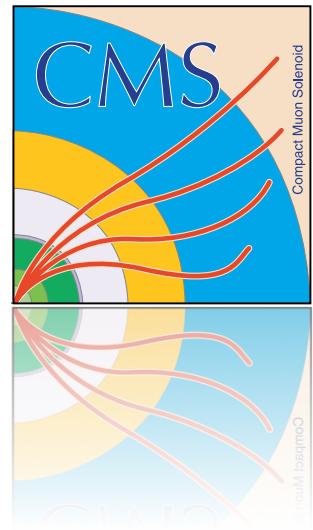




Massachusetts  
Institute of  
Technology

YgolundecT  
to astutism!



# Experimental projections for sensitivity to HH production in the Standard Model

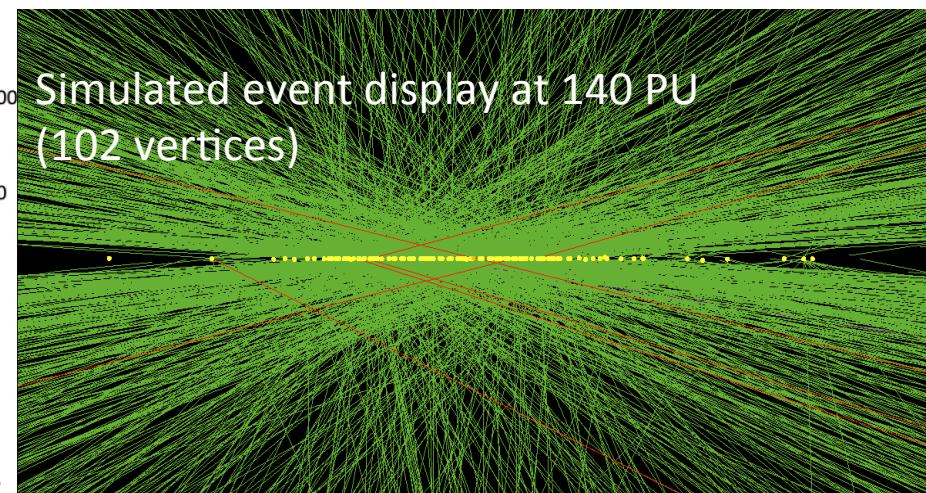
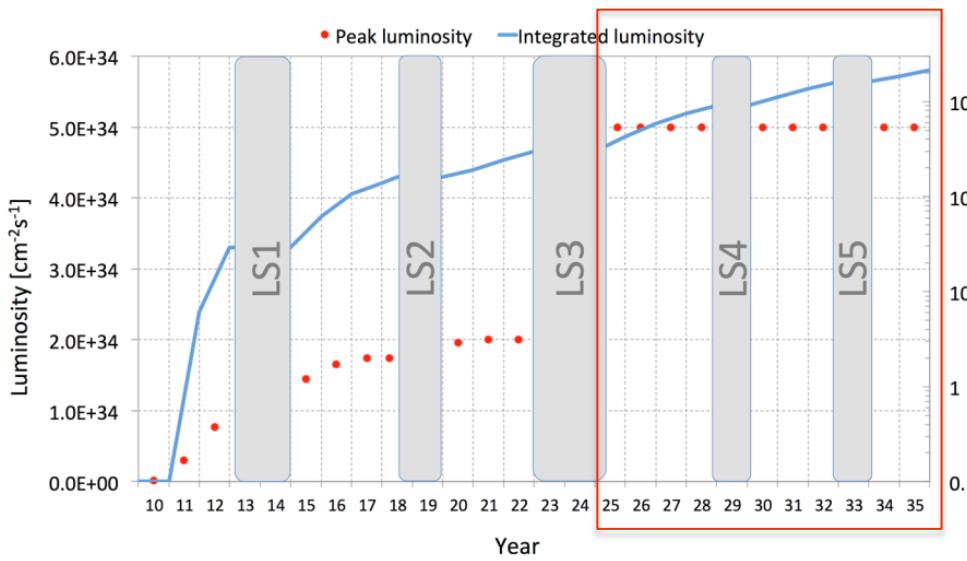
Physics at the High-Luminosity LHC, 2015

Aram Apyan

On behalf of the ATLAS and CMS collaborations

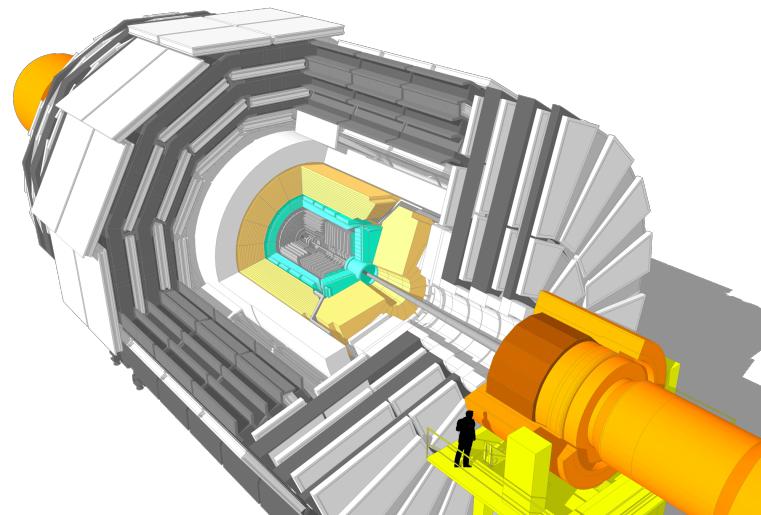
# HL-LHC

- Challenging environment for detectors and reconstruction
  - 140 average simultaneous interactions
  - High level radiation doses
- ATLAS and CMS have comprehensive detector upgrade plans to cope with these challenges



# Phase II upgrade program

- Comprehensive program to cope with HL-LHC challenges
  - Set of upgrades to many of major of detector elements
- Main highlights:
  - ATLAS
    - Replace inner tracker
    - Upgrade muon/calorimeter electronics
    - New L0/L1 trigger scheme
  - CMS
    - High granularity endcap calorimeter
    - New tracker: coverage up to  $|\eta|$  of 4
    - L1 hardware with tracks and rate up to 750 kHz



# SM Higgs pair production

---

- One of the exciting prospects of HL-LHC
  - Cross section at  $\sqrt{s}=14$  TeV is 40.7 fb [NNLO]
  - Challenging measurement
    - Preliminary results from ATLAS and CMS
- Final states studied by experiments
  - $b\bar{b}\gamma\gamma$  [320 expected events at HL-LHC,  $3000\text{fb}^{-1}$ ]
    - ATLAS: ATL-PHYS-PUB-2014-019
    - CMS: Preliminary studies shown at ECFA 2014 . Updates for CMS Phase II TP, work in progress
  - $b\bar{b}WW$  [30000 expected events at HL-LHC,  $3000\text{fb}^{-1}$ ]
    - CMS: Preliminary studies shown at ECFA 2014
  - $b\bar{b}\tau\tau$  [8900 expected events at HL-LHC,  $3000\text{fb}^{-1}$ ]
    - New preliminary studies from CMS today

# Extrapolation strategy

---

- Take the current Phase II detector performance obtained using fully simulated studies as baseline
- Computationally not feasible to perform the whole study with fully simulated Phase II samples
- HH->bb $\gamma\gamma$ :
  - Parameterized object performance applied on truth level
  - Scale the efficiencies, fake rates, and resolutions taken from Phase II fully simulated samples
- HH->bb $\tau\tau$ , bbWW:
  - Delphes fast simulation is used
  - Take the input parameterizations of the Phase II detector from Phase II fully simulated samples

# HH->bb $\gamma\gamma$ analysis description: ATLAS

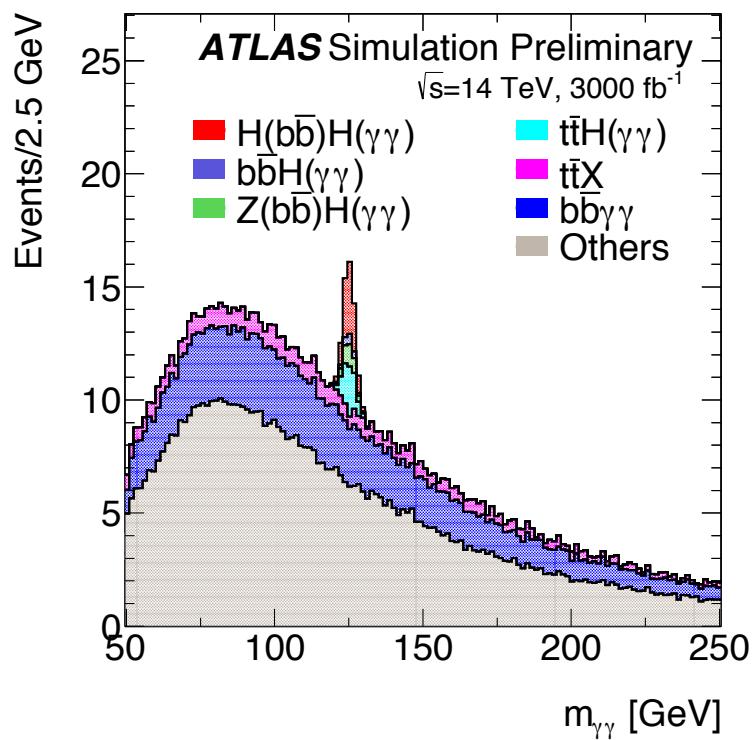
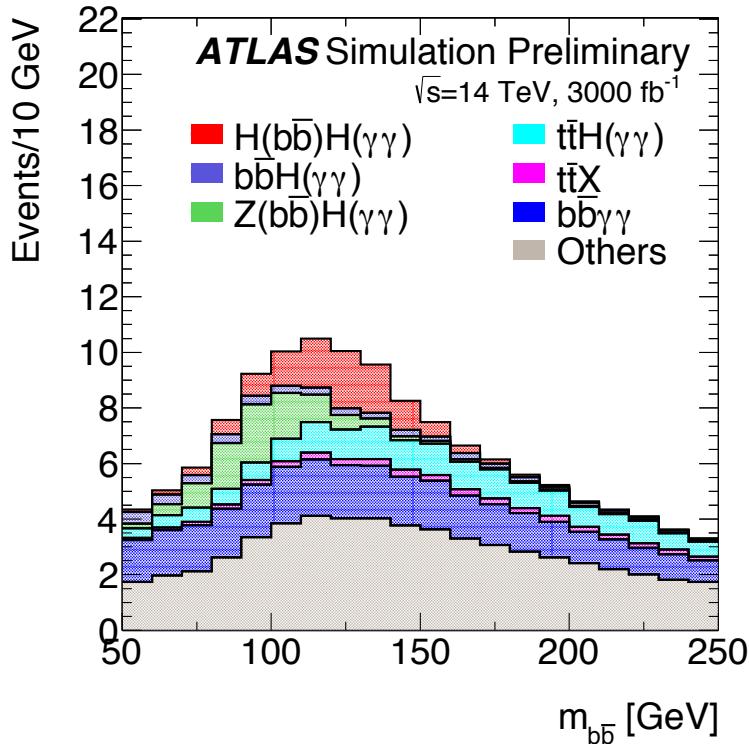
## Event Selection Criteria

$\geq 2$ isolated photons, with $p_T > 30$ GeV, $ \eta  < 1.37$ or $1.52 <  \eta  < 2.37$
$\geq 2$ jets identified as $b$ -jets with leading/subleading $p_T > 40/25$ GeV, $ \eta  < 2.5$
No isolated leptons with $p_T > 25$ GeV, $ \eta  < 2.5$
$< 6$ jets with $p_T > 25$ GeV, $ \eta  < 2.5$
$0.4 < \Delta R^{b\bar{b}} < 2.0$ , $0.4 < \Delta R^{\gamma\gamma} < 2.0$ , $\Delta R^{\gamma b} > 0.4$
$100 < m_{b\bar{b}} < 150$ GeV, $123 < m_{\gamma\gamma} < 128$ GeV
$p_T^{\gamma\gamma}, p_T^{b\bar{b}} > 110$ GeV

- Detector performance

- ~70% b-tagging efficiency with 30% (1%) fake rates for c-jets (light jets)
- 76% photon identification efficiency (plateau) with 0.25% jet->photon fake rates
- 2% (5%) electron to photon miss-identification probability in barrel (endcap)

# Mass distributions



The distributions of  $m_{bb} / m_{\gamma\gamma}$  in  $3000 \text{ fb}^{-1}$  after applying all the selection criteria except for  $m_{bb} / m_{\gamma\gamma}$ . The individual shaped of the contributions are obtained using the events surviving event selection before the mass criteria and angular cuts are applied, but normalized to the number of expected events after the full event selection. The  $ttX$  contribution includes  $tt(\geq 1 \text{ lepton})$  and  $tt\gamma$ , while ‘Others’ includes  $cc\gamma\gamma$ ,  $b\bar{b}\gamma j$ ,  $bbjj$  and  $j j\gamma\gamma$ .

# ATLAS results

Expected yields ( $3000 \text{ fb}^{-1}$ ) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM} = 1)$	$8.4 \pm 0.1$	$6.7 \pm 0.1$	$1.8 \pm 0.1$
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM} = 0)$	$13.7 \pm 0.2$	$10.7 \pm 0.2$	$3.1 \pm 0.1$
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM} = 2)$	$4.6 \pm 0.1$	$3.7 \pm 0.1$	$0.9 \pm 0.1$
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM} = 10)$	$36.2 \pm 0.8$	$27.9 \pm 0.7$	$8.2 \pm 0.4$
$b\bar{b}\gamma\gamma$	$9.7 \pm 1.5$	$5.2 \pm 1.1$	$4.5 \pm 1.0$
$c\bar{c}\gamma\gamma$	$7.0 \pm 1.2$	$4.1 \pm 0.9$	$2.9 \pm 0.8$
$b\bar{b}\gamma j$	$8.4 \pm 0.4$	$4.3 \pm 0.2$	$4.1 \pm 0.2$
$b\bar{b}jj$	$1.3 \pm 0.2$	$0.9 \pm 0.1$	$0.4 \pm 0.1$
$jj\gamma\gamma$	$7.4 \pm 1.8$	$5.2 \pm 1.5$	$2.2 \pm 1.0$
$t\bar{t}(\geq 1 \text{ lepton})$	$0.2 \pm 0.1$	$0.1 \pm 0.1$	$0.1 \pm 0.1$
$t\bar{t}\gamma$	$3.2 \pm 2.2$	$1.6 \pm 1.6$	$1.6 \pm 1.6$
$t\bar{t}H(\gamma\gamma)$	$6.1 \pm 0.5$	$4.9 \pm 0.4$	$1.2 \pm 0.2$
$Z(b\bar{b})H(\gamma\gamma)$	$2.7 \pm 0.1$	$1.9 \pm 0.1$	$0.8 \pm 0.1$
$b\bar{b}H(\gamma\gamma)$	$1.2 \pm 0.1$	$1.0 \pm 0.1$	$0.3 \pm 0.1$
<b>Total Background</b>	$47.1 \pm 3.5$	$29.1 \pm 2.7$	$18.0 \pm 2.3$
$S / \sqrt{B}(\lambda/\lambda_{SM} = 1)$	1.2	1.2	0.4

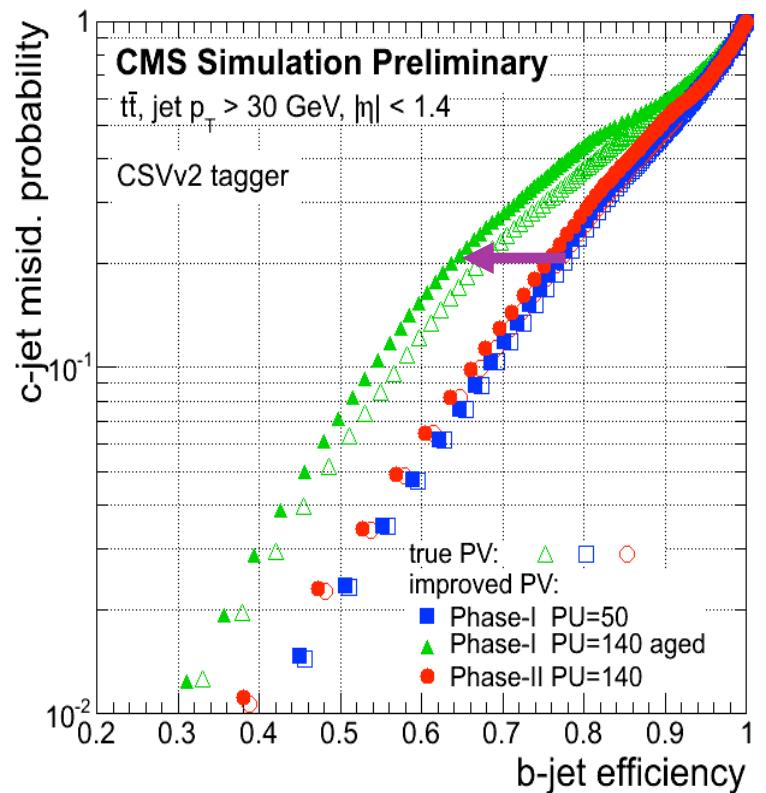
- Split events into 2 categories [barrel-barrel and at least one photon in endcap]
- $\sim 1.3 \sigma$  significance

# HH->bb $\gamma\gamma$ analysis description: CMS

- Event selection
  - 2 photons:  $p_T > 40 \text{ GeV}$  and  $p_T > 20 \text{ GeV}$ ,  $|\eta| < 2.5$ 
    - Veto photons if an electron is reconstructed within  $\Delta R$  of 0.1
  - 2 b-tagged jets,  $p_T > 30 \text{ GeV}$ ,  $|\eta| < 2.4$
- Kinematic selection
  - Additional lepton veto [ $p_T > 10 \text{ GeV}$ ]
  - Less than 4 jets with  $|\eta| < 2.4$  and  $p_T > 30 \text{ GeV}$
  - $\Delta R_{bb}$  and  $\Delta R_{\gamma\gamma}$  less than 2.0, min of  $\Delta R_{\gamma b} > 1.5$
- Two categories considered
  1. Both photons in barrel
  2. At least one photon in endcap
- Likelihood fit signal extraction
  - 2D fit of  $M_{bb}$  and  $M_{\gamma\gamma}$
  - Mass fit window of  $100 \text{ GeV} < M_{\gamma\gamma} < 150 \text{ GeV}$  and  $70 \text{ GeV} < M_{bb} < 200 \text{ GeV}$  is used

# Object performance

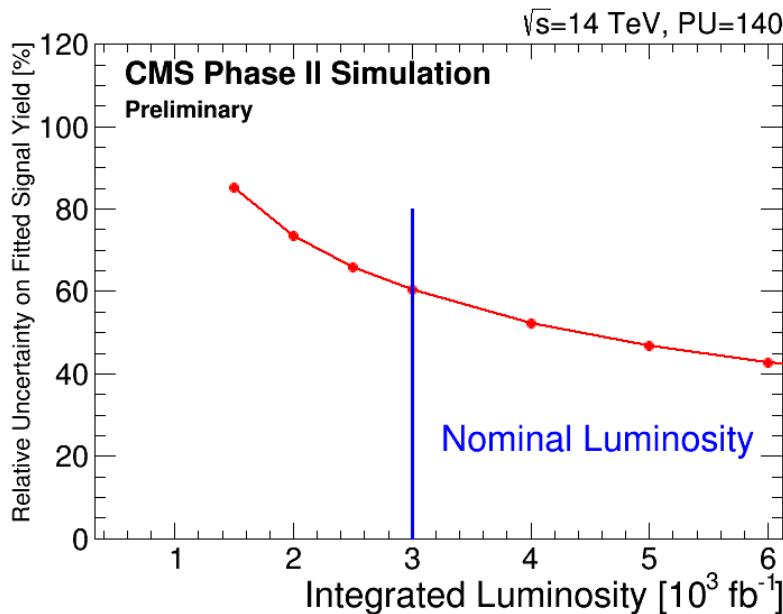
- b-tagging performance
  - 75% b-tagging efficiency
  - 20% charm jet efficiency
  - 1% light jet efficiency
- 61% (58%) photon selection efficiency in barrel (endcap)
  - 1% electron->photon fake rate
  - (0.1-0.5)% jet->photon fake rate
- Will be updated to CMS phase II detector performance numbers for TP: work in progress



# CMS results

Process / Selection Stage	$HH$	$ZH$	$t\bar{t}H$	$b\bar{b}H$	$\gamma\gamma + \text{jets}$	$\gamma + \text{jets}$	$\text{jets}$	$t\bar{t}$
Object Selection & Fit Mass Window	22.8	29.6	178	6.3	2891	1616	292	113
Kinematic Selection	14.6	14.6	3.3	2.0	128	96.9	20	20
Mass Windows	9.9	3.3	1.5	0.8	8.5	6.3	1.1	1.1

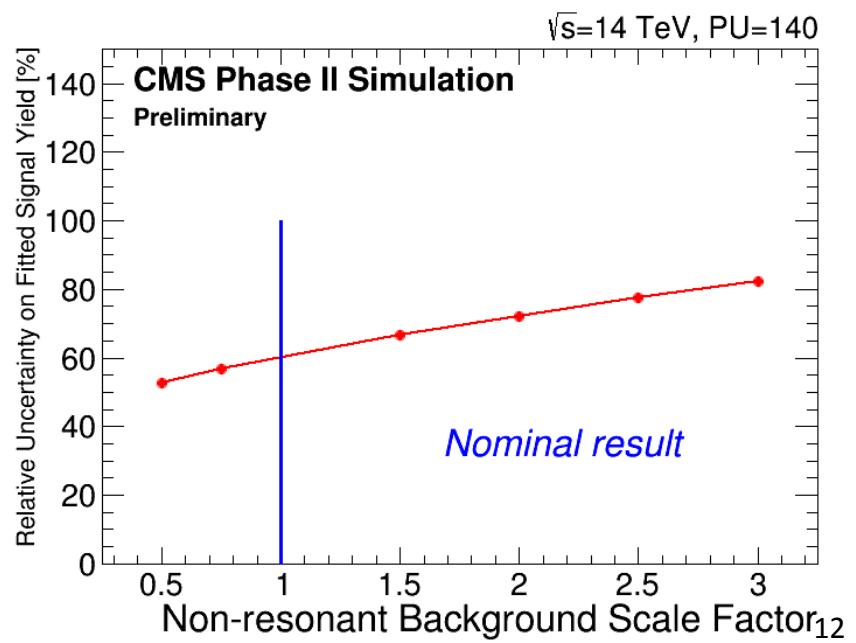
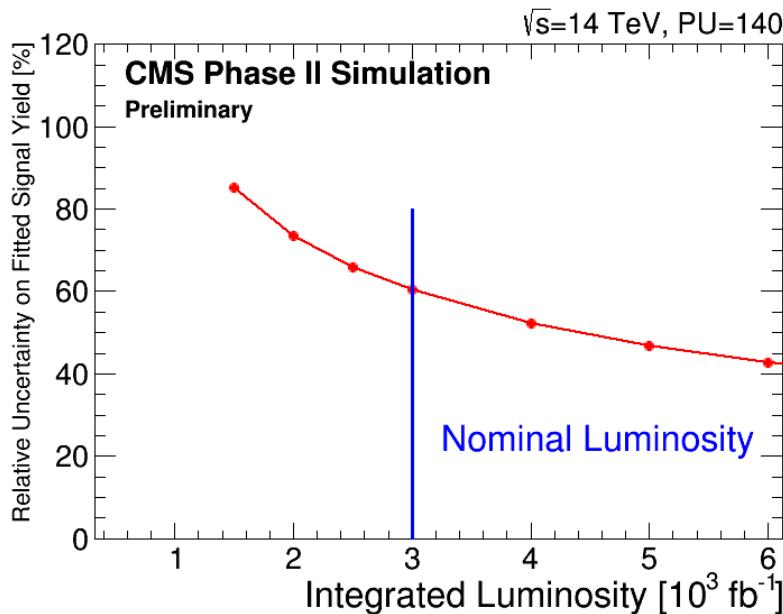
Table 3: The expected event yields of the signal and background processes for  $3000 \text{ fb}^{-1}$  of integrated luminosity are shown at various stages of the cut-based selection for the both photons in the barrel region. Mass window cuts are 120 GeV to 130 GeV for  $M_{\gamma\gamma}$  and 105 GeV to 145 GeV for  $M_{bb}$ . A large fit mass window, 100 GeV to 150 GeV for  $M_{\gamma\gamma}$  and 70 GeV to 200 GeV for  $M_{bb}$ , is used for the likelihood fit analysis. The statistical uncertainties on the yields are of the order of percent or smaller.



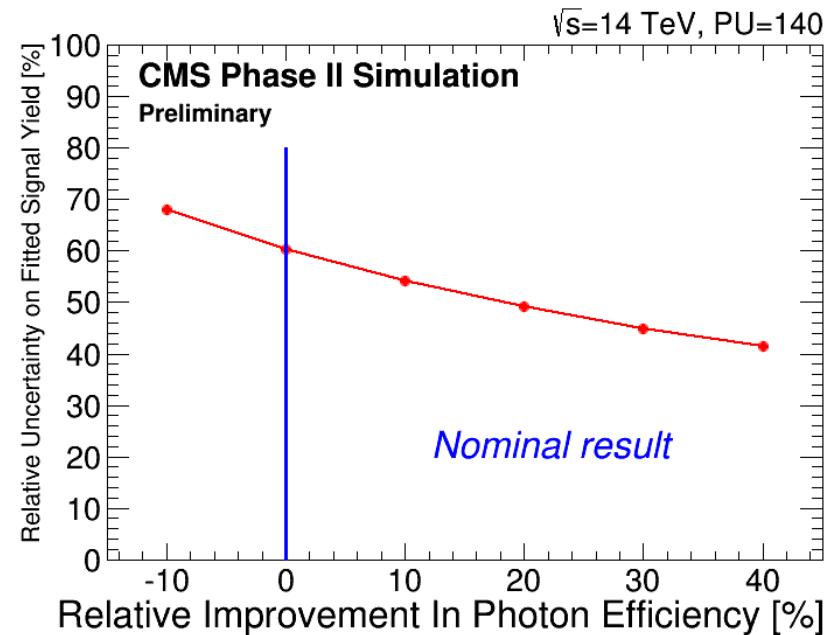
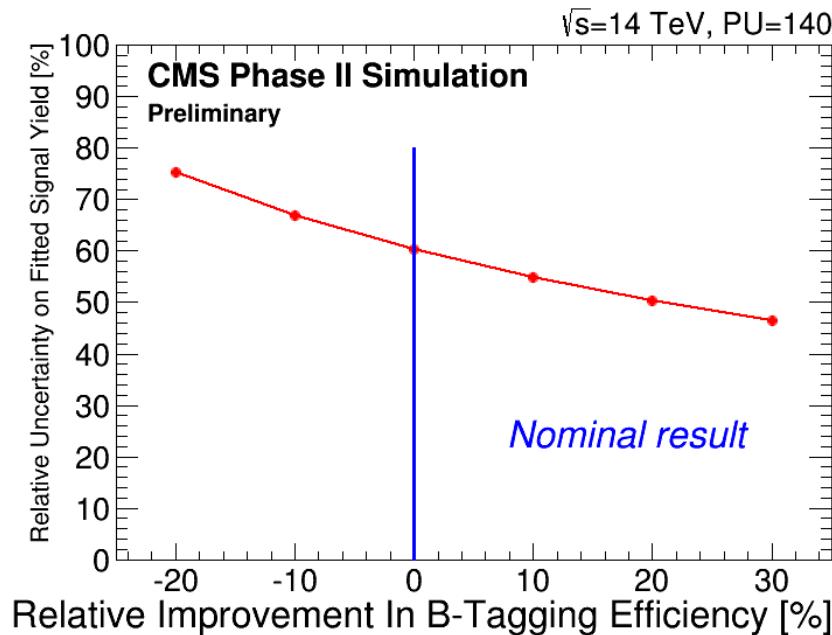
# CMS results

Process / Selection Stage	$HH$	$ZH$	$t\bar{t}H$	$b\bar{b}H$	$\gamma\gamma + \text{jets}$	$\gamma + \text{jets}$	$\text{jets}$	$t\bar{t}$
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# Impact of upgrade improvements



- The average expected relative uncertainty on the di-Higgs cross section measurement is shown as a function of the b-tagging efficiency (left) and the photon efficiency (right).

# $b\bar{b}\tau\tau$ analysis overview

---

- Challenging analysis
  - Overwhelming  $t\bar{t}$  background
- $\tau_\mu \tau_h$ , and  $\tau_h \tau_h$  final states are considered
  - The most sensitive channels
- Analysis strategy
  - Using Delphes fast simulation (tuned to Phase II performance)
  - Select events compatible with  $h \rightarrow \tau\tau$  and  $h \rightarrow b\bar{b}$  decays
  - Fit for signal using  $m_{T2}$  mass variable ( $\tau_h \tau_h$ ) or BDT discriminant ( $\tau_\mu \tau_h$ )

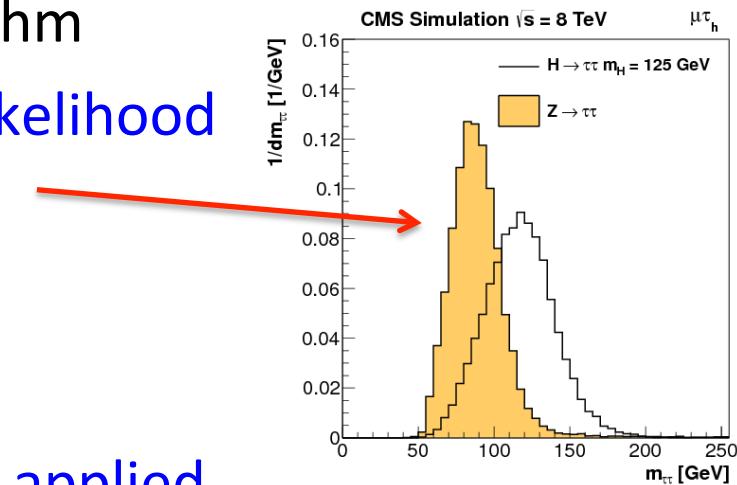
# Object selection

---

- Two b-tagged jets:  $|\eta| < 2.4$  and  $p_T > 30 \text{ GeV}$ 
  - ~65% b-tagging efficiency with 10% fake rates for c-jets
- Two final di-tau states considered
  - $\tau_\mu \tau_h$  final state
    - 1 tau tagged jets ( $|\eta| < 2.1$ ) and 1 muon ( $|\eta| < 2.5$ ) with  $p_T > 30 \text{ GeV}$
  - $\tau_h \tau_h$  final state
    - 2 tau tagged jets with  $|\eta| < 2.1$  and  $p_T > 60 \text{ GeV}$  (or leading  $p_T > 90 \text{ GeV}$  and sub-leading  $p_T > 45 \text{ GeV}$ )
- Jets originating from hadronic  $\tau$  decays required to contain an isolated track
  - Reduces backgrounds with light jets faking hadronic taus
  - Efficiency of tau identification: ~55% with <0.5% of fake rate

# Mass window cuts

- Missing energy resolution is critical for di-tau mass reconstruction and  $m_{T2}$ 
  - 20 GeV resolution
  - Achievable with sophisticated pileup rejection techniques
- $m_{\tau\tau}$  mass reconstruction algorithm
  - Event by event maximum likelihood
  - Used for Run 1 H- $\rightarrow\tau\tau$  result
  - $110\text{GeV} < m_{\tau\tau} < 140\text{GeV}$
- $m_{bb}$  mass
  - No b-jet energy corrections applied
  - $90\text{GeV} < m_{bb} < 130\text{GeV}$



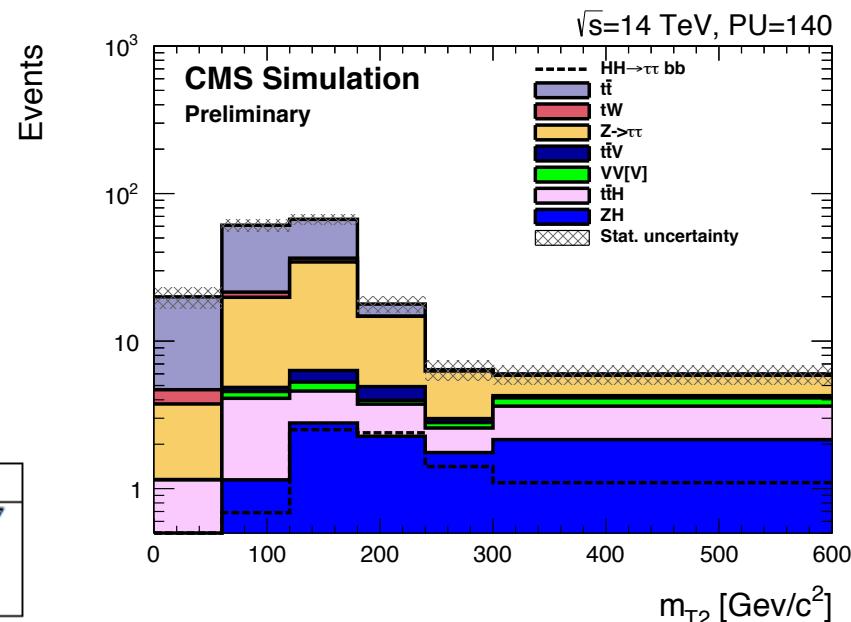
# $\tau_h \tau_h$ results

- Stransverse mass (\*) variable  $m_{T_2}$  to separate  $t\bar{t}$  from signal
  - $t\bar{t}$  bounded above by  $m_{top}$
  - SM hh can reach  $\sqrt{s}/2$
- Fit the full spectrum for signal
- Significance  $\sim 0.7\sigma$

Selection	$HH$	$ZH$	$t\bar{t}H$	$Z \rightarrow \tau\tau$
Baseline selection	$23.6 \pm 0.5$	$104.7 \pm 3.5$	$204.6 \pm 5.8$	$479.3 \pm 7.7$
Mass windows	$8.3 \pm 0.3$	$10.1 \pm 1.0$	$9.8 \pm 1.3$	$60.3 \pm 3.3$
Signal	$4.9 \pm 0.2$	$6.2 \pm 0.8$	$3.8 \pm 0.8$	$14.7 \pm 1.6$

Selection	$t\bar{t}$	$tW$	$t\bar{t}V$	$VV(V)$
Baseline selection	$7662 \pm 69$	$734.4 \pm 19.4$	$189.4 \pm 10.0$	$128.9 \pm 16.7$
Mass windows	$88.4 \pm 7.5$	$4.8 \pm 1.6$	$2.7 \pm 0.9$	$2.1 \pm 0.7$
Signal	$3.2 \pm 1.4$	$0.1 \pm 0.1$	$1.3 \pm 0.7$	$1.0 \pm 0.5$

Signal region= $m_{T_2} > 180$  GeV



(\*) arXiv:1309.6318v1

# $\tau_\mu \tau_h$ and combined results

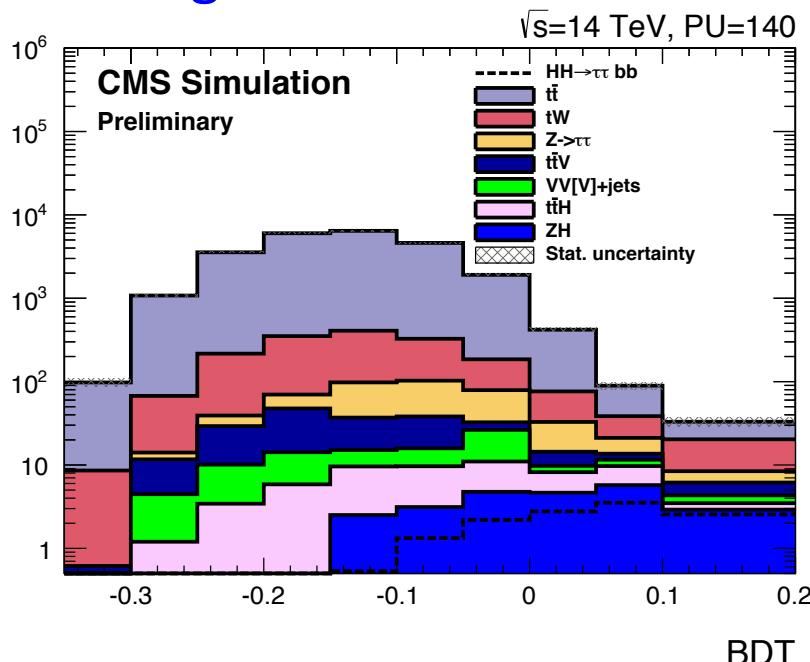
- BDT discriminant for signal extraction
  - Exploit the boosted kinematics of the signal
- Significance  $\sim 0.5\sigma$

Selection	$HH$	$ZH$	$t\bar{t}H$	$Z \rightarrow \tau\tau$
Baseline selection	$39.2 \pm 0.6$	$213.7 \pm 4.7$	$1175.8 \pm 12.9$	$3711.7 \pm 34.1$
Mass window	$13.0 \pm 0.4$	$24.4 \pm 1.5$	$37.7 \pm 2.3$	$234.5 \pm 8.6$
Signal	$6.1 \pm 0.3$	$8.6 \pm 0.9$	$4.5 \pm 0.8$	$9.7 \pm 1.7$

Selection	$t\bar{t}$	$tW$	$t\bar{t}V$	$VV(V)$
Baseline selection	$(3.84 \pm 0.00) \times 10^5$	$(3.72 \pm 0.00) \times 10^4$	$4154 \pm 39$	$1418 \pm 90$
Mass window	$(2.3 \pm 0.0) \times 10^4$	$1232 \pm 33$	$119.4 \pm 7.4$	$49.6 \pm 2.3$
Signal	$63.5 \pm 7.3$	$29.2 \pm 4.8$	$3.9 \pm 1.3$	$2.7 \pm 0.7$

Signal region =  $bdt > 0.05$

Events



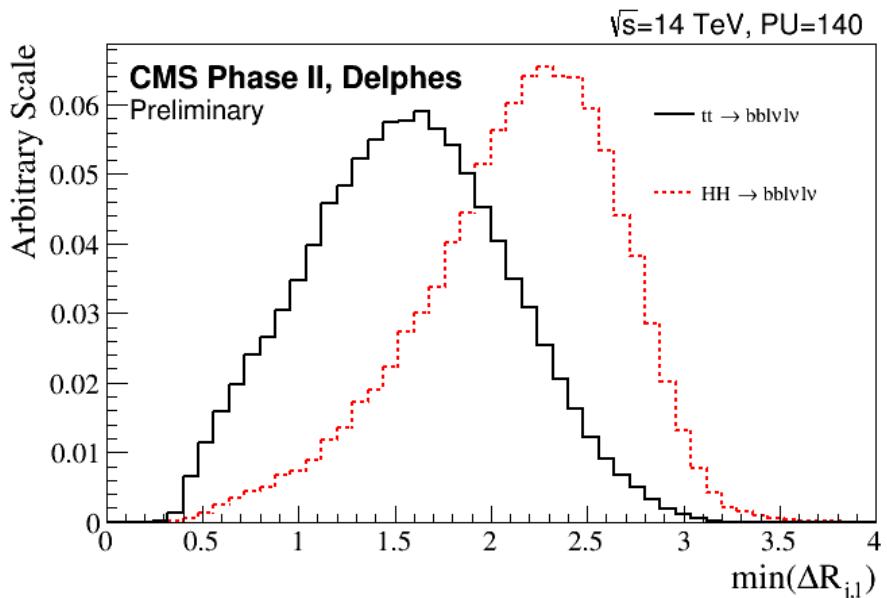
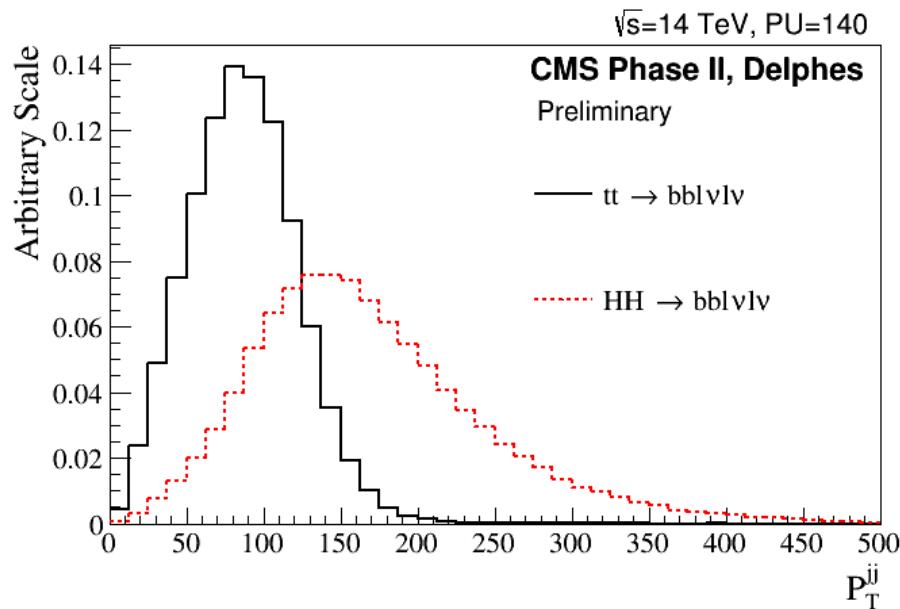
- Combined result:
  - Significance of  $\sim 0.9 \sigma$
  - Uncertainty on the cross section:  $\sim 115\%$

# HH->bbWW analysis description

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- Search for  $\text{HH} \rightarrow \text{bbWW} \rightarrow \text{bbllll}$ 
  - Based on Delphes fast simulation tuned to CMS Phase II detector
  - Considering only the main  $t\bar{t}$  background
  - The rest of the SM processes are negligible
- Event pre-selection:
  - 2 b-jets Medium WP,  $p_T > 30 \text{ GeV}$   
2 leptons, muons:  $p_T > 20 \text{ GeV}$ , electrons:  $p_T > 25 \text{ GeV}$
  - MET  $> 20 \text{ GeV}$   
Clean up cuts ( $m_{jj}, m_{||}, \Delta R_{jj}, \Delta R_{||}, \Delta \phi_{jj,||}$ )
- Analysis Optimization:
  - Neural network discriminant from kinematic variables
  - Variables:  $M_{||}, M_{jj}, \Delta R_{||}, \Delta R_{jj}, \Delta R_{j||}, \text{MET}, \Delta \phi_{||,jj}, p_{jj}, \text{and } M_{\tau}$

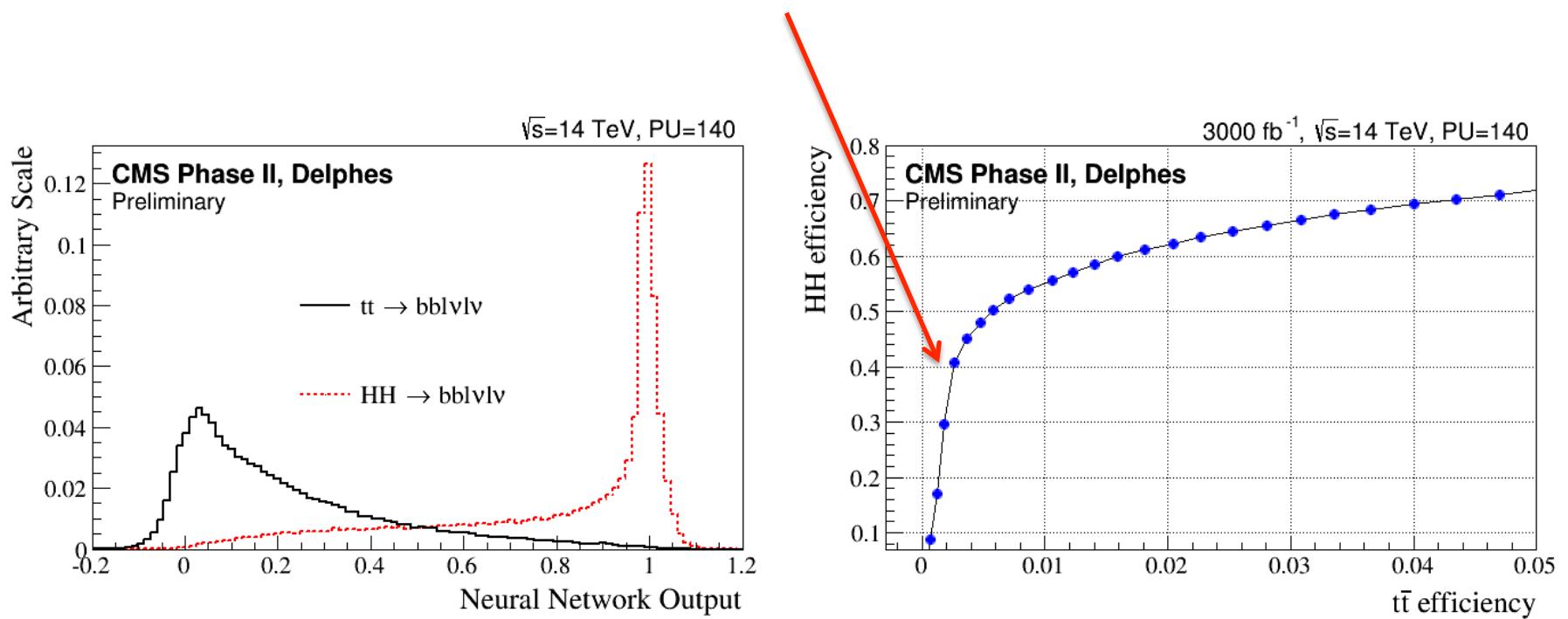
# Input variables to Neural Network



- (Left)  $p_{jj}$  distribution comparing the  $HH$  and  $tt$  shape differences. Variable used as input for the Neural Network discriminator.
- (Right)  $\min(\Delta R_{j,l})$  distribution comparing the  $HH$  and  $tt$  shape differences. Variable used as input for the Neural Network discriminator.

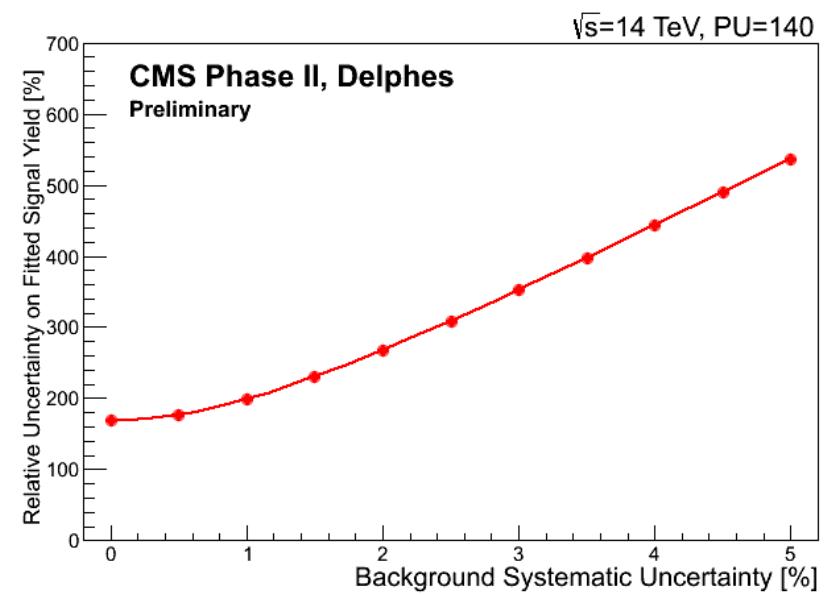
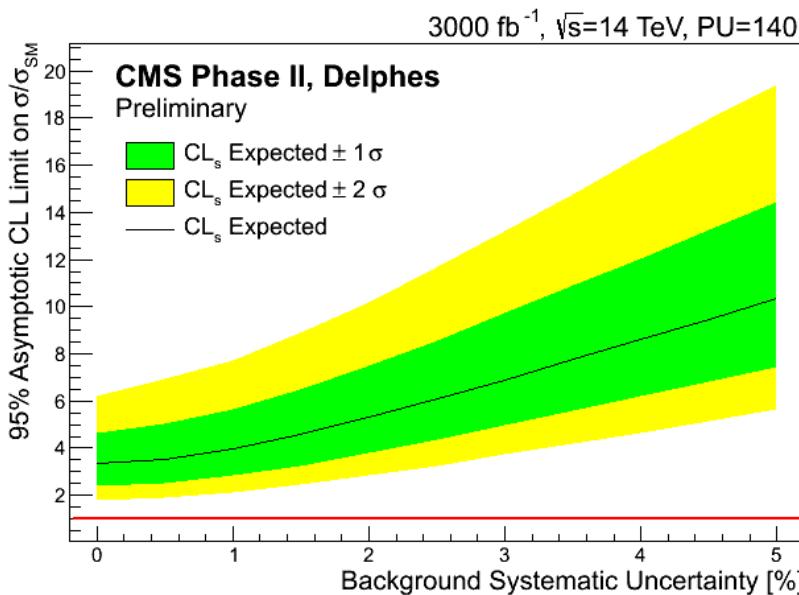
# HH->bbWW analysis

- Neural Network discriminant to suppress tt
  - Signal region: Neural Network output > 0.97



# HH->bbWW results

- Results are quoted as a function of the background systematic uncertainty
  - Data driven techniques will likely constrain the uncertainties to the percent level



# Summary

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- Preliminary Higgs pair-production studies by ATLAS and CMS experiments
  - $bb\gamma\gamma$ ,  $bb\tau\tau$ , and  $bbWW$  final states investigated
  - Both experiments assume Phase II detector performance
  - Combination of several channels and results from both experiments will be useful to claim evidence
- Results can be further improved
  - Investigation of additional final states (e.g.  $bbbb$ )
  - Identification techniques for boosted topologies
- BSM non-resonant di-Higgs production accessible in Run 2

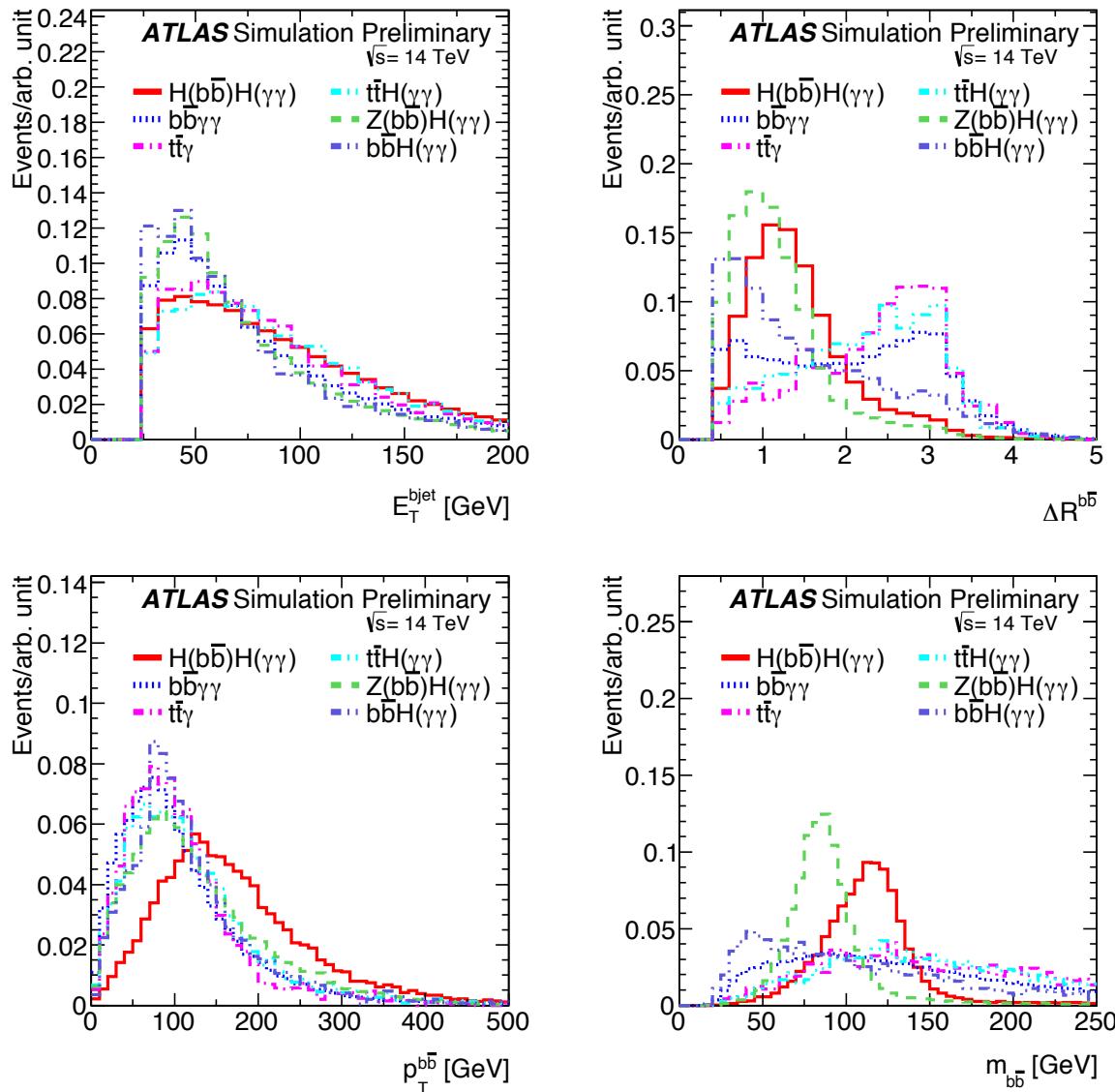
# **BACKUP**

# Delphes

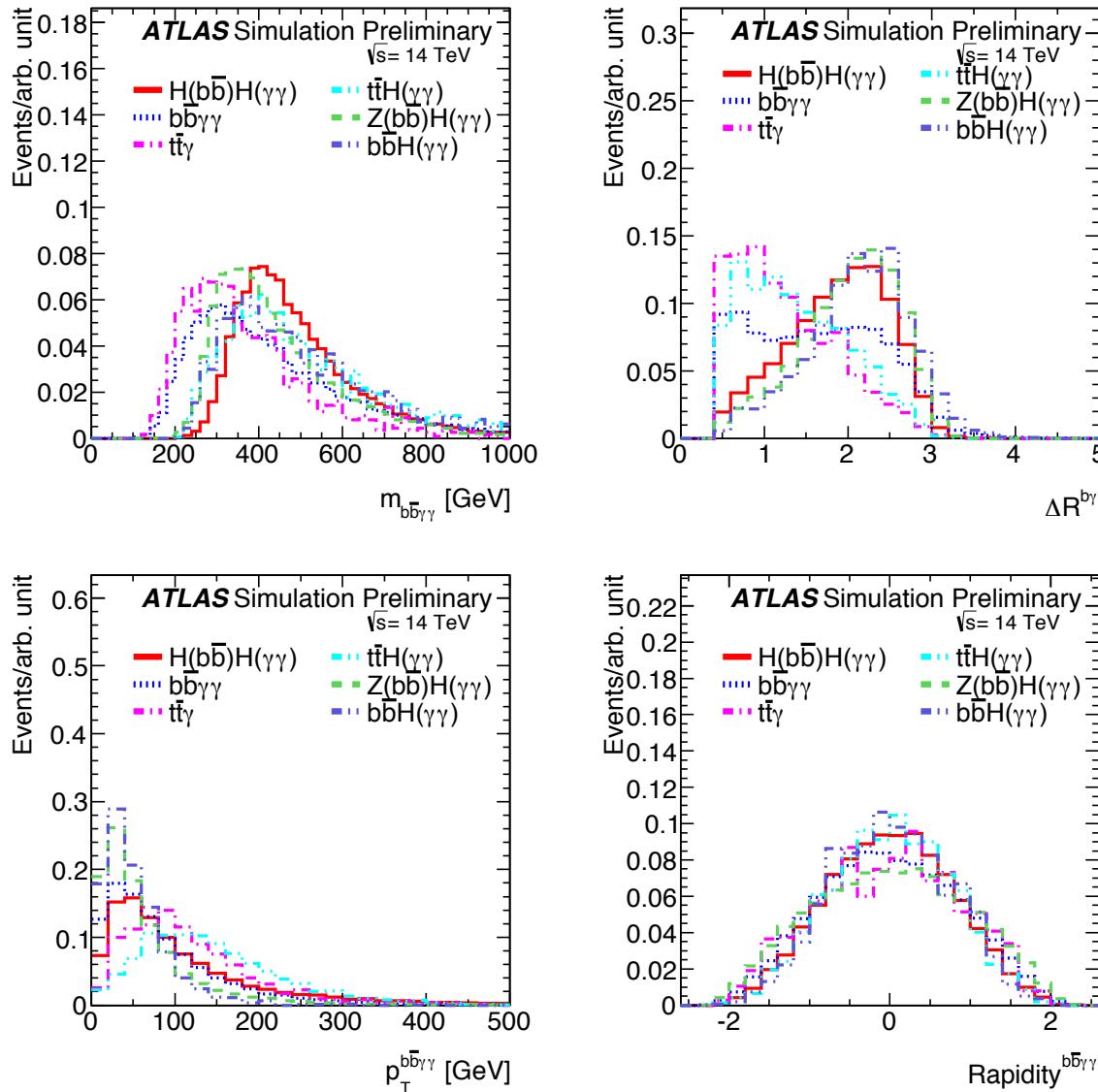
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- Delphes fast simulation for upgrade studies
  - Track propagation system embedded in magnetic field
  - Electromagnetic and hadronic calorimeters
- What Delphes does ‘quasi-realistically’
  - Jets
  - Missing Energy
  - Object Isolation
  - Impact of Pileup on the above
- What Delphes does parametrically
  - Electron/Muon reconstruction efficiency
  - Electron/Muon resolution
  - B-tagging and Tau ID efficiency

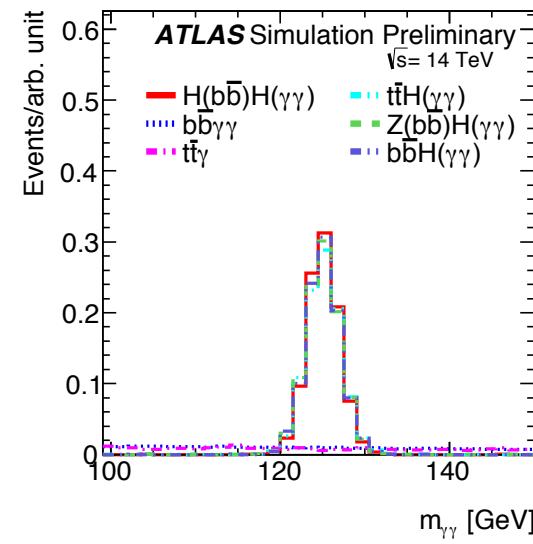
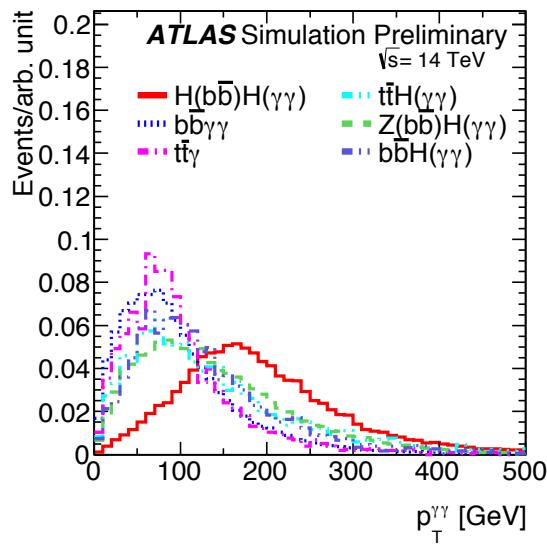
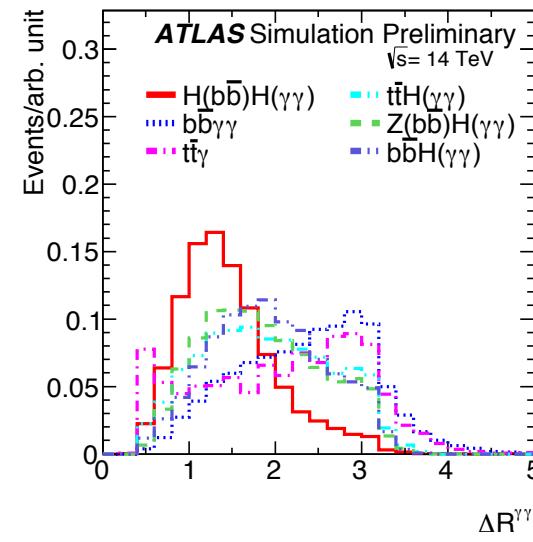
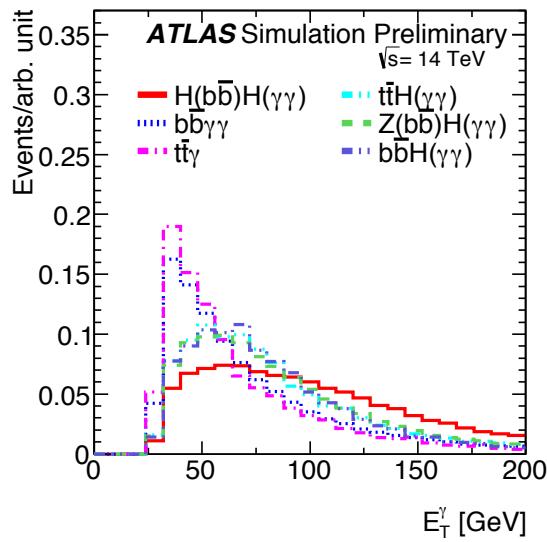
# Kinematic distributions: $b\bar{b}\gamma\gamma$



# Kinematic distributions: $b\bar{b}\gamma\gamma$



# Kinematic distributions: $b\bar{b}\gamma\gamma$



# BSM models

