# MEASUREMENTS OF HIGGS BOSON PRODUCTION AND PROPERTIES IN THE ZZ DECAY CHANNEL USING THE CMS DETECTOR

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*on behalf of the CMS Collaboration*

39th **I**nternational **C**onference on **H**igh **E**nergy **P**hysics

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# OVERVIEW

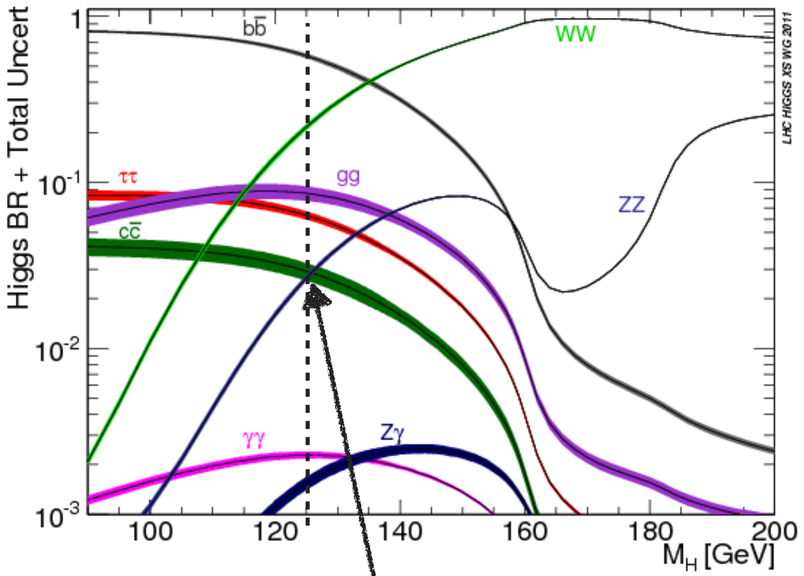


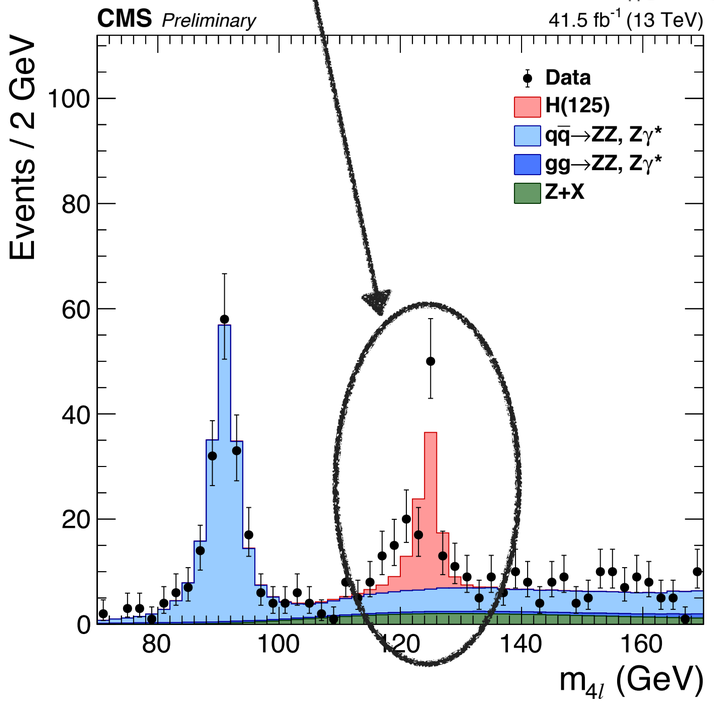
- The **H→ZZ→4l** (l=e,μ) channel:
  - Large S/B ratio, excellent resolution, complete reconstruction of the final state
  - "Golden channel" for discovery and properties measurements

- In this talk new results from **CMS-PAS-HIG-18-001**
  - Results with **41.5/fb** collected in **2017**
  - **Combination** with published analysis **JHEP 11 (2017) 047** of 35.9/fb collected in 2016


New with respect to 2016 analysis:

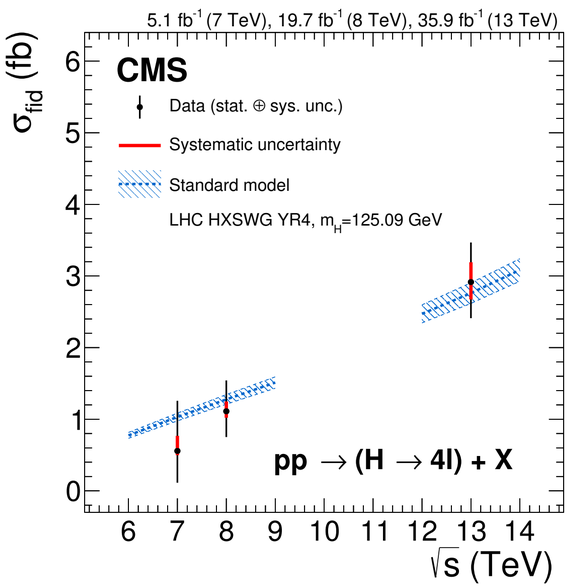
- Improved BDT electron ID
- New ttH categories
- New discriminants targeting VBF and VH production modes

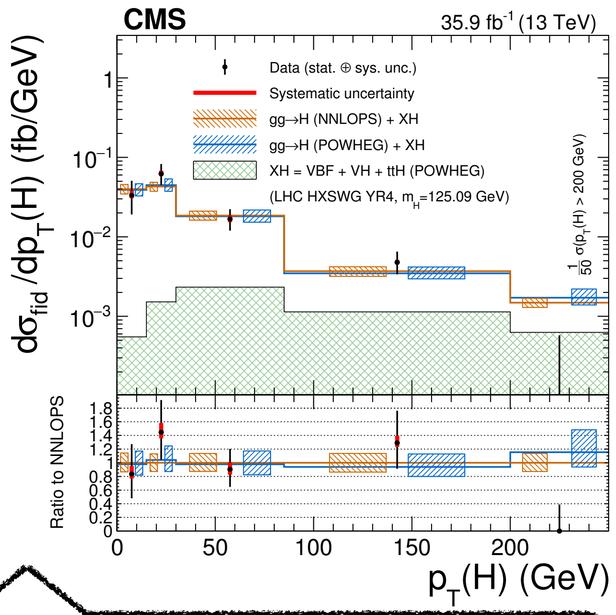


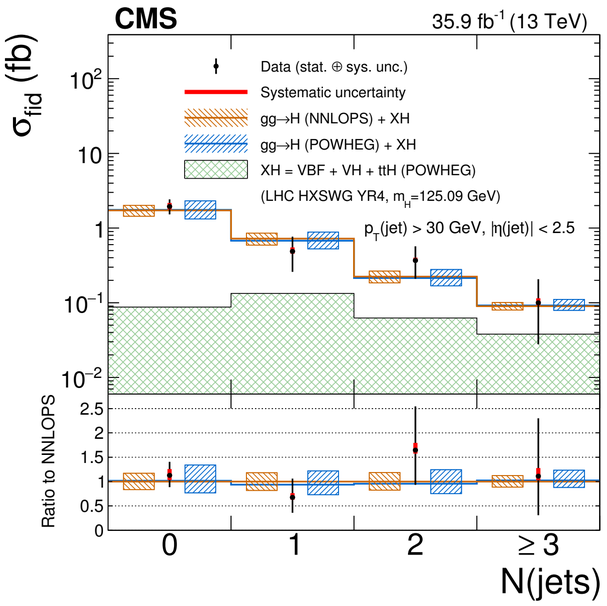



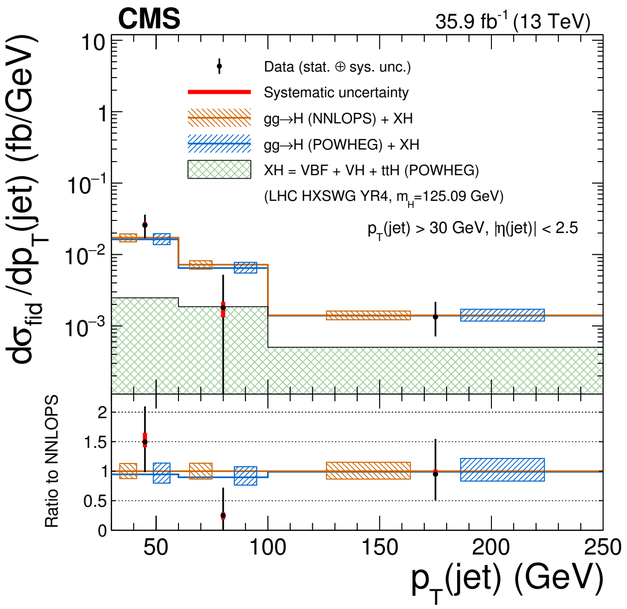
# RESULTS WITH 2016 DATA





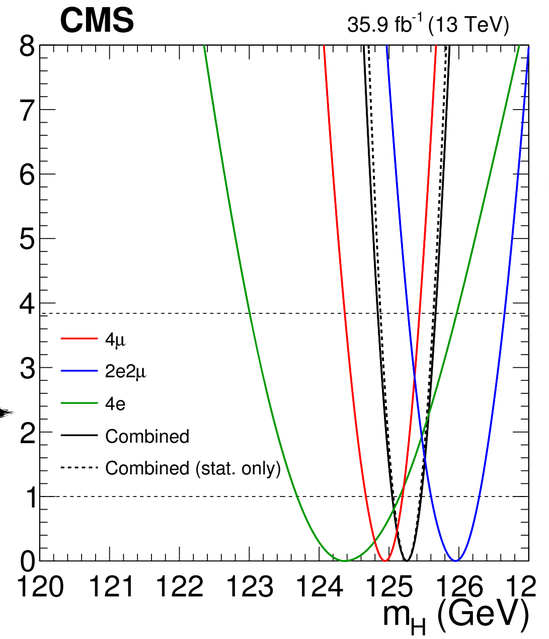



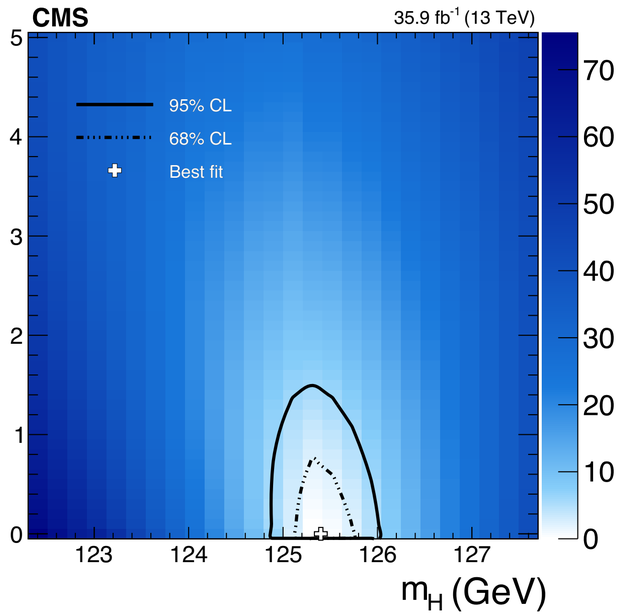

$$\sigma_{fid} = 2.92^{+0.48}_{-0.44}(stat)^{+0.28}_{-0.24}(syst)fb$$

More on differential cross section measurements in talk by Vittorio today at 10:00




$$m_H = 125.26 \pm 0.20(stat) \pm 0.08(syst)GeV$$
$$\Gamma_H < 1.10GeV \; at \; 95\,\%\, C.L.$$

More on mass and width measurements in talk by Nicholas tomorrow at 15:00

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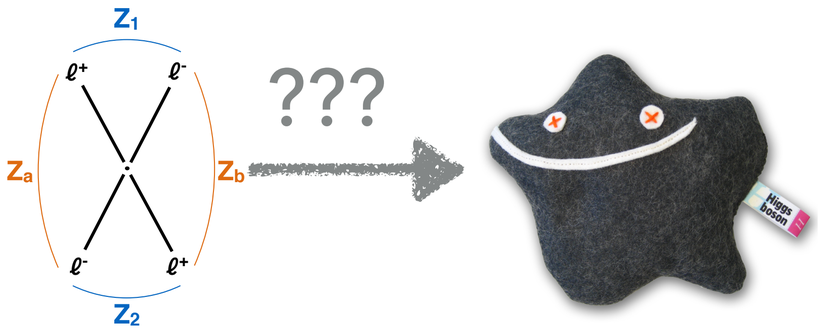
# ANALYSIS STRATEGY



- Analysis strongly depends on (efficiency)$^4$ of selecting leptons:
  - electrons (muons) reconstructed down to 7 (5) GeV
  - new electron identification BDT now includes electron isolation variables and is retrained for the upgraded pixel detector leading to strongly reduced misidentification of electrons NEW & IMPROVED
  - time-dependent lepton momentum calibrations
  - thorough corrections for efficiencies in data measured by Tag&Probe

- ZZ candidates built from selected leptons




- Background and signal modelling:
  - Irreducible: qq→ZZ and gg→ZZ from simulation with additional QCD and EW k-factors as a function of $m_{4l}$
  - Reducible: Z+X estimated from data in control regions using 2 independent methods
  - Signal: ggH, VBF, WH, ZH, ttH, bbH, tqH production modes considered from simulation NEW & IMPROVED

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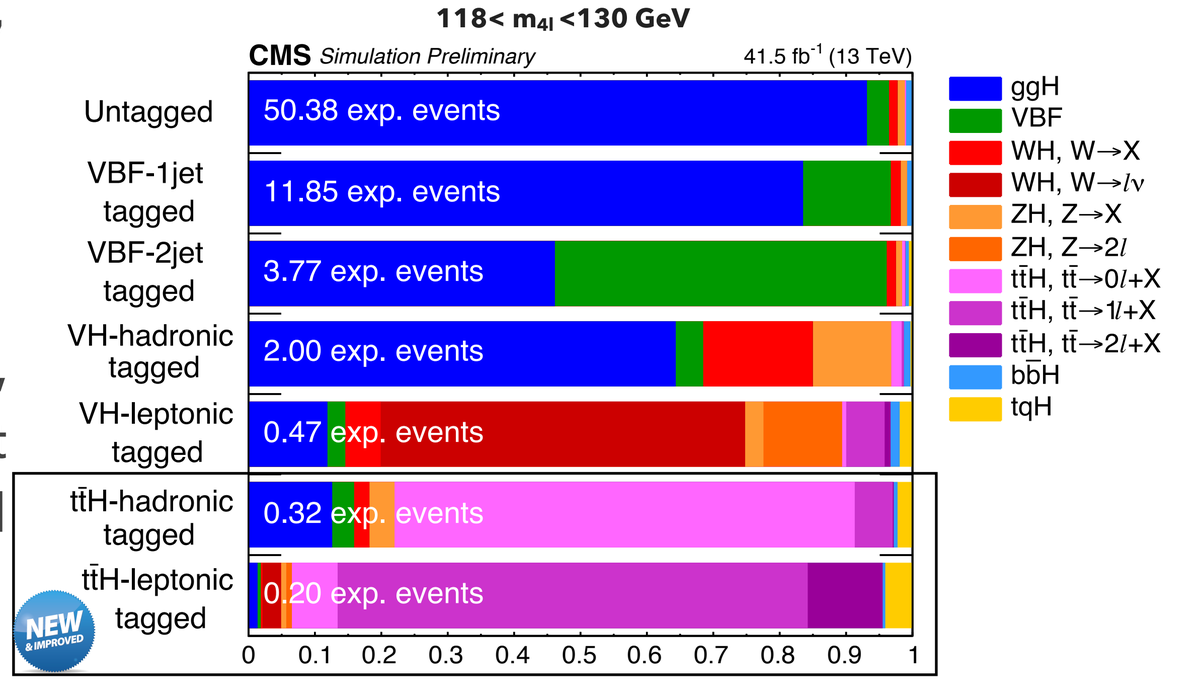
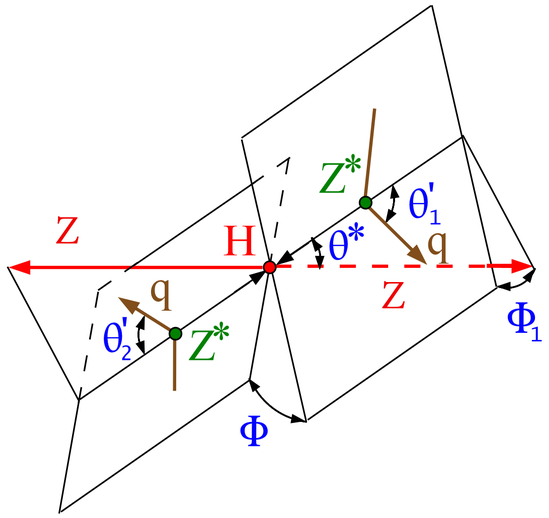
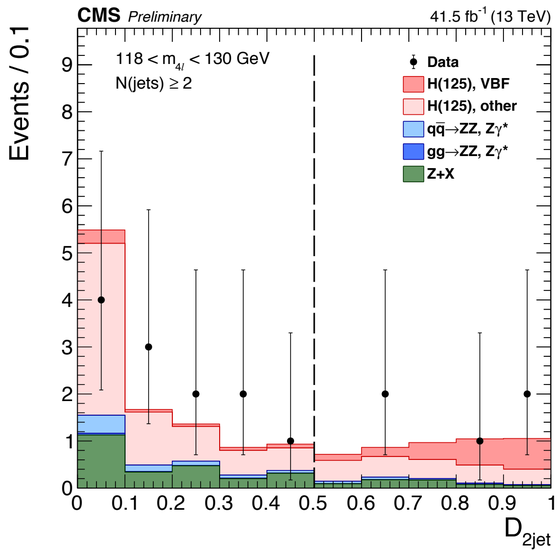
# EVENT CATEGORISATION

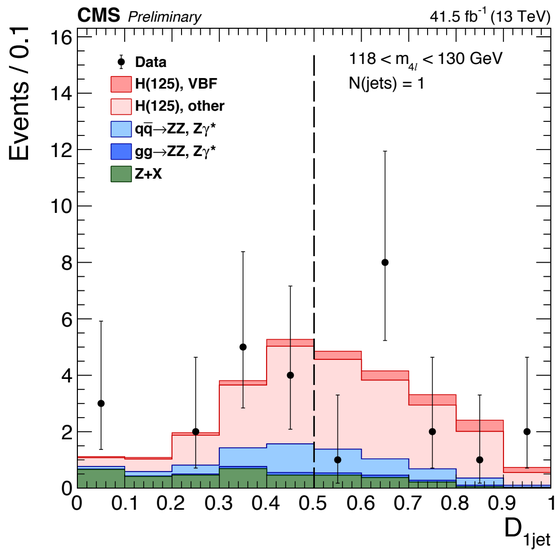


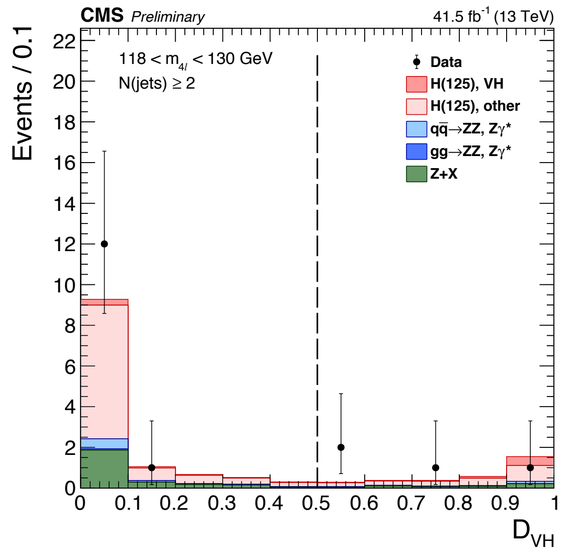
- ZZ candidates classified into 7 categories:
  - hunt for H(125) production modes
  - new ttH categories
  - selection based on number of jets, b-tags, extra leptons and cuts on the 3 matrix-element based production discriminants ($D_{2jet}$, $D_{1jet}$ and $D_{VH}$)

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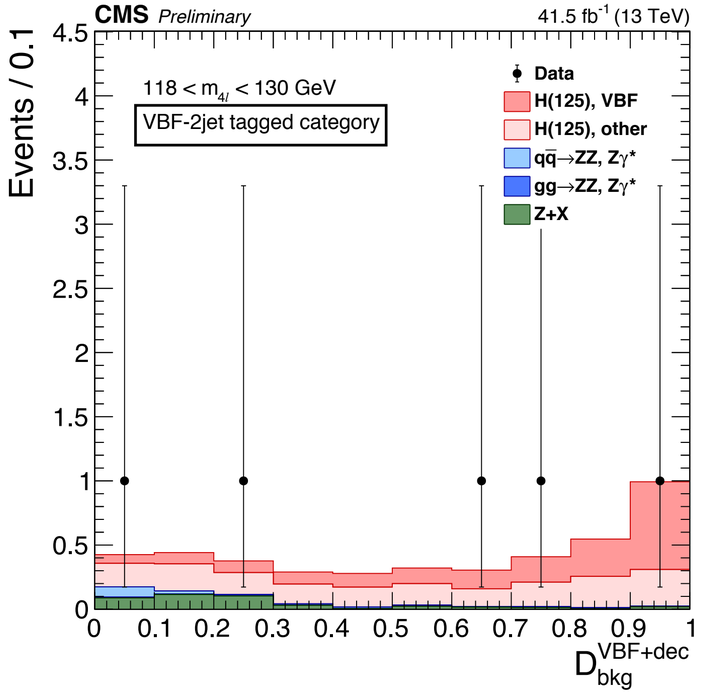
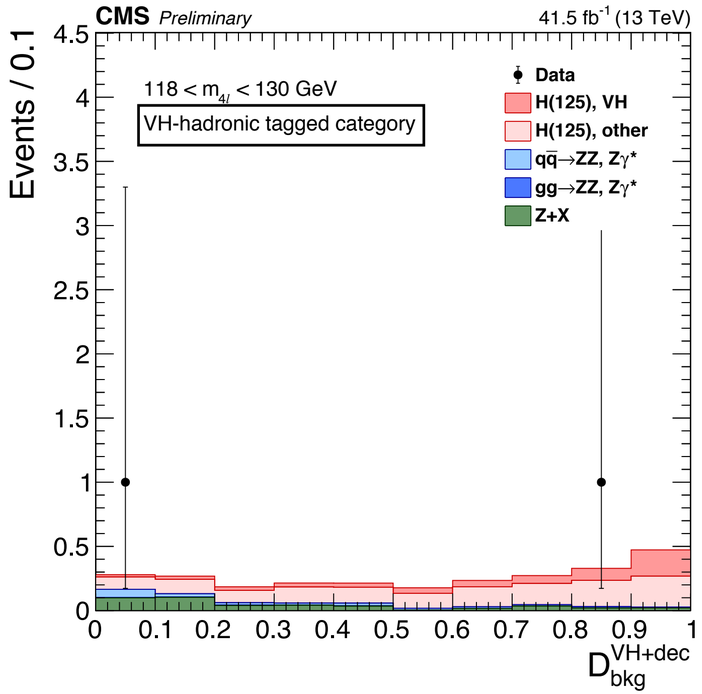
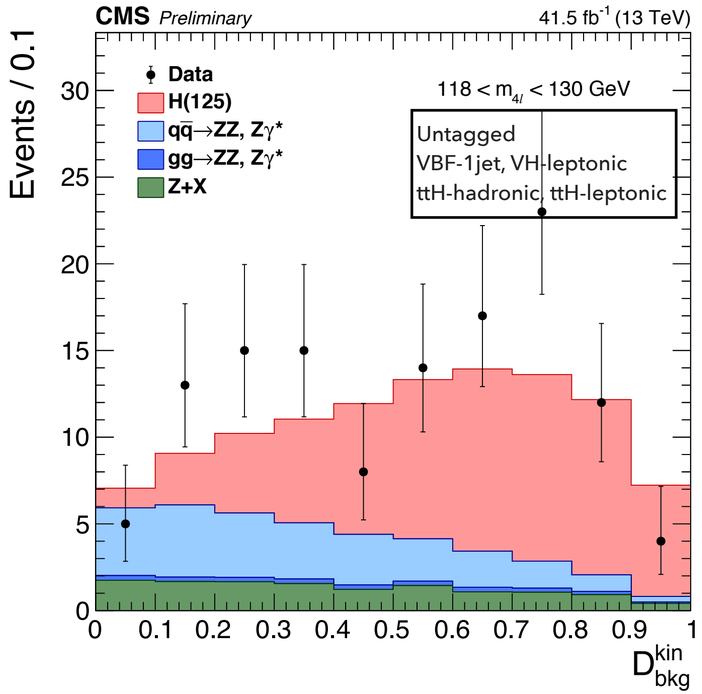
# OBSERVABLES



- Two observables used in all PDFs: **$m_{4l}$** and **kinematic discriminant**
- **Previously** in all categories **decay only** based $D_{bkg}^{kin}$ was used
- **Now** depending on event category **3 different** kinematic discriminants used:
  - $D_{bkg}^{kin}$ provides separation between Higgs signal and SM backgrounds
  - New discriminants developed providing separation of VBF ($D_{bkg}^{VBF+dec}$) and VH ($D_{bkg}^{VH+dec}$) from gluon fusion signal and SM backgrounds using **additional jet information** (information about production) in combination with decay variables to build matrix elements



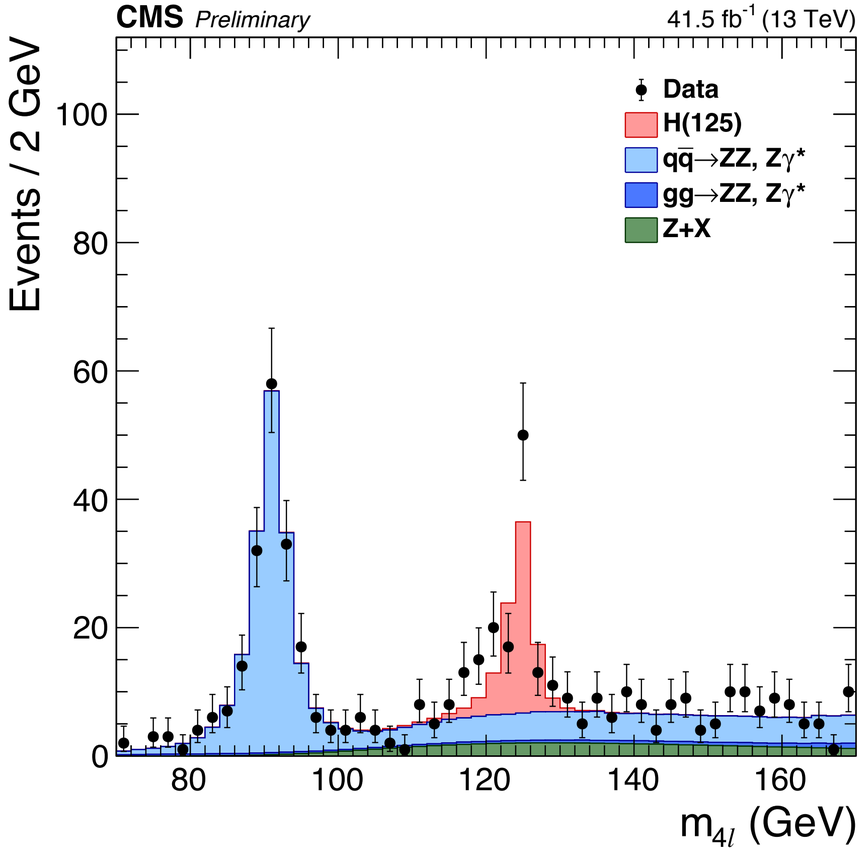



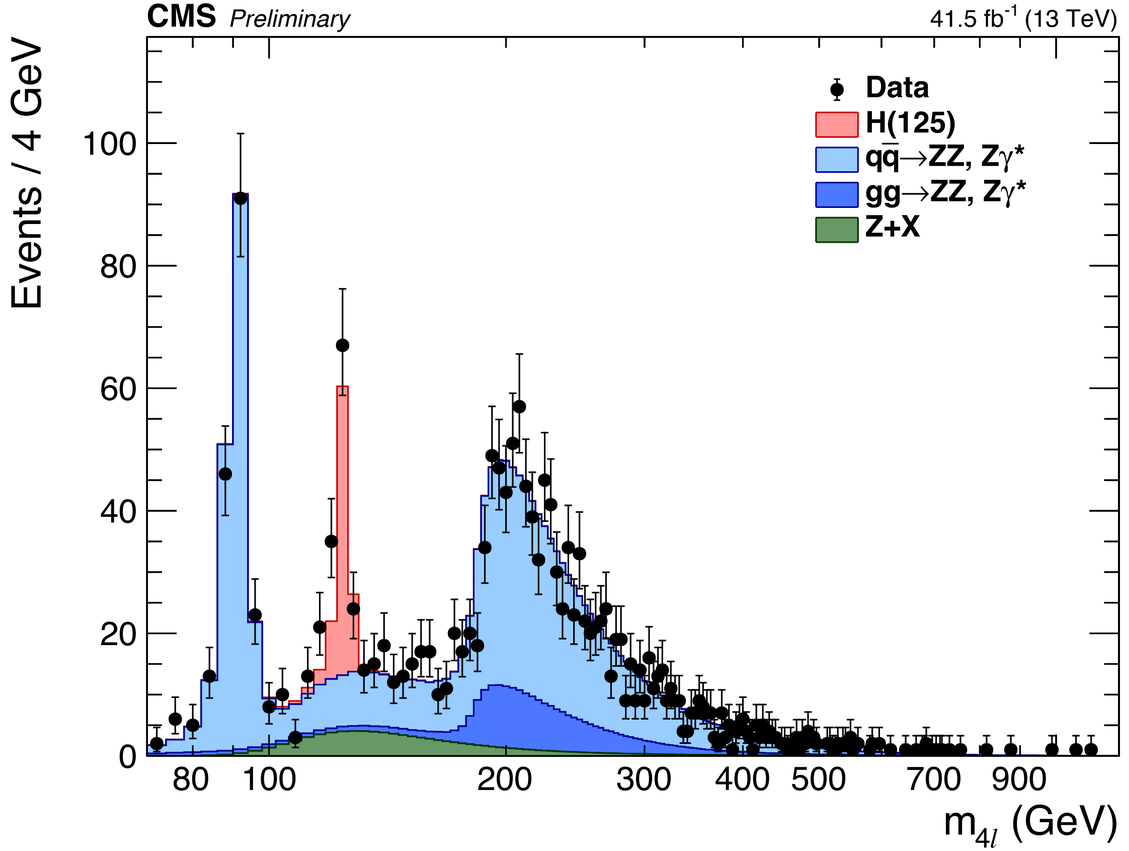
# RESULTS OF EVENT SELECTION



- Good data/MC agreement over the whole $m_{4l}$ range in all 3 final states (4e, 4μ, 2e2μ)

| Channel | 4e | $4\mu$ | $2e2\mu$ | $4\ell$ |
|---|---|---|---|---|
| $q\bar{q} \to ZZ$ | $235^{+32}_{-36}$ | $443^{+36}_{-40}$ | $572^{+50}_{-54}$ | $1250^{+104}_{-114}$ |
| $gg \to ZZ$ | $49.1^{+8.7}_{-8.8}$ | $81.8^{+11.2}_{-10.7}$ | $121.5^{+17.1}_{-16.3}$ | $252.4^{+35.1}_{-33.5}$ |
| Z + X | $17.1^{+6.4}_{-6.1}$ | $35.4^{+12.7}_{-11.4}$ | $47.8^{+16.4}_{-15.8}$ | $100.3^{+21.3}_{-20.6}$ |
| Sum of backgrounds | $301^{+39}_{-43}$ | $560^{+43}_{-47}$ | $741^{+62}_{-65}$ | $1602^{+126}_{-135}$ |
| Signal ($m_H = 125$ GeV) | $13.9^{+1.9}_{-2.1}$ | $28.9^{+2.5}_{-2.6}$ | $35.8 \pm 3.3$ | $78.5^{+7.0}_{-7.1}$ |
| Total expected | $315^{+41}_{-45}$ | $589^{+45}_{-49}$ | $777^{+64}_{-67}$ | $1681^{+131}_{-140}$ |
| Observed | 307 | 602 | 797 | 1706 |



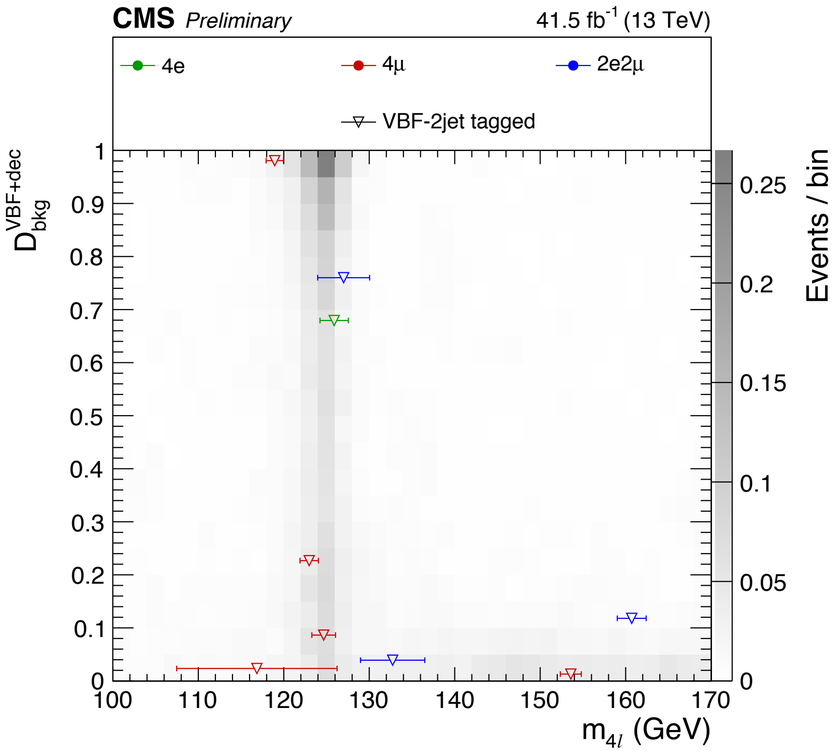



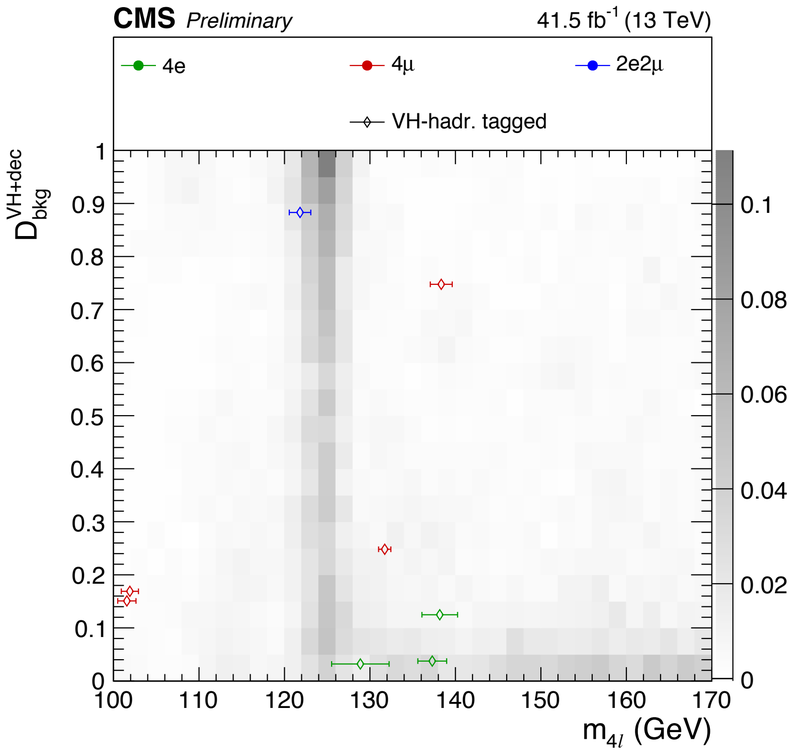
# MEASUREMENT STRATEGY

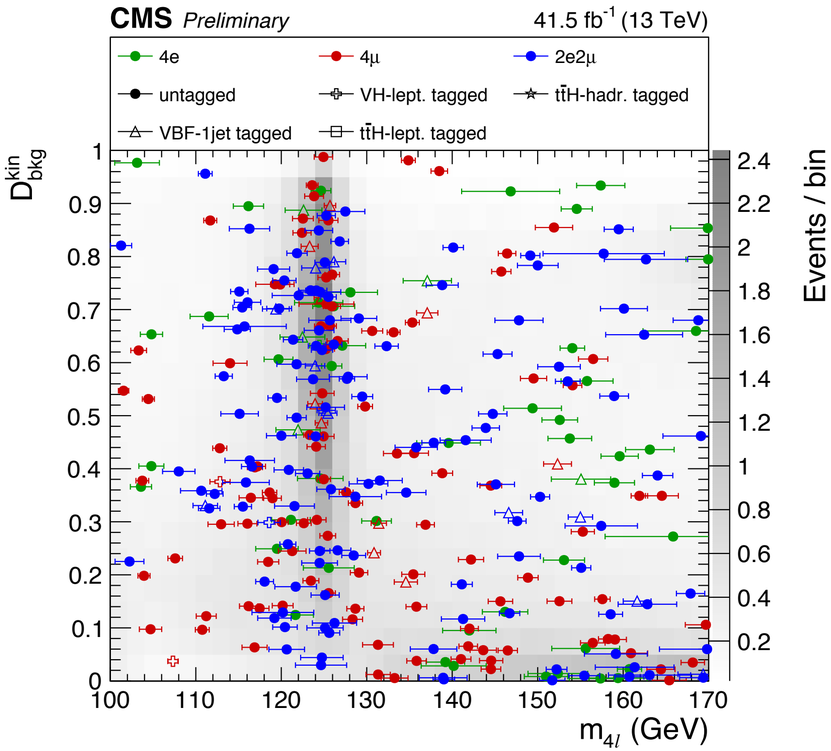


- 2D maximum-likelihood fit in 3 final states x 7 categories
  - mass dimension un-binned, uses signal shape parametrised as a function of $m_{4l}$
  - 2D templates normalized to 1 for each bin of $m_{4l}$

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



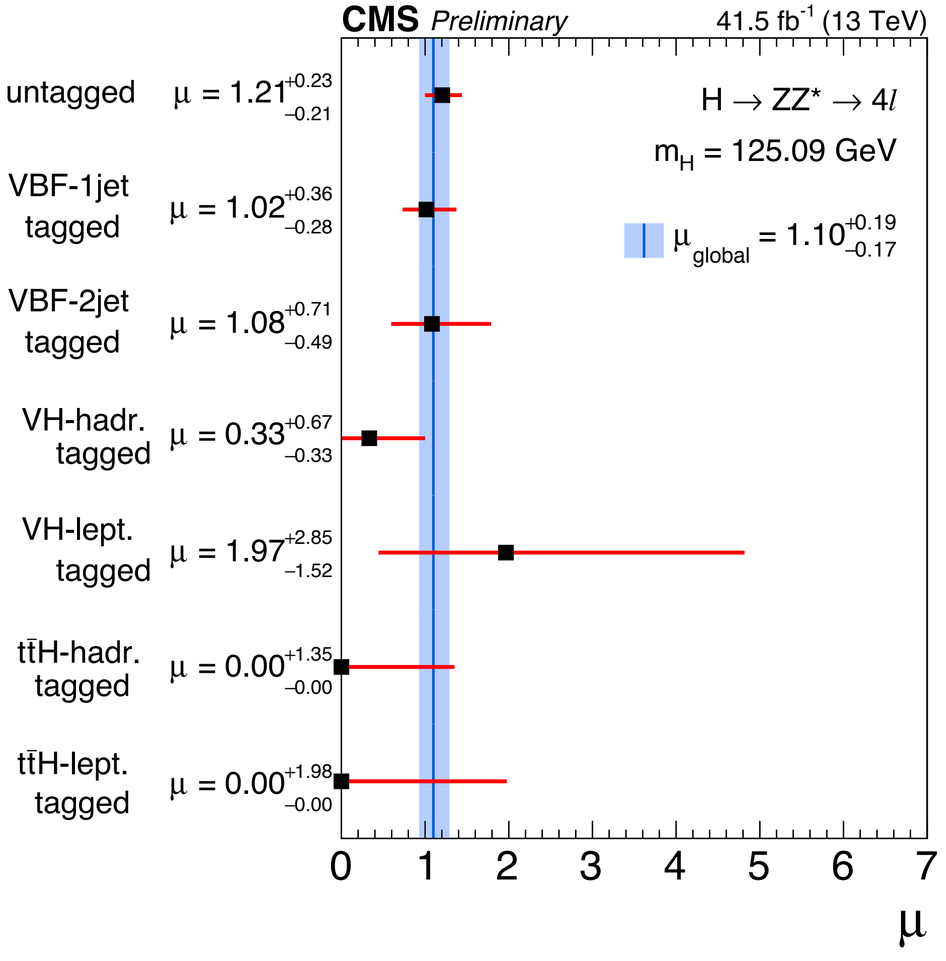



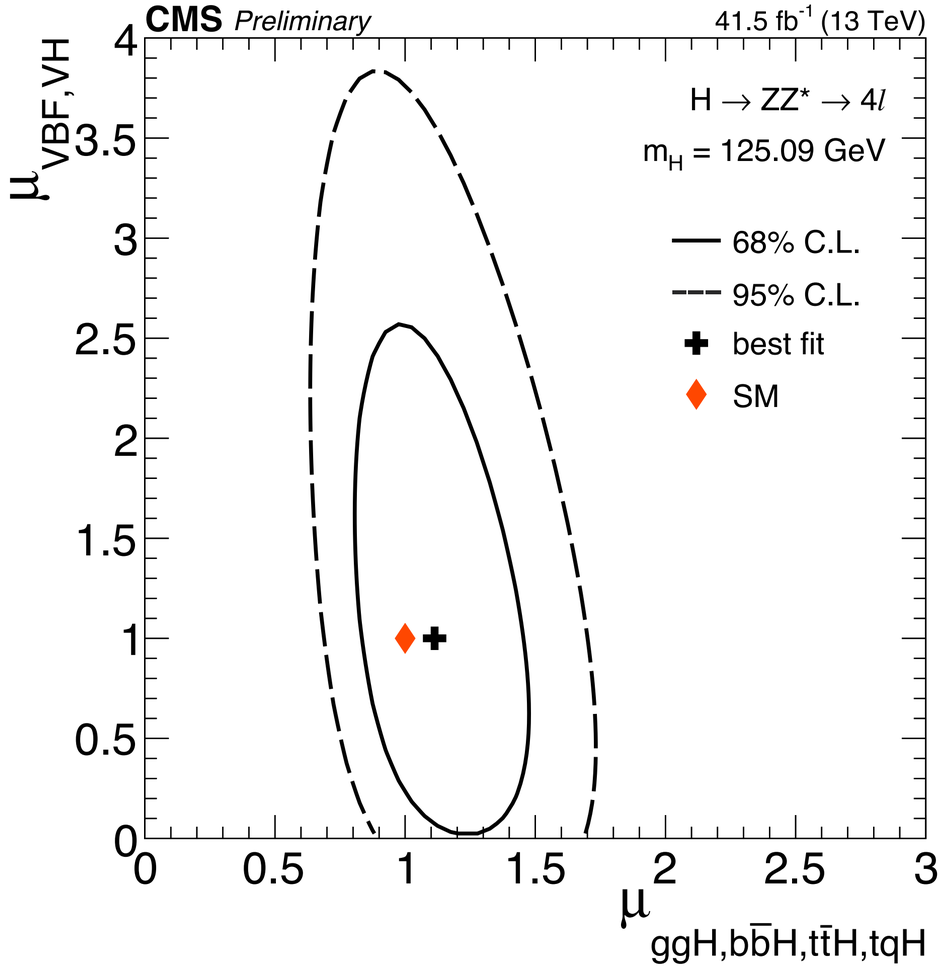
# PROBING H(125) PRODUCTION MODES



- Combined signal strength at $m_H$=125.09 GeV $\mu = 1.10^{+0.14}_{-0.13}(stat)^{+0.13}_{-0.11}(syst)$
  - Extract signal strength in every category
  - Extract signal strength of production processes in a 2-parameter model

$$\mu_{VBF,VH} = 1.00^{+0.96}_{-0.71}$$
$$\mu_{ggH,t\bar{t}H,b\bar{b}H,tqH} = 1.11^{+0.23}_{-0.21}$$

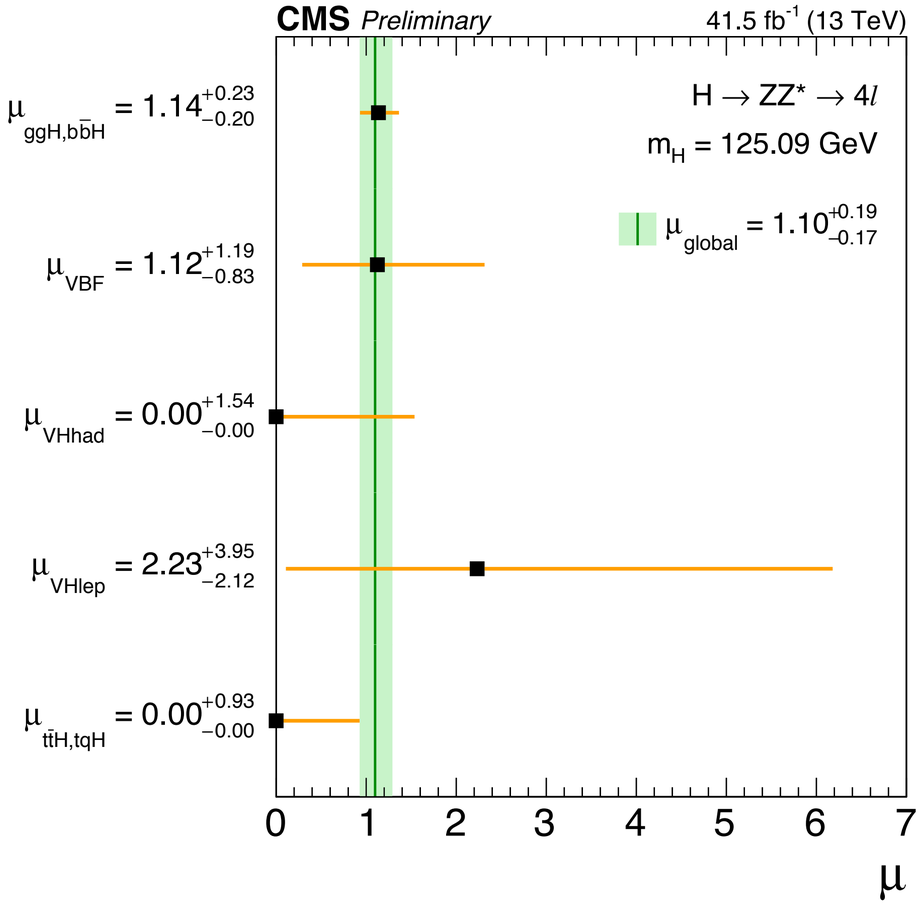


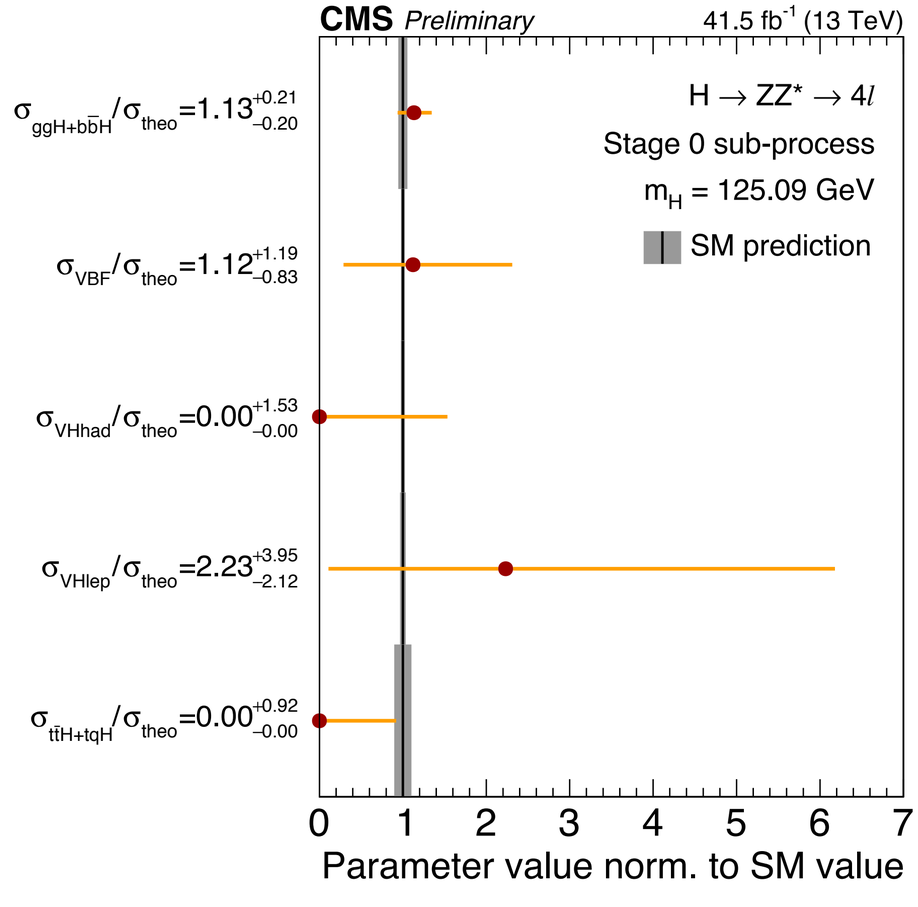



# PROBING H(125) PRODUCTION MODES



- Extract signal strength of production processes in a 5-parameter model
- Define simplified fiducial volume as $|y_H| < 2.5$ and remove theoretical uncertainties on the overall signal cross section

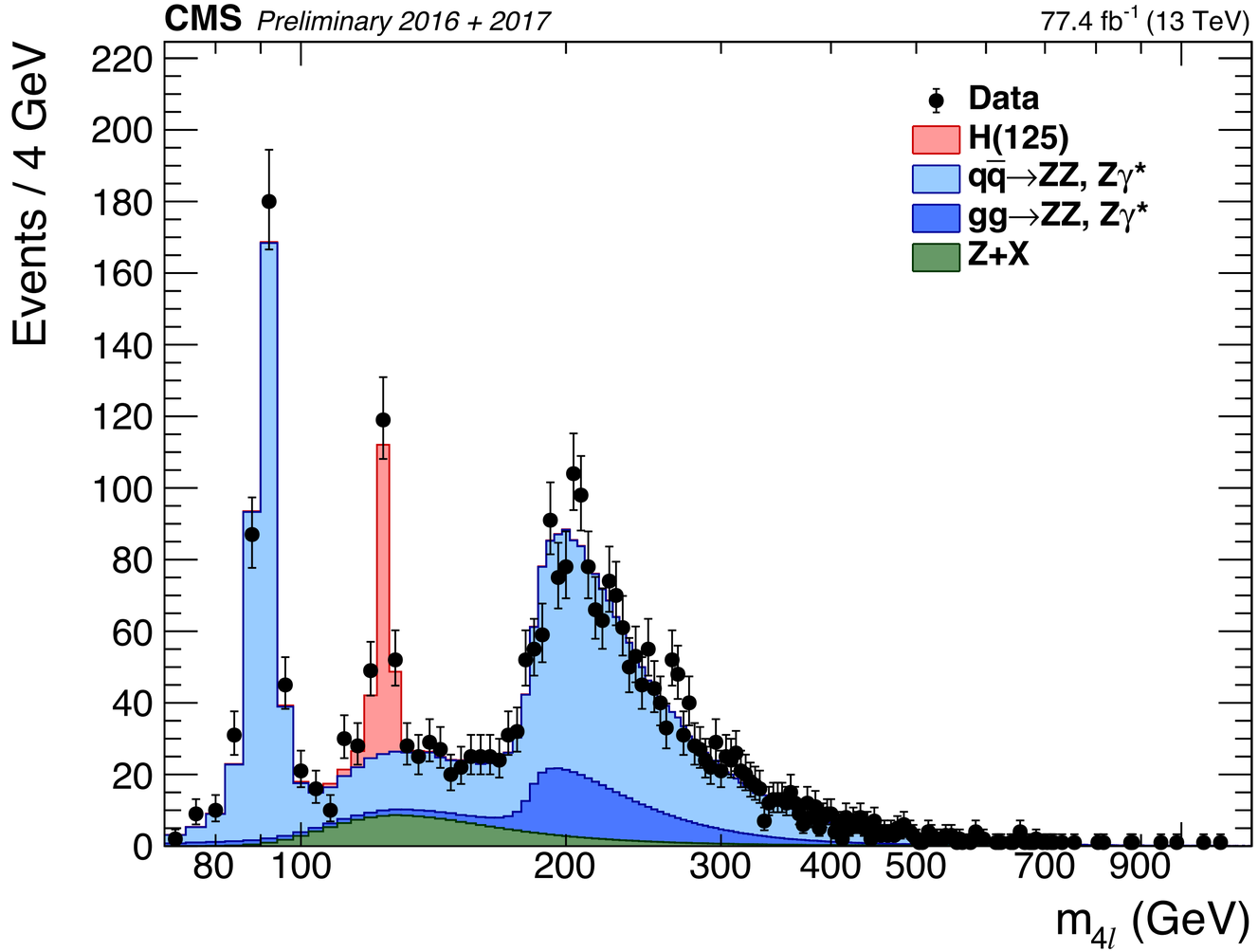


# COMBINING 2016 AND 2017 DATA



- A combined fit to 2016 and 2017 data is performed to extract signal strength of production processes in a 2 and 5-parameter model

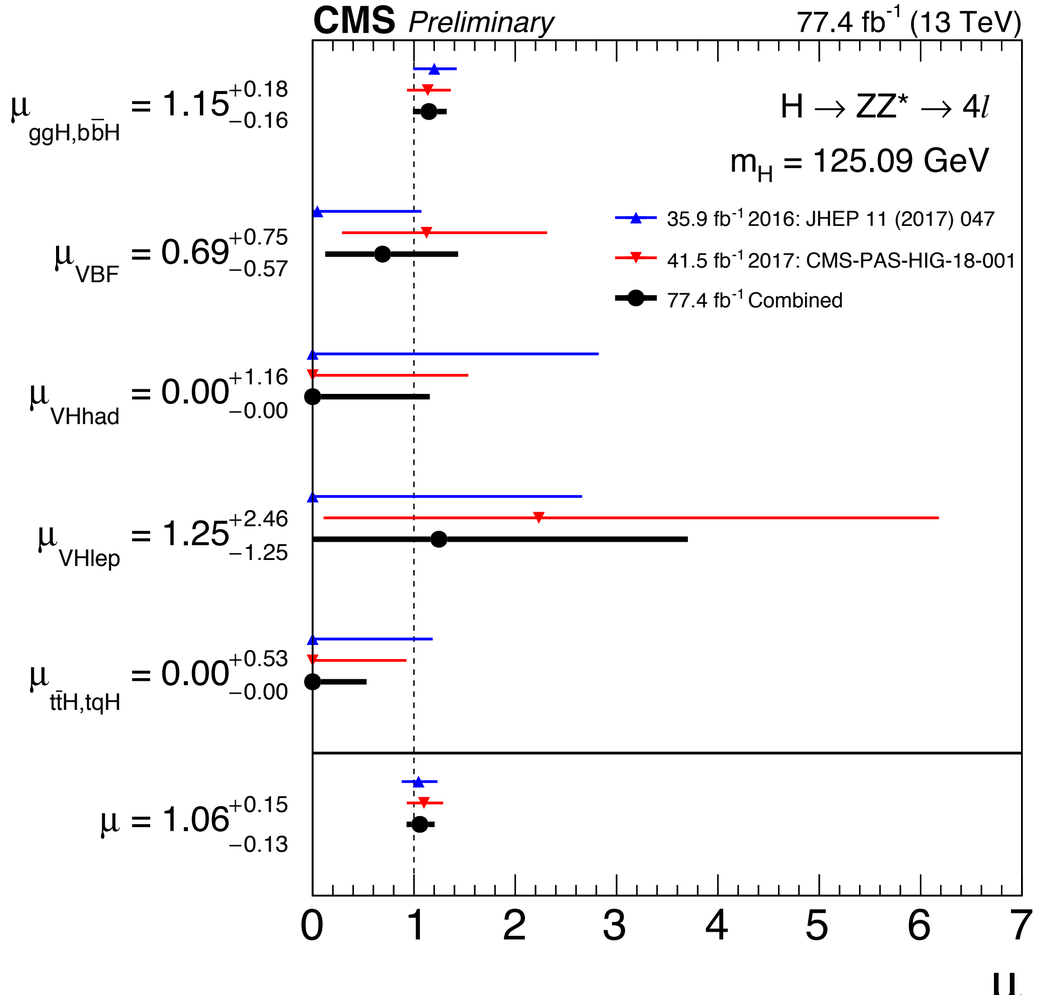


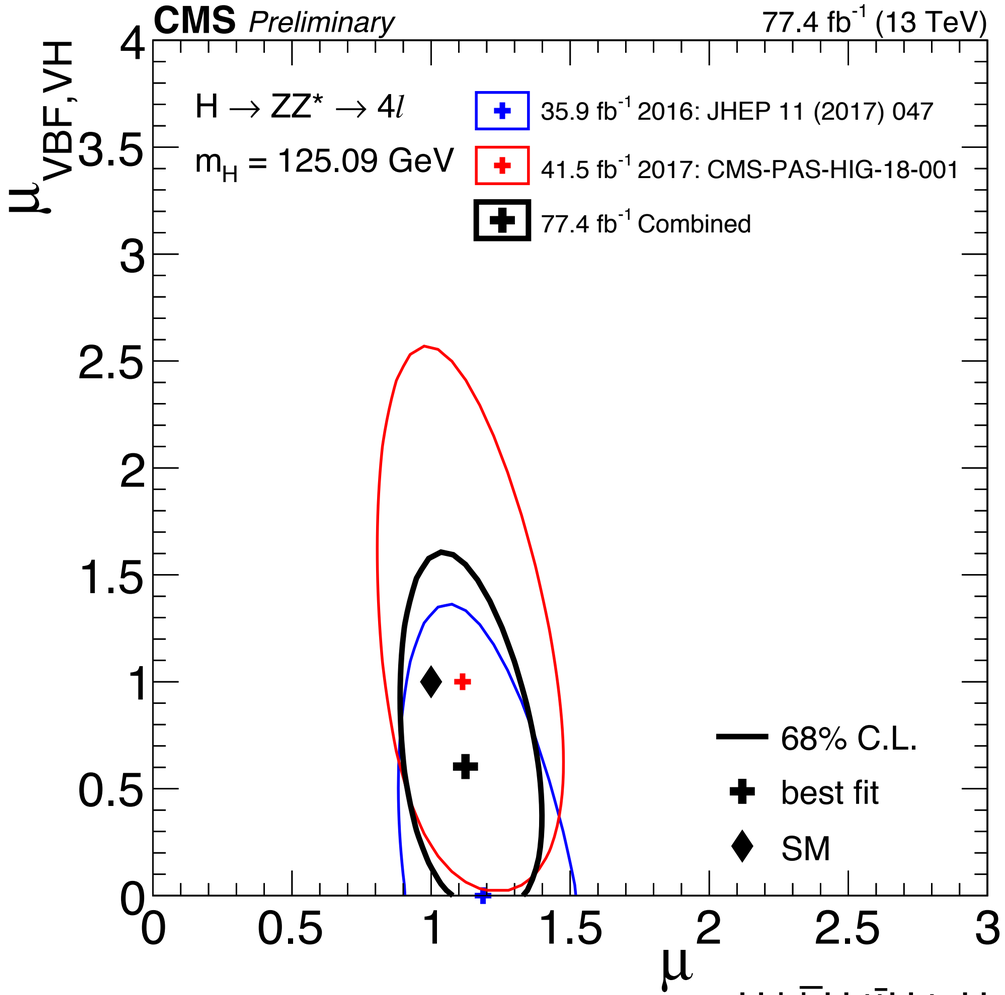
# COMBINATION RESULTS



$$\mu = 1.06 \pm 0.10(stat)^{+0.08}_{-0.06}(exp\,.\,syst)^{+0.07}_{-0.05}(th\,.\,syst)$$

$$\mu_{VBF,VH} = 0.60^{+0.62}_{-0.49}$$
$$\mu_{ggH,t\bar{t}H,b\bar{b}H,tqH} = 1.12^{+0.16}_{-0.18}$$



# SUMMARY



- Properties of Higgs boson in **H→ZZ→4l** at $\sqrt{s}$=13 TeV using **2017** data presented
  - Several improvements introduced
  - All measurements compatible with SM predictions

$$\mu = 1.10^{+0.19}_{-0.17}$$

- CMS **Combination** of 2016 and 2017 data
  - Improves on previously published CMS results
  - Precision compatible with LHC Run I combination
  - Inclusive analysis no longer dominated by statistical uncertainties

$$\mu = 1.06 \pm 0.10(stat)^{+0.11}_{-0.08}(syst)$$

- More than **100/fb** of data expected in Run II
  - Full Run II analysis will reach new levels of precision in Higgs properties measurements

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# BACKUP

# MATRIX ELEMENT DISCRIMINANTS



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

$$\mathcal{D}_{\text{bkg}}^{\text{VBF+dec}} = \frac{\mathcal{P}_{\text{sig}}^{\text{VBF+VH+dec}}(\vec{\Omega})}{\mathcal{P}_{\text{sig}}^{\text{VBF+VH+dec}}(\vec{\Omega}) + c^{\text{VBF2jet}}(m_{4\ell}) \times (\mathcal{P}_{\text{bkg}}^{\text{VBS+VVV}}(\vec{\Omega}) + \mathcal{P}_{\text{bkg}}^{\text{QCD+dec}}(\vec{\Omega}))}$$

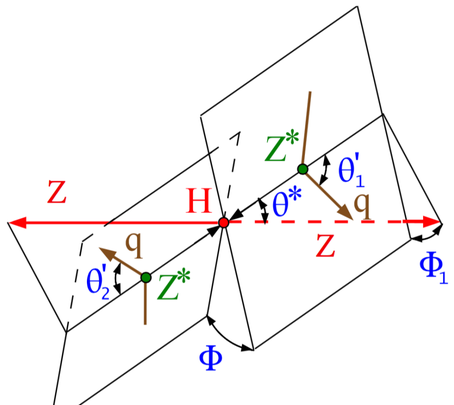
$$\mathcal{D}_{\text{bkg}}^{\text{VH+dec}} = \frac{\mathcal{P}_{\text{sig}}^{\text{VBF+VH+dec}}(\vec{\Omega})}{\mathcal{P}_{\text{sig}}^{\text{VBF+VH+dec}}(\vec{\Omega}) + c^{\text{had.VH}}(m_{4\ell}) \times (\mathcal{P}_{\text{bkg}}^{\text{VBS+VVV}}(\vec{\Omega}) + \mathcal{P}_{\text{bkg}}^{\text{QCD+dec}}(\vec{\Omega}))},$$

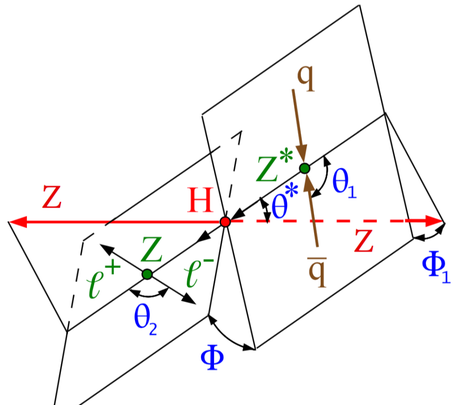
$$\mathcal{D}_{\text{2jet}} = \left[1 + \frac{\mathcal{P}_{\text{HJJ}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}{\mathcal{P}_{\text{VBF}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\text{1jet}} = \left[1 + \frac{\mathcal{P}_{\text{HJ}}(\vec{\Omega}^{\text{H+J}}|m_{4\ell})}{\int d\eta_{\text{J}}\,\mathcal{P}_{\text{VBF}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\text{WH}} = \left[1 + \frac{\mathcal{P}_{\text{HJJ}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}{\mathcal{P}_{\text{ZH}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\text{ZH}} = \left[1 + \frac{\mathcal{P}_{\text{HJJ}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}{\mathcal{P}_{\text{WH}}(\vec{\Omega}^{\text{H+JJ}}|m_{4\ell})}\right]^{-1}$$

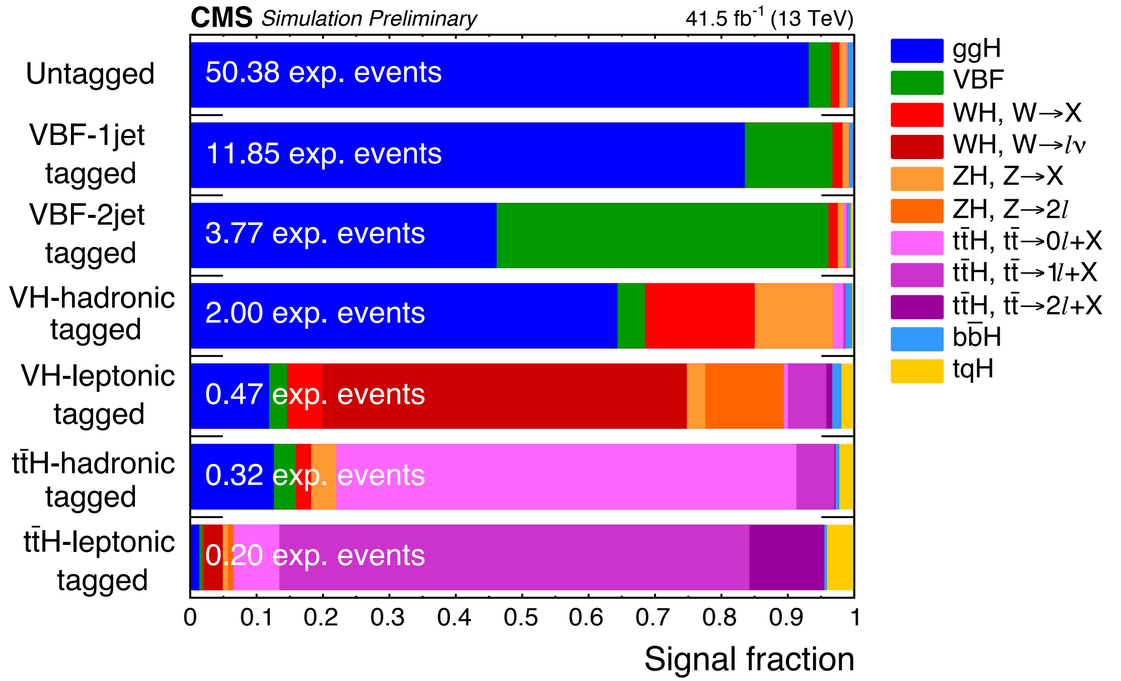


# EVENT CATEGORIES



- **VBF-2jet-tagged category** requires exactly 4 leptons. In addition there must be either 2 or 3 jets of which at most 1 is b-tagged, or at least 4 jets and no b-tagged jets. Finally, $\mathcal{D}_{\text{2jet}} > 0.5$ is required.
- **VH-hadronic-tagged category** requires exactly 4 leptons. In addition there must be 2 or 3 jets, or at least 4 jets and no b-tagged jets. Finally, $\mathcal{D}_{\text{VH}} \equiv \max(\mathcal{D}_{\text{ZH}}, \mathcal{D}_{\text{WH}}) > 0.5$ is required.
- **VH-leptonic-tagged category** requires no more than 3 jets and no b-tagged jets in the event, and exactly 1 additional lepton or 1 additional pair of opposite sign same flavor leptons. This category also includes events with no jets and at least 1 additional lepton.
- **$\mathrm{t\bar{t}}$H-hadronic-tagged category** requires at least 4 jets of which at least 1 is b-tagged and no additional leptons.
- **$\mathrm{t\bar{t}}$H-leptonic-tagged category** requires at least 1 additional lepton in the event.
- **VBF-1jet-tagged category** requires exactly 4 leptons, exactly 1 jet and $\mathcal{D}_{\text{1jet}} > 0.5$.
- **Untagged category** consists of the remaining events.



# SYSTEMATIC UNCERTAINTIES



| Summary of relative systematic uncertainties | |
|---|---|
| Common experimental uncertainties | |
| Luminosity | 2.3 % |
| Lepton identification/reconstruction efficiencies | 3. – 12.5 % |
| Background related uncertainties | |
| Reducible background fake rate variation (Z+X) | 31 – 45 % |
| Signal related uncertainties | |
| Lepton energy scale | 0.05 – 0.3 % |
| Lepton energy resolution | 20 % |

| Summary of inclusive theory uncertainties | |
|---|---|
| QCD scale (gg) | $\pm$ 3.9 % |
| PDF set (gg) | $\pm$ 3.2 % |
| Bkg K factor (gg) | $\pm$ 10 % |
| QCD scale (VBF) | +0.4/-0.3 % |
| PDF set (VBF) | $\pm$ 2.1 % |
| QCD scale (WH) | +0.5/-0.7 % |
| PDF set (WH) | $\pm$ 1.9 % |
| QCD scale (ZH) | +3.8/-3.1 % |
| PDF set (ZH) | $\pm$ 1.6 % |
| QCD scale ($t\bar{t}H$) | +5.8/-9.2 % |
| PDF set ($t\bar{t}H$) | $\pm$ 3.6 % |
| BR($H \to ZZ \to 4\ell$) | 2 % |
| QCD scale ($q\bar{q} \to ZZ$) | +3.2/-4.2 % % |
| PDF set ($q\bar{q} \to ZZ$) | +3.1/-3.4 % |
| Electroweak corrections ($q\bar{q} \to ZZ$) | $\pm$ 0.1 % |

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# SYSTEMATIC UNCERTAINTIES - CATEGORISATION



**Summary of theory uncertainties in categorization**

| Category | QCD scale | PDF set | EW corr. |
|---|---|---|---|
| **gg** | | | |
| Untagged | +4.9 /-1.2 % | - | - |
| VBF 2 -jet | +39.9 /-9.4 % | ± 0.5 % | - |
| Had. VH | +60 /-30 % | ± 0.3 % | - |
| Lep. VH | +3.5 /-4.6 % | ± 0.2 % | - |
| ttH Lep. | +45.5 /-12.8 % | ± 0.4 % | - |
| ttH Hadr. | +11.9 /-29.9 % | ± 0.6 % | - |
| VBF 1-jet | +24.8 /-7.5 % | ± 0.2 % | - |
| **VBF** | | | |
| Untagged | +8.5/-2.2 % | ± 0.1 % | - |
| VBF 2 -jet | +8.4/-1.7 % | ± 0.1 % | - |
| Had. VH | +13.3/-10.0 % | +0.1/-0.2 % | - |
| Lep. VH | +72/-79 % | +0.9/-1.0 % | - |
| ttH Lep. | +2.6/-4.4 % | +12.0/-13.0 % | - |
| ttH Had. | +30.9/-24.0 % | +0.8/-0.9 % | - |
| VBF 1-jet | +2.2/-1.7 % | ± 0.1 % | - |
| **WH – leptonic** | | | |
| Untagged | +9.0/-9.2 % | ± 0.1 % | - |
| VBF 2 -jet | +41.5/-25.0 % | ± 1.1 % | - |
| Had. VH | +53.4/-29.1 % | ± 1.2 % | - |
| Lep. VH | +7.8/-6.4 % | ± 0.1 % | - |
| ttH Lep. | +35.9/-57.3 % | ± 0.1 % | - |
| ttH Had. | +53.5/-16.0 % | ± 1.2 % | - |
| VBF 1-jet | +17.2/-27.8 % | ± 0.1 % | - |
| **WH – hadronic** | | | |
| Untagged | +7.1/-7.5 % | ± 0.1 % | - |
| VBF 2 -jet | +13.6/-11.0 % | ± 1.1 % | - |
| Had. VH | +8.5/-2.1 % | ± - % | - |
| Lep. VH | +63/-43 % | ± 0.2 % | - |
| ttH Lep. | +73.3/-9.8 % | ± 1.4 % | - |
| ttH Had. | +59/-35.5 % | ± 1.0 % | - |
| VBF 1-jet | +3.8/-3.4 % | ± 0.2 % | - |
| **ZH – leptonic** | | | |
| Untagged | +0.3/-6.1 % | ± 0.1 % | - |
| VBF 2 -jet | +29.1/-17.9 % | ± 1.5 % | - |
| Had. VH | +9.0/-2.3 % | ± 0.3 % | - |
| Lep. VH | +7.6/-3.6 % | ± 0.1 % | - |
| ttH Lep. | +8.1/-38.3 % | ± 1.7 % | - |
| ttH Had. | +3.6/-16.8 % | ± 1.4 % | - |
| VBF 1-jet | +6.9/-3.5 % | ± 0.3 % | - |
| **ZH – hadronic** | | | |
| Untagged | +0.3/-6.1 % | ± 0.1 % | - |
| VBF 2 -jet | +29.1/-17.9 % | ± 1.2 % | - |
| Had. VH | +9.0/-2.3 % | ± 0.1 % | - |
| Lep. VH | +7.6/-3.6 % | ± 0.1 % | - |
| ttH Lep. | +8.1/-38.3 % | ± 0.5 % | - |
| ttH Had. | +3.6/-16.8 % | ± 1.4 % | - |
| VBF 1-jet | +6.9/-3.5 % | ± 0.5 % | - |
| **$t\bar{t}H$ – leptonic** | | | |
| Untagged | +6.9/-2.9 % | ± 0.1 % | - |
| VBF 2 -jet | +27.2/-8.0 % | ± 0.3 % | - |
| Had. VH | +9.1/-12.8 % | ± 0.3 % | - |
| Lep. VH | +2.2/-8.8 % | ± 0.1 % | - |
| ttH Lep. | +2.6/-4.3 % | ± 0.1 % | - |
| ttH Had. | +12.9/-8.2 % | ± 0.2 % | - |
| VBF 1-jet | +25.8/-7.9 % | ± 0.2 % | - |
| **$t\bar{t}H$ – hadronic** | | | |
| Untagged | +21.8/-5.8 % | ± 0.1 % | - |
| VBF 2 -jet | +46.5/-8.9 % | ± 0.5 % | - |
| Had. VH | +16.3/-6.2 % | ± 0.1 % | - |
| Lep. VH | +36.3/-11.2 % | ± 0.7 % | - |
| ttH Lep. | +73.5/-6.8 % | ± 0.4 % | - |
| ttH Had. | +17.6/-3.9 % | ± 0.1 % | - |
| VBF 1-jet | +14.9/-47.3 % | ± 0.4 % | - |
| **$q\bar{q} \to ZZ$** | | | |
| Untagged | - % | ± 0.1 % | - |
| VBF 2 -jet | ± 0.2 % | ± 0.1 % | - |
| Had. VH | ± 0.1 % | ± 0.2 % | - |
| Lep. VH | ± 0.2 % | ± 0.1 % | ± 1.0 % |
| ttH Lep. | +3.4/-1.7 % | ± 12.0 % | ± 0.1 % |
| ttH Had. | +3.4/-1.7 % | ± 1 % | ± 0.1 % |
| VBF 1-jet | ± 0.2 % | ± 0.1 % | - |

| Process | Category | JES | b-tagging |
|---|---|---|---|
| gg sig. or bkg. | UnTagged | 0.9798 / 1.0191 | - / - |
| gg sig. or bkg. | VBF1jTagged | 1.0434 / 0.9419 | - / - |
| gg sig. or bkg. | VBF2jTagged | 1.2240 / 0.8468 | 0.9987 / 1.0012 |
| gg sig. or bkg. | LepVHTagged | 0.9923 / 1.0000 | 0.9961 / 1.0000 |
| gg sig. or bkg. | HadVHTagged | 1.0764 / 0.9430 | 1.0000 / 1.0005 |
| gg sig. or bkg. | ttHLepTagged | 1.1830 / 1.0000 | 1.0536 / 1.0000 |
| gg sig. or bkg. | ttHHadTagged | 1.1216 / 0.8195 | 1.1063 / 0.9048 |
| VBF sig. | UnTagged | 0.9732 / 1.0584 | 0.9997 / 1.0001 |
| VBF sig. | VBF1jTagged | 0.9199 / 1.0610 | - / - |
| VBF sig. | VBF2jTagged | 1.0823 / 0.9009 | 0.9998 / 1.0003 |
| VBF sig. | LepVHTagged | 0.9941 / 1.0000 | 0.9961 / 1.0000 |
| VBF sig. | HadVHTagged | 1.0457 / 0.9582 | - / - |
| VBF sig. | ttHLepTagged | 1.0809 / 1.0000 | 1.0536 / 1.0000 |
| VBF sig. | ttHHadTagged | 1.2087 / 0.8411 | 1.0614 / 0.9361 |
| WH-leptonic sig. | UnTagged | 0.9743 / 1.0196 | - / - |
| WH-leptonic sig. | VBF1jTagged | 1.0583 / 0.9271 | - / - |
| WH-leptonic sig. | VBF2jTagged | 1.2386 / 0.8331 | 0.9998 / 1.0022 |
| WH-leptonic sig. | LepVHTagged | 0.9976 / 1.0016 | 0.9991 / 1.0009 |
| WH-leptonic sig. | HadVHTagged | 1.0949 / 0.9406 | - / - |
| WH-leptonic sig. | ttHLepTagged | 1.1183 / 0.9235 | 1.0438 / 0.9569 |
| WH-leptonic sig. | ttHHadTagged | 1.1007 / 0.8613 | 1.0624 / 0.9355 |
| WH-hadronic sig. | UnTagged | 0.9809 / 1.0235 | 0.9996 / 1.0007 |
| WH-hadronic sig. | VBF1jTagged | 0.9527 / 1.0353 | - / - |
| WH-hadronic sig. | VBF2jTagged | 1.1201 / 0.9001 | 0.9981 / 1.0013 |
| WH-hadronic sig. | LepVHTagged | 0.9922 / 1.0000 | 0.9971 / 1.0000 |
| WH-hadronic sig. | HadVHTagged | 1.0290 / 0.9656 | 0.9997 / 1.0003 |
| WH-hadronic sig. | ttHLepTagged | 1.0934 / 1.0000 | 1.0345 / 1.0000 |
| WH-hadronic sig. | ttHHadTagged | 1.1383 / 0.9001 | 1.0567 / 0.9301 |
| ZH-leptonic sig. | UnTagged | 0.9788 / 1.0173 | 0.9996 / 1.0000 |
| ZH-leptonic sig. | VBF1jTagged | 1.0366 / 0.9873 | - / - |
| ZH-leptonic sig. | VBF2jTagged | 1.1519 / 0.8450 | 1.0000 / 1.0049 |
| ZH-leptonic sig. | LepVHTagged | 0.9984 / 1.0021 | 0.9988 / 1.0016 |
| ZH-leptonic sig. | HadVHTagged | 1.0344 / 0.9540 | - / - |
| ZH-leptonic sig. | ttHLepTagged | 1.0473 / 0.9371 | 1.0363 / 0.9521 |
| ZH-leptonic sig. | ttHHadTagged | 1.1507 / 0.8306 | 1.0425 / 0.9729 |
| ZH-hadronic sig. | UnTagged | 0.9896 / 1.0174 | 0.9996 / 1.0006 |
| ZH-hadronic sig. | VBF1jTagged | 0.9421 / 1.0467 | - / - |
| ZH-hadronic sig. | VBF2jTagged | 1.1326 / 0.9004 | 0.9977 / 1.0019 |
| ZH-hadronic sig. | LepVHTagged | - / - | 0.9838 / 1.0000 |
| ZH-hadronic sig. | HadVHTagged | 1.0151 / 0.9734 | - / - |
| ZH-hadronic sig. | ttHLepTagged | - / - | 1.0462 / 1.0000 |
| ZH-hadronic sig. | ttHHadTagged | 1.1334 / 0.8918 | 1.0161 / 0.9804 |
| ttH-leptonic sig. | UnTagged | 0.9656 / 1.0349 | 0.9932 / 1.0046 |
| ttH-leptonic sig. | VBF1jTagged | 0.7857 / 0.9644 | - / - |
| ttH-leptonic sig. | VBF2jTagged | 1.0033 / 0.9772 | 0.9867 / 1.0099 |
| ttH-leptonic sig. | LepVHTagged | 0.9529 / 1.0556 | 0.9667 / 1.0414 |
| ttH-leptonic sig. | HadVHTagged | 0.9387 / 1.0654 | 0.9987 / 1.0039 |
| ttH-leptonic sig. | ttHLepTagged | 1.0089 / 0.9894 | 1.0063 / 0.9922 |
| ttH-leptonic sig. | ttHHadTagged | 1.0788 / 0.9314 | 1.0116 / 0.9907 |
| ttH-hadronic sig. | UnTagged | 0.9617 / 1.0472 | 0.9822 / 1.0207 |
| ttH-hadronic sig. | VBF1jTagged | 0.9339 / 1.1479 | - / - |
| ttH-hadronic sig. | VBF2jTagged | 0.9718 / 1.0126 | 0.9774 / 1.0330 |
| ttH-hadronic sig. | LepVHTagged | 0.9181 / 1.0382 | 0.9655 / 1.0165 |
| ttH-hadronic sig. | HadVHTagged | 0.8949 / 1.0879 | 0.9873 / 1.0163 |
| ttH-hadronic sig. | ttHLepTagged | 1.0179 / 0.9917 | 1.0075 / 0.9964 |
| ttH-hadronic sig. | ttHHadTagged | 1.0338 / 0.9661 | 1.0104 / 0.9872 |
| tq sig. | UnTagged | 0.9811 / 1.0244 | 1.0002 / 0.9997 |
| tq sig. | VBF1jTagged | 0.8522 / 1.1452 | - / - |
| tq sig. | VBF2jTagged | 1.0116 / 0.9721 | 0.9947 / 1.0092 |
| tq sig. | LepVHTagged | 0.9879 / 1.0102 | 0.9933 / 1.0015 |
| tq sig. | HadVHTagged | 0.9478 / 1.0511 | - / - |
| tq sig. | ttHLepTagged | 1.0133 / 0.9888 | 1.0549 / 0.9876 |
| tq sig. | ttHHadTagged | 1.1768 / 0.8450 | 1.0107 / 0.9715 |
| bb sig. | UnTagged | 0.9733 / 1.0248 | 0.9992 / 1.0005 |
| bb sig. | VBF1jTagged | 1.0262 / 0.9449 | - / - |
| bb sig. | VBF2jTagged | 1.3053 / 0.7929 | 0.9967 / 1.0044 |
| bb sig. | LepVHTagged | 0.9955 / 1.0042 | 0.9853 / 1.0152 |
| bb sig. | HadVHTagged | 1.1004 / 0.9233 | 0.9977 / 1.0026 |
| bb sig. | ttHLepTagged | 1.0369 / 0.9655 | 1.0162 / 0.9832 |
| bb sig. | ttHHadTagged | 1.6079 / 0.5978 | 1.0162 / 0.9815 |
| qq bkg. | UnTagged | 0.9862 / 1.0087 | - / - |
| qq bkg. | VBF1jTagged | 1.0765 / 0.9409 | - / - |
| qq bkg. | VBF2jTagged | 1.4252 / 0.7386 | - / - |
| qq bkg. | LepVHTagged | - / - | 0.9987 / 1.0024 |
| qq bkg. | HadVHTagged | 1.1059 / 0.9654 | - / - |
| qq bkg. | ttHLepTagged | - / - | 1.0380 / 0.9333 |
| qq bkg. | ttHHadTagged | 1.5051 / 1.0000 | - / - |

# IMPACTS OF SYSTEMATICS



$$\mu = 1.10^{+0.14}_{-0.13}(stat)^{+0.13}_{-0.11}(syst)$$

| Systematic source | Impact |
|---|---|
| Lepton efficiency | ~6% |
| QCD scale ggH | ~4% |
| PDF ggH | ~3% |
| Luminosity | ~3% |
| Branching fraction | ~2% |
| others | < 2% |

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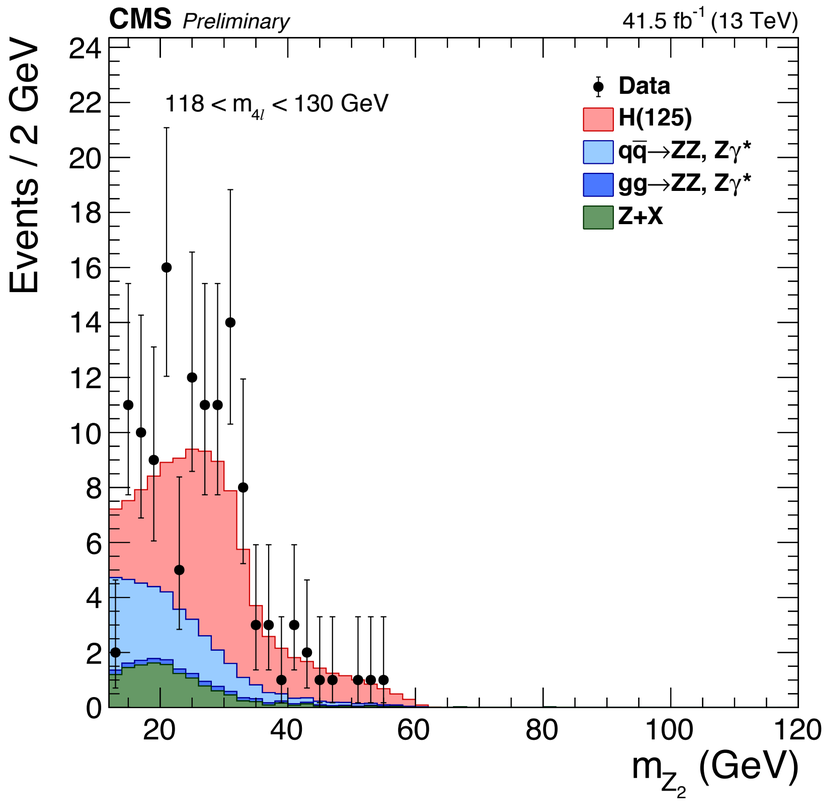
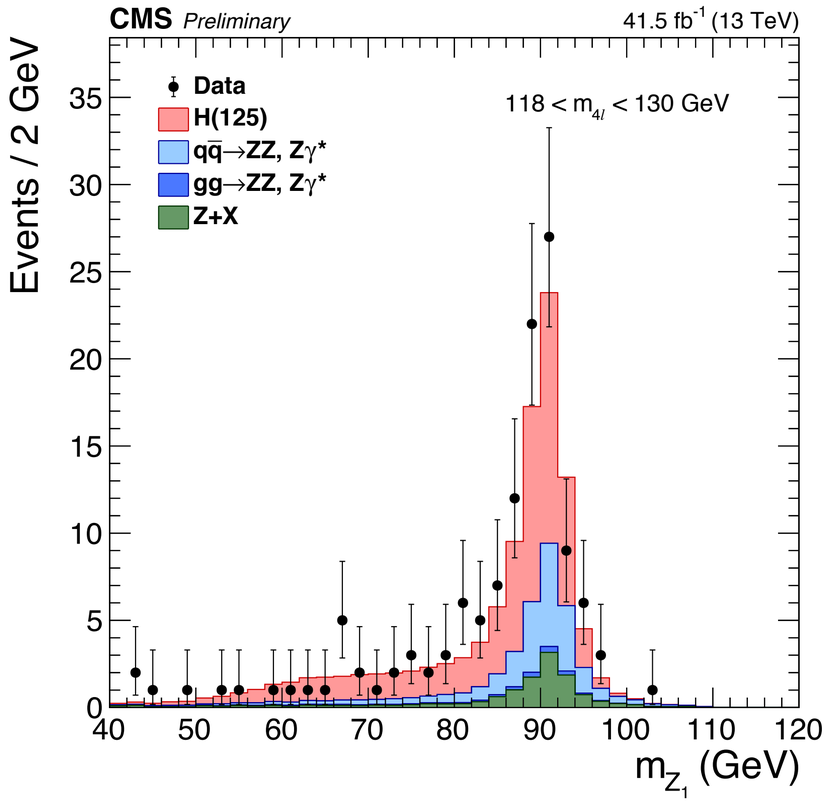
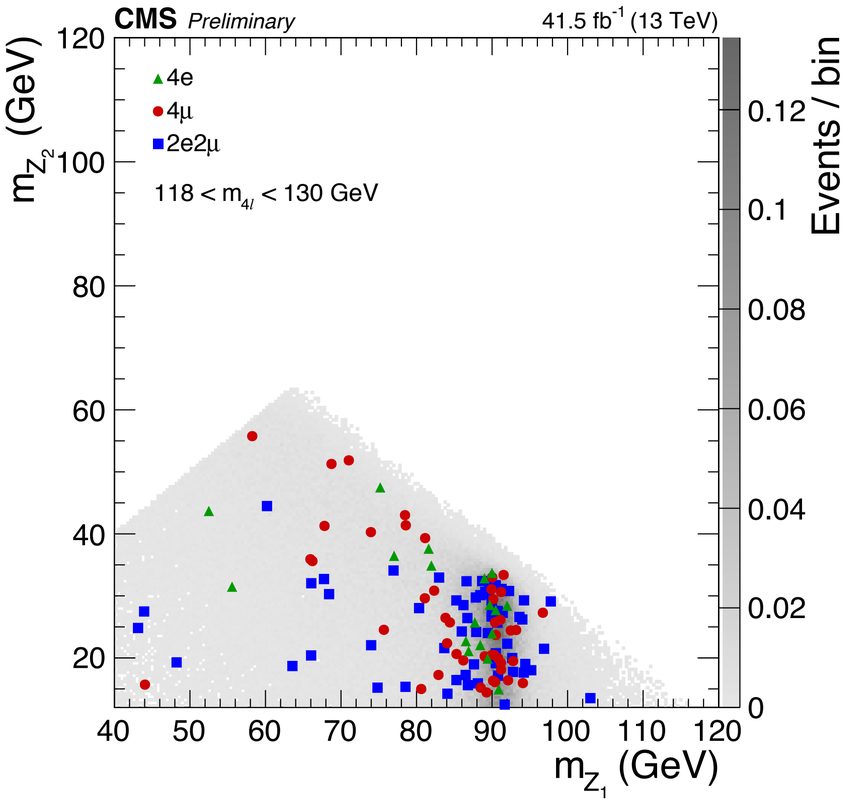
# Z DISTRIBUTIONS





# YIELDS 2016 VS 2017



**2017 - 41.5/fb**

| **Channel** | 4e | $4\mu$ | $2e2\mu$ | $4\ell$ |
|---|---|---|---|---|
| $q\bar{q} \to ZZ$ | $235^{+32}_{-36}$ | $443^{+36}_{-40}$ | $572^{+50}_{-54}$ | $1250^{+104}_{-114}$ |
| $gg \to ZZ$ | $49.1^{+8.7}_{-8.8}$ | $81.8^{+11.2}_{-10.7}$ | $121.5^{+17.1}_{-16.3}$ | $252.4^{+35.1}_{-33.5}$ |
| $Z + X$ | $17.1^{+6.4}_{-6.1}$ | $35.4^{+12.7}_{-11.4}$ | $47.8^{+16.4}_{-15.8}$ | $100.3^{+21.3}_{-20.6}$ |
| Sum of backgrounds | $301^{+39}_{-43}$ | $560^{+43}_{-47}$ | $741^{+62}_{-65}$ | $1602^{+126}_{-135}$ |
| Signal ($m_H = 125$ GeV) | $13.9^{+1.9}_{-2.1}$ | $28.9^{+2.5}_{-2.6}$ | $35.8 \pm 3.3$ | $78.5^{+7.0}_{-7.1}$ |
| Total expected | $315^{+41}_{-45}$ | $589^{+45}_{-49}$ | $777^{+64}_{-67}$ | $1681^{+131}_{-140}$ |
| Observed | 307 | 602 | 797 | 1706 |

**2016 - 35.9/fb**

| Channel | 4e | $4\mu$ | $2e2\mu$ | $4\ell$ |
|---|---|---|---|---|
| $q\bar{q} \to ZZ$ | $193^{+19}_{-20}$ | $360^{+25}_{-27}$ | $471^{+33}_{-36}$ | $1024^{+69}_{-76}$ |
| $gg \to ZZ$ | $41.2^{+6.3}_{-6.1}$ | $69.0^{+9.5}_{-9.0}$ | $102^{+14}_{-13}$ | $212^{+29}_{-27}$ |
| Z+X | $21.1^{+8.5}_{-10.4}$ | $34^{+14}_{-13}$ | $60^{+27}_{-25}$ | $115^{+32}_{-30}$ |
| Sum of backgrounds | $255^{+24}_{-25}$ | $463^{+32}_{-34}$ | $633^{+44}_{-46}$ | $1351^{+86}_{-91}$ |
| Signal | $12.0^{+1.3}_{-1.4}$ | $23.6 \pm 2.1$ | $30.0 \pm 2.6$ | $65.7 \pm 5.6$ |
| Total expected | $267^{+25}_{-26}$ | $487^{+33}_{-35}$ | $663^{+46}_{-47}$ | $1417^{+89}_{-94}$ |
| Observed | 293 | 505 | 681 | 1479 |

# YIELDS IN CATEGORIES



| | Event Category | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Untagged | VBF-1j | VBF-2j | VH-lept. | VH-hadr. | ttH-lept. | ttH-hadr. | Inclusive |
| $q\bar{q} \to ZZ$ | 22.72 | 1.91 | 0.13 | 0.23 | 0.19 | 0.00 | 0.01 | 25.19 |
| $gg \to ZZ$ | 1.93 | 0.30 | 0.03 | 0.04 | 0.02 | 0.00 | 0.00 | 2.32 |
| $Z + X$ | 9.60 | 0.80 | 0.56 | 0.17 | 0.56 | 0.04 | 0.15 | 11.87 |
| Sum of backgrounds | 34.25 | 3.00 | 0.72 | 0.44 | 0.77 | 0.04 | 0.16 | 39.38 |
| Uncertainties | $^{+2.79}_{-2.91}$ | $^{+0.30}_{-0.29}$ | $^{+0.14}_{-0.13}$ | $^{+0.04}_{-0.05}$ | $^{+0.12}_{-0.12}$ | $^{+0.01}_{-0.01}$ | $^{+0.10}_{-0.03}$ | $^{+3.29}_{-3.39}$ |
| ggH | 46.94 | 9.90 | 1.74 | 0.06 | 1.29 | $< 0.01$ | 0.04 | 59.96 |
| $qq \to qqH$ | 1.68 | 1.57 | 1.89 | 0.01 | 0.08 | $< 0.01$ | 0.01 | 5.24 |
| WH-lep | 0.18 | 0.02 | 0.01 | 0.28 | 0.01 | 0.01 | $< 0.01$ | 0.50 |
| WH-had | 0.48 | 0.16 | 0.05 | 0.00 | 0.32 | $< 0.01$ | 0.01 | 1.02 |
| ZH-lep | 0.29 | 0.02 | 0.01 | 0.07 | 0.03 | $< 0.01$ | $< 0.01$ | 0.43 |
| ZH-had | 0.32 | 0.10 | 0.03 | 0.00 | 0.23 | $< 0.01$ | 0.01 | 0.69 |
| $t\bar{t}H$ | 0.11 | $< 0.01$ | 0.02 | 0.03 | 0.04 | 0.18 | 0.25 | 0.65 |
| $b\bar{b}H$ | 0.48 | 0.10 | 0.02 | 0.01 | 0.02 | $< 0.01$ | $< 0.01$ | 0.63 |
| tqH | 0.03 | $< 0.01$ | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.09 |
| Signal | 50.51 | 11.87 | 3.79 | 0.47 | 2.03 | 0.20 | 0.33 | 69.21 |
| Uncertainties | $^{+4.68}_{-4.74}$ | $^{+1.41}_{-1.45}$ | $^{+0.68}_{-0.59}$ | $^{+0.04}_{-0.04}$ | $^{+0.28}_{-0.25}$ | $^{+0.03}_{-0.02}$ | $^{+0.05}_{-0.04}$ | $^{+6.13}_{-6.21}$ |
| Total expected | 84.76 | 14.87 | 4.51 | 0.91 | 2.80 | 0.24 | 0.49 | 108.58 |
| Uncertainties | $^{+6.52}_{-6.71}$ | $^{+1.59}_{-1.63}$ | $^{+0.74}_{-0.64}$ | $^{+0.07}_{-0.07}$ | $^{+0.32}_{-0.29}$ | $^{+0.03}_{-0.03}$ | $^{+0.11}_{-0.05}$ | $^{+8.21}_{-8.42}$ |
| Observed | 103 | 14 | 5 | 2 | 2 | 0 | 0 | 126 |

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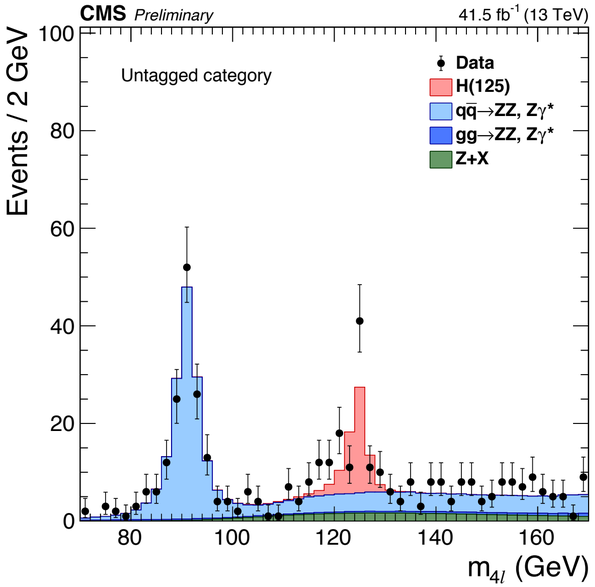
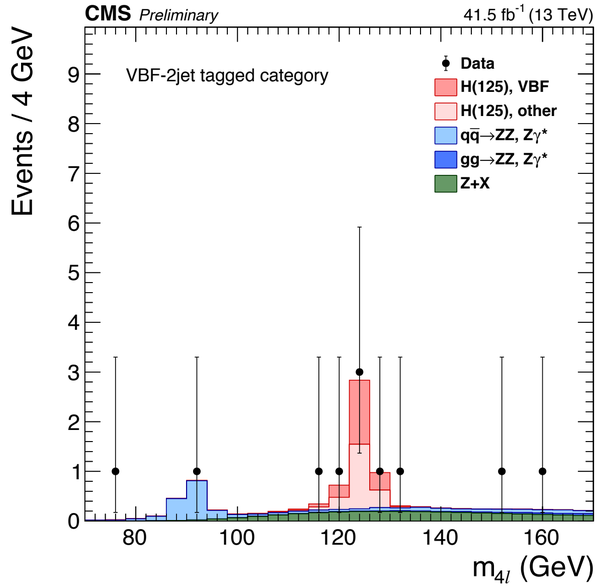
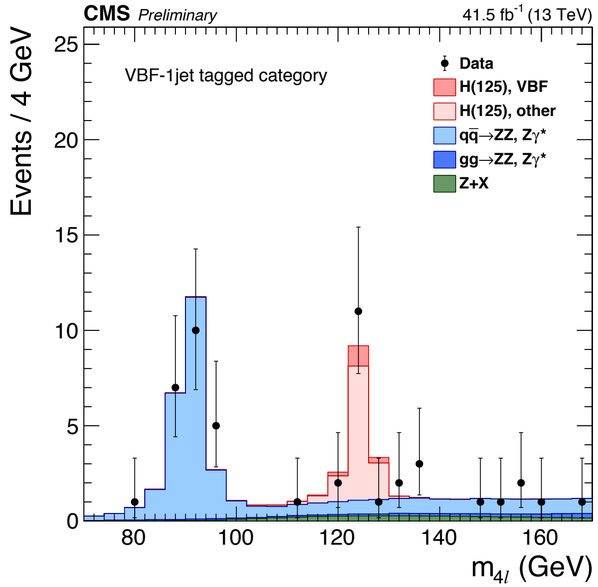
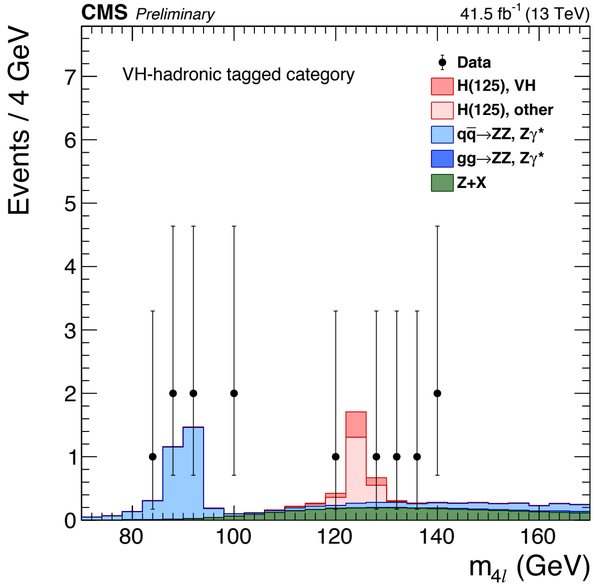
# DISTRIBUTIONS IN CATEGORIES

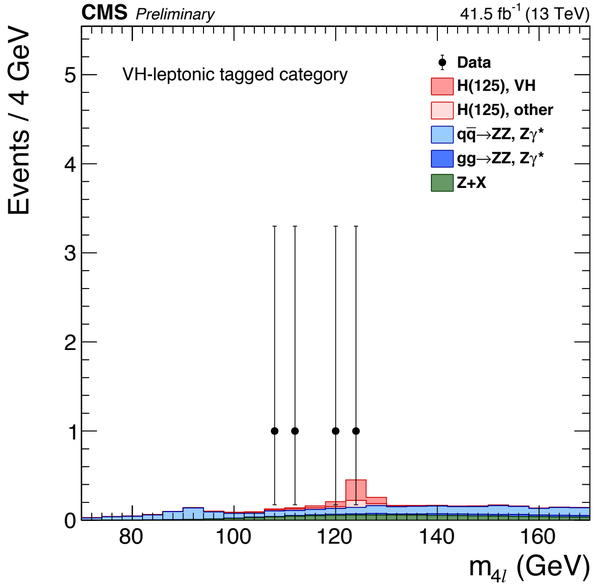


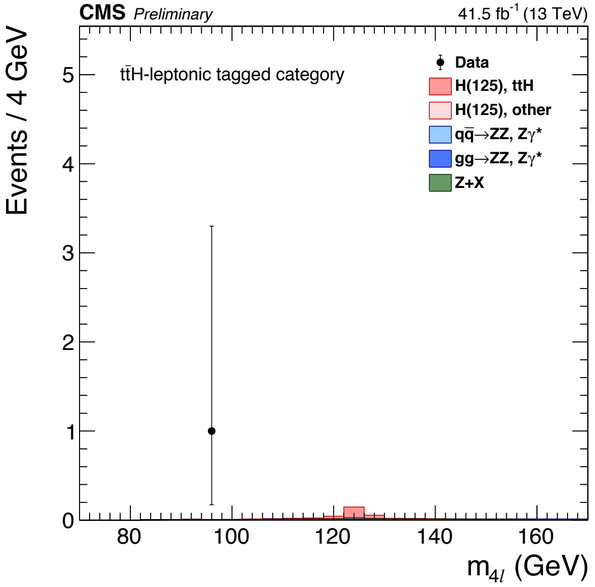


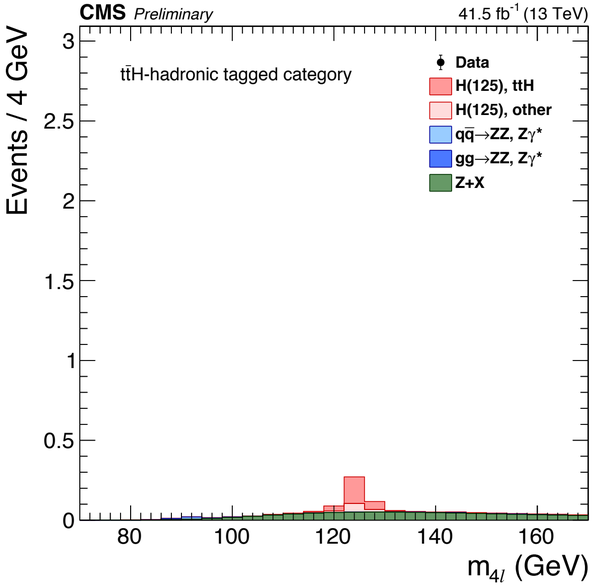



# SIGNAL STRENGTH



Table 3: Expected and observed signal-strength modifiers with 2017 data.

| | Inclusive | $\mu_{ggH,b\bar{b}H}$ | $\mu_{VBF}$ | $\mu_{VHhad}$ | $\mu_{VHlep}$ | $\mu_{t\bar{t}H,tqH}$ |
|---|---|---|---|---|---|---|
| Expected | $1.00^{+0.14}_{-0.13}(\text{stat})^{+0.11}_{-0.09}(\text{syst})$ | $1.00^{+0.22}_{-0.20}$ | $1.00^{+1.19}_{-0.79}$ | $1.00^{+3.24}_{-1.00}$ | $1.00^{+3.36}_{-1.00}$ | $1.00^{+2.47}_{-1.00}$ |
| Observed | $1.10^{+0.14}_{-0.13}(\text{stat})^{+0.13}_{-0.11}(\text{syst})$ | $1.14^{+0.23}_{-0.20}$ | $1.12^{+1.19}_{-0.83}$ | $0.00^{+1.54}_{-0.00}$ | $2.23^{+3.95}_{-2.12}$ | $0.00^{+0.93}_{-0.00}$ |

Table 4: Expected and observed signal-strength modifiers for combined 2016 and 2017 data.

| | Inclusive | $\mu_{ggH,b\bar{b}H}$ | $\mu_{VBF}$ | $\mu_{VHhad}$ | $\mu_{VHlep}$ | $\mu_{t\bar{t}H,tqH}$ |
|---|---|---|---|---|---|---|
| Expected | $1.00 \pm 0.10(\text{stat})^{+0.08}_{-0.06}(\text{exp. syst})^{+0.07}_{-0.05}(\text{th. syst})$ | $1.00^{+0.17}_{-0.16}$ | $1.00^{+0.86}_{-0.67}$ | $1.00^{+2.39}_{-1.00}$ | $1.00^{+2.30}_{-1.00}$ | $1.00^{+1.80}_{-1.00}$ |
| Observed | $1.06 \pm 0.10(\text{stat})^{+0.08}_{-0.06}(\text{exp. syst})^{+0.07}_{-0.05}(\text{th. syst})$ | $1.15^{+0.18}_{-0.16}$ | $0.69^{+0.75}_{-0.57}$ | $0.00^{+1.16}_{-0.00}$ | $1.25^{+2.46}_{-1.25}$ | $0.00^{+0.53}_{-0.00}$ |

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# TTH CATEGORIES



## 2016

| | ttH-lept. | ttH-hadr. |
|---|---|---|
| $q\bar{q} \to ZZ$ | 0.00 | 0.01 |
| $gg \to ZZ$ | 0.00 | 0.00 |
| Z + X | 0.04 | 0.15 |
| Sum of backgrounds | 0.04 | 0.16 |
| Uncertainties | $^{+0.01}_{-0.01}$ | $^{+0.10}_{-0.03}$ |
| ggH | $< 0.01$ | 0.04 |
| $qq \to qqH$ | $< 0.01$ | 0.01 |
| WH-lep | 0.01 | $< 0.01$ |
| WH-had | $< 0.01$ | 0.01 |
| ZH-lep | $< 0.01$ | $< 0.01$ |
| ZH-had | $< 0.01$ | 0.01 |
| $t\bar{t}H$ | 0.18 | 0.25 |
| $b\bar{b}H$ | $< 0.01$ | $< 0.01$ |
| tqH | 0.01 | 0.01 |
| Signal | 0.20 | 0.33 |
| Uncertainties | $^{+0.03}_{-0.02}$ | $^{+0.05}_{-0.04}$ |
| Total expected | 0.24 | 0.49 |
| Uncertainties | $^{+0.03}_{-0.03}$ | $^{+0.11}_{-0.05}$ |
| Observed | 0 | 0 |

## 2017

| | $t\bar{t}H$ |
|---|---|
| $q\bar{q} \to ZZ$ | 0.01 |
| $gg \to ZZ$ | $<0.0$ |
| Z+X | 0.27 |
| Sum of backgrounds | 0.28 |
| uncertainties | $^{+0.09}_{-0.07}$ |
| $gg \to H$ | 0.10 |
| VBF | 0.02 |
| WH | 0.02 |
| ZH | 0.02 |
| $t\bar{t}H$ | 0.35 |
| Signal | 0.51 |
| uncertainties | $^{+0.06}_{-0.06}$ |
| Total expected | 0.79 |
| uncertainties | $^{+0.14}_{-0.12}$ |
| Observed | 0 |