Measurement of Higgs boson width and first evidence of its off-shell production

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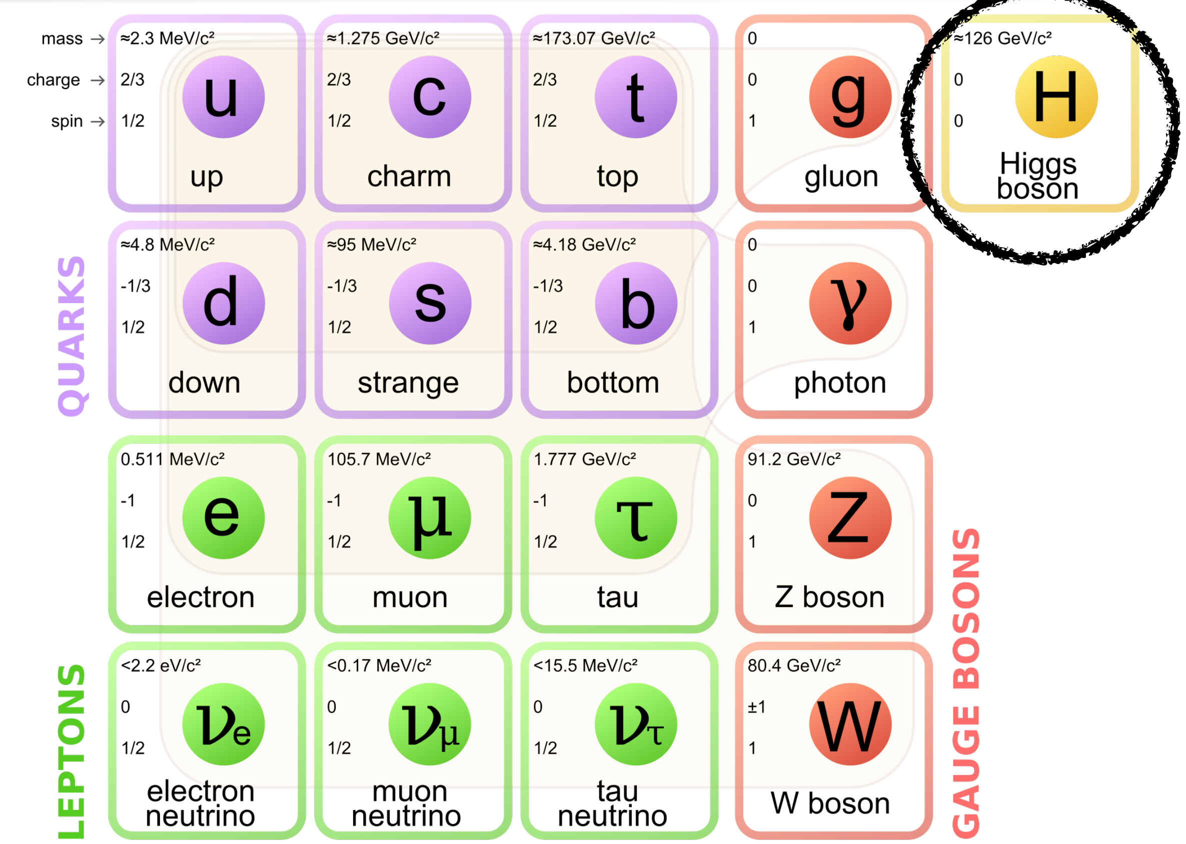
Seminar@ 京沪云坛
September 23, 2022

Outline

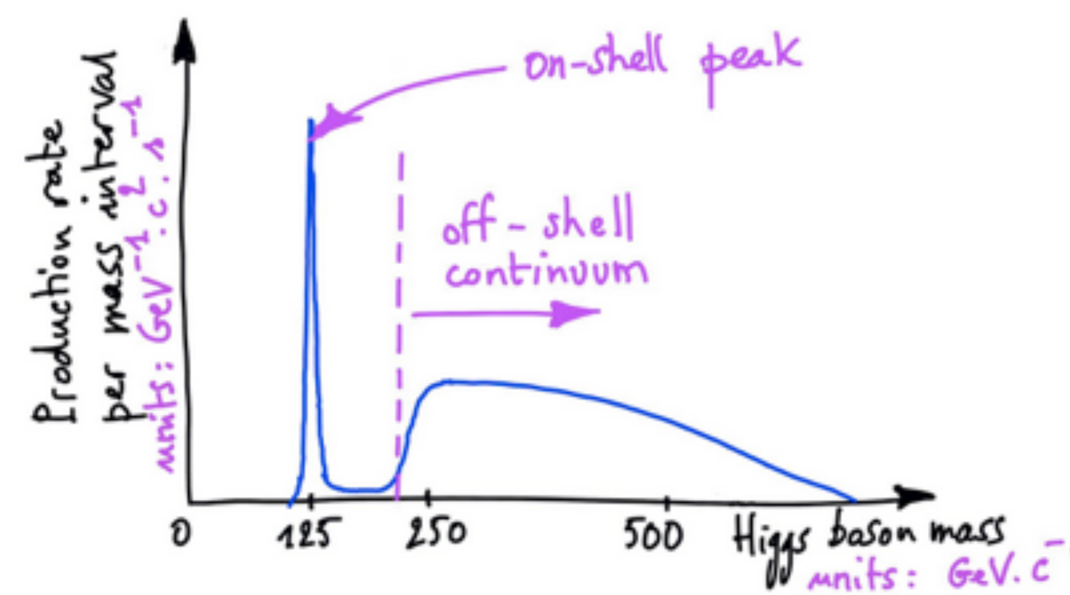
- Introduction
- CMS detector
- Physics Objects Performance
- Analysis Strategies
  - $H \rightarrow ZZ \rightarrow 4l$ on-shell analysis
  - $H \rightarrow ZZ \rightarrow 4l$ off-shell analysis
  - $H \rightarrow ZZ \rightarrow 2l2\nu$ off-shell analysis (more details)
- Summary

Higgs is so peculiar

- The only scalar in fundamental particles
- Responsible for EWSB and explain the origin of mass
- Its mass is at EW scale O(100GeV), 10^{17} times smaller than Planck scale
- Its special mass lineshape.

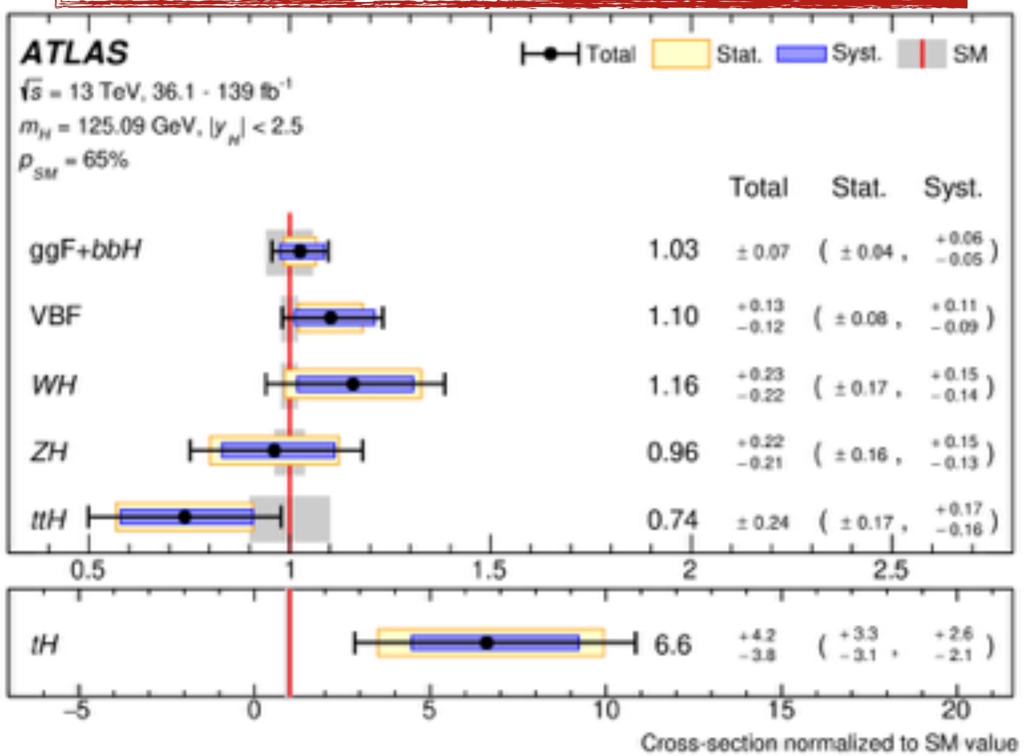


Important to measure its properties.

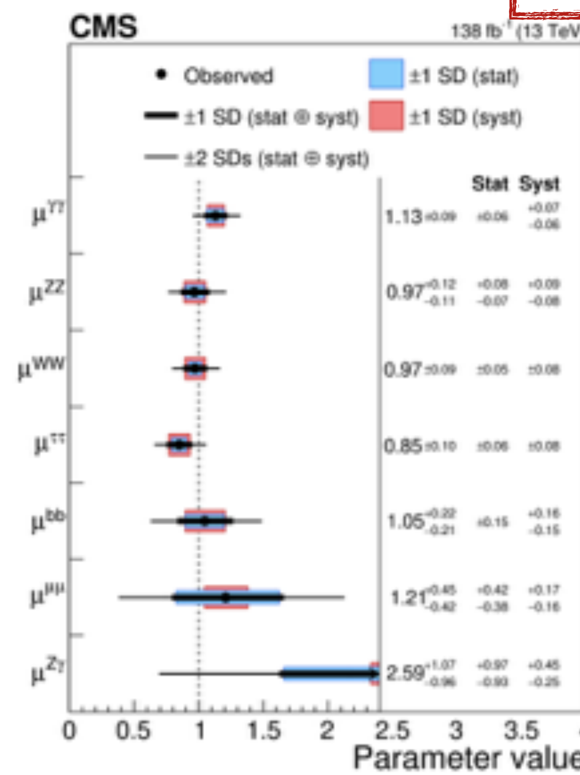


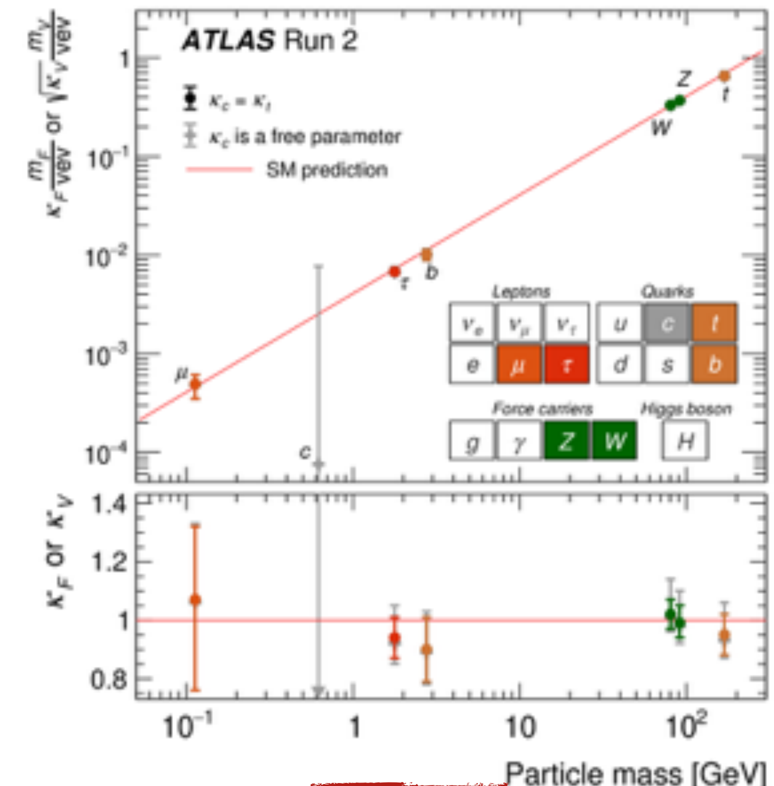
Higgs Properties Measurements

σ for main production modes

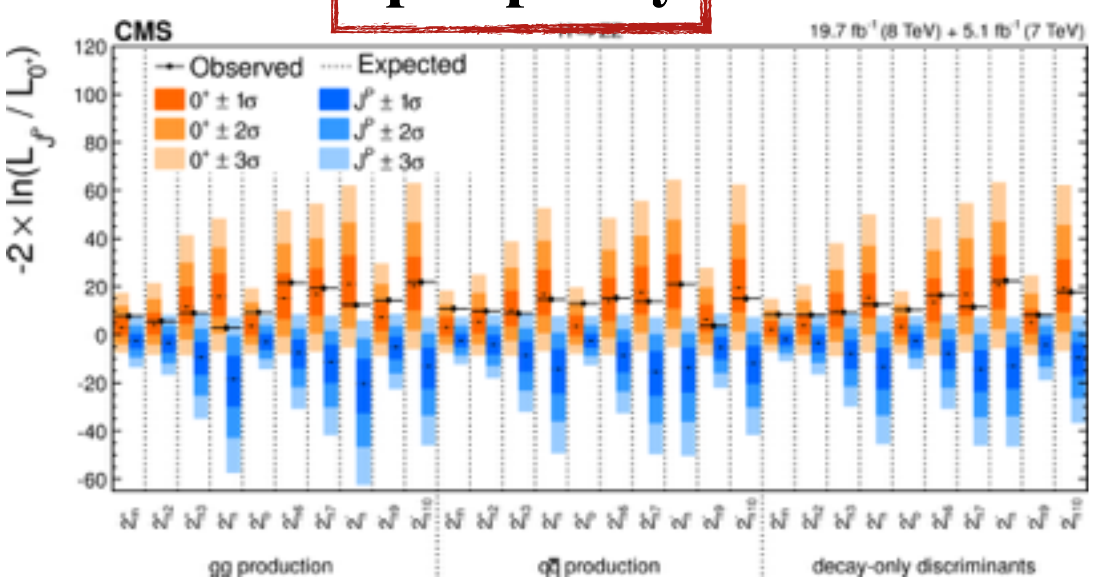


couplings

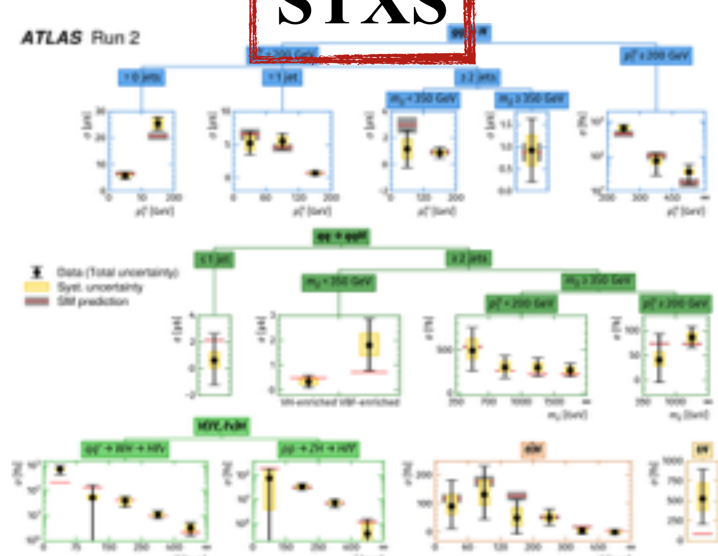




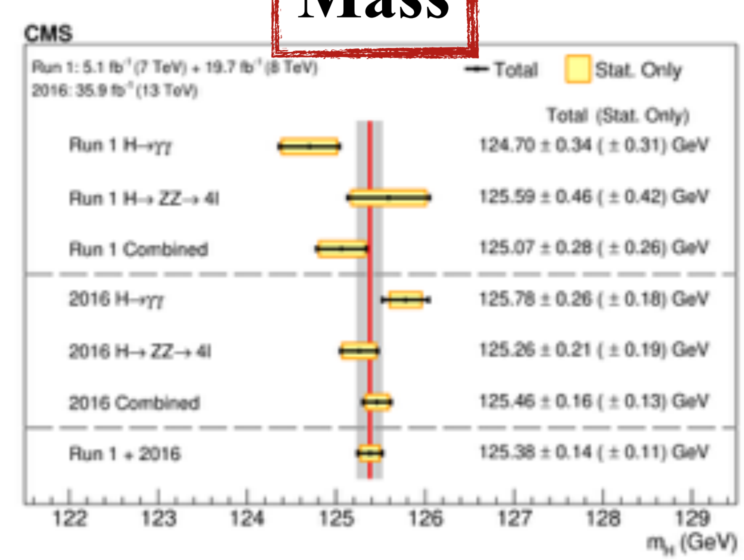
spin-parity



STXS



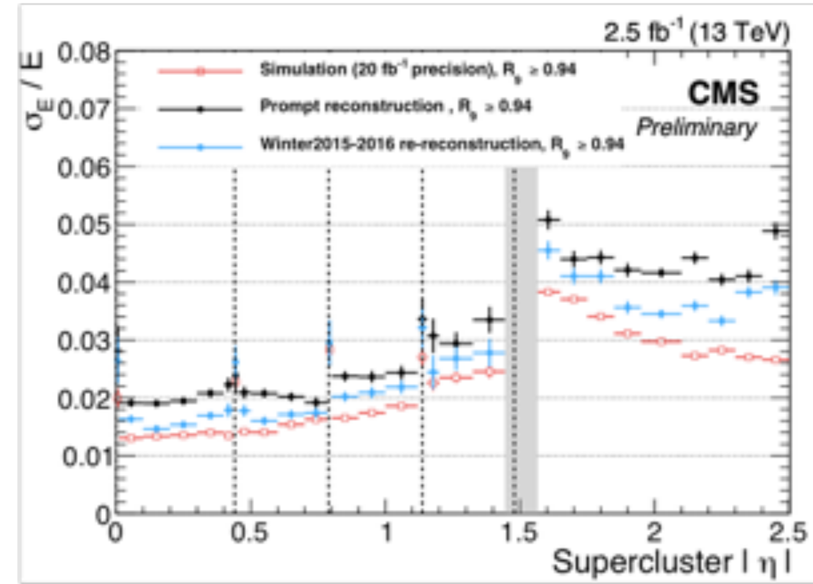
Mass



Higgs Width

- **Predicted width in SM Γ_H: 4.1MeV**

- **Due to detector response, the reconstructed Higgs mass is smeared $\sigma \sim$ 1-2GeV**



relative energy resolution for e

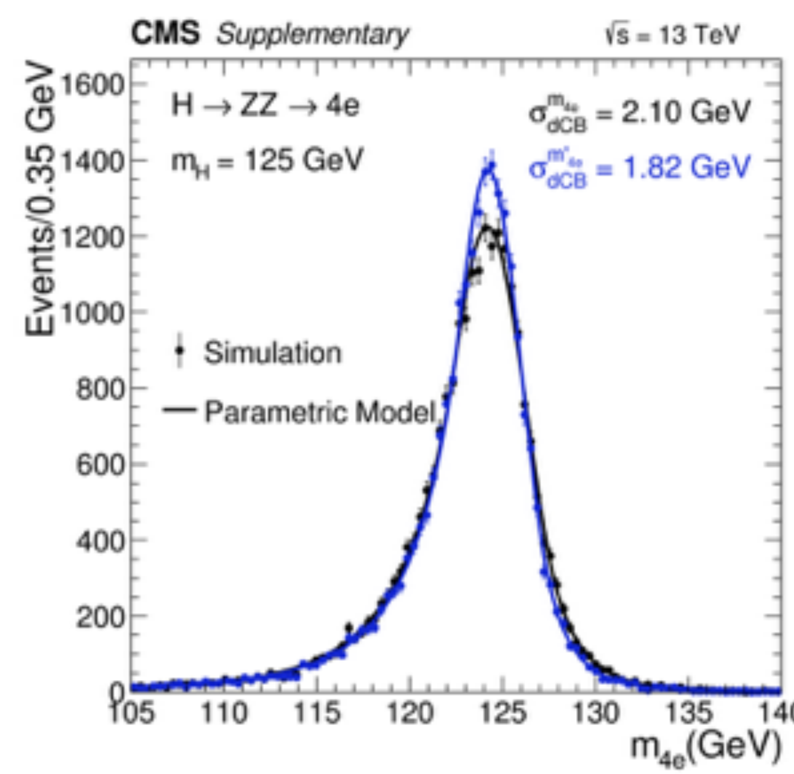
e.g for an electron E_e~50GeV, σ_e~1GeV

$$m_H = \sqrt{(E_{e1} + E_{e2} + E_{e3} + E_{e4})^2 - (\overrightarrow{p_{4e}})^2}$$

σ_{mH}~ $2\times\sigma_e = 2$GeV

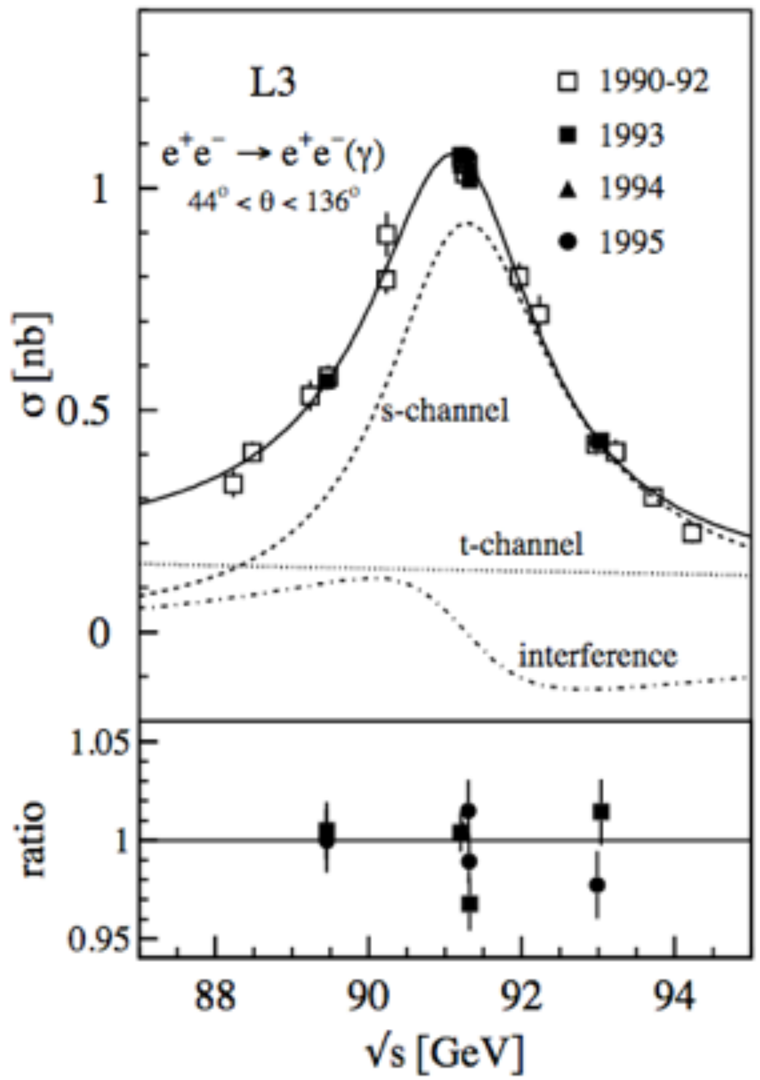
↑

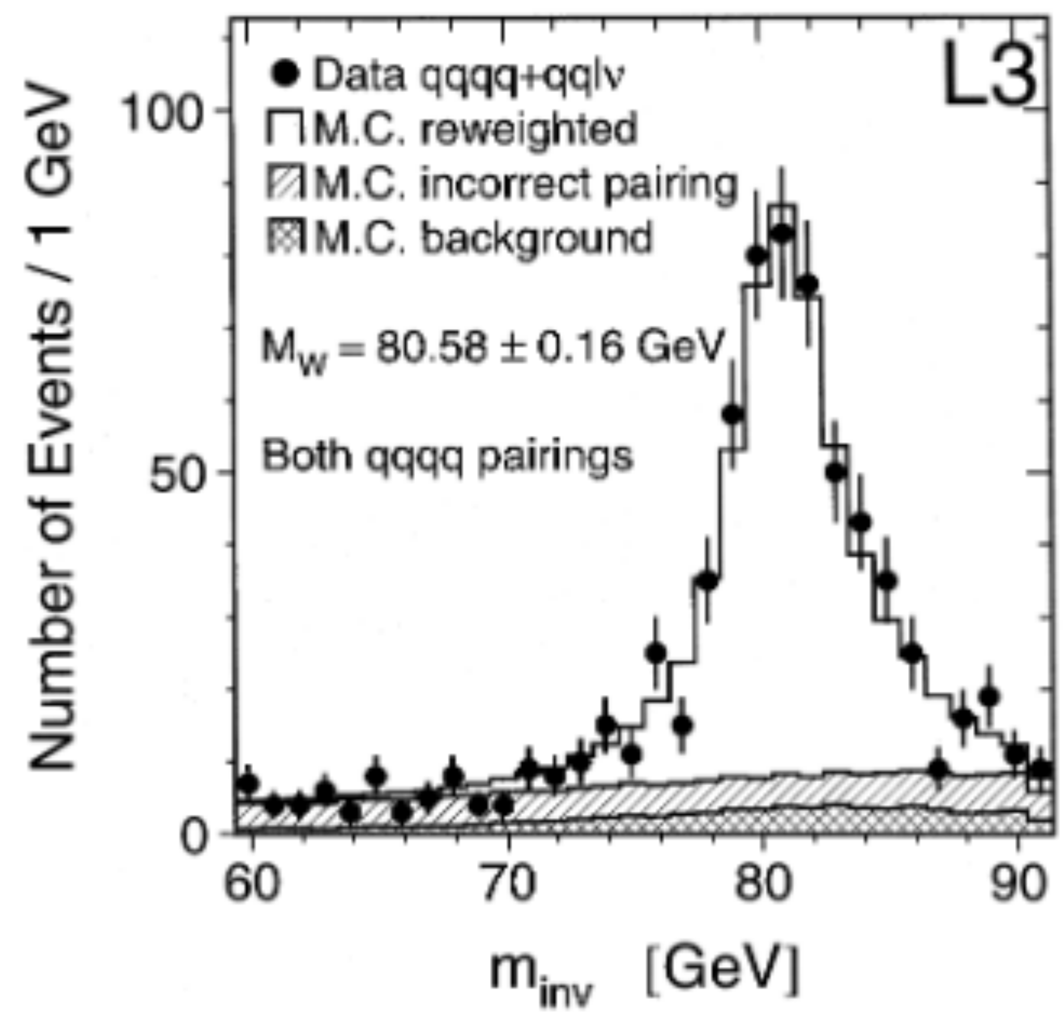
500 times SM Γ_H ~ 4.1MeV



- **Difficult to measure Higgs width through on-shell pole**

W, Z width measurements @ LEP



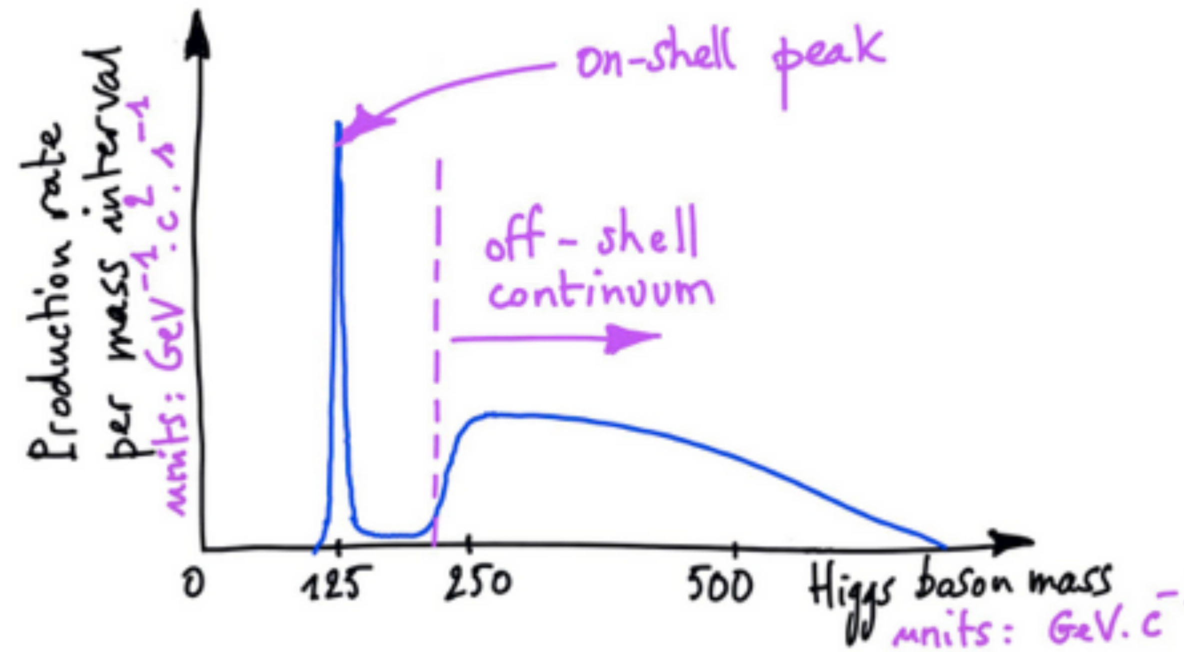


- Γ_Z = 2.4952 ± 0.0023 GeV (in PDG)
- Measure the $Z \to e^+e^-$ cross section at different √s around Z pole.
- Fit the lineshape to extract Γ_Z

- Γ_W = 2.085 ± 0.042 GeV (in PDG)
- Directly fit the invariant mass of qq or lν to extract Γ_W
- Affected by the jet or lepton resolution

Indirect way to measure Γ_H

- **Higgs production rate:**



$$d\sigma \propto \frac{g_{\text{prod}}^2 g_{\text{dec}}^2}{\left(q_H^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2} dq_H^2$$

⇨ $\sigma^{\text{on-shell}} \propto \frac{g_{\text{prod}}^2 g_{\text{dec}}^2}{\Gamma_H} \propto$ $\mu_{\text{on-shell}}$

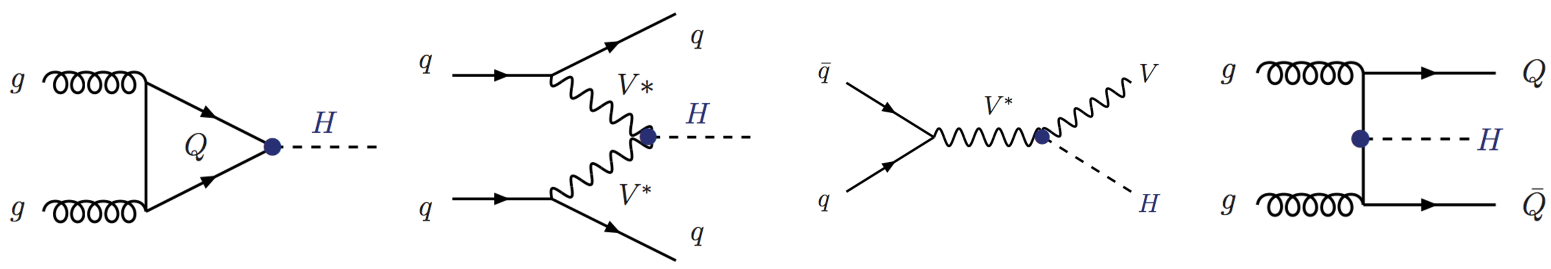
⇨ $\sigma^{\text{off-shell}} \propto \int \frac{g_{\text{prod}}^2 g_{\text{dec}}^2}{\left(q_H^2 - m_H^2\right)^2} dq_H^2 \propto$ $\mu_{\text{off-shell}} \propto \mu_{\text{on-shell}} \times \Gamma_H / \Gamma_{SM}$

- **By measuring the signal strengths in on-shell and off-shell, and take their ratio, we could measure Γ_H**

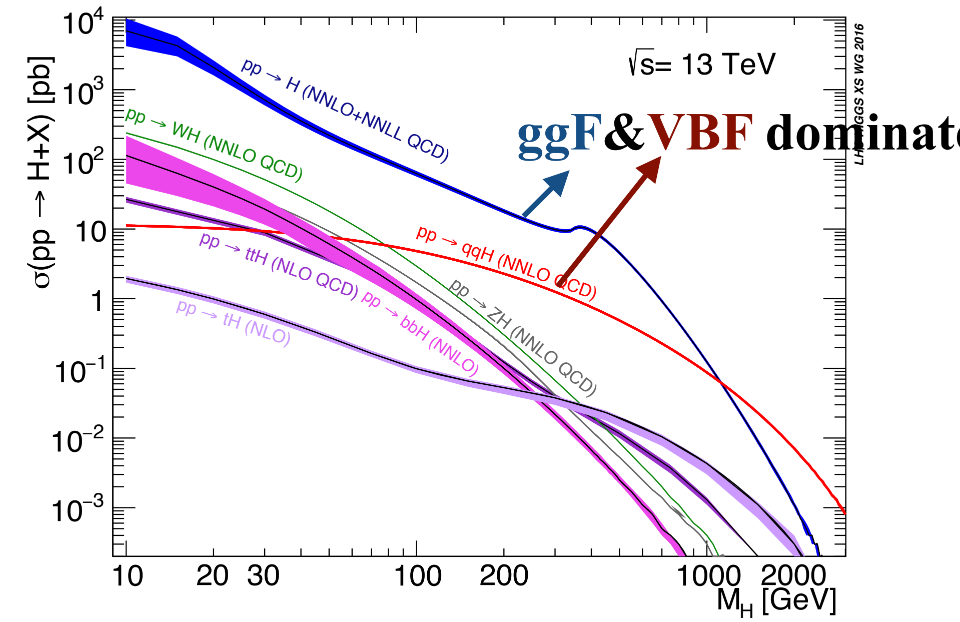
$$\Gamma_H / \Gamma_{SM} = \frac{\mu_{off-shell}}{\mu_{on-shell}}$$

Off-shell Higgs

- **Production modes for both on-shell and off-shell:**
  ggF, VBF, VH, ttH

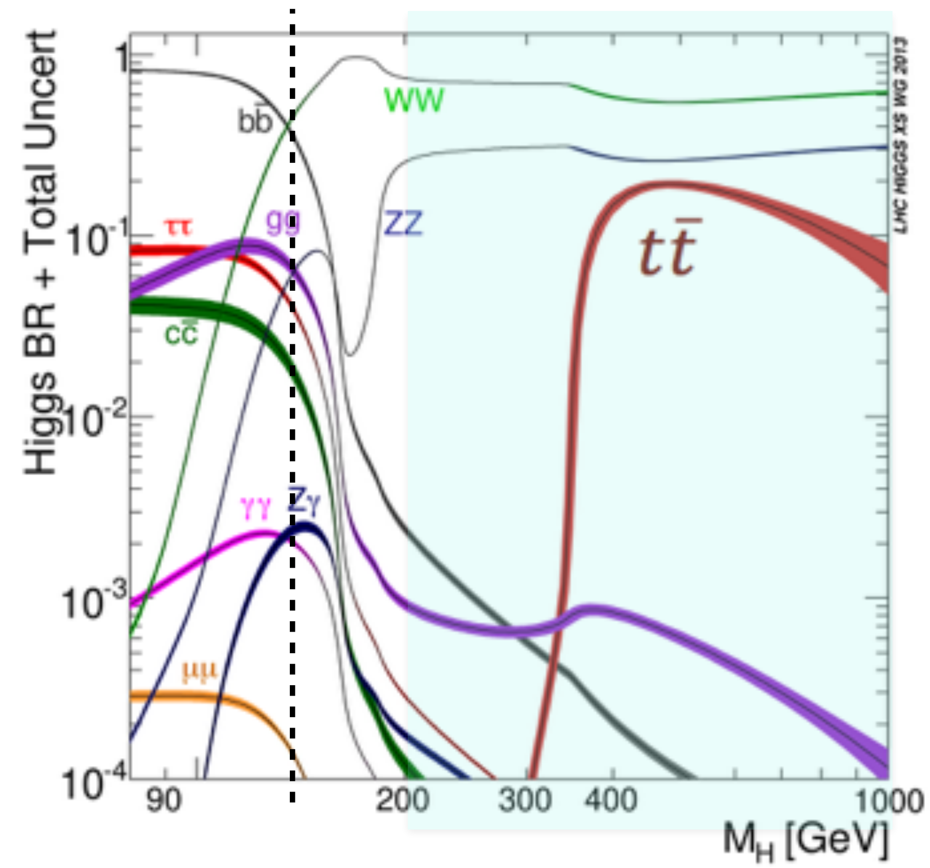


ggF **VBF** **VH** **ttH**



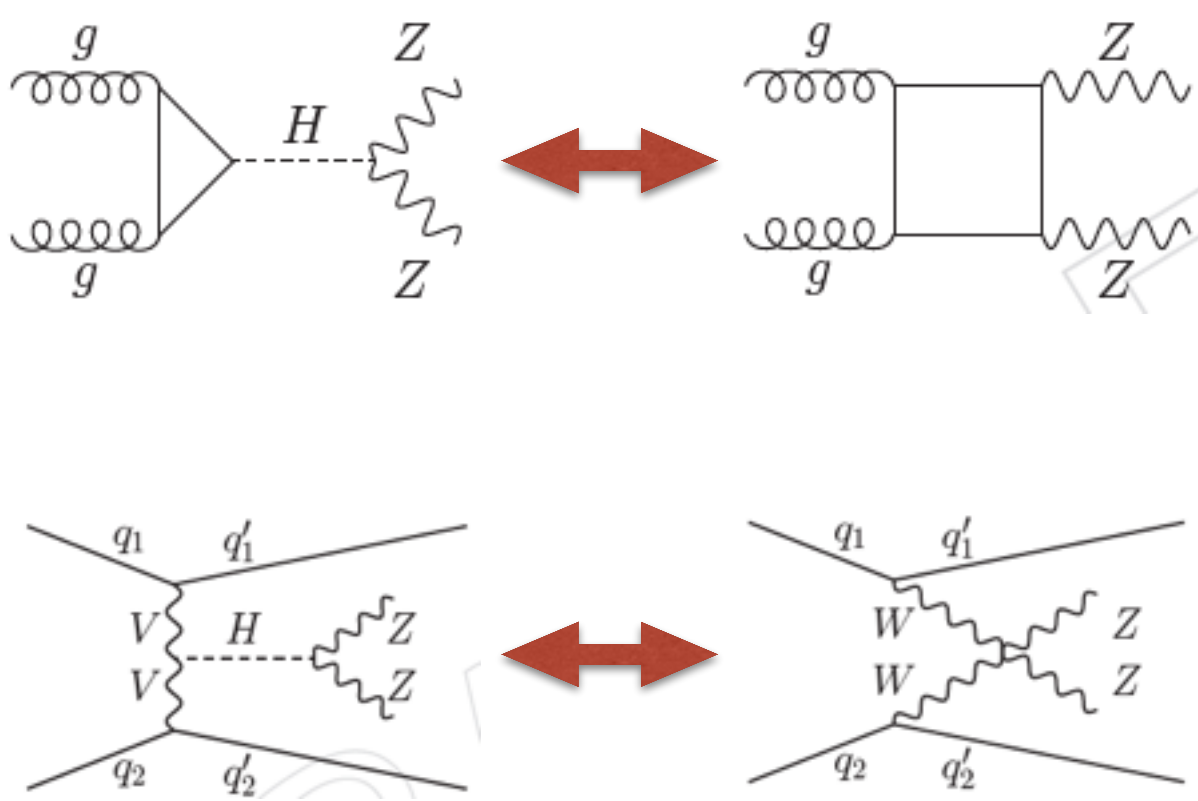
- **Main decay modes for off-shell Higgs:**
  WW, ZZ, tt

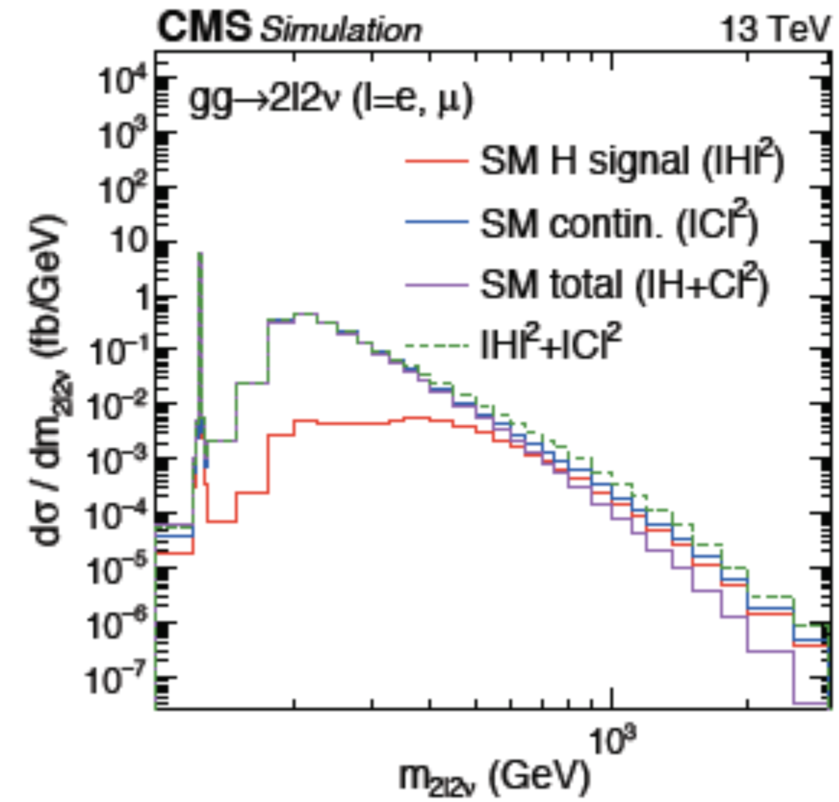
- **For width measurement, since we need to combine with on-shell, the best decay channel to be studied: ZZ**

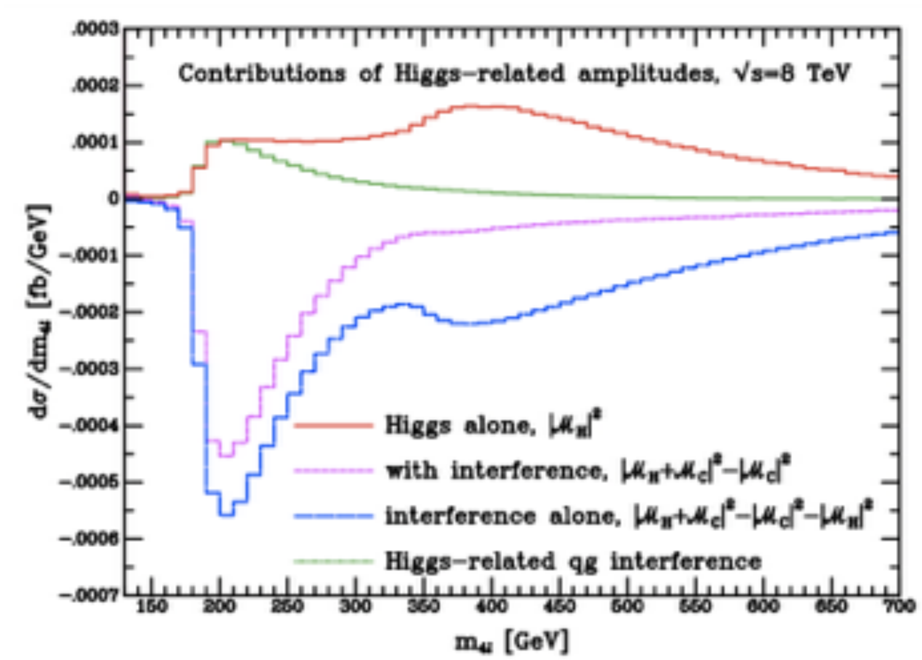


Off-shell Higgs in ZZ channel

- **Difficulties for probing off-shell Higgs:**
  - low production rate: ~10% of total xs
  - large destructive interference with continuum background







HVV anomalous couplings

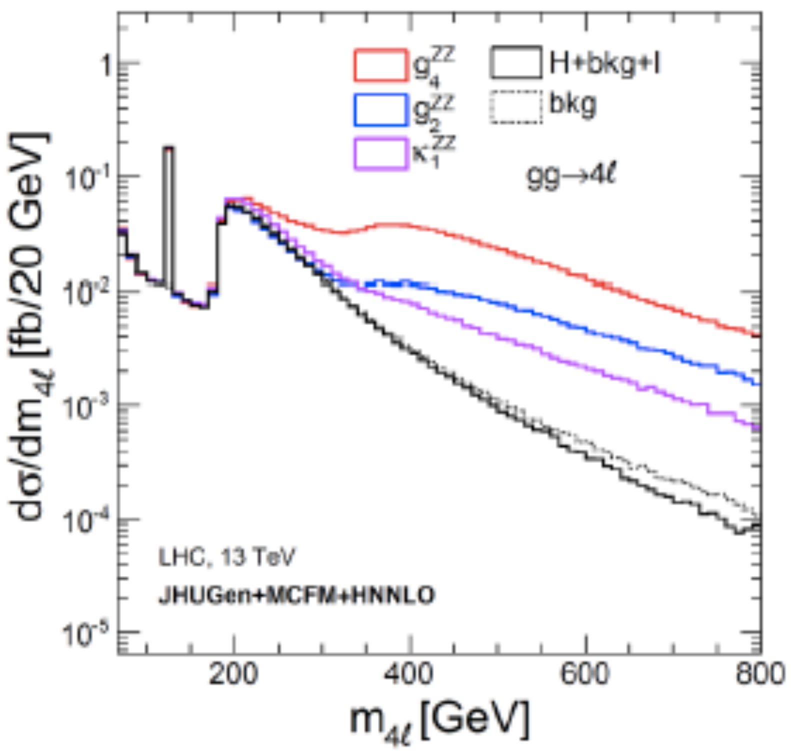
- **Could probe the HVV anomalous couplings in ZZ final states**

$$A(HVV) \sim \left[\boldsymbol{a_1} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2 + q_{V2}^2)}{\Lambda_1^2} + \cdots \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + |a_2|\, e^{i\phi_{a2}}\, f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + |a_3|\, e^{i\phi_{a3}}\, f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

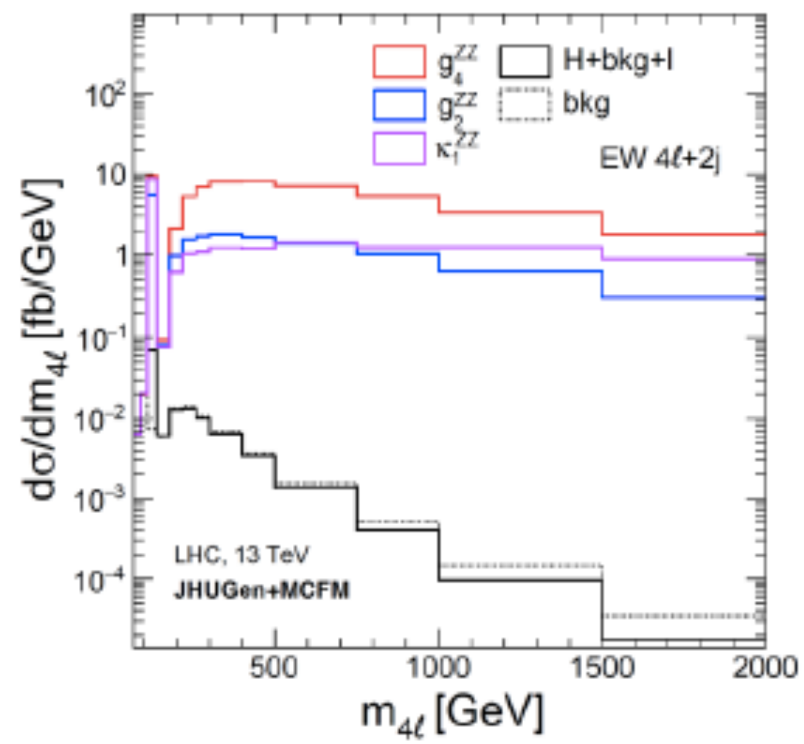
In SM, a_1=2 and the rest are 0.

- **Define:** $$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j}, \quad a_j = a_1, a_2, a_3, \frac{1}{\Lambda_1^2}$$

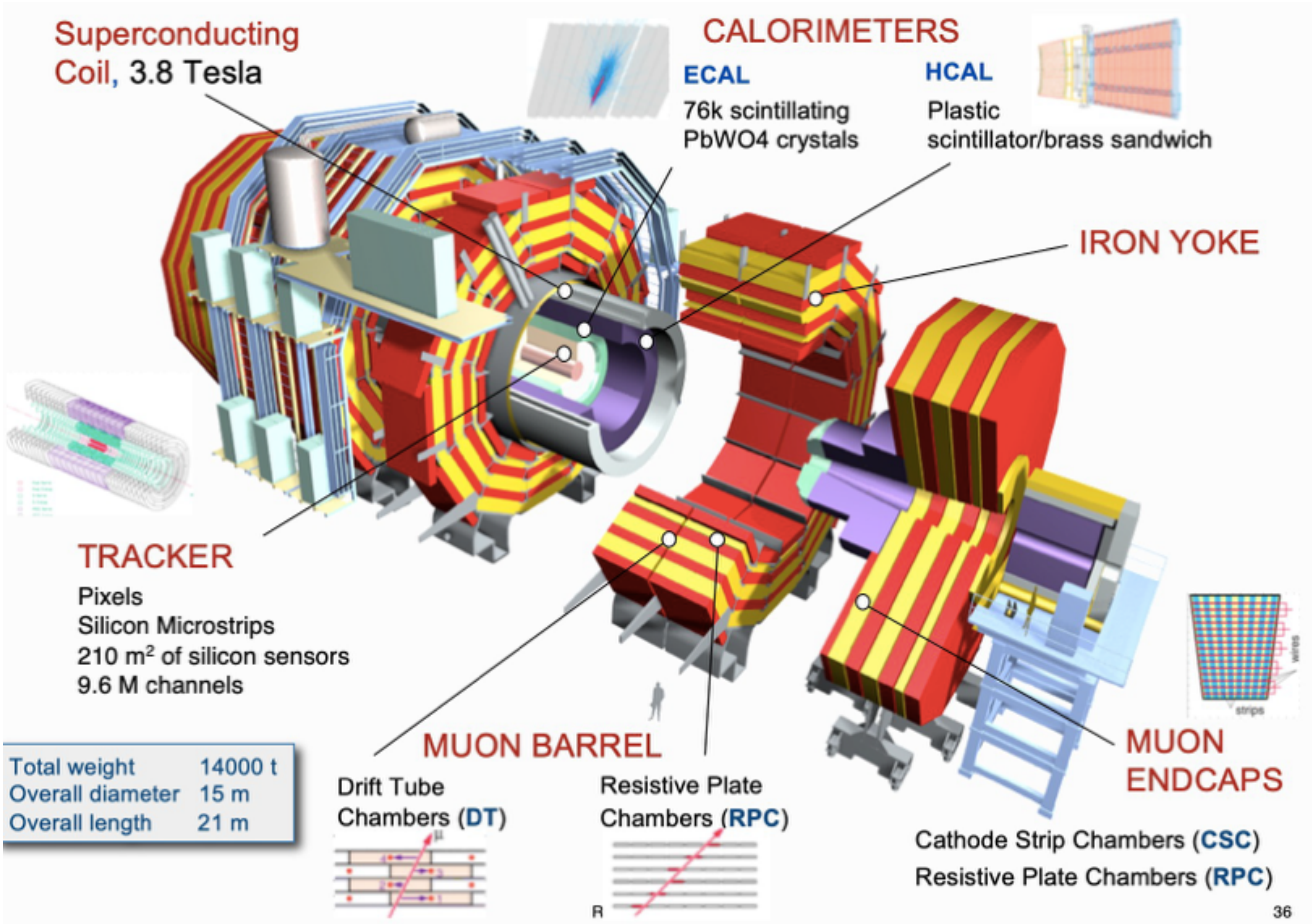
- **Measure** $f_{ai} \cos(\Phi_{ai})$ **by assuming** $a_i \geq 0, \cos(\Phi_{ai}) = \pm 1$ **to probe HVV Anomalous couplings**



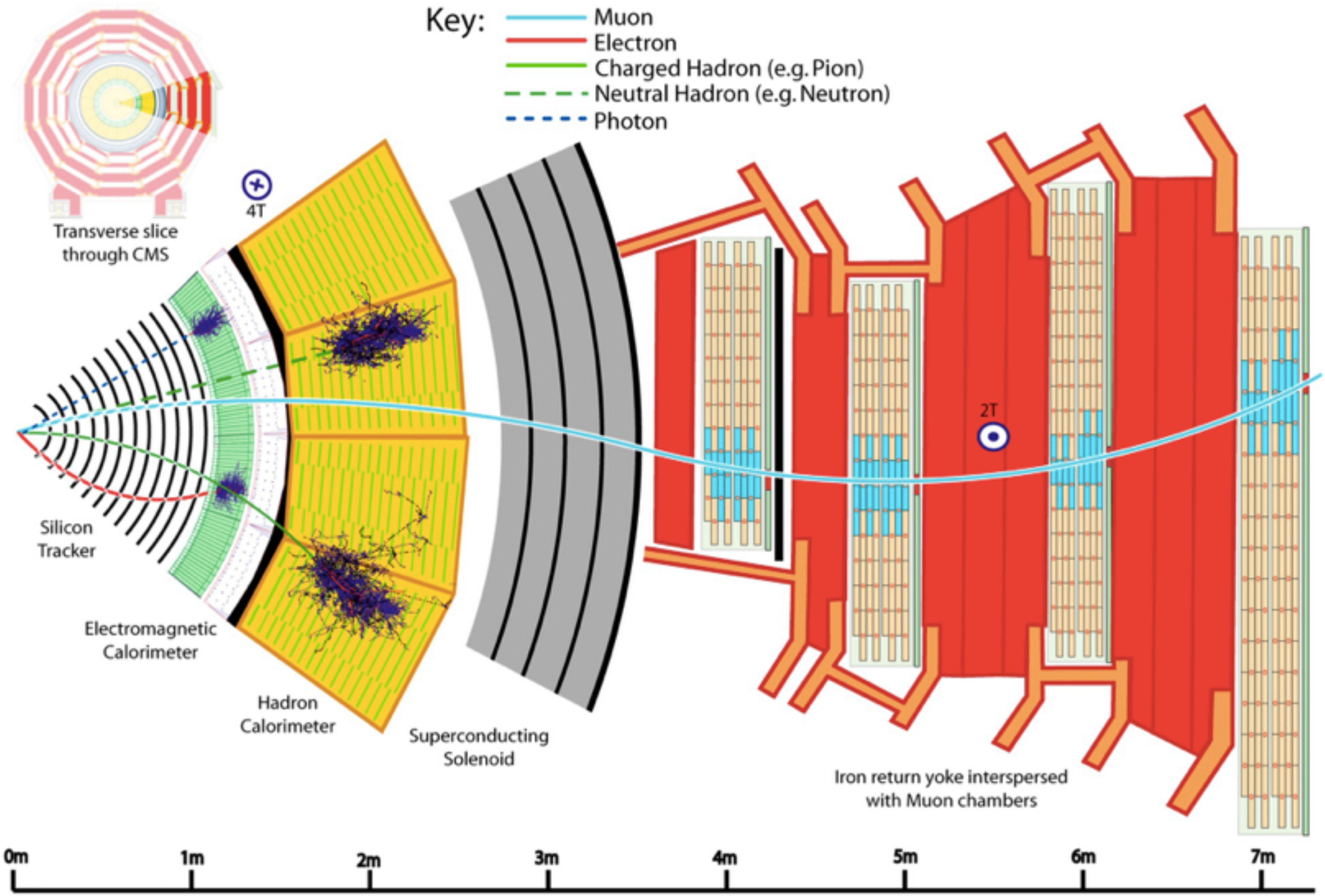
$\kappa_1 \sim \Lambda_1^{-2}$
$g_2 \sim a_2$
$g_4 \sim a_3$



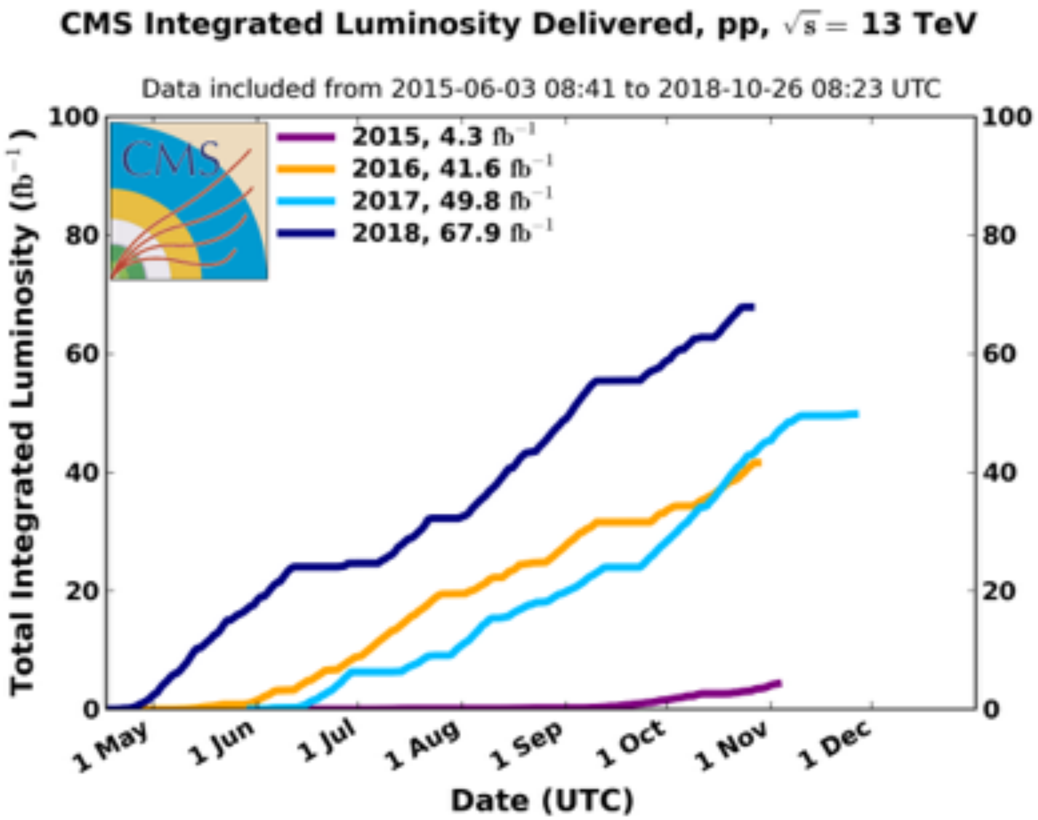
CMS detector

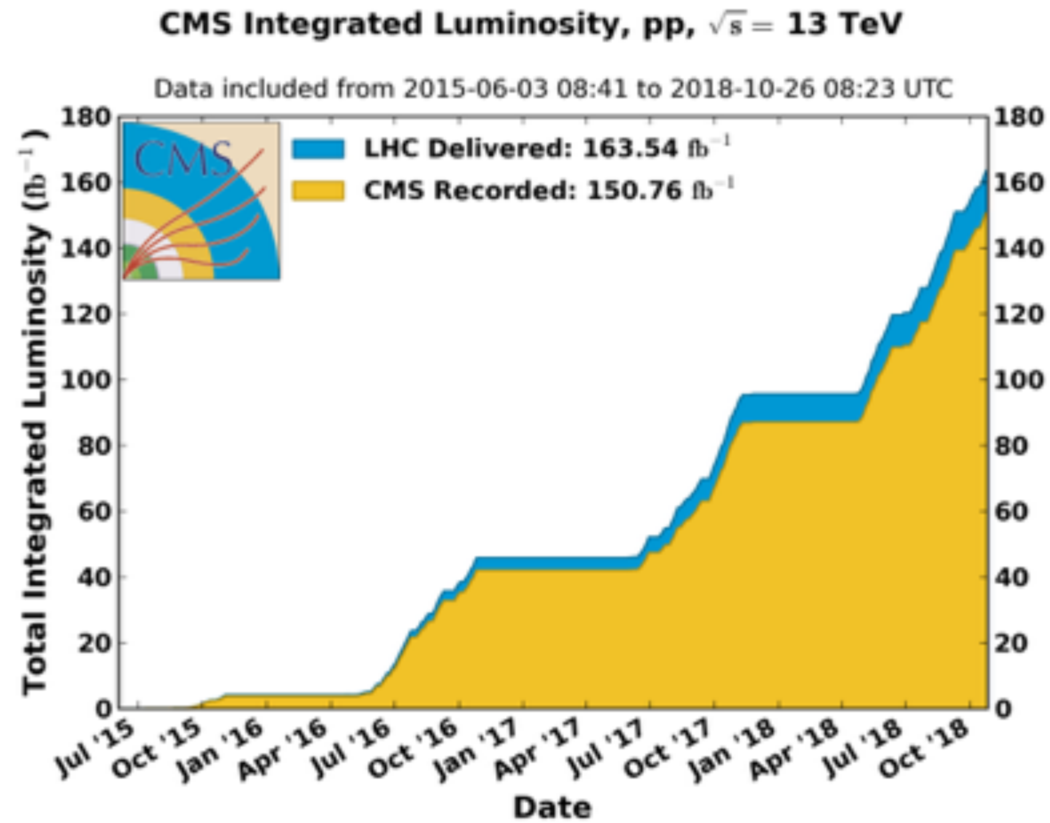


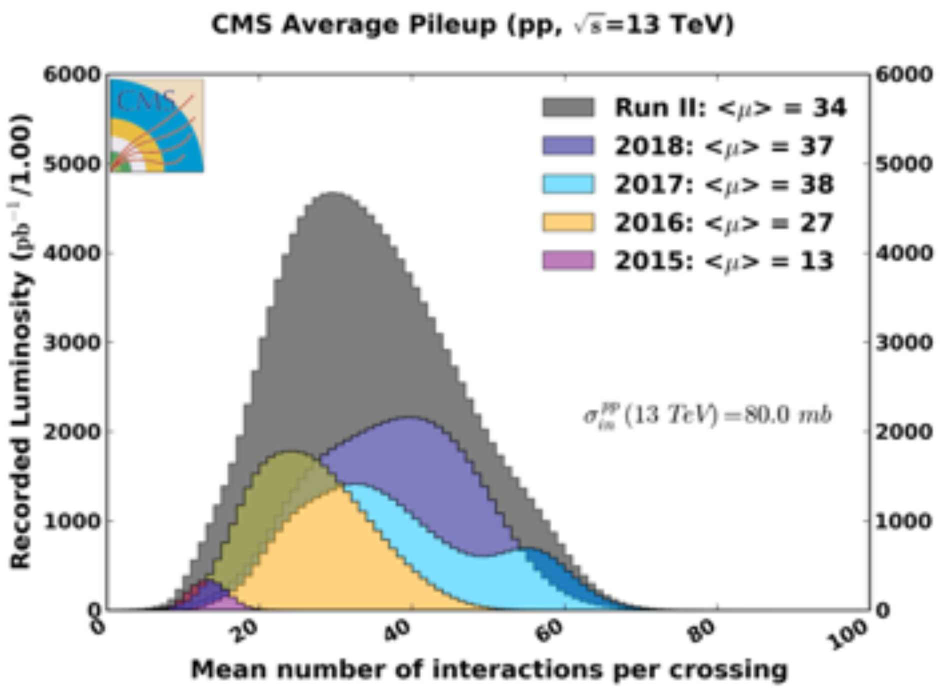
How particles detected ?



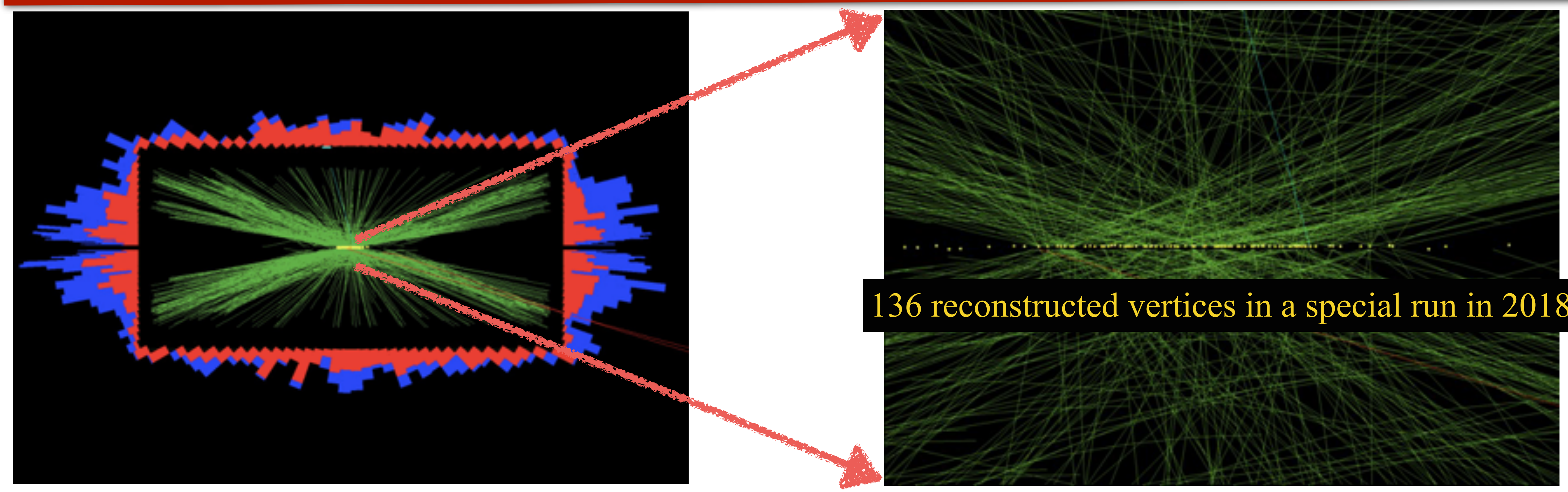
CMS recorded data in Run 2



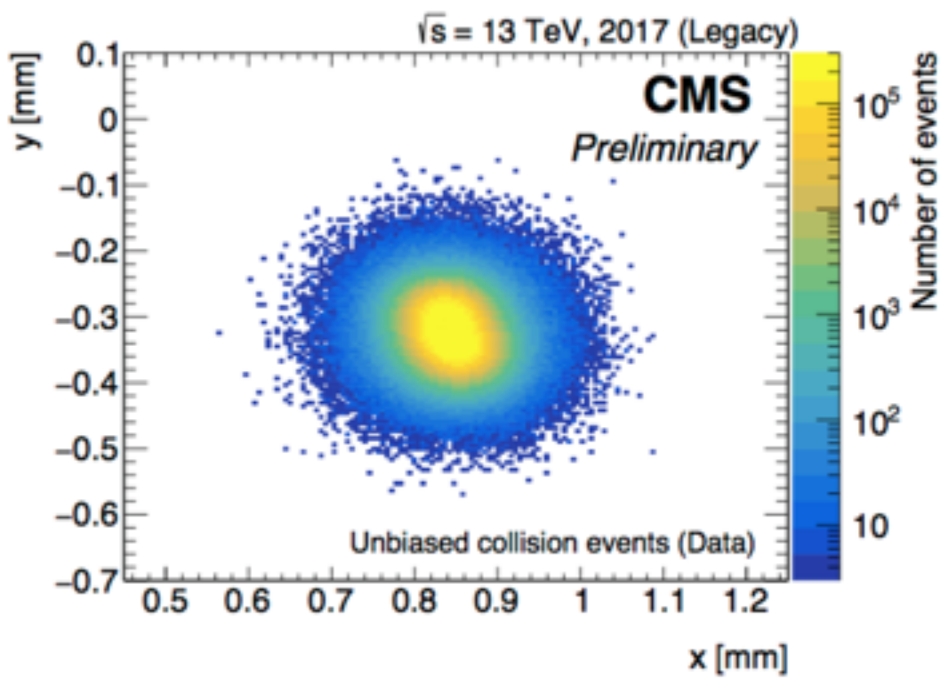




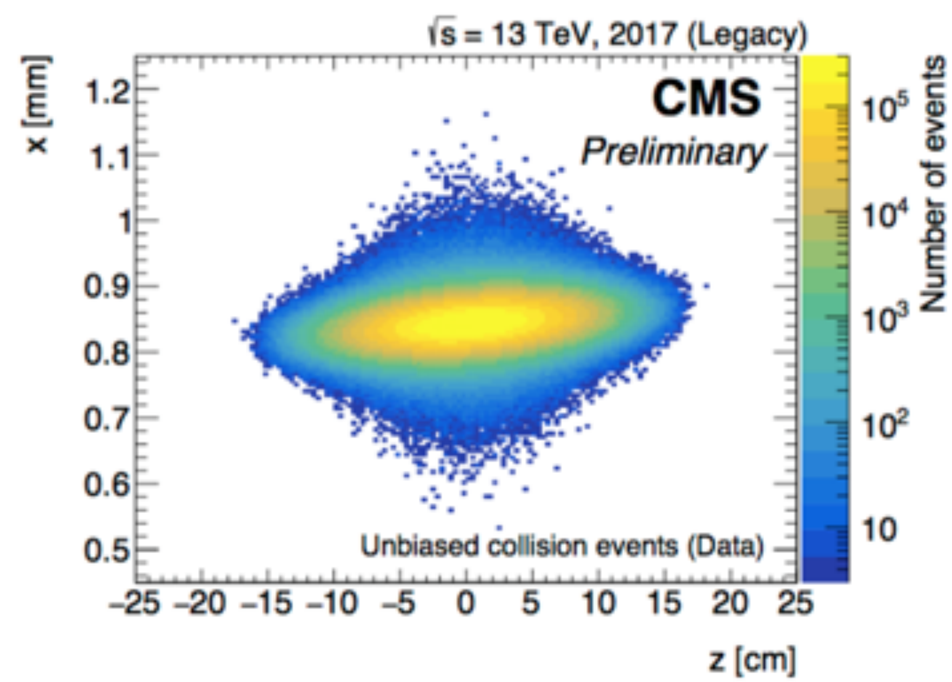
Vertex Reconstruction



Primary vertex position x-y

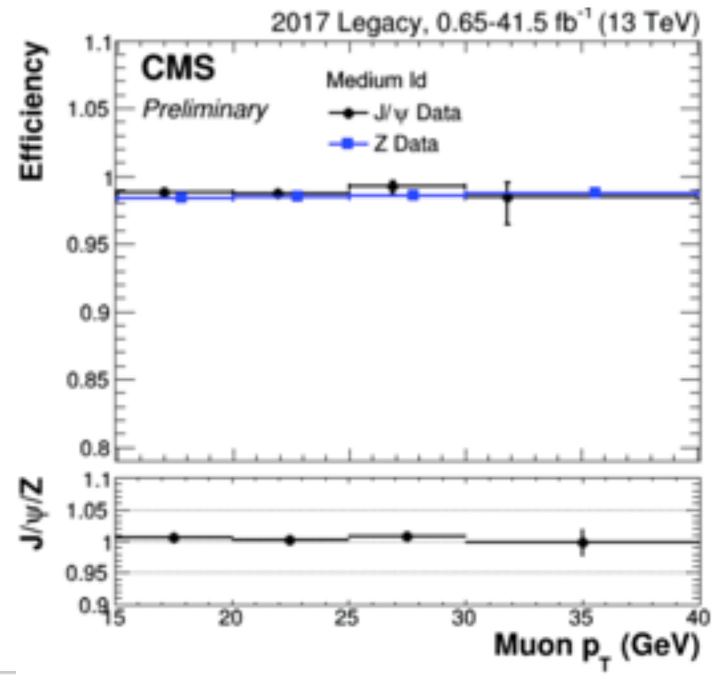


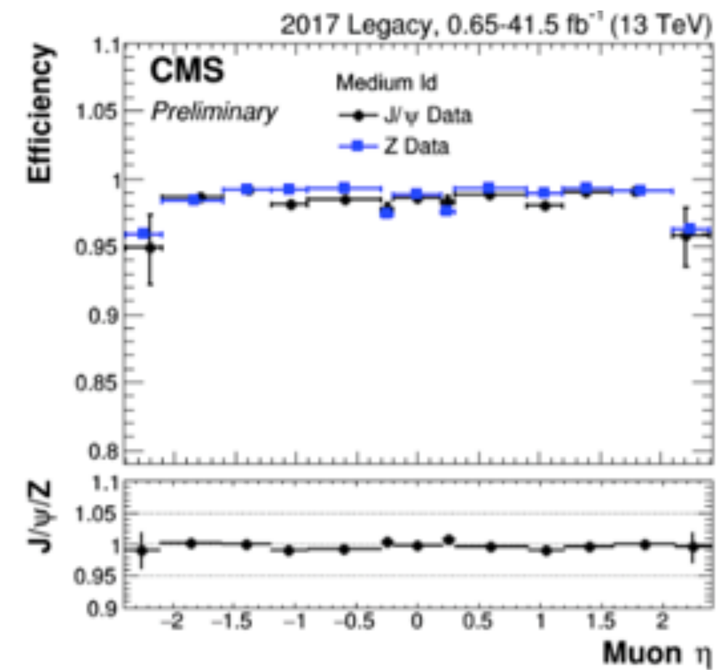
Primary vertex position x-z

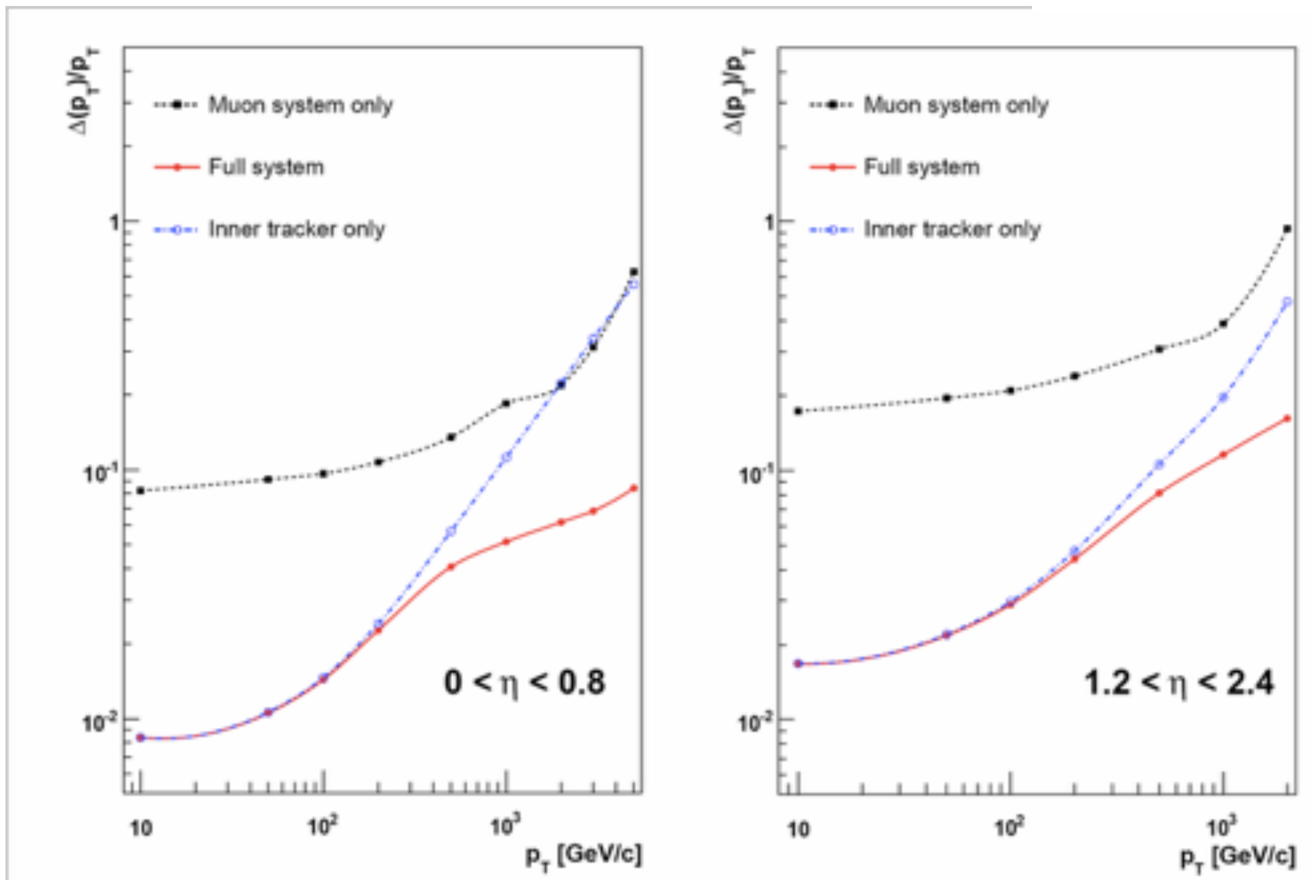


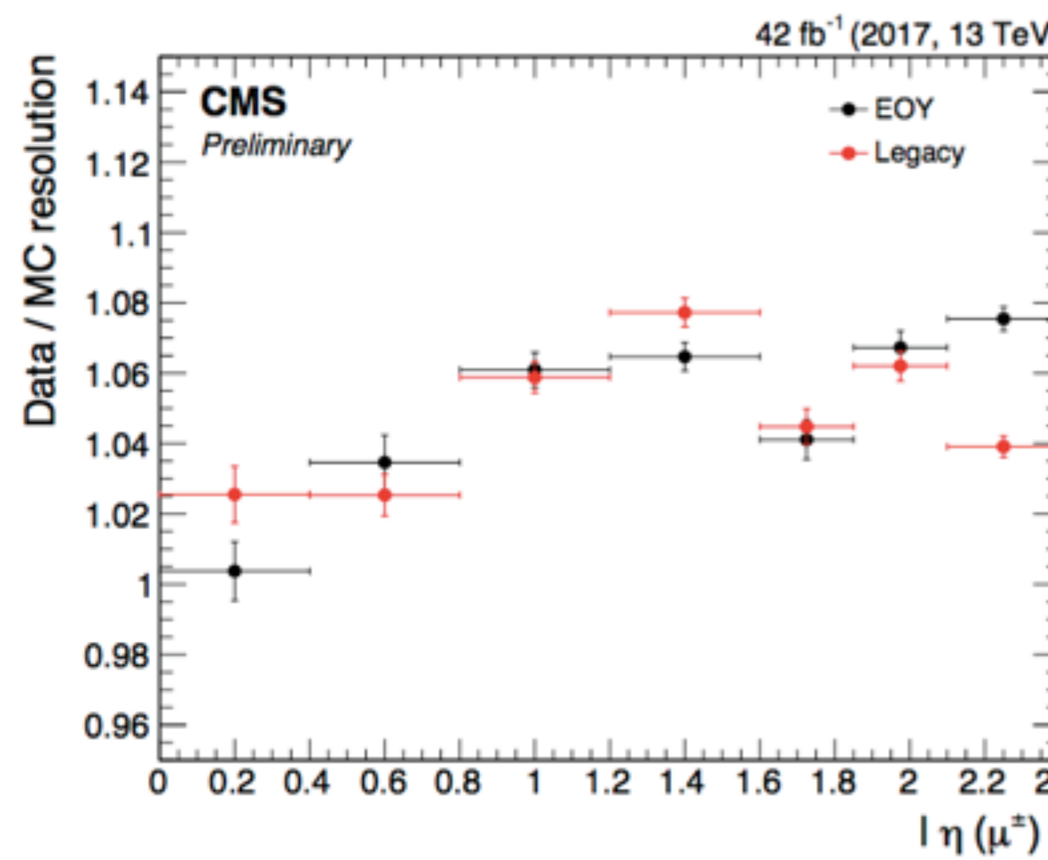
Muon reconstruction and resolution

- **Medium ID efficiency**
  - loose muon with a tracker track with requirements on muon segment compatibility.
  - measured with T&P method

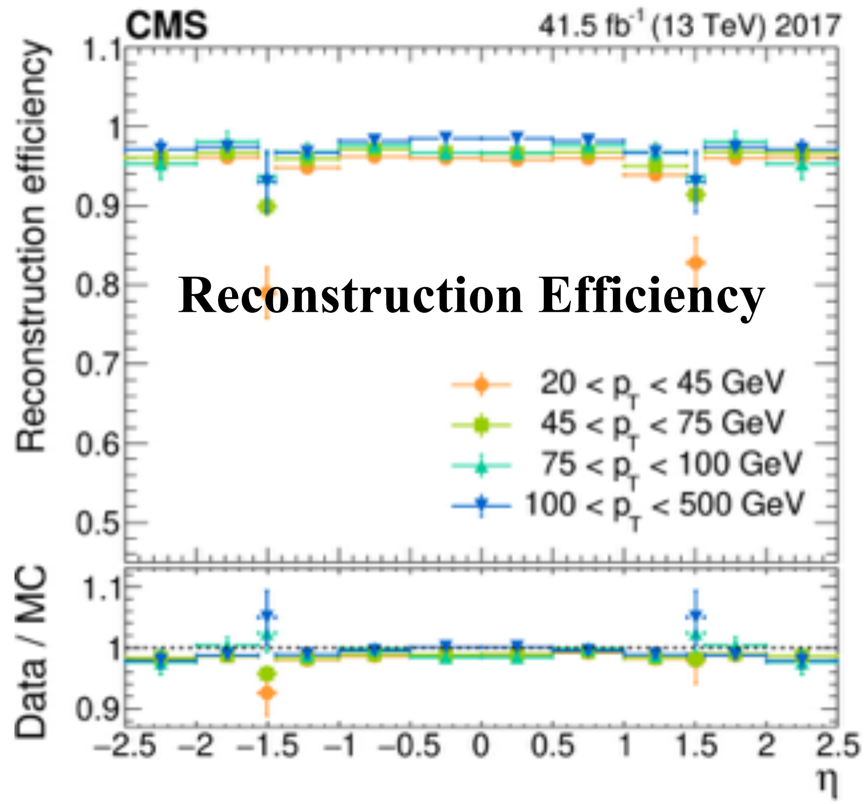


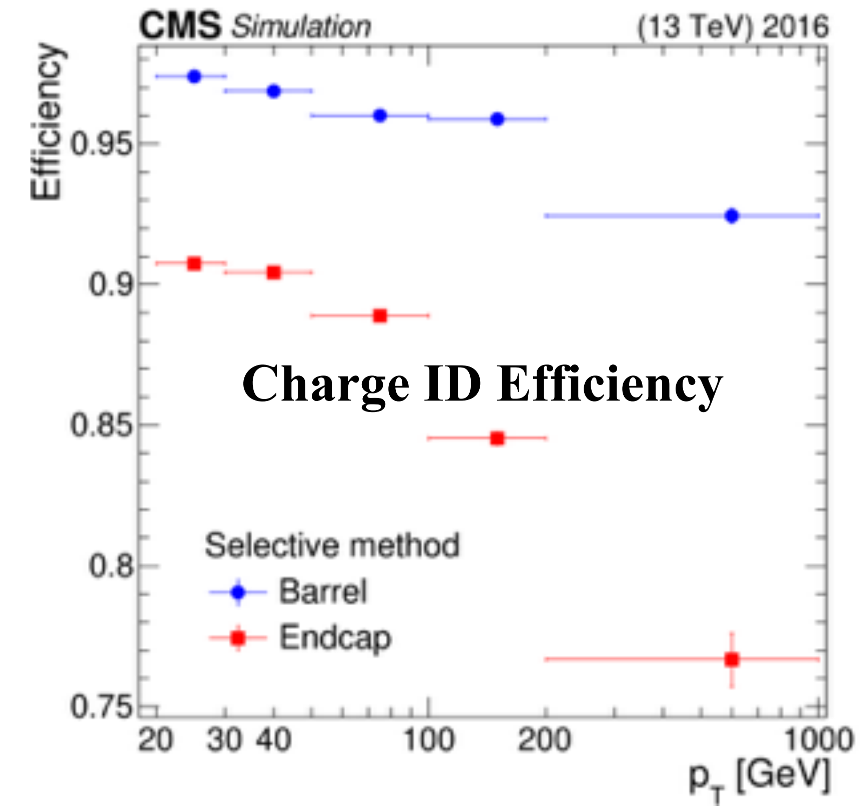


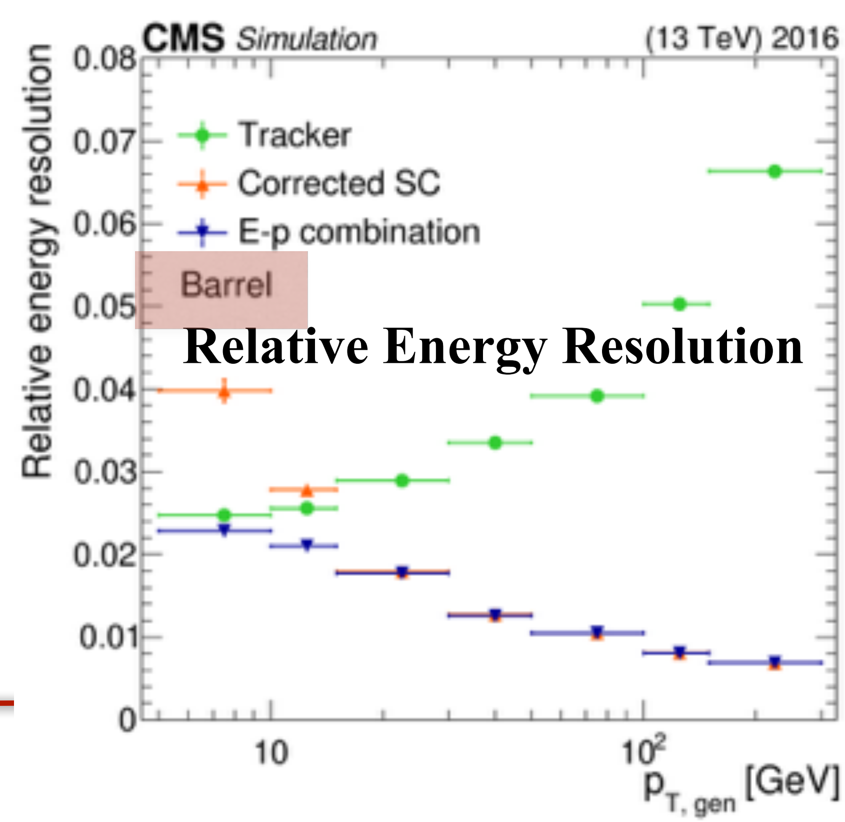


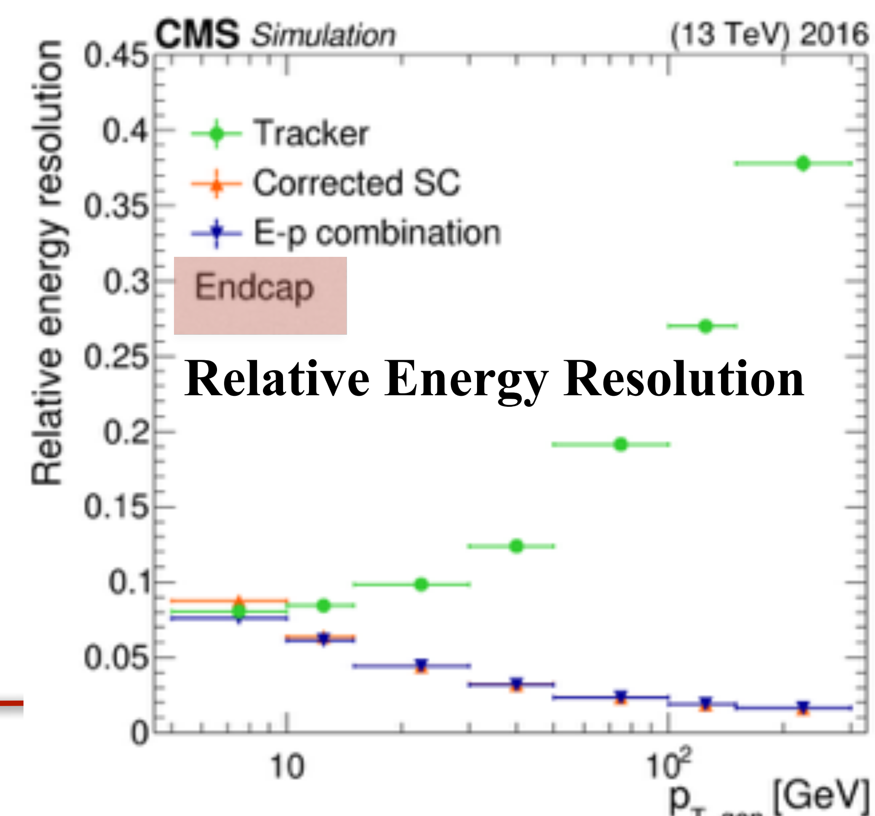


Electron reconstruction and resolution



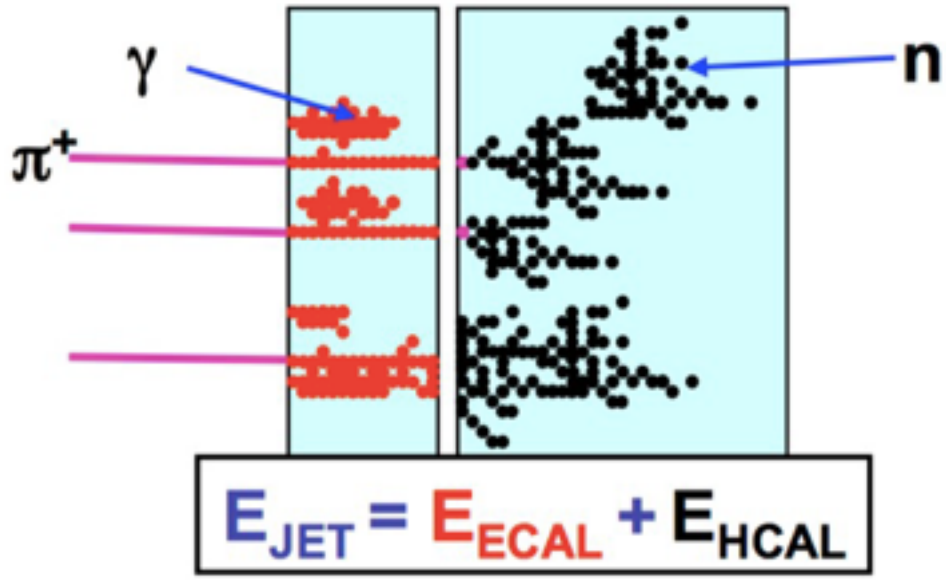


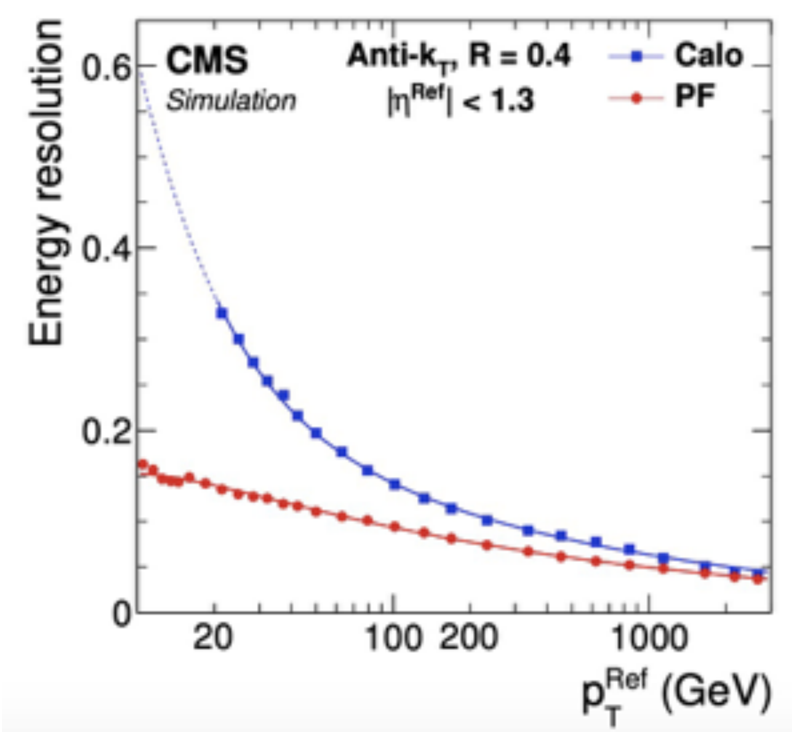


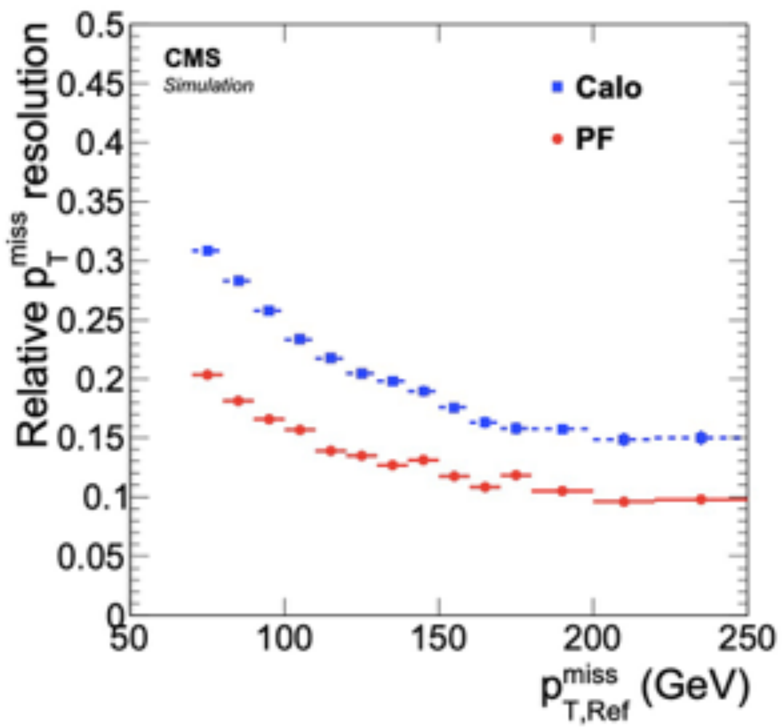


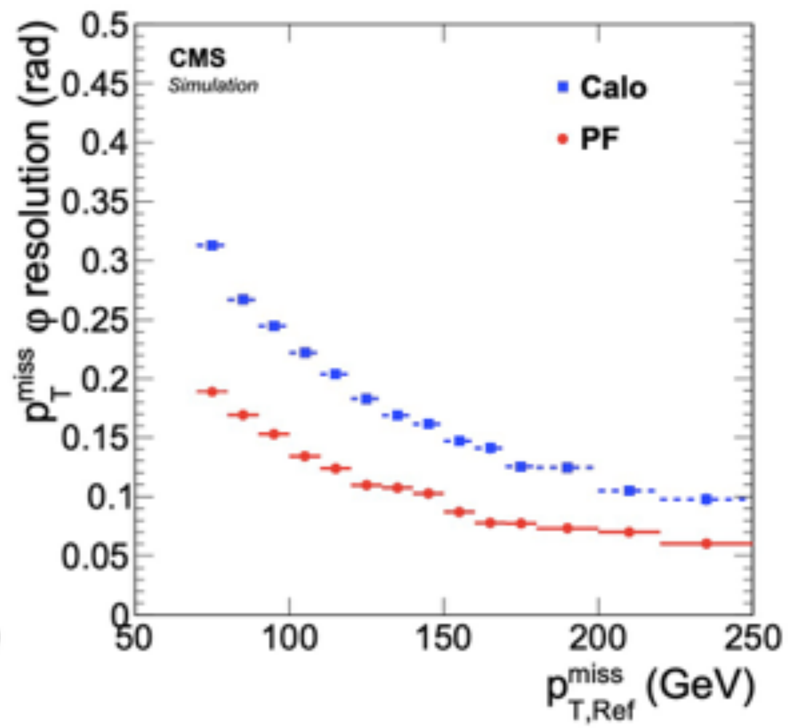
MET Resolution

- **MET resolution significantly improved with Particle Flow Algorithm (PFA)**



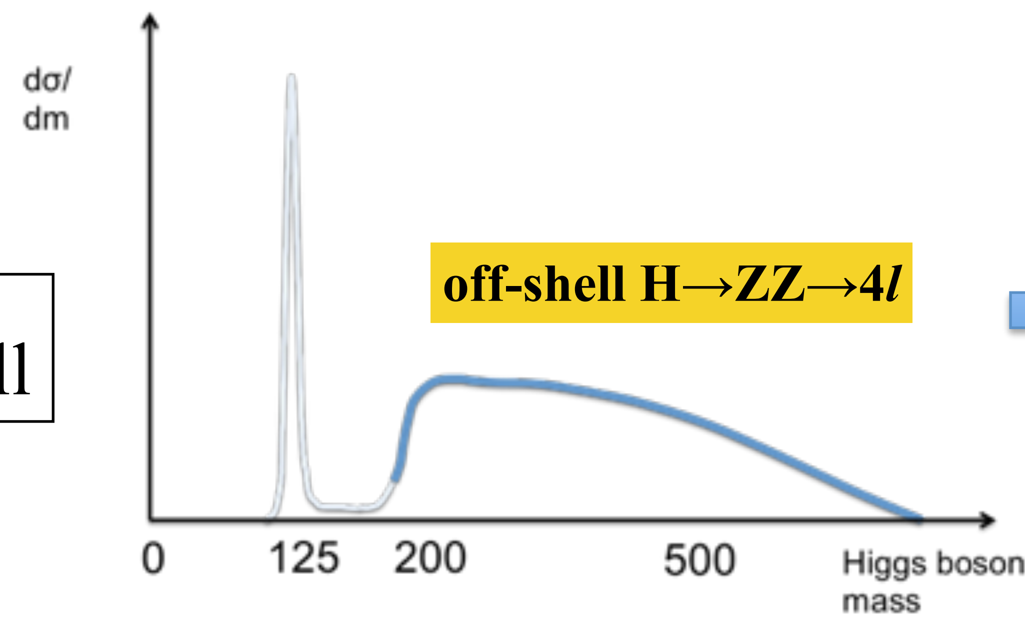


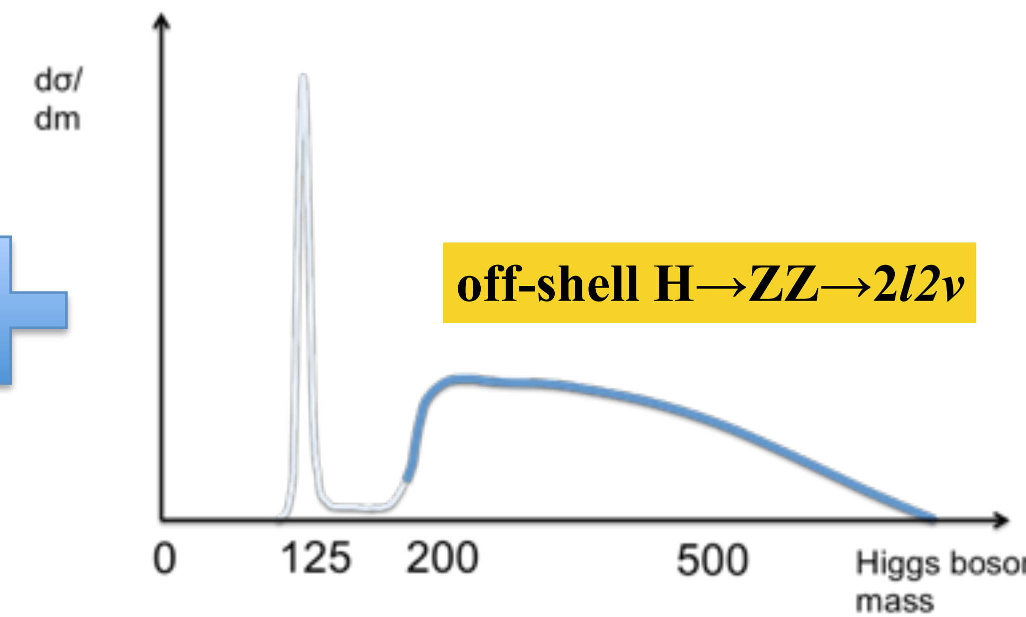




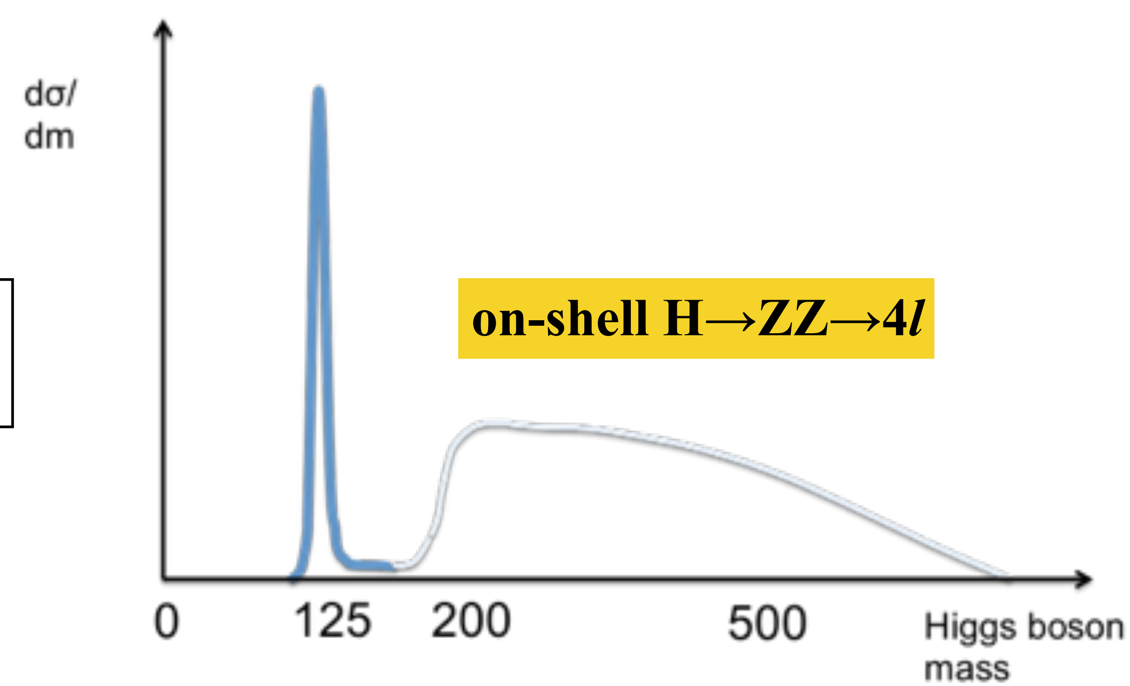
Analyses Involved

$\mu_{\text{off-shell}}$





$\mu_{\text{on-shell}}$



Object/Event selection for $H \rightarrow ZZ \rightarrow 4l$

- Loose ID and isolated e(μ) with $p_T > 7(5)$GeV, $|\eta| < 2.5(2.4)$
- Vertex $d_{xy} < 0.5$cm, $d_z < 1$ cm, $SIP_{3D} < 3$
- Any OS-SF pair $12 < m_{ll\gamma} < 120$ GeV
- For any ZZ candidates, define Z_1 candidate with $m_{ll\gamma}$ closest to m_Z:
    - $m_{Z1} > 40$ GeV; $pT(l1) > 20$ GeV; $pT(l2) > 10$ GeV
    - $\Delta R > 0.02$ between each of the four leptons
    - mII > 4 GeV for OS pairs (regardless of flavour)
    - Reject 4μ and 4e candidates where the alternative pair ZaZb satisfies $m_{Za} - m_Z < |m_{Z1} - m_Z|$ and $m_{Zb} < 12$ GeV
    - $m_{4l} > 70$ GeV
- If more than one ZZ candidate is left, choose the one of highest $\mathcal{D}bkg^{kin}$.
- If $\mathcal{D}bkg^{kin}$ is the same, take the one with Z_1 mass closest to m_Z.

Analysis Strategy for on-shell H→ZZ→4*l*

using 2015-2018 data

- **MELA matrix element discriminants for production or decay of 4l system (+associated particles) in event categorisation or observables used in the fit:**

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

sig: signal hypo.
alt: alternative hypo.

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

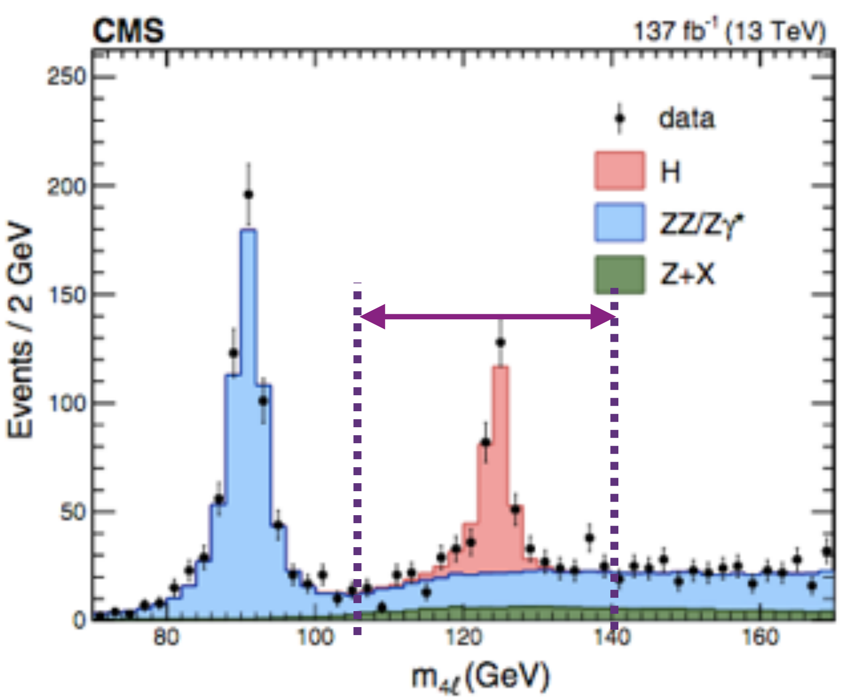
sig: signal hypo.
alt: alternative hypo.
int: with interference hypo.

- **Event categorisation for 2016-2018 data:** VBF-2jet, else VH-hadronic, else VH-leptonic, else VBF-1jet, else boosted, or else untagged.

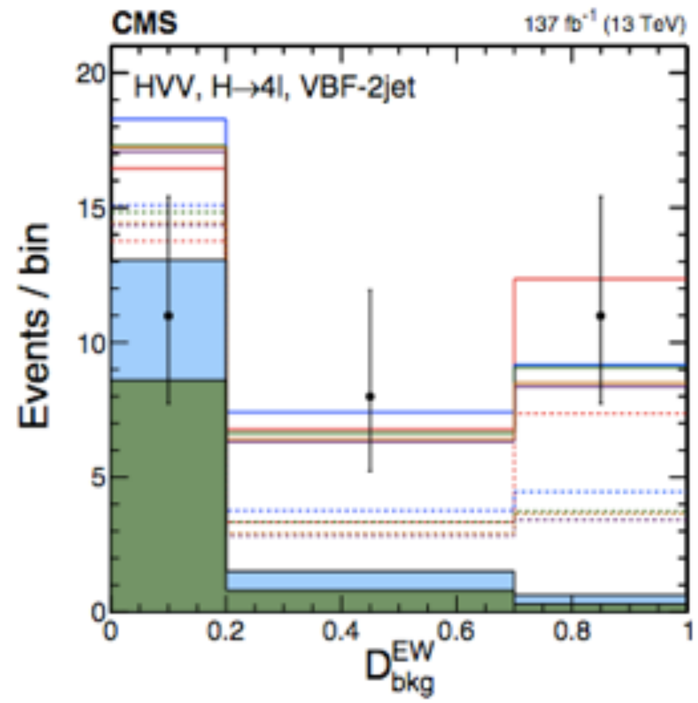
Category	Selection	Observables $\vec{x}$ for fitting
Boosted	$p_{\mathrm{T}}^{4\ell} > 120\,\mathrm{GeV}$	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
VBF-1jet	$\mathcal{D}_{\mathrm{1jet}}^{\mathrm{VBF}} > 0.7$	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
VBF-2jet	$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VBF}} > 0.5$	$\mathcal{D}_{\mathrm{bkg}}^{\mathrm{EW}}, \mathcal{D}_{0h+}^{\mathrm{VBF+dec}}, \mathcal{D}_{0-}^{\mathrm{VBF+dec}}, \mathcal{D}_{\Lambda1}^{\mathrm{VBF+dec}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\mathrm{VBF+dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{VBF}}, \mathcal{D}_{CP}^{\mathrm{VBF}}$
VH-hadronic	$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VH}} > 0.5$	$\mathcal{D}_{\mathrm{bkg}}^{\mathrm{EW}}, \mathcal{D}_{0h+}^{\mathrm{VH+dec}}, \mathcal{D}_{0-}^{\mathrm{VH+dec}}, \mathcal{D}_{\Lambda1}^{\mathrm{VH+dec}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\mathrm{VH+dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{VH}}, \mathcal{D}_{CP}^{\mathrm{VH}}$
VH-leptonic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
Untagged	none of the above	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0h+}^{\mathrm{dec}}, \mathcal{D}_{0-}^{\mathrm{dec}}, \mathcal{D}_{\Lambda1}^{\mathrm{dec}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\mathrm{dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{dec}}, \mathcal{D}_{CP}^{\mathrm{dec}}$

- **No event categorisation for 2015 data, use observables** $D_{bkg}, D_{BSM}^{dec}, D_{int}^{dec}$ **in the fit.**

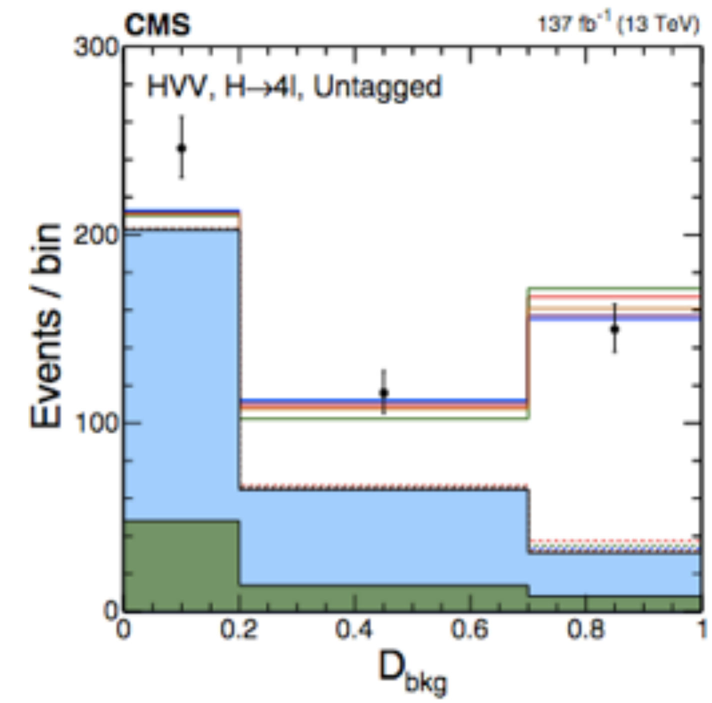
Event distributions



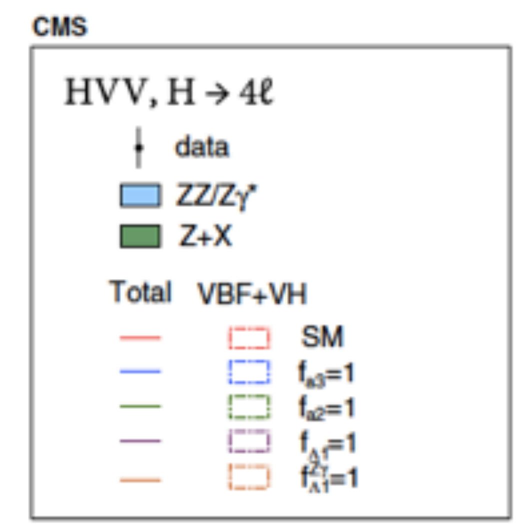
inclusive m_{4l}



VBF-2jet D_{bkg}^{EW}



Untagged D_{bkg}



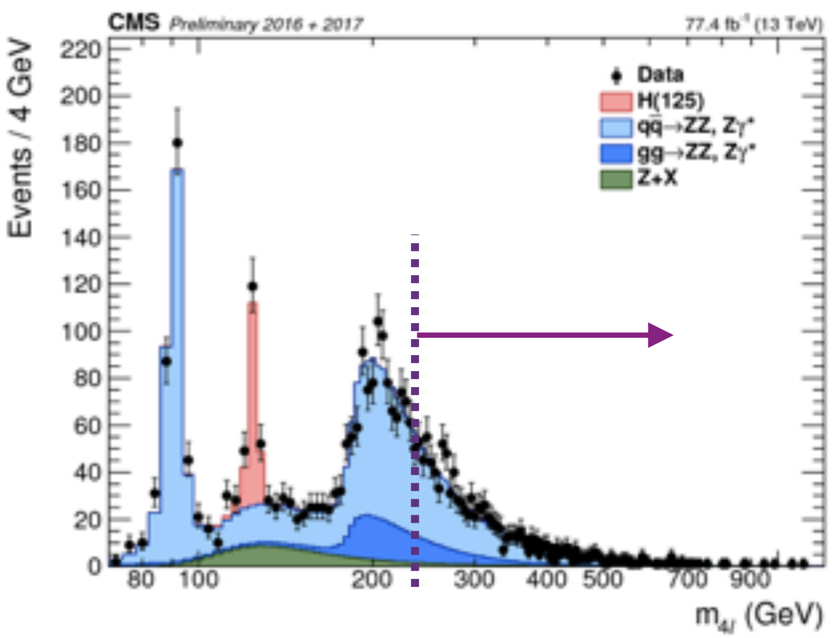
- **105 < m_{4l} < 140 GeV is used in the on-shell analysis.**
- **Example distributions for VBF-2jet and Untagged categories shown.**

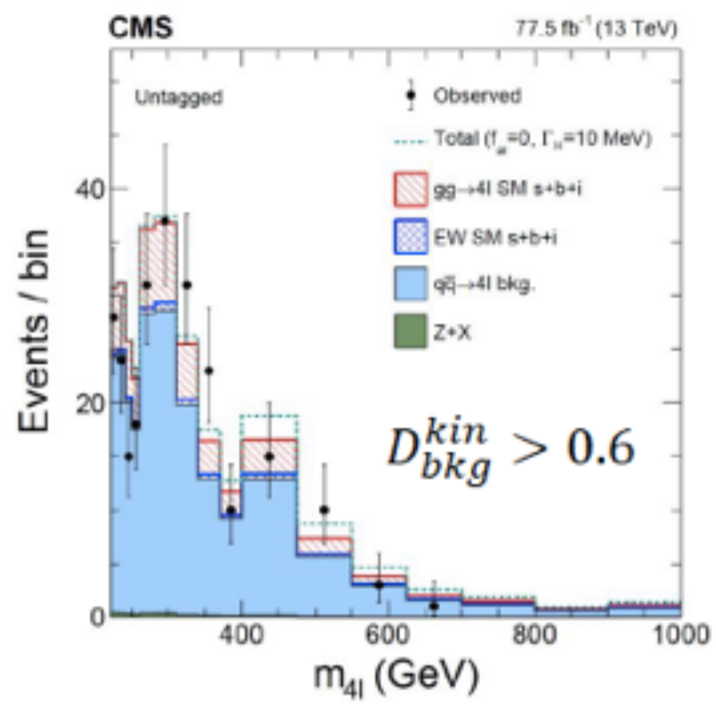
Analysis Strategy for off-shell H→ZZ→4*l*

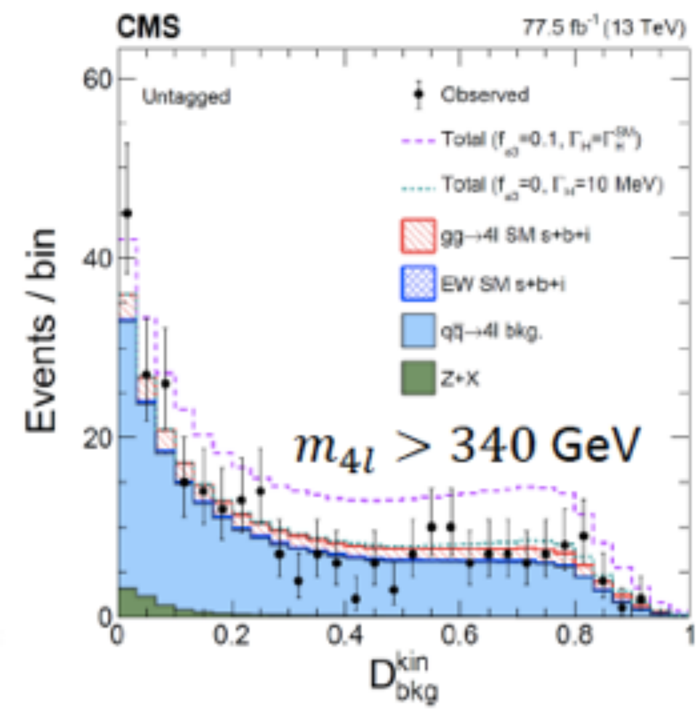
- **Only look at the off-shell region (m_{4l} > 220 GeV) with 2016+2017 data.**
- **Also use MELA discriminants for the event categorisation and observables in the fit.**
- **Event categorisation:** VBF-tagged, else VH-hadronic, else untagged.

Category	VBF-tagged	VH-tagged	Untagged
Selection	$\mathcal{D}_{\text{2jet}}^{\text{VBF}}$ or $\mathcal{D}_{\text{2jet}}^{\text{VBF,BSM}} > 0.5$	$\mathcal{D}_{\text{2jet}}^{WH}$ or $\mathcal{D}_{\text{2jet}}^{WH,\text{BSM}}$, or $\mathcal{D}_{\text{2jet}}^{ZH}$ or $\mathcal{D}_{\text{2jet}}^{ZH,\text{BSM}} > 0.5$	Rest of events
SM obs.	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{\text{VBF+dec}}$, $\mathcal{D}_{\text{bsi}}^{\text{VBF+dec}}$	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{VH\text{+dec}}$, $\mathcal{D}_{\text{bsi}}^{VH\text{+dec}}$	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{\text{kin}}$, $\mathcal{D}_{\text{bsi}}^{gg,\text{dec}}$
a_3 obs.	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{\text{VBF+dec}}$, $\mathcal{D}_{0-}^{\text{VBF+dec}}$	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{VH\text{+dec}}$, $\mathcal{D}_{0-}^{VH\text{+dec}}$	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{\text{kin}}$, $\mathcal{D}_{0-}^{\text{dec}}$
a_2 obs.	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{\text{VBF+dec}}$, $\mathcal{D}_{0h+}^{\text{VBF+dec}}$	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{VH\text{+dec}}$, $\mathcal{D}_{0h+}^{VH\text{+dec}}$	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{\text{kin}}$, $\mathcal{D}_{0h+}^{\text{dec}}$
Λ_1 obs.	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{\text{VBF+dec}}$, $\mathcal{D}_{\Lambda1}^{\text{VBF+dec}}$	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{VH\text{+dec}}$, $\mathcal{D}_{\Lambda1}^{VH\text{+dec}}$	$m_{4\ell}$, $\mathcal{D}_{\text{bkg}}^{\text{kin}}$, $\mathcal{D}_{\Lambda1}^{\text{dec}}$

Event distributions







- m_{4l} > 220 GeV is used in the off-shell analysis.
- Example distributions for Untagged category.
- Some selection applied to the plots in order to enhance the signal contribution.

Analysis strategy for off-shell H→ZZ→2*l*2*ν*

- **Due to the undetectable neutrinos, unable to reconstruct the Higgs mass peak. Difficult to perform on-shell analysis in this channel.**
- **NEW off-shell analysis in ZZ→2*l*2*ν* with 2016-2018 data. Several improvements in methodology w.r.t Run 1. Will describe in detail.**
- **Observables:**
  - main observable is transverse mass m_T

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

  - missing transverse momentum $p_{\mathrm{T}}^{\mathrm{miss}}$
  - MELA discriminants $D_{2jet}^{VBF(,BSM)}$ when $N_j \geq 2$ by assuming $\eta_{\nu\nu} = \eta_{ll}$ to discriminate VBF from ggF or discriminate SM from BSM

$$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VBF},a_i} = \frac{\mathcal{P}_{\mathrm{VBF}}^{a_i}}{\mathcal{P}_{\mathrm{VBF}}^{a_i} + \mathcal{P}_{\mathrm{QCD\ H+2jet}}^{\mathrm{SM}}}$$

- **Event categorisation** based on jet multiplicity (N_j=0, 1, ≥ 2) and lepton flavour (ee, μμ)

Object/Event selection for H→ZZ→2l2ν

Quantity	Requirement
p_T^{ℓ}	$p_T^{\ell} \geq 25\,\text{GeV}$ on both leptons
$\lvert\eta_\ell\rvert$	< 2.4 on μ, < 2.5 on e
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - 91.2\rvert < 15\,\text{GeV}$
$p_T^{\ell\ell}$	$\geq 55\,\text{GeV}$
N_ℓ	Exactly two leptons with tight isolation, no extra leptons with loose isolation and $p_T \geq 5\,\text{GeV}$
N_{trk}	No isolated tracks satisfying the selection requirements
N_γ	No photons with $p_T \geq 20\,\text{GeV}$, $\lvert\eta\rvert < 2.5$ satisfying the baseline selection requirements
p_T^{j}	$\geq 30\,\text{GeV}$, used in selecting jets
$\lvert\eta_j\rvert$	< 4.7, used in selecting jets
N_b	No b-tagged jets based on the loose working point
p_T^{miss}	$\geq 125\,\text{GeV}$ if $N_j < 2$, $\geq 140\,\text{GeV}$ otherwise
$\Delta\phi_{\text{miss}}^{\ell\ell}$	> 1.0 between $\vec{p}_T^{\,\ell\ell}$ and $\vec{p}_T^{\,\text{miss}}$
$\Delta\phi_{\text{miss}}^{\ell\ell+\text{jets}}$	> 2.5 between $\vec{p}_T^{\,\ell\ell} + \sum \vec{p}_T^{\,\text{j}}$ and $\vec{p}_T^{\,\text{miss}}$
$\min \Delta\phi_{\text{miss}}^{\text{j}}$	> 0.25 if $N_j = 1$, > 0.5 otherwise among all $\vec{p}_T^{\,\text{j}}$ and $\vec{p}_T^{\,\text{miss}}$ combinations

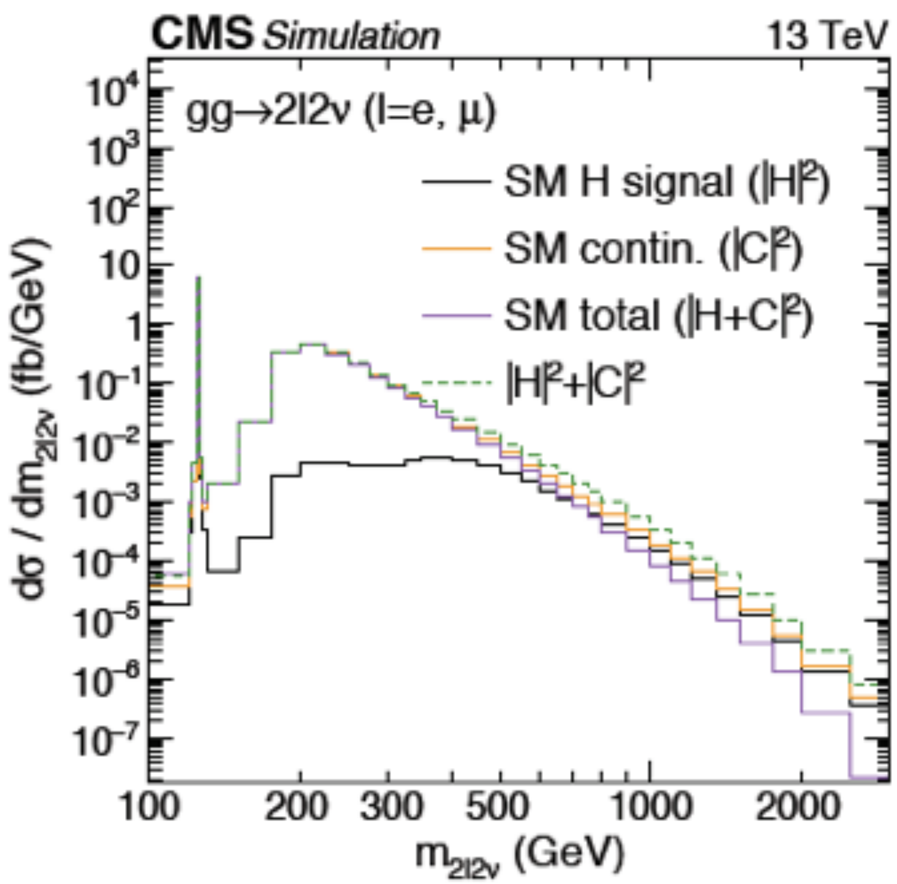
Signal and backgrounds

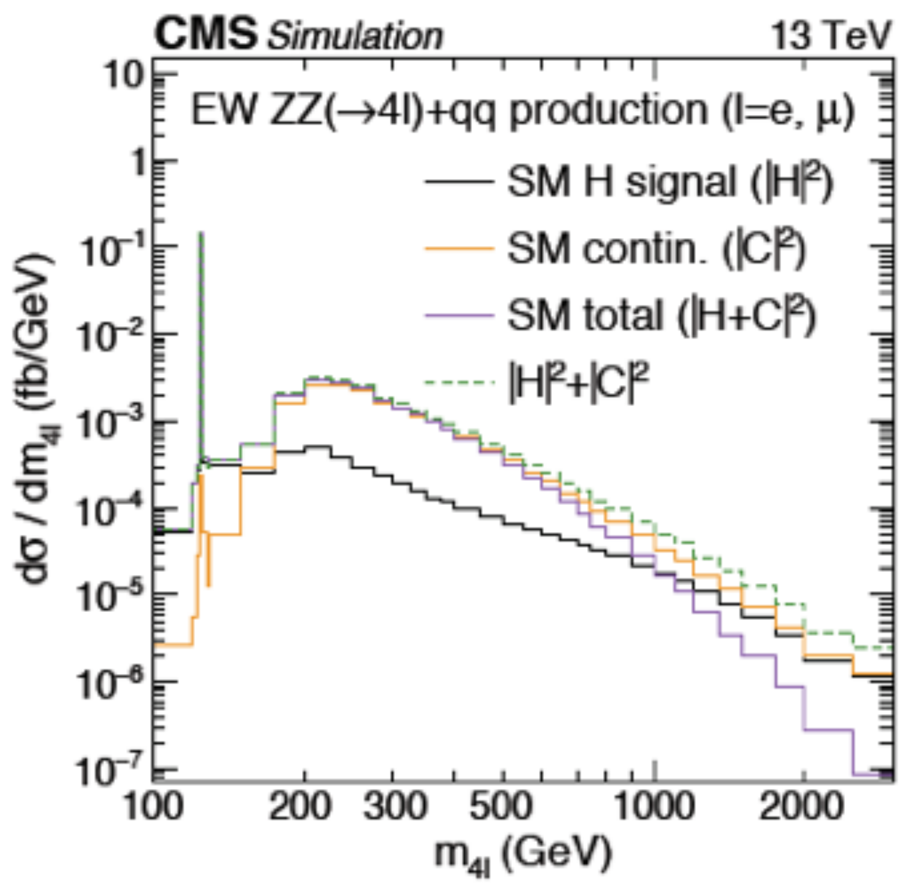
- **ggF and VBF/VH signal**

- **ggZZ and VBS ZZ (interfering backgrounds)**
- **qq→ZZ, WZ**
  - dominant background, constrained by 3l WZ Control Region (CR)
- **Instrumental** $p_{\mathrm{T}}^{\mathrm{miss}}$
  - mostly from Z+jets events, estimated from single photon CR
- **Non-resonant (ttbar, WW)**
  - reweighting eμ events from Data
- **tZ+X:** very small contribution, estimated fully from MC.

Signal and interfering backgrounds

- **Signals (ggH, VBF), interfering backgrounds (ggZZ, VBS ZZ) and their interference obtained by:**
  - POWHEG samples (NLO) with different Higgs pole mass (from 125GeV to 3TeV) for Higgs production and JHUGen for Higgs decay
  - Reweighting by MELA package and Stitching together





Non-interfering backgrounds

- **qq→ZZ, WZ**
  - dominant backgrounds at high m_T
  - estimated from MC simulation
  - constrained by 3*l* WZ Control Region (CR)
- **Instrumental** p_T^{miss}
  - mostly comes from Z+jets events
  - estimated from single photon CR
- **Non-resonant (ttbar, WW)**
  - estimated from reweighting eμ events from Data by trigger or lepton efficiencies.
- **tZ+X:** very small contribution, estimated fully from MC.

qq→ WZ/ZZ background

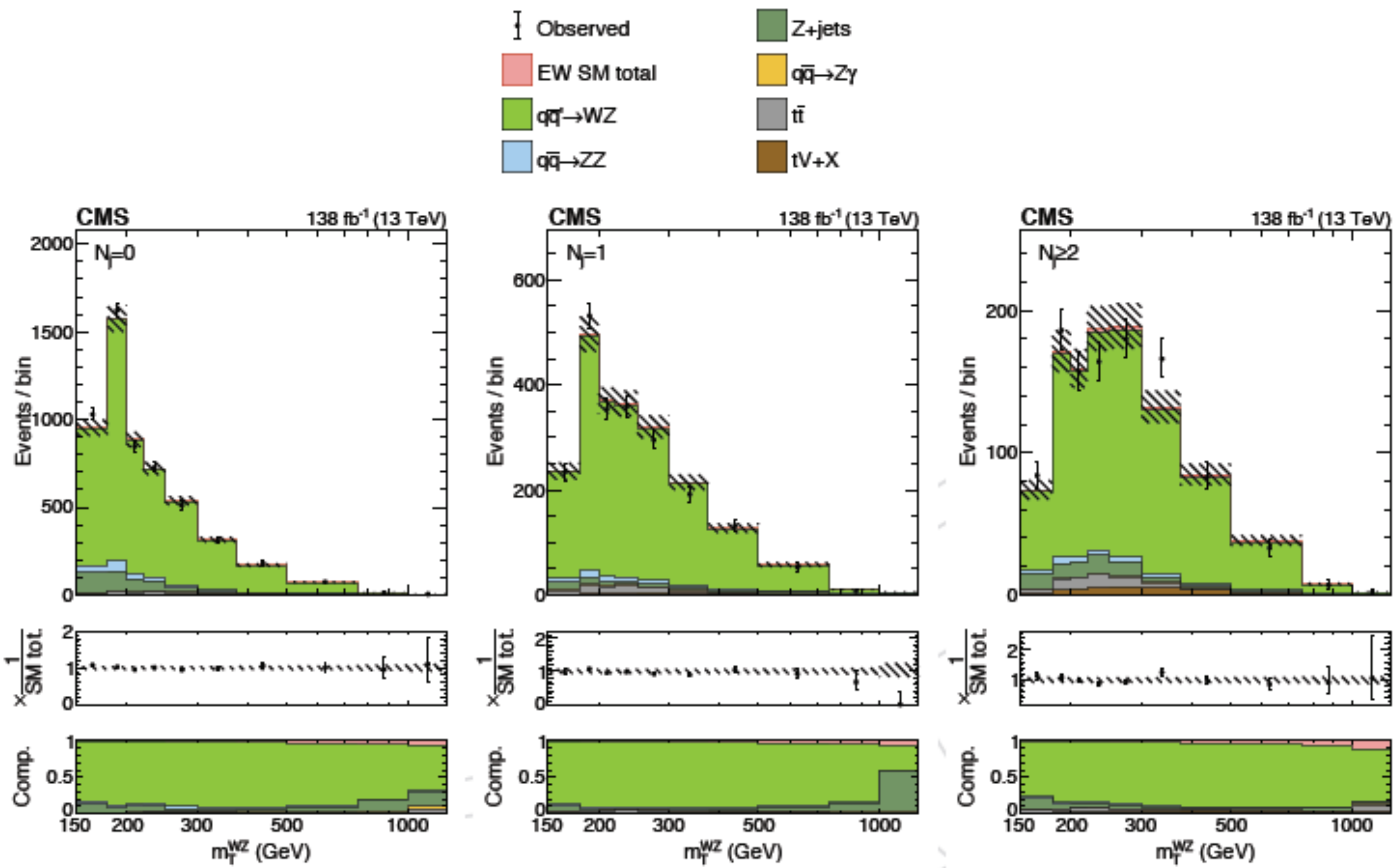
Quantity	Requirement
$p_T^{\ell_{Z1}}$	$\geq 30\,\text{GeV}$ on leading-p_T lepton forming the Z candidate
$p_T^{\ell_{Z2}}$	$\geq 20\,\text{GeV}$ on subleading-p_T lepton forming the Z candidate
$p_T^{\ell_W}$	$\geq 20\,\text{GeV}$ on the remaining ℓ_W from the W boson
$\lvert\eta_\ell\rvert$	< 2.4 on μ, < 2.5 on e
$m_{\ell\ell}$	Use the opposite-sign, same-flavor dilepton pair with smallest $\lvert m_{\ell\ell} - 91.2\rvert < 15\,\text{GeV}$ to define the Z candidate
N_ℓ	Exactly three leptons with tight isolation, no extra leptons with loose isolation and $p_T \geq 5\,\text{GeV}$
N_{trk}	No isolated tracks satisfying the selection requirements
N_γ	No photons with $p_T \geq 20\,\text{GeV}$, $\lvert\eta\rvert < 2.5$ satisfying the baseline selection requirements
p_T^j	$\geq 30\,\text{GeV}$, used in selecting jets
$\lvert\eta_j\rvert$	< 4.7, used in selecting jets
N_b	No b-tagged jets based on the loose working point
p_T^{miss}	$\geq 20\,\text{GeV}$
$m_T^{\ell_W}$	$\geq 20\,\text{GeV}$ ($10\,\text{GeV}$) for $\ell_W = \mu$ ($\ell_W = \text{e}$), where $m_T^{\ell_W} = \sqrt{2 p_T^{\ell_W} p_T^{\text{miss}} \left(1 - \cos\Delta\phi_{\text{miss}}^{\ell_W}\right)}$ is the transverse mass between $\vec{p}_T^{\,\ell_W}$ and $\vec{p}_T^{\,\text{miss}}$
$A \times m_T^{\ell_W} + p_T^{\text{miss}} \geq 120\,\text{GeV}$, with $A = 1.6\ (4/3)$ for $\ell_W = \mu\ (\text{e})$	
$\Delta\phi_{\text{miss}}^{Z}$	> 1.0 between $\vec{p}_T^{\,Z}$ and $\vec{p}_T^{\,\text{miss}}$
$\Delta\phi_{\text{miss}}^{3\ell+\text{jets}}$	> 2.5 between $\vec{p}_T^{\,3\ell} + \sum \vec{p}_T^{\,j}$ and $\vec{p}_T^{\,\text{miss}}$
$\min \Delta\phi_{\text{miss}}^{j}$	> 0.25 among all $\vec{p}_T^{\,j}$ and $\vec{p}_T^{\,\text{miss}}$ combinations

- **3*l* WZ CR (selection as left)**
- **Additional k-factors for NLO EW and NNLO QCD corrections applied.**
- **Joint fit with this CR with m_T^{WZ} as the observable:**

$$m_T^{WZ^2} = \left[\sqrt{p_T^{\ell\ell^2} + m_{\ell\ell}^2} + \sqrt{\left|\vec{p}_T^{\,\text{miss}} + \vec{p}_T^{\,\ell_W}\right|^2 + m_W^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,\ell_W}\right|^2$$

- **Constrain both the normalisation and the shapes for WZ/ZZ in SR.**

3*l* WZ CR distributions

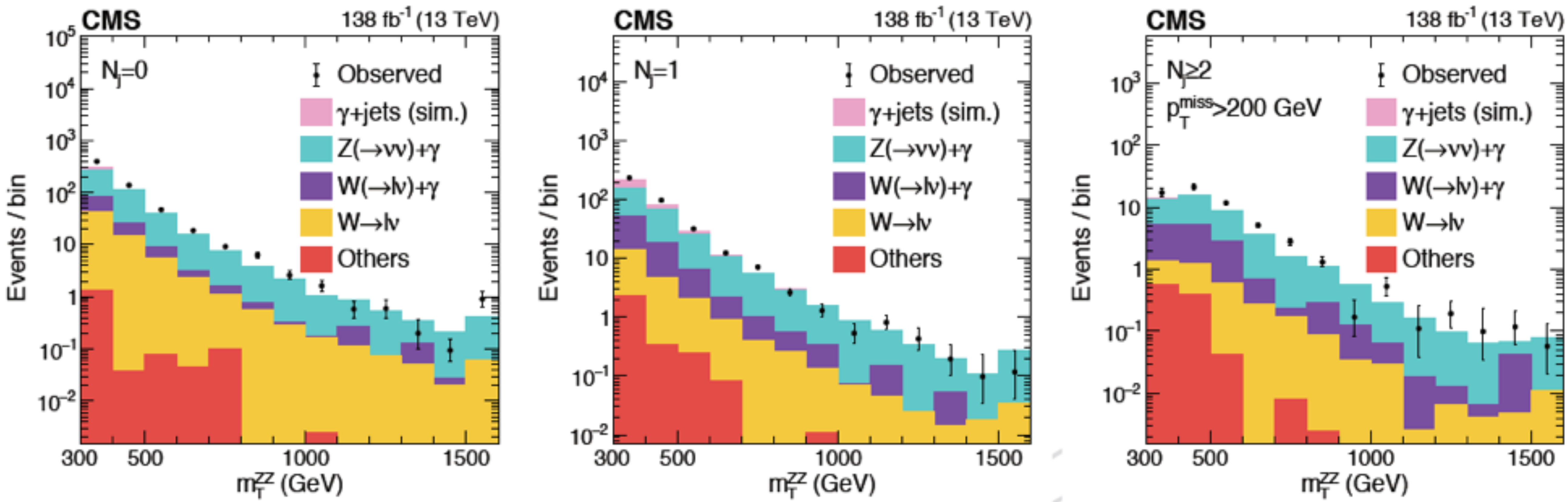


- **Good agreement between Data and MC.**

Instrumental p_T^{miss}

- **Significant contribution from Z+jets events in SR**
  - large cross section of Z+jets process
  - miscalibration of jets or neutrinos from hadrons
- **Estimated with γ+jets CR (γ as a proxy for Z)**
  - bad modelling of p_T^{miss} in MC Z+jets
  - single, isolated γ expected to preserve similar kinematics as Z boson.
  - relatively higher statistics in γ+jets CR than Z+jets events.
- **Transfer factors derived in terms of Vertices, boson η and boson p_T**
- **Genuine MET contributions for high MET region subtracted:**
  - $Z(\to\nu\nu)\gamma$: estimated by $ll\gamma$ CR
  - W+jets: estimated by single electron CR
  - others: from MC

γ+jets CR distributions



- γ+jets simulation could not model well data since it is LO!
- We are estimating the size of the Z+jets contribution by γ+jets in data.

Non-resonant background (tt, WW, H→WW, ττ)

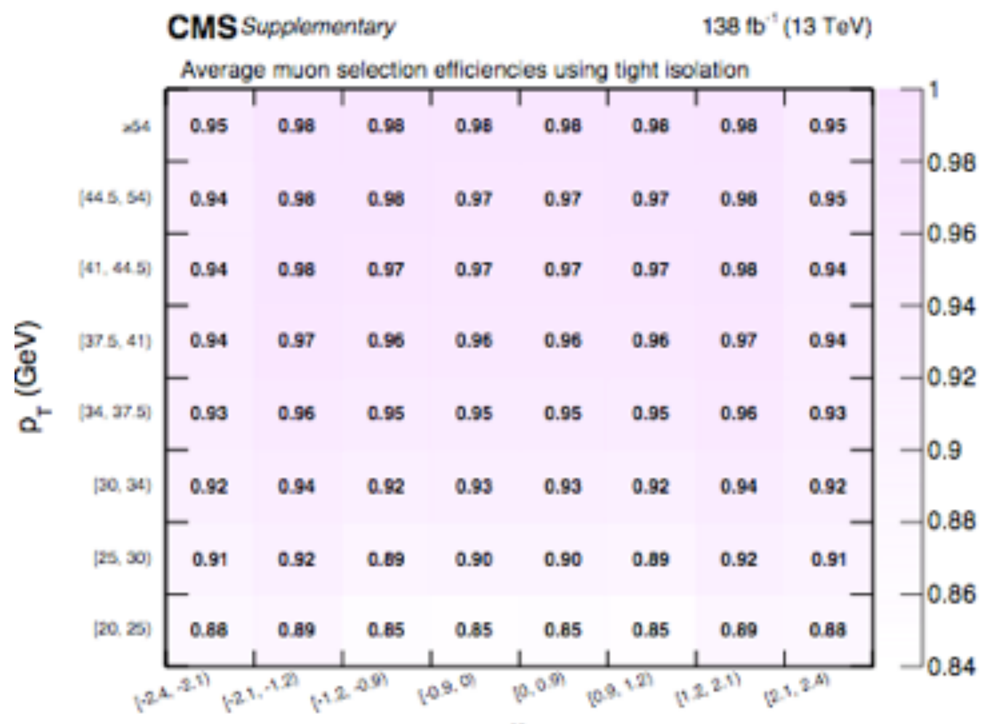
- **Two isolated leptons not from the same mother particle, thus no Z peak**
- **Flavour symmetry: $N_{ee} = N_{\mu\mu} = 1/2\, N_{e\mu}$**
- **Use eμ CR, reweighted by the trigger and lepton efficiencies:**

$$w_{e\mu}^{1\ell 2} = \frac{1}{2} \times \frac{\epsilon_{\ell 1}^{\rm reco} \cdot \epsilon_{\ell 2}^{\rm reco}}{\epsilon_{\mu}^{\rm reco} \cdot \epsilon_{e}^{\rm reco}} \times \frac{\epsilon_{\ell\ell}^{\rm trigger}}{\epsilon_{\mu e}^{\rm trigger}} \times f_{\rm corr}^{\ell 1 \ell 2}(p_{\rm T}^{\rm miss})$$

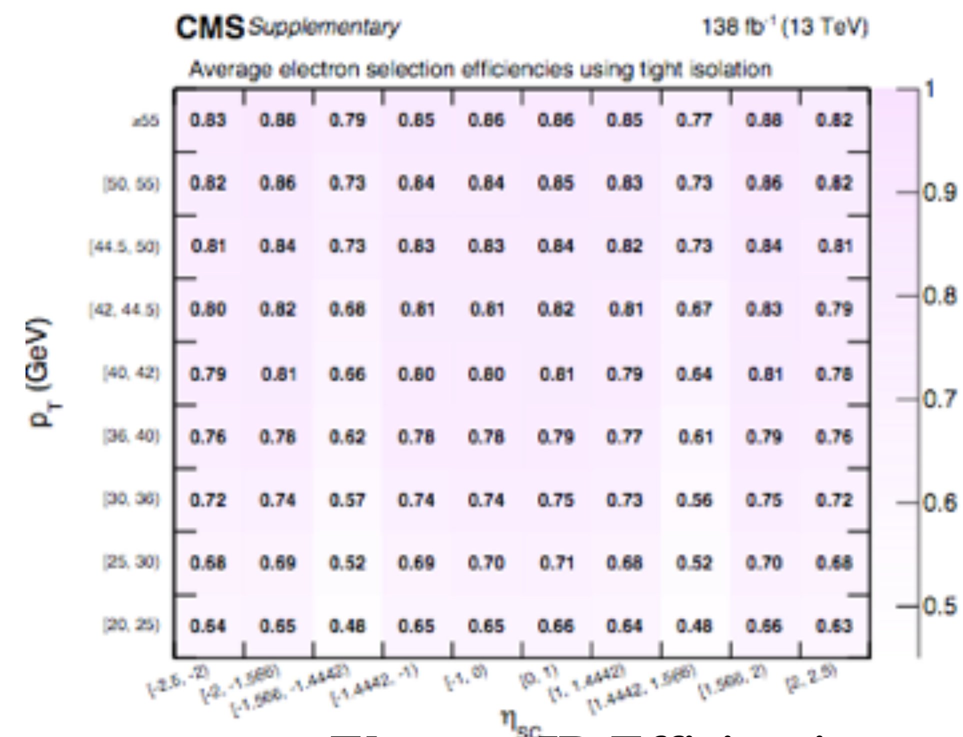
where $f_{\rm corr}^{\ell 1 \ell 2}$ is the residual $p_{\rm T}^{\rm miss}$ difference because of unclustered energy between $e\mu$ and other $\ell\ell$ events. This correction is derived from the sideband with the inverted b-tagging requirment,

$$50\ {\rm GeV} \le m_{\ell\ell} < 201.2\ {\rm GeV} \ \cup\ p_{\rm T}^{\ell\ell} \ge 25\ {\rm GeV} \ \cup\ \sim {\rm SR}$$

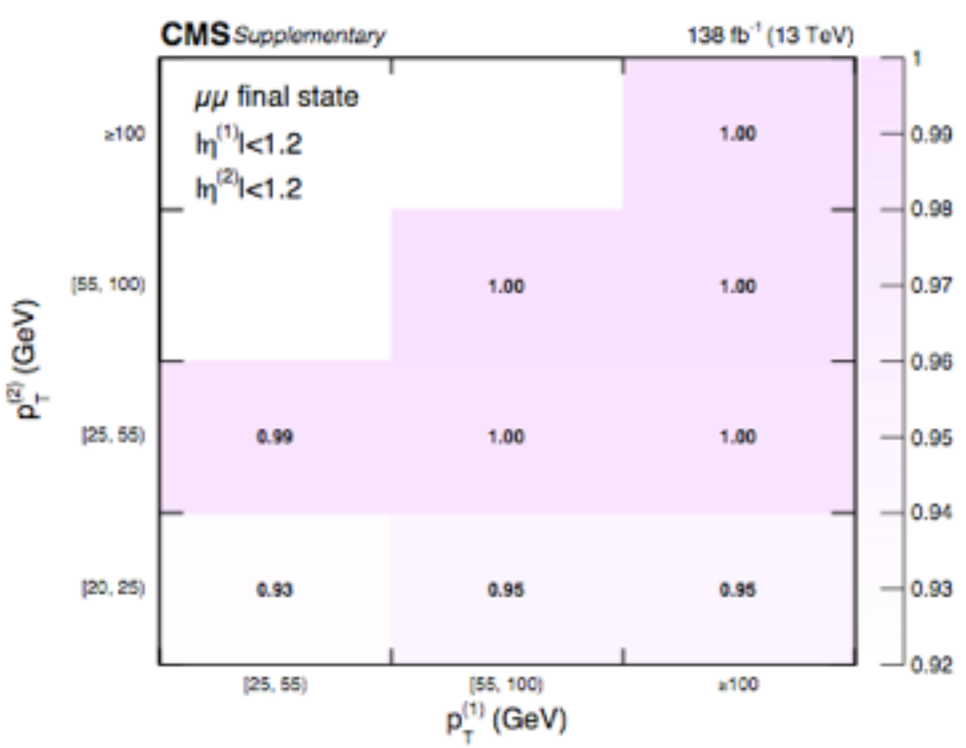
Measured efficiencies

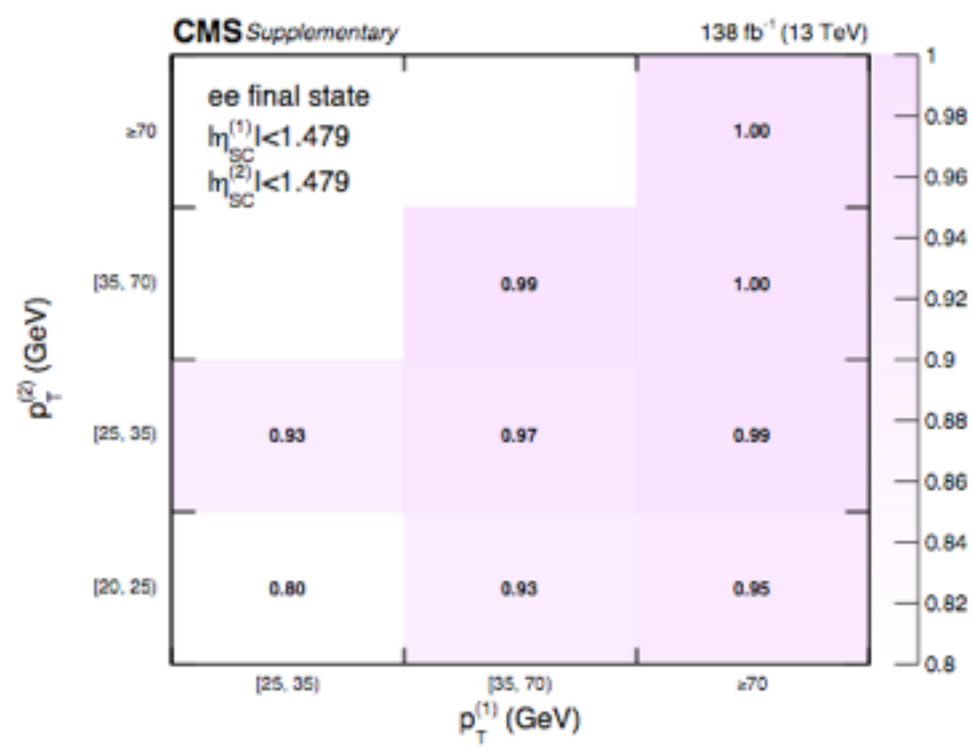


Muon ID Efficiencies



Electron ID Efficiencies

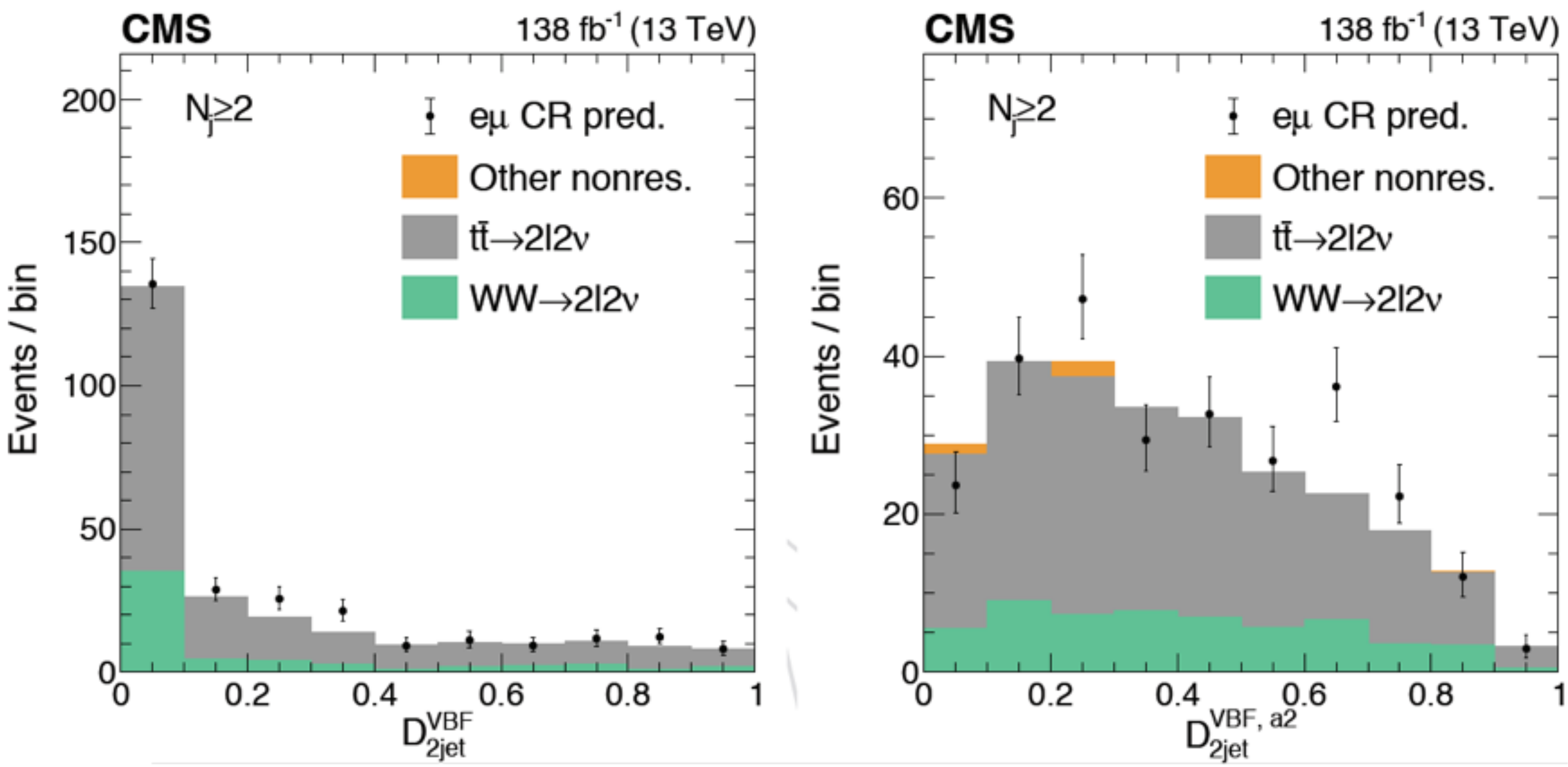




μμ trigger Efficiencies

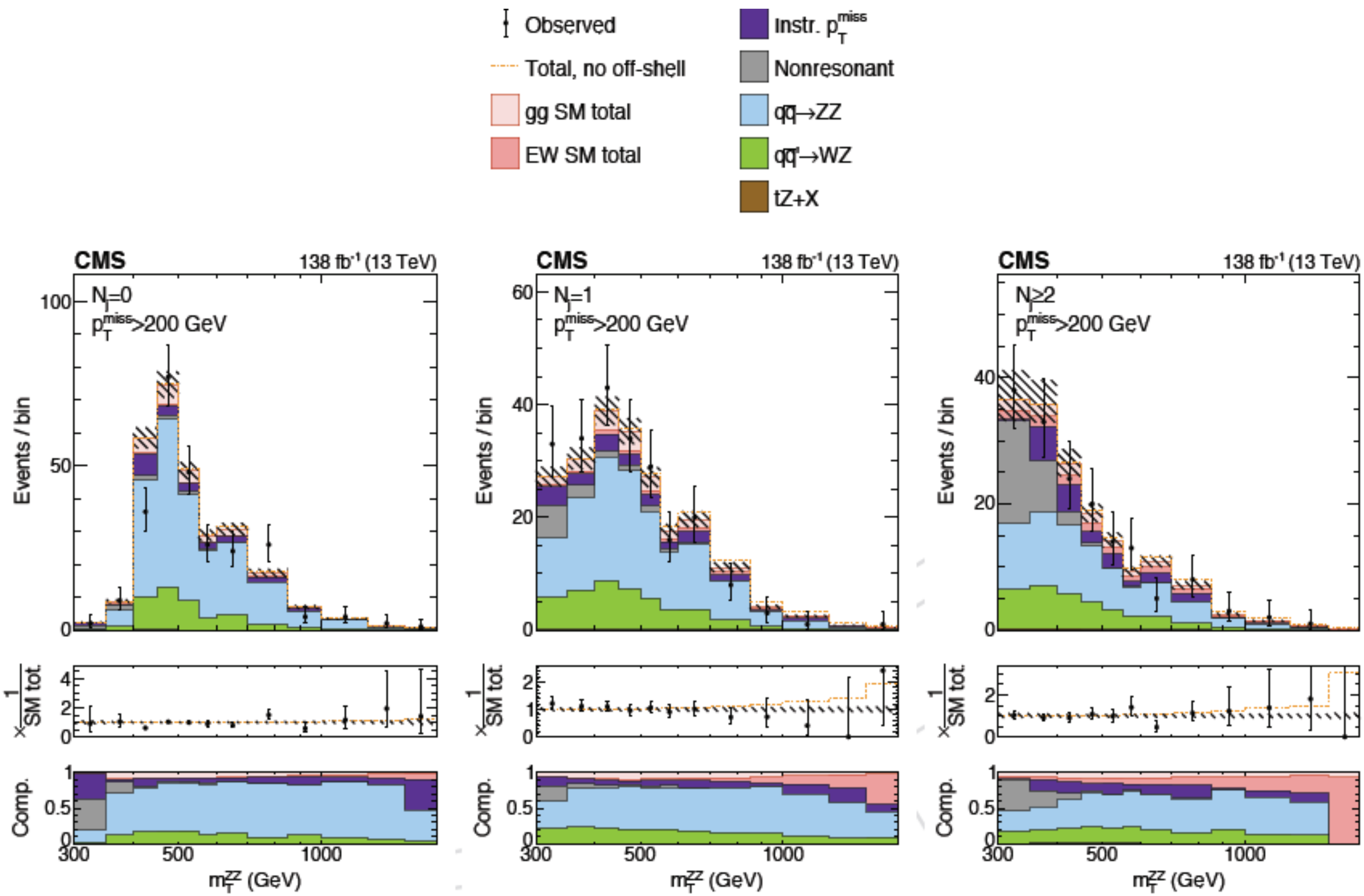
ee trigger Efficiencies

Estimated Non-resonant background in SR

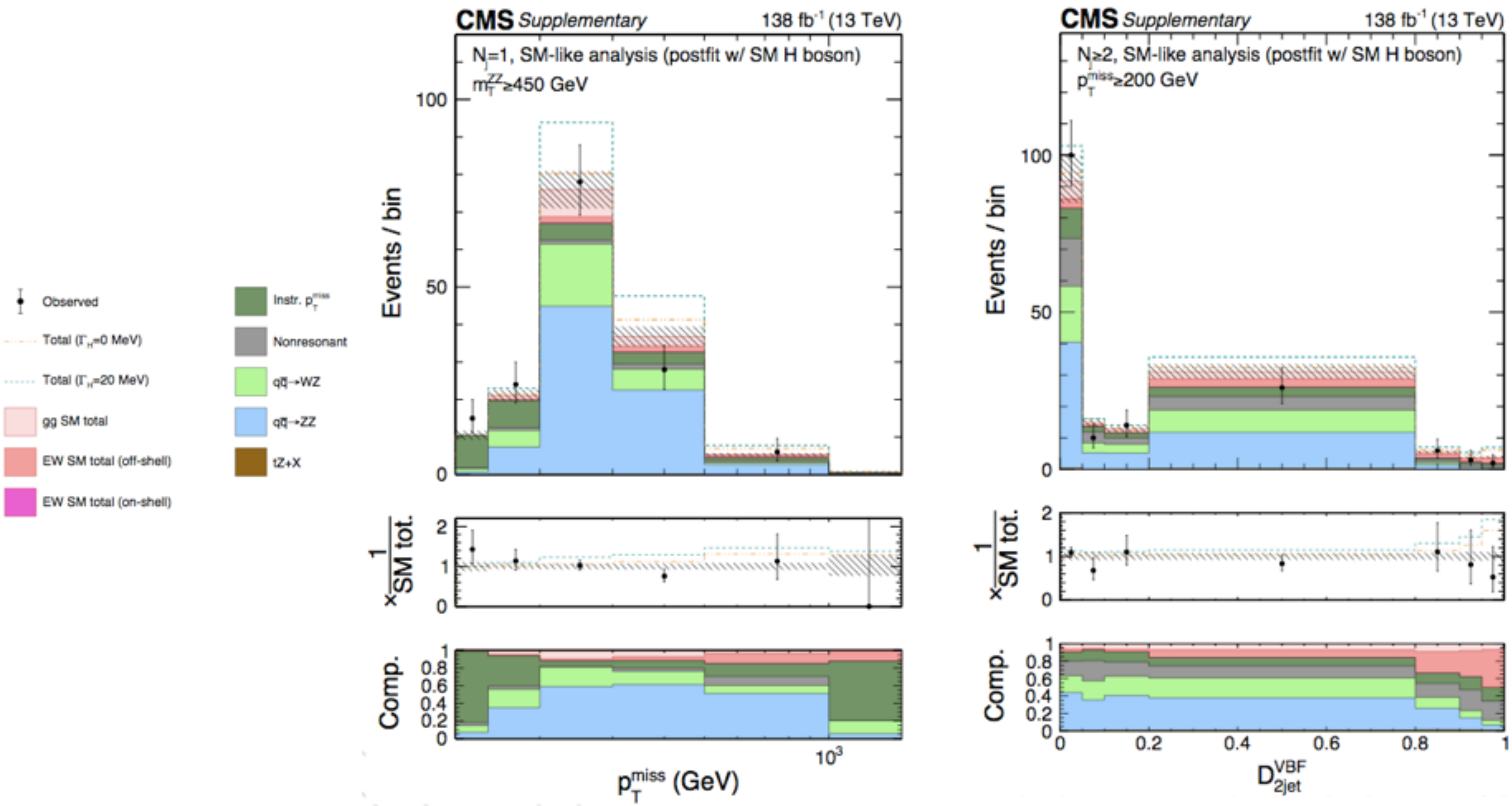


- **Data-driven estimation agrees with MC prediction.**
- **Smaller uncertainty from data-driven estimation.**

m_T^{ZZ} distribution after all selections

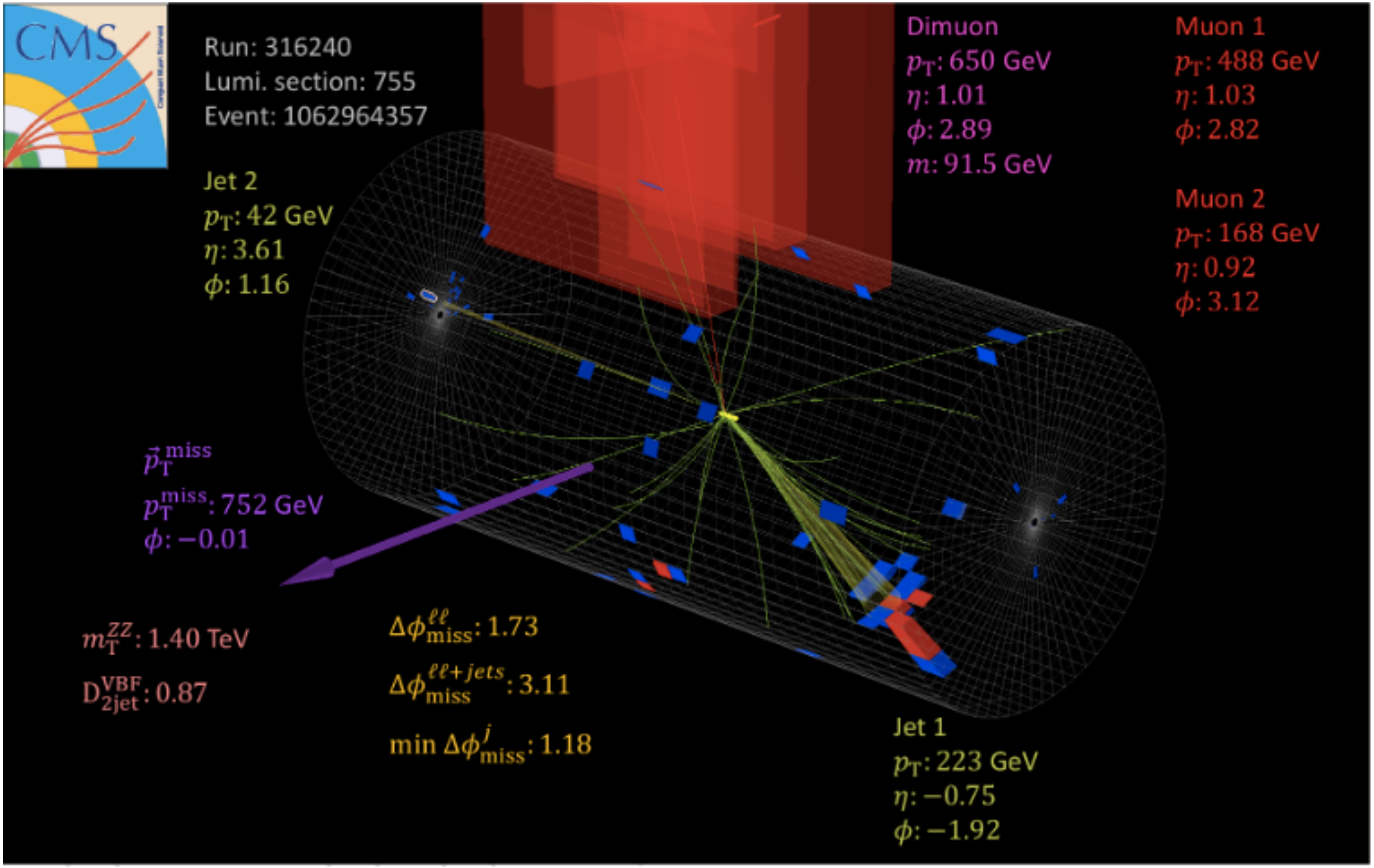


Other observables distributions



- **Observed data favours SM off-shell Higgs other than no off-shell (Γ_H =0) hypothesis especially in high m_T^{ZZ} and $D_{2jet}^{VBF}\to 1$ regions.**

Event display for a VBF/VBS candidate



- **observed event with m_T^{ZZ} =1.4TeV and D_{2jet}^{VBF}=0.87, will be very likely a VBF/VBS candidate.**

Event yields

Table 1: Comparisons between the number of observed events in the $2\ell 2\nu$ channel with postfit expectations from the SM and no–off-shell scenarios as a function of N_j for low and high m_T^{ZZ}. An additional requirement of $p_T^{miss} \geq 200\,GeV$ has been imposed for $N_j \geq 2$.

	m_T^{ZZ}	$N_j = 0$	$Nj = 1$	$N_j \geq 2$
SM	$< 450\,GeV$	1056^{+46}_{-46}	615^{+32}_{-31}	92^{+7}_{-8}
No off.	$< 450\,GeV$	1064^{+46}_{-47}	620^{+32}_{-32}	93^{+7}_{-8}
Data	$< 450\,GeV$	989	643	95
SM	$\geq 450\,GeV$	223^{+13}_{-13}	150^{+10}_{-9}	64^{+5}_{-5}
No off.	$\geq 450\,GeV$	232^{+13}_{-13}	161^{+10}_{-10}	71^{+5}_{-5}
Data	$\geq 450\,GeV$	217	151	66

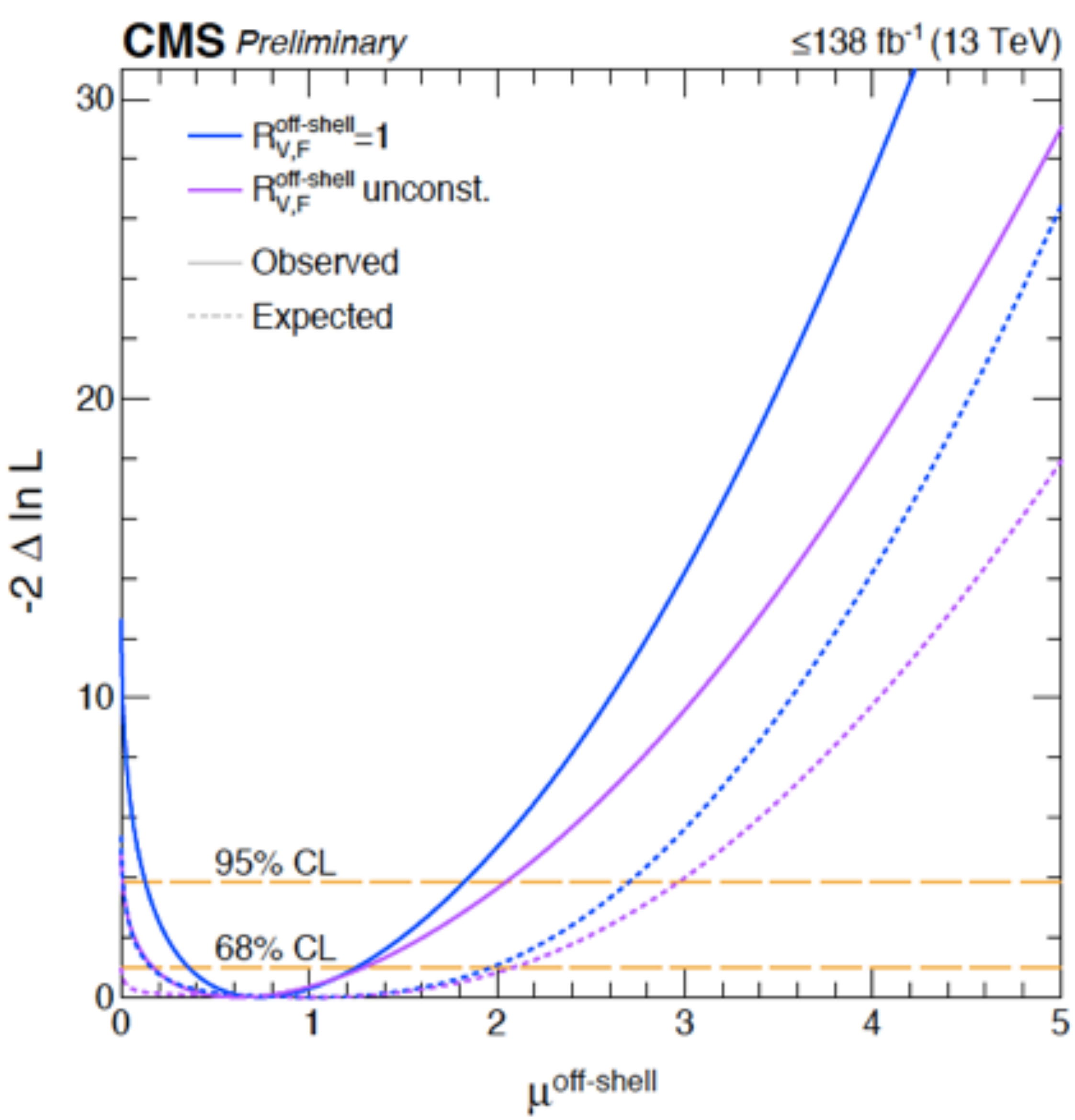
- **For more sensitive region (m_T^{ZZ} >450 GeV), data clearly consistent with SM expectation, disfavour no off-shell hypothesis.**

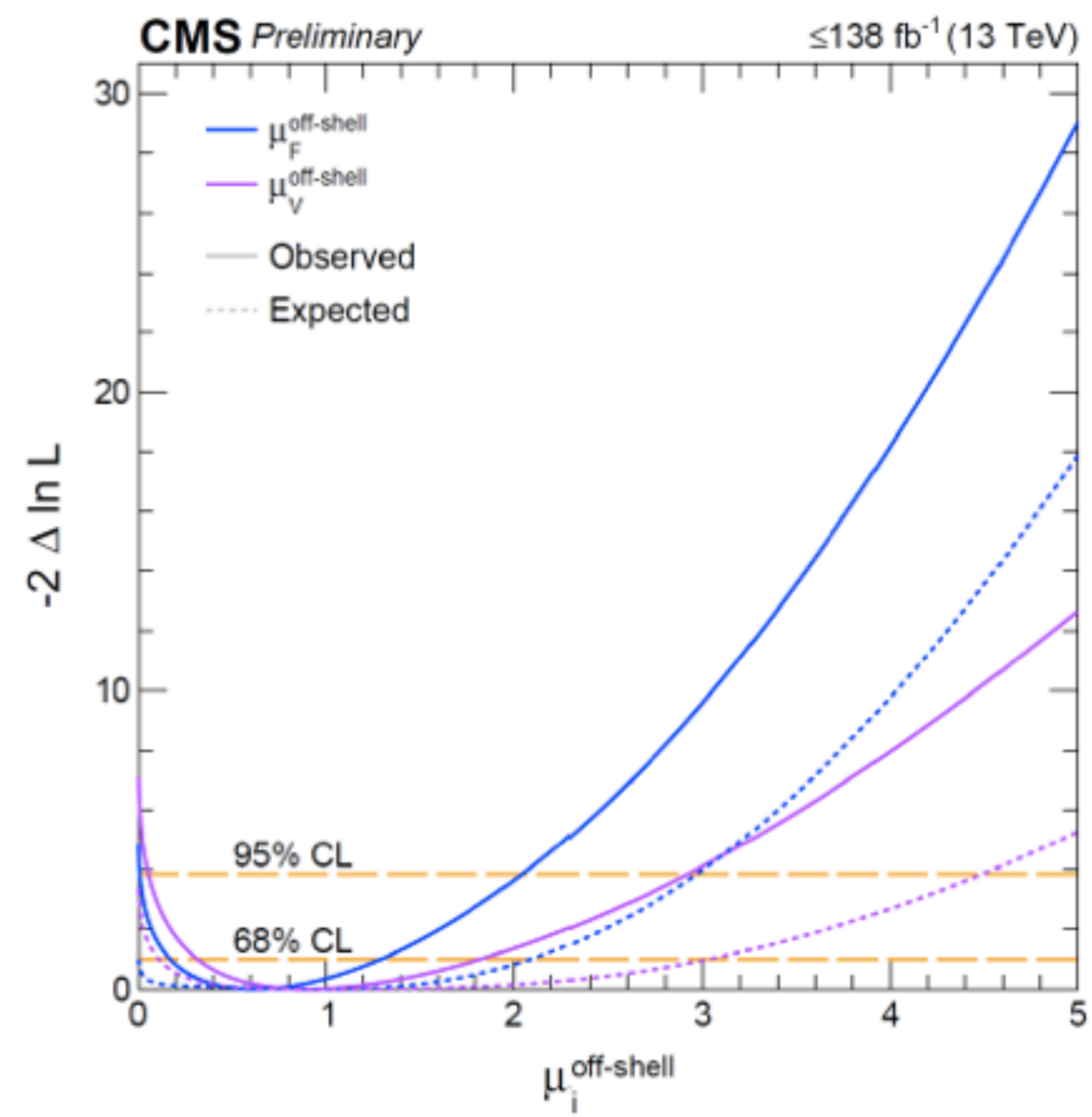
Systematic Uncertainties

Uncertainties on both normalisation and shape are accounted.

- **Theoretical uncertainties**
  - renormalisation scale and factorisation scale (up to 30%)
  - α_s (m_Z) and PDF variations (up to 20%)
  - simulation of the second jet in gg samples (up to 20%)
  - scale and tune variations of PYTHIA
  - NLO EW corrections (qq→ZZ, WZ)
  - uncorrelated uncertainties for normalisation in 3l WZ CR
- **Experimental uncertainties**
  - Luminosity (between 1.2% and 2.5%)
  - Pile-up, JES, JER, and MET resolution uncertainty
  - simulation of the second jet in gg samples (up to 20%)
  - uncertainties on lepton, trigger, pile-up jet ID, b-tagging efficiencies

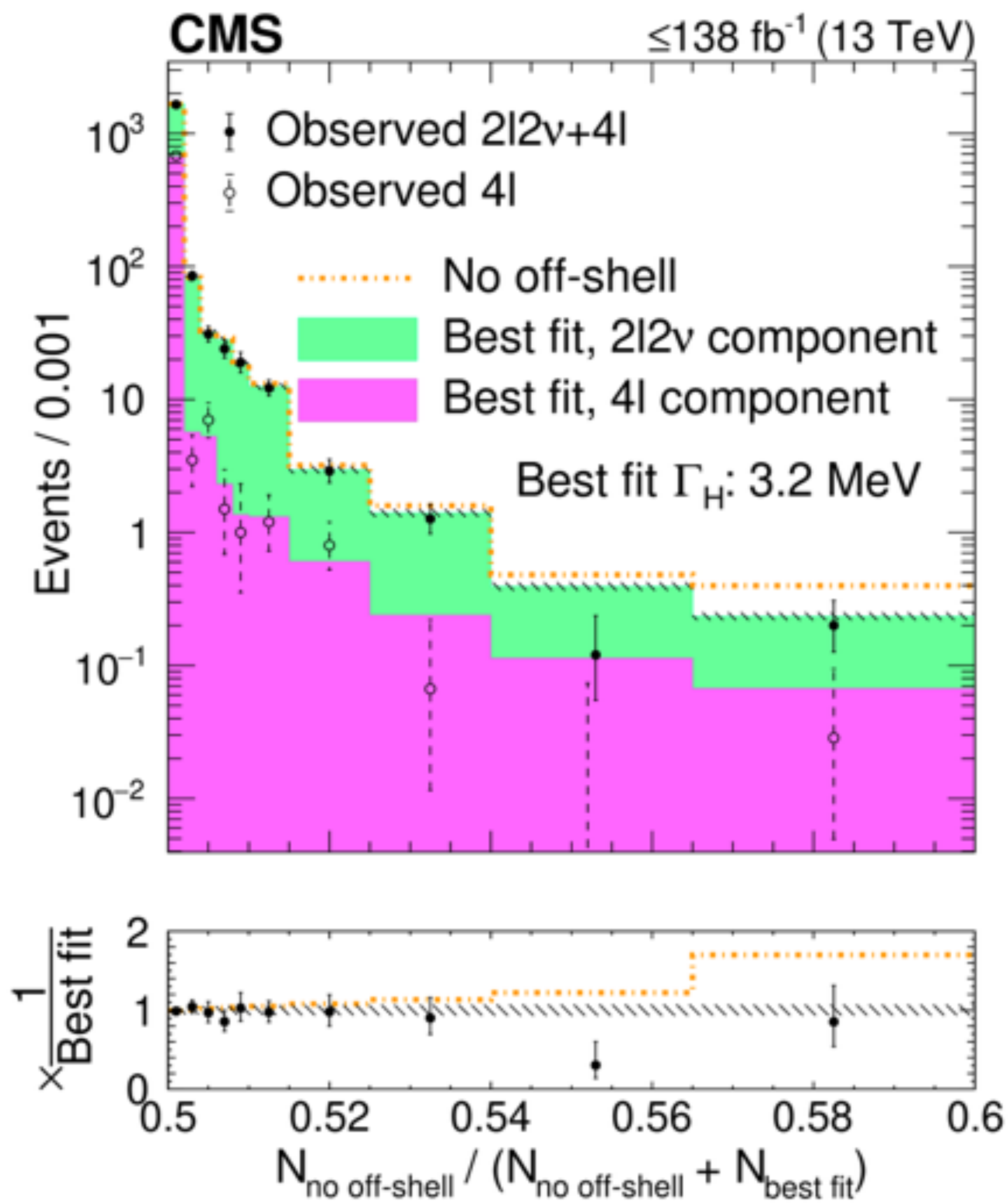
Evidence for off-shell from 2*l*2ν+4*l*

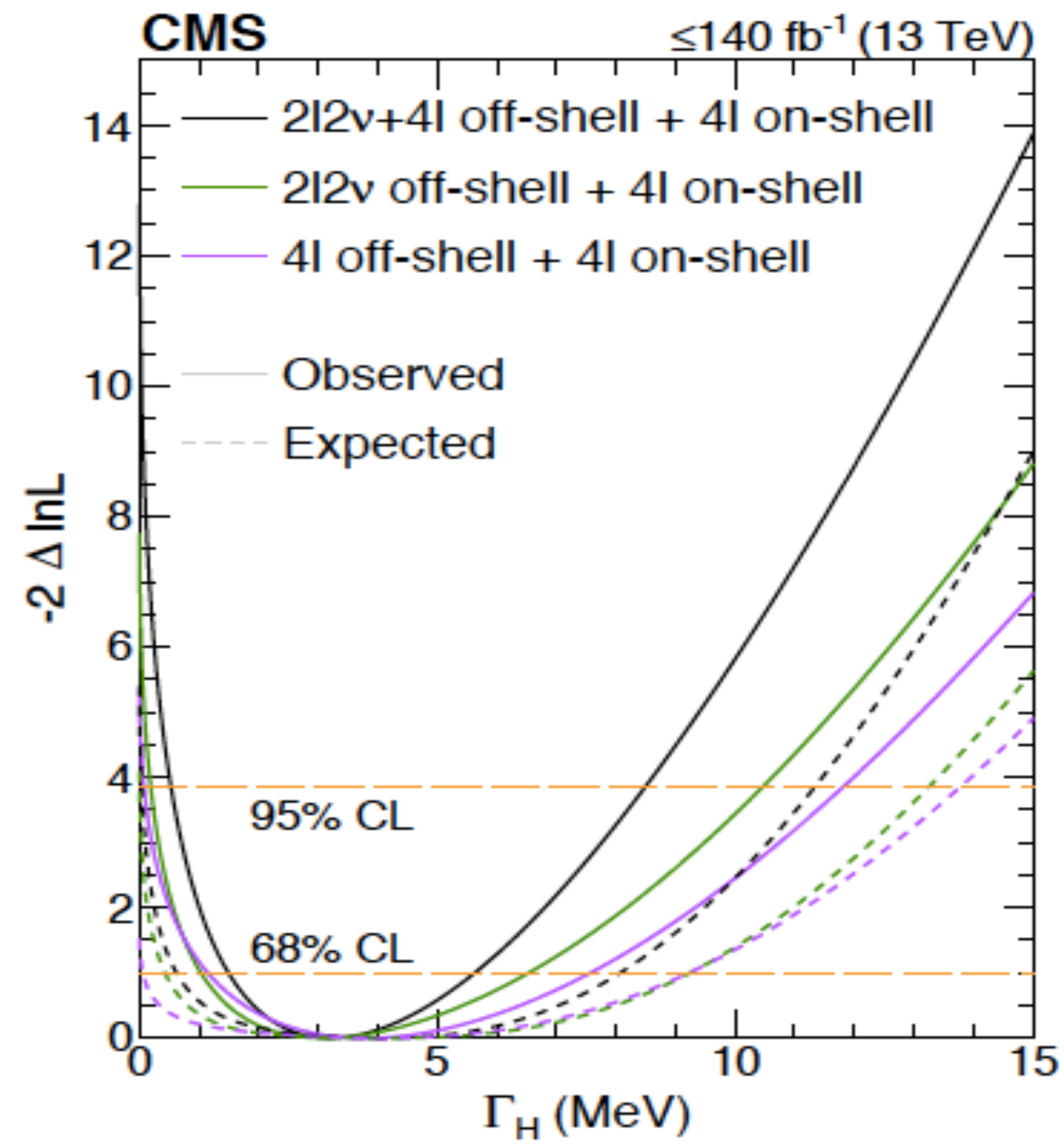




- **No off-shell hypothesis ($\mu_{off\text{-}shell}$=0) excluded by more than 99.9% CL, i.e off-shell Higgs sensitivity 3.6σ**
- **Both No off-shell ggF production ($\mu_F^{off\text{-}shell}$=0) and No off-shell EW production ($\mu_V^{off\text{-}shell}$=0) excluded more than 95% CL.**

Measured Higgs width



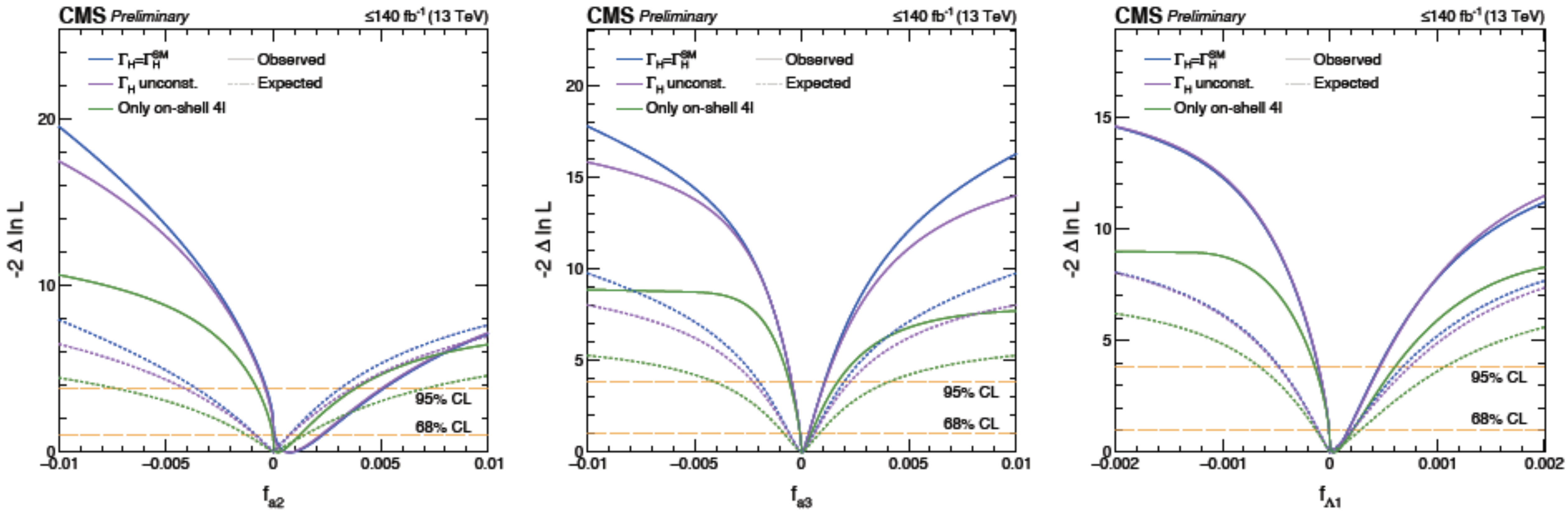


- **Observed** $\Gamma_H = 3.2^{+2.4}_{-1.7}\text{MeV}$

$2l2\nu$+$4l$ combined results summary

Param.	Cond.	c.v.	Observed 68% | 95% CL	Expected 68% | 95% CL
$\mu_F^{off.}$	$\mu_V^{off.}$ (u)	0.62	$[0.17, 1.3] \mid [0.0060, 2.0]$	$[2 \cdot 10^{-5}, 2.1] \mid < 3.0$
$\mu_V^{off.}$	$\mu_F^{off.}$ (u)	0.90	$[0.31, 1.8] \mid [0.051, 2.9]$	$[0.11, 3.0] \mid < 4.5$
$\mu^{off.}$	$R_{V,F}^{off.} = 1$	0.74	$[0.36, 1.3] \mid [0.13, 1.8]$	$[0.16, 2.0] \mid [0.0086, 2.7]$
	$R_{V,F}^{off.}$ (u)	0.62	$[0.17, 1.3] \mid [0.0061, 2.0]$	$[4 \cdot 10^{-5}, 2.1] \mid [1 \cdot 10^{-5}, 3.0]$
Γ_H	SM-like	3.2	$[1.5, 5.6] \mid [0.53, 8.5]$	$[0.62, 8.1] \mid [0.035, 11.3]$
Γ_H	f_{a2} (u)	3.4	$[1.6, 5.7] \mid [0.60, 8.4]$	$[0.52, 8.0] \mid [0.015, 11.3]$
Γ_H	f_{a3} (u)	2.7	$[1.3, 4.8] \mid [0.47, 7.3]$	$[0.53, 8.0] \mid [0.015, 11.3]$
Γ_H	$f_{\Lambda 1}$ (u)	2.7	$[1.3, 4.8] \mid [0.46, 7.2]$	$[0.55, 8.1] \mid [0.019, 11.3]$

HVV anomalous coupling limits



Parameter ($\times10^5$)	Scenario	b.f.	Observed 68% | 95% CL	Expected 68% | 95% CL
f_{a2}	$\Gamma_H = \Gamma_H^{SM}$	79	$[6.6, 225]$ | $[-32, 514]$	$[-78, 70]$ | $[-359, 311]$
	Γ_H unconst.	72	$[2.7, 216]$ | $[-38, 503]$	$[-82, 73]$ | $[-413, 364]$
f_{a3}	$\Gamma_H = \Gamma_H^{SM}$	2.2	$[-6.4, 32]$ | $[-46, 107]$	$[-55, 55]$ | $[-198, 198]$
	Γ_H unconst.	2.4	$[-6.2, 33]$ | $[-46, 110]$	$[-58, 58]$ | $[-225, 225]$
$f_{\Lambda1}$	$\Gamma_H = \Gamma_H^{SM}$	2.9	$[-0.62, 17]$ | $[-11, 46]$	$[-11, 20]$ | $[-47, 68]$
	Γ_H unconst.	3.1	$[-0.56, 18]$ | $[-10, 47]$	$[-11, 21]$ | $[-48, 75]$

best fit values

- **Improvement from adding off-shell information is of O(10%) at 95% CL**

Summary

- Combination of H→ZZ→2*l*2*v* and H→ZZ→4*l* off-shell analyses results in finding the first evidence of off-shell Higgs production at LHC

- Combine ZZ on-shell and off-shell analyses to measure Γ_{H}, gives

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\mathrm{MeV}$$

Reaching ~50% precision for the first time!

- Off-shell events further constrain HVV anomalous couplings.

- Paper Accepted by Nature Physics on June 21!

CMS physics briefing: https://cms.cern/news/life-higgs-boson

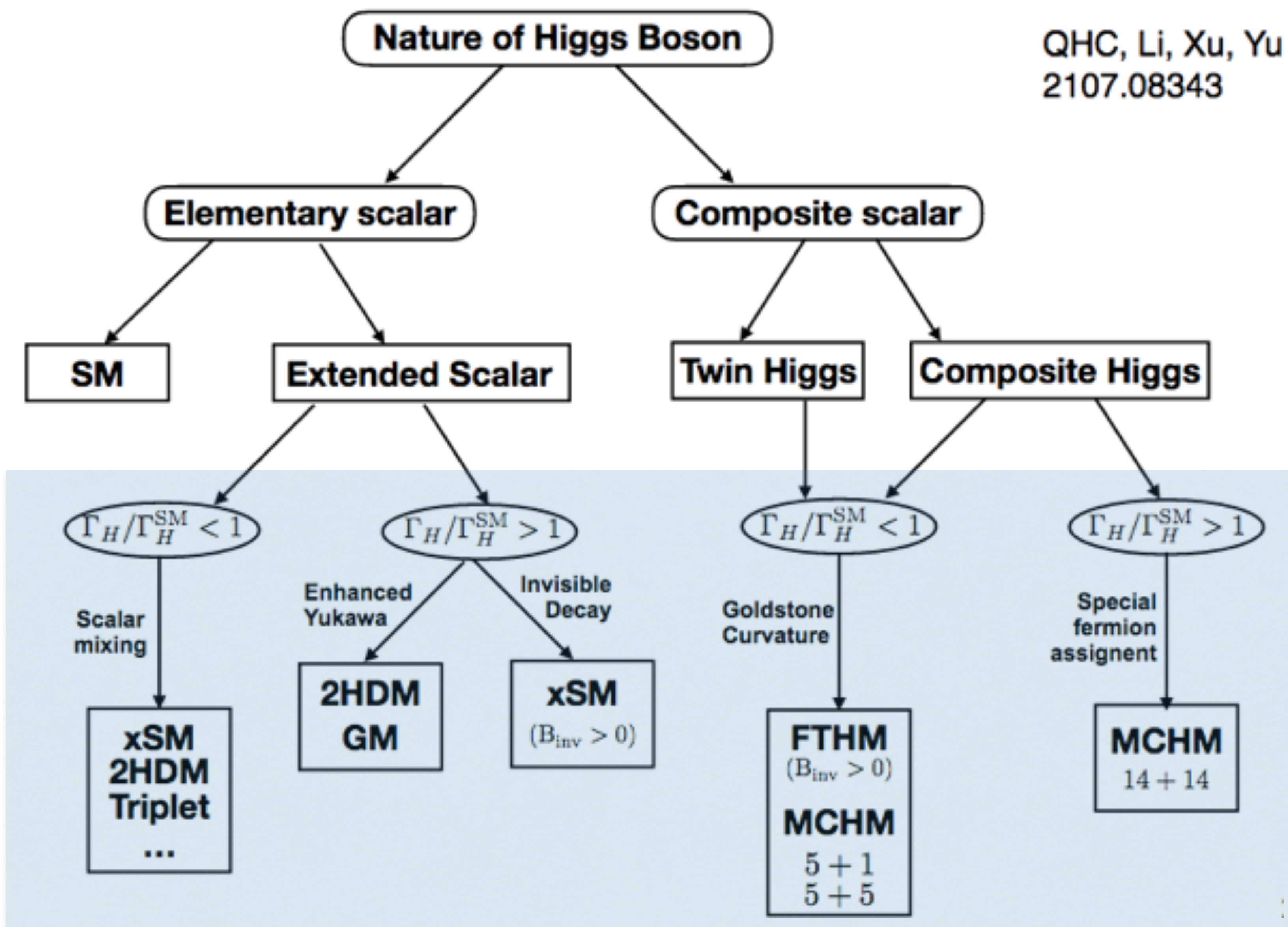
CERN news: https://home.cern/news/news/physics/cms-homes-higgs-bosons-lifetime

环球科学： https://mp.weixin.qq.com/s/SDgXu8aM8k2omyLR0R5sfQ

SCI-NEWS： http://www.sci-news.com/physics/higgs-boson-width-10336.html

What if Γ_H deviates from SM

4. Higgs boson width



- Stay tuned for more exciting results with more data and more advanced analysis techniques.

https://indico.ihep.ac.cn/event/14180/session/0/contribution/93/material/slides/0.pdf


thank you

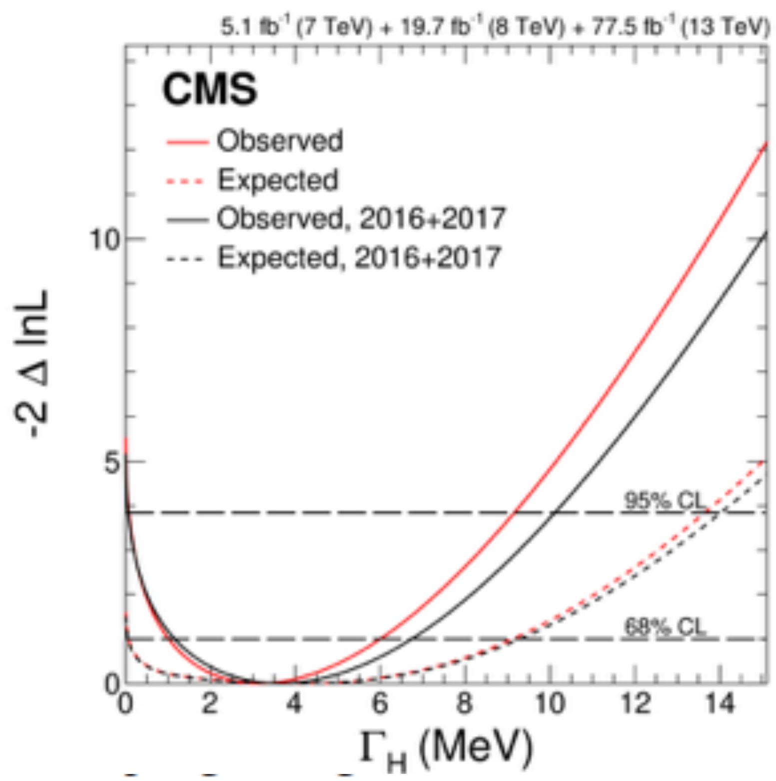
- backup

Previous results on width measurement

- **CMS: H→ZZ→4*l***

on-shell: Run 1 + Run 2 ($77.5fb^{-1}$)

off-shell: Run 2 ($77.5fb^{-1}$)



68% [95%]

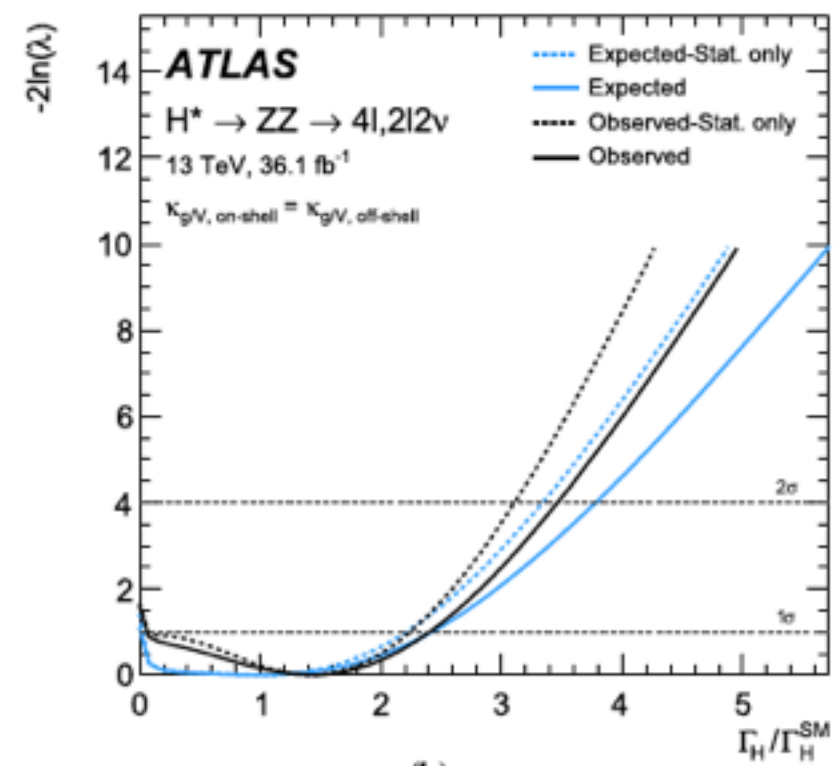
Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

Parameter	Observed	Expected
$\mu^{\text{off-shell}}$	$0.78^{+0.72}_{-0.53}$ [0.02, 2.28]	$1.00^{+1.20}_{-0.99}$ [0.0, 3.2]
$\mu_F^{\text{off-shell}}$	$0.86^{+0.92}_{-0.68}$ [0.0, 2.7]	$1.0^{+1.3}_{-1.0}$ [0.0, 3.5]
$\mu_V^{\text{off-shell}}$	$0.67^{+1.26}_{-0.61}$ [0.0, 3.6]	$1.0^{+3.8}_{-1.0}$ [0.0, 8.4]

- **ATLAS: H→ZZ→4*l* & H→ZZ→2*l*2*v***

on-shell: Run 2 ($36.1fb^{-1}$)

off-shell: Run 2 ($36.1fb^{-1}$)



The 95% CL upper limits on $\mu_{\text{off-shell}}$, Γ_H/Γ_H^{SM} and R_{gg}. Both the observed and expected limits are given. The 1σ (2σ) uncertainties represent 68% (95%) confidence intervals for the expected limit. The upper limits are evaluated using the CL_s method, with the SM values as the alternative hypothesis for each interpretation.

		Observed	Expected		
			Median	$\pm1\ \sigma$	$\pm2\ \sigma$
$\mu_{\text{off-shell}}$	$ZZ\to4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]
	$ZZ\to2\ell2\nu$ analysis	5.3	4.4	[3.4, 5.5]	[2.8, 7.0]
	Combined	3.8	3.4	[2.7, 4.2]	[2.3, 5.3]
Γ_H/Γ_H^{SM}	Combined	3.5	3.7	[2.9, 4.8]	[2.4, 6.5]
R_{gg}	Combined	4.3	4.1	[3.3, 5.6]	[2.7, 8.2]

Additional results on $\mu_{\text{off-shell}}$

Table 4: Constraints on the $\mu_F^{\text{off-shell}}$, $\mu_V^{\text{off-shell}}$, and $\mu^{\text{off-shell}}$ parameters are summarized. The constraints on $\mu^{\text{off-shell}}$ are obtained with $R_{V,F}^{\text{off-shell}}$ unconstrained or $= 1$. The measurements are presented using the $2\ell 2\nu$ analysis alone, or with the inclusion of off-shell 4ℓ events. The designation 'c.v.' stands for the central value obtained in the likelihood scan, and the expected central value is always unity, so it is not quoted explicitly.

Parameter	Condition	c.v.	Observed 68% | 95% CL	Expected 68% | 95% CL
$\mu_F^{\text{off-shell}}$ $(2\ell 2\nu + 4\ell)$	$\mu_V^{\text{off-shell}}$ unconst.	0.62	$[0.17, 1.3] \mid [0.0060, 2.0]$	$[2\cdot 10^{-5}, 2.1] \mid < 3.0$
$\mu_F^{\text{off-shell}}$ $(2\ell 2\nu)$	$\mu_V^{\text{off-shell}}$ unconst.	0.41	$[0.014, 1.4] \mid < 2.6$	$< 2.5 \mid < 3.7$
$\mu_V^{\text{off-shell}}$ $(2\ell 2\nu + 4\ell)$	$\mu_F^{\text{off-shell}}$ unconst.	0.90	$[0.31, 1.8] \mid [0.051, 2.9]$	$[0.11, 3.0] \mid < 4.5$
$\mu_V^{\text{off-shell}}$ $(2\ell 2\nu)$	$\mu_F^{\text{off-shell}}$ unconst.	1.1	$[0.28, 2.4] \mid [0.016, 3.8]$	$[0.07, 3.2] \mid < 4.8$
$\mu^{\text{off-shell}}$ $(2\ell 2\nu + 4\ell)$	$R_{V,F}^{\text{off-shell}} = 1$	0.74	$[0.36, 1.3] \mid [0.13, 1.8]$	$[0.16, 2.0] \mid [0.0086, 2.7]$
	$R_{V,F}^{\text{off-shell}}$ unconst.	0.62	$[0.17, 1.3] \mid [0.0061, 2.0]$	$[4\cdot 10^{-5}, 2.1] \mid [1\cdot 10^{-5}, 3.0]$
$\mu^{\text{off-shell}}$ $(2\ell 2\nu)$	$R_{V,F}^{\text{off-shell}} = 1$	0.74	$[0.25, 1.5] \mid [0.043, 2.3]$	$[0.11, 2.3] \mid [2\cdot 10^{-4}, 3.2]$
	$R_{V,F}^{\text{off-shell}}$ unconst.	0.41	$[0.014, 1.4] \mid [2\cdot 10^{-5}, 2.6]$	$[3\cdot 10^{-5}, 2.5] \mid [6\cdot 10^{-6}, 3.7]$

HVV anomalous coupling from on-shell

CMS-HIGS-19-009

Parameter	Scenario		Observed	Expected
f_{a3}	Approach 1	best fit	0.00004	0.00000
	$f_{a2} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	68% CL	$[-0.00007, 0.00044]$	$[-0.00081, 0.00081]$
		95% CL	$[-0.00055, 0.00168]$	$[-0.00412, 0.00412]$
	Approach 1	best fit	-0.00805	0.00000
	float $f_{a2}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	68% CL	$[-0.02656, 0.00034]$	$[-0.00086, 0.00086]$
		95% CL	$[-0.07191, 0.00990]$	$[-0.00423, 0.00422]$
	Approach 2	best fit	0.00005	0.0000
	float $f_{a2}, f_{\Lambda 1}$	68% CL	$[-0.00010, 0.00061]$	$[-0.0012, 0.0012]$
		95% CL	$[-0.00072, 0.00218]$	$[-0.0057, 0.0057]$
f_{a2}	Approach 1	best fit	0.00020	0.0000
	$f_{a3} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	68% CL	$[-0.00010, 0.00109]$	$[-0.0012, 0.0014]$
		95% CL	$[-0.00078, 0.00368]$	$[-0.0075, 0.0073]$
	Approach 1	best fit	-0.24679	0.0000
	float $f_{a3}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	68% CL	$[-0.41087, -0.15149] \cup [-0.00008, 0.00065]$	$[-0.0017, 0.0014]$
		95% CL	$[-0.66842, -0.08754] \cup [-0.00091, 0.00309]$	$[-0.0082, 0.0073]$
	Approach 2	best fit	-0.00002	0.0000
	float $f_{a3}, f_{\Lambda 1}$	68% CL	$[-0.00178, 0.00103]$	$[-0.0060, 0.0033]$
		95% CL	$[-0.00694, 0.00536]$	$[-0.0206, 0.0131]$
$f_{\Lambda 1}$	Approach 1	best fit	0.00004	0.00000
	$f_{a3} = f_{a2} = f_{\Lambda 1}^{Z\gamma} = 0$	68% CL	$[-0.00002, 0.00022]$	$[-0.00016, 0.00026]$
		95% CL	$[-0.00014, 0.00060]$	$[-0.00069, 0.00110]$
	Approach 1	best fit	0.18629	0.00000
	float $f_{a3}, f_{a2}, f_{\Lambda 1}^{Z\gamma}$	68% CL	$[-0.00002, 0.00019] \cup [0.07631, 0.27515]$	$[-0.00017, 0.00036]$
		95% CL	$[-0.00523, 0.35567]$	$[-0.00076, 0.00134]$
	Approach 2	best fit	0.00012	0.0000
	float f_{a3}, f_{a2}	68% CL	$[-0.00021, 0.00141]$	$[-0.0013, 0.0030]$
		95% CL	$[-0.00184, 0.00443]$	$[-0.0056, 0.0102]$
$f_{\Lambda 1}^{Z\gamma}$	Approach 1	best fit	-0.00001	0.0000
	$f_{a3} = f_{a2} = f_{\Lambda 1} = 0$	68% CL	$[-0.00099, 0.00057]$	$[-0.0026, 0.0020]$
		95% CL	$[-0.00387, 0.00301]$	$[-0.0096, 0.0082]$
	Approach 1	best fit	-0.02884	0.0000
	float $f_{a3}, f_{a2}, f_{\Lambda 1}$	68% CL	$[-0.09000, -0.00534] \cup [-0.00068, 0.00078]$	$[-0.0027, 0.0026]$
		95% CL	$[-0.29091, 0.03034]$	$[-0.0099, 0.0096]$

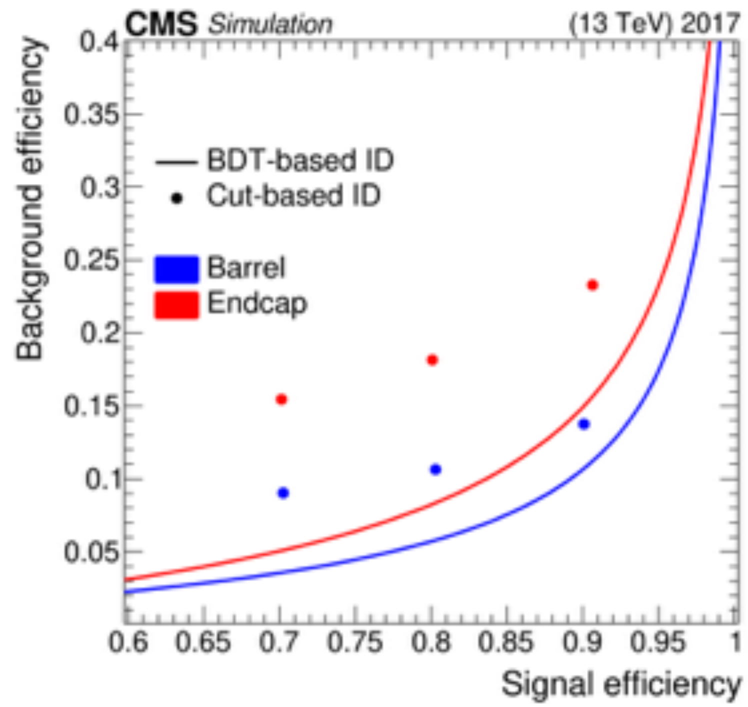
HVV anomalous coupling from 4l on-shell + off-shell

TABLE VI. Summary of allowed 68% C.L. (central values with uncertainties) and 95% C.L. (in square brackets) intervals for the anomalous coupling parameters $f_{ai}\cos(\phi_{ai})$ obtained from the analysis of the combination of Run 1 (only on-shell) and Run 2 (on-shell and off-shell) data sets. Three constraint scenarios are shown: using only on-shell events, using both on-shell and off-shell events with the Γ_H left unconstrained, or with the constraint $\Gamma_H = \Gamma_H^{\mathrm{SM}}$.

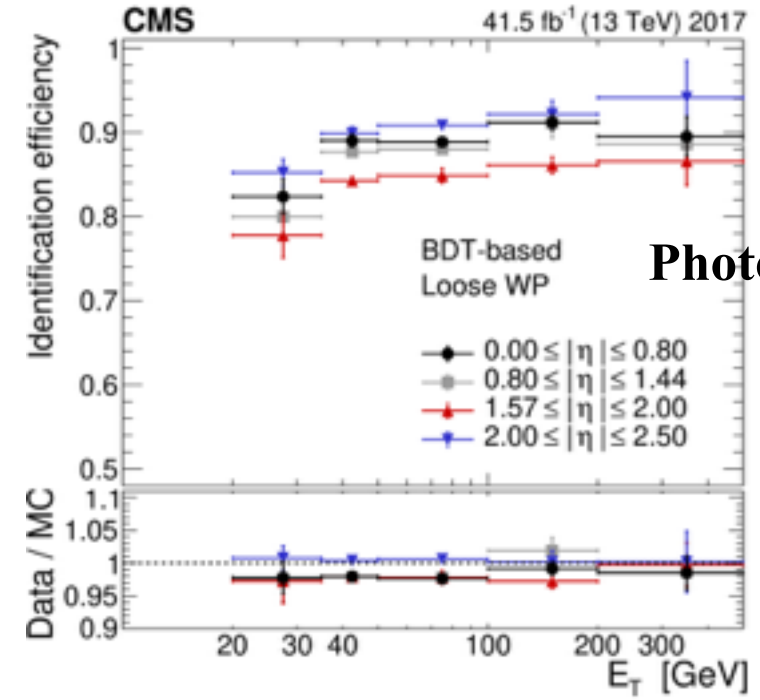
Parameter	Scenario	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	On-shell	$-0.0001^{+0.0004}_{-0.0015}$ [−0.163, 0.090]	$0.0000^{+0.0019}_{-0.0019}$ [−0.082, 0.082]
	Any Γ_H	$0.0000^{+0.0003}_{-0.0010}$ [−0.0165, 0.0087]	$0.0000^{+0.0015}_{-0.0015}$ [−0.038, 0.038]
	$\Gamma_H = \Gamma_H^{\mathrm{SM}}$	$0.0000^{+0.0003}_{-0.0009}$ [−0.0067, 0.0050]	$0.0000^{+0.0014}_{-0.0014}$ [−0.0098, 0.0098]
$f_{a2}\cos(\phi_{a2})$	On-shell	$0.0004^{+0.0026}_{-0.0006}$ [−0.0055, 0.0234]	$0.0000^{+0.0030}_{-0.0023}$ [−0.021, 0.035]
	Any Γ_H	$0.0004^{+0.0026}_{-0.0006}$ [−0.0035, 0.0147]	$0.0000^{+0.0019}_{-0.0017}$ [−0.015, 0.021]
	$\Gamma_H = \Gamma_H^{\mathrm{SM}}$	$0.0005^{+0.0025}_{-0.0006}$ [−0.0029, 0.0129]	$0.0000^{+0.0012}_{-0.0016}$ [−0.010, 0.012]
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	On-shell	$0.0002^{+0.0030}_{-0.0009}$ [−0.209, 0.089]	$0.0000^{+0.0012}_{-0.0006}$ [−0.059, 0.032]
	Any Γ_H	$0.0001^{+0.0015}_{-0.0006}$ [−0.090, 0.059]	$0.0000^{+0.0013}_{-0.0007}$ [−0.017, 0.019]
	$\Gamma_H = \Gamma_H^{\mathrm{SM}}$	$0.0001^{+0.0015}_{-0.0005}$ [−0.016, 0.068]	$0.0000^{+0.0013}_{-0.0006}$ [−0.015, 0.018]
$f_{\Lambda 1}^{Z\gamma}\cos(\phi_{\Lambda 1}{}^{Z\gamma})$	On-shell	$0.0000^{+0.3554}_{-0.0087}$ [−0.17, 0.61]	$0.0000^{+0.0091}_{-0.0100}$ [−0.098, 0.343]

Photon Identification and Energy Correction

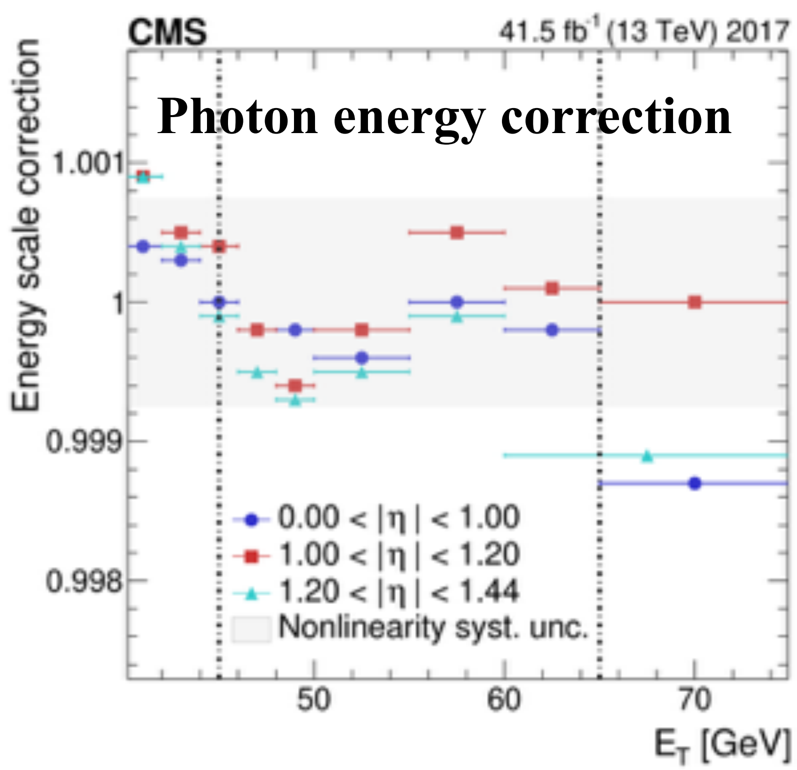
Photon ID ROC



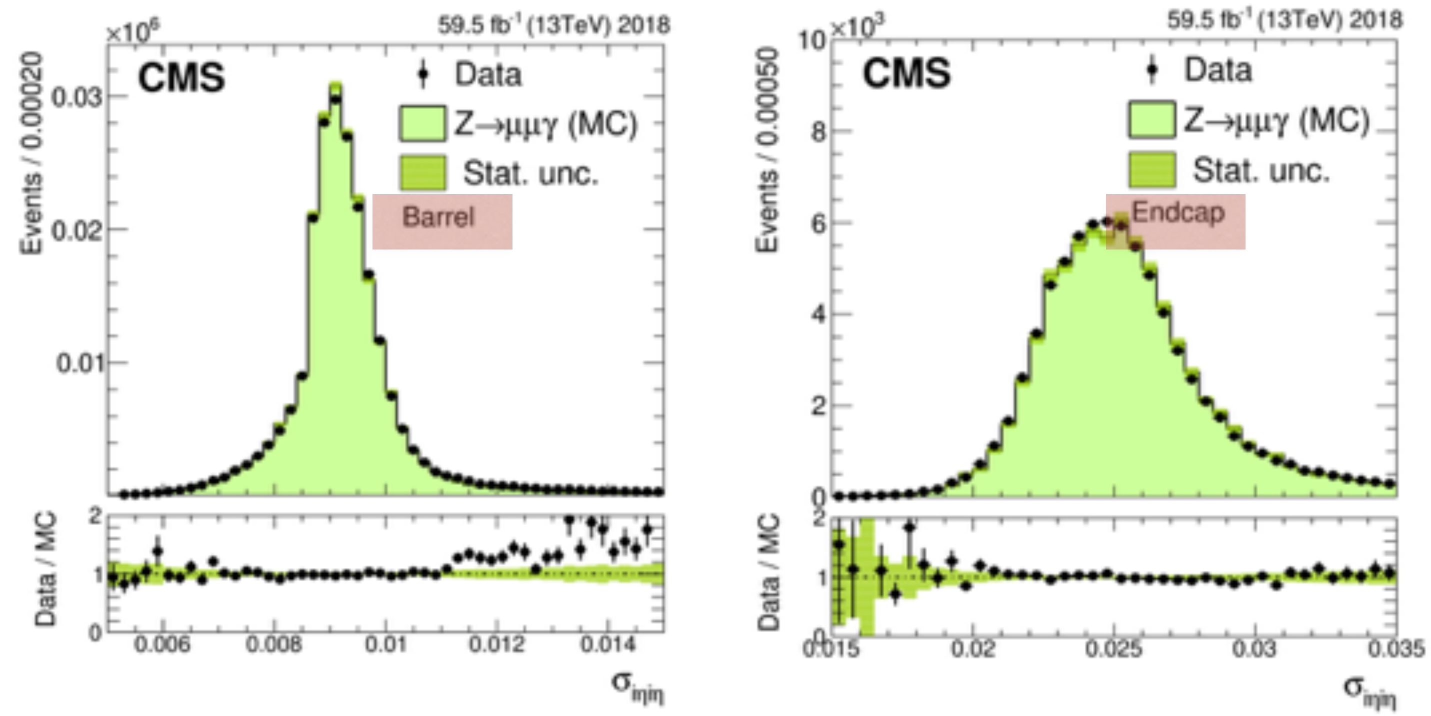
Photon BDT-ID vs E_T



Photon energy correction

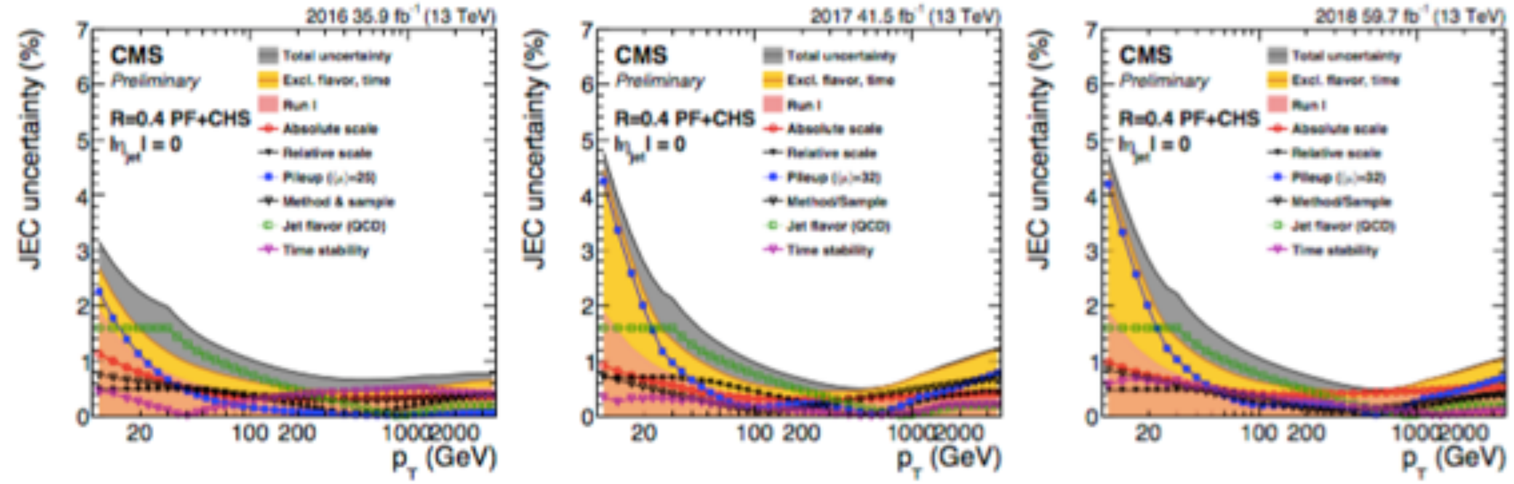


Photon $\sigma_{i\eta i\eta}$ distribution



Jet energy correction and resolution performance

- **JEC performed sequentially:**
  - pileup offset subtraction
  - detector response from MC
  - residual correction in data or Data/MC



- **JER**
  - measured with dijet and Z/γ + jets p_T balance methods in data and simulated events after JEC applied
  - SFs derived for $p_T \geq 100$GeV with dijet and $p_T < 100$GeV with Z/γ + jets
  - SFs of 1.1-1.2, larger in EC-HF transition region of $|\eta| \in [2.5, 3]$