Searching for Higgs Pair Production with the CMS Electromagnetic Calorimeter

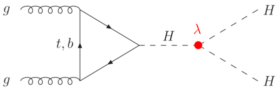
Abraham Tishelman-Charny

Northeastern University

SLAC: Fundamental Physics Directorate seminar

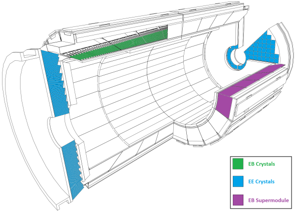
Thursday, 7 April 2022

- Finishing PhD with **Northeastern University**. Based at **CERN** with **CMS collaboration**



- Leading CMS HH→WW$\gamma\gamma$ working group composed of 13 members from 3 institutes, first CMS search of ***HH→WW$\gamma\gamma$***

- CMS **Electromagnetic Calorimeter** (ECAL):
  - Run coordinator
  - Trigger team member



Next Section

Search for Higgs pair production: Introduction

- 2012: Higgs boson discovered by CMS and ATLAS
- Want to measure properties including **mass** and **couplings** to SM particles - fundamental to **SM**
- Can search for **BSM physics**, using Higgs as a bridge

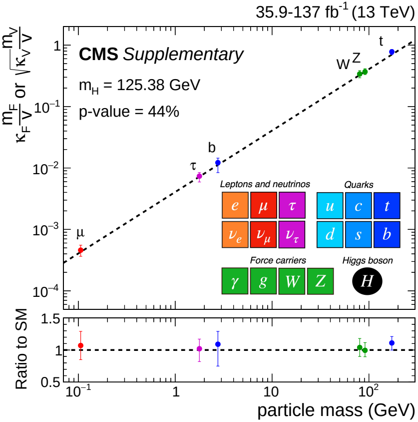


Figure 1: Higgs couplings to SM particles: [CMS-HIG-19-006]

- **Higgs self-coupling**: has direct impact on shape of Higgs potential:

$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

$$\lambda = 0.13, v = 246 \text{ GeV}$$

- Self-coupling λ predicted by SM. Want to compare to experiment to see what **nature has to say!**

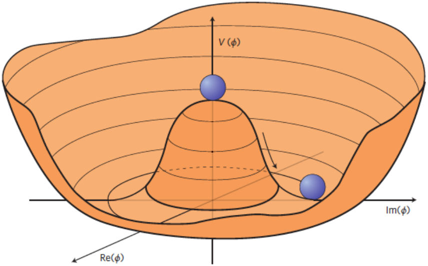
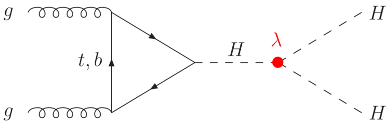
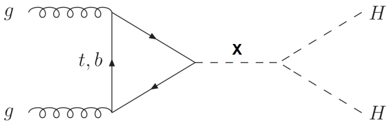


Figure 2: Higgs potential

- Higgs self-coupling constant directly accessed through **Higgs pair production**
- BSM scenarios, such as those predicting a heavy resonance coupling to Higgs can be searched for via Higgs pair production



(a) di-Higgs triangle diagram with self-coupling λ



(b) Heavy resonance decaying into two Higgs

- Left: **Non-resonant** production. Right: **Resonant** production.

Resonant Higgs Pair Production

- **Resonant higgs pair production**
  BSM example: Warped Extra Dimensions (WED)
- Search for heavy resonant particle: Graviton
- Predicted by Kaluza–Klein models - offer solution to hierarchy problem
- Can search via decays to SM higgs bosons

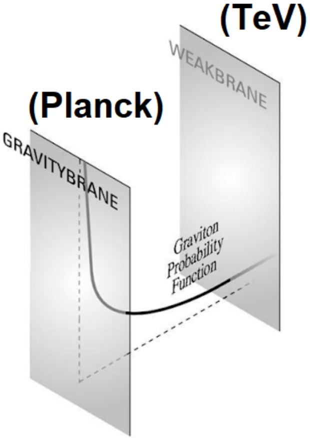
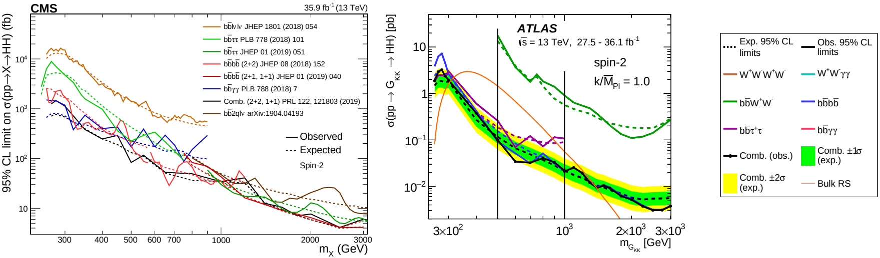


Figure 3: Warped extra dimensions: [arXiv:1404.0102]

Search for Higgs pair production: Existing results

- Search for heavy resonance from WED theory has been performed by CMS and ATLAS:



(a) CMS: [ref.]   (b) ATLAS: [ref.]

Figure 4: Resonance searches with 2016 data

- No heavy resonance observed, but can **rule out** models predicting certain masses, if upper limit is less than predicted value.
- Combining HH channels increases sensitivity!

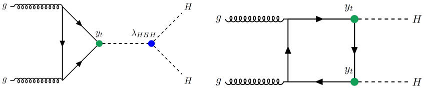
Non-resonant Higgs Pair Production

- In addition to direct SM or BSM model search, a model-independent search for new physics can be performed using an EFT (Effective Field Theory) alteration of the SM lagrangian
- Allows for BSM search over **large range** of scenarios

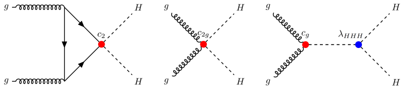
$$\mathcal{L}_{BSM} = -\kappa_\lambda \lambda_{HHH}^{SM} v H^3 - \frac{m_t}{v}(\kappa_t H + \frac{c_2}{v} H^2)(\bar{t}_L t_R + h.c.) + \frac{\alpha_S}{12\pi v}(c_g H - \frac{c_{2g}}{2v} H^2) G_{\mu\nu}^a G^{a,\mu\nu}$$

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}, \ \lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2}, \ \kappa_t = \frac{y_t}{y_t^{SM}}, \ y_t^{SM} = \frac{\sqrt{2} m_t^2}{v}$$

Effective Field Theory Parameterized BSM Lagrangian

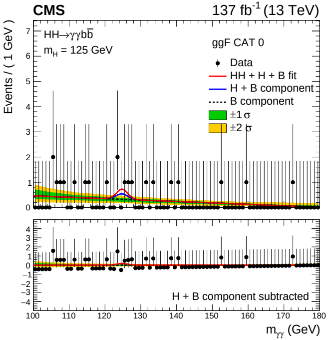


SM-like processes

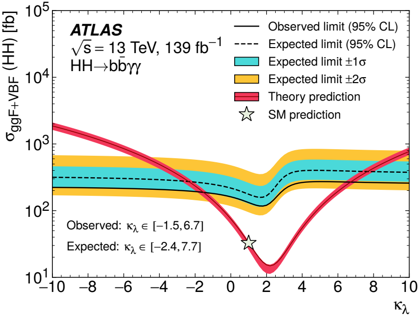


Pure BSM processes

- Higgs pair production: Searched in multiple HH final states by CMS and ATLAS with LHC Run 2 dataset, including HH→bb$\gamma\gamma$:



(a) bb$\gamma\gamma$ Signal region: [CMS-HIG-19-018]



(b) Higgs self-coupling modifier scan: [ATLAS Run 2 bb$\gamma\gamma$]

- Can measure SM sensitivity, deviations from SM

Search for HH→WW$\gamma\gamma$: Introduction

- Performing first CMS search of ***HH→WW$\gamma\gamma$*** with Run 2 dataset
- Useful traits:
  - Relatively **large** SM branching ratio: $\Gamma(H \rightarrow WW) \approx 0.215$ [ref]
  - **Clean** H→ $\gamma\gamma$ signature
- **All three final states** of the W boson pair considered to maximize sensitivity

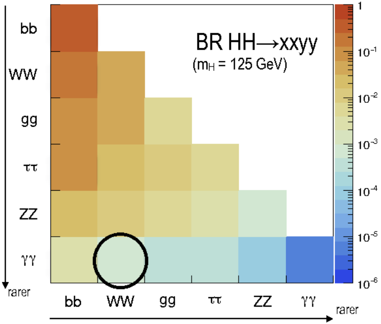
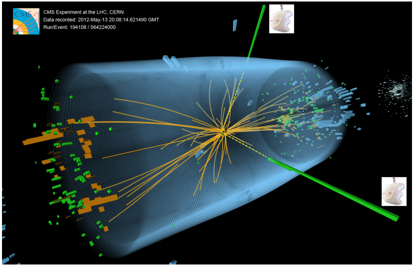
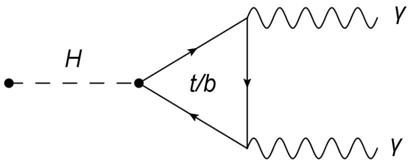


Figure 5: Branching ratios of HH final states

- Main handle of search: $\boldsymbol{H} \rightarrow \gamma\gamma$
- Want to select events with a good **di-Photon candidate**



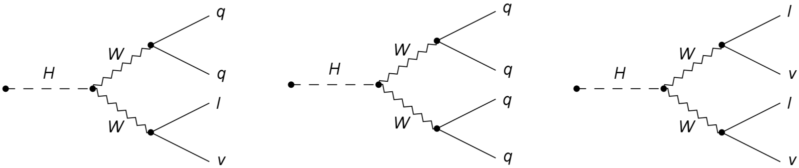
(a) 2012 Higgs to $\gamma\gamma$ **event** display at CMS



(b) H→ $\gamma\gamma$ diagram

- Select events with at least 2 highly **energetic**, **isolated** photon signatures

- In order to tag three WW final states, select CMS events with isolated **leptons** and **jets**.

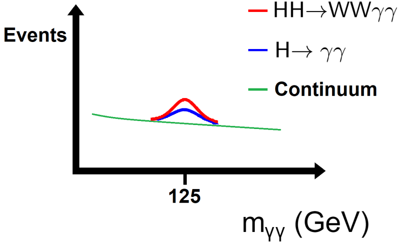


Semi-leptonic Fully-hadronic Fully-leptonic

- Keep three final states orthogonal via **number of leptons** so that channels can be combined - avoid double counting events.

Search for HH→WW$\gamma\gamma$: Strategy

- HH search performed with **resonant background**
- Want to define a region with a high signal to background ratio
- To maximize HH sensitivity, need to maximize separation of $H \to \gamma\gamma$ and continuum background from HH



- Main H backgrounds: VH($\to \gamma\gamma$), ttH($\to \gamma\gamma$)
- Main continuum backgrounds: Nonresonant $\gamma\gamma$, W$\gamma\gamma$Jets, W+jets

Disclaimer

Results with "Work in progress" have not yet been through the CMS Collaboration approval process, and are not yet public - as this analysis is now in the approval process.

- **Semi-leptonic** final state: High hadronic W branching ratio ≈ 67%, clean lepton signature (lower BR, higher efficiency).
- Apply standard photon, lepton, jet selections.
- Use a **Multiclassifier Deep Neural Network** to separate: HH, H→ $\gamma\gamma$, continuum background
- Improved final state's expected sensitivity by factor of ≈ **2** with respect to basic cut based analysis
- Use output score to **categorize** events into **four** DNN score categories

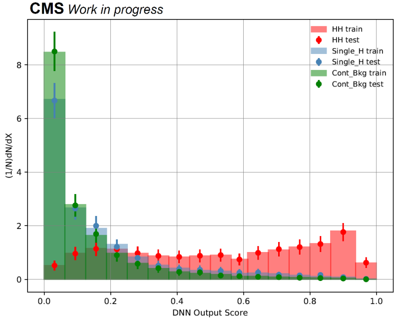


Figure 6: Normalized HH, H, and continuum background DNN output shapes

- High scaled photon p_T scores lead to higher HH DNN scores
- Variables related to semi-leptonic WW$\gamma\gamma$ topology are **important** for discrimination

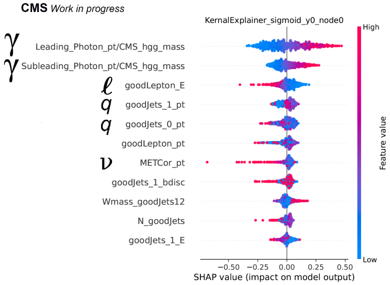
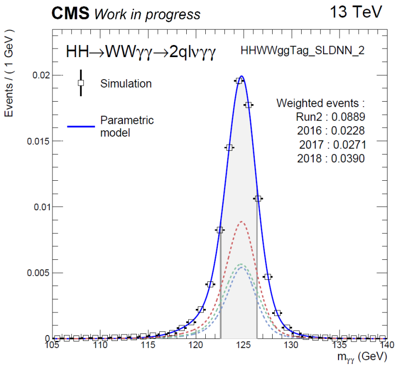


Figure 7: Leading importance variables for HH node

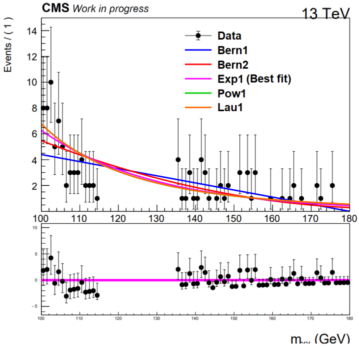
Search for HH→WW$\gamma\gamma$: Modelling

- Same method used to model **HH** signal and $\boldsymbol{H} \rightarrow \gamma\gamma$ resonant background
- Fit a sum of gaussians to histogram of di-Photon mass in **signal region**: $115 < m_{\gamma\gamma} < 135$ GeV
- Number of gaussians to use for fit determined by **f-test** - function that best fits shape

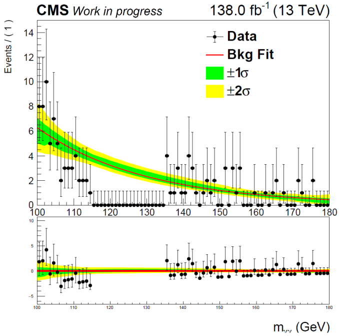


Search for HH→WW$\gamma\gamma$: Modelling

- Fit falling functions to data sidebands:



(a) Fit of multiple functions



(b) Final model with uncertainty

- Use this technique to model **continuum background** in **signal region**

Non-resonant Higgs Pair Production

- By fitting the background model to the asimov dataset (background + signal), we extract the **expected 95% CL upper limits** on $\frac{\sigma_{HH}}{\sigma_{HH}^{SM@NLO}}$
- Including FL and FH final states improves sensitivity by ≈ 17%
- Sensitivity driven by **semi-leptonic** final state

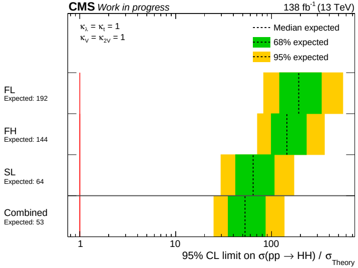
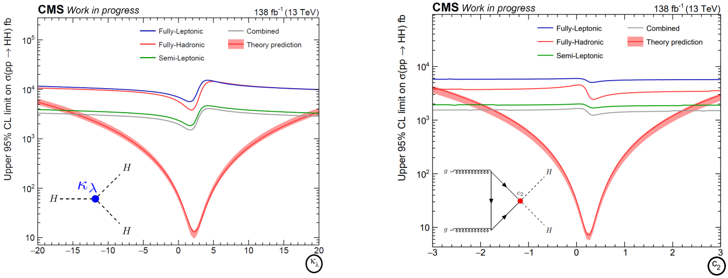


Figure 8: Expected 95% CL upper limits on $\frac{\sigma_{HH}}{\sigma_{HH}^{SM@NLO}}$, where $\sigma_{HH}^{SM@NLO} = 31.05$ fb

Search for HH→WW$\gamma\gamma$: Expected EFT results

Non-resonant Higgs Pair Production

$$\mathcal{L}_{BSM} = -\kappa_\lambda \lambda^{SM}_{HHH} vH^3 - \frac{m_t}{v}(\kappa_t H + \frac{c_2}{v} H^2)(\bar{t}_L t_R + h.c.) + ...$$



(a) κ_λ scan (b) c_2 scan

Figure 9: EFT results of three channels, and combination of HH→WW$\gamma\gamma$

- Expected constraints: [-14.50 $< \kappa_\lambda <$ 18.38], [-1.72 $< c_2 <$ 2.21]
- For both results, order of sensitivity same as SM search: SL, FH, FL.

Non-resonant Higgs Pair Production

$$\mathcal{L}_{BSM} = -\kappa_\lambda \lambda_{HHH}^{SM} v H^3 - \frac{m_t}{v}(\kappa_t H + \frac{c_2}{v} H^2)(\bar{t}_L t_R + h.c.) + \frac{\alpha_S}{12\pi v}(c_g H - \frac{c_{2g}}{2v} H^2) G^a_{\mu\nu} G^{a,\mu\nu}$$

- Perform search for 20 EFT benchmarks as additional BSM search: [JHEP04(2016)126], [JHEP03(2020)091]
- Each benchmark: set of values for **five EFT parameters**. Example, Benchmark 1: $\{\kappa_\lambda, \kappa_t, c_2, c_g, c_{2g}\} = \{7.5, 1, \text{-}1, 0, 0\}$
- Expected 95% CL limits set on 20 benchmarks in fb.
- Order of sensitivity same as SM search: SL, FH, FL.

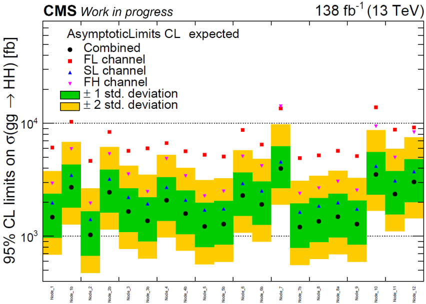


Figure 10: EFT benchmark results

Search for HH→WW$\gamma\gamma$: Future studies

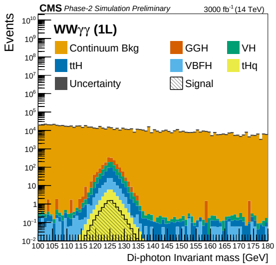
- Analyzing current data, while **keeping an eye on the future** via **projection studies** - computation of **expected results** using simulation of physics processes in HL-LHC conditions

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

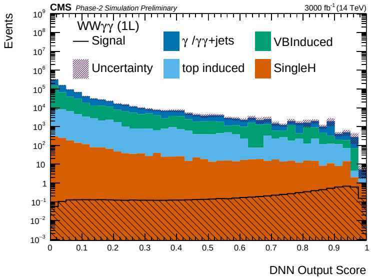
Figure 11: Projection of HL-LHC di-Higgs significance with 3000 fb^{-1}, 14 TeV: [ref.]

- Many but not all final states considered. To maximize likelihood of HH discovery at HL-LHC, important to consider additional channels.

- Completed projection of HH→WWγγ and HH→WWττ: [CMS-PAS-FTR-21-003]



(a) di-photon mass



(b) DNN output score

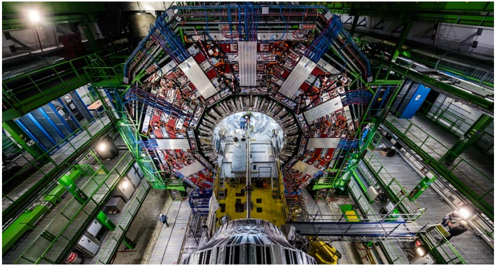
Figure 12: Signal and background processes: Simulated for HL-LHC

- Run 2 WWγγ strategy implemented. Projected significance of 0.21 σ reported for HH→WWγγ: **HL-LHC upgrades vital to make the most of the data!**

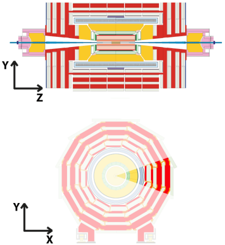
Next Section

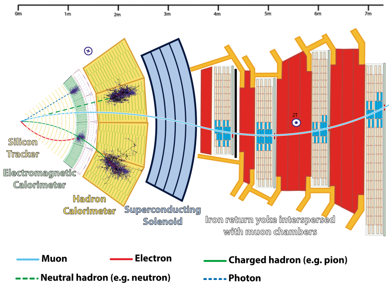
The CMS Detector

- The CMS (Compact Muon Solenoid) experiment is a general-purpose particle detector, stationed on the LHC near Geneva Switzerland



- CMS is made of multiple layers in order to detect **different particles**:

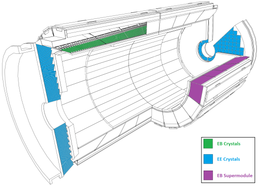


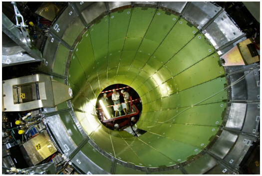


- Photons leave no tracks in silicon tracker, but leave **hits** in ECAL.

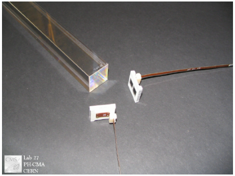
The CMS ECAL

- CMS **Electromagnetic Calorimeter** (ECAL): **EB** (ECAL Barrel) and **EE** (ECAL Endcaps), made of **75,848** $PbWO_4$ (Lead Tungstate) crystals.
- Purpose: Precisely measure energies of **electrons and photons**, **EM fractions of jets**
- EM interacting particles strike crystals, scintillation light produced, EM showers reach back of crystal and detected by radiation tolerant **photodetectors** (APDs [Avalanche Photo Diodes] in EB and VPTs [Vacuum Photo Triodes] in EE).





(a) ECAL Barrel

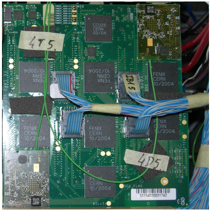


(b) Crystal and APD

(c) Half of one endcap

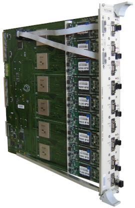
ECAL: Trigger path

- ECAL trigger sends energy sums to CMS Level-1 trigger at 40 MHz
  - **Energy sums** formed in ECAL on-detector electronics (ASICs)
  - Through **Trigger Concentrator Card**, send to Level-1 (L1) trigger, form e/γ (Maybe from $\boldsymbol{H} \to \gamma\gamma$**!**), τ, jet candidates
  - If L1 trigger identifies interesting event, **Level-1 accept** signal sent to CMS to read out event to DAQ



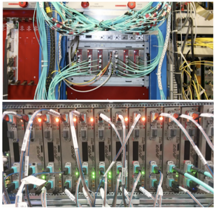
(a) ECAL Front-end card

→



(c) ECAL Trigger concentrator card

→

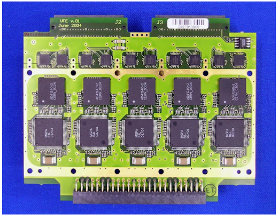


(e) Level-1 Calorimeter trigger cards

- Max rate of Level-1 accepts: **100 kHz**

ECAL: Energy sums

- The basic building blocks of ECAL energy sums are **strips**
  - The energy in a 1x5 channel region, corresponding to an ECAL VFE card
- Strip E_T values are computed in ASICs on the front-end card.



(a) Very Front End card

(b) Front of FE card with ASIC chips [ref.]

ECAL: Spikes

- In EB, non-signal-like pulses called **spikes** are prevalent. They are:
  - Caused by the direct ionization of APDs
  - Generally **isolated**, **high energy**, and often **out-of-time**

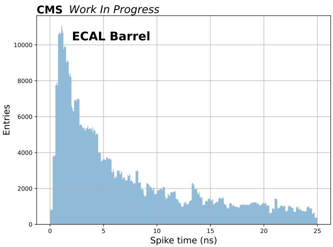


Figure 13: Spike timing distribution

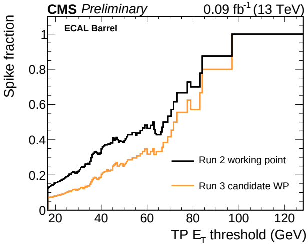


Figure 14: Spike contamination

- Have a L1 spike tagger that rejects many (but not all) spikes above 16 GeV - updating working point for Run 3 provides additional rejection above this threshold.
- Fundamental to remove spikes
- **There is room for improvement**

- In ECAL electronics, have the possibility to compute **two** energy sums in parallel:

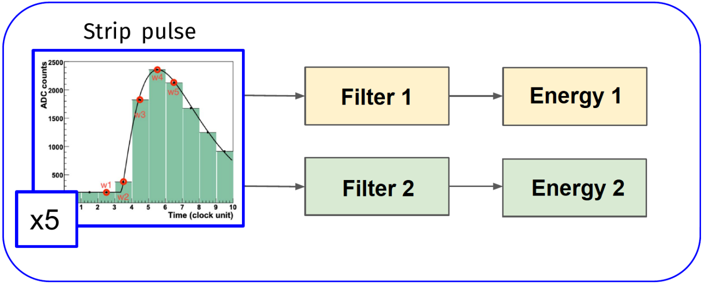


Figure 15: Double amplitude schematic

- Duplicates the data path
- Until now, second filter **never** used by ECAL
- Potential use of this new feature under investigation

ECAL: Out-of-time tagging

- Strategy: Tune **two energies**: Have second filter return greater amplitude for out-of-time signals, if $>$ first, kill signal or tag at L1.
- Possible advantages for physics:
  - Reduce spike rate at L1: Increase L1 rate for **physics**, increase data yields
  - Potentially tag **out-of-time** signals such as those from Long Lived Particles (LLPs)

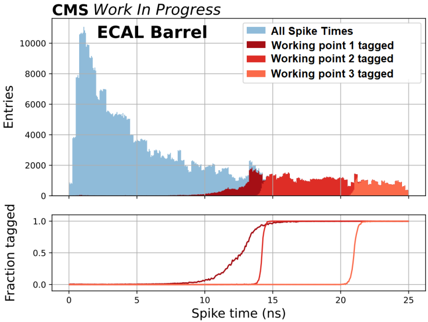
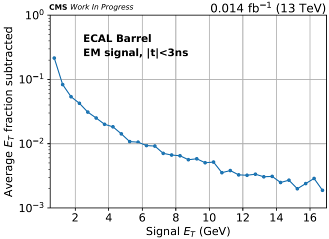


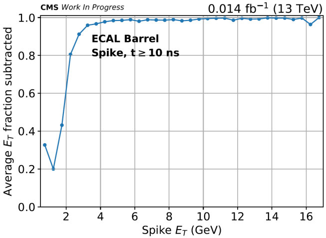
Figure 16: Simulated **spike timing distribution** and parts **tagged** by working points

ECAL: Data Re-emulation

- Estimated performance on in-time EM signals and out-of-time spikes by re-emulating 2018 CMS data, with double energy sums in **killing mode**:



(a) Expected signal efficiency



(b) Expected spike rejection

- Results in the following expected performance for $E_T > 5$ GeV:
  - $<$ 1% of energy subtracted from in-time EM signals
  - $\geq$ 95% of energy subtracted from out-of-time spikes

ECAL: Run Coordination

- **ECAL Run Coordinator** since September 2021

Figure 17: CMS control room

- Coordinated ECAL running activities through recent commissioning periods:
  - July - August 2021: Cosmic running with **no** magnetic field
  - Start of October 2021: Cosmic running **with** magnetic field
  - End of October 2021: LHC pilot beam, with **beam splashes** and **low intensity collisions**

ECAL: 2021 Beam Splashes

- October 2021: CMS received beam splashes:

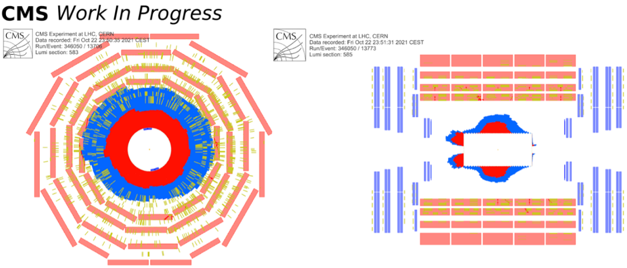
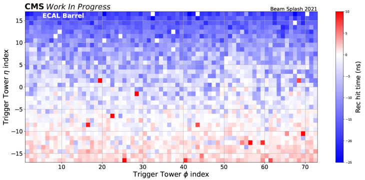


Figure 18: CMS Beam Splash event

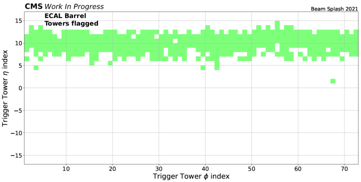
- A beam splash occurs when the LHC proton bunch is redirected onto the beam collimators upstream of CMS, resulting in a shower of particles (chiefly muons) that traverse CMS.
- The red (ECAL) and blue (HCAL) portions represent calorimeter energy deposits

ECAL: 2021 Beam Splashes

- Expect a **timing spread** from beam splashes
- Perfect time to test ECAL out-of-time tagging!



(a) ECAL timings

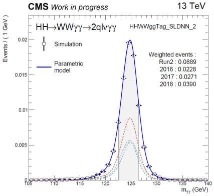


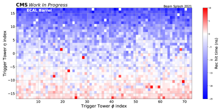
(b) Hits tagged as out-of-time

- <u>**The mechanism works in ECAL!**</u>
- **First instance** of in-situ out-of-time tagging at ECAL L1. Effective communication from Run Coordinators crucial for **planning** and **carrying out** tests like these
- Will continue testing feature through 2022

Next Section

- Higgs boson used to:
  - Better understand SM
  - Hunt for BSM
  - **Both** can be explored with **Higgs pair production**
- Sensitivity of searches improved by adding final states:
  - CMS is increasing its HH phase space: Adding HH→WW$\gamma\gamma$
- Precise and accurate detectors **imperative** for tagging final states. CMS ECAL vital for HH→WW$\gamma\gamma$, via H→ $\gamma\gamma$
- ECAL trigger team investigating new feature for LHC Run 3: Out-of-time tagging at L1
- Effective **run coordination** important for smooth detector running and new feature commissioning





Thank you for your attention!

4 Backup

Backup

- $G^{a}_{\mu\nu}$ is the gluon field strength tensor
- κ_{λ} - measure of deviation of Higgs boson trilinear coupling from its SM expectation λ^{SM}_{HHH}
- κ_{t} - measure of deviation of coupling between Higgs bosons and two top quarks from its SM expectation y^{SM}_{t}
- c_{2} - coupling between two Higgs bosons and two top quarks
- c_{g} - coupling between one Higgs bosons and two gluons
- c_{2g} - coupling between two Higgs bosons and two gluons

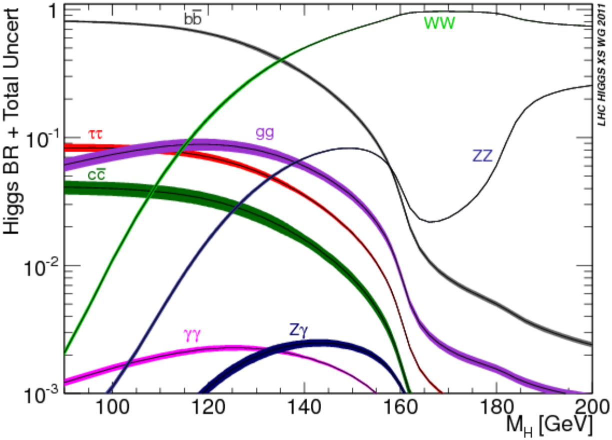


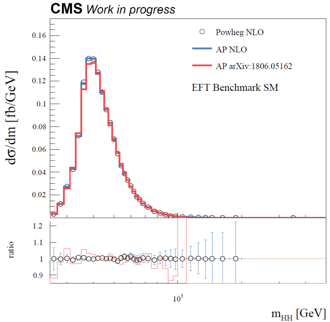
Figure 19: Higgs branching ratios vs. Higgs mass

Samples: Reweighing

- Reweighting technique used to obtain NLO distributions with **per event weights**:

$$w(m_{HH}, |\cos\theta^*|) = \frac{d\sigma_f(m_{HH}, |\cos\theta^*|)}{d\sigma_i(m_{HH}, |\cos\theta^*|)} \cdot \frac{\sigma_i}{\sigma_f}$$

- Ratio of differential cross sections between original and target
- Compute custom coefficients of analytical parameterization from privately produced samples in order to derive event weights. Can use to reweigh **any** HH sample → any benchmark at **NLO**:



Predicted analytic parameterization matches Powheg generated SM HH at NLO. Expect to be able to reweigh any HH sample to SM at NLO

EFT benchmarks

- In other refs, LO distribution has a dip for 8, not found in updated ref. Chose diff point of cluster 8 which does show a dip, and which we call 8a.

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
SM	1.0	1.0	0.0	0.0	0.0
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
8a	1.0	1.0	0.5	$\frac{0.8}{3}$	0.0
1b	3.94	0.94	$\frac{-1}{3}$	0.75	-1
2b	6.84	0.61	$\frac{1}{3}$	0.0	1.0
3b	2.21	1.05	$\frac{-1}{3}$	0.75	-1.5
4b	2.79	0.61	$\frac{1}{3}$	-0.75	-0.5
5b	3.95	1.17	$\frac{-1}{3}$	0.25	1.5
6b	5.68	0.83	$\frac{1}{3}$	-0.75	-1.0
7b	-0.10	0.94	1.0	0.25	0.5

Table 1: Parameter values of the benchmarks 1-12 [1], 8a [2], 1b-7b [3] and the Standard Model.

Samples: Background

- Background samples for **DNN**:
  - $\gamma\gamma$+Jets
  - γ+Jet
  - tt$\gamma\gamma$
  - ttγ+Jets
  - tt+Jets
  - W+Jets
  - W$\gamma\gamma$+Jets
  - Wγ+Jets
  - DYJetToLL_M-50
  - WW

- **Single Higgs** backgrounds for all final states' **signal region**:
  - GluGluHToGG
  - VBFHToGG
  - VHToGG
  - ttHJetToGG

- **Left:** Samples used for Semileptonic and Fullyhadronic DNNs, **not** used to model the background.
- **Right:** Single Higgs samples used to model **resonant background** in signal region

Cut #	Cut
1	(leadingPhoton.full5x5_r9 $>$ 0.8) or (leadingPhoton.egChargedHadronIso $<$ 20) or $\left(\frac{\text{leadingPhoton.egChargedHadronIso}}{\text{leadingPhoton.pt}} < 0.3\right)$ Leading γ 5x5 dominates its cluster's energy deposit
2	(subLeadingPhoton.full5x5_r9 $>$ 0.8) or (subLeadingPhoton.egChargedHadronIso $<$ 20) or $\left(\frac{\text{subleadingPhoton.egChargedHadronIso}}{\text{subleadingPhoton.pt}} < 0.3\right)$ Subleading γ 5x5 dominates its cluster's energy deposit
3	(leadingPhoton.hadronicOverEm $<$ 0.08) and (subLeadingPhoton.hadronicOverEm $<$ 0.08) Small associated hadronic deposits
4	(leadingPhoton.pt $>$ 35.0) and (subLeadingPhoton.pt $>$ 25.0) Pt thresholds
5	($\|$leadingPhoton.superCluster.eta$\|$ $<$ 2.5) and ($\|$subLeadingPhoton.superCluster.eta$\|$ $<$ 2.5) Superclusters in ECAL Pseudorapidity Range
6	($\|$leadingPhoton.superCluster.eta$\|$ $<$ 1.4442) or ($\|$leadingPhoton.superCluster.eta$\|$ $>$ 1.566) Avoid leading γ near ECAL transition (EB to EE)
7	($\|$subLeadingPhoton.superCluster.eta$\|$ $<$ 1.4442) or ($\|$subLeadingPhoton.superCluster.eta$\|$ $>$ 1.566) Avoid subleading γ near ECAL transition (EB to EE)
8	(leadPhotonId $>$ -0.9) and (subLeadPhotonId $>$ -0.9) Loose ID cuts

Figure 20: Diphoton preselections

- **Vertex:**
  - Use $\mathbf{0}^{th}$ vertex of each event Vertex efficiency w.r.t. GEN for $|\Delta Z| < 0.1cm$ is $> 99\%$
- **Photons:**
  - The standard $H \to \gamma\gamma$ pre-selections are applied, including Leading (Subleading) photon $p_T > 35$ (25) GeV
- **Electrons:**

Variable	Selection
p_T [GeV]	> 10
$\|\eta\|$	$(0 < \|\eta\| < 1.4442)$ or $(1.566 < \|\eta\| < 2.5)$
ID	Loose Cut Based
$\Delta R(e^-, \gamma)$	> 0.4
$\Delta R(track_{e^-}, SC_{e^-})$	> 0.4
$\|m_{e^-\gamma}$ - 91.187$\|$ [GeV]	> 5

Electron object requirements

- **Muons:**

Variable	Selection
p_T [GeV]	> 10
$\|\eta\|$	< 2.4
ID	Tight
$\Delta R(\mu, \gamma)$	> 0.4
$\Delta R(\mu, jet)$	> 0.4
ISO_μ	< 0.15

Muon object requirements

$$ISO_\mu = \frac{(sumChargedHadronPt_\mu + max(0, sumNeutralHadronEt_\mu + sumPhotonEt_\mu - \frac{sumPUPt_\mu}{2}))}{p_T^\mu} \quad (1)$$

- **Jets (AK4):**

Variable	Selection
p_T [GeV]	> 25
$\|\eta\|$	< 2.4
ID	Tight
PU Jet ID	Loose
$\Delta R(j, \gamma_l)$	> 0.4
$\Delta R(j, \gamma_{sl})$	> 0.4
$\Delta R(j, e^-)$	> 0.4
$\Delta R(j, \mu)$	> 0.4

Jet requirements

- **MET:**
  - Semi-Leptonic: No selection, input to DNN
  - Fully-Leptonic: **20 GeV** selection applied
  - Fully-Hadronic: No selection

Background modelling

- Many fit functions considered for fit to data sidebands
- All functions with p-value $>$ 0.05 are used to determine ± 1 and $\pm 2\sigma$ uncertainty bands on best fit
- In this case: Best fit function is an order-1 exponential

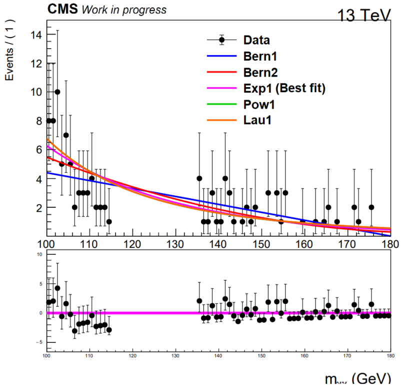
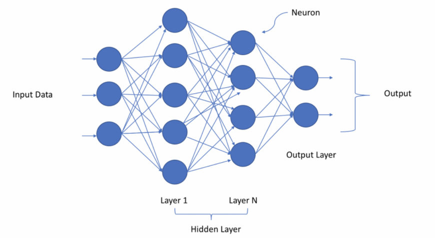


Figure 21: Semileptonic background model, all fit functions

Semileptonic HH→WW$\gamma\gamma$ DNN

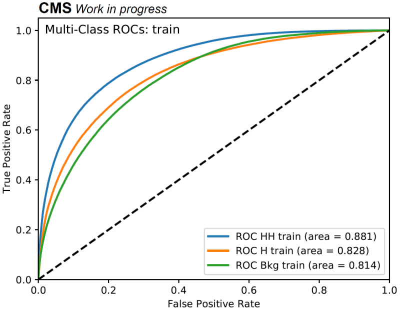
- Perform training with:
  - **Keras** with **Tensorflow** backend
  - **Feed-forward** Neural Network
  - Backwards-Propagation
  - **Multiclassifier** DNN



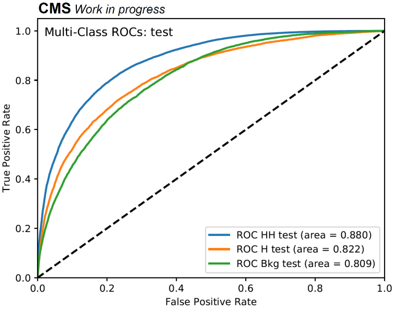
Example DNN

- Input Variables:
  - **Leading Photon**: $\frac{E}{m_{\gamma\gamma}}$, $\frac{p_T}{m_{\gamma\gamma}}$, η, ϕ, Hgg Photon ID
  - **Subleading Photon**: $\frac{E}{m_{\gamma\gamma}}$, $\frac{p_T}{m_{\gamma\gamma}}$, η, ϕ, Hgg Photon ID
  - **Leading Jet**: E, p_T, η, ϕ, DeepJet bScore
  - **Subleading Jet**: E, p_T, η, ϕ, DeepJet bScore
  - **Lepton**: E, p_T, η, ϕ
  - Number of Jets
  - MET
  - M_T(lepton, MET)
  - Invmass(jet$_0$, jet$_1$), Invmass(jet$_1$, jet$_2$)

- Trained on 2017 backgrounds, Semileptonic LO signal **reweighed** to NLO, and **single Higgs** (VH($\gamma\gamma$) and ttH($\gamma\gamma$)Jet). Observe the following ROC curves for training + test events:



(a) Training ROCs



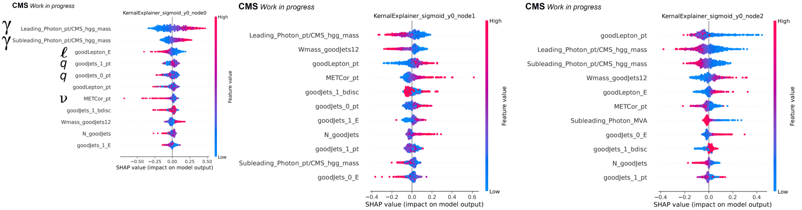
(b) Test ROCs

DNN Training Performance

- No overtaining evidence from ROC curves

Semileptonic HH→WW$\gamma\gamma$ DNN

- Can compute Shapley scores, corresponding to variable importance taking input variable correlation into account:

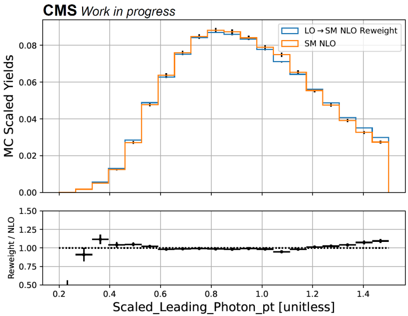


(a) HH node (b) H node (c) Continuum bkg. node

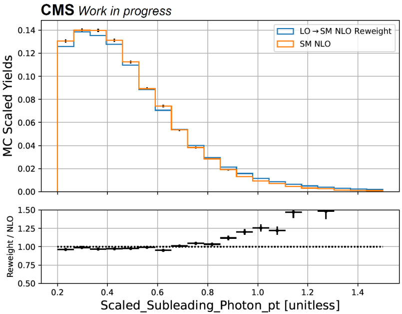
Leading importance semileptonic DNN variables

- High scaled lead/sublead photon p_T leads importance for HH as **expected**
- VH($\gamma\gamma$) and ttH($\gamma\gamma$) identified by high Lepton p_T, MET, lower inv. mass of W→qq
- Low lepton p_T, scaled lead/sublead photon p_T strongly identifies continuum background

- Reweight 12 samples generated at LO to SM at NLO using previously described reweighting in order to have more HH statistics for training. Validated that input features of 12 reweighted samples agree well with generated SM at NLO:



(a) Leading photon

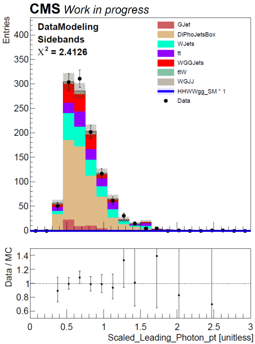


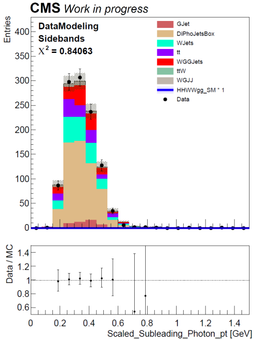
(b) Subleading photon

Photon p_T / $m_{\gamma\gamma}$

Semileptonic HH→WW$\gamma\gamma$ DNN

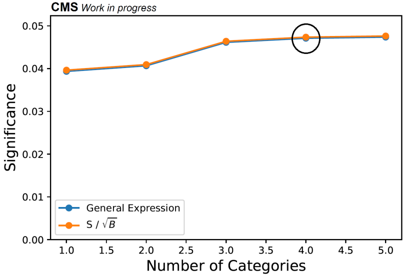
- Combine background MC, extract event weights by performing kinematic reweighting, taking ratio of data / MC in N-D space (N-variables x Nbins-for-variable)
- Variables used: Leading and subleading Jet p_T, lepton p_T, scaled leading and subleading photon p_T. Data / MC in data sidebands has good agreement in leading importance variables:





CatN	DNN Min	DNN Max	S	B_{SR}	$Data_{Sideband}$	Significance
0	0.89	1.0	0.03568	0.81037	8.0	0.03935
1	0.84	0.89	0.02267	1.84053	12.0	0.01668
2	0.63	0.84	0.07483	15.73924	111.0	0.01885
3	0.1	0.63	0.13379	494.07101	3457.0	0.00602

(a) Result of categorization

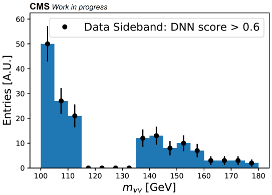


(b) Significance vs. Ncats

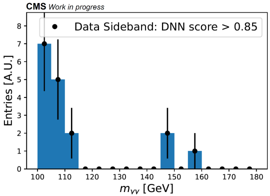
- Sideband reweighting and smoothing applied to Background events in **signal region** to optimize categorization
- Right-hand plot: Sum significance in **quadrature** among categories
- Use **four** categories as very small improvement going from 4→5 categories, most sensitive category boundary unchanged

Categorization: Semileptonic

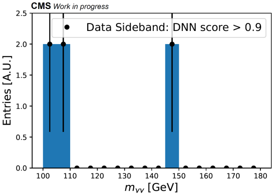
- Data and each semileptonic signal sample has DNN score **evaluated** event by event, categorized into four categories based on DNN score
- Checked data sideband events in different DNN score regions:



(a) DNN score > 0.6



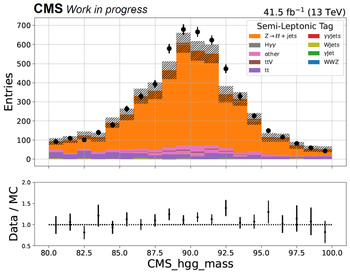
(b) DNN score > 0.85



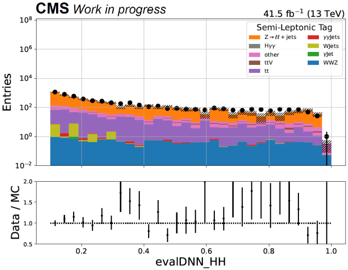
(c) DNN score > 0.9

- **No clear sculpting** of data sideband shape from DNN - Retains falling shape within statistical uncertainty
- **No evidence of bias seen** on data sideband shape - No expected correlation between DNN score and $m_{\gamma\gamma}$

- Evaluated DNN in **control region**: **Require** photon electron veto, expect Z→ee phase space:



(a) Data / MC of di-Electron mass



(b) DNN score

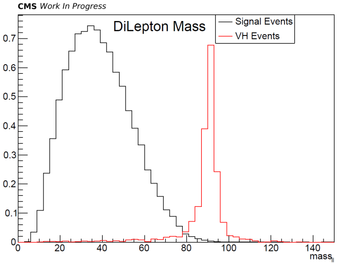
- Good Data / MC agreement in control region, disagreements appear due to statistics
- WWZ with similar signal topology (two real Ws, Z→ ee faking H→ $\gamma\gamma$, signal peaks near **one**
- Further validates DNN and **signal MC**

Selections: Fullyleptonic

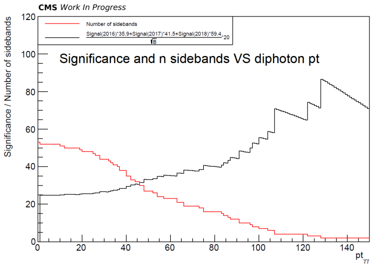
- The **common object selections** are applied to all objects
- Events are then categorized as **Fully-Leptonic** if they pass the following selections:
  - ≥ 2 leptons
  - The p_T of the leading lepton > 20 GeV
  - The p_T of the subleading lepton > 10 GeV
  - Third lepton veto: No additional leptons with $p_T > 10$ GeV
  - MET > 20 GeV
  - $p_T^{\gamma\gamma} > 91$ GeV
  - Veto events with 80 GeV $< m_{ll} <$ 100 GeV
  - No events with a jet with DeepJet bscore greater than medium WP
- These selections are applied to all fullyleptonic signal samples and data

Selections: Fullyleptonic

- In the fullyleptonic final state, optimize individual selections:
  - Can remove most of resonant VH($\gamma\gamma$) background with a selection on **di-lepton mass**. Expect lower invariant mass from WW leptons since they come from different W bosons
  - Expect large diphoton pT from H$\rightarrow \gamma\gamma$, use to discriminate from **continuum** background



(a) $m_{\ell\ell}$



(b) Diphoton pT selection optimization

Categorization: Fully-Hadronic

- Training selections:
  - At least one diphoton passing the standard $H \to \gamma\gamma$ pre-selections
  - **Exactly 0 leptons** passing the common lepton selections
  - **At least 4 AK4 Jets** passing the common jet selections
- Train a **binary DNN** to separate fullyhadronic $WW\gamma\gamma$ from:

MC Samples
DiPhoJetsBox_MGG-80toInf
GJet_40toInf $\Rightarrow$ Data-Driven QCD
HT-binned QCD $\Rightarrow$ Data-Driven QCD
$tt\gamma\gamma$+0Jets
$tt\gamma$+Jets

Backgrounds in Fully-Hadronic DNN

- Separately train a **binary DNN** to separate $HH \to bb\gamma\gamma$ from the above MC + $WW\gamma\gamma$

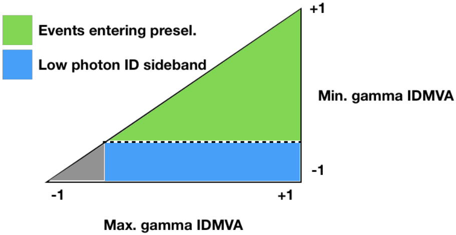
- Same input variables used for WW$\gamma\gamma$ identifier and bb$\gamma\gamma$ killer binary DNNs:

- Similar input variables as semileptonic DNN:
  - **Leading Photon**: $\frac{E}{m_{\gamma\gamma}}$, $\frac{p_T}{m_{\gamma\gamma}}$, η, ϕ
  - **Subleading Photon**: $\frac{E}{m_{\gamma\gamma}}$, $\frac{p_T}{m_{\gamma\gamma}}$, η, ϕ
  - **Three leading Jets**: E, p_T, η, ϕ, DeepJet bScore

- Some extra input variables specific to the fullyhadronic DNNs:
  - ΔR(γ, γ)
  - Sum of two leading DeepJet scores
  - Minimum Hgg photon ID
  - **Leading W candidate:** p_T, η, mass
  - **Subleading W candidate:** p_T, η, mass
  - **Higgs$\rightarrow$WW candidate:** p_T, η, mass

Categorization: Fullyhadronic

- Perform a data driven QCD + GJet background estimation
- Same strategy as [Run 2 CMS ttH])

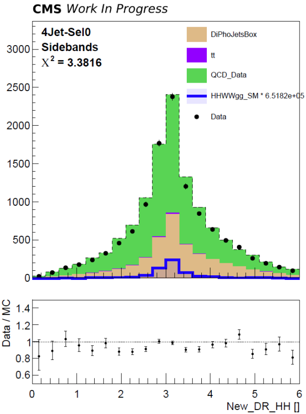


Data driven QCD + Gjet strategy

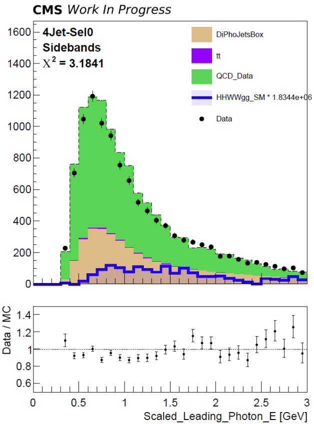
- Background estimation events: -0.9 < Minimum (among diphoton) Hgg photon ID < -0.7

Categorization: Fullyhadronic

- Data driven QCD + GJet aids in good Data / MC agreement in data sidebands - Two DNN input variables:



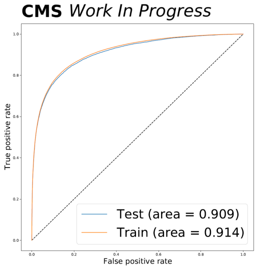
(a) ΔR(HH)



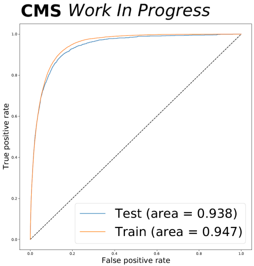
(b) Scaled leading photon Energy

Categorization: Fullyhadronic

- Trained on 2017 backgrounds, Fullyhadronic / bb$\gamma\gamma$ NLO SM signal. Observe the following ROC curves for training + test events:



(a) WW$\gamma\gamma$ Identifier



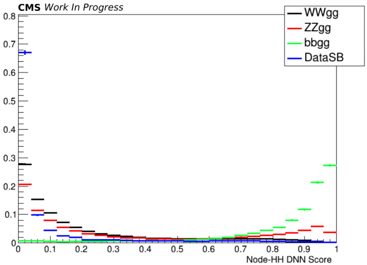
(b) bb$\gamma\gamma$ killer

DNN Training Performance

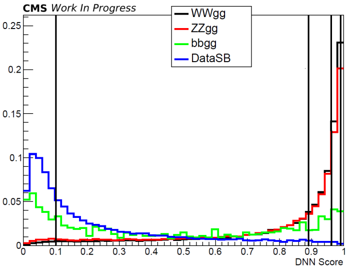
- No overtaining evidence from ROC curves

Categorization: Fullyhadronic

- A selection on the $bb\gamma\gamma$ killer output score of < 0.6 is made to remove $bb\gamma\gamma$ while keeping $WW\gamma\gamma$:



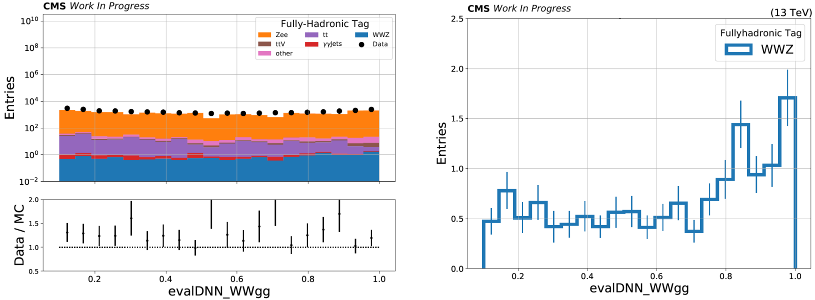
(a) $bb\gamma\gamma$ killer score - normalized to unity



(b) $WW\gamma\gamma$ DNN score - normalized to unity

- $bb\gamma\gamma$ killer separates $bb\gamma\gamma$ shape well from $VV\gamma\gamma$ and data sidebands
- With help of $bb\gamma\gamma$ killer score, $bb\gamma\gamma$ sample peaks at $WW\gamma\gamma$ DNN score < 0.1. Effective overlap between $WW\gamma\gamma$ and $bb\gamma\gamma$ phase spaces is $\approx 2.49\%$. Remaining $bb\gamma\gamma$ included as HH signal.

- Evaluated DNN in **control region**: **Require** photon electron veto, expect Z$\rightarrow$ee phase space:



(a) Data / MC of DNN score (b) WWZ DNN score

- Good Data / MC agreement in control region, disagreements appear due to statistics
- WWZ with similar signal topology (two real Ws, Z$\rightarrow$ ee faking H$\rightarrow \gamma\gamma$, signal peaks near **one**
- Validates **robustness** of DNN and validates **signal MC**

ECAL signal progenitor

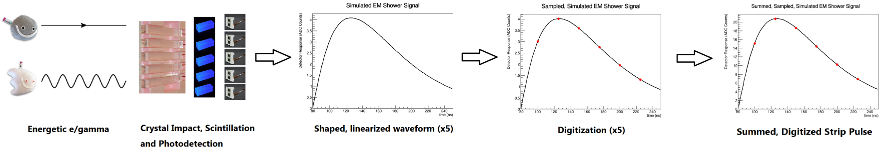


Figure 22: ECAL Sample Acquisition for E_T Calculation

- **Simplified** version of an ECAL hit from a **single** electron or photon
- In reality, also have bremsstrahlung radiation from electron, $\gamma \to ee$ pair production - need to recover for full energy of original particle! Do this as part of **offline** reconstruction (ECAL clustering)

Spikes

- In EB, non-signal-like pulses called spikes are prevalent. They are:
  - Caused by the direct ionization of APDs
  - Generally isolated, high energy, and often out-of-time

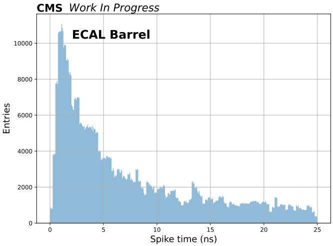


Figure 23: Spike timing distribution

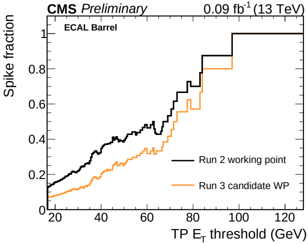


Figure 24: Spike contamination

- Have a L1 spike tagger that rejects many (but not all) spikes above 16 GeV - updating working point for Run 3 provides additional rejection above this threshold.
- Want to use double weights to reject out-of-time spikes, and hopefully also some of those below 16 GeV

[b]0.75

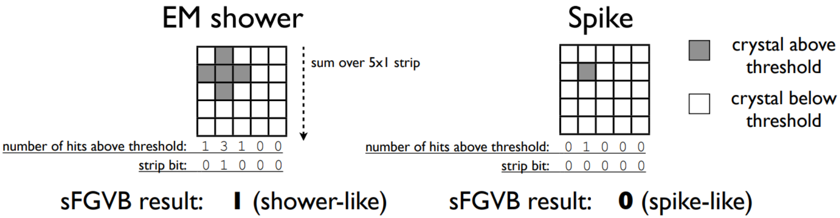
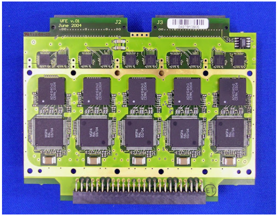


Figure 3. Operation of the strip Fine-Grained Veto Bit (sFGVB) on an electromagnetic shower (left) and a spike-like energy deposit (right).

Figure 25: [D. Petyt, Figure 3]

ECAL: Trigger primitives

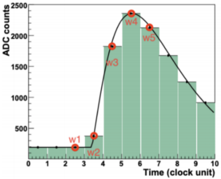
- The basic building blocks of Trigger Primitives (TPs) are strips
  - The energy in a 1x5 channel region, corresponding to an ECAL VFE card
- Strip E_T values are computed in FENIX ASICs on the front-end card.



(a) Very Front End card

(b) Front of FE card with FENIX chips [11]

- Trigger primitive E_T is computed as the sum of digitized signal pulse amplitudes times pre-determined weights:



$$E_T = \sum_{i=1}^{5} S_i \times w_i$$

Sample	0	1	2	3	4	5	6	7	8	9
EB	0	0	-0.5625	-0.546875	0.25	0.484375	0.375	0	0	0
EE	0	0	-0.65625	-0.515625	0.25	0.515625	0.40625	0	0	0

Figure 26: Run 2 EB, EE Weights derived from Pre Run 2 Test Beam

- The greatest weight is assigned to sample 5 (the peak)
- This is done for each strip (5 XTALS in EB), and strip values are summed to compute an E_T value for a TT (Trigger Tower)

ECAL: Double Weights

- During LS2, discovered in the ECAL on-detector ASIC manual:
  - "A second filter is implemented in for error detection (identical coefficients are required) and future use (80 MHz bunch crossing rate at SLHC, odd filter with "odd" coefficients)"

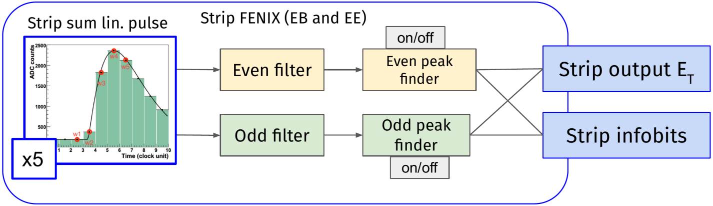


Figure 27: Double weights schematic

- Duplicates the data path: EVEN and ODD, with their own respective weights, which we call **double weights**
- Until now, this ODD filter has never been used by ECAL
- I have been the primary investigator in the potential use of this new feature during LS2

Numerical Optimization: Introduction

- Optimizing a second set of weights to maximize signal efficiency and spike rejection is a multivariate problem:
  - Realistic signal energy
  - Spike energy spectrum
  - Spike time
  - PU
- Scanning only OOT Pulse times is a rigid process that does not account for each of these parameters
- Optimization strategy:
  - Use a fast standalone simulation to produce a large number of events ($\approx$ 1M) with a realistic timing and energy spectrums
  - Formulate problem as a loss minimization $\rightarrow$ Can guide this more easily
  - Find a second set of weights which maximizes signal efficiency and spike rejection with the gradient descent method
- Evaluating spike case, but mechanism is flexible. Can use for other purpose like tagging OOT signals
  - Have not committed to a use. Can evaluate either

Numerical Optimization: Loss Function

- Loss function:

$$L = (\lambda_{Signal} \times L_{SigEff}) + (\lambda_{Spike} \times L_{SpikeRej}) + (\lambda_{Norm} \times W2LossNorm) + W2LossLimit$$

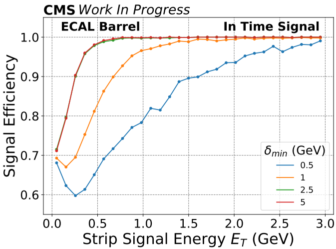
$$L_{SigEff} = \begin{cases} if\,(L_{SigEff} \geq \delta_{min}): & (A_{w2,d1} - A_{w1,d1}) \\ if\,(L_{SigEff} < \delta_{min}): & 0 \end{cases}$$

$$L_{SpikeEff} = \begin{cases} if\,(L_{SpikeEff} \geq \delta_{min}): & (A_{w1,d2} - A_{w2,d2}) \\ if\,(L_{SpikeEff} < \delta_{min}): & 0 \end{cases}$$

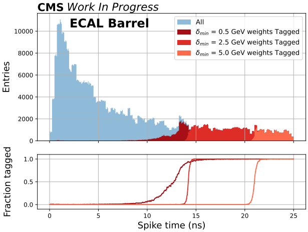
Figure 28: Loss Function

- Signal loss decreased when second set of weights returns lower value than first set (Save Signal)
- Spike loss decreased when second set of weights returns greater values than first set (Reject Spike)

- A standalone simulation has been developed to evaluate the potential of the double-weights mechanism for out-of-time signal tagging



(a) Expected signal efficiencies



(b) Expected spike rejection

Figure 29: Standalone sim. results for different double weights working points

- Different sets of ODD weights result in different signal efficiencies, and spike rejections
- The working point with $\delta_{min} = 2.5$ GeV provides a good balance of signal efficiency at low E_T, and out-of-time spike rejection.

Efficiencies: Table

δ_{min} (GeV)	Signal efficiency (%)	Spike rejection (%)
0.5	78.2	77.6
2.5	95.6	62.5
5.0	95.7	19.2

- This table displays the performance of three double weights working points on simulated EM signals and spikes.
- Only signals with $E_T \leq 3$ GeV are considered, as the efficiency in the standalone simulation of signals with $E_T > 3$ GeV is near 100%.
- Only spikes which are at least 10 ns out-of-time are considered in the making of this table, because the working points considered are not effective at tagging in-time signals.
- Moving from the 2.5 GeV to 5.0 GeV working point returns a very minimal gain in signal efficiency (0.1%), and a large fraction of spike rejection is lost (43.3%). This indicates that $\delta_{min} = 2.5$ GeV provides a good compromise between signal efficiency at low E_T and overall spike rejection.

Hardware Mechanisms: Options

- Have identified three potential mechanisms for zeroing or tagging spike TPs in hardware:

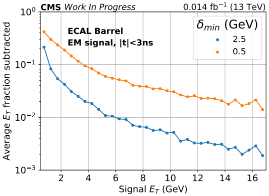
	Config 1	Config 2	Config 3
Strip output	Largest of ODD,EVEN	Largest of ODD,EVEN	EVEN
TCP output	EVEN sum	EVEN sum	EVEN+ODD sum
TCP infobit	ODD>EVEN	FGbit	ODD>EVEN
Zeroing in FENIX	YES	YES	NO
Monitoring/flagging	YES	NO	YES
New TCC f/w	NO	NO	YES
FG bit	NO	YES	NO
New Layer 2 f/w	YES	NO	YES*
Zeroing granularity	strip	strip	tower

Figure 30: Possible Hardware Mechanisms

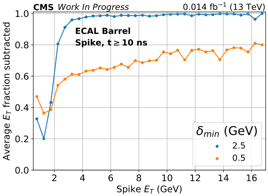
- Config 1) FENIX strip Zeroing + flagging
- Config 2) FENIX strip Zeroing, no flagging
- Config 3) No FENIX zeroing + flagging → Lose FG bit
- Strip zeroing possible, more granular than spike killer where TT is killed

Estimated performance

- Estimated double weights performance on in-time EM signals and out-of-time spikes by re-emulating 2018 CMS data with two working points



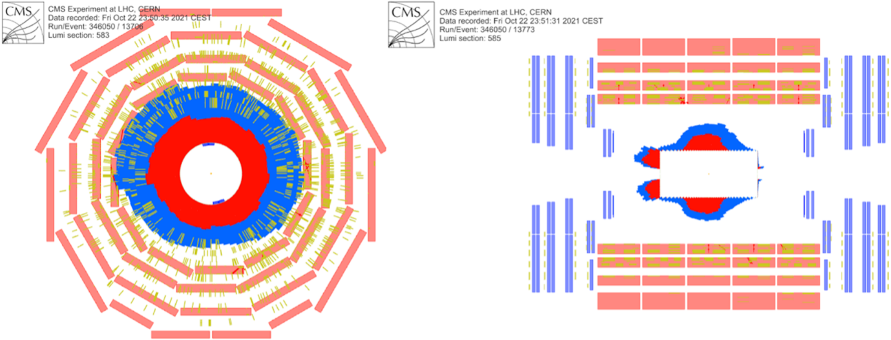
(a) Expected signal efficiency



(b) Expected spike rejection

- In CMS data, the $\delta_{min} = 2.5$GeV working point results in improved signal efficiency and spike rejection
- This results in the following expected performance of ECAL double weights for TPs with $E_T > 5$ GeV:
  - Less than 1% of energy subtracted from in-time EM signals
  - More than 95% of energy subtracted from out-of-time spikes

CMS *Work In Progress*



- These plots show CMS event displays recorded during a "beam splash" event in October 2021. A beam splash occurs when the LHC proton bunch is redirected onto the beam collimators upstream of CMS, resulting in a shower of particles (chiefly muons) that traverse CMS.
- The red (ECAL) and blue (HCAL) portions represent calorimeter energy deposits