HH production at the High-Luminosity LHC with CMS

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on behalf of CMS collaboration

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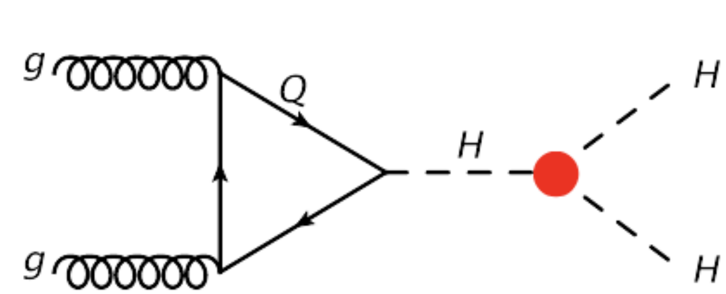
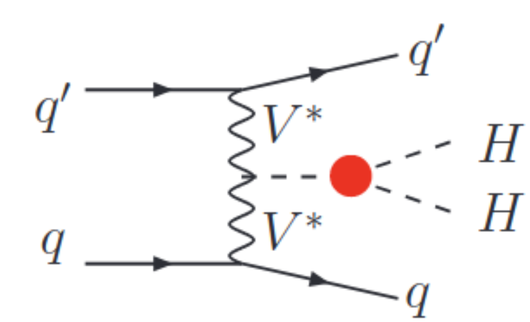
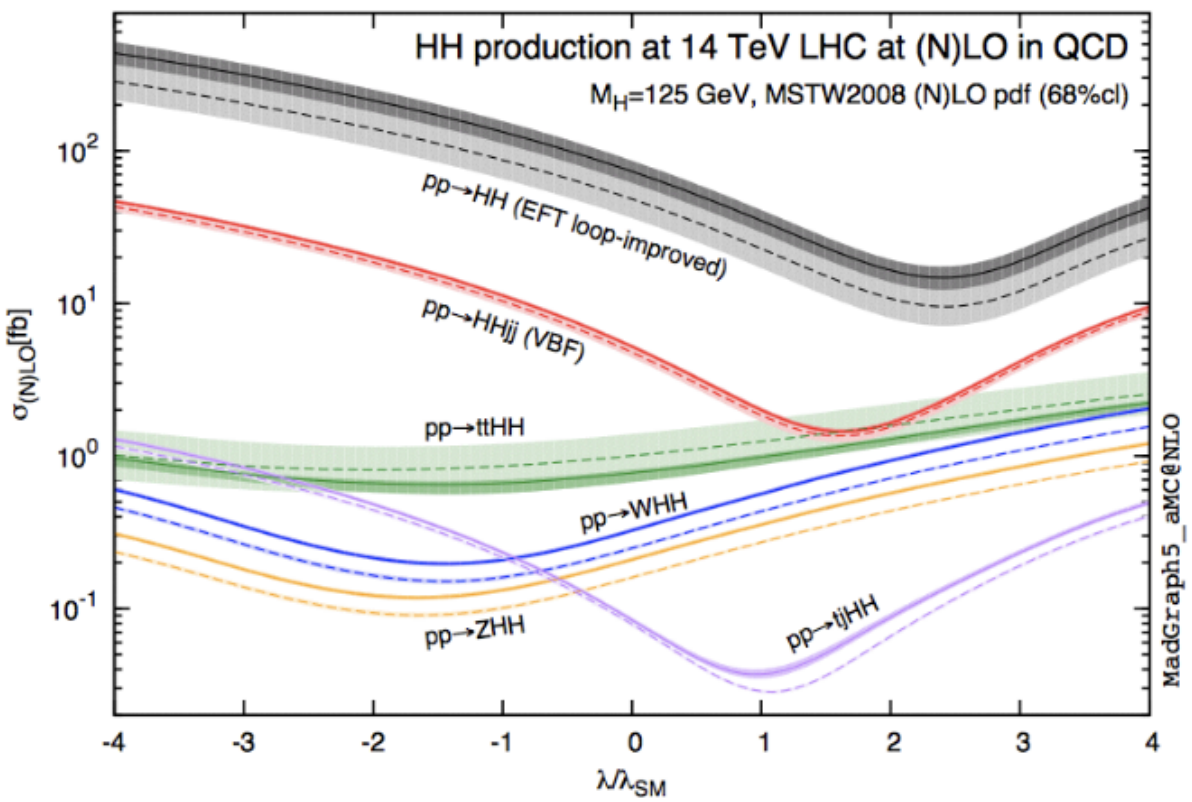


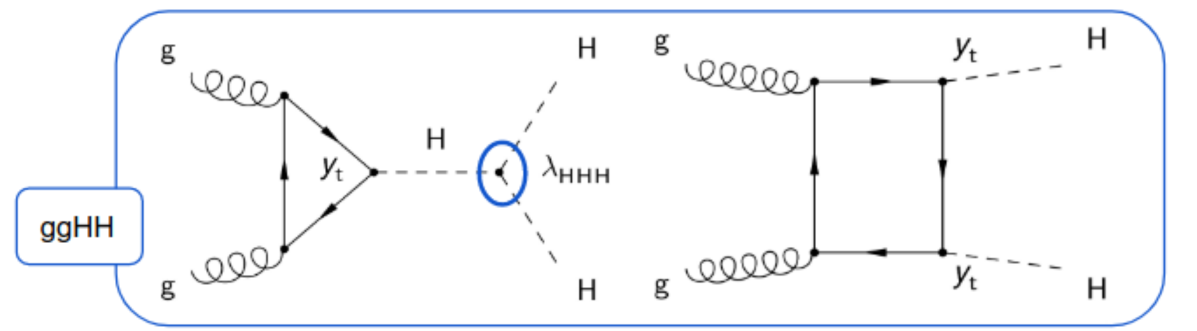


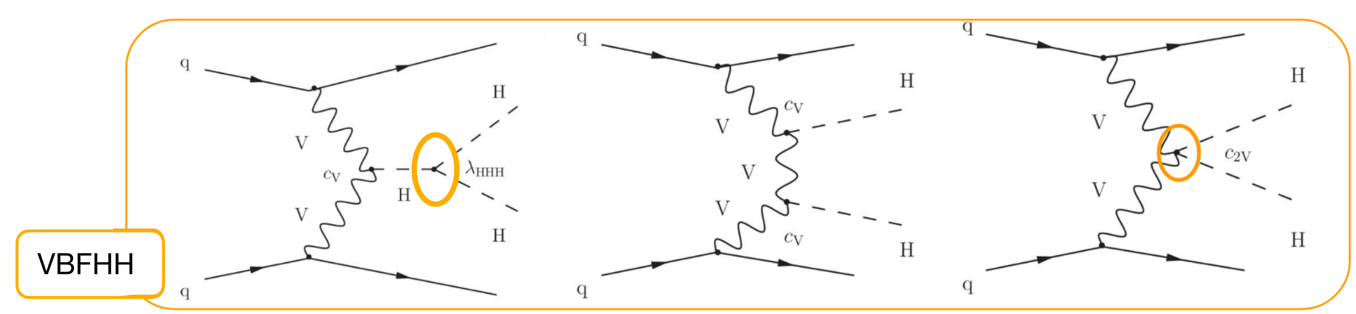
- HH production can be used to directly study Higgs boson self-coupling and Higgs potential
- Extremely challenging to measure at LHC but accessible at HL-LHC

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 \qquad \kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

- λ_3 probed via HH production







HL-LHC Timeline

- An objective of increasing the integrated luminosity by **a factor of 10** beyond the LHC's design value
- Detector upgrades to cope with higher pileup (**200**) and radiation damage
  - Installation of upgraded detectors planned to take place between 2026 and 2028

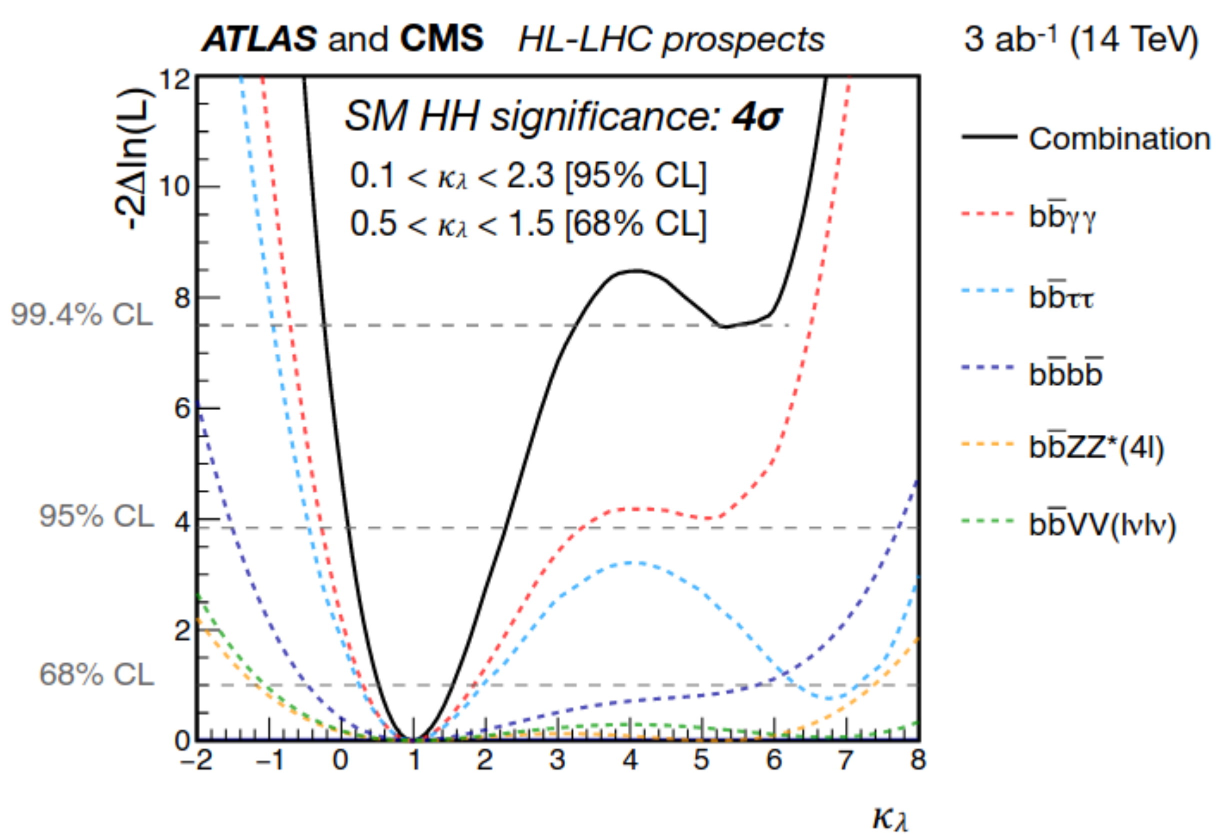
- Higgs production at HL-LHC: 170M Higgs bosons - **120k HH pairs** for 3 ab-1

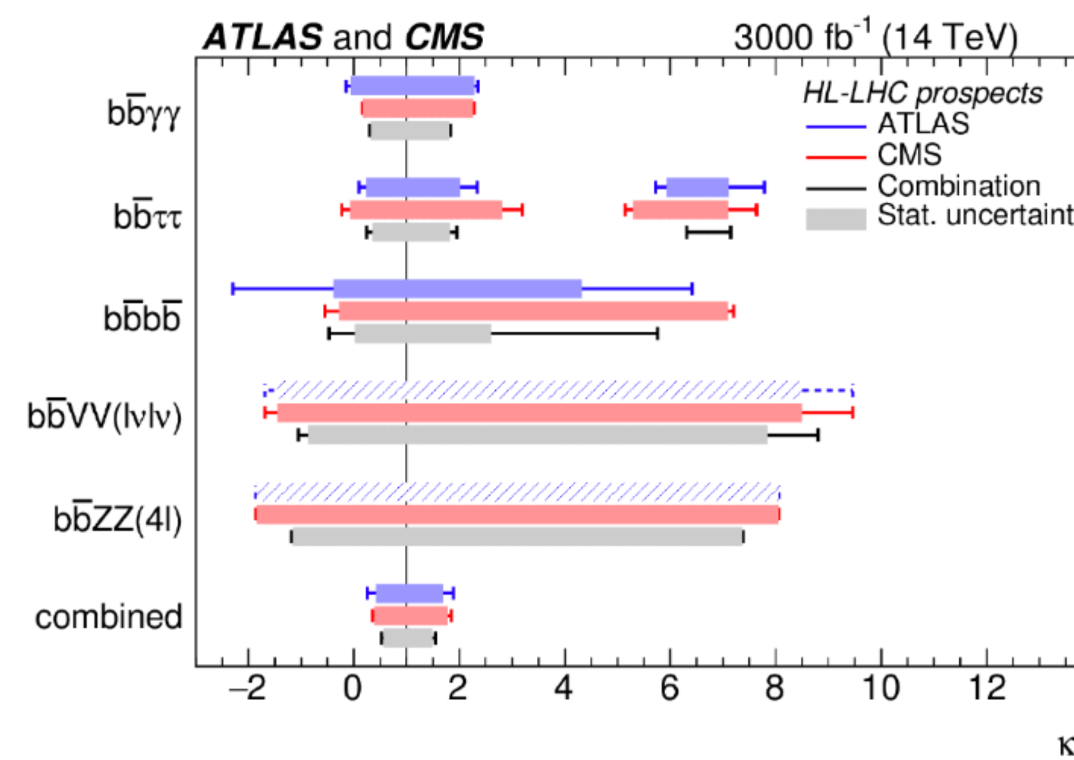
Overview of HL-LHC Studies

arXiv:1902.00134

- Yellow Report '18: Higgs Physics at the HL-LHC and HE-LHC
  - Five decay channels were explored (only in ggHH mode)
  - HH production expected to reach 4.0σ significance with CMS + ATLAS combination
  - Accessible to Higgs self-coupling: 50% precision from ggHH mode

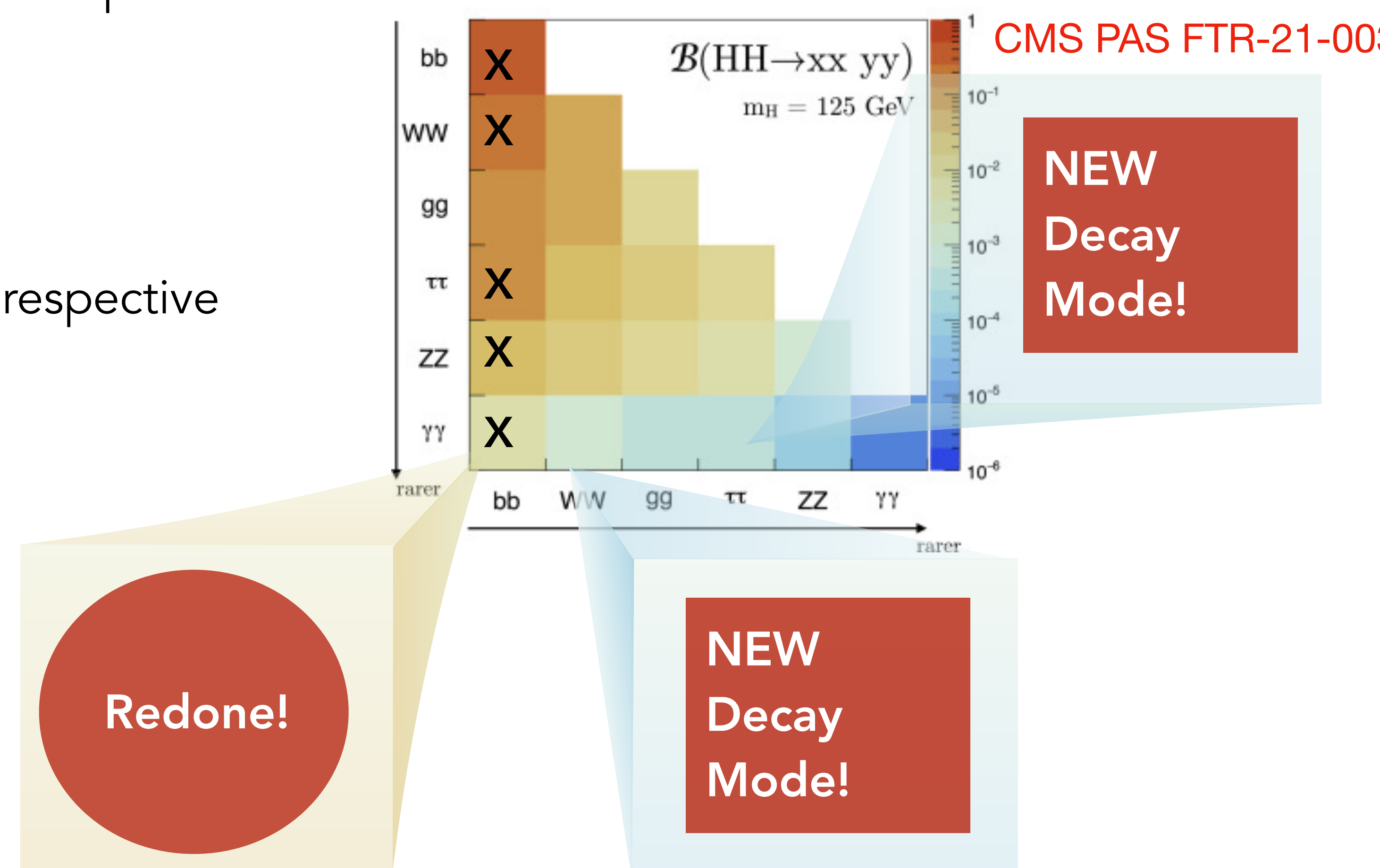
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	





- Analyses performed with DELPHES CMS HL-LHC samples
- Systematic uncertainties same as YR '18
- One decay mode redone
- Addition of two new decay modes
- Analysis strategy based on Run-2 Analysis of the respective channel
- New production mode explored: **ttHH**
- All non-resonant searches

X: Explored in YR '18



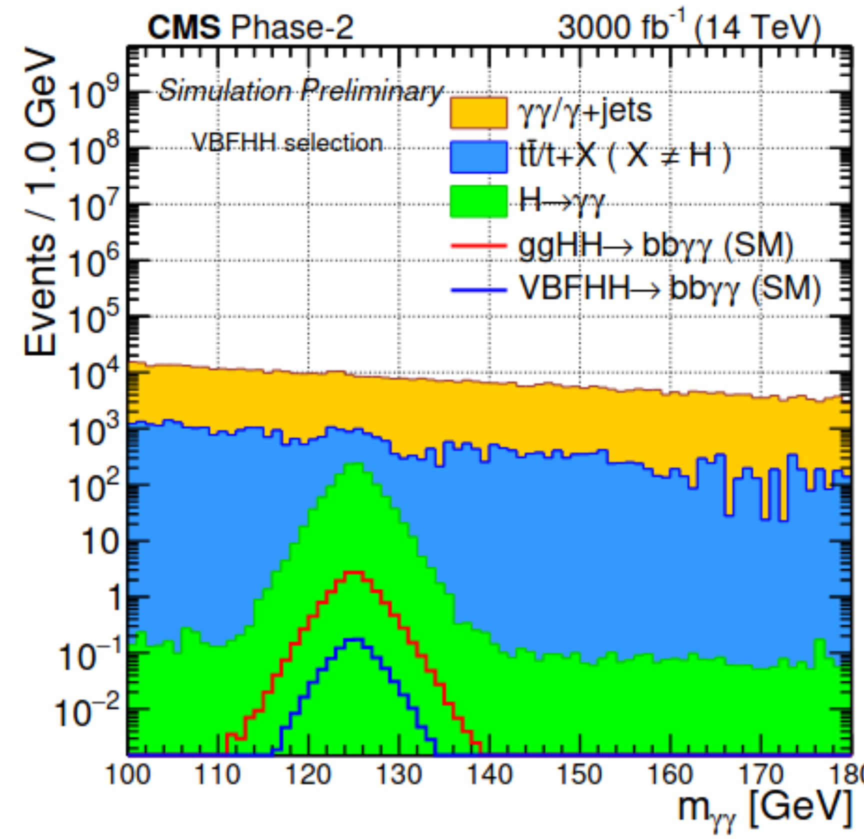
CMS PAS FTR-21-004

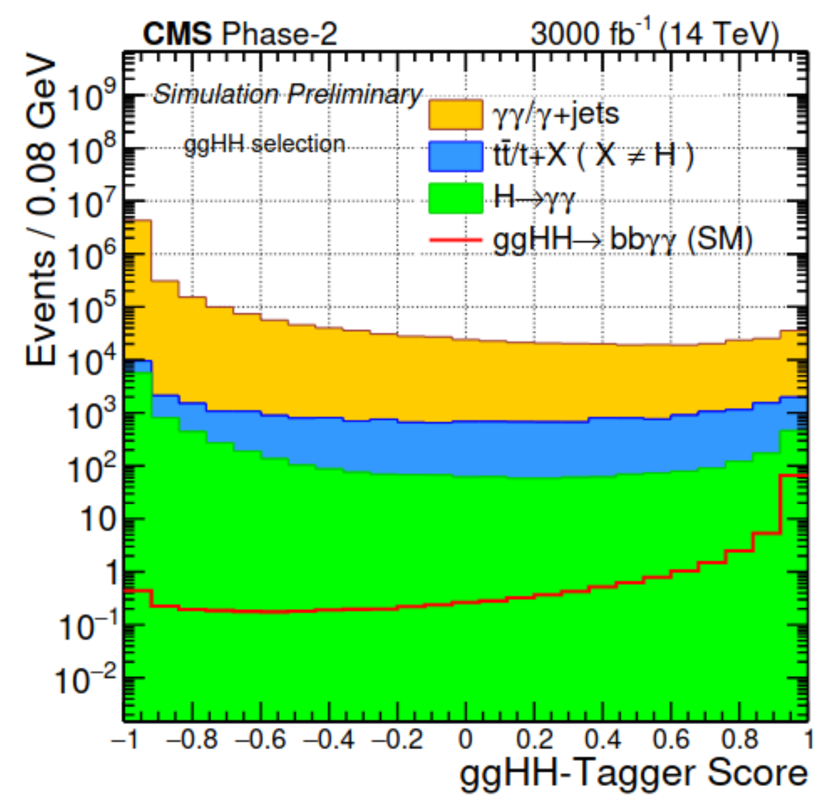
CMS PAS FTR-21-003

- The large BR (about 58%) for the decay H → bb combined with the rare (BR of about 0.2%) but distinguishable decay mode of H → γγ makes **bbγγ** highly sensitive for studying the HH production
- Redone for ggHH production mode, also added **VBFHH**
- Backgrounds of two types:
    - Resonant/Single Higgs Bkg
    - Non-Resonant/Continuum Bkg
- VBFHH selection characterized by the presence of two additional energetic jets at the high |η| region
    - The events without the VBF jets form the ggHH-selection
- Categorization based on four-body mass + MVA score

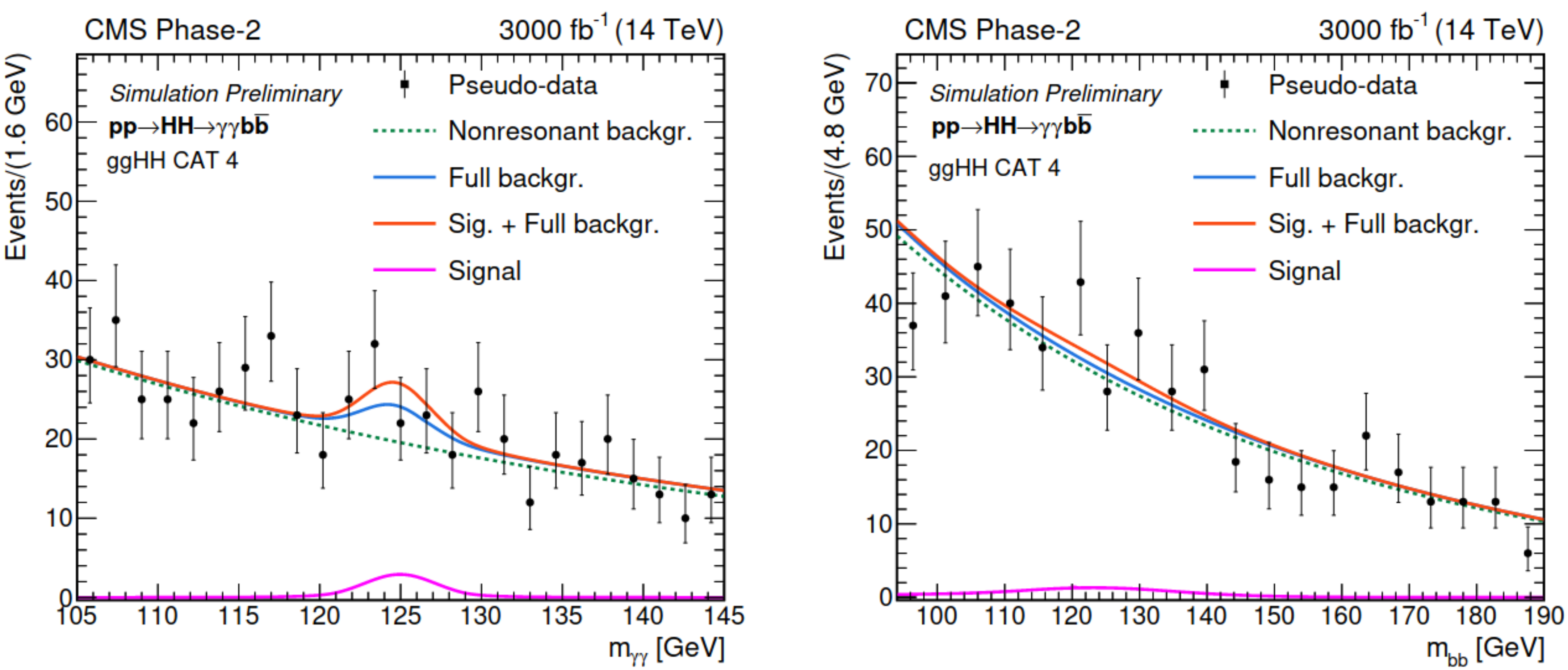
$$\boxed{\widetilde{M}_X = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250\ \mathrm{GeV}}$$

- MVA for signal vs bkg discrimination
    - BDT, ttH Killer
    - NN, ggHH and VBFHH tagger



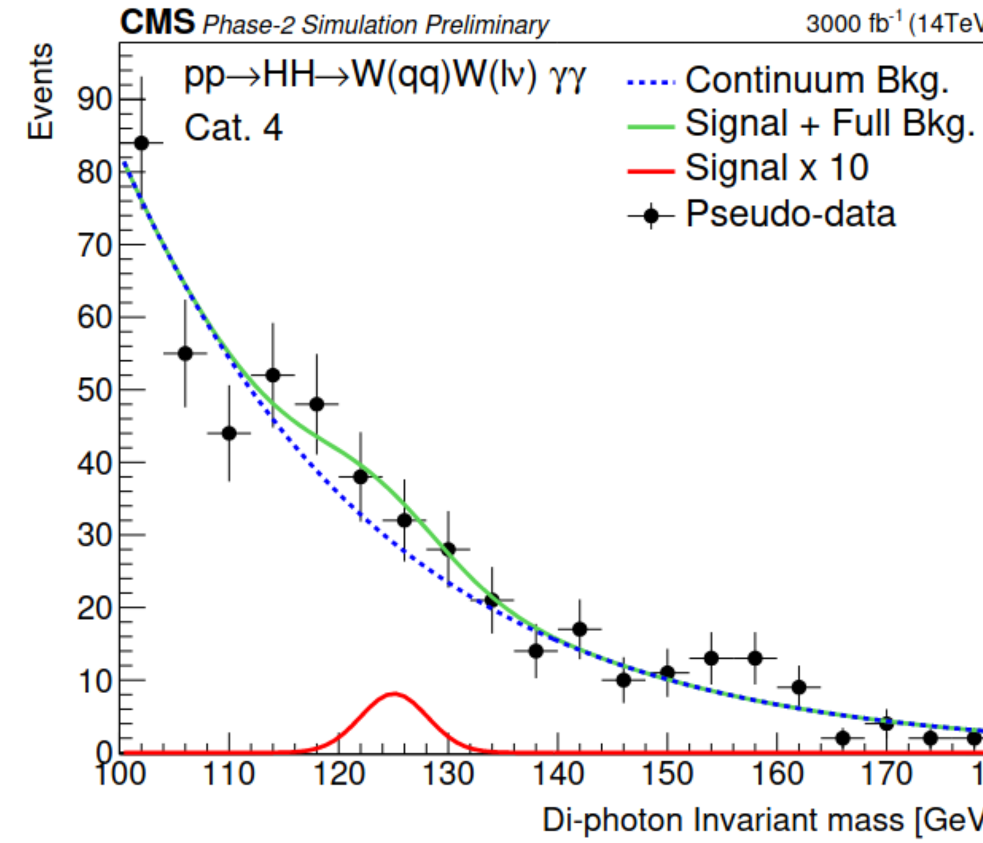


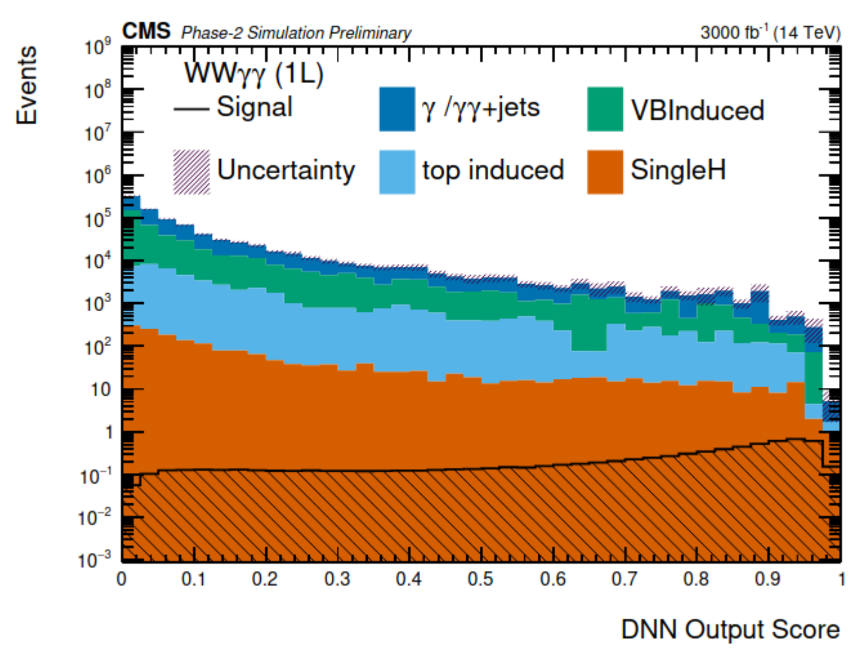
- Compared to YR'18:
  - Improved ttH rejection (from 75% rejection to 85% (ggHH) and 90% (VBFHH))
  - Improved photon and b-jet identification (new MTD detector)
- Signal extraction with 2D fit in mbb and m**γγ**

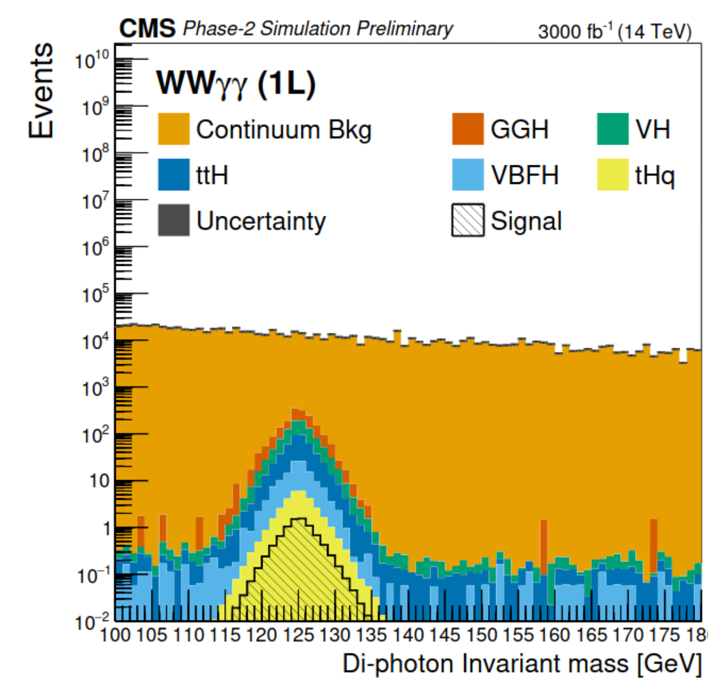


- The extracted significance for the inclusive HH signal is **2.16 σ** including systematic uncertainties
  - YR '18 significance 1.8**σ**

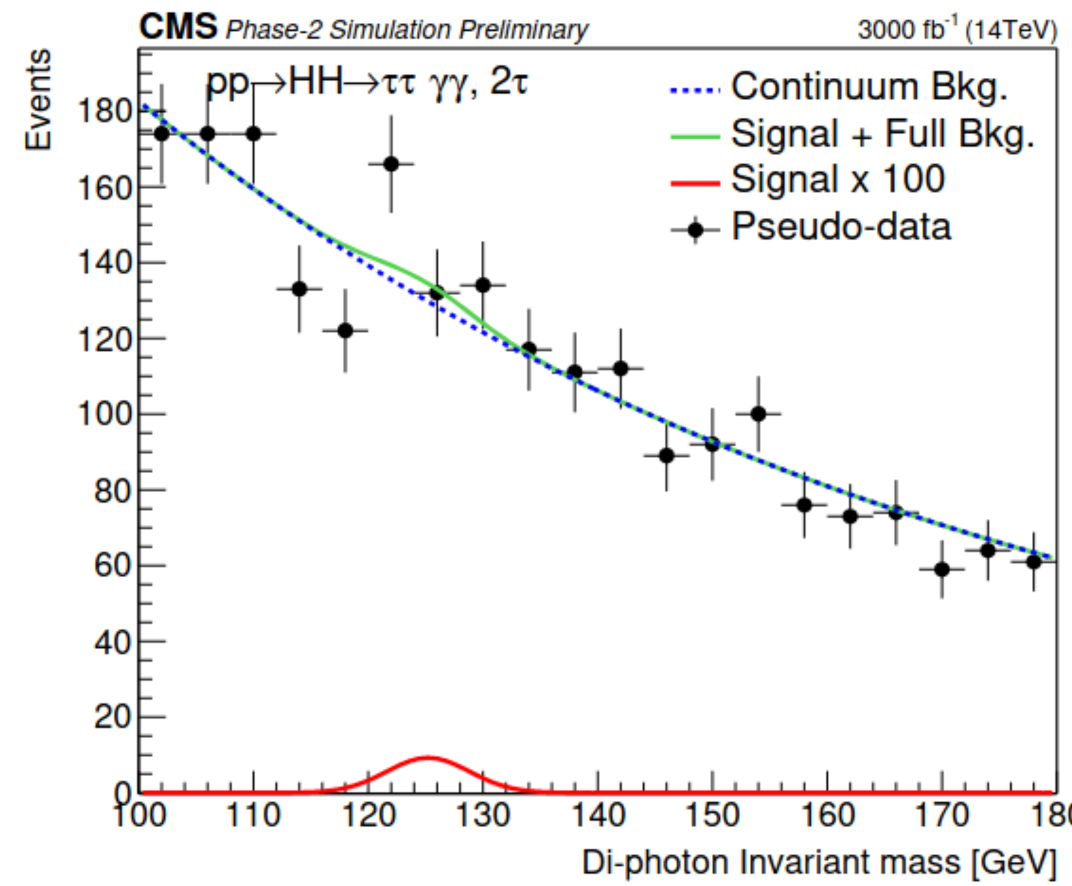
- The first study providing significance numbers for HL-LHC in this channel
  - Benefiting from the distinguishable H → γγ process
  - Out of three decay modes of W boson (**WW→qqlv**, **WW→lvlv**, WW→qqqq,) two are studied
  - Fully-hadronic final state was dropped because of the lack of QCD bkg (the dominant bkg) modelling
- Considered only ggHH production mode
- Backgrounds of two types:
  - Resonant/Single Higgs Bkg
  - Non-Resonant/Continuum Bkg
- Categorization based on lepton number in the final state
  - number of τs kept at zero to stay exclusive w.r.t **ττγγ**
- Multi-class DNNs as the discriminator
- Signal extraction with 1D fit in mγγ
- The extracted significance for the HH signal is **0.21σ** including systematic uncertainties

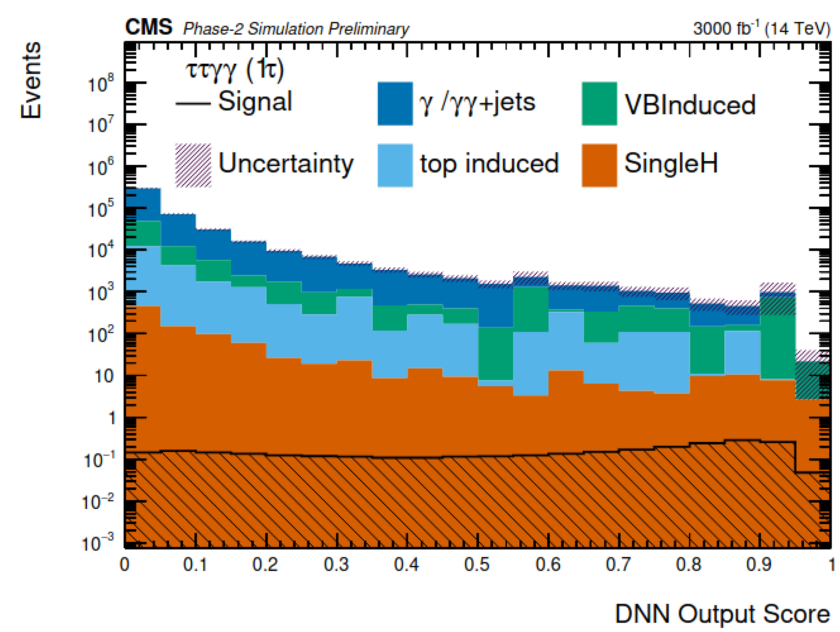


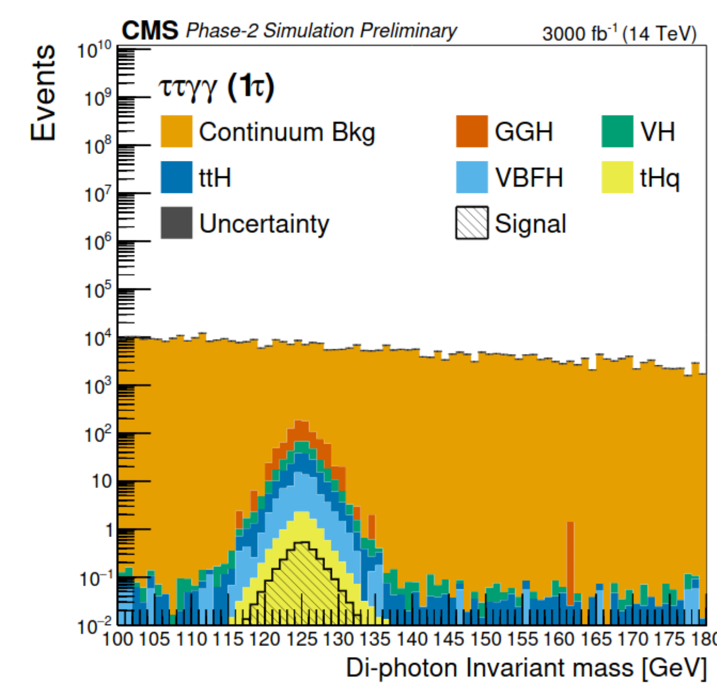


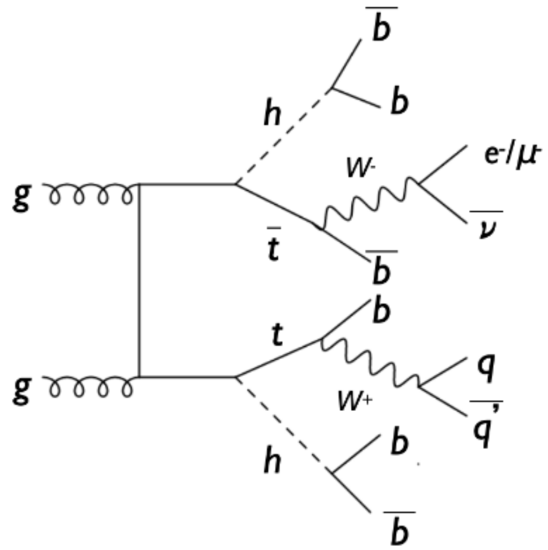


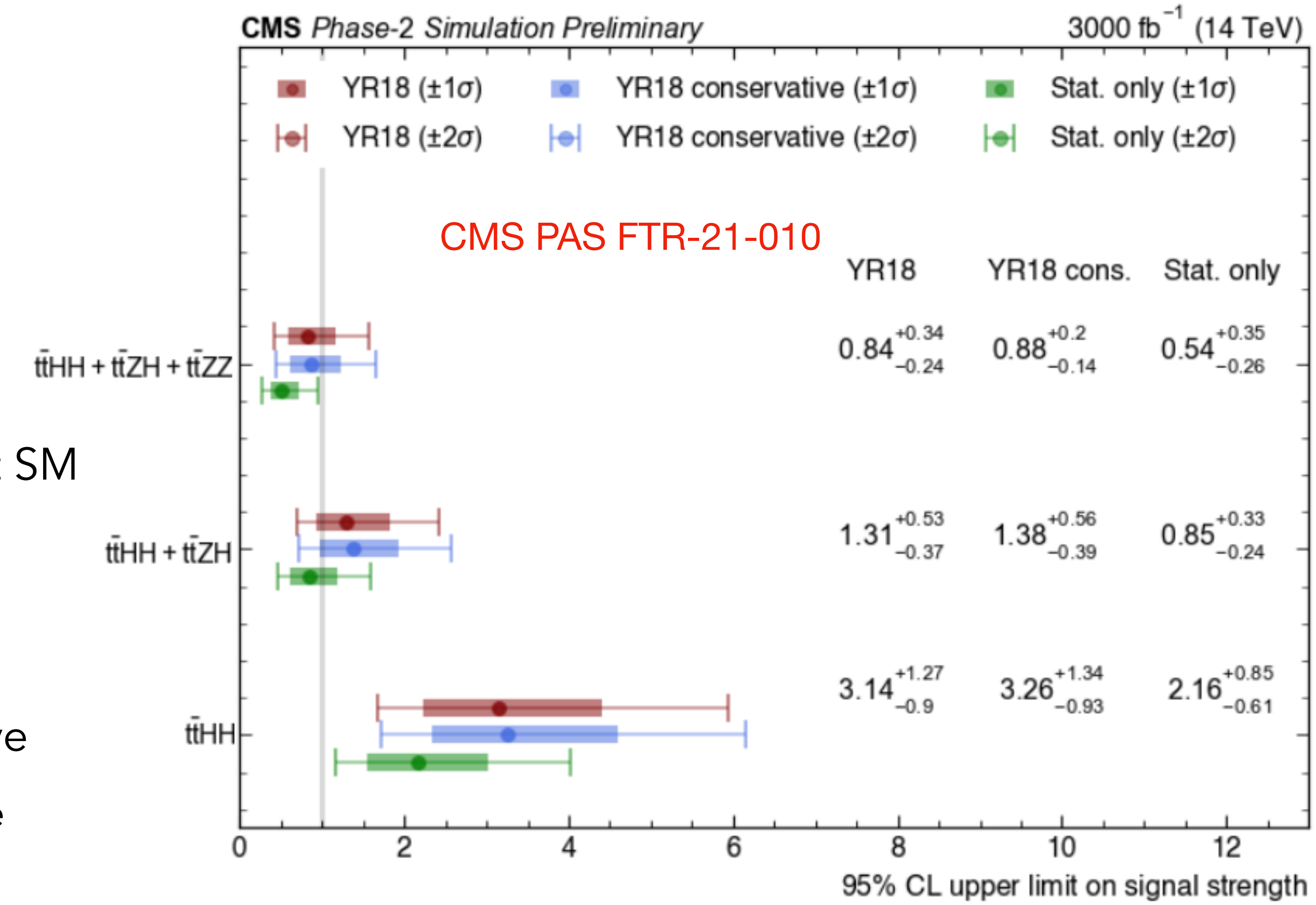
- The first study providing significance numbers for HL-LHC in this channel
  - Benefiting from the distinguishable H → γγ process
  - Explored in two final states; 1**τ** and 2**τ**
- Considered only ggHH production mode
- Backgrounds of two types:
  - Resonant/Single Higgs Bkg
  - Non-Resonant/Continuum Bkg
- Categorization based on tau number in the final state
  - number of e,μs kept at zero to stay exclusive w.r.t **WWγγ**
- Multi-class DNNs as the discriminator
- Signal extraction with 1D fit in mγγ
- The extracted significance for the HH signal is **0.08σ** including systematic uncertainties
- Combined significance from the two channels is **0.22σ** including systematics











- The third largest cross section among different SM di-Higgs production processes
- Allows access to the triple Higgs coupling via approximately 20% of the total cross section
- Allows studying the process in BSM perspective
  - Minimal Composite scenarios possibly accessible at the HL-LHC (MCHM5 and MCHM14)
- Main backgrounds ttZZ and ttZH
  - Due to very similar kinematic characteristics of Z → bb and H → bb decays
- Deep neural network based discriminators used to separate signal from background
- Categorization based on b-jet multiplicity

Expected upper limit σ(ttHH) < 3.14 x SM

Combined production : 0.84 X SM

Conclusions & Prospects

- Measurement of Higgs self coupling in HL-LHC is very exciting!
- Snowmass '21 improved YR '18 HL-LHC prospects by the addition of
  - New decay channels
  - New production modes
  - New analysis/MVA techniques
- Preliminary combinations show a combined significance of 4.6σ (ATLAS + CMS)
- Very promising to reach the 5σ discovery at HL-LHC, so stay tuned!

Updated!

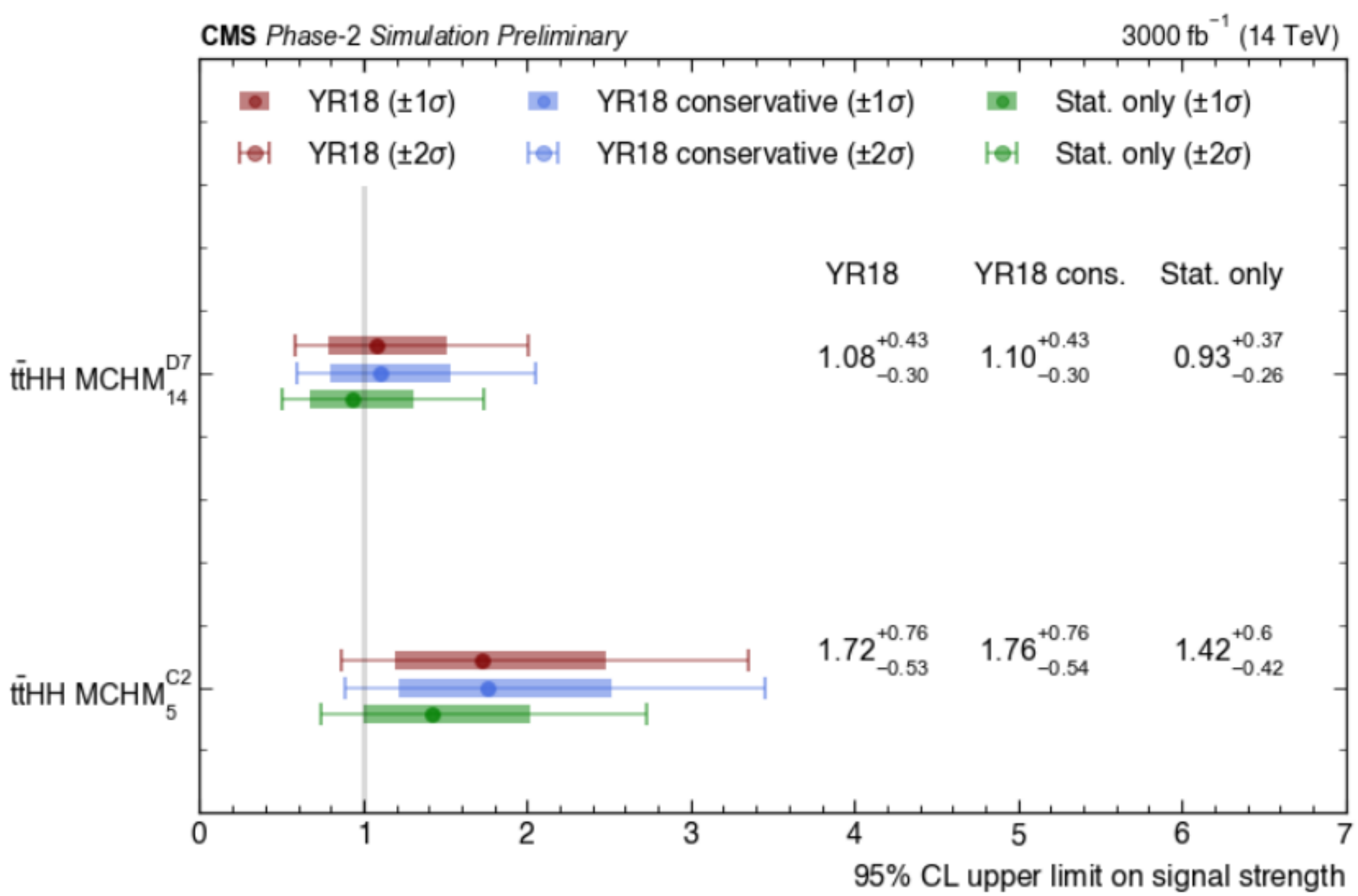
Channel	Significance Stat. + syst.	Stat. only
bbbb	0.95	1.2
bb$\tau\tau$	1.4	1.6
bbWW($\ell\nu\ell\nu$)	0.56	0.59
bb$\gamma\gamma$	~~1.8~~ 2.16 σ	~~1.8~~
bbZZ($\ell\ell\ell\ell$)	0.37	0.37
$WW\gamma\gamma + \tau\tau\gamma\gamma$	0.22 σ	

Expected upper limit σ(ttHH) < 3.14 x SM

Backup

- Scenario 1: Run 2 systematic uncertainties (conservative scenario)
- Scenario 2: Based on estimates of ultimate performance for experimental uncertainties, a factor of 1/2 reduction for theoretical uncertainties

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%


CMS Phase-2 Simulation Preliminary
3000 fb^{-1} (14 TeV)
YR18 (±1σ)
YR18 conservative (±1σ)
Stat. only (±1σ)
YR18 (±2σ)
YR18 conservative (±2σ)
Stat. only (±2σ)
YR18
YR18 cons.
Stat. only
$t\bar{t}HH$ MCHM$^{D7}_{14}$
$1.08^{+0.43}_{-0.30}$
$1.10^{+0.43}_{-0.30}$
$0.93^{+0.37}_{-0.26}$
$t\bar{t}HH$ MCHM$^{C2}_{5}$
$1.72^{+0.76}_{-0.53}$
$1.76^{+0.76}_{-0.54}$
$1.42^{+0.6}_{-0.42}$
0
1
2
3
4
5
6
7
95% CL upper limit on signal strength