Study of HH production at the High-Luminosity LHC with CMS

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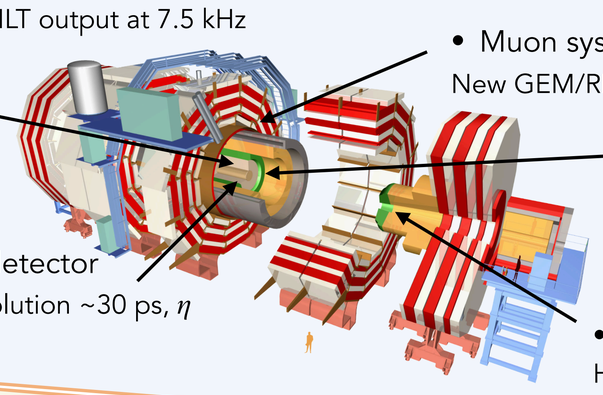
HL-LHC Timeline

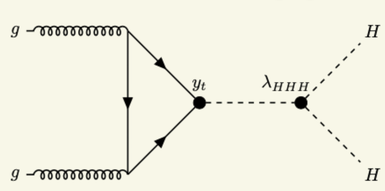
- An objective of increasing the integrated luminosity by **a factor of 10** beyond the LHC's design value
- Detector upgrades to cope with higher pileup (**200**) and radiation damage
- Installation of upgraded detectors planned to take place between 2026 and 2028

CMS Phase-2 Upgrade

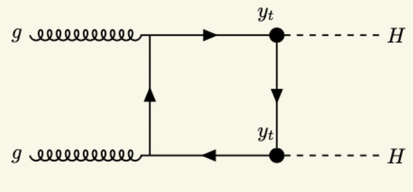
- Upgrade to trigger and DAQ
  Tracks in L1-Trigger, HLT output at 7.5 kHz
- Tracker
  New outer tracker, increased granularity, η coverage ~ 3.8
- MIP Timing detector
  Higher time resolution ~30 ps, η coverage ~ 3
- Muon system
  New GEM/RPC, η coverage ~ 2.8
- Barrel Calorimeter
  Higher ECAL precision timing, new back-end boards for ECAL/HCAL
- Endcap Calorimeter
  High Granularity Calorimeter (HGCAL)



Higgs Pair Production



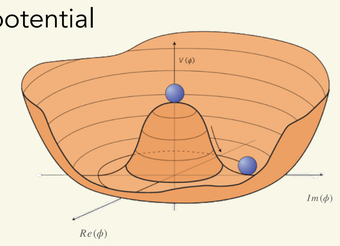
$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$



- Higgs self-coupling probes the nature of the Higgs potential

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 \nu H^3 + \frac{1}{4}\lambda_4 H^4$$

- λ_3 probed directly via HH production



YR '18 Systematics

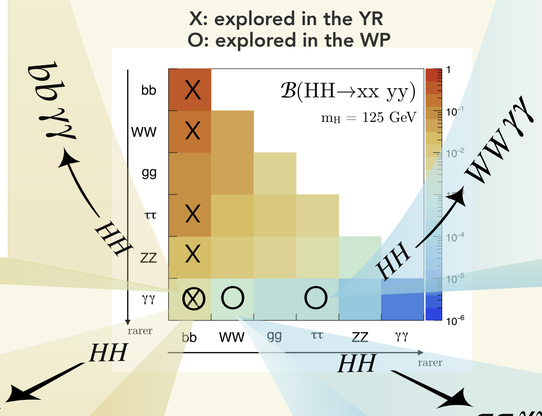
Source	Component	Run 2 Uncertainty	Projection minimum uncertainty
Muon ID		1-2%	0.5%
Electron ID		1-2%	0.5%
Photon ID		0.5-2%	0.25-1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1-0.2%
	Relative	0.1-3%	0.1-0.5%
	Pileup	0-2%	Same as Run 2
	Method and sample	0.5-5%	No limit
	Jet flavour	1.5%	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%

YR '18 Summary

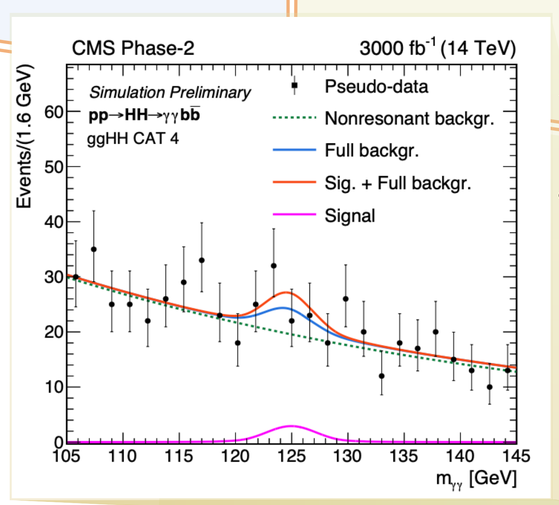
Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bb$\tau\tau$	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bb$\gamma\gamma$	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

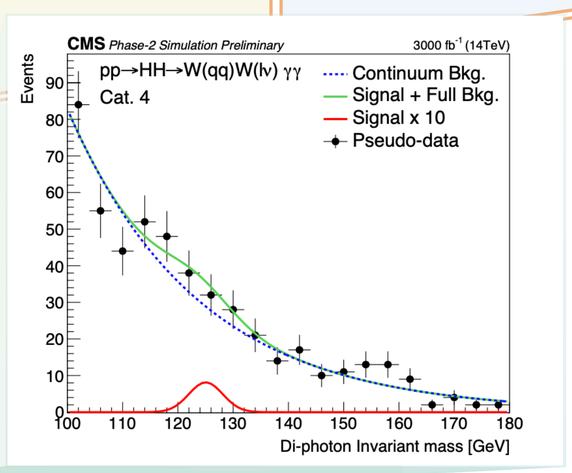
SNOWMASS Studies

- Focus on most sensitive HH decay channels

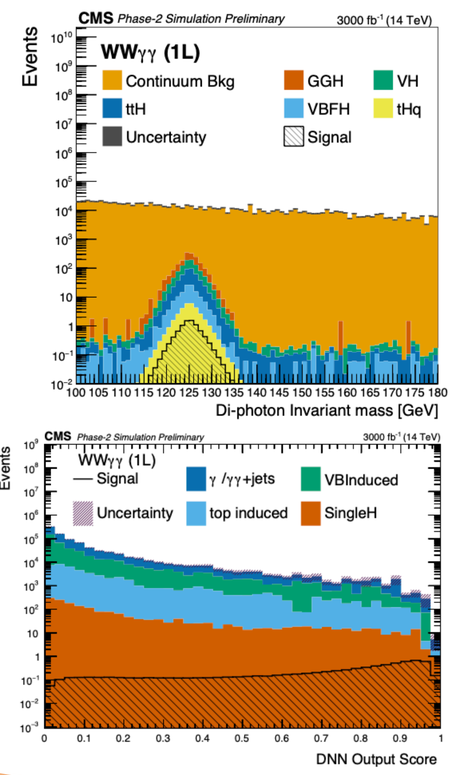


- DELPHES CMS HL-LHC simulation samples
- YR '18 systematics
- Analysis strategy based on Run-2 analysis

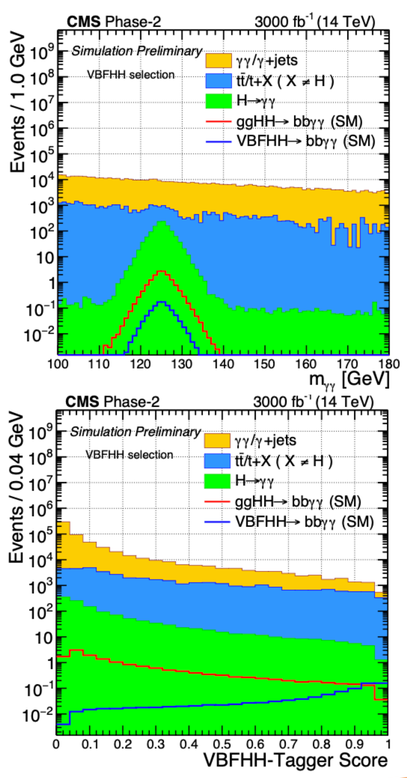


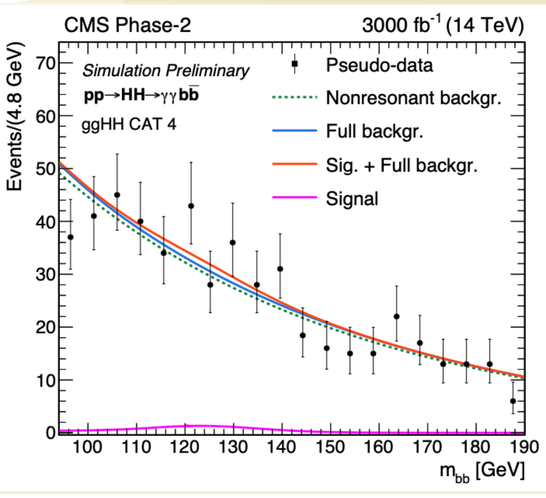


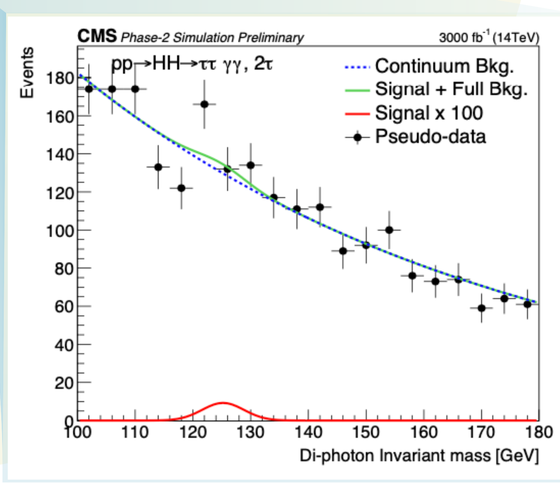
- First study of HL-LHC projection of these two channels
- Signal extraction: 1D fit in $m_{\gamma\gamma}$
- DNN as the discriminant
- Signal definition (ggHH only):
  - $ww\gamma\gamma$ (FL+SL) + $\tau\tau\gamma\gamma$
- Explored in four final states:
  - Targeting decays of W in 1 Lepton and 2 Lepton final states (L=$e^{\pm}$ or $\mu^{\pm}$)
  - 1τ and 2τ final states for $\tau\tau\gamma\gamma$



- Compared to YR'18:
  - Improved ttH rejection
  - Addition of VBF-HH categories and hence tagger BDTs for ggHH and VBF-HH
  - Improved photon and b-jet identification
  - Overall, ~%20 improvement
- Signal extraction: 2D fit in $m_{\gamma\gamma}$ and m_{bb}
- BDT as the discriminant

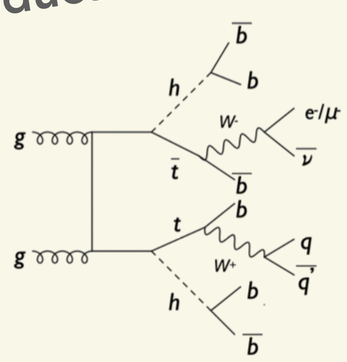






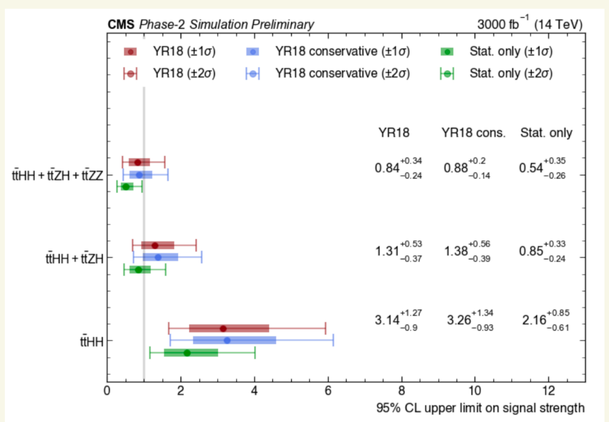
ttHH Production Mode

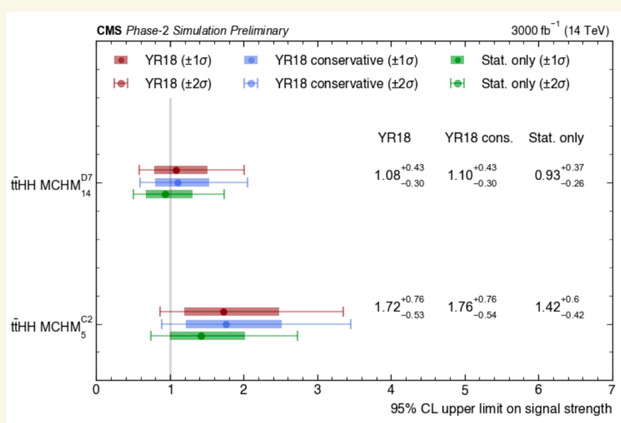
- Third largest cross-section among HH production mechanisms
- Provides complimentary constraint on κ_λ
- Provides sensitivity to BSM models



- Multiclass DNNs as the discriminant
- Categorization based on the number of b-jets
- Expected upper limit
  - $\sigma(ttHH) < 3.14$ x SM

The nonresonant ttHH production in the semileptonic decay of the top pair and the Higgs pair decay into b quarks





Results & Summary

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	

- Measurement of the Higgs self-coupling is one of the most exciting physics goals of the HL-LHC
- YR18 HL-LHC study: 4σ evidence of SM HH with ATLAS and CMS results combined
- Snowmass studies have improved YR18 projections via new analysis techniques, new production (VBFHH, ttHH) and decay channels ($WW\gamma\gamma$,$\tau\tau\gamma\gamma$)
- Next step is the combination of these updated results with ATLAS - soon to be done for SNOWMASS report
- Once we study the HH with HL-LHC data, we are optimistic that we will be able to observe Higgs self-coupling!

STAY TUNED

References

[1] CMS Collaboration, "Snowmass White Paper Contribution:Physics with the Phase-2 ATLAS and CMS Detectors , CMS PAS FTR-22-001

[2] E.M. Cepeda et al., "Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC", Technical Report, CERN, 2019

[3] M. Gouzevitch, A. Carvalho , "A review of Higgs boson pair production", Rev.Phys. 5,2020

Scan for the SNOWMASS White Paper

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