Measurement of the Higgs boson differential fiducial cross sections in the four-lepton decay channel in pp collisions at 13 TeV

Eur. Phys. J. C 81 (2021) 488

Mingshui Chen (IHEP), Li Yuan, Tongguang Cheng, Qianying Guo,
Tahir Javaid (Beihang University)
On behalf of CMS collaboration

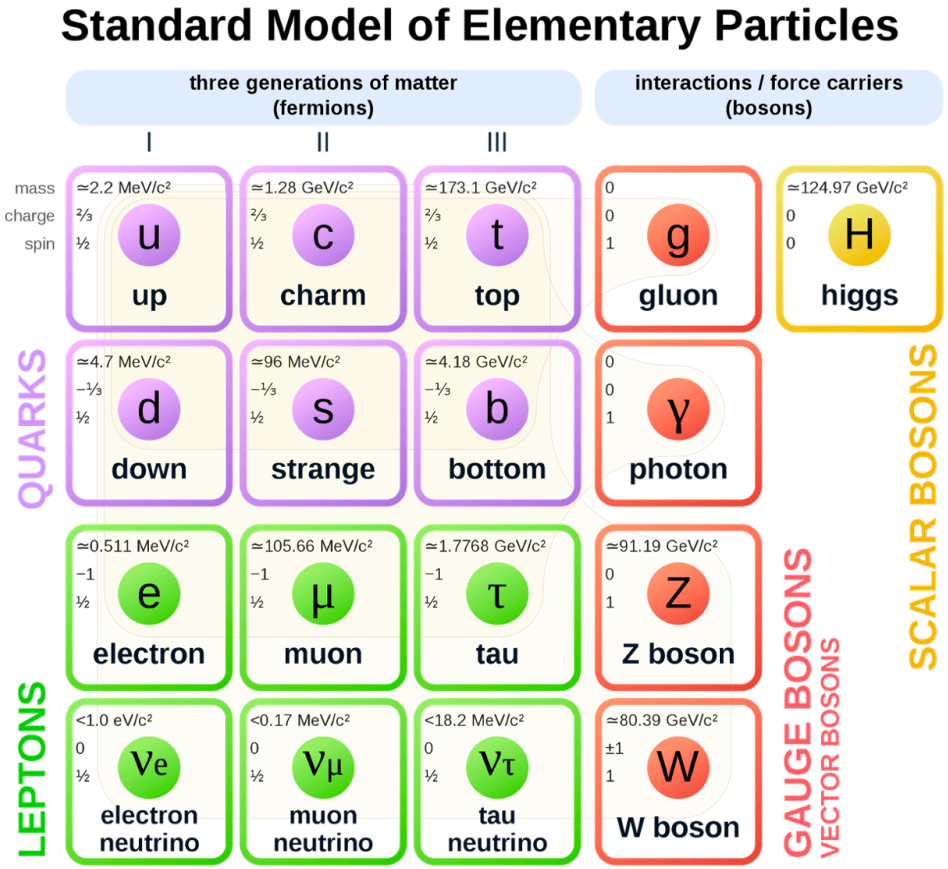
Higgs Potential 2022, Peking University

Outline

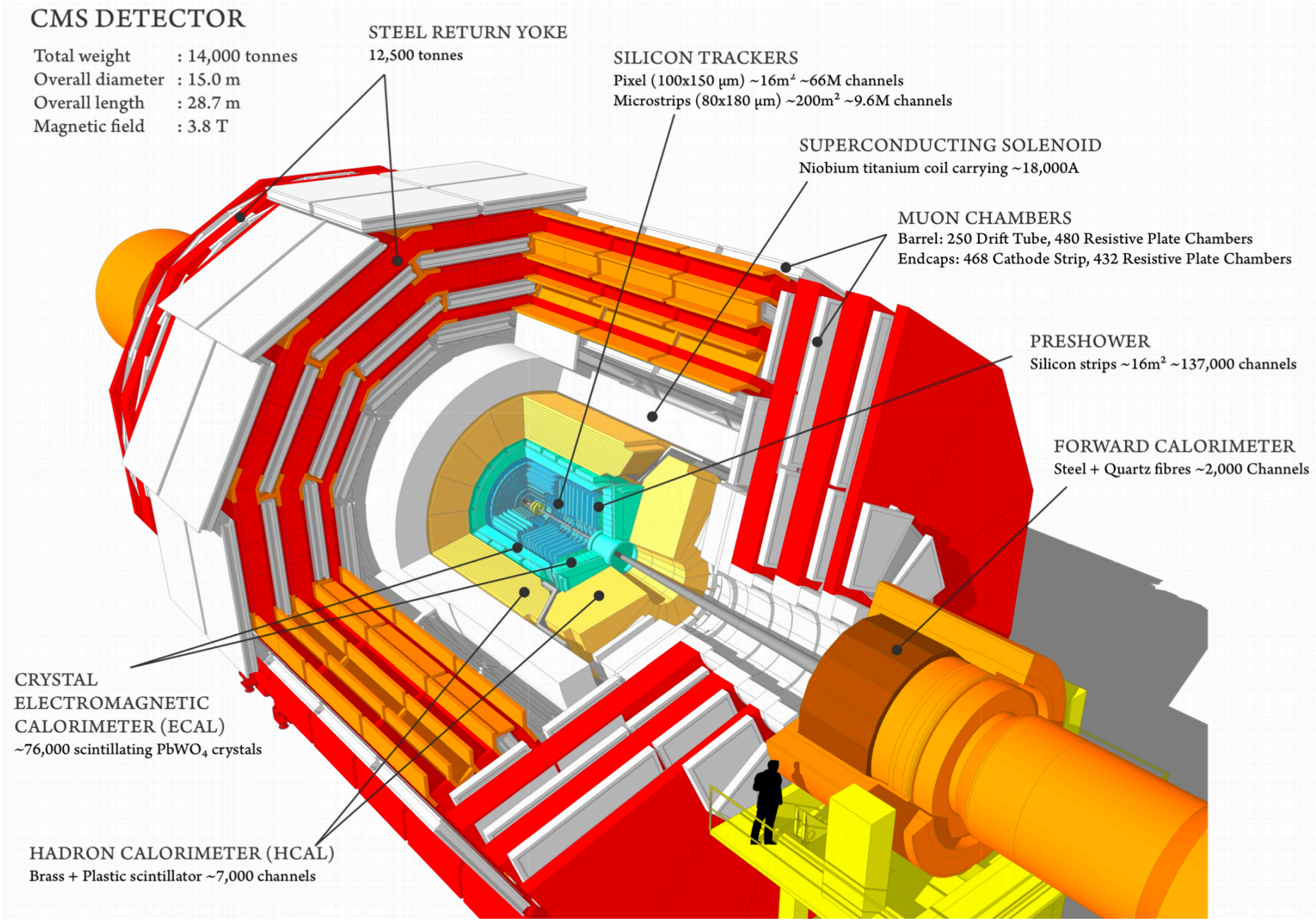
- **Theoretical Background and motivation**
- **The CMS detector**
- **Higgs production and decay (LHC)**
  - Motivation for 4 lepton decay channel
- **Higgs Differential Cross section measurement / Analysis strategy**
  - Motivation
  - Event Selection and reconstructions
  - Overview and definition of fiducial volume
  - Extracting the cross section
- **Systematic Uncertainties**
- **Results**
- **Outlook**
- **Summary**

Theoretical Background

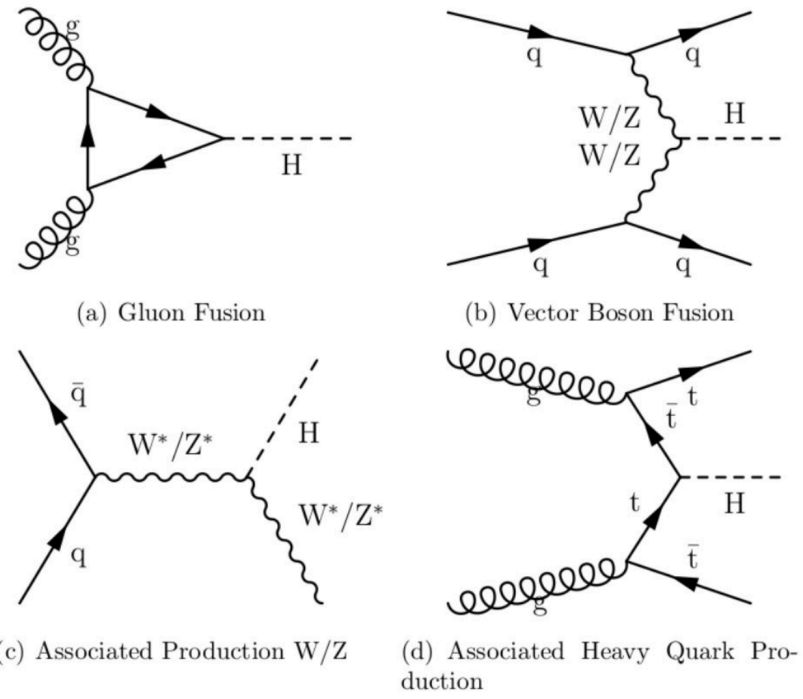
- Standard Model: A framework conceived to describe the fundamental particles and nature of interactions (gauge fields)
  - Higgs mechanism: for massive gauge bosons
- The discovery of the Higgs boson in 2012 opened a new sector of investigations
  - Higgs properties measurements
  - Search for new / invisible particles interacting with the Higgs
- SM an incomplete theory: It cannot explain many observations: Gravity, baryon asymmetry, dark matter, B meson Decay Anomalies , etc

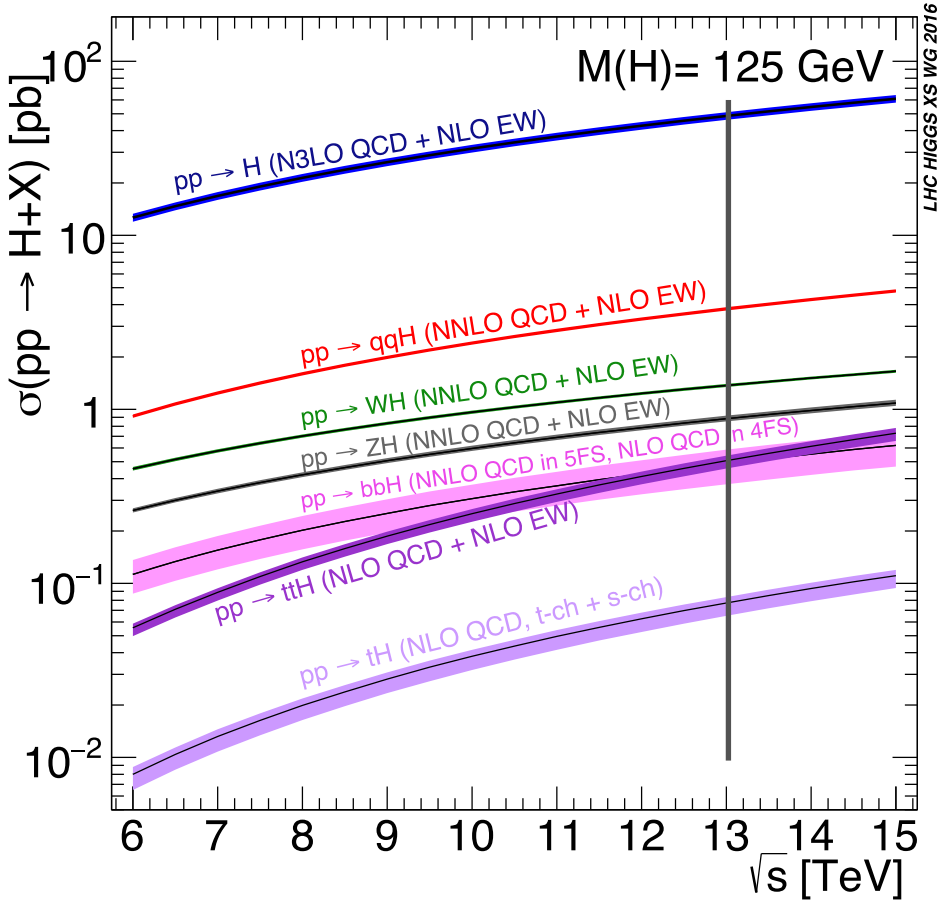


The CMS detector



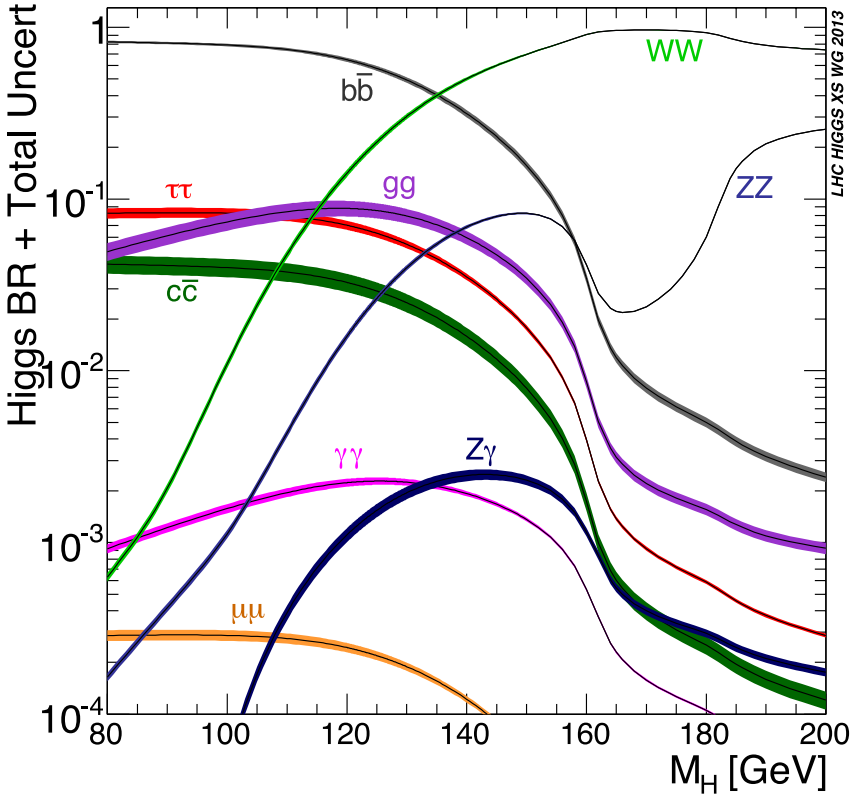
Higgs Production at LHC

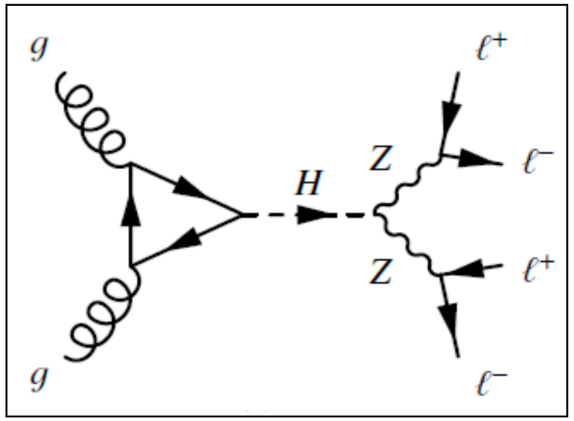




- Significant increase in production cross section from 8 TeV (Run1 2012) to 13TeV (Run2)
- $\sigma_{13TeV} / \sigma_{8TeV}$ of Higgs: ggH ~2.3, VBF ~2.4, VH ~2.0 and ttH ~3.9
  - background increased by a factor of ~2

Higgs Decays: H → ZZ → 4l decay mode and its motivation





✳ σ × Br (H → ZZ → 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

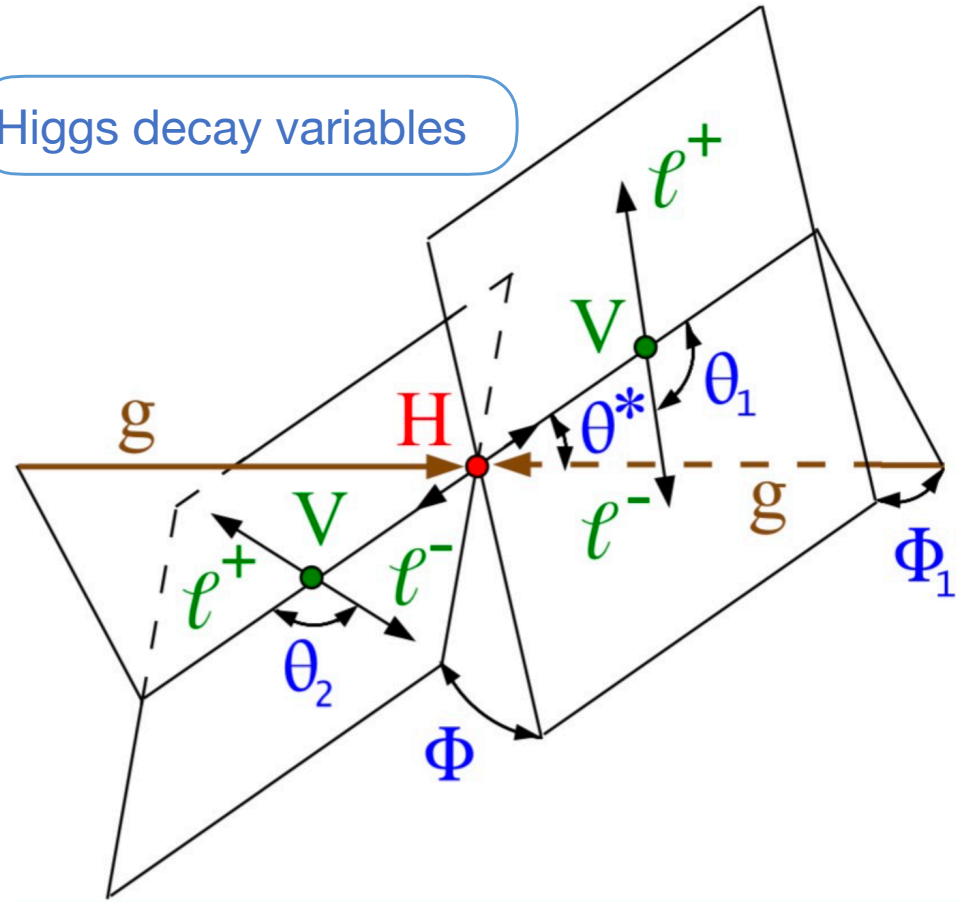
Motivation for the measurements

✳Inclusive and Differential measurements performed

✳Possible differential measurement observables

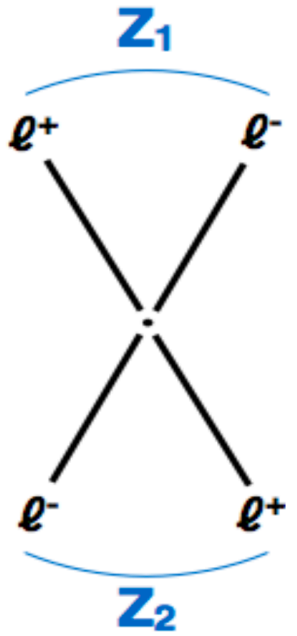
- **Higgs kinematics:** Rapidity and transverse momentum (p_T) of the four-lepton system
  - sensitive to production modes, QCD modeling, PDF
- **Jet observables :** njets, leading jet p_T
  - VBF sensitive variables; sensitive to production modes, QCD modelling
- **Decay variables:** like $|\cos\theta^*|$
  - Sensitive to spin/CP of Higgs boson

Higgs decay variables



Event selection and reconstructions

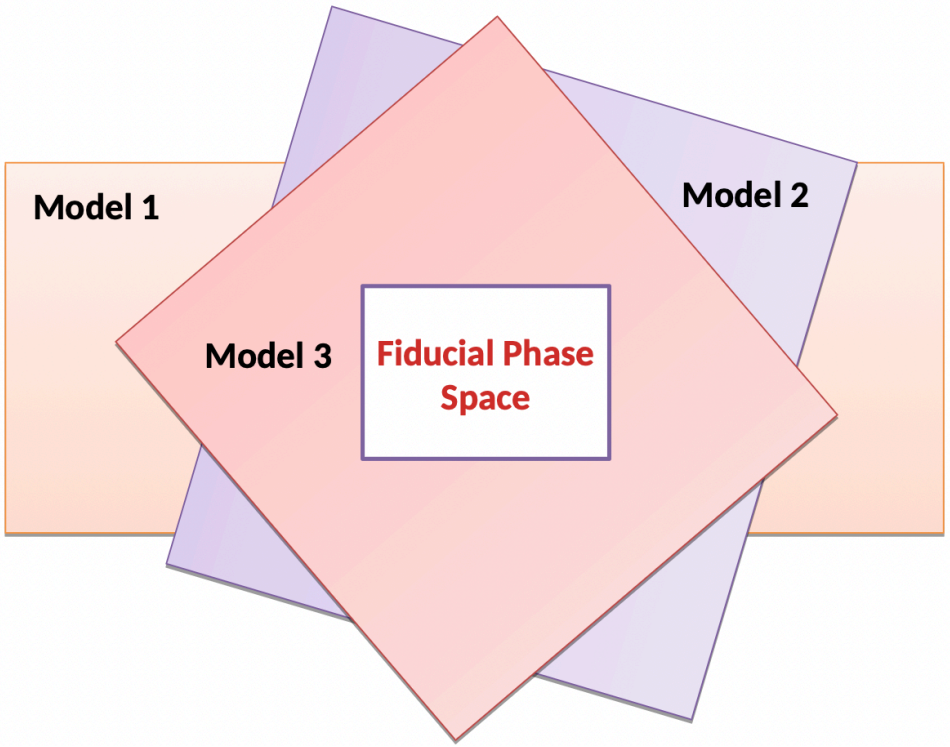
- Loose e (μ) passing selections $P_T > 7(5)$GeV; $|\eta| < 2.5(2.4)$; vertex cut $d_{xy} < 0.5\ cm$; $d_z < 1\ cm$; $SIP_{3D} < 4$; BDT Selections (RelPFIso($\Delta R = 0.3$) < 0.35);
- Z candidate
  - Any OS-SF pair that satisfy $12 < m_{ll(\gamma)} < 120$ GeV
- Build all possible ZZ candidates defined as pairs of non-overlapping Z candidate; define Z_1 candidate with $m_{ll(\gamma)}$ closest to the POG m(Z) mass
  - $m_{Z1} > 40$ GeV; $P_T(l1) > 20$ GeV; $P_T(l2) > 10$ GeV
  - $\Delta R > 0.02$ between each of the four leptons
  - $m_{ll} > 4$ GeV for OS pairs (regardless of flavour)
  - Reject 4μ and 4e candidates where the alternative pair Z_aZ_b satisfies $|m_{Za} - m_Z| < |m_{Z1} - m_Z|$ and $m_{Zb} < 12$ GeV
  - $m_{4l} > 70$ GeV
- Z_1 is chosen from lepton pairs whose mass is closest to PDG Z mass
- Z_2 is chosen from the candidates whose lepton pair gives higher pT sum



Overview and definition of the fiducial volume

✳Fiducial cross sections are necessary because acceptance has a strong model dependence e.g. between SM production modes by up to 60%

- ◉Correction for detector effects on the measurement
- ◉Easy interpretations for theorists

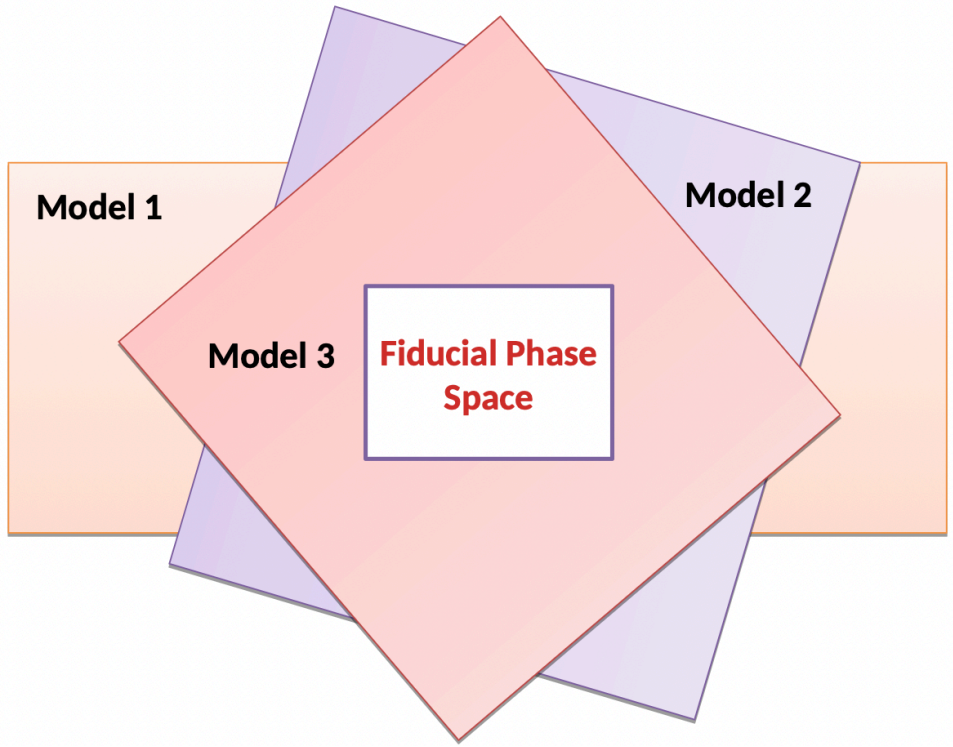


Signal process	$\mathcal{A}_{\text{fid}}$	ϵ	f_{nonfid}	$(1 + f_{\text{nonfid}})\epsilon$
ggH (POWHEG)	0.402 ± 0.001	0.598 ± 0.002	0.054 ± 0.001	0.631 ± 0.002
VBF	0.445 ± 0.002	0.615 ± 0.002	0.043 ± 0.001	0.641 ± 0.003
WH	0.329 ± 0.002	0.604 ± 0.003	0.078 ± 0.002	0.651 ± 0.004
ZH	0.340 ± 0.003	0.613 ± 0.005	0.082 ± 0.004	0.663 ± 0.006
$t\bar{t}H$	0.315 ± 0.004	0.588 ± 0.007	0.181 ± 0.009	0.694 ± 0.010

Overview and definition of the fiducial volume

✳Fiducial cross sections are necessary because acceptance has a strong model dependence e.g. between SM production modes by up to 60%

- ◉Correction for detector effects on the measurement
- ◉Easy interpretations for theorists



Cross section

$$\sigma_i = \frac{N_{reco,i}}{\epsilon_i * A_i * L * B}$$

bin i

Number of measured signal events

Branching fraction

Integrated luminosity

Correction for detector efficiency

Acceptance

Fiducial cross section = cross section in fiducial volume (cuts applied to generated events)

$$\sigma_{fid,i} * B = \frac{N_{reco,i}}{\epsilon_i * L}$$

Fiducial volumes depend on event selection/decay channel

Overview and definition of the fiducial volume

Eur. Phys. J. C 81 (2021) 488

Defined to closely match the detector's acceptance.

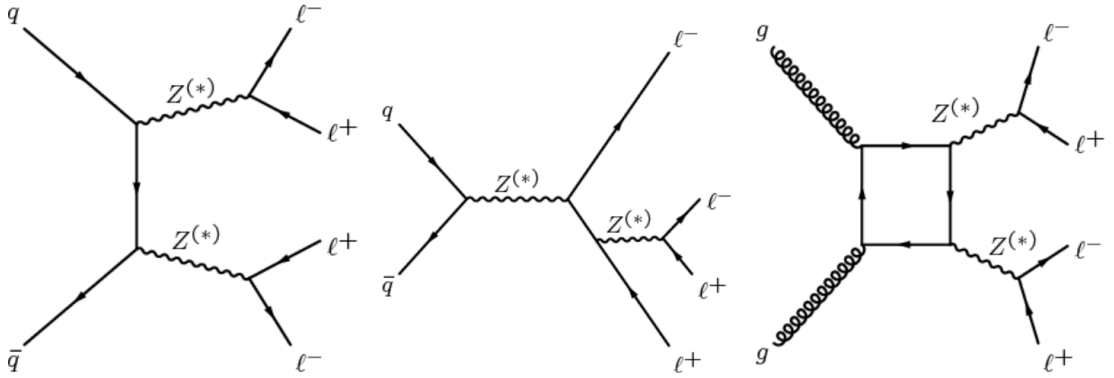
Requirements for the $H \to 4\ell$ fiducial phase space

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)	$\lvert\eta\rvert < 2.5\ (2.4)$
Sum of scalar 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	
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	$\Delta R(\ell_i, \ell_j) > 0.02$ 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	$105 < m_{4\ell} < 140\,\text{GeV}$

Background Estimation (2 types)

✳ **Irreducible** background

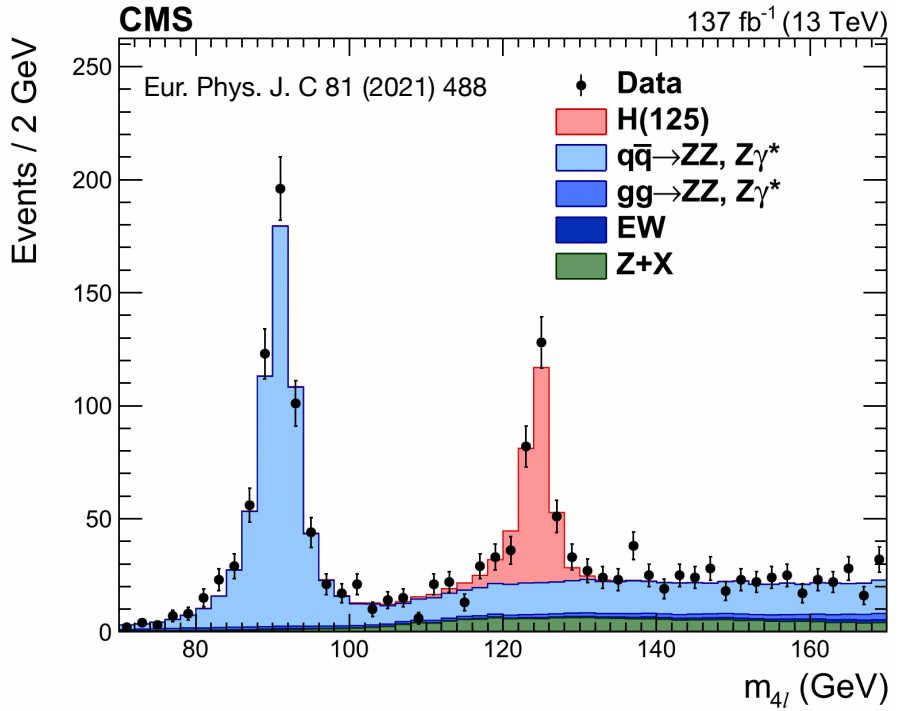
- ◉ Production of ZZ via $q\bar{q}$ annihilation or gluon fusion
- ◉ Estimated using **simulation**



(a) s-channel (b) t-channel (c) ggZZ-box

✳ **Reducible** background (Z+X)

- ◉ Secondary leptons produced by heavy-flavor jets
- ◉ Misidentified as leptons from decay of heavy-flavor hadron, in-flight decays of light mesons within jets, or (for electrons) decay of charged hadrons overlapping with π^0decays.
- ◉ Estimated with **data** using independent OSSF method and SSSF method
  - Fake rates calculated in Z+l control region
  - Z+X yields estimated in 2 orthogonal regions of Z+ll control region
  - Final estimate combination of 2 methods



Distribution of reconstructed four-lepton invariant mass

Measuring the cross section

Measured by performing a maximum likelihood fit of the signal and background parameterisations to the observed 4l mass distribution

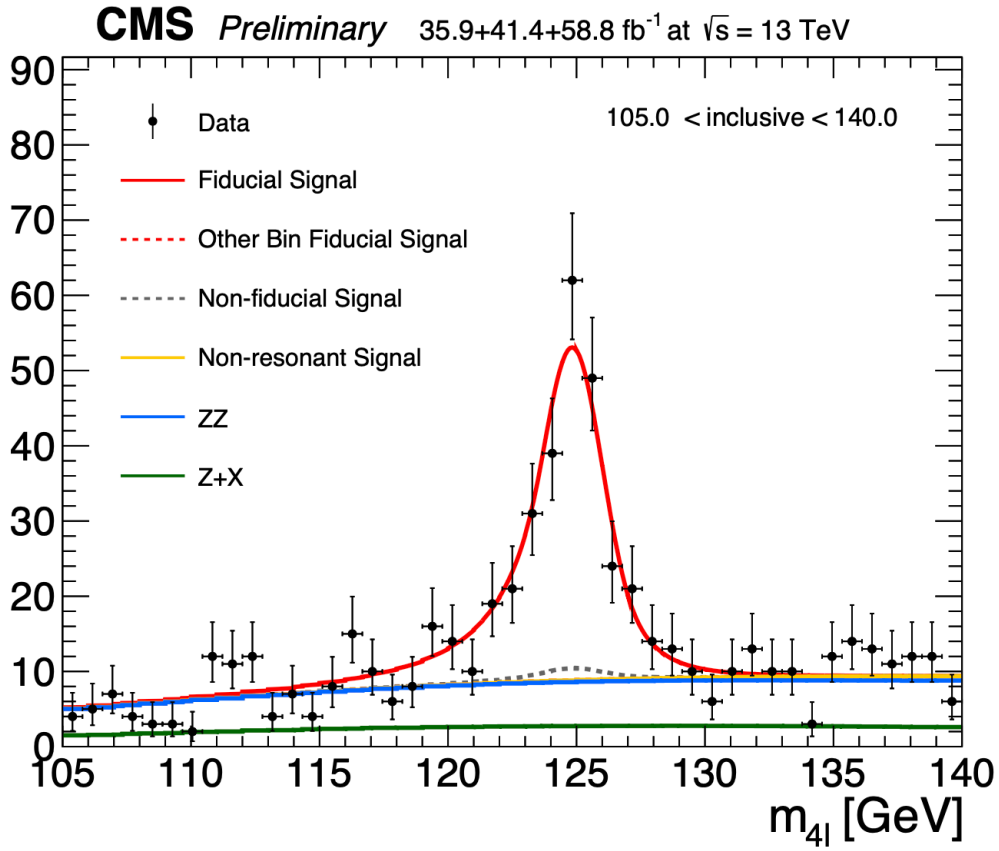
Fiducial signal | Non-resonant signal | Non fiducial signal | Background contribution

$$N^{f,i}_{obs}(m_{4\ell}) = N^{f,i}_{fid}(m_{4\ell}) + N^{f,i}_{nonres}(m_{4\ell}) + N^{f,i}_{nonfid}(m_{4\ell}) + N^{f,i}_{bkg}(m_{4\ell})$$

$$= \left(1 + f^{f,i}_{nonfid}\right) \cdot \sigma^{f,j}_{fid} \cdot \epsilon^{f}_{i,j} \cdot \mathcal{L} \cdot \mathcal{P}_{res}(m_{4\ell})$$ Parameter of interest

$$+ N^{f,i}_{nonres} \cdot \mathcal{P}_{nonres}(m_{4\ell}) + N^{f,i}_{bkg} \cdot \mathcal{P}_{bkg}(m_{4\ell}),$$

Probability density function for resonant, non-resonant and background



Result of a simultaneous fit

Measurements are performed considering Higgs mass = 125.38 GeV

Systematic Uncertainties

✳ **Experimental** uncertainties

- ◉ Depending on the year of data taking
- ◉ Integrated luminosity
- ◉ Lepton identification and reconstruction efficiency

✳ **Theoretical** uncertainties

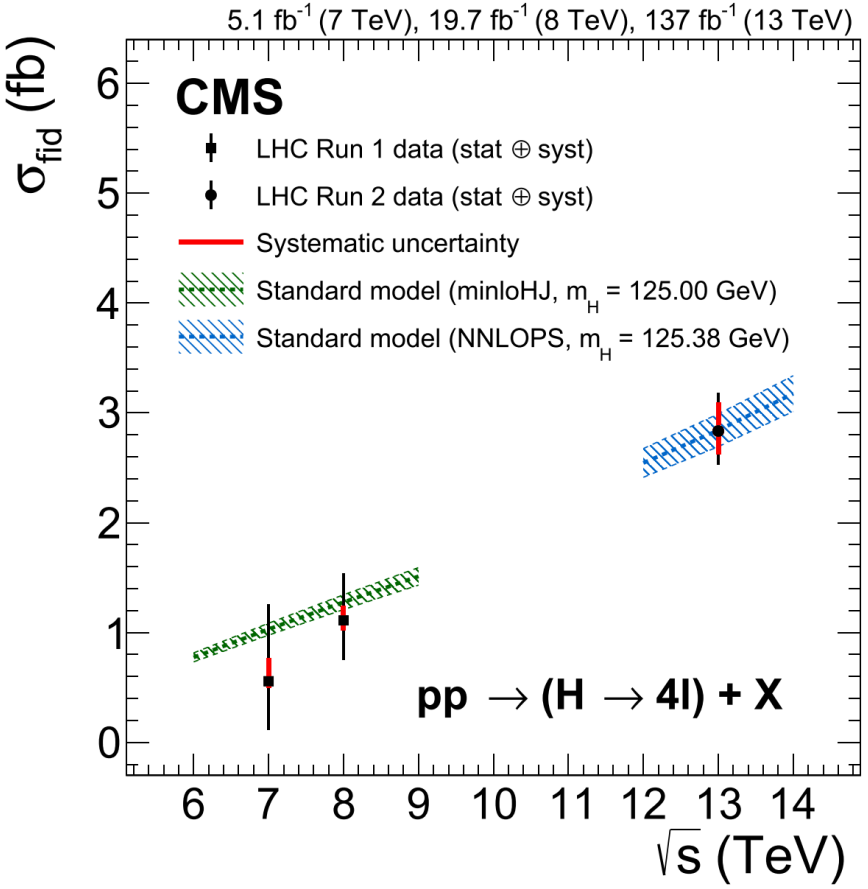
- ◉ Renormalization and factorization scale and choice of PDF set

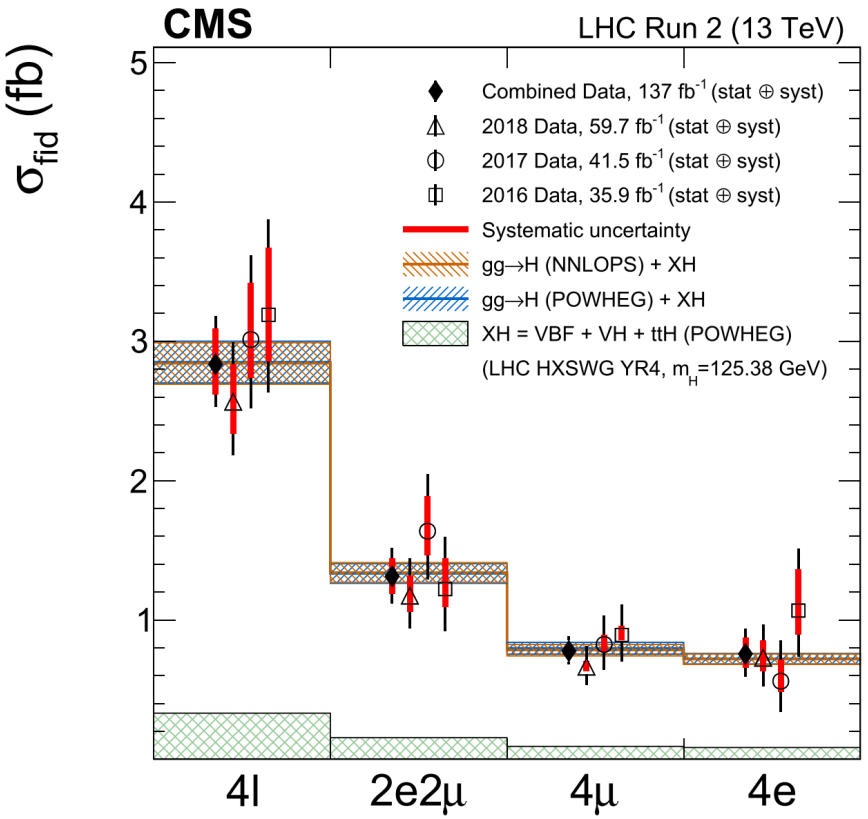
Summary of inclusive theory uncertainties	
BR($H \to ZZ \to 4\ell$)	2 %
QCD scale ($q\bar{q} \to ZZ$)	+3.2/-4.2 % %
PDF set ($q\bar{q} \to ZZ$)	+3.1/-3.4 %
Electroweak corrections ($q\bar{q} \to ZZ$)	± 0.1 %

✳ In combination of the three-year data, the theoretical uncertainties and experimental ones related to leptons or jets are treated as **correlated** while all other ones from experimental sources are taken as **uncorrelated**.

Common experimental uncertainties			
	2016	2017	2018
Luminosity	2.6 %	2.3 %	2.5 %
Lepton identification/reconstruction efficiencies	1.2 – 15.5 %	1.1 – 12 %	0.7 – 11 %
Background related uncertainties			
Reducible background (Z+X)	31 – 42 %	31 – 38 %	31 –37 %
Signal related uncertainties			
Lepton energy scale	0.04 – 0.3 %	0 %	0%
Lepton energy resolution	20 %	20 %	20 %

Results: Inclusive cross section





Measured cross section at 137 /fb

$$\sigma_{\text{fid}} = 2.84^{+0.34}_{-0.31} = 2.84^{+0.23}_{-0.22}\,(\text{stat})^{+0.26}_{-0.21}\,(\text{syst})\,\text{fb}$$

Previous CMS measurement at 35.9 /fb (HIG-16-041)

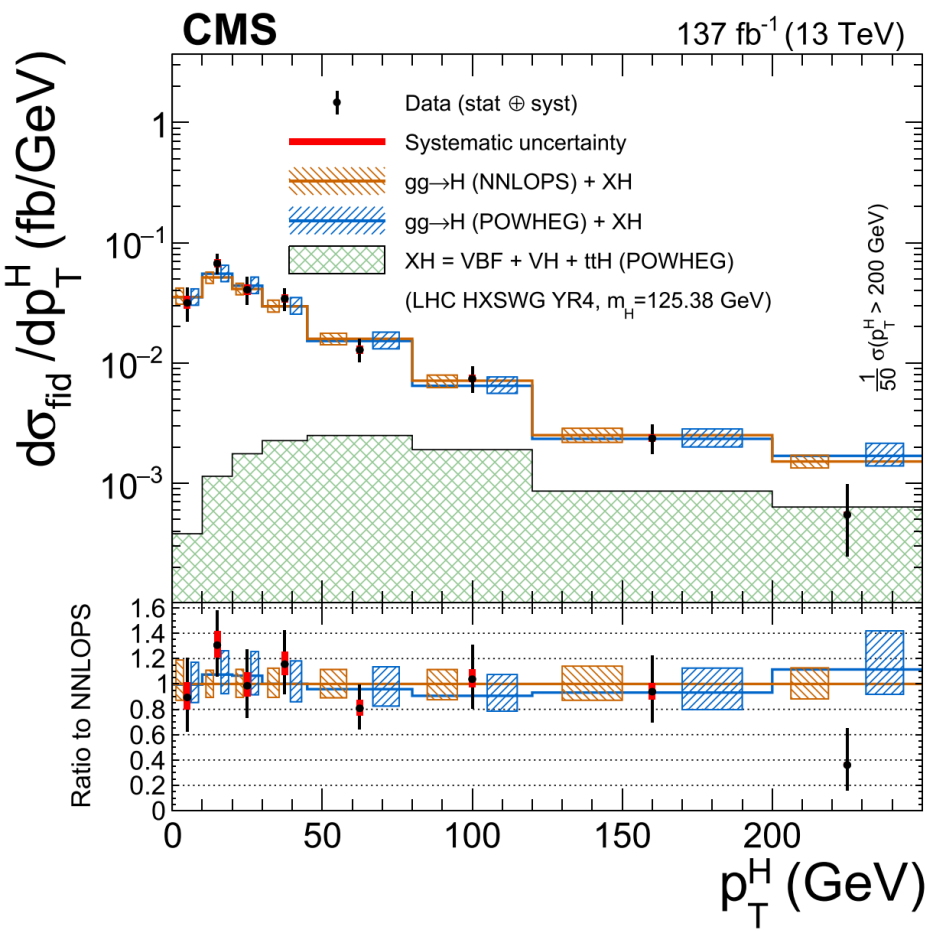
$$\sigma_{\text{fid}} = 2.92\ ^{+0.48}_{-0.44}\,(\text{stat})\ ^{+0.28}_{-0.24}\,(\text{syst})\,\text{fb}.$$

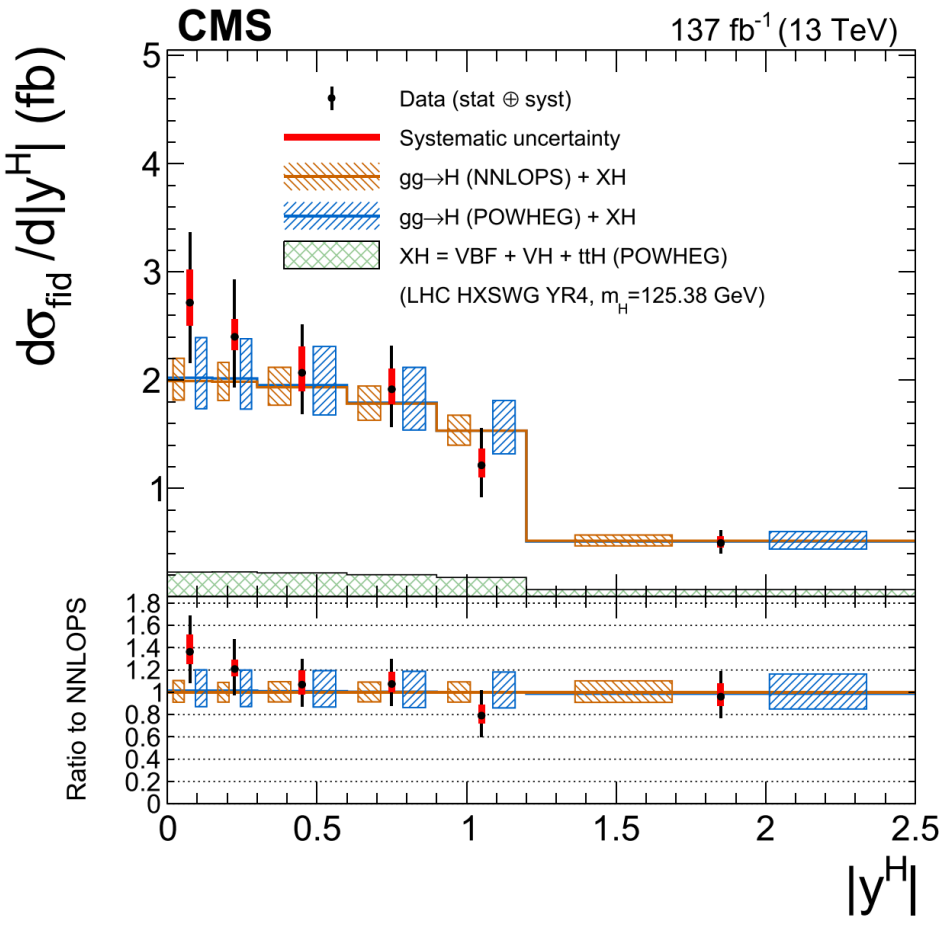
- Results consistent with SM predictions within the associated uncertainties
- More precise w.r.t CMS earlier measurements

Results: Differential cross section

Eur. Phys. J. C 81 (2021) 488

- Differential cross section measured for $p_T(H)$, $|y(H)|$, N(jet), $p_T(jet)$ (Jets are studied with abs(eta)<2.5)
- Unfolding performed by including response matrix in the likelihood
- Compared to predictions from POWHEG and NNLOPS
- Explored more fine bins of observables w.r.t earlier measurements on the differential observables.

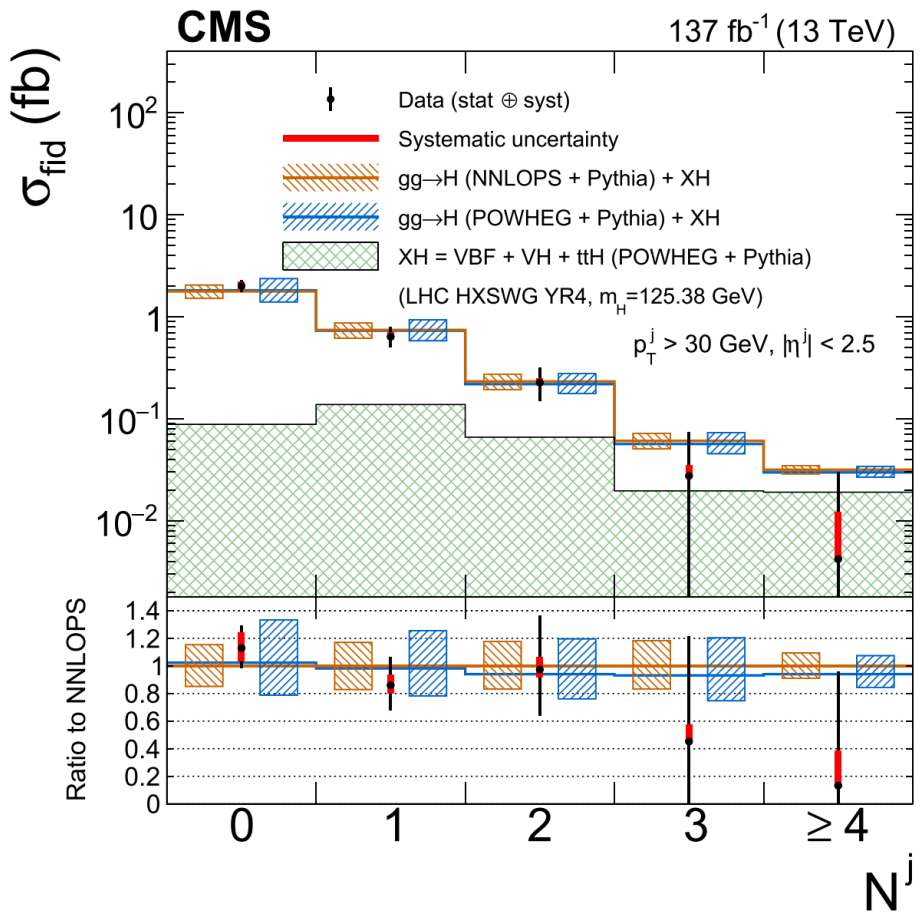


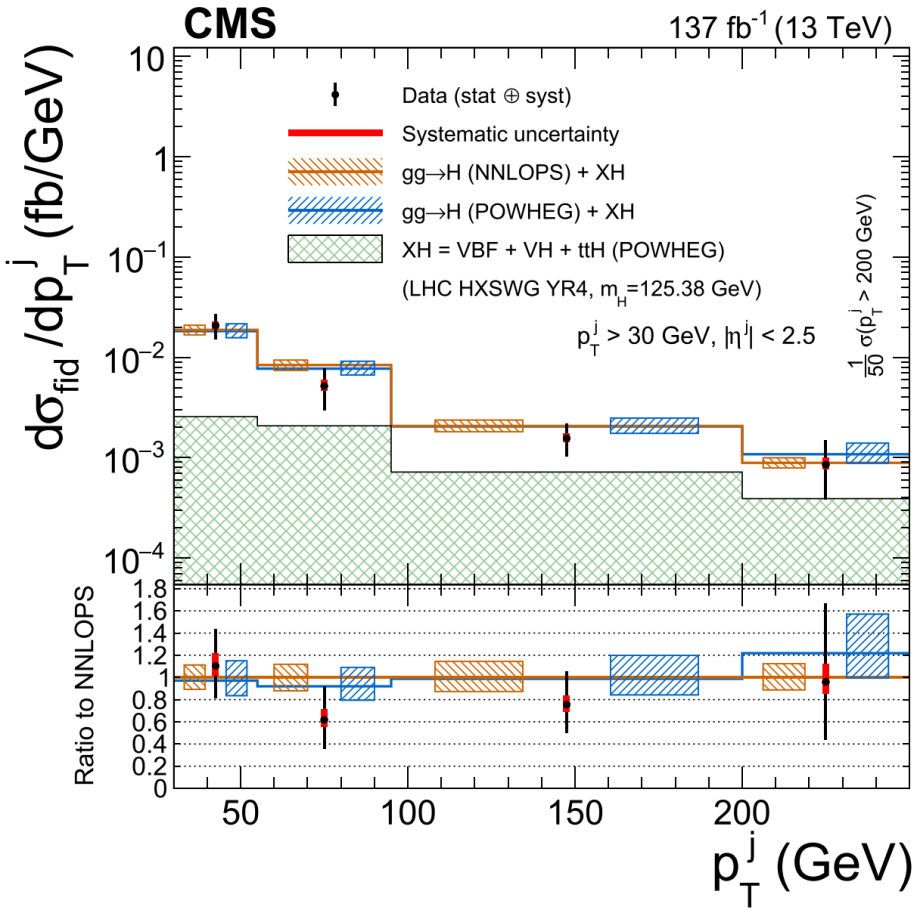


Results: Differential cross section

Eur. Phys. J. C 81 (2021) 488

- Differential cross section measured for $p_T(H)$, $|y(H)|$, N(jet), $p_T(jet)$
- Unfolding performed by including response matrix in the likelihood
- Compared to predictions from POWHEG and NNLOPS
- Explored more fine bins of observables w.r.t earlier measurements on the differential observables.





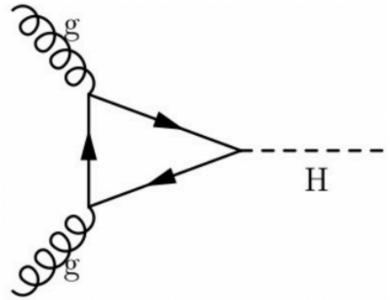
Outlook

✳ Previous efforts / studies / measurements for differential cross section in HZZ4l decay channel:

- Differential Fiducial Cross section measurement (Run I data) **JHEP 04 (2016) 005**
- Inclusive Fiducial Cross section measurement (2015 data) **CMS PAS HIG-15-004**
- Full set of properties measurement (2016 data) **JHEP 11 (2017) 047**

✳ Ongoing work (In approval): **CMS Cadiline: HIG-21-009**

- More differential observables considered; **1D** and **2D** adopting the same strategy w.r.t **Eur. Phys. J. C 81 (2021) 488**
- Constraints on the effective Hbb and Hcc couplings (κb/κc)
  - Follow-up on dedicated Run 1 paper **(HIG-14-028)**
- Constraint on the Higgs boson trilinear self-coupling (κλ)
  - Being performed for the **first time** with single Higgs decay channel and at 138/fb
  - Earlier analyses: **HIG-19-005** (inclusive only), **FTR-18-020** (differential, but a projection studies instead of a measurement)



✳ Staty tuned.

Summary

✳ Higgs boson differential cross section measurements in four-lepton final state at $\sqrt{s} = 13TeV$ are presented

- ◉ Using the CMS data corresponding to an integrated luminosity of 137 fb^{-1}
- ◉ Differential cross sections as a function of the transverse momentum and rapidity of the Higgs boson, the number of associated jets, and the transverse momentum of the leading associated jet are reported

✳ All results are consistent with the Standard Model predictions, within their uncertainties.

“ Whoever travels a path in search of knowledge, Allah makes easy for him a path to Paradise ”

Prophet Muhammad (PBUH); Ref: Sahih Muslim 2699

Thank you

Objects

➢Selected electrons

- Loose electrons
  - $P_T > 7$GeV; $|\eta| < 2.5$
  - $d_{xy} < 0.5\ cm$; $d_z < 1\ cm$;$SIP_{3D} < 3$
- BDT ID+Iso in 6 ($|\eta|$, P_T)bins
- Reduction of fakes for same signal efficiency when witch from TMVA(V1) to **xgboost**(V2) library for BDT training

➢Selected muons

- Loose muons
  - $P_T > 5$GeV; $|\eta| < 2.4$
  - $d_{xy} < 0.5\ cm$; $d_z < 1\ cm$;$SIP_{3D} < 3$
- PF μ ID and tracker high P_T ID
- RelPFIso($\Delta R = 0.3$) < 0.35

➢FSR photon

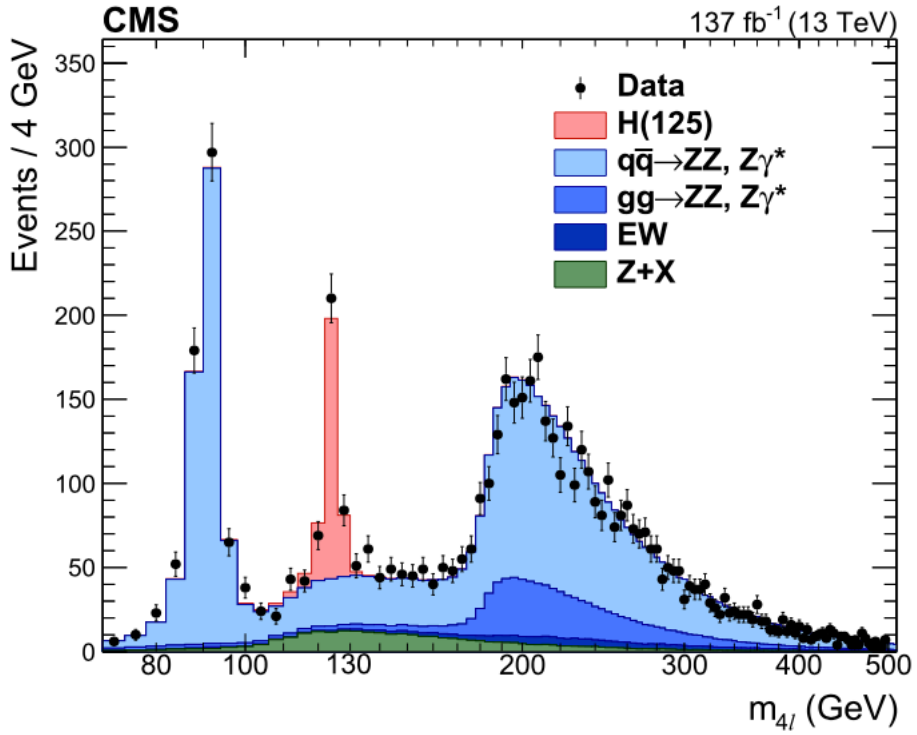
- $P_{T,\gamma} > 2$ GeV; $|\eta^{\gamma}| < 2.4$;relPFIso<1.8
- Electron SC veto by PF reference
- Associated γ to the closest loose lepton
- $\Delta R(\gamma, l) < 0.5$; $\frac{\Delta R(\gamma, l)}{E_{T,\gamma}^2} < 0.012$; choose photon with lowest $\frac{\Delta R(\gamma, l)}{E_{T,\gamma}^2}$
- Remove selected FSRs from lepton isolation cone for all loose leptons

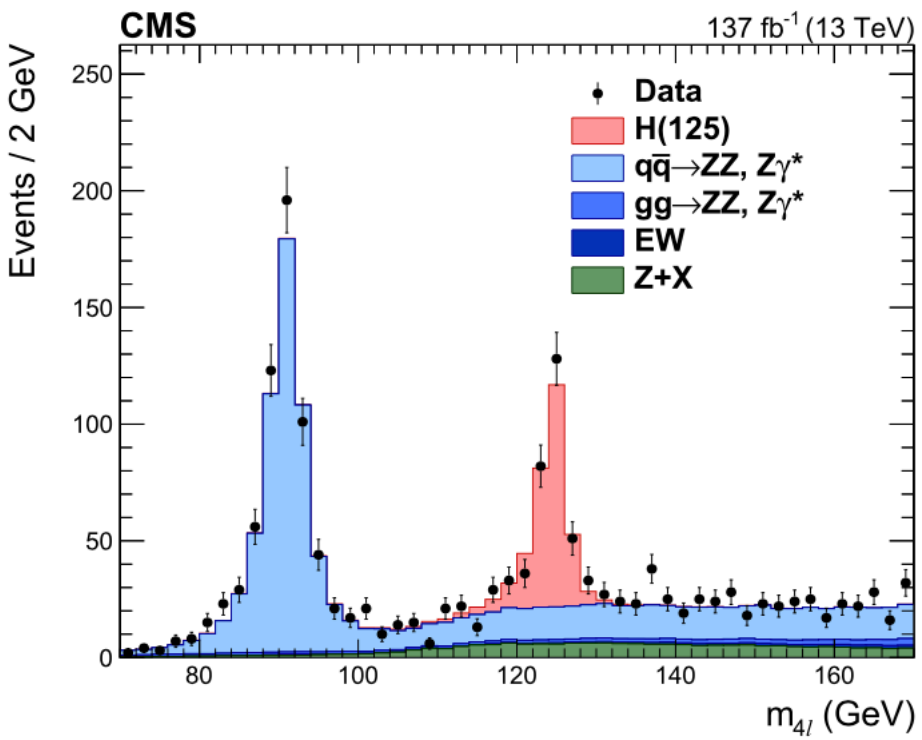
➢JETS

- AK4 PFCHs jets
- $P_T > 30$ GeV; $|\eta| < 4.7$; Tight PF jet ID
- Cleaned $\Delta R(jet, l/\gamma) > 0.4$
- Tight PU Jet ID
- B-tagger:
  - DeepCSV medium WP
  - B-tagging SF applied

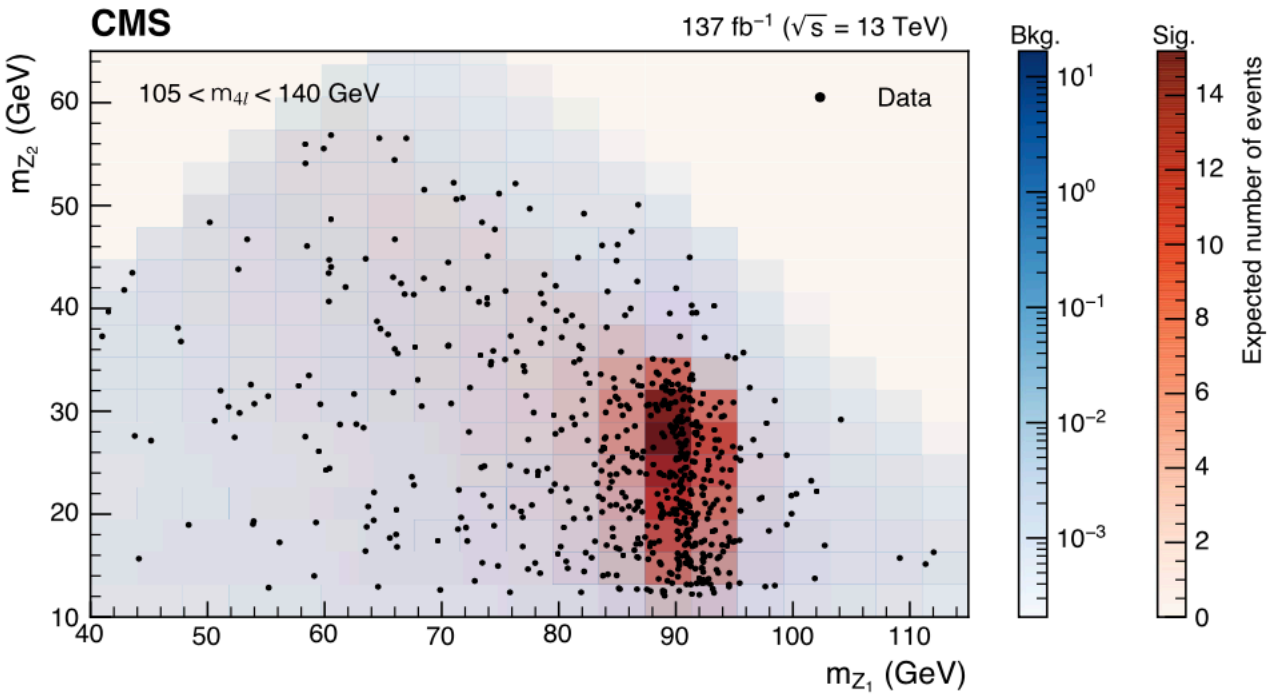
Distribution of m_{4l} of Run-2 data

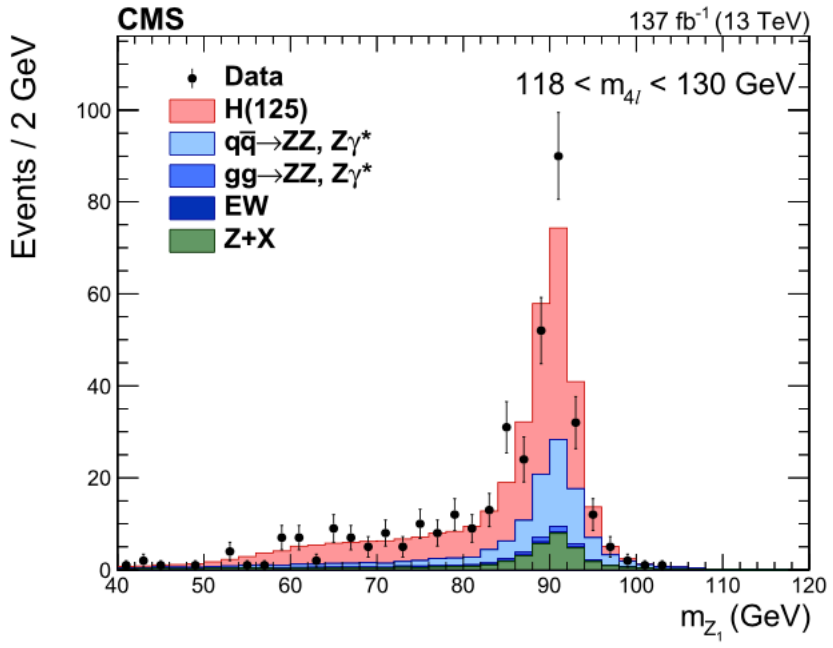
Eur. Phys. J. C 81 (2021) 488

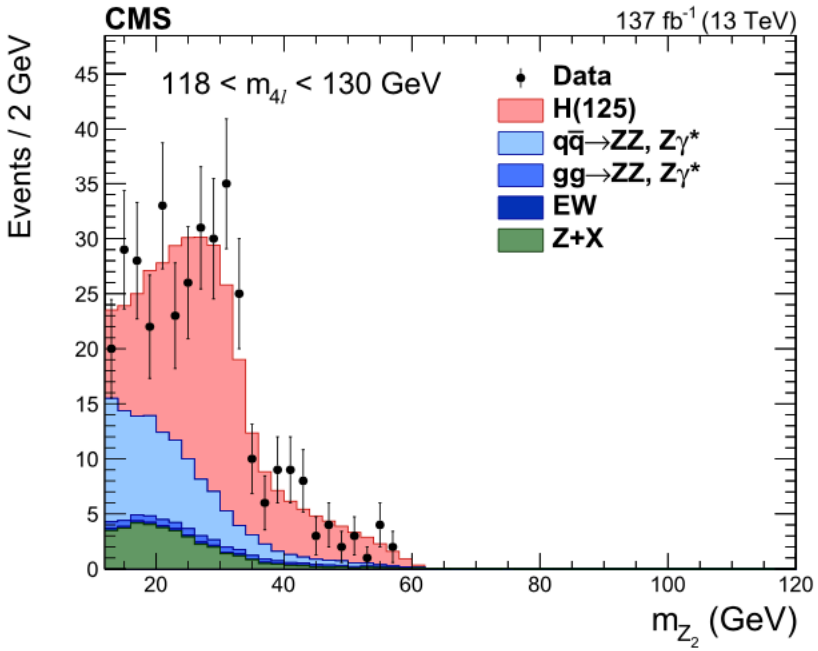




Distribution of Z_1 and Z_2







Eur. Phys. J. C 81 (2021) 488