

UC SANTA BARBARA



U.S. DEPARTMENT OF
ENERGY

Office of Science

CMS off-shell Higgs boson measurements

(from [Nature Phys. 18 11 \(2022\)](#) and related analyses)

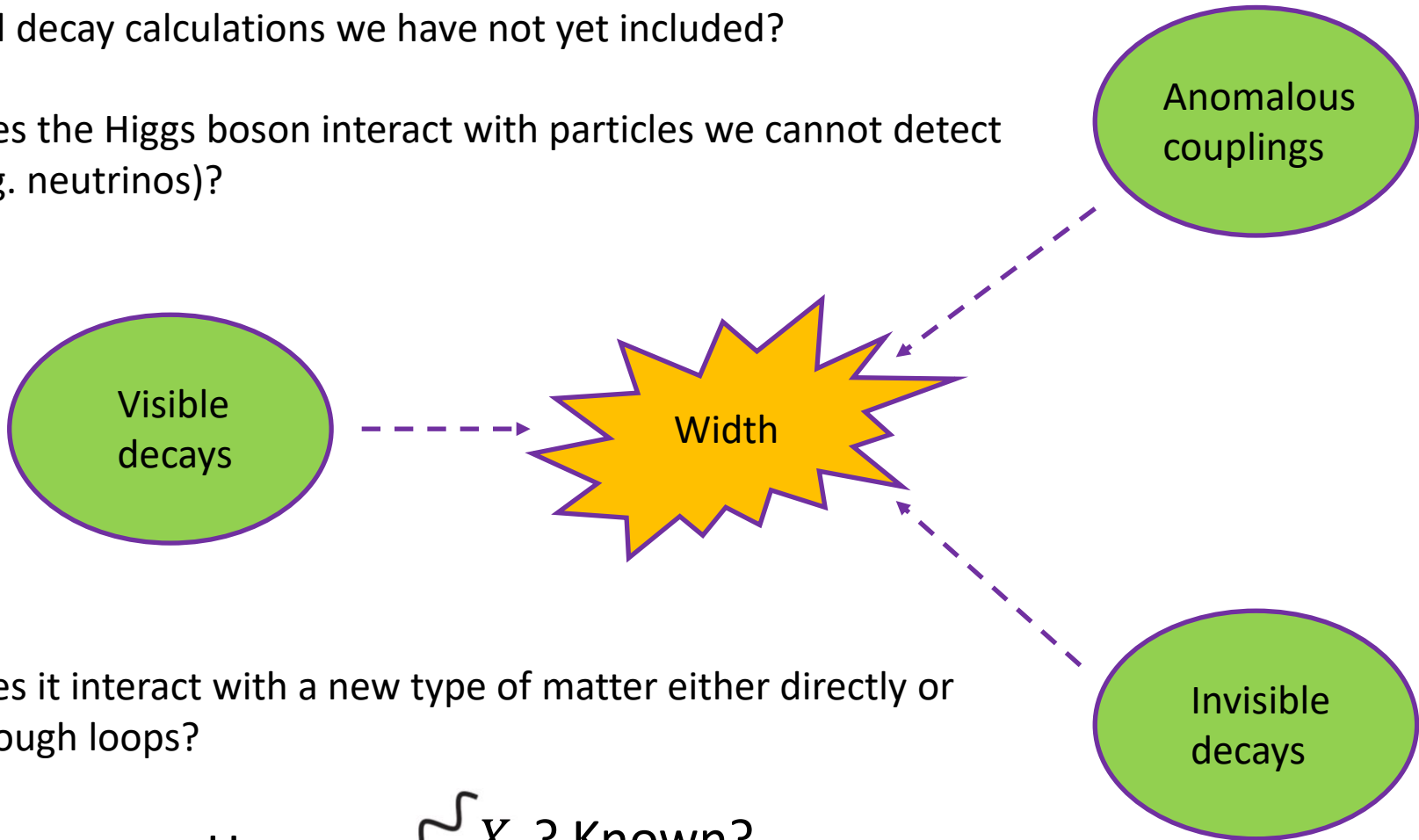
Ulascan Sarica
on behalf of
the CMS Collaboration

MBI 2023
Aug. 31, 2023

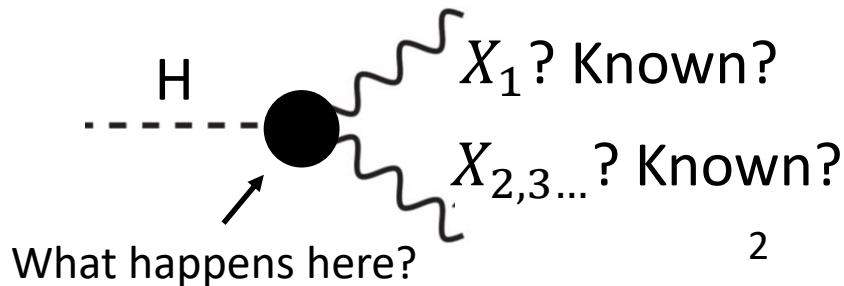
Why measure the Higgs boson width?

Are there subdominant contributions to our current production and decay calculations we have not yet included?

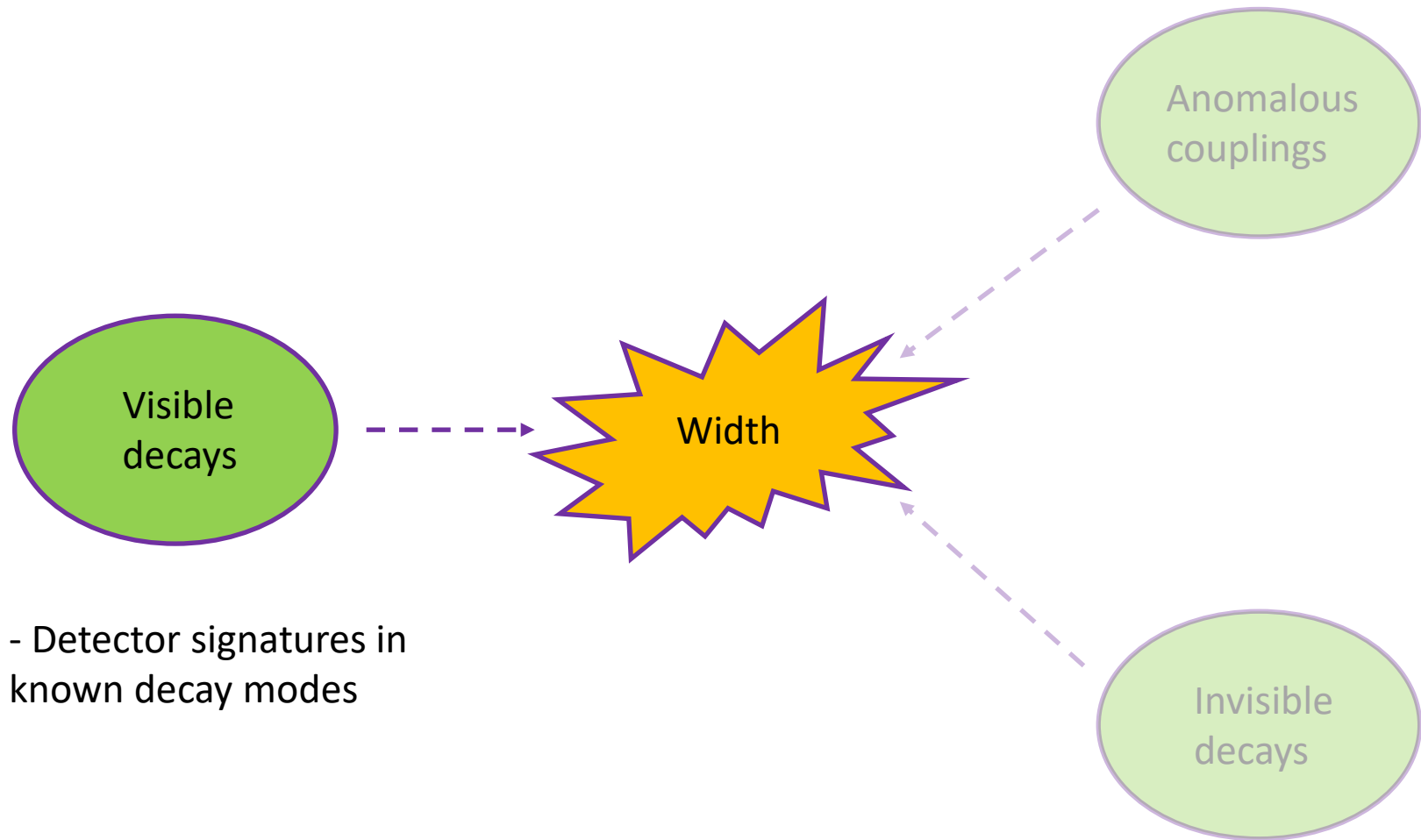
Does the Higgs boson interact with particles we cannot detect (e.g. neutrinos)?



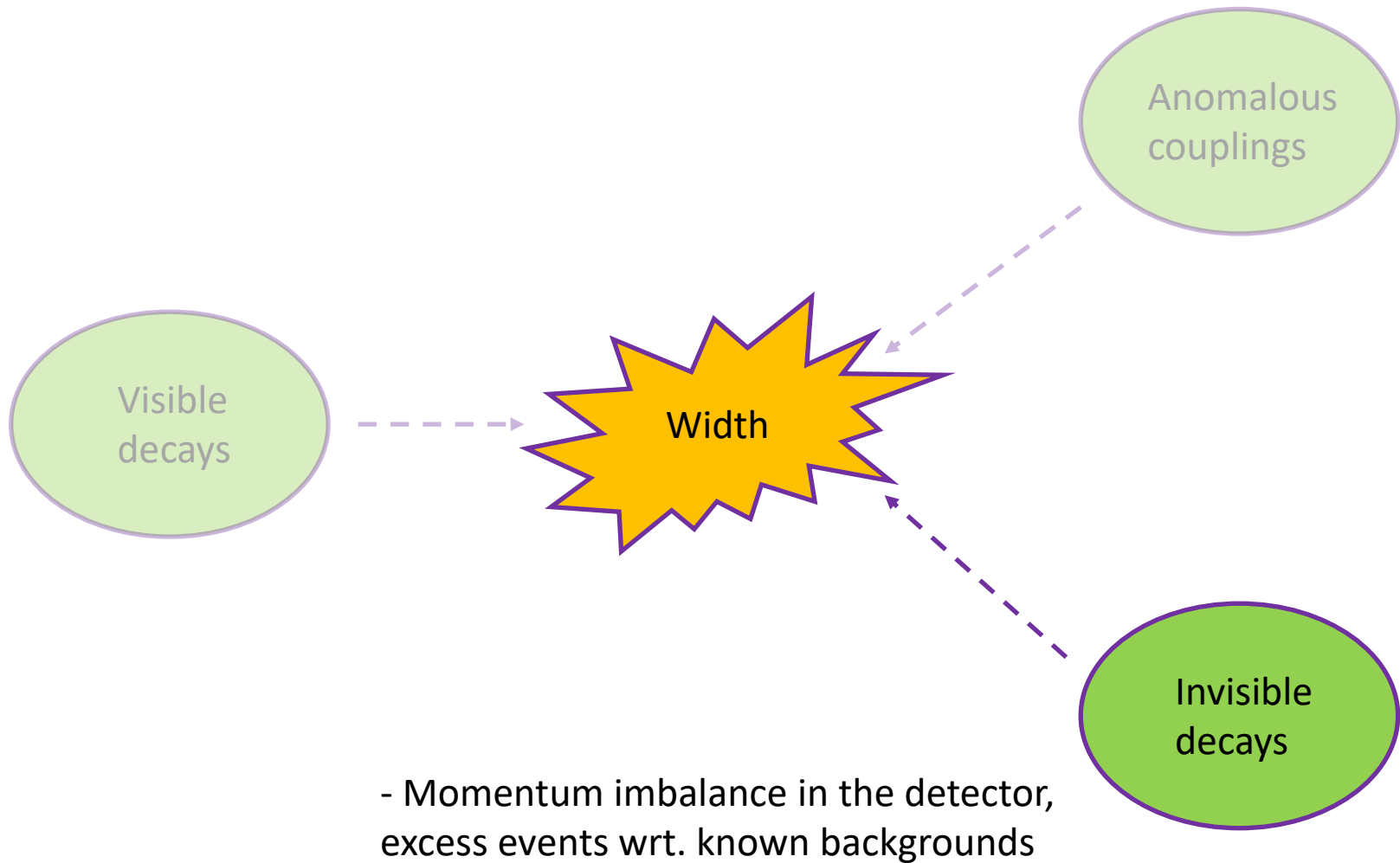
Does it interact with a new type of matter either directly or through loops?



What can we measure?

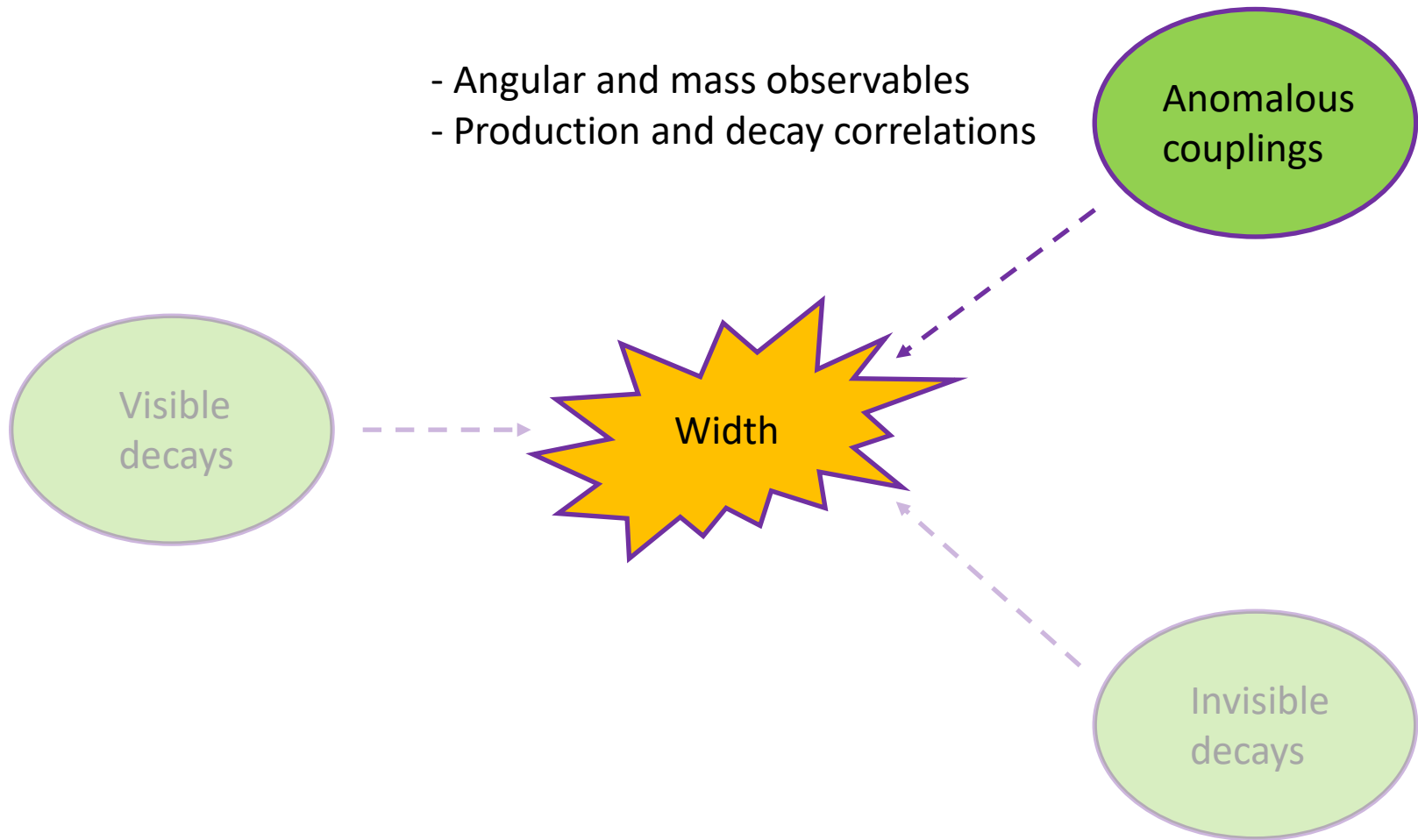


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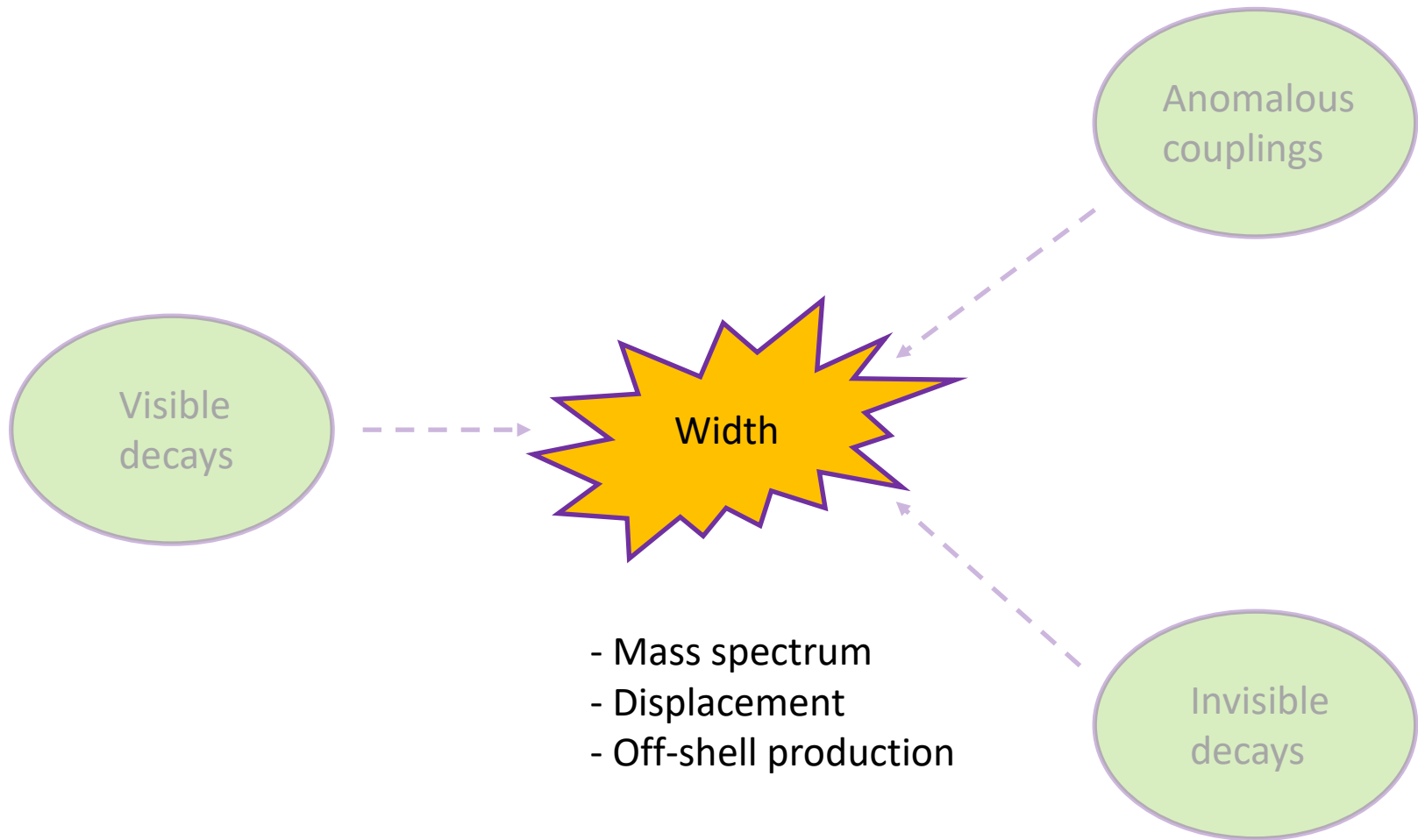


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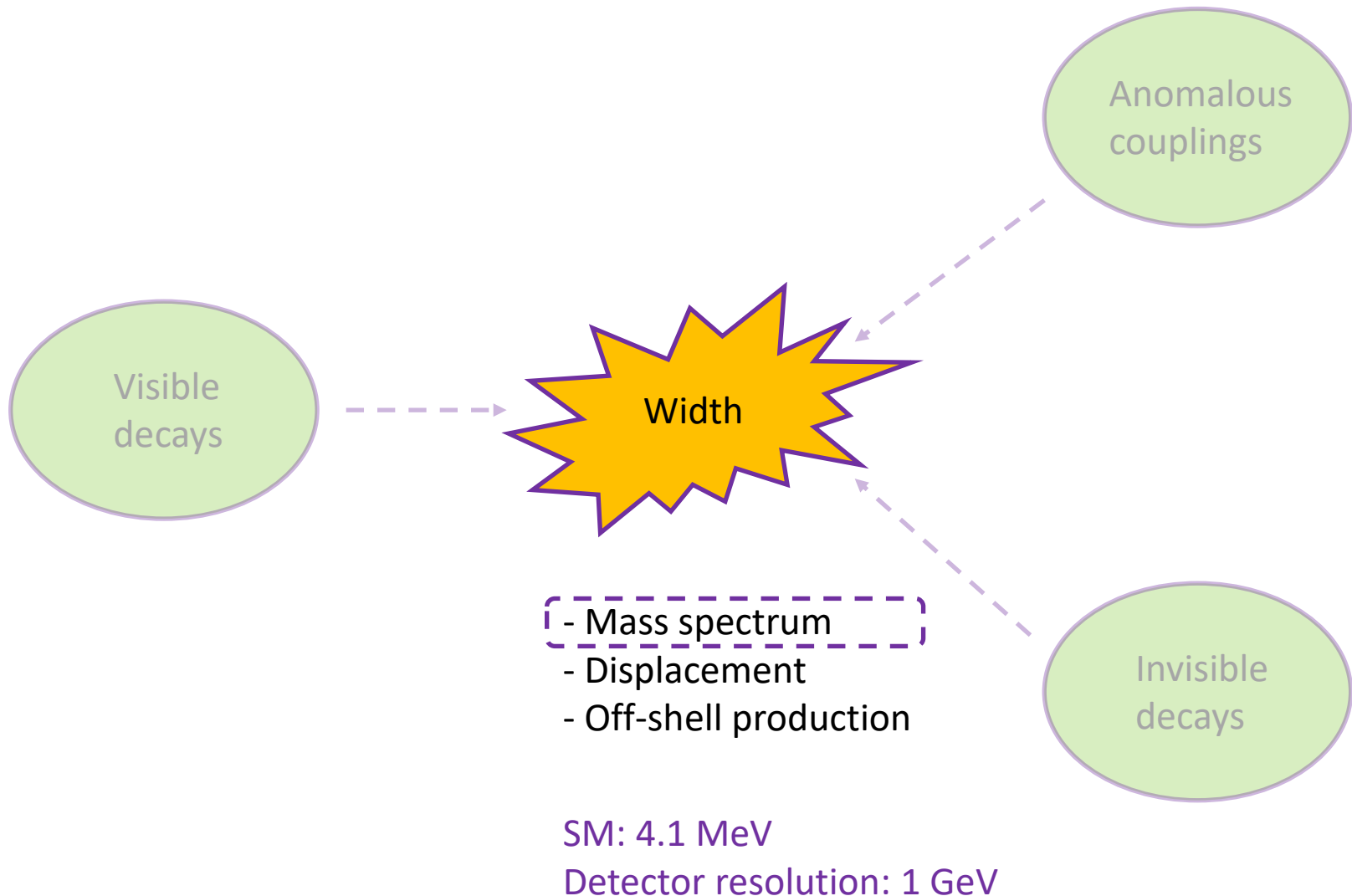
- Angular and mass observables
- Production and decay correlations



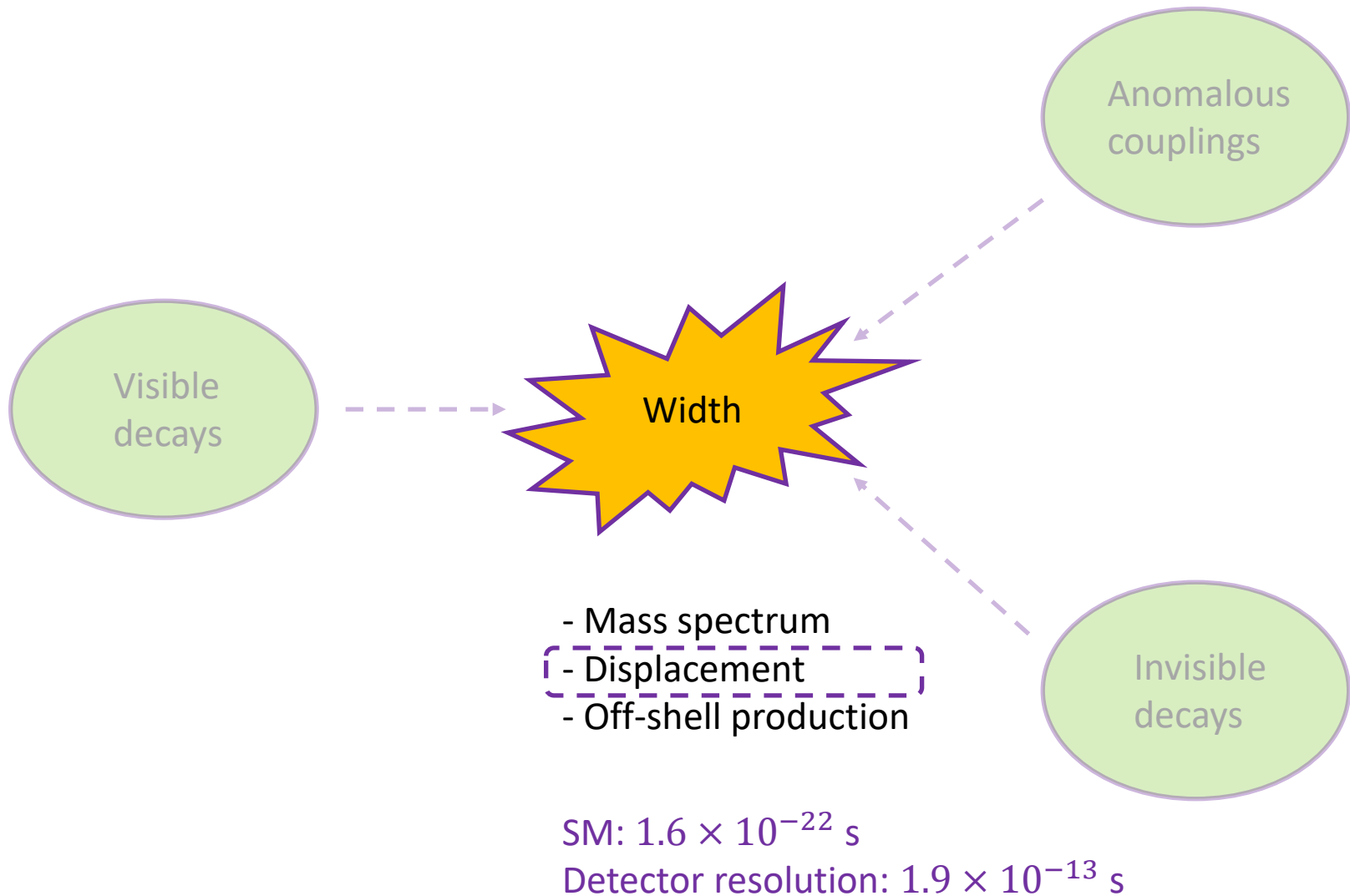
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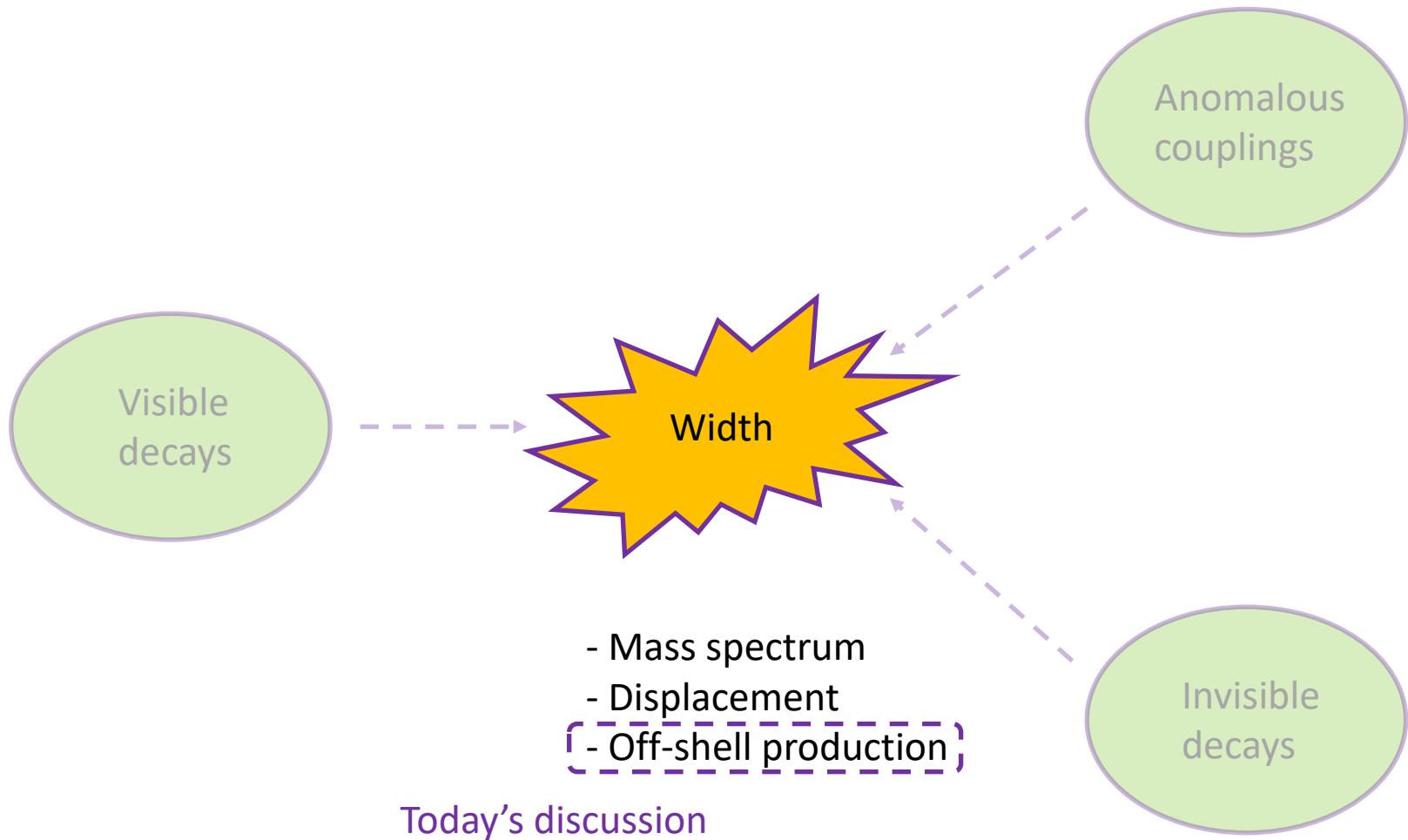
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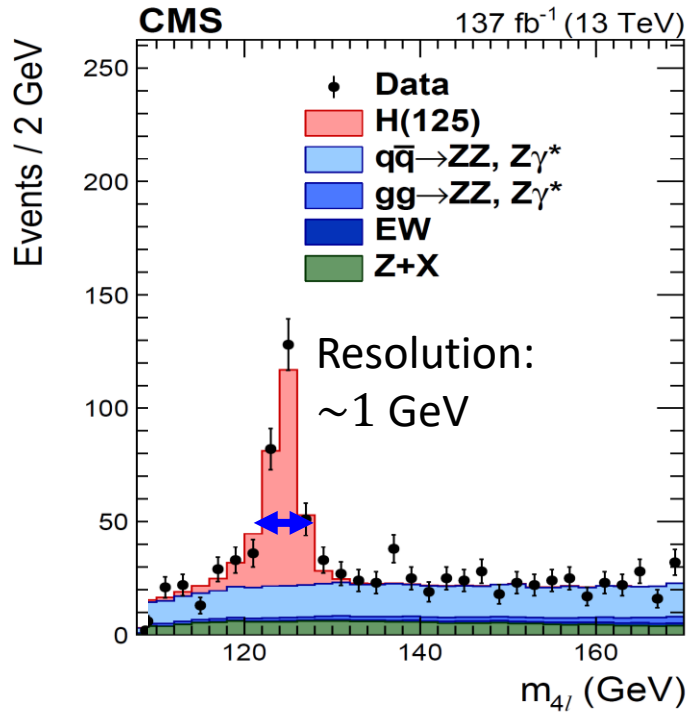
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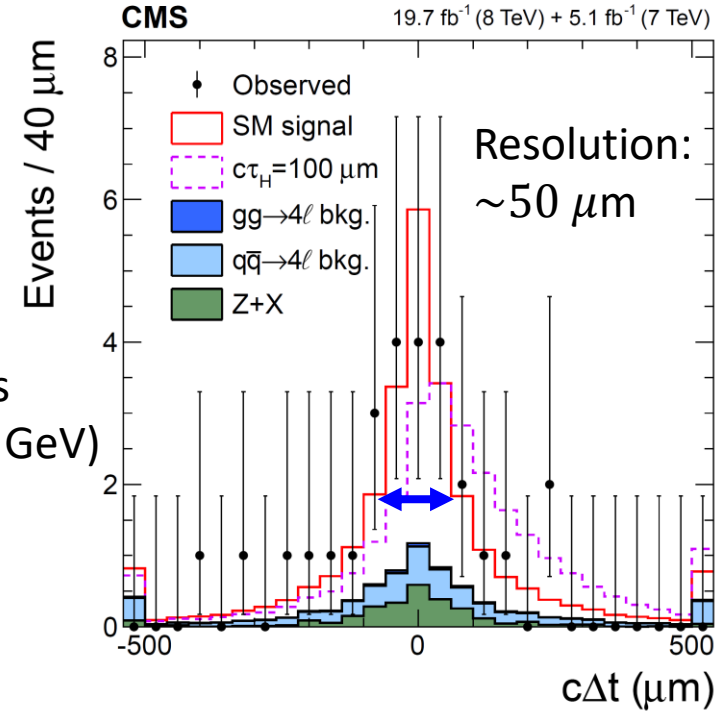


Conventional ways for width/lifetime



$\Gamma_H < 1.1$ GeV
 $(\tau_H > 6.0 \times 10^{-25}$ s)
 [1]

$\tau_H < 1.9 \times 10^{-13}$ s
 $(\Gamma_H > 3.5 \times 10^{-12}$ GeV)
 [2]



SM $\Gamma_H = 0.0041$ GeV, $c\tau_H = 4.8 \times 10^{-8} \mu\text{m}$

\rightarrow Mass resolution: ~ 1 GeV

$\rightarrow 4\ell$ vertex resolution: $\sim 50 \mu\text{m}$

Γ_H and τ_H too small to be measured directly

[1] [CMS Collaboration; JHEP 11 047 \(2017\)](#)

[2] [CMS Collaboration; PRD 92 072010 \(2015\)](#)

Off-shell Higgs boson production

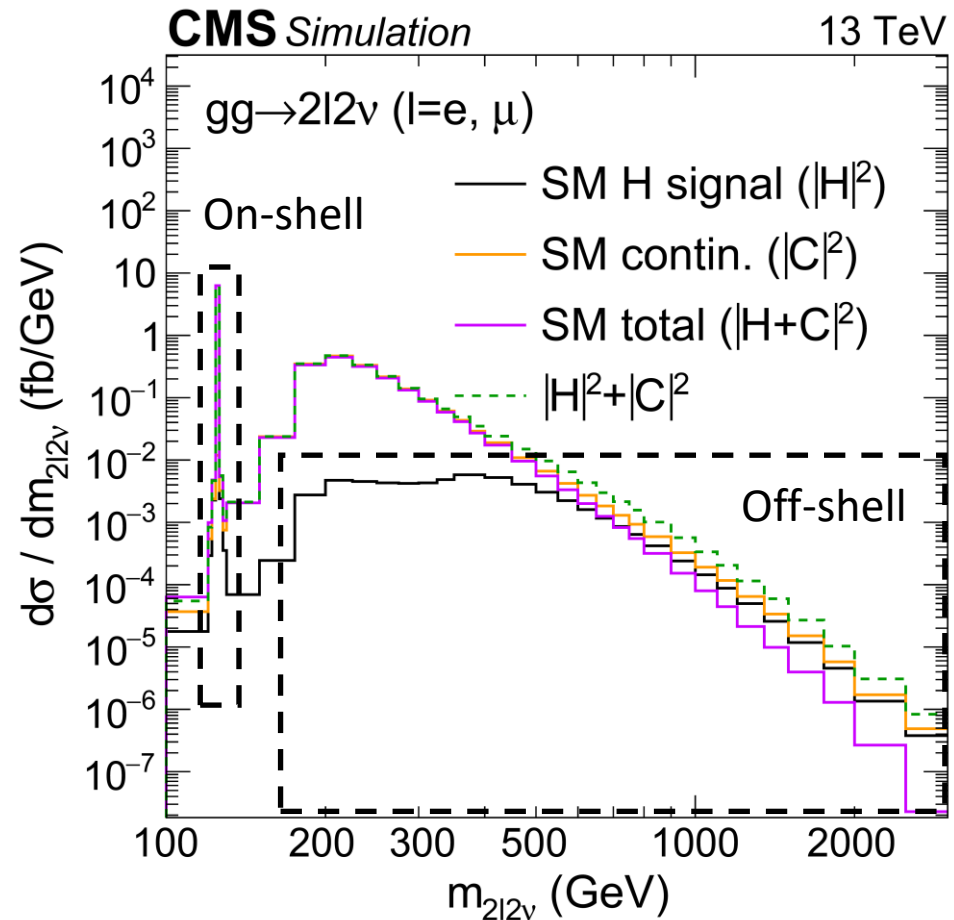
In $H \rightarrow VV$ ($V = Z, W$), $m_V < m_H < 2m_V$:

→ Either H is on-shell and one V is off-shell, or H is off-shell and both V s are on-shell

→ Both V s going on-shell allows $\sim 10\%$ of events in the SM to produce an off-shell Higgs boson [1].

Possible to measure two off-shell production mechanisms:

- $\mu_F^{\text{off-shell}}$ (gg)
- $\mu_V^{\text{off-shell}}$ (EW: VBF, VH)
- Can also measure an overall $\mu^{\text{off-shell}}$



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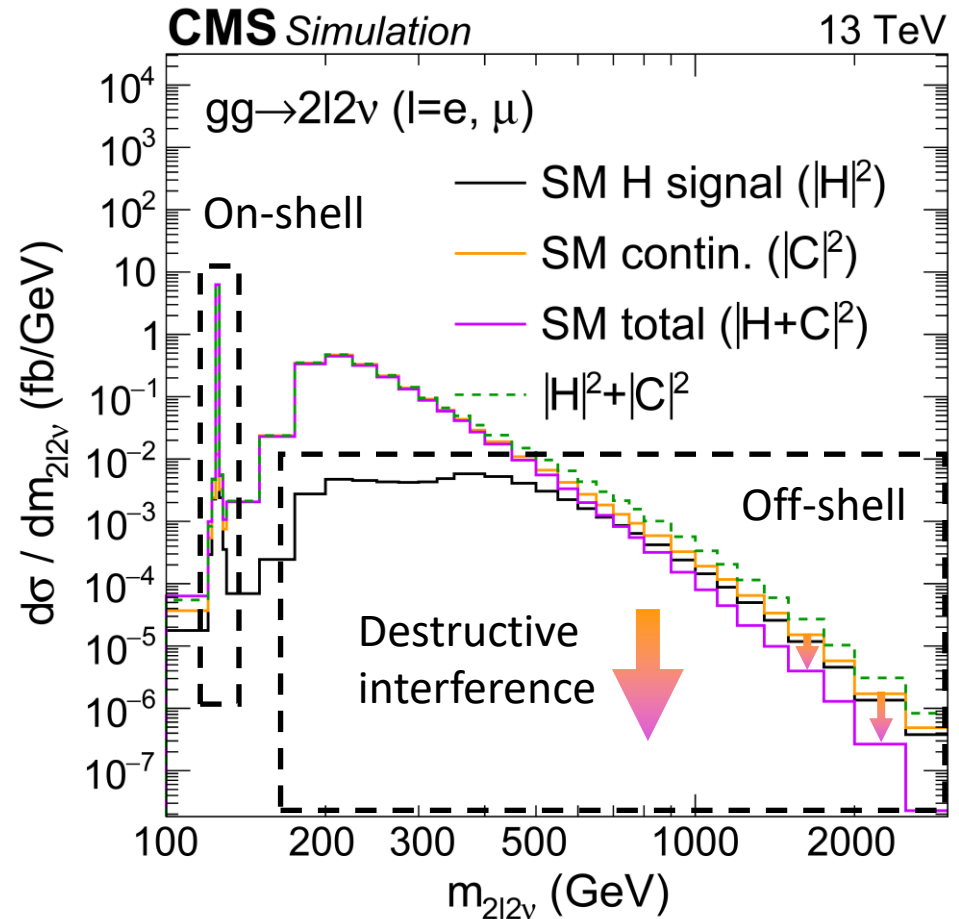
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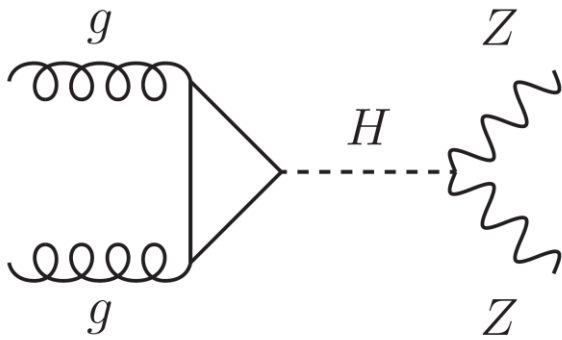
Higgs-mediated diagrams interfere destructively with continuum VV production:

- Large in magnitude
- \sim Twice the size of the Higgs signal
- Necessary in the SM to ensure unitarity

[1] [Kauer, N. and Passarino, G.; JHEP 08 116 \(2012\)](#)
([arxiv:1206.4803](#))

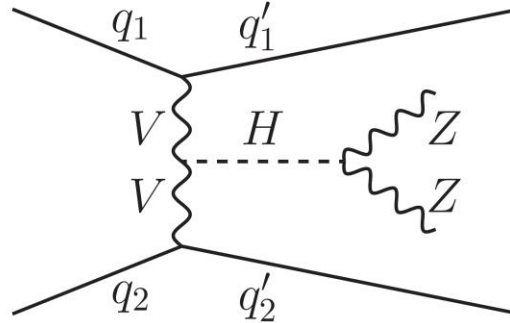
Diagrams of off-shell Higgs production

$gg \rightarrow H \rightarrow ZZ$:

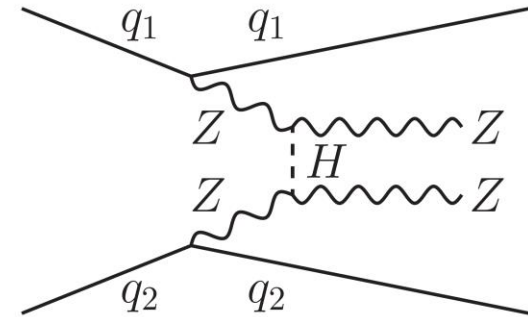


$gg \rightarrow H$ production
dominant at lower masses
in the off-shell region

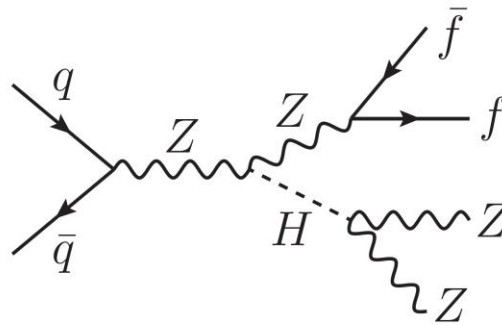
VBF (s-channel):



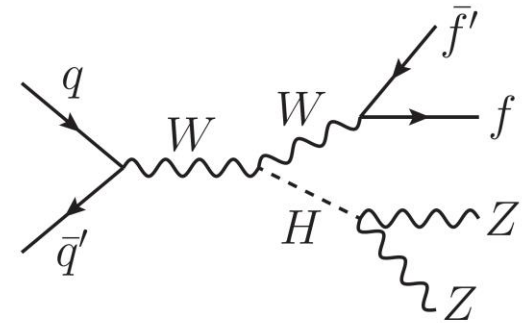
VBF (t-channel):



ZH (s-, t-, u-channels):



WH :



EW production more dominant at higher masses in
the off-shell region (mostly VBF in the SM)

Off-shell method for the width

Combine with on-shell signal strength measurement to extract Γ_H [1]:

$$\sigma = \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \dots dm^2$$

On-shell

$$\sigma \propto \frac{g_{prod}^2 g_{dec}^2}{\Gamma_H} \propto \mu_{prod}$$

Measure on-shell signal strength
from final states ZZ or WW

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$$\sigma \sim \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_H^2)^2} \dots dm^2 \propto \mu_{prod}^{off-shell}$$

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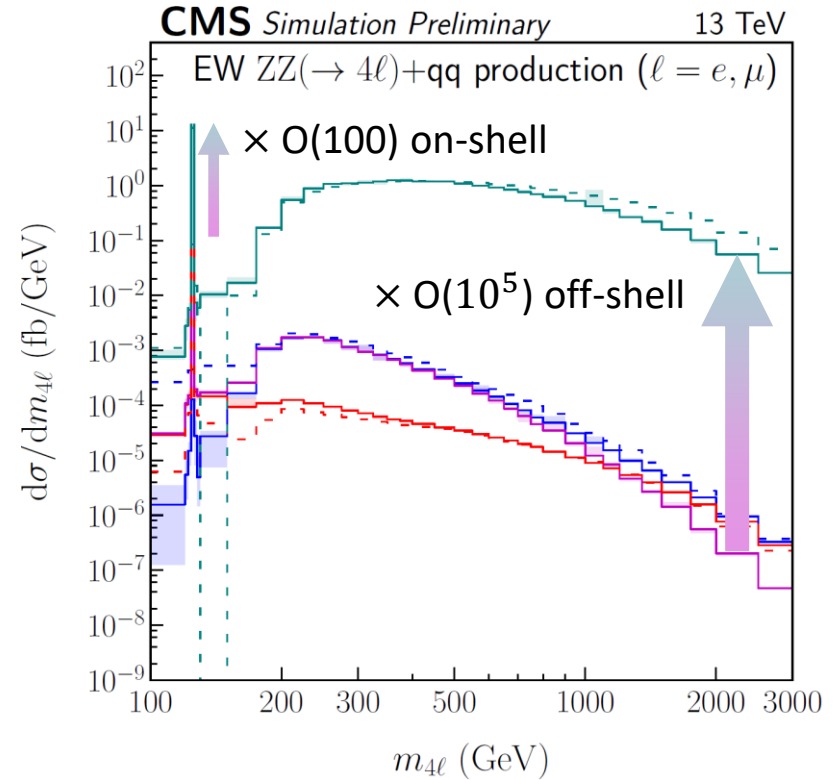
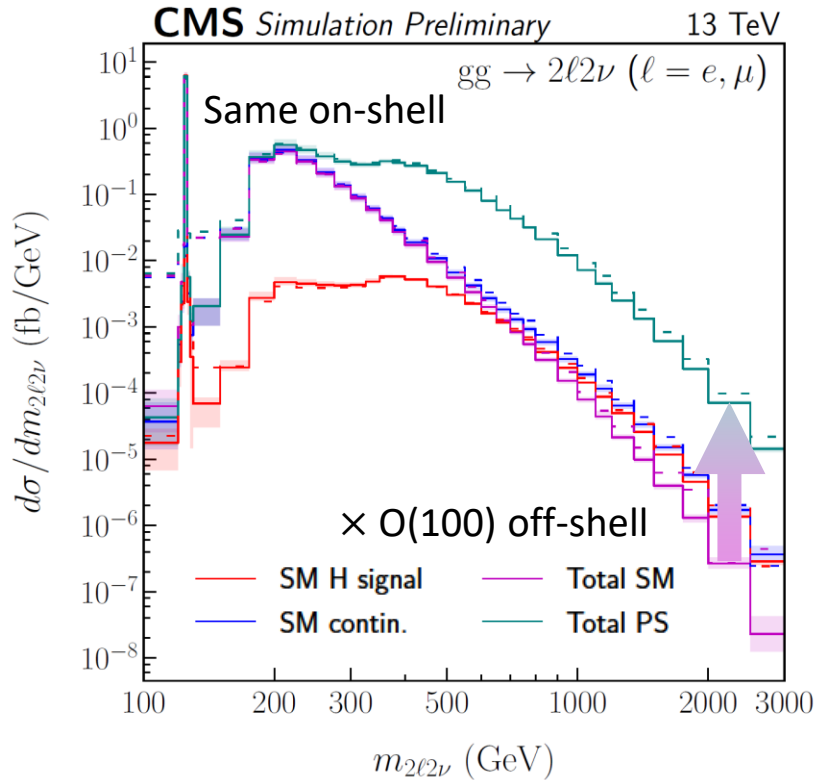
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$$\sigma \sim \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_H^2)^2} \dots dm^2 \propto \mu_{prod} \cdot \Gamma_H$$

Measure on-shell signal strength from final states ZZ or WW

Ratio of off-shell to on-shell signal strengths for each production mode gives Γ_H

Off-shell & BSM HVV couplings



$$A(HVV) \sim \left[a_1 - e^{i\phi_{\Lambda_1}} \frac{(q_{V1}^2 + q_{V2}^2)}{\Lambda_1^2} + \dots \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$

$$+ |a_2| e^{i\phi_{a_2}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + |a_3| e^{i\phi_{a_3}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

HVV amplitude
 $\propto \Lambda_1, a_2, a_3$ BSM contributions
 + SM-like a_1 term

Same a_1 (SM) or a_3 (PS) couplings,
 different on-shell and off-shell enhancements
 in gg and EW production modes

Analysis ingredients

Need high-mass ZZ events that contain off-shell Higgs boson contributions

→ Can be done in both 4ℓ (high- $m_{4\ell}$) and $2\ell 2\nu$ (high- $m_{\ell\ell}^{ZZ}$) final states

→ $BR(2\ell 2\nu) \sim 6 \times BR(4\ell)$

→ 4ℓ cleaner in bkg. (only irreducible) while

$2\ell 2\nu$ also has instrumental components.

→ About equal statistical importance in the results from the two channels

Need on-shell H(125) events to extract Γ_H

→ 4ℓ only (not possible with neutrinos)

→ Little background

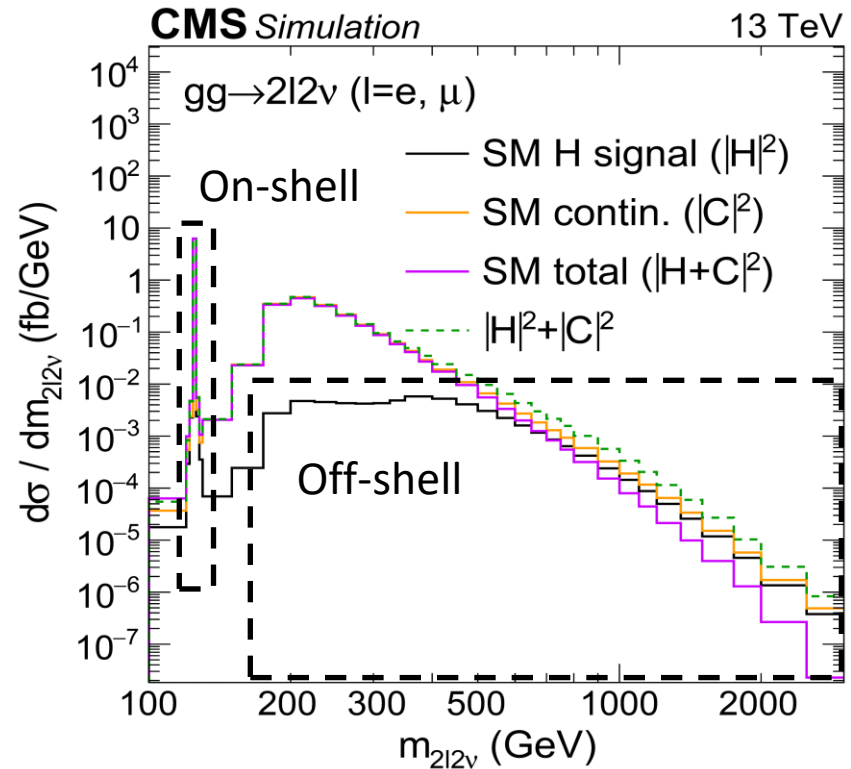
Extract physics using a combined fit to 117 multidimensional distributions:

24 distributions in off-shell $2\ell 2\nu$ (2326 events)

→ Analysis also combines 18 distributions from a $WZ \rightarrow 3\ell\nu$ CR (8541 events)

18 distributions in off-shell 4ℓ (1407 events), and 57 distributions in on-shell 4ℓ (621 events)

In off-shell categories, event counts are typically different from the SM by $\sim 10\text{-}50\%$ (larger at higher masses) for $\mu^{\text{off-shell}} = 0$ (or ~ 2.5)



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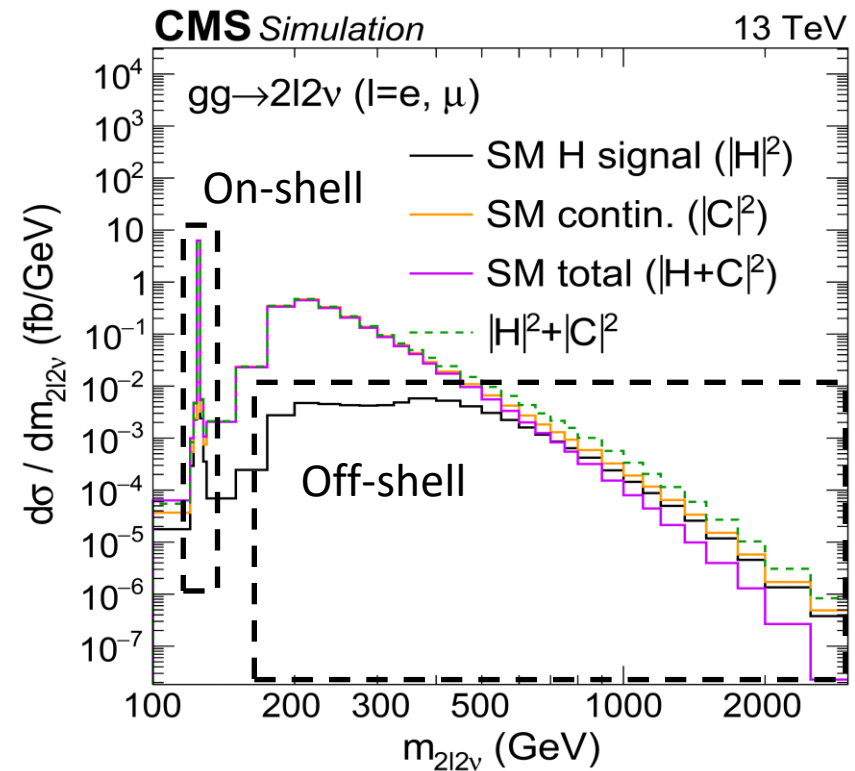
→ Little background

Biggest challenge in analysis is to extract off-shell information from the tails:

→ Limited statistics, e.g., in $2\ell 2\nu$ with $N_j \geq 2$, $p_T^{\text{miss}} > 200$ GeV, and $m_T^{ZZ} > 450$ GeV, off-shell $|H|^2$:H-C interf.:total expected = 10:-17:64 (events)

→ Need precise control over instrumental and irreducible backgrounds

→ Need theory input, e.g. for NLO EW corrections in $q\bar{q} \rightarrow ZZ, WZ$, for increased precision



Off-shell 4ℓ : Analysis strategy

CMS-HIG-18-002: Analysis of off-shell ($m_{4\ell} > 220$ GeV) 2016+2017 data [1]

→ All momenta are known in $4\ell \Rightarrow$ Use MELA matrix element discriminants

→ Can compute for Higgs production, decay, or both; or backgrounds

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

sig. vs alt.

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

sig.-alt.
interference

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sig. vs alt. sig.-alt. interference

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

Mass shape is the most sensitive to off-shell production

→ Any off-shell analysis uses a mass-sensitive observable

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sig. vs alt. sig.-alt. interference

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SM obs.	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VBF+dec}}, \mathcal{D}_{\text{bsi}}^{\text{VBF+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VH+dec}}, \mathcal{D}_{\text{bsi}}^{\text{VH+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}}, \mathcal{D}_{\text{bsi}}^{\text{gg,dec}}$

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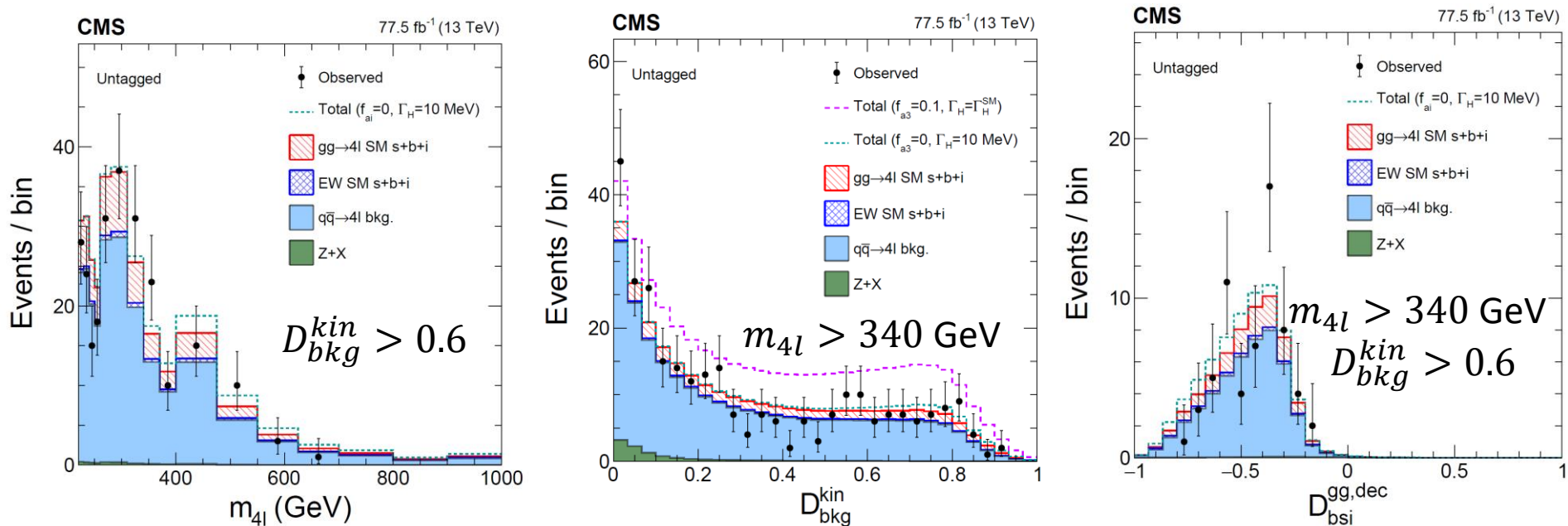
→ Any off-shell analysis uses a mass-sensitive observable

+ Discriminant for signal vs bkg

+ Discriminant for Higgs-continuum ZZ interference

(or SM vs BSM if constraining anomalous couplings)

Off-shell 4ℓ : Event distributions



Example distributions from the untagged category

Selection requirements are applied on the plots to enhance Higgs contributions

Stacked histograms for prefit SM distributions ($\Gamma_H = 4.1 \text{ MeV}$), cyan for $\Gamma_H = 10 \text{ MeV}$, magenta for an on-shell 10% PS (a_3) mixture

On-shell 4ℓ : Analysis strategy

CMS-HIG-19-009: Analysis of on-shell 4ℓ 2016-2018 data [1]

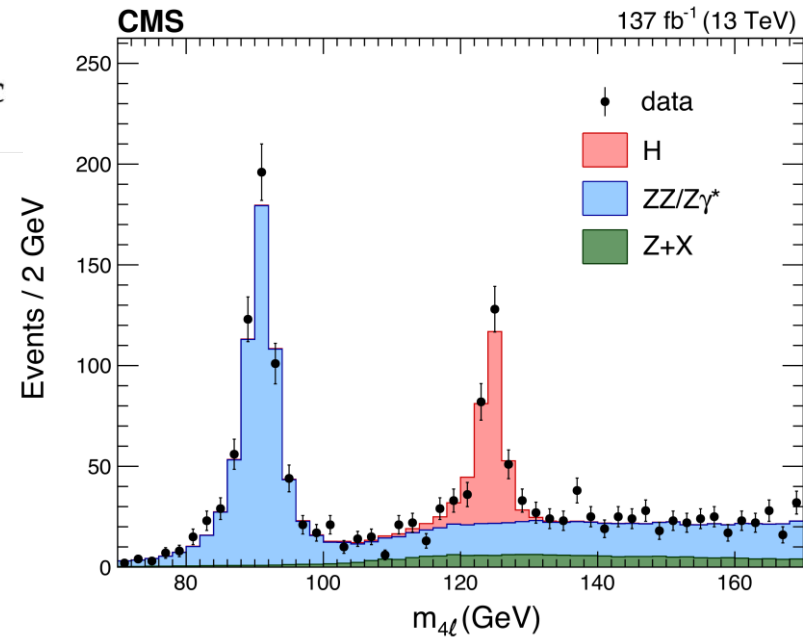
- Utilizes a finer categorization and more discriminants as observables
- Same categorization and observables for all couplings
- Example from untagged category:

$$\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0h+}^{\text{dec}}, \mathcal{D}_{0-}^{\text{dec}}, \mathcal{D}_{\Lambda 1}^{\text{dec}}, \mathcal{D}_{\Lambda 1}^{\text{Z}\gamma, \text{dec}}, \mathcal{D}_{\text{int}}^{\text{dec}}, \mathcal{D}_{\text{CP}}^{\text{dec}}$$

SM vs BSM
SM-BSM interf.

Provides extensive set of results

- Provides the following input to off-shell analysis:
 - on-shell μ_F and μ_V
 - on-shell BSM HVV contribution fractions f_{ai}



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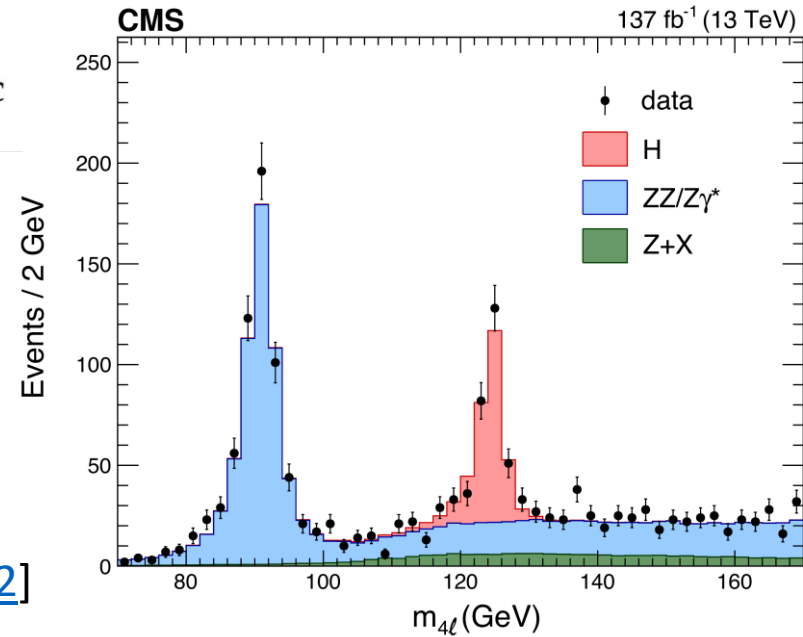
$$D_{\text{bkg}}, \underbrace{D_{0h+}^{\text{dec}}, D_{0-}^{\text{dec}}, D_{\Lambda 1}^{\text{dec}}, D_{\Lambda 1}^{\text{Z}\gamma, \text{dec}}}_{\text{SM vs BSM}}, \underbrace{D_{\text{int}}^{\text{dec}}, D_{\text{CP}}^{\text{dec}}}_{\text{SM-BSM interf.}}$$

Provides extensive set of results

- Provides the following input to off-shell analysis:
 - on-shell μ_F and μ_V
 - on-shell BSM HVV contribution fractions f_{ai}

CMS-HIG-17-011: Analysis of on-shell 4ℓ 2015 data [2]

- Inclusive in categorization
- Observables: $D_{\text{bkg}}, D_{\text{BSM}}^{\text{dec}}, D_{\text{int}}^{\text{dec}}$ as in the untagged category above.
 - The BSM discriminant depends on the analyzed coupling.



[1] [PRD 104 052004 \(2021\)](#) ([arxiv:2104.12152](#))

[2] [PLB 775 1 \(2017\)](#) ([arxiv:1707.00541](#))

Off-shell $2\ell 2\nu$: Analysis strategy

CMS-HIG-21-013: Analysis of off-shell $ZZ \rightarrow 2\ell 2\nu$ 2016-2018 data [1]

→ Main observable: Transverse ZZ mass defined through

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

→ $p_{\text{T}}^{\text{miss}}$ also used as an observable since it is sensitive to backgrounds

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CMS-HIG-21-013: Analysis of off-shell $ZZ \rightarrow 2\ell 2\nu$ 2016-2018 data [1]

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

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→ Categorization in bins of the number of jets: $N_j = 0, 1, \geq 2$

→ Also uses the MELA discriminants $D_{2jet}^{VBF(BSM)}$ when $N_j \geq 2$ by assuming $\eta_{\nu\nu} = \eta_{\ell\ell}$

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Interpretation parameters	$N_j < 2$	$N_j \geq 2$
$\mu_F^{\text{off-shell}}, \mu_V^{\text{off-shell}}, \mu^{\text{off-shell}}$	$m_T^{ZZ}, p_T^{\text{miss}}$	$m_T^{ZZ}, p_T^{\text{miss}}, D_{2jet}^{VBF}, D_{2jet}^{VBF,a2}$
$\Gamma_H (f_{ai} = 0)$	$m_T^{ZZ}, p_T^{\text{miss}}$	$m_T^{ZZ}, p_T^{\text{miss}}, D_{2jet}^{VBF}, D_{2jet}^{VBF,a2}$
Γ_H, f_{a2}	$m_T^{ZZ}, p_T^{\text{miss}}$	$m_T^{ZZ}, p_T^{\text{miss}}, D_{2jet}^{VBF}, D_{2jet}^{VBF,a2}$
Γ_H, f_{a3}	$m_T^{ZZ}, p_T^{\text{miss}}$	$m_T^{ZZ}, p_T^{\text{miss}}, D_{2jet}^{VBF}, D_{2jet}^{VBF,a3}$
$\Gamma_H, f_{\Lambda 1}$	$m_T^{ZZ}, p_T^{\text{miss}}$	$m_T^{ZZ}, p_T^{\text{miss}}, D_{2jet}^{VBF}, D_{2jet}^{VBF,\Lambda 1}$

Off-shell $2\ell 2\nu$: Noninterfering backgrounds

$q\bar{q} \rightarrow ZZ, WZ$:

→ Dominant backgrounds at high m_{T}^{ZZ}

→ Shapes and normalizations taken from all possible variations of the simulation

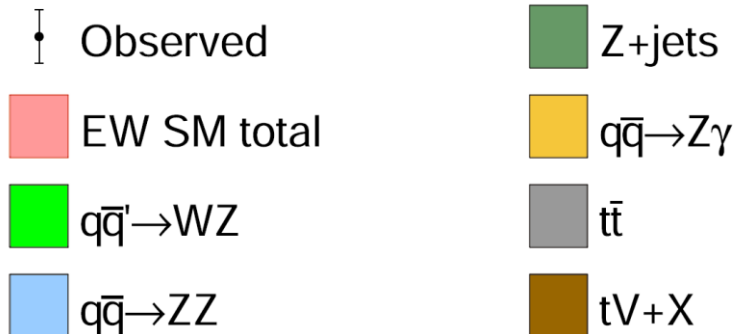
→ Final estimate performed with a joint fit to a 3ℓ WZ CR

$q\bar{q} \rightarrow ZZ, WZ$ background

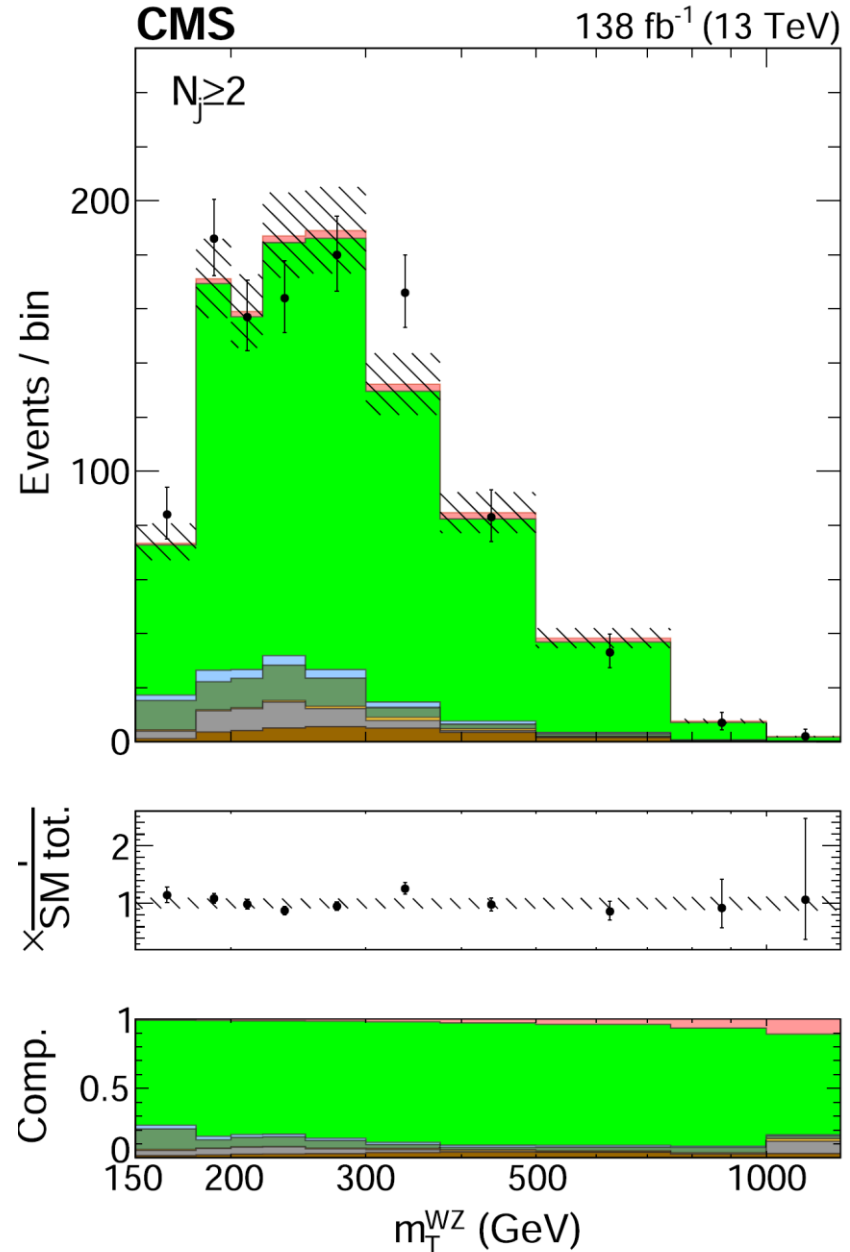
$q\bar{q} \rightarrow ZZ$ is an irreducible background to $H \rightarrow ZZ$
 $\rightarrow 2\ell 2\nu$ also picks up lost-lepton contributions
 from $q\bar{q}' \rightarrow WZ$

Estimation strategy: MC-based with data handle

- \rightarrow Select a $3\ell + p_T^{\text{miss}}$ sample of WZ prod.
- \rightarrow Has minimal Higgs contribution
- \rightarrow Kinematic behavior of ZZ and WZ similar
- \rightarrow Take shapes and common uncertainties from simulation
- \rightarrow Calibrate signal region MC shapes using a joint fit with this control sample



30



Off-shell $2\ell 2\nu$: Noninterfering backgrounds

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- Final estimate performed with a joint fit to a 3ℓ WZ CR

Instrumental $p_{\text{T}}^{\text{miss}}$:

- Comes primarily from the $p_{\text{T}}^{\text{miss}}$ tail of Z +jets
- Estimated from the single-photon CR by reweighting photons to $Z \rightarrow \ell\ell$

Instrumental p_T^{miss}

$Z(\rightarrow \ell\ell)+\text{jets}$ events with large cross section can contaminate the signal region when there are mismeasured jets or large unclustered energy.

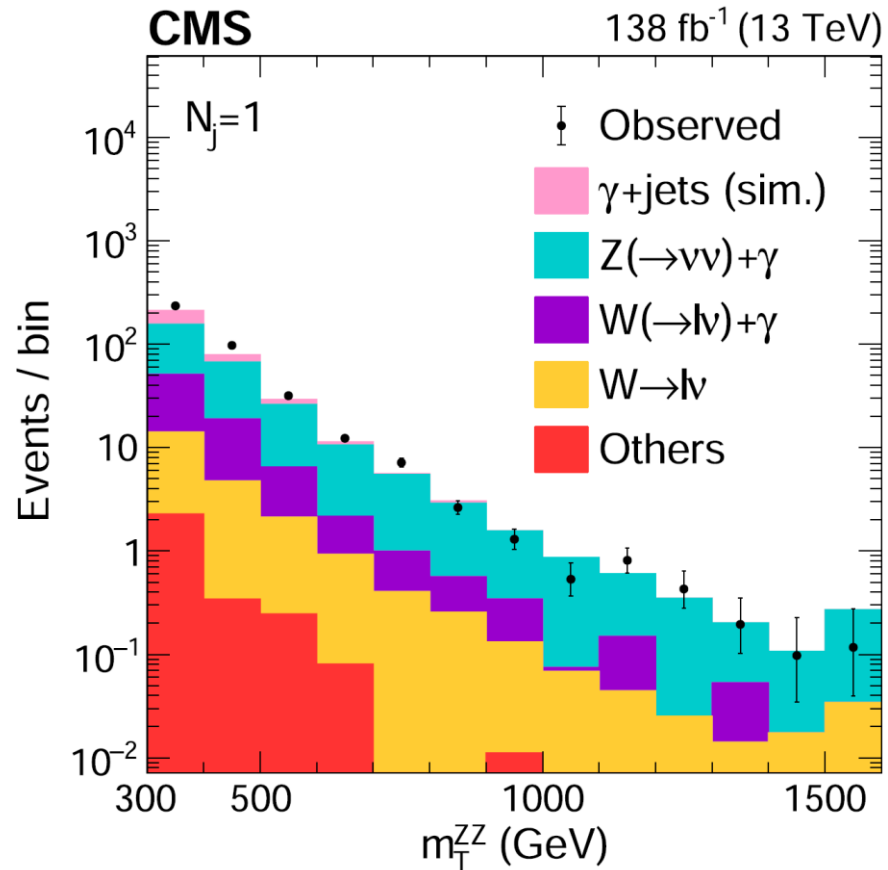
→ Small smearing and tight selection, but event rate is high.

Estimation strategy: Data-driven

→ Select $\gamma+\text{jets}$ data to model p_T^{miss} response

→ Calibrate γ kinematics to those for the Z

→ Subtract real- p_T^{miss} processes (histograms up to $Z(\rightarrow \nu\nu)\gamma$)



Off-shell $2\ell 2\nu$: Noninterfering backgrounds

$q\bar{q} \rightarrow ZZ, WZ$:

→ Dominant backgrounds at high m_{T}^{ZZ}

→ Shapes and normalizations taken from all possible variations of the simulation

→ Final estimate performed with a joint fit to a 3ℓ WZ CR

Instrumental $p_{\text{T}}^{\text{miss}}$:

→ Comes primarily from the $p_{\text{T}}^{\text{miss}}$ tail of Z +jets

→ Estimated from the single-photon CR by reweighting photons to $Z \rightarrow \ell\ell$

Nonresonant ($t\bar{t}, WW$):

→ Estimated from reweighting $e\mu$ events for trigger and lepton efficiencies

Nonresonant ($t\bar{t}$, WW) background

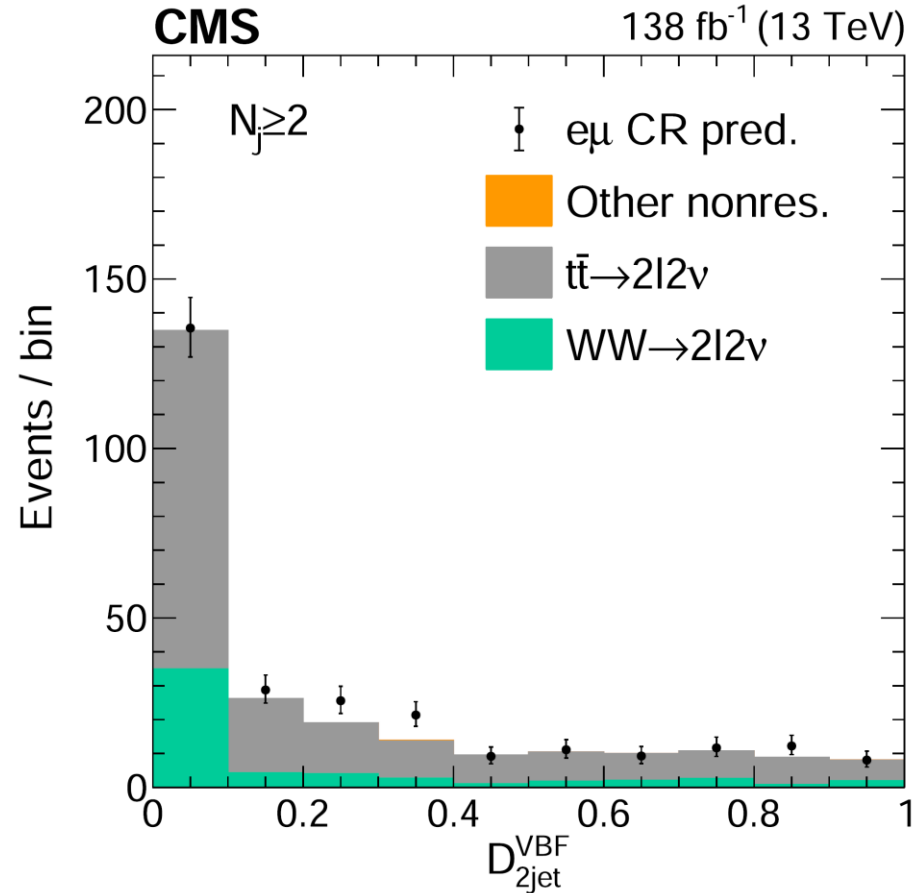
SR has non- $Z(\rightarrow \ell\ell)$ contributions with a real $\ell\ell$ pair (fully leptonic $t\bar{t}$, WW decays).

Estimation strategy: Data-driven

→ Pick $e\mu$ events with otherwise identical reqs.

→ Rate of $e\mu = 2 \times$ rate of ee or $\mu\mu$

→ Reweight for lepton and trigger efficiencies to reproduce ee and $\mu\mu$ behavior



Off-shell $2\ell 2\nu$: Noninterfering backgrounds

$q\bar{q} \rightarrow ZZ, WZ$:

- Dominant backgrounds at high m_{T}^{ZZ}
- Shapes and normalizations taken from all possible variations of the simulation
- Final estimate performed with a joint fit to a 3ℓ WZ CR

Instrumental $p_{\text{T}}^{\text{miss}}$:

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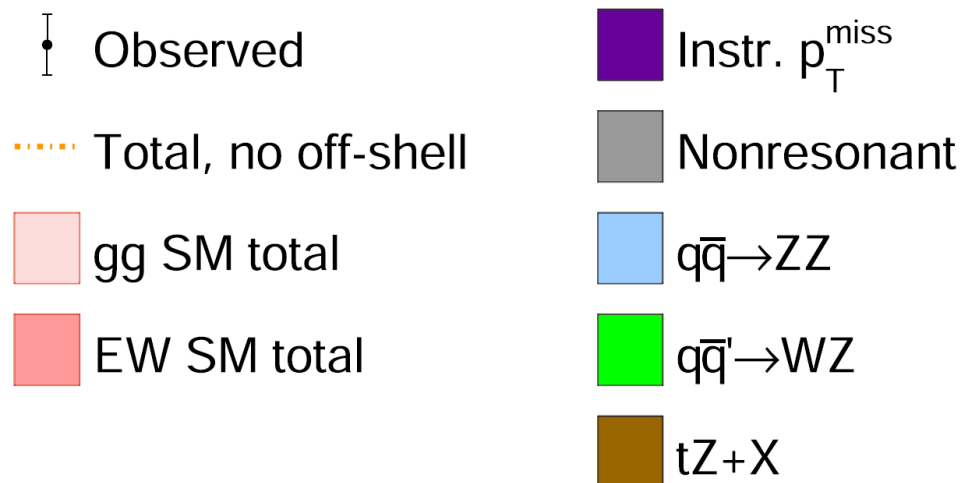
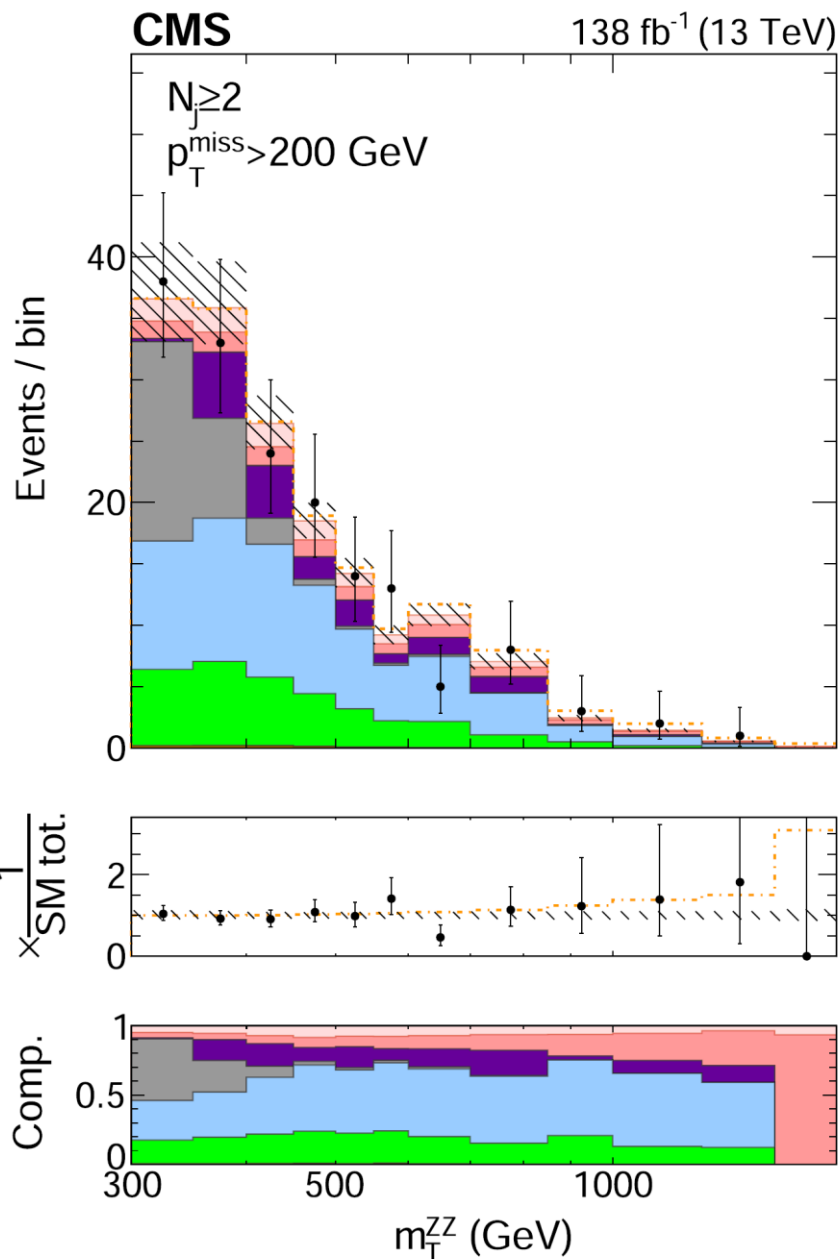
Nonresonant ($t\bar{t}, WW$):

- Estimated from reweighting $e\mu$ events for trigger and lepton efficiencies

$tZ + X$:

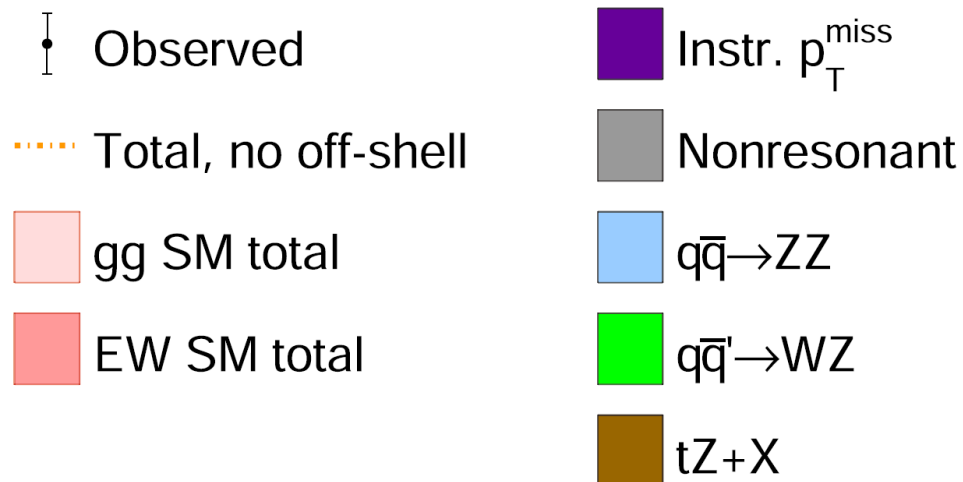
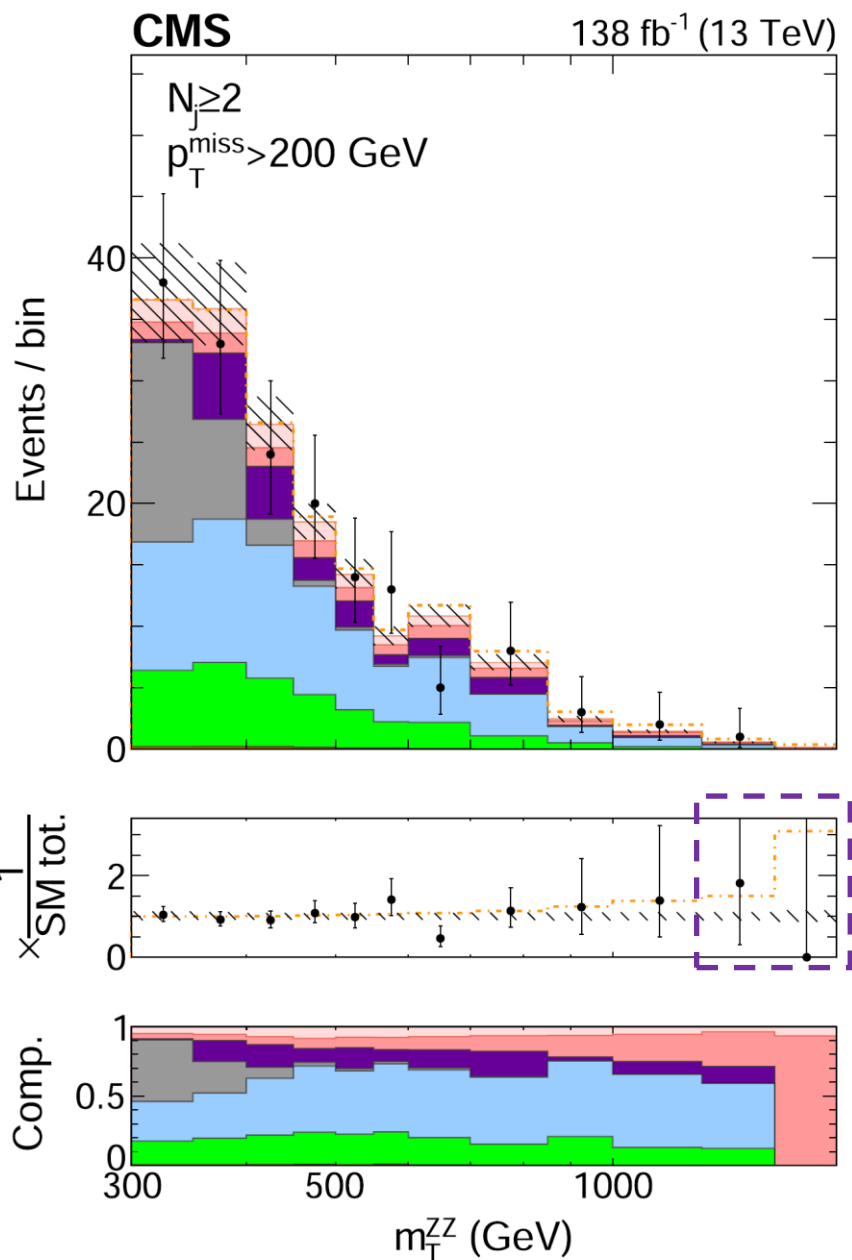
- Minor contribution
- Estimated fully from simulation

Off-shell $2\ell 2\nu$: Event distributions



Example from $N_j \geq 2, p_T^{\text{miss}} > 200$ GeV

Off-shell $2\ell 2\nu$: Event distributions

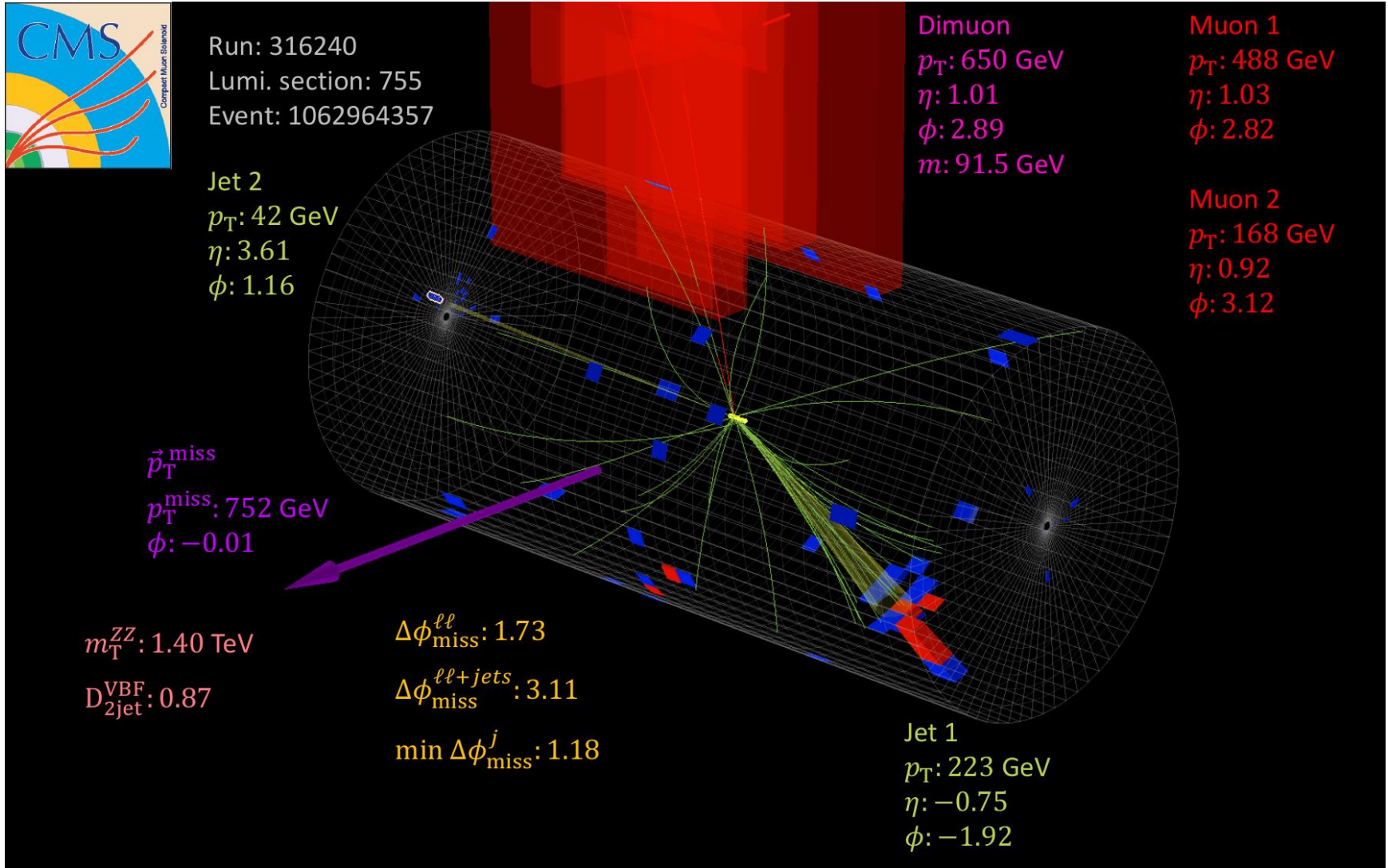


Example from $N_j \geq 2$, $p_T^{\text{miss}} > 200$ GeV

No – off-shell ($\Gamma_H = 0$ MeV) hypothesis inconsistent with observed data

→ Visible at high m_T^{ZZ}

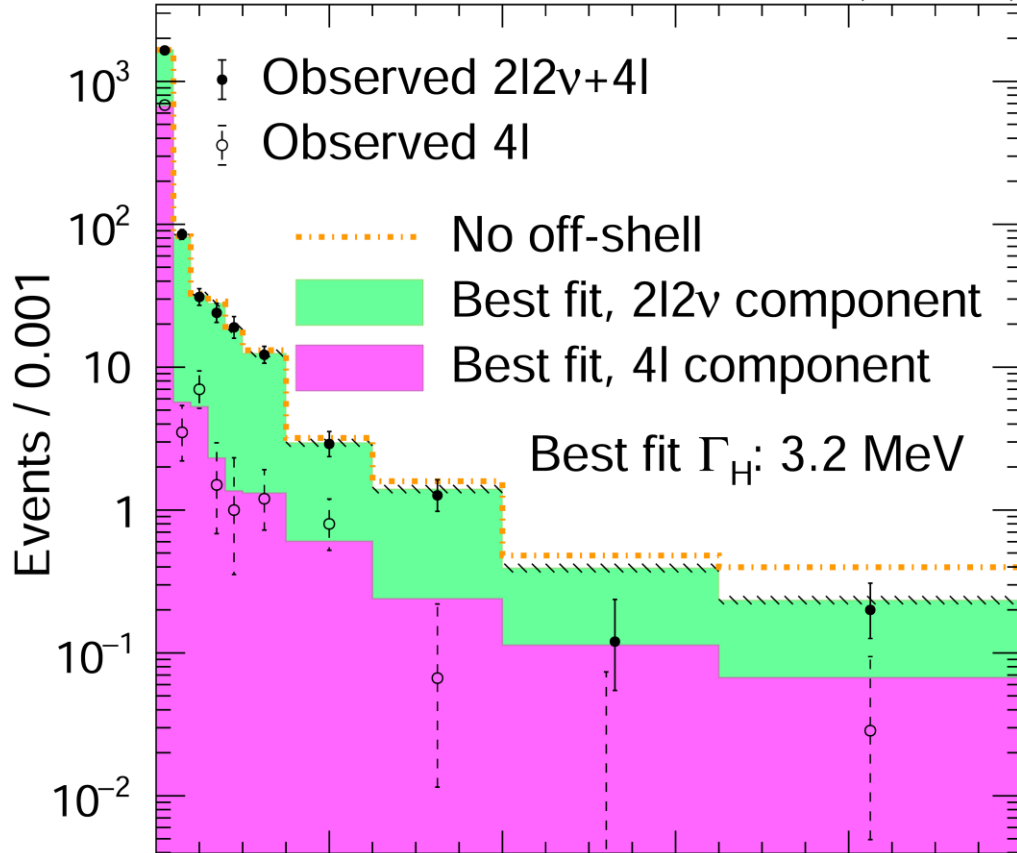
Off-shell $2\ell 2\nu$: Golden VBF/VBS event



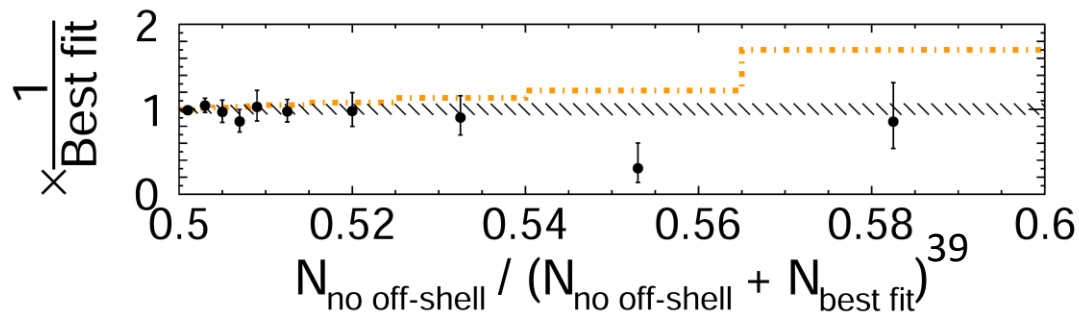
Here is a clean VBF/VBS $ZZ(\rightarrow 2\mu 2\nu)+2$ jets candidate at high mass with large $D_{2\text{jet}}^{\text{VBF}}$ value, as also evident from the two high-rapidity jets at opposite hemispheres.

Evidence for off-shell from $2\ell 2\nu + 4\ell$

CMS $\leq 138 \text{ fb}^{-1}$ (13 TeV)

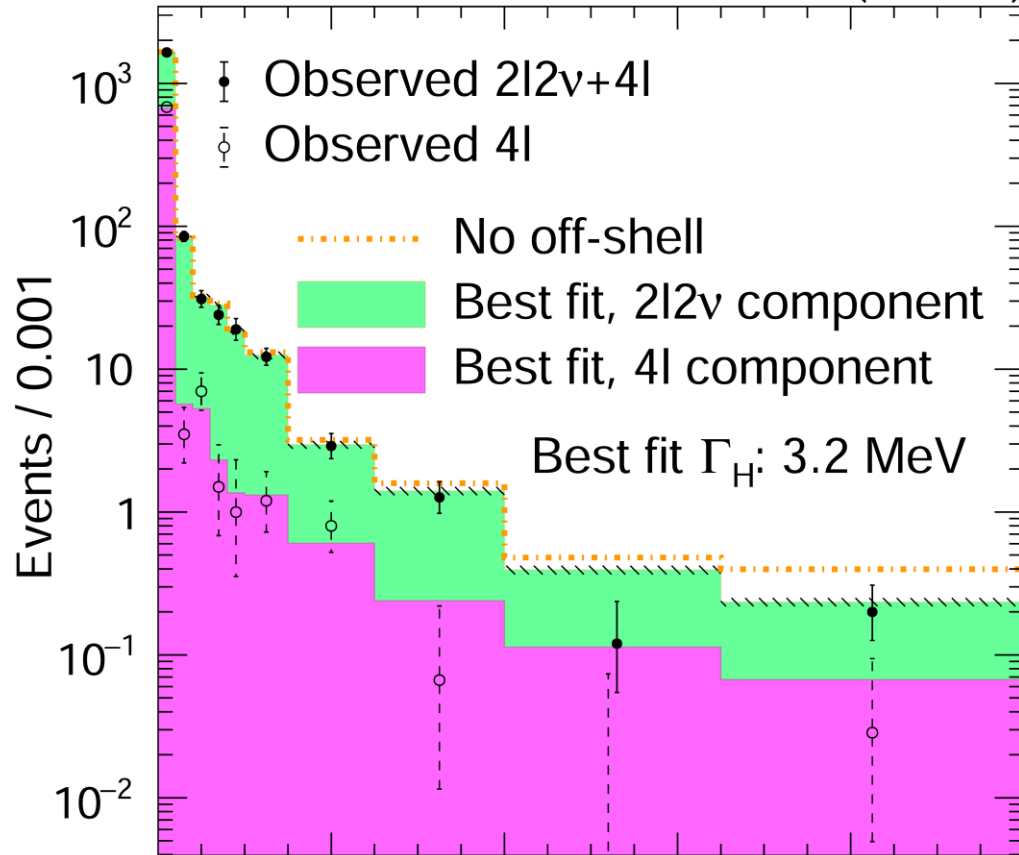


Plotted is a bin-by-bin ratio over the histograms of all observables and categories.



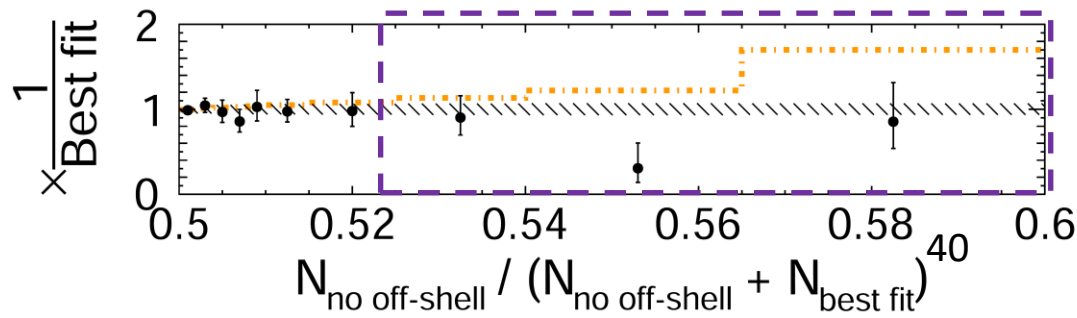
Evidence for off-shell from $2\ell 2\nu + 4\ell$

CMS $\leq 138 \text{ fb}^{-1}$ (13 TeV)

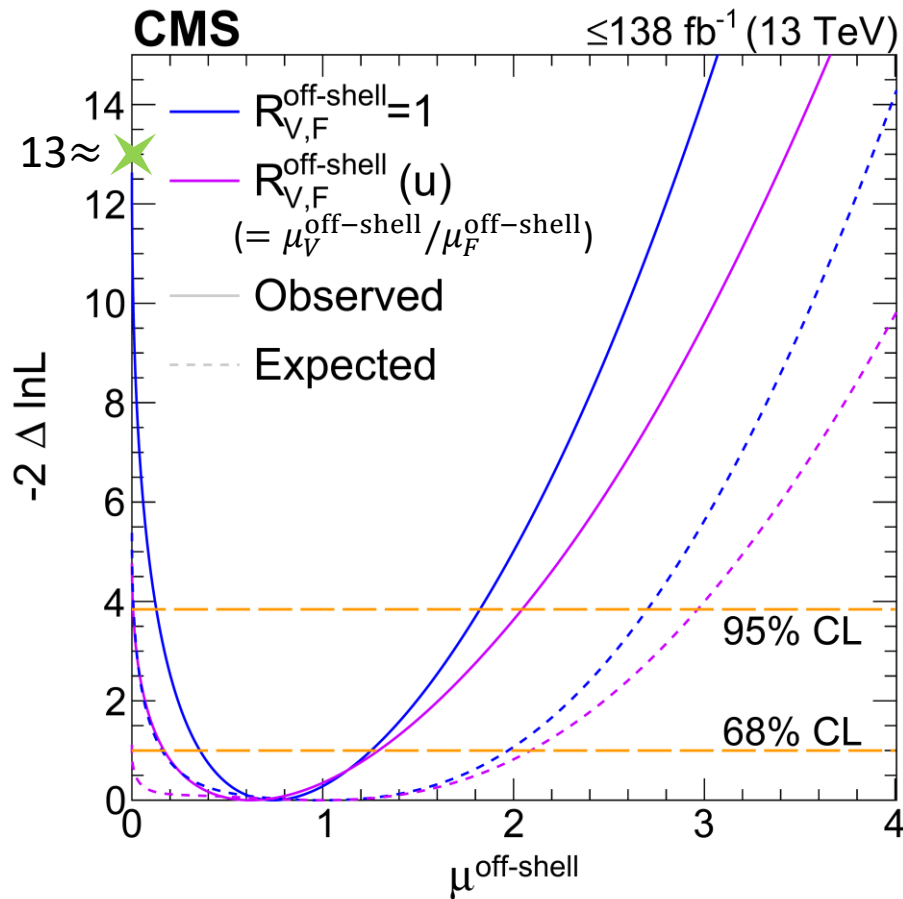


Plotted is a bin-by-bin ratio over the histograms of all observables and categories.

Once all bins and channels are considered, significance reaches 3.6 standard deviations.

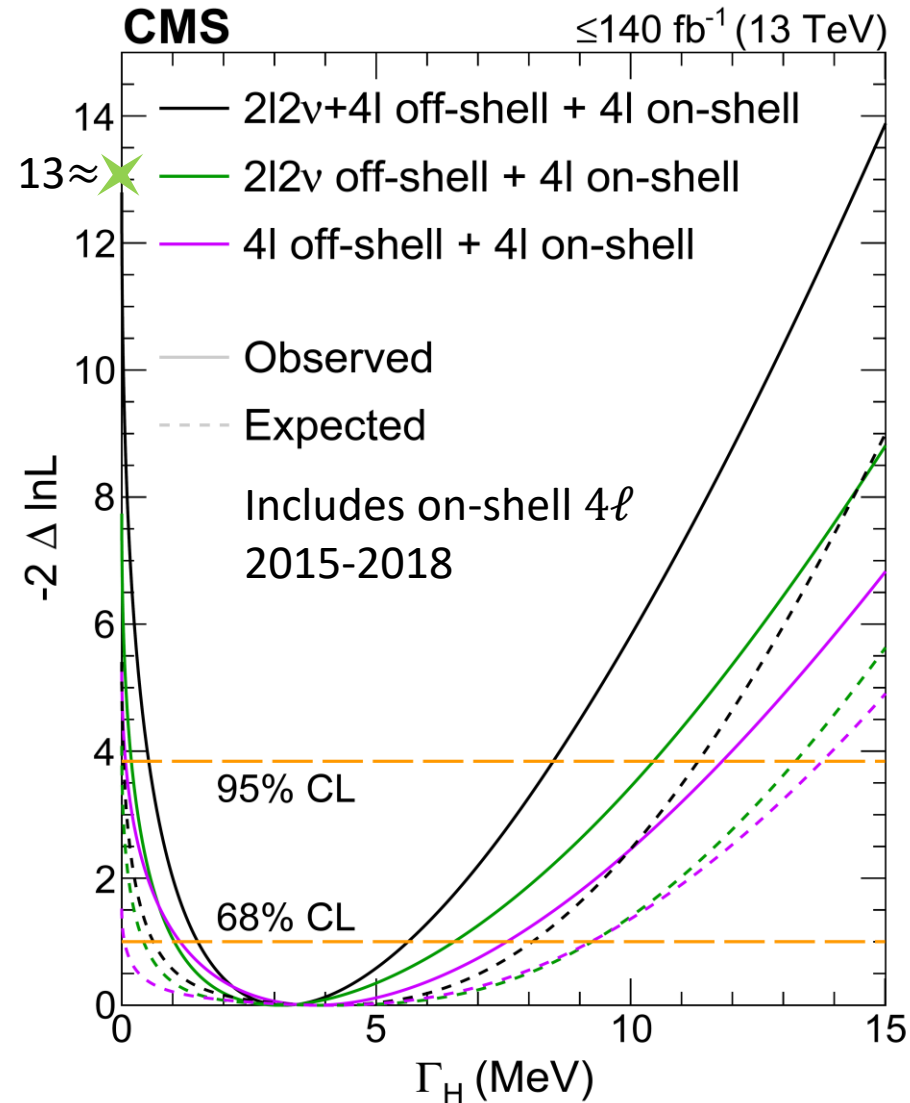


Evidence for off-shell from $2\ell 2\nu + 4\ell$



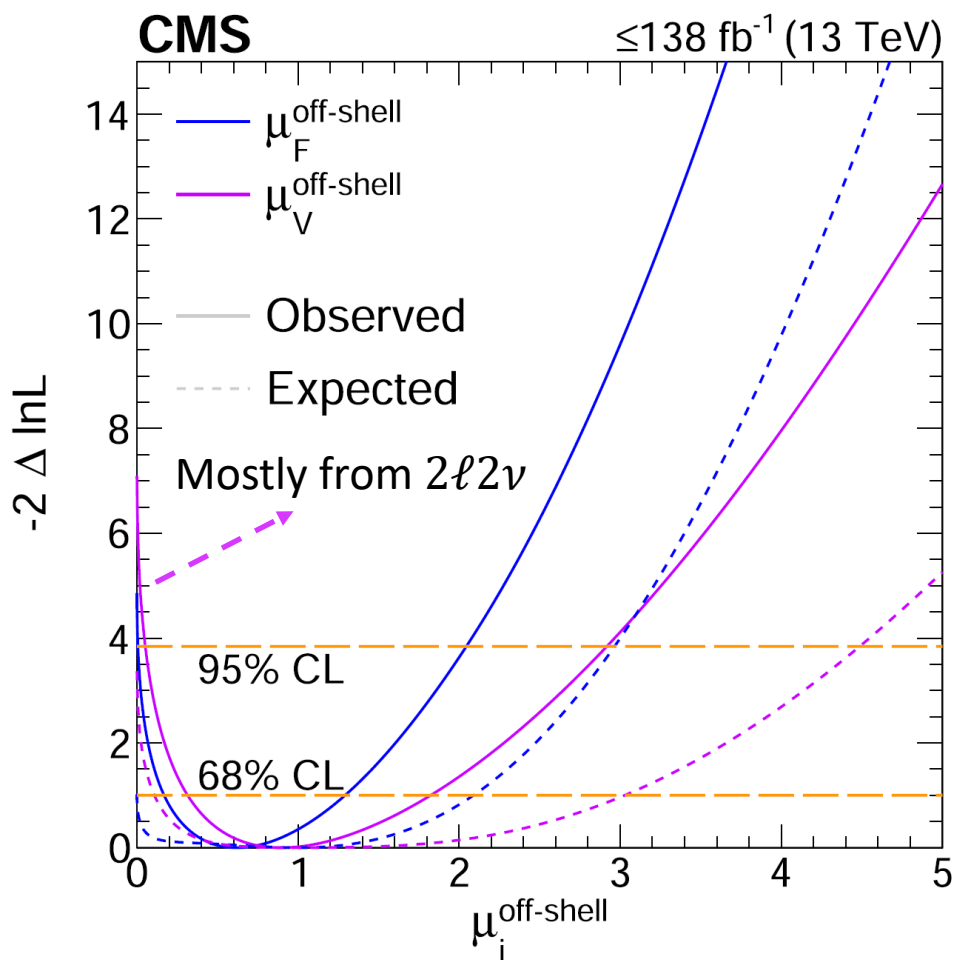
No – off-shell scenario ($\mu^{\text{off-shell}} = 0$)
 is excluded at $p=0.0003$ (3.6 std. devs.)

→ Similar results from ATLAS
 (see [backup](#))



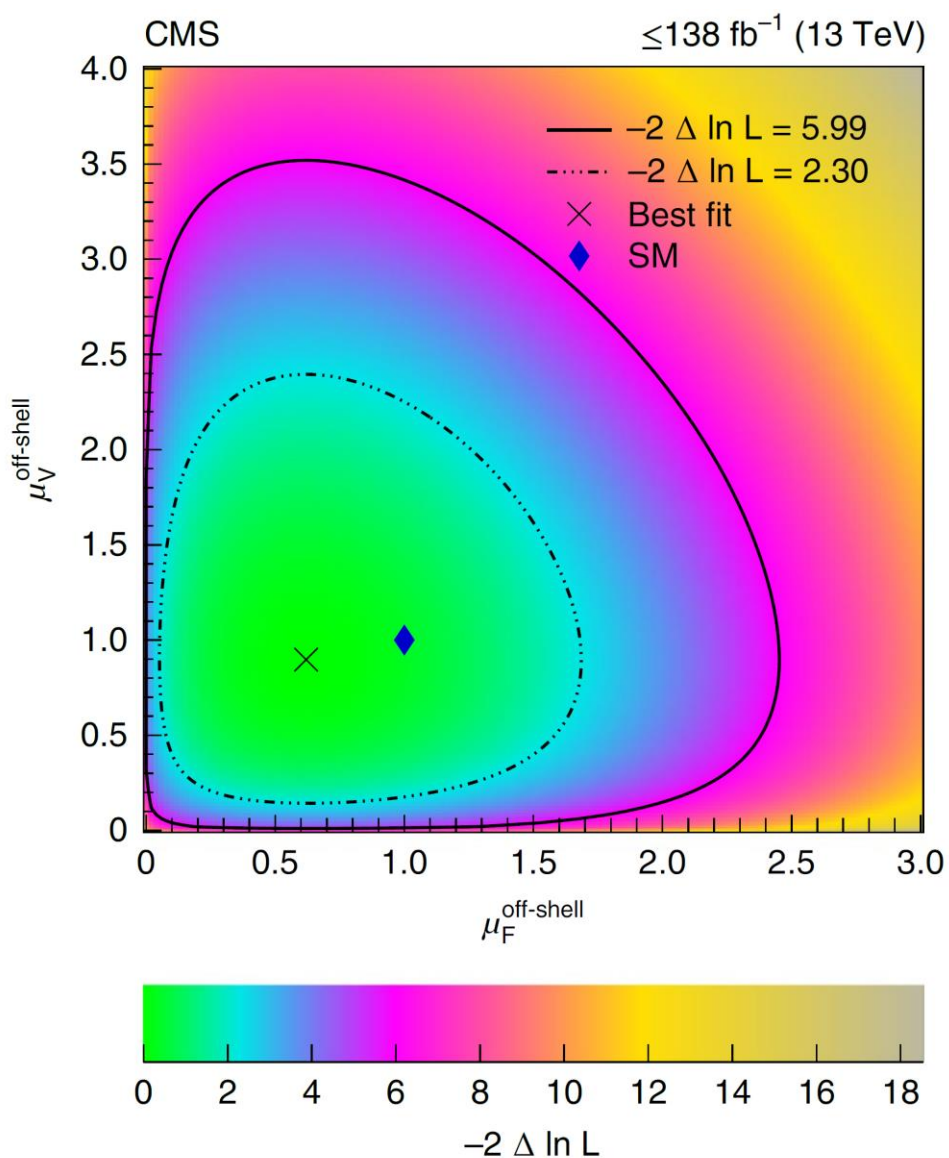
Observed $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV
 $[0.5, 8.5]$ MeV @ 95% CL

Off-shell combination: $\mu_F^{\text{off-shell}}$, $\mu_V^{\text{off-shell}}$

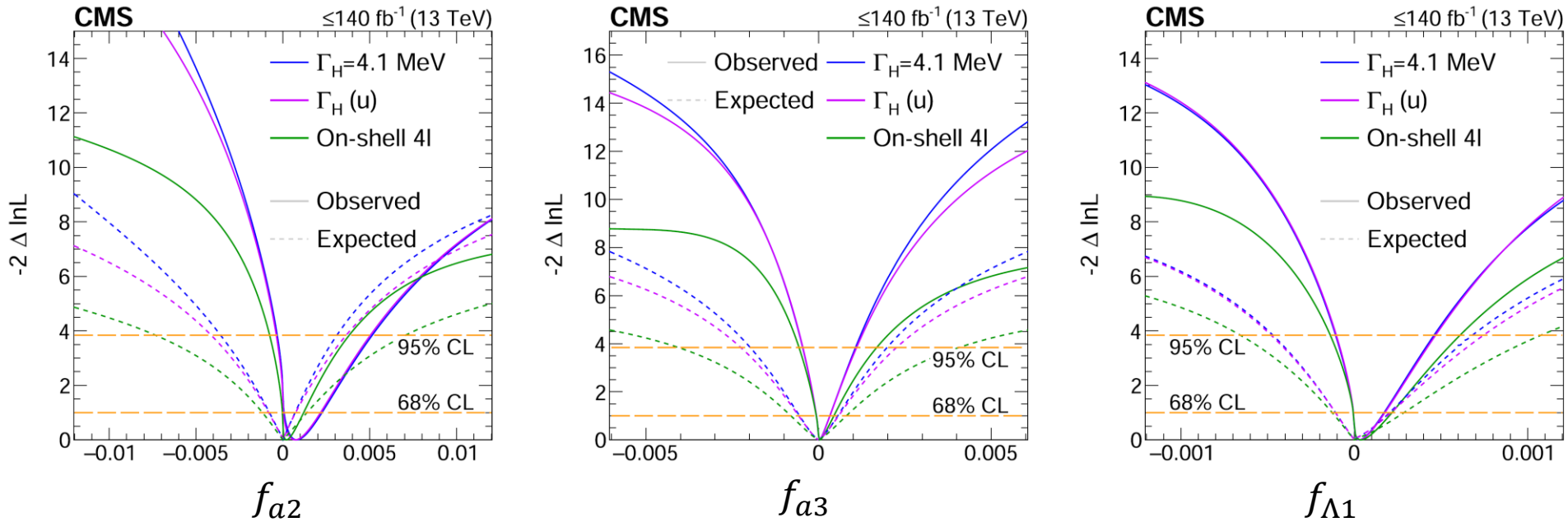


Joint constraints on

$\mu_F^{\text{off-shell}}$ (gg production) and
 $\mu_V^{\text{off-shell}}$ (EW production)



Anomalous HVV couplings from off-shell

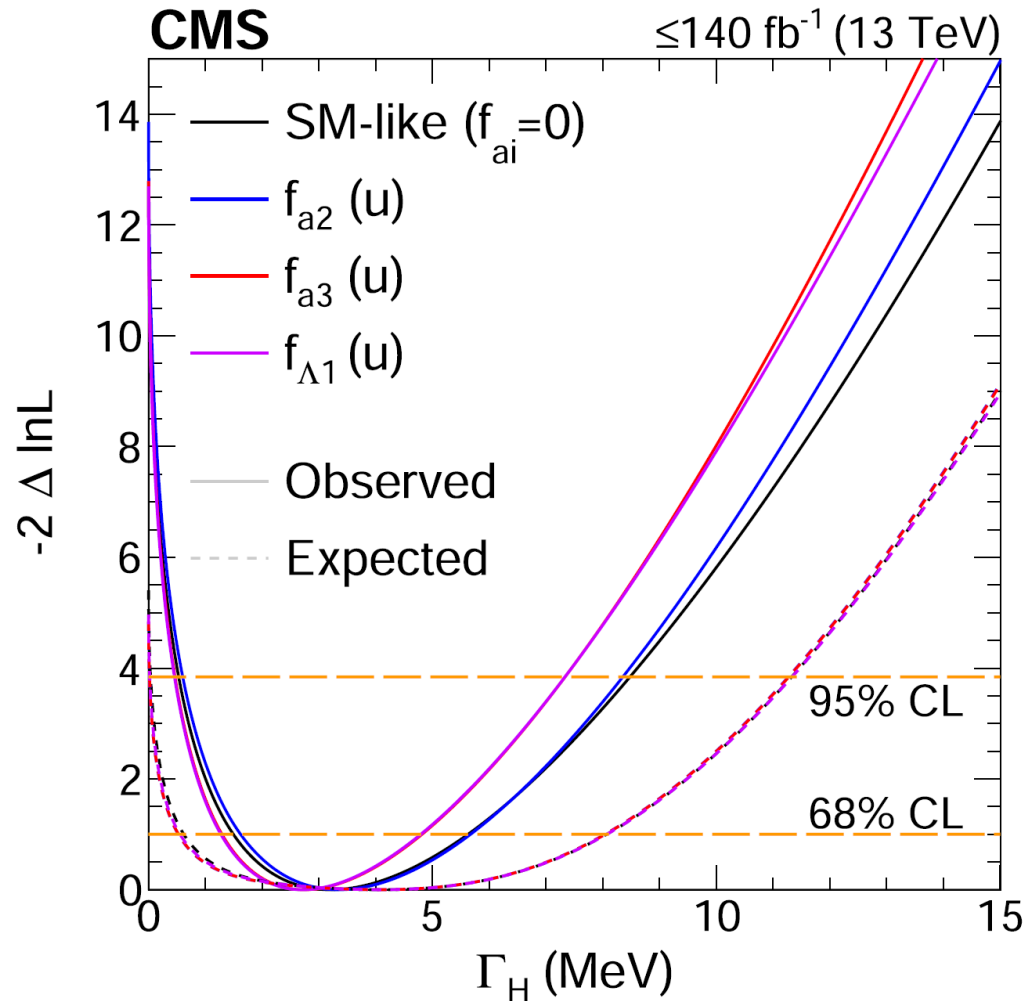


$O(10^{-5} - 10^{-3})$ constraints on fractional BSM contributions

$O(10\%)$ improvement from adding off-shell information

Other on-shell - only measurements [1] are consistent with these results and the SM, and constrain these couplings even further.

Anomalous HVV couplings from off-shell



Measurement of the width is also stable when different anomalous HVV couplings are tested.

Summary

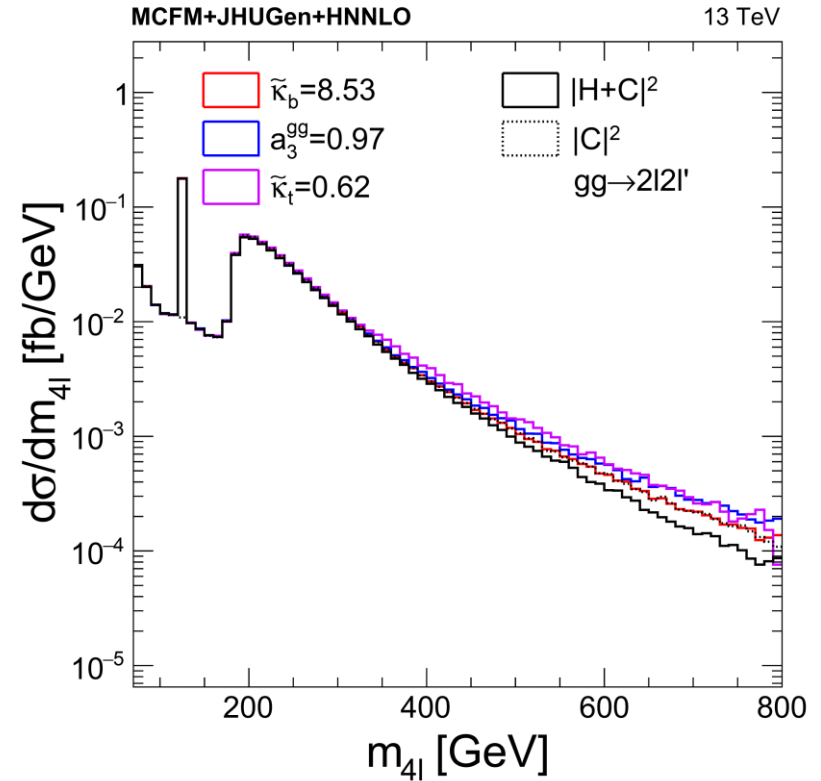
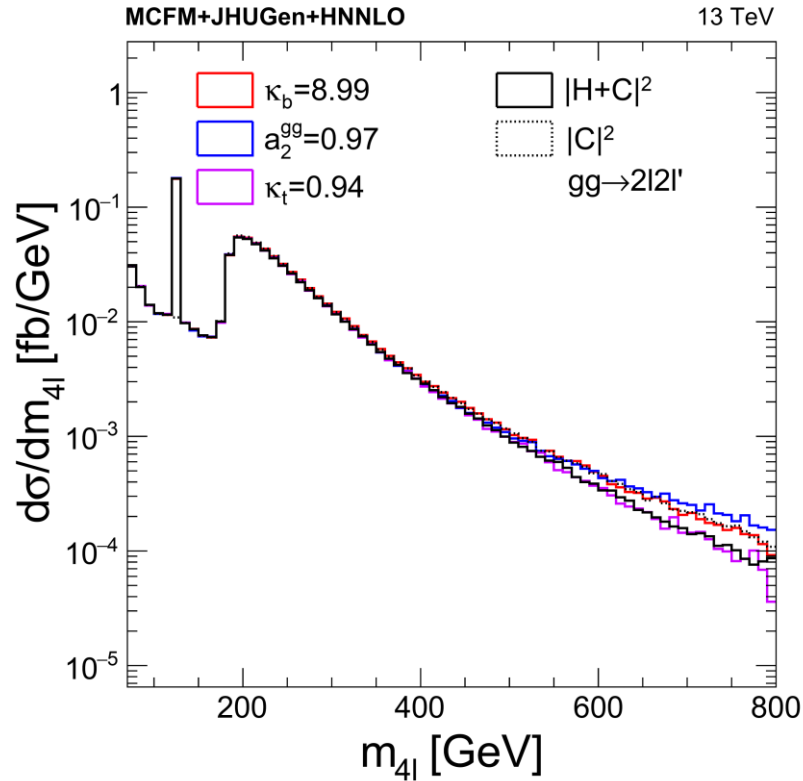
Presented the current status of the off-shell analysis:

- Off-shell Higgs production in VV final states Important in the SM for unitarity
- Combination with on-shell information can allow us to measure the total width
 - Large deviations can hint at BSM couplings to the Higgs boson
- Analysis consists of 4ℓ off-shell and on-shell, and $2\ell 2\nu$ off-shell components
 - Particular emphasis is given today on the most recent $2\ell 2\nu$ off-shell analysis
 - Additional WZ CR promising to constraint the main non-interfering $q\bar{q} \rightarrow ZZ$ bkg.
- Evidence for off-shell Higgs boson contributions in the $ZZ \rightarrow 4\ell + 2\ell 2\nu$ final state
- Best total width measurement from CMS is now $\Gamma_H = 3.2_{-1.7}^{+2.4}$ MeV.
 - Measurement is stable if anomalous HVV couplings, which have the largest impact on kinematics, are considered.

Stay tuned for more exciting results as we continue to collect data in Run 3 and develop analysis methods further!

Back-up

Off-shell & BSM ggH couplings



Effects [1] only visible for a *purely BSM Higgs boson* beyond ~ 500 GeV, couplings constrained to a fraction of these values [2]

$$A(ggH) \sim \sum_f \kappa_f F_f(q_1, q_2 | m_f) + \tilde{\kappa}_f \tilde{F}_f(q_1, q_2 | m_f) + |a_2| e^{i\phi_{a_2}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + |a_3| e^{i\phi_{a_3}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Similar conclusions from couplings that affect the continuum [3,4]

[1] [Sarica, U. Springer Theses \(2019\)](#)

[2] [CMS Collaboration \(2022\); arxiv:2205.05120](#)

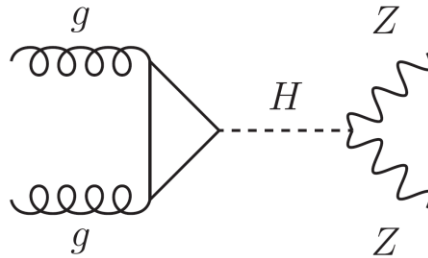
[2] [LHC Higgs Off-shell Subgroup; CDS:2801789 \(2022\)](#)

[3] [SMEFIT Collaboration; JHEP 11 089 \(2021\) \(arxiv:2105.00006\)](#)

No sensitivity with current number of events, so we assume gg couplings are as in the SM.

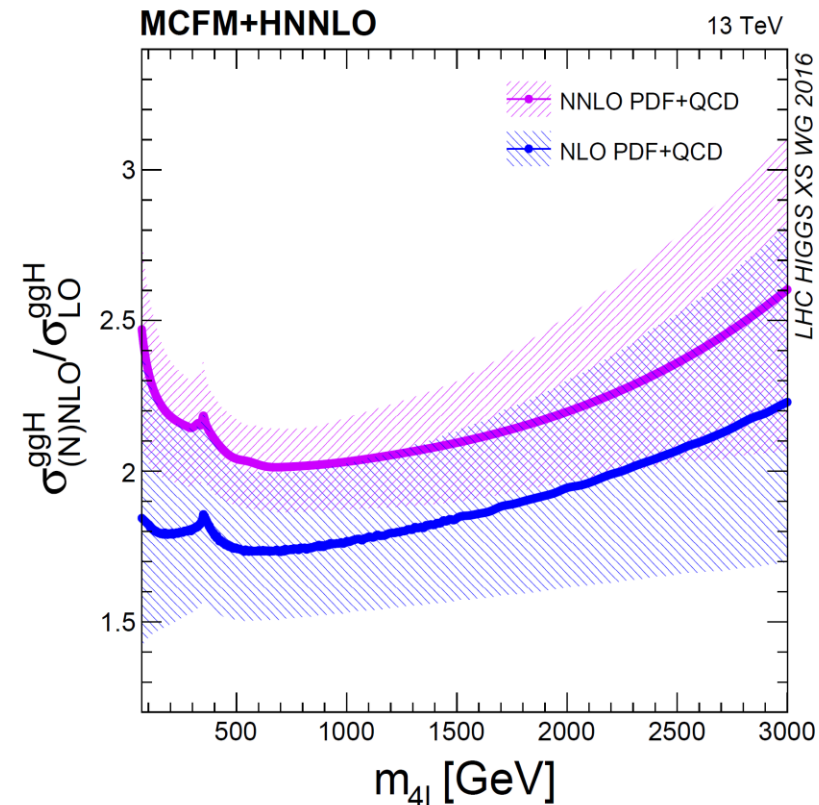
Gluon fusion: Higgs amplitude

$$gg \rightarrow H \rightarrow ZZ:$$



Full cross section calculation is available at different orders for the different components:
 $\rightarrow gg \rightarrow H \rightarrow ZZ$: N^3LO in QCD around $m_H = 125$ GeV, NNLO for the full m_{ZZ} dependence, NLO or LO for event simulation [1]

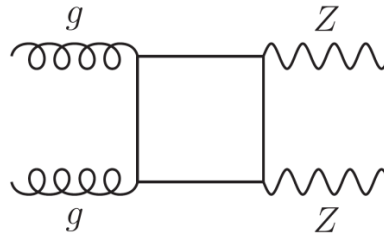
\rightarrow K-factors are large for NLO/LO (~ 1.7 - 1.8), smaller and flatter for NNLO/NLO (~ 1.2 - 1.3), and the $N^3LO/NNLO$ K-factor is 1.10.



[1] [LHC Higgs WG; CERN-2017-002-M \(arxiv:1610.07922\)](#)

Gluon fusion: Continuum amplitude

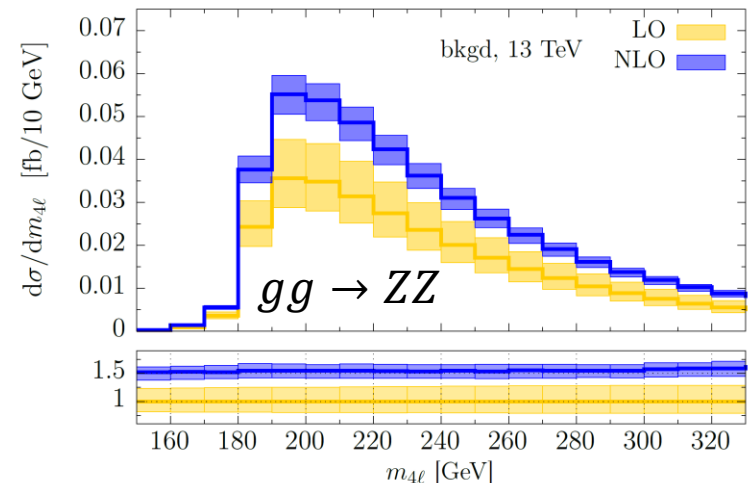
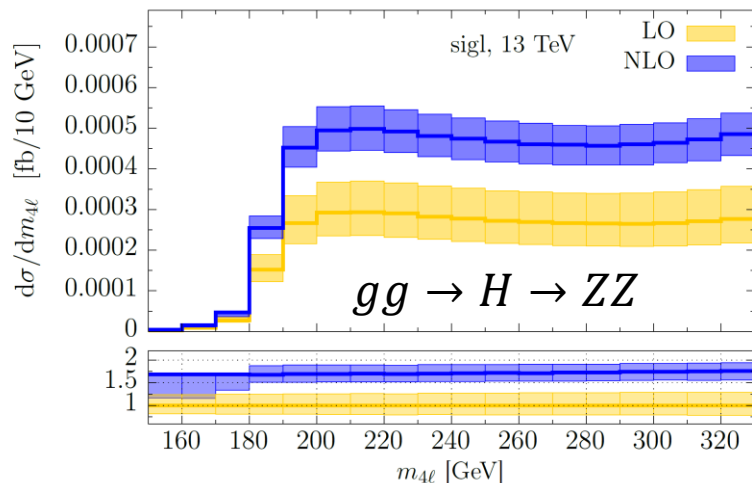
$$gg \rightarrow ZZ:$$



Full cross section calculation is available at different orders for the different components:
 → $gg \rightarrow ZZ$ continuum (and interference): Only full calculation and simulation with loop effects available at LO in QCD

→ Approximate NLO calculations [1] show K-factors for $gg \rightarrow ZZ$ continuum, $gg \rightarrow H \rightarrow ZZ$, and their interference within $\sim 10\%$ suggesting corrections are mostly of soft/collinear nature

→ Current procedure is to use K-factors for $gg \rightarrow H \rightarrow ZZ$ on all components, and unc. $\kappa_{ggZZ} = 1 \pm 0.1$ on continuum with related scale $\sqrt{\kappa_{ggZZ}}$ on interference.



Gluon fusion: Event generation

For the Higgs amplitude contribution, continuum ZZ, or interference, MC event generation can be done in two ways [1]:

→ Use JHUGen/MCFM to produce events at LO in QCD, apply NNLO K-factors and N³LO flat normalization

→ Relies on Pythia for jet multiplicity and kinematics

→ Use POWHEG to produce $gg \rightarrow H$, JHUGen for $H \rightarrow ZZ$, and the MELA matrix elements from JHUGen/MCFM (instead of event generation) to obtain continuum ZZ and interference.

→ POWHEG cannot produce off-shell line shape. Instead, produce samples for Higgs samples at $m_H = 125, 160 \dots 200 \dots 3000$ GeV, which have increasingly larger widths.

→ $h_{\text{fact}} = m_H/10 + 37.5$ GeV to match p_T^H to NNLO+NNLL HRES predictions.

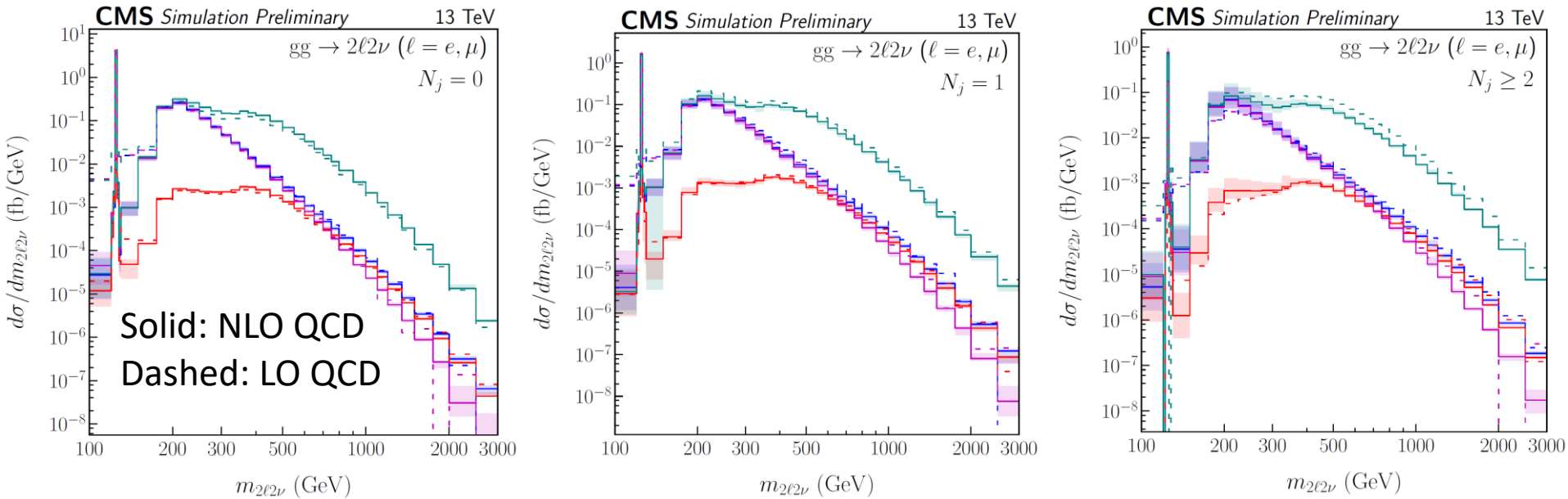
→ For the $gg \rightarrow H(125) \rightarrow ZZ$ amplitude, the only differences in these samples are the **propagator** and the correction of the m_{ZZ} line shape for the **evolution of BR($H \rightarrow ZZ$)**.

The **former** is just reweighting the propagator to a BW($m_H = 125$ GeV, $\Gamma_H = 4.1$ MeV), so it is basically part of the MELA reweighting procedure, and the **latter** is added as a modification of event weights when running the JHUGen decay step.

→ The samples are glued together in the end to produce the full spectrum. The mathematical formulation is provided extensively in the note.

→ We observe this approach produces stable results in jet multiplicity and other kinematics after Pythia parton shower.

Gluon fusion: Jet-exclusive



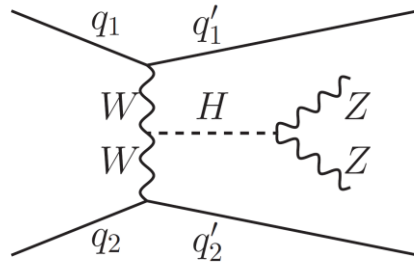
Analyses need better control over jet multiplicity and kinematics than what MC LO in QCD + parton shower can provide.

When split by jet (*) multiplicity, $N_j = 0, 1$ have similar levels of agreement
→ LO m_{ZZ} distortion at $N_j \geq 2$ understood to be because of parton shower effects

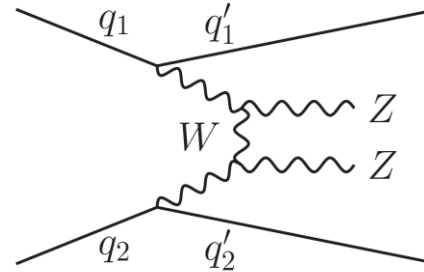
(*) Gen.-level anti- k_T $\Delta R = 0.4$ jets with $p_T > 30$ GeV, $|\eta| < 4.7$

EW production simulation

$$q_1 q_2 \rightarrow q'_1 q'_2 H \rightarrow q'_1 q'_2 Z Z:$$



$$q_1 q_2 \rightarrow q'_1 q'_2 Z Z:$$



Matrix element (MELA) and event simulation (MCFM/JHUGen) available for SM or BSM Higgs hypotheses, and continuum at LO in QCD consistently.

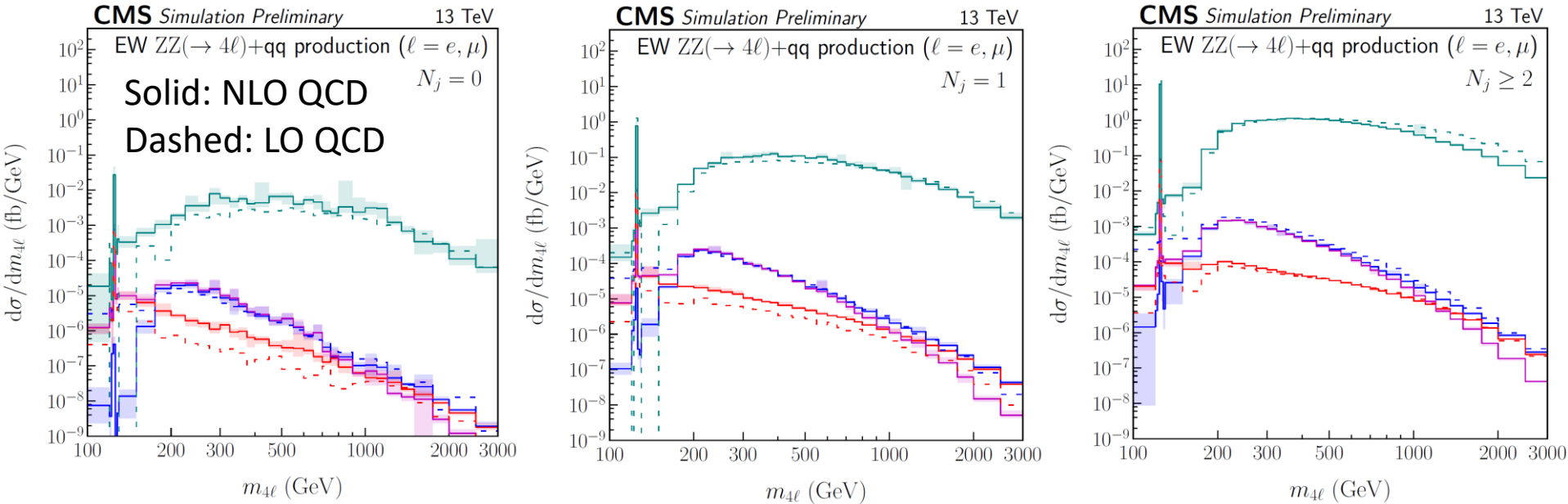
→ Improve event simulation technique for jet kinematics [1] by

- starting with POWHEG+JHUGen samples for NLO VBF, and ZH and WH NLO + MiNLO HVJ)
- apply MELA ME reweighting

→ Account for the extra partons from POWHEG by merging four-momenta of gluons (or $g \rightarrow q\bar{q}$ decays) to the closest quark

→ We check that the LO topology is approximated decently.

EW process: Jet-exclusive distributions



Analyses need better control over jet multiplicity and kinematics than what MC LO in QCD + parton shower can provide.

When events are split by jet multiplicity and equivalent selection requirements are placed on the LO and NLO MC, we find differences in $N_j = 0, 1$.

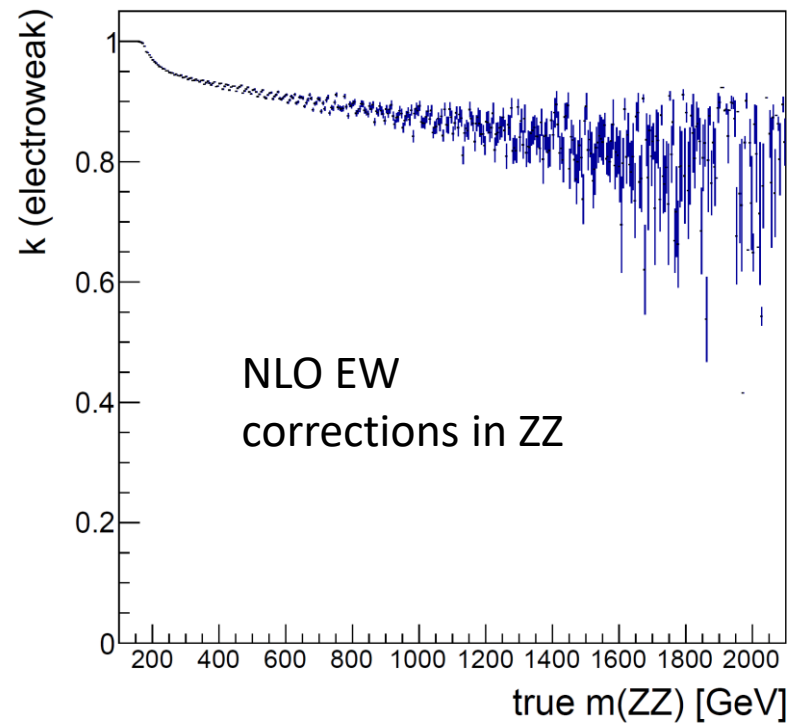
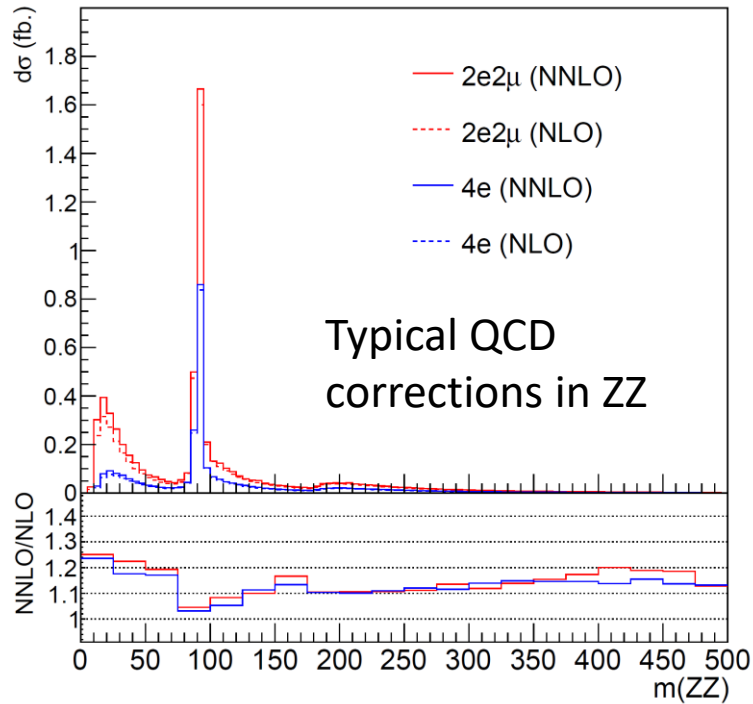
→ Discrepancies are understood to be from imprecise parton shower modelling in the LO MC.

EW processes: Recasting NLO topology to LO

The MELA and MELAANALYTICS packages impose several rules on the merging procedure for the EW processes in order to make sensible predictions:

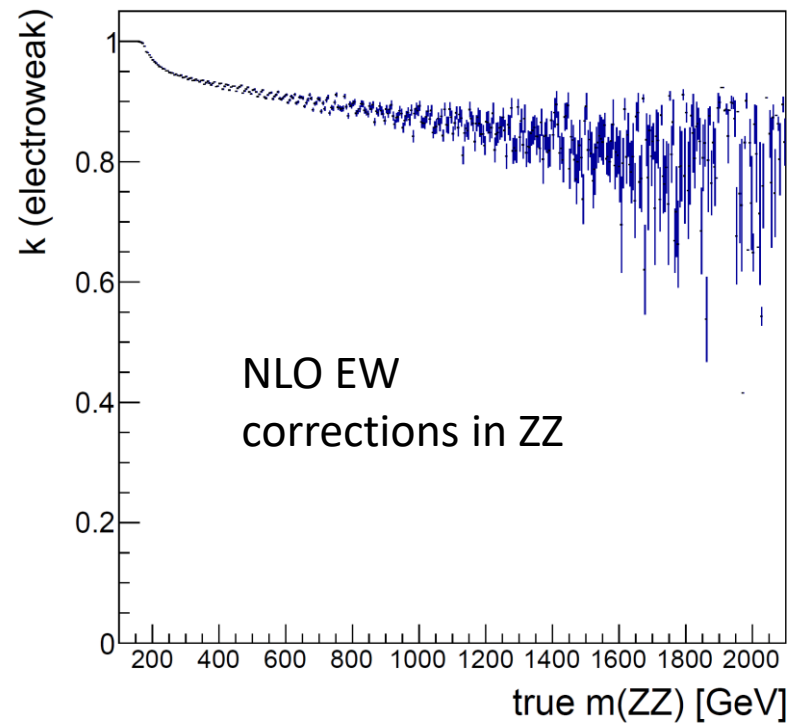
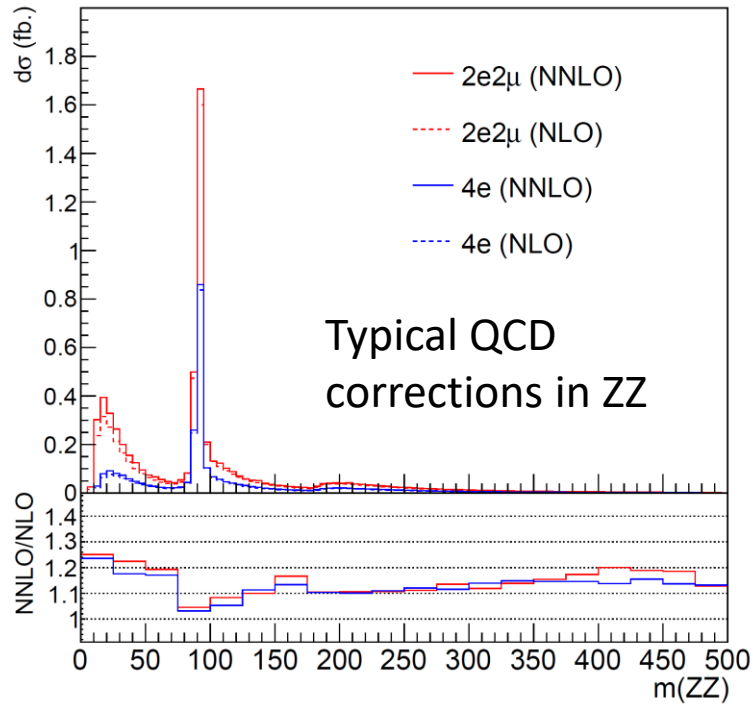
- An incoming gluon is never merged into an incoming quark. This rule is invoked implicitly as the q^2 of the incoming partons is always the largest compared to that of any other pair of partons in the event.
- Gluons are never merged into the decay products of the H boson from the JHUGen step as they are produced during the production of the H boson with no prior knowledge about the boson's decay.
- Gluons are also never merged into the decay products of the associated W or Z boson in the VH samples. Doing so distorts the BW nature of these resonances significantly.
- All merging is done in the convention of outgoing particles. This means the four-momenta and charge of incoming particles are reversed in the intermediate steps when those of the two merged particles are summed.
- When an incoming gluon is merged into an outgoing quark, the charge (i.e., PDG id) and the four-momentum of the quark are reversed in the final step of the LO topology construction. This reversion is done so that the event topology ensures having exactly two incoming quarks as expected in the LO matrix elements.
- In the VH samples, when extra gluons are encountered, the merging of individual gluons and that of a combined gluon (i.e., from a $g \rightarrow gg$ process) are all considered separately.
- In the VH samples, it is also possible to encounter two extra quarks instead of gluons. These extra quarks are merged into a gluon substitute first, as they are from a $g \rightarrow q\bar{q}$ branching process, before the merging of this gluon substitute is considered.
- Every merging permutation is considered, rated with the product of the dot-products between the merged quarks and gluons, and those that do not produce an incoming-outgoing parton composition that is compatible with the main physics process of the sample (i.e., VBF, ZH, or WH) are skipped.
- A momentum redistribution procedure is applied on the incoming and outgoing particles associated with H boson production so that the resultant topology features massless particles, which is what is required from the use of massless spinors in matrix elements. Denoting the momenta of the two final incoming or outgoing partons as p_1 and p_2 , an intermediate four-momentum k is added to p_1 and subtracted from p_2 such that $|p_1 + k|^2 = |p_2 - k|^2 = 0$. This step is common to any matrix element computed using the MELA package. Because event-by-event reweighting is done through a ratio of matrix elements, which are invariant under any arbitrary boost of the event topology, and because factors coming from PDFs cancel in the ratio, the common boost of all particles does not affect reweighting as long as momentum conservation is maintained strictly, and is therefore adjusted arbitrarily.

$q\bar{q} \rightarrow ZZ, WZ$ simulation



- POWHEG simulation at NLO in QCD is used for the non-interfering ZZ and WZ backgrounds.
- NNLO QCD corrections can be calculated as a function of m_{ZZ} .
 - Relative uncertainties from the MC close to NNLO QCD cross section uncertainties
 - Keep the relative uncs. as in the MC to predict the uncertainty in different kinematic regions and jet categories

$q\bar{q} \rightarrow ZZ, WZ$ simulation



POWHEG simulation at NLO in QCD is used for the non-interfering ZZ and WZ backgrounds.

→ NLO EW corrections typically reach -20% in ZZ (-10% in WZ) at ~ 1 TeV [1].

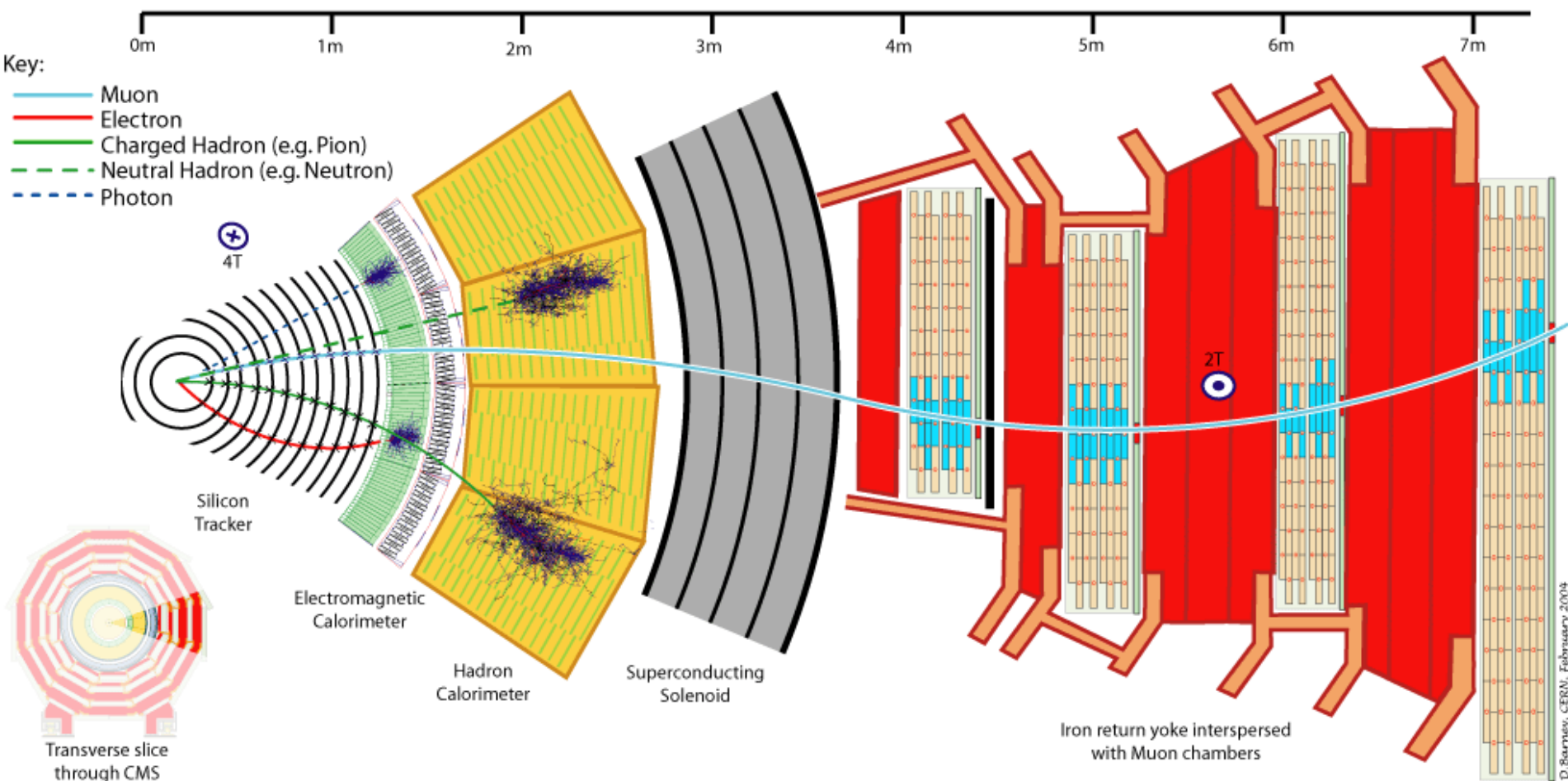
→ Assign the following uncertainty prescription [2] based on $\rho = \frac{|\sum_i \vec{p}_T^i|}{\sum_i |\vec{p}_T^i|}$ over leptons:

$$\delta = \begin{cases} (1 - K_{QCD}^{NLO})(1 - K_{EW}^{NLO}) & \text{if } \rho < 0.3 \\ (1 - K_{EW}^{NLO}) & \text{otherwise} \end{cases}$$

[1] Bierweiler, A. et al.; JHEP 12 071 (2013) (arxiv:1305.5402) 56

[2] Gieseke, S. et al.; EPJ C 74 2988 (2014) (arxiv:1401.3964)

Particle reconstruction in a nutshell



Use particle-flow algorithm [1]:

- Correlate basic detector info. from different layers to identify muons, electrons, photons, and charged and neutral hadrons

PF ID is the basis for particle identification before additional clustering or selection reqs.

[1] [CMS Collaboration; JINST 12 P10003 \(2017\)](#)
([arxiv:1706.04965](#))

Typical lepton efficiencies

Detector is very efficient in reconstructing leptons.

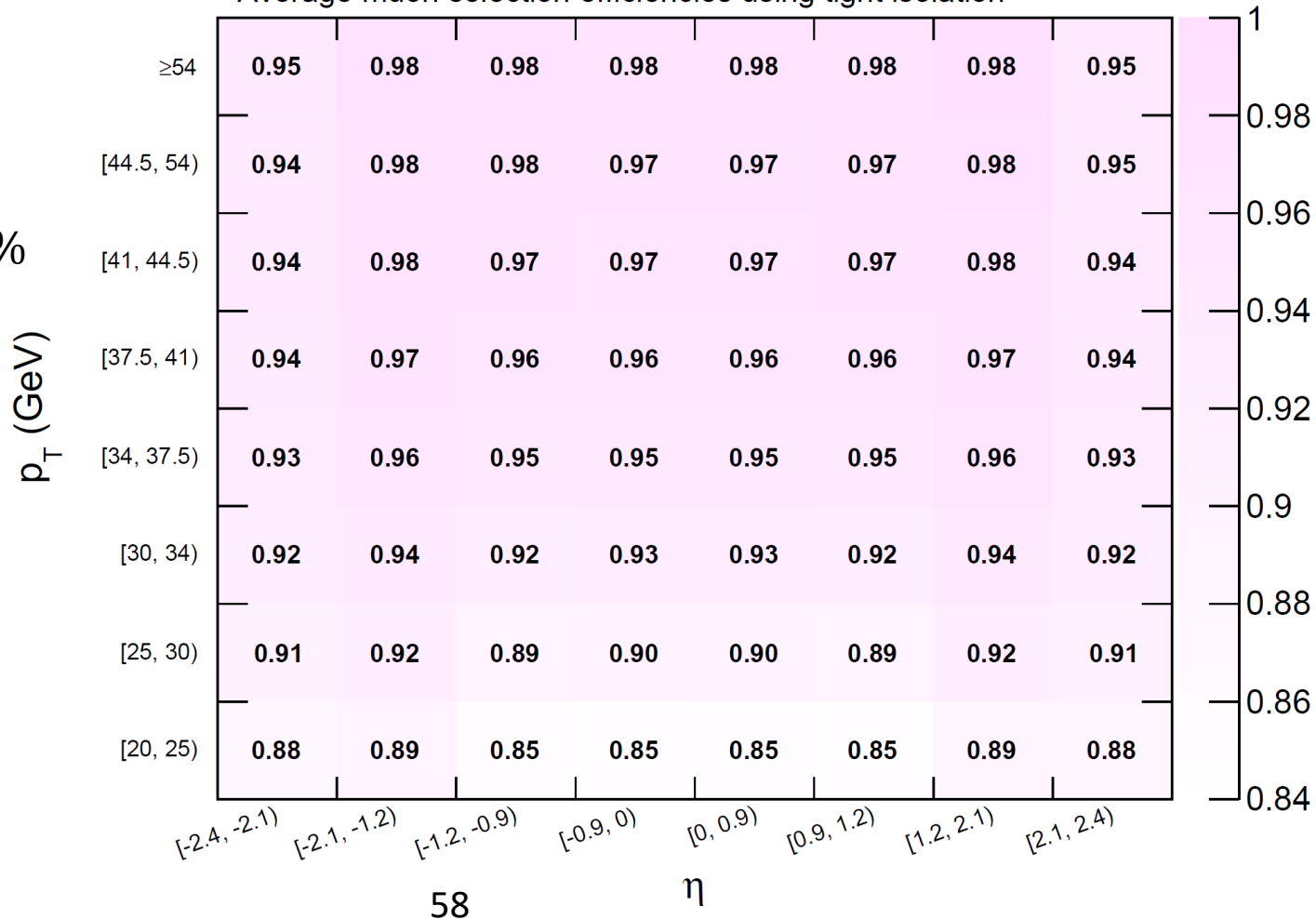
→ Here are exemplary lepton selection efficiencies.

CMS *Supplementary*

138 fb⁻¹ (13 TeV)

Average muon selection efficiencies using tight isolation

Muons: ~85% – 98%



Typical lepton efficiencies

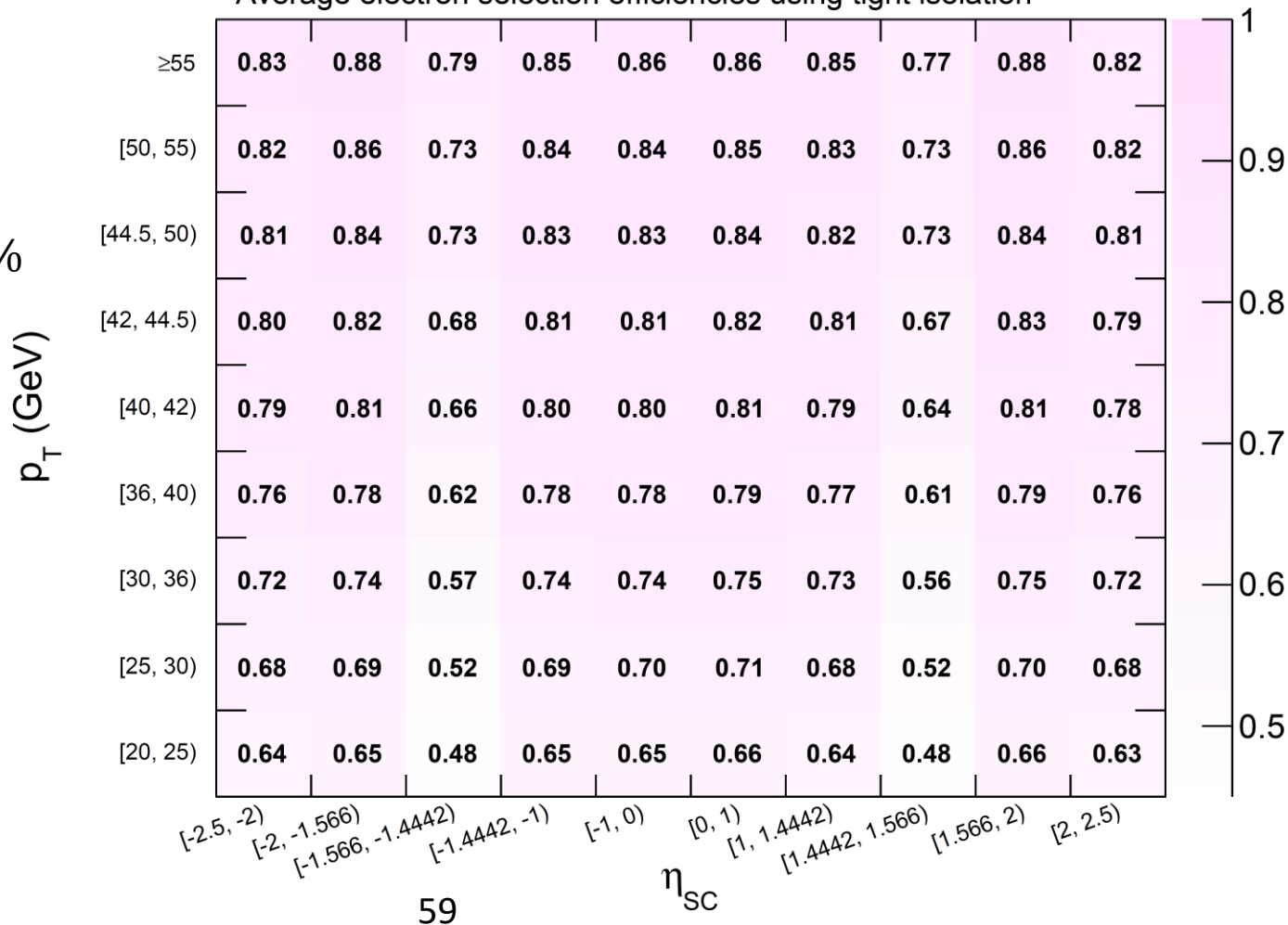
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→ Here are exemplary lepton selection efficiencies.

CMS *Supplementary*

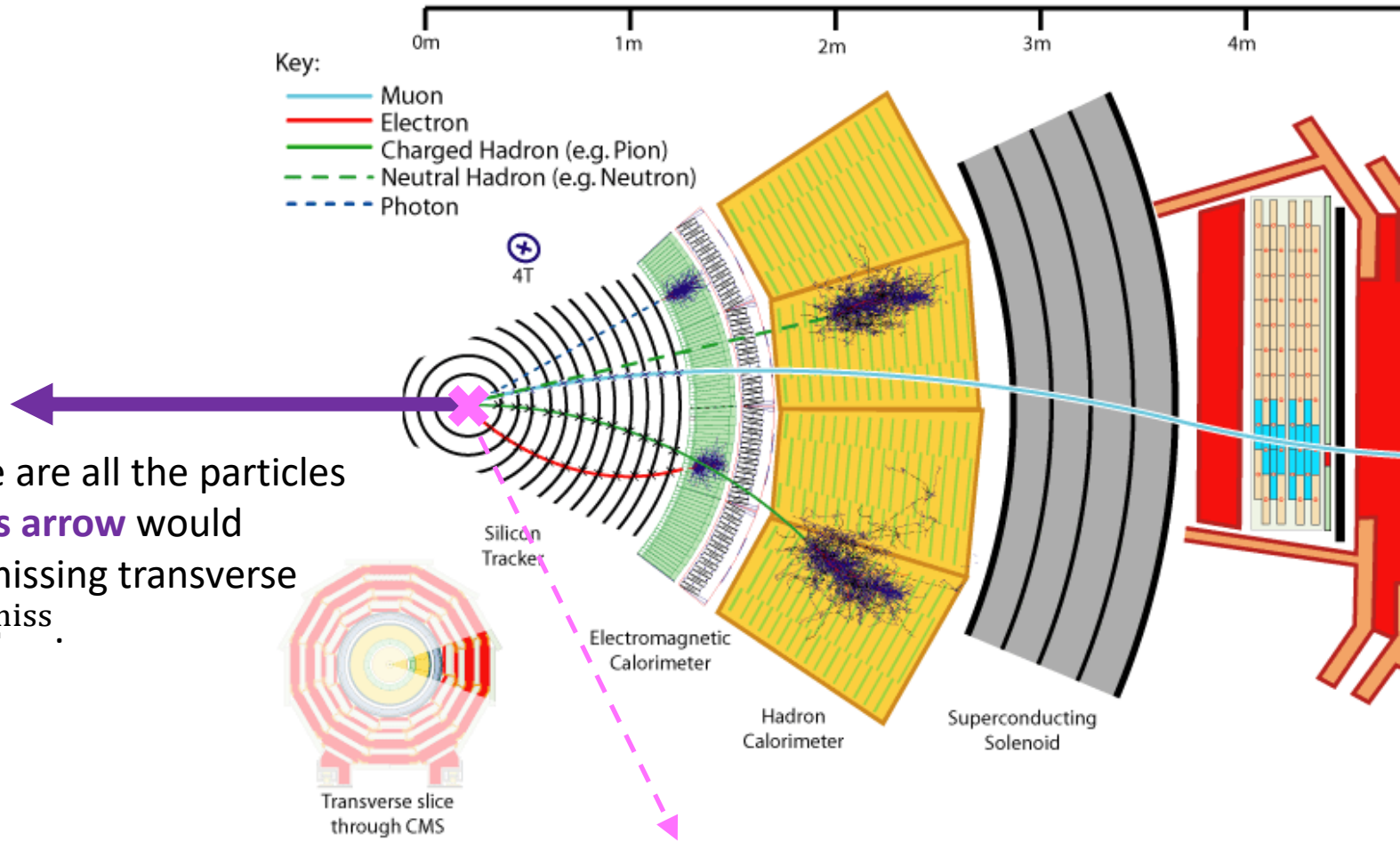
138 fb⁻¹ (13 TeV)

Average electron selection efficiencies using tight isolation



Electrons: ~48% – 88%

Transverse momentum of neutrinos



Assuming these are all the particles in an event, **this arrow** would represent the missing transverse momentum, p_T^{miss} .

Total transverse momentum from the collision should be 0.

Full table of observables for off-shell 4ℓ

Category	VBF-tagged	VH-tagged	Untagged
Selection	$\mathcal{D}_{2\text{jet}}^{\text{VBF}}$ or $\mathcal{D}_{2\text{jet}}^{\text{VBF,BSM}} > 0.5$	$\mathcal{D}_{2\text{jet}}^{\text{WH}}$ or $\mathcal{D}_{2\text{jet}}^{\text{WH,BSM}}$, or $\mathcal{D}_{2\text{jet}}^{\text{ZH}}$ or $\mathcal{D}_{2\text{jet}}^{\text{ZH,BSM}} > 0.5$	Rest of events
SM obs.	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VBF+dec}}, \mathcal{D}_{\text{bsi}}^{\text{VBF+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VH+dec}}, \mathcal{D}_{\text{bsi}}^{\text{VH+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}}, \mathcal{D}_{\text{bsi}}^{\text{gg,dec}}$
a_3 obs.	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VBF+dec}}, \mathcal{D}_{0-}^{\text{VBF+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VH+dec}}, \mathcal{D}_{0-}^{\text{VH+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}}, \mathcal{D}_{0-}^{\text{dec}}$
a_2 obs.	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VBF+dec}}, \mathcal{D}_{0h+}^{\text{VBF+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VH+dec}}, \mathcal{D}_{0h+}^{\text{VH+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}}, \mathcal{D}_{0h+}^{\text{dec}}$
Λ_1 obs.	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VBF+dec}}, \mathcal{D}_{\Lambda_1}^{\text{VBF+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VH+dec}}, \mathcal{D}_{\Lambda_1}^{\text{VH+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}}, \mathcal{D}_{\Lambda_1}^{\text{dec}}$

Full table of observables for on-shell 4ℓ

2016-2018 categorization follows the order

- VBF-2 jet
- VH-hadronic
- VH-leptonic (1 lepton or an $\ell^+ \ell^-$ pair)
- VBF-1 jet
- Boosted
- Untagged

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

Off-shell $2\ell 2\nu$: Event selection

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

Requirements are mainly aimed toward reducing

- instrumental p_T^{miss} smearing from Z +jets
- $t\bar{t} \rightarrow 2\ell 2\nu 2b$
- $WW \rightarrow 2\ell 2\nu$

Off-shell $2\ell 2\nu: q\bar{q} \rightarrow ZZ, WZ$

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

Estimated using POWHEG simulation at NLO in QCD

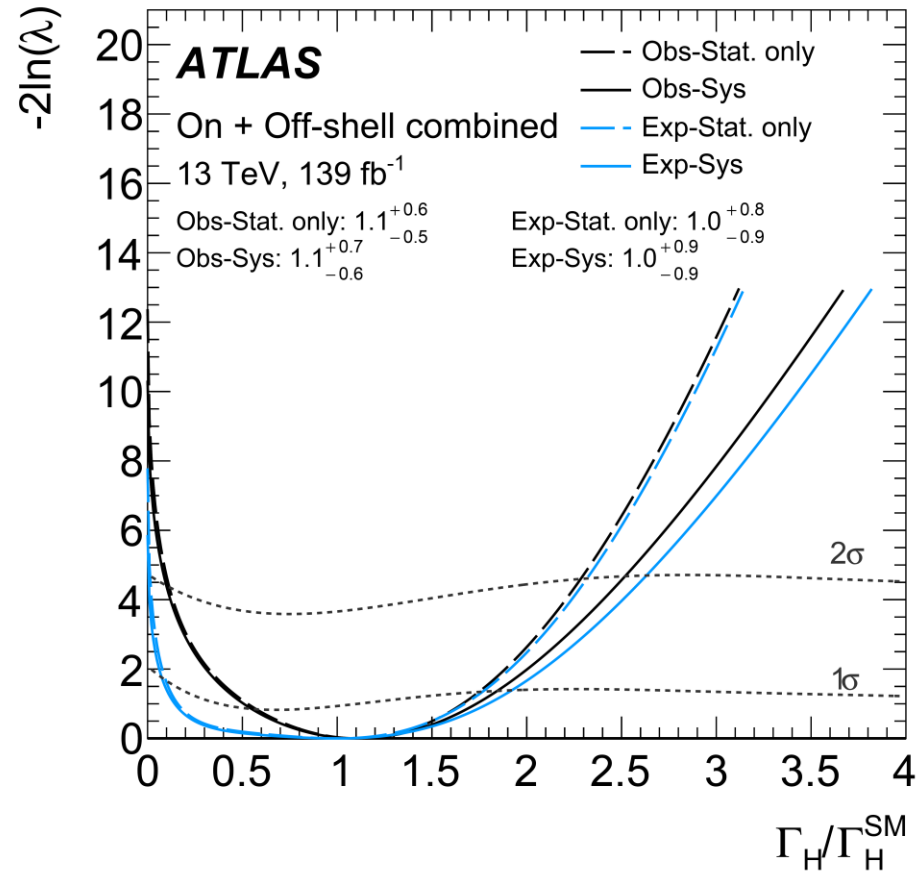
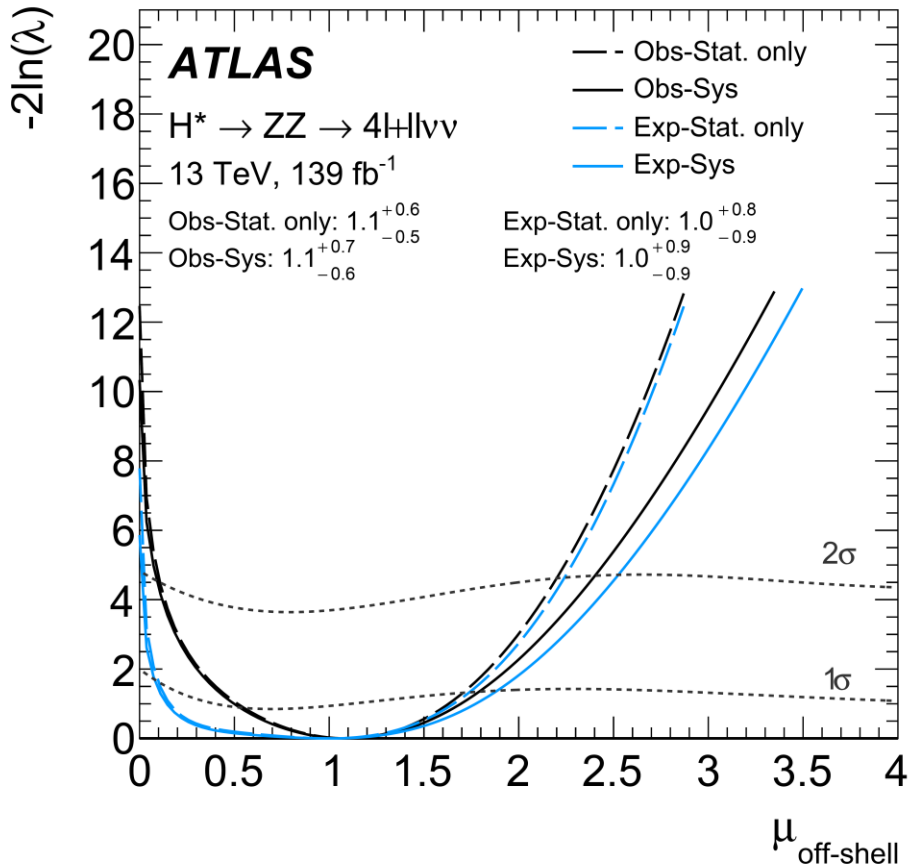
→ Additional K-factors for NLO EW and NNLO QCD corrections are applied.

→ A joint fit with a 3ℓ WZ CR is done with common nuisance parameters and m_T^{WZ} as the only observable:

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

→ Events in the CR are categorized for the same N_j bins, and $\ell_W = e, \mu$.

Evidence for off-shell from ATLAS

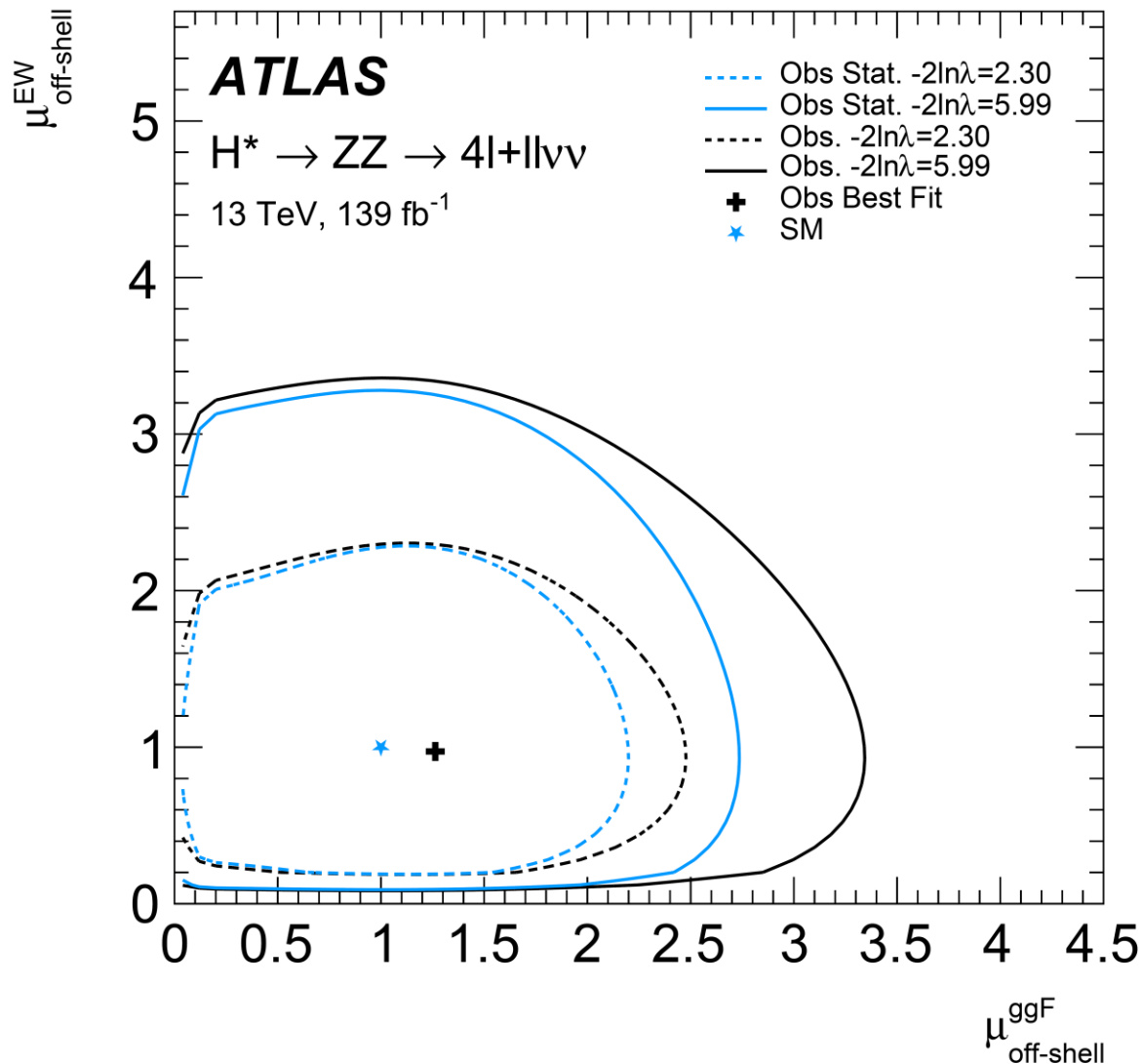


No – off-shell scenario ($\mu^{\text{off-shell}} = 0$)
 is excluded at 3.2 std. devs.

→ Note that dotted curves on the left
 are for Neyman construction (toys)

Observed $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
 [0.5, 10.5] MeV @ 95% CL

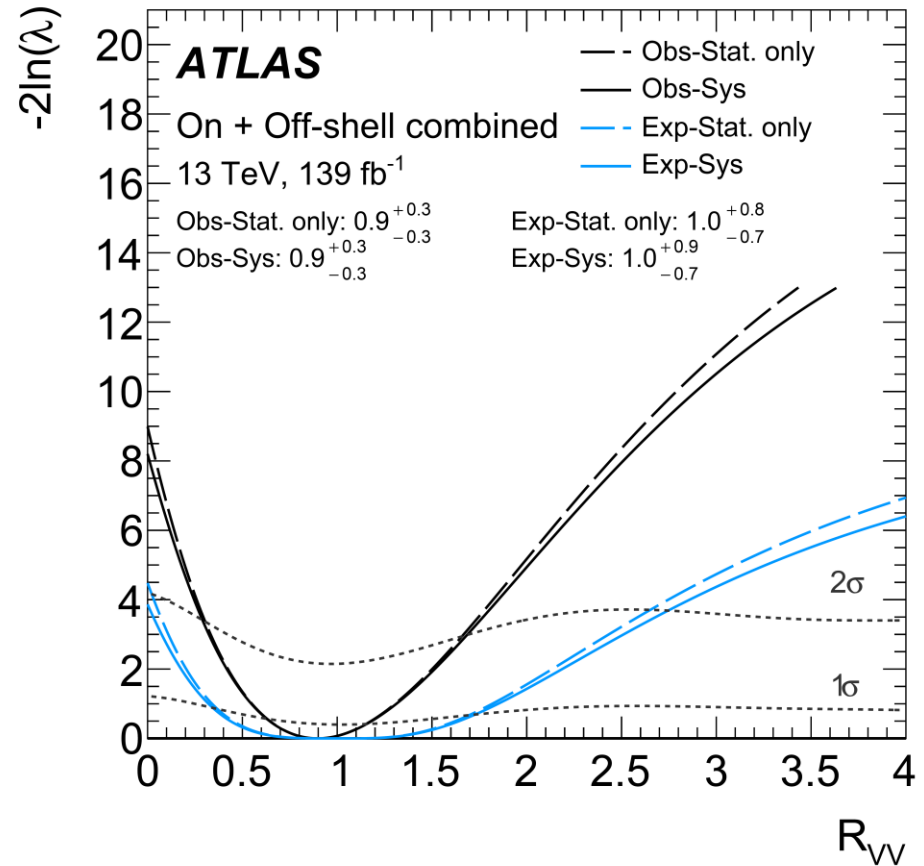
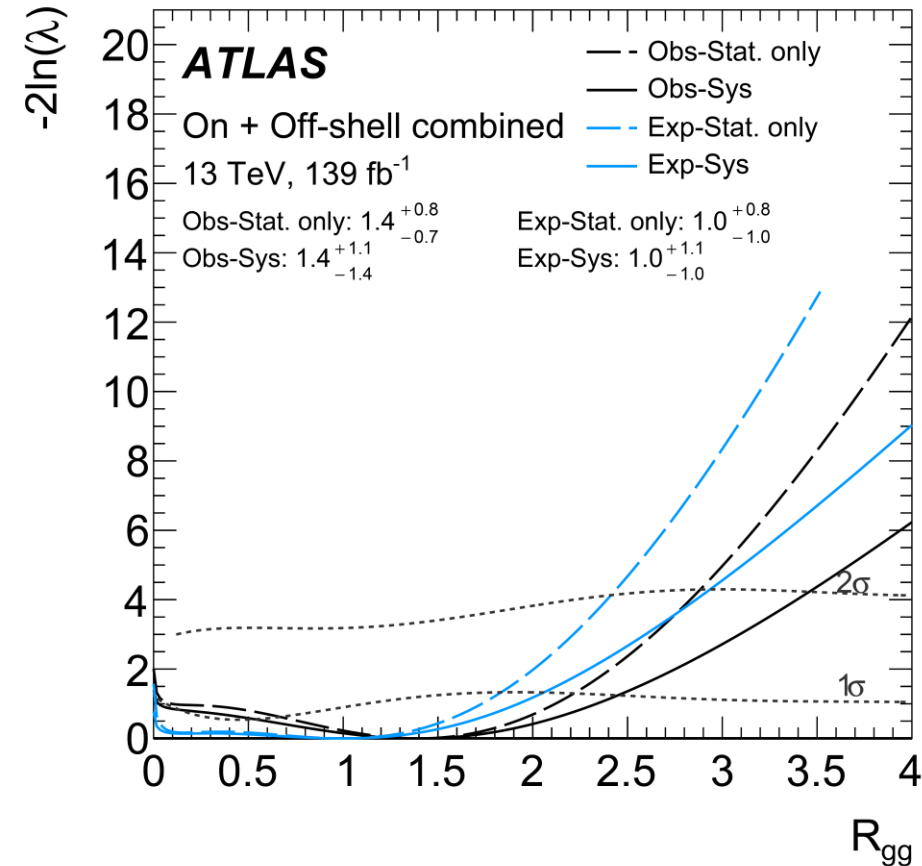
$\mu_{\text{off-shell}}^{\text{ggF}}$ and $\mu_{\text{off-shell}}^{\text{EW}}$ (ATLAS)



Joint constraints on
 $\mu_{\text{off-shell}}^{\text{ggF}}$ and $\mu_{\text{off-shell}}^{\text{EW}}$

Result in agreement with CMS
and the SM

R_{gg} and R_{VV} (ATLAS)



Results also interpreted in terms of off-shell/on-shell coupling multipliers, w/ $\Gamma_H = 4.1$ MeV:
 $\rightarrow R_{gg} = \kappa_{g,\text{off-shell}}^2 / \kappa_{g,\text{on-shell}}^2$ and $R_{VV} = \kappa_{V,\text{off-shell}}^2 / \kappa_{V,\text{on-shell}}^2$
 \rightarrow Results consistent with the SM