Higgs mass and width measurement in the $H \rightarrow ZZ \rightarrow 4\ell$ channel at CMS-PhaseII
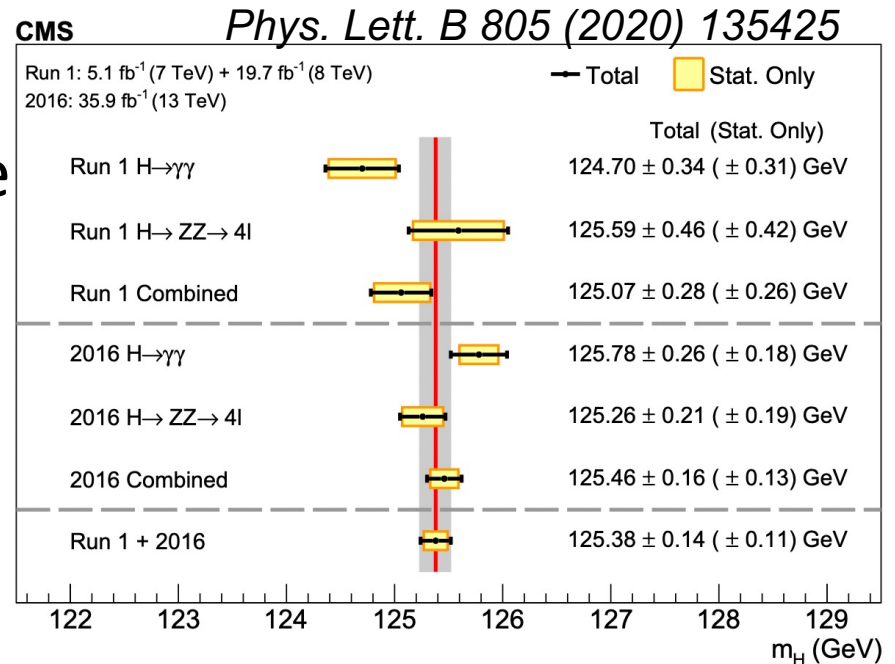
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Introduction

- The Higgs boson mass is one of the most important free parameters of the Standard Model.

- Its value should be measured precisely since it determines all other Higgs boson properties.

- The precision will be improved a lot thanks to the large statistic with HL-LHC.

- A projection study will be presented.

CMS

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Run 1: 5.1 fb^{-1} (7 TeV) + 19.7 fb^{-1} (8 TeV)

2016: 35.9 fb^{-1} (13 TeV)

— Total   Stat. Only

	Total (Stat. Only)
Run 1 H→γγ	124.70 ± 0.34 (± 0.31) GeV
Run 1 H→ ZZ→ 4l	125.59 ± 0.46 (± 0.42) GeV
Run 1 Combined	125.07 ± 0.28 (± 0.26) GeV
2016 H→γγ	125.78 ± 0.26 (± 0.18) GeV
2016 H→ ZZ→ 4l	125.26 ± 0.21 (± 0.19) GeV
2016 Combined	125.46 ± 0.16 (± 0.13) GeV
Run 1 + 2016	125.38 ± 0.14 (± 0.11) GeV

122   123   124   125   126   127   128   129
m_H (GeV)

CMS approach to $H \to ZZ \to 4\ell$

Latest CMS result on the Higgs boson mass, in the $H \to ZZ \to 4\ell$ channel, uses 2016 data, $(36\ fb^{-1})$

No $m(\mathrm{Z_1})$ constraint	3D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\mathrm{mass}}, \mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}})$	2D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\mathrm{mass}})$	1D: $\mathcal{L}(m_{4\ell})$
Expected m_{H} uncertainty change	+8.1%	+11%	+21%
Observed m_{H} (GeV)	125.28±0.22	125.36±0.24	125.39±0.25
With $m(\mathrm{Z_1})$ constraint	3D: $\mathcal{L}(m_{4\ell}', \mathcal{D}_{\mathrm{mass}}', \mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}})$	2D: $\mathcal{L}(m_{4\ell}', \mathcal{D}_{\mathrm{mass}}')$	1D: $\mathcal{L}(m_{4\ell}')$
Expected m_{H} uncertainty change	—	+3.2%	+11%
Observed m_{H} (GeV)	125.26±0.21	125.30±0.21	125.34±0.23
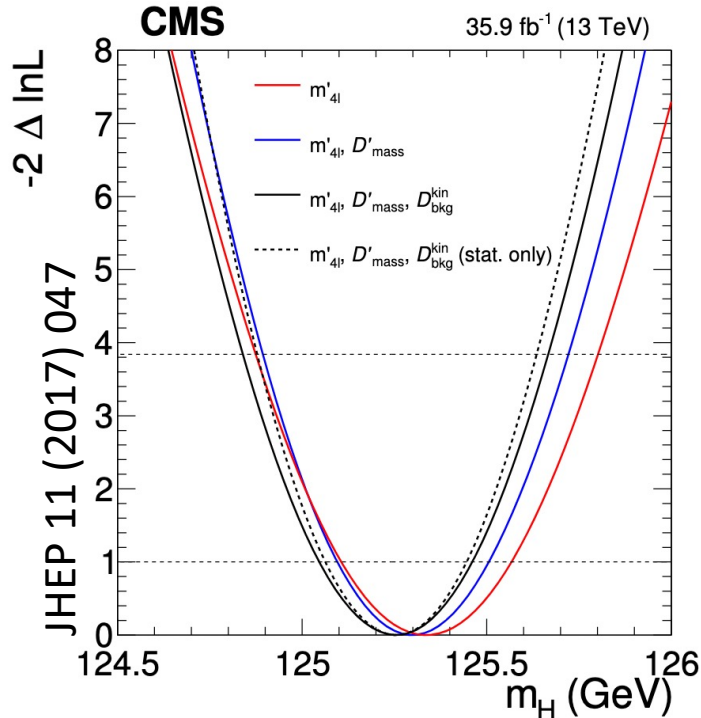
- 3D likelihood
  - Four-lepton invariant mass
  - Event-by-event mass uncertainty
  - Kinematic discrimant

$$\left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}^{q\bar{q}}(\vec{\Omega}^{\mathrm{H}\to 4\ell}|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}^{gg}(\vec{\Omega}^{\mathrm{H}\to 4\ell}|m_{4\ell})} \right]^{-1}$$
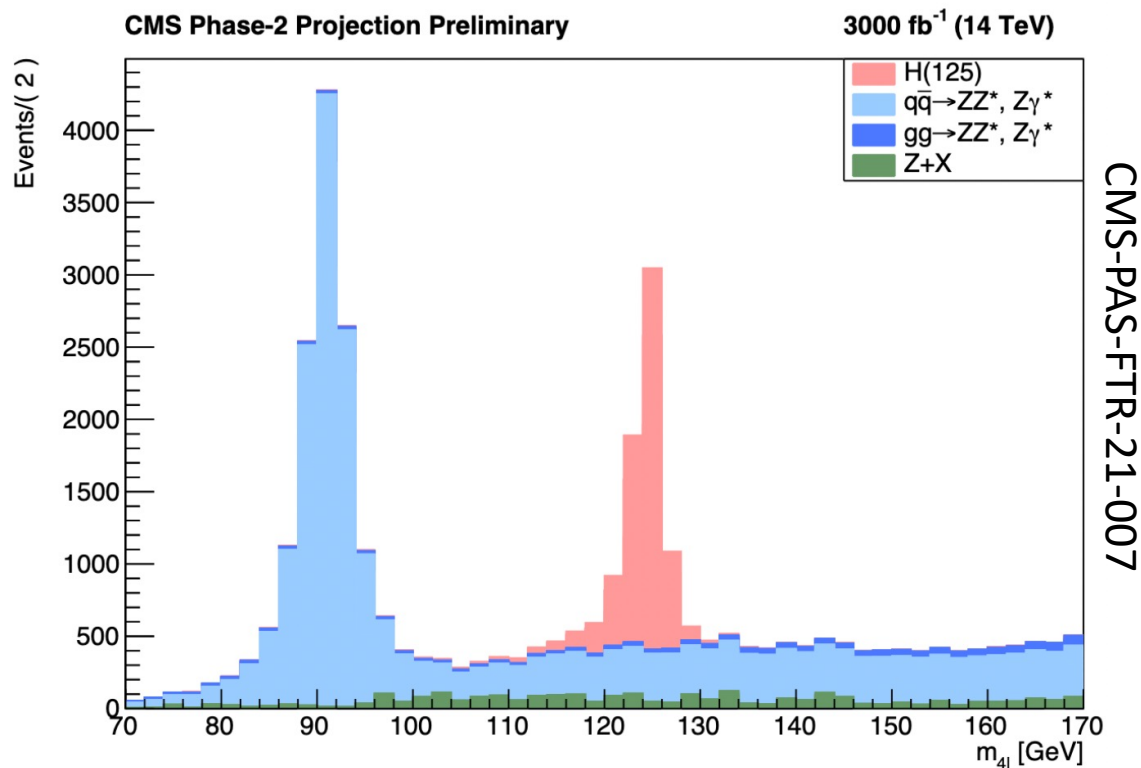
- On-shell Z mass constraint improves the m_{4l} resolution.

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Projection method

The projection results for High-Luminosity LHC has been obtianed under the following assumptions:

- Detector performance such as acceptance, efficiency, and resolution are considered to have the same values as Run 2.

- Signal cross sections are scaled according to the YR4.

- Background cross sections are scaled according to the parton luminosity ratio.

- Systematic uncertanties are extracted from full Run 2 target analysis.

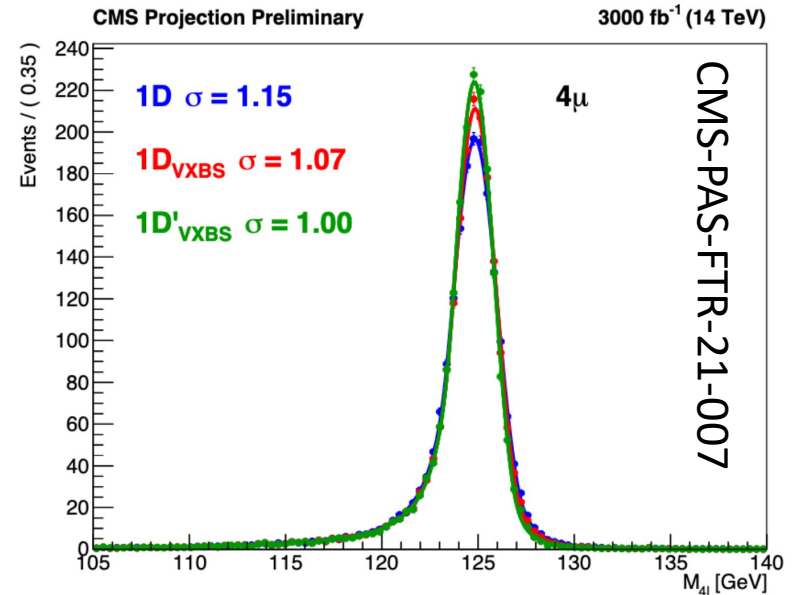- Based on simulations, scaling luminosity to 3000 fb^{-1}

Expected mass distribution

CMS Phase-2 Projection Preliminary   3000 fb^{-1} (14 TeV)

Legend:
- H(125)
- $q\bar{q} \rightarrow ZZ^*, Z\gamma^*$
- $gg \rightarrow ZZ^*, Z\gamma^*$
- Z+X

Events/(2) vs m_{4l} [GeV]

CMS-PAS-FTR-21-007

Expected yield	Inclusive	4μ	4e	$2e2\mu$	$2\mu2e$
ggZZ	528	232	101	115	80
qqZZ	5191	2082	781	1464	866
Z+X	1647	495	348	424	381
Tot background	7367	2809	1230	2002	1327
Signal	5922	2195	1027	1544	1157

Lepton momentum improvement

- New approach
  - Muons are constrained to the beam spot.
  - Improve $m_{4\mu}$ resolution ~7%
  - No impact in 4e final state, electron energy measurement is dominated by ECAL.

- On-shell Z mass constraint
  - Calibrating the momentum of the leading lepton pair momentum using the on-shell Z boson shape improves m_{4l} resolution by ~7%

- Categorisation
  - Classify events based on their relative mass resolution improving final precision 10%

CMS Projection Preliminary   3000 fb^{-1} (14 TeV)

1D σ = 1.15
1D$_{VXBS}$ σ = 1.07
1D'$_{VXBS}$ σ = 1.00

4μ

Events / (0.35)

CMS-PAS-FTR-21-007

M$_{4l}$ [GeV]

Modelling

- Signal normalisation
  - Expected event yields from 5 mass points simulations
  - Fit the distribution with second order polynomial

- Signal parameterisation
  - Double side crystal function for mass measurement
  - DSCB convoluted with a Breit-Wigner for width

- Final pdf are built for each mass error category respectively

- Irreducible background
  - Yields are estimated from simulations
  - mode their mass distributions using third order of Bernstein function

- Reducible background
  - Data-driven method

Expected mass result

- Several scenarios about the dominant systematic uncertainties considered.

Systematic uncertainty	Baseline	Optimistic	Pessimistic	YR
Muon momentum scale	0.01%	0.005%	0.01%	0.05%
Electron momentum scale	0.15%	0.05%	0.15%	0.10-0.30%
Lepton momentum resolution	10%	5%	10%	5%

- Final result with baseline systematic uncertainties:

$m_{4\ell}$ expected uncertainty (MeV)	4μ	4e	$2e2\mu$	$2\mu2e$
Total	32	206	107	112
Syst impact	15	189	94	95

$$m_H = 125.38 \pm 0.03\ [\,0.022\,(stat.) \pm 0.020\,(syst.)]\textbf{GeV}$$

- Final result with two alternatives:

| $m_{4\ell}$ expected uncertainty (MeV)	inclusive	4μ	4e	$2e2\mu$	$2\mu2e$
Optimistic					
Total	26	30	105	60	67
Syst impact	16	11	64	31	32
Stat only	22	28	83	51	59
Pessimistic					
Total	30	32	206	107	112
Syst impact	20	15	189	94	95
Stat only	22	28	83	51	59

Expected width result

Expected width uncertainty in MeV

Γ_H expected upper limit (MeV)	inclusive	4μ	4e	2e2μ	2μ2e
Total	177	225	633	362	422
Syst impact	150	188	492	275	323
Stat only	94	124	398	235	272

Expected width uncertainty with optimistic and pessimistic

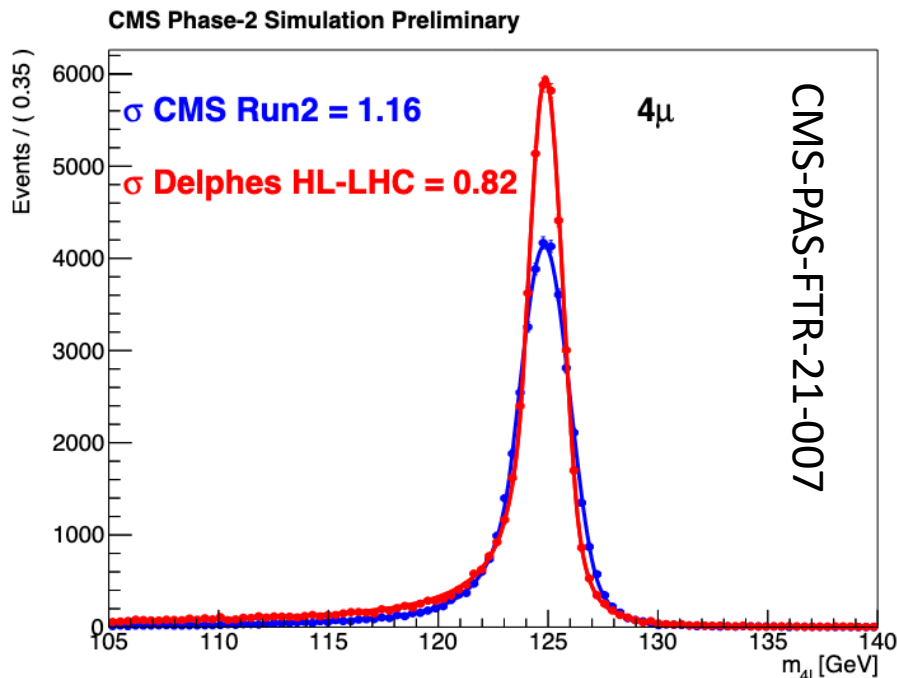| Γ_H expected upper limit (MeV)	Projection	Optimistic	Pessimistic
Total	177	155	177
Syst impact	150	123	150
Stat only	94		
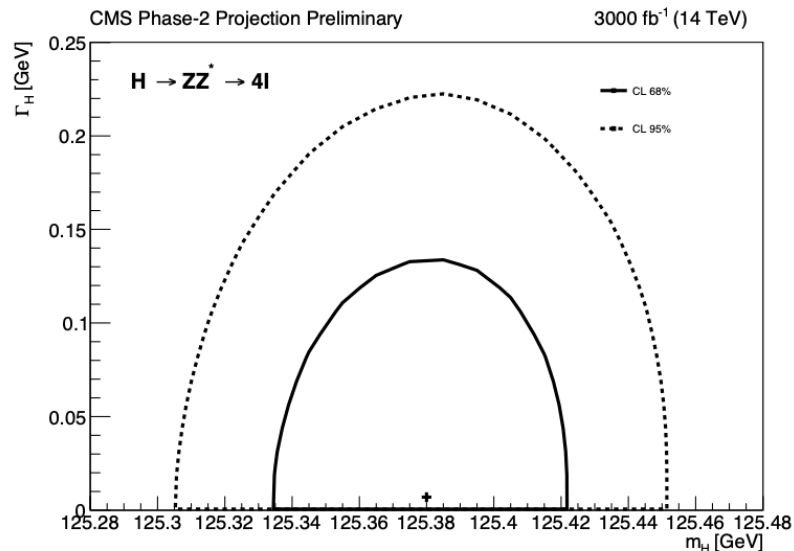
Expected mass and width 2D likelihood scan

Further improvement

- Detector upgrades impact
  - Thanks to the new tracker. $m_{4\mu}$ resolution improves ~25%
  - Electron acceptance increase from $|\eta|$ <2.5 to 3.0
  - Muon acceptance increase from $|\eta|$<2.4 to 2.8

- Mass improvement
  - $m_{4\mu}$ drives the final result.
  - Consider the detector upgrades, with optimistic systematic uncertainties, $m_{4\mu}$ sensitivity can reach 25MeV.
  - Inclusive 20MeV.

$$m_H = 125.38 \pm 0.02 \text{ GeV}$$

CMS Phase-2 Simulation Preliminary

σ CMS Run2 = 1.16

σ Delphes HL-LHC = 0.82

4μ

CMS-PAS-FTR-21-007

Summary

- Projection of the Higgs boson mass and width measurement in $H \to ZZ \to 4\ell$ decay channel at CMS-Phase2 has been presented.

- At the end of $3000 fb^{-1}$, with current detector status:
  - $\boldsymbol{m_H = 125.38 \pm 0.03}$ **GeV**
- Considering the detector upgrades and optimistic systematic uncertainties:
  - $\boldsymbol{m_H = 125.38 \pm 0.02}$ **GeV**

- Width precision
  - $\boldsymbol{\Gamma_H}$ **= 0 + 177 MeV**

Thanks for your attention