

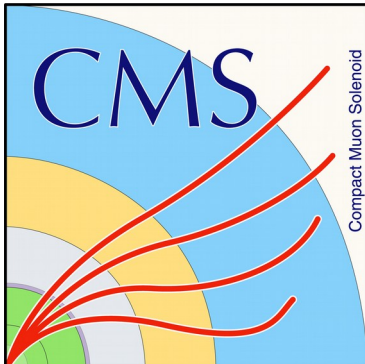
Recent Off-shell Higgs result by CMS

20th LHCWG Workshop

Nov 15th 2023

Savvas Kyriacou

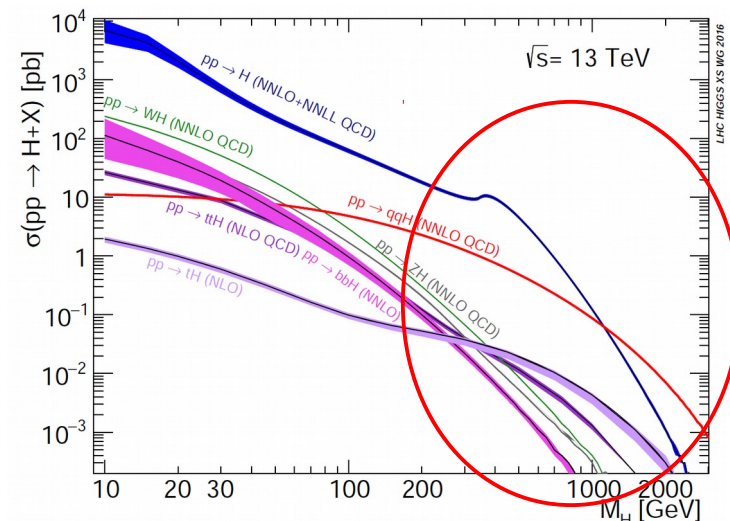
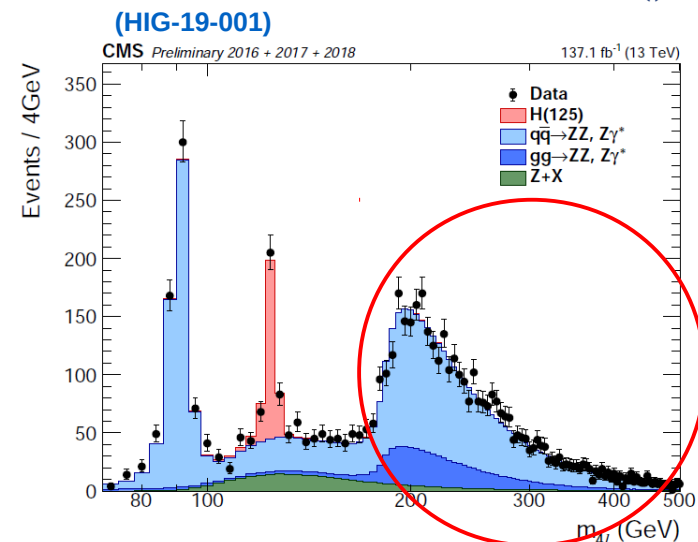
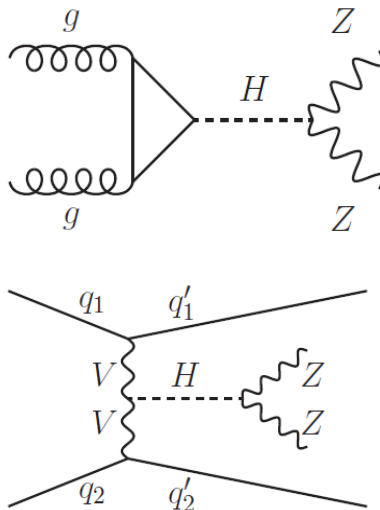
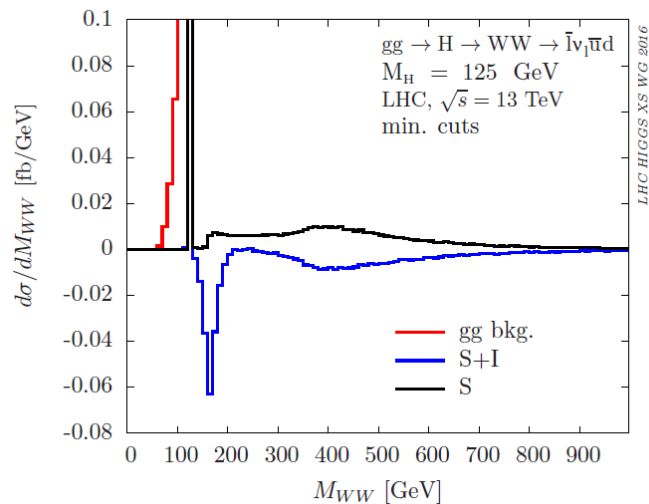
On behalf of the
CMS collaboration



JOHNS HOPKINS
UNIVERSITY

Off-shell Higgs studies in 4l

- Off-shell production of the Higgs
- Enhanced cross-section $> 2MZZ$
- Signal + background interfere destructively

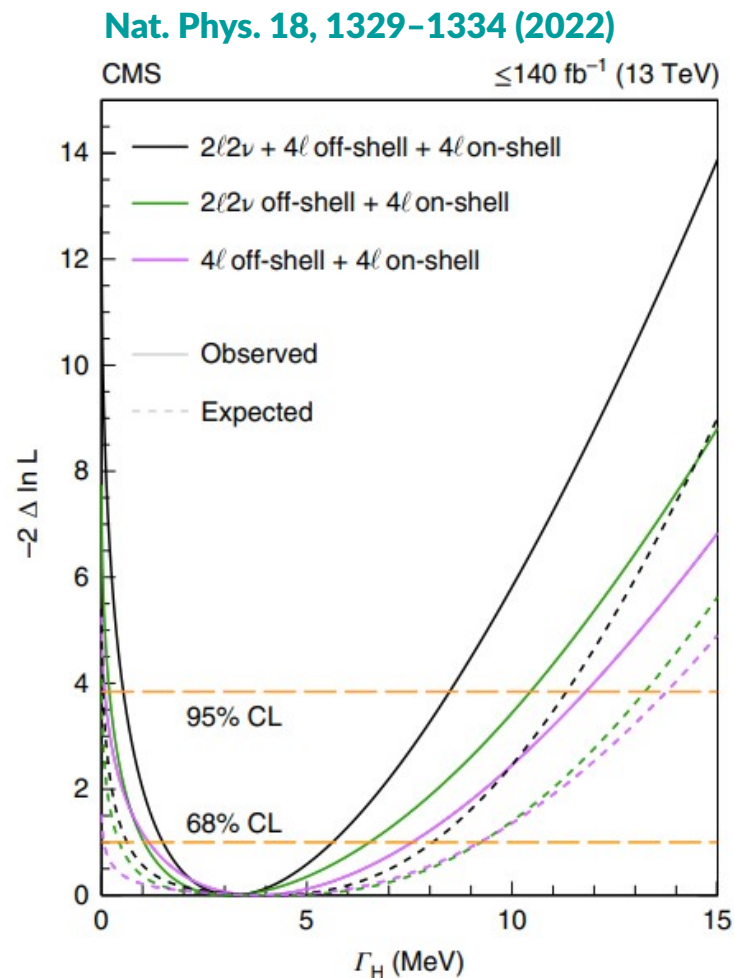
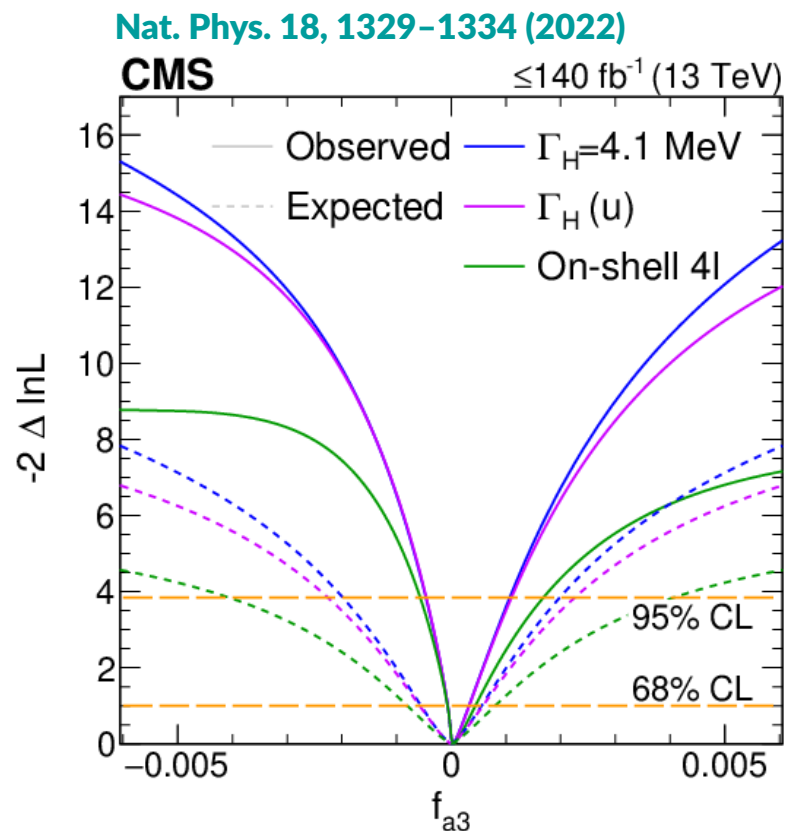


Off-shell Higgs studies in 4l



HIG-21-019
link

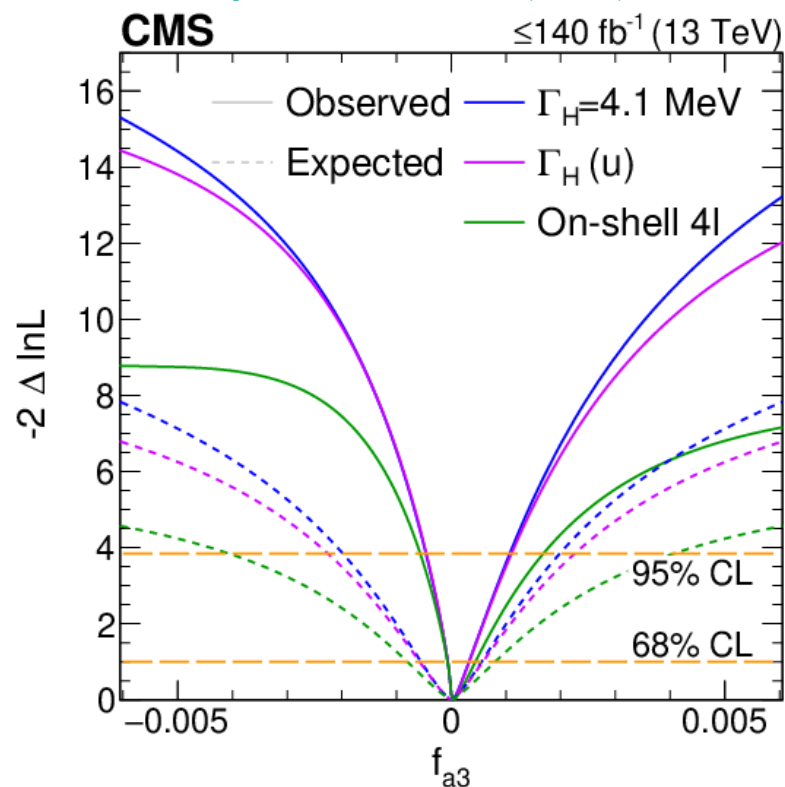
Measure **Width**
Anomalous couplings



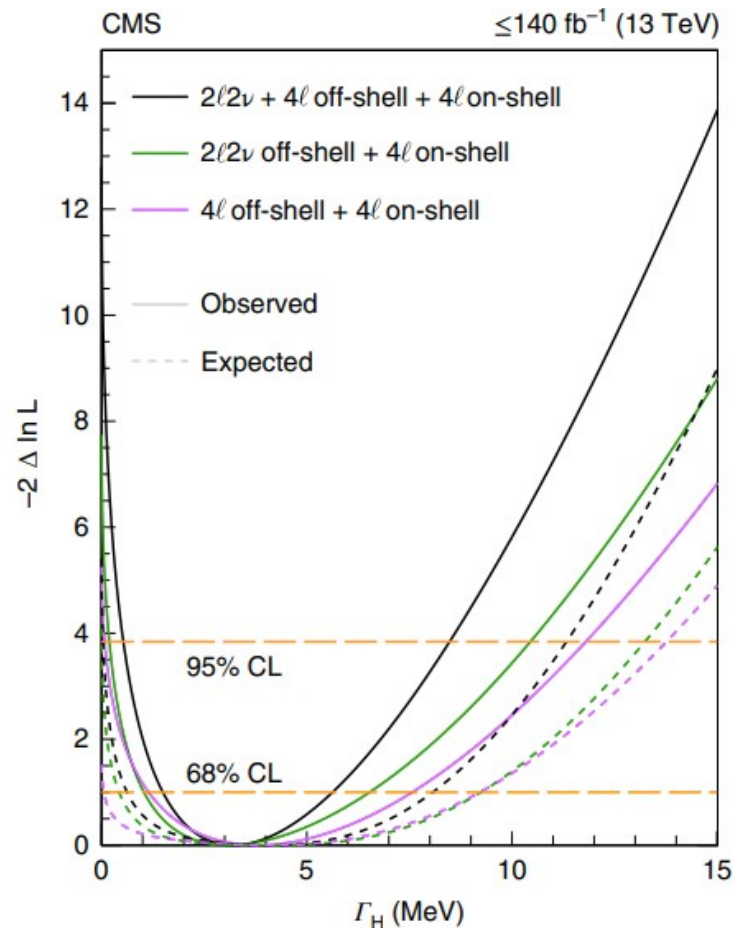
Off-shell Higgs studies in 4l

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Nat. Phys. 18, 1329–1334 (2022)



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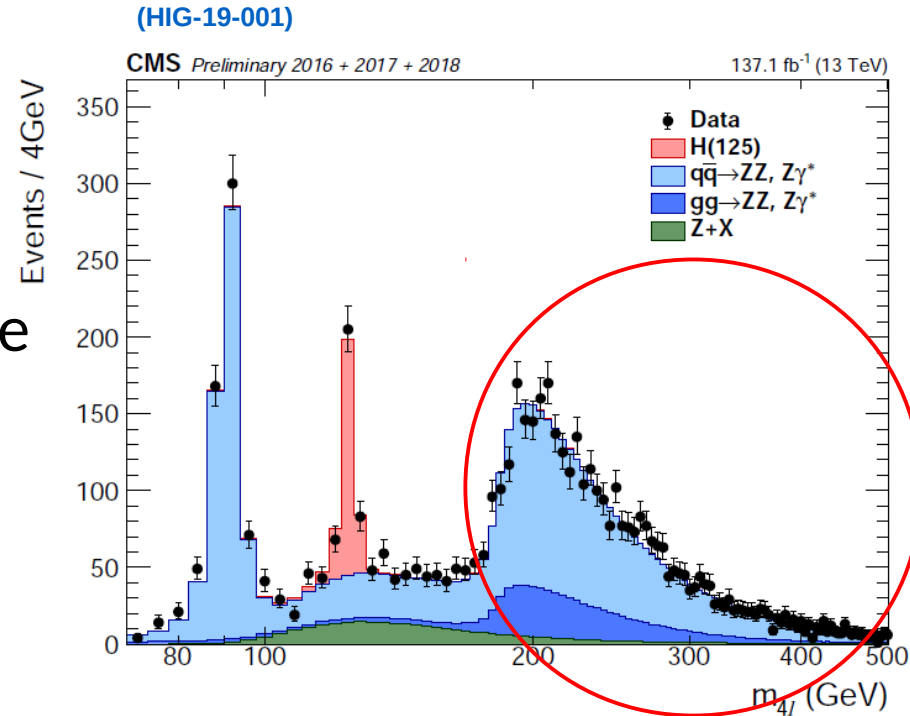
Off-shell Higgs studies in $H \rightarrow 4\ell$

- Measure Higgs width:
 - test of Higgs on-shell vs off-shell production
 - test of Higgs \rightarrow SM particles
 - test/complimentary for $H \rightarrow$ invisible

$$\frac{d\sigma_{pp \rightarrow H \rightarrow ZZ}}{dM_{4\ell}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4\ell}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

$$\Gamma_H^{\text{SM}} = 4.1 \text{ MeV}$$

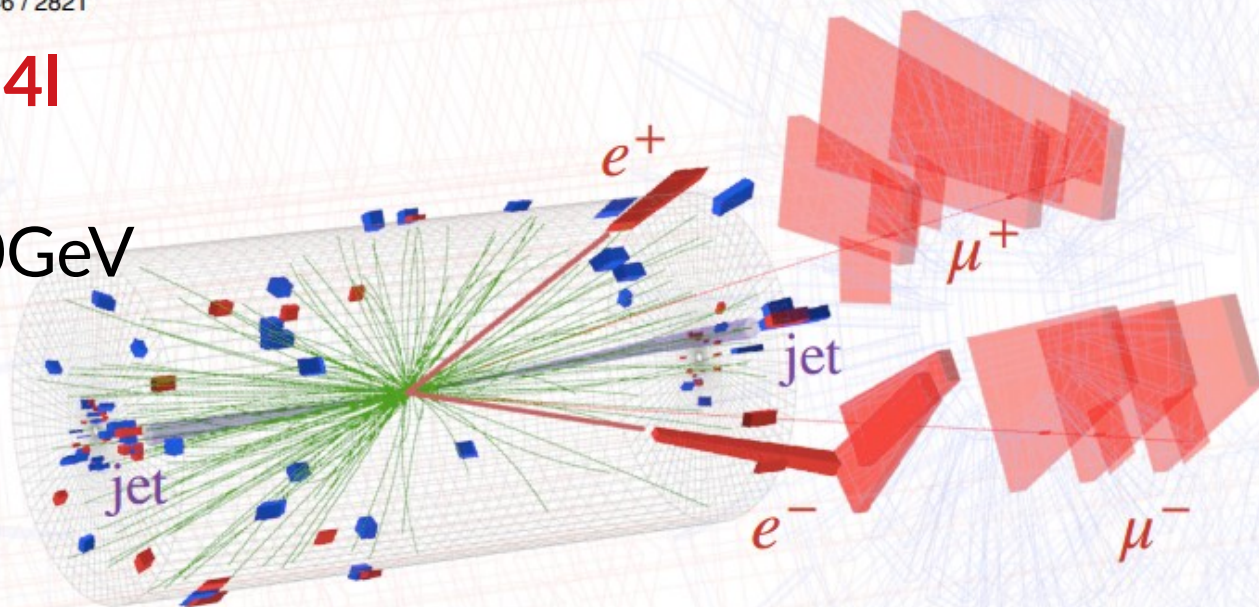
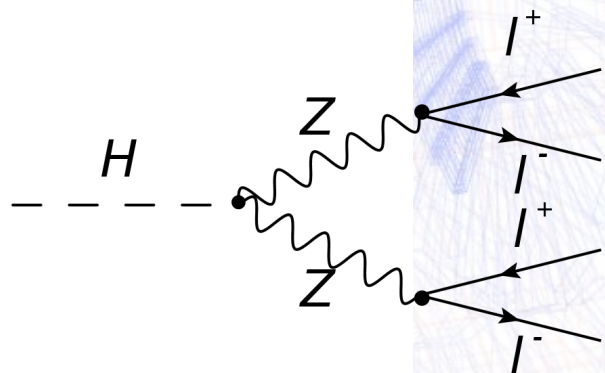
$$\frac{\sigma_{vv \rightarrow H \rightarrow 4\ell}^{\text{off-shell}}}{\sigma_{vv \rightarrow H \rightarrow 4\ell}^{\text{on-shell}}} \propto \Gamma_H$$



Off-shell Higgs studies in $H \rightarrow 4l$

CMS Experiment at LHC, CERN
 Data recorded: Thu Jun 28 14:00:31 2018 EDT
 Run/Event 318874 / 88897146
 Lumi section: 54
 Orbit/Crossing: 14097746 / 2821

- Analyze **Full Run2 $H \rightarrow 4l$**
- Select events in $H \rightarrow ZZ \rightarrow 4l$ with $m_{4l} > 220 \text{ GeV}$
- Measure $\mu^{\text{off-shell}}$, Γ



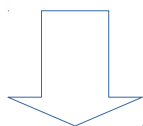
$$pp \rightarrow H \text{ jet jet} + X$$

$$\downarrow$$

$$e^+ e^- \mu^+ \mu^-$$

Off-shell Higgs studies in $H \rightarrow 4l$

- Analyze Full Run2 $H \rightarrow 4l$
- Select events in $H \rightarrow ZZ \rightarrow 4l$ with $m_{4l} > 220\text{GeV}$



- **Perform template fit**
- Measure $\mu^{\text{off-shell}}, \Gamma$

Constrain $\frac{\Gamma_H}{\Gamma_0}$

on-shell:

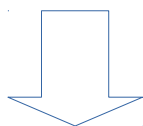
$$\mathcal{P}_{jk}(\vec{x}; \vec{\zeta}_{jk}, \vec{\zeta}) = \mu_j \mathcal{P}_{jk}^{\text{sig}}(\vec{x}; \vec{\zeta}_{jk}) + \mathcal{P}_{jk}^{\text{bkg}}(\vec{x}; \vec{\zeta}_{jk})$$

off-shell:

$$\mathcal{P}_{jk}(\vec{x}; \vec{\zeta}_{jk}, \vec{\zeta}) = \frac{\mu_j \Gamma_H}{\Gamma_0} \mathcal{P}_{jk}^{\text{sig}}(\vec{x}; \vec{\zeta}_{jk}) + \sqrt{\frac{\mu_j \Gamma_H}{\Gamma_0}} \mathcal{P}_{jk}^{\text{int}}(\vec{x}; \vec{\zeta}_{jk}) + \mu_j \mathcal{P}_{jk}^{\text{cross}}(\vec{x}; \vec{\zeta}_{jk}) + \mathcal{P}_{jk}^{\text{bkg}}(\vec{x}; \vec{\zeta}_{jk})$$

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Constrain $\mu^{\text{off-shell}}$

- **Perform template fit**
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on-shell:

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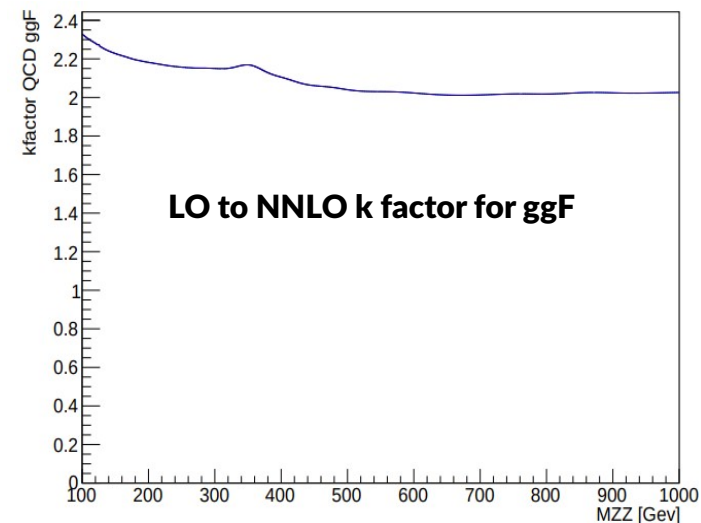
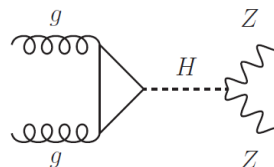
off-shell:

$$\mathcal{P}_{jk}(\vec{x}; \vec{\zeta}_{jk}, \zeta) = \frac{\mu_j \Gamma_H}{\Gamma_0} \mathcal{P}_{jk}^{\text{sig}}(\vec{x}; \vec{\zeta}_{jk}) + \sqrt{\frac{\mu_j \Gamma_H}{\Gamma_0}} \mathcal{P}_{jk}^{\text{int}}(\vec{x}; \vec{\zeta}_{jk}) + \mu_j \mathcal{P}_{jk}^{\text{cross}}(\vec{x}; \vec{\zeta}_{jk}) + \mathcal{P}_{jk}^{\text{bkg}}(\vec{x}; \vec{\zeta}_{jk})$$

Signal + Background modeling

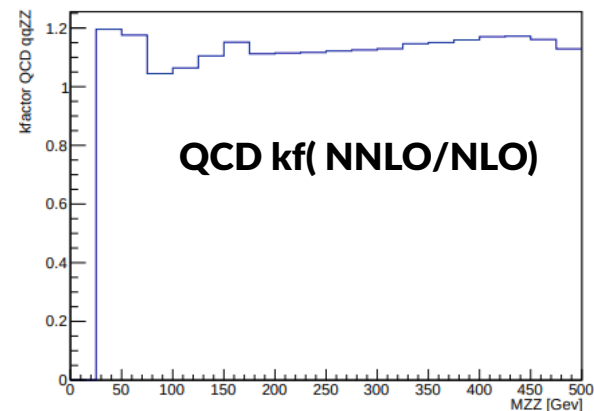
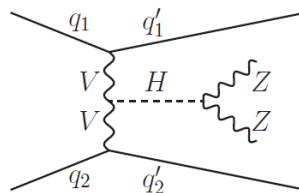
Gluon Fusion

- JHUGen + MCFM
- **LO QCD generation +kf(NNLO/LO) shape**
- **LO EW generation**
- +kf(**N3LO QCD** + **NLO EW**) for xsection YR4 (estimated to 14.5% effect)
- Powheg+JHUGen also used in tagged categories



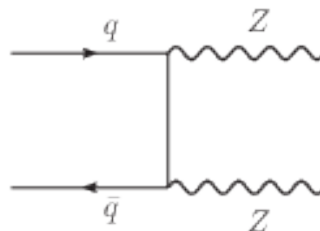
EW processes (VBF,VH)

- JHUGen + MCFM
- **LO QCD generation**
- **LO EW generation**
- +kf(**NNLO QCD** + **NLOEW**) for xsection YR4 (estimated to 3.9% effect)
- Phantom also used



qqZZ background

- POWHEG
- **NLO QCD generation +kf(NNLO/NLO)**
- **LO EW generation + kf (NLO/LO)**

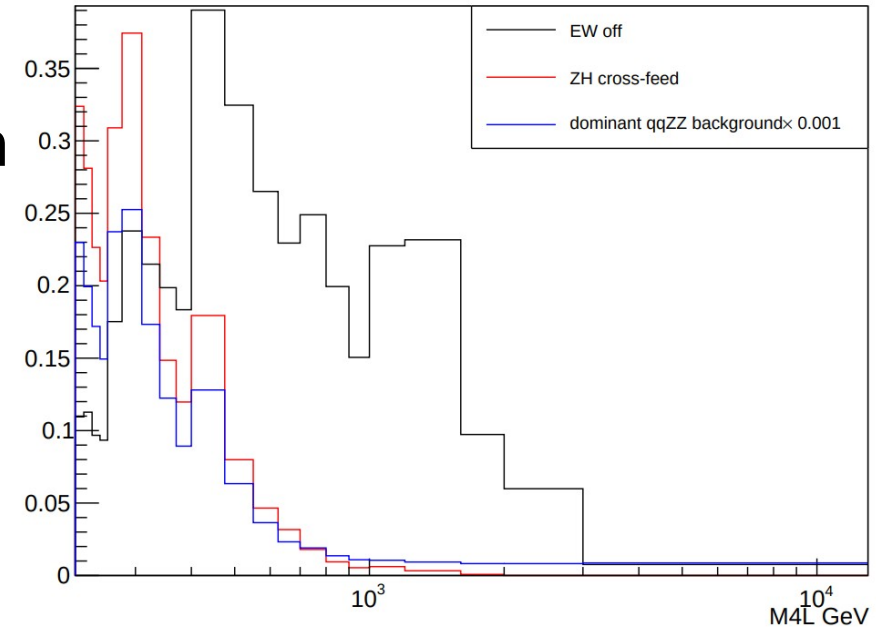


Z+X data driven background estimation

Jet simulation important for categorization: Perform Parton shower/generator comparisons

Cross-feed

- ZH125(Z→2l)(H →2l+X)
- Genuine on-shell signal contribution
- Considerable contamination in M4L > 220 GeV
- Background-like



on-shell:

$$\mathcal{P}_{jk}(\vec{x}; \vec{\zeta}_{jk}, \vec{\zeta}) = \mu_j \mathcal{P}_{jk}^{\text{sig}}(\vec{x}; \vec{\zeta}_{jk}) + \mathcal{P}_{jk}^{\text{bkg}}(\vec{x}; \vec{\zeta}_{jk})$$

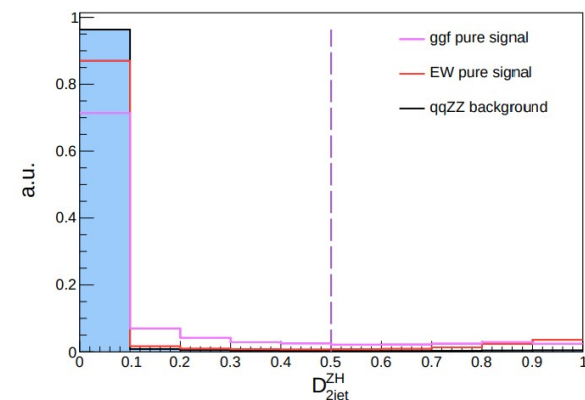
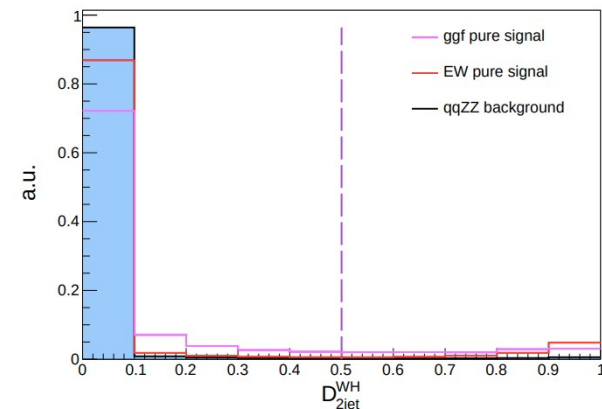
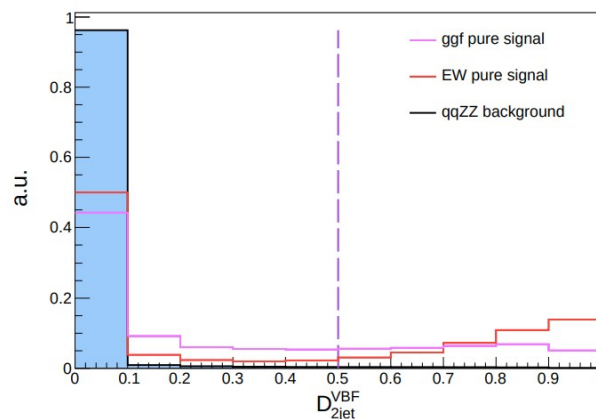
off-shell:

$$\mathcal{P}_{jk}(\vec{x}; \vec{\zeta}_{jk}, \vec{\zeta}) = \frac{\mu_j \Gamma_H}{\Gamma_0} \mathcal{P}_{jk}^{\text{sig}}(\vec{x}; \vec{\zeta}_{jk}) + \sqrt{\frac{\mu_j \Gamma_H}{\Gamma_0}} \mathcal{P}_{jk}^{\text{int}}(\vec{x}; \vec{\zeta}_{jk}) + \mu_j \mathcal{P}_{jk}^{\text{cross}}(\vec{x}; \vec{\zeta}_{jk}) + \mathcal{P}_{jk}^{\text{bkg}}(\vec{x}; \vec{\zeta}_{jk})$$

Event Categorization

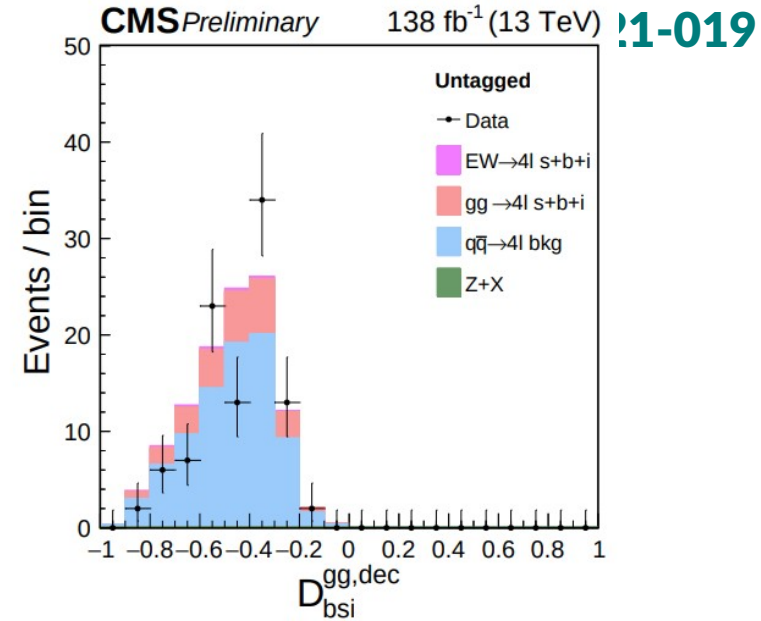
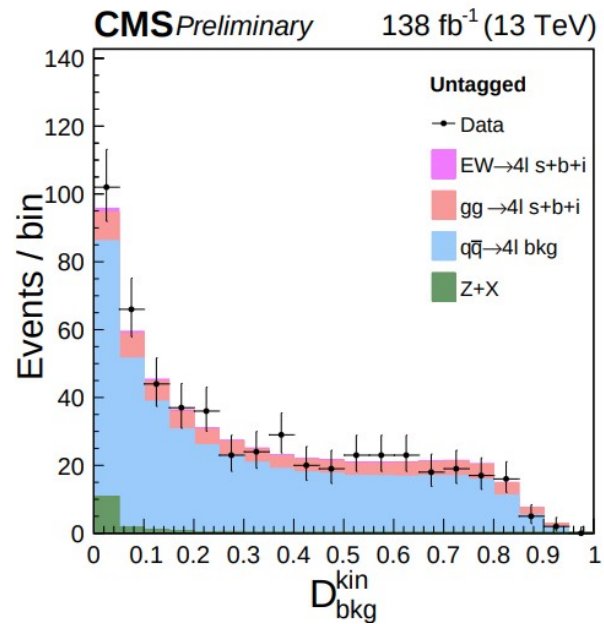
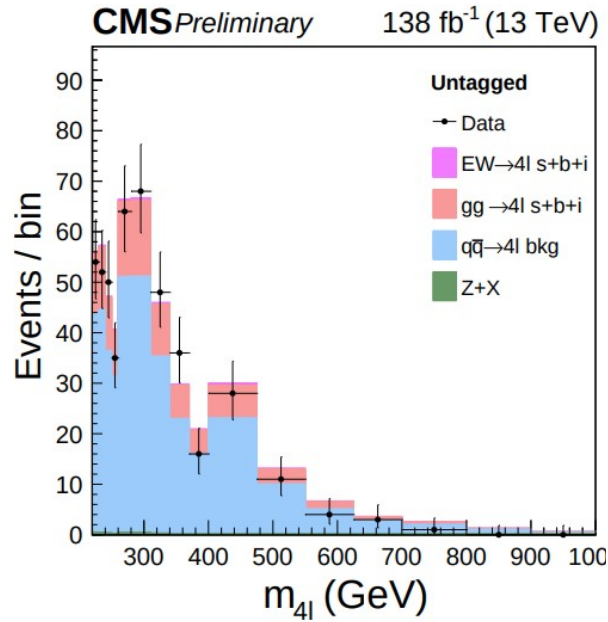
- Analyze Full Run2 $H \rightarrow 4l$
- Select events in $H \rightarrow ZZ \rightarrow 4l$ with $m_{4l} > 220\text{GeV}$
- Merge years + final states into single observation
- 3 exclusive categories
 - VBFtagged
 - VHtagged
 - Untagged

Allows to measure μ_V, μ_F



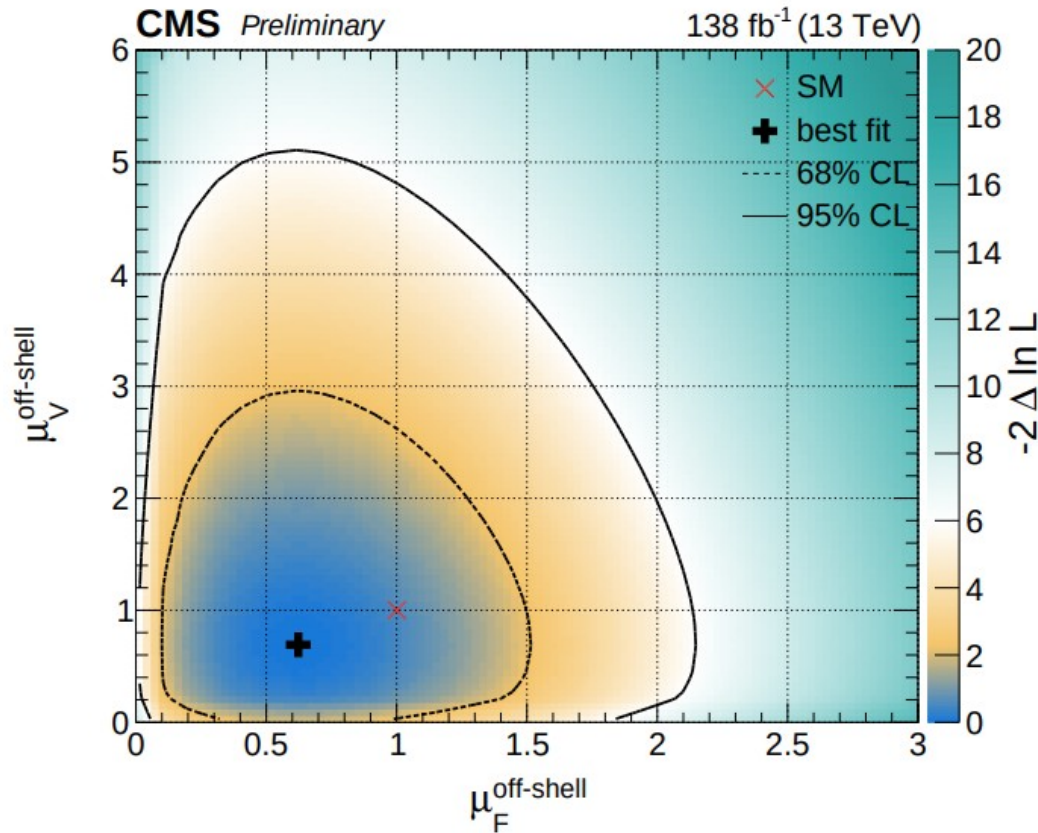
Category	VBF-tagged	VH-tagged	Untagged
Selection	$D_{2jet}^{VBF} > 0.5$	D_{2jet}^{ZH} or $D_{2jet}^{WH} > 0.5$	Rest of events

Observables



- **Observables:**
M4L + 2 discriminants
- Measurement is statistically limited
- Background backgrounds theory uncertainties dominate

NEW Full RUN2 4l !



2D scan of the off-shell signal strength parameters

Parameter	Observed	Expected
$\mu^{\text{off-shell}}$	$0.64^{+0.50}_{-0.37}$ [0.06, 1.69]	$1.00^{+0.99}_{-0.97}$ [0.00, 2.80]
$\mu_F^{\text{off-shell}}$	$0.62^{+0.57}_{-0.41}$ [0.03, 1.81]	$1.00^{+1.05}_{-1.00}$ [0.00, 2.93]
$\mu_V^{\text{off-shell}}$	$0.69^{+1.32}_{-0.63}$ [0.00, 3.91]	$1.00^{+3.34}_{-1.00}$ [0.00, 7.65]

Results

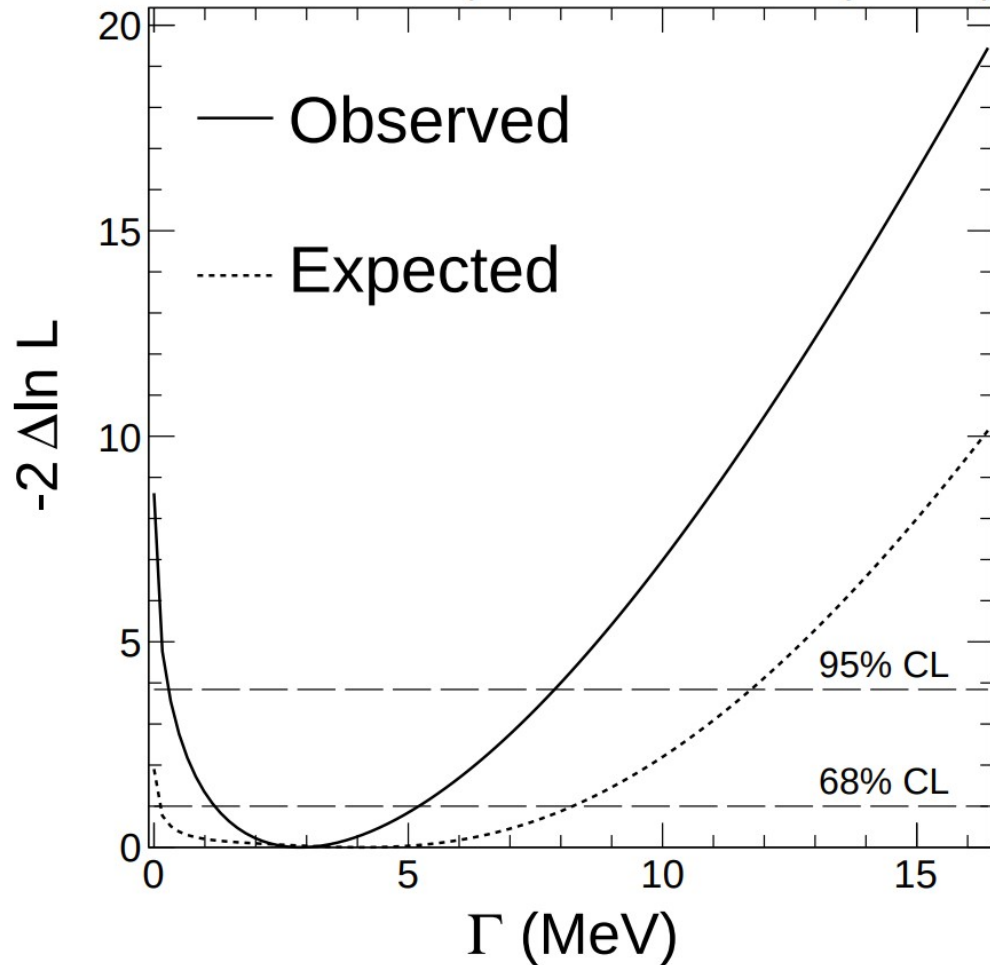


HIG-21-019
[link](#)

NEW Full RUN2 4l !

CMS Preliminary

138 fb⁻¹ (13 TeV)



Observed

$$\Gamma_H \text{ (MeV)} = 2.9^{+2.3}_{-1.7} [0.3, 7.9]$$

Expected

$$= 4.1^{+4.1}_{-4.0} [0.0, 11.7]$$

Summary



HIG-21-019
[link](#)

- Presented recent results from CMS on off-shell Higgs studies
- New Full Run2 analysis of $H \rightarrow 4l$ decays

$$\Gamma_H \text{ (MeV)} = 2.9^{+2.3}_{-1.7} [0.3, 7.9]$$

Higgs Width - on-shell measurement

HIG-21-019
(link)

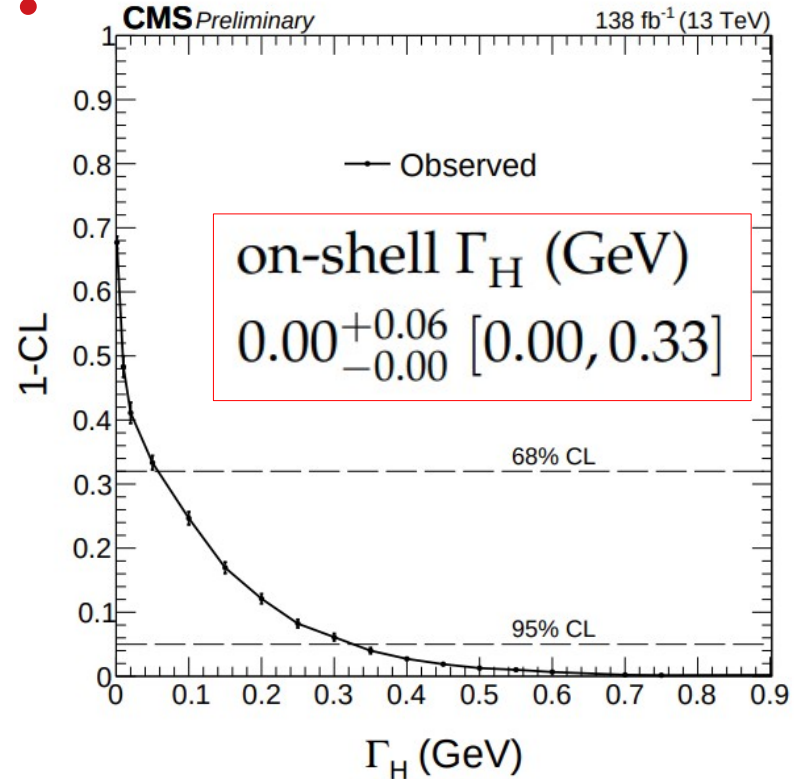


2019

- SM: given $m_H \rightarrow \Gamma_H$ can be calculated
- Measure Higgs width
 - Test of Higgs \rightarrow SM particles
 - A test/complimentary for $H \rightarrow$ invisible particles
- Techniques:
 - **Using the onshell region (mass pole shape)**
 - Using signal strength in on-shell and off-shell production

$$\Gamma_H^{\text{SM}} = 4.1 \text{ MeV}$$

NEW!



- > Convolute (DSCB + Laundau) x Breit-Wigner
- > Fit m4l line shape
- > measurement **limited by detector resolution**