Search for Higgs Decay to Two Muons

Qianying Guo
Peking University
on behalf of CMS H→μμ working group

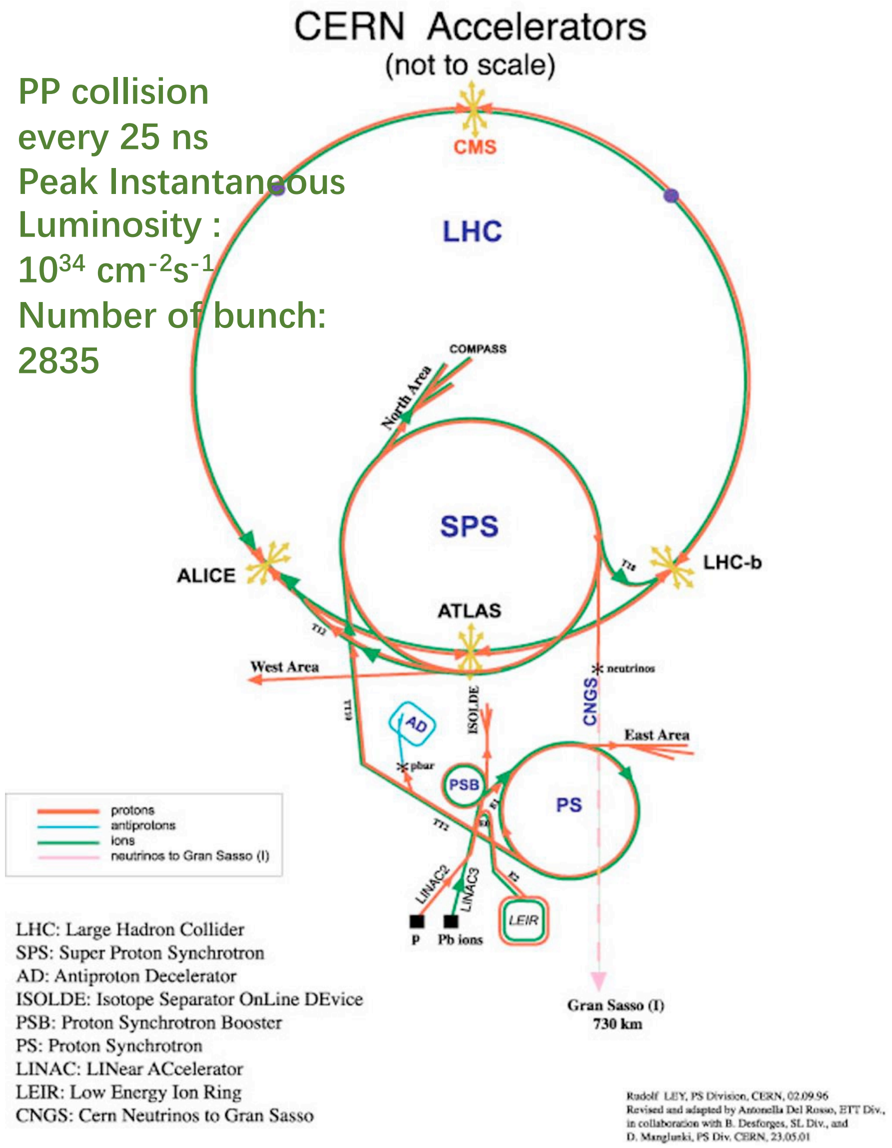
Muon Physics and Muon Technologies Innovation Academic Forum, 12 July, 2026

Outline

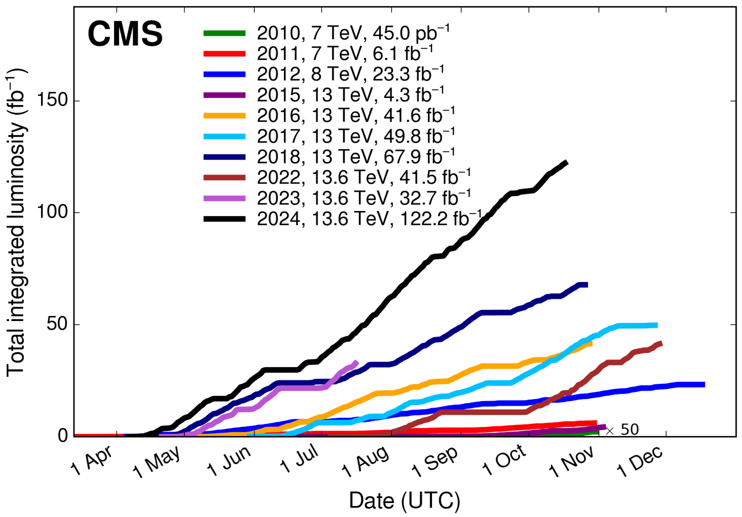
- Introduction of LHC and CMS experiment
- Analysis Motivation
- Muon Performance
- Jet Behavior
- Analysis Strategies by channels
- Summary and outlook

Large Hadron Collider (LHC)

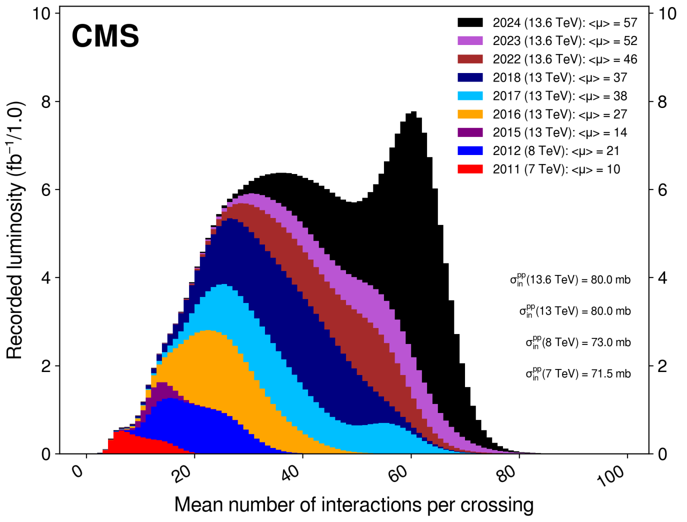
PP collision every 25 ns
Peak Instantaneous Luminosity : 10^{34} $cm^{-2}s^{-1}$
Number of bunch: 2835



- Accelerator with the largest energy
  - 900GeV → 7TeV → 8TeV →13TeV →13.6TeV
  - 27km ring, locates at CERN
  - 4 large detectors installed: ATLAS, CMS, LHCb, ALICE
  - p-p, p-P_b , P_b-P_b collisions

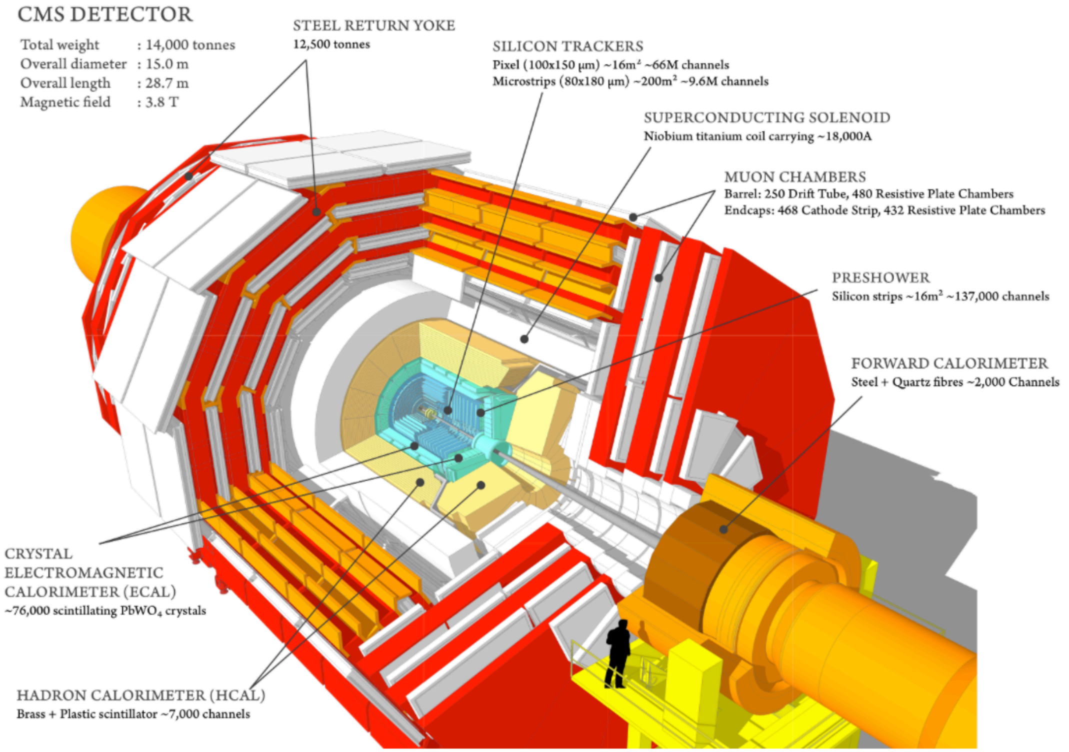


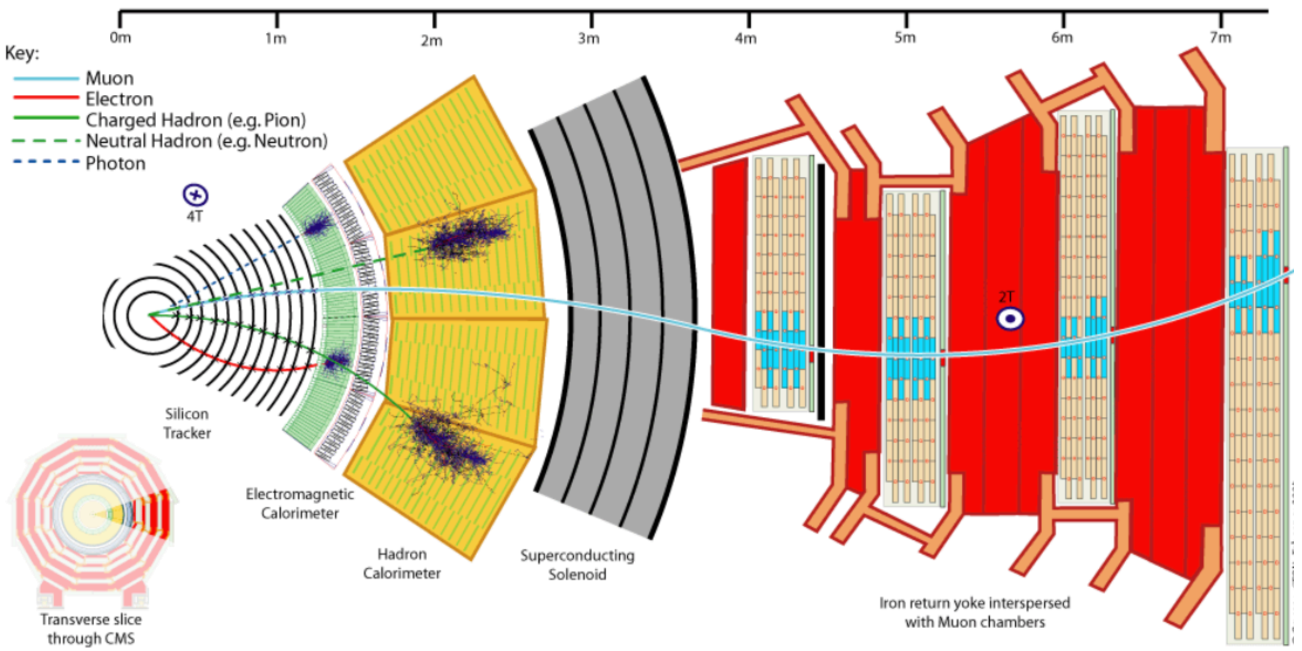
Delivered luminosity versus time for 2010-2012, 2015-2018, and 2022-2024 (pp data only)



Number of interactions per bunch crossing

CMS detector

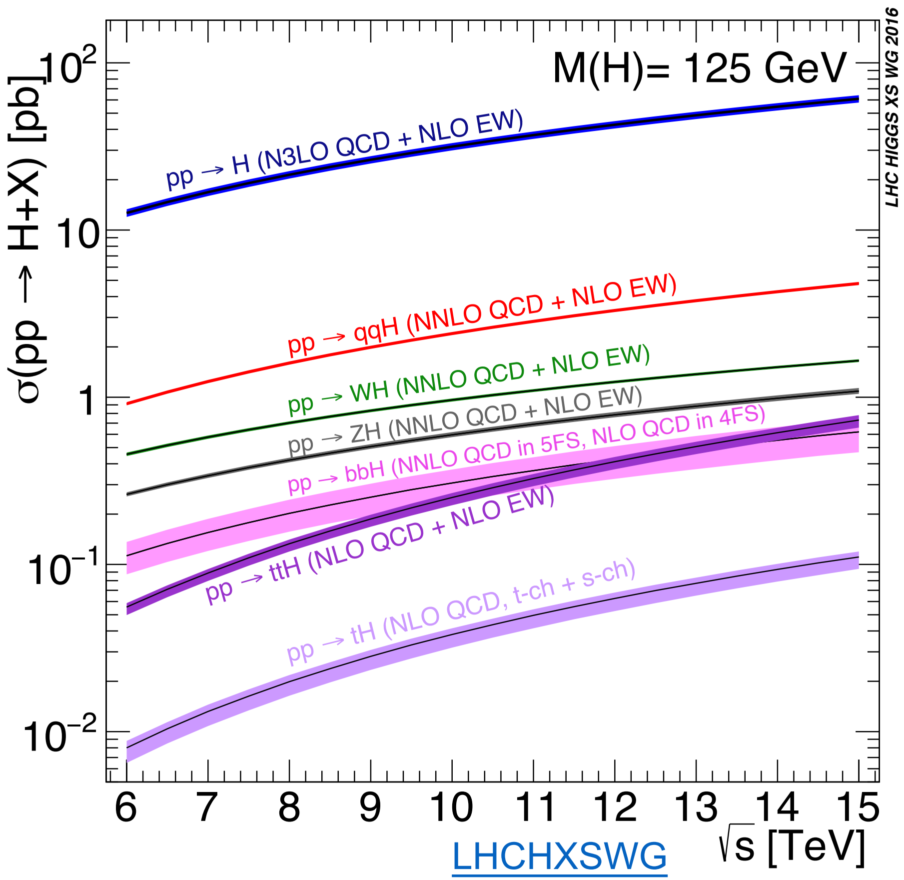




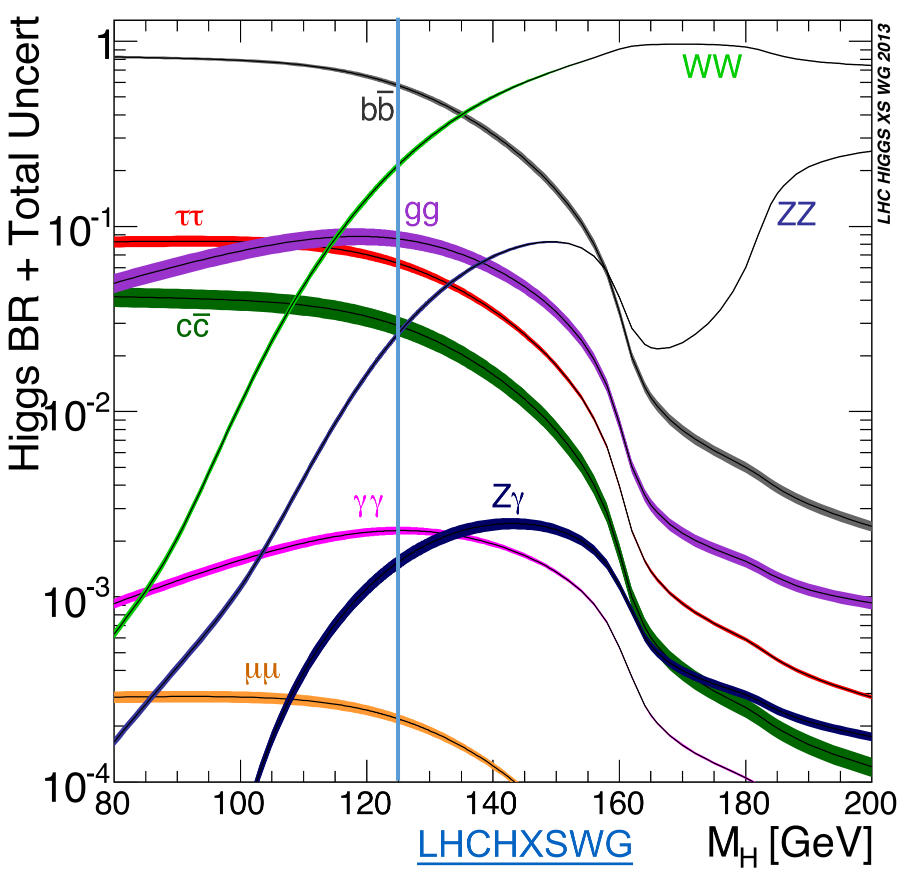
Five types of particles interact with each sections of the detector

- CMS is 21 meters long, 15m in diameter, and weighs about 14,000 tonnes.
- Consist of Inner tracker; Electromagnetic Calorimeter; Hadronic Calorimeter; Magnet; Muon chamber

Higgs Production and Decay at LHC



LHCHXSWG



LHCHXSWG

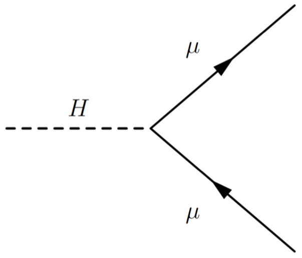
- Main production model and its cross section at 13TeV and Higgs mass of 125GeV
  - Gluon-Gluon Fusion: 48.58 pb
  - VBF: 3.782pb
  - VH: 1.373pb(WH); 0.8839pb(ZH)
  - ttH: 0.5071pb

- H rare decay channel H →μμ is our interest in Run III

Motivation of H → μμ

- Probe Higgs couplings to second generation fermion via H→μμ.
- Experimentally challenging search:
  - Relatively rare decay mode:

$$\mathcal{B}(\mathrm{H} \to \mu^+\mu^-) = 2.18 \times 10^{-4}$$

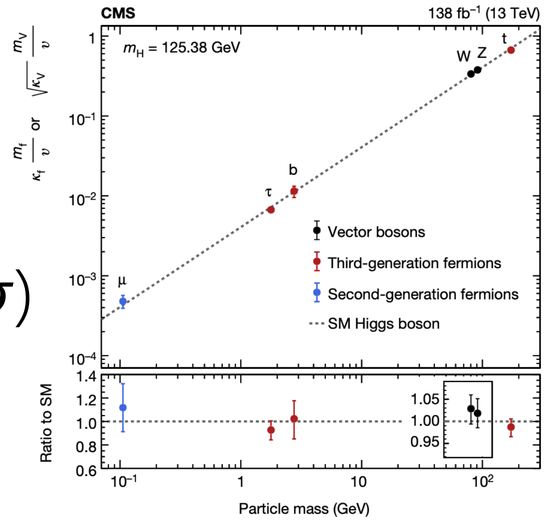


  - Very large DY background ⇒ very small S/B with inclusive selections.

- Measurement:
  - Run 2: 2016-2018: 137 fb^{-1}

    ⇒ observed (expected) significance is 2.98σ (2.48σ)

  - Run 3: 2022-2026: 311.89 fb^{-1}
  - **Targets: improve sensitivity toward observation of the decay, approaching 5σ regime**



Nature 607 (2022) 60–68

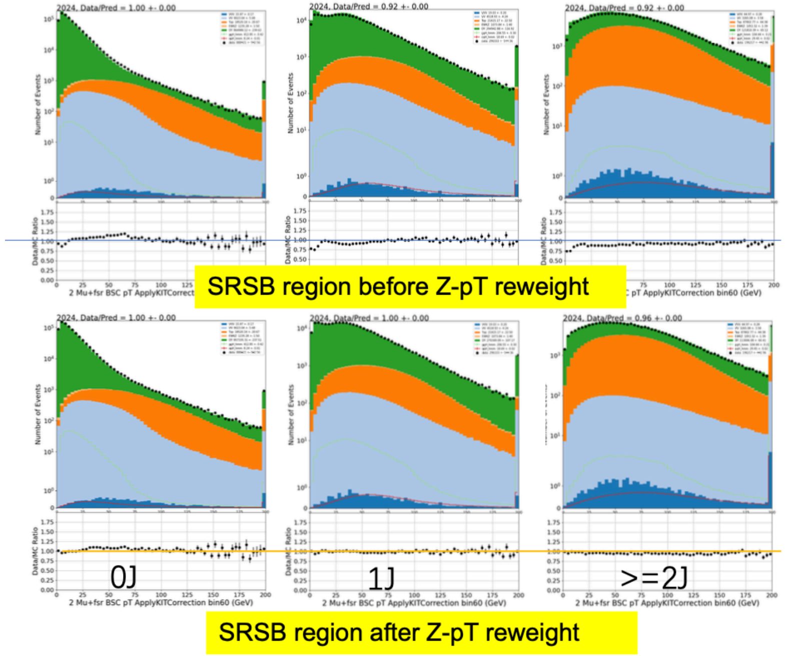
Object selections

- Muons: $p_T > 20$ GeV, $|\eta| < 2.4$, Medium Id, Loose iso
- Electrons: $p_T > 20$ GeV, $|\eta| < 2.4$, mvaIsoWP90, ECal gap veto
- Jets: $p_T > 25$ GeV, $|\eta| < 4.7$, Pass POG Tight ID

  No overlap with PF muons or electrons ($\Delta R \leq 0.4$)

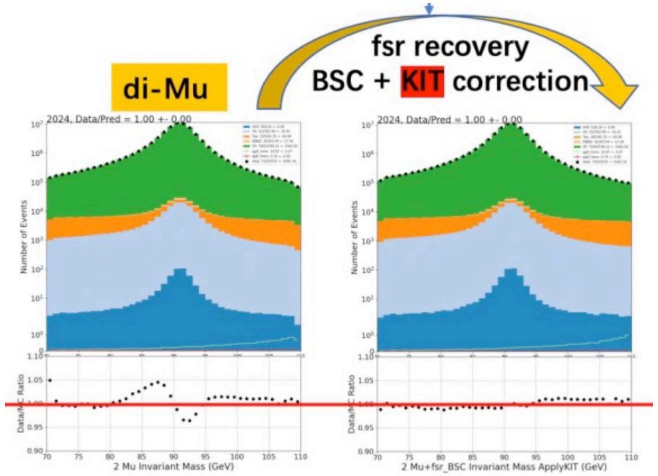
  Using jet veto maps

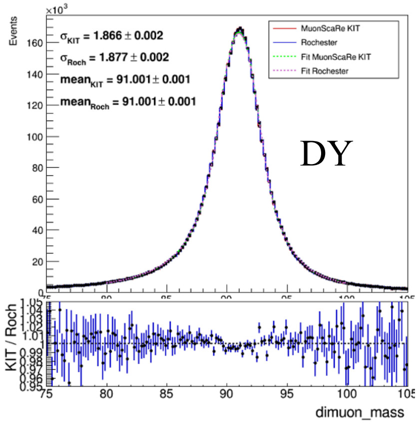
MC corrections: PU reweighting, MuonScaReKIT Correction, JEC, Muon Medium ID SF, Muon Loose PF Iso SF, Z-pT reweighting, Event by event mass resolution

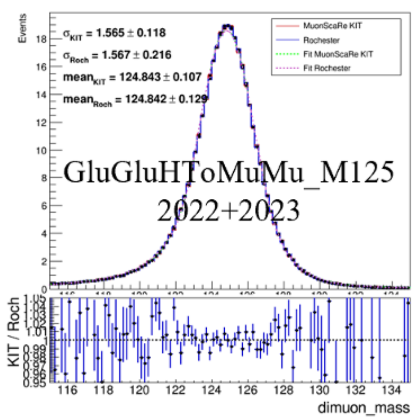


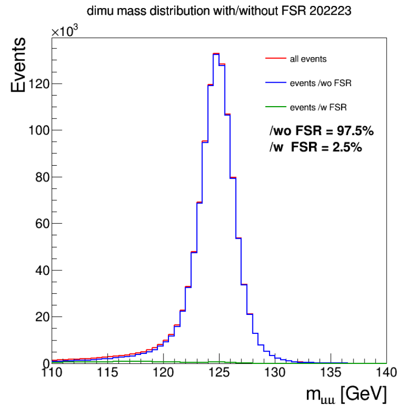
Muon performance

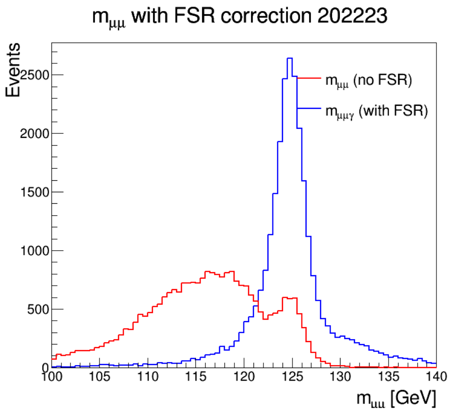
- Beam Spot Constraint (BSC) implemented
  - Replacing Run 2 GeoFit correction
  - Improve event-by-event resolution
- FSR Photons recovery
- Rochester/ScaRe KIT corrections
  - Good performance in both cases
  - Currently, ScaRe KIT is the recommended as it is actively maintained and well supported











Jet Behaviors

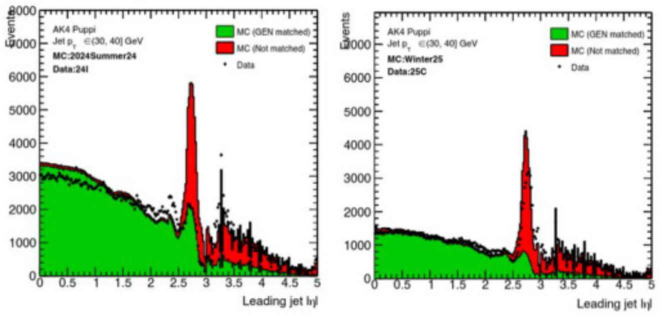
- Mismodeling of forward jets reduces the analysis sensitivity
  - HE spikes: $2.5 < |\eta| < 3.0$
  - HF: $|\eta| > 3.0$
- Current era-specific recommendations suggested by JetMET and PPD

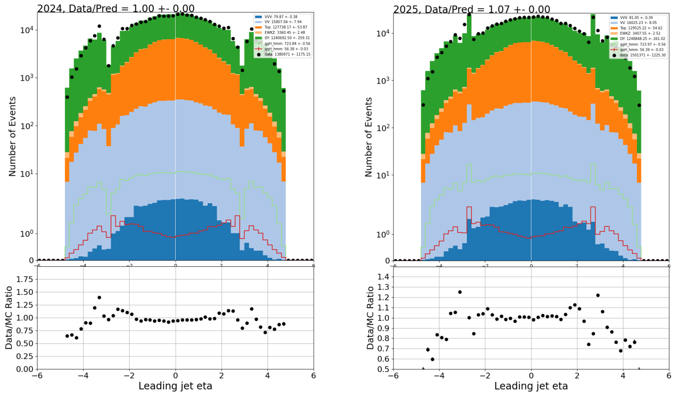
Year	HF (3 < |eta| < 5)	HE (2.5 < |eta| <3)	2.0 < |eta| < 2.5
2022	Require pT > 50 GeV	Require pT > 50 GeV + JER for gen-matched only	-
2023	Require pT > 50 GeV	Require pT > 50 GeV + JER for gen-matched only	-
2024	Fixed	Require pT > 50 GeV + JER for gen-matched only	For MC-truth corrected pT < 30 GeV use L2L3Residual correction factor of MC-truth corrected pT = 30 GeV in 2.0 < |eta| < 2.5
2025	Fixed but worsening by radiation damage	Much improved. Enough for analysers?	Should not be a problem but please check!

ref

- Multiple strategies tested (pileup discr., BDTs, forward jet studies)
  - Further studies needed to assess the real gain
  - No easy solution for HF, since it may due to calibration issues

2024 2025





Run-III Analysis Strategy

- Following the Run-II analysis strategies and seeking for the improvement

Events with two prompt, isolated, and oppositely charged muons

ttH channel

- Phase-space containing at least **one medium** or two **loose b-tagged** jets
- Based on the presence of addition leptons (μ,e)

ttH hadronic | *ttH leptonic*

VH channel

- Targeting **leptonic decays** of W/Z
- Veto events with b-jets already belonging to the ttH channel

WH leptonic → 3μ or 2μ1e final states

ZH leptonic → 4μ or 2μ2e final states

VBF channel

- Veto ttH events
- Veto VH events
- Select events with two jets with **VBF-like kinematics**

$p_T^{j1} > 35\ GeV$

$p_T^{j2} > 25\ GeV$

$m_{jj} > 400\ GeV$

$|\Delta\eta_{jj}| > 2.5$

ggH channel

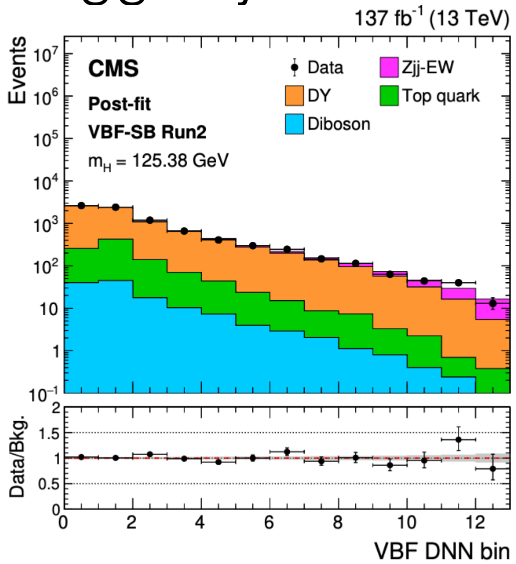
- Collects all the events not selected by the other channels
- Phase-space dominated by events with zero or one additional jet and no extra leptons apart from the H(μμ) candidate

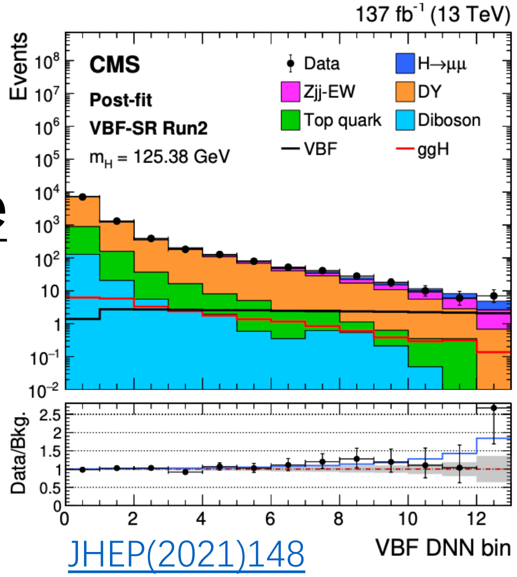
- Signal is extracted with a **simultaneous fit** across all categories to observables chosen for each category.

VBF Channel

- Select the events with neither additional charged leptons nor b-tagged jets and a pair of jets with large mjj and Δηjj

- **Analysis Strategy**
  - Signal extraction is fully <u>based on MC</u>
    - Low signal event statistic
    - Reliable background modeling (DY+jets, VBF Z)
  - Train a DNN to distinguish signal from background including the dimuon mass as input.
  - VBF H→μμ signal is extracted by **<u>fitting DNN output score</u>** in data directly to background shape predictions from simulation





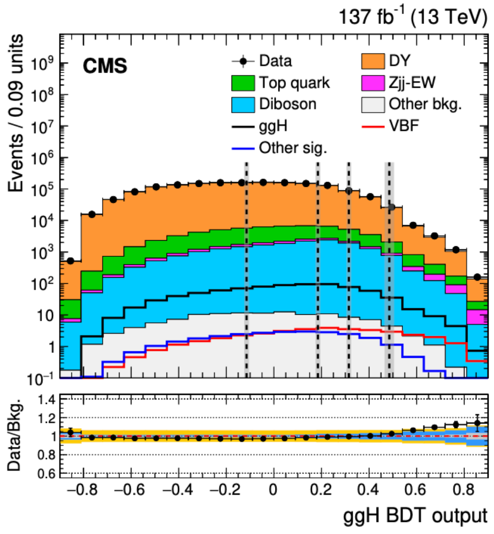
JHEP(2021)148

ggH Channel

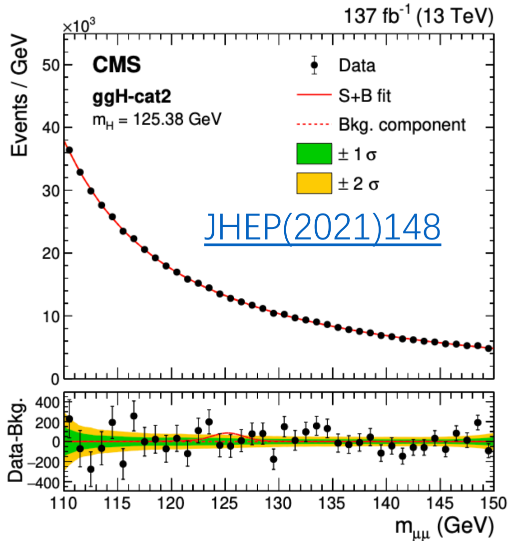
- Phase space dominated by 0–1 jet events with only the μμ pair and multi-jet events are kept if not VBF-like.

- **Analysis Strategy**
  - Extract the signal by **<u>fitting dimuon invariant mass</u>**
    - Signal: sharp peak at 125 GeV; Background: smooth, falling distribution

    → Enables <u>data-driven background estimation via analytical fit</u>



- BDT used to separate Higgs signals from expected backgrounds
- Divide event in categories characterized by different S/B

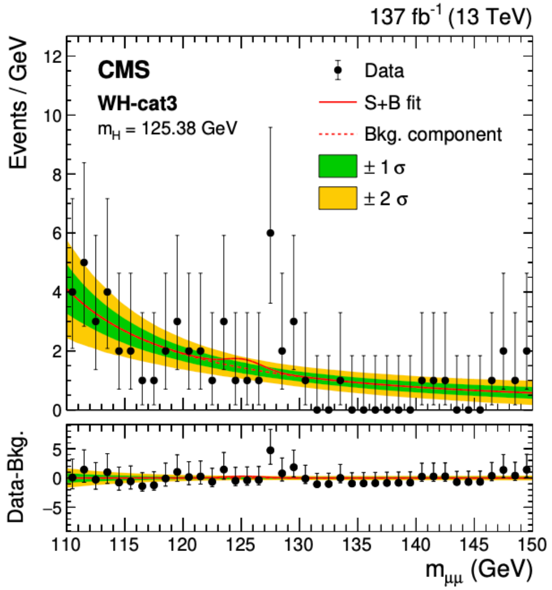


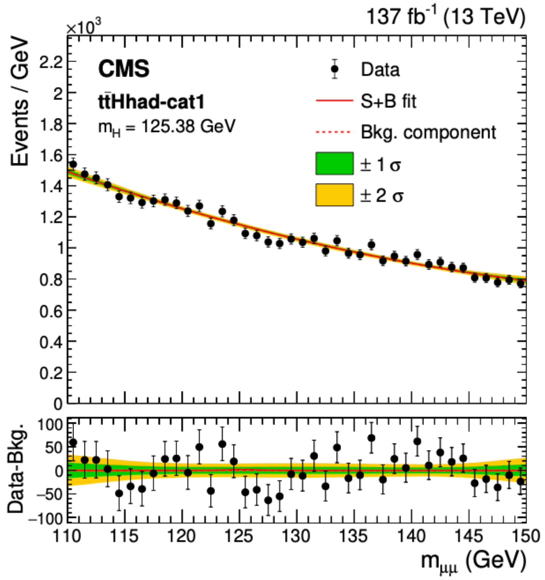
$$B_{cat}(m_{\mu\mu}, \vec{\alpha}, \vec{\beta}) = N_B \times F_{core}(m_{\mu\mu}, \vec{\alpha}) \times T_{SMF}(m_{\mu\mu}, \vec{\beta})$$

- Signal model: m(μμ) described with a Double Crystal-ball function.
- Background modeling: Core-PDF method
- Core background function built as discrete profile of two physics-inspired (Breit-Wigner, FEWZ) and an agnostic (sum of exponentials) function.

VH and ttH Channel

- Analysis strategy for the two channel in Run-II is similar to ggH channel.
- VH: Select one (two) additional lepton(s) consistent with W(Z) boson leptonic
- ttH: At least one (two) additional jet(s) passing the DeepCSV medium (loose) WP
- Background fit with BWZ function (VH),simple exponential (ttH-lep) and polynomial (ttH-had)
- In Run-III, we exploit some improvement in these channel

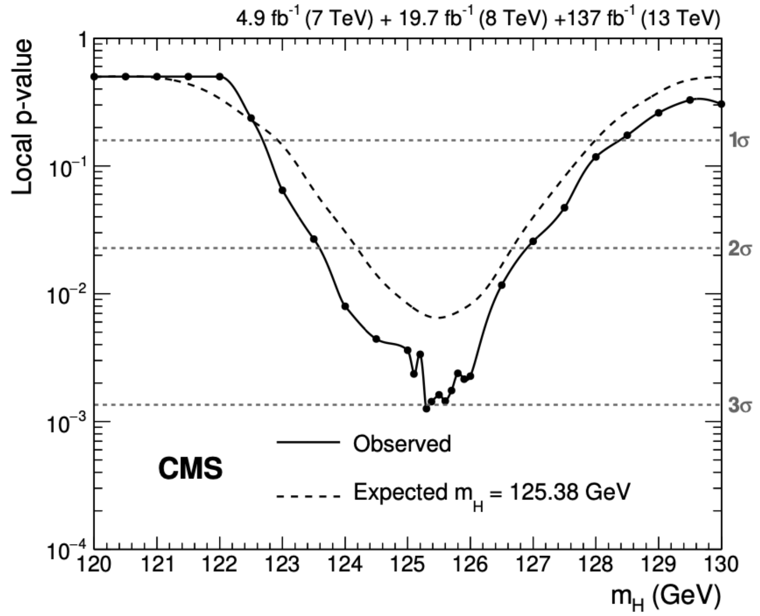


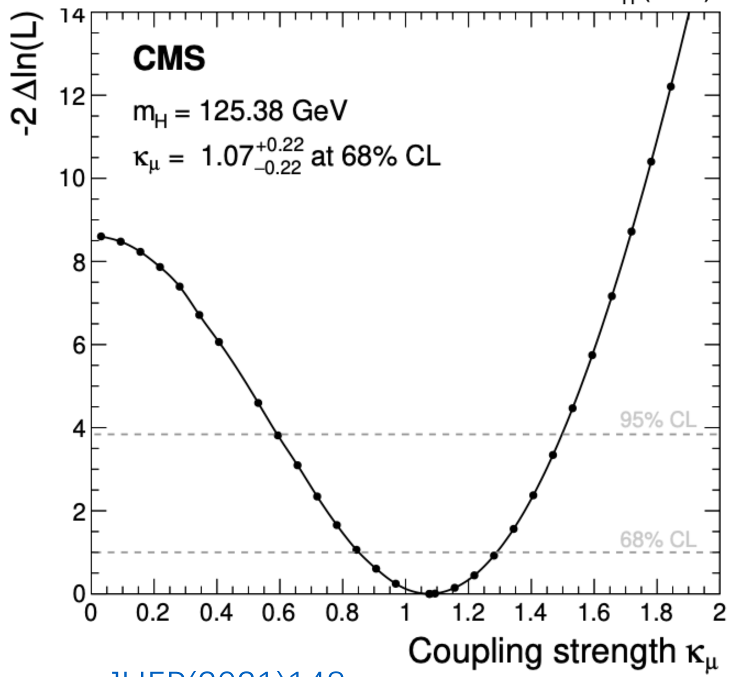


JHEP(2021)148

Run-II Analysis --- Results

- Measurement of H→μμ combines four separate analyses targeting ggH, VBF, VH, and ttH production.
- Final results are obtained from combination with CMS Run-1 H→μμ search.
- Measured signal strength
$$\mu = 1.19^{+0.40}_{-0.39}(\text{stat})^{+0.15}_{-0.14}(\text{syst})$$
- Observed (expected) significance is 2.98σ (2.48σ).
- Higgs coupling to muons relative to SM Kμ is constrained at 95% CL to [0.59, 1.50].
- **Observe evidence for Higgs boson decay to muons.**





JHEP(2021)148

Summary

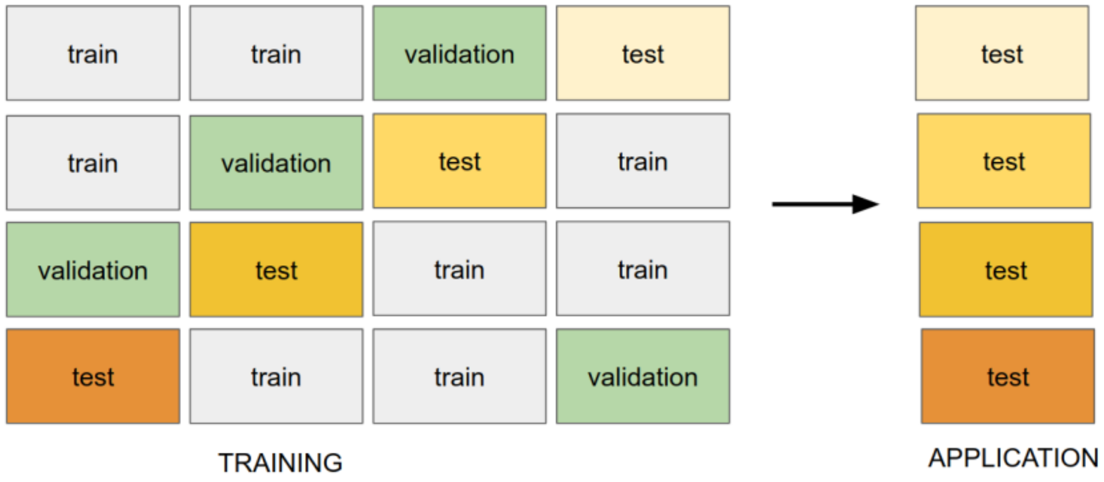
- First experimental evidence of $H \to \mu\mu$ decay
- Observed significance: 3σ with CMS Run-2 dataset (13 TeV, 137 fb^{-1})
- Results consistent with the Standard Model Higgs–muon Yukawa coupling
- Run-3 analysis ongoing, aiming for improved precision and potential discovery
- Analysis developments are actively progressing across all channels, with the ggH and VBF categories being the primary focus due to their sensitivity and impact on the final results.

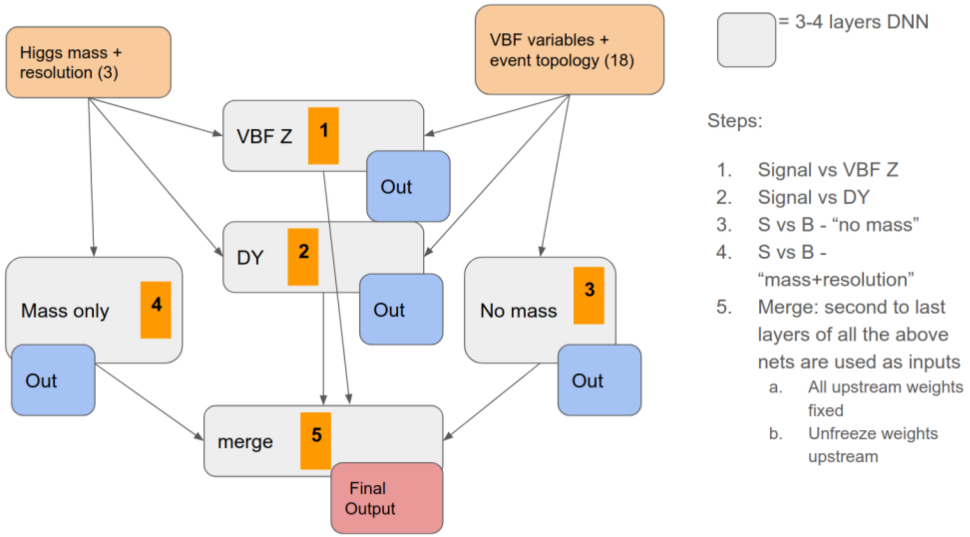
Thanks a lot for your attention!

Backup

VBF Channel

- Run 2 DNN use 4-fold training strategy and DNN structure as below





DNN training

Samples:

- Sig:/VBFHto2Mu_M-125_TuneCP5_withDipoleRecoil_13p6TeV_powheg-pythia8/*/NANOAODSIM
- Bkg:
    - /DYto2Mu-2Jets_MLL-105To160_TuneCP5_13p6TeV_amcatnloFXFX-pythia8/*/NANOAODSIM
    - /TTto2L2Nu_TuneCP5_13p6TeV_powheg-pythia8/*/NANOAODSIM
    - /TWminusto2L2Nu_TuneCP5_13p6TeV_powheg-pythia8/*/NANOAODSIM
    - /TbarWplusto2L2Nu_TuneCP5_13p6TeV_powheg-pythia8/*/NANOAODSIM
    - /EWK_2L2J_TuneCH3_13p6TeV_madgraph-herwig7/*/NANOAODSIM

*= Run3Summer22NanoAODv12-130X_mcRun3_*_realistic_v5-v2 (for 2022, 2022EE, 2023, 2023BPix)

Train Variables:

- $\mathrm{M}(\mu\mu), \Delta\mathrm{M}(\mu\mu), \Delta\mathrm{M}(\mu\mu)\_\mathrm{rel}, P_T(\mu\mu), \log(P_T(\mu\mu)), Rapidity(\mu\mu),$
- $Mass(jj), \log(\mathrm{M}(jj)), R_{p_T}, z^*, \Delta\eta(jj)$
- $P_T(j_1), \eta(j_1), P_T(j_2), \eta(j_2), \phi(j_1), \phi(j_2)$, $\min(\eta)$, N^{soft}

DNN training

DNN train results