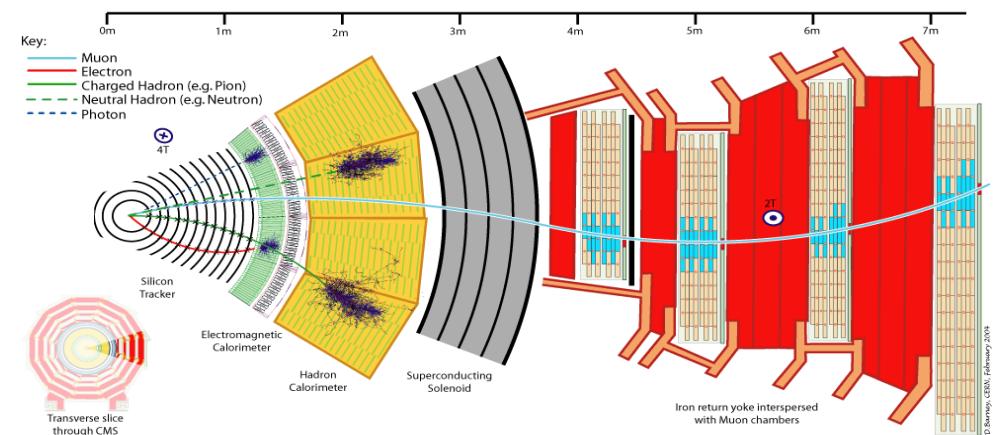
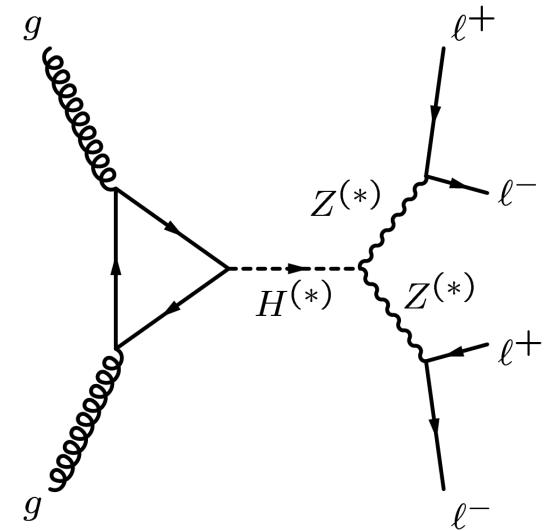


# The CMS results on $H \rightarrow ZZ \rightarrow 4l$ at 13 TeV

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Obergurgl (Austria)  
On the behalf of  
The CMS Collaboration

# Introduction

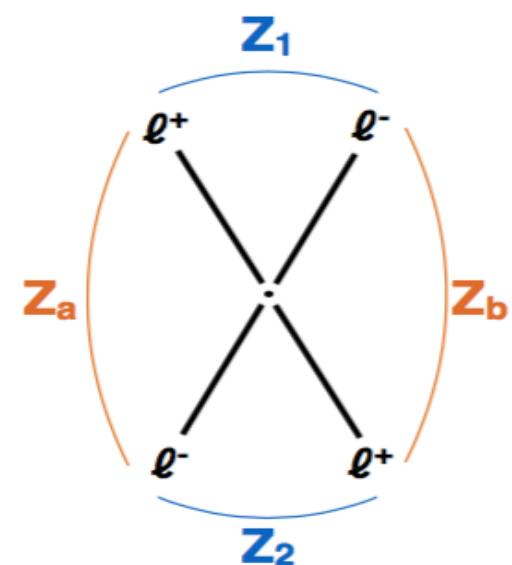
- The present analysis is done with 2015 data set ( $2.8 \text{ fb}^{-1}$ )
- 125 GeV Higgs boson and its properties e.g. :
  - Signal Strength
  - Fiducial cross section
- The global analysis strategy is similar to Run 1
- The Analysis steps are optimized for the new conditions at 13 TeV e.g. :
  - Trigger
  - Lepton Selection
  - FSR Recovery
  - ZZ Candidate Selection

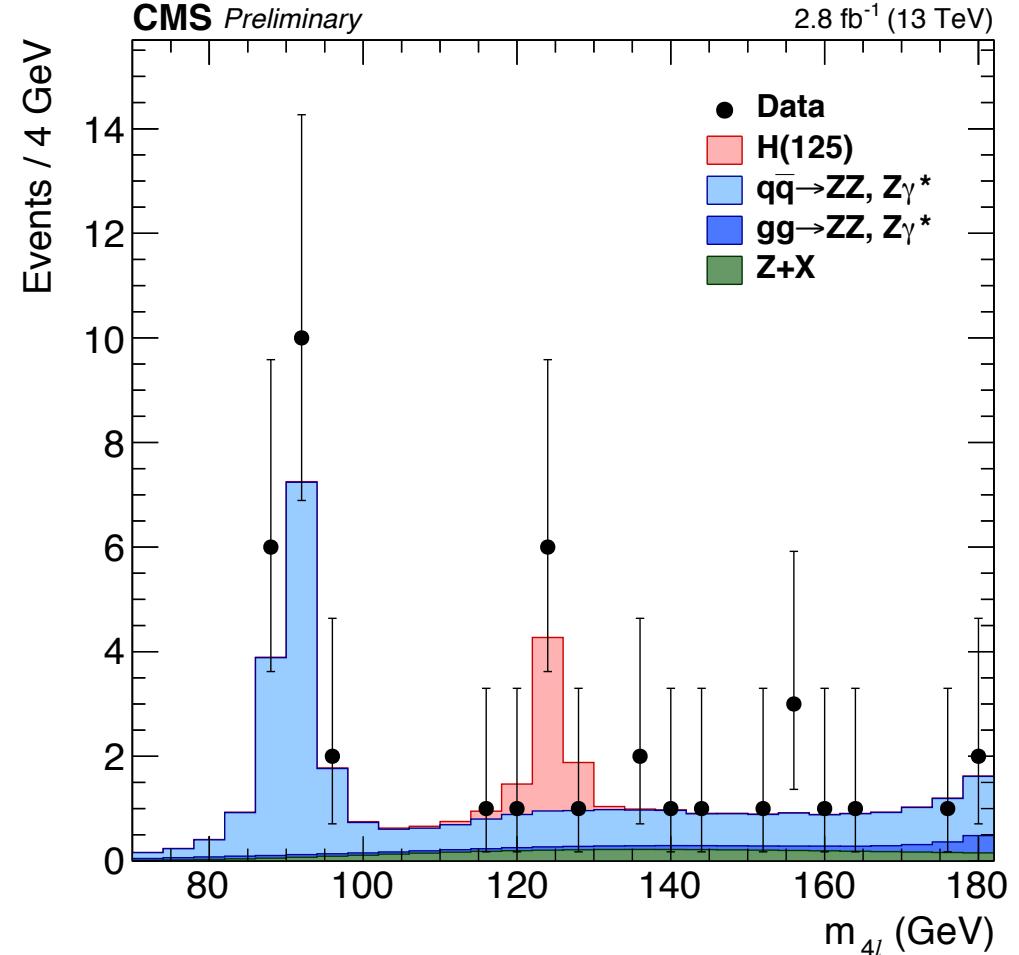
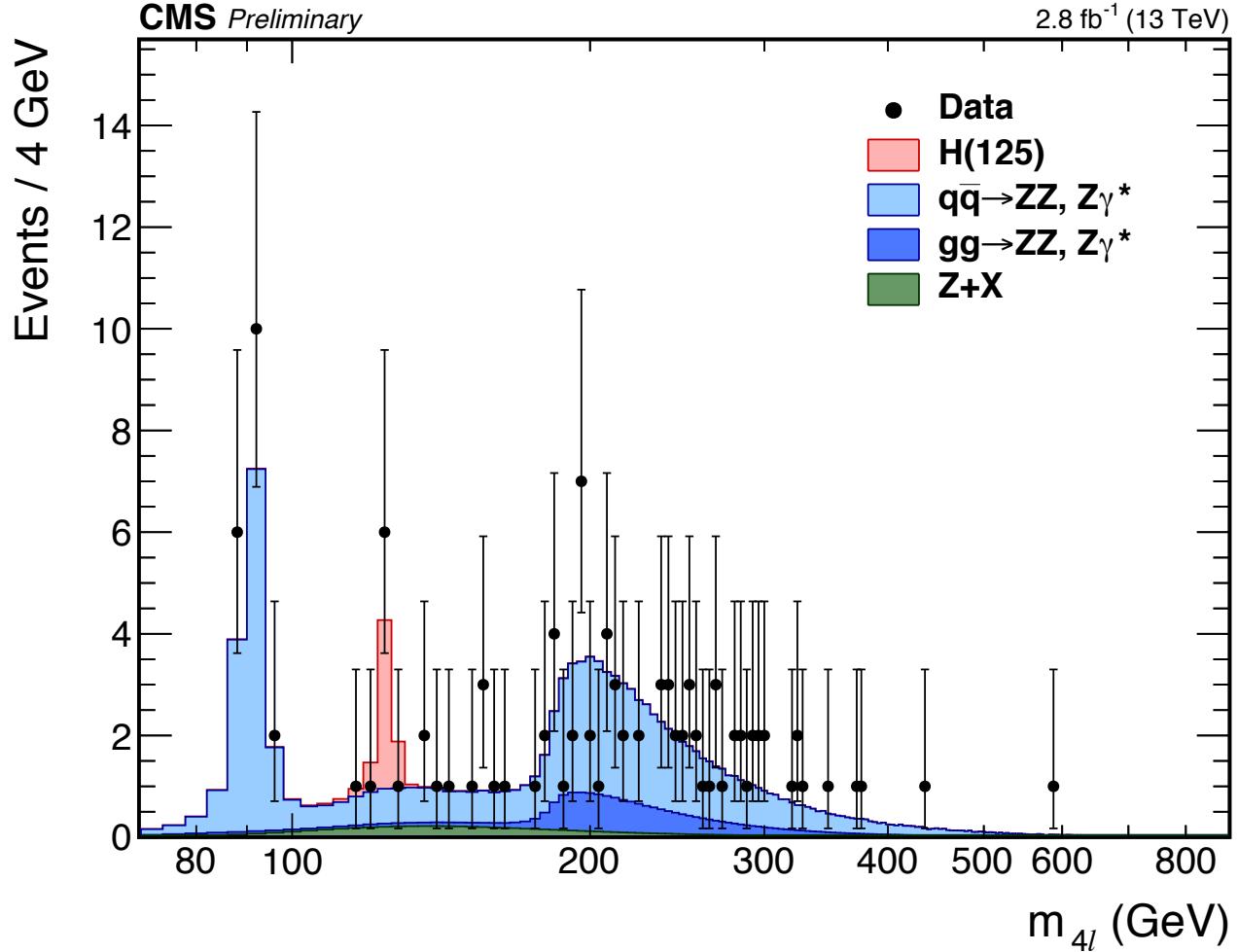


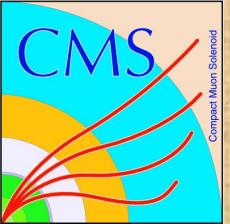
# Event Selection

- Z candidate (OSSF) pairs of selected leptons with  $12 < m_{ll} < 120$  GeV
- $Z_1$  close to PDG  $Z^0$  mass,  $m_{Z_1} > 40$  GeV,  $Z_2$  other one
- $\Delta R(l_i, l_j) > 0.02$  where  $i \neq j$
- $p_{T,1} > 20$  GeV,  $p_{T,2} > 10$  GeV
- $m_{4l} > 70$  GeV
- $m_{l^+l^-} > 4$  GeV Reject low-mass hadronic resonances.
- Reject candidates with alternating pairing  $Z_a Z_b$ :  

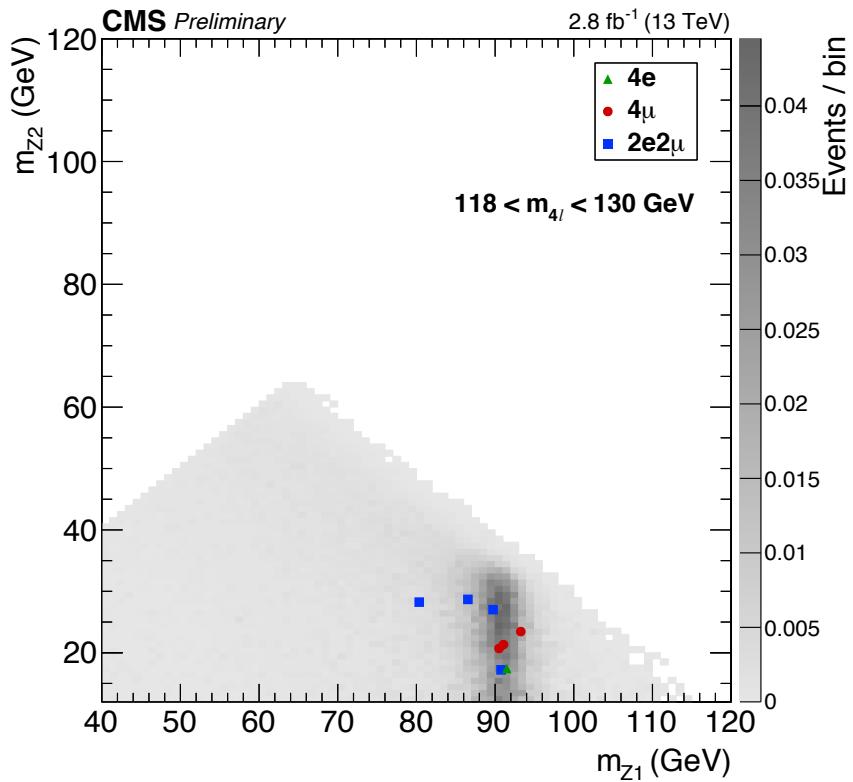
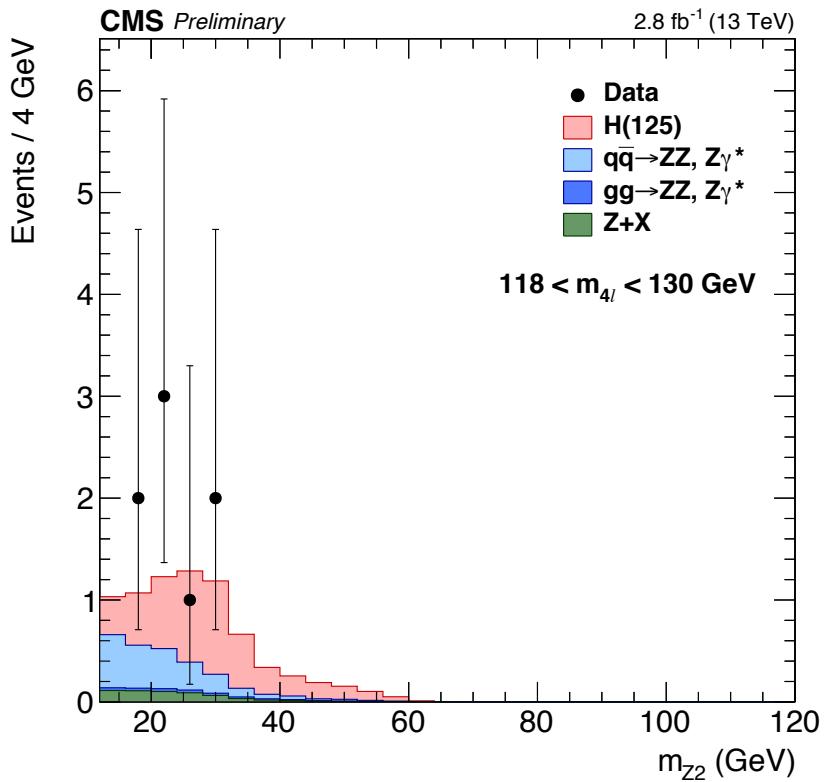
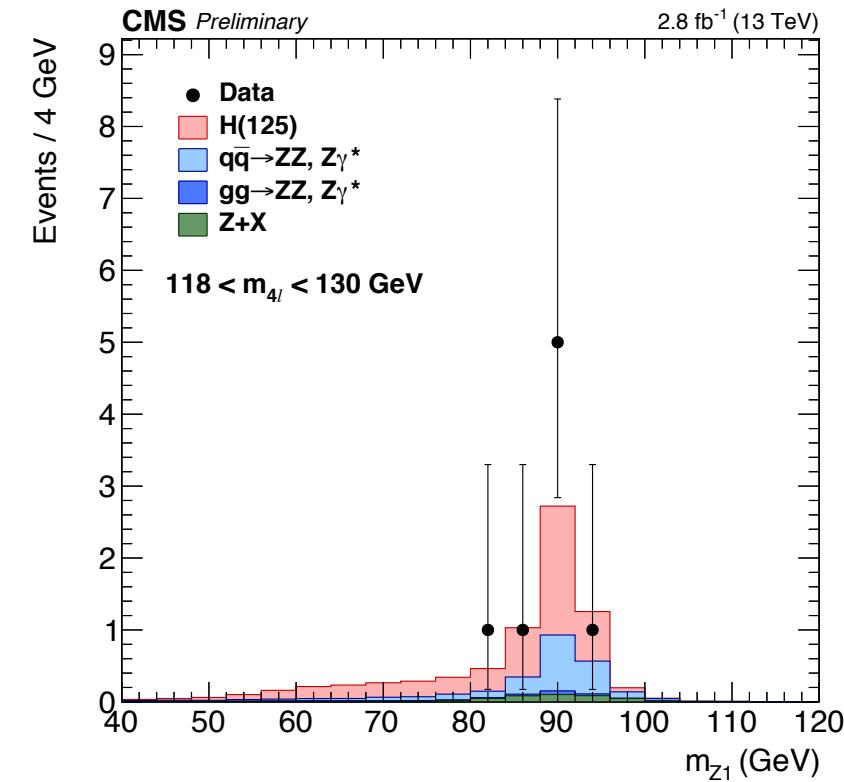
$$|m_{Z_a} - m_Z| < |m_{Z_1} - m_Z| \text{ and } m_{Z_b} < 12 \text{ GeV}$$
- If the number of ZZ Candidates  $> 1$ , select:
  - The one with  $Z_1$  mass close to PDG  $Z^0$
  - $Z_2$  with largest scalar sum of lepton  $p^T$







# Distribution of $m_{Z_1}$ , $m_{Z_2}$



# Matrix-Element Discriminants

- Two ME-based kinematic discriminant are defined:
- $D_{\text{bkg}}^{\text{kin}}$  separates  $\text{gg} \rightarrow H \rightarrow 4l$  from  $\text{ZZ} \rightarrow 4l$ :

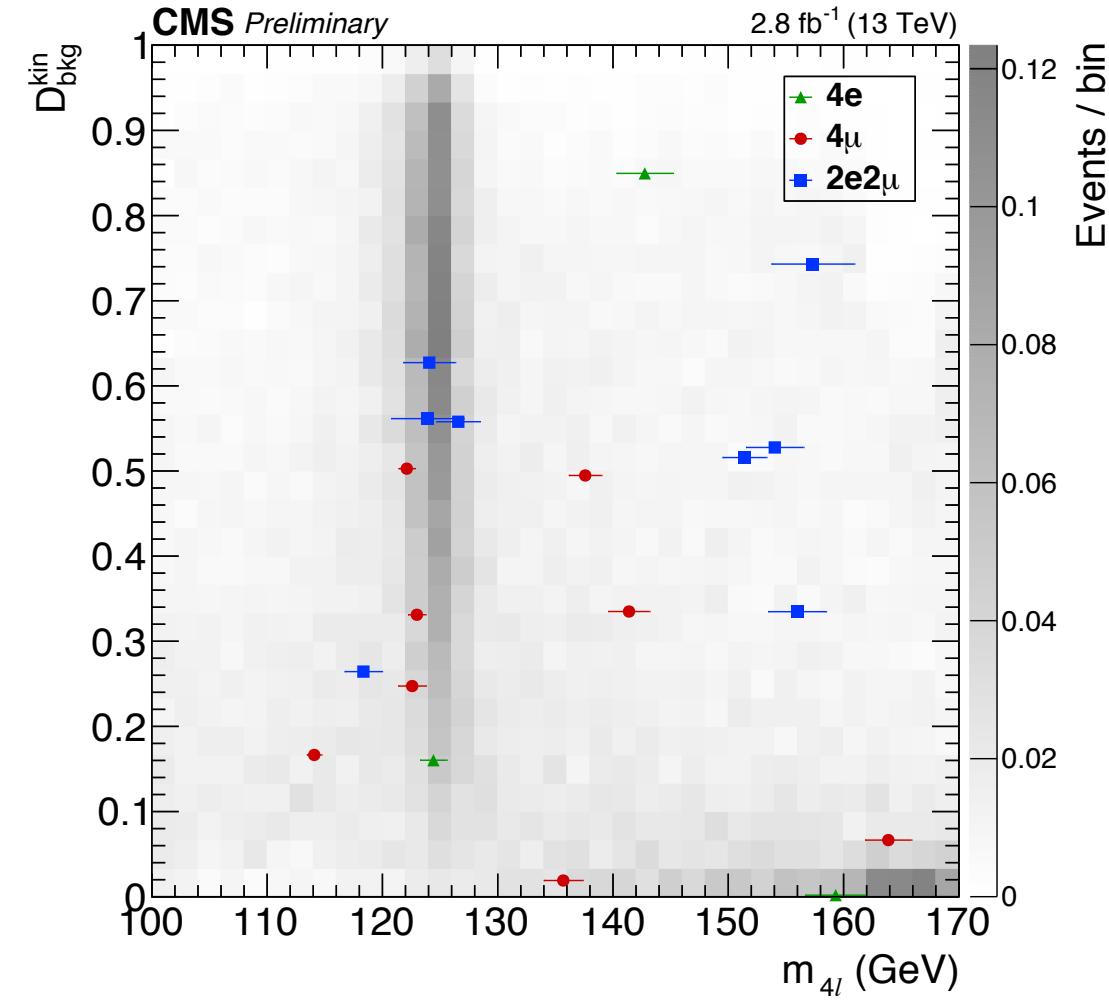
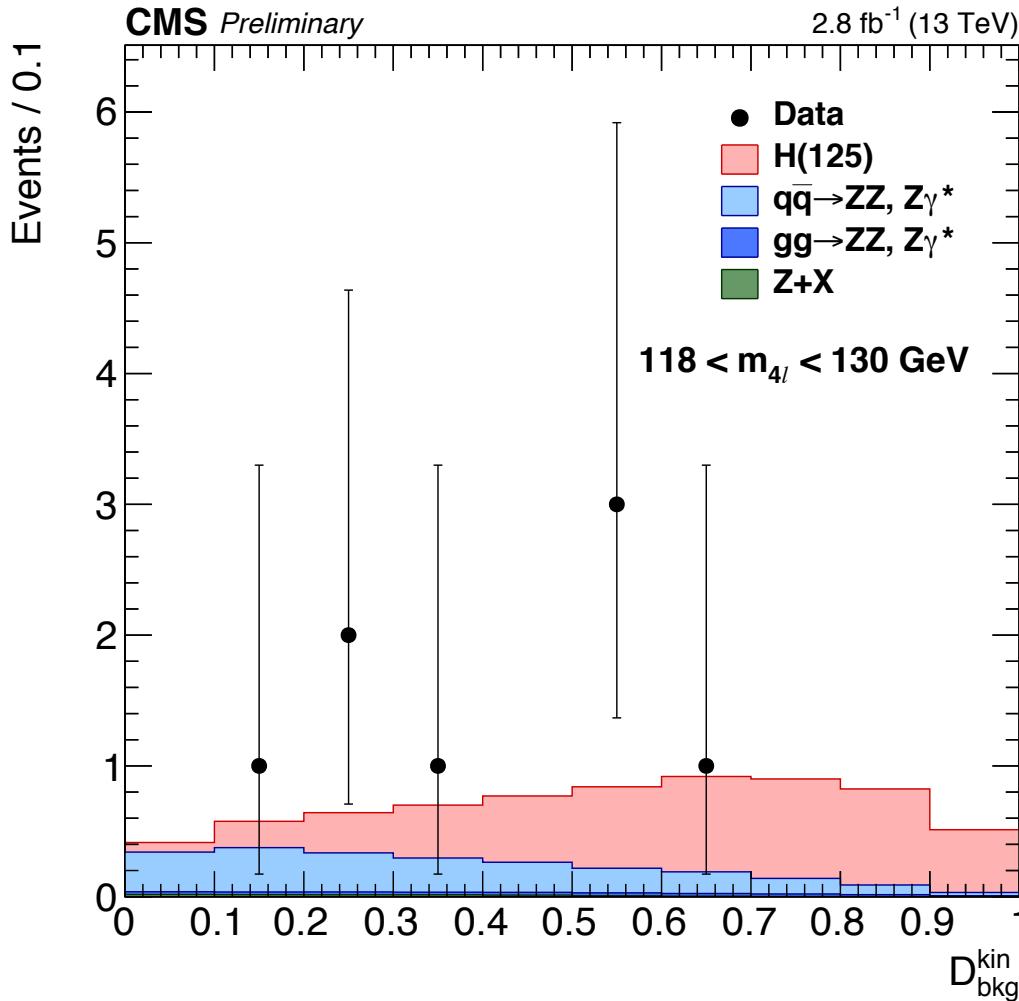
$$D_{\text{bkg}}^{\text{kin}} = \left[ 1 + \frac{\mathcal{P}_{\text{bkg}}^{\text{q}\bar{q}}(\vec{\Omega}^{H \rightarrow 4l} | m_{4l})}{\mathcal{P}_{\text{sig}}^{\text{gg}}(\vec{\Omega}^{H \rightarrow 4l} | m_{4l})} \right]^{-1}$$

- $D_{\text{jet}}$  separates VBF from both  $\text{gg}H \rightarrow H + 2\text{jets}$  and  $\text{gg}/q\bar{q} \rightarrow 4\ell + 2\text{jets}$  background.

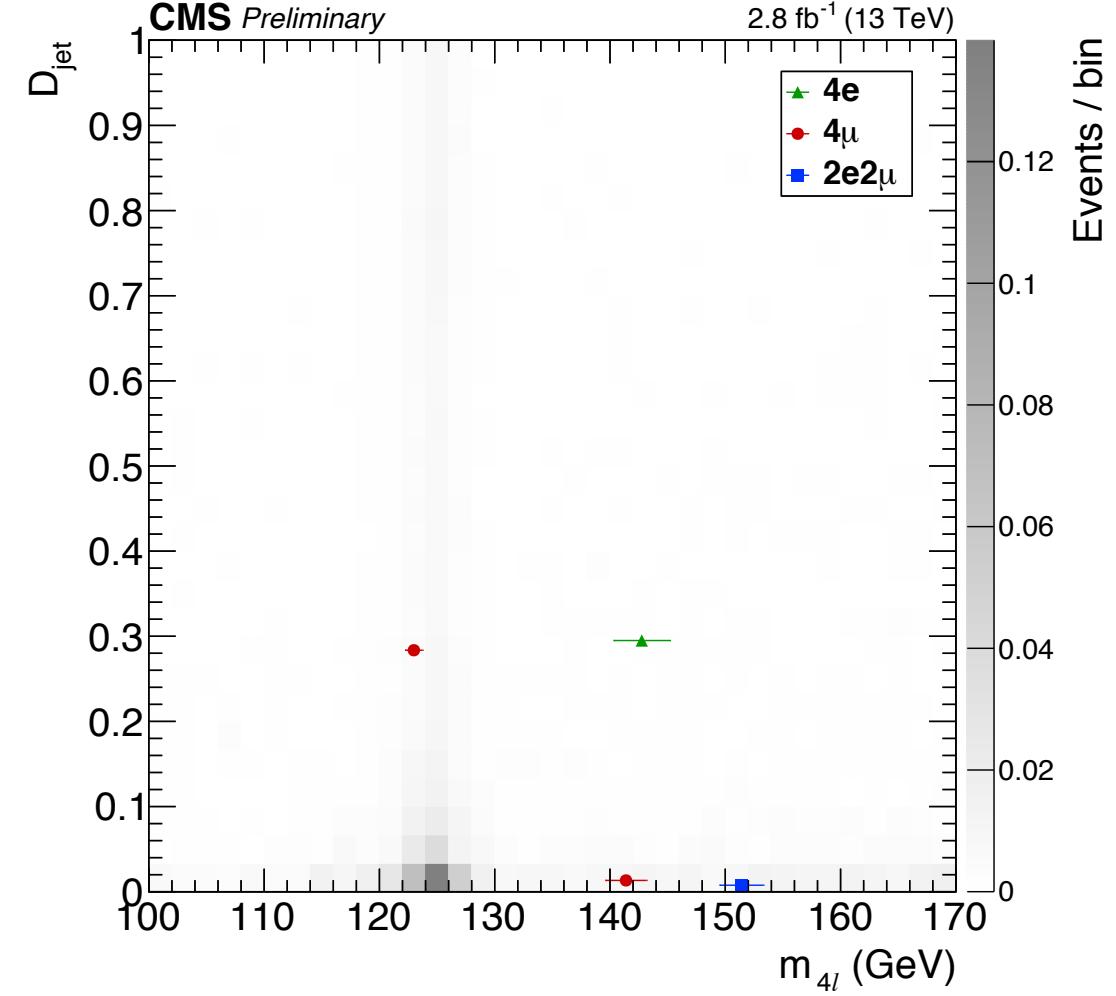
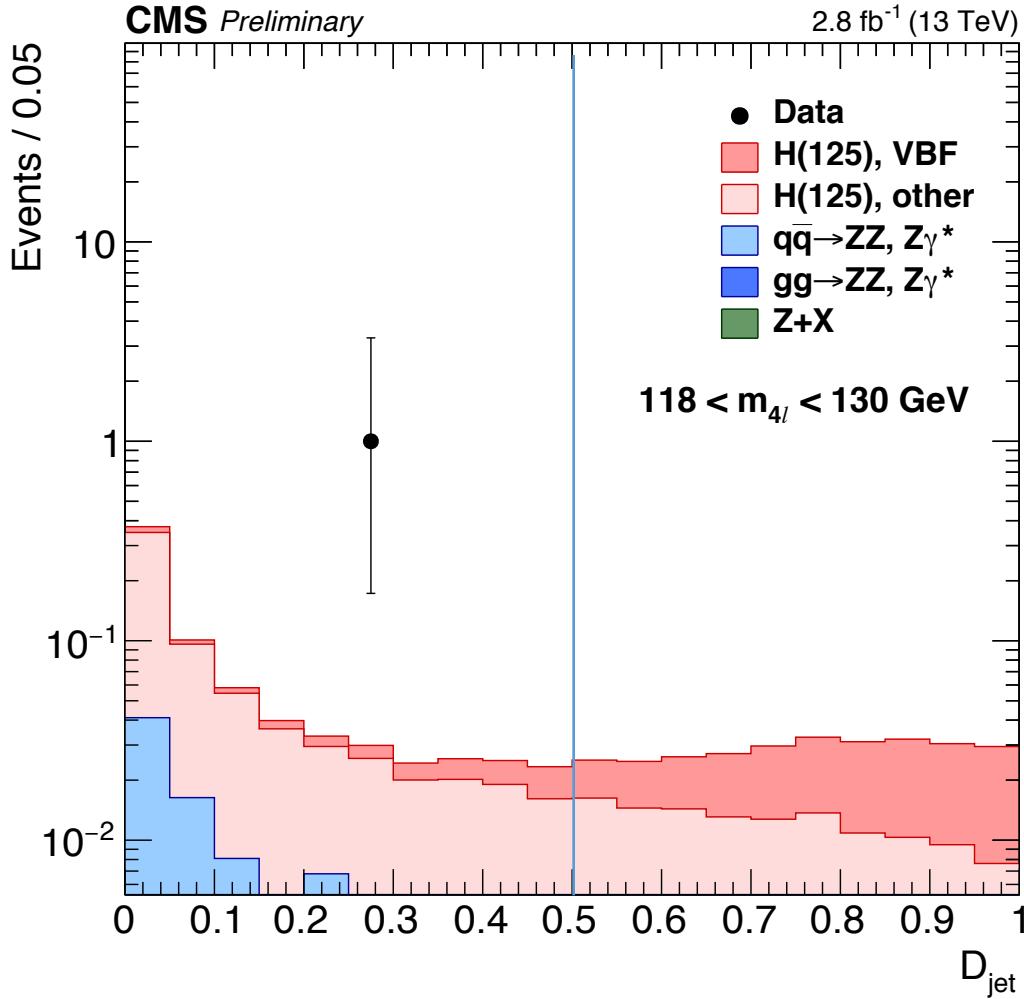
$$D_{\text{jet}} = \left[ 1 + \frac{\mathcal{P}_{\text{HJJ}}(\vec{\Omega}^{H \rightarrow \text{HJJ}} | m_{4l})}{\mathcal{P}_{\text{VBF}}(\vec{\Omega}^{H \rightarrow \text{HJJ}} | m_{4l})} \right]^{-1}$$

- Events are categorized in to two mutually exclusive categories:
  - **VBF-tagged Category:** At least 2 jets +  $D_{\text{jet}} > 0.5$
  - **Untagged category:** Remaining events

# Distribution of $D_{\text{bkg}}^{\text{kin}}$



# Distribution of $D_{\text{jet}}$

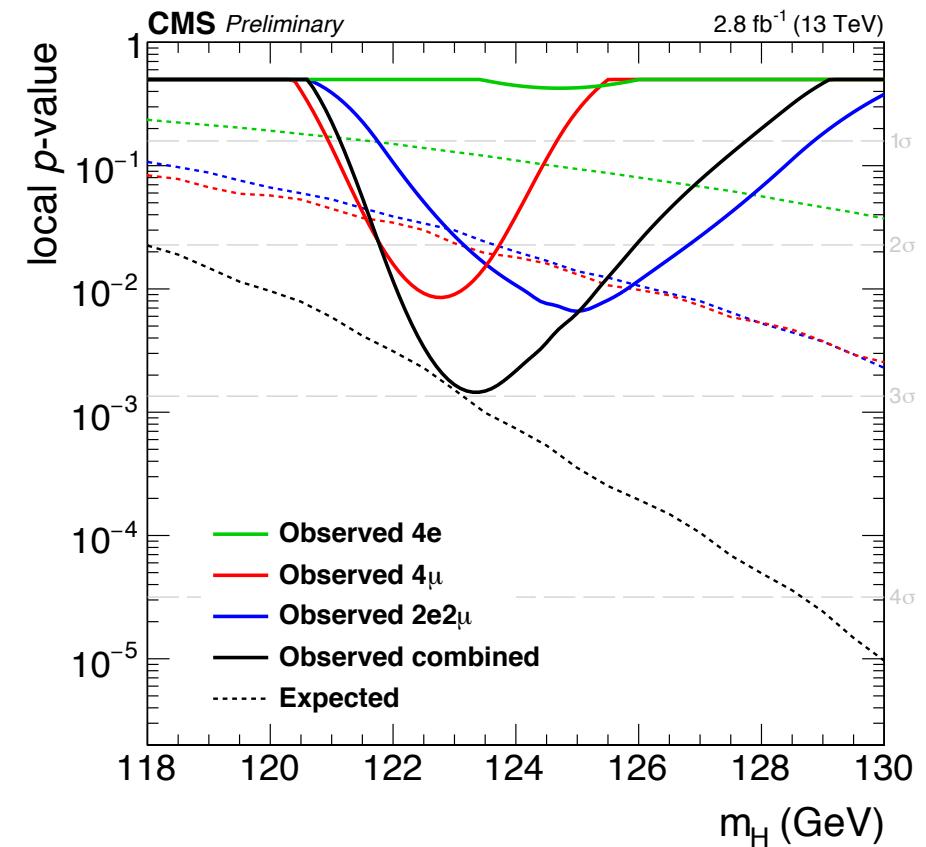


# Significance of excess

- A Two-Dimensional likelihood fit is done for the p-value and signal strength:

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

- Total six channels( 2 categories  $\times$  3 final states)
- minimum p-value reached at 123.4 GeV:
  - observed significance:  $3.0\sigma$
  - expected significance:  $3.1\sigma$
- at 125.09 GeV:
  - observed significance:  $2.5\sigma$
  - expected significance:  $3.4\sigma$





Compact Muon Solenoid

# Signal Strength



- The Signal Strength for  $m_H = 125.09$  GeV is  $\mu = \sigma/\sigma_{SM} = 0.82^{+0.57}_{-0.43}$  for the inclusive event sample.

Category	Signal Strength for a $m_H = 125.09$ GeV
Untagged	$0.89^{+0.62}_{-0.46}$
VBF-tagged	$0.0^{+1.7}_{-0.0}$

# Fiducial Cross Section (I)

## Requirements for the $H \rightarrow 4\ell$ fiducial phase space

### Lepton kinematics and isolation

Leading lepton $p_T$	$p_T > 20 \text{ GeV}$
Next-to-leading lepton $p_T$	$p_T > 10 \text{ GeV}$
Additional electrons (muons) $p_T$	$p_T > 7(5) \text{ GeV}$
Pseudorapidity of electrons (muons)	$ \eta  < 2.5(2.4)$
Sum of scalar $p_T$ of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 \cdot p_T$

### Event topology

Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the $Z_1$ candidate	$40 \text{ GeV} < m_{Z_1} < 120 \text{ GeV}$
Inv. mass of the $Z_2$ candidate	$12 \text{ GeV} < m_{Z_2} < 120 \text{ GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4 \text{ GeV}$
Inv. mass of the selected four leptons	$105 \text{ GeV} < m_{4\ell} < 140 \text{ GeV}$

# Fiducial Cross Section (II)

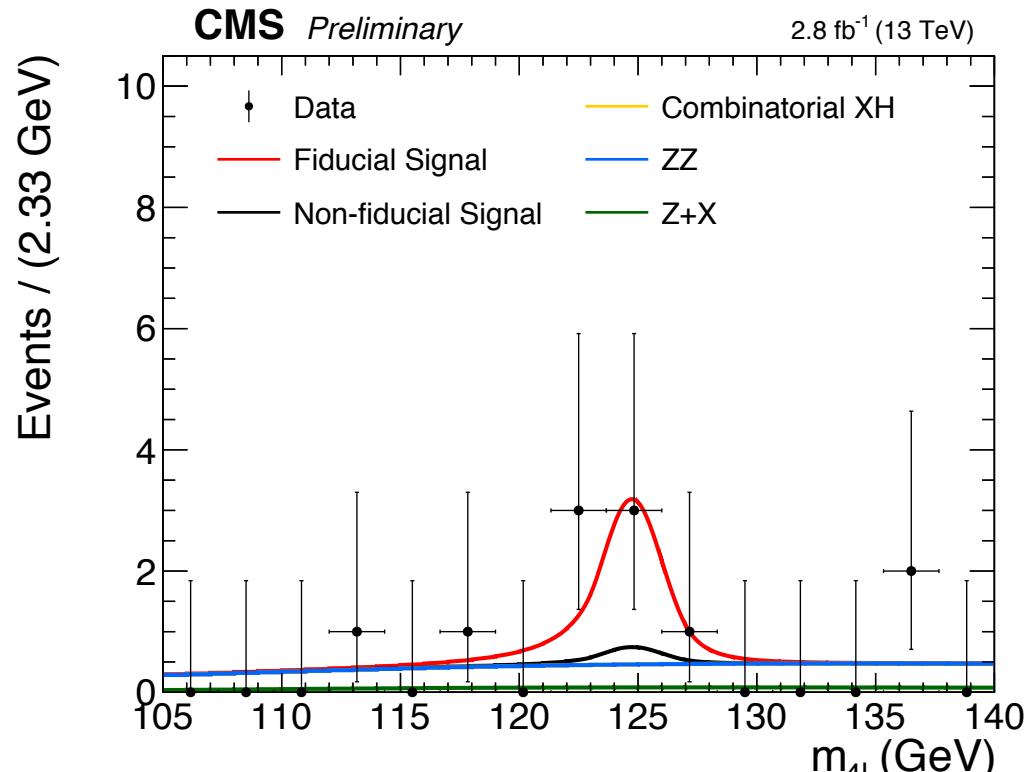
- Maximum likelihood fit, simultaneously in all final states, assuming  $mH = 125.0$  GeV

- The integrated fiducial cross section is measured to be:

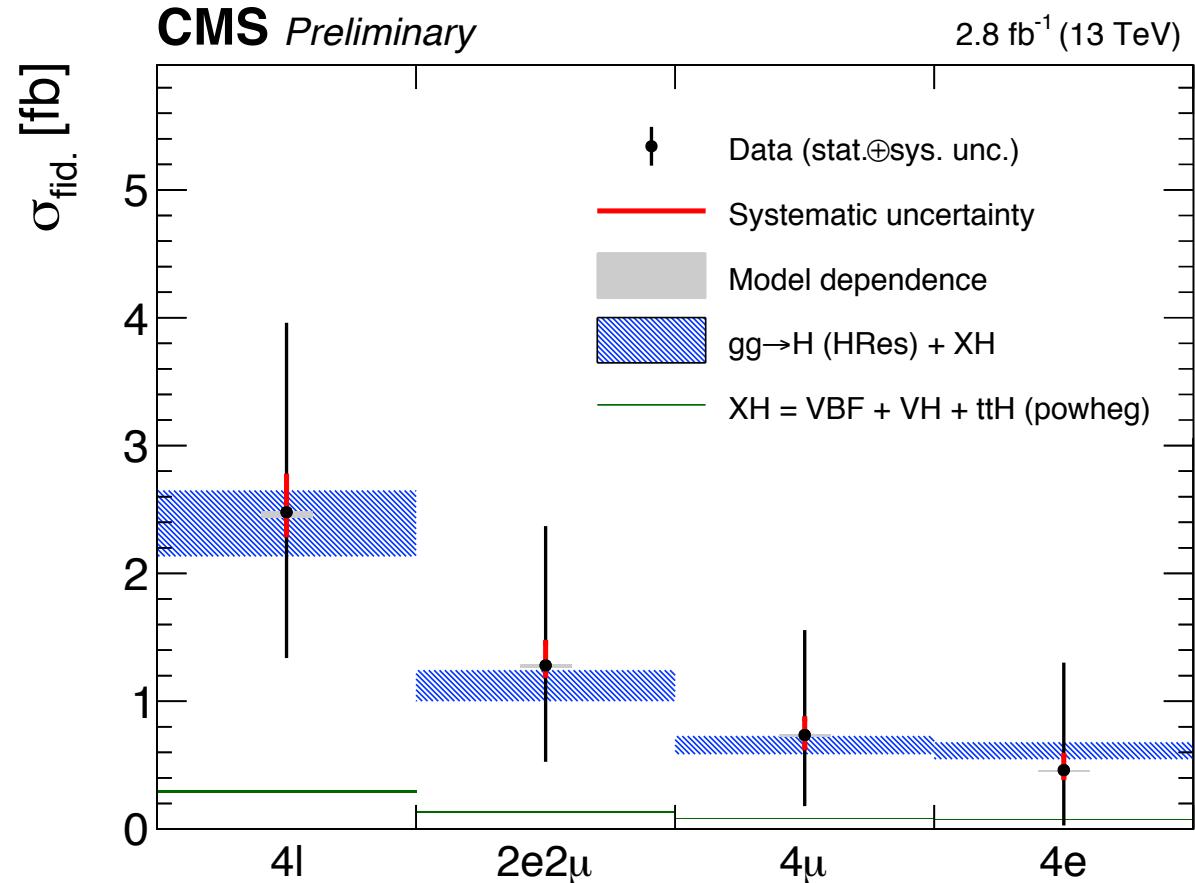
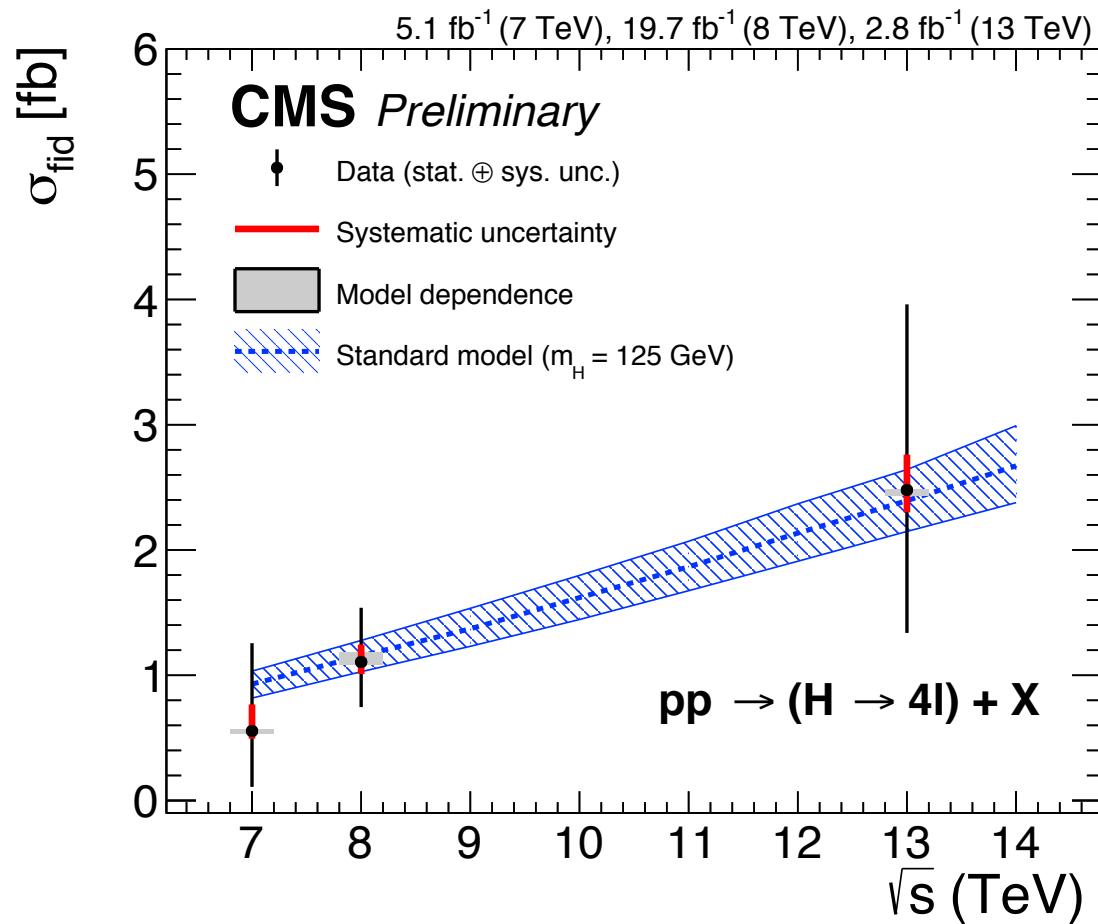
$$\sigma_{\text{fid.}} = 2.48^{+1.47}_{-1.13} (\text{stat.} \oplus \text{sys.})^{+0.01}_{-0.04} (\text{model dep.}) \text{ fb}$$

- The SM expectation:

$$\sigma_{\text{fid.}}^{\text{SM}} = 2.39 \pm 0.25 \text{ fb}$$



# Fiducial Cross Section (III)



# Conclusions

- A first study for the  $H \rightarrow ZZ \rightarrow 4\ell (e, \mu)$  is presented using  $2.8 \text{ fb}^{-1}$  data collected with CMS experiment in 2015.
- An excess consistent with the 125 GeV Higgs boson is seen, and several measurements are presented:
  - $2.5\sigma$  observed ( $3.4\sigma$  expected) significance at 125.09 GeV
  - at 125.09 GeV,  $\mu = 0.82^{+0.57}_{-0.43}$  (stat. $\oplus$  sys.)
  - Model independent fiducial cross section at 125.0 GeV:  
$$\sigma_{\text{fid.}} = 2.48^{+1.47}_{-1.13} (\text{stat.}\oplus\text{sys.})^{+0.01}_{-0.04} (\text{model dep.}) \text{ fb}$$
- All results are consistent within uncertainties, with the expectation for the SM Higgs boson.

THANKS



# Back-Up Slides

# Fiducial Cross Section

- Number of expected events:

$$\begin{aligned}
 N_{\text{obs}}^f(m_{4l}) &= N_{\text{fid}}^f(m_{4l}) + N_{\text{nonfid}}^f(m_{4l}) + N_{\text{comb}}^f(m_{4l}) + N_{\text{bkg}}^f(m_{4l}) \\
 &= \epsilon^f \cdot (1 + f_{\text{nonfid}}^f) \cdot \sigma_{\text{fid}}^f \cdot \mathcal{L} \cdot \mathcal{P}_{\text{res}}(m_{4l}) + N_{\text{comb}}^f \cdot \mathcal{P}_{\text{comb}}(m_{4l}) + N_{\text{bkg}}^f \cdot \mathcal{P}_{\text{bkg}}(m_{4l})
 \end{aligned}$$

- $\mathcal{P}_{\text{res}}(m_{4l})$  = Shape of resonant signal Contribution
- $\mathcal{P}_{\text{comb}}(m_{4l})$  = Shape of non resonant signal Contribution
- $\epsilon^f$  = Efficiency of an event in the fiducial volume to pass the selection.
- $f_{\text{nonfid}}^f$  = fraction of the non fiducial signal component

- Model dependence: (= variation of  $(1 + f_{\text{nonfid}}^f)\epsilon$ ) when the relative fraction of every production mode is varied within experimental constraints) increases wrt. Run I due to the change in reco-level isolation  
**→** also quote the results in an updated fiducial volume.

Signal process	$\mathcal{A}_{\text{fid}}$	$\epsilon$	$f_{\text{nonfid}}$	$(1 + f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
gg $\rightarrow$ H	$0.382 \pm 0.001$	$0.697 \pm 0.001$	$0.118 \pm 0.001$	$0.779 \pm 0.001$
VBF	$0.422 \pm 0.001$	$0.707 \pm 0.001$	$0.086 \pm 0.001$	$0.768 \pm 0.002$
WH	$0.277 \pm 0.001$	$0.686 \pm 0.002$	$0.164 \pm 0.002$	$0.799 \pm 0.003$
ZH	$0.302 \pm 0.002$	$0.697 \pm 0.003$	$0.172 \pm 0.003$	$0.817 \pm 0.004$
t $\bar{t}$ H	$0.239 \pm 0.001$	$0.687 \pm 0.003$	$0.419 \pm 0.007$	$0.975 \pm 0.006$