

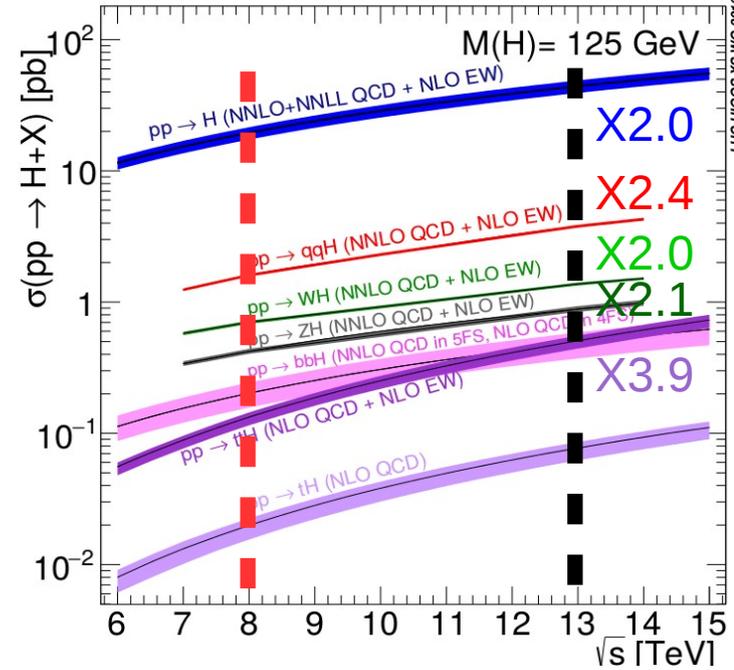
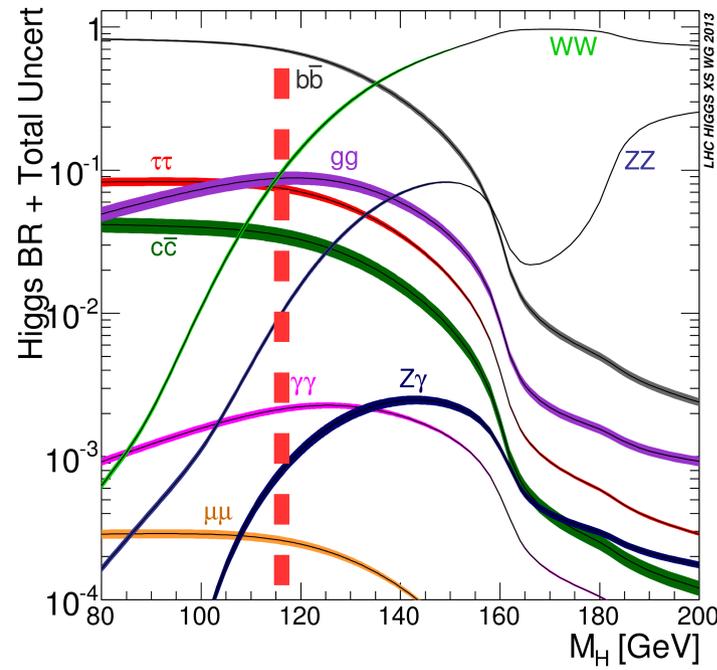
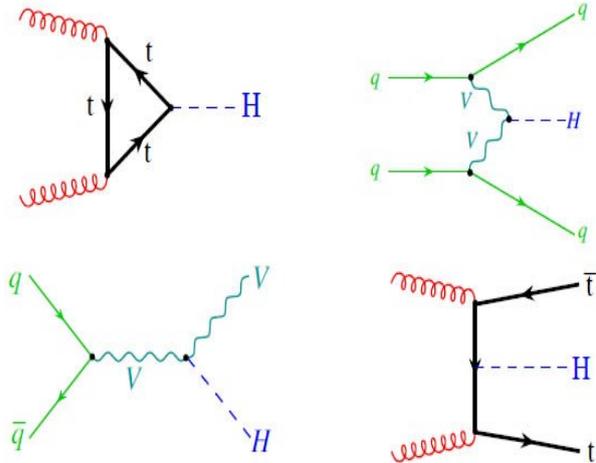
Higgs boson production in the four-lepton final state with CMS

Second China LHC Physics Workshop
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On behalf of the CMS Collaboration

Higgs boson production and decay



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

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

The $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\ell=e,\mu$) 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)

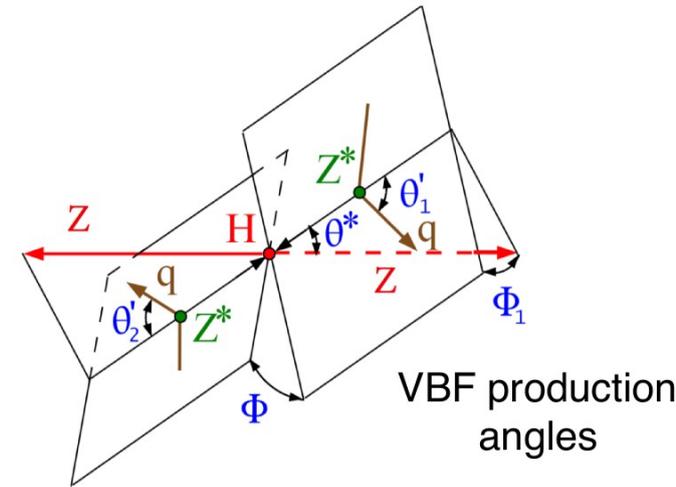
Events categories



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

→ discriminants are sensitive to $gg/qqbar \rightarrow H$ production modes

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

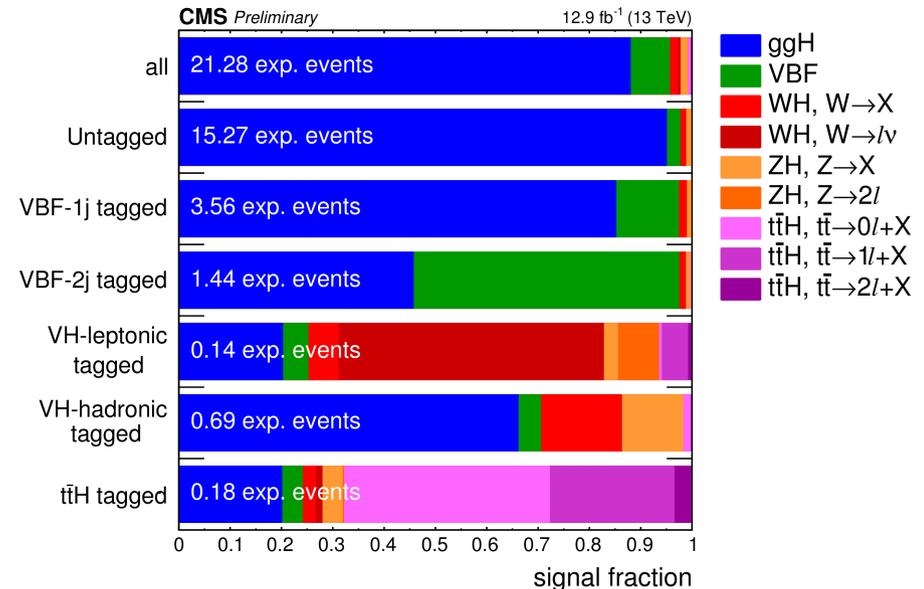


→ Other new discriminants for production modes are

$$D_{1\text{jet}}, D_{2\text{jet}} \text{ (for VBF)}, D_{\text{WH}}, D_{\text{ZH}}$$

We look for H(125) GeV in 6 event 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]





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

VBF-2jet-tagged event



VBF-2jet-tagged $H \rightarrow ZZ^* \rightarrow 2e2\mu$ candidate

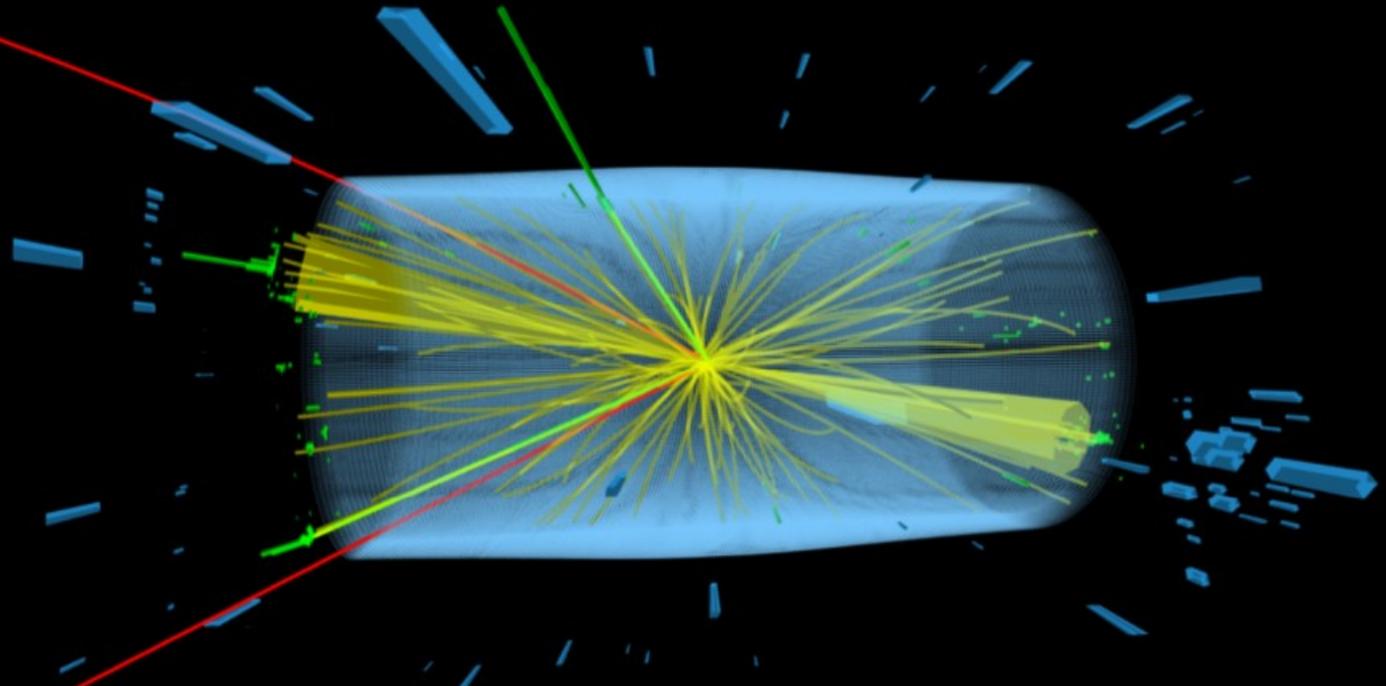
$m_{4\ell} = 124.93 \text{ GeV}$, $D_{\text{bkg}}^{\text{kin}} = 0.694$



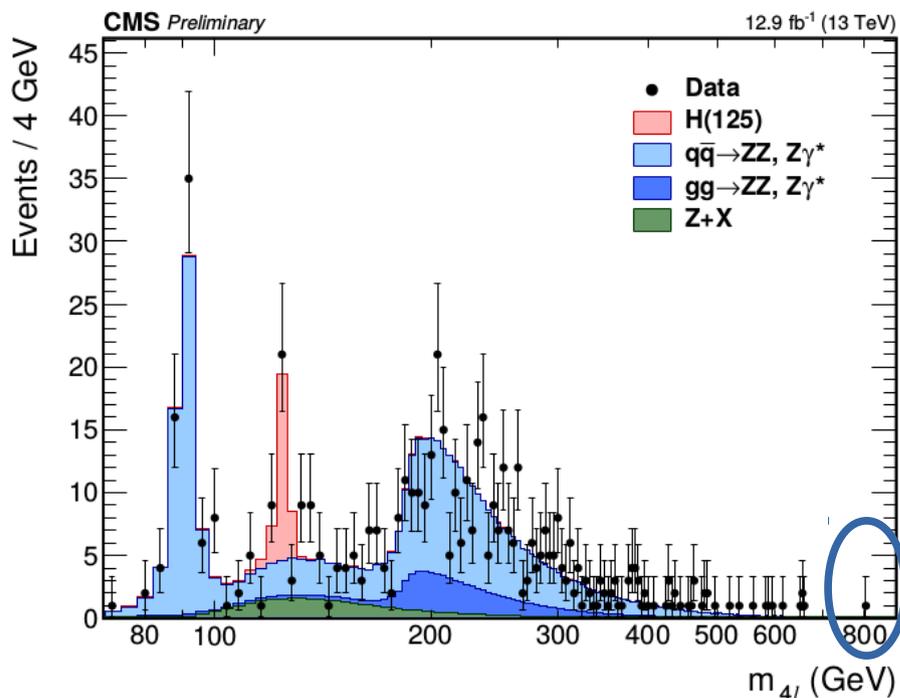
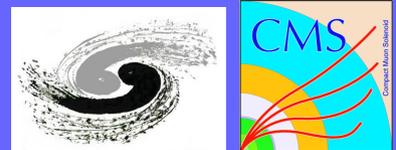
CMS Experiment at the LHC, CERN

Data recorded: 2016-Jul-08 23:47:39.259242 GMT

Run / Event / LS: 276525 / 2665335317 / 1561



Events selection



Nice agreement between expected and observed events are found in 3 final states (4e, 4 μ , 2e2 μ) 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.	t \bar{t} H	Total
$q\bar{q} \rightarrow ZZ$	7.27	0.82	0.06	0.10	0.11	0.01	8.36
$gg \rightarrow ZZ$	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

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

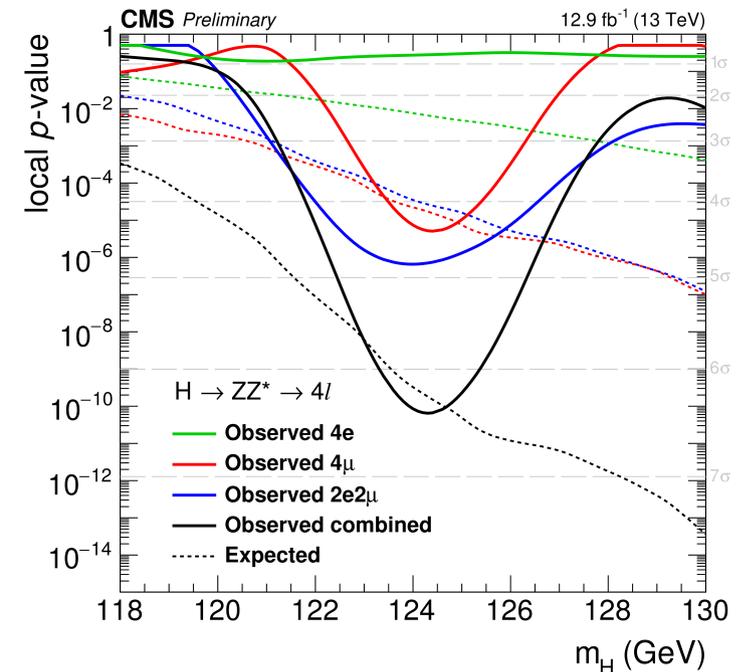
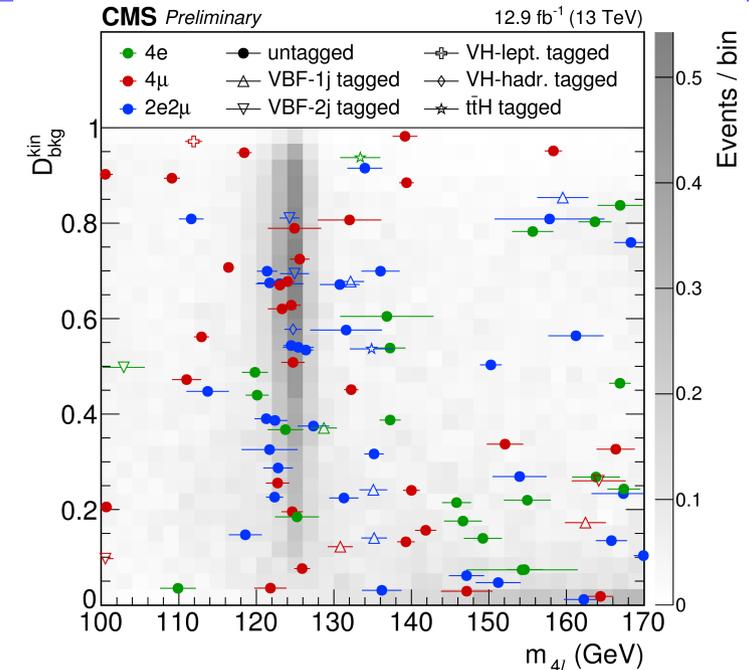
Minimum p-value found at $m_H = 124.3$ GeV

→ 6.4σ obs. (6.3σ exp.) significance

At $m_H = 125.09$ GeV which is Run I CMS

and ATLAS combination result

→ 6.2σ obs. (6.5σ exp.) significance



Mass measurement

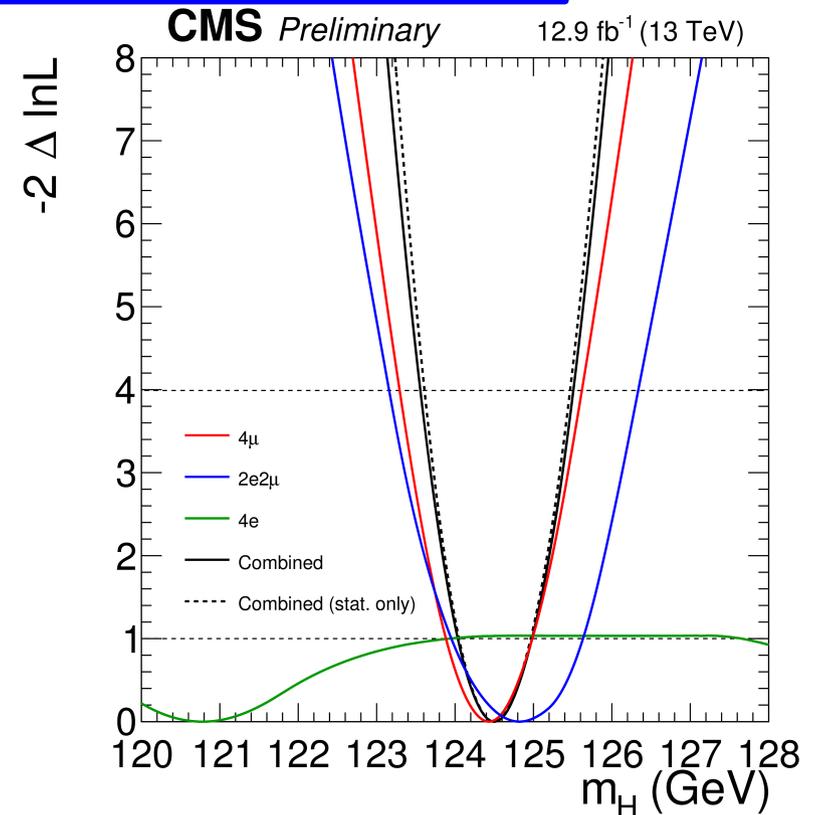
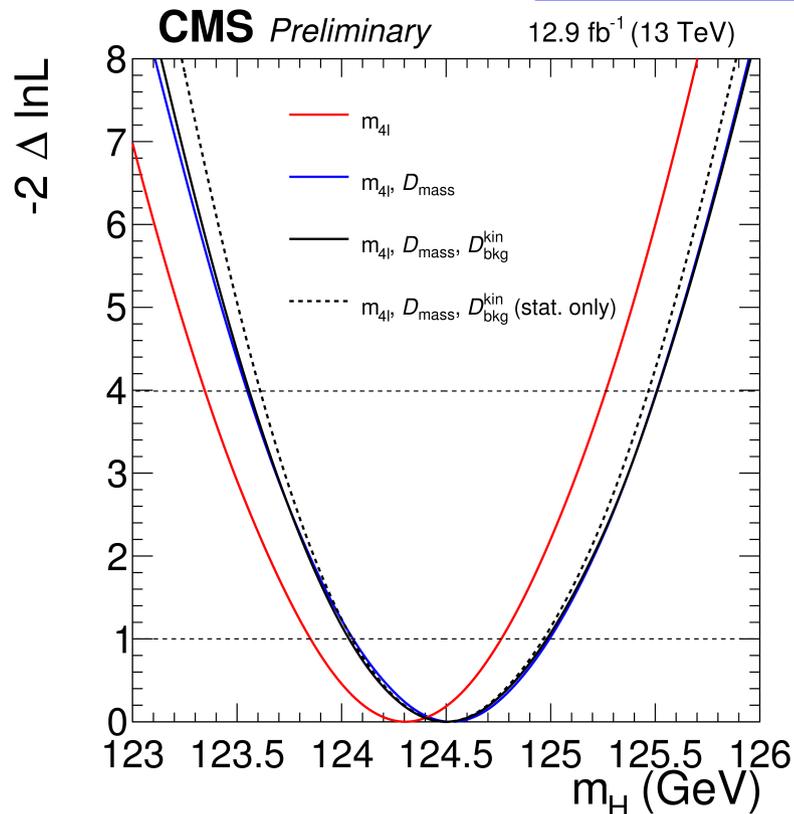


Mass measurement is extracted using per event mass uncertainties which bring 8% improvement in mass resolution

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

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

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



Signal strength results

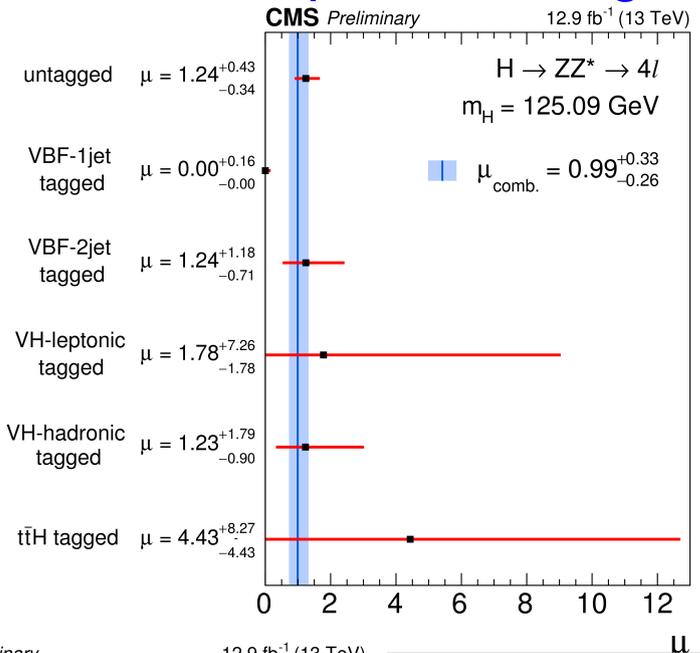


Extracted Signal strength at $m_H = 125.09$ GeV

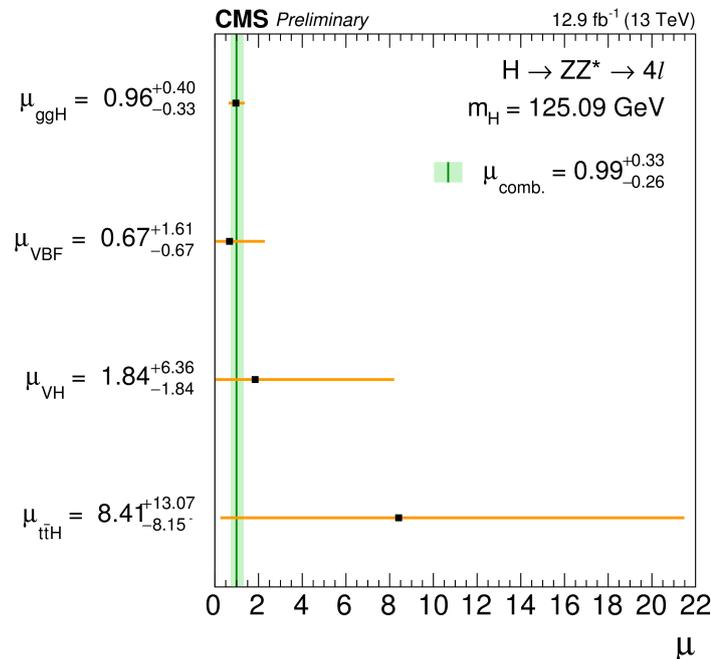
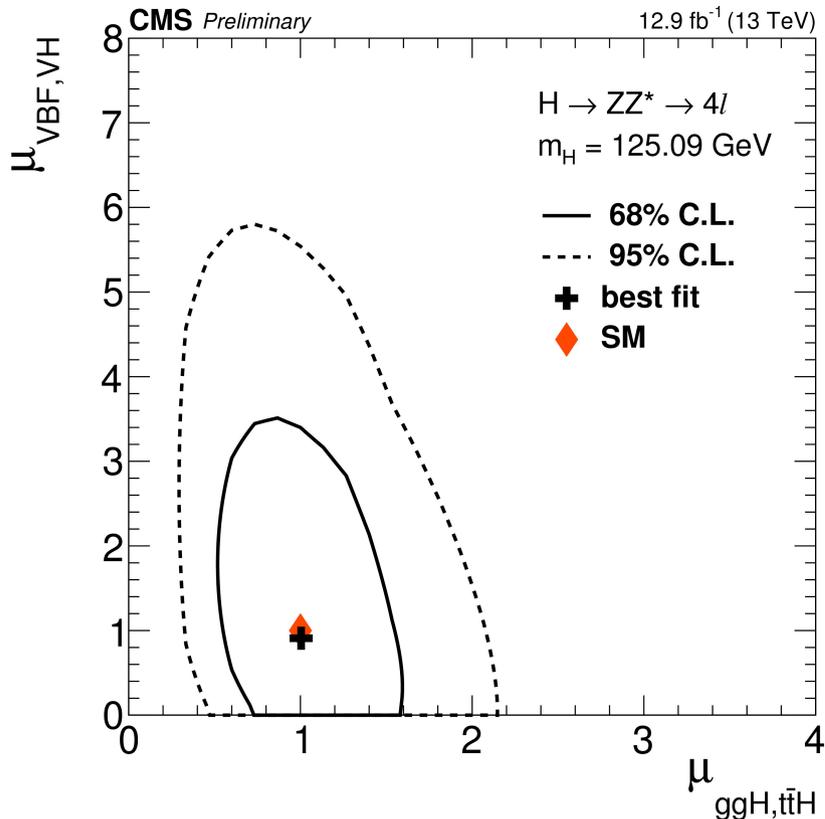
→ combined

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

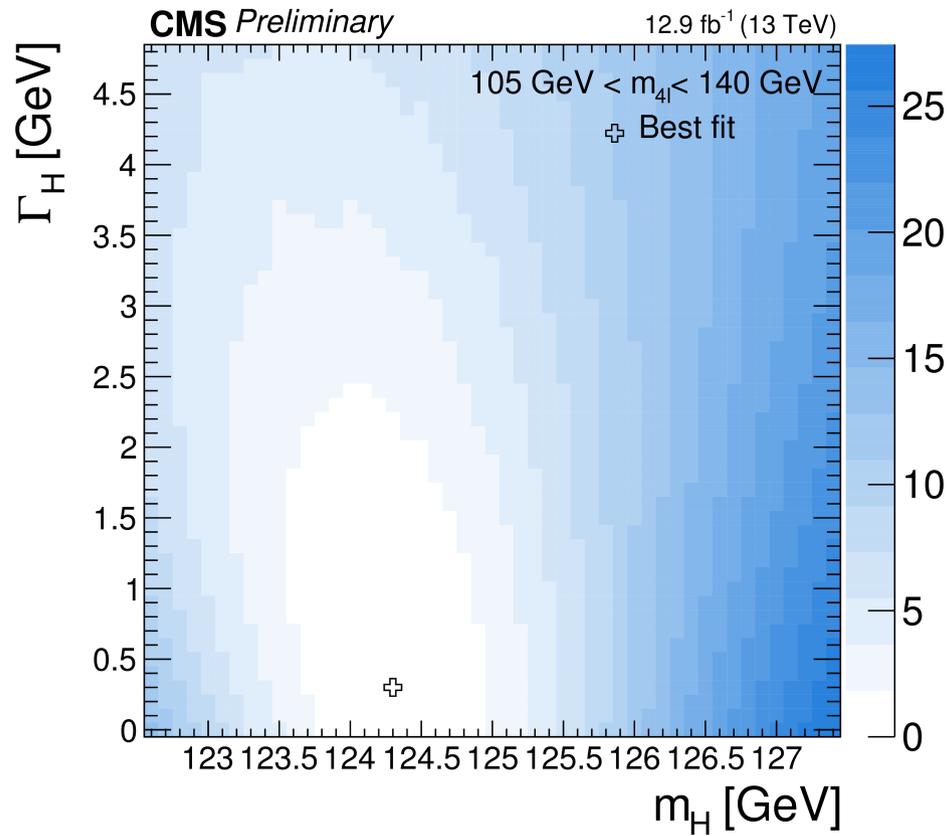
μ In all categories



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

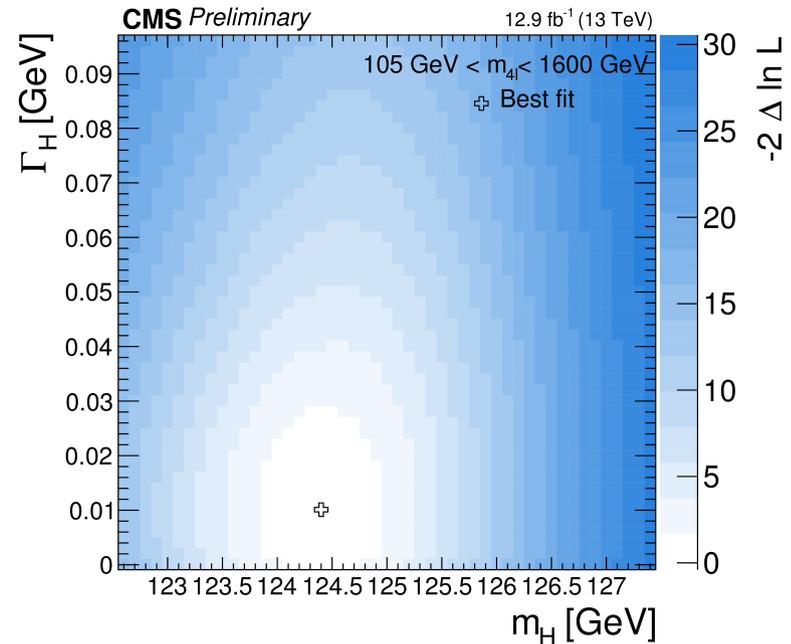
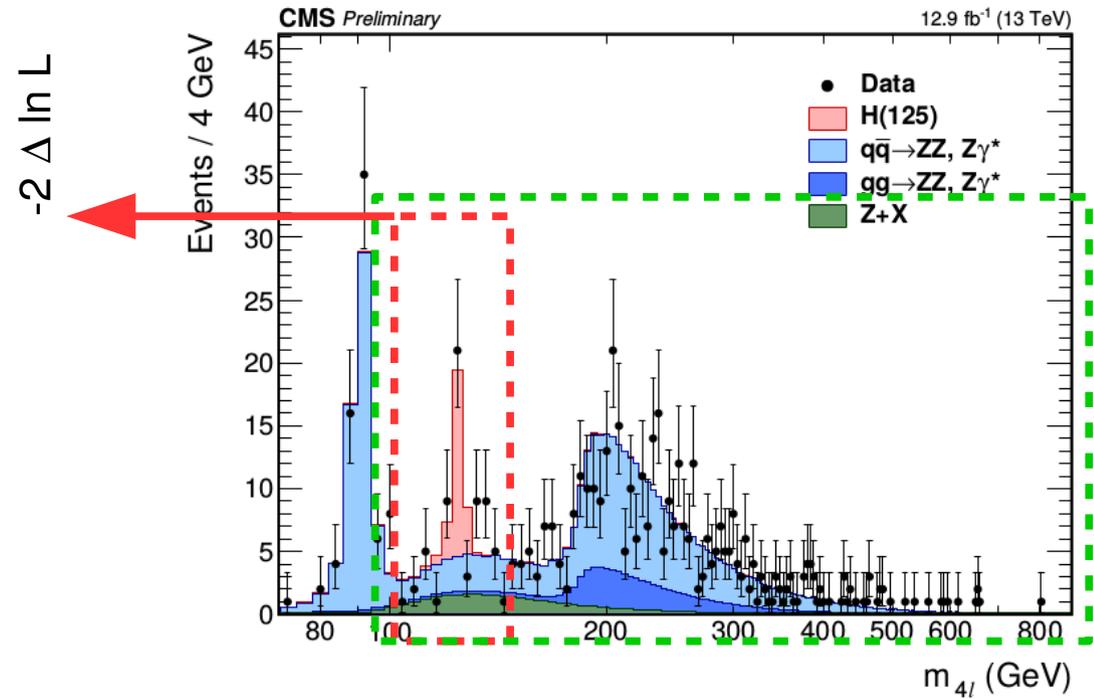


Width-mass measurement

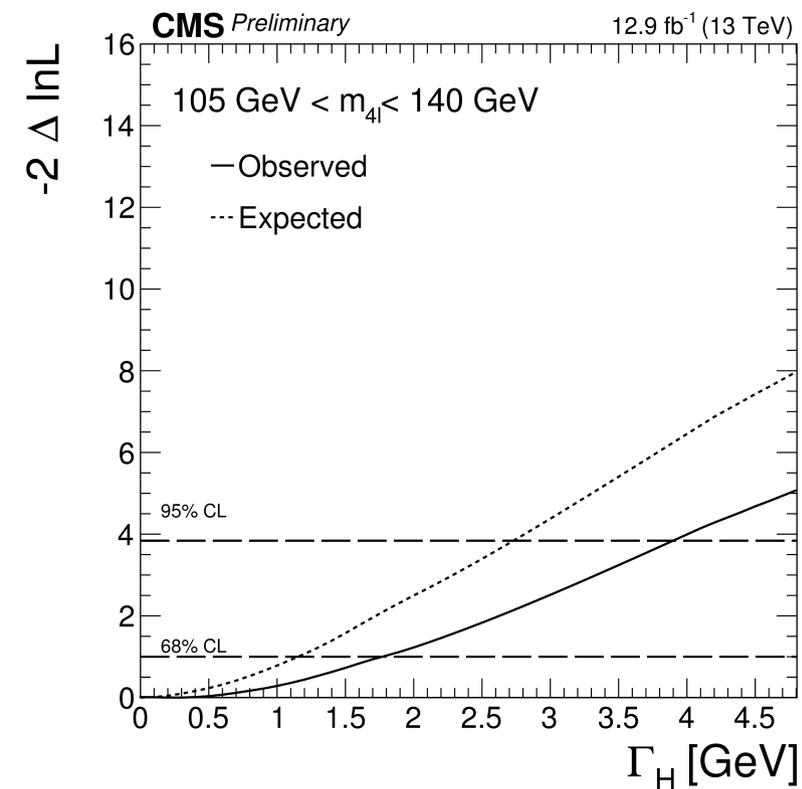


On shell

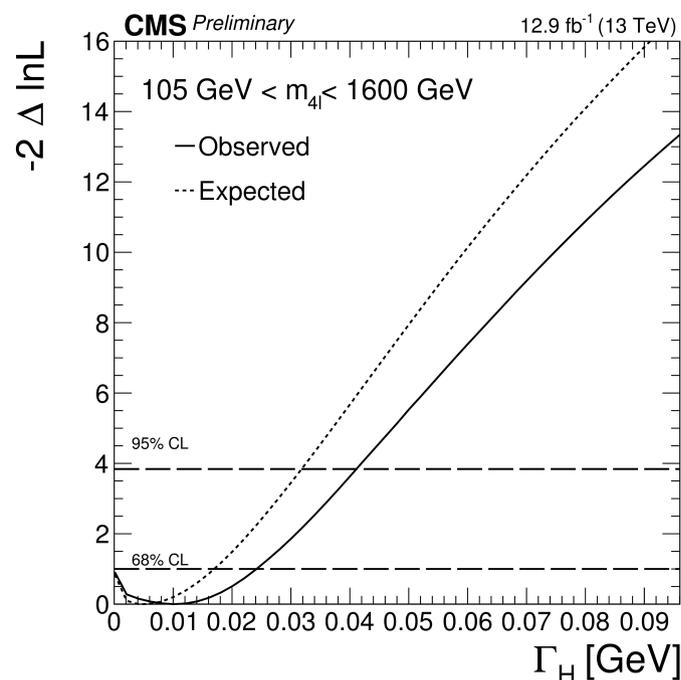
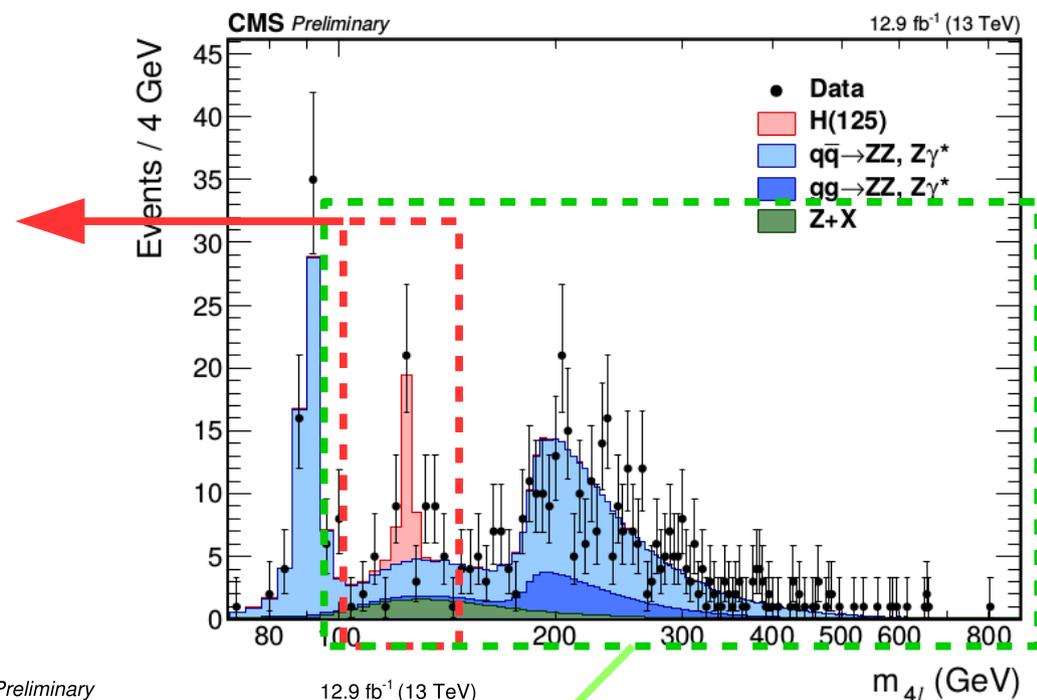
On shell+ Off shell



Width-mass measurement(cont.)

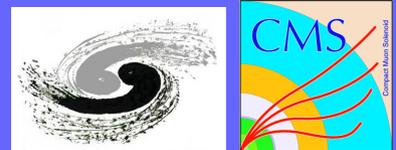


On shell
Expected $\Gamma_H = 2.7$ GeV
Observed $\Gamma_H = 3.9$ GeV



On shell+ Off shell
Exp. $\Gamma_H = 32$ MeV
Obs. $\Gamma_H = 41$ 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 $H \rightarrow 4\ell$ 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	$p_T > 7 \text{ (5) GeV}$
Pseudorapidity of electrons (muons)	$ \eta < 2.5 \text{ (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, $p_T > 30 \text{ GeV}$ and $|\eta| < 4.7$
- 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



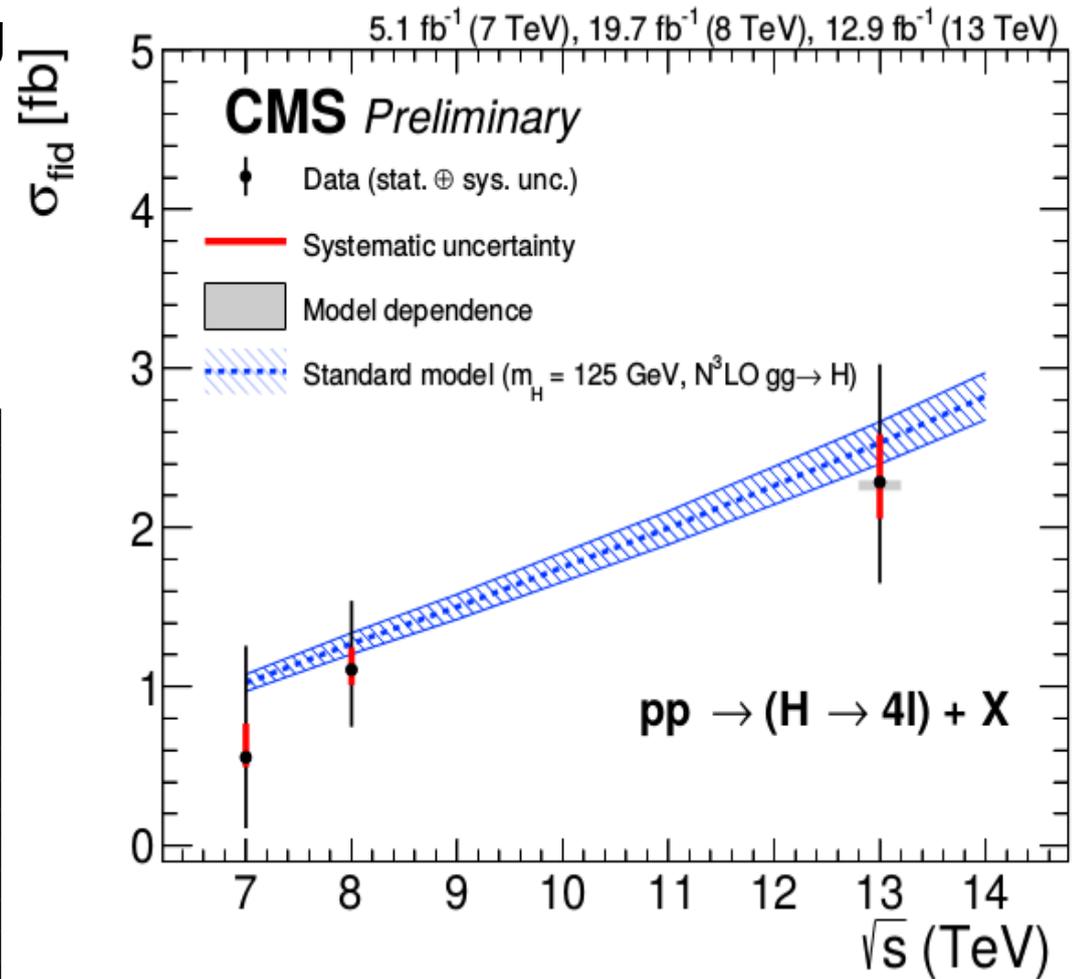
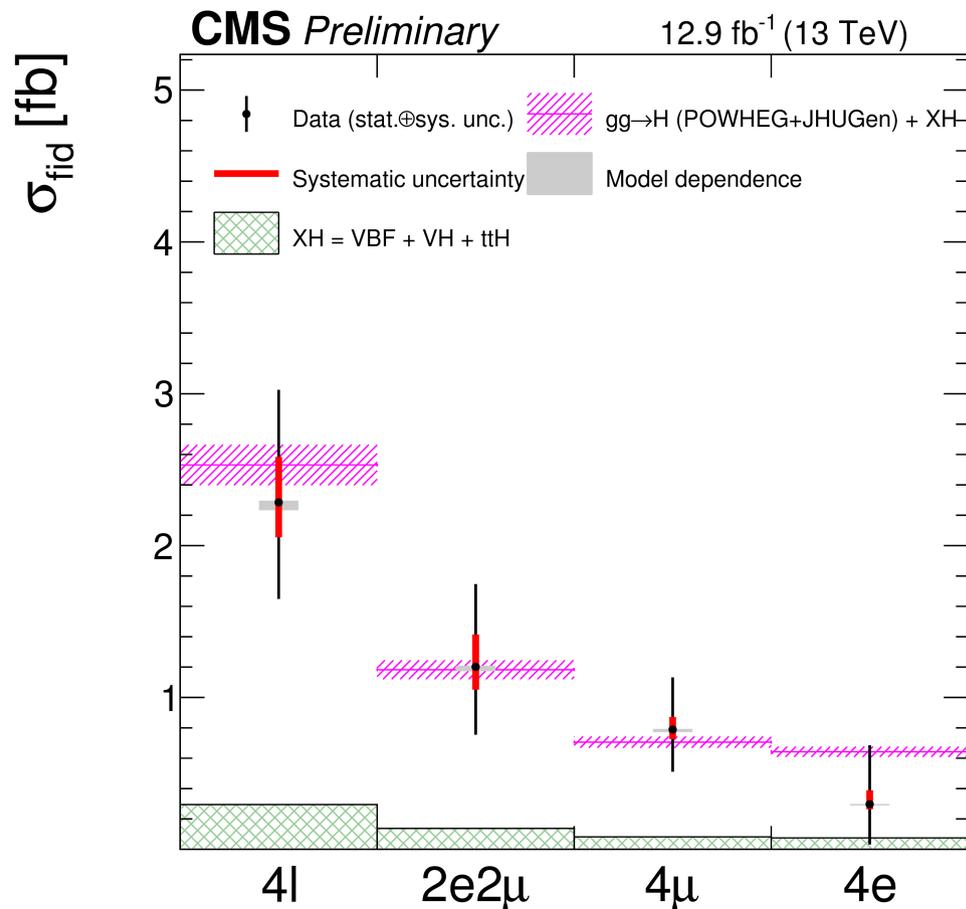
- Model dependence of the measurement procedure is estimated by repeating the measurement using the efficiencies and non-fiducial ratios from a range of different models of production
- We quote the full model dependence without any experimental constraints as a separate systematic effect

Signal process	\mathcal{A}_{fid}	ϵ	f_{nonfid}	$(1 + f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
gg→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



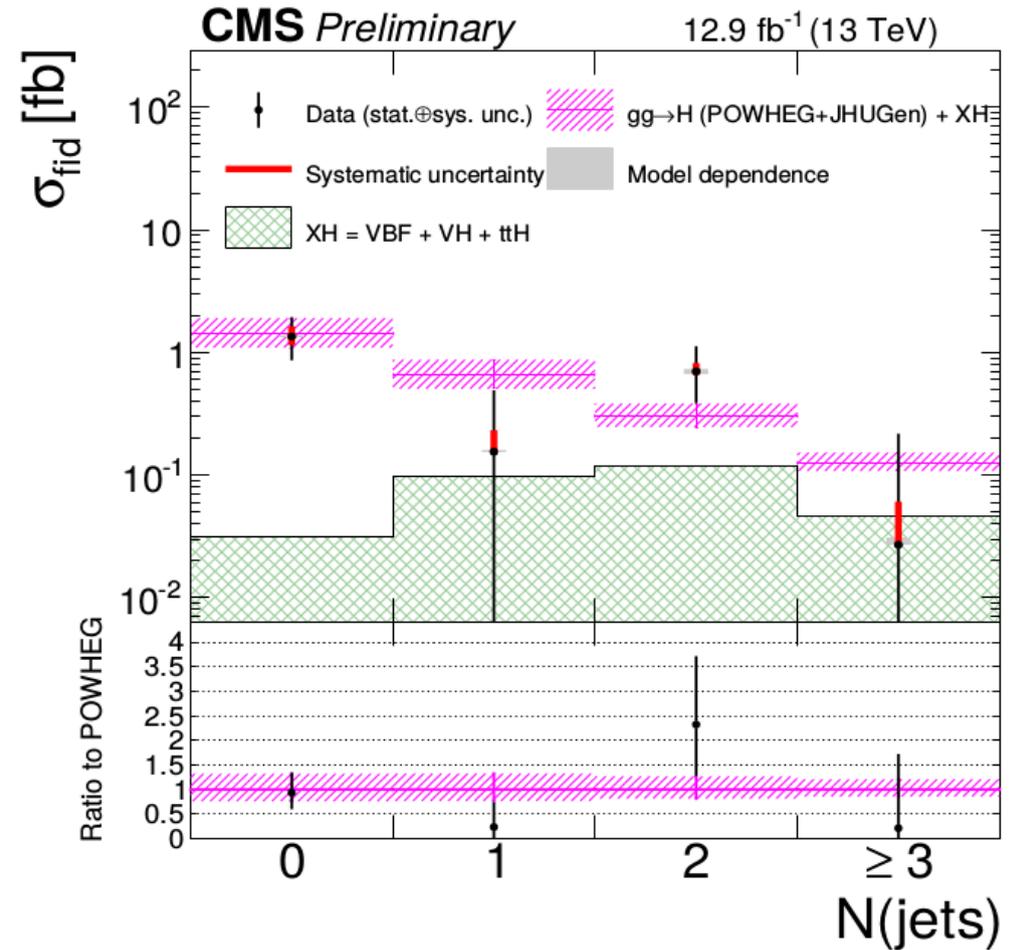
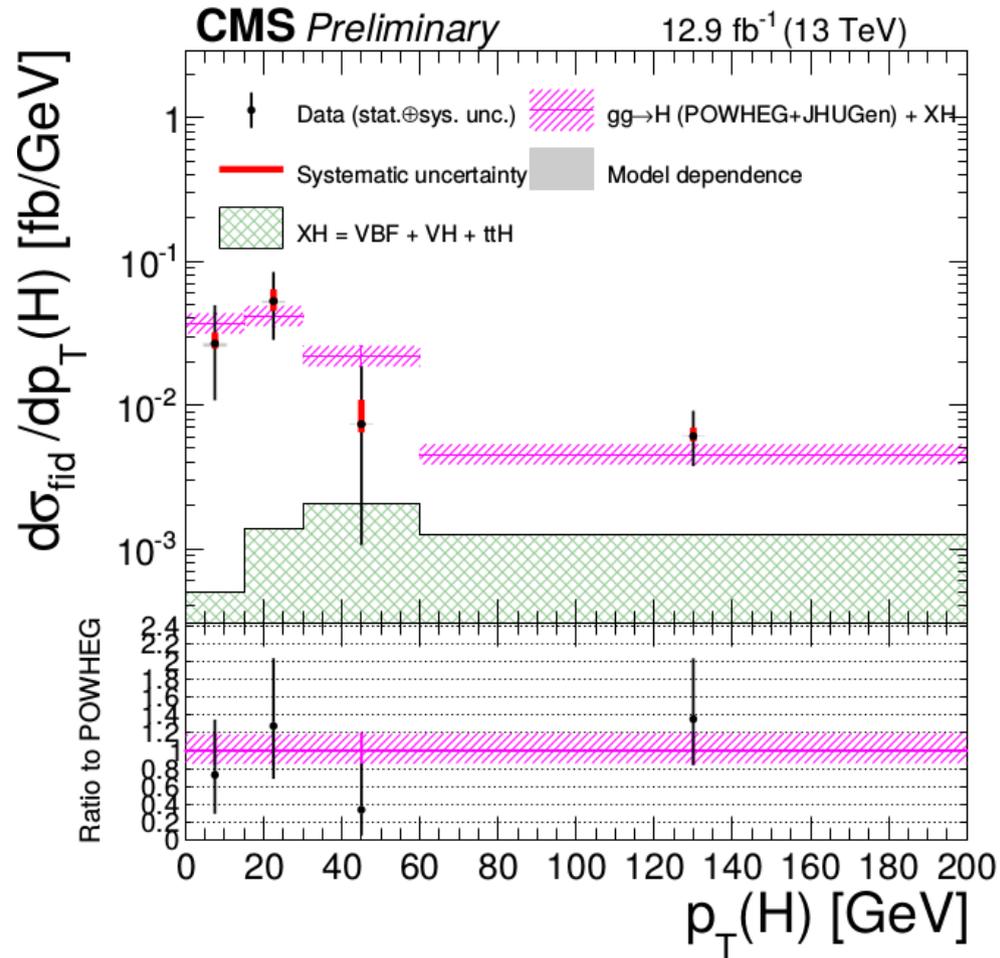
- The acceptance is calculated using Powheg at 13 TeV and HRes for 7,8 TeV
- All total cross sections taken from LHCHSWG



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

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

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



Measured complete set of Higgs boson properties using $H \rightarrow ZZ^* \rightarrow 4\ell$
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

$$\mu_{ggH}, \mu_{VBF}, \mu_{VH}, \text{ and } \mu_{ttH}$$

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

→ Differential measurements as function $p^T(H)$, $N(\text{Jets})$

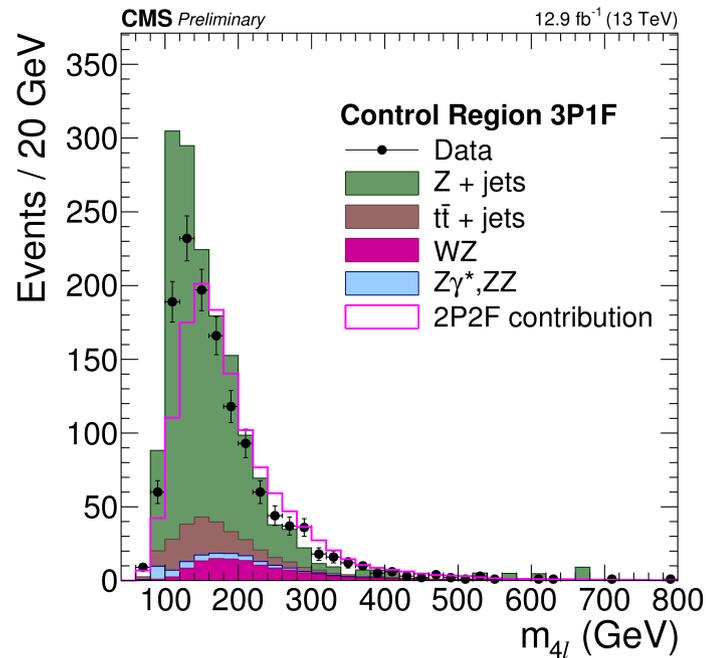
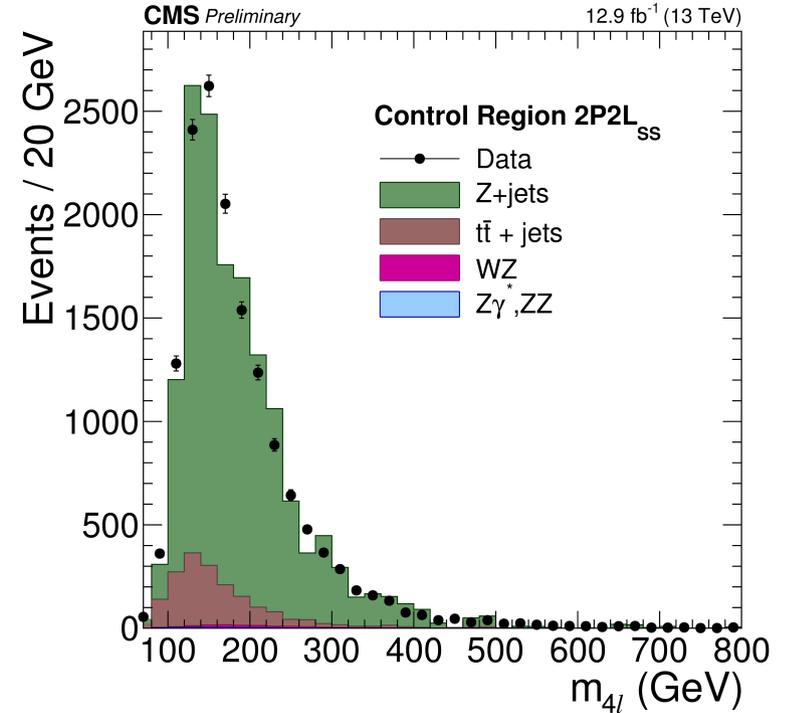
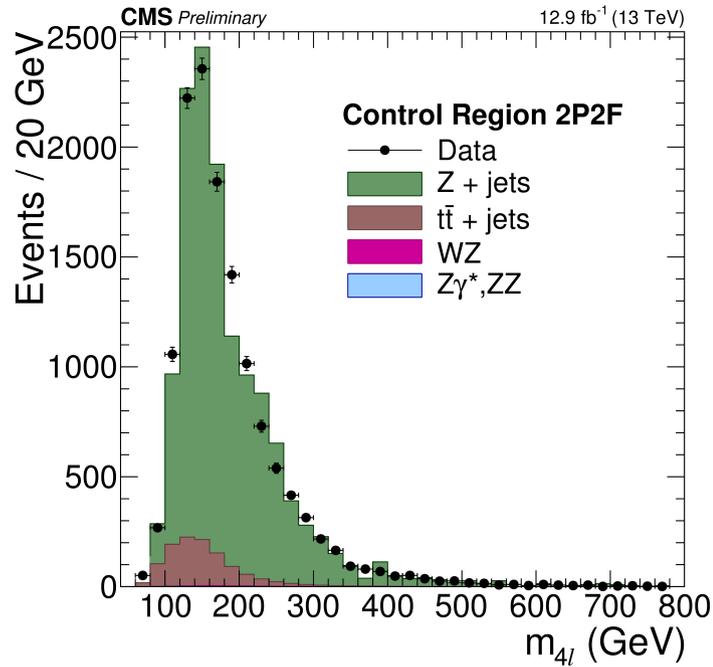
CMS has recorded data corresponds to $\sim 40 \text{ fb}^{-1}$ integrated luminosity in 2016 (X3 times by the results presented).

New results would be published soon (Moriond'17)

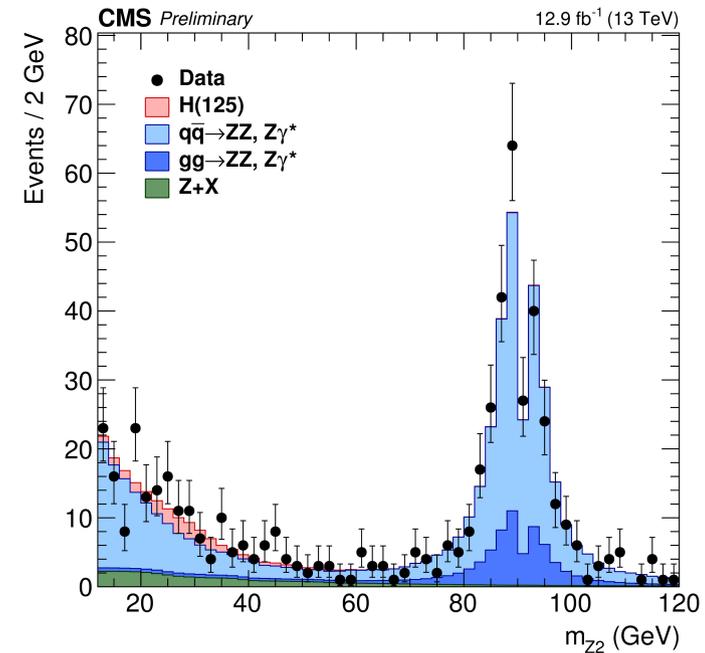
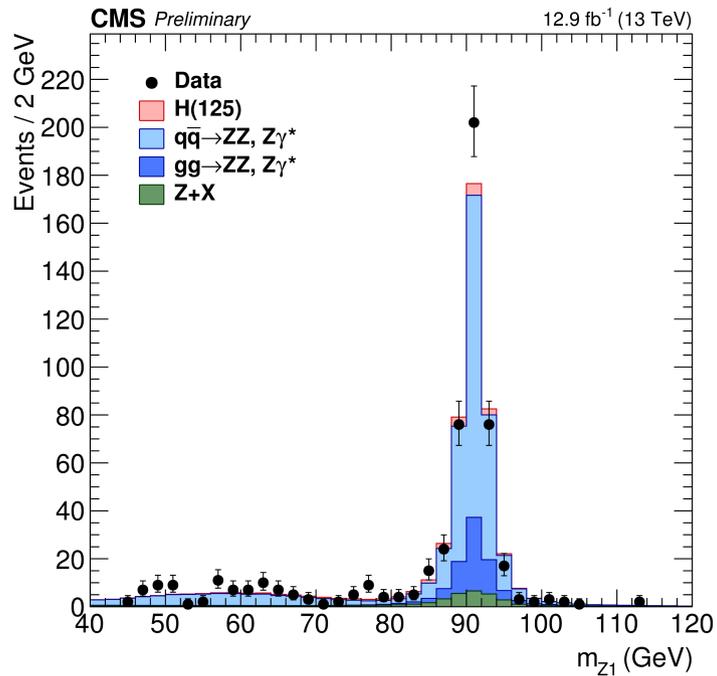
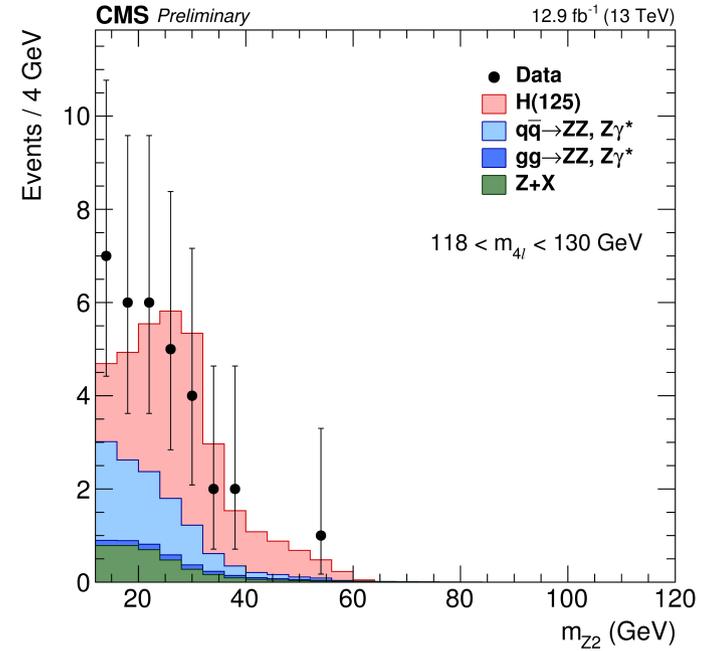
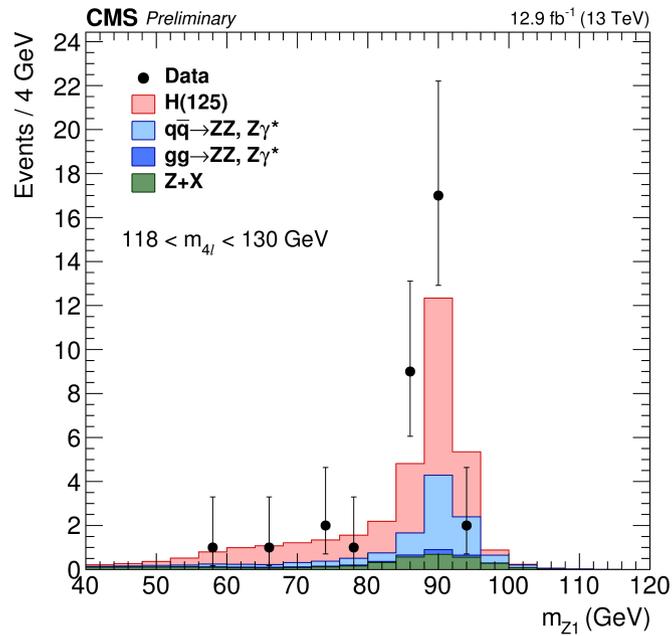


Backup

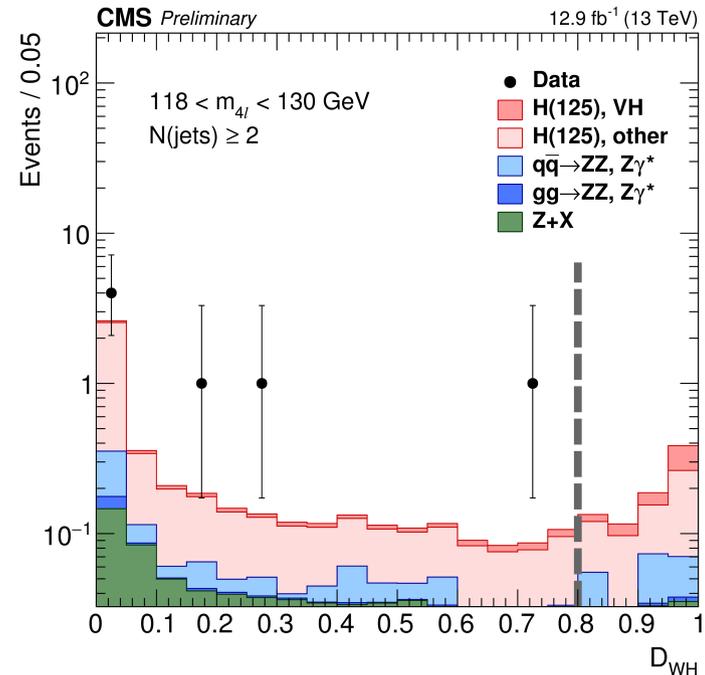
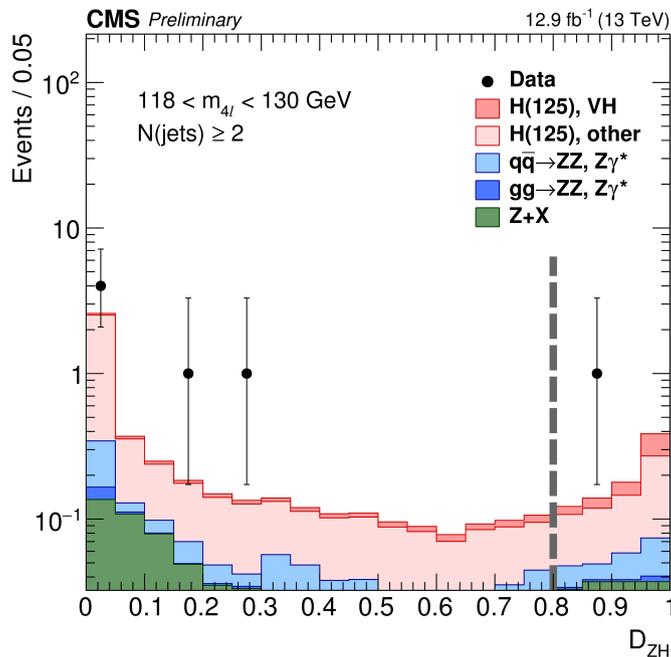
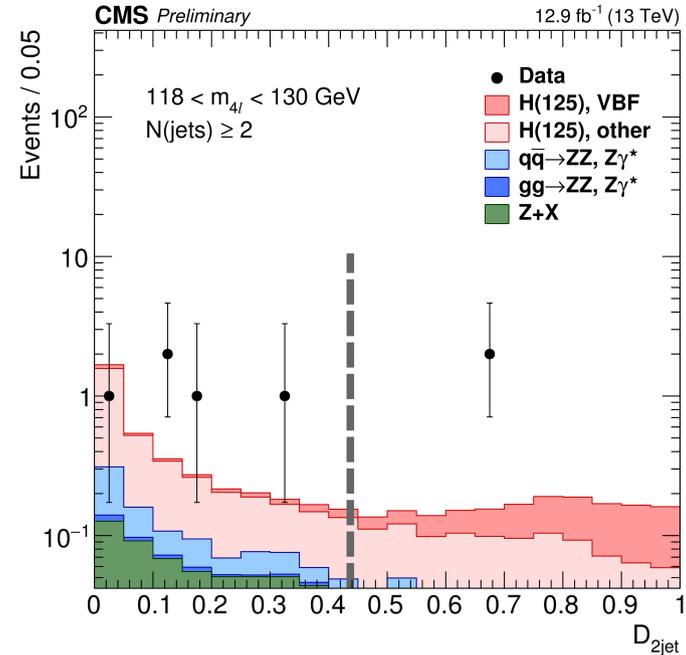
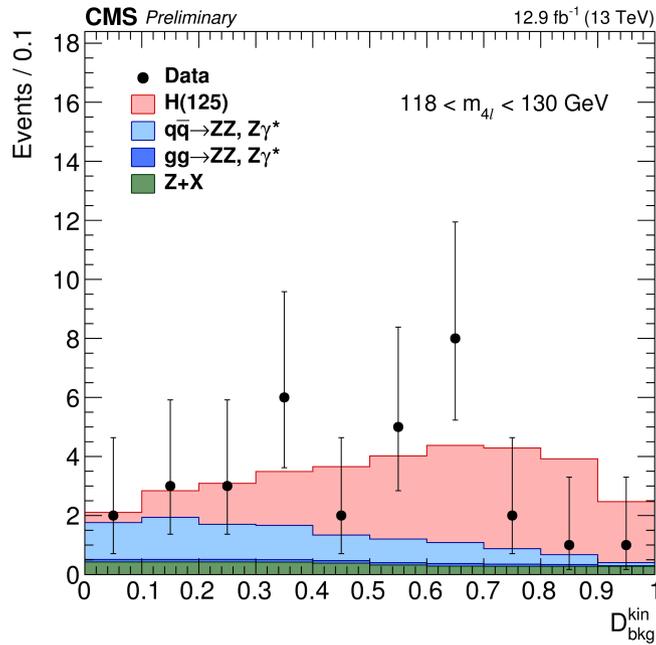
Control region for Z+X



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 \rightarrow 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
 \rightarrow 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
 \rightarrow VH-leptonic tagged category
 4. ≥ 4 jets + ≥ 1 b-tag;
or ≥ 5 leptons \rightarrow ttH tagged category
 5. exactly 4 leptons + exactly 1 jet + high D 1jet value
 \rightarrow VBF-1jet tagged category
 6. other events \rightarrow untagged category

