Probing the Higgs via pair production in the two W boson two photon channel at CMS: Past, present, and future

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Northeastern University: Thesis defense

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Outline

Next Section

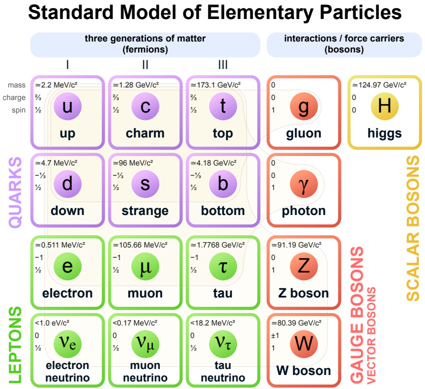
- 2012: The Higgs boson is experimentally discovered by the CMS and ATLAS collaborations [PLB 716 (2012) 30], [PLB 716 (2012) 1-29]:

CERN: July 4th 2012

- Final missing particle of the Standard Model (SM) **experimentally discovered**
- "Golden" channels for discovery: H$\rightarrow \gamma\gamma$, H$\rightarrow$ZZ$\rightarrow 4\ell$

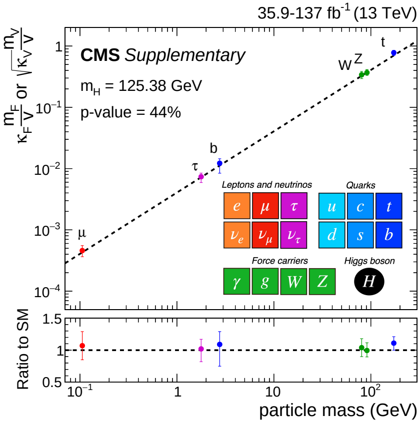
Introduction: The Standard Model

- Standard model (SM): A Quantum Field Theory, most successful theory of particle physics to date. Agrees with the **vast majority** of observation
- Predicts **particles** and **forces**
- **Successful but incomplete**: Does not define mechanism for gravitational force, neutrino mass → Part of motivation for Beyond the Standard Model **BSM** physics



Particles described by the SM

- Following the discovery of a new particle, what are we interested in doing?
- Want to measure properties including **mass** and **couplings** to SM particles - fundamental to **SM**
- Can search for **BSM physics**, using Higgs as a bridge



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

Introduction: Higgs discovery anniversary

- 4 July 2022: Scientific symposium marking **10 year anniversary**

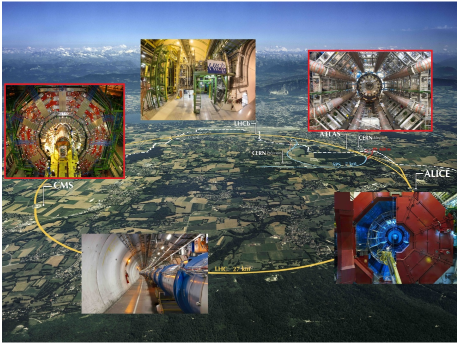
CERN: July 4^{th} 2022

- In 10 years since discovery, Higgs has been **extensively** studied
- Vast ongoing Higgs program, requires the proper **experimental setup**

Next Section

Experimental setup: The LHC

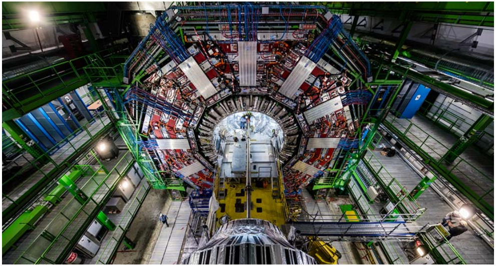
- **The LHC:** Large Hadron Collider - straddles the Swiss-French border near Geneva, Switzerland
- Circumference: **27 km (17 miles)**. Accelerates and collides **particles** with superconducting magnets



- Provides collisions to experiments: CMS, ATLAS, LHCb, ALICE
- Primarily **proton-proton** collisions

Experimental setup: CMS

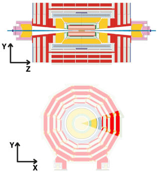
- The CMS (Compact Muon Solenoid) experiment is a general-purpose particle detector, stationed on the LHC

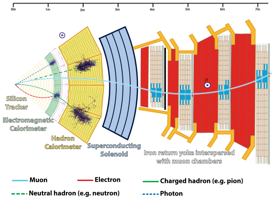


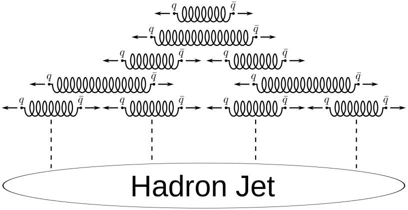
- **General purpose:** Perform searches for Dark Matter, Supersymmetry, rare processes (including HH), precision measurements, b-physics, ...
- Dimensions 21m long, 15m high and 15m wide.

Experimental setup: CMS

- CMS is made of multiple layers in order to detect **different particles**: Inner silicon tracker, calorimeters, solenoid magnet, muon chambers



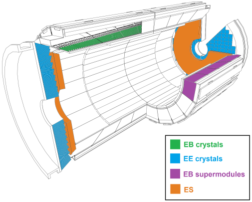


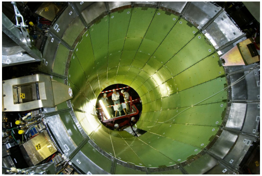


- Different particles and **jets** leave different signatures in the detector
- Crucial for the ability to detect the **many Higgs final states**

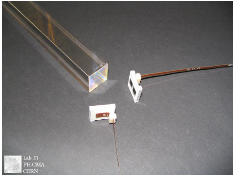
Experimental setup: The CMS ECAL

- 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).
- **Designed with H$\rightarrow \gamma\gamma$ in mind**





(a) ECAL Barrel



(b) Crystal and APD

(c) Half of one endcap

Experimental setup: Long term schedule

- Schedule: $\approx$ 4 year runs separated by multi-year shutdown periods

- There is a long term plan, up to 2038!
- **Past:** Run 2 (2015-18)
- **Present:** Run 3 (2022-25)
- **Future:** HL-LHC (High luminosity LHC) (2029-2038)

Next Section

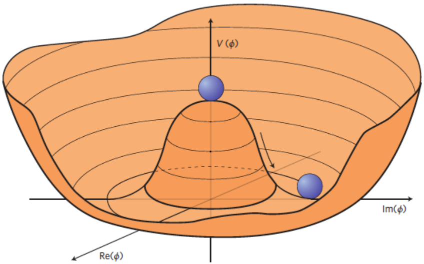
Next Subsection

- Part of SM: **Higgs potential**
- After electroweak symmetry breaking:

$$V(h) = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

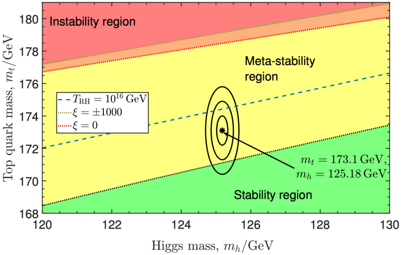
$$\lambda = 0.13, v = 246 \text{ GeV}$$

- Higgs interacts with **itself** and **massive particles**
- Self-coupling λ predicted by SM. Want to compare to experiment to see what **nature has to say!**

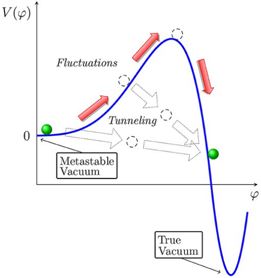


Higgs potential

- Higgs potential shape determines the higgs **vacuum expectation value**, and **type** of stability:



(a) Stability vs. top, Higgs masses

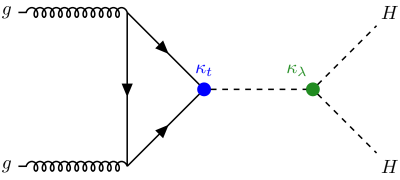


(b) Meta-stable potential [ref.]

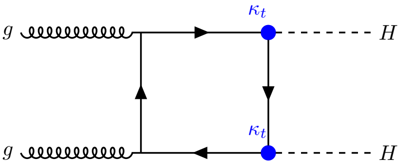
- Current measurements predict **meta-stable** minimum.
- Measurement of the higgs self-coupling would be a **direct measurement** of higgs potential, could verify or refute this

Run 2 HH→WW$\gamma\gamma$: Higgs pair production

- Higgs pair production: Production of **two Higgs bosons** in a single process - **predicted by SM**
- Direct access to **Higgs self-coupling**.



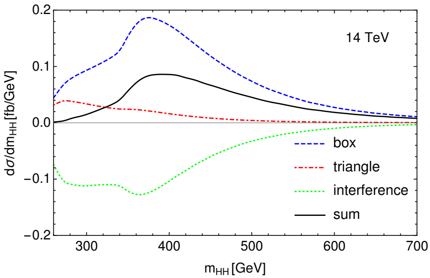
(a) Triangle diagram



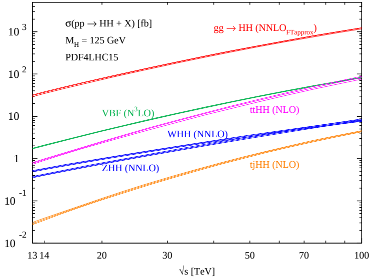
(b) Box diagram

- Want to search for this process in data to confirm it exists
- Also allows for a measurement of this parameter

- Large contribution from **box diagram**
- Large **destructive interference**



(a) Diagram interference



(b) HH Production modes

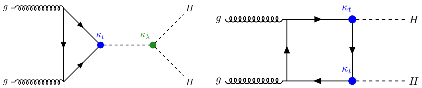
- **Higgs pair production is rare** - about **1000** times less likely to be produced compared to a **single Higgs boson**
- At a p-p collider, most likely process is **gluon-gluon fusion** ($\sigma_{HH}^{GF} \approx 31.05$ fb at 13 TeV)

- In addition to direct SM 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

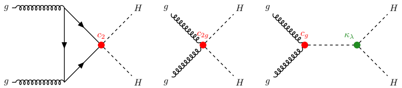
$$\mathcal{L}_{BSM} = -\kappa_\lambda \lambda_{HHH}^{SM} v H^3 - \frac{m_t}{v}(\kappa_t H + \frac{c_2}{v} H^2)(\bar{t_L} t_R + h.c.) + \frac{\alpha_S}{12\pi v}(c_g H - \frac{c_{2g}}{2v} H^2) G_{\mu\nu}^a G^{a,\mu\nu}$$

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

Effective Field Theory Parameterized BSM Lagrangian



SM-like processes



Pure BSM processes

Next Subsection

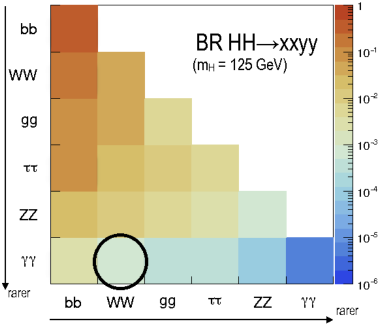
1. Introduction
2. Experimental setup
3. Past: Run 2 search for Higgs pair production in the WW$\gamma\gamma$ channel
   - Theoretical background
   - Strategy
   - Signal and background modelling
   - Results
4. Present: Run 3 ECAL trigger optimization and commissioning
5. Future: Phase II prospects for HH measurements at the HL-LHC
6. Summary

Run 2 HH→WW$\gamma\gamma$: Strategy

- To search for rare HH process, search for H(WW), H($\gamma\gamma$) final state - ***HH→WW$\gamma\gamma$*** with Run 2 dataset

- Useful traits:
  - Relatively **large** SM branching ratio: $\Gamma(H \rightarrow WW) \approx 22\%$
  - **Clean** H→ $\gamma\gamma$ signature

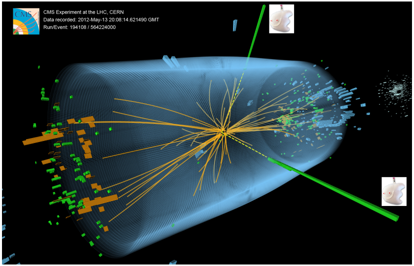
- **All three final states** of the W boson pair considered to maximize sensitivity



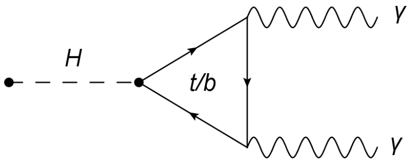
Branching ratios of HH final states

Run 2 HH→WW$\gamma\gamma$: Strategy

- Main handle of search: $\boldsymbol{H} \rightarrow \gamma\gamma$
- Want to select events (proton-proton interactions) with a good **di-Photon candidate** (detected by ECAL)



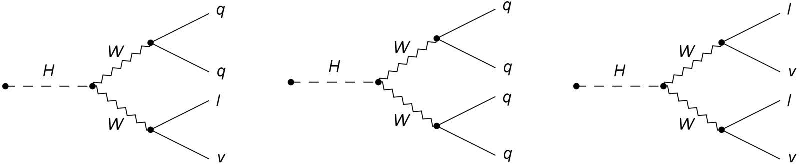
(a) 2012 Higgs to $\gamma\gamma$ **event** display at CMS



(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 **energetic** (high p_T), **isolated leptons** and **jets** (detected by ECAL and rest of CMS detector):

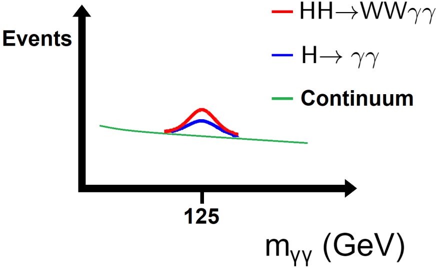


Semi-leptonic **(SL)** Fully-hadronic **(FH)** Fully-leptonic **(FL)**

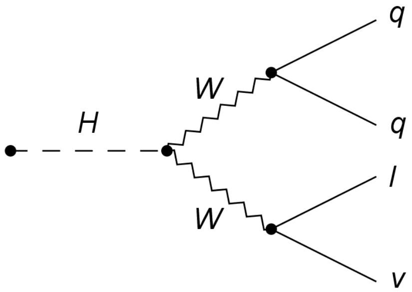
- Keep three final states orthogonal via **number of leptons** (1, 0, 2) for (SL, FH, FL) so that channels can be combined - avoid double counting events.

Run 2 HH→WW$\gamma\gamma$: Strategy

- HH signal peaks at **Higgs mass**
- HH search performed with **resonant** and **continuum** background components
- 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



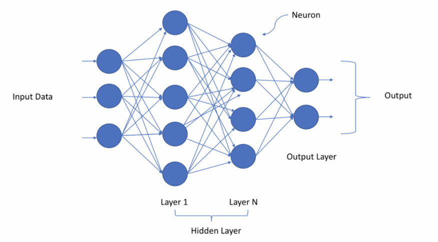
- **Semi-leptonic** final state: High hadronic W branching ratio $\approx$ 67%, clean lepton signature (lower BR, higher efficiency).
- Apply standard photon, lepton, jet selections.
- Use a **Multiclassifier Deep Neural Network** to separate: HH, H→ $\gamma\gamma$, continuum background
- Use output score to **categorize** events into **four** DNN score categories



Semi-leptonic final state

Run 2 HH$\rightarrow$WW$\gamma\gamma$: Semi-leptonic DNN

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

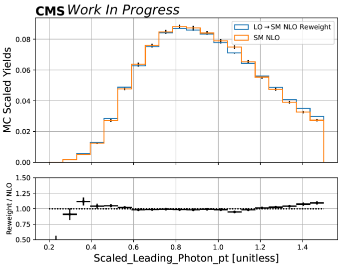


Example DNN

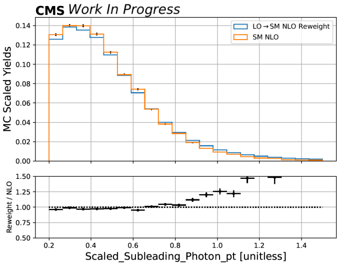
- Input Variables:
  - **Leading Photon**: $\frac{E}{m_{\gamma\gamma}}$, $\frac{p_T}{m_{\gamma\gamma}}$, η, ϕ, Photon ID
  - **Subleading Photon**: $\frac{E}{m_{\gamma\gamma}}$, $\frac{p_T}{m_{\gamma\gamma}}$, η, ϕ, Photon ID
  - **Leading Jet**: E, p_T, η, ϕ, DeepJet bScore
  - **Subleading Jet**: E, 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$_2$)

Run 2 HH→WW$\gamma\gamma$: Semi-leptonic DNN

- Train DNN on **simulation** to avoid bias from data, and optimize for HH signal
- **Signal:** Reweight HH signal events at LO to NLO from independent sample for training, Reweighted events model SM HH signal well



(a) Scaled Leading Photon p_T



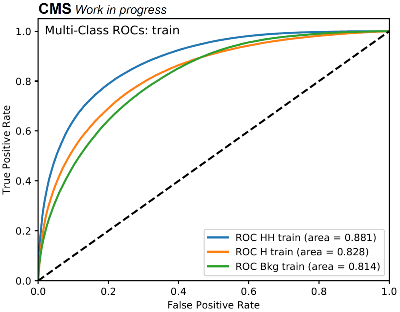
(b) Scaled subleading photon p_T

LO to NLO reweighted quantities

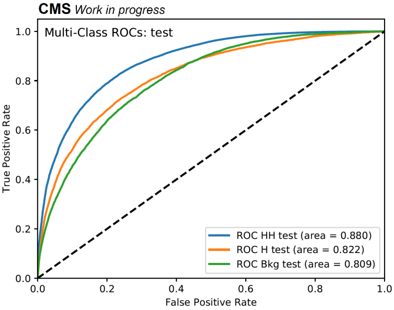
- **Continuum background:** Use simulation, improve modelling by applying 6-D kinematic reweighting, from important variables
- **Single Higgs:** Train on VH, ttH - topologically better at faking SL HH

Run 2 HH→WW$\gamma\gamma$: Semi-leptonic DNN

- Separate events into training **(90% stats)** and test **(10% stats)** subsets
- Can evaluate DNN performance by checking **ROC** (receiver operating characteristic) curves:



(a) Training ROCs

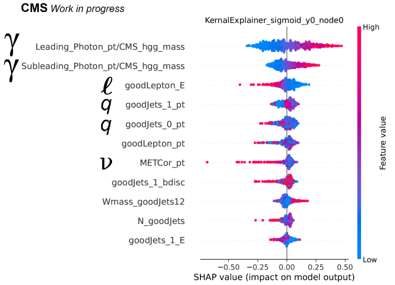


(b) Test ROCs

DNN Training Performance

- **No evidence** of overtraining, ROC curves are similar for training and test sets

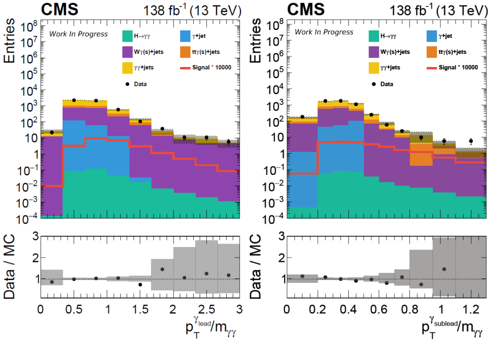
- High scaled photon p_T scores lead to higher HH DNN scores
- Variables related to semi-leptonic WW$\gamma\gamma$ topology are **important** for discrimination



Leading importance variables for HH node

Run 2 HH→WW$\gamma\gamma$: Semi-leptonic

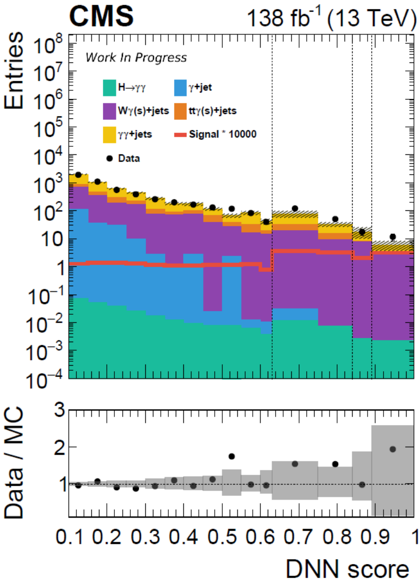
- Events with DNN score < 0.1 **not used in analysis**, due to very low signal to background ratio
- Relatively good agreement, DNN trained well to identify HH in data
- MC **not used** for signal and background modelling, **only** for DNN optimization. An y disagreement indicates **suboptimal**, but not biased, DNN



Data / MC after training

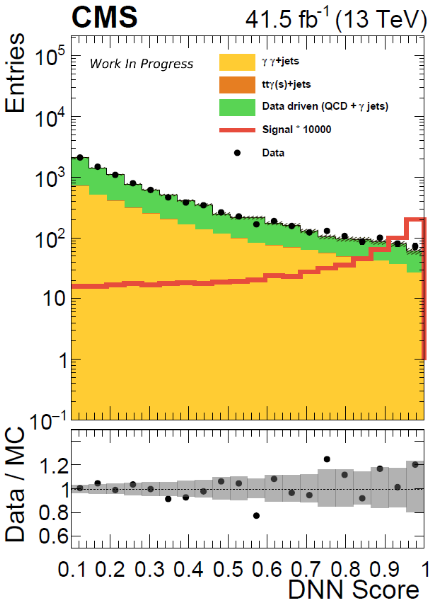
Run 2 HH→WW$\gamma\gamma$: Semi-leptonic categorization

- Perform simultaneous optimization of category boundaries to **maximize expected sensitivity**
- Final DNN category boundaries **drawn as vertical lines**: [0.1, 0.63, 0.84, 0.89, 1.0]
- Relatively good agreement, expect DNN trained well to identify HH, H, continuum background processes in data
- Any disagreement indicates suboptimal, but not biased, DNN



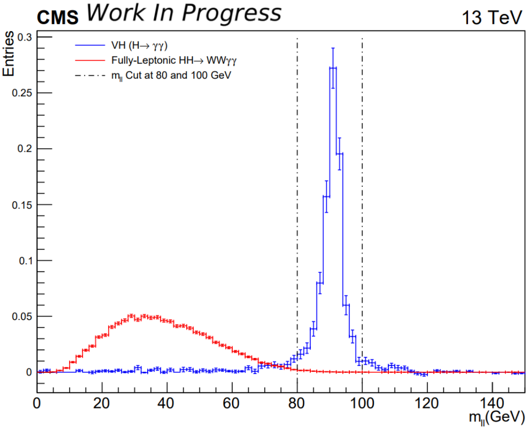
Run 2 HH→WW$\gamma\gamma$: Fully-hadronic

- Fully-hadronic final state: Major background is **multi-jet QCD**, model with **data-driven** method. Also have HH→bb$\gamma\gamma$ background
- Invoke dedicated bb$\gamma\gamma$ killer to remove bb$\gamma\gamma$ events
- Train separate binary DNN to separate HH→WW$\gamma\gamma$ signal from continuum background
- DNN separates HH→WW$\gamma\gamma$ signal well from backgrounds



Run 2 HH→WW$\gamma\gamma$: Fully-leptonic

- Require exactly 2 leptons
- Lead (sublead) lepton $p_T >$ 20 (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 (b-tag MVA) greater than medium WP

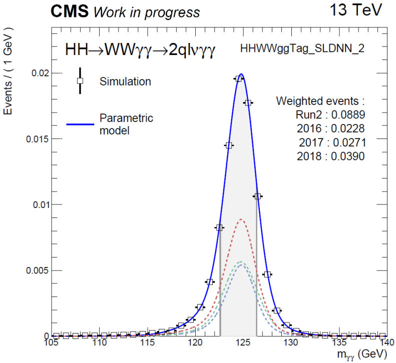


FL selection on di-lepton mass - removes VH background, preserves signal

Next Subsection

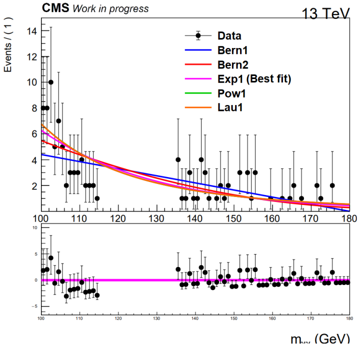
Run 2 HH→WWγγ: HH, H modelling

- Same method used to model **HH** signal and $\boldsymbol{H} \to \gamma\gamma$ 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
- **Same strategy** for HH and H fitting followed for **all final states and categories**

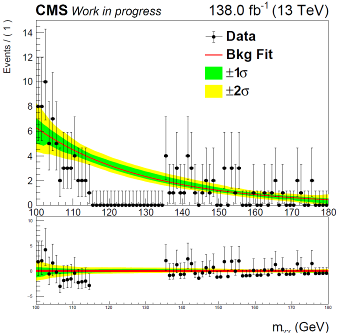


Run 2 HH→WW$\gamma\gamma$: Continuum modelling

- Fit falling functions to data sidebands:
- Fit without using the data in the signal region to avoid bias (blinding)



(a) Fit of multiple functions

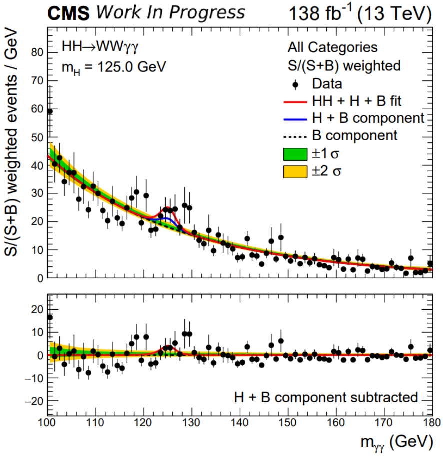


(b) Final model with uncertainty

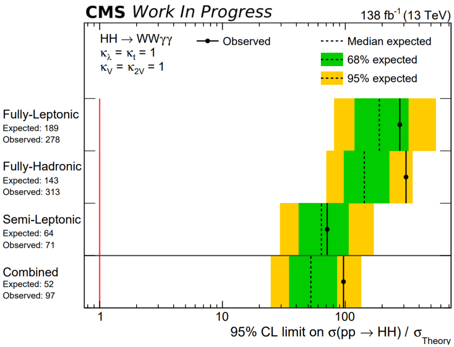
- Use this technique to model **continuum background** in **signal region**

Run 2 HH→WW$\gamma\gamma$: Fit to data

- Uncertainties included:
  - **Theoretical uncertainties** on HH and H XS, BR
  - Integrated **luminosity** and **Trigger**
  - **Electron** and **muon** reconstruction, ID and isolation efficiency
  - **Photon** ID, shower shape, energy scale, resolution
  - **Jet** energy scale and resolution
  - B-tagging
- 7 analysis categories combined, weighted by S/(S+B) per category
- What quantifiable results can we extract from this?



- Not enough signal to claim evidence or discovery, but can set **upper limits** on σ_{HH}.
- Combined observed (expected) upper limit on HH production of **97 (52)** times the SM prediction - 3.0 (1.6) pb
- Observed upper limit raised by **fully-hadronic** state, from more events than expected around diphoton mass = 125 GeV
- More sensitive than cut-based ATLAS analysis with 2016 data: Upper limit of 7.7 (5.4) pb on SM HH production.

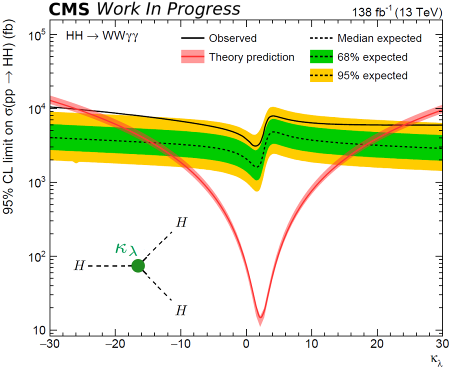


Run 2 HH→WW$\gamma\gamma$: κ_λ scan

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

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

- By linearly combining NLO samples, can extract **upper limit** on a variety of κ_λ points from -30 to 30.
- Observed (expected) constraint on κ_λ of -25.8 (-14.4) to 24.1 (18.3) times SM value
- Observed constraint is not as tight as expected contraint due to fully-hadronic channel

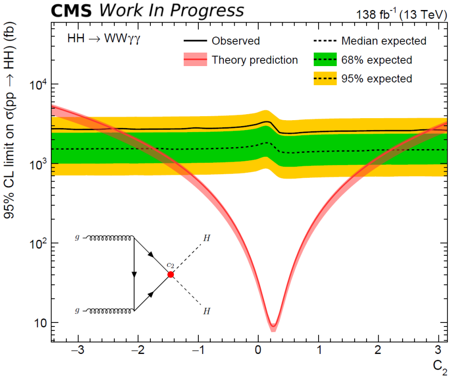


Run 2 HH→WW$\gamma\gamma$: c_2 scan

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

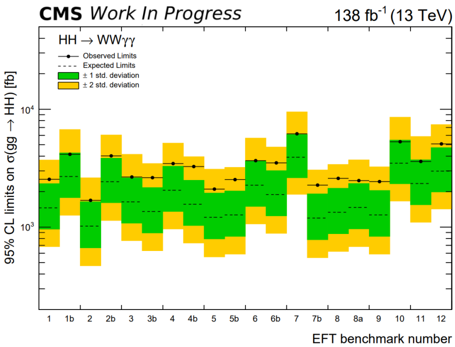
$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}},\ \lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2},\ \kappa_t = \frac{y_t}{y_t^{SM}},\ y_t^{SM} = \frac{\sqrt{2} m_t^2}{v}$$

- By linearly combining reweighted NLO samples, can extract **upper limit** on a variety of c_2 points from -3.5 to 3.5
- Observed (expected) constraint on c_2 -2.4 (-1.7) to 2.9 (2.2)
- Observed constraint is not as tight as expected constraint due to fully-hadronic channel



Run 2 HH→WWγγ: EFT benchmark results

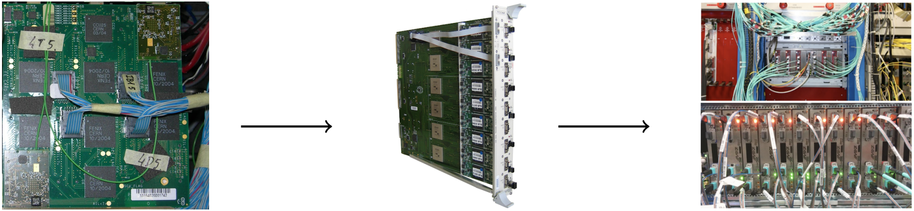
- Set limits on EFT benchmark points - maximum cross section of each process based on data
- Reweight NLO samples to 20 EFT benchmarks for addition BSM searches: [JHEP04(2016)126], [JHEP03(2020)091]
- Each benchmark: set of values for **five EFT parameters**. Example, Benchmark 1: $\{\kappa_\lambda, \kappa_t, c_2, c_g, c_{2g}\} = \{7.5, 1, -1, 0, 0\}$
- Observed (expected) range of 1.7 - 6.2 (1.0 - 3.9) pb. No significant excess of events observed



Next Section

Run 3 optimization: Trigger path

- ECAL trigger sends energy sums to CMS Level-1 trigger at 40 MHz
  - **Energy sums** formed in ECAL on-detector electronics: Application-Specific Integrated Circuits (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

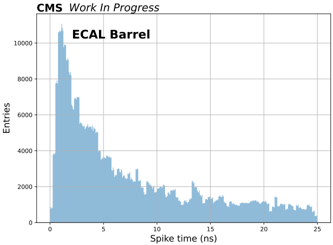
(c) ECAL Trigger concentrator card

(e) Level-1 Calorimeter trigger cards

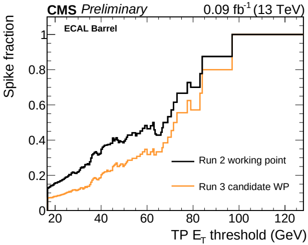
- Max rate of Level-1 accepts: **<u>100 kHz</u>**

Run 3 optimization: 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**, as progenitors travel detector



Spike timing distribution

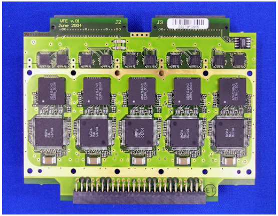


Spike contamination

- 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**

Run 3 optimization: Energy sums

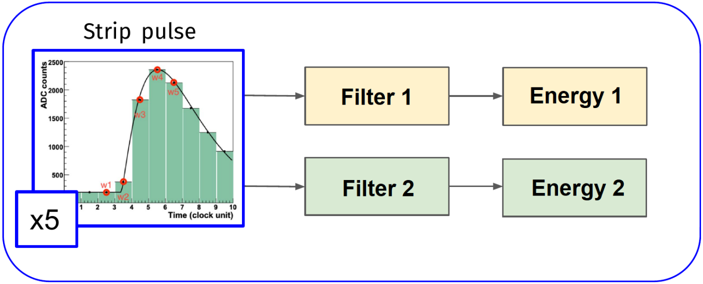
- The basic building blocks of ECAL energy sums are **strips**
  - The energy in a 1x5 channel region, corresponding to an ECAL VFE (Very front end)
- Strip E_T values are computed in ASICs on the front-end card.



(a) Very Front End card

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

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

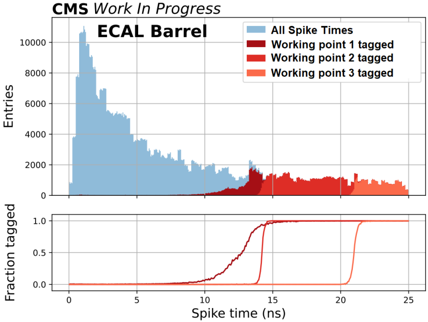


Double amplitude schematic

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

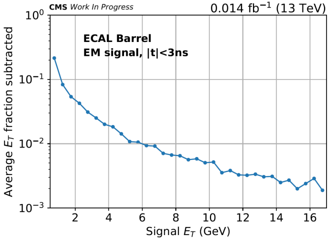
Run 3 optimization: Out-of-time tagging

- 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**, including HH with photons and electrons, increase data yields
  - Potentially tag **out-of-time** signals such as those from Long Lived Particles (LLPs)

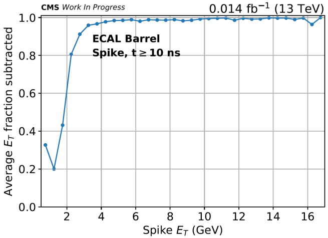


Simulated **spike timing distribution** and parts **tagged** by working points

- 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

Run 3 optimization: Commissioning

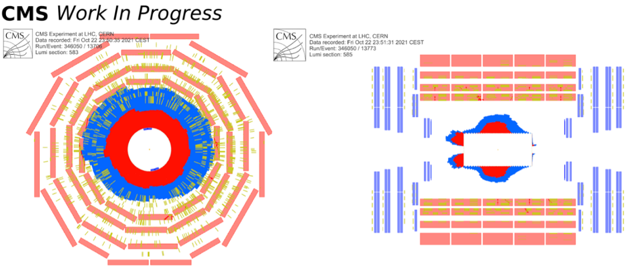
- 2021: Began starting LHC and CMS back up again!
- Good time to test new features

CMS control room

- 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**

Run 3 optimization: 2021 Beam Splashes

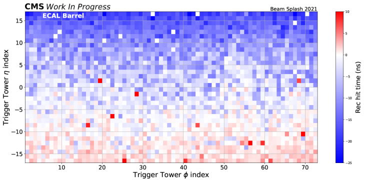
- October 2021: CMS received beam splashes:



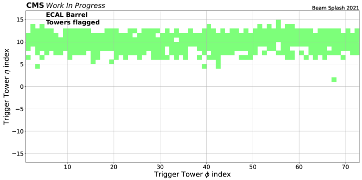
CMS Beam Splash event

- 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

- 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

- **The mechanism works in ECAL!**
- **First instance** of in-situ out-of-time tagging at ECAL L1.

Run 3 optimization: Start of LHC Run 3

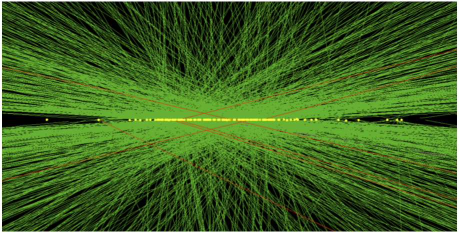
- LHC Run 3 officially began **5 July 2022**

- Will continue investigating this feature to be used during LHC Run 3 to improve physics sensitivity - for **HH** and other processes

Next Section

Phase II: HL-LHC pros and cons

- The LHC will be upgraded during LS3 (2026-28) to the HL-LHC in order to provide more luminosity to detectors. **More data for analysis** ($\approx$ 90% of total)
- **Pros:** Higher luminosity dataset, expect $\approx 3000\ \text{fb}^{-1}$. More data w.r.t LHC, and therefore more **sensitive** search - about **93,000 HH** pairs!
- **Cons:** Huge pileup - $\approx$ 140 simultaneous interactions!!

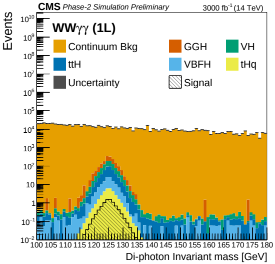


HL-LHC simulated event with 140 concurrent interaction vertices

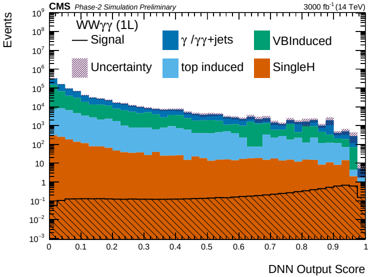
- **LHC:** Higgs discovery was a major goal
- **HL-LHC:** Higgs **pair production** discovery will be a major goal

Phase II: HH→WW$\gamma\gamma$and $\tau\tau\gamma\gamma$ projections

- 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
- Completed projection of HH→WW$\gamma\gamma$ and HH→ $\tau\tau\gamma\gamma$:



(a) di-photon mass



(b) DNN output score

- Followed analysis strategy **very similar** to Run 2 analysis.

  Projected significance: 0.22 σ

Phase II: HL-LHC projections

- $\boldsymbol{WW\gamma\gamma+\tau\tau\gamma\gamma}$ projection added by CMS:

HH Channel	ATLAS	CMS
bbbb	0.61	0.95
bb$\tau\tau$	2.8	1.4
bb$\gamma\gamma$	2.2	2.16
bbVV($\ell\ell\nu\nu$)	-	0.56
bbZZ(4ℓ)	-	0.37
$\boldsymbol{WW\gamma\gamma+\tau\tau\gamma\gamma}$	-	**0.22**

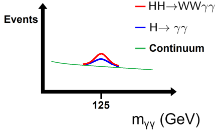
Projected HH significance at HL-LHC

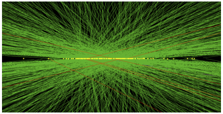
- **No one channel** expected to discover HH - **crucial** to analyze many channels and **combine**
- A few caveats of projection results:
  - Cannot make use of any **data-driven** techniques
  - Do not have dedicated offline reconstruction optimizations: E.g. energy regressions (corrections)
  - Dedicated analysis teams to investigate this future dataset

Next Section

Summary

- Higgs boson used to:
  - Better understand SM
  - Hunt for BSM
  - **Both** can be explored with **Higgs pair production**
- First CMS search for HH→WW$\gamma\gamma$ performed, observed (expected) upper limits extracted:
  - σ_{HH}: **97 (52) times SM prediction**
  - Constraint on Higgs self-coupling: **-25.8 (-14.4) to 24.1 (18.3)** times SM value
  - Constraint on qqHH: **-2.4 (-1.7) to 2.9 (2.2)**
  - 20 EFT benchmarks: **1.7 - 6.2 (1 - 3.9) pb**
- Precise and accurate detectors **imperative** for tagging final states. CMS ECAL vital for HH→WW$\gamma\gamma$, via H→ $\gamma\gamma$
- Investigating new feature for LHC Run 3: Out-of-time tagging at L1, to improve **Run 3 physics sensitivity**
- Future projection completed for HH→WW$\gamma\gamma$ and $\tau\tau\gamma\gamma$ at HL-LHC: **0.22σ**





- Thank you to the thesis committee:

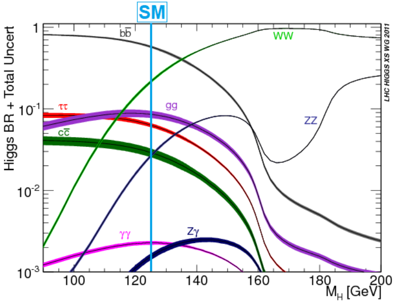
  Professor Toyoko Orimoto, Chair
  Professor Emanuela Barberis
  Professor James Halverson
  Professor Darien Wood

Thank you for your attention!

7 Backup

Backup

- Advantage of the Higgs: Has many **decay modes**, handles for analysis
- Major factors in experimental analysis **sensitivity**:
  - Process branching ratio
  - Object reconstruction efficiency
  - Differentiation from backgrounds
- Different BSM searches with non 125 GeV Higgs may be more sensitive to certain final states

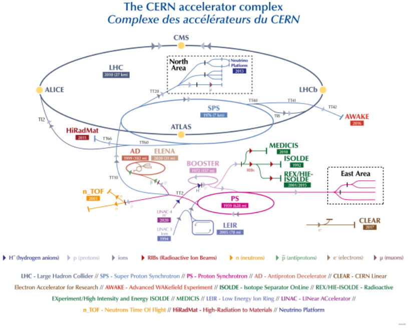


Higgs branching ratios vs. mass

CERN accelerator complex

- CERN accelerator complex:

- Accelerates particles to **high energies**, collide to produce massive particles, study physical processes
- Final stage: LHC

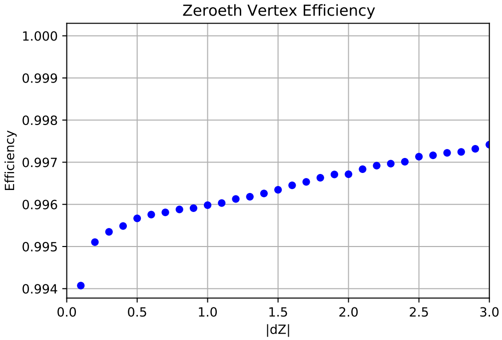


CERN accelerator complex

- Accelerates **protons** and **heavy ions**

Vertex efficiency

- Selecting the highest sum p_T^2 vertex is within 0.1cm of the GEN level vertex $>$ 99% of the time for the SL signal



SL vertex efficiency

Lagrangian Terms

- $G^a_{\mu\nu}$ 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_t^{SM}
- 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

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

Diphoton preselections

Run 2 HH→WW$\gamma\gamma$: Common selections

- **Vertex:**
  - Use $\mathbf{0^{th}}$ vertex (largest Σp_T^2) of each event. Vertex efficiency w.r.t. GEN for $|\Delta Z| < 0.1cm$ is $> 99\%$
- **Photons:**
  - Select **energetic**, **isolated** photons: Leading (Subleading) photon $p_T > 35$ (25) GeV, $\Delta R (= \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2})$ with other objects > 0.4

- **Electrons:**

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

Electron object requirements

- **Muons:**

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

Muon object requirements

$$R_{iso} = \left[\sum_{\substack{charged\\hadrons}} p_T + max\left(0, \sum_{\substack{neutral\\hadrons}} p_T + \sum_{photons} p_T - p_T^{\mathrm{PU}}\right)\right] / p_T^l \quad (1)$$

Run 2 HH→WW$\gamma\gamma$: Common selections

- **Jets:**

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

- Events fall into the (FH, SL, FL) category if they contain Exactly (0, 1, 2) leptons passing the above selections
- FH category requires at least 4 jets passing above jet selections

Run 2 HH→WW$\gamma\gamma$: Preselection yields

- Preselections remove **vast majority** of continuum and resonant backgrounds (>99%), but still large remaining yields ($\approx$ 2-1000 events)
- Preserve $\approx$ 10-34% of HH signal events
- However HH signal yield very **low**, so will employ further techniques and selections for further signal over background optimization

Process	No selection	SL	FH	FL
$\gamma\gamma$+jets	302978	542 (0.179%)	6247 (2.062%)	2.77 (0.001%)
tt$\gamma\gamma$	44.0507	11 (25%)	26 (58%)	0.149 (0.3%)
ttγ+jets	765	155 (20%)	402 (53%)	- (-%)
ttW+jets	5.04	- (-%)	2.8 (56%)	- (-%)
γ+jet	830909	1061 (0.002%)	2466 (0.002%)	- (-%)
QCD	1653618	- (-%)	- (-%)	- (-%)
tt+jets	23.56	3.34 (81%)	18.8 (55%)	- (-%)
W+1jet	5838	245 (0.329%)	- (-%)	- (-%)
W+2jets	5589	353 (0.343%)	204 (0.232%)	- (-%)
Total continuum	2812863	2371 (0.0008%)	9368 (0.0033%)	2.92 (0.0%)
gg→H→ $\gamma\gamma$	2227	2.556 (0.115%)	18.39 (0.826%)	- (-%)
ttH(→ $\gamma\gamma$)	23.9	5.9 (25%)	14.42 (60%)	0.0545 (0.23%)
qq→H→ $\gamma\gamma$	158	0.371 (0.235%)	1.068 (0.675%)	- (-%)
VH(→ $\gamma\gamma$)	85.55	10.05 (11.8%)	4.43 (5.2%)	0.0832 (0.097%)
Total H	2494	19 (0.0076%)	38 (0.015%)	0.14 (0.0001%)
SL HH→WW$\gamma\gamma$	0.3042	**0.1044 (34%)**	- (-%)	- (-%)
FH HH→WW$\gamma\gamma$	0.3012	- (-%)	**0.0966 (32%)**	- (-%)
FL HH→WW$\gamma\gamma$	0.0741	- (-%)	- (-%)	**0.0098 (13%)**

Simulation yields with 2017 MC before and after preselections

Preselection yield details

MC Sample	Before preselection	SL (efficiency)	FH (efficiency)	FL (efficiency)
DiPhotonJetsBox_M40_80	1138.8964	- (-%)	- (-%)	- (-%)
DiPhotonJetsBox_MGG-80toInf	302977.6194	542.4641 (0.179%)	6246.9949 (2.062%)	2.7749 (0.001%)
DYJetsToLL_M-50	7525.2616	- (-%)	- (-%)	- (-%)
THQ_ctcvcp	3.4592	0.5789 (16.735%)	1.0579 (30.582%)	0.0012 (0.034%)
TTGG_0Jets	44.0507	10.9847 (24.936%)	25.6024 (58.12%)	0.1487 (0.338%)
TTGJets_TuneCP5	765.4892	154.6684 (20.205%)	402.1377 (52.533%)	- (-%)
TTToHadronic	903.4816	- (-%)	- (-%)	- (-%)
ttWJets	5.0469	- (-%)	2.8337 (56.147%)	- (-%)
W3JetsToLNu	1041.188	- (-%)	- (-%)	- (-%)
W4JetsToLNu	985.8018	- (-%)	- (-%)	- (-%)
WGGJets	534.8559	- (-%)	- (-%)	- (-%)
WGJJToLNu_EWK_QCD	367.5752	- (-%)	- (-%)	- (-%)
WGJJToLNuGJJ_EWK	65.3279	- (-%)	- (-%)	- (-%)
WWTo1L1Nu2Q	337.0574	- (-%)	- (-%)	- (-%)
WW_TuneCP5	189.1288	- (-%)	- (-%)	- (-%)
GJet	830909.3171	1061.0649 (0.002%)	2466.3582 (0.002%)	- (-%)
QCD	1653618.4935	- (-%)	- (-%)	- (-%)
TTJets	23.5628	3.3477 (81.397%)	18.8106 (55.121%)	- (-%)
W1Jet	5838.2419	245.2825 (0.329%)	- (-%)	- (-%)
W2Jets	5589.4864	352.6322 (0.343%)	204.2186 (0.232%)	- (-%)
Total	2812863.3417	2371.0234 (0.0008%)	9368.014 (0.0033%)	2.9248 (0.0%)

2017 Continuum Background MC before and after preselections for each final state, and process efficiency. Note that for processes with less than 1000 unweighted MC events after a selection (100 for the fully-leptonic preselections), a null value is shown.

Preselection yield details

MC Sample	Before preselection	SL	FH	FL
DiPhotonJetsBox_M40_80	0.0405%	-%	-%	-%
DiPhotonJetsBox_MGG-80toInf	10.7711%	22.8789%	66.6843%	94.8755%
DYJetsToLL_M-50	0.2675%	-%	-%	-%
THQ_ctcvcp	0.0001%	0.0244%	0.0113%	0.0397%
TTGG_0Jets	0.0016%	0.4633%	0.2733%	5.0849%
TTGJets_TuneCP5	0.0272%	6.5233%	4.2927%	-%
TTToHadronic	0.0321%	-%	-%	-%
ttWJets	0.0002%	-%	0.0302%	-%
W3JetsToLNu	0.037%	-%	-%	-%
W4JetsToLNu	0.035%	-%	-%	-%
WGGJets	0.019%	-%	-%	-%
WGJJToLNu_EWK_QCD	0.0131%	-%	-%	-%
WGJJToLNuGJJ_EWK	0.0023%	-%	-%	-%
WWTo1L1Nu2Q	0.012%	-%	-%	-%
WW_TuneCP5	0.0067%	-%	-%	-%
GJet	29.5396%	44.7513%	26.3274%	-%
QCD	58.7877%	-%	-%	-%
TTJets	0.0008%	0.1412%	0.2008%	-%
W1Jet	0.2076%	10.345%	-%	-%
W2Jets	0.1987%	14.8726%	2.18%	-%
Total	100%	100%	100%	100%

Preselection yield details

MC Sample	Before preselection	SL (efficiency)	FH (efficiency)	FL (efficiency)
GluGluHToGG	2226.7151	2.5556 (0.115%)	18.3933 (0.826%)	- (-%)
ttHJetToGG	23.8639	5.9022 (24.733%)	14.4288 (60.463%)	0.0545 (0.228%)
VBFHToGG	158.1456	0.3712 (0.235%)	1.0675 (0.675%)	- (-%)
VHToGG	85.5536	10.0542 (11.752%)	4.4384 (5.188%)	0.0832 (0.097%)
Total MC	2494.2782	18.8832 (0.0076%)	38.328 (0.0154%)	0.1377 (0.0001%)

2017 Single Higgs MC before and after preselections for each final state, and process efficiency. Note that for processes with less than 100 unweighted MC events after a selection, a null value is shown.

Preselection yield details

MC Sample	Before preselection	SL	FH	FL
GluGluHToGG	89.2729%	13.5335%	47.9892%	-%
ttHJetToGG	0.9567%	31.2564%	37.6455%	39.5654%
VBFHToGG	6.3403%	1.9657%	2.7853%	-%
VHToGG	3.43%	53.2444%	11.5801%	60.4214%
Total	100%	100%	100%	100%

Contribution w.r.t total 2017 Single Higgs MC for various phase spaces: Before and after preselections for each final state. Note that for processes with less than 1000 unweighted MC events after a selection (100 for the fully-leptonic preselections), a null value is shown.

Preselection yield details

MC Sample	Before preselection	SL (efficiency)	FH (efficiency)	FL (efficiency)
Semi-leptonic HH$\rightarrow WW\gamma\gamma$	0.3042	0.1044 (34.306%)	- (-%)	- (-%)
Fully-hadronic HH$\rightarrow WW\gamma\gamma$	0.3012	- (-%)	0.0966 (32.07%)	- (-%)
Fully-leptonic HH$\rightarrow WW\gamma\gamma$	0.0741	- (-%)	- (-%)	0.0098 (13.214%)

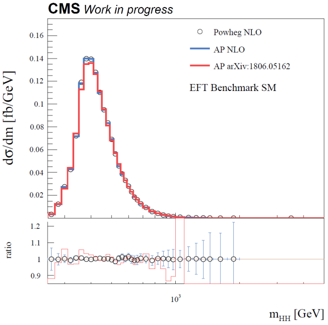
2017 HH MC before and after preselections for each final state, and process efficiency. Note that for processes with less than 100 unweighted MC events after a selection, a null value is shown.

Samples: Reweighing

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

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

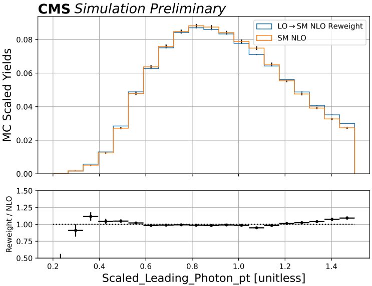
- Ratio of differential cross sections between original and target
- Compute custom coefficients of analytical parameterization from privately produced samples in order to derive event weights. Can use to reweigh **any** HH sample $\rightarrow$ any benchmark at **NLO**:



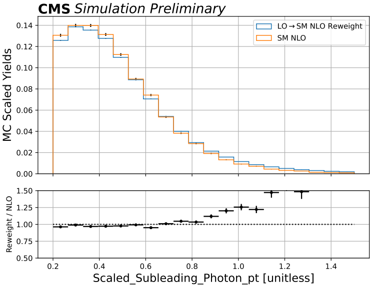
Predicted analytic parameterization matches Powheg generated SM HH at NLO. Expect to be able to reweigh any HH sample to SM at NLO

Run 2 HH→WW$\gamma\gamma$: Semi-leptonic DNN

- Reweight HH signal events at LO to NLO from independent sample for training:



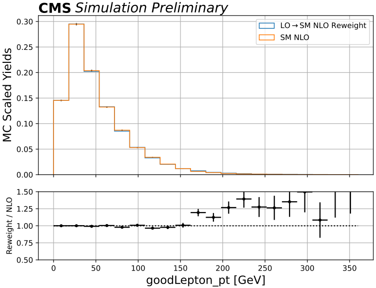
(a) Scaled Leading Photon p_T



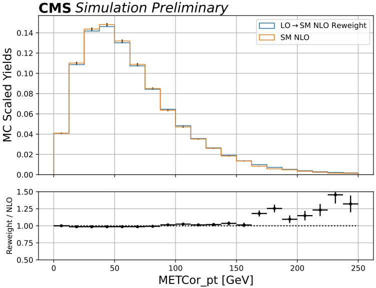
(b) Scaled subleading photon p_T

Reweighted quantities

- Reweighted events model SM HH signal well
- Use for training, statistically independent from SM at NLO generated samples for signal modelling



(a) Lepton p_T



(b) MET

Lepton and MET

Semi-leptonic SM DNN training details

Class	Unweighted Yield	Weighted Yield	Class Weight	Class Weight * Weighted Yield
HH	866833	2.232871	388214	866833
H	78108	1.057757	819501	866833
Continuum Background	61408	16104	53.8278	866833

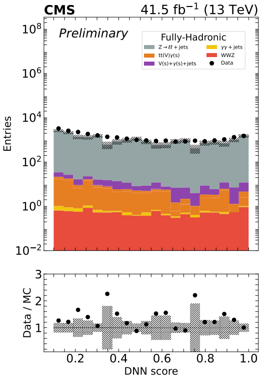
Unweighted and weighted yields, and class weights applied during Semi-Leptonic DNN training, without data sideband scale. Weighted class yields are reweighted by class weights to the unweighted HH yield.

Semi-leptonic SM DNN training details

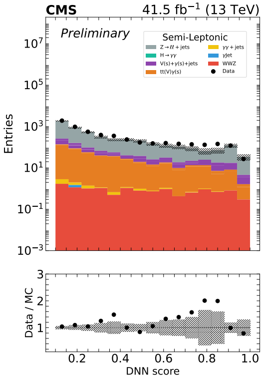
MC Sample	Unweighted	Weighted
DiPhoJetsBox_MGG-80toInf	5108	581.97343
GJet_40toInf	110	48.26491
tt$\gamma\gamma$+0Jets	4633	17.01703
ttγ+Jets	1564	52.52178
tt+Jets	288	51.77128
W1Jets_pT_150-250	1298	64.88303
W1Jets_pT_250-400	341	7.42416
W1Jets_pT_400-inf	217	1.80622
W1Jets_pT_50-150	23	13.60197
W2Jets_pT_150-250	1612	60.29933
W2Jets_pT_250-400	777	12.25016
W2Jets_pT_400-inf	531	3.05085
W2Jets_pT_50-150	59	27.52279
WGGJets	360	132.12192
WGJJToLNu_EWK_QCD	140	30.91906
ttWJets	74	0.5721

Unweighted and weighted training MC yields in the sideband region, including semi-leptonic training pre-selections and only events with a DNN output score > 0.1.

- Evaluate DNNs in a control region with **inverted diphoton electron veto** requirement, leads to Z→ee-like region

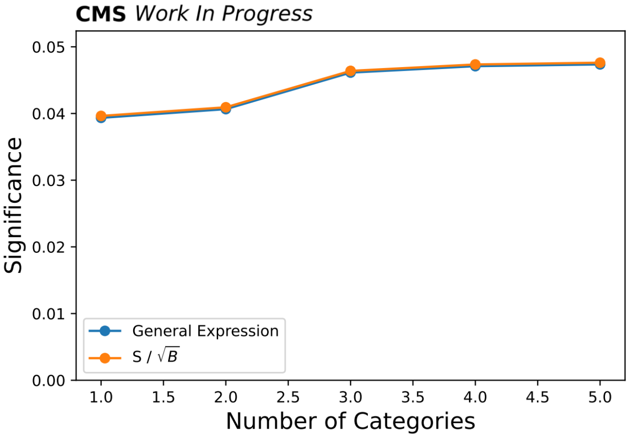


(a) FH DNN score.



(b) SL DNN score.

Semi-leptonic sig vs. NCats



- Total significance vs. number of categories in DNN categorization optimization. Total significance computed as category significances summed in quadrature. S = weighted HH events, B = weighted number of MC events modeling the continuum background in the signal region plus the number of weighted single H events.

Run 2 HH→WW$\gamma\gamma$: Semi-leptonic categorization

- Categorize events based on DNN score
- Optimize category boundaries by **signal sensitivity**, estimated by **HH** and **simulated background** in signal region
- Vary number of bins [10, 20, ... , 1520] and categories [1-5], perform simultaneous optimization of all category boundaries
- Result: Largest expected significance at **90 equally sized bins** width 1/90 between DNN scores 0.1 to 1.0.

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

Semi-Leptonic DNN Category Boundaries and yields in signal region for 4 Categories

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

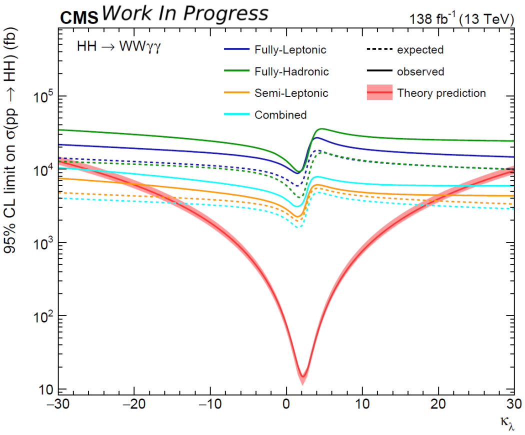
Parameter values of the benchmarks 1-12 [1], 8a [2], 1b-7b [3] and the Standard Model.

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

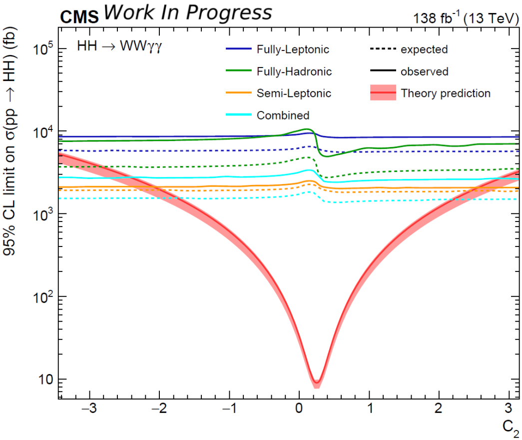
- **Left:** Samples used for Semileptonic and Fullyhadronic DNNs, **not** used to model the background.
- **Right:** Single Higgs samples used to model **resonant background** in signal region

Per channel Run 2 HH→WW$\gamma\gamma$results



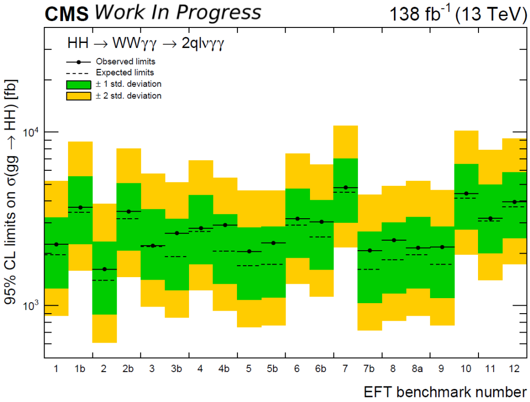
Per channel kl scan

Per channel Run 2 HH→WWγγ results



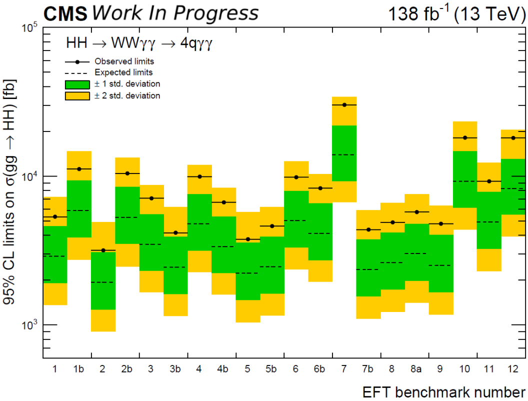
Per channel c2 scan

Per channel Run 2 HH→WWγγ results



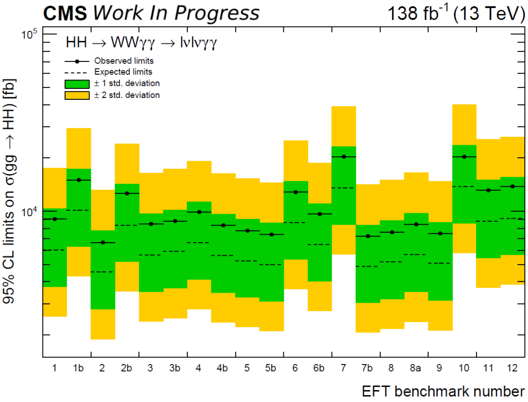
Semileptonic 20 EFT benchmarks upper limits

Per channel Run 2 HH→WW$\gamma\gamma$results



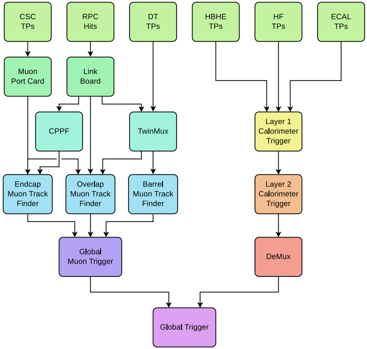
Fullyhadronic 20 EFT benchmarks upper limits

Per channel Run 2 HH→WW$\gamma\gamma$results



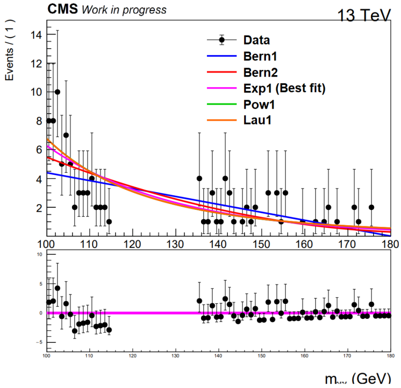
Fullyleptonic 20 EFT benchmarks upper limits

CMS L1 trigger



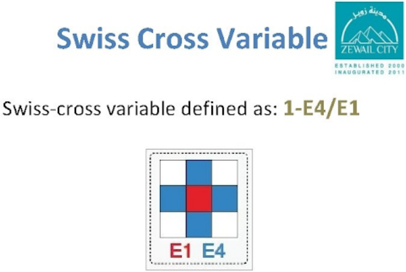
CMS L1 trigger

- 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

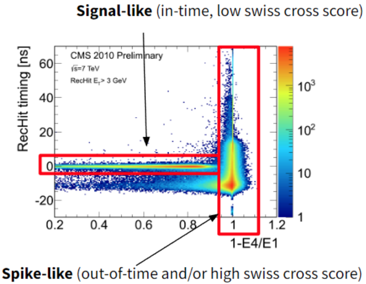


Semileptonic background model, all fit functions

Spikes



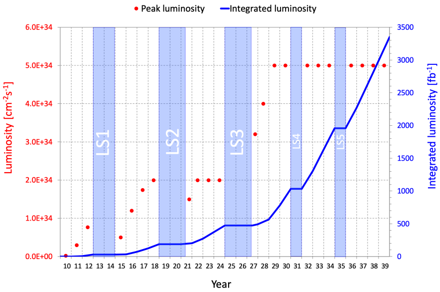
(a) Swiss cross definition



(b) Reconstructed time vs. swiss cross score

Phase II: HL-LHC luminosity

- The LHC will be upgraded during LS3 (2026-28) to the HL-LHC in order to provide more luminosity to detectors. **More data for analysis**



Lumi vs. time

- HL-LHC will provide about **90%** of the total LHC+HL-LHC dataset
- Experiments must plan accordingly to prepare for corresponding collision conditions
- **LHC:** Higgs discovery was a major goal
- **HL-LHC:** Higgs **pair production** discovery will be a major goal