First evidence for off-shell Higgs boson production and width measurement at CMS

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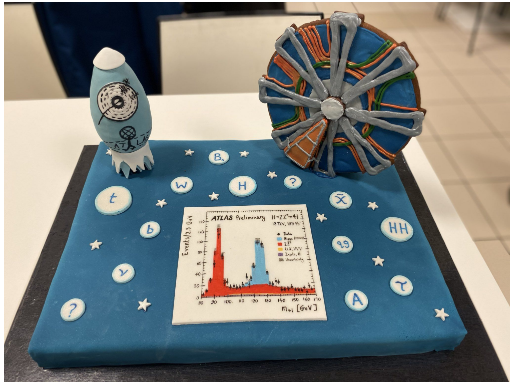
Theoretical motivation

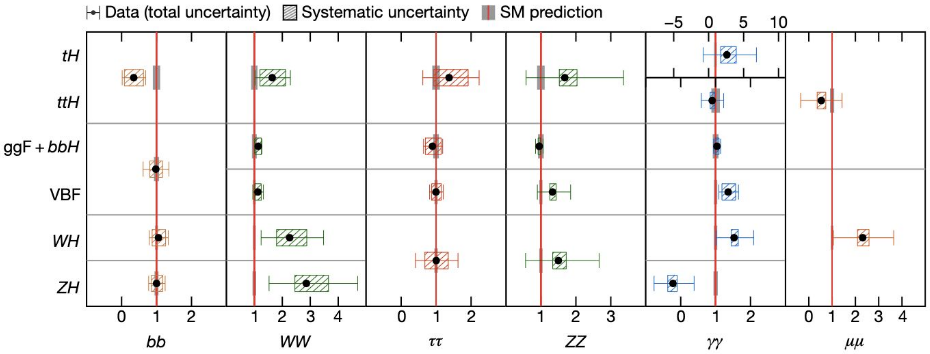


- 10 years since the discovery of Higgs boson

- ATLAS and CMS have measured several parameters such as couplings, cross-sections, etc. (all consistent with SM)

- So far not been able to confirm **off-shell behaviour of the Higgs** and **large uncertainties on decay width** $\Gamma_H = 3.4^{+2.8}_{-2.2}$ MeV

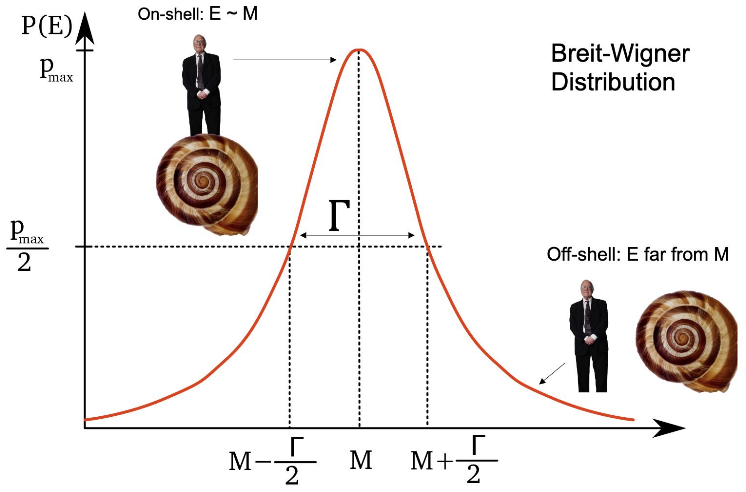
- Important processes/quantities as can be **sensitive to BSM**



Summary of Higgs boson rate measurements compared to SM predictions (taken from here)

Decay width and Off-shell vs. On-shell Higgs

- Predicted **Higgs width (Γ_H) too narrow** compared to the experimental resolution **to be measured just from invariant mass distribution** (predicted Γ_H= 4.1 MeV, exp. resolution ~ 1 GeV)
- Why not try to measure the Higgs lifetime (τ_H) directly?
- Off-shell Higgs to the rescue!
- The **ratio of the rates of off-shell production to on-shell Higgs production** is **sensitive to Γ_H** .



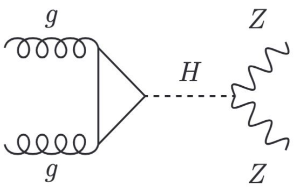
Sketch of Breit-Wigner distribution

$$\frac{\mathrm{d}\sigma_{pp\to H\to ZZ}}{\mathrm{d}M_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}.$$

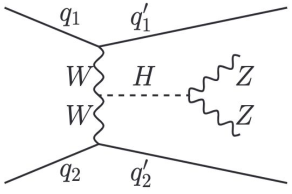
Theory Paper

Analysis overview

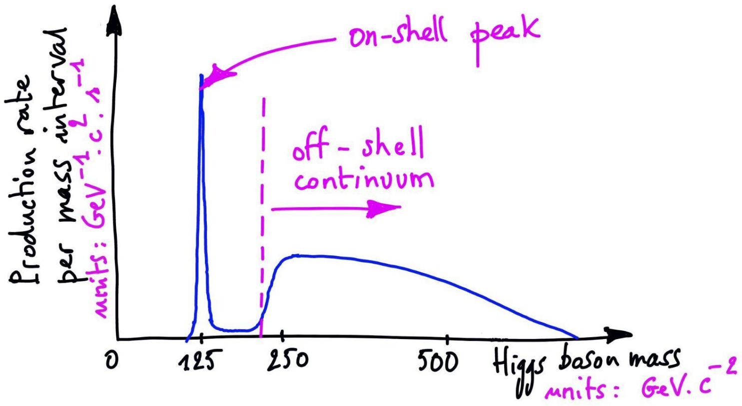
- Rate of **off-shell Higgs production** is enhanced in *ZZ* final state when the *Z*s are produced on-shell, improving statistics. Two signal strength parameters defined to differentiate ggF and VBF processes:
  - $\mu_F^{\text{off-shell}}$ (ggF) and $\mu_V^{\text{off-shell}}$ (VBF)
    - $\mu^{\text{off-shell}}$ (overall signal strength)
  - $R_{V,F}^{\text{off-shell}} = \mu_V^{\text{off-shell}} / \mu_F^{\text{off-shell}}$
- Combination of previous on-shell and off-shell production in $H \to ZZ \to 4\ell$ with *new* off-shell measurement of $H \to ZZ \to 2\ell 2\nu$
- Interference effects with *ZZ* continuum background important. More on this later.
- Aiming to improve upon the previous best results that used only 4ℓ channel



gluon-gluon fusion (ggF)



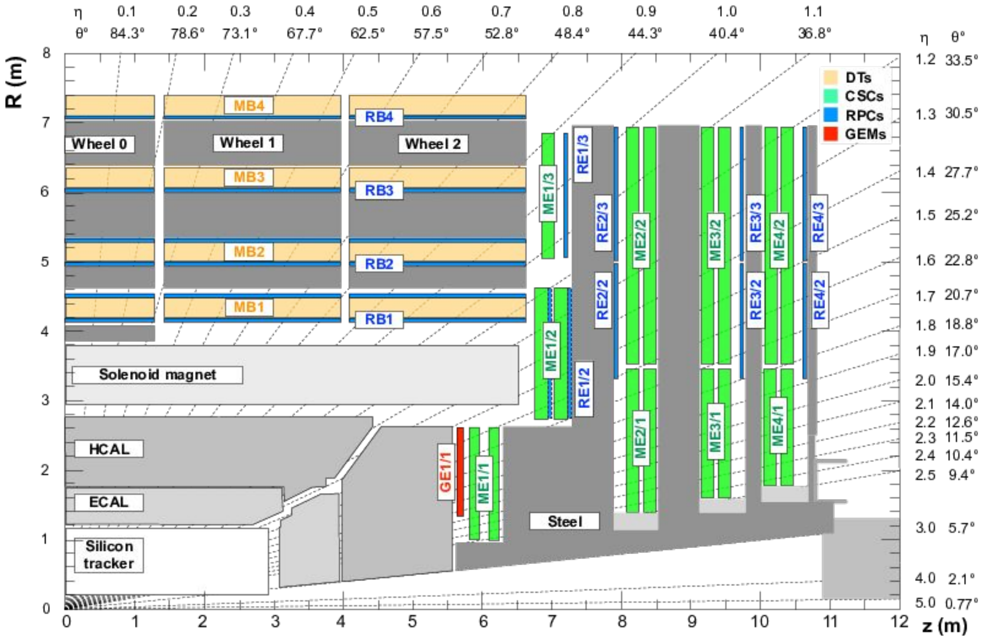
vector boson fusion (VBF)



Dummy reconstructed mass distribution from $H \to ZZ$ decay (taken from here)

The CMS experiment

- One of the two **general purpose detectors** alongside ATLAS
- Consists of a 3.8 T superconducting solenoid to curve the trajectories of charged particles
- Four major components:
    - **Inner Tracker**
    - Electromagnetic Calorimeter (**ECAL**)
    - Hadronic Calorimeter (**HCAL**)
    - Muon System (**MS**)

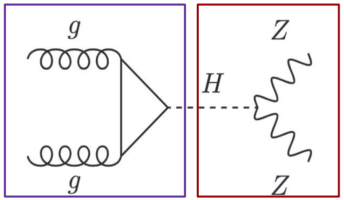


A schematic diagram showing different sub-detector components in the CMS detector along with their (z,R,η) coordinates (taken from here)

Datasets

- **Data: Run I and Run-II for 4ℓ, full Run-II for 2ℓ2ν** (L = 140 fb^{-1}) collected by single & double muon triggers
- **MC: [1] Signal**
  - *ggH, VBF, ZH*, and *WH*
  - Negative interferences - reweighted by *MELAANALYTICS*

H production: *POWHEG2*
(125 GeV < m_H < 3 TeV)



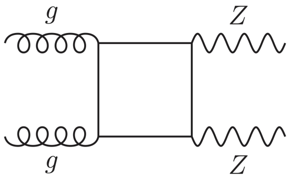
* ggH process is rescaled by N3LO K-factor

H decay: *JHUGEN*

[2] Background

- *di-boson*: *POWHEG2* + NNLO QCD, NLO EWK corrections

e.g.



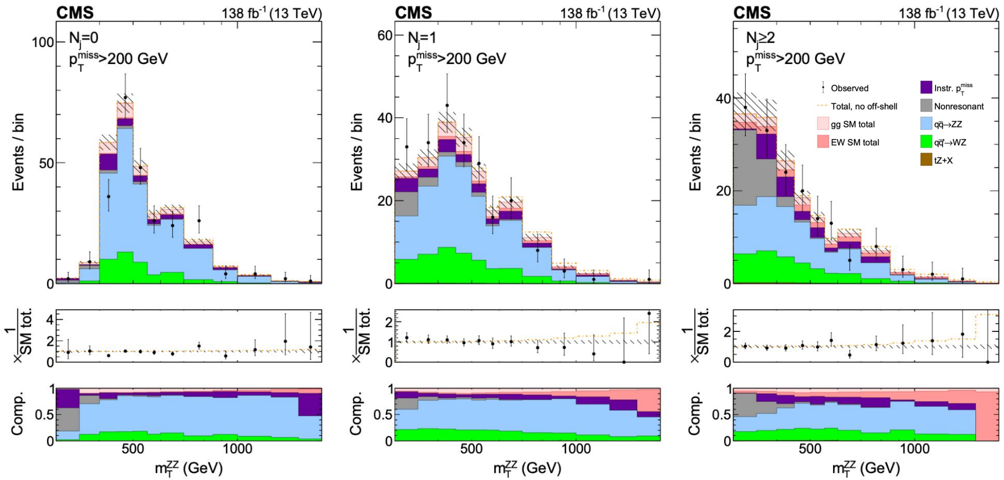
- others: MG5 & aMC@NLO + MLM/FXFX merging

- All MC samples are *showered by PYTHIA8*
- Also use CMS central underlying event tunes, PDF sets, and detector simulations

Kinematic observables and signal region selection

Kinematic observables:

- p_T^{miss} (provides a good signal/background discrimination)
- m_T^{ZZ} computed using p_T^{miss} (m^{ZZ} for the 4ℓ channel)
- matrix element (MELA) kinematic discriminant to identify VBF processes for events with $N_j \geq 2$



m_T^{ZZ} distributions for SR events with 0, 1 and ≥ 2 jets

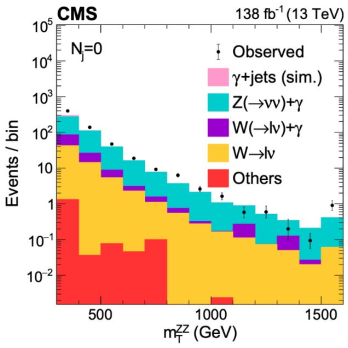
Signal region:

- **Di-Lepton** selection
  - e^+e^- or $\mu^+\mu^-$
  - $|m_{\ell\ell} - m_Z| < 15$ GeV
  - $p_T^{\ell\ell} > 55$ GeV
- **MET** requirements:
  - $p_T^{miss} > 125$ GeV (> 140 GeV) for $N_j < 2$ (≥ 2)
  - $\Delta\varphi(p_T^{miss}$, any obj) cuts are set to reduce mis-reconstructed METs
- **Veto** events with:
  - *b*-tagged jets
  - additional loosely identified ℓ or γ
  - isolated tracks

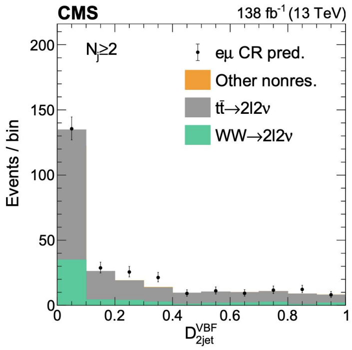
Background estimation and Control Region (CR)

- **Interfering** processes with signal (Monte Carlo simulated)
  - *ZZ, WZ, WW*

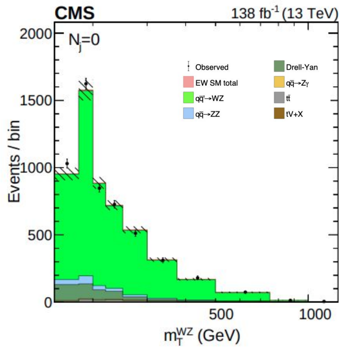
- **Non-interfering** processes (data-driven estimated)
  - **Drell-Yan** (DY) process - estimated from ***γ* + jets CR**
  - ***tt, WW*** - estimated from ***eμ CR***
  - ***WZ, WW*** - estimated from **trilepton *CR***



***γ* + jets**



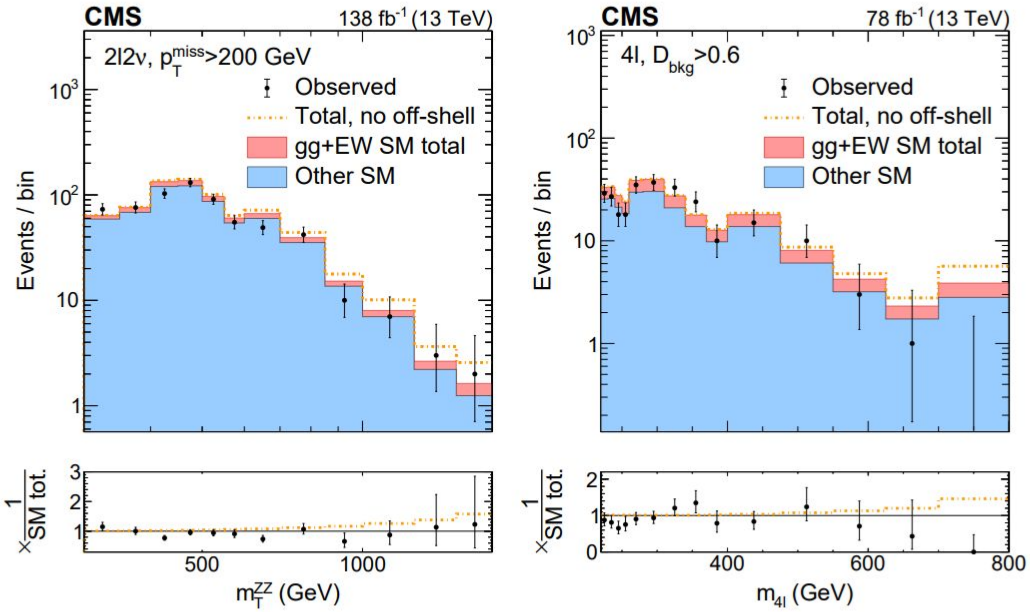
eμ CR



trilepton

Fit to data

- Signal strengths (μ's) and Γ_H extracted using fits to SR and CRs
  - Binned extended maximum likelihood fit over various kinematic distributions
  - Fit variables: $m^{4\ell}$ and MELA discriminants (4ℓ); m_T^{ZZ} and p_T^{miss} ($2\ell2\nu$)
  - Data split into categories:
    - On-/off-shell
    - Lepton flavour
    - Jet multiplicity



Distributions of off-shell data, fitted to model assuming SM couplings (stacked histogram), and fitted to model assuming no off-shell production (gold) in m_T^{ZZ} ($2\ell2\nu$, left) and m^{4l} (4ℓ, right). Summed over jet multiplicity.

Systematic uncertainties

- **Theoretical uncertainties**
  - Simulation of extra jet in gg samples depending on jet multiplicity (up to 20%)
  - α_S (up to 30%)
  - PDF uncertainties in the cross section calculation (up to 20%)
    - Depends on processes and m_T^{ZZ} or $m_{4\ell}$
  - NLO EW corrections to the *qq(bar)* → *Z(W)Z* process (up to 20%)

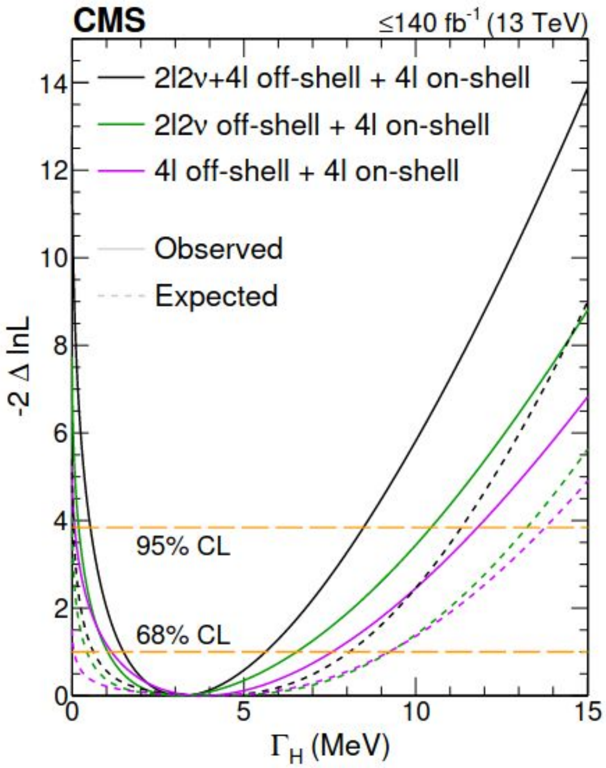
- **Experimental uncertainties**
  - Lepton reconstruction and trigger efficiency (typically 1% per lepton)
  - Integrated luminosity (1.2% - 2.5% depending on data-taking period)
  - Pile-up, jet energy scale, and jet energy resolution

Most of the systematics have sizeable effects on both shape and normalization

Results on Higgs decay width

Param.	Cond.	Observed 68% | 95% CL	Expected 68% | 95% CL
Γ_H	$2\ell 2\nu + 4\ell$	$3.2^{+2.4}_{-1.7} \mid ^{+5.3}_{-2.7}$	$^{+4.0}_{-3.48} \mid ^{+7.2}_{-4.065}$
Γ_H	$2\ell 2\nu$	$3.1^{+3.4}_{-2.1} \mid ^{+7.3}_{-2.91}$	$^{+5.1}_{-3.67} \mid ^{+9.1}_{-4.099}$
Γ_H	4ℓ	$3.8^{+3.8}_{-2.7} \mid ^{+8.0}_{-3.727}$	$^{+5.1}_{-4.047} \mid < 13.8$

- Γ_H measurements extracted from profiled likelihood scan
- **No off-shell hypothesis** ($\Gamma_H = 0$) can be **excluded** at 99.97% CL (3.6 standard deviations)
- Constraints stable within 1 MeV (0.1 MeV) for upper (lower) limits when allowing BSM anomalous *HVV* couplings to vary from zero

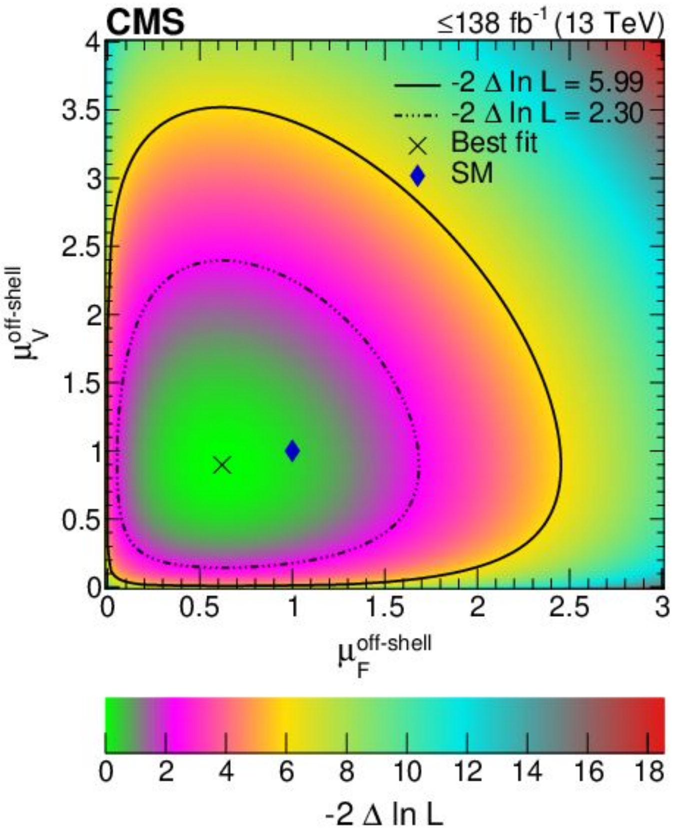


Observed and expected one-parameter scan over Γ_H

Results on signal strength parameters

Param.	Cond.	Observed 68% | 95% CL	Expected 68% | 95% CL
$\mu_F^{off.}$	$\mu_V^{off.}$ (u)	$0.62^{+0.68}_{-0.45} \,\vert^{+1.38}_{-0.614}$	$^{+1.1}_{-0.99998} \,\vert < 3.0$
$\mu_V^{off.}$	$\mu_F^{off.}$ (u)	$0.90^{+0.9}_{-0.59} \,\vert^{+2.0}_{-0.849}$	$^{+2.0}_{-0.89} \,\vert < 4.5$
$\mu^{off.}$	$R_{V,F}^{off.} = 1$	$0.74^{+0.56}_{-0.38} \,\vert^{+1.06}_{-0.61}$	$^{+1.0}_{-0.84} \,\vert^{+1.7}_{-0.9914}$
	$R_{V,F}^{off.}$ (u)	$0.62^{+0.68}_{-0.45} \,\vert^{+1.38}_{-0.6139}$	$^{+1.1}_{-0.99996} \,\vert^{+2.0}_{-0.99999}$

- 2D constraints on ($\mu_F^{off\text{-}shell}$, $\mu_V^{off\text{-}shell}$) also extracted from profile likelihood scans
- The total rate of off-shell Higgs boson production is constrained with different assumptions on $R_{V,F}^{off\text{-}shell}$
  - No assumptions: constrained in interval [0.0061, 2.0] at 95% confidence level
- **Signal strengths consistent with SM** ($\mu = 1$)

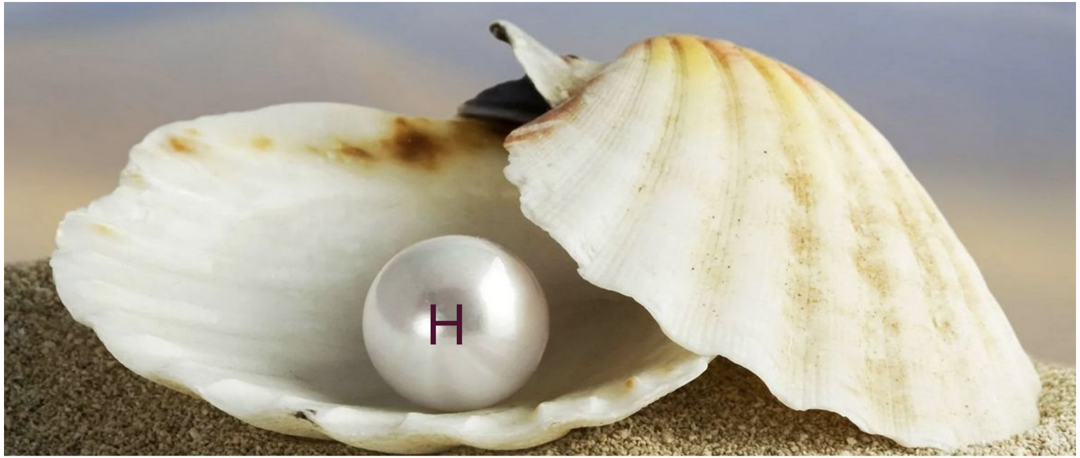


Two parameter likelihood scan of $\mu_F^{off\text{-}shell}$ and $\mu_V^{off\text{-}shell}$

Summary

- **By combining $2\ell2\nu$ with previous 4ℓ channel results, obtained first evidence for off-shell Higgs boson production (99.97% CL)** and **most precise** measurement of total Higgs decay width and lifetime:
  - $\boldsymbol{\Gamma_H = 3.2^{+2.4}_{-1.7}}$ **MeV** at 68% CL
  - 7.7×10^{-23} s $< \tau_H <$ 1.3×10^{-21} s at 95% CL

- Measurements consistent with SM expectation and **no hint of BSM physics**

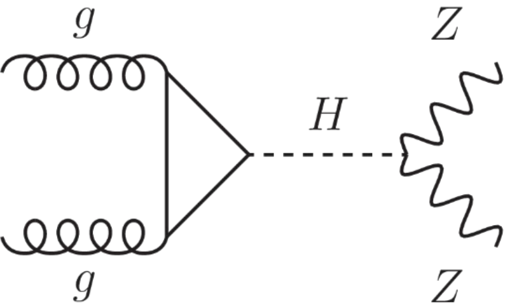



Thank you for your attention!
GROUPA Collaboration, 2022

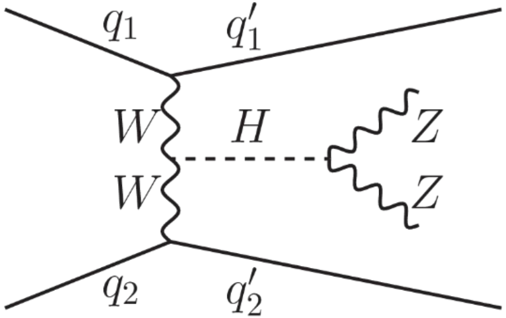

Backup

H→ZZ signal

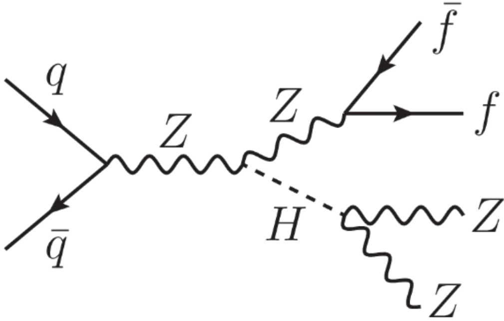
$gg \to H \to ZZ$:



$q_1 q_2 \to q_1' q_2' H \to q_1' q_2' ZZ$:

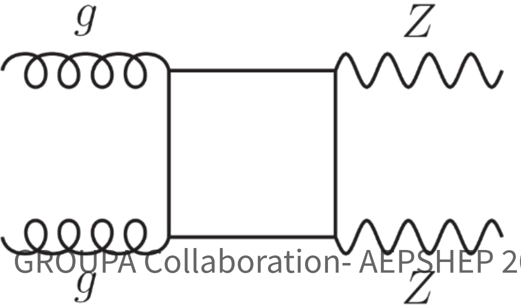


$q\bar{q} \to ZH \to ZZZ$:

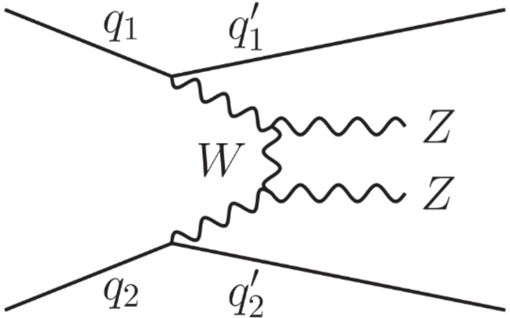


ZZ continuum background

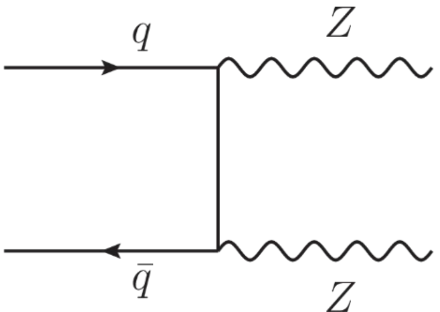
$gg \to ZZ$:



$q_1 q_2 \to q_1' q_2' ZZ$:

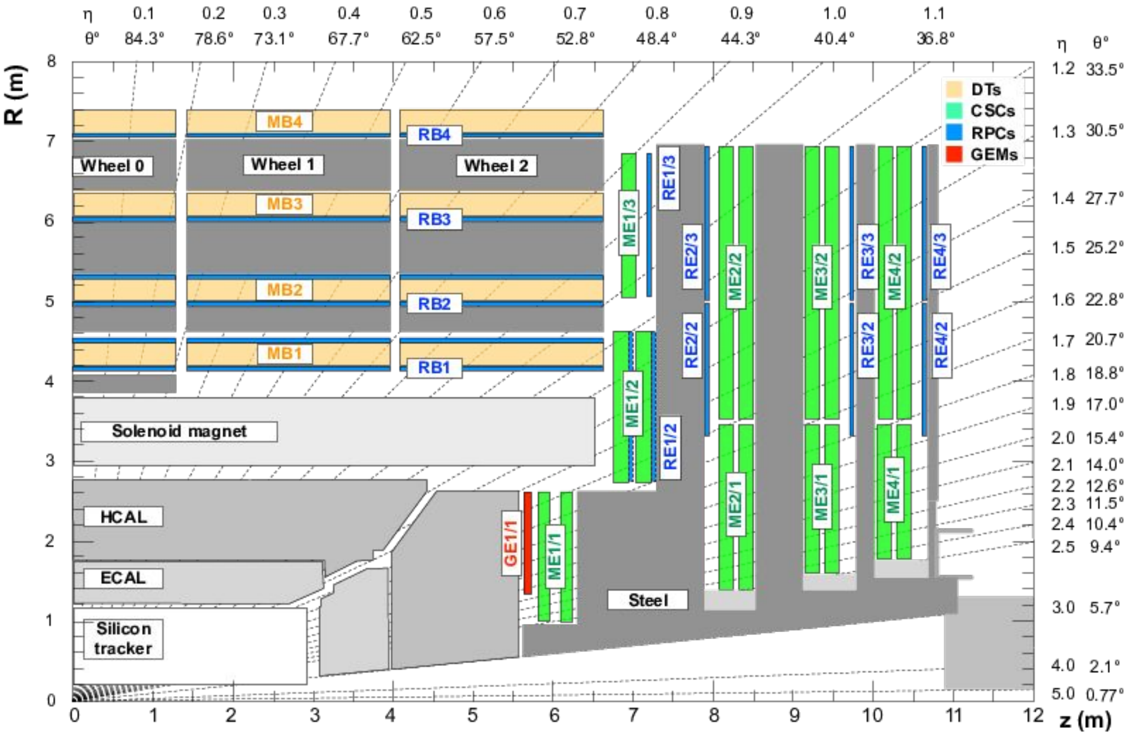


$q\bar{q} \to ZZ$:



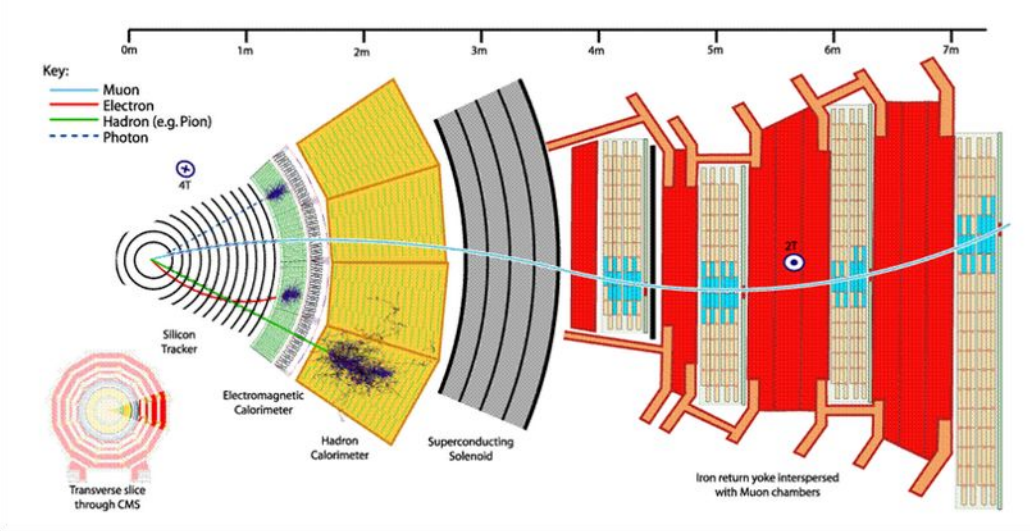
Compact Muon Solenoid (CMS) Experiment

- The principal feature of the CMS detector is a superconducting solenoid providing an axial magnetic field of 3.8 T inside which an inner tracker, an electromagnetic calorimeter (ECAL), and a hadron calorimeter (HCAL) reside.
- The inner tracker is composed of a silicon pixel detector and a silicon strip tracker, and measures trajectories of charged particles in the pseudorapidity range $|\eta| < 2.5$.
- With up to four layers of gas-ionization detectors of four technologies (DT, CSC, RPC, and the recently added GEMs) positioned outside the solenoid and sandwiched between the layers of the steel flux-return yoke, the muon detection system covers $|\eta| < 2.4$.

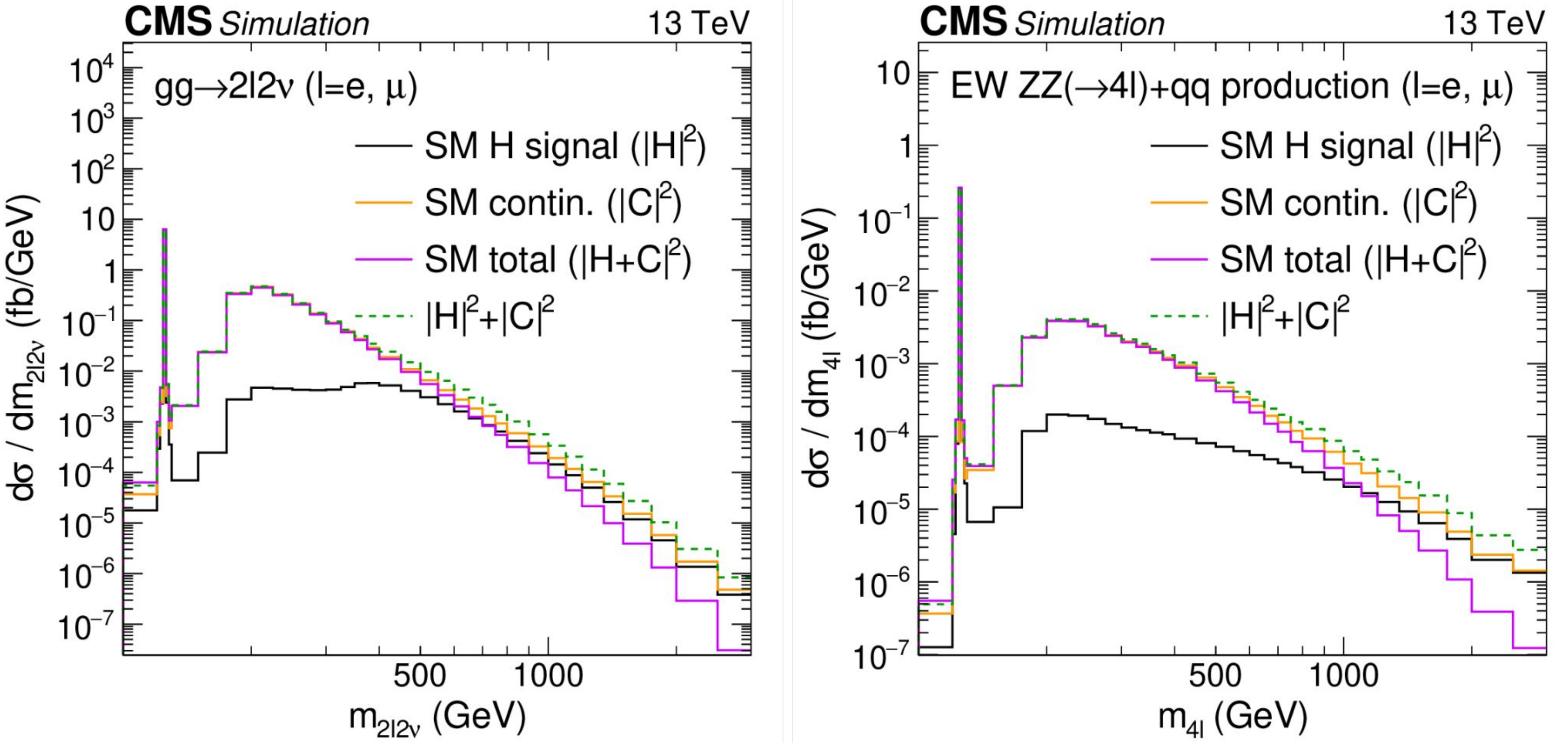


Particle trajectories in the CMS detector

- Electrons and Photons are captured by the ECAL
- Hadrons primarily deposit their energies in the HCAL
- Muons are detected by the Muon System
- Neutrinos do not interact with any tracking components

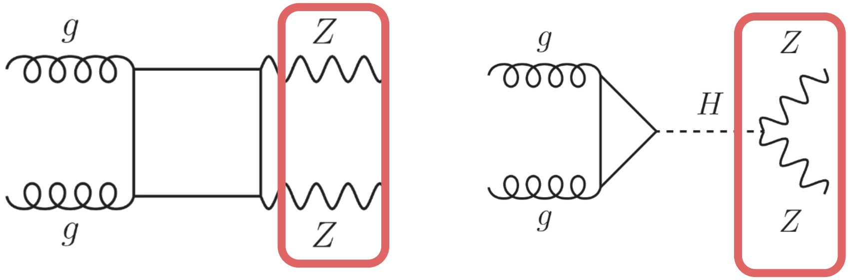


Event simulation

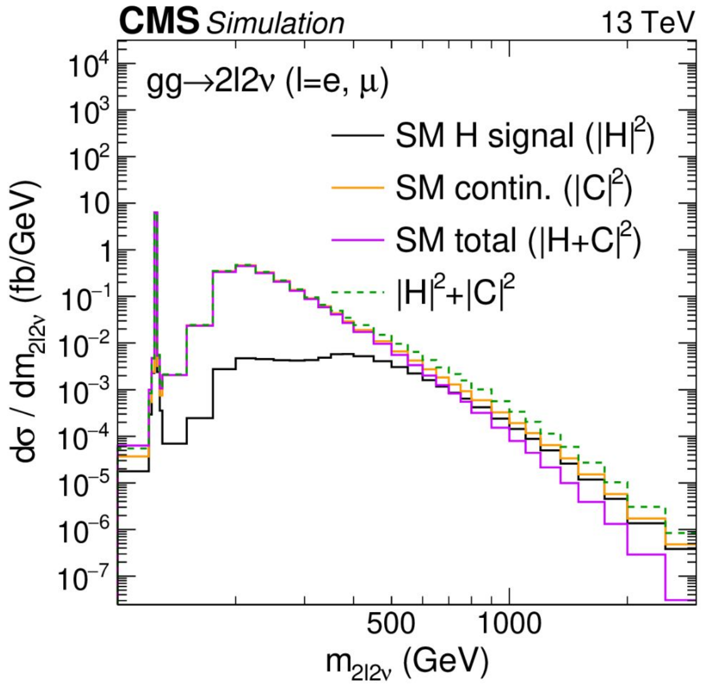


Negative interference

- ***ZZ* continuum production** is larger than $H \rightarrow ZZ$ and introduces complications
- **Interference** between modes sharing the same final states is **important at higher off-shell masses**
- Destructive interference expected $|H|^2+|C|^2 > |H+C|^2$



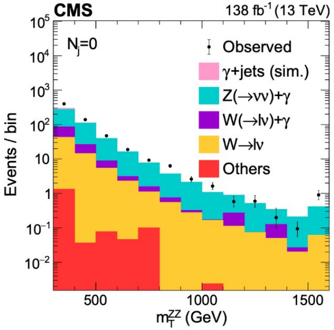
Feynman diagrams showing continuum contribution coming from $gg \rightarrow ZZ$ (left) vs. $H \rightarrow ZZ$ (right)

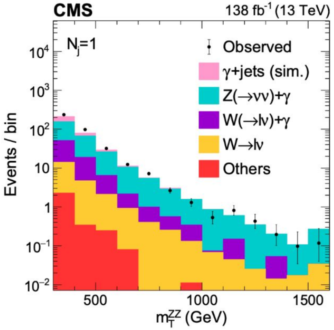


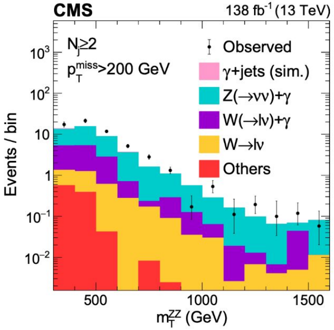
SM calculations of $m_{2\ell 2\nu}$ for $gg \rightarrow 2\ell 2\nu$ process

Control region plots

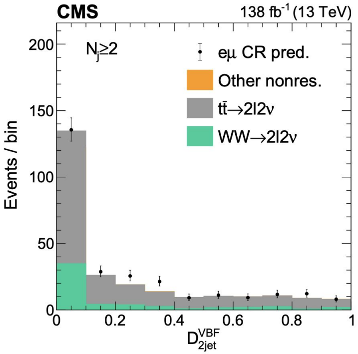
γ+jets CR

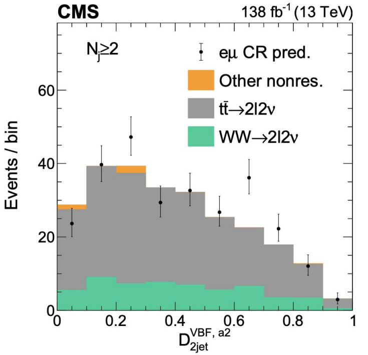




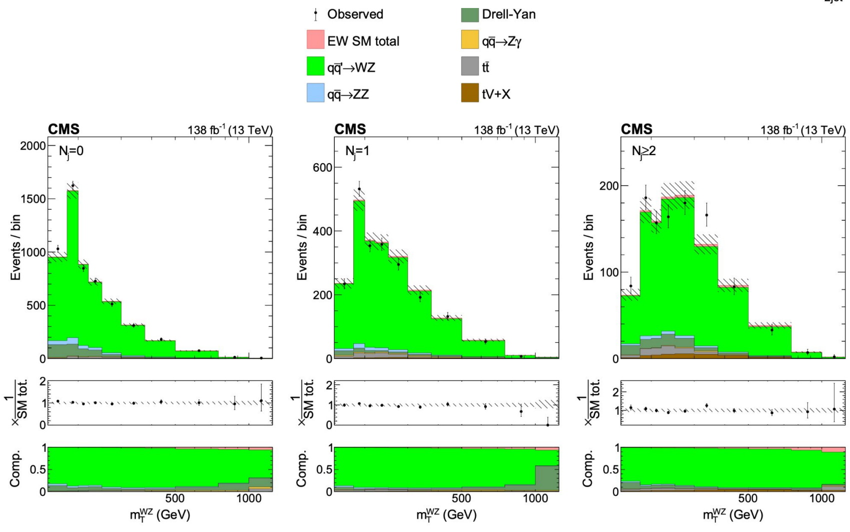


eμ CR



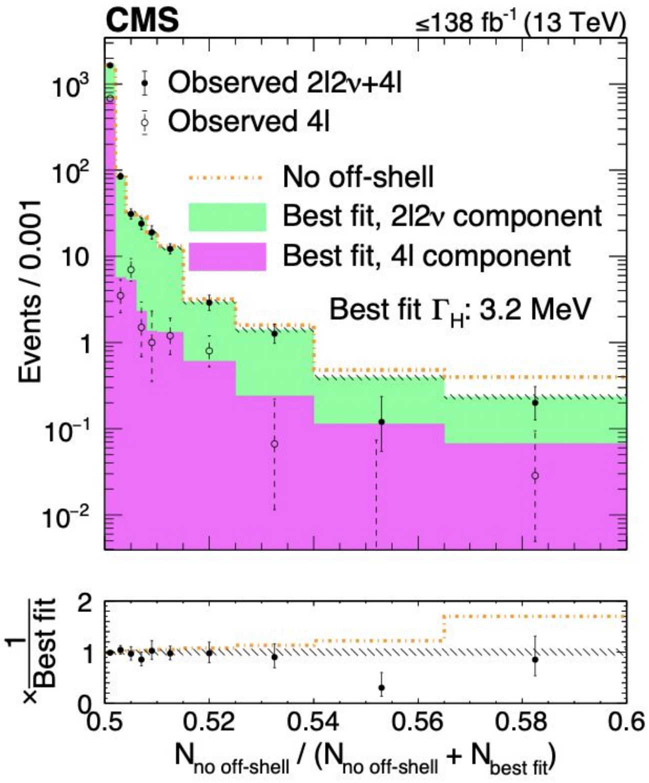


trilepton CR



Exclusion of no off-shell hypothesis

- The ratios are taken after separate fits to the no off-shell hypothesis ($N_{\text{no off-shell}}$) and the best overall fit ($N_{\text{best fit}}$).
- From the last two bins, the exclusion is noted to be most apparent.



Matrix element kinematic discriminant (using MELA)

- MELA -Matrix Element Likelihood Approach
- Complete set of mass and angular input observables Ω to describe kinematics at LO in QCD.
- The probability of a certain process P is calculated usi characterized by Ω
  - “sig” - signal model
  - “alt” - alternative model (can also be background)
  - “int” - interference between the two models
- The probabilities P are calculated from the matrix elements provided by the MELA package and are normalized
- Discriminants are constructed to discriminate different hypothesis

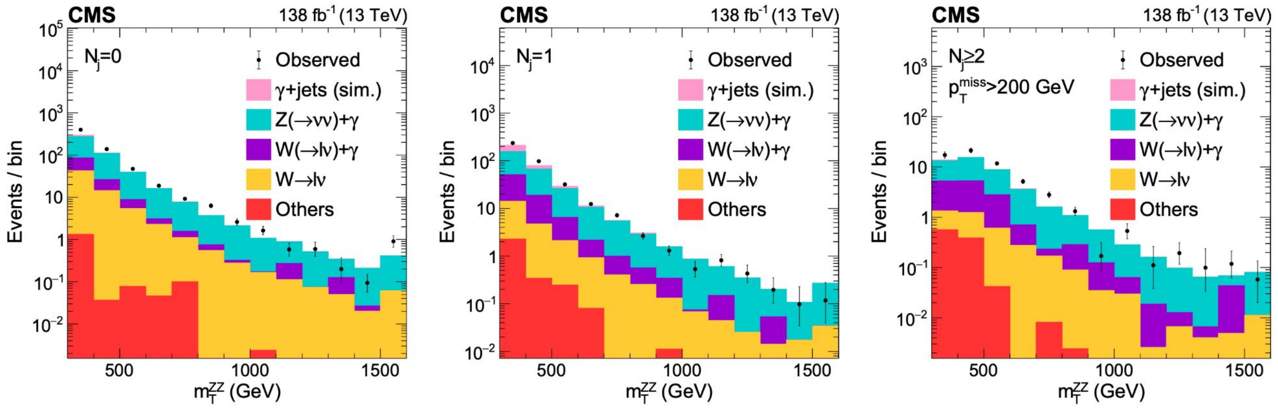
$$\mathcal{D}_{\text{alt}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) + \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}$$

$$\mathcal{D}_{\text{int}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})\mathcal{P}_{\text{alt}}(\mathbf{\Omega})}},$$

Control region selection

Three different control regions are defined:

1. γ + jets (for background from Z + jets with same properties)
2. $e\mu$ (for background from $pp \rightarrow tt$ and $pp \rightarrow WW$)
3. trilepton $qq(bar) \rightarrow WZ$ (for background from $qq(bar) \rightarrow ZW$ and $qq(bar) \rightarrow ZZ$)



m_T^{ZZ} distributions for events in the γ + jets CR with 0, 1 and ≥ 2 jets

Trigger & Object selection

Event trigger	
$2l2\nu$ SR	Single & di-lepton trigger
eμ CR	
$3l$ WZ CR	
γ+jets	Photon trigger
efficiency	78~100%

Jets	
anti-k_T	dist. param. of 0.4
Suppress jet from pileup interaction	p_T>30 GeV. $\|\eta\|$ <4.7, ΔR>0.4
b jet ID,	$\|\eta\|$<2.5 (2.4 for 2016) using DEEPJET /w loose working point
Efficiency	75~95%

Photons
ECAL /wo track
p_T>20 GeV
$\|\eta\|$ <2.5
Shower shape & isolation

Muon(electron using BDT)	
PF algorithm	ΔR<0.3
Loose isolation	p_T>5 GeV,
Tight Isolation	$\|\eta\|$<2.4 ($\|\eta\|$<2.5)

Signal region selection	
2l2nu	vetoes
Opposite sign, same flavor leptons	b-tagged jet
p_T>25 GeV	Loosely isolated lepton /w p_T>5 GeV
$\|m_{ll\text{-}}-m_Z\|$<15 GeV	Loosely identified photons /w p_T>20 GeV
p_T^{ll}>55 GeV	Event with isolated reconstructed tracks /w p_T>10 GeV
p_T^{miss}>125 GeV for N_j<2, p_T^{miss}>140 GeV for else	
$\Delta\phi^{ll}_{miss}$>1.0 between p_T^{miss} and p_T^{ll}, $\Delta\phi^{ll+jets}_{miss}$>2.5 between p_T^{miss} and $p_T^{ll}+\Sigma p^j_T$, $\Delta\phi^{j}_{miss}$>0.25 (0.50) between p_T^{miss} and p_T^j for N_j	

Background Estimation and Control Region

- Two types of backgrounds coming from Interfering and Non-interfering processes
- Interfering processes with signal
  - gg → ZZ, WZ, WW ← **Monte Carlo simulated**
- Non-interfering processes
  - Drell-Yan process ← **Data-driven** estimated from **γ+jets**
  - pp → top quark pair, WW (not from gg) ← **Data-driven** estimated from **eμ channel**
  - qq(bar) → WZ, WW ← **Data-driven** estimated from **trilepton channel**

Data driven method: Mimics the shapes of background from the data in a certain control region (with subtraction of other process shapes in the control region)

Drell-Yan process: The kinematics of γ+jets process are similar to it if the γ is replaced with Z/γ*

pp → top quark pair, WW : Events of these processes with eμ is similar to ee and μμ events

qq(bar) → WZ, ZZ : Two lepton pairs having closed to m_Z is chosen and the other one is regarded as ν

Event selection

- $2l2\nu$
  - Opposite sign, same flavor required (e^+e^- or $\mu^+\mu^-$)
  - Di-lepton selection: $|m_{ll} - m_Z| < 15$ GeV, $p_T^{ll} > 55$ GeV
  - MET selection: $p_T^{miss} > 125(140)$ GeV for $N_j < 2 (N_j \geq 2)$
  - Background veto: Events with a b-tagged jet, loosely identified photon or lepton, or additional isolated track
- $4l$
  - Di-lepton selection: $m_{ll} > 4$ GeV
  - Z candidate selection: $40(12) < m_{ll} < 120$ GeV for first(second) Z candidate
  - On-shell(Off-shell) h candidate selection: $105 < m_h < 140$ GeV($m_h > 220$ GeV)

Kinematic observables and signal region selection

Kinematic observables:

- p_T^{miss} (provides signal/background discrimination)
- m_T^{ZZ} computed using p_T^{miss} (m^{ZZ} for the 4 leptons channel)
- matrix element (MELA) kinematic discriminant to identify VBF processes for events with $N_j \geq 2$

Mathematical definition of m_T^{ZZ}

$$\left(m_{\mathrm{T}}^{\mathrm{ZZ}}\right)^2 = \left[\sqrt{p_{\mathrm{T}}^{\ell\ell\,2} + m_{\ell\ell}{}^2} + \sqrt{p_{\mathrm{T}}^{\mathrm{miss}\,2} + m_{\mathrm{Z}}{}^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}\right|^2,$$

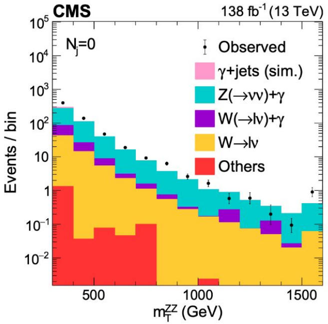
where $\vec{p}_{\mathrm{T}}^{\,\ell\ell}$ and $m_{\ell\ell}$ are the dilepton transverse momentum vector and invariant mass, respectively, and m_{Z}, the Z boson pole mass, is taken to be 91.2 GeV [27].

Signal region:

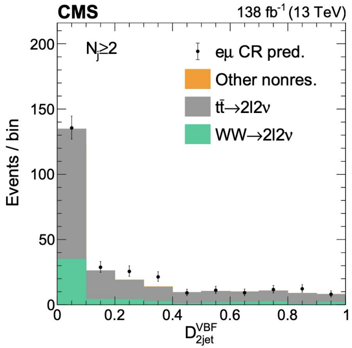
- **Lepton** selection
  - 2 opposite sign, tightly isolated, same-flavor leptons with $p_T > 25$ GeV
  - m_{ll} within 15 GeV of m_Z
  - $p_T^{ll} > 55$ GeV
- **Veto** events with:
  - *b*-tagged jets
  - additional loosely isolated leptons or photons with $p_T > 20$ GeV
  - isolated reconstructed tracks of $p_T > 10$ GeV
- **Other** criteria:
  - lower bound on the unsigned azimuthal opening angle between p_T^{miss} and other objects in the event
  - $p_T^{miss} > 125$ GeV (> 140 GeV) for $N_j < 2$ (≥ 2)

Background estimation and Control Region

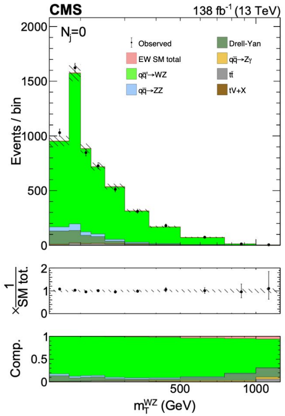
- **Three** different **control regions** are defined:
    - ***γ + jets*** (for background from *Z* + jets with same properties)
    - ***eμ*** (for background from *pp → tt* and *pp → WW*)
    - trilepton ***qq(bar) → WZ*** (for background from *qq(bar) → ZW* and *qq(bar) → ZZ*)
- Naively speaking, $N_{\text{Data Driven Bkg}} = \varepsilon(N_{\text{Data}} - N_{\text{BKMC}})$ (BKMC: Background Monte Carlo, ε: scaling factor)



Scaling for *γ + jets*:
By a comparison of *γ* + jets with DY + jets in a low p^T_{miss} region (p^T_{miss} < 125 GeV)



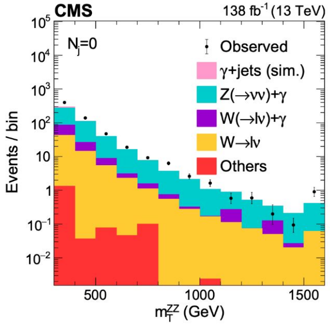
Scaling for *eμ*:
The difference in trigger and reconstruction efficiencies between *eμ* and *ee* or *μμ* final states



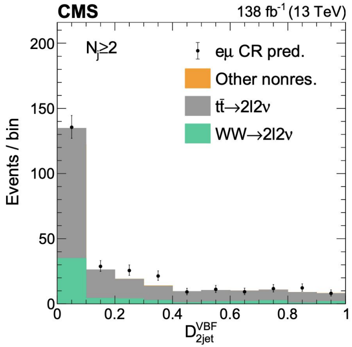
Scaling for trilepton:
No additional scaling

Background estimation and Control Region

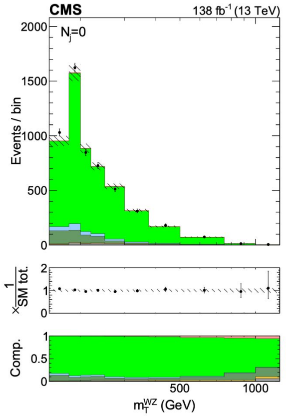
- Two types of backgrounds coming from interfering and non-interfering processes
- **Interfering** processes with signal (Monte Carlo simulated)
  - *gg → ZZ, WZ, WW*
- **Non-interfering** processes (data-driven estimated)
  - Drell-Yan (DY) process ← **γ + jet** control region
  - *pp → tt, pp → WW* (not from *gg*) ← **eμ** control region
  - *qq(bar) → WZ, qq(bar) → WW* ← **Trilepton** control region



***γ* + jets control region**



***eμ* control region**



Trilepton control region