Annual Summary for Beihang CMS Group

Li Yuan
Beihang University

HEPSummerDays
July 15, 2022

Outline

- **Manpower**
- **Analyses published in last year (Since June 2021)**
  - Alignment and Performance of silicon tracker
  - Differential XS / STXS in $H\rightarrow ZZ\rightarrow 4l$
  - Width measurement in $H\rightarrow ZZ\rightarrow 2l2\nu$ (in detail)
- **International Conference talks**
- **Summary**

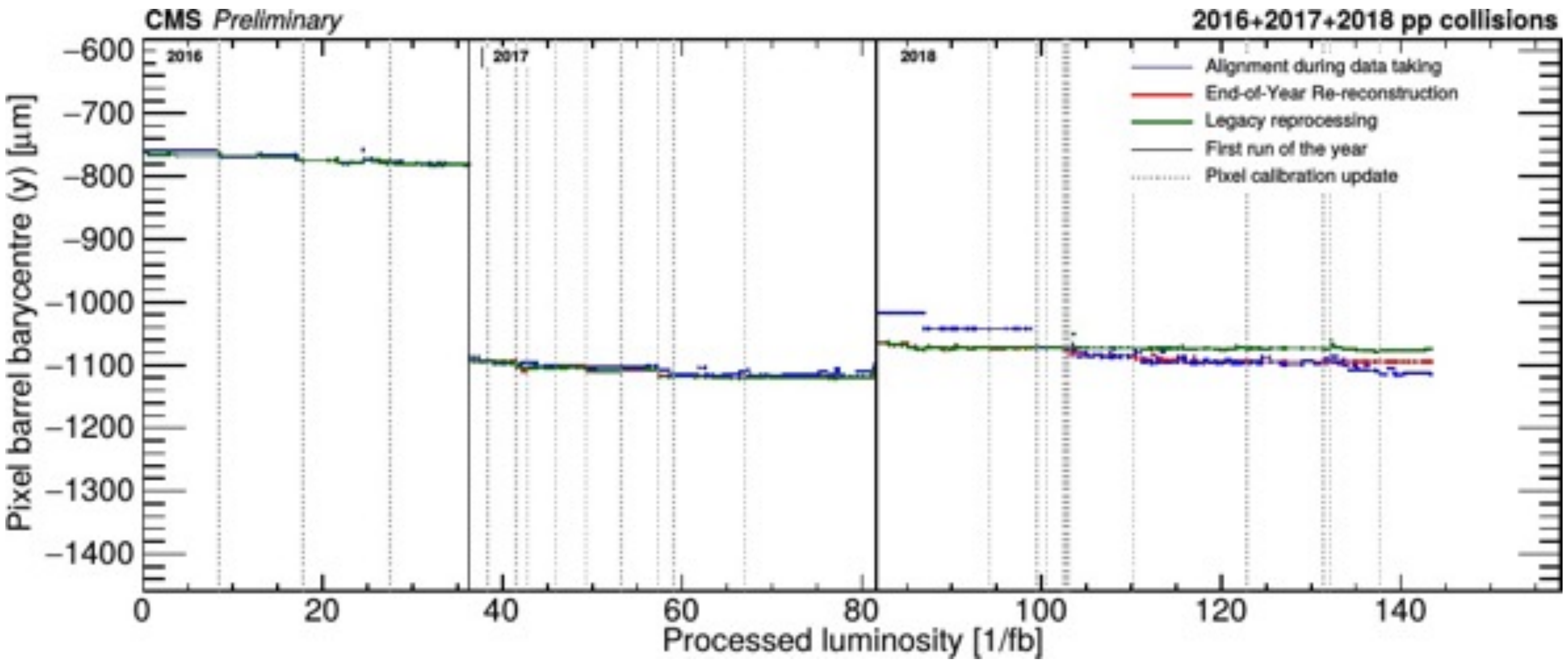
Manpower

Index	Name	Position	Author
1	Hong Gao	Master	No
2	Yunyang Liu	Internship	No
3	Qianying Guo	Ph.D	No
4	Hanwen Wang	Ph.D	No
5	Tahir Javaid	Postdoc	Yes
6	Monika Mittal	Postdoc	Yes
7	Li Yuan	Associate Prof.	Yes
8	Tongguang Cheng	Prof.	Yes

Alignment and Performance of Silicon tracker

NIM A 1037 (2022) 166795

- **TRK-20-001:** Alignment strategies and Performance of CMS silicon tracker during LHC Run-2
- **Published in NIM A.**



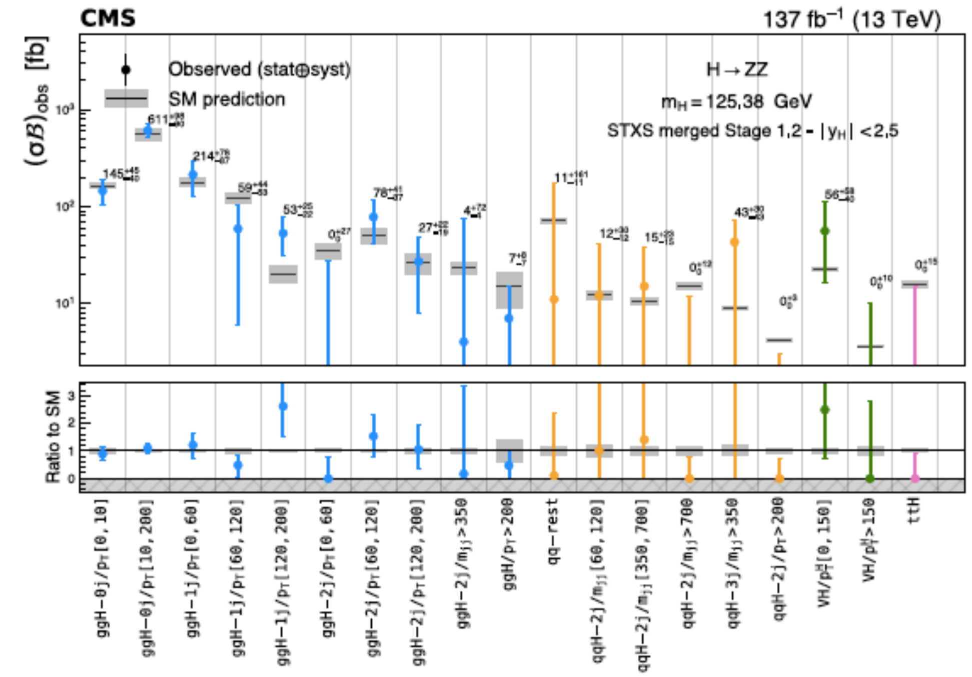
- **Tongguang made significant contributions.**

1. **Managed and coordinated Run-2 alignment/calibration re-optimization (UL)**
2. **Developed and managed pixel quality automatic calibration which is an importance input for tracking and tracker alignment**
3. **Setup a script that can trace the barycentre of pixel detector and its substructures as a measure of radiation damage effect**

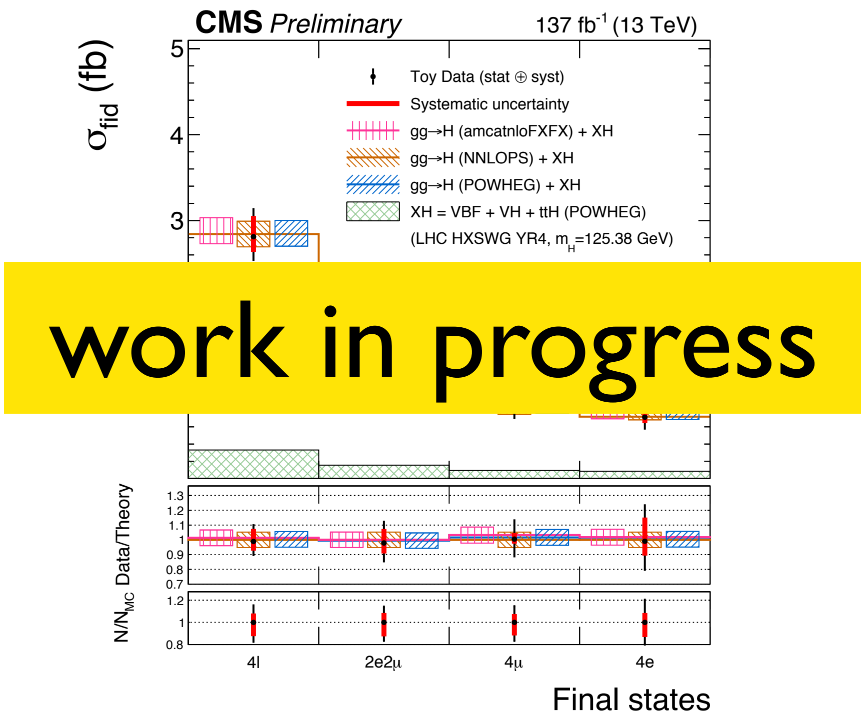
Differential XS / STXS in H→ZZ→4l

EPJC 81 (2021) 488

- **HIG-19-001:** XS / STXS based on full Run 2 data, included in **Nature 607(2022) 60**
- **Uncertainty on μ: ~12%**
  - **Tahir and Qianying (Collaboration with IHEP) made significant contribution.**
  - **Tahir gave the pre-approval talk.**



- **HIG-21-009:** refined analysis with more differential observables
- **Unblinded. To be approved soon.**
  - **Tahir and Qianying (Collaboration with IHEP) heavily involved in the analysis.**

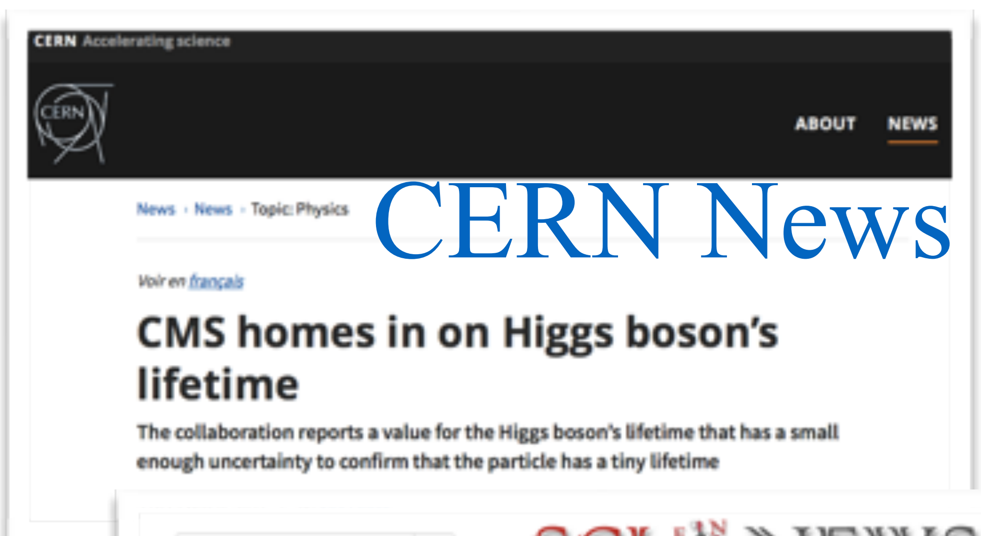


Higgs Width Measurement in ZZ→2l2ν

- **HIG-21-013:** Measurement of the Higgs boson width and first evidence of its offshell contribution to ZZ
- **Accepted by Nature Physics**
- **Highlight in Higgs 2021**

- **Measured $\Gamma_H = 3.2^{+2.4}_{-1.7}$MeV.**
- **First evidence of the offshell Higgs**

- **Li is the analysis contact and paper editor**
- **Hanwen gave the pre-approval talk.**



Higgs Width

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

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

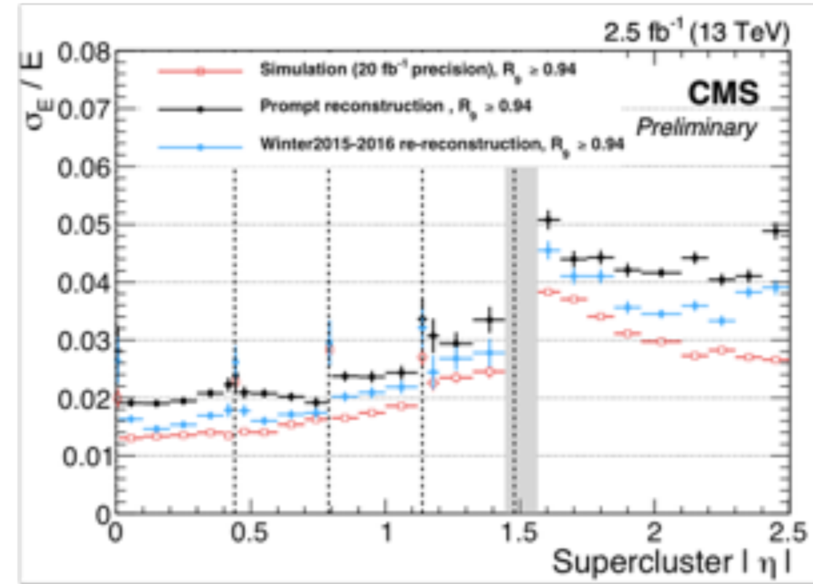
e.g for an electron E_e~50GeV, σ_e~1GeV

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

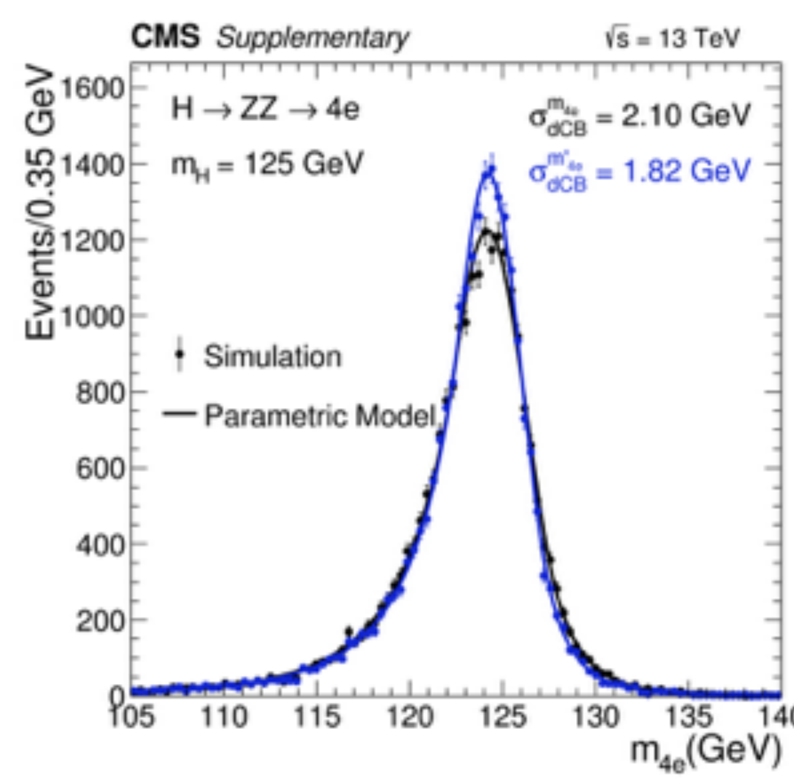
$\sigma_{mH} \sim 2\times\sigma_e = 2$GeV

500 times SM $\Gamma_H \sim$ 4.1MeV

Unable to measure Higgs Width through on-shell pole



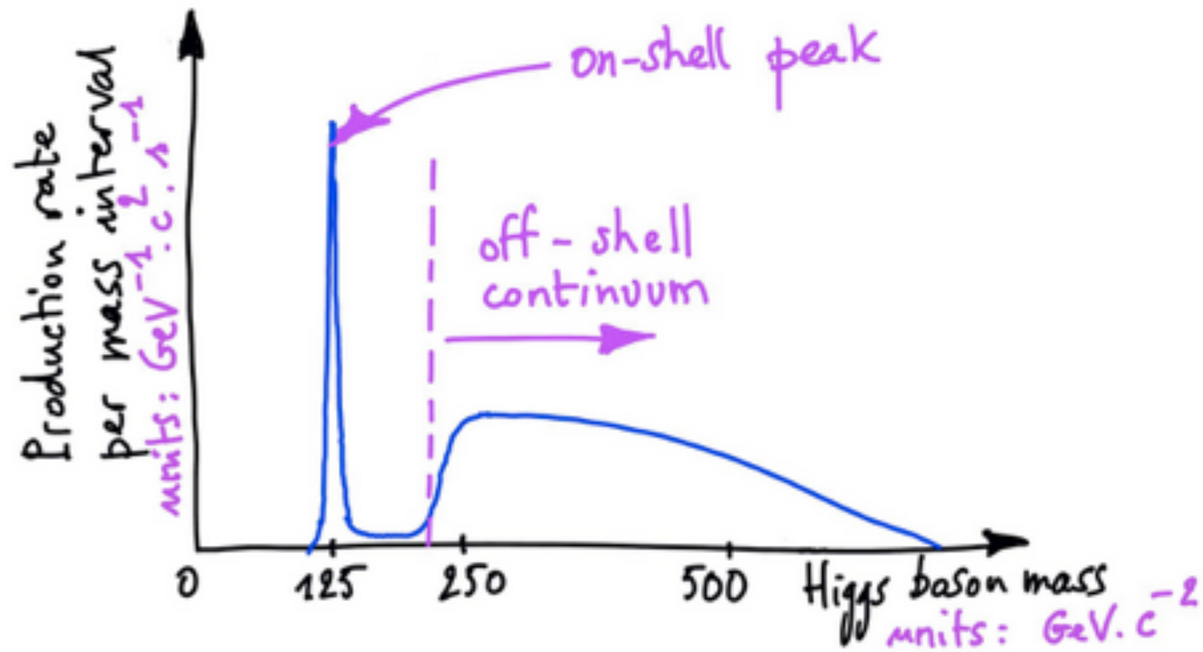
relative energy resolution for e



Indirect way to measure Γ_H

- **Higgs production rate:**

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



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

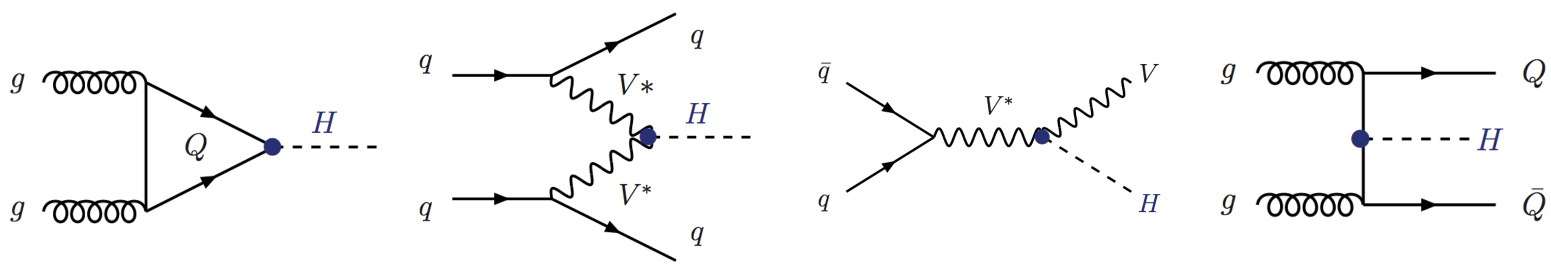
$$\Rightarrow \quad \sigma^{\text{off-shell}} \propto \int \frac{g_{\text{prod}}^2 g_{\text{dec}}^2}{\left(q_H^2 - m_H^2\right)^2} dq_H^2 \propto \boxed{\mu_{\text{off-shell}} \propto \mu_{\text{on-shell}} \times \Gamma_H/\Gamma_{SM}}$$

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

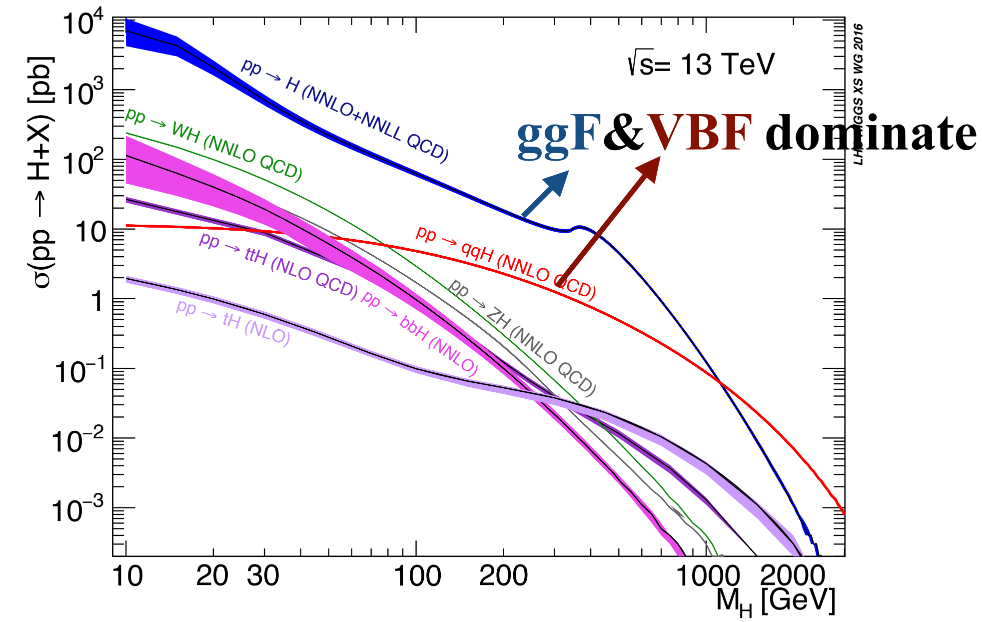
$$\Gamma_H/\Gamma_{SM} = \frac{\mu_{off-shell}}{\mu_{on-shell}}$$

Off-shell Higgs

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

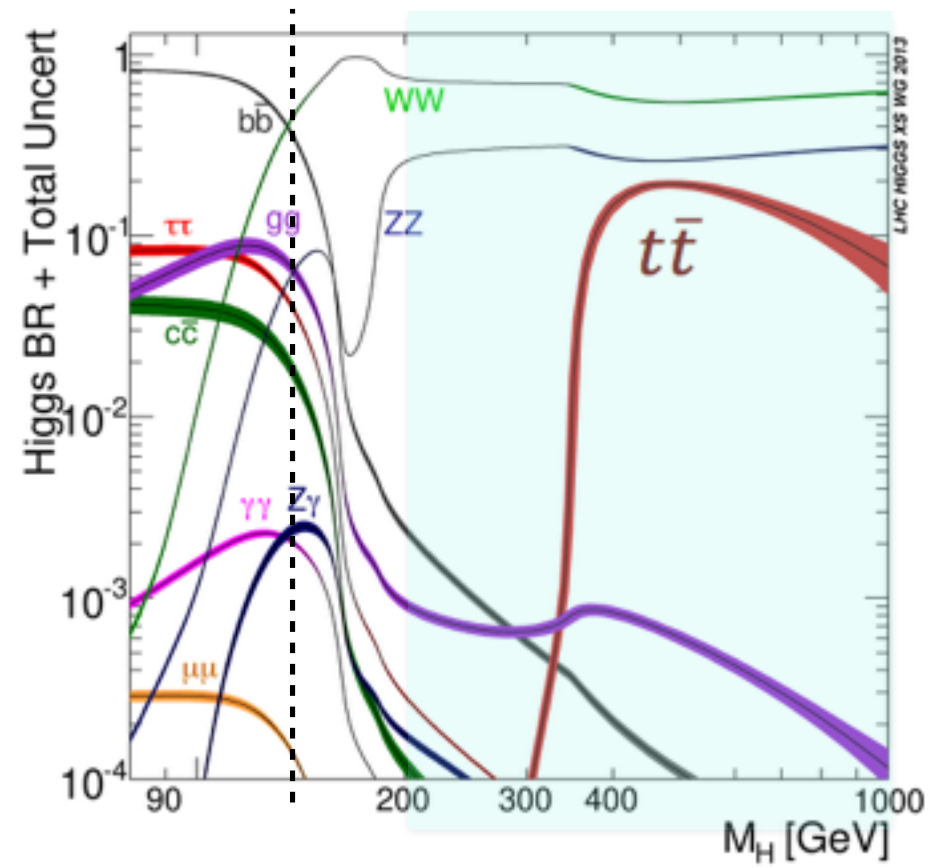


ggF **VBF** **VH** **ttH**



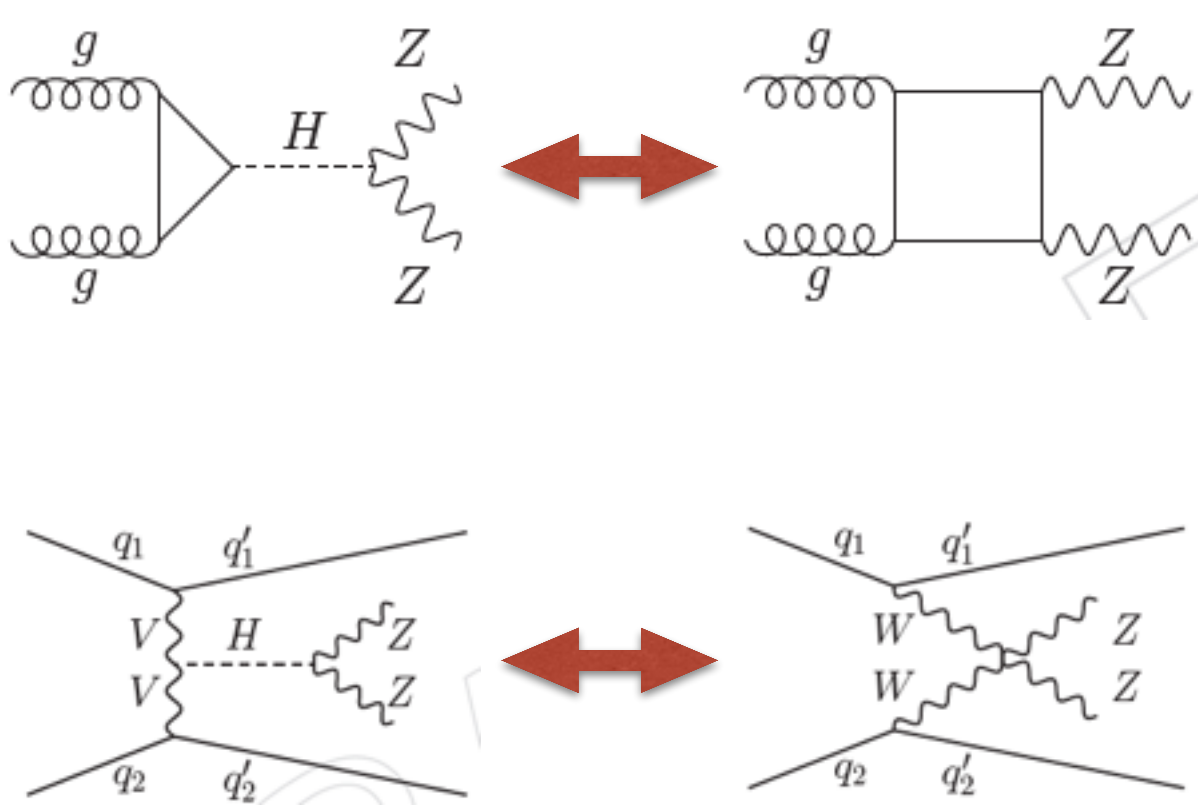
- **Main decay modes for off-shell Higgs:**
  WW, ZZ, tt

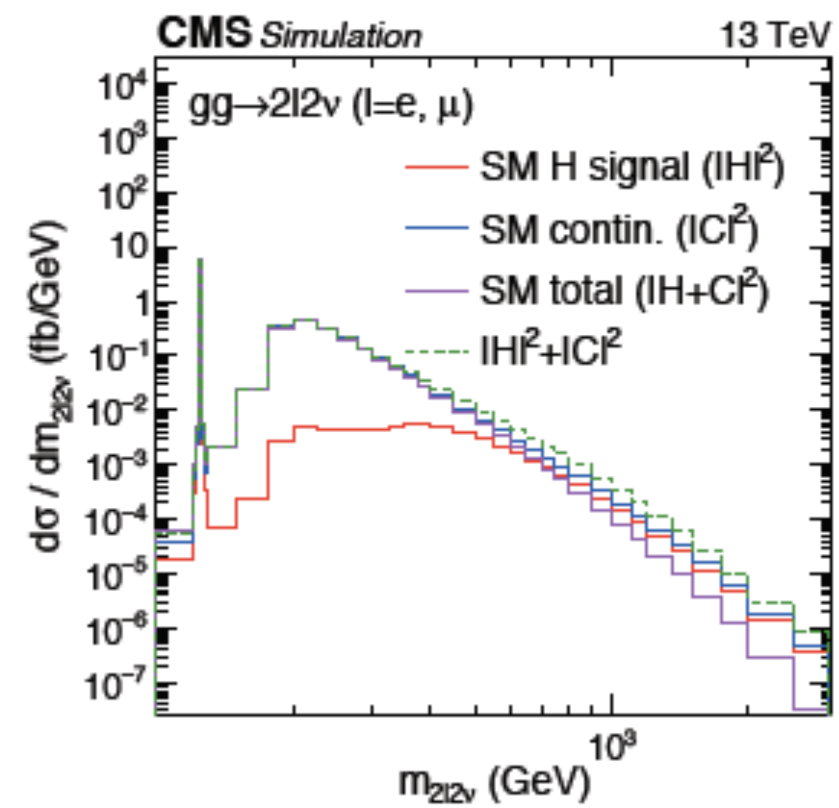
- **For width measurement, since we need to combine with on-shell, the best decay channel to be studied: ZZ**

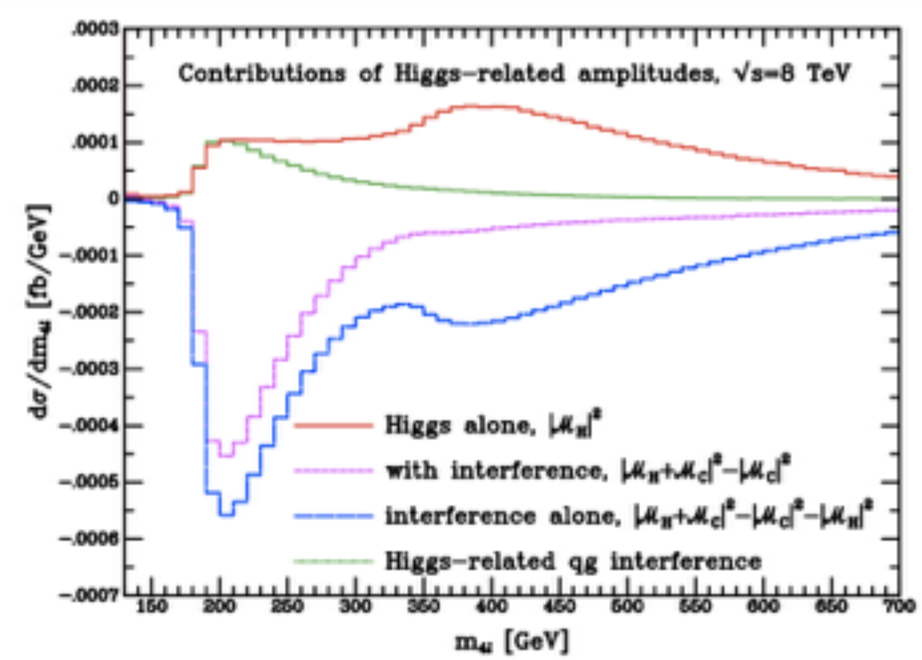


Off-shell Higgs in ZZ channel

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

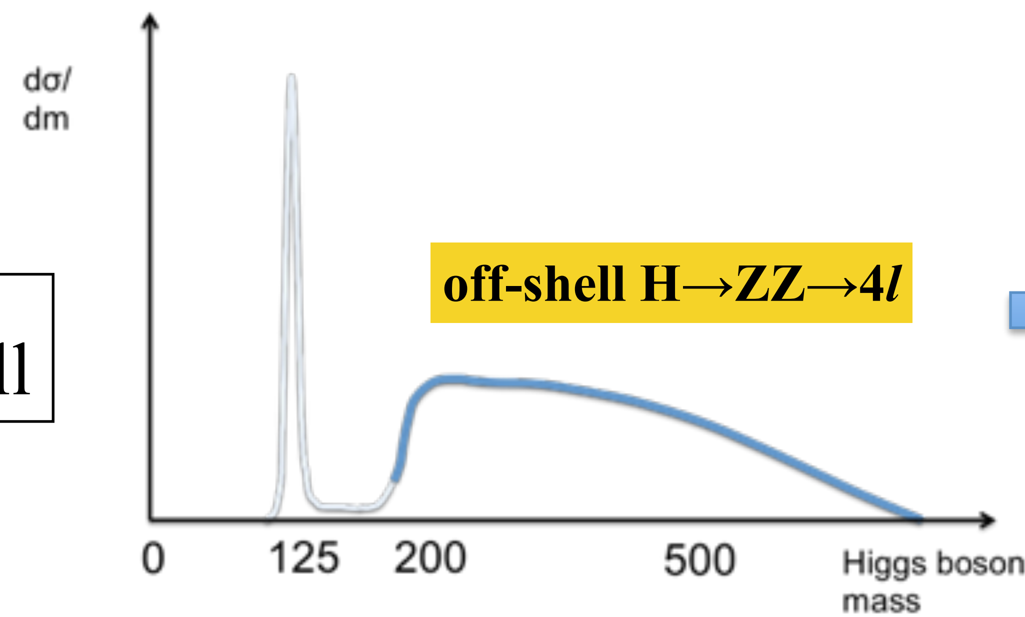






Analyses Involved

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



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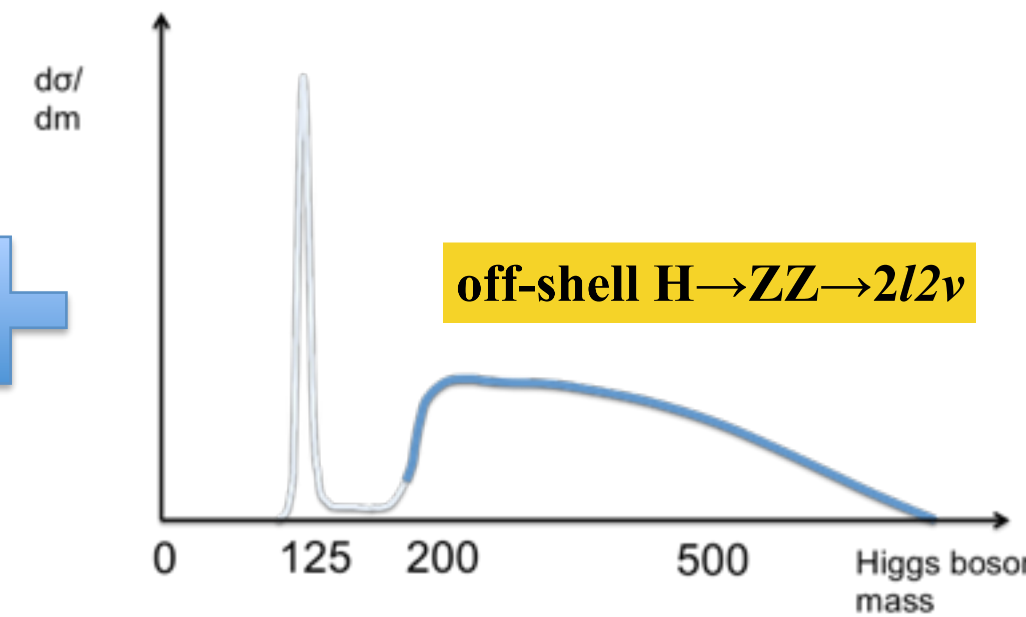
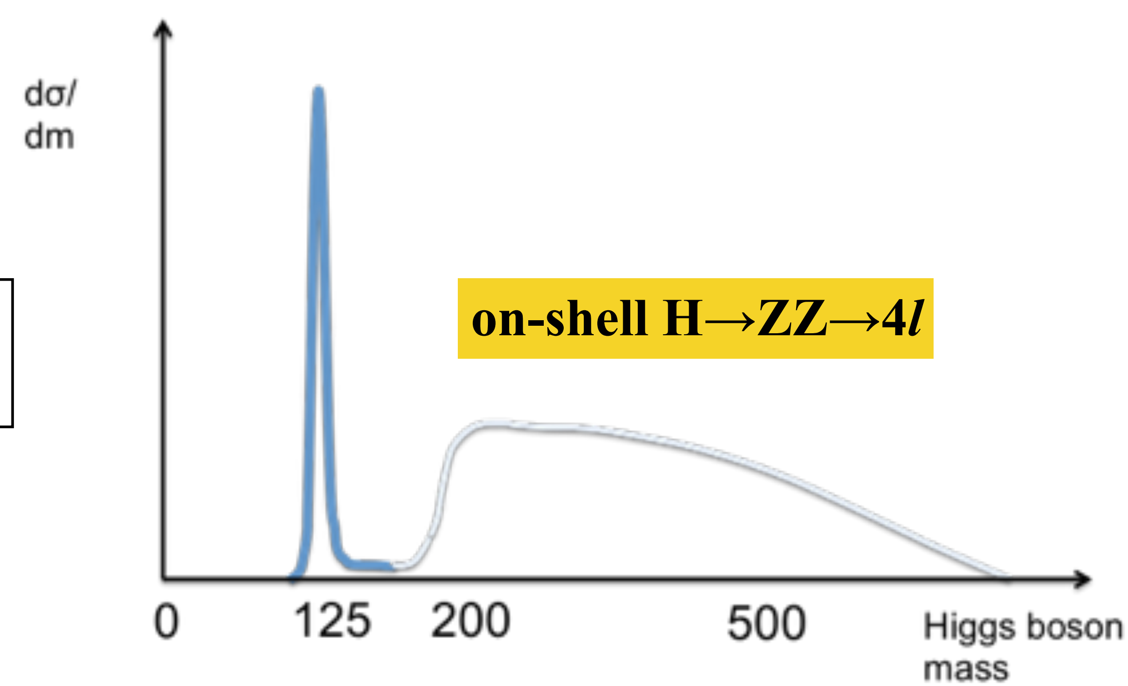


$\mu_{\text{on-shell}}$



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

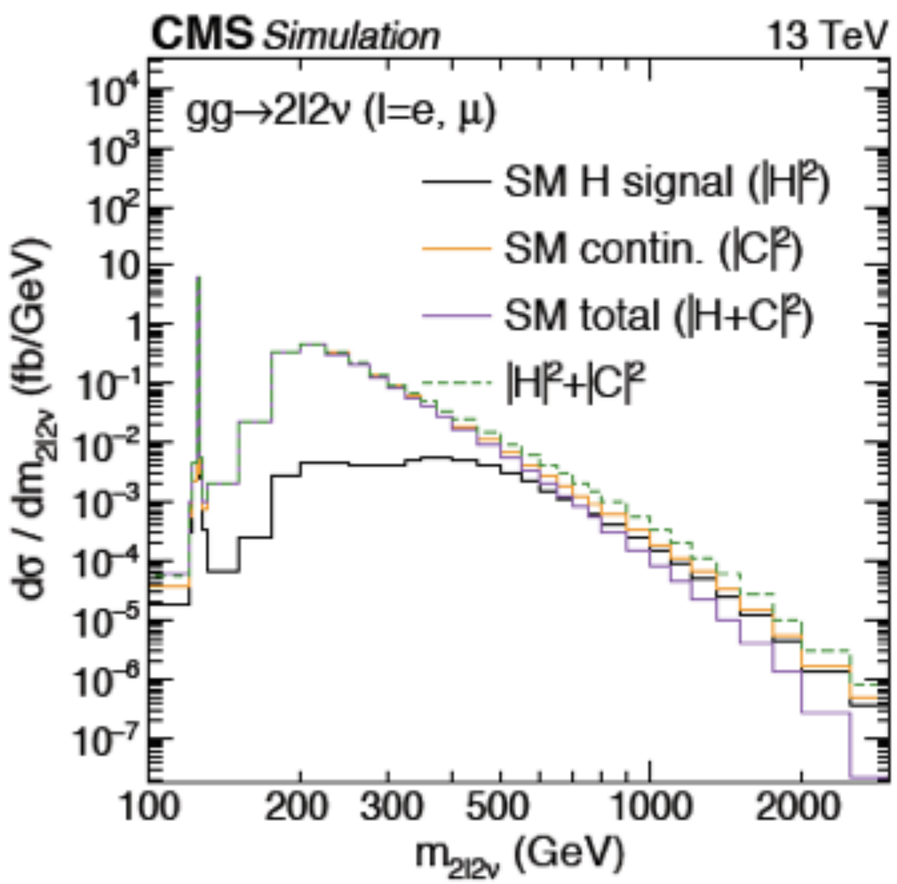
Signal and backgrounds

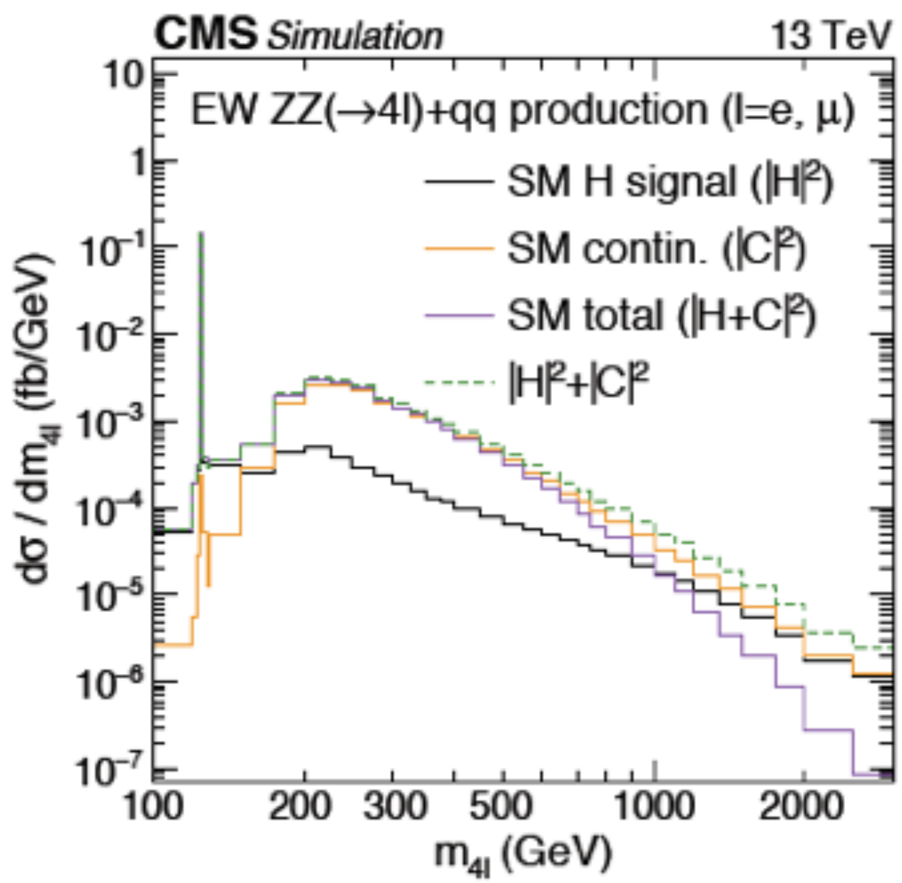
- **ggF and VBF signal**

- **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





qq→ WZ/ZZ background

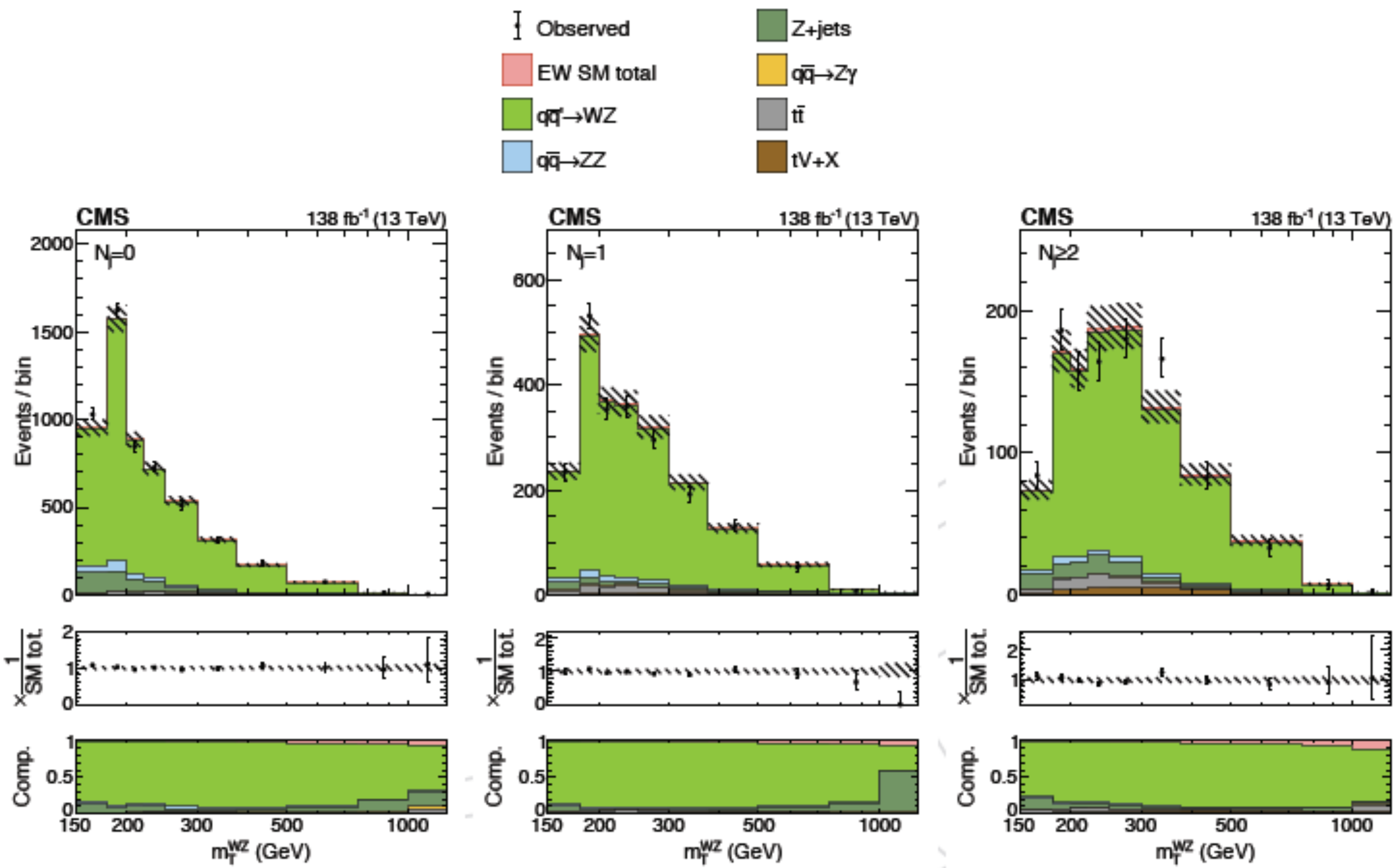
Quantity	Requirement
$p_T^{\ell_{Z1}}$	$\geq 30\,\text{GeV}$ on leading-p_T lepton forming the Z candidate
$p_T^{\ell_{Z2}}$	$\geq 20\,\text{GeV}$ on subleading-p_T lepton forming the Z candidate
$p_T^{\ell_W}$	$\geq 20\,\text{GeV}$ on the remaining ℓ_W from the W boson
$\lvert\eta_\ell\rvert$	< 2.4 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 $\ell_W = \mu$ (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

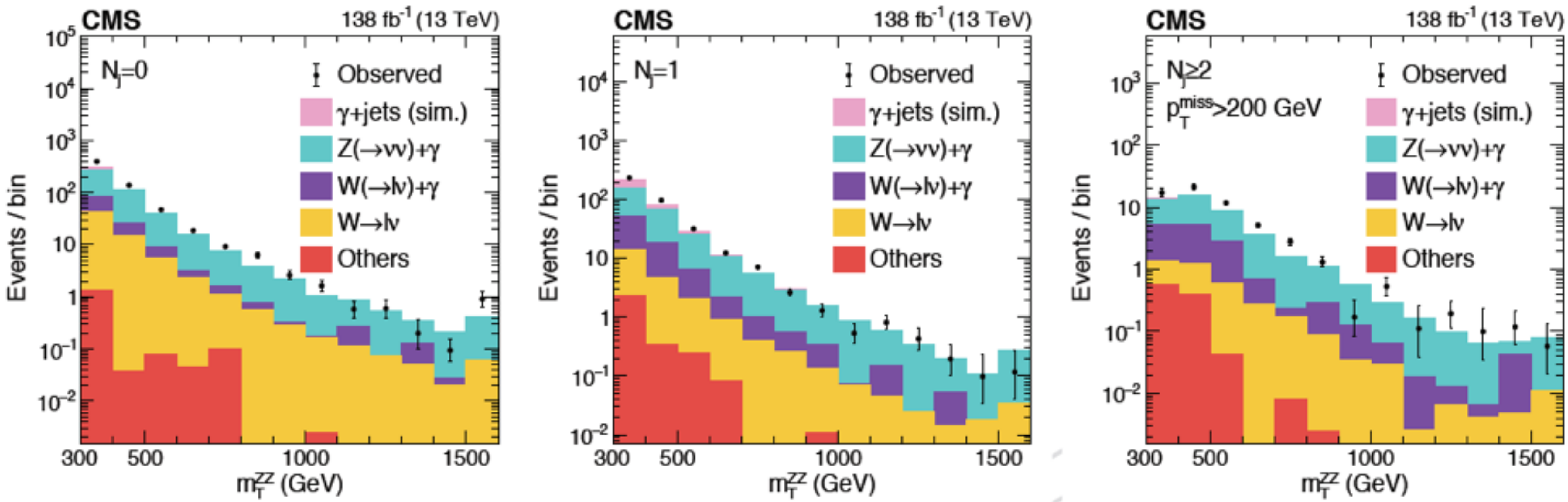


- **Good agreement between Data and MC.**

Instrumental $p_{\mathrm{T}}^{\mathrm{miss}}$

- **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 $p_{\mathrm{T}}^{\mathrm{miss}}$ 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:**
  - $Z(\rightarrow\nu\nu)\gamma$: estimated by ll$\gamma$ CR
  - W+jets: estimated by single electron CR
  - others: from MC

γ+jets CR distributions

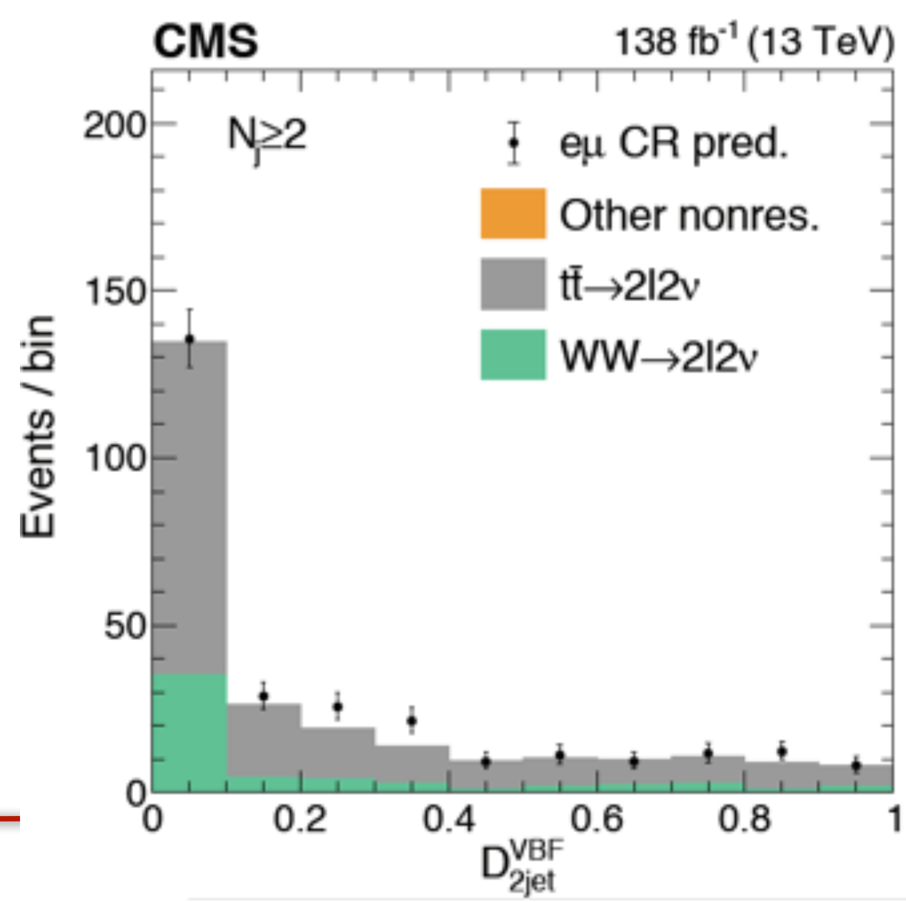


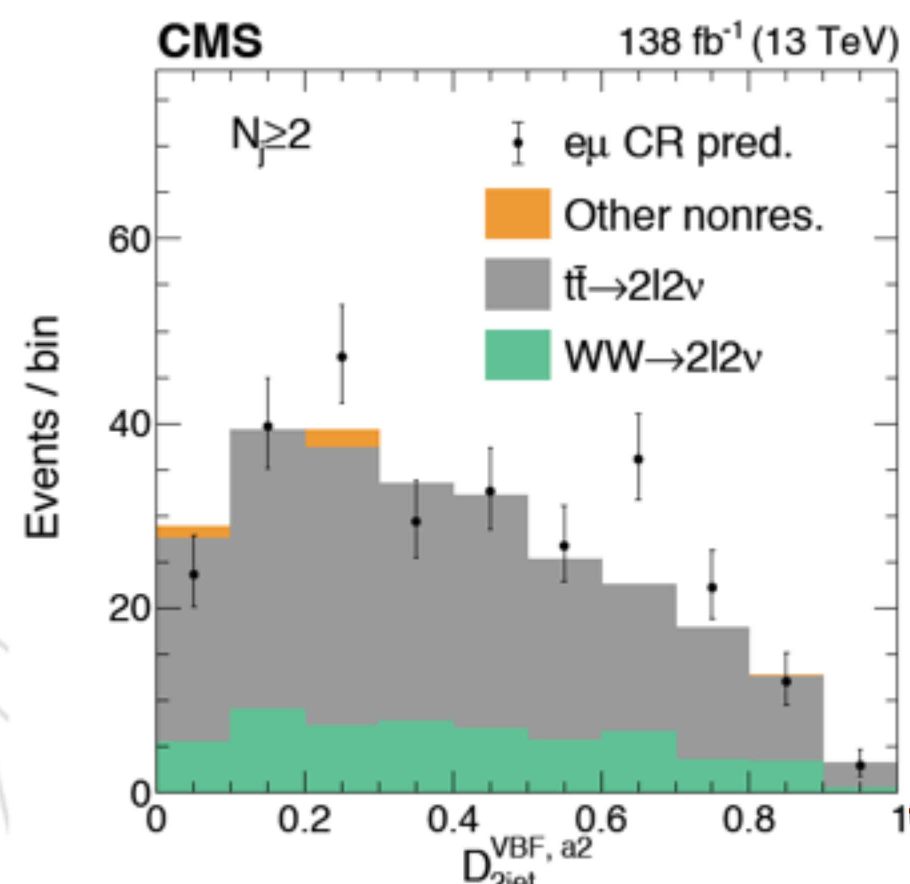
- γ+jets simulation could not model well data since it is LO!
- We are estimating the size of the Z+jets contribution by γ+jets in data.

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

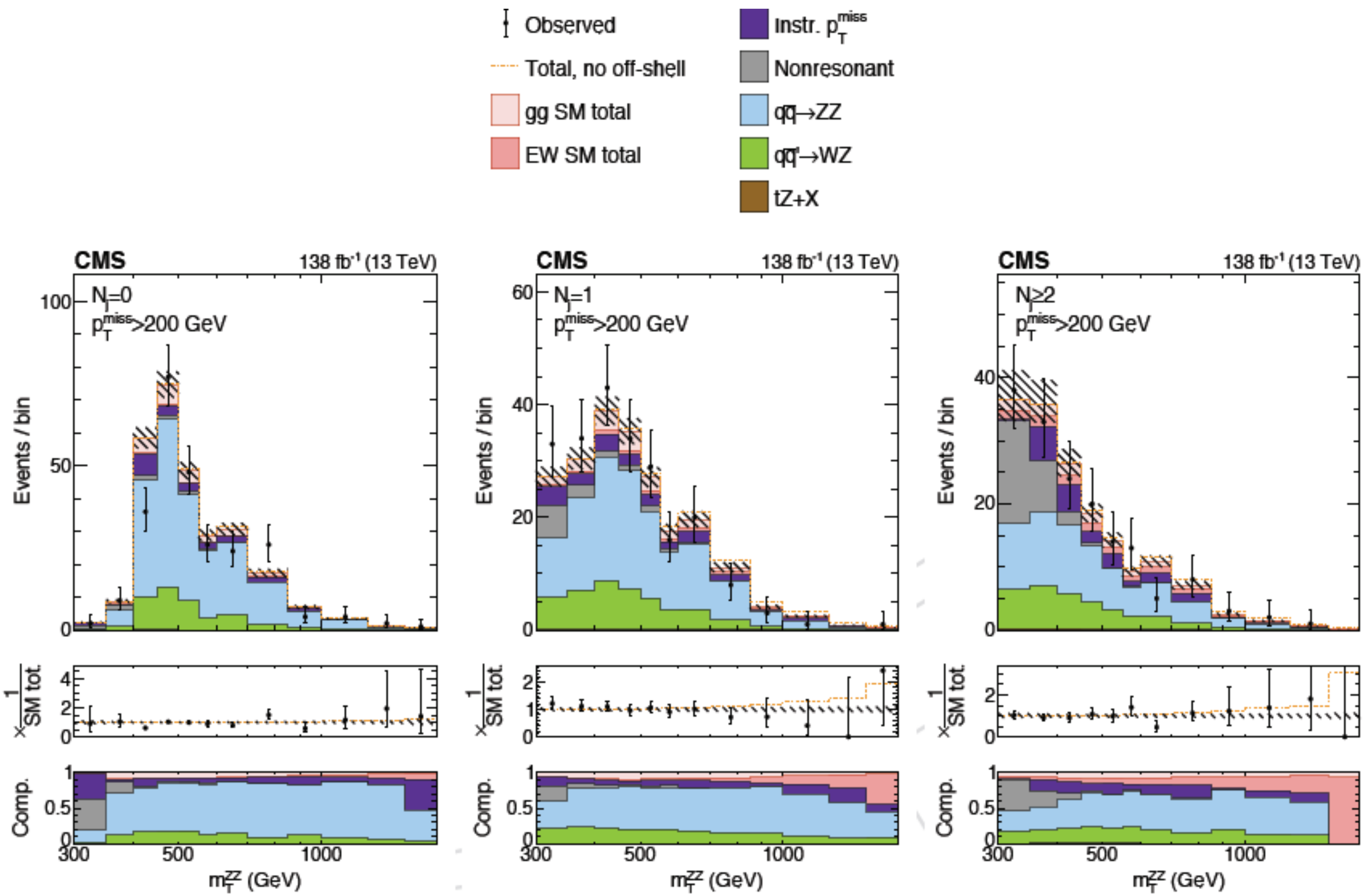
- Two isolated leptons not from the same mother particle, thus no Z peak
- Flavour symmetry: $N_{ee} = N_{\mu\mu} = 1/2\, N_{e\mu}$
- Use eμ CR, reweighted by the trigger and lepton efficiencies:

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





m_T^{ZZ} distribution after all selections

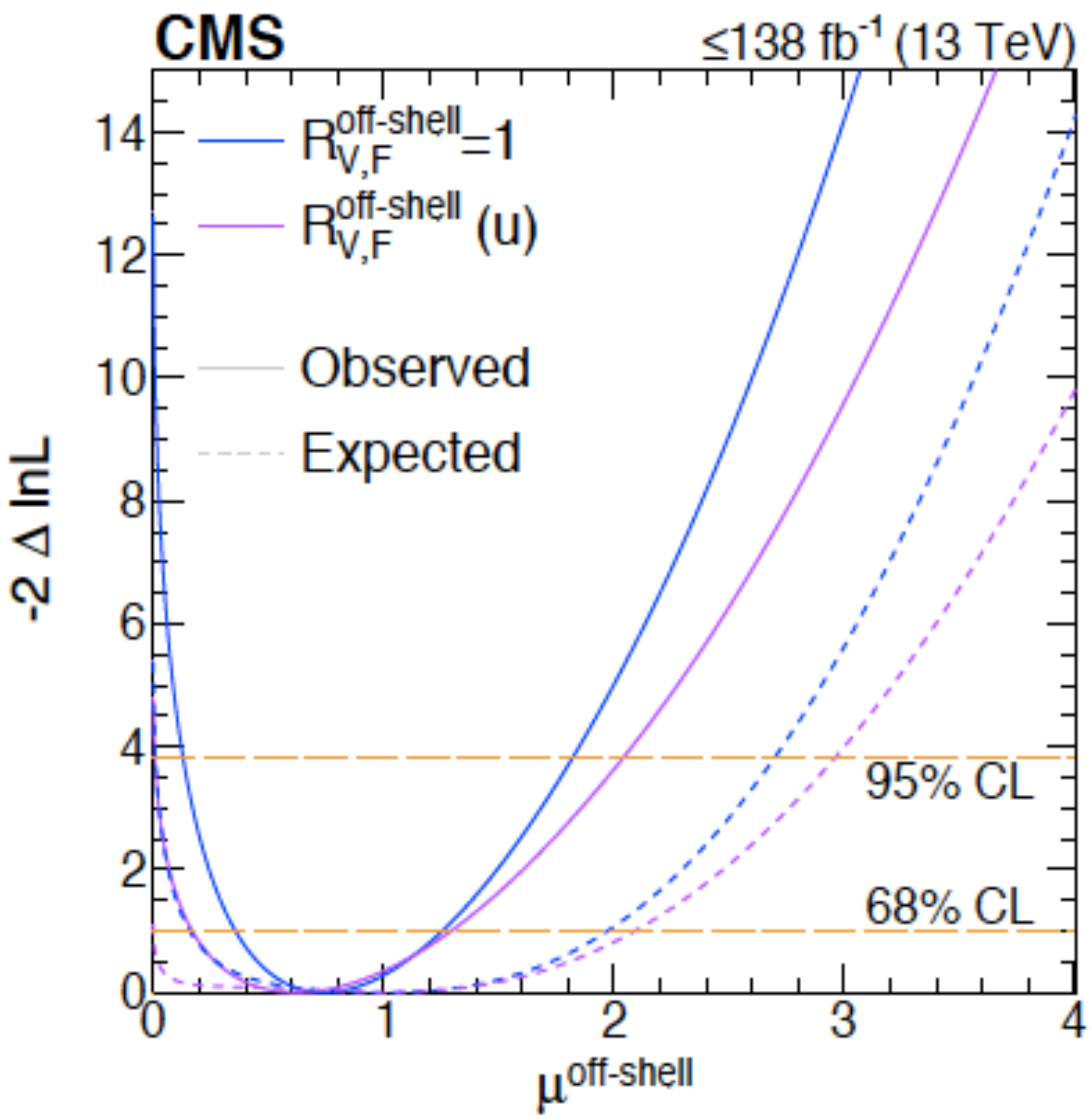


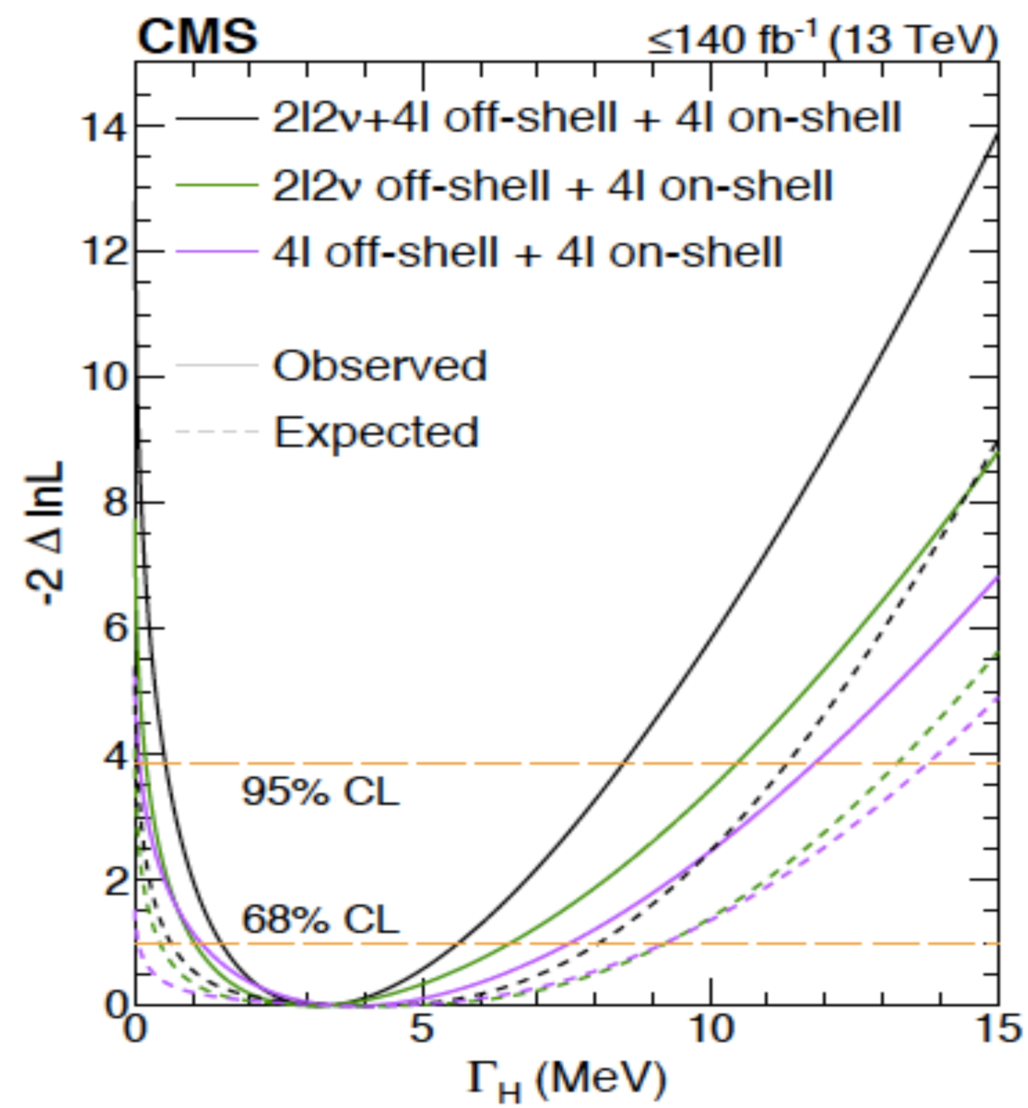
Systematic Uncertainties

Uncertainties on both normalisation and shape are accounted.

- **Theoretical uncertainties**
  - renormalisation scale and factorisation scale (up to 30%)
  - αs (mZ) 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 Higgs and Measured Width





- No off-shell hypothesis ($\mu_{off\text{-}shell}$=0) excluded by more than 99.9% CL, i.e off-shell Higgs sensitivity **3.6σ**
- 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	$[1.3, 4.8] \mid [0.46, 7.2]$	$[0.55, 8.1] \mid [0.019, 11.3]$

- **Constrain HVV anomalous couplings (in backup).**

International Conference Talks

1. Hanwen Wang, "Measurements on Higgs boson width and anomalous couplings with on-shell and offshell production in ZZ decay channel", **FPCP2021**, June 07~11, 2021
2. Hanwen Wang, Measurements on Higgs boson width and anomalous couplings with on-shell and off-shell production in ZZ decay channels at CMS experiment, **TeVPA2021**, Oct 25-29, 2021
3. Tongguang Cheng, "CMS, performance highlights", **LHCP 2022**, May 16-21, 2022
4. Monika Mittal, "The GEM GE1/1 station of the CMS muon detector: status, commissioning and operation in magnetic field", **ICHEP 2022**, July 6-13, 2022

- **Li Yuan: CMS Conference Committee Member (2021.10 -)**

Summary

- Focus on Higgs property measurements and new physics search.
- Highlight in the Higgs width measurement (Accepted by **Nat.Phys.**)

First evidence of off-shell Higgs!

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

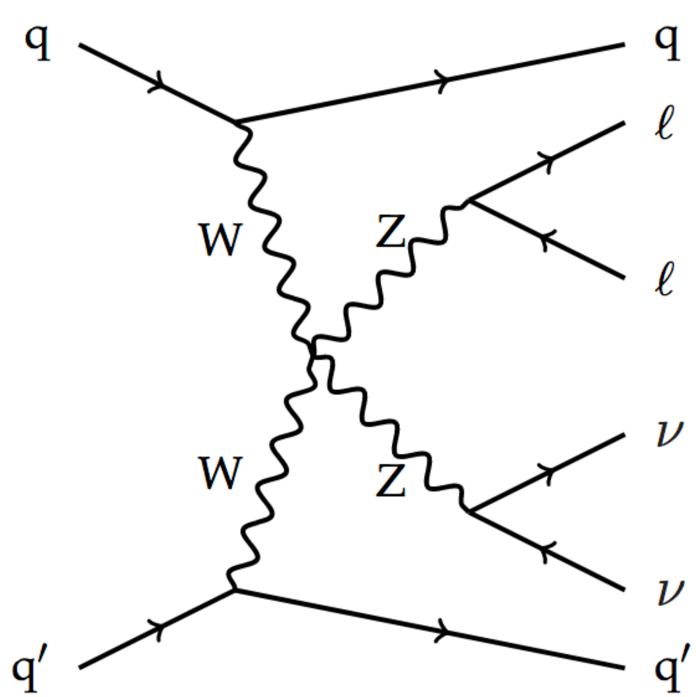
Reaching ~50% precision for the first time!

- Explore more interesting/challenging physics topics in the future.
- Involved in the phase II upgrade projects: GEM and MTD. More and more contribution in the future.
- Many Thanks for the support from IHEP and other universities!


thank you

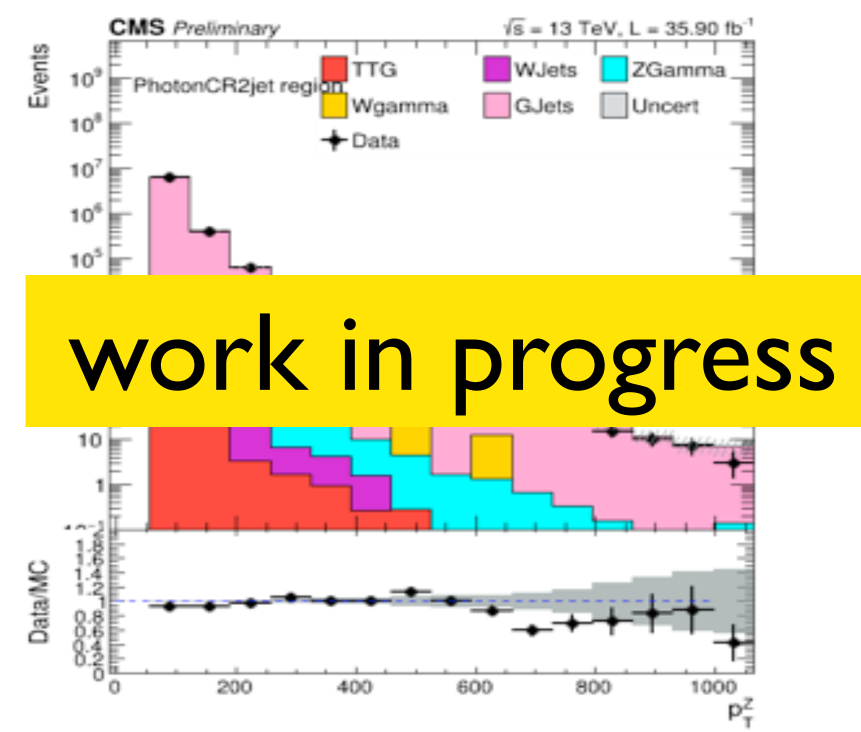
- backup

VBS study in ZZ→2l2ν

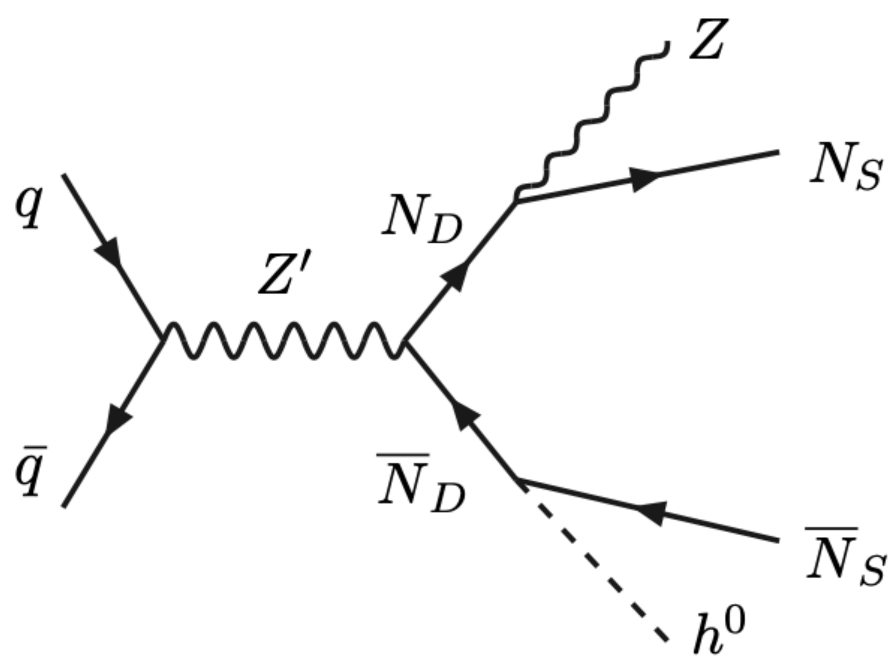


- Analysis based on full Run 2 data
- Final state:
  - Two OSSF leptons (e+e- or μ+μ-)
  - Two neutrinos (large MET)
  - Two energetic jets with large Δη and large dijet invariant mass
- Close to pre-approval

- Monika/Hanwen/Li heavily involved in the analysis.
- optimisation of event selection.
- data-driven estimation of DY bkg based on photon+jets CR.



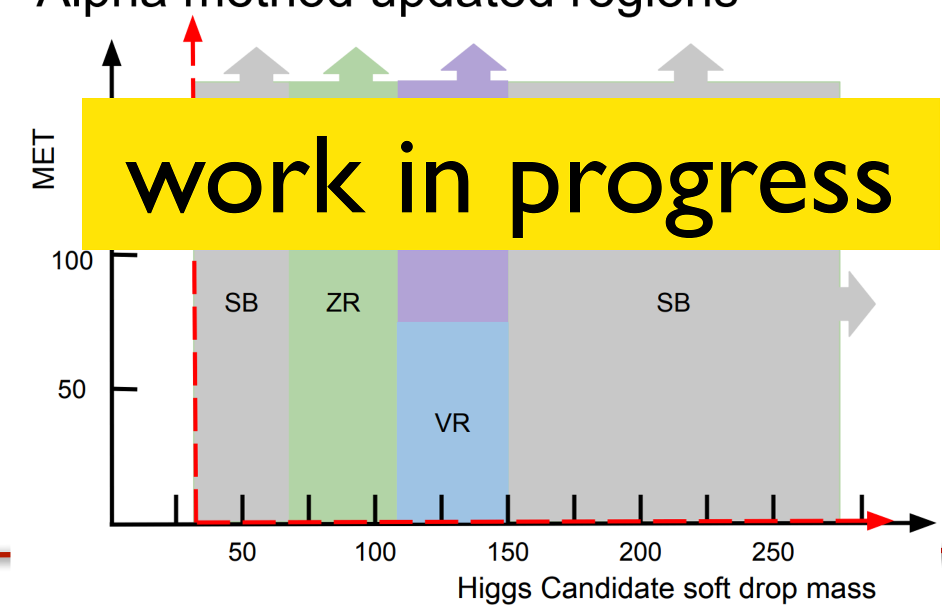
Search for Z' through cascade decay



- Leptophobic boson signals with leptons, jets and missing energy
- Assuming Z' decay through some intermediate state
- Final state:
  - Two OSSF leptons (e+e- or μ+μ-)
  - Boosted H→bb
  - Ns (anomalons do not decay): MET
- Close to pre-approval

- Tongguang heavily involved in the analysis.
- MET and soft drop mass used to define SR and CR

Alpha method updated regions

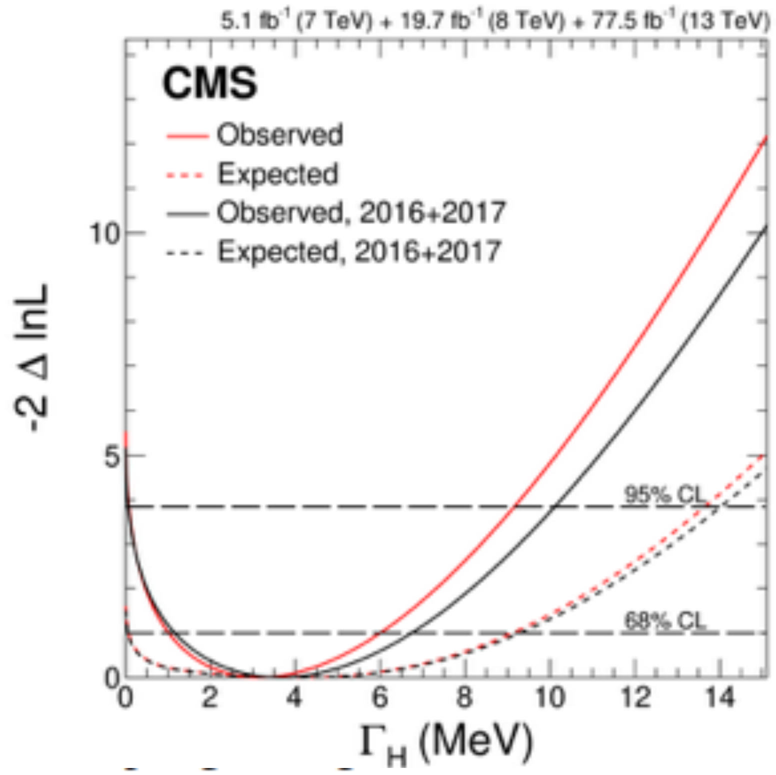


Previous results on width measurement

- **CMS: H→ZZ→4*l***

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

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



68% [95%]

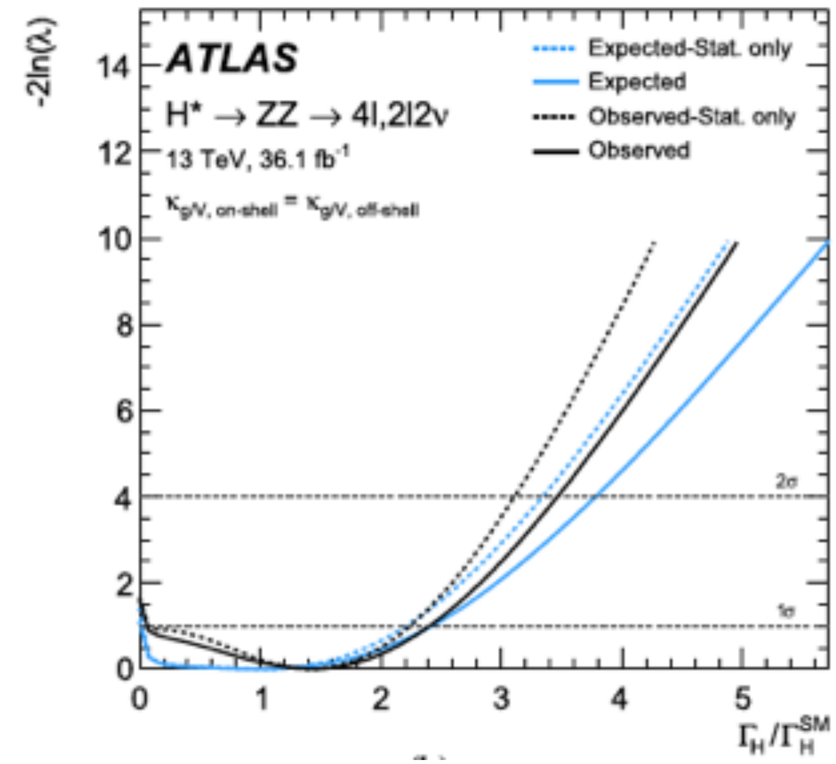
Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

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 $\mu_{\text{off-shell}}$, $\Gamma_H/\Gamma_H^{\text{SM}}$ 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	$\pm 1\,\sigma$	$\pm 2\,\sigma$
$\mu_{\text{off-shell}}$	$ZZ \to 4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]
	$ZZ \to 2\ell 2\nu$ 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]
$\Gamma_H/\Gamma_H^{\text{SM}}$	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	$[0.17, 1.3]$ | $[0.0060, 2.0]$	$[2\cdot 10^{-5}, 2.1]$ | < 3.0
$\mu_F^{\text{off-shell}}$ ($2\ell 2\nu$)	$\mu_V^{\text{off-shell}}$ unconst.	0.41	$[0.014, 1.4]$ | < 2.6	< 2.5 | < 3.7
$\mu_V^{\text{off-shell}}$ ($2\ell 2\nu + 4\ell$)	$\mu_F^{\text{off-shell}}$ unconst.	0.90	$[0.31, 1.8]$ | $[0.051, 2.9]$	$[0.11, 3.0]$ | < 4.5
$\mu_V^{\text{off-shell}}$ ($2\ell 2\nu$)	$\mu_F^{\text{off-shell}}$ unconst.	1.1	$[0.28, 2.4]$ | $[0.016, 3.8]$	$[0.07, 3.2]$ | < 4.8
$\mu^{\text{off-shell}}$ ($2\ell 2\nu + 4\ell$)	$R_{V,F}^{\text{off-shell}} = 1$	0.74	$[0.36, 1.3]$ | $[0.13, 1.8]$	$[0.16, 2.0]$ | $[0.0086, 2.7]$
	$R_{V,F}^{\text{off-shell}}$ unconst.	0.62	$[0.17, 1.3]$ | $[0.0061, 2.0]$	$[4\cdot 10^{-5}, 2.1]$ | $[1\cdot 10^{-5}, 3.0]$
$\mu^{\text{off-shell}}$ ($2\ell 2\nu$)	$R_{V,F}^{\text{off-shell}} = 1$	0.74	$[0.25, 1.5]$ | $[0.043, 2.3]$	$[0.11, 2.3]$ | $[2\cdot 10^{-4}, 3.2]$
	$R_{V,F}^{\text{off-shell}}$ unconst.	0.41	$[0.014, 1.4]$ | $[2\cdot 10^{-5}, 2.6]$	$[3\cdot 10^{-5}, 2.5]$ | $[6\cdot 10^{-6}, 3.7]$

HVV anomalous couplings

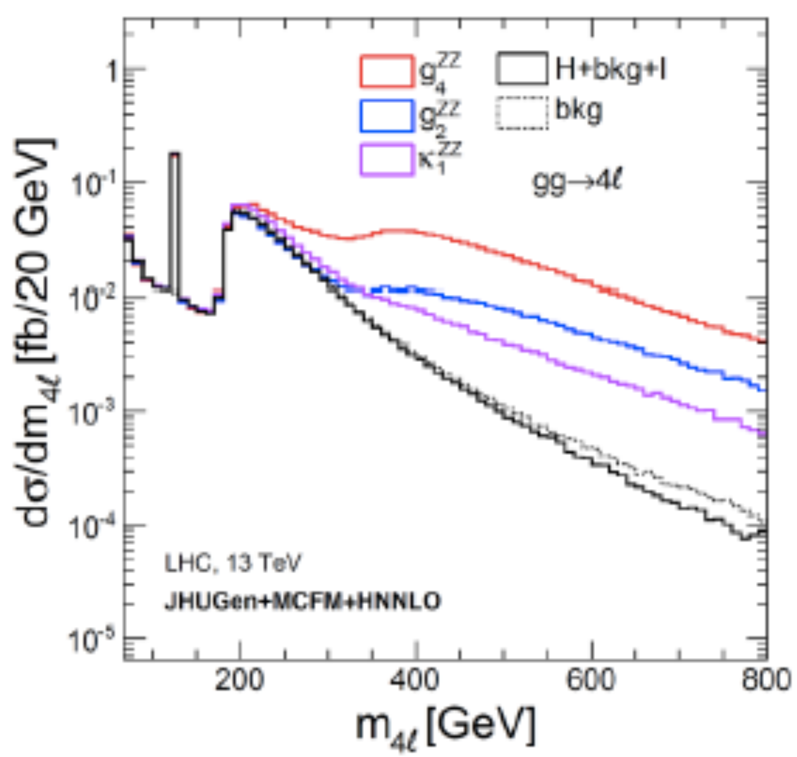
- **Could probe the HVV anomalous couplings in ZZ final states**

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

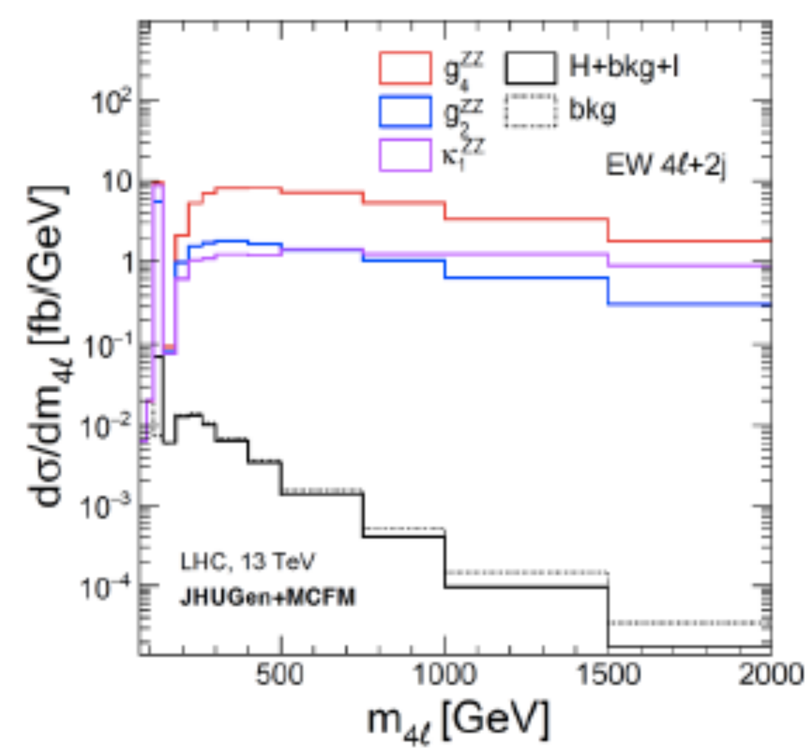
In SM, a_1=2 and the rest are 0.

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

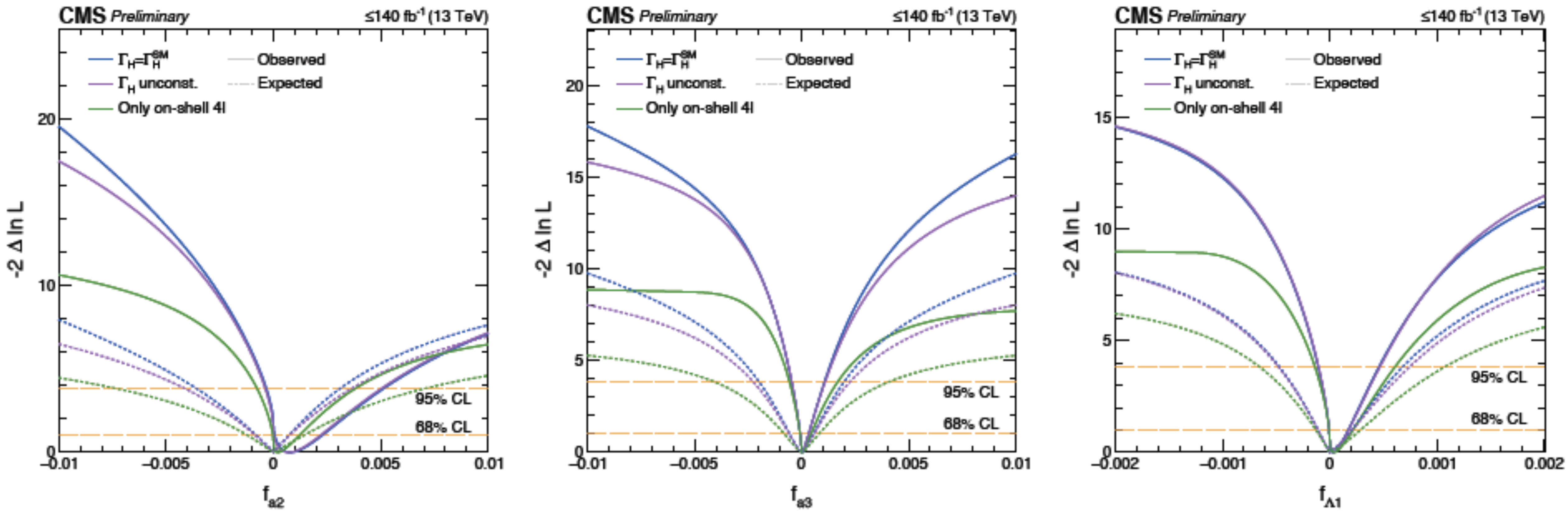
- **Measure** $f_{ai}\cos(\Phi_{ai})$ **by assuming** $a_i \geq 0, \cos(\Phi_{ai}) = \pm 1$ **to probe HVV Anomalous couplings**



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



HVV anomalous coupling limits



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

best fit values

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

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	$[-0.29091, 0.03034]$	$[-0.0099, 0.0096]$

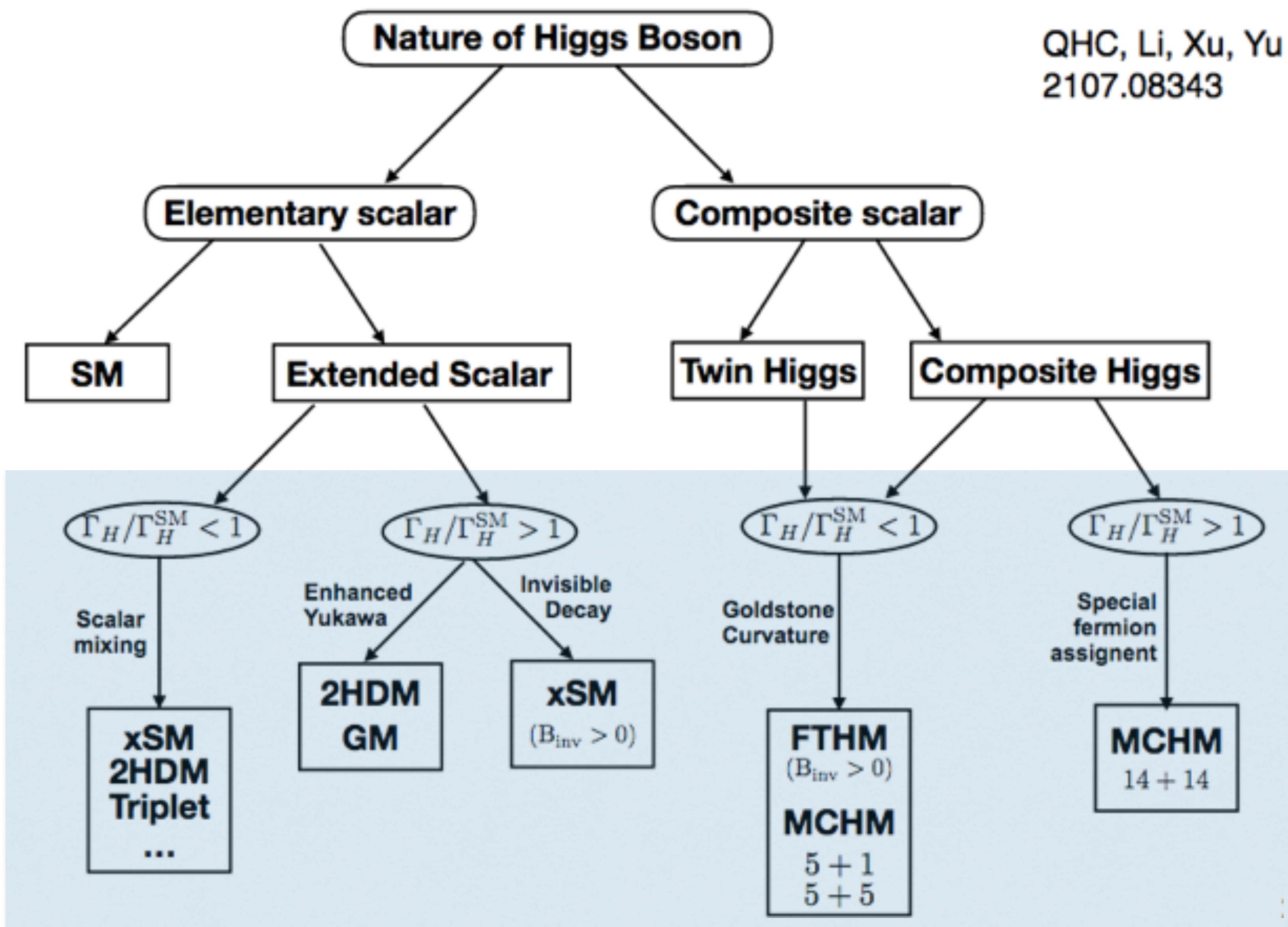
HVV anomalous coupling from 4l on-shell + off-shell

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]
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	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]
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}{}^{Z\gamma})$	On-shell	$0.0000^{+0.3554}_{-0.0087}$ [−0.17, 0.61]	$0.0000^{+0.0091}_{-0.0100}$ [−0.098, 0.343]

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