Evidence for H → μμ with CMS Run II Data and Projected Sensitivity at the HL-LHC

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On behalf of H→μμ working group

1. Introduction

1.1. Higgs Boson Properties

- Since the Higgs boson discovery in 2012, CMS and ATLAS have measured **Higgs mass, width, couplings, and CP properties** with steadily improving precision.
- In Runs 1 and 2, **Higgs boson couplings to gauge bosons and third generation fermions** (τ, b, t) **were established** with ≥5σ significance.
- **Probe Higgs couplings to second generation fermion via H→μμ**
  - Extend probe of Higgs interactions in mass scale by more than an order of magnitude.
  - A **precise measurement** of the muon Yukawa coupling can constrain or reveal deviations from the Standard Model, exploiting possible new physics in the Higgs sector.

1.2. H → μμ Decay Mode

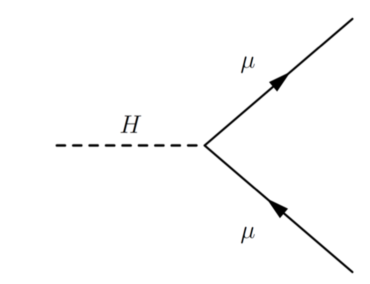

Figure 1: Feynman diagram for Higgs to two muons decay

- 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.

2. Run2 Analysis

- Dataset: 137 fb^{-1} of 13 TeV pp collisions (2016–2018 CMS Run-2)
- Events selection
  - Single-muon triggers
  - Required to contain two identified and isolated muons with opposite charge
  - Mass window cut 110 < Mμμ < 150 GeV
- Dimuon mass resolution improvements:
  - Track-fit correction using interaction point → 3–10% better dimuon mass resolution.
  - FSR photon recovery → +2% signal efficiency, ~3% mass resolution gain.
- Sensitivity is enhanced by **categorizing events according to the Higgs production processes**.
- Signal is extracted with a **simultaneous fit** across all categories to observables chosen for each category.

2.1. ggH

- Phase space dominated by 0–1 jet events with only the μμ pair and multi-jet events are kept if not VBF-like.
- **Event selection:**
  - No extra leptons (beyond H→μμ candidate)
  - b-jet veto: no medium b-tags, <2 loose b-tags
  - Jet categories: 0, 1, ≥2 jets (exclude events with m_{jj} > 400 GeV and $\Delta\eta_{jj}$ > 2.5 → VBF-like)
- **Background**
  - Drell–Yan (dominant);
  - tt and Dibosons (WW, WZ, ZZ)

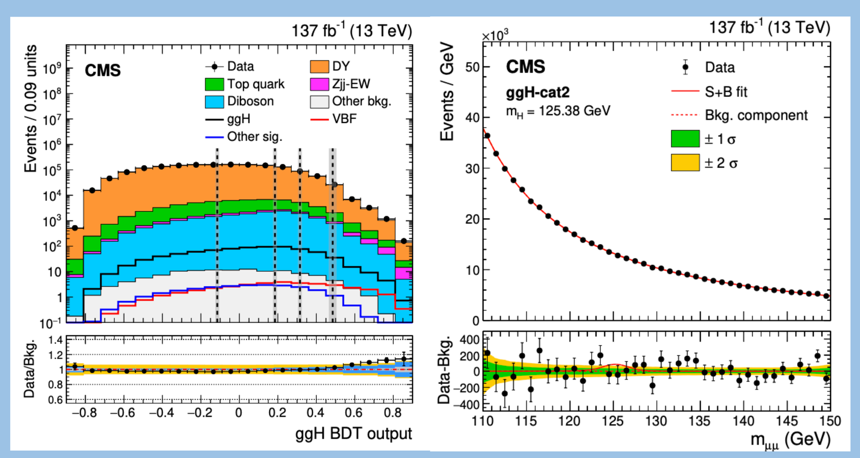

Figure 2: BDT output distribution in the ggH channel (left), data and total background extracted from a S+B fit performed in one ggH subcategory (right)

- **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
- Signal model: m(μμ) in signal events 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.

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

2.2. VBF

- **Event selection:**
  - No extra leptons (beyond H→μμ candidate)
  - b-jet veto: no medium b-tags, <2 loose b-tags
  - Jet categories: 2 jets (events with pT_{j1}>35GeV; pT_{j2}>25GeV; m_{jj} > 400 GeV and $\Delta\eta_{jj}$ > 2.5 → VBF-like)
- **Background**
  - Drell–Yan (dominant); EWK-LLJJ (subdominant);
  - tt and Dibosons (WW, WZ, ZZ)
- **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

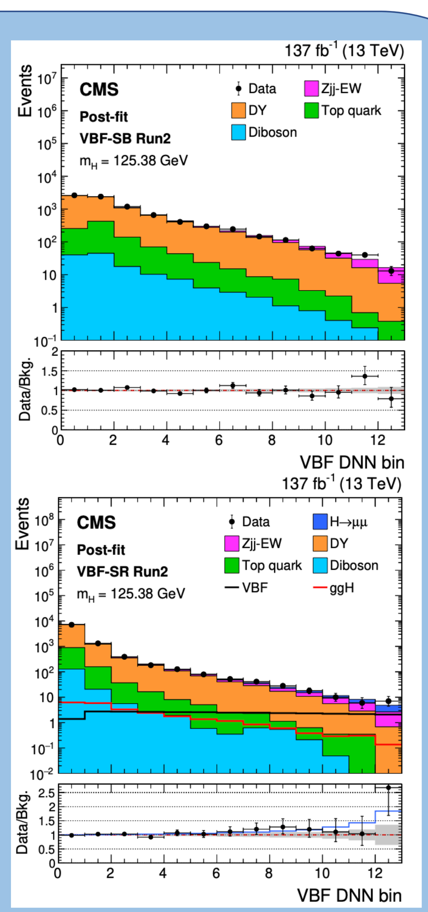

Figure 3: DNN output distribution in VBF-SB (upper) and VBF-SR (lower) regions

2.3. VH

- Select one (two) additional lepton(s) consistent with W(Z) boson leptonic decay (electrons or muons).
- Separate WH and ZH categories with dedicated BDTs and categories optimized following same procedure as ggH channels.
- Background fit with BWZ function.

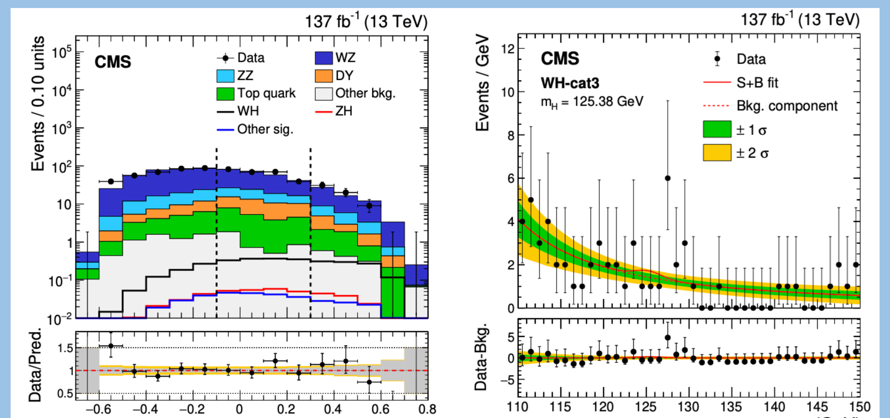

Figure 4: BDT output distribution in the WH channel (left), data and total background extracted from a S+B fit performed in one WH subcategory (right)

2.4. ttH

- At least one (two) additional jet(s) passing the DeepCSV medium (loose) WP.
- Separate categories targeting leptonic and hadronic decays.
  - Categories optimized following same strategy as ggH channel.
- Dominant background from tt and ttZ (mostly for ttH leptonic).
- Background fit with simple exponential (ttH-lep) or polynomial (ttH-had)

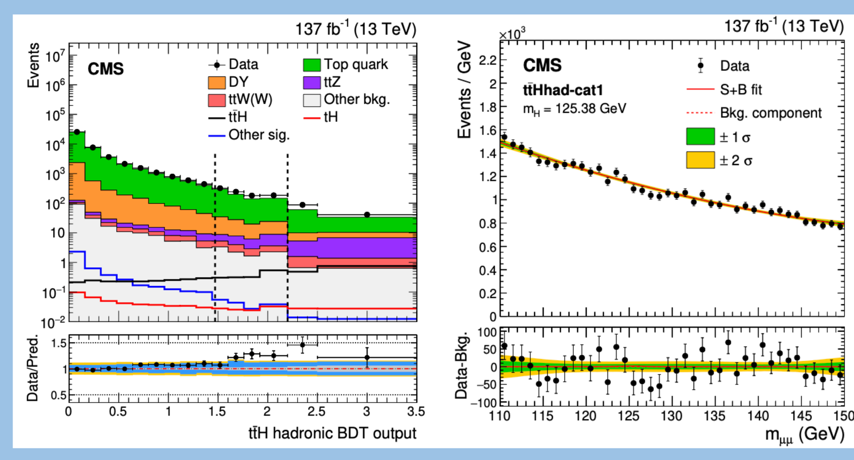

Figure 5: BDT output distribution in the ttH hadronic channel (left), data and total background extracted from a S+B fit performed in one ttH hadronic subcategory (right)

2.5. Combination

- 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 $\mu = 1.19^{+0.40}_{-0.39}(\mathrm{stat})^{+0.15}_{-0.14}(\mathrm{syst})$
  - Obsered (expected) significance 2.98σ (2.48σ)
- Higgs coupling to muons relative to SM κ_μ constrained at 95% CL to [0.59, 1.50]
- We observe evidence for the Higgs boson decay to muons

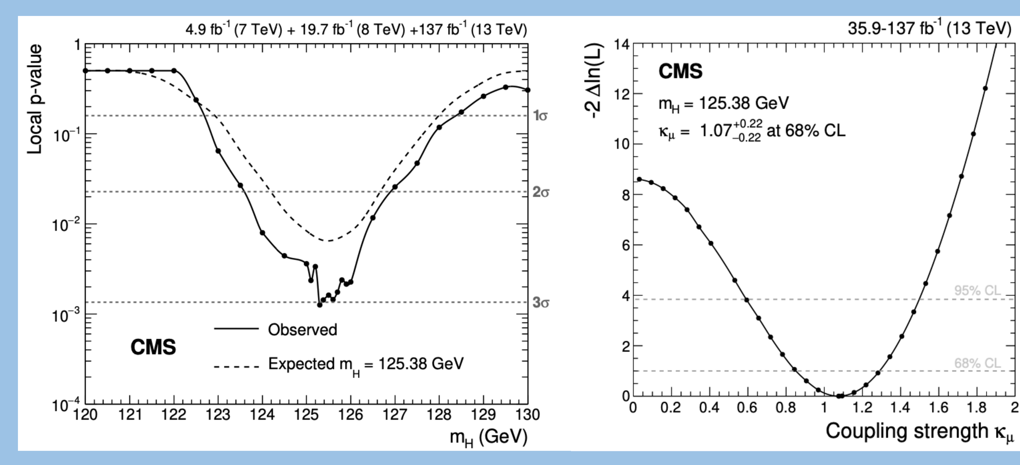

Figure 6: Local p-values derived from combined fit as a function of mH (left) and observed profile likelihood ratio as a function of κ_μ (right)

3. HL-LHC Prospects: Higgs → μμ Decay

- **HL-LHC & Detector Upgrades**
  - HL-LHC conditions: √s = 14 TeV, $\mathcal{L}$ up to 3 ab⁻¹
  - CMS Phase-2 upgrades:
    - Extended muon detector coverage in |η| up to ~2.8 (versus 2.4 in Run-2)
    - Improved tracker, trigger, muon system, better muon momentum
    - ~30% improved dimuon mass resolution
- **HL-LHC Extrapolation Strategy**
  - Use Run-2 H→μμ analysis Strategy (categories, fit model, profile likelihood).
  - Extrapolate yields to √s = 14 TeV and 3 ab^{-1}; include cross-section changes and acceptance gains.
  - Two uncertainty scenarios considered:
    - S1: systematic uncertainties stay like Run-2.
    - S2: experimental systematics scale down with $\sqrt{\mathcal{L}}$ (until some floor), theoretical uncertainties halved.
- **HL-LHC Projection Results**
  - HL-LHC (3 ab^{-1}):
    - Signal strength uncertainty: ~8.5% (S1), ~7.0% (S2).
    - Coupling modifier uncertainty: ~4.3% (S1), ~3.5% (S2).
  - <u>With only 14 TeV data, 5σ significance could be be achieved with $\mathcal{L} \simeq$ 300-350 fb^{-1}.</u>
  - HL-LHC data will make it possible to measure the Higgs–muon coupling with high precision.

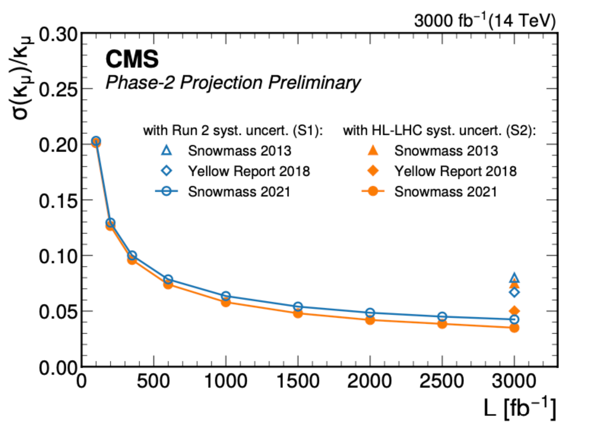

Figure 7: Uncertainty on coupling modifier κ_μ

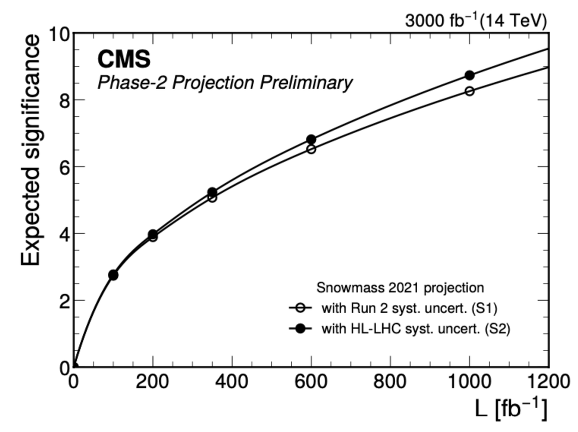

Figure 8: Extrapolation of the expected significance for S1 and S2 uncertainty scenarios

4. Summary and Plan

- First experimental evidence of H → μμ 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.
- HL-LHC era will enable precision Higgs flavor physics, probing Yukawa couplings at the few-percent level.

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[1] CMS Collaboration, JHEP 01 (2021) 148
[2] CMS Collaboration, CMS PAS FTR-21-006

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