



Evidence for $H \rightarrow \mu\mu$ with CMS Run II Data and Projected Sensitivity at HL-LHC

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Outline

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- Summary

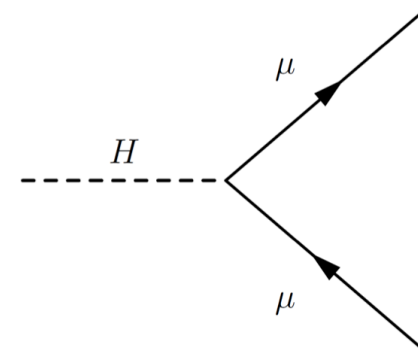
Motivation of $H \rightarrow \mu\mu$

- Since the Higgs discovery in 2012, CMS and ATLAS have measured Higgs mass, width, couplings, and CP properties with steadily improving precision.
- Next frontier: Probe Higgs couplings to second generation fermion via $H \rightarrow \mu\mu$.

- Experimentally challenging search:

- Relatively rare decay mode:

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



- Very large DY background $\Rightarrow$ very small S/B with inclusive selections.

Datasets and Selections

- Dataset: 137 fb^{-1} of 13 TeV pp collisions (2016–2018 CMS Run-2)
- Event selections
 - Single-muon triggers
 - Required to contain two identified and isolated muons with opposite charge
 - Mass window cut $110 < M_{\mu\mu} < 150 \text{ GeV}$
- Dimuon mass resolution improvements:
 - Track-fit correction using interaction point $\rightarrow$ 3–10% better dimuon mass resolution
 - FSR photon recovery $\rightarrow$ +2% signal efficiency, $\sim$ 3% mass resolution gain

Run-II Analysis Strategy

- Events are **categorized according to Higgs production processes** to improve sensitivity
- Signal is extracted with a **simultaneous fit** across all categories to observables chosen for each category

ttH channel

- Phase-space containing at least **one medium** or two **loose b-tagged** jets
- Based on the presence of additional 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

ZH leptonic

3 μ or 2 μ 1e
final states

4 μ or 2 μ 2e
final states

VBF channel

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

$$p_T^{j1} > 35 \text{ GeV}$$

$$p_T^{j2} > 25 \text{ GeV}$$

$$m_{jj} > 400 \text{ GeV}$$

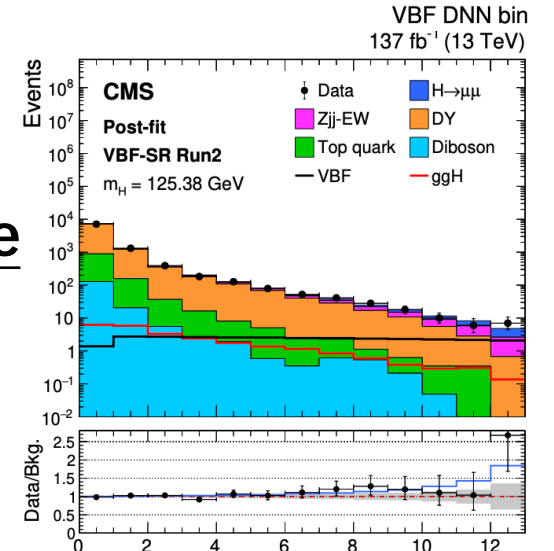
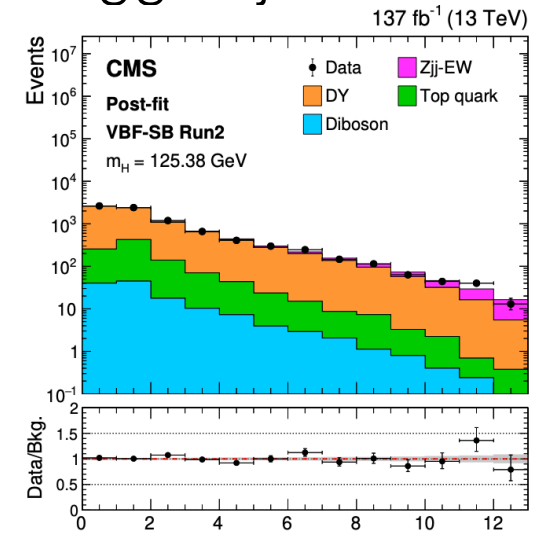
$$|\Delta\eta_{jj}| > 2.5$$

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($\mu\mu$) candidate

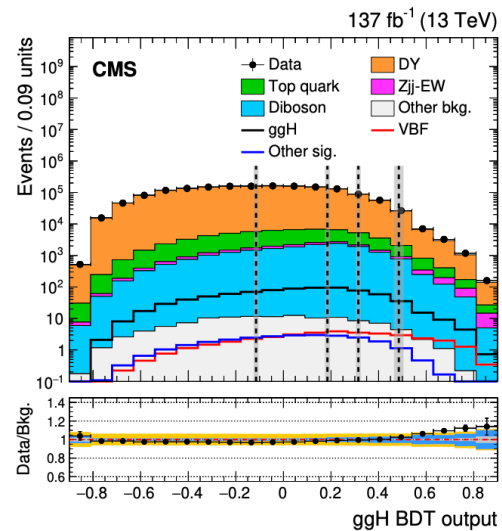
VBF Channel

- Select the events with neither additional charged leptons nor b-tagged jets and a pair of jets with large m_{jj} and $\Delta\eta_{jj}$
- **Analysis Strategy**
 - Signal extraction is fully based on MC
 - 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 $H \rightarrow \mu\mu$ signal is extracted by fitting DNN output score in data directly to background shape predictions from simulation

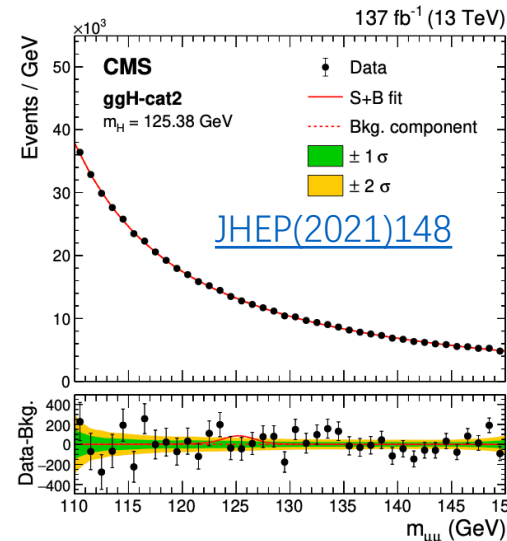


ggH Channel

- Phase space dominated by 0–1 jet events with only the $\mu\mu$ pair and multi-jet events are kept if not VBF-like.
- Analysis Strategy**
 - Extract the signal by **fitting dimuon invariant mass**
 - Signal: sharp peak at 125 GeV; Background: smooth, falling distribution
 - Enables data-driven background estimation via analytical fit



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

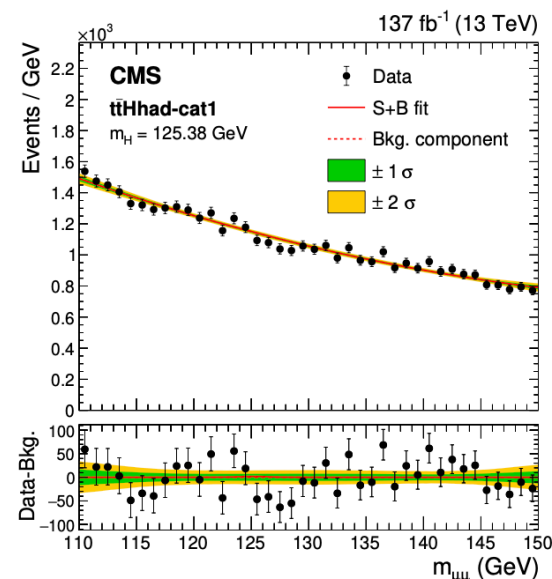
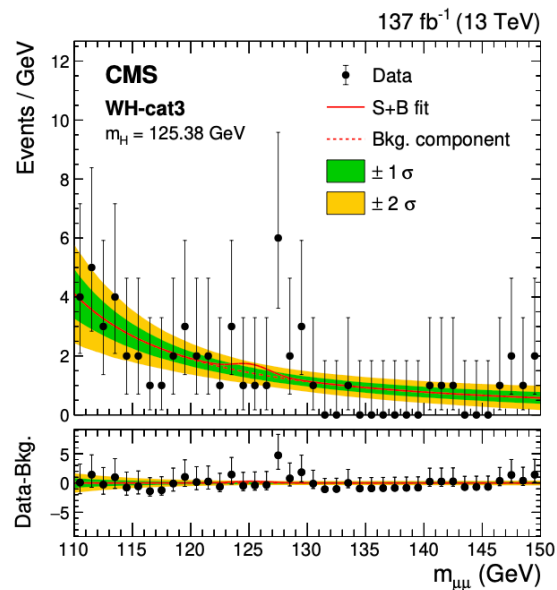


- Signal model: $m(\mu\mu)$ described with a Double Crystal-ball function.
- Background modeling: Core-PDF method
- Core background function built as discrete profile of two physics-inspired (Breit-Wigner, FEWZ) and an agnostic (sum of exponentials) function.

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

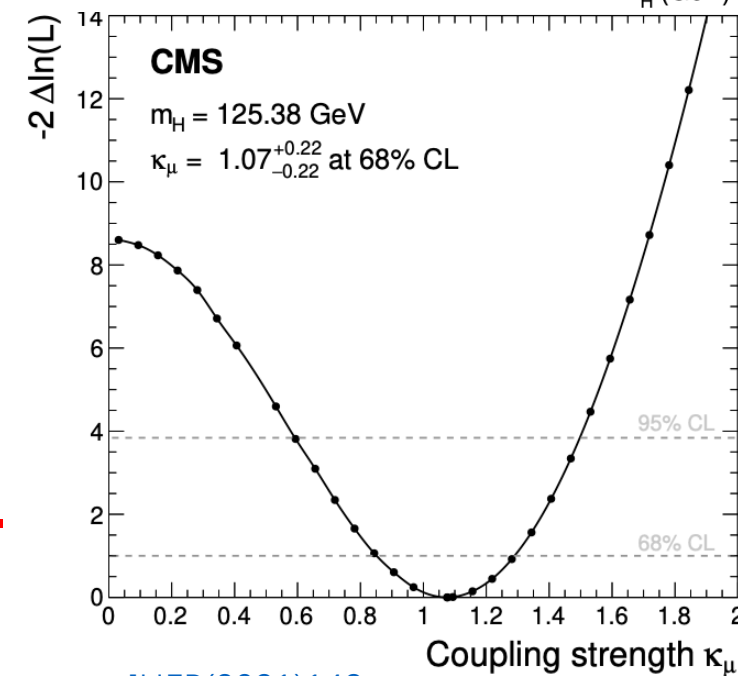
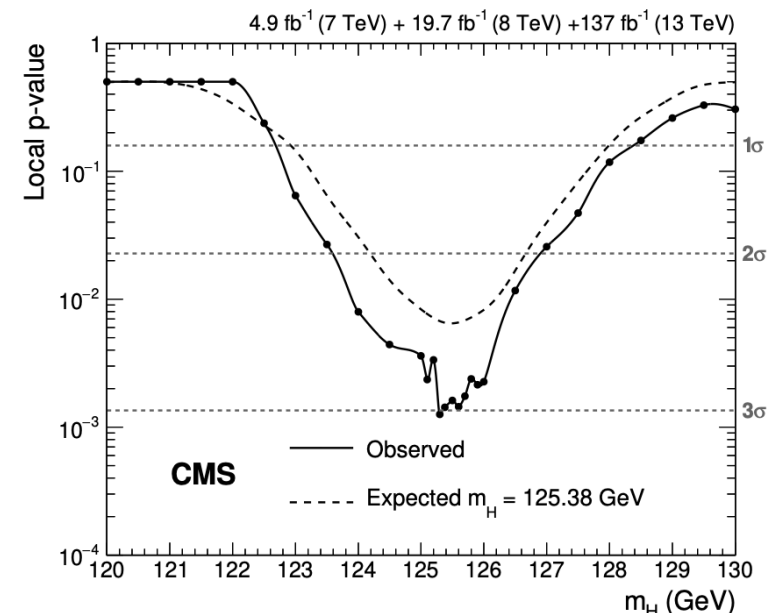
VH and ttH Channel

- 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)



Run-II Analysis --- Results

- Measurement of $H \rightarrow \mu\mu$ combines four separate analyses targeting ggH, VBF, VH, and ttH production.
- Final results are obtained from combination with CMS Run-1 $H \rightarrow \mu\mu$ 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 κ_μ is constrained at 95% CL to $[0.59, 1.50]$.
- **Observe evidence for Higgs boson decay to muons.**



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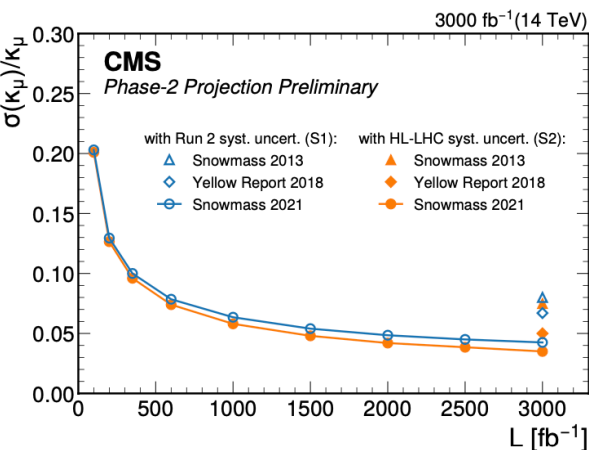
HL-LHC Prospects: Higgs $\rightarrow \mu\mu$ Decay

- **HL-LHC & Detector Upgrades**

- HL-LHC conditions: $\sqrt{s} = 14$ TeV, $\mathcal{L}$ up to 3 ab^{-1}
- CMS Phase-2 upgrades $\rightarrow \sim 30\%$ improved dimuon mass resolution

- **HL-LHC Extrapolation Strategy**

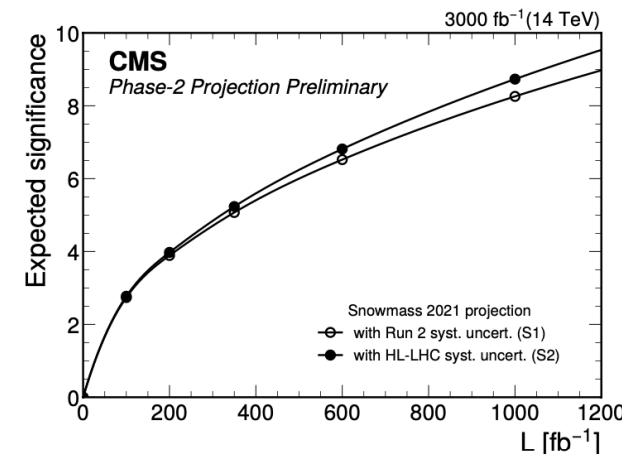
- Use Run-2 $H \rightarrow \mu\mu$ analysis Strategy
- Extrapolate yields to $\sqrt{s} = 14$ TeV and 3 ab^{-1} ; include cross-section changes and acceptance gains.
- Two uncertainty scenarios considered:
 - S1: systematic uncertainties stay like Run-2.
 - S2: experimental systematics scale down with $\sqrt{\mathcal{L}}$ (until some floor), theoretical uncertainties halved.



HL-LHC Projection Results

- HL-LHC (3 ab^{-1}):
 - Signal strength uncertainty: $\sim 8.5\%$ (S1), $\sim 7.0\%$ (S2)
 - K_μ uncertainty: $\sim 4.3\%$ (S1), $\sim 3.5\%$ (S2).
- With only 14 TeV data, 5σ significance could be achieved with $\mathcal{L} \simeq 300\text{--}350 \text{ fb}^{-1}$.

[CMS PAS FTR-21-006](#)



HL-LHC will make it possible to measure Higgs–muon coupling with high precision. 10

Summary

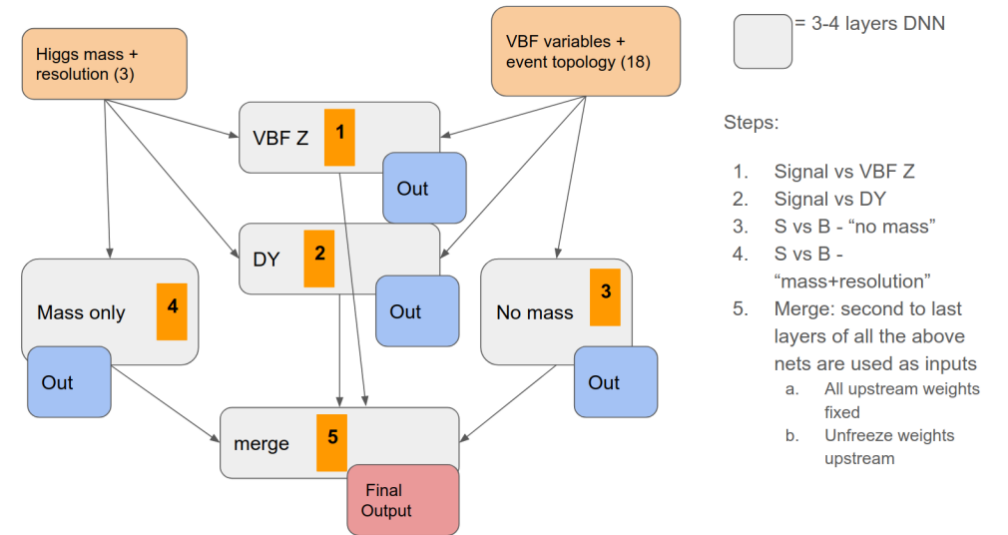
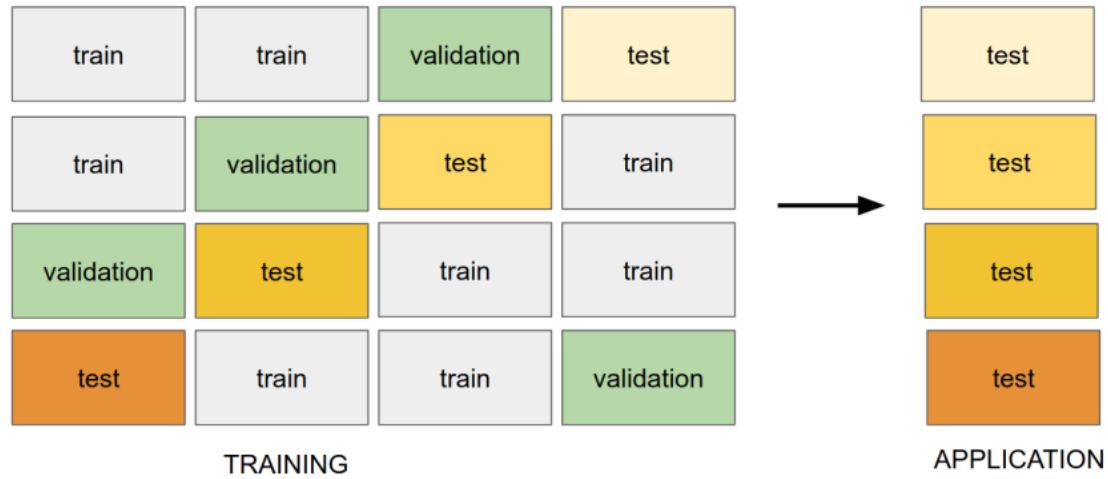
- First experimental evidence of $H \rightarrow \mu\mu$ decay
- Observed significance: 3σ with CMS Run-2 dataset (13 TeV, 137 fb^{-1})
- Results consistent with the Standard Model Higgs–muon Yukawa coupling
- Run-3 analysis ongoing, aiming for improved precision and potential discovery
- HL-LHC era will enable precision Higgs flavor physics, probing Yukawa couplings at the few-percent level.

Thanks a lot for your attention!

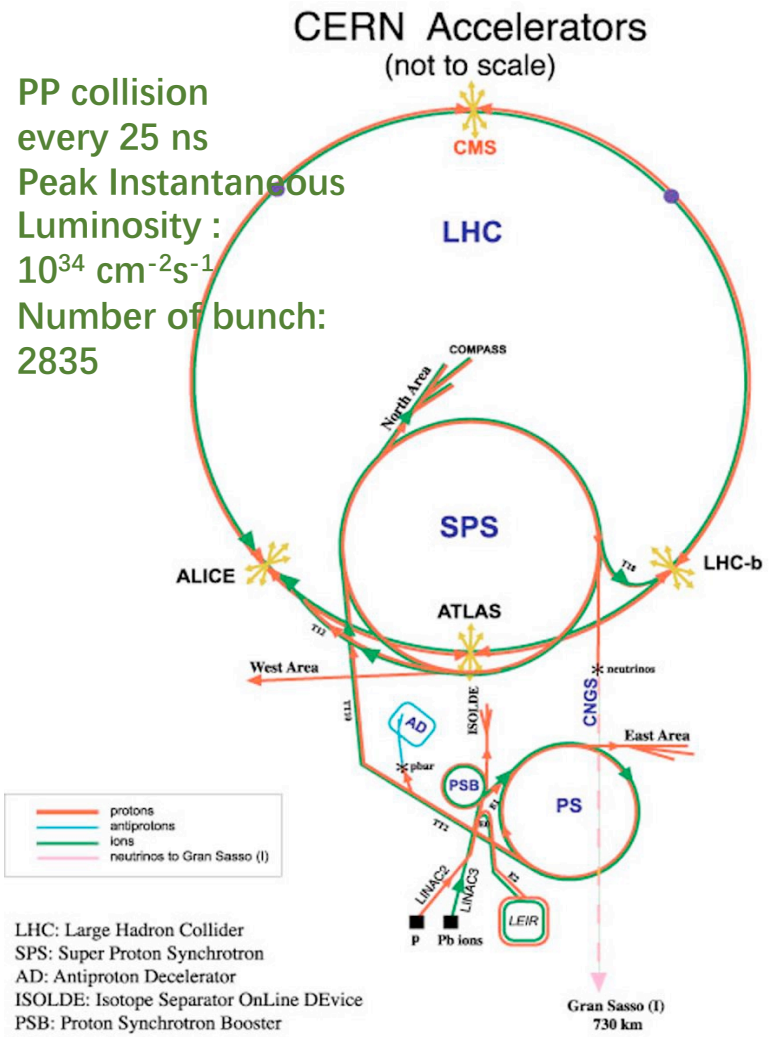
Backup

VBF Channel

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



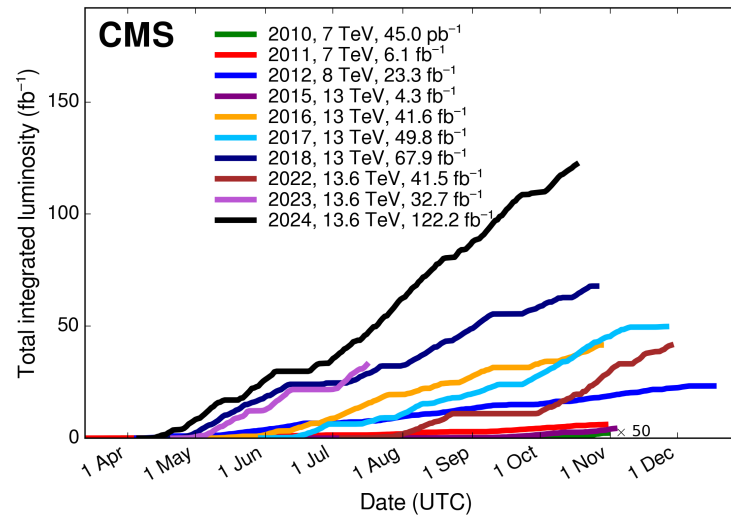
Large Hadron Collider (LHC)



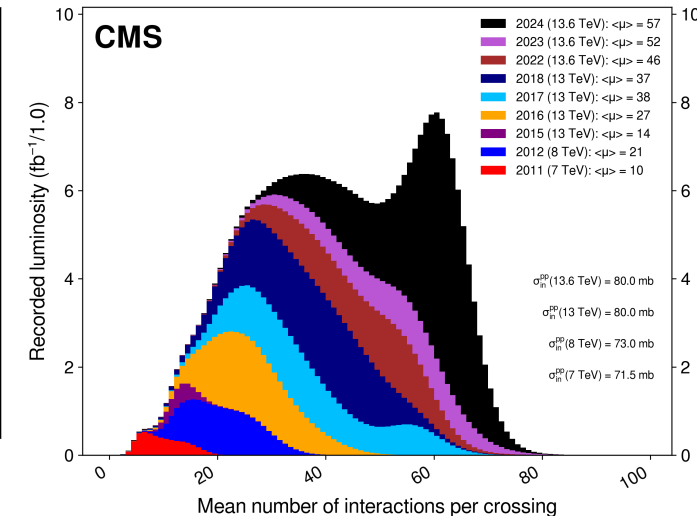
LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and
D. Mangunki, PS Div. CERN, 23.05.01

- Accelerator with the largest energy
 - 900GeV $\rightarrow$ 7TeV $\rightarrow$ 8TeV $\rightarrow$ 13TeV $\rightarrow$ 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)

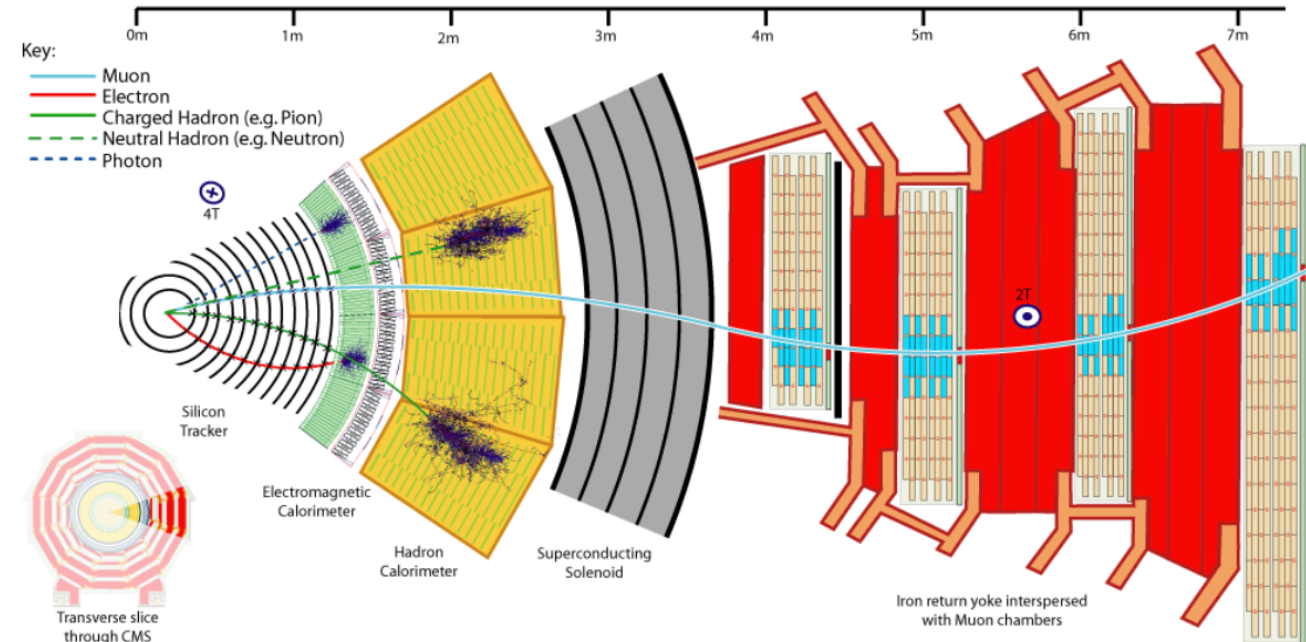
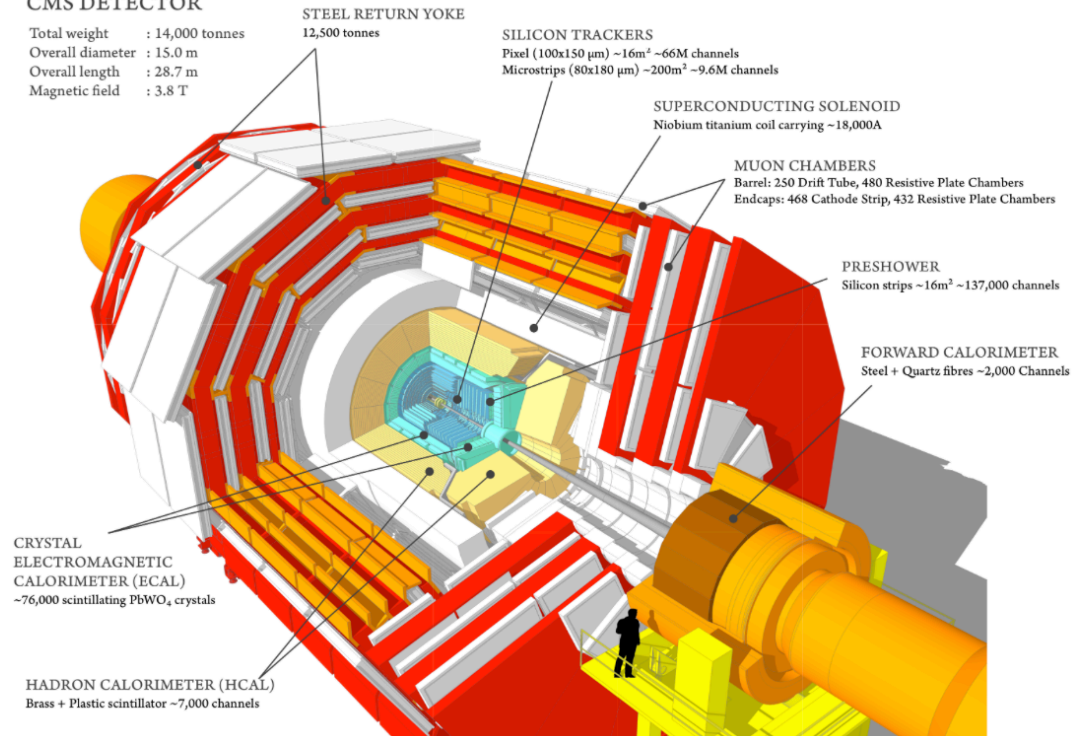


Number of interactions per
bunch crossing

CMS detector

CMS DETECTOR

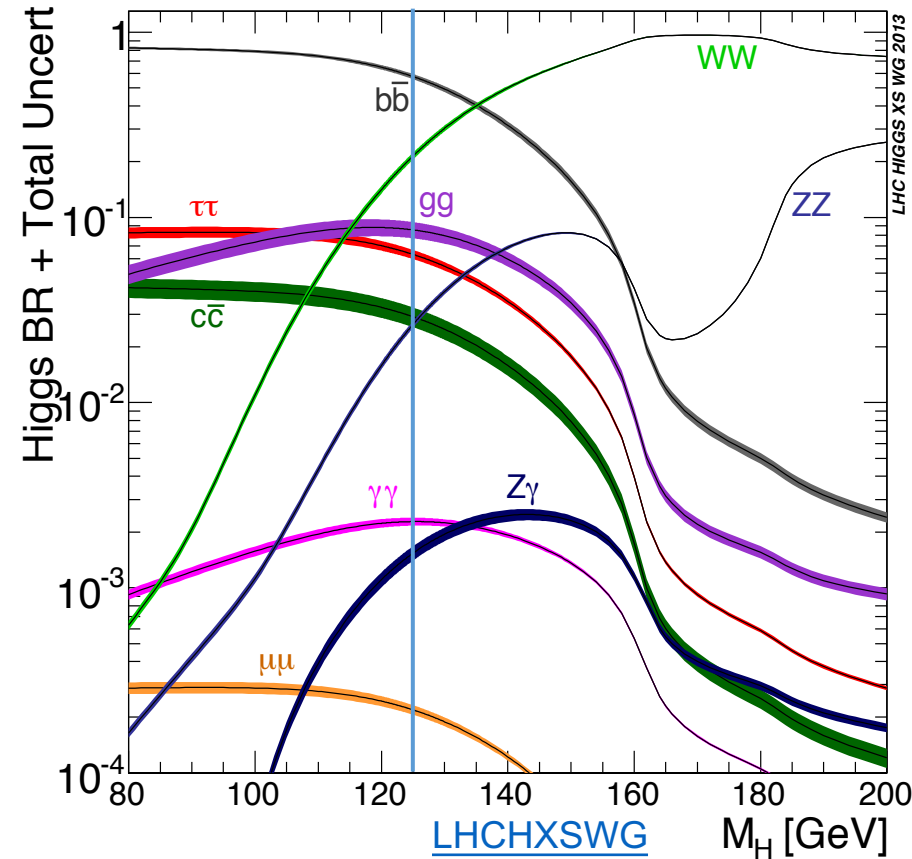
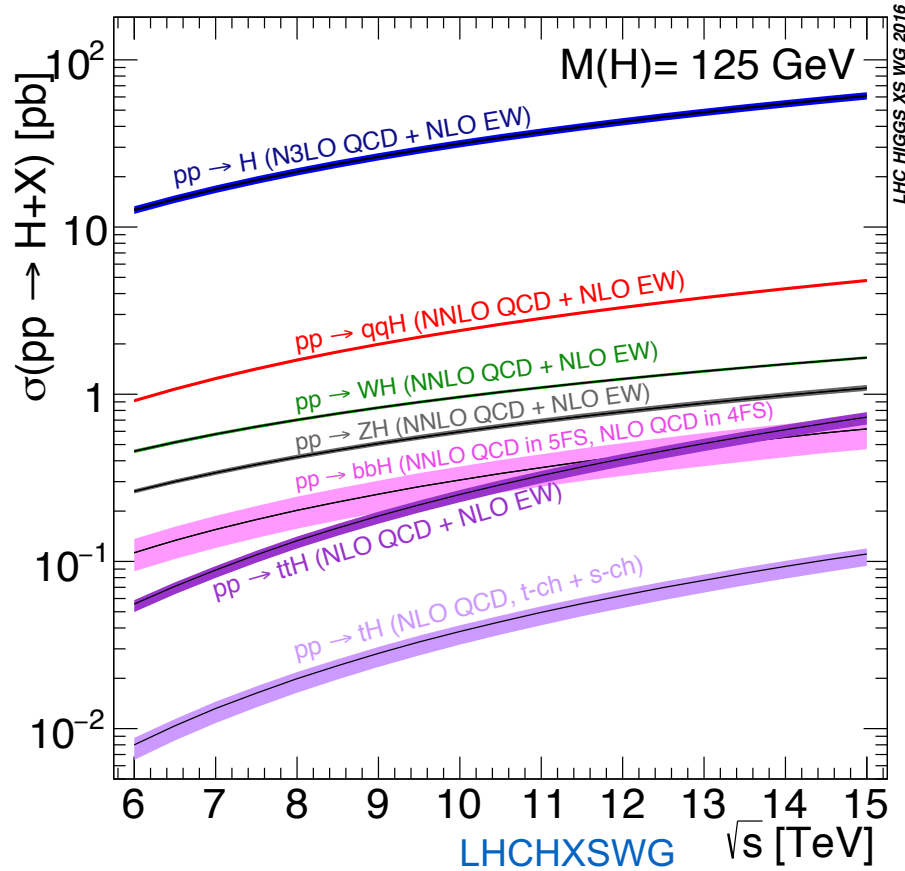
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



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



□ 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 $H \rightarrow \mu\mu$ is our interest in Run III

Object selections

- Muons: $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$, Medium Id, Loose iso
 - Electrons: $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$, mvaIsoWP90, ECal gap veto
 - Jets: $p_T > 25 \text{ GeV}$, $|\eta| < 4.7$, Pass POG Tight ID
No overlap with PF muons or electrons ($\Delta R \leq 0.4$)
Using jet veto maps
-

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