Prospects for HH measurements at the HL-LHC
Overview of CMS projection status

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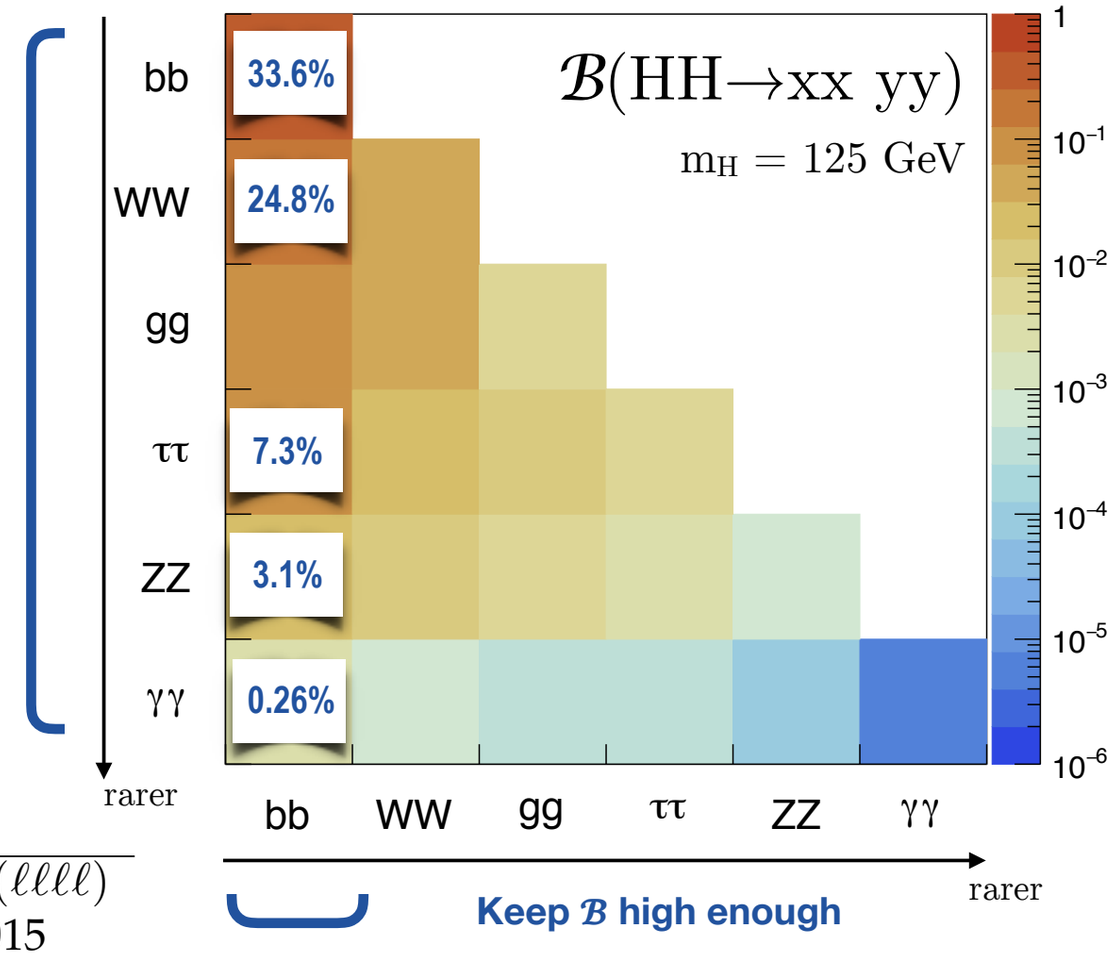
Overview

- **Goal:** Establish the HH CMS sensitivity at the HL-LHC
  - exercise of projecting Run II analysis done for ECFA (2.3 fb^{-1}) and detector Technical Design Report
  - extrapolation of Run 2 analyses does not allows to study new channels or new ideas to better exploit the HL-LHC potential
  - $\Longrightarrow$ develop full analysis using a parametrised CMS detector response with Delphes
- **How:** Five analyses and combination
  - bb$\gamma\gamma$
  - bbWW($2\ell 2\nu$)
  - bbbb
  - bb$\tau\tau$
  - bbZZ(4ℓ)



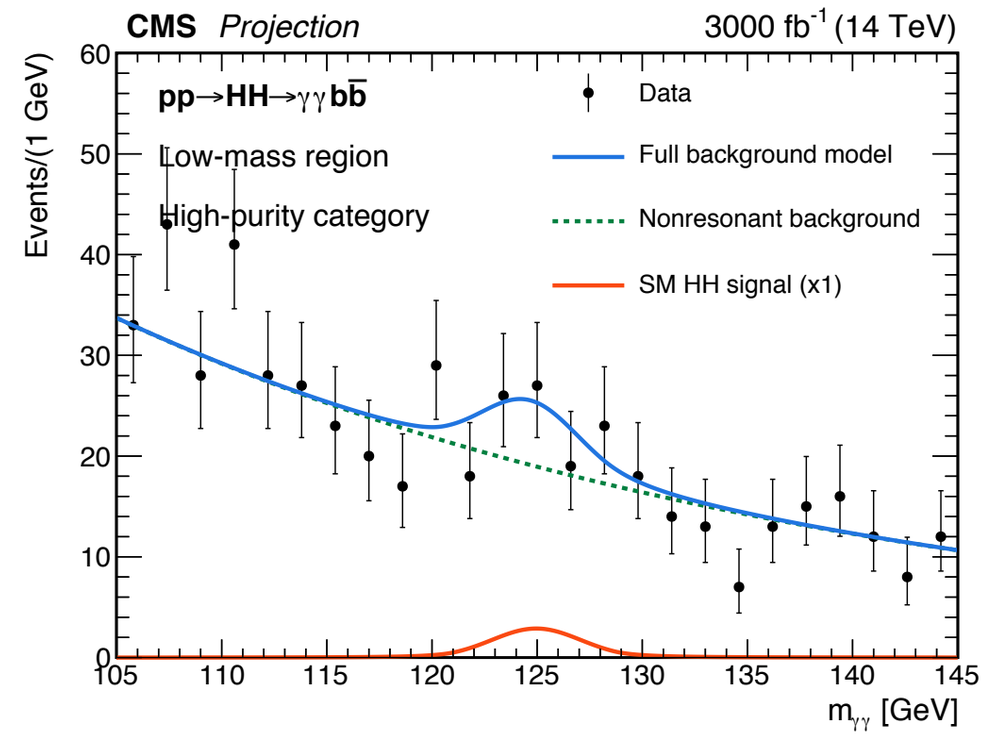
Channel	bbbb	bb$\tau\tau$	bbWW($\ell\nu\ell\nu$)	bb$\gamma\gamma$	bbZZ($\ell\ell\ell\ell$)
$\mathcal{B}$ [%]	33.6	7.3	1.7	0.26	0.015
Number of events	37000	8000	1830	290	17

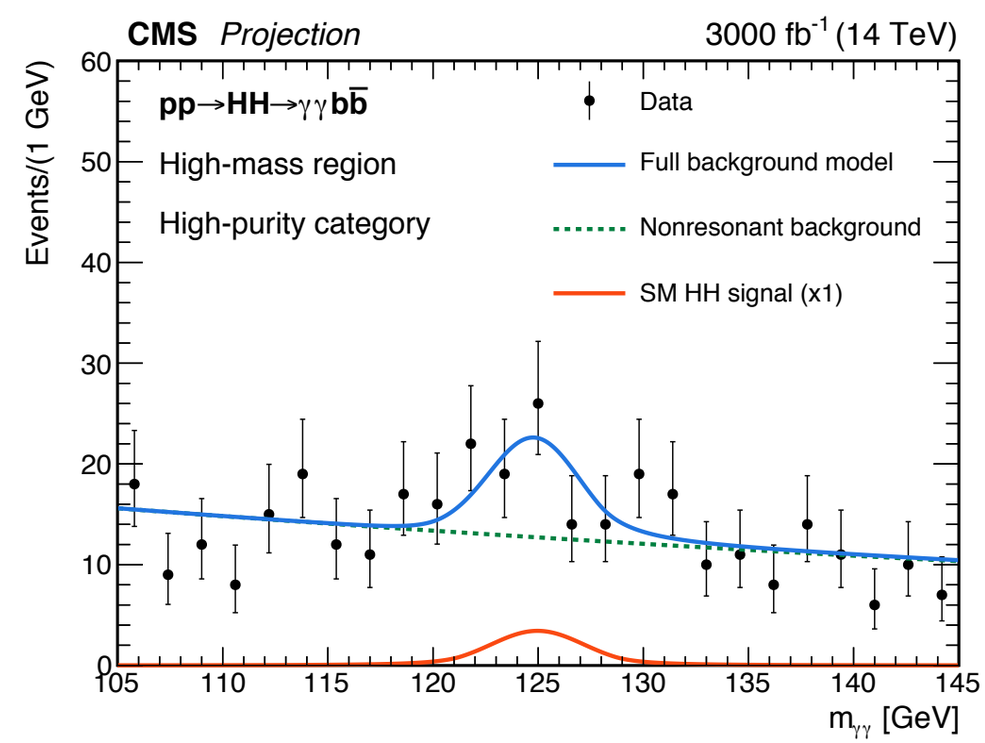
bb$\gamma\gamma$

- Analysis strategy
  - preselection of events containing $\gamma\gamma$ and bb pairs
  - rejection of ttH background with a dedicated BDT (75% reduction for 90% signal efficiency)
  - classification of events based on $M_X = m_{jj\gamma\gamma} - m_{\gamma\gamma} - m_{jj} + 250$ GeV into low and high mass categories
  - MVA event categorisation BDT that separates the background and the HH signal into low and high purity
  - ($m_{\gamma\gamma}$, m_{jj}) plane to look for a signal

$bb\gamma\gamma$

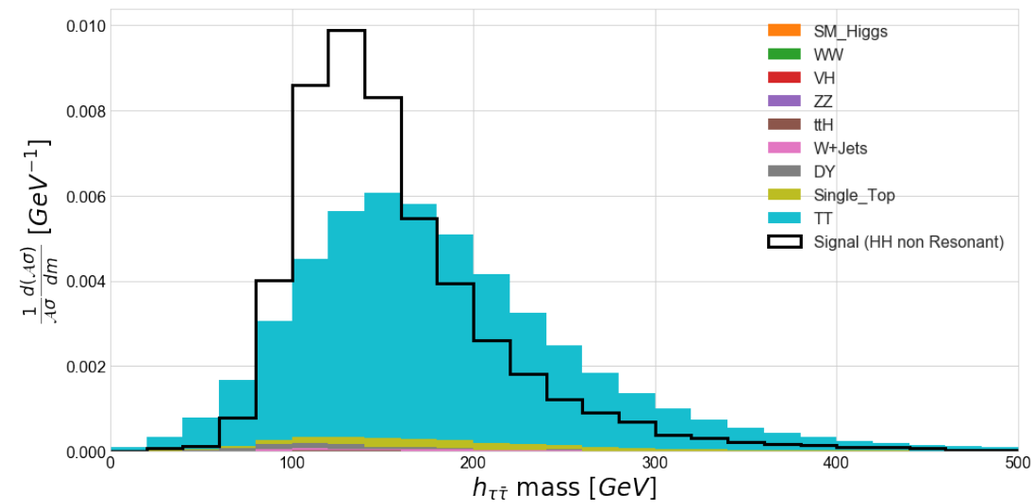
- Simultaneous fit on the $m_{\gamma\gamma}$ and m_{jj} distributions for the analysis categories
- Results: 1.8σ significance, 1.1 x σ_{HH}^{SM} limit
  - largely sensitive to the assumed $m_{\gamma\gamma}$ resolution
  - a few optimisations on the selections and MC generation are in the pipeline

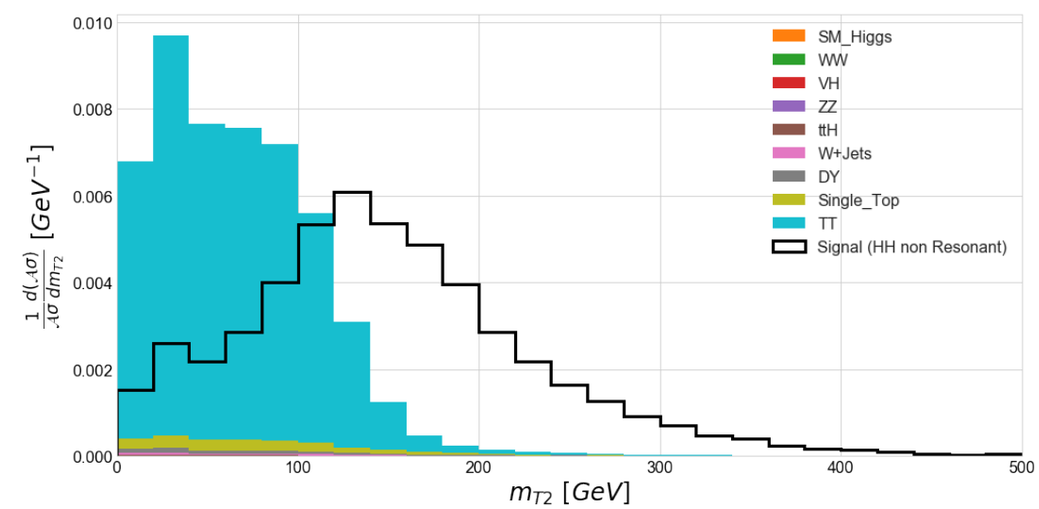




$bb\tau\tau$

- 3 $\tau\tau$ categories: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$
- Analysis strategy
  - preselect events based on μ, e, τ_h and b jet content
  - look for the presence of a signal using the output of a neural network
- State of the art techniques applied for the NN development
  - 27 basic + 21 reconstructed + 4 global features
  - deep learning techniques, with optimal data preprocessing, study of the activation functions, and data augmentation

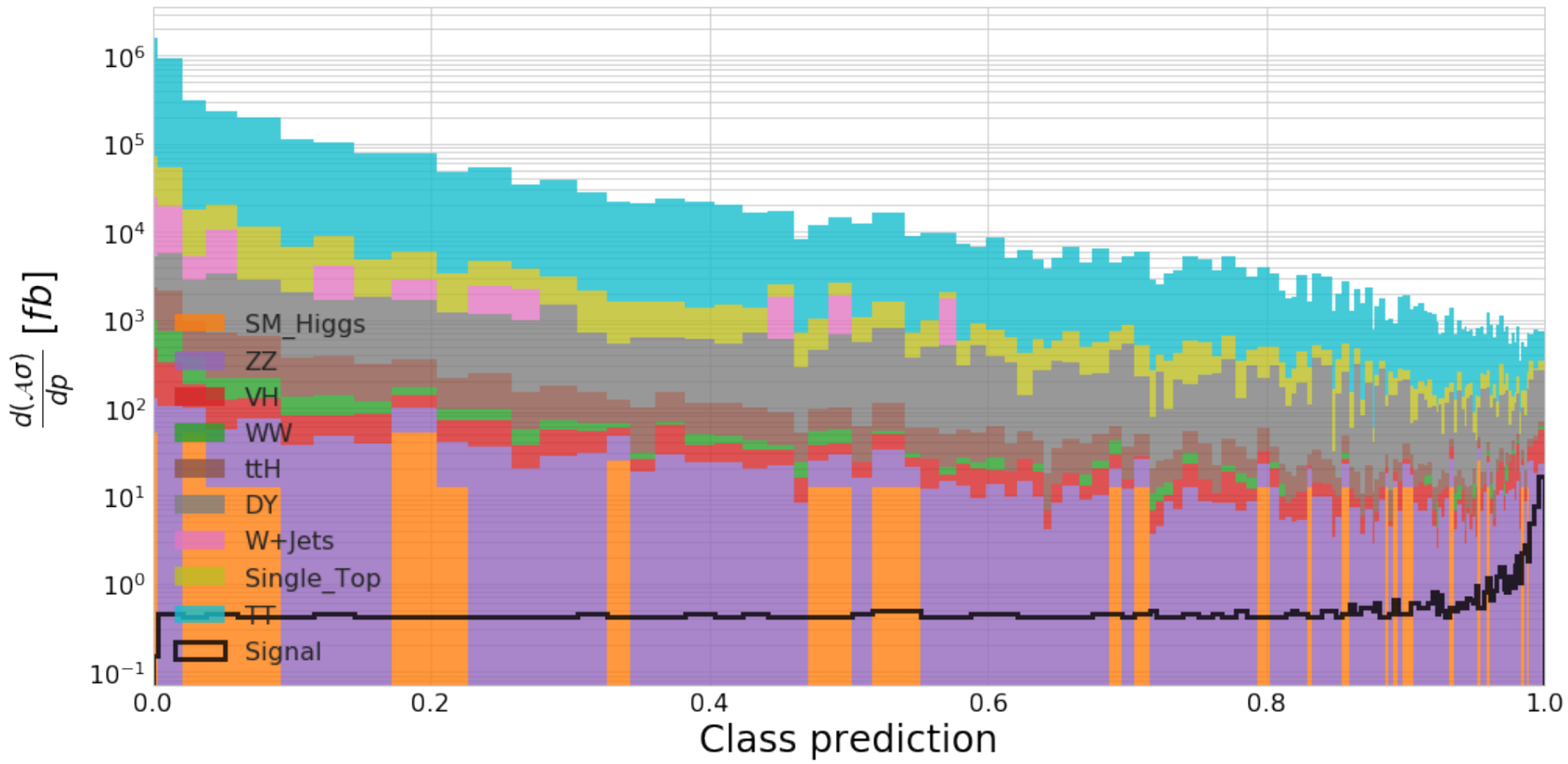




Examples of input features

$bb\tau\tau$

- Simultaneous fit of the NN output for the 3 decay channels
- Systematic uncertainties applied following the YR5 recommendations
- Results: 1.3σ significance, 1.5 x σ_{HH}^{SM} limit
  - without systematics: 1.5σ significance, 1.3 x σ_{HH}^{SM} limit

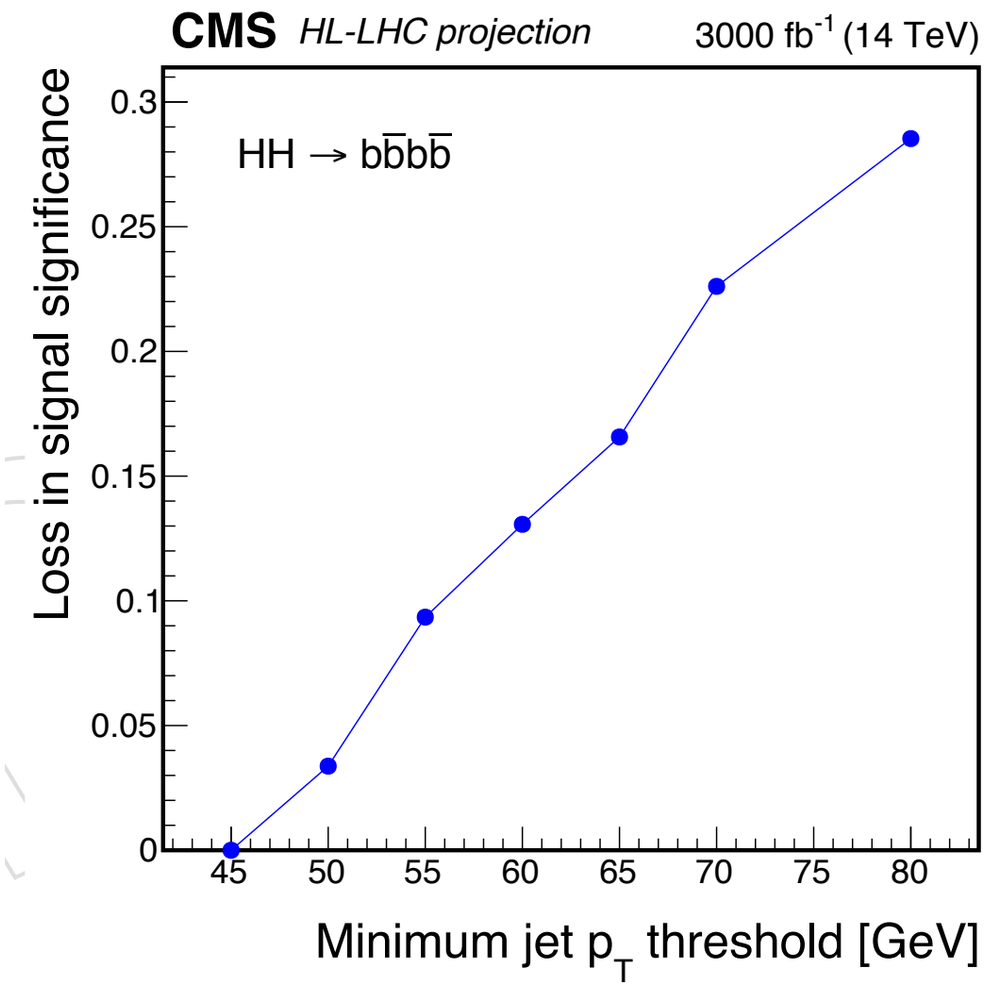


bbbb

- Analysis strategy:
  - preselect events with 4 jets of $p_T > 45$ GeV, $|\eta| < 3.5$, all jets b-tagged
  - build H_1 and H_2 as the jet pairs giving the minimal (H_1, H_2) mass difference
  - define the signal region in the (m_{H1}, m_{H2}) plane as

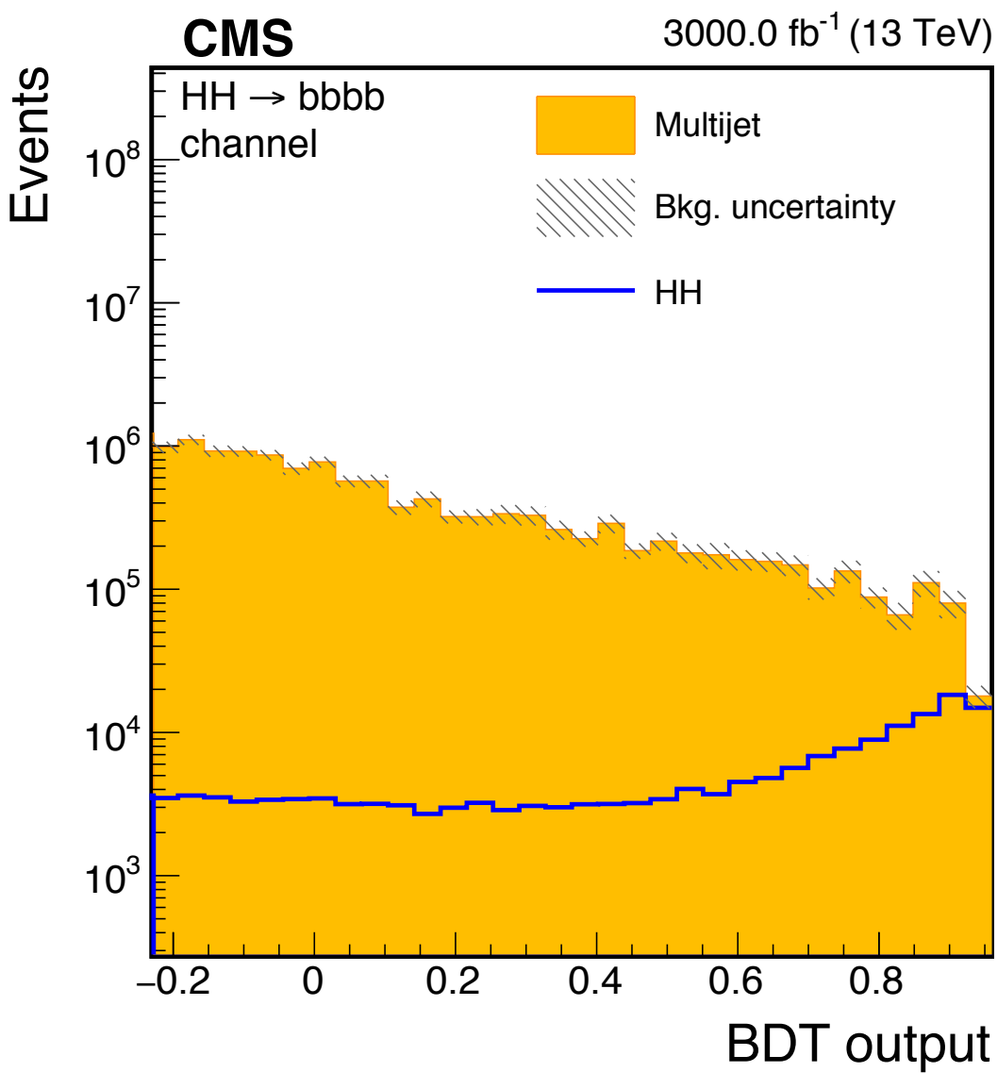
$$\sqrt{(m_{H_1} - 120\,\mathrm{GeV})^2 + (m_{H_2} - 120\,\mathrm{GeV})^2} < 40\,\mathrm{GeV}$$

    (note: improvements from b jet energy regression are not considered)
  - train a BDT to separate the background processes from the HH signal
  - use the BDT output as the fitted variable to look for a signal
- Usage of boosted categories also envisaged



Jet trigger threshold is a potential analysis limitation at the HL-LHC
The loss of significance vs minimal p_T threshold has been studied

bbbb



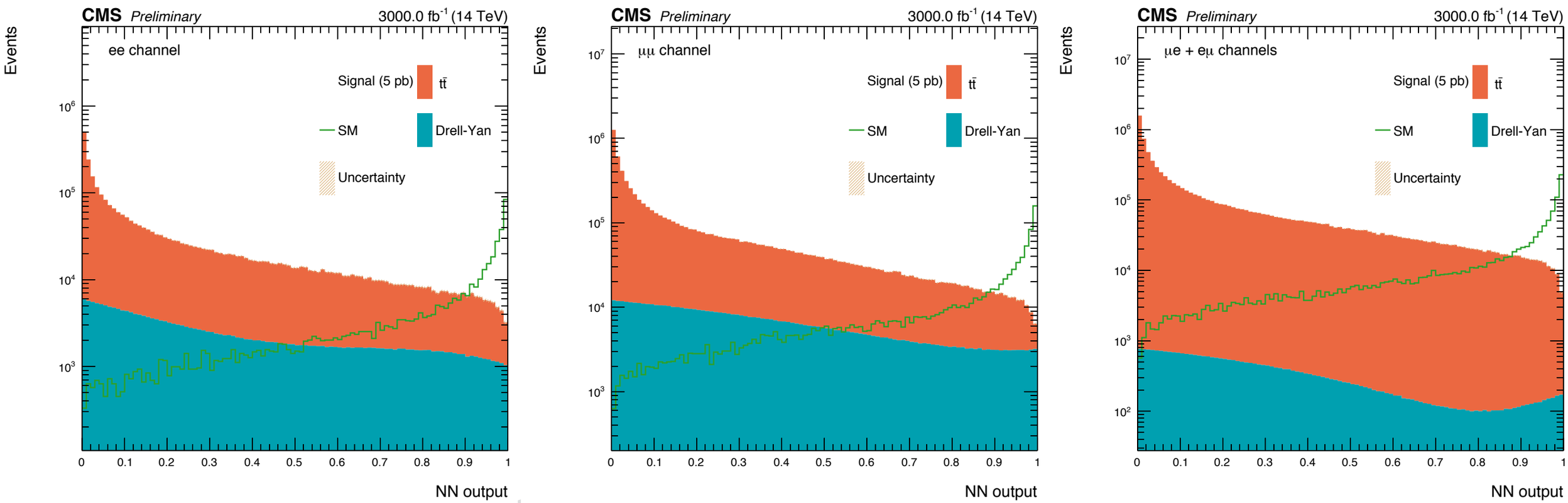
- High yields at low BDT score → backgrounds well constrained
  - almost no impact from syst. uncertainties
  - plan to consider variations of the most sensitive bins to evaluate impact of background uncertainty
    - but an aggressive assumption on the background estimation can be made for HL-LHC
- Results: 1.5σ significance, 1.3 × σ_{HH}^{SM} limit

bbWW ($2\ell\ 2\nu$)

- Using the fully leptonic WW final states: ee, μe, $\mu\mu$
- Select isolated leptons and two b jets in the event
- Large irreducible backgrounds: ttbar, DY
- Use a discriminant (neural network) based on kinematic properties to look for the signal
  - 9 input angular and mass variables
- Trigger and preselection: same thresholds as Run 2 applied
  - assumes lepton triggers will be used and 100% efficient in the analysis phase space
  - systematic uncertainties: following YR5 recommendations

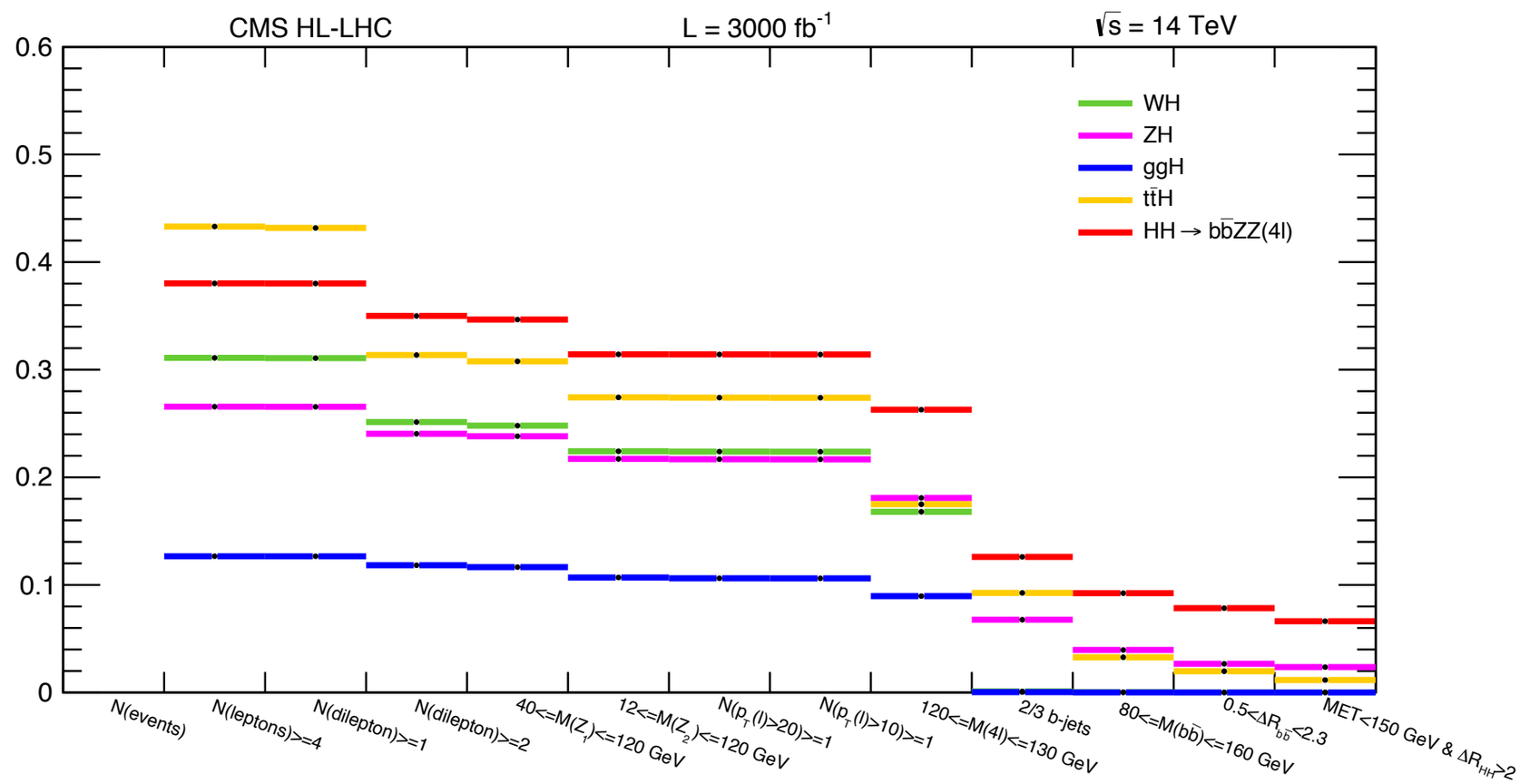
bbWW ($2\ell\ 2\nu$)

- Signal extracted from the NN output
  - simultaneous fit in the 3 categories
  - DY background modelling shown to impact the sensitivity by less than 5%
- Results: 0.4σ significance, 4.4 x σ_{HH}^{SM} limit



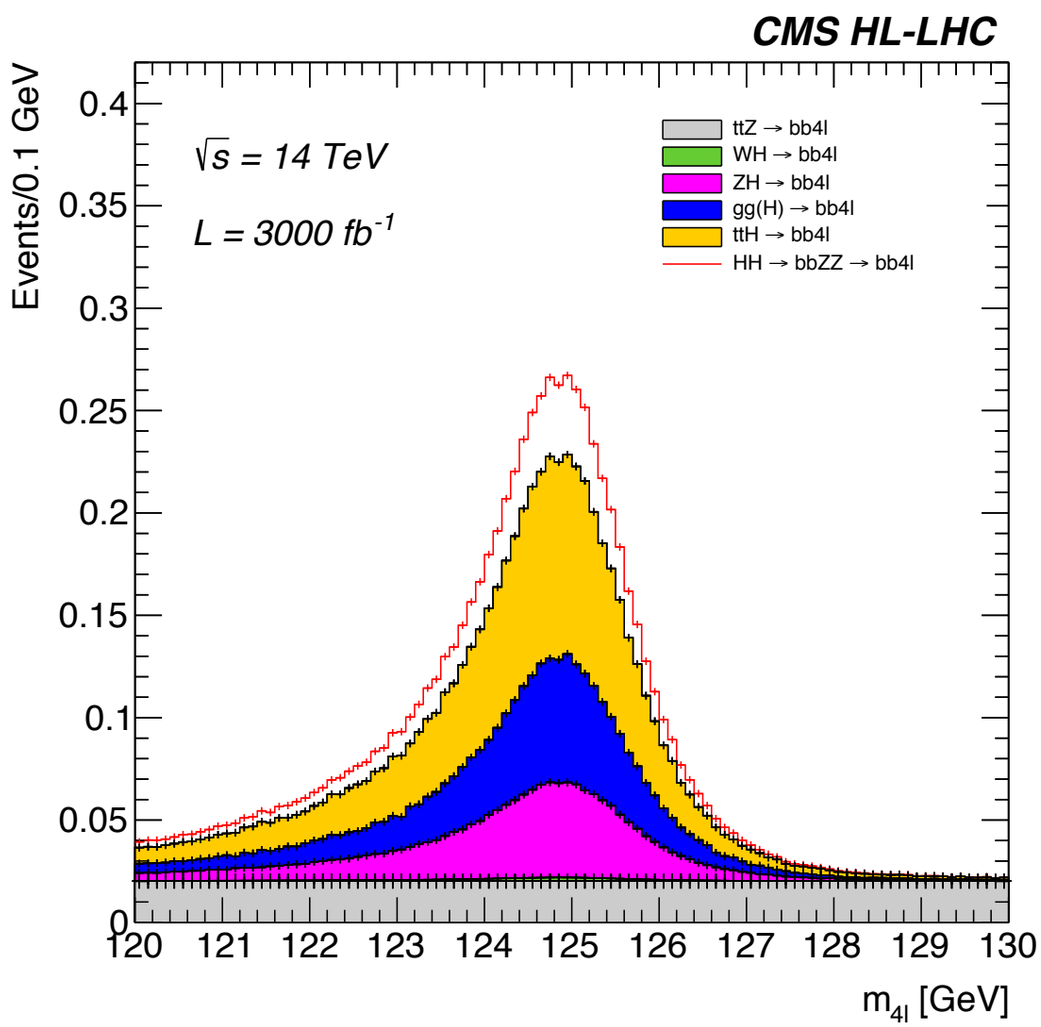
bbZZ (4ℓ)

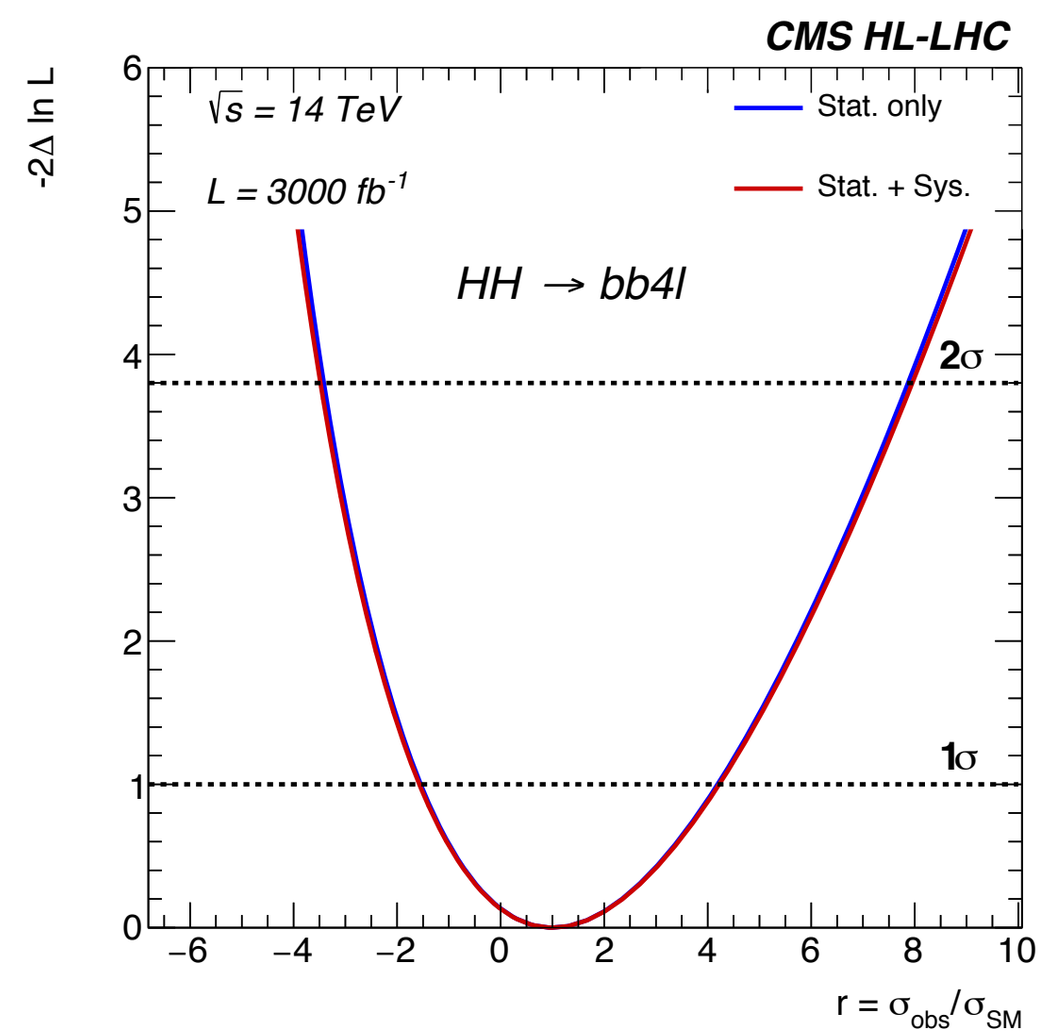
- Very rare but clean final state, yet unexplored at the LHC
- Powerful H→4ℓ signature ⟹ single H processes as dominant backgrounds
- Consider the $4e$, 4μ, $2e2\mu$ final states
- Loose preselection of leptons and jets, leptons combined to build the Z and Z* candidates
- Select events with $m_{4\ell}$ compatible with m_H
- Large acceptance because of low p_T of leptons
  - mostly limited by b tagging and p_T threshold
  - large acceptance for anomalous λ_{HHH} (small m_{HH})



bbZZ (4ℓ)

- Counting experiment with events around m_H
- YR 5 systematics included, but the analysis sensitivity is totally stat. dominated
- Results: 0.4σ significance, 6.7 × σ_{HH}^{SM} limit





Status and next steps

- SM analysis for the five decay channels ready
- Working on the combination of the 5 final states
  - close to 3σ from a naïve sum in quadrature, a few improvements in the pipeline
- Extend the set of results
  - anomalous λ_{HHH} couplings, exclusion of the $\lambda_{HHH} = 0$ hypothesis
  - likelihood scan
  - for bbbb only in boosted topologies, constraints on contact interactions (since they impact the high m_{HH} regime)
- Editing status:
  - text with analysis and result description not yet in the YR draft
  - SM results close to be finalised

Channel	Significance $[\sigma]$	95% CL limit on $\mu = \sigma_{\mathrm{HH}}/\sigma_{\mathrm{HH}}^{\mathrm{SM}}$
bbbb	1.5	1.3
bb$\tau\tau$	1.3	1.5
bbWW($\ell\nu\ell\nu$)	0.4	4.4
bb$\gamma\gamma$	1.8	1.1
bbZZ($\ell\ell\ell\ell$)	0.4	6.7

Combination with ATLAS

- ATLAS and CMS have differences in their results
  - different hierarchies of sensitivities: discussed between the authors and understood in terms of object performance, analysis strategy, and assumptions on the projection
  - CMS explores 5 channels, ATLAS projects 3 channels, similar overall sensitivity
  - $\Longrightarrow$ complementary approach giving a broad overview of the HL-LHC reach
- Analyses affected by systematic uncertainties that are mostly uncorrelated between the experiments (bkg estimation method, object performance, etc..)
  - correlations between experiments are expected to be negligible
  - $\Longrightarrow$ propose a “simple” combination at the likelihood level (sum of $\log\mathscr{L}$) to project reliably the HL-LHC reach for HH
  - same framework for both the projected combination of the SM HH signal sensitivity and the projected λ_{HHH} measurement

Conclusions

- The CMS Collaboration has projected the sensitivity to HH production using 5 decay channels (bbbb. bbWW, bbZZ, bb$\tau\tau$, bb$\gamma\gamma$)
  - full analyses based on Delphes CMS upgraded detector simulation
  - innovative techniques (e.g. machine learning) and rare channels (bbZZ(4ℓ)) studied for the first time to assess the possibilities at the HL-LHC
  - result in the five decay channels ready, combination in preparation
  - overall sensitivity close to 3σ with a few optimisations in the pipeline
  - extension of the results to λ_{HHH} measurements in progress
- Draft of the CMS projection section still to be inserted in the YR
- Propose a likelihood based approach for the combination with ATLAS
  - expect naïvely to reach a sensitivity beyond 4 sigma for the SM HH signal