others.
$\tau\tau \rightarrow 2\ell + \nu$s events are considered but not used in the bb$\tau\tau$ analysis → X → bbWW

bbbb events suppressed by small τ mistag probabilty.
No overlap with bbWW because of extra lepton veto. → X → bb$\tau\tau$

A few bb$\tau\tau$ events pass the bbbb preselections, but are rejected by the MVA discriminants and requiring 4 b-tagged jets.
No overlap with bbWW because of extra lepton veto. → X → bbbb

Absence of phase space overlap is checked with data event lists selected by the analyses

Making sure that analyses are orthogonal is an important step for a combined result

An example: the HH → bbbb case

2 large area b jets

Resonant fully merged

1 large area + 2 standard b jets

Resonant semi merged

Analyses developed with the same techniques and same analysis team
Simple orthogonalisation by vetoing fully merged events in semi merged analysis

No combination of analyses
Simply switch of analysis at 1 TeV

Cannot switch of analysis for nonresonant signals
Veto events accepted by the resolved search in the (semi) merged analysis

4 standard b jets

Resonant resolved

4 standard b jets

Nonresonant resolved

bbbb orthogonalisation particularly challenging because of several analyses involved
Harmonising the methods and analysis strategy will help to make combination easier

Systematic uncertainties

Highest impact uncertainties for the SM HH signal:

τ energy scale →

bbbb high BDT score bins →

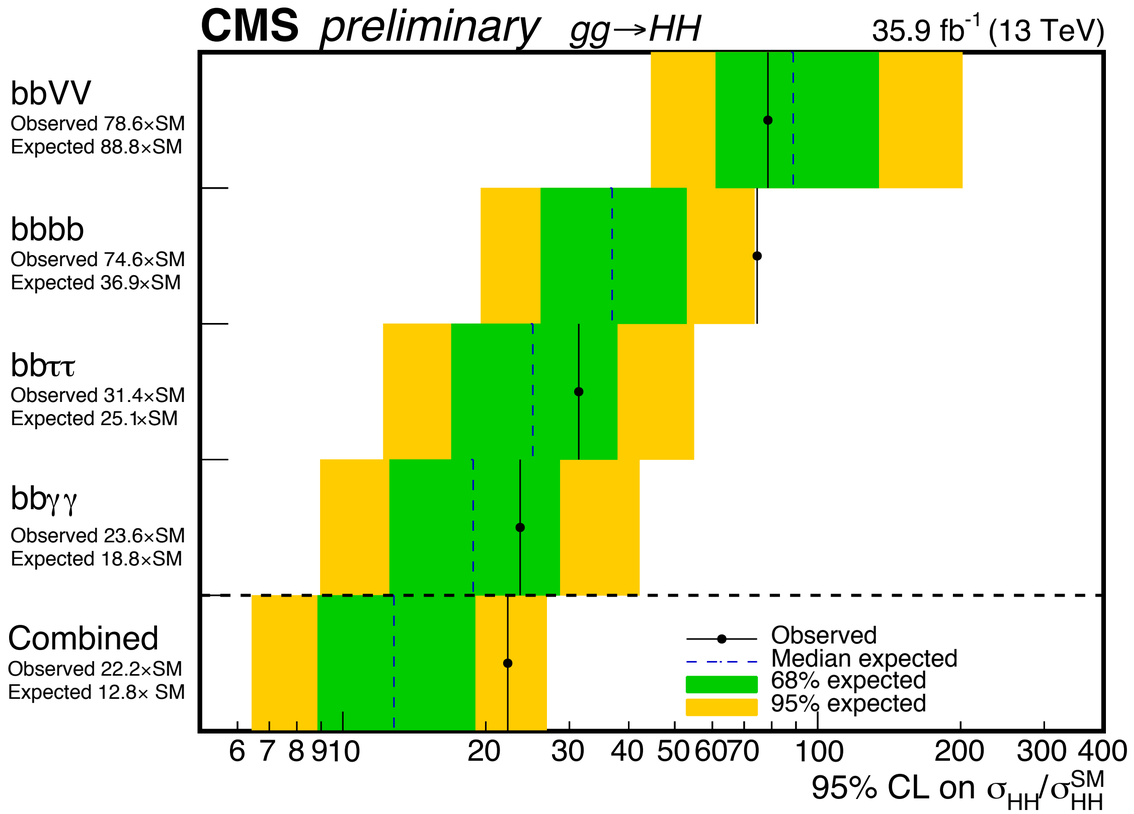
$m_{\gamma\gamma}$ signal shape →

Combined result is statistically dominated: 3.5% effect on the limits from syst. uncertainties

- **Luminosity**: fully correlated for all channels
- **Trigger**: assumed uncorrelated
- **Object reconstruction, efficiency and scale**: correlated across the same objects
  - b tag uncertainties play a special role: split in heavy and light flavour sources
  - jet uncertainties split in 27 uncorrelated sources to avoid artificial constraints
- **Bin-by-bin templated shapes**: uncorrelated
- **Analysis specific** (lineshapes, control regions, …) : uncorrelated
- **Background modelling** (QCD, DY): assumed uncorrelated because of different methods used
- **Theory** (bkg): correlated for the same processes across channels
- **Theory** (HH): correlated for all channels

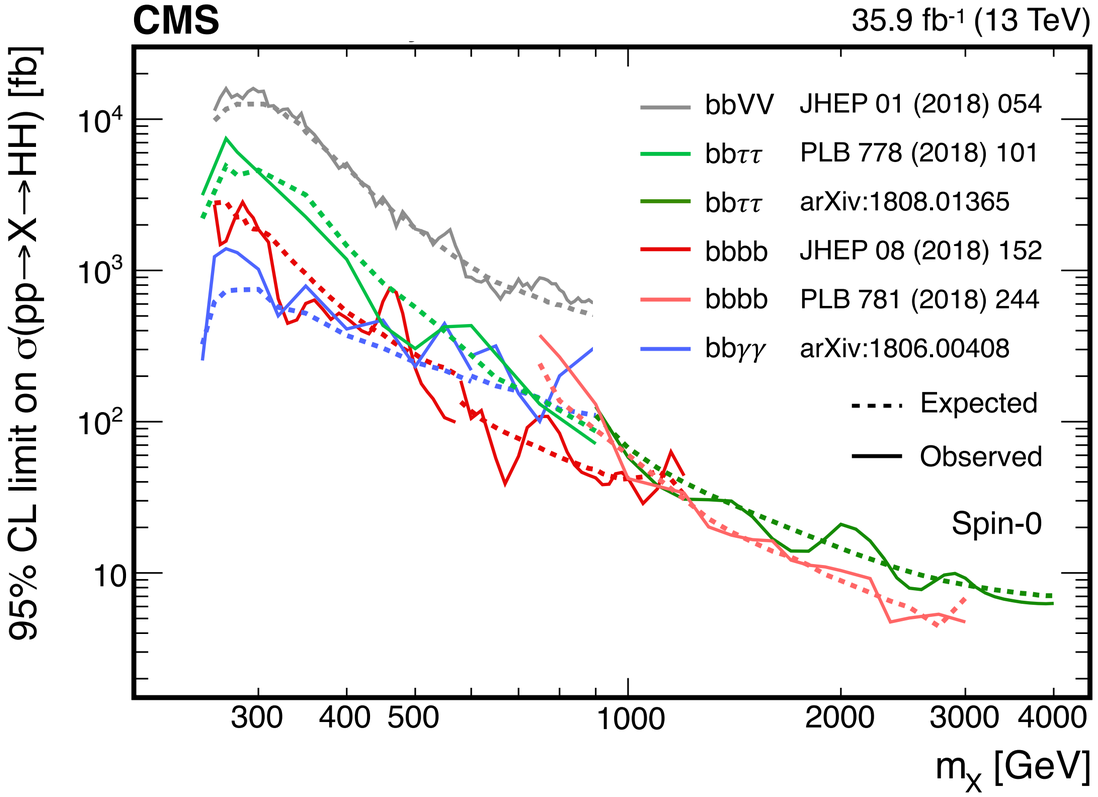
Results : SM signal

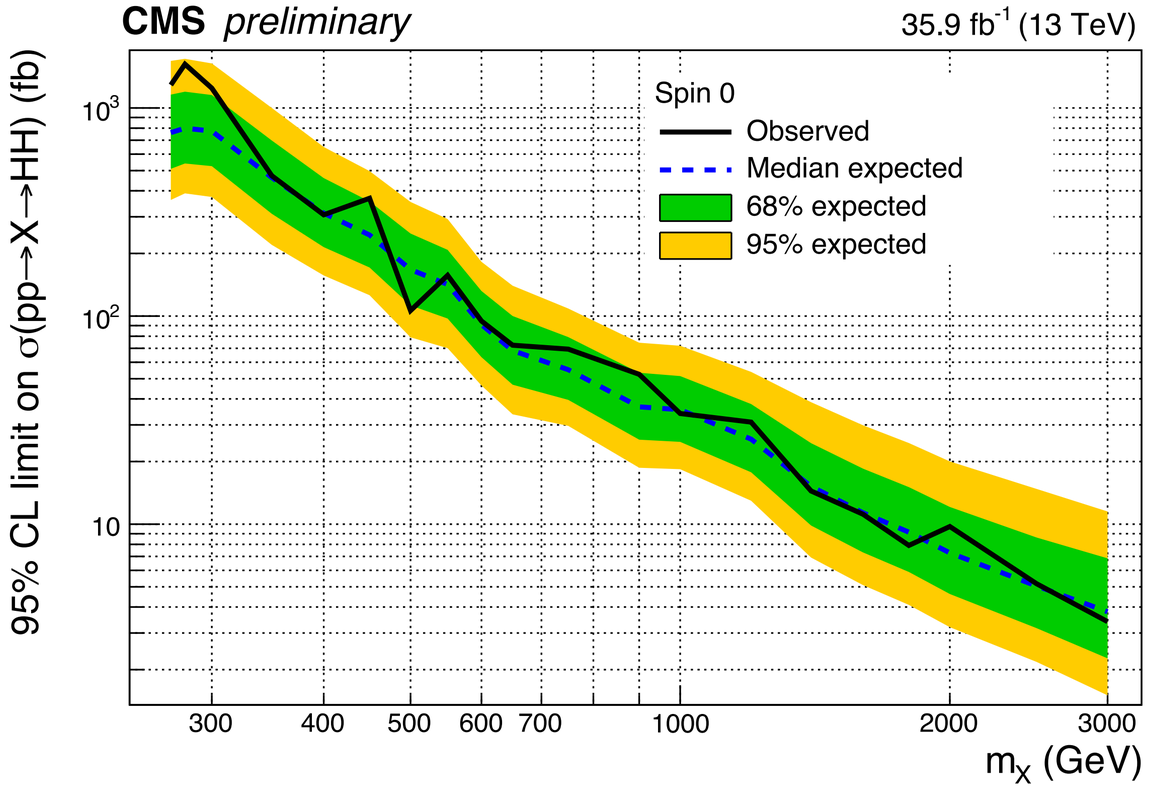
- **Most sensitive result to date** on SM HH production
- Sensitivity improved by a factor of ~4 over Run I combined result
- A hierarchy in the sensitivity can be observed…
  - bb$\gamma\gamma$ → bb$\tau\tau$ → bbbb → bbVV
- … but **no "golden channel"**: important contribution from all analyses to the combined result
  - even more evident in the exploration of BSM HH production



Combined limit on σ / σ_{SM}
Observed : 22.2
Expected : 12.8

Results : resonant production



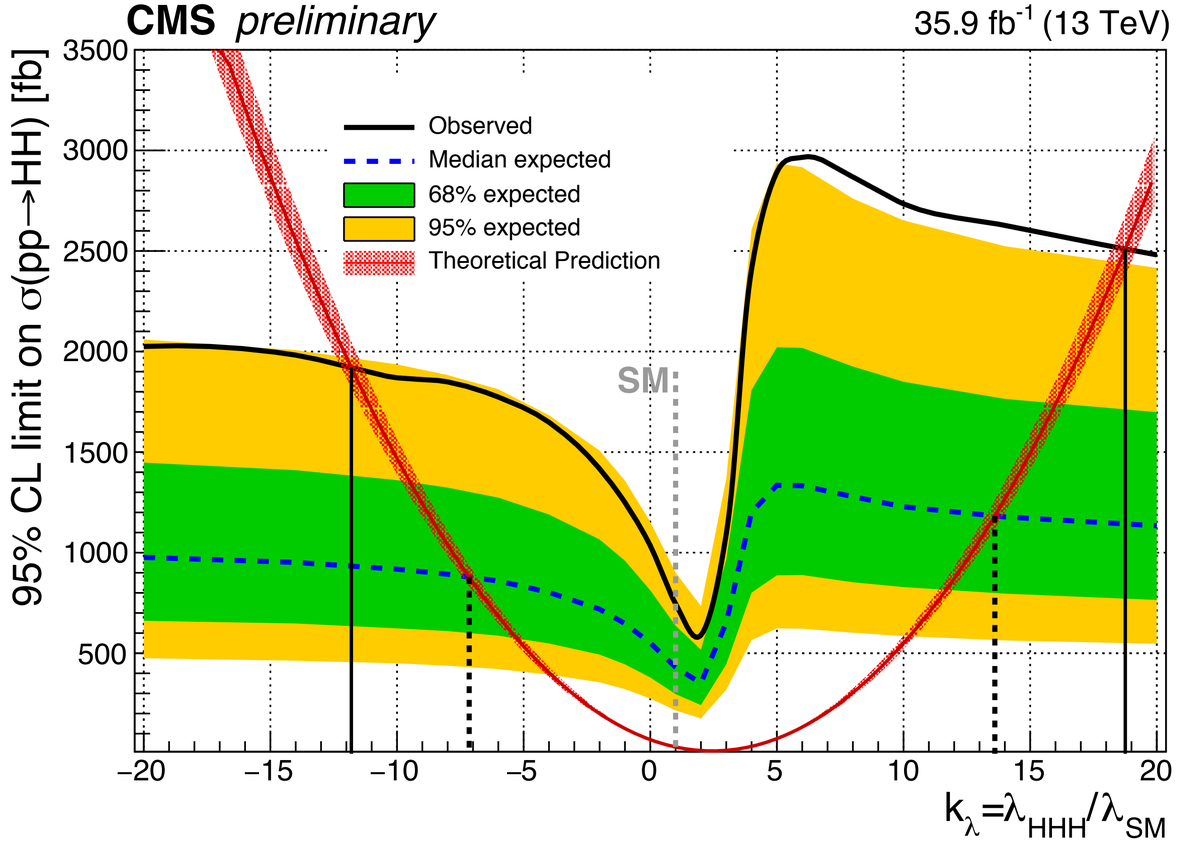


- Limits also set for spin 2 resonances
- Assumes narrow resonance width
- Basic assumption: SM BR for H decays

The combination takes advantage of channel complementarity to improve the sensitivity to resonances from 250 GeV to 3 TeV

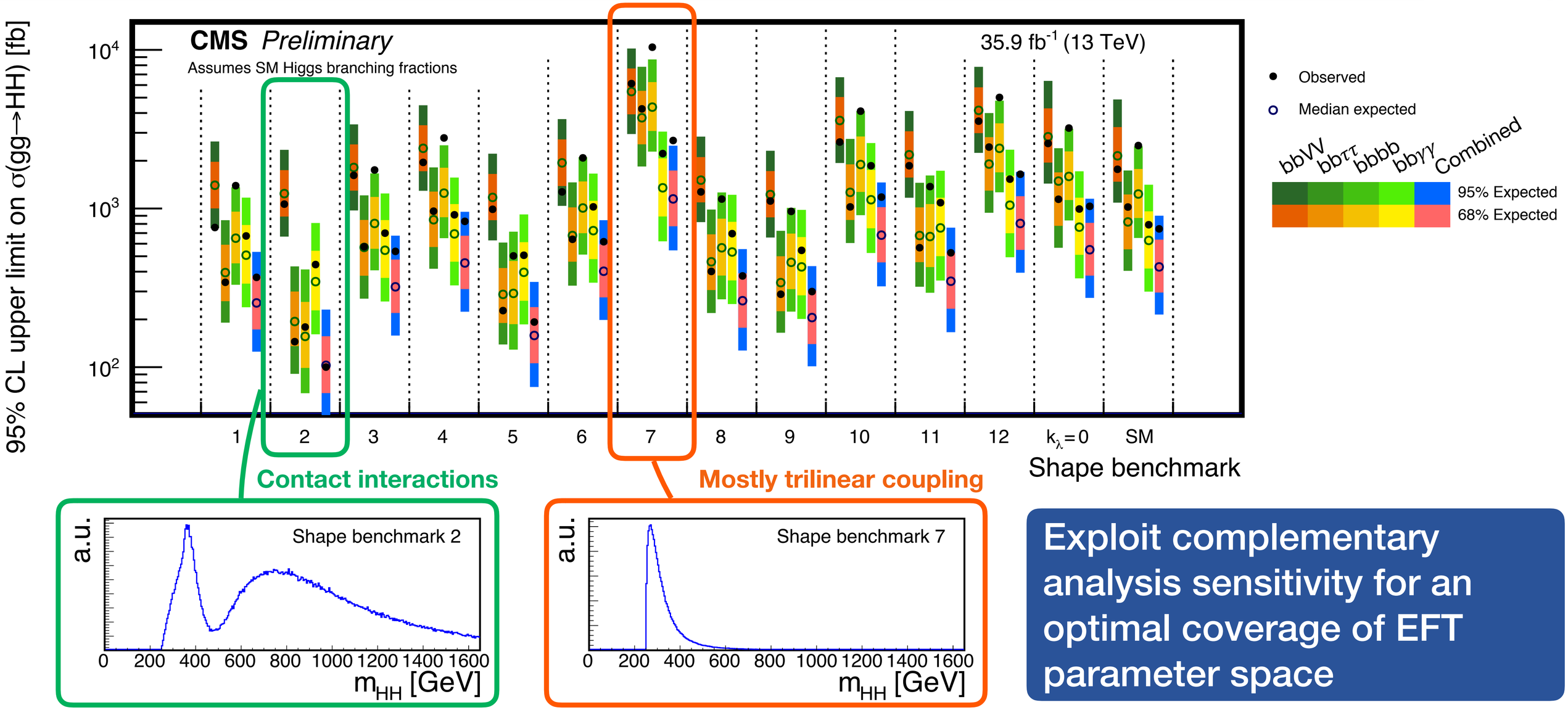
Results : anomalous trilinear coupling

- Shape of the upper limit directly related to the interference between the box and triangle diagrams
  - changes in the m_{HH} spectrum $\Longrightarrow$ changes in the analyses acceptance and background discrimination
  - λ_{HHH} values smaller than SM prediction are easier to probe : we may be sure that the Higgs boson self couples before observing an HH signal!



Constraint on $k_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$
Observed : $-11.8 < k_\lambda < 18.8$
Expected : $-7.1 < k_\lambda < 13.6$

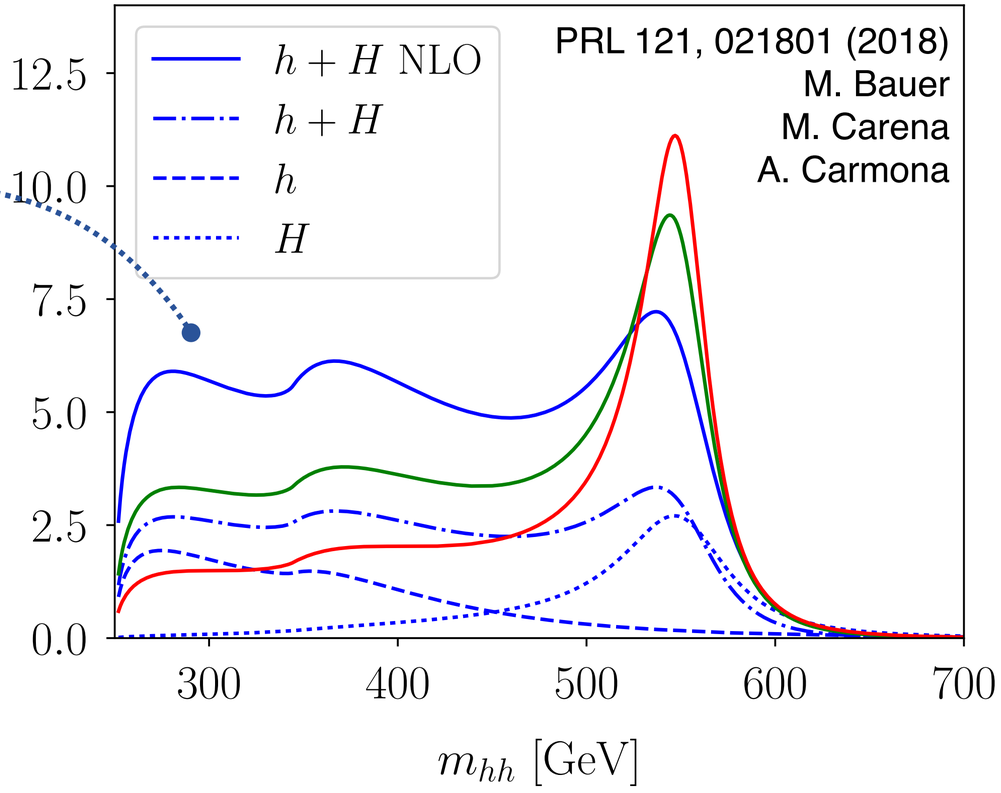
Results : BSM nonresonant production



Exploit complementary analysis sensitivity for an optimal coverage of EFT parameter space

A few personal considerations

- Going beyond the SM signal is crucial to fully explore the physics behind HH production
  - shape benchmarks : useful guidance but not fully general. How to make HH results widely useful for the theory community?
  - would differential upper limits in m_{HH} (from signals in exclusive m_{HH} bins at gen level injected into the analyses) be useful and usable?
- Not trivial to treat the SM Higgs backgrounds in the exploration of EFT anomalous couplings
  - $\Longrightarrow$ suppress single H processes as much as possible
  - $\Longrightarrow$ combination with single Higgs searches
- Analyses statistically limited $\Longrightarrow$ ATLAS and CMS combination to fully exploit the LHC potential
  - many subtle differences in signal modelling, analysis strategy, etc. that we need to start understanding
  - important to be aligned on the set of results



SM + BSM scalar mixing in models with enhanced charm coupling.
Clearly not a resonant signal, but not covered by the shape benchmarks.

Conclusions

- Combination of HH analyses is necessary to improve the CMS sensitivity to HH production
  - similar sensitivity to SM signal from many analyses
  - complementary coverage of BSM parameter space
- Checks of the phase space overlap and proper treatment of systematic uncertainties are a necessary step for a reliable combined result
- The combined limit is to date the most sensitive result to SM HH production
  - combined limits on resonant production
  - combined limits on anomalous trilinear coupling
  - EFT parameter space explored using shape benchmark signals
- The combined results are statistically limited and expected to improve with larger datasets
  - also a good motivation towards and ATLAS and CMS combination
- The trilinear coupling is elusive $\Longrightarrow$ a combination with single Higgs measurement (λ_{HHH} constraints from NLO effects) would be a further step in our understanding
- Our future capability to observe HH will rely on a phenomenologically rich program of experimental searches that explore and combine many final states

Additional material

Benchmark shapes

- Each benchmark shape corresponds to a specific choice of the 5 EFT couplings
- The choice does not have a special physical meaning: it is only meant to represent a **shape**, not a special point in the EFT parameter space

Benchmark nr.	k_λ	k_t	c_2	c_g	$\mathrm{c}_{2\mathrm{g}}$
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	-1.0
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	-1.0	1.0
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	1.0	-1.0
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0