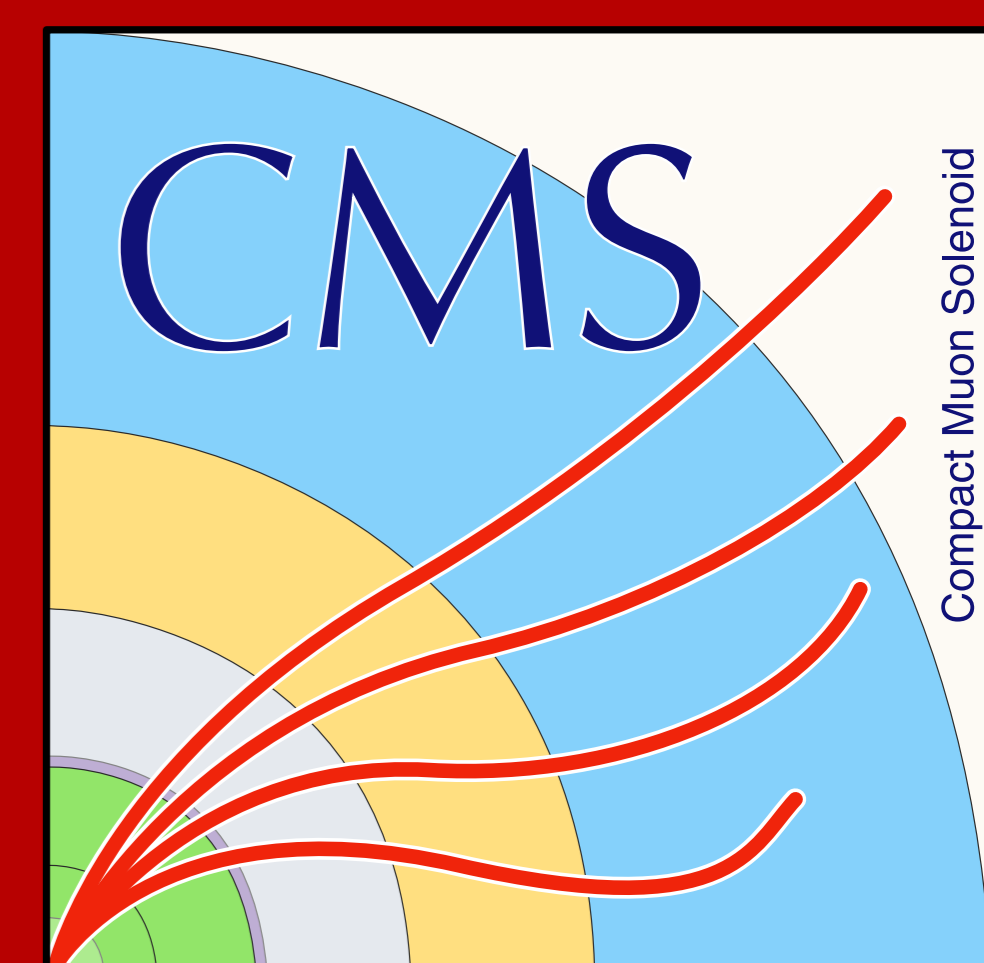


# Measurement of the ZZ production cross section and Z to 4ℓ branching fraction in pp collisions at $\sqrt{s} = 13$ TeV with the CMS Detector



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## Abstract

Four-lepton production in proton-proton collisions,  $pp \rightarrow (Z/\gamma^*) (Z/\gamma^*) \rightarrow 2\ell 2\ell'$ , ( $\ell, \ell' = e$  or  $\mu$ ), is studied at a center-of-mass energy of 13 TeV with the CMS detector at the LHC. The data sample corresponds to an integrated luminosity of  $2.6 \text{ fb}^{-1}$ . The ZZ production cross section is measured to be  $\sigma(pp \rightarrow ZZ) = 14.6_{-1.8}^{+1.9} (\text{stat})_{-0.3}^{+0.5} (\text{syst}) \pm 0.2 (\text{theo}) \pm 0.4 (\text{lumi}) \text{ pb}$ , for events with two Z bosons produced in the mass range  $60 < m_{\ell\ell} < 120 \text{ GeV}$ . The Z boson branching fraction to four leptons is measured to be  $\mathcal{B}(Z \rightarrow 4\ell) = 4.9_{-0.7}^{+0.8} (\text{stat})_{-0.2}^{+0.3} (\text{syst})_{-0.1}^{+0.2} (\text{theo}) \pm 0.1 (\text{lumi}) \times 10^{-6}$  for the four-lepton invariant mass in the range  $80 < m_{4\ell} < 100 \text{ GeV}$  and dilepton mass  $m_{\ell\ell} > 4 \text{ GeV}$  for all opposite-sign, same-flavor lepton pairs. The results agree with standard model predictions.

## Introduction

### Multiboson production of massive vector bosons: ZZ

- Precision test of the electroweak gauge structure of Standard Model
- Small cross section, but clean  $ZZ \rightarrow 2\ell 2\ell'$  ( $\ell, \ell' = e, \mu$ ) signal visible in small data set
- Resonant Z and Higgs boson production
- Nonresonant ZZ production
  - Primary irreducible background to Higgs measurements
- Potential early sign of new physics
  - Anomalous triple and quartic gauge couplings
  - Resonant production of new particles decaying to ZZ

## Data and Monte Carlo Samples

### Data Sample

- Sample of  $\sqrt{s} = 13$  TeV proton-proton collisions collected by CMS during 2015 LHC run
- Integrated luminosity of the sample is  $2.6 \pm 0.07 \text{ fb}^{-1}$

### Simulated Samples

- $q\bar{q} \rightarrow ZZ$  signal samples generated at next-to-leading order (NLO) with POWHEG 2.0
  - Scaled to next-to-next-to-leading order (NNLO) cross section
- $gg \rightarrow ZZ$  signal samples generated at leading order (LO) with MCFM
  - Scaled to next-to-leading order (NLO) cross section
- PYTHIA used for parton showering, hadronization, and underlying event simulation.
- Detector response simulated with GEANT4.

## Event Selection

### Full spectrum

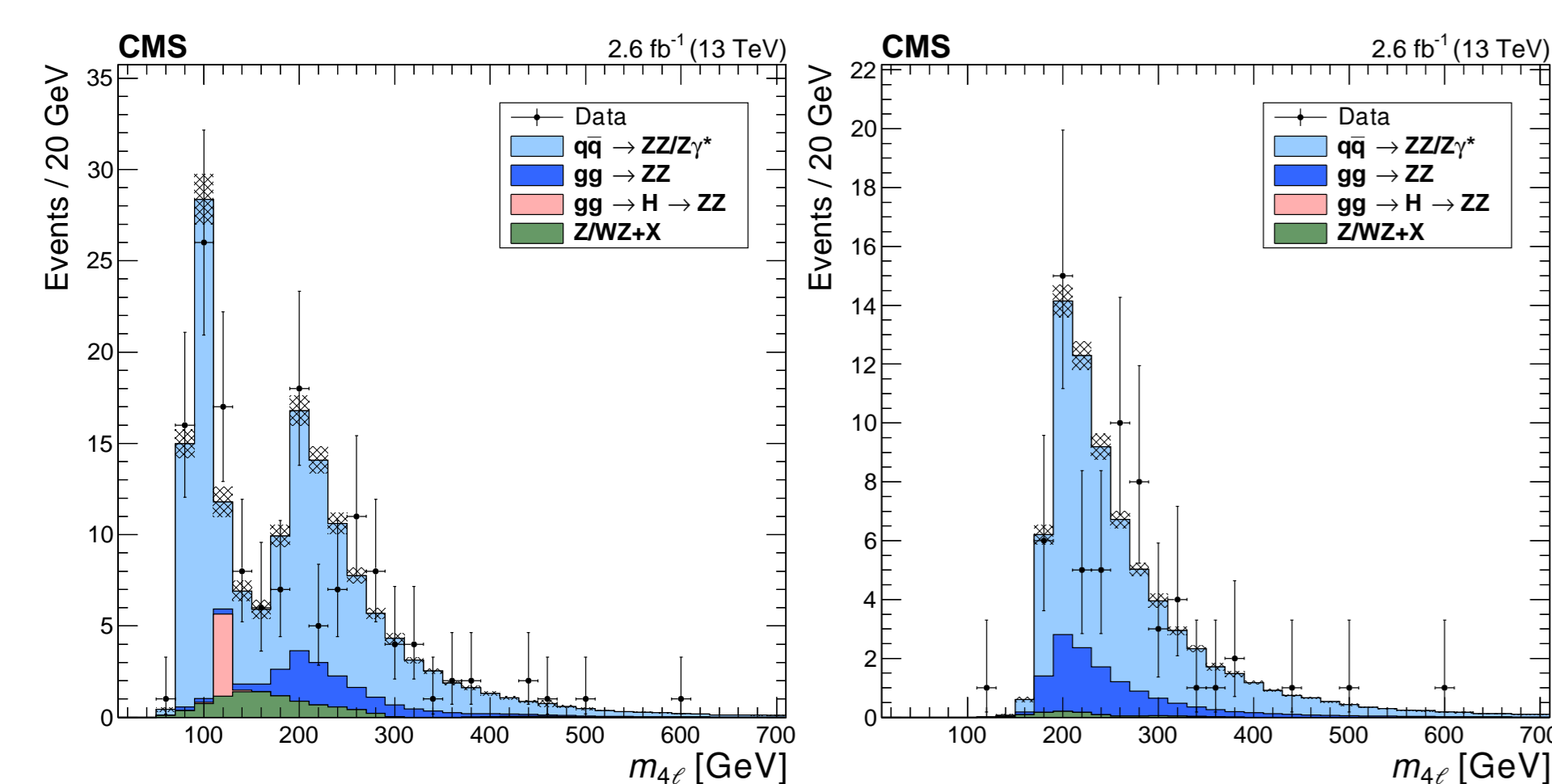
- Isolated di-lepton trigger, triple-lepton trigger, or single-electron trigger
- Z boson candidates  $Z_1$  and  $Z_2$  formed from pairs of opposite-sign, same-flavor electrons or muons
  - Leptons must pass identification and isolation criteria
  - $40 < m_{Z_1} < 120 \text{ GeV}$ ,  $4 < m_{Z_2} < 120 \text{ GeV}$
- All opposite-sign lepton pairs  $m_{\ell\ell} > 4 \text{ GeV}$

### Z $\rightarrow 4\ell$ Branching Fraction Measurement

- $80 < m_{4\ell} < 100 \text{ GeV}$

### ZZ cross section measurement

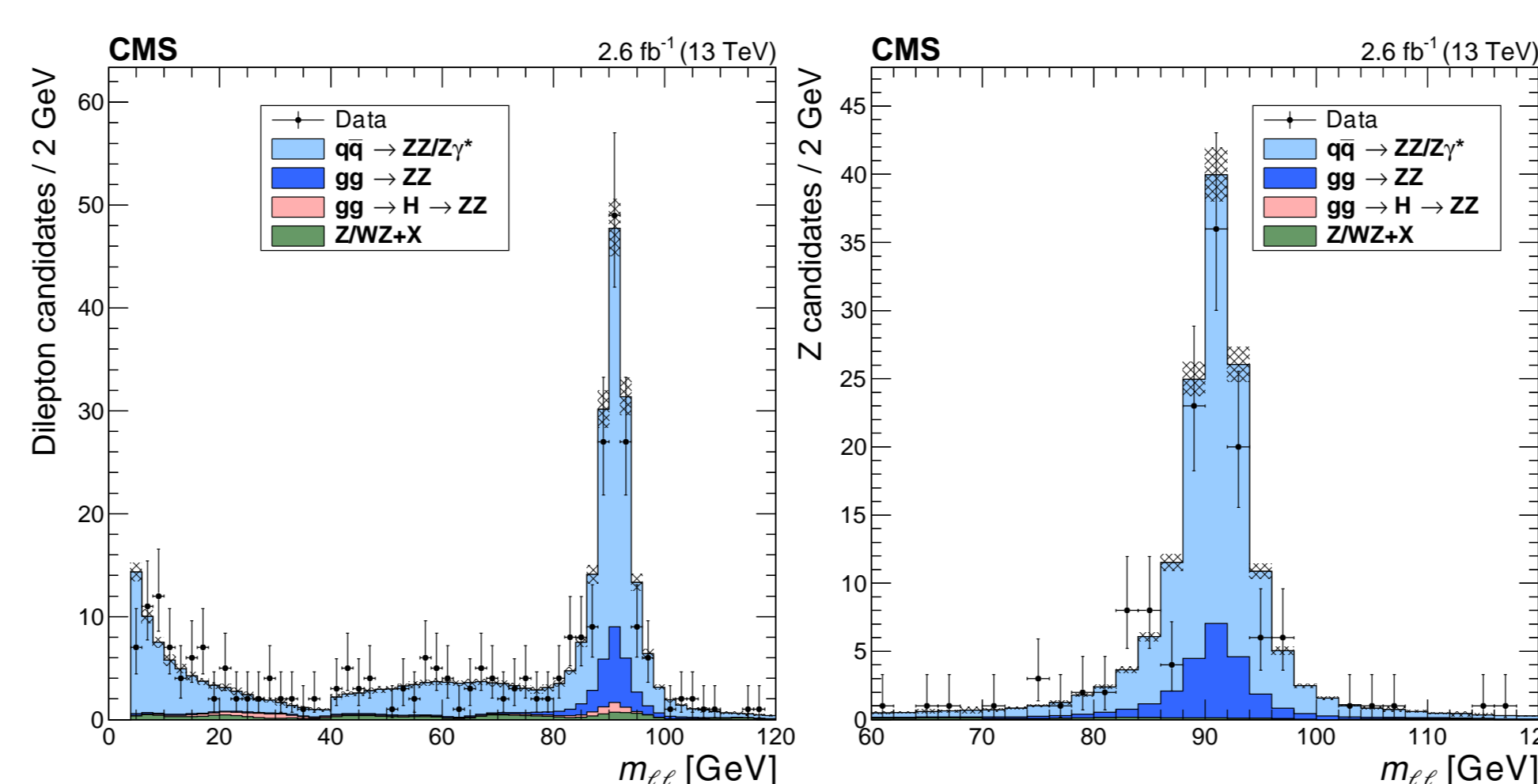
- $60 < m_{Z_1, Z_2} < 120 \text{ GeV}$



Distribution of the reconstructed four-lepton mass summed for all decay channels in the full spectrum selection (left) and the ZZ cross section measurement selection (right).

## Background Estimation

- Major background contributions arise from WZ+jets, Z+jets, and  $t\bar{t}$  events with jet fragments misidentified as signal leptons
  - Difficult to model accurately; contribution estimated from data
- Background yield in signal region extrapolated from Z +  $\ell\ell'$  control regions where one or both  $\ell'$  fails ID or isolation
- Probability for failing particle to pass all selections ("fake rate") found in Z +  $\ell_{\text{loose}}$  control sample
- Fake rates used to reweight each control region to its corresponding contribution to the selected signal



Reconstructed mass of all dilepton pairs in events passing (left) the full spectrum selection and (right) the ZZ cross section measurement selection.

## Largest Systematic Uncertainties

Uncertainty	Z $\rightarrow 4\ell$	ZZ $\rightarrow 4\ell$
ID efficiency	2–6%	0.4–0.9%
Isolation efficiency	1–6%	0.3–1.1%
Trigger efficiency	2–4%	2%
PDF	1%	1%
QCD Scales	1%	1%
Integrated luminosity	2.7%	2.7%

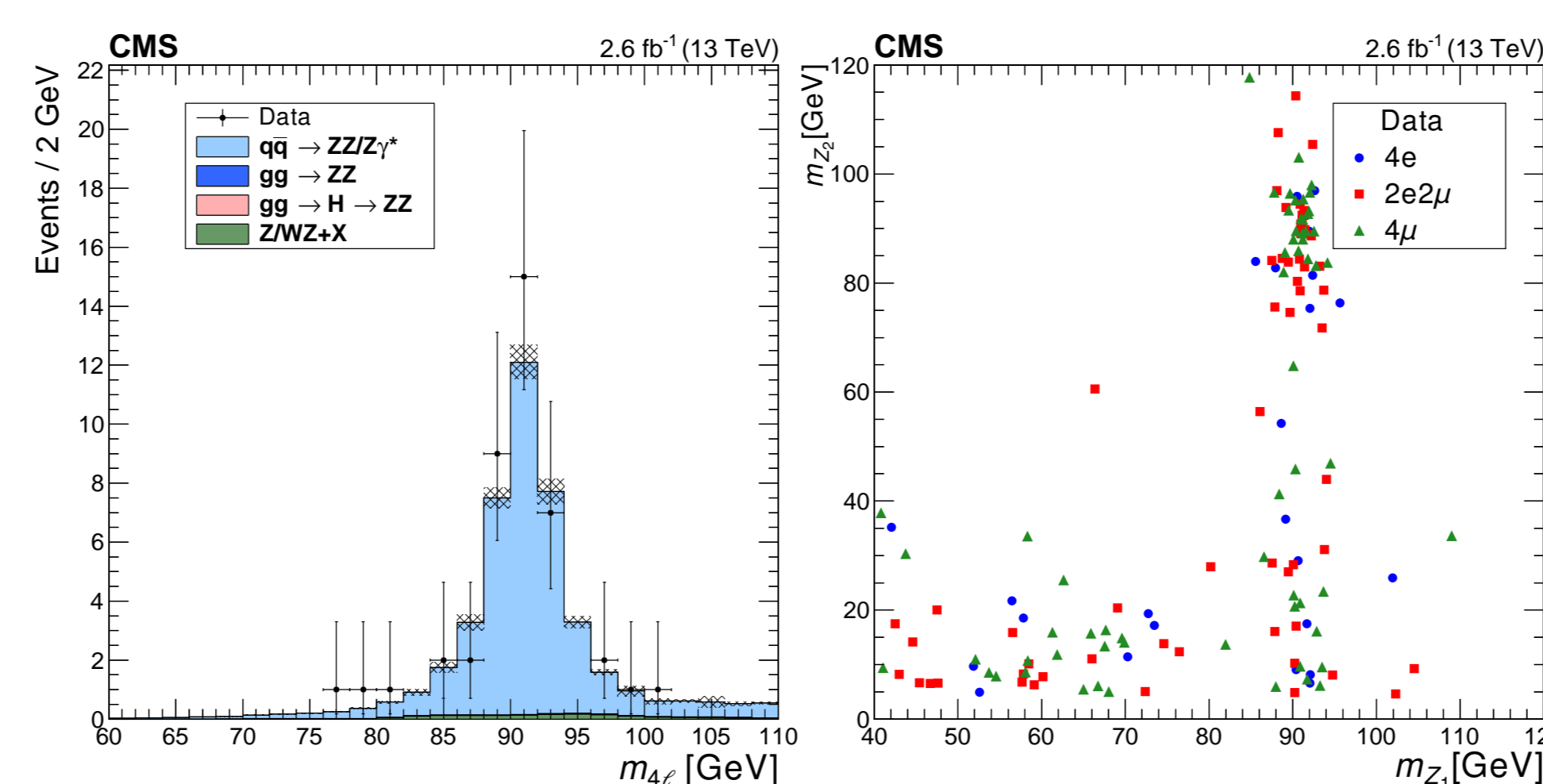
## Event Yields

### ZZ cross section measurement

Decay channel	$N_{ZZ}^{\text{exp}}$	Background	Total expected	Observed
4 $\mu$	$21.80 \pm 0.15 \pm 0.46$	$0.00_{-0.00}^{+0.24+0.10}$	$21.80_{-0.15-0.46}^{+0.28+0.47}$	26
2e2 $\mu$	$36.15 \pm 0.20 \pm 0.81$	$0.60 \pm 0.34 \pm 0.24$	$36.75 \pm 0.34 \pm 0.85$	30
4e	$14.87 \pm 0.12 \pm 0.36$	$0.81 \pm 0.26 \pm 0.33$	$15.68 \pm 0.26 \pm 0.48$	8
Total	$72.82 \pm 0.27 \pm 1.00$	$1.42_{-0.43-0.41}^{+0.49+0.42}$	$74.23_{-0.45-1.08}^{+0.56+1.08}$	64

### ZZ $\rightarrow 4\ell$ branching fraction measurement

Decay channel	$N_{ZZ}^{\text{exp}}$	Background	Total expected	Observed
4 $\mu$	$16.88 \pm 0.14 \pm 0.62$	$0.31 \pm 0.30 \pm 0.12$	$17.19 \pm 0.33 \pm 0.63$	17
2e2 $\mu$	$15.88 \pm 0.14 \pm 0.87$	$0.37 \pm 0.27 \pm 0.15$	$16.25 \pm 0.31 \pm 0.88$	16
4e	$5.58 \pm 0.08 \pm 0.53$	$0.21 \pm 0.10 \pm 0.08$	$5.78 \pm 0.13 \pm 0.53$	6
Total	$38.33 \pm 0.21 \pm 1.19$	$0.89 \pm 0.42 \pm 0.22$	$39.22 \pm 0.47 \pm 1.21$	39



(left) Reconstructed four-lepton mass of events passing the Z  $\rightarrow 4\ell Z \rightarrow 4\ell$  branching fraction measurement selections. (right) Reconstructed mass of  $Z_2$  plotted against the reconstructed mass of  $Z_1$  in events passing the full spectrum selection. In each event,  $Z_1$  is the dilepton pair with mass closest to the nominal  $m_Z$ .

## Bibliography

Measurement of the ZZ production cross section and Z  $\rightarrow \ell^+\ell^-\ell'^+\ell'^-$  branching fraction in pp collisions at  $\sqrt{s} = 13$  TeV, CMS Collaboration, **Phys. Lett. B763 (2016) 280–303**, CMS-SMP-16-001, CERN-EP-2016-174 <http://cds.cern.ch/record/2202723>

## ZZ Cross Section Measurement

$pp \rightarrow ZZ \rightarrow 2\ell 2\ell'$  cross section calculated from simultaneous fit of observed yields in each channel

### Fiducial definitions

Measurement	Fiducial requirements
Common requirements	$p_T^{\ell_1} > 20 \text{ GeV}$ , $p_T^{\ell_2} > 10 \text{ GeV}$ , $p_T^{\ell_{3,4}} > 5 \text{ GeV}$ , $ \eta  < 2.5$ , $m_{\ell\ell} > 4 \text{ GeV}$ (any opposite-sign same-flavor pair)
Z $\rightarrow 4\ell$	$m_{Z_1} > 40 \text{ GeV}$ , $80 < m_{4\ell} < 100 \text{ GeV}$
ZZ $\rightarrow 4\ell$	$60 < m_{Z_1}, m_{Z_2} < 120 \text{ GeV}$

### Measured fiducial cross sections

$$\sigma_{\text{fid}}(pp \rightarrow Z \rightarrow 4\ell) = 30.5_{-4.7}^{+5.2} (\text{stat})_{-1.4}^{+1.8} (\text{syst}) \pm 0.8 (\text{lumi}) \text{ fb},$$

$$\sigma_{\text{fid}}(pp \rightarrow ZZ \rightarrow 4\ell) = 34.8_{-4.2}^{+4.6} (\text{stat})_{-0.8}^{+1.2} (\text{syst}) \pm 0.9 (\text{lumi}) \text{ fb}.$$

### Measured total ZZ cross section

Total ZZ cross section is found by correcting for detector acceptance and efficiency of reconstruction and selection, and Z  $\rightarrow \ell\ell$  branching ratio.

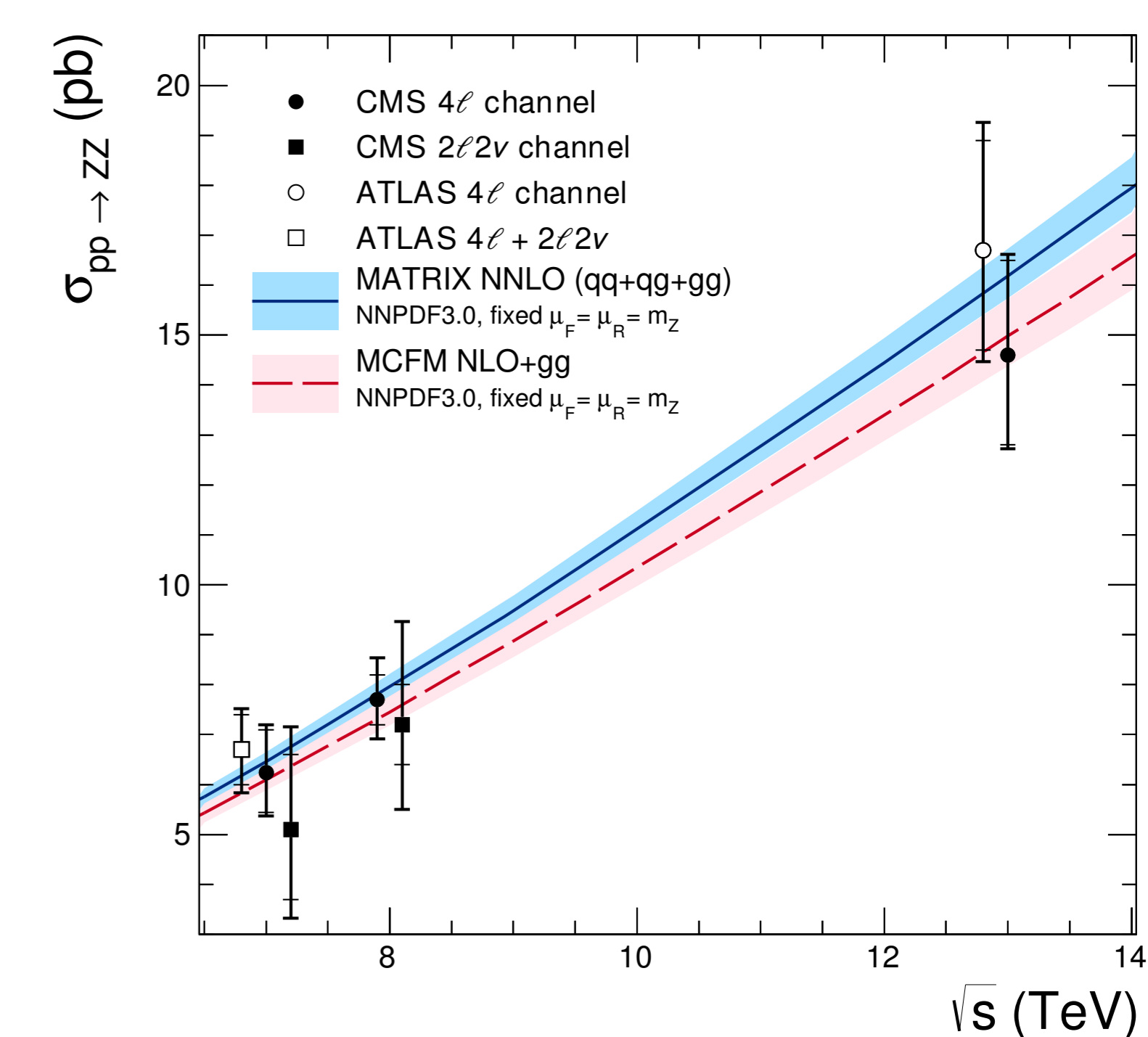
$$\sigma(pp \rightarrow ZZ) = 14.6_{-1.8}^{+1.9} (\text{stat})_{-0.3}^{+0.5} (\text{syst}) \pm 0.2 (\text{theo}) \pm 0.4 (\text{lumi}) \text{ pb}$$

for both Z bosons with mass 60–120 GeV.

### Theoretical predictions

Total cross sections can be compared to predictions from theory

- $16.2_{-0.4}^{+0.6} \text{ pb}$ 
  - MATRIX NNLO, fixed scales  $\mu_R = \mu_F = m_Z$
- $14.5_{-0.4}^{+0.5} \pm 0.2 \text{ pb}$ 
  - POWHEG + MCFM NLO, fixed scales  $\mu_R = \mu_F = m_Z$



Total ZZ cross section results from the CMS and ATLAS experiments compared to predictions from MATRIX and MCFM using NNPDF3.0 PDF sets and fixed scales  $\mu_R = \mu_F = m_Z$ . Measurements at same  $\sqrt{s}$  offset for clarity.

## Z branching fraction measurement

Total Z  $\rightarrow 4\ell$  cross section found to be

$$\sigma(pp \rightarrow Z)\mathcal{B}(Z \rightarrow 4\ell) = 250_{-39}^{+43} (\text{stat})_{-11}^{+15} (\text{syst}) \pm 4 (\text{theo}) \pm 7 (\text{lumi}) \text{ fb}.$$

The Z  $\rightarrow 4\ell$  branching fraction may then be computed as

$$\mathcal{B}(Z \rightarrow 4\ell) = \frac{\sigma(pp \rightarrow Z \rightarrow 4\ell)}{\sigma_{\text{fid}}(pp \rightarrow Z \rightarrow 2\ell) / \mathcal{B}(Z \rightarrow 2\ell)},$$

where the dileptonic Z cross section  $\sigma(pp \rightarrow Z \rightarrow 2\ell) = 1870_{-40}^{+50} \text{ pb}$  calculated with FEWZ v2.0 in the mass range 60–120 GeV, and the factor  $C_{80-100}^{60-120} = 0.926 \pm 0.001$  corrects for the difference in mass windows. The measured value is

$$\mathcal{B}(Z \rightarrow 4\ell) = 4.9_{-0.7}^{+0.8} (\text{stat})_{-0.2}^{+0.3} (\text{syst})_{-0.1}^{+0.2} (\text{theo}) \pm 0.1 (\text{lumi}) \times 10^{-6},$$

which may be compared to  $4.6 \times 10^{-6}$ , computed with MADGRAPH5\_AMC@NLO.