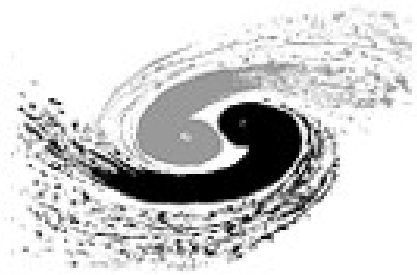
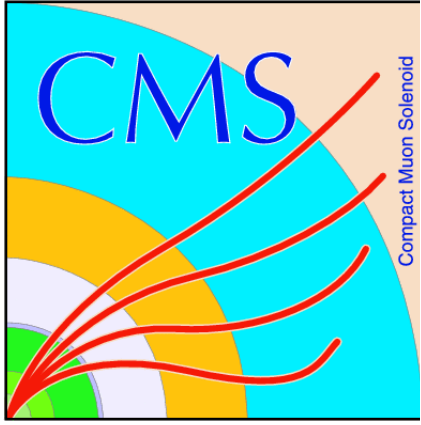




Higgs boson production in the four-lepton final state with CMS

中国物理学会高能物理分会第十二届全国粒子物理学术会议
2016 年 8 月 22 日至 26 日，合肥

Muhammad Ahmad
Institute of High Energy Physics, Chinese Academy of sciences
On behalf of CMS and ATLAS Collaboration

Overview

The $H \to ZZ^* \to 4\ell$ (ℓ=e,μ) channel at the LHC:

→ Large S/B ratio, excellent resolution, complete reconstruction of the final state.

→ 'Golden channel' for discovery and property measurements.

This talk will focus new CMS RUN II results with 12.9 fb^{-1} collected in 2016

→ Similar sensitivity to H(125) as RUN I results

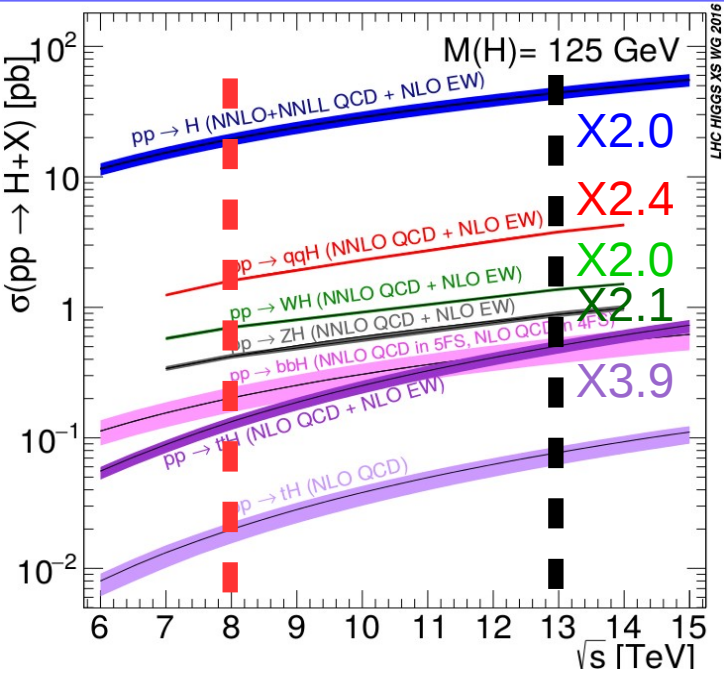
New w.r.t Moriond'16 results:

→ New 6 categories sensitive to all 5 production modes

→ Fid. cross section and mass measurement with 2016 data

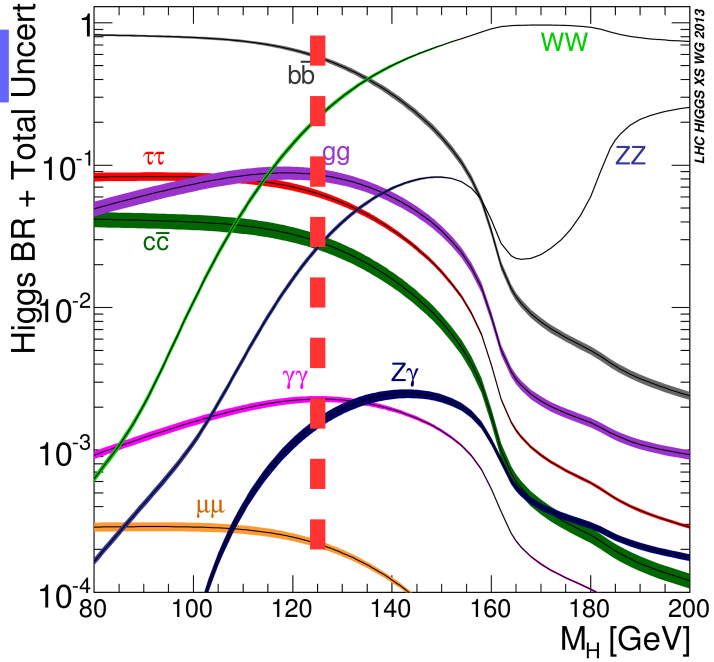
→ Width (onshell/onshell+offshell production)

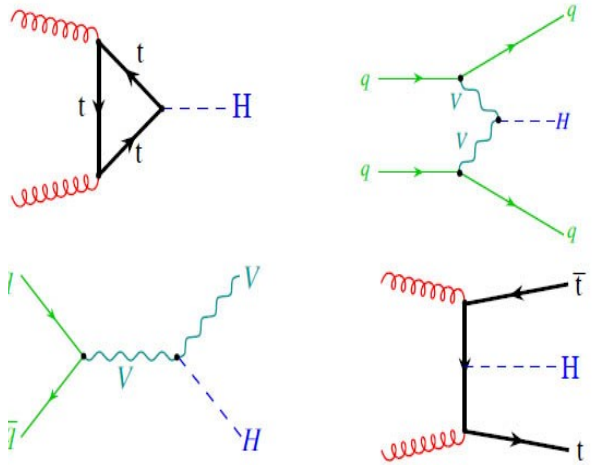
→ Search for heavy Higgs-mass resonance (In Tong guang talk)



Ref. : CMS-PAS-HIG-16-033

Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001



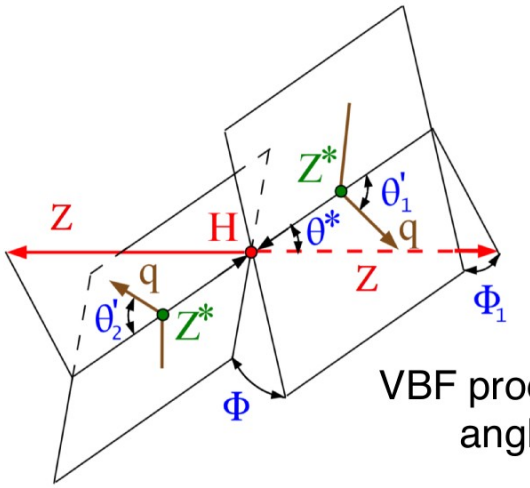


Events categories

Matrix-element (MELA) based discriminants are defined based on angular information of the event using JHUGen and MCFM

→ discriminants are sensitive to gg/qqbar → H production modes

$$\mathcal{D}^{\text{kin}}_{\text{bkg}} = \left[1 + \frac{\mathcal{P}^{\text{q}\bar{\text{q}}}_{\text{bkg}}(\vec{\Omega}^{\text{H}\to 4\ell}|m_{4\ell})}{\mathcal{P}^{\text{gg}}_{\text{sig}}(\vec{\Omega}^{\text{H}\to 4\ell}|m_{4\ell})}\right]^{-1}$$



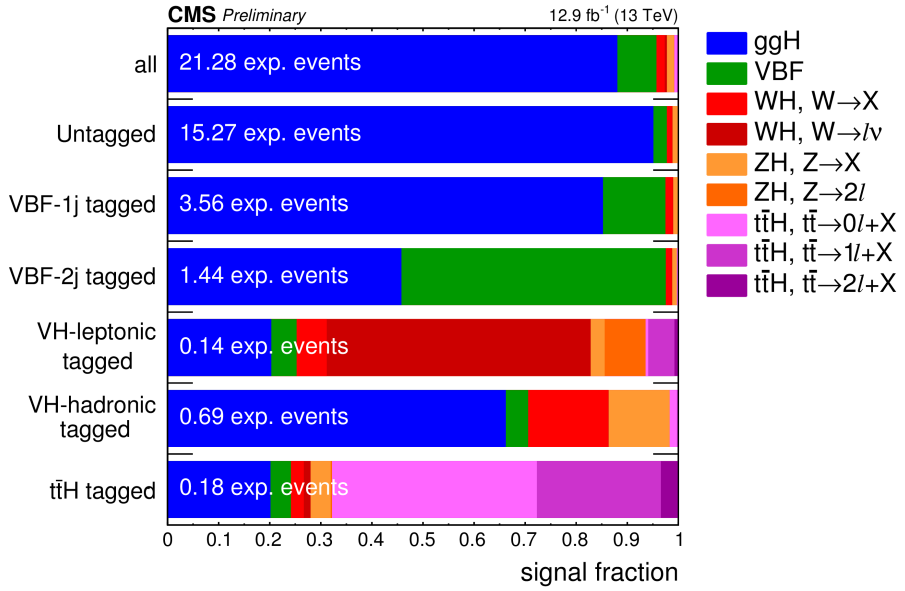
VBF production angles

→ Other new discriminants for production modes are D_{1jet}, D_{2jet} (for VBF), D_{WH}, D_{ZH}

We look for H(125) GeV in 6 events categories, based on number of jets , b tagged jets, additional leptons and cuts on discriminating variables

More details in backup

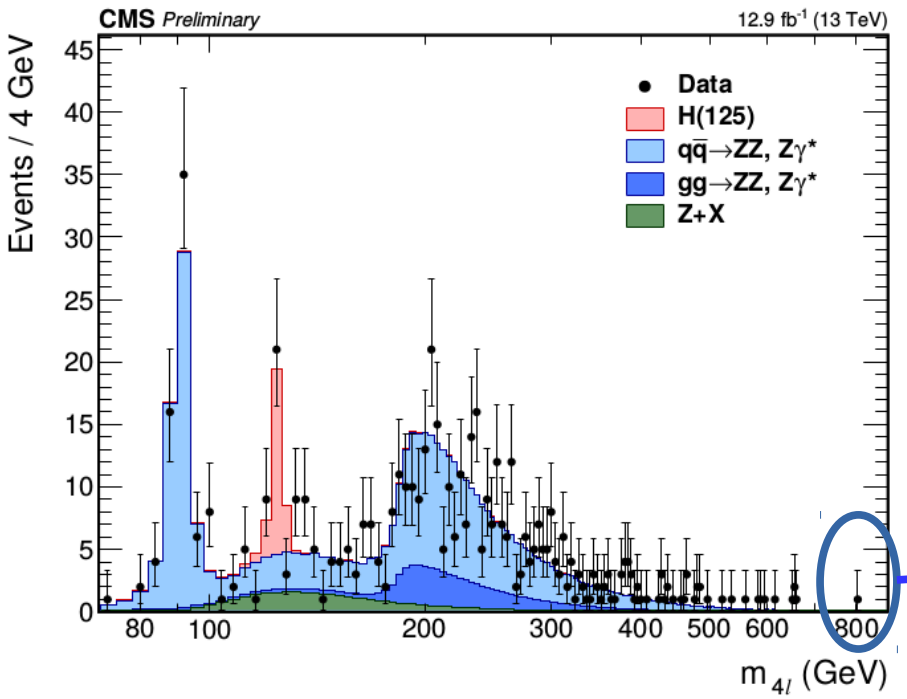
Expectation in [118, 130 GeV]



Systematic uncertainties

Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	6.2 %
Lepton identification/reconstruction efficiencies	6 – 11 %
Background related uncertainties	
QCD scale ($q\bar{q} \to ZZ$, $gg \to ZZ$)	3 – 10 %
PDF set ($q\bar{q} \to ZZ$, $gg \to ZZ$)	3 – 5 %
Electroweak corrections ($q\bar{q} \to ZZ$)	1 – 15 %
$gg \to ZZ$ K factor	10 %
Reducible background (Z+X)	40 – 55 %
Event categorization (experimental)	2 – 18 %
Event categorization (theoretical)	3 – 20 %
Signal related uncertainties	
QCD scale ($q\bar{q} \to$ VBF/VH, $gg \to$ H/$t\bar{t}$H)	3 – 10 %
PDF set ($q\bar{q} \to$ VBF/VH, $gg \to$ H/$t\bar{t}$H)	3 – 4 %
BR($H \to ZZ \to 4\ell$)	2 %
Lepton energy scale	0.04 – 0.3 %
Lepton energy resolution	20 %
Event categorization (experimental)	2 – 15 %
Event categorization (theoretical)	8 – 20 %

Events selection



Nice agreement between expected and observed events are found in 3 final states (4e, 4μ, 2e2μ) in the whole range of m_{4l} distribution

Highest-mass candidate: 802 GeV

Observed events in [118, 130 GeV]

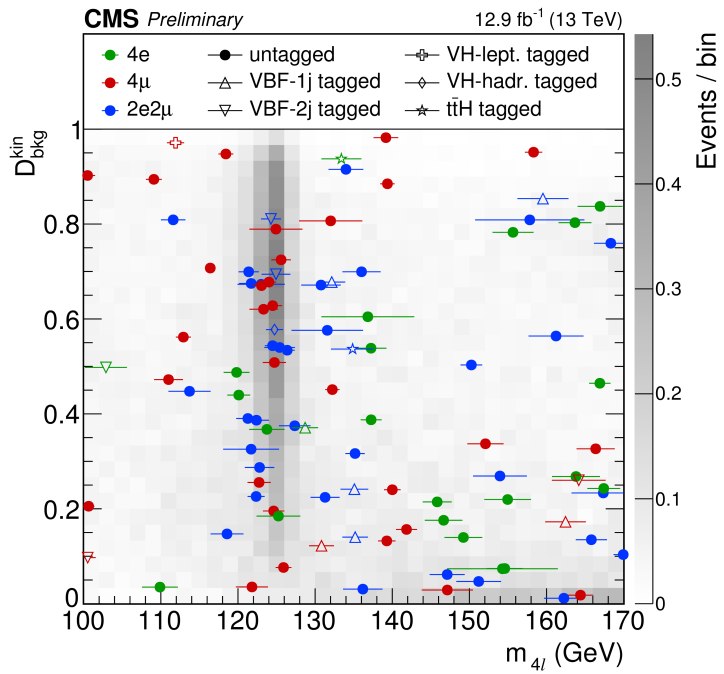
Category	Untagged	VBF-1j	VBF-2j	VH-lept.	VH-hadr.	tt̄H	Total
$q\bar{q} \to ZZ$	7.27	0.82	0.06	0.10	0.11	0.01	8.36
$gg \to ZZ$	0.62	0.11	0.01	0.01	0.01	0.00	0.77
$Z + X$	3.83	0.32	0.24	0.05	0.08	0.10	4.64
Sum of backgrounds	11.73	1.25	0.32	0.16	0.20	0.11	13.77
Signal ($m_H = 125\,GeV$)	15.51	3.62	1.45	0.14	0.70	0.19	21.61
Total expected	27.24	4.87	1.77	0.30	0.90	0.30	35.38
Observed	29	1	2	0	1	0	33

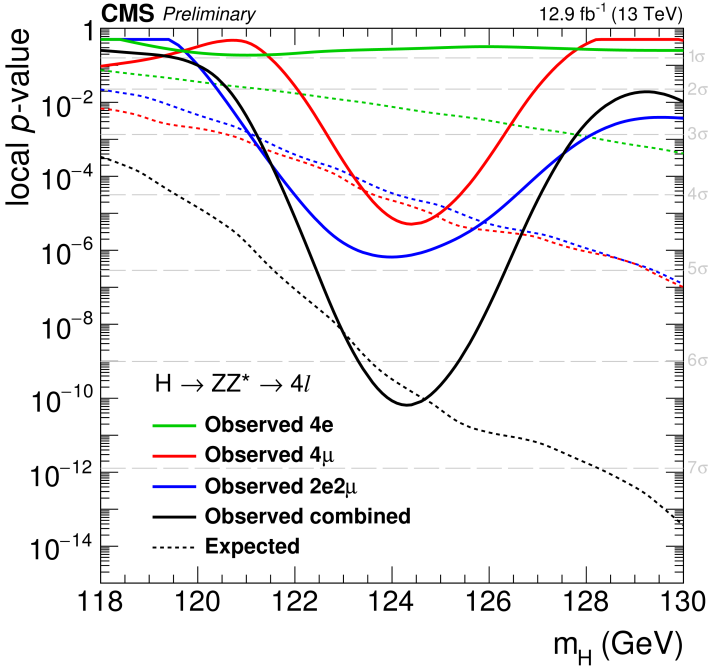
Significance results

Signal strength and p-values has been extracted in all 3 final states and 6 event categories by simultaneous fitting of 2D likelihood

$$\mathcal{L}_{2D}(m_{4\ell}, \mathcal{D}^{\text{kin}}_{\text{bkg}}) = \mathcal{L}(m_{4\ell})\mathcal{L}(\mathcal{D}^{\text{kin}}_{\text{bkg}}|m_{4\ell})$$

Minimum p-value found at m_H = 124.3 GeV
→ 6.4σ obs. (6.3σ exp.) significance
At m_H = 125.09 GeV which is Run-1 CMS and ATLAS combination result
→ 6.2σ obs. (6.5 σ exp.) significance





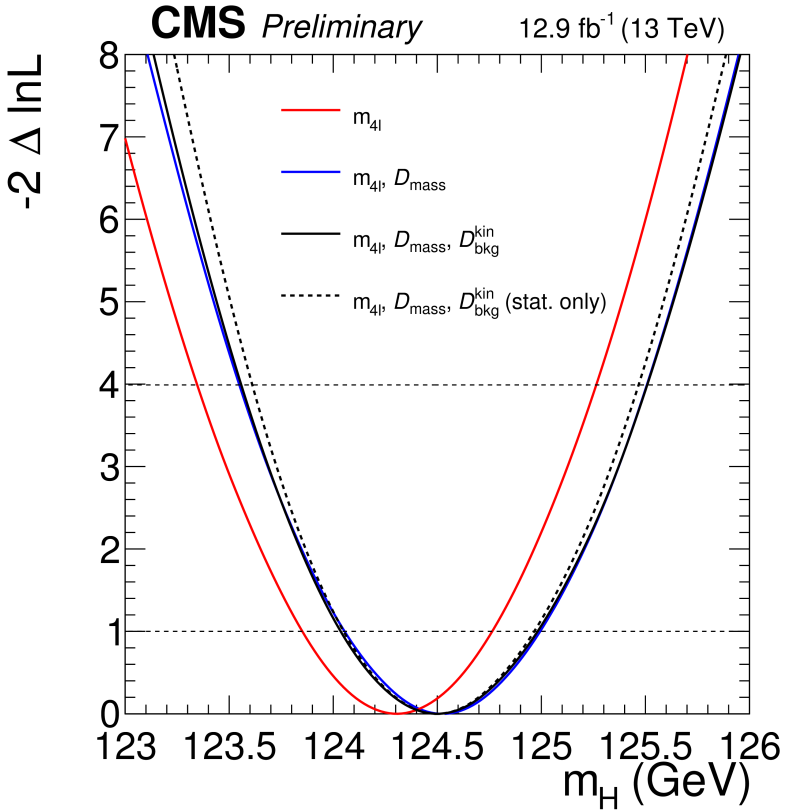
Mass measurement

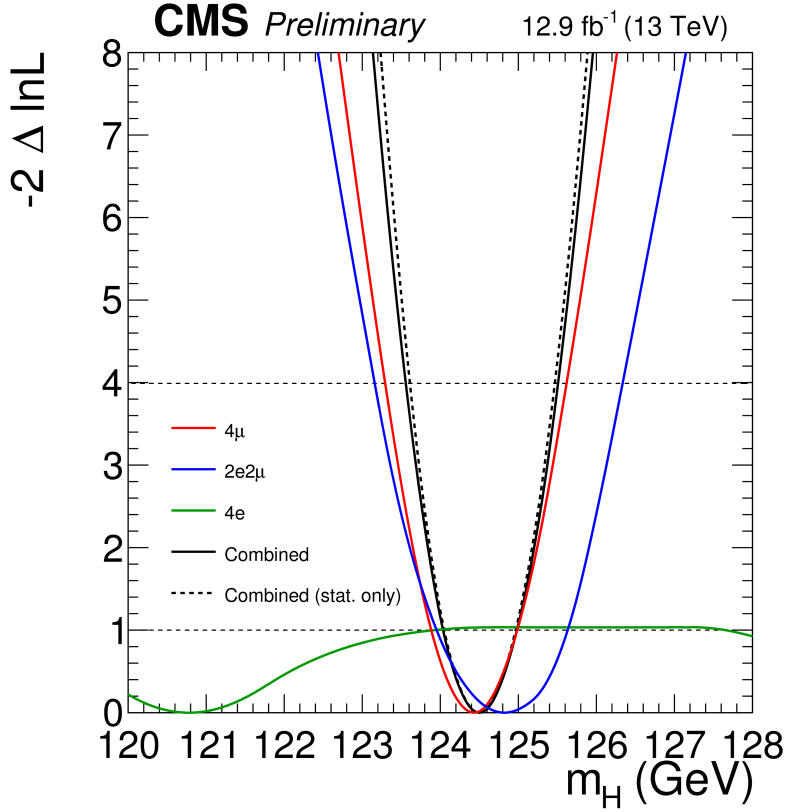
Mass measurement is extracted using per event mass uncertainties which bring 8% improvement in mass resolution

→ Propagate per lepton momentum uncertainties to four lepton candidate corrected in data/MC using Z events

3D fit based on $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$ profiling the signal strength μ

$$m_H = 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})$$





Signal strength results

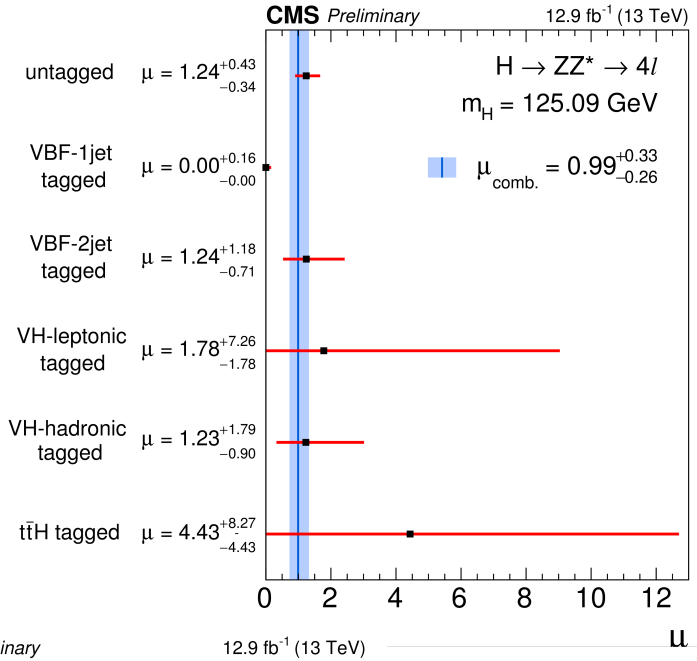
Extracted Signal strength at $m_H = 125.09$ GeV

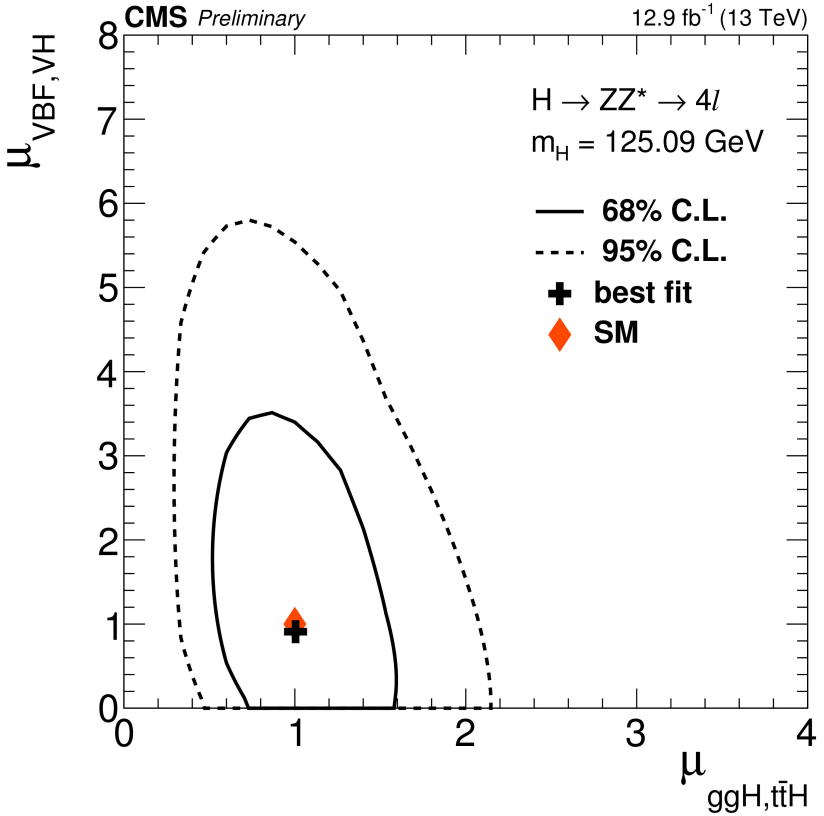
→ combined

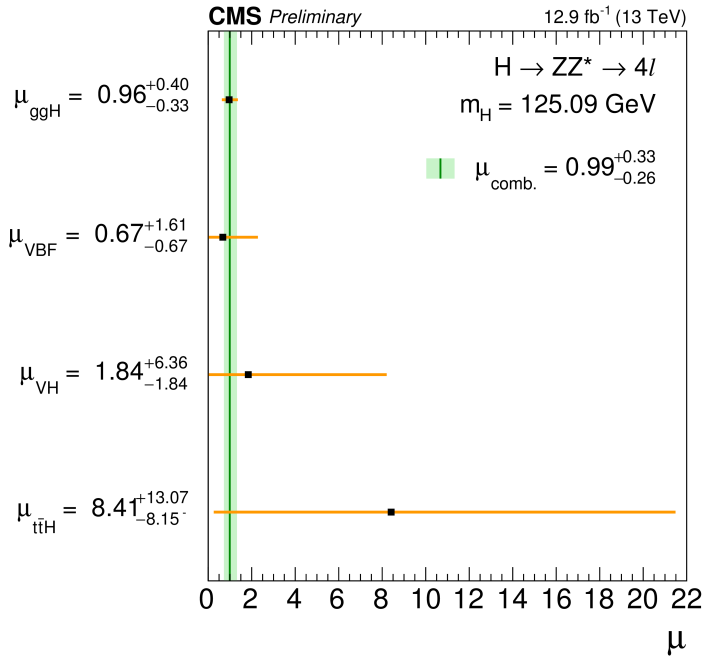
$$\mu = \sigma/\sigma_{SM} = 0.99^{+0.33}_{-0.26}$$

Extracted signal strength for production modes in a 2 parameter model and a 4 parameter model

μ In all categories

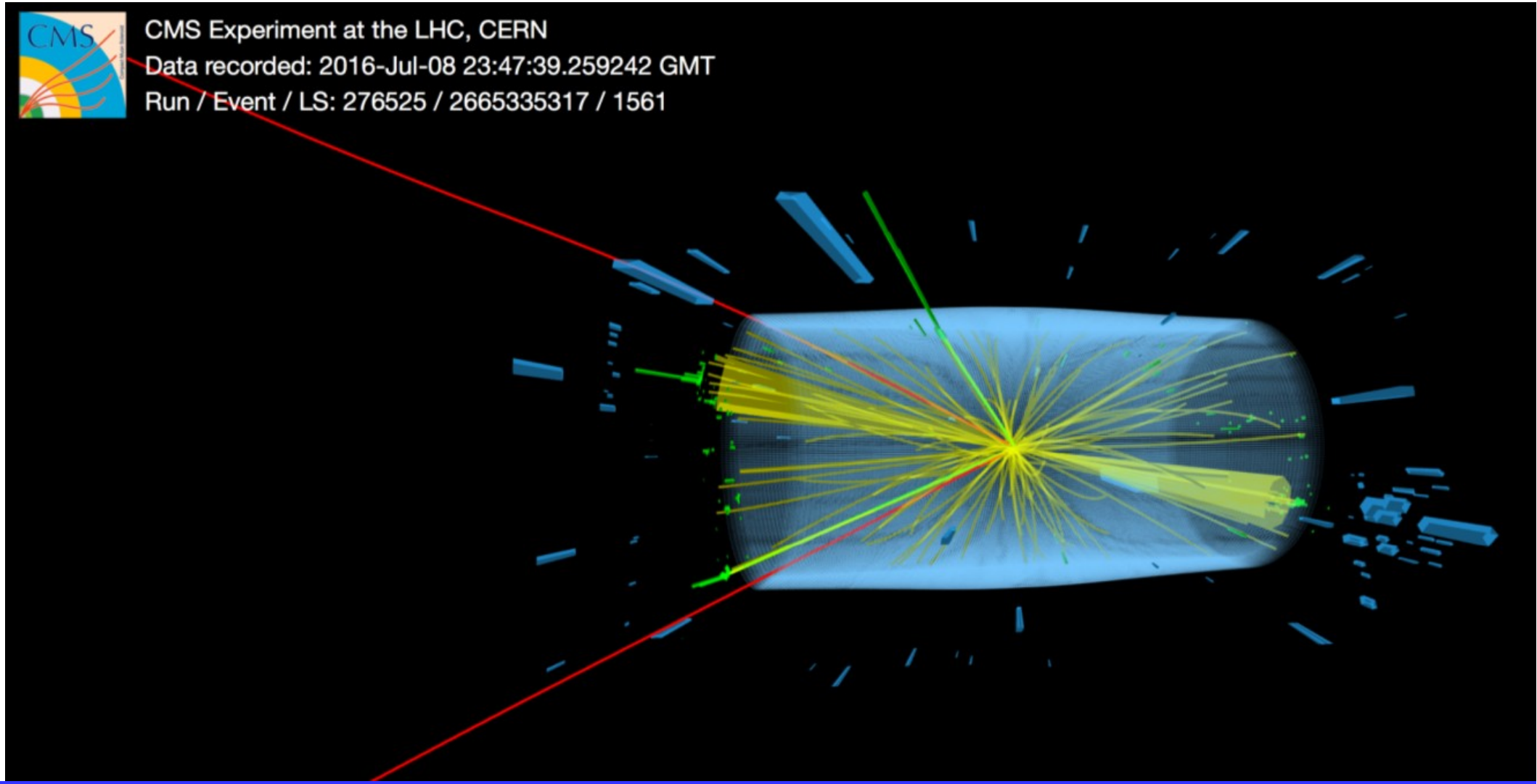




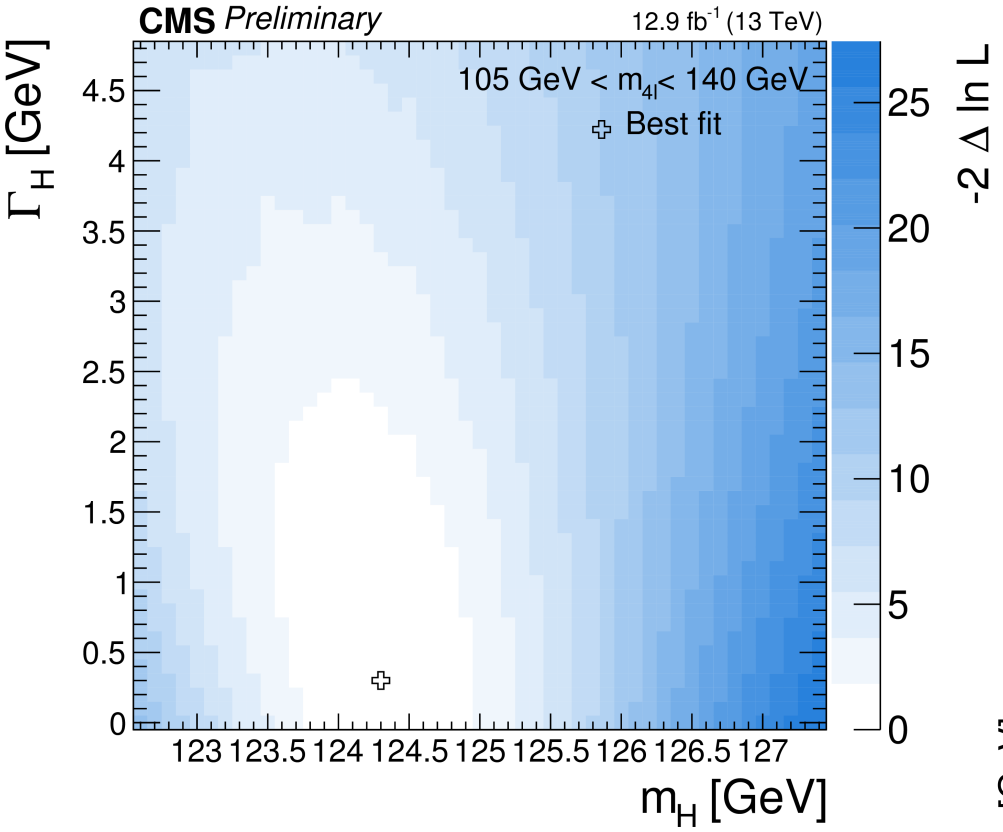


VBF-2jet-tagged event

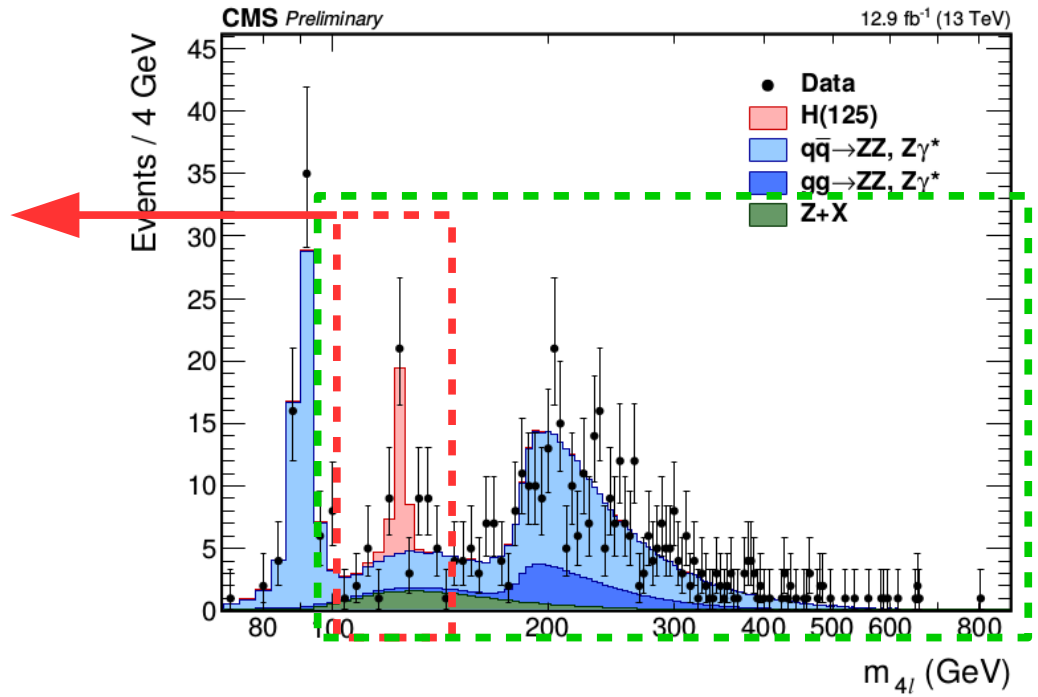
VBF-2jet-tagged $H \rightarrow ZZ^* \rightarrow 2e2\mu$ candidate
$m_{4\ell} = 124.93$ GeV, $D_{bkg}^{kin} = 0.694$

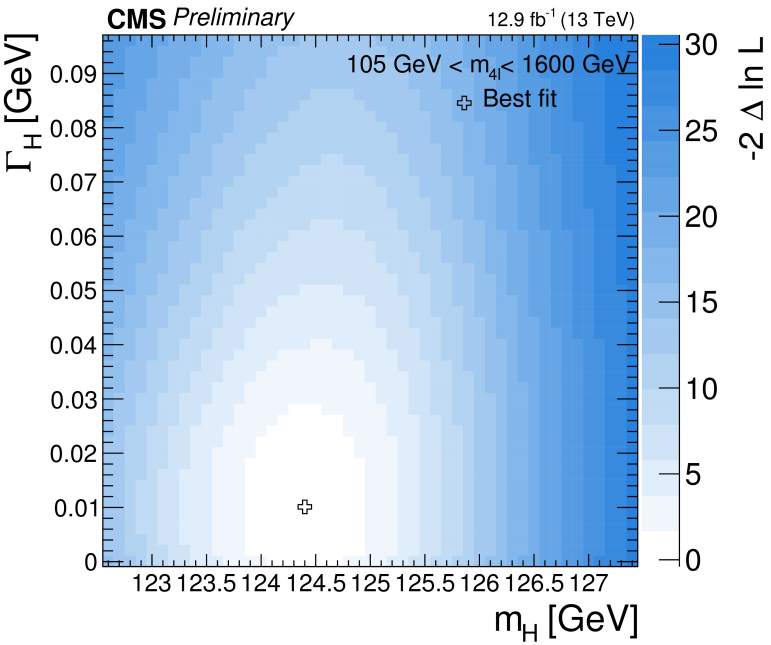


Width-mass measurement



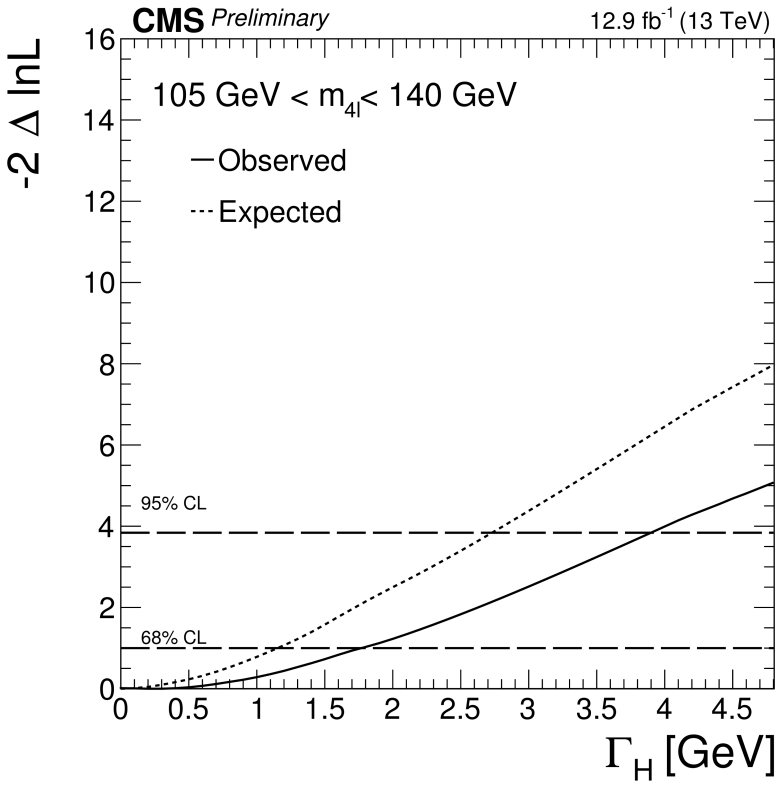
On shell

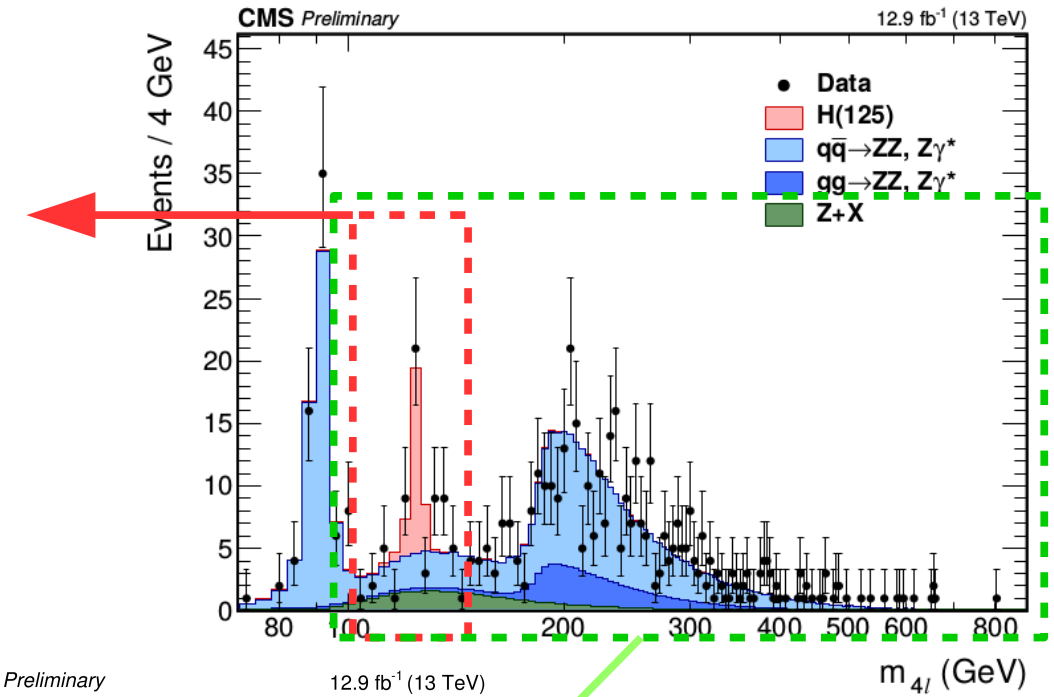


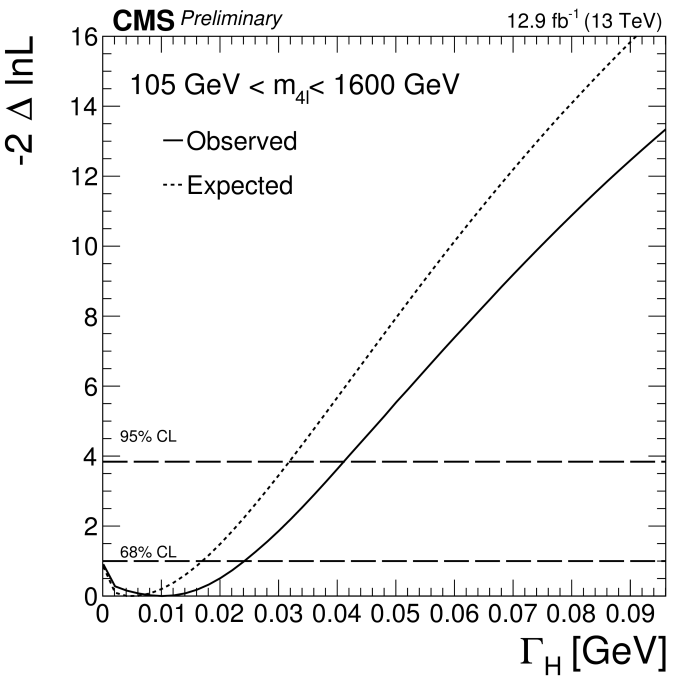


On shell+ 0ff shell

Width-mass measurement(cont.)







On shell
Expected Γ_H = 2.7 GeV
Observed Γ_H = 3.9 GeV

On shell+ 0ff shell
Exp. Γ_H =32 MeV
Obs. Γ_H = 41 MeV

Fiducial cross section

The fiducial volume definition is chosen to closely match the reconstruction level selection, defined using leptons at the hard scattering level

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20\,\text{GeV}$
Sub-leading lepton p_T	$p_T > 10\,\text{GeV}$
Additional electrons (muons) p_T	$p_T > 7\ (5)\,\text{GeV}$
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5\ (2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 p_T$
Event topology	
Existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m(Z_1) < 120\,\text{GeV}$
Inv. mass of the Z_2 candidate	$12 < m(Z_2) < 120\,\text{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$
Inv. mass of any opposite-sign lepton pair	$m(\ell_i^+ \ell_j^-) > 4\,\text{GeV}$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140\,\text{GeV}$

- For jets, p^T>30 GeV and |η|<4.7
- A crucial point is the inclusion of isolation in the fiducial selection
  → Does not include neutrinos or FSR photons
  → Without isolation, the difference in efficiency between production modes can be more than 50%

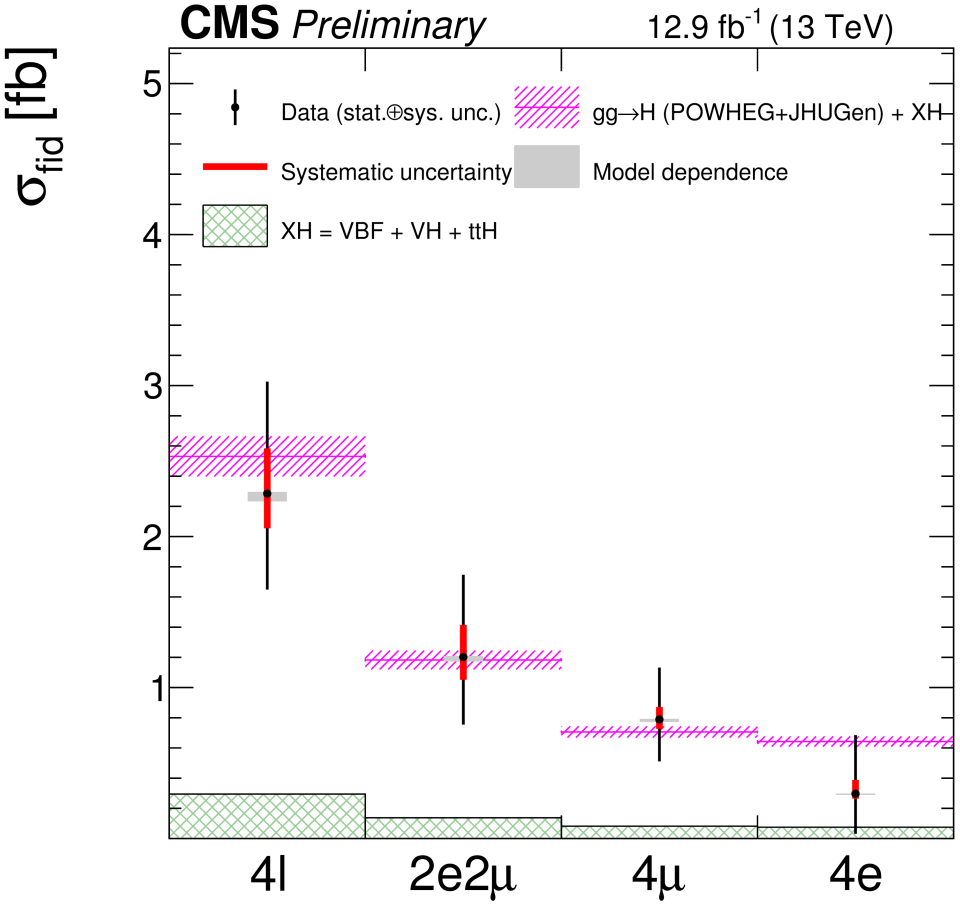
Fiducial cross section

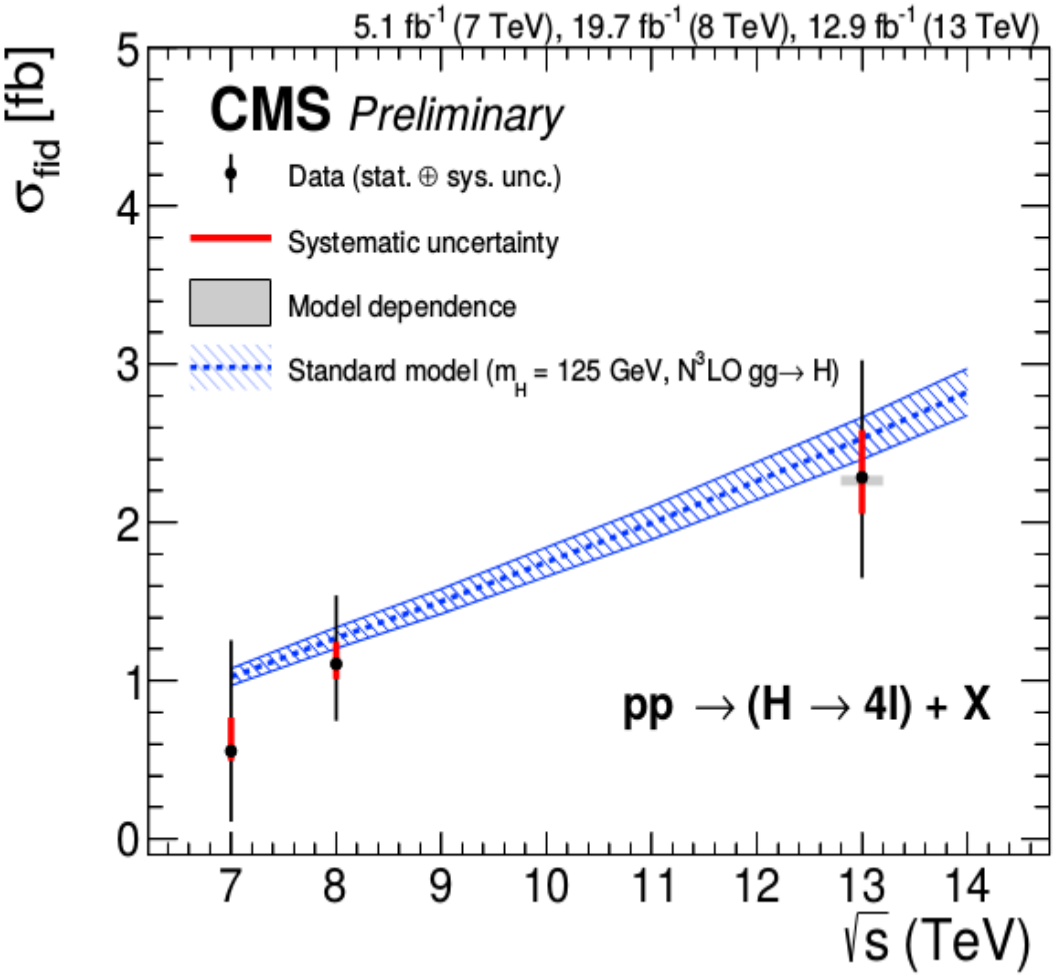
- Model dependence of the measurement procedure is estimated by repeating the measurement using the efficiencies and non-fiducial ratios from a range of different models of production
- We quote the full model dependence without any experimental constraints as a separate systematic effect

Signal process	$\mathcal{A}_{\text{fid}}$	ϵ	f_{nonfid}	$(1+f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
$gg \to H$	0.371	0.608 ± 0.001	0.121 ± 0.001	0.682 ± 0.002
VBF	0.422	0.614 ± 0.002	0.089 ± 0.001	0.669 ± 0.002
WH	0.283	0.587 ± 0.002	0.241 ± 0.003	0.729 ± 0.003
ZH	0.307	0.611 ± 0.003	0.207 ± 0.004	0.738 ± 0.005
ttH	0.238	0.573 ± 0.004	0.593 ± 0.011	0.914 ± 0.009

Inclusive cross section results

- The acceptance is calculated using Powheg at 13 TeV and HRes for 7,8 TeV
- All total cross sections taken from LHCHXSWG

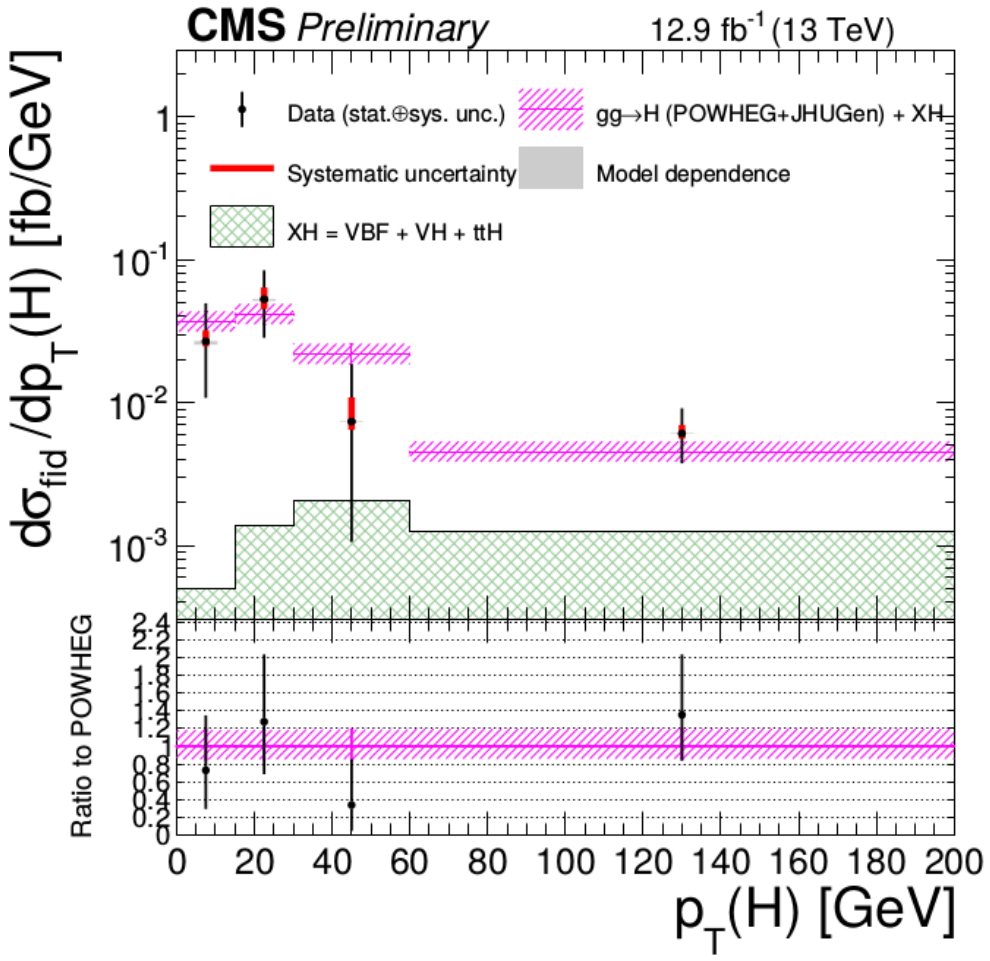


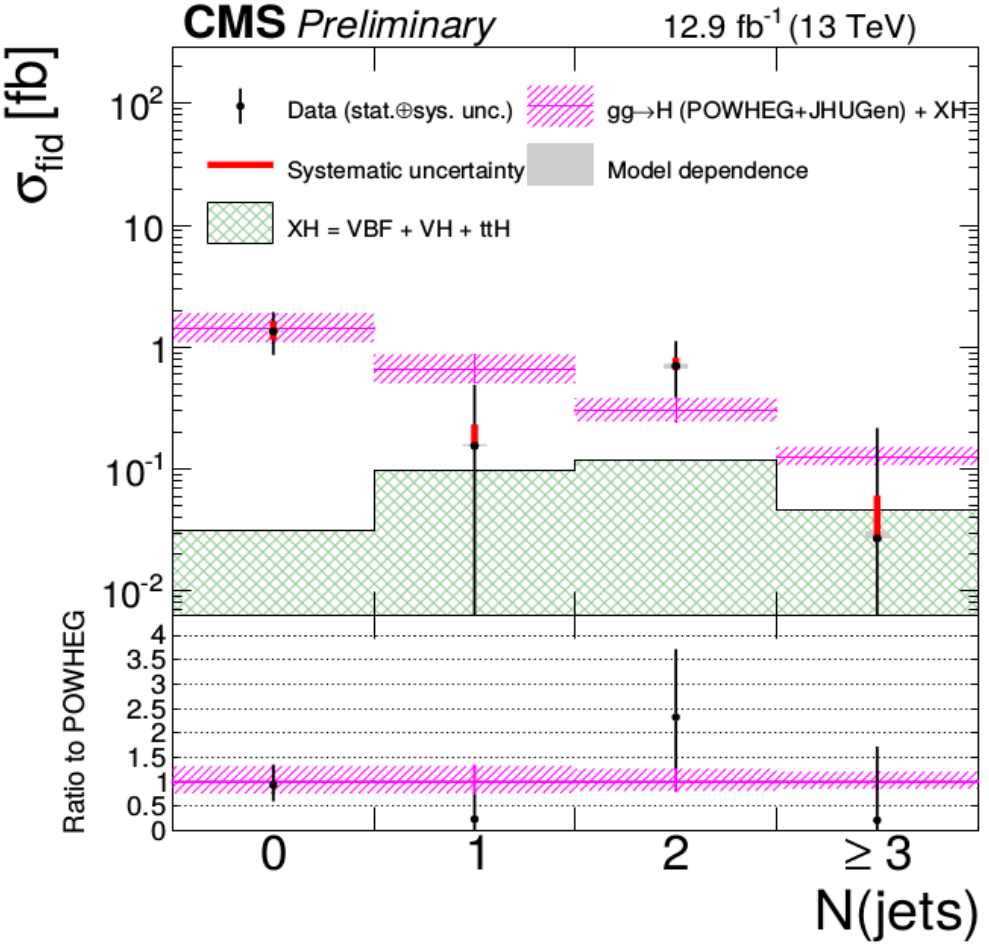


$$\sigma_{\text{fid.}} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})\ \text{fb}$$

$$\sigma^{\text{SM}}_{\text{fid.}} = 2.53 \pm 0.13\ \text{fb}$$

Differential cross section results





Differential variables $P_T(H)$ and N(jets)

Sensitive to PDFs of colliding proton and relative contribution of different Higgs boson production mechanisms

Summary

Measured complete set of Higgs boson properties using $H \to ZZ^* \to 4\ell$ at $\sqrt{s}$ = 13 TeV using 12.9 fb^{-1}

→ Rediscovered Higgs boson, significance observed 6.2σ (expected 6.9σ) at m_H = 125.09 GeV

→ Mass of Higgs boson measured to be $124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})$

→ combined signal strength $\mu = \sigma/\sigma_{SM} = 0.99^{+0.33}_{-0.26}$

→ Measured signal strength in all production modes

μ_{ggH} , μ_{VBF} , μ_{VH} , and μ_{ttH}

→ Measured Fid. Cross section $\sigma_{\text{fid.}} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})$ fb

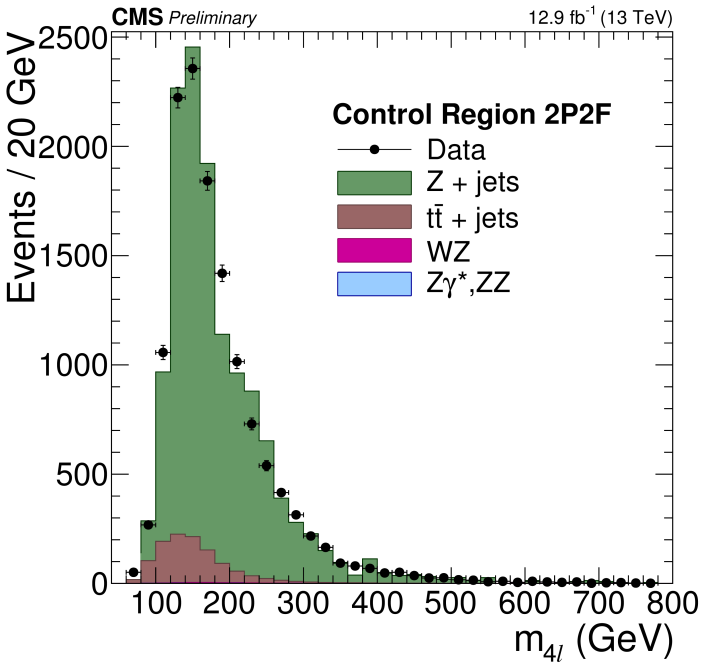
→ Differential measurements as function p^T(H), N(Jets)

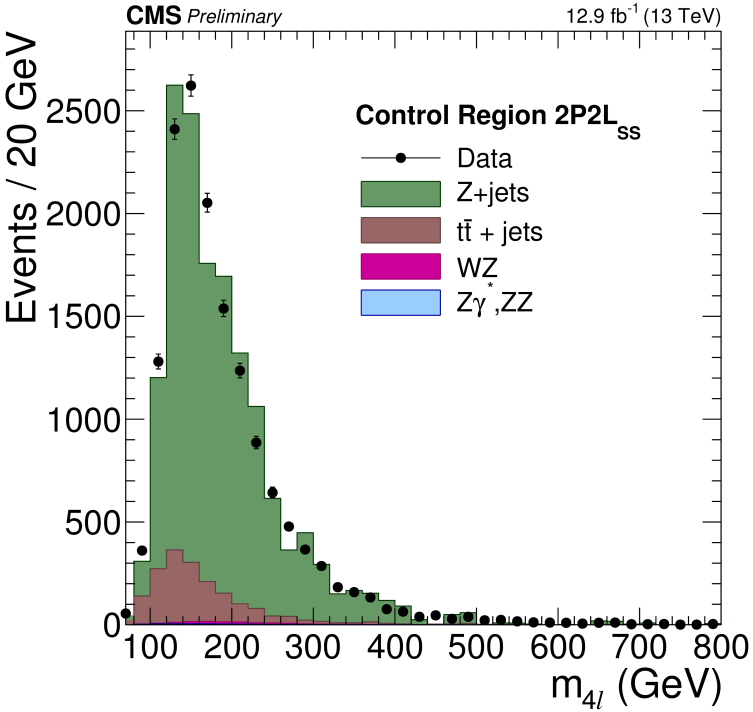
CMS is expected to record ~30-40 fb^{-1} integrated luminosity (X3 times) by end of year

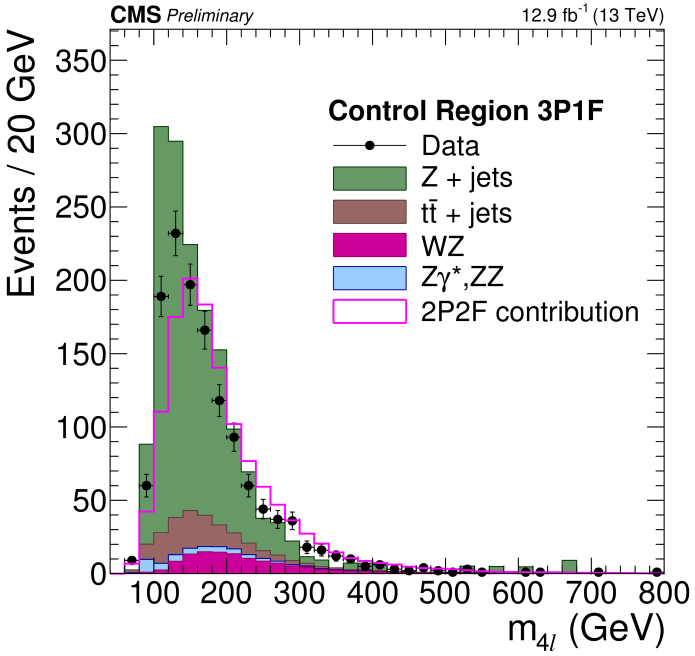
New results would be published soon

Backup

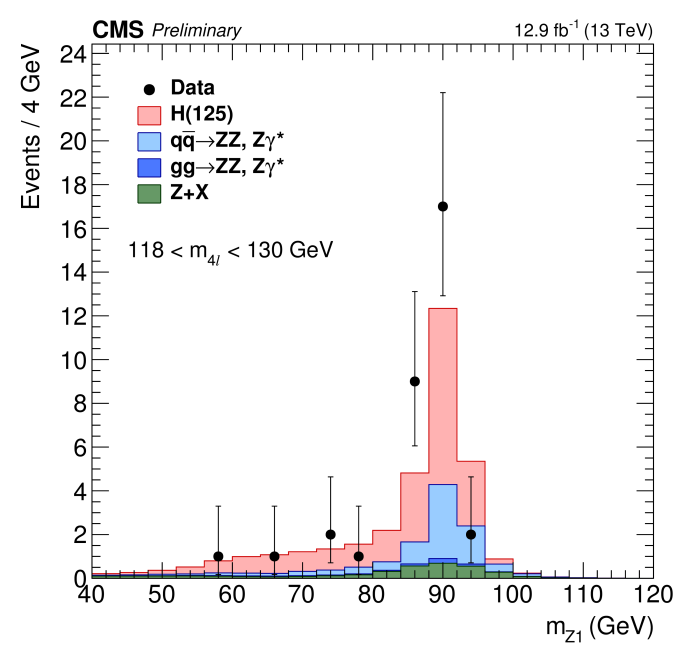
Control region for Z+X

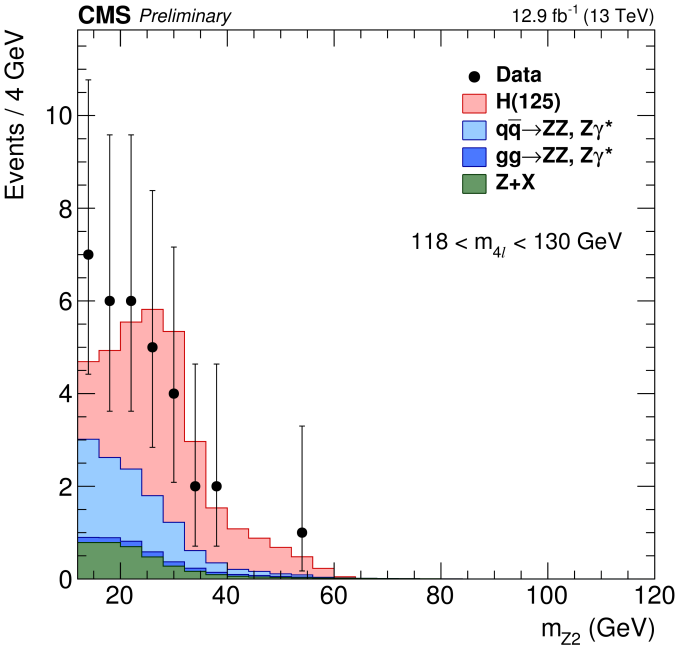


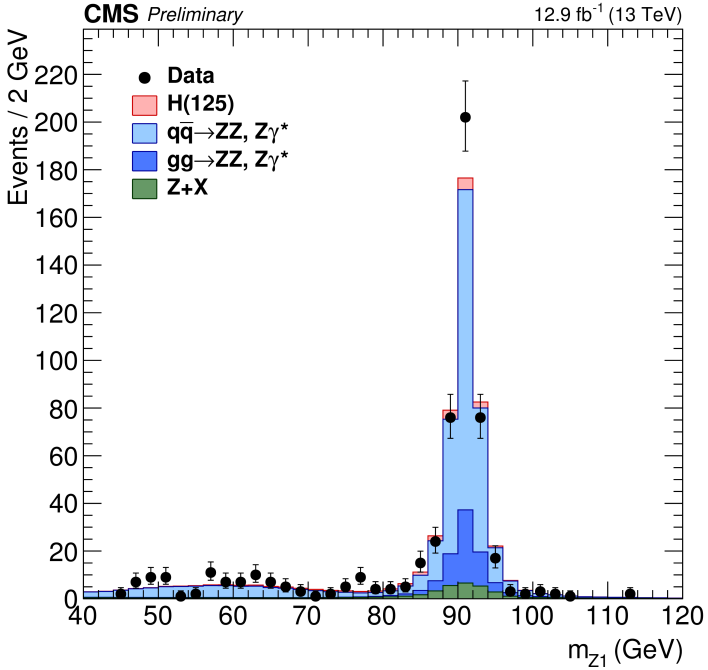


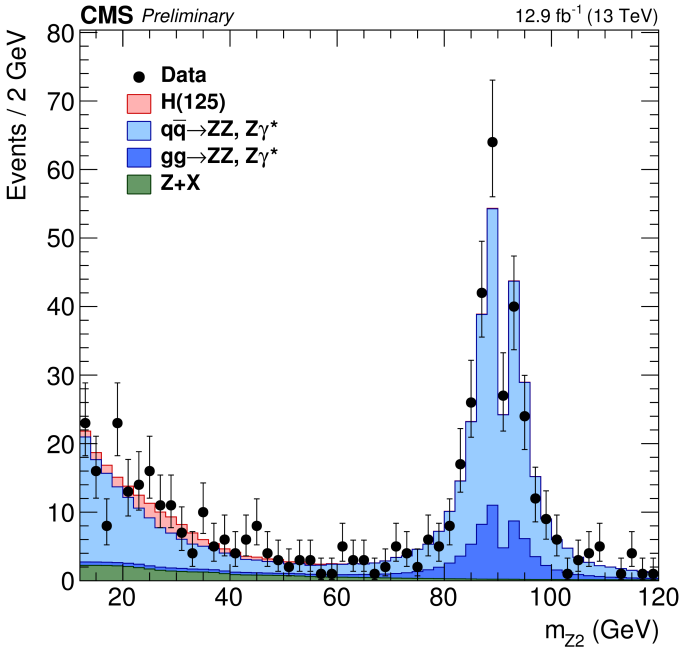


Z1 and Z2 inv. mass

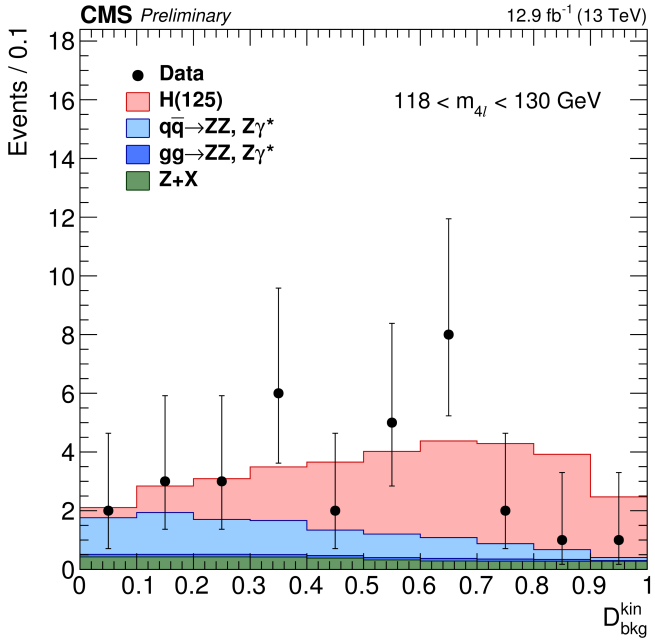


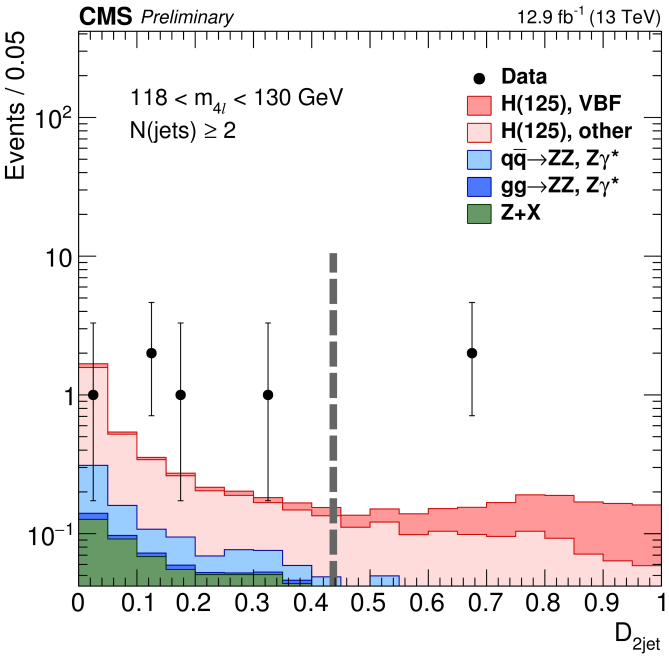


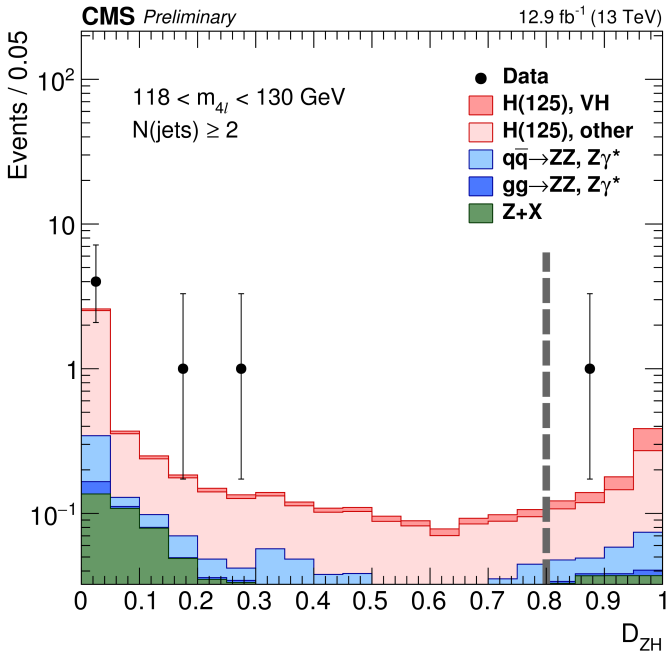


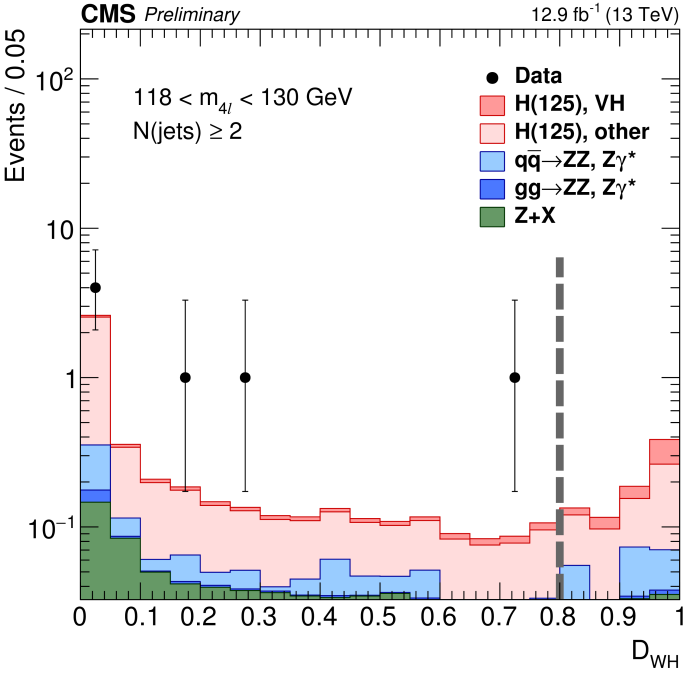


Discriminants









Event Categories

6 mutually exclusive categories,
defined applying following criteria in this exact order:
1. exactly 4 leptons + {2-3 jets with ≤1 b-tag or ≥4 jets with 0 b-tag}
+ high D 2jet value ➔ VBF-2jet tagged category
2. exactly ≥4 leptons + {2-3 jets with ≤1 b-tag or 4 jets with 0 b-tag}
+ high D WH or D ZH value;
or 2-3 jets + 2 b-tags
➔ VH-hadronic tagged category
3. ≤3 jets + 0 b-tag + {exactly 5 leptons or
≥1 pair of additional opposite-sign leptons};
or 0 jet + ≥5 leptons
➔ VH-leptonic tagged category
4. ≥4 jets + ≥1 b-tag;
or ≥5 leptons ➔ ttH tagged category
5. exactly 4 leptons + exactly 1 jet
+ high D 1jet value
➔ VBF-1jet tagged category
6. other events ➔ untagged category