

# The Third China LHC Physics Workshop (CLHCP 2017)

Dec 22<sup>nd</sup> to Dec 24<sup>th</sup>



中国科学院  
CHINESE ACADEMY OF SCIENCES

## Higgs mass measurement in $H \rightarrow ZZ \rightarrow 4l$ channel

By:

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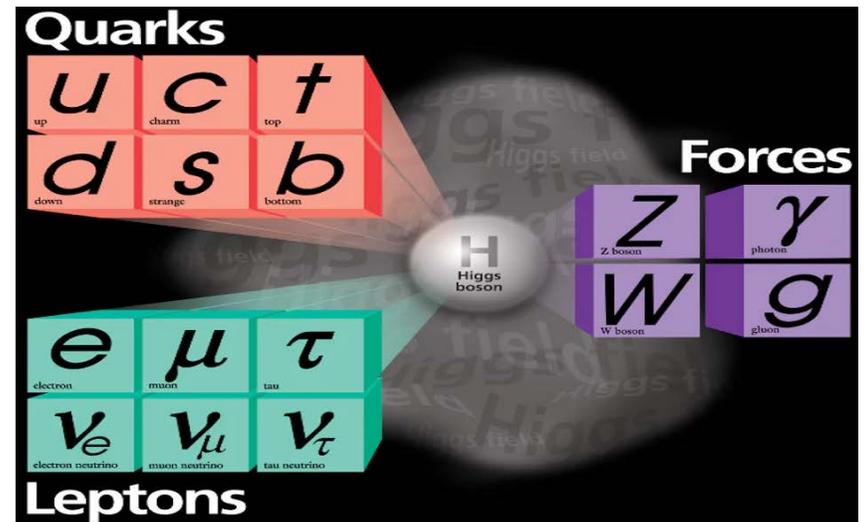
On the behalf of CMS Collaboration



- **Introduction**
- **Analysis strategy and elements**
  - Event reconstruction and Selection
  - Signal and background modelling
  - Systematic uncertainties
- **Results and comparisons**
- **Summary**

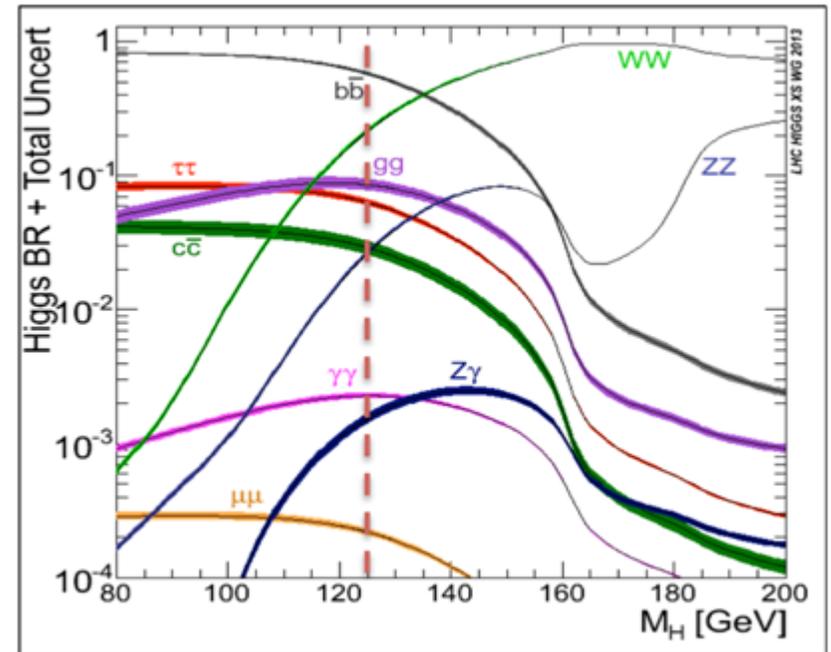
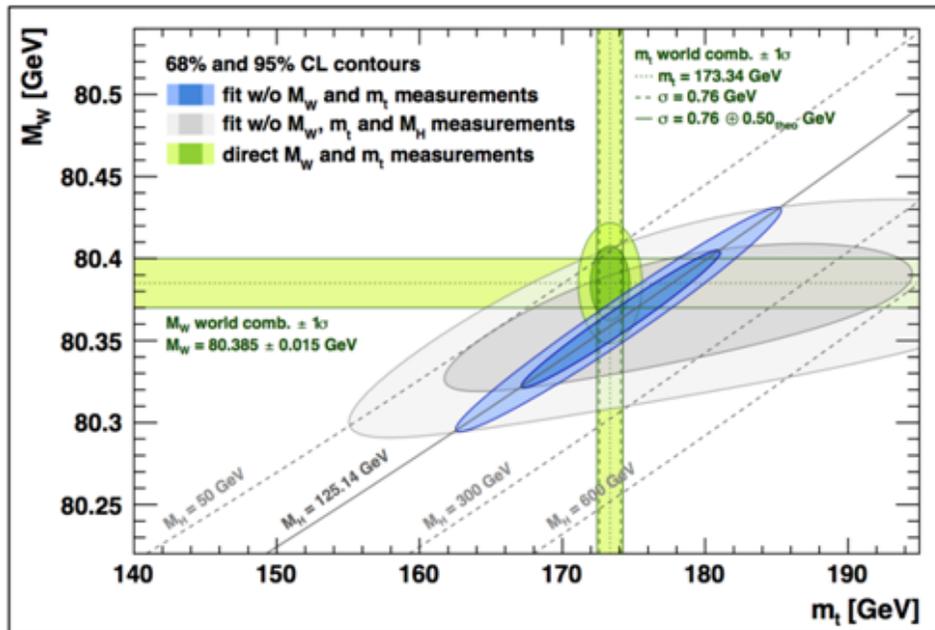
# Why Higgs...?

- ❖ Origin of mass
  - ❖ How world came into being
- ❖ Underpins SM of particle physics
  - ❖ How certain particles acquire mass
- ❖ The electroweak force
  - ❖ Helps to explain how EM and Weak forces can be unified
  - ❖ Long term goal: Grand Unification
- ❖ Supersymmetry
- ❖ Dark Matter
- ❖ **Validation of LHC**



# Higgs Mass

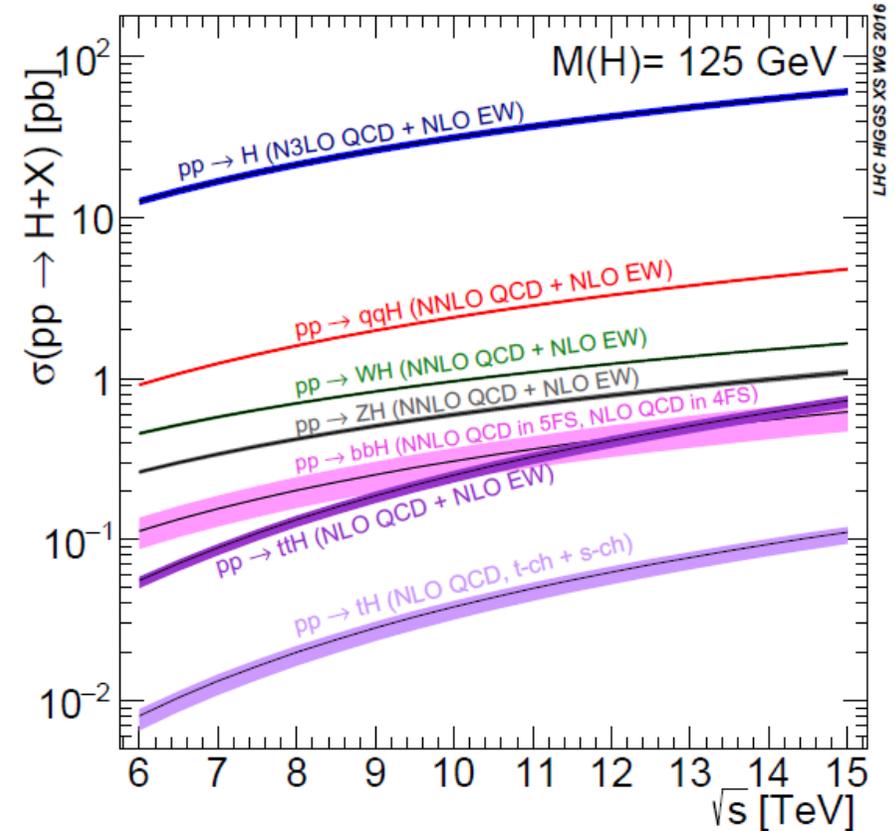
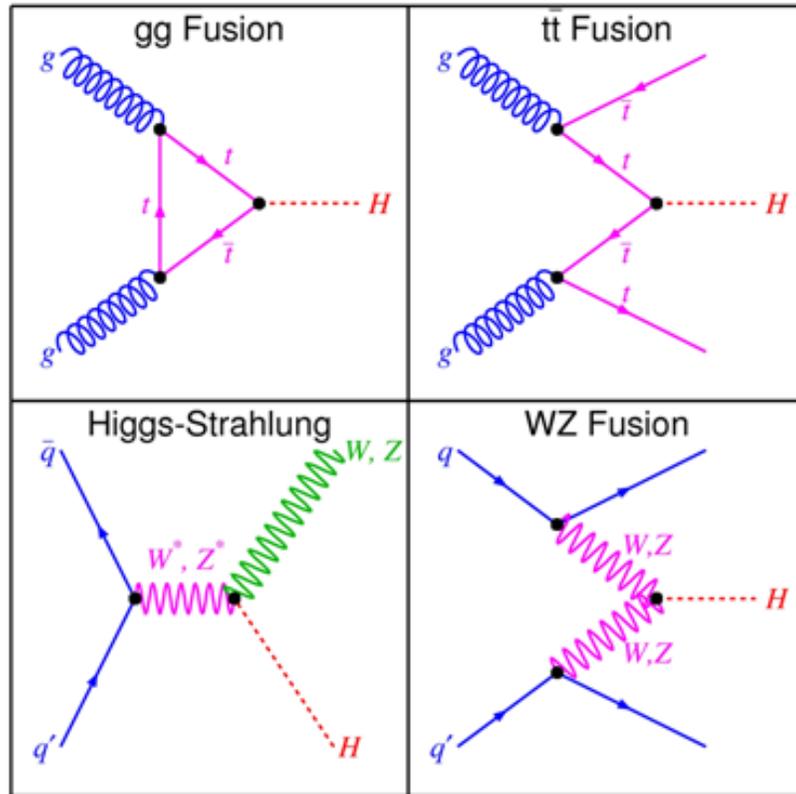
- ❖ A free parameter in the SM
- ❖ Fundamental position in the SM:
  - ❖ Calculation of the Higgs boson production and decay rates
  - ❖ Precise knowledge necessary to test the coupling structure



Consistency tests of SM parameters

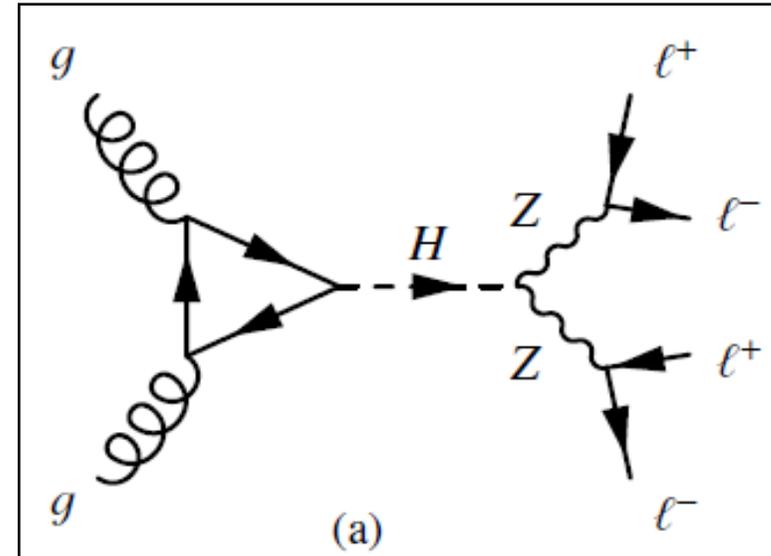
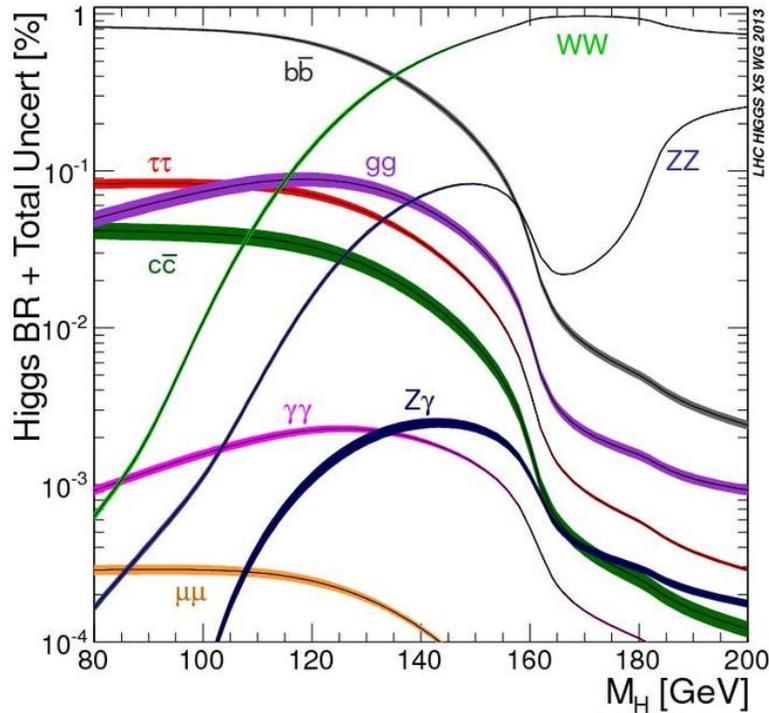
For HWW/HZZ:  $(\Delta\text{BR}/\text{BR})/\Delta m_H \approx 8\%/GeV$

# Higgs Production at Large Hadron Collider (LHC)



- Significant increase in production cross section from 8 TeV (Run1 2012) to 13TeV (Run2)
- $\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$  of Higgs: ggH  $\sim 2.3$ , VBF  $\sim 2.4$ , VH  $\sim 2.0$  and ttH  $\sim 3.9$ 
  - ❖ background increased by a factor of  $\sim 2$

# H → ZZ → 4l decay mode and its motivation



$\sigma \times \text{Br}(H \rightarrow ZZ \rightarrow 4l)$  quite small

- ❖ Needs highest selection efficiency possible
- Efficient lepton identification over a broad  $P_t$  range

Event Signature:

- ❖ 4 leptons (4e, 4μ, 2e2μ)
- ❖ Large S/B ratio (> 2:1)
- ❖ Good mass resolution (1-2%)
- ❖ Four isolated leptons from one point in 3D space
- ❖ Benefits from excellent electron and muon energy resolution

# Event selection and reconstruction

- ❖ Rel. isolation to isolate the z boson prompt leptons from EW decay ones,  $\mathcal{I}^\ell < 0.35$  within  $\Delta R=0.3$

where,

$$\mathcal{I}^\ell \equiv \left( \sum p_T^{\text{charged}} + \max \left[ 0, \sum p_T^{\text{neutral}} + \sum p_T^\gamma - p_T^{\text{PU}}(\ell) \right] \right) / p_T^\ell \quad \text{and} \quad \Delta R(i, j) = \sqrt{(\eta^i - \eta^j)^2 + (\phi^i - \phi^j)^2}$$

- ❖ Build Z candidates from OSSF pairs.
- ❖ For each ZZ candidate, defined  $Z_1$  candidate with  $m_{\ell\ell(\gamma)}$  closest to the PDG mass, the other as  $Z_2$ .

Lepton kinematics and isolation	
Leading lepton $p_T$	$p_T > 20 \text{ GeV}$
Subleading 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 $p_T$ of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Invariant mass of the $Z_1$ candidate	$40 < m_{Z_1} < 120 \text{ GeV}$
Invariant mass of the $Z_2$ candidate	$12 < m_{Z_2} < 120 \text{ GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Invariant mass of any opposite-sign lepton pair	$m_{\ell^+\ell^-} > 4 \text{ GeV}$
Invariant mass of the selected four leptons	$105 < m_{4\ell} < 140 \text{ GeV}$

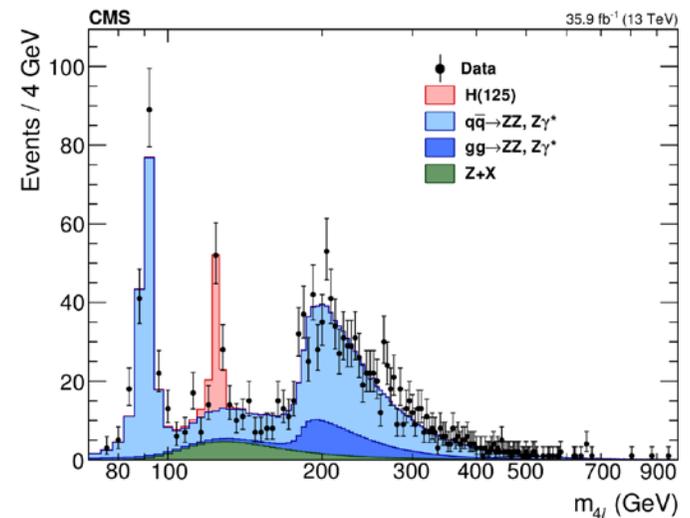
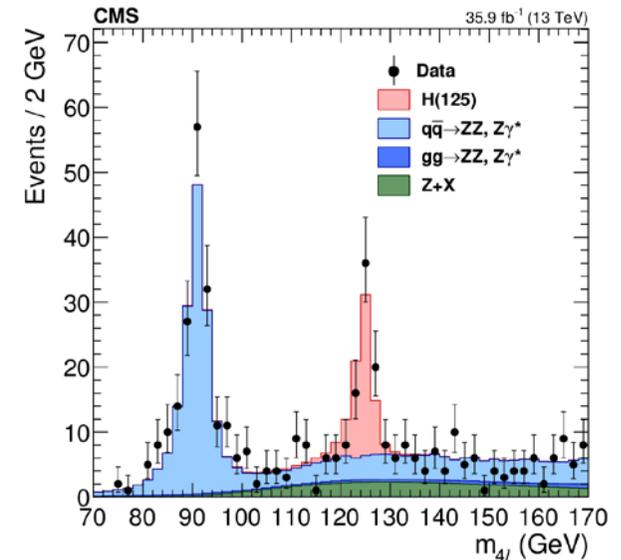
# Background Estimation & Kinematic mass distributions

## Irreducible:

- ❖ Production of ZZ via  $q\bar{q}$  annihilation or gluon fusion
- ❖ estimated using **simulation**

## Reducible:

- ❖ Secondary leptons produced by heavy flavor jets
- ❖ Z+jets,  $t\bar{t}$ , WZ...important at low  $m_{4l}$
- ❖ Misidentified leptons coming from decays of heavy flavor hadrons, in-flight decays of light mesons within jets, or (for electrons) the decay of charged hadrons overlapping with  $\pi^0$  decays
- ❖ OSSF method
  - ❖ Two control regions: 2P2F and 3P1F
- ❖ SSSF method
  - ❖ One control region (2P2LSS)

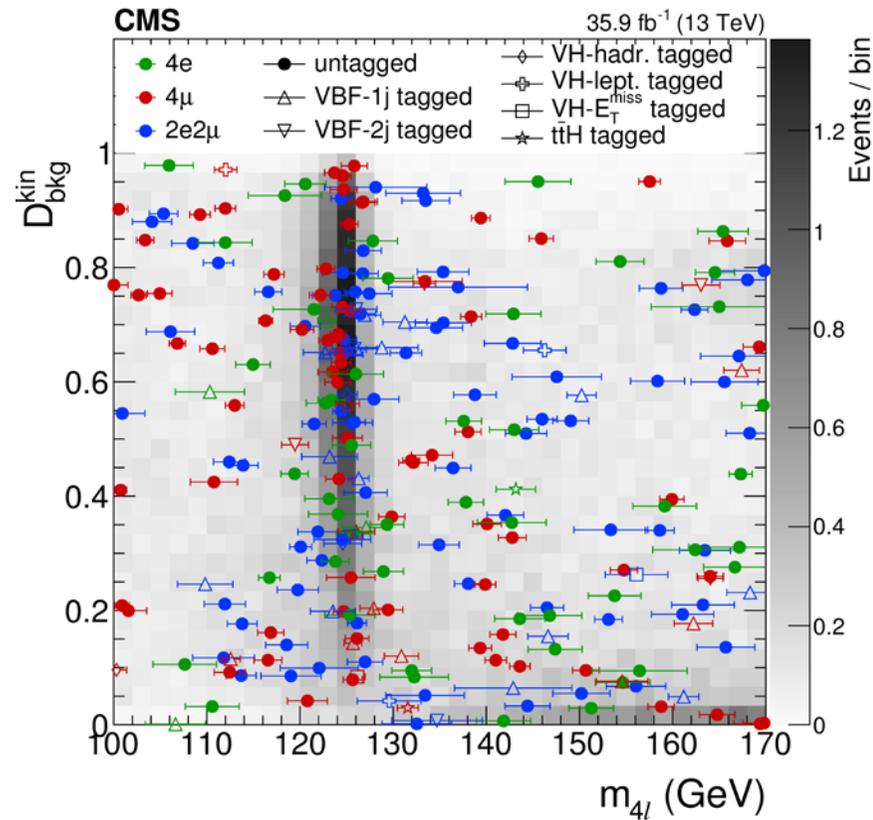


Distribution of reconstructed four-lepton invariant mass

# Observables

- ❖ 4 lepton invariant mass :  $m_{4l}$
- ❖ Event-by-event mass uncertainty :  $D_{mass} = \sigma_{m_{4l}} / m_{4l}$   
propagated from individual lepton  $p_T$  resolution  
(Corrected in data/MC using  $Z \rightarrow ll$  events)
- ❖ Matrix element kinematic discriminants:

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

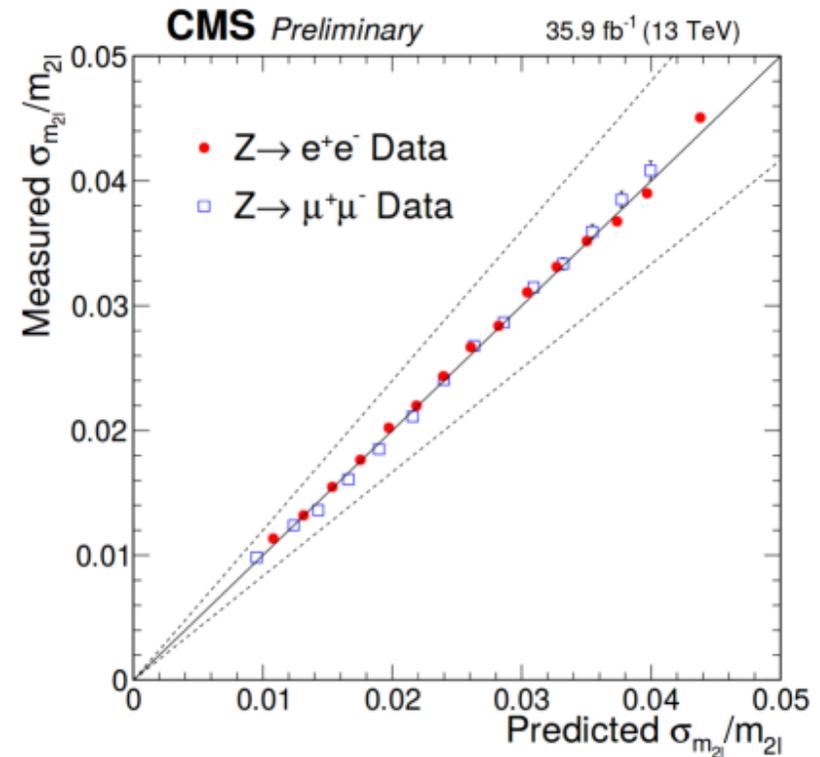


CMS-HIG-16-041

## Correction of per-event mass error

- ❖ Event by event mass error: lepton momentum error propagated to  $m_{4l}$
- ❖ Important for mass measurement when statistics are limited

- ❖ Huge effort on mass resolution validation by comparing measured mass resolution with the predicted di-lepton mass resolution using the event-by-event mass uncertainty for  $Z \rightarrow \ell\ell$  events in data.
- ❖ The dashed lines denote a  $\pm 20\%$  region, used as the systematic uncertainty on the resolution.



# Z<sub>1</sub> Mass Constraint

- ❖ Define Z<sub>1</sub> (l+l pair) as intermediate Z boson with mass closer to PDG mass
  - ❖ Significantly on-shell
- ❖ Perform kinematic fit using Z<sub>1</sub> mass as constraint
  - ❖ kinematic fit using Z<sub>1</sub> leptons
  - ❖ Expected 8% improvement in m<sub>H</sub> uncertainty

Likelihood to be maximized:

$$L(p_T^1, p_T^2 | p_T^{reco1}, \sigma p_T^1, p_T^{reco2}, \sigma p_T^2) = \text{Gauss}(p_T^{reco1} | p_T^1, \sigma p_T^1) \cdot \text{Gauss}(p_T^{reco2} | p_T^2, \sigma p_T^2) \cdot L(m_{l_2} | m_Z, m_H)$$

## Inputs

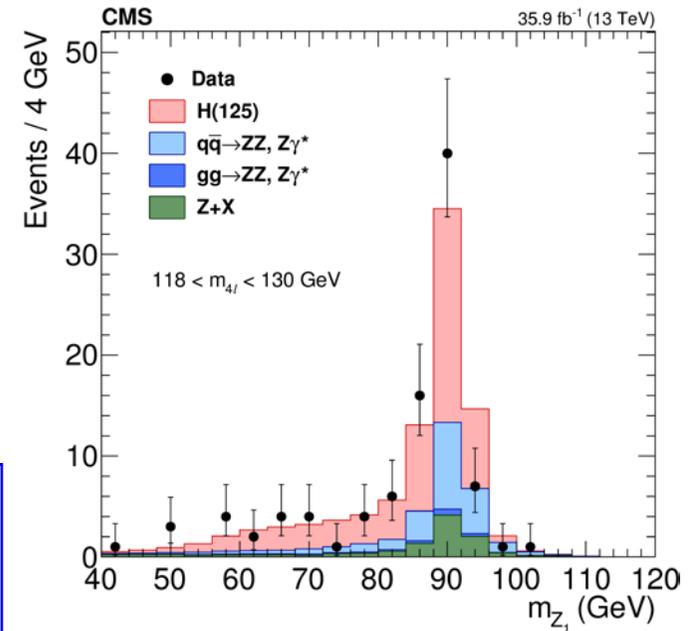
$p_T^{reco1}, p_T^{reco2}$ : reconstructed lepton  $p_T$   
 $\sigma p_T^1, \sigma p_T^2$ : lepton  $p_T$  resolution

## Outputs

$p_T^1, p_T^2$ : refitted lepton  $p_T$   
 $\sigma(p_T^1), \sigma(p_T^2)$ : refitted lepton  $p_T$  resolution

## Constraint :

$L(m_{l_2} | m_Z, m_H)$ : Z<sub>1</sub> lineshape at generator level from SM Higgs sample with  $m_H = 125\text{GeV}$   $m_{l_2}$  is calculated from  $p_T^1$  and  $p_T^2$

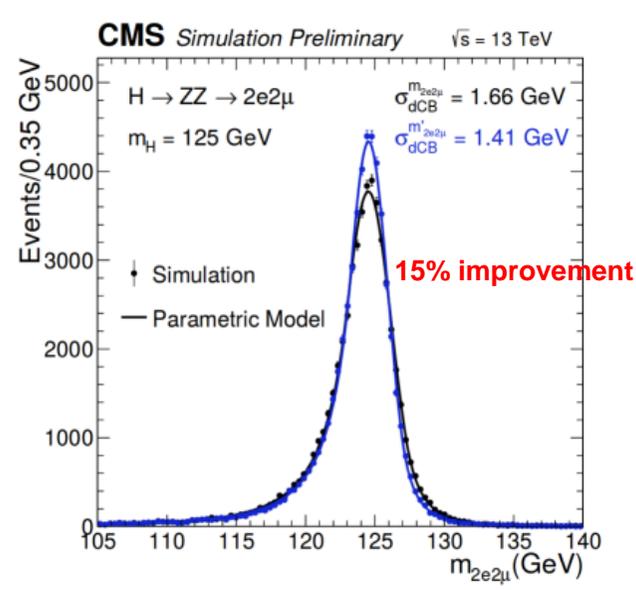
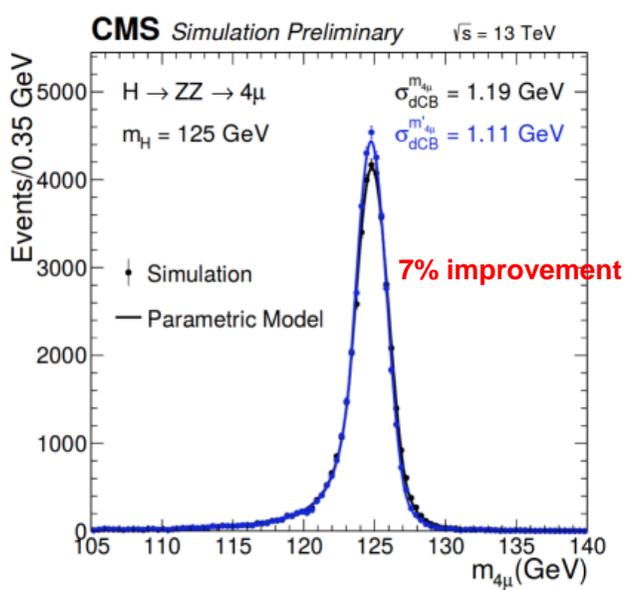
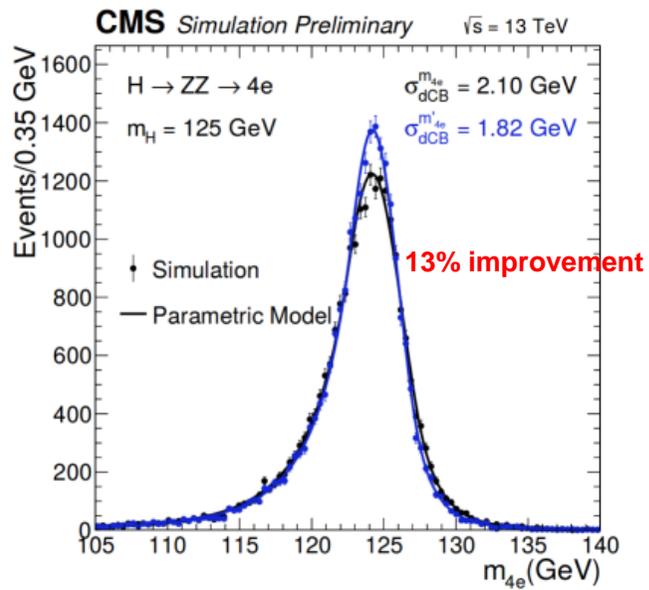
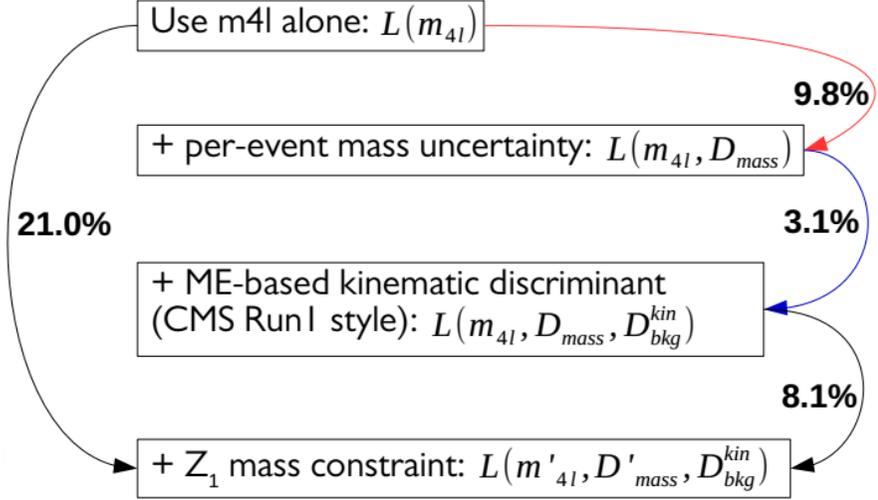


→ Use refitted lepton  $p_T$  and uncertainty to recalculate  $m_{4l}$  and  $D_{mass}$

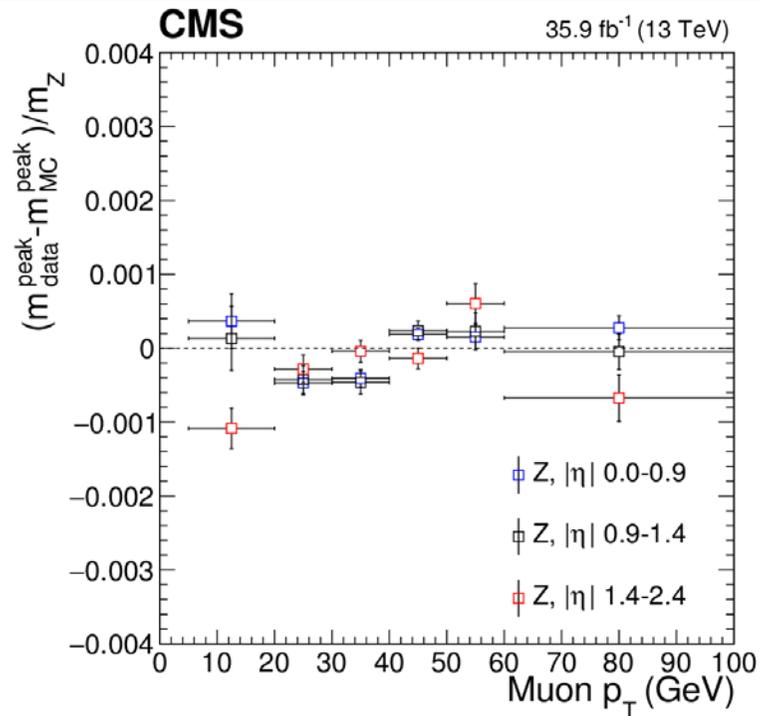
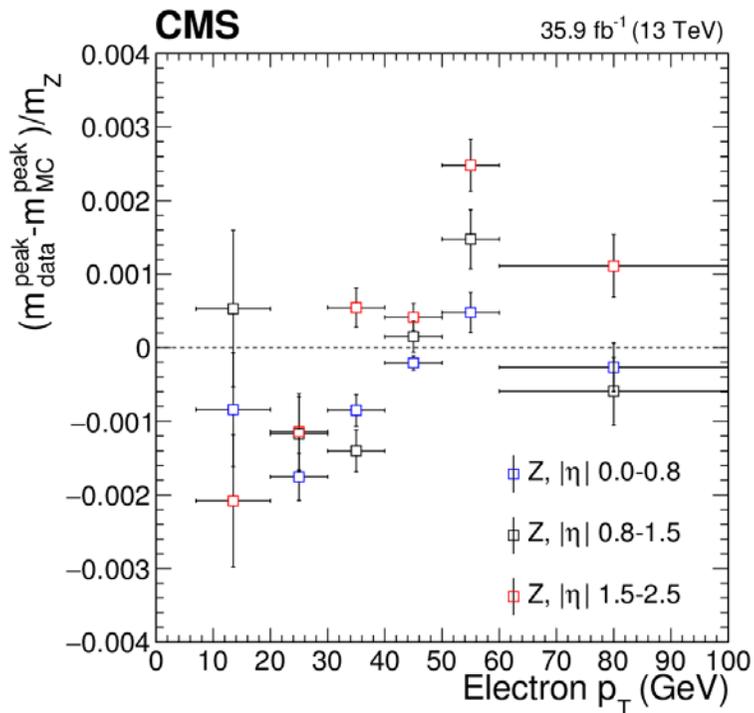
# Mass Measurement

## Precision gain

- ❖ Perform 3D fit:  $\mathcal{L}(m_{4\ell}, D_{mass}, D_{bkg}^{kin})$   
Per event mass error corrected in data/MC using  $Z \rightarrow \ell\ell$  events
- ❖ Mass resolution improved by performing kinematic fit using  $Z_1$  leptons
  - ❖ Expected 8% improvement in  $m_H$  uncertainty



# Lepton Energy Scale Uncertainty



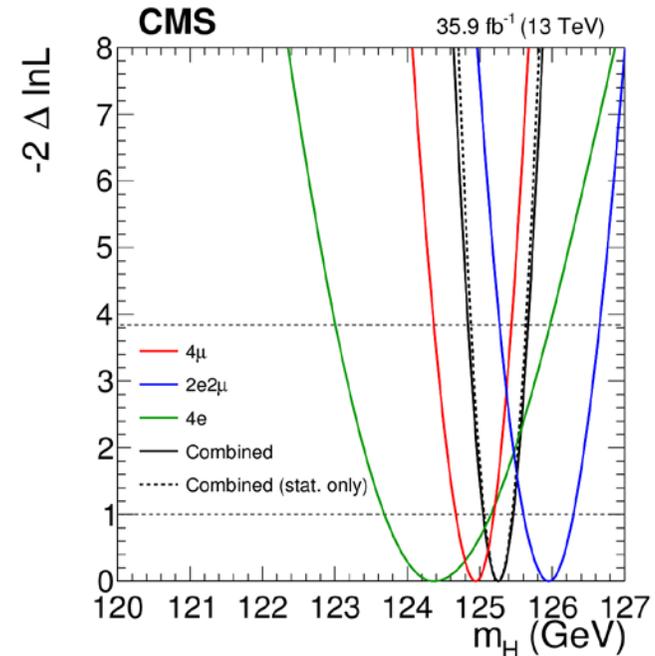
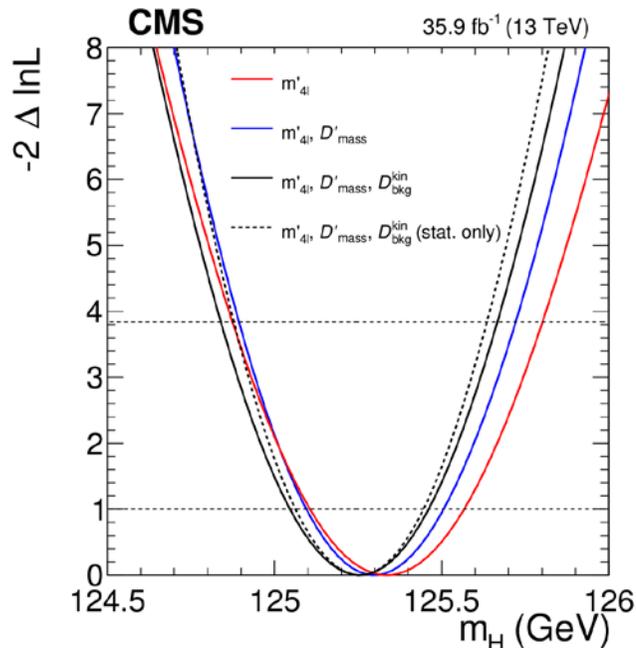
- ❖ Events are separated into categories based on the  $p_T$  and  $\eta$  of one of the two leptons in data/MC
- ❖ Fit di-lepton mass distributions to a Breit-Wigner parameterization convolved with a double-sided Crystal Ball (CB) function
- ❖ Extract offset in the measured peak position with respect to the nominal Z-boson mass
- ❖ Relative difference between data and simulation is propagated to the reconstructed four-lepton mass from simulated Higgs-boson events
- ❖ The uncertainty is determined to be **0.04%**, **0.3%** and **0.02** for the **4 $\mu$** , **4e** and **2e2 $\mu$**  channels, respectively

# Mass Measurement Results

Use per event mass uncertainty + ME-based kinematic discriminant + Z1 mass constraint

No $m(Z_1)$ constraint	3D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}}, \mathcal{D}_{\text{bkg}}^{\text{kin}})$	2D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}})$	1D: $\mathcal{L}(m_{4l})$
Expected $m_H$ uncertainty change	—	+3.6%	+16%
Observed $m_H$ (GeV)	$125.28 \pm 0.22$	$125.36 \pm 0.24$	$125.39 \pm 0.25$
With $m(Z_1)$ constraint	3D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\text{mass}}, \mathcal{D}_{\text{bkg}}^{\text{kin}})$	2D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\text{mass}})$	1D: $\mathcal{L}(m'_{4l})$
Expected $m_H$ uncertainty change	-8.1%	-4.7%	+2.5%
Observed $m_H$ (GeV)	$125.26 \pm 0.21$	$125.30 \pm 0.21$	$125.34 \pm 0.23$

$$m_H = 125.26 \pm 0.20(\text{stat.}) \pm 0.08(\text{sys.}) \text{ GeV}$$



## Comparison

CMS (4l)

13TeV, 35.9 fb<sup>-1</sup>

$m_H = 125.26 \pm 0.20(\text{stat.}) \pm 0.08(\text{syst.}) \text{ GeV}$

ATLAS (4l)

13TeV, 36.1 fb<sup>-1</sup>

$m_H = 124.88 \pm 0.37(\text{stat.}) \pm 0.05(\text{syst.}) \text{ GeV}$

ATLAS (Combined)

$m_H = 124.98 \pm 0.19(\text{stat.}) \pm 0.21(\text{syst.}) \text{ GeV}$

LHC Run 1

$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}$

CMS ( $\gamma\gamma$ )

13TeV, 35.9 fb<sup>-1</sup>

$m_H = 125.4 \pm 0.2(\text{stat.}) \pm 0.2(\text{syst.}) \text{ GeV}$

ATLAS ( $\gamma\gamma$ )

13TeV, 36.1 fb<sup>-1</sup>

$m_H = 125.11 \pm 0.21(\text{stat.}) \pm 0.36(\text{syst.}) \text{ GeV}$

**Higgs mass measurement results are best to date!**

[CMS-HIG-16-041](#)

[CMS-HIG-16-040](#)

[ATLAS-CONF-2017-046](#)

## Summary

- ❖ Latest results of Higgs measurements in four-lepton final state in pp collisions at  $\sqrt{s} = 13$  TeV (full 2016 dataset) are presented
- ❖ Mass measurements have been performed, exceeding the sensitivity of previous results
- ❖ Measurements compatible with SM predictions

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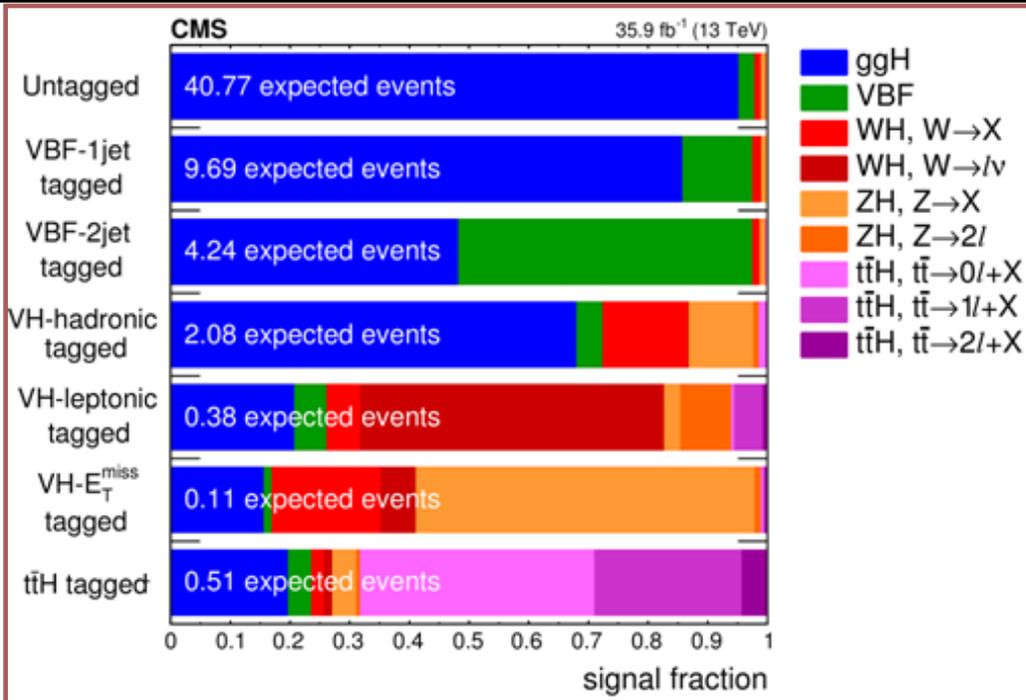
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Thank You  
For  
Paying  
Attention  
!!!

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# BACKUP SLIDES

# Event Categorization

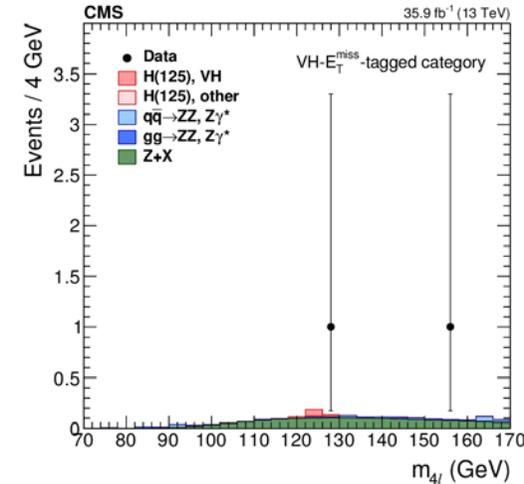
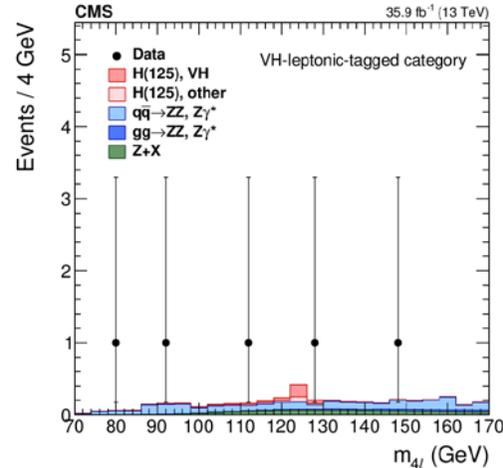
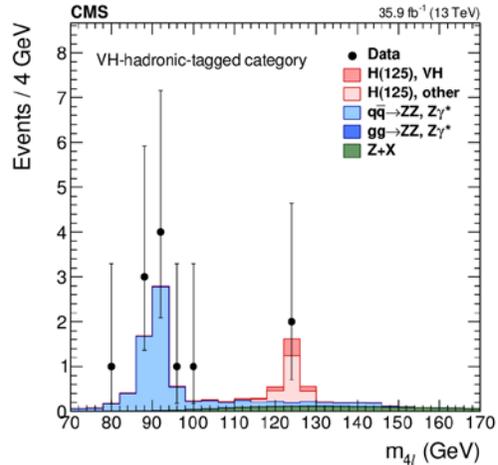
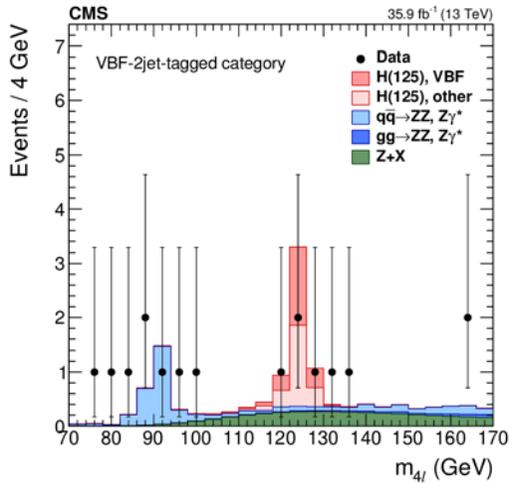
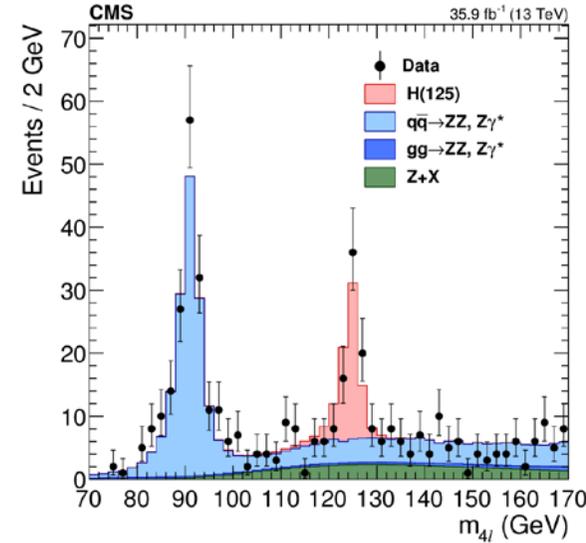
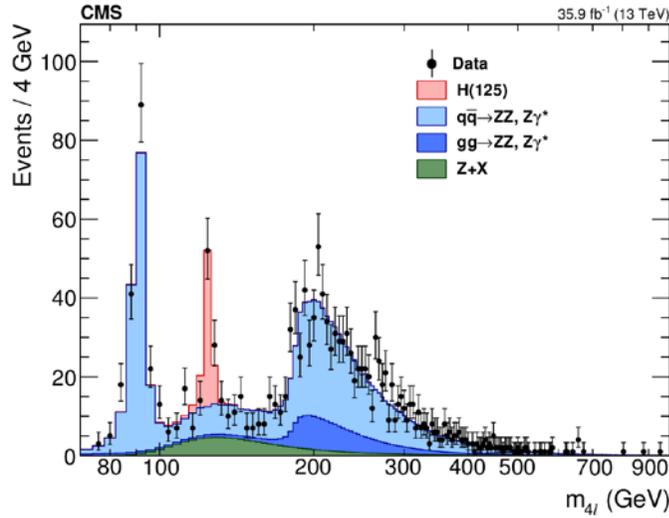


- ❖ Categories based on hadronic activity have significant ggH contamination
  - ❖ ~50% in VBF 2-jet tagged
- ❖ Categories with lepton/MET tags very pure, but low event yield expected
- ❖ Events classified into 7 mutually exclusive event categories targeting main SM production modes
- ❖ Performed using jet/lepton/ b-tag multiplicity, MET, and production discriminants

- ❖ **VBF-2jet-tagged category:** 4l, there must be either two or three jets of which at most one is b-tagged, or four or more jets none of which are b-tagged.  $D_{2\text{jet}} > 0.5$  is required.
- ❖ **VH-hadronic-tagged category** requires exactly four leptons. In addition, there must be two or three jets, or four or more jets none of which are b-tagged.  $D_{\text{VH}} \equiv \max(D_{\text{ZH}}, D_{\text{WH}}) > 0.5$  is required
- ❖ **VH-leptonic-tagged category** requires no more than three jets and no b-tagged jets in the event, and exactly one additional lepton or one additional pair of OS, same-flavor leptons. This category also includes events with no jets and at least one additional lepton.
- ❖ **ttH-tagged category** requires at least four jets of which at least one is b tagged, or at least one additional lepton.
- ❖ **VH-  $E_T^{\text{miss}}$  -tagged category** requires exactly four leptons, no more than one jet and  $E_T^{\text{miss}}$  greater than 100 GeV.
- ❖ **VBF-1jet-tagged category** requires exactly four leptons, exactly one jet and  $D_{1\text{jet}} > 0.5$

# Kinematic mass distributions

Distribution of reconstructed four-lepton invariant mass



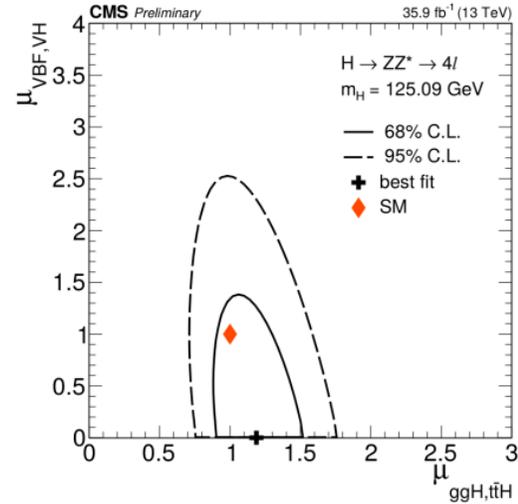
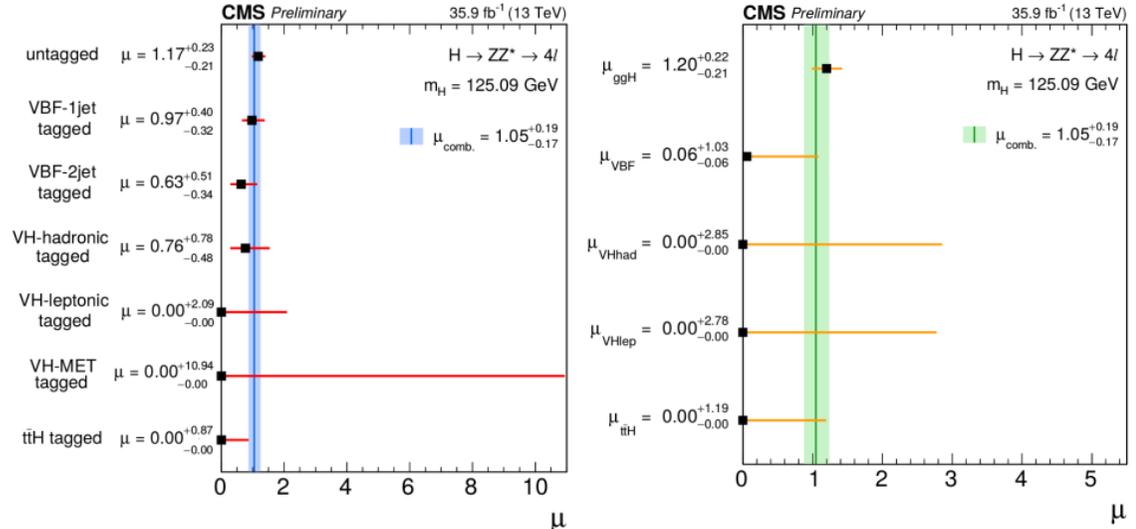
# Event selection and reconstruction

- ❖ **Particle Flow** algorithm; **PF candidates:** charged & neutral hadrons, photons, electrons, or muons
- ❖ Rel. isolation to isolate the z boson prompt leptons from EW decay ones,  $\mathcal{I}^\ell < 0.35$  within  $\Delta R=0.3$  where
 
$$\mathcal{I}^\ell \equiv \left( \sum p_T^{\text{charged}} + \max \left[ 0, \sum p_T^{\text{neutral}} + \sum p_T^\gamma - p_T^{\text{PU}}(\ell) \right] \right) / p_T^\ell \quad \text{and} \quad \Delta R(i, j) = \sqrt{(\eta^i - \eta^j)^2 + (\phi^i - \phi^j)^2}$$
- ❖ Build Z candidates from OSSF pairs which satisfy  $12 < m_{\ell\ell(\gamma)} < 120$  GeV
- ❖ For each ZZ candidate, defined  $Z_1$  candidate with  $m_{\ell\ell(\gamma)}$  closest to the PDG mass, the other as  $Z_2$ .
- ❖ If  $>1$  ZZ cand., choose the one with highest  $D_{\text{bkg}}^{\text{kin}}$ . If  $>1$  ZZ cand. with same  $D_{\text{bkg}}^{\text{kin}}$ , choose the one with  $m(Z_1)$  closest to PDG  $m(Z)$ :
  - ❖ For Fiducial cross section, choose ZZ cand. with  $m(Z_1)$  closest to PDG  $m(Z)$ . If  $>1$  ZZ cand. with same  $Z_1$ , choose the  $Z_2$  with highest scalar  $p_T$  sum.

Lepton kinematics and isolation	
Leading lepton $p_T$	$p_T > 20$ GeV
Subleading lepton $p_T$	$p_T > 10$ GeV
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Pseudorapidity of electrons (muons)	$ \eta  < 2.5$ (2.4)
Sum $p_T$ of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Invariant mass of the $Z_1$ candidate	$40 < m_{Z_1} < 120$ GeV
Invariant mass of the $Z_2$ candidate	$12 < m_{Z_2} < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Invariant mass of any opposite-sign lepton pair	$m_{\ell^+\ell^-} > 4$ GeV
Invariant mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

# Signal Strength

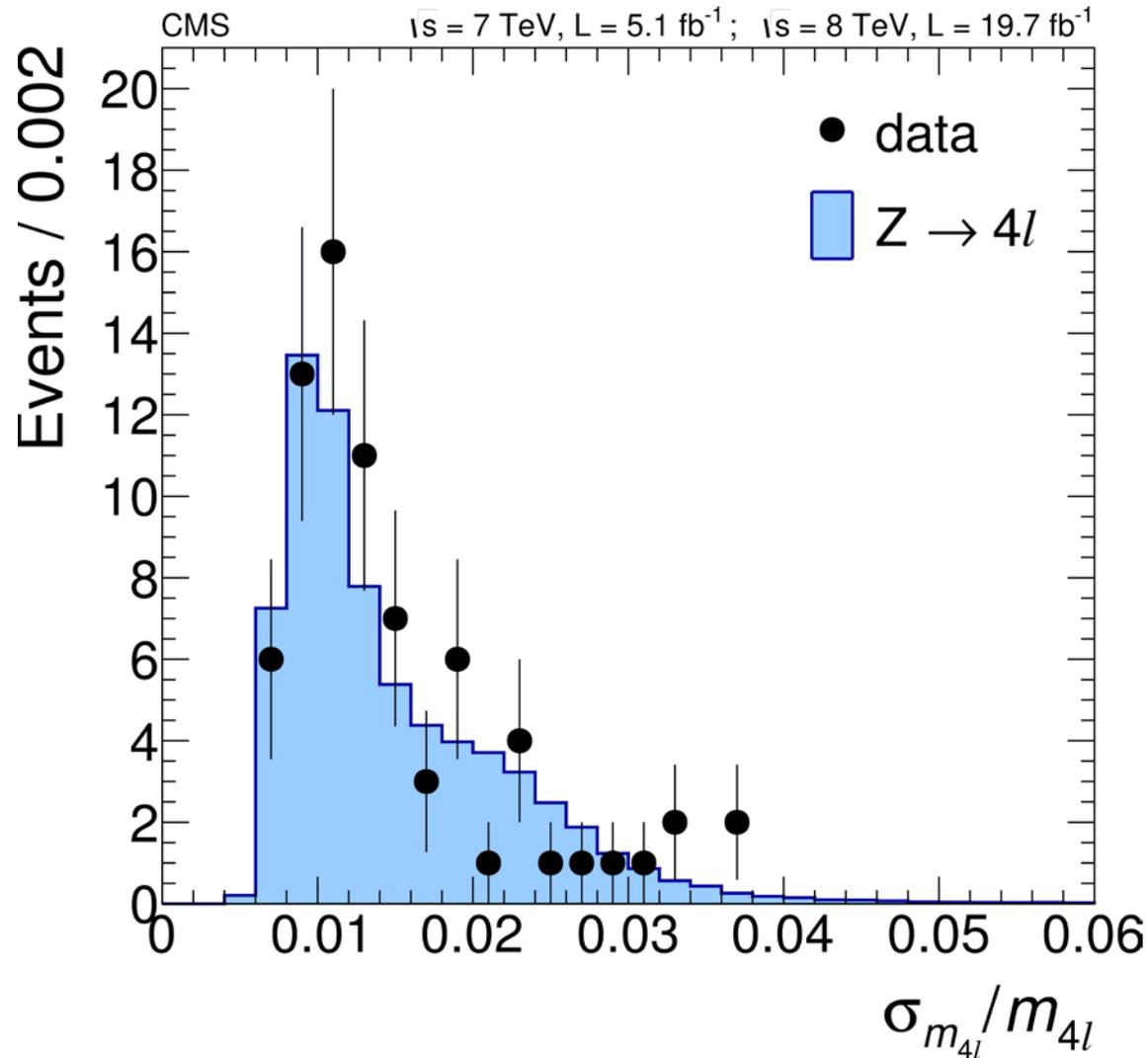
- ❖ Signal strength extracted with 2D fit:
 
$$\mathcal{L}_{2D}(m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}}) = \mathcal{L}(m_{4\ell})\mathcal{L}(\mathcal{D}_{\text{bkg}}^{\text{kin}} | m_{4\ell})$$
- ❖ Slight excess in untagged category drives down the signal strength of VBF, VH (significant yield in hadronic categories)
- ❖ Low  $\mathcal{D}_{\text{bkg}}^{\text{kin}}$  values for events near 125 GeV in leptonic categories
- ❖ Also present 2D scan of  $\mu_{\text{VBF,VH}}$  vs  $\mu_{\text{ggH,ttH}}$



	Inclusive	$\mu_{\text{ggH}}$	$\mu_{\text{VBF}}$	$\mu_{\text{VHhad}}$	$\mu_{\text{VHlep}}$	$\mu_{\text{ttH}}$
Expected	$1.00^{+0.15}_{-0.14}(\text{stat.})^{+0.10}_{-0.09}(\text{sys.})$	$1.00^{+0.23}_{-0.21}$	$1.00^{+1.25}_{-0.97}$	$1.00^{+3.97}_{-1.00}$	$1.00^{+3.94}_{-1.00}$	$1.00^{+3.24}_{-1.00}$
Observed	$1.05^{+0.15}_{-0.14}(\text{stat.})^{+0.11}_{-0.09}(\text{sys.})$	$1.20^{+0.22}_{-0.21}$	$0.06^{+1.03}_{-0.06}$	$0.00^{+2.85}_{-0.00}$	$0.00^{+2.78}_{-0.00}$	$0.00^{+1.19}_{-0.00}$

CMS-HIG-16-041

# Z4l data/mc comparison



CMS-HIG-13-002

# LHC Run 1 Mass Measurement

