

Prospects for HH measurements at the HL-LHC

Overview of CMS projections

The HH Yellow Report team

A. Benaglia, M. Bengala, O. Bondu, L. Borgonovi, S. Braibant, L. Cadamuro, A. Carvalho, C. Delaere, N. de Filippis, E. Fontanesi, M. Gallinaro, M. Gouzevitch, J. R. Komaragiri, D. Majumder, K. Mazumdar, F. Monti, G. Ortona, L. Panwar, N. Sahoo, R. Santo, G. Strong, M. Vidal, S. Wertz

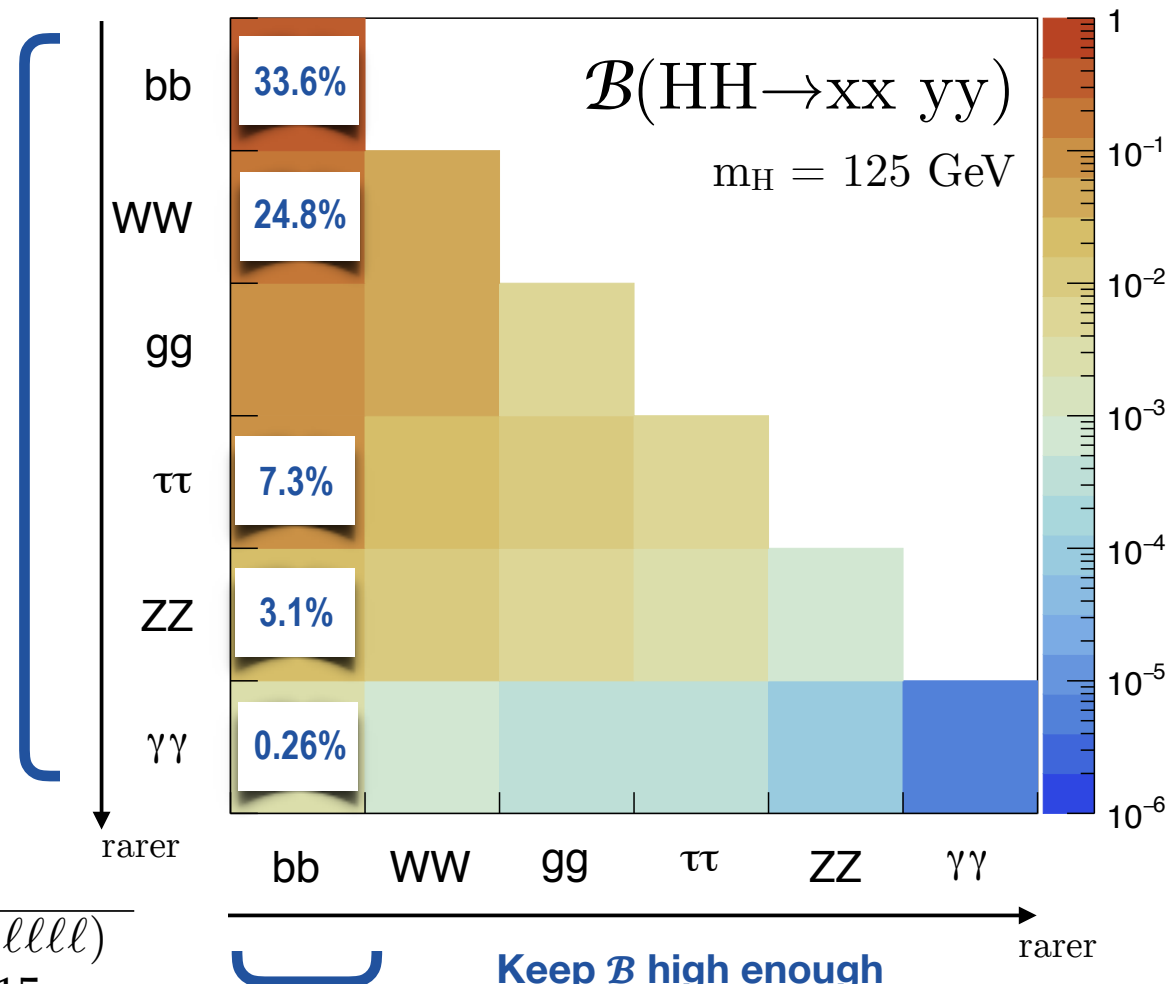
Informal CMS-ATLAS HH YR meeting, October 19th, 2018

- **Goal:** Establish the HH CMS sensitivity at the HL-LHC
 - exercise of projecting Run II analysis done for ECFA (2.3 fb⁻¹) and for ECAL/HGCal/Tracker TDR
 - we learned that systematics have limited impact on the results, while analysis techniques and detector performance (b tag, resolution, ...) play a crucial role
 - ⇒ develop full analysis using a parametrised CMS detector response with Delphes

■ **How:** Five analyses and combination

- bbγγ
- bbWW(2ℓ2ν)
- bbbb
- bbττ
- bbZZ(4ℓ)

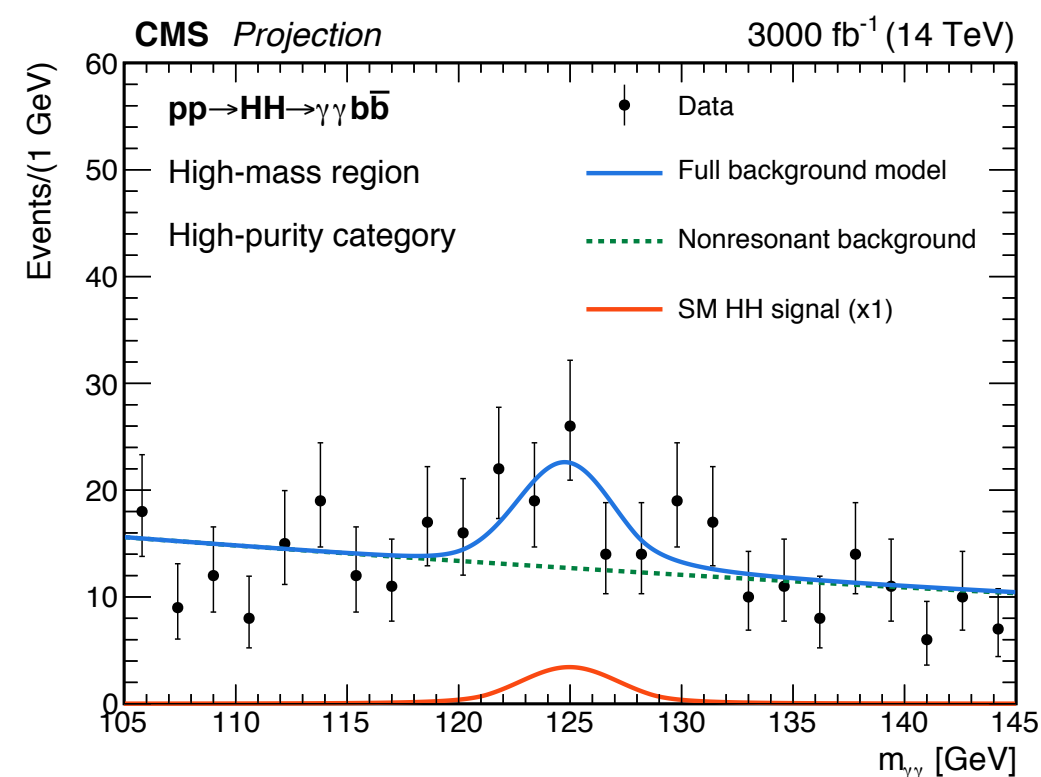
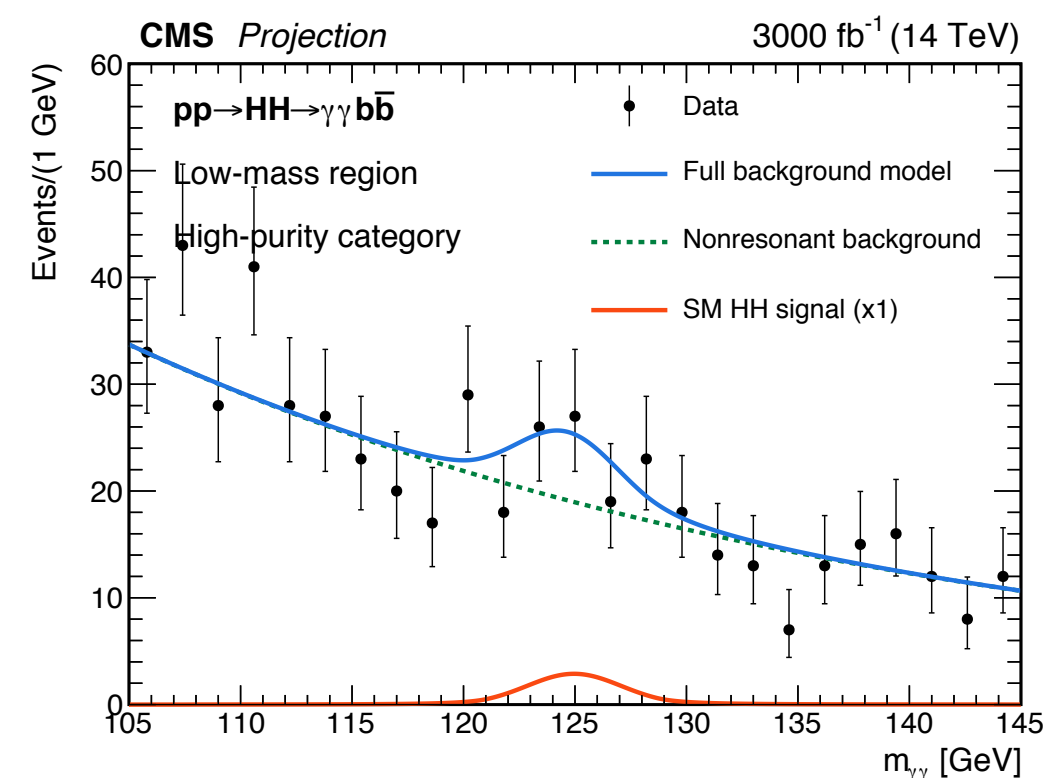
Trade-off
between \mathcal{B} and
purity



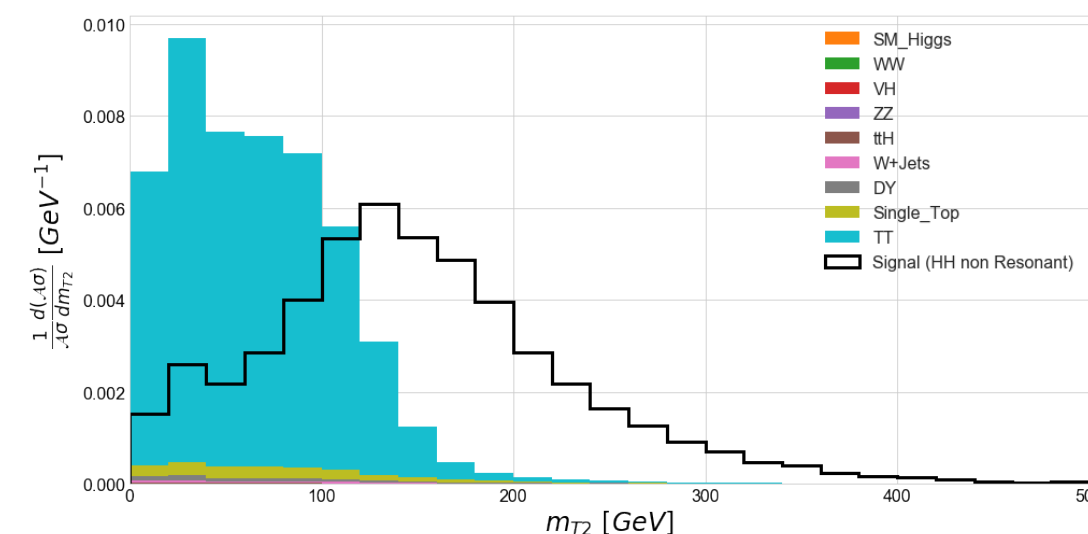
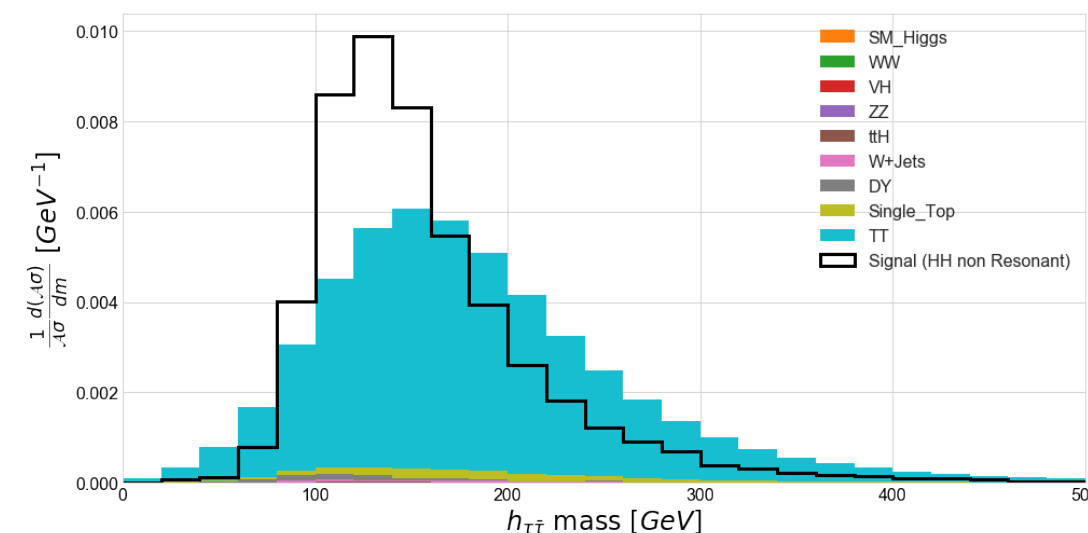
Channel	bbbb	bbττ	bbWW(ℓνℓν)	bbγγ	bbZZ(ℓℓℓℓ)
\mathcal{B} [%]	33.6	7.3	1.7	0.26	0.015
Number of events	37000	8000	1830	290	17

- 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

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

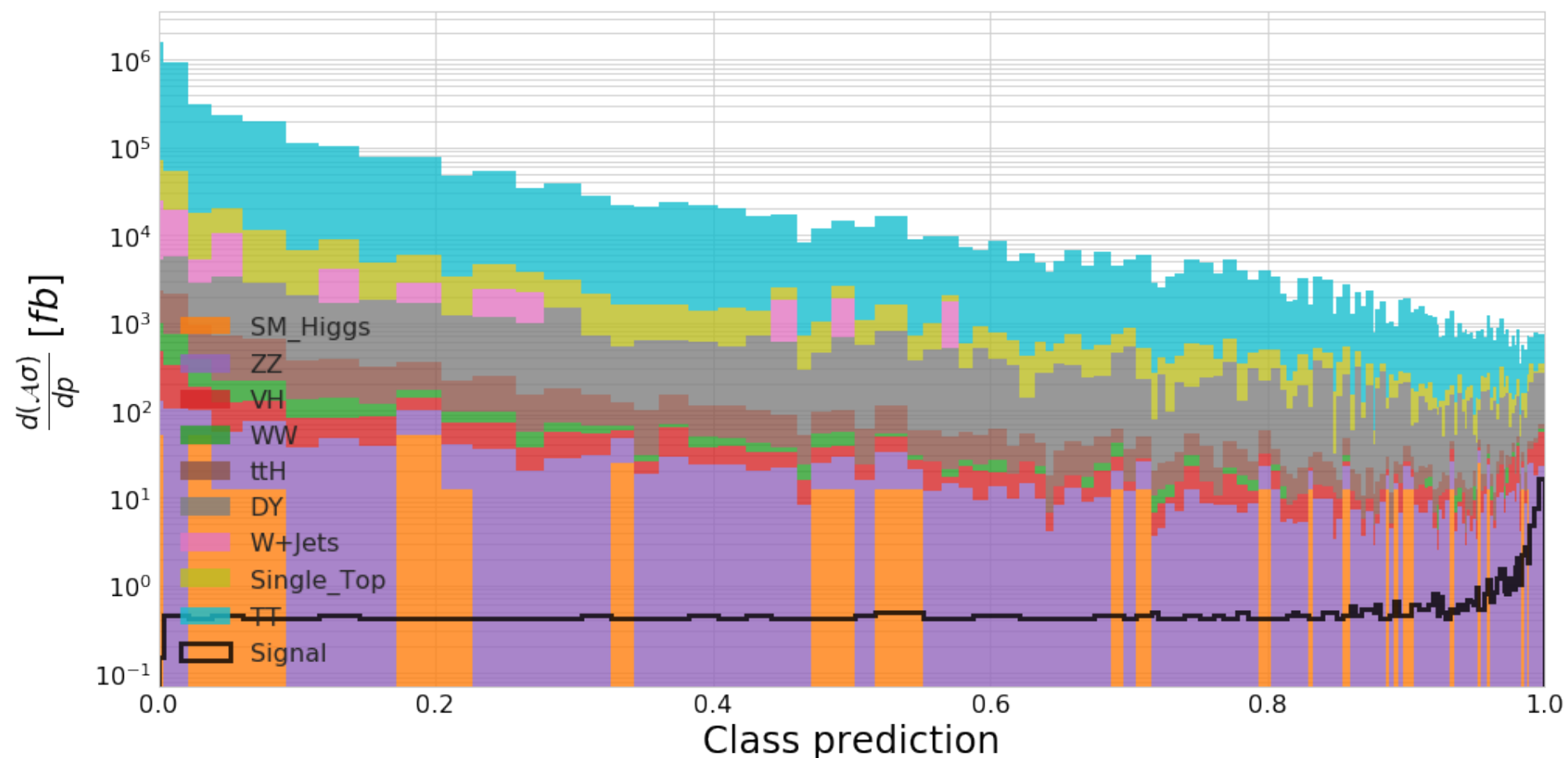


- 3 $\tau\tau$ categories: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$
- Analysis strategy
 - preselect events based on μ , e , τ_h and b jet content
 - look for the presence of a signal using the output of a neural network
- State of the art techniques applied for the NN development
 - 27 basic + 21 reconstructed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



Examples of input features

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



■ Analysis strategy:

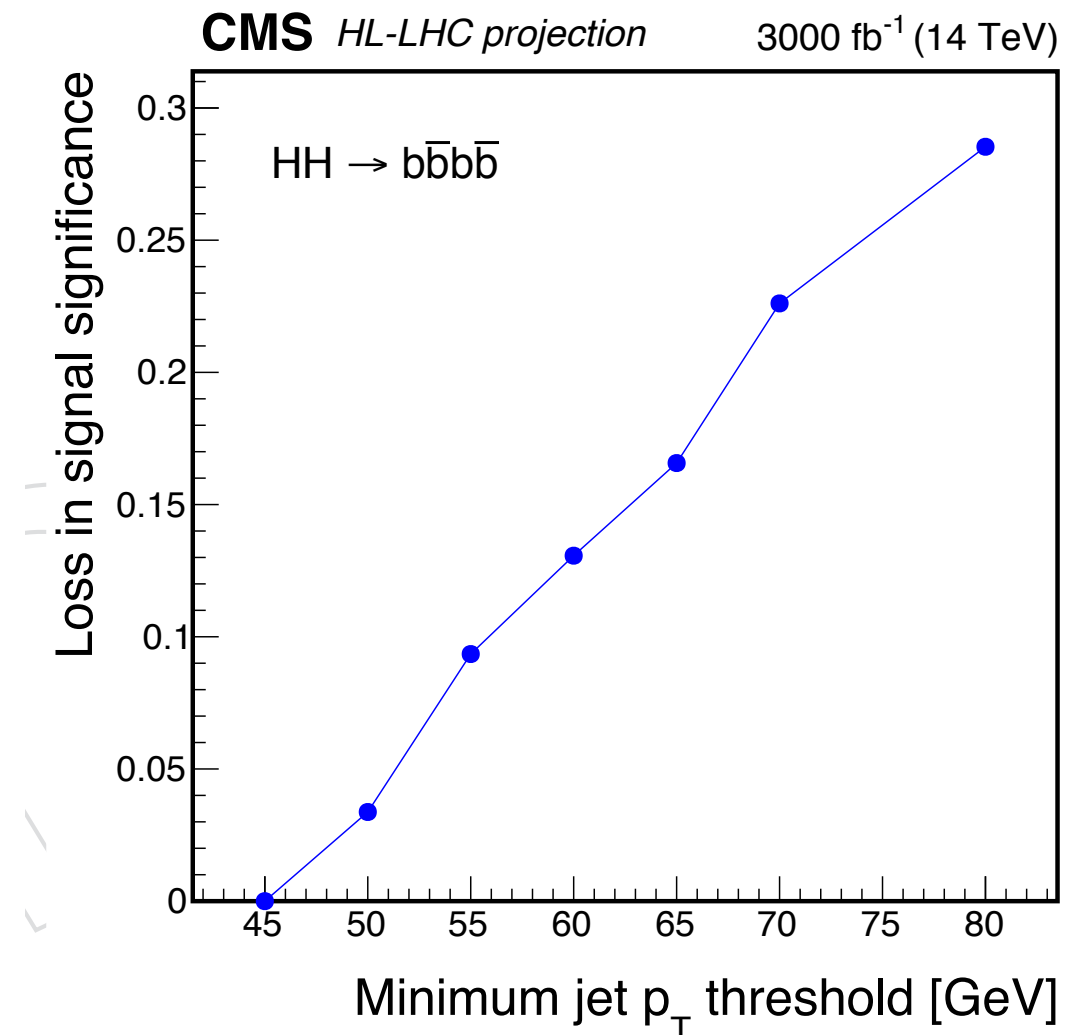
- preselect events with 4 jets of $p_T > 45$ GeV, $|\eta| < 3.5$, all jets b-tagged
- build H_1 and H_2 as the jet pairs giving the minimal (H_1, H_2) mass difference
- define the signal region in the (m_{H_1}, m_{H_2}) plane as

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

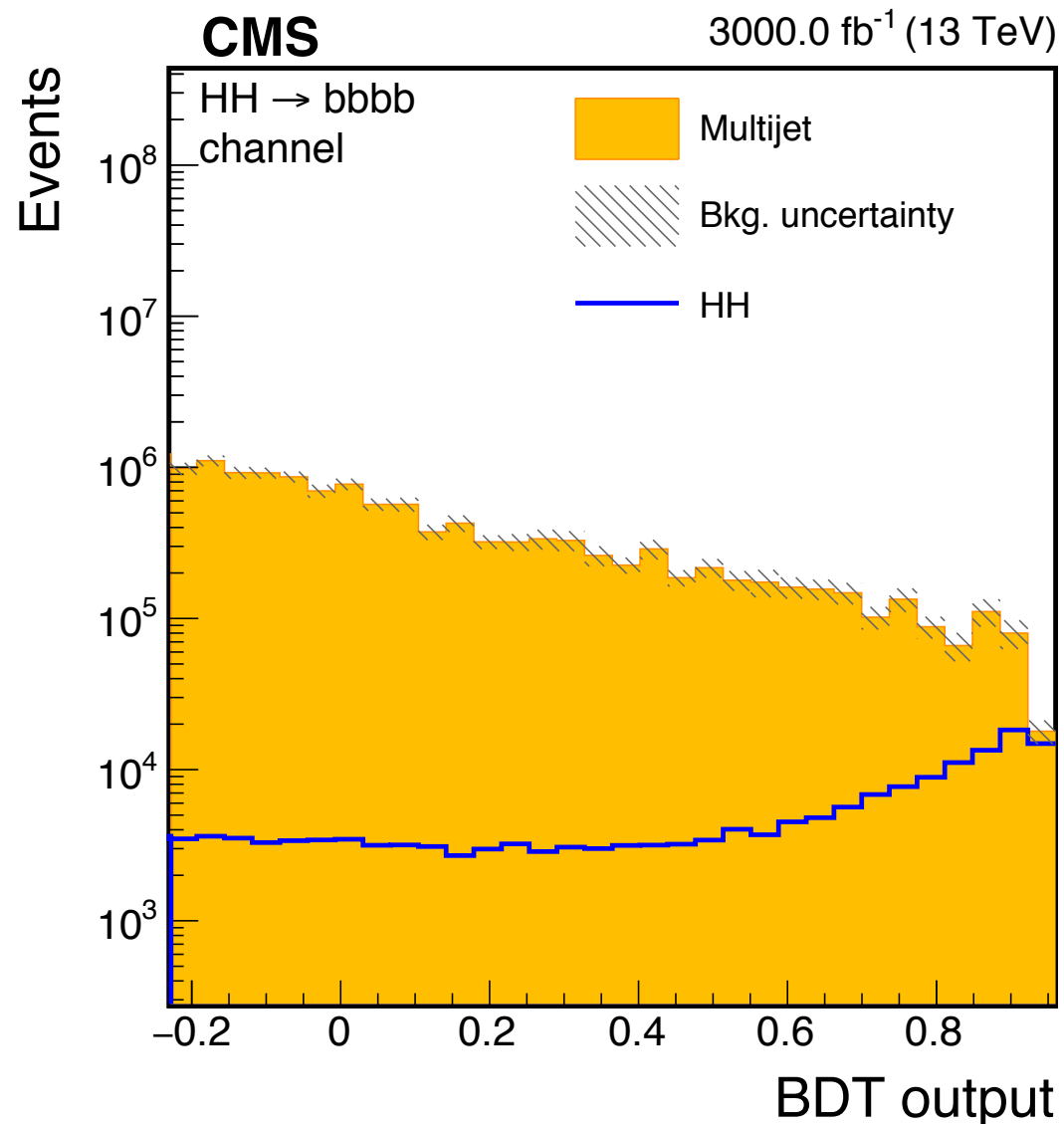
(note: improvements from b jet energy regression are not considered)

- 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



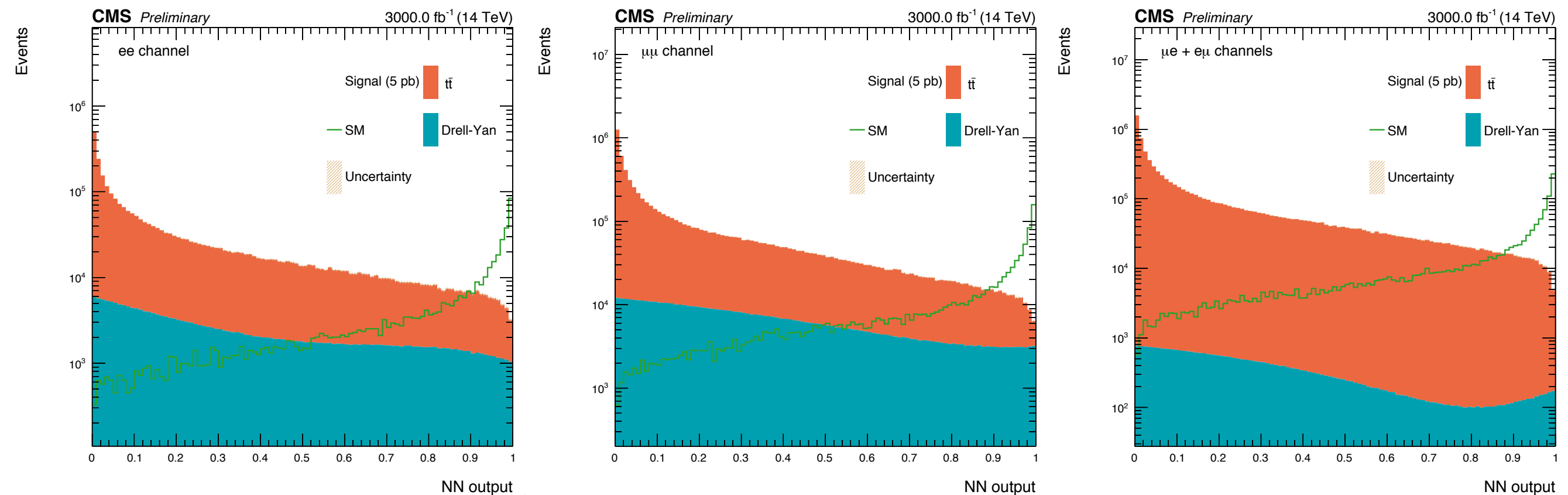
- High yields at low BDT score → backgrounds well constrained
 - almost no impact from syst. uncertainties
 - plan to consider variations of the most sensitive bins to evaluate impact of background uncertainty
 - but an aggressive assumption on the background estimation can be made for HL-LHC
- Results: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

- Using the fully leptonic WW final states: ee , μe , $\mu\mu$
- Select isolated leptons and two b jets in the event
- Large irreducible backgrounds: $t\bar{t}$, 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 ℓ 2 ν)

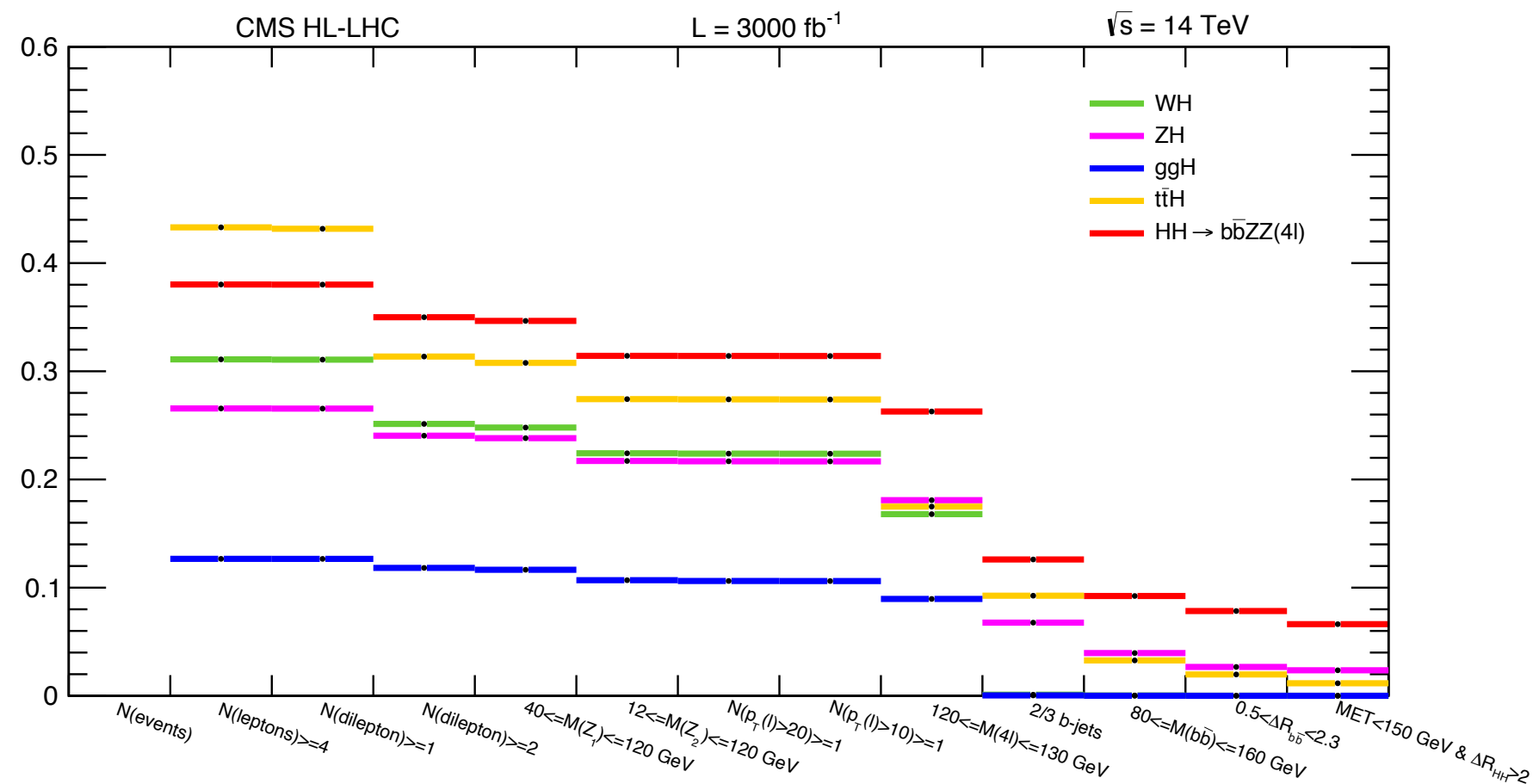


- Signal extracted from the NN output
 - simultaneous fit in the 3 categories
 - DY background modelling shown to impact the sensitivity by less than 5%
- Results: 0.4 σ significance, $4.4 \times \sigma_{HH}^{SM}$ limit

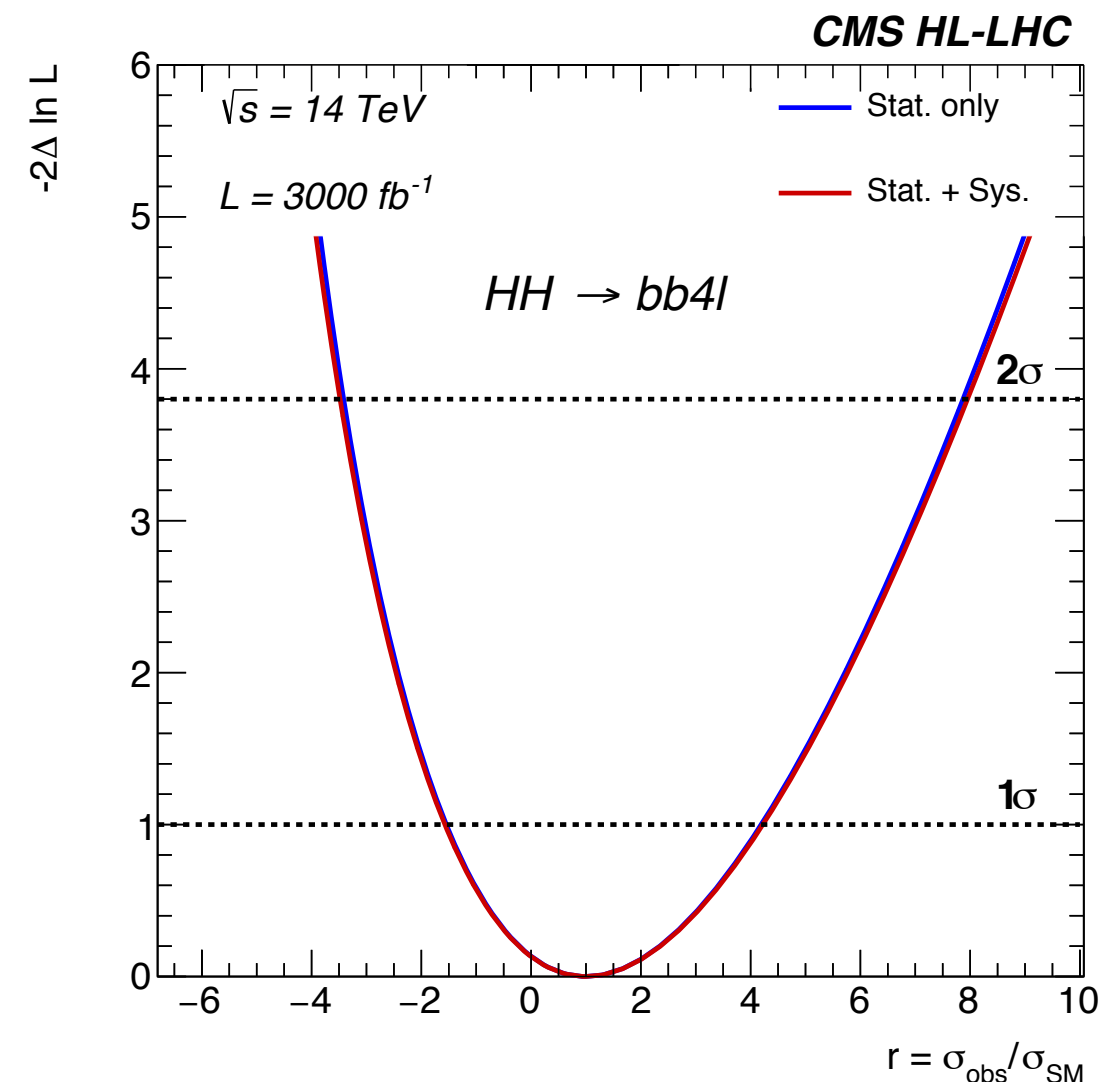
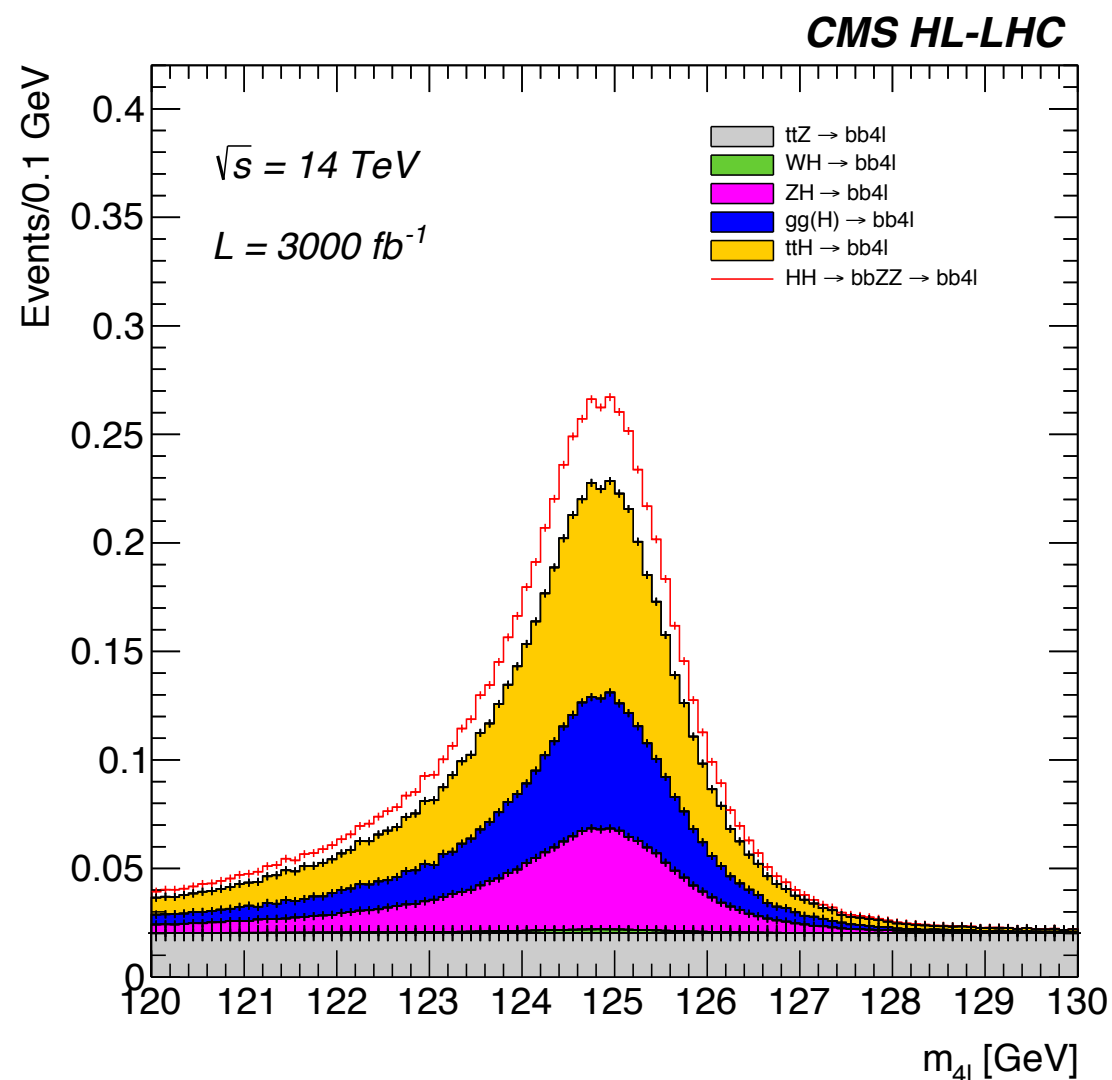


- Very rare but clean final state, yet unexplored at the LHC
- Powerful $H \rightarrow 4\ell$ signature \Rightarrow single H processes as dominant backgrounds
- Consider the $4e$, 4μ , $2e2\mu$ final states
- Loose preselection of leptons and jets, leptons combined to build the Z and Z^* candidates
- 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})



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



- Combine the 5 final states
 - from a naïve sum in quadrature, not far from 3σ , with a few improvements in the pipeline
- Extend the set of results
 - anomalous λ_{HHH} couplings
 - likelihood scan
 - exclusion of the $\lambda_{HHH} = 0$ hypothesis
 - for bbbb only in boosted topologies, constraints on contact interactions (impact the high m_{HH} regime)
- Prepare the ground for simple combination with the ATLAS results

Channel	Significance [σ]	95% CL limit on $\mu = \sigma_{HH}/\sigma_{HH}^{SM}$
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