Search for off-shell production of the Higgs boson and measurement of its total width with the ATLAS experiment

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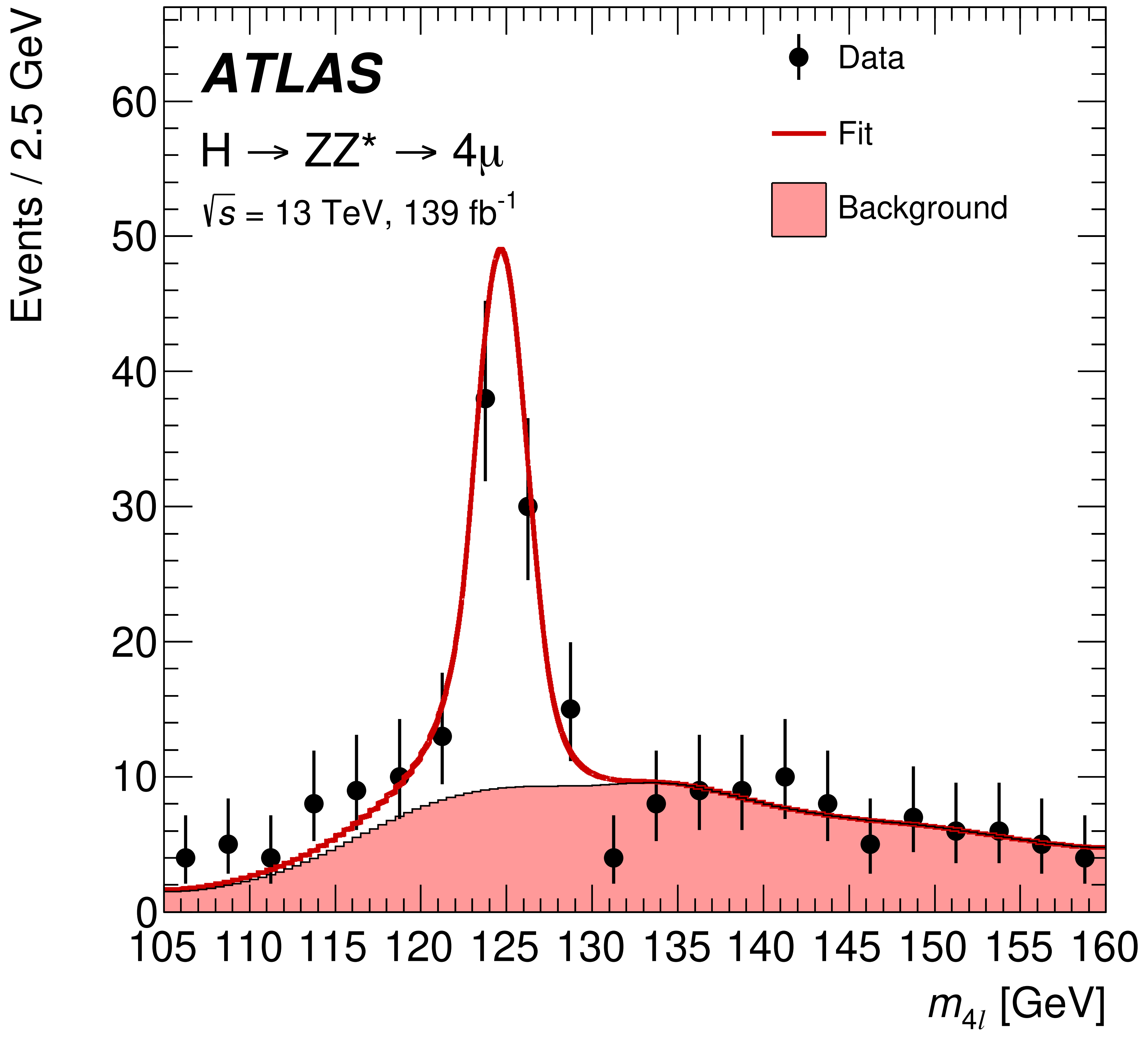
DIS2023, East Lansing, Michigan

Off-shell Production and the Higgs Boson Width

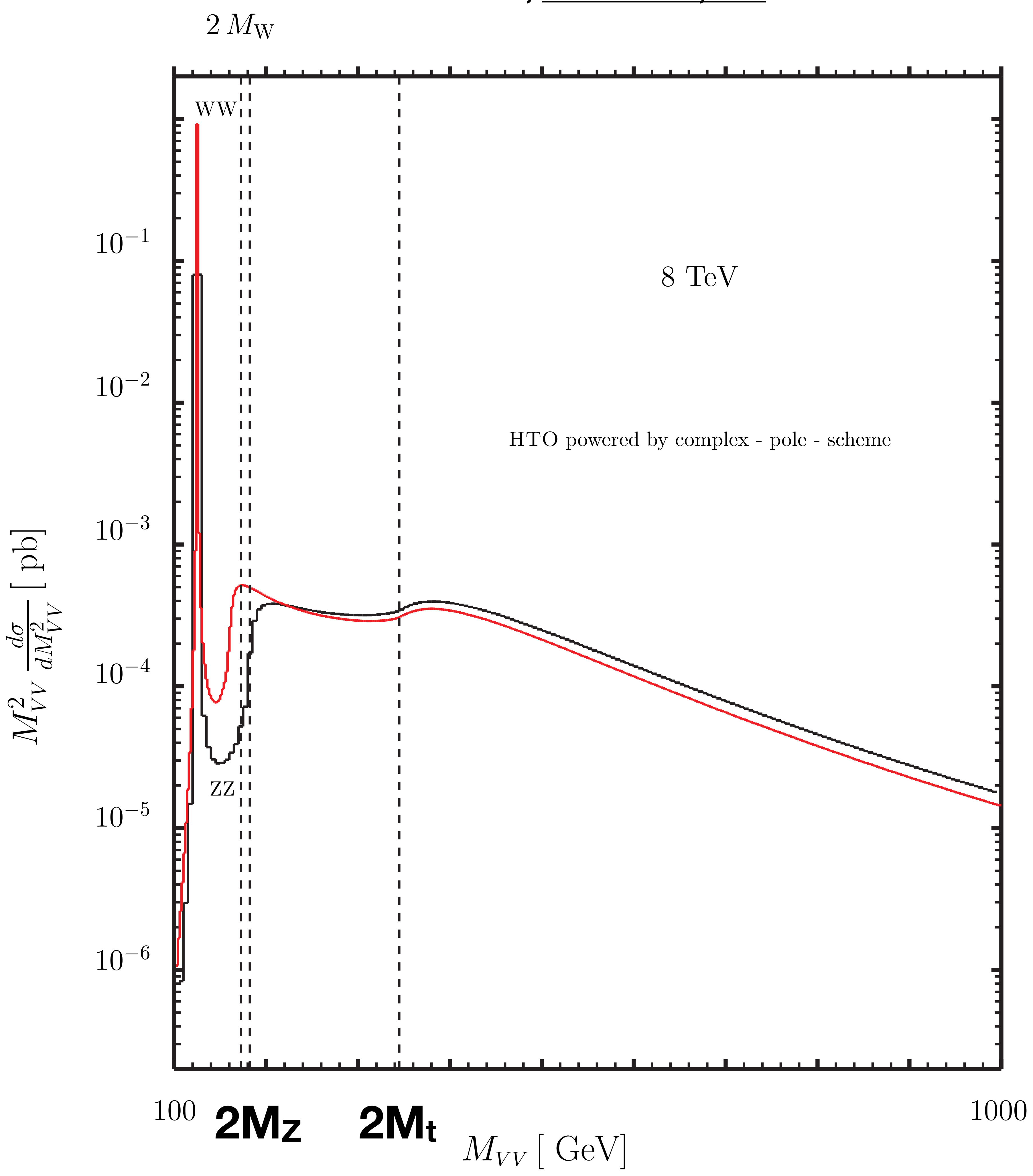
arXiv:2207.00320



- Higgs peak in the $H \rightarrow ZZ \rightarrow 4\mu$ channel
- Best achievable resolution is still >1 GeV
- Predicted Γ_H of 4.1 MeV cannot be directly observed

Off-shell Production and the Higgs Boson Width

Kauer & Passarino, JHEP 2012, 116



- Solution: move away from the mass peak

Off-shell Production and the Higgs Boson Width

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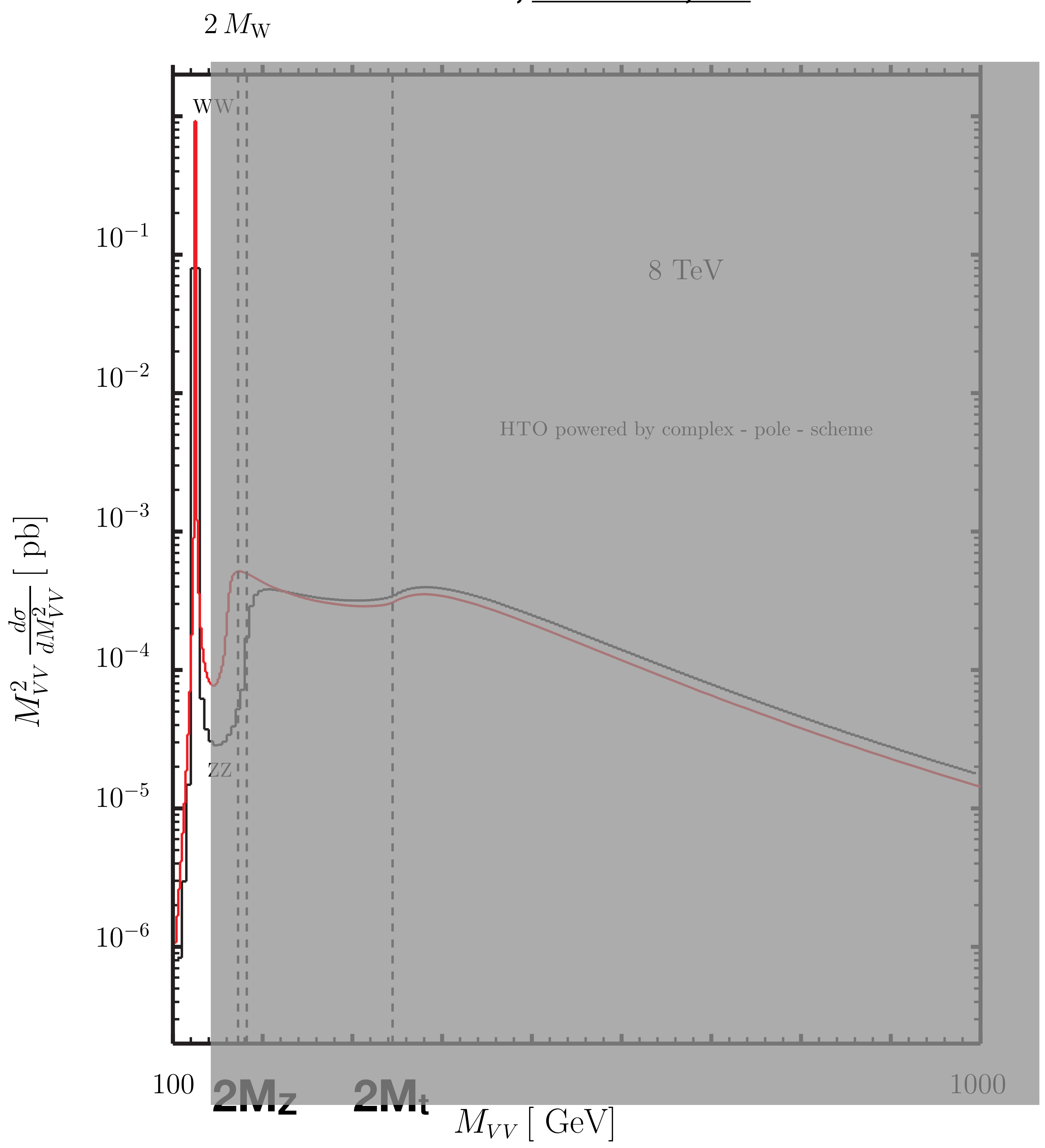

- Solution: move away from the mass peak
- On-shell, production ~ $1/\Gamma_H$

Off-shell Production and the Higgs Boson Width

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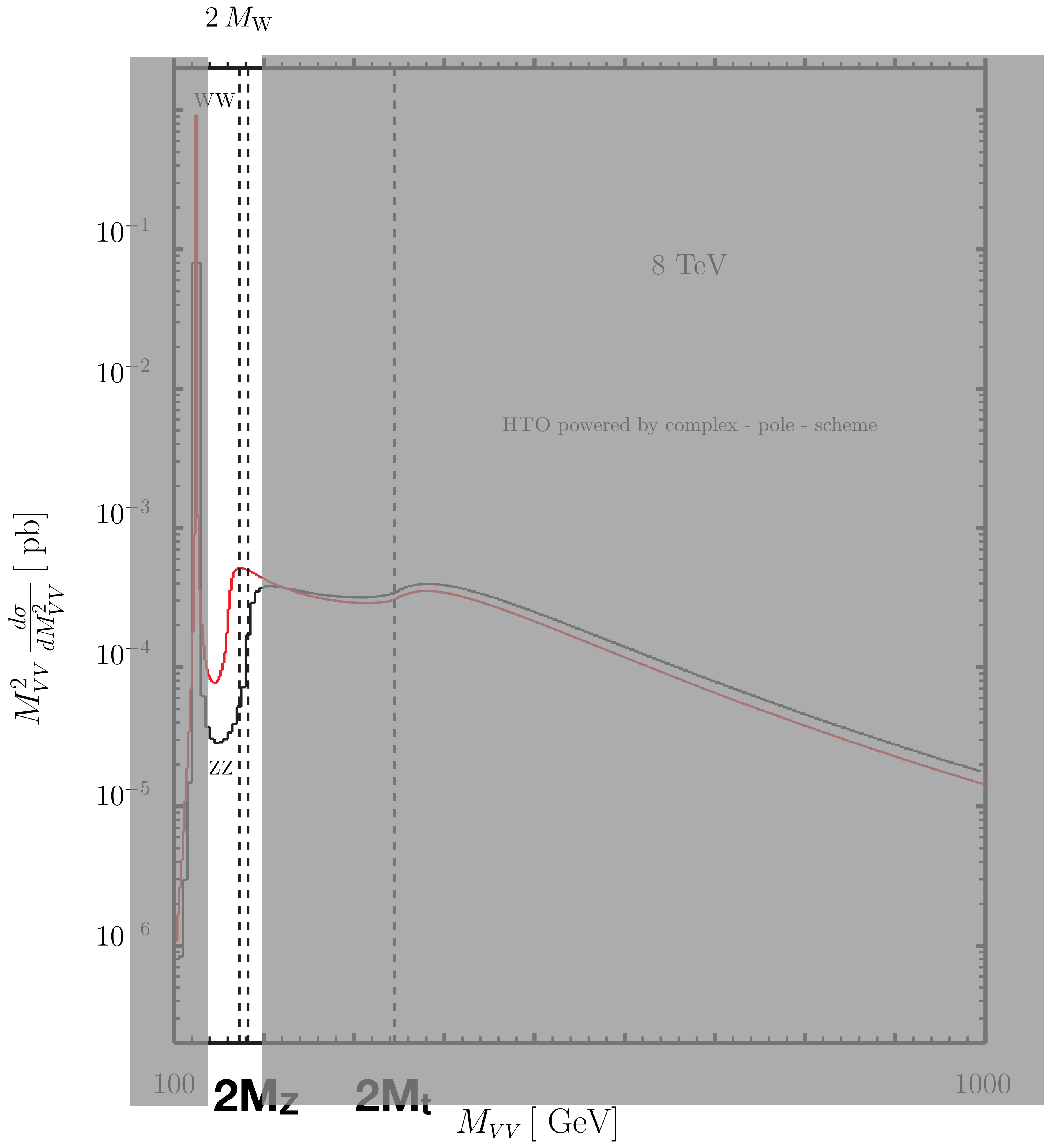
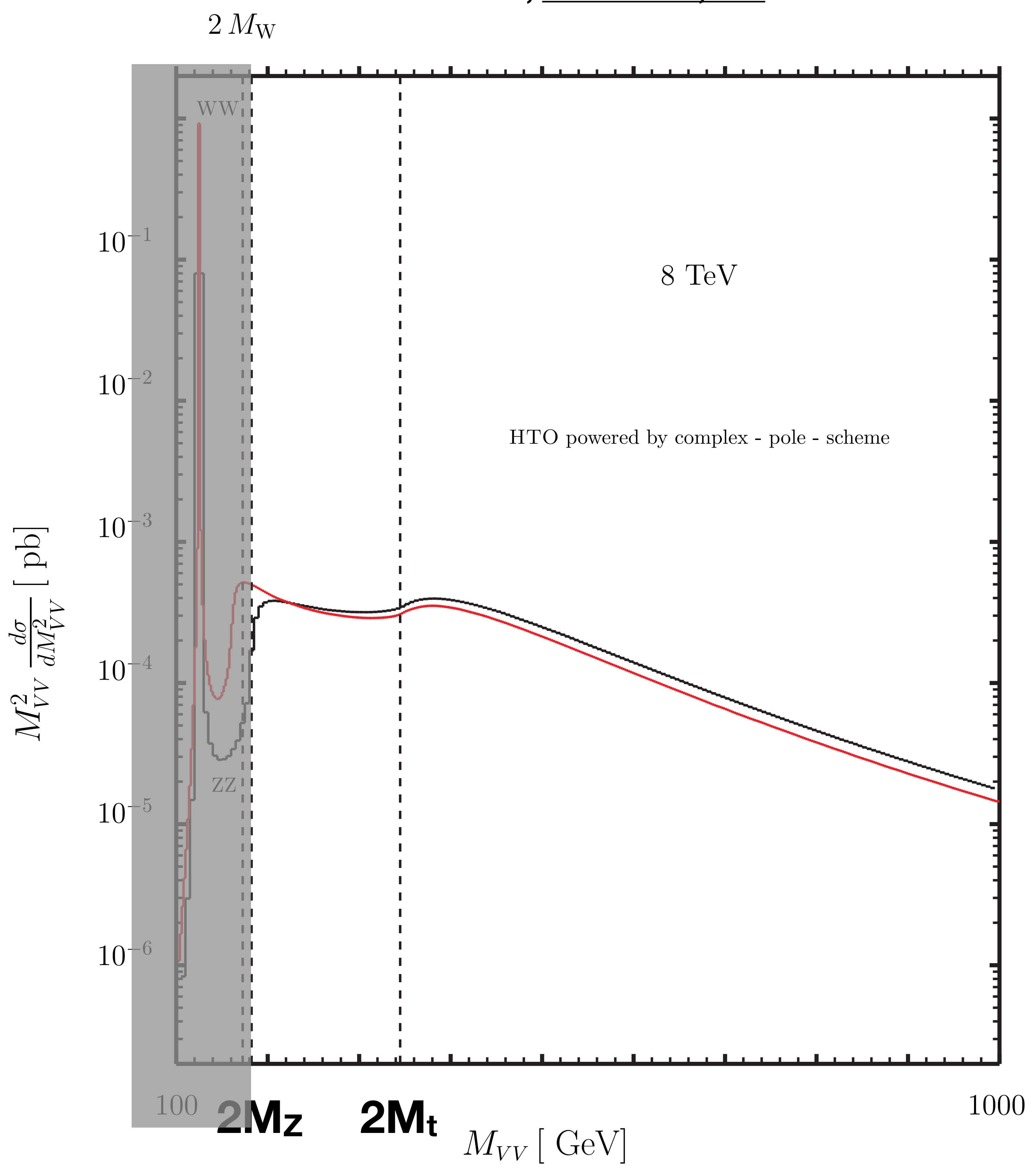


- Solution: move away from the mass peak
- But in the ZZ channel, as m_{ZZ} approaches $2m_Z$, this is not longer the case
  - The additional decay phase space dominates over the dropoff due to the q^2 dependence of the propagator

Off-shell Production and the Higgs Boson Width

Kauer & Passarino, JHEP 2012, 116



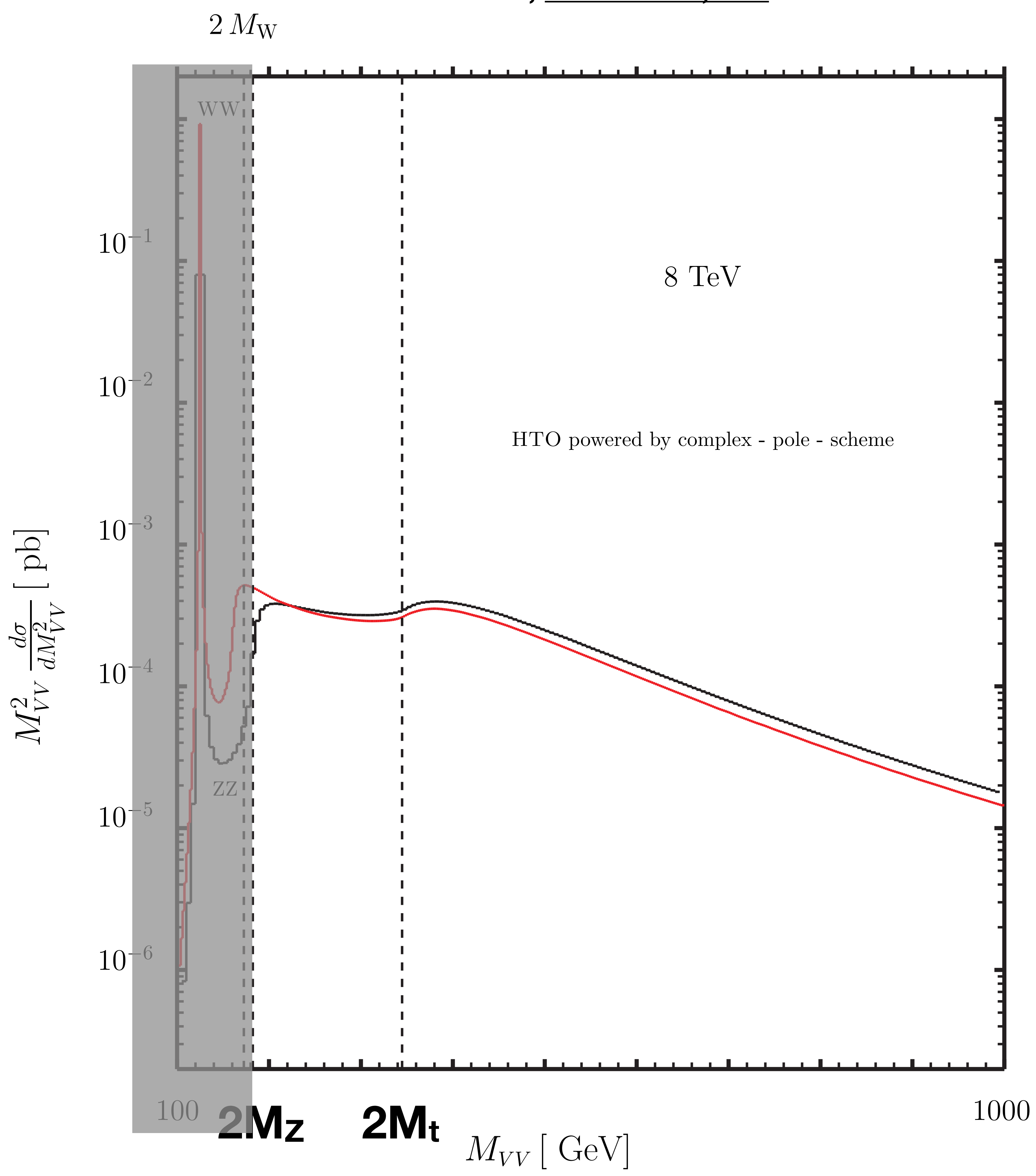
- Solution: move away from the mass peak

- Above $2m_Z$, the production cross-section is no longer dependent on the width

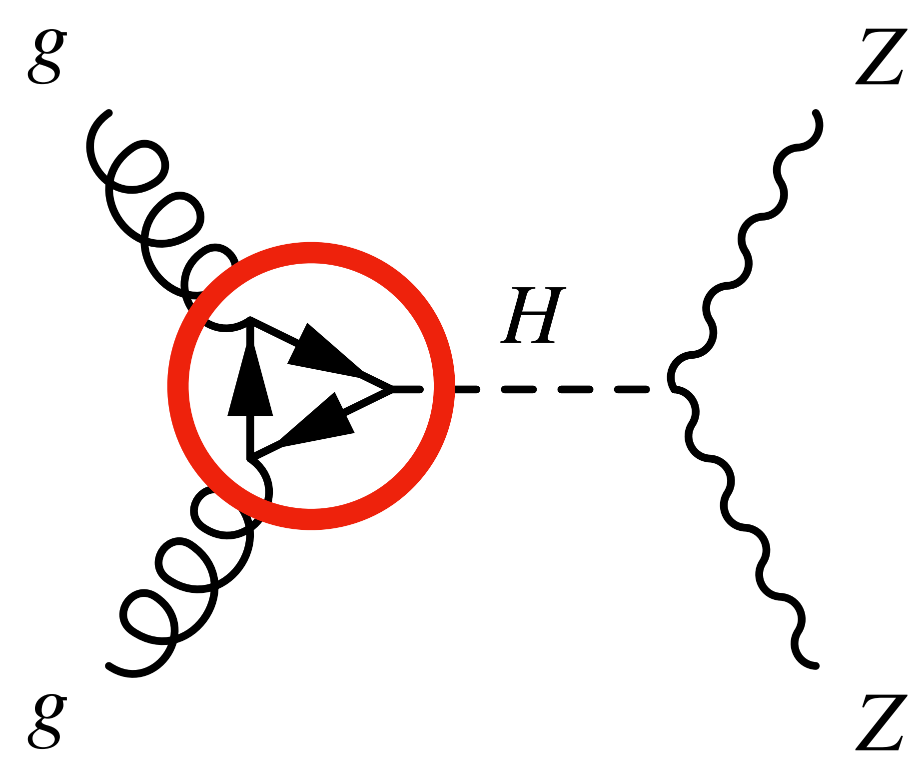
- Therefore Γ_H can be obtained from a ratio of on-shell and off-shell production

Off-shell Production and the Higgs Boson Width

Kauer & Passarino, JHEP 2012, 116



- Solution: move away from the mass peak
  - **Important assumption: g_{ggH} follows the SM prediction**
  - **→ No new particles enter the quark loop, so on-shell and off-shell production are the same**



- Above $2m_Z$, the production cross-section is no longer dependent on the width
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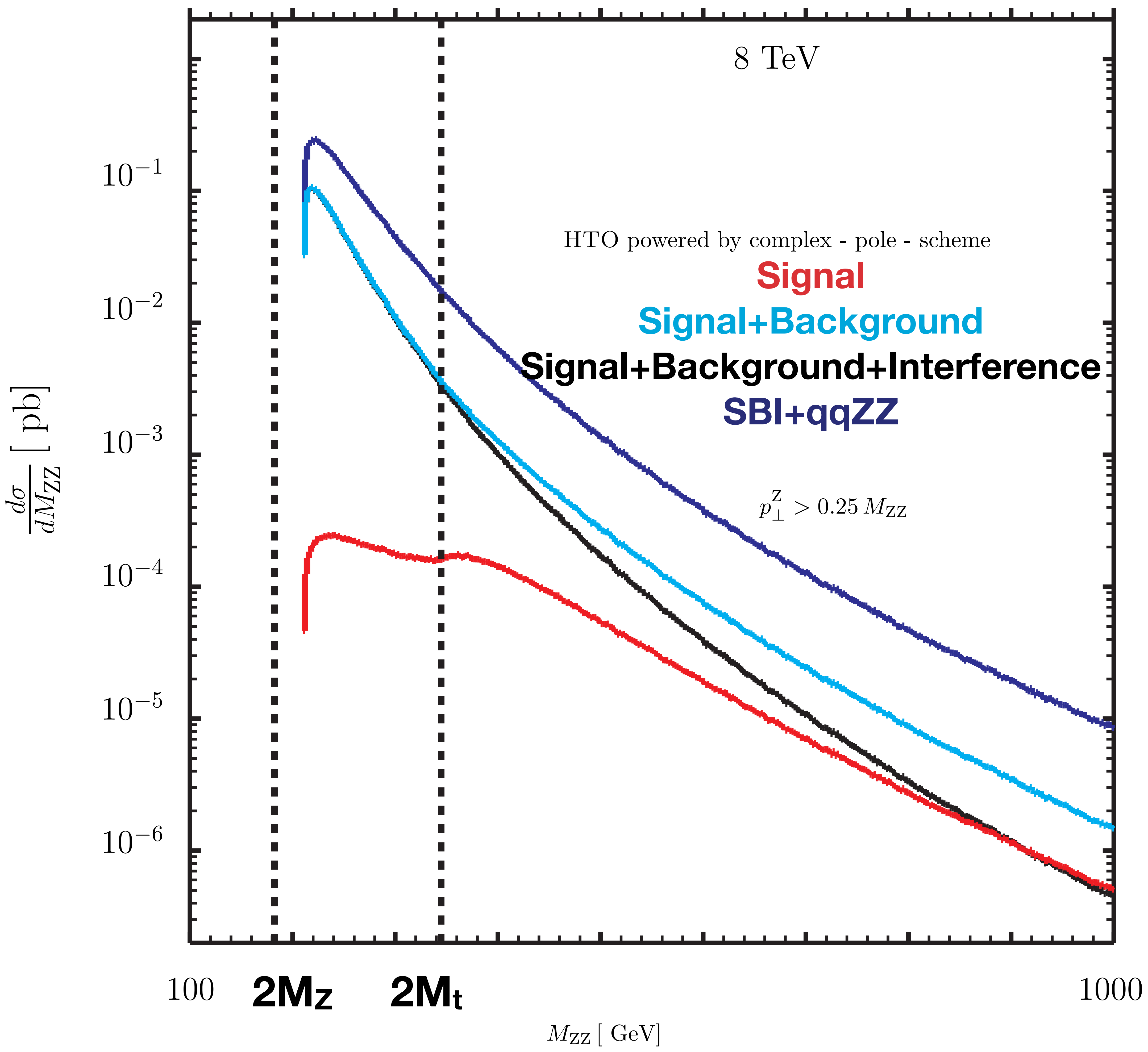
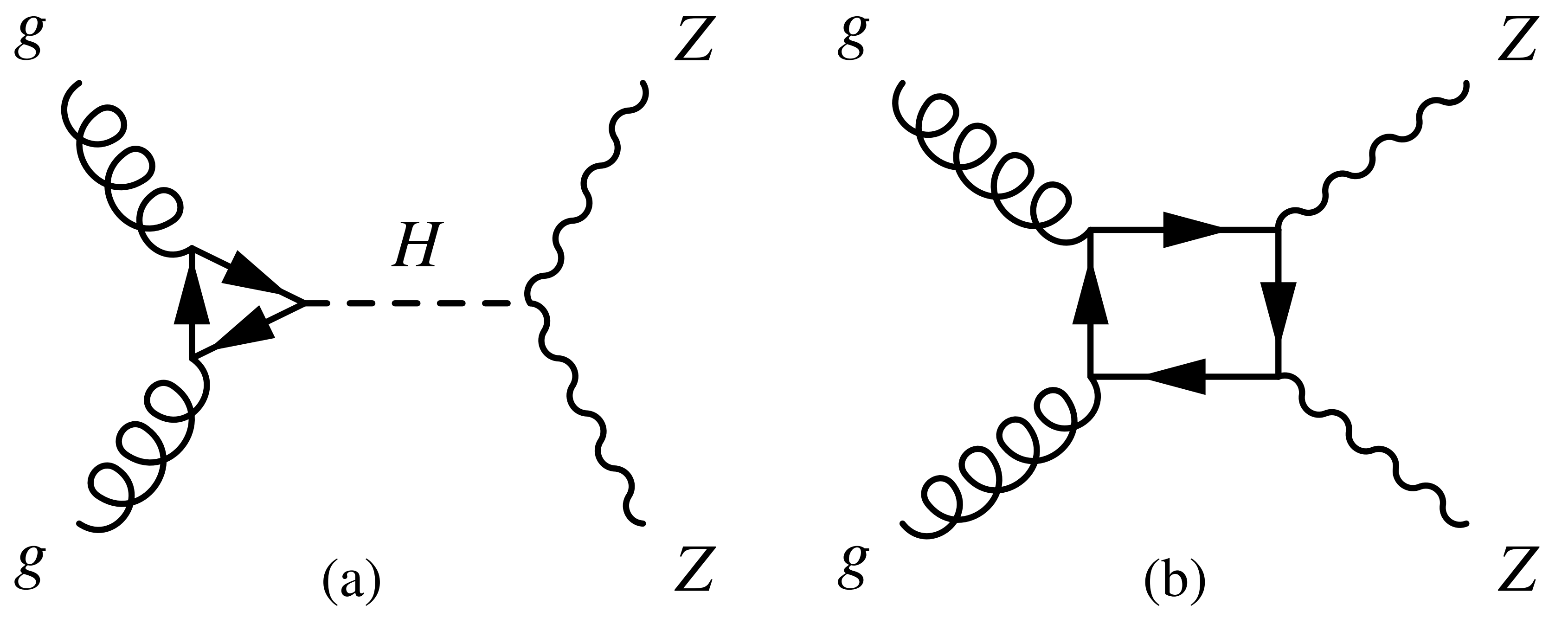
Signal-Background Interference

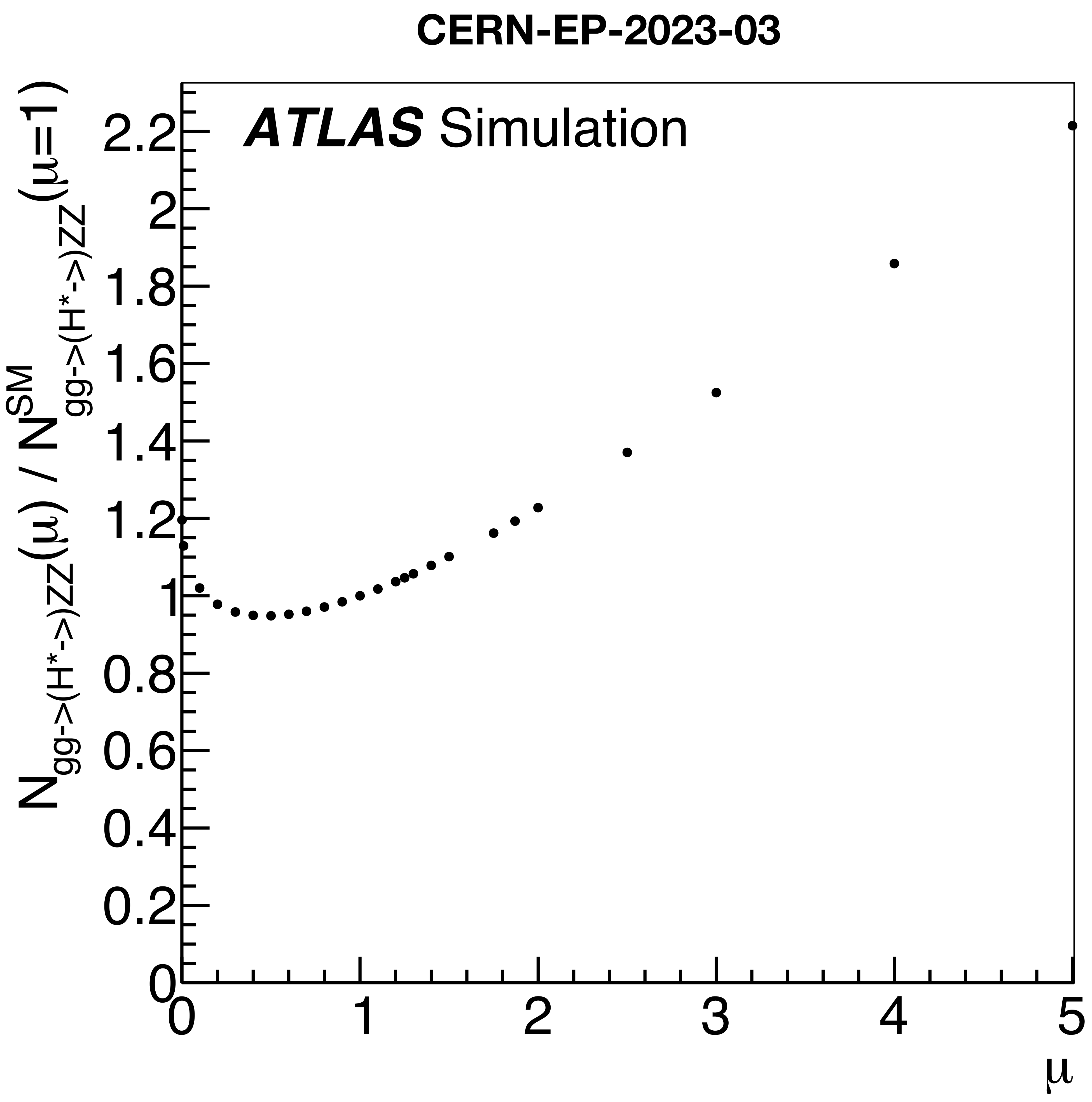
Kauer & Passarino, JHEP 2012, 116

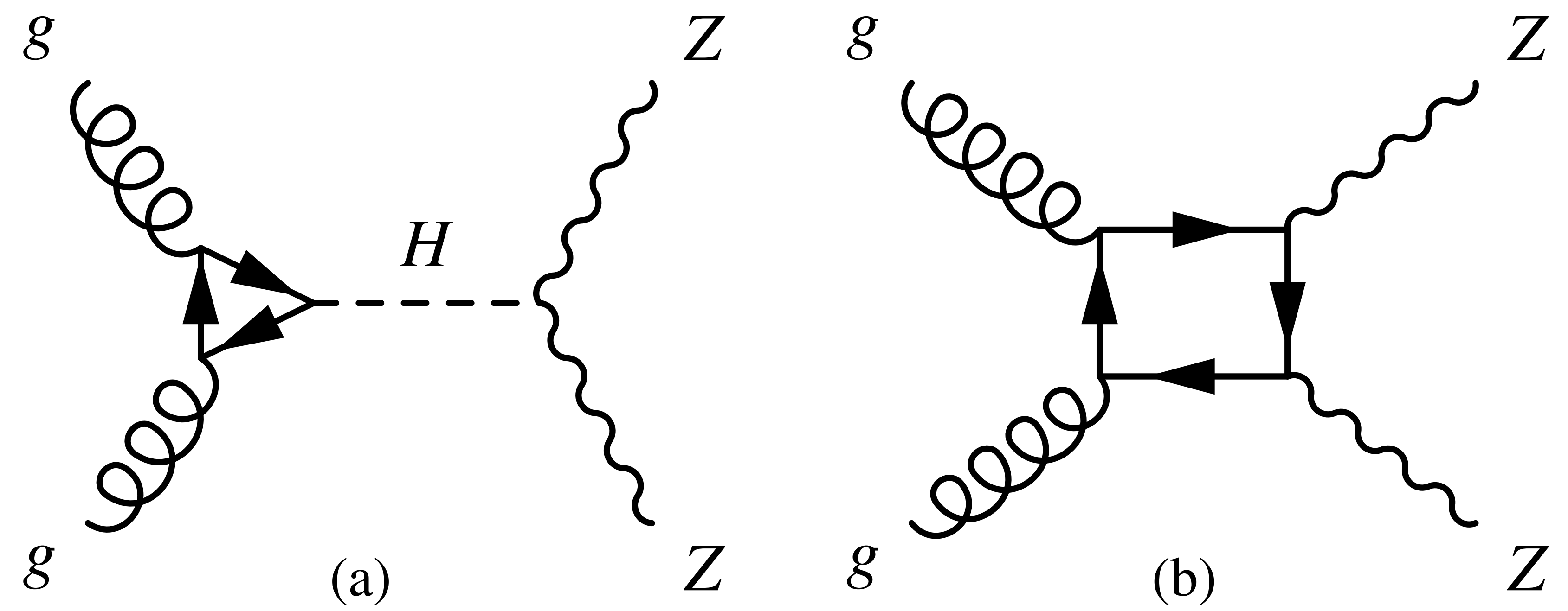




- The signal gg→H*→ZZ and background gg→ZZ process interfere
  - We measure a deficit in the background, not a signal
- Signal scales with μ_{offshell} but the interference goes as $\sqrt{\mu_{\text{offshell}}}$

Signal-Background Interference





- Yield dependence on μ_{offshell} is therefore not linear
    - Asymptotic approximation does not hold
    - → Confidence intervals have to be derived using the Neyman construction

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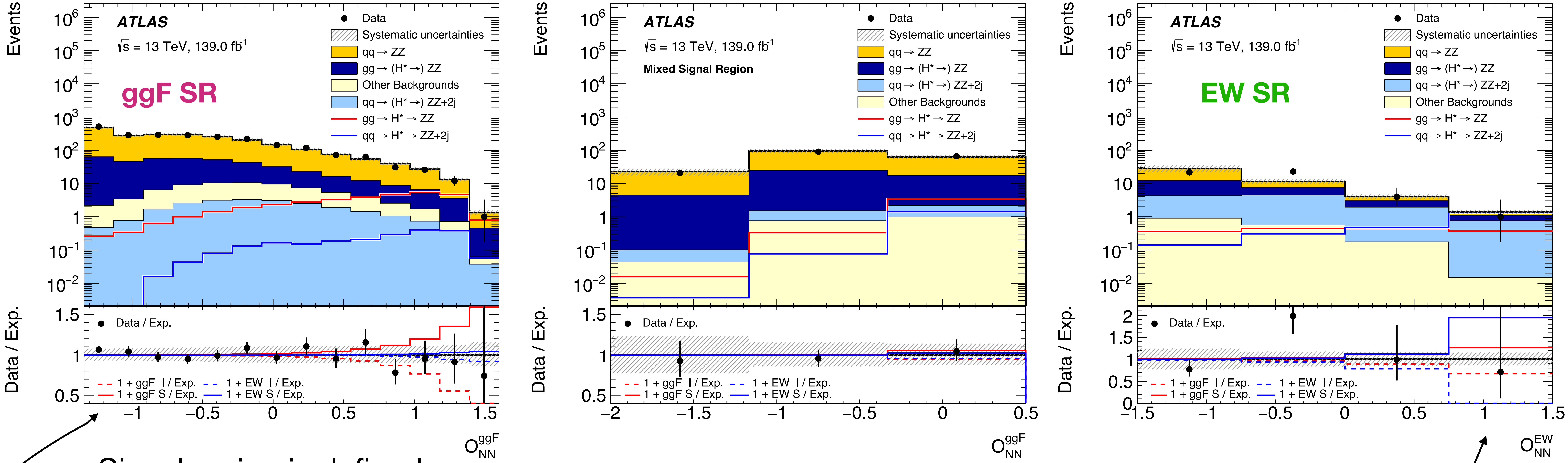
4l Final State

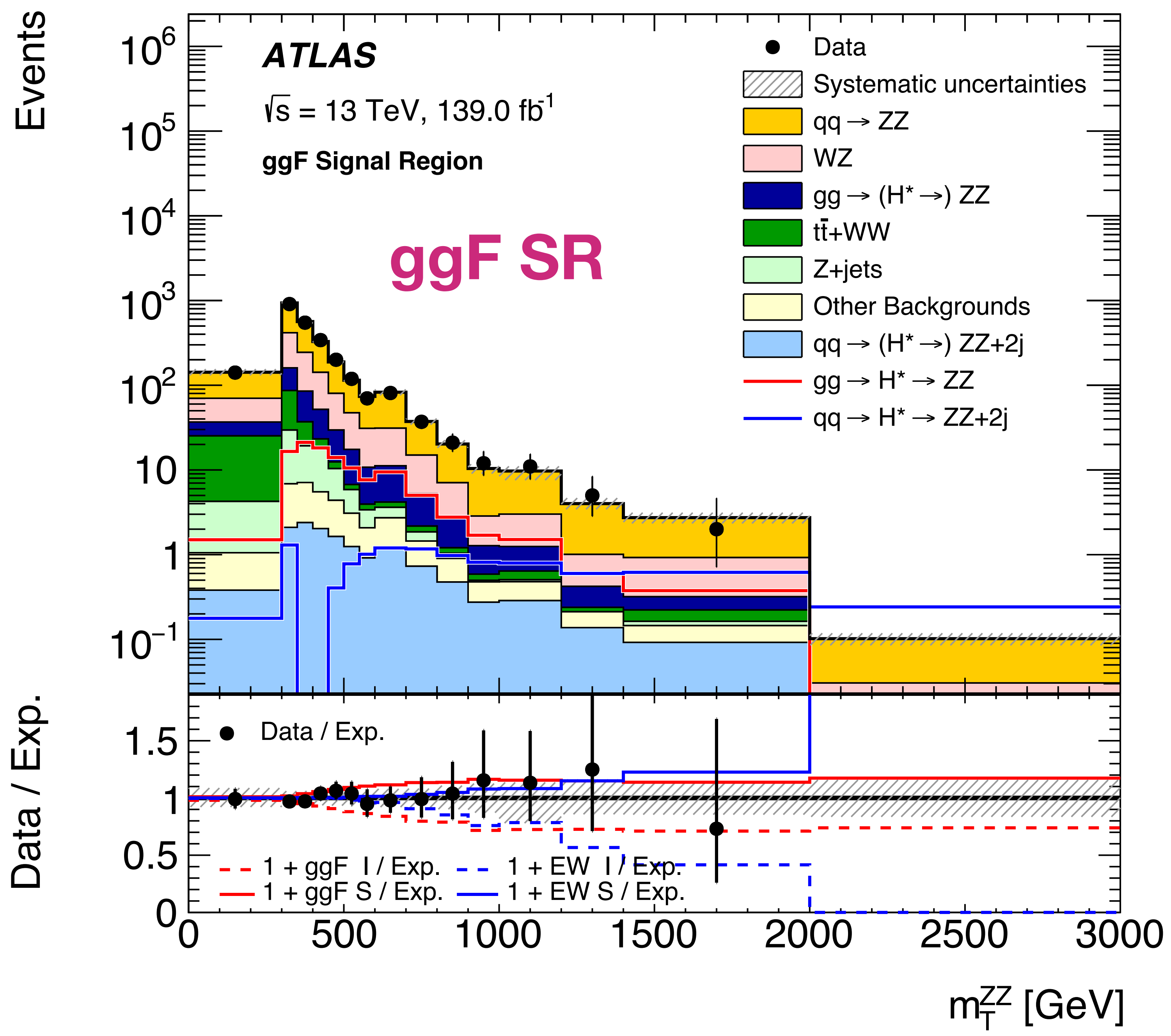


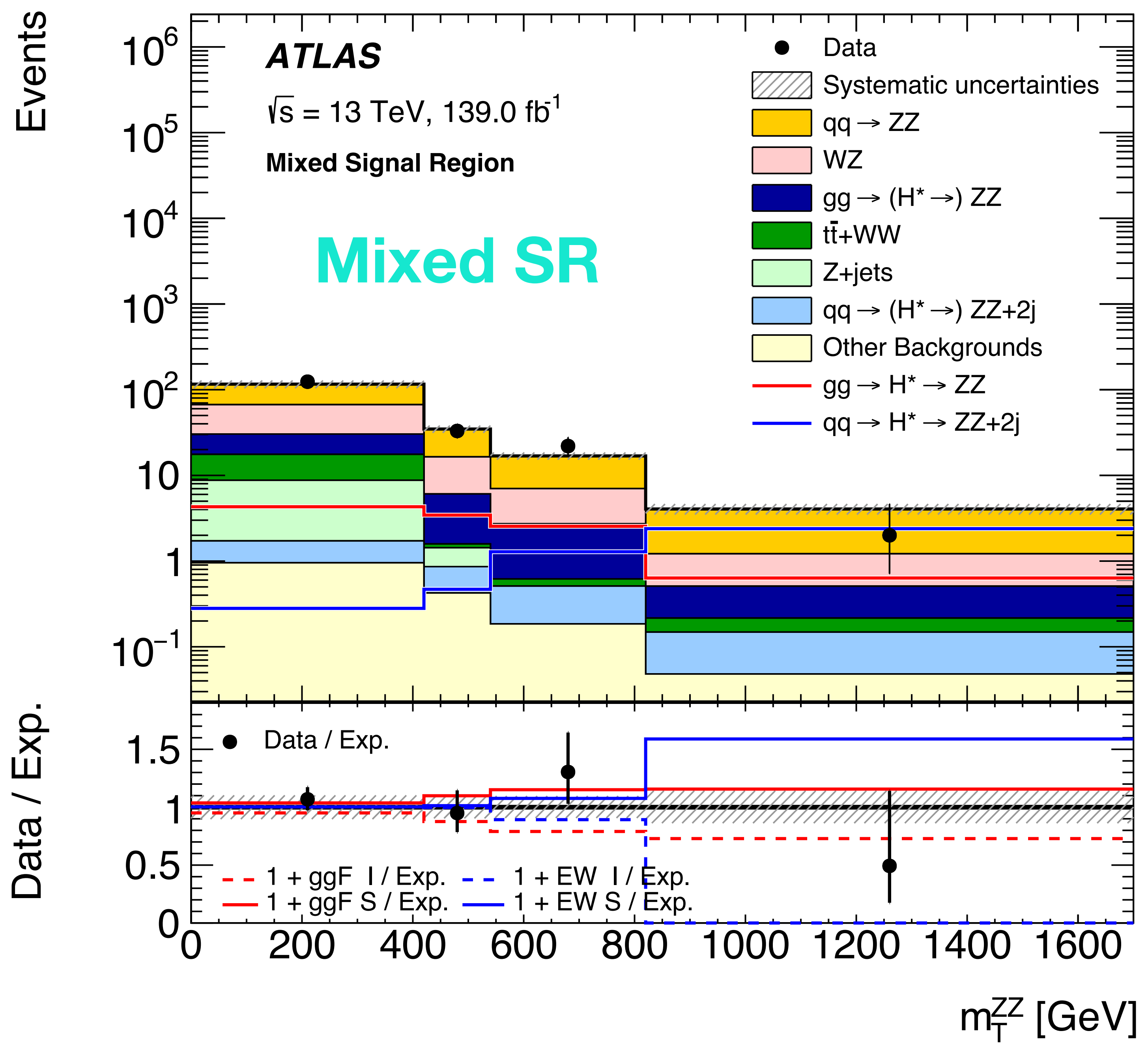
- Signal region is defined as $m_{4l} \geq 220$ GeV
  - Mixed (1-jet) and EW (2-jet) SRs are defined targeting EW (VBF+VH) production
  - Remaining events form the ggF SR

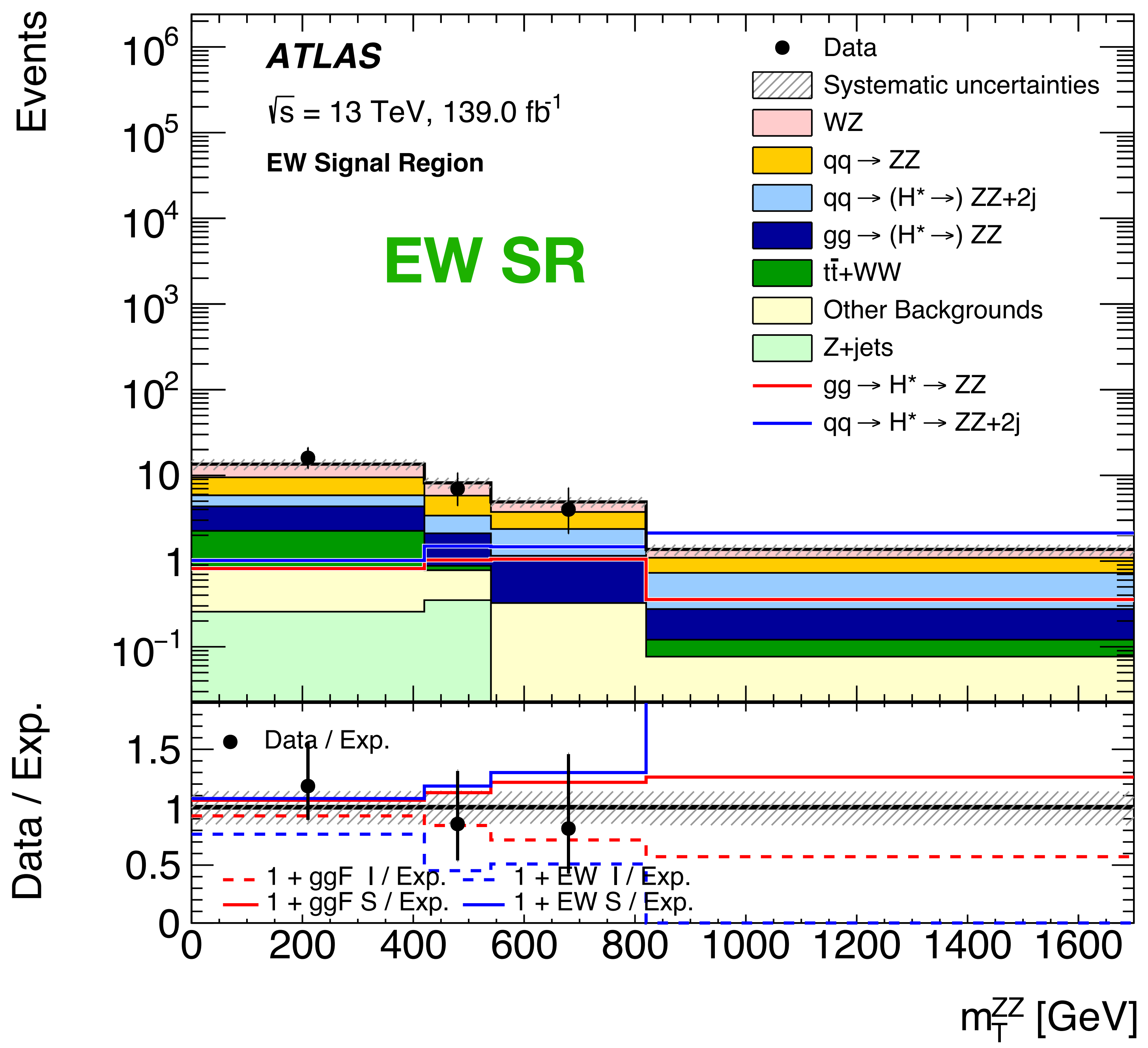
- qqZZ production is the dominant background
  - Constrained using data CRs, $180 < m_{4l} < 220$ GeV, $N_{jets} = 0, 1, \geq 2$
  - Other backgrounds are mainly ttV and VVV, fakes from Z+jet and ttbar are negligible

- NNs trained to separate ggF and EW signal from non-interfering qqZZ and interfering gg and qq backgrounds

2l2v Final State







- Same SRs as for the 4l final state
- qqZZ production is still the dominant background
  - Constrained using 4l CRs
  - Separate CRs constructed to constrain WZ, Z+jets, and non-resonant backgrounds
- Transverse mass m_T^{ZZ} is used as the observable $m_{\mathrm{T}}^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_{\mathrm{T}}^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$

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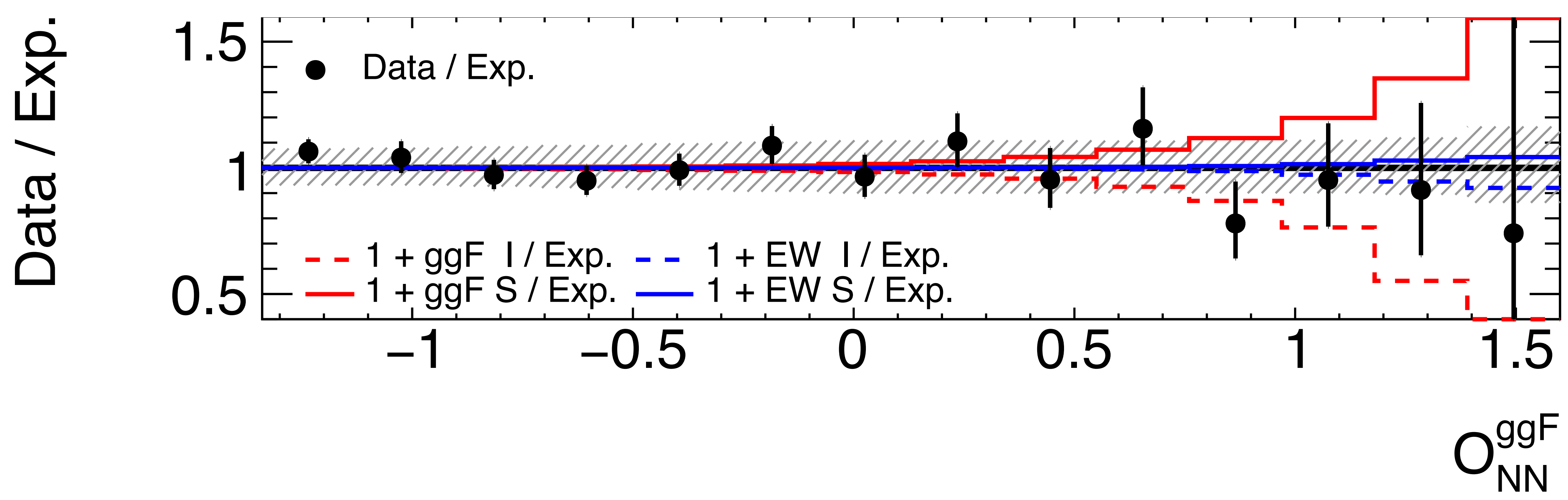
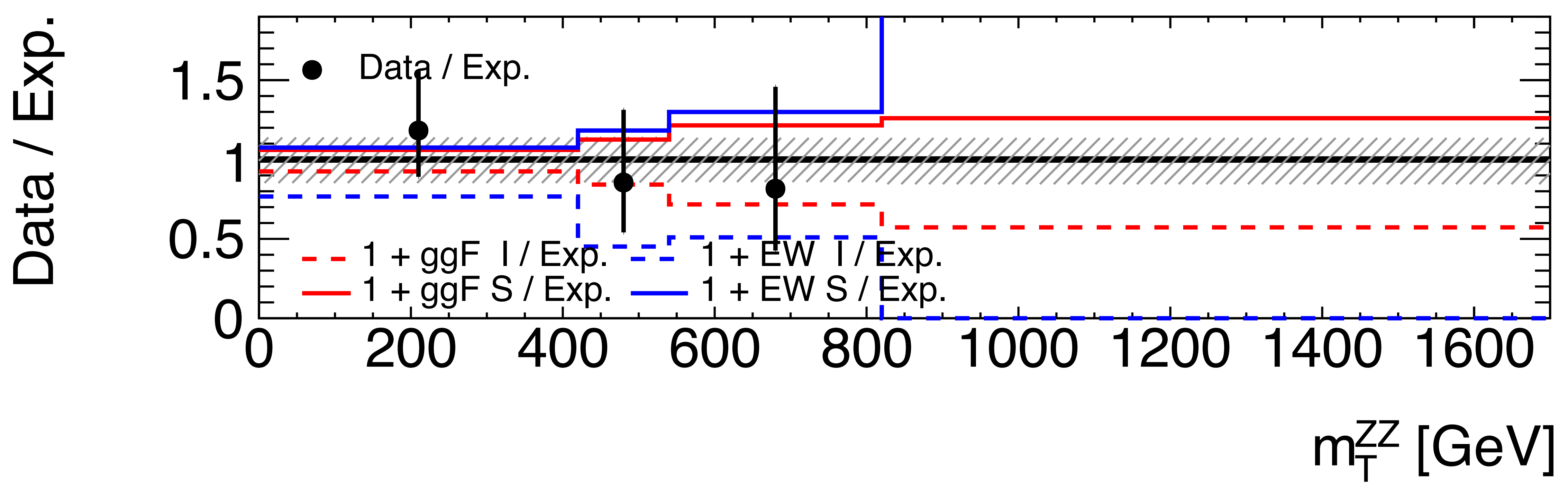
Observables

4l ggF SR

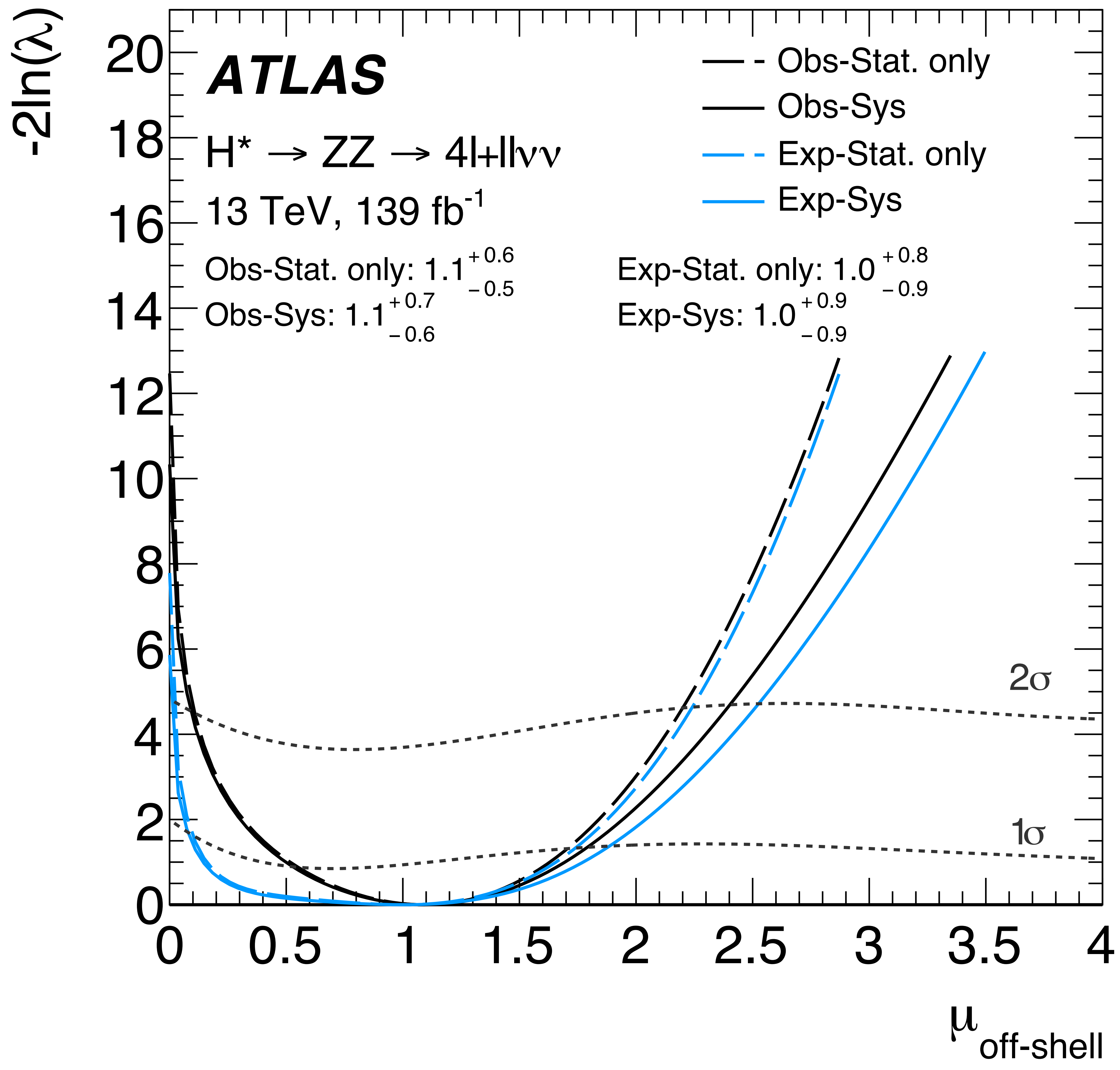


2l2v EW SR



- Observables do a good job of enhancing S/B at higher values
  - For both ggF and EW production
- Interference (dashed) goes opposite to signal (solid)

Measurement of Off-shell Production

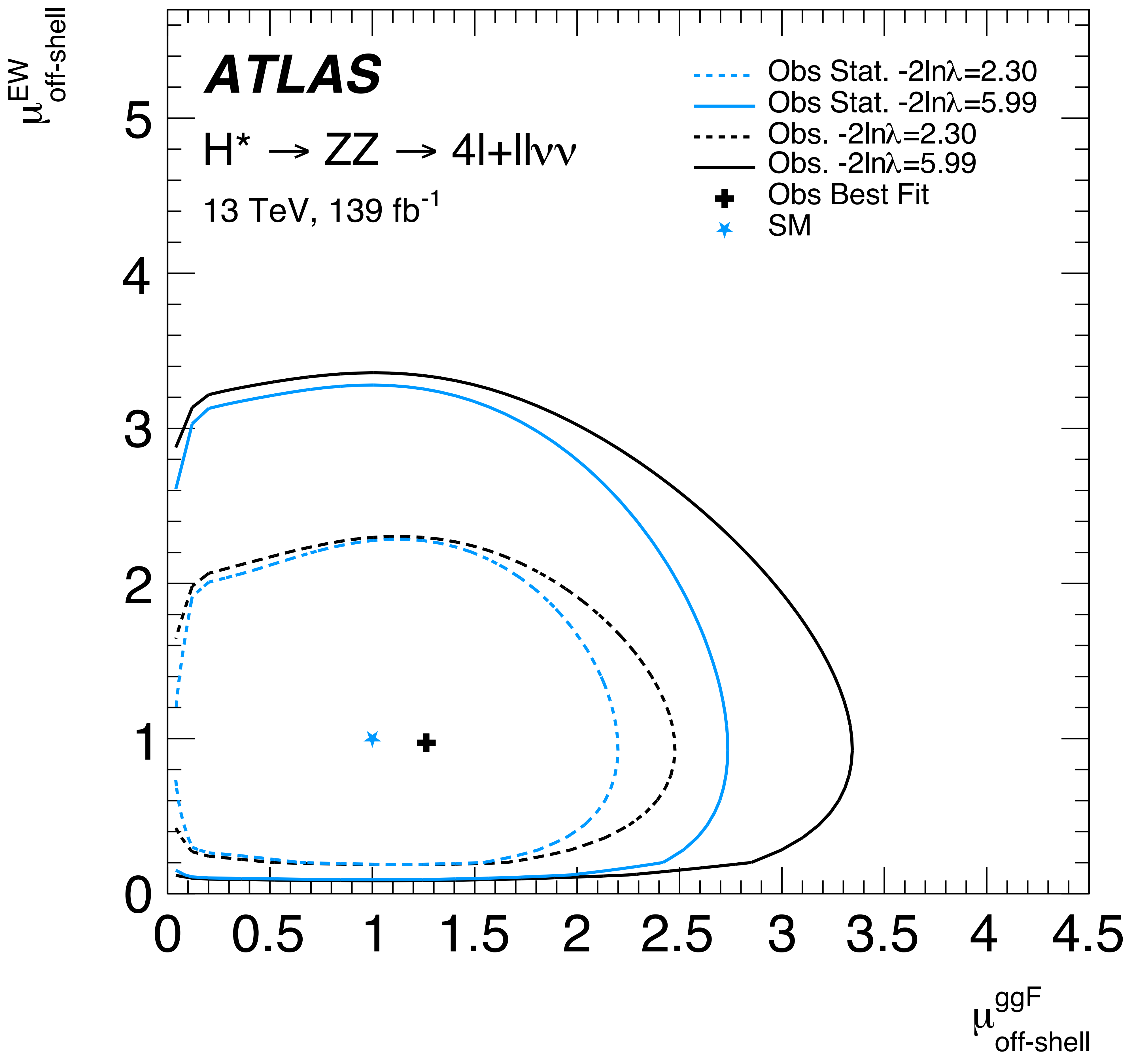


- Both channels combined in final result
- Not in the asymptotic limit → confidence intervals are constructed from pseudoexperiments
  - Curves instead of straight lines on the scan
- Measured value of $\mu_{\text{off-shell}}$=1.1, 95% CL upper limit of 2.4→3.3σ evidence for off-shell production
  - Stat-limited measurement
  - Main systematics from jets and background theory
- Background scale factors are consistent with the SM

Normalization factor	Fitted value
μ_{qqZZ}	1.11 ± 0.07
μ_{qqZZ}^{1j}	0.90 ± 0.10
μ_{qqZZ}^{2j}	0.88 ± 0.26

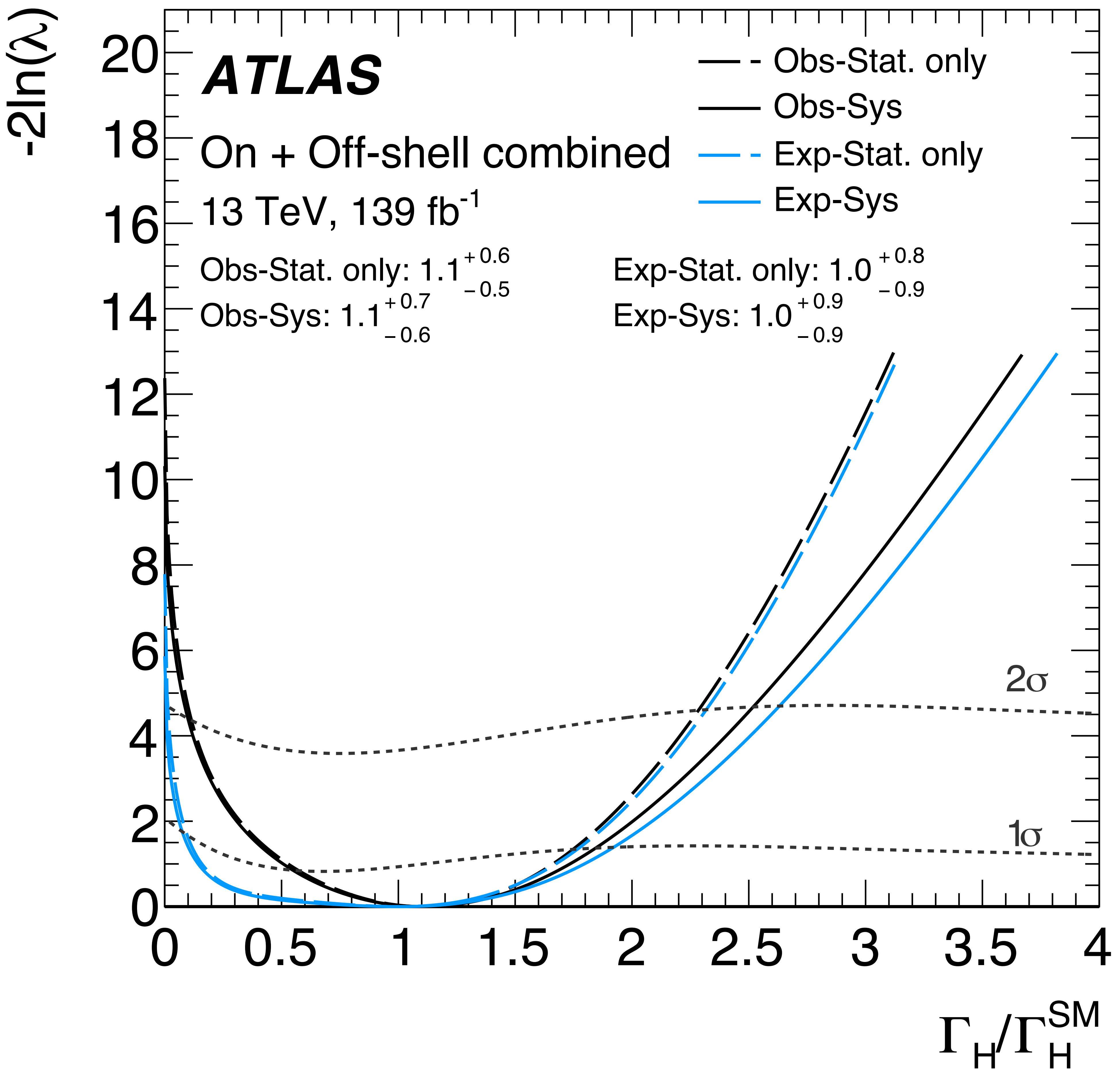
Normalization factor	Fitted value
$\mu_{3\ell}$	1.06 ± 0.03
$\mu_{3\ell}^{1j}$	0.92 ± 0.10
$\mu_{3\ell}^{2j}$	0.75 ± 0.19
μ_{Zj}	0.90 ± 0.19
$\mu_{e\mu}$	1.08 ± 0.09

Measurement of Off-shell Production



- Simultaneous measurement of off-shell EW and ggF production
  - Instead of assuming the same μ value for both
  - Contours correspond to 68% and 95% limits in asymptotic approximation
  - Valid within 5-10%
- Good agreement with the SM observed

Higgs Width Interpretation



- By combining with the results of previous on-shell measurements, can constrain Γ_H
- $\Gamma_H=4.5^{+3.3}_{-2.5}$ MeV, with 95% CL limits of $0.5<\Gamma_H<10.5$ MeV
  - Again using the Neyman construction for confidence intervals
- Good agreement observed with the SM
  - Assuming SM ggH production

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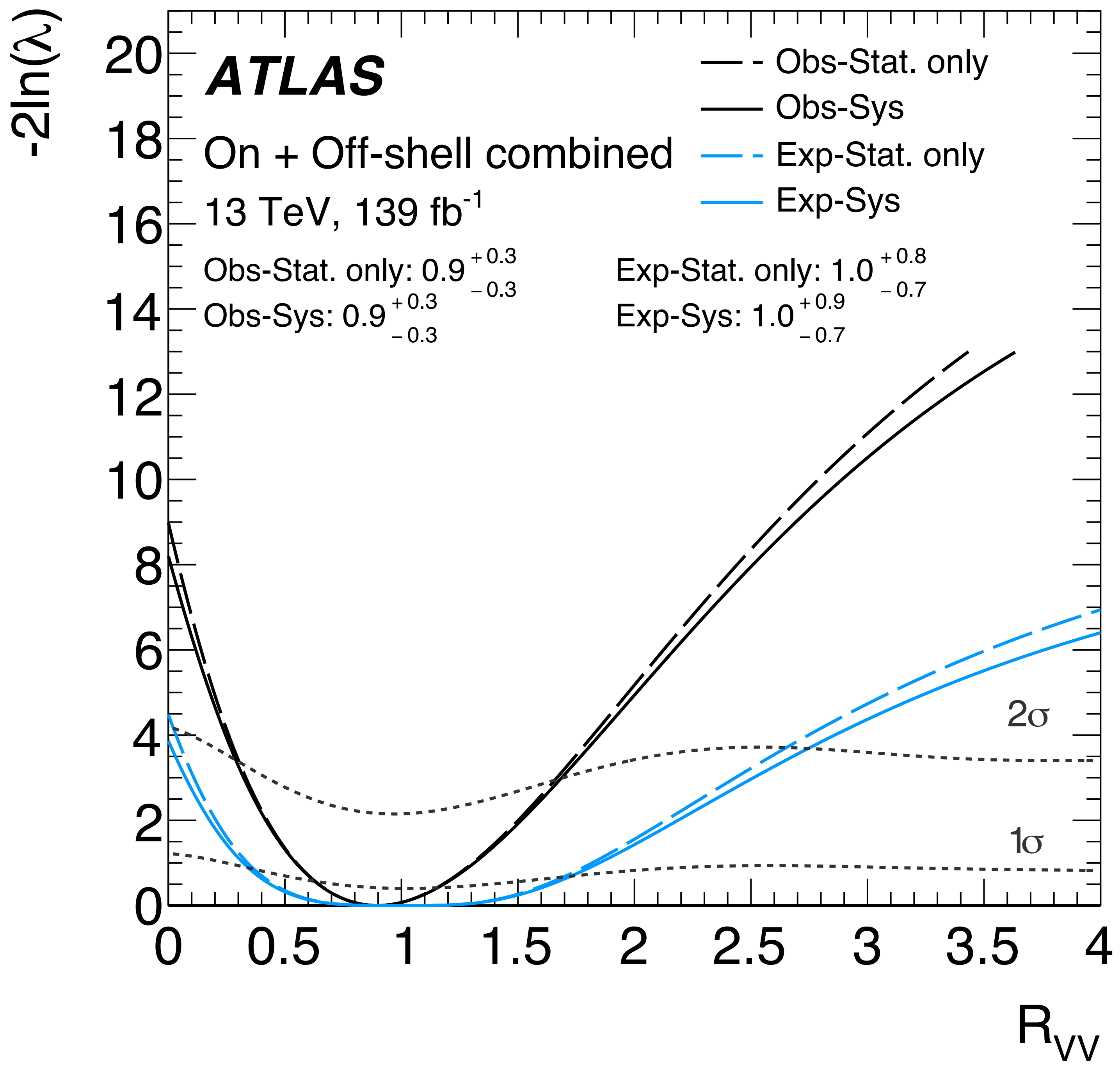
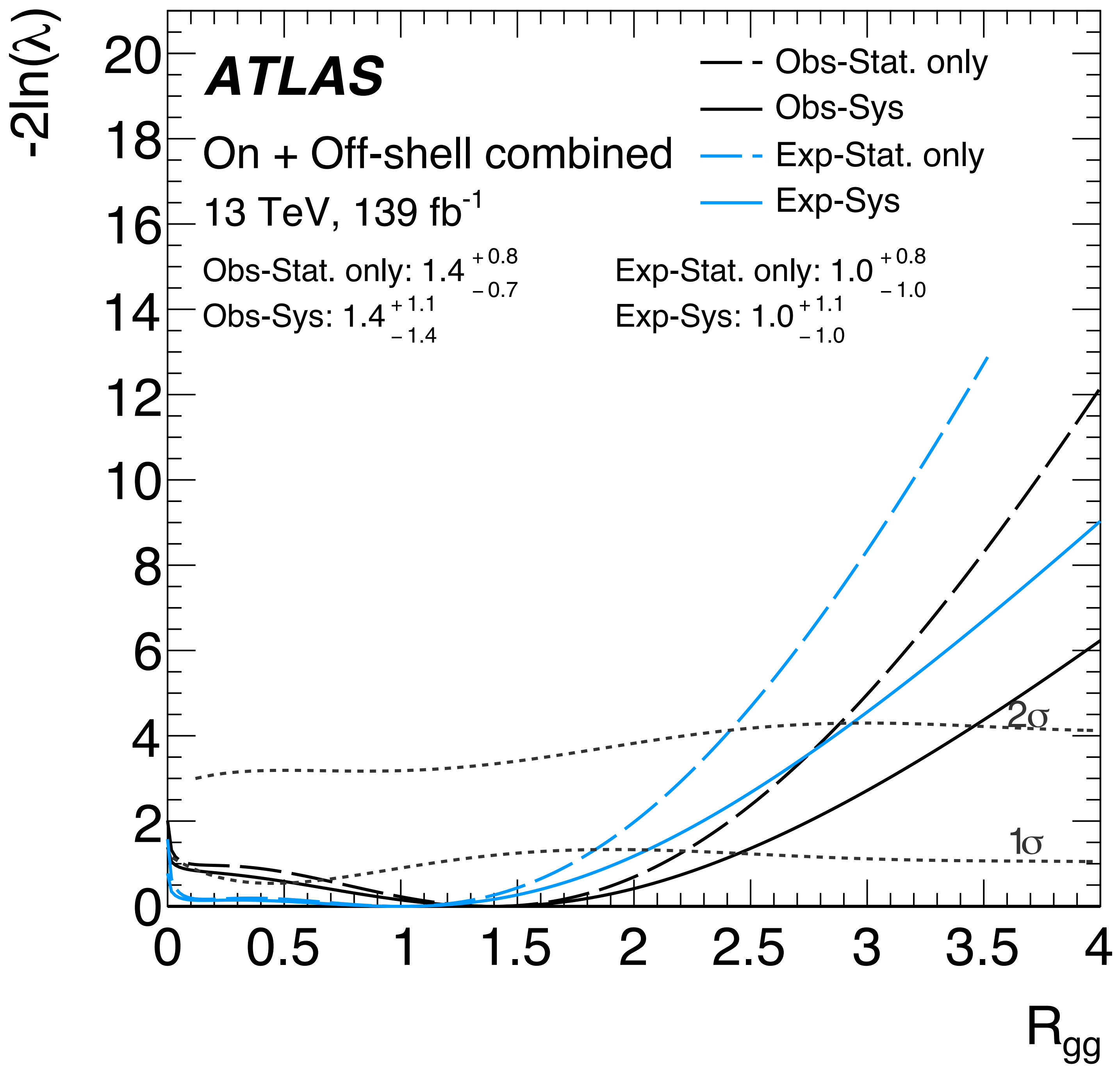
Couplings Interpretation





- Can also use the combination to constrain the ratio of on-shell and off-shell couplings
  - Separately for EW and ggF; R_{VV}=1 for R_{gg} determination and vice versa
  - Assuming the SM width

- Good agreement with the SM observed; $R_{VV}=0.9^{+0.3}_{-0.3}$, $R_{gg}=1.4^{+1.1}_{-1.4}$

Summary and Outlook

- Evidence of off-shell production in the $H \rightarrow ZZ$ decay channel
- Measured Γ_H to be $4.5^{+3.3}_{-2.5}$ MeV
  - Under the assumption that off-shell and on-shell production are the same
  - Also of ratio of on- and off-shell coupling modifiers, assuming Γ_H matches the SM prediction
- Statistics-limited measurement so additional data from Run-3 will be welcome

Backup

4l SR and CR Definitions

EW SR	Mixed SR	ggH SR	0-jet 4l CR	1-jet 4l CR	2-jet 4l CR
$N_{jets}\geq 2$	$N_{jets}=1$	$N_{jets}=0$ or ($N_{jets}=1$ and $\lvert\eta_j\rvert<2.2$) or ($N_{jets}\geq 2$ and $\Delta\eta_{jj}<4$)	$N_{jets}=0$	$N_{jets}=1$	$N_{jets}\geq 2$
$\Delta\eta_{jj}>4$	$\lvert\eta_j\rvert>2.2$		$180<m_{4l}<220$ GeV	$180<m_{4l}<220$ GeV	$180<m_{4l}<220$ GeV
$m_{4l}>220$ GeV	$m_{4l}>220$ GeV	$m_{4l}>220$ GeV			

- Unprescaled single-lepton triggers
- 3 leading lepton p_T thresholds are 20, 15, and 10 GeV
- $\Delta R(l,l')>0.1$
- $50<m_{ll}<115$ GeV
- Four leptons must pass a vertex fit

2l2v SR and CR Definitions

EW SR	Mixed SR	ggH SR	0-jet 3l CR	1-jet 3l CR	2-jet 3l CR	eμ CR	Zjets CR
$N_{jets} \geq 2$	$N_{jets}=1$	$N_{jets}=0$ OR	$N_{jets}=0$	$N_{jets}=1$	$N_{jets} \geq 2$	OFOS pair	
$\Delta\eta_{jj}>4$	$\lvert\eta_j\rvert>2.2$	($N_{jets}=1$, $\lvert\eta_j\rvert<2.2$) OR ($N_{jets} \geq 2$, $\Delta\eta_{jj}<4$)	3rd lepton with $p_T>20$ GeV	3rd lepton with $p_T>20$ GeV	3rd lepton with $p_T>20$ GeV		
7 GeV l_3 veto	7 GeV l_3 veto	7 GeV l_3 veto	7 GeV l_4 veto	7 GeV l_4 veto	7 GeV l_4 veto	7 GeV l_3 veto	7 GeV l_3 veto
$E_T^{miss}>120$ GeV	$E_T^{miss}>120$ GeV	$E_T^{miss}>120$ GeV	$m_t^W>60$ GeV	$m_t^W>60$ GeV	$m_t^W>60$ GeV	$E_T^{miss}>120$ GeV	$E_T^{miss}>120$ GeV
$\Delta R_{ll}<1.8$	$\Delta R_{ll}<1.8$	$\Delta R_{ll}<1.8$	$m_T(W) = \sqrt{2p_T^{\ell} E_{\mathrm{T}}^{\mathrm{miss}}(1 - cos\Delta\phi)}$			$\Delta R_{ll}<1.8$	$\Delta R_{ll}<1.8$
$\Delta\phi(p_{T,ll}, E_T^{miss})>2.5$	$\Delta\phi(p_{T,ll}, E_T^{miss})>2.5$	$\Delta\phi(p_{T,ll}, E_T^{miss})>2.5$				$\Delta\phi(p_{T,ll}, E_T^{miss})>2.5$	$\Delta\phi(p_{T,ll}, E_T^{miss})>2.5$
$\Delta\phi(jet_{>100}, E_T^{miss})>0.4$	$\Delta\phi(jet_{>100}, E_T^{miss})>0.4$	$\Delta\phi(jet_{>100}, E_T^{miss})>0.4$				$\Delta\phi(jet_{>100}, E_T^{miss})>0.4$	
E_T^{miss} signif>10	E_T^{miss} signif>10	E_T^{miss} signif>10	E_T^{miss} signif>3	E_T^{miss} signif>3	E_T^{miss} signif>3	E_T^{miss} signif>10	E_T^{miss} signif<9
b-jet veto	b-jet veto	b-jet veto	b-jet veto	b-jet veto	b-jet veto	b-jet veto	b-jet veto

- Unprescaled single-lepton triggers
- Lepton $p_T>20$ GeV
- $76<m_{ll}<106$ GeV

Leading Systematic Uncertainties

Process	Uncertainty	Final State	Value (%)
	ggF Signal Region		
$qq \to ZZ$	QCD Scale	$2\ell 2\nu$	4–40
$qq \to ZZ + 2j$	QCD Scale	4ℓ	21–28
$qq \to ZZ + 2j$	QCD Scale	$2\ell 2\nu$	22–37
$qq \to ZZ + 2j$	Parton Shower	$2\ell 2\nu$	1–67
$gg \to H^* \to ZZ$	Parton Shower	4ℓ	27
$gg \to H^* \to ZZ$	Parton Shower	$2\ell 2\nu$	8–45
$gg \to ZZ$	Parton Shower	4ℓ	38
$gg \to ZZ$	Parton Shower	$2\ell 2\nu$	6–43
$WZ + 0j$	QCD Scale	$2\ell 2\nu$	1–54
	1-jet Signal Region		
$gg \to H^* \to ZZ$	Parton Shower	4ℓ	27
$gg \to H^* \to ZZ$	QCD Scale	$2\ell 2\nu$	13–18
$gg \to ZZ$	Parton Shower	4ℓ	38
$gg \to ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$qq \to ZZ$ (EW)	QCD Scale	$2\ell 2\nu$	7–18
	2-jet Signal Region		
$qq \to ZZ + 2j$	QCD Scale	4ℓ	18–26
$qq \to ZZ + 2j$	QCD Scale	$2\ell 2\nu$	8–32
$gg \to H^* \to ZZ$	Parton Shower	4ℓ	27
$gg \to ZZ$	Parton Shower	4ℓ	38
$gg \to ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$WZ + 2j$	QCD Scale	$2\ell 2\nu$	20–22
	$qq \to ZZ$ Control Regions		
$qq \to ZZ + 2j$	QCD Scale	4ℓ	26
	Three-lepton Control Regions		
$WZ + 2j$	QCD Scale	$2\ell 2\nu$	28

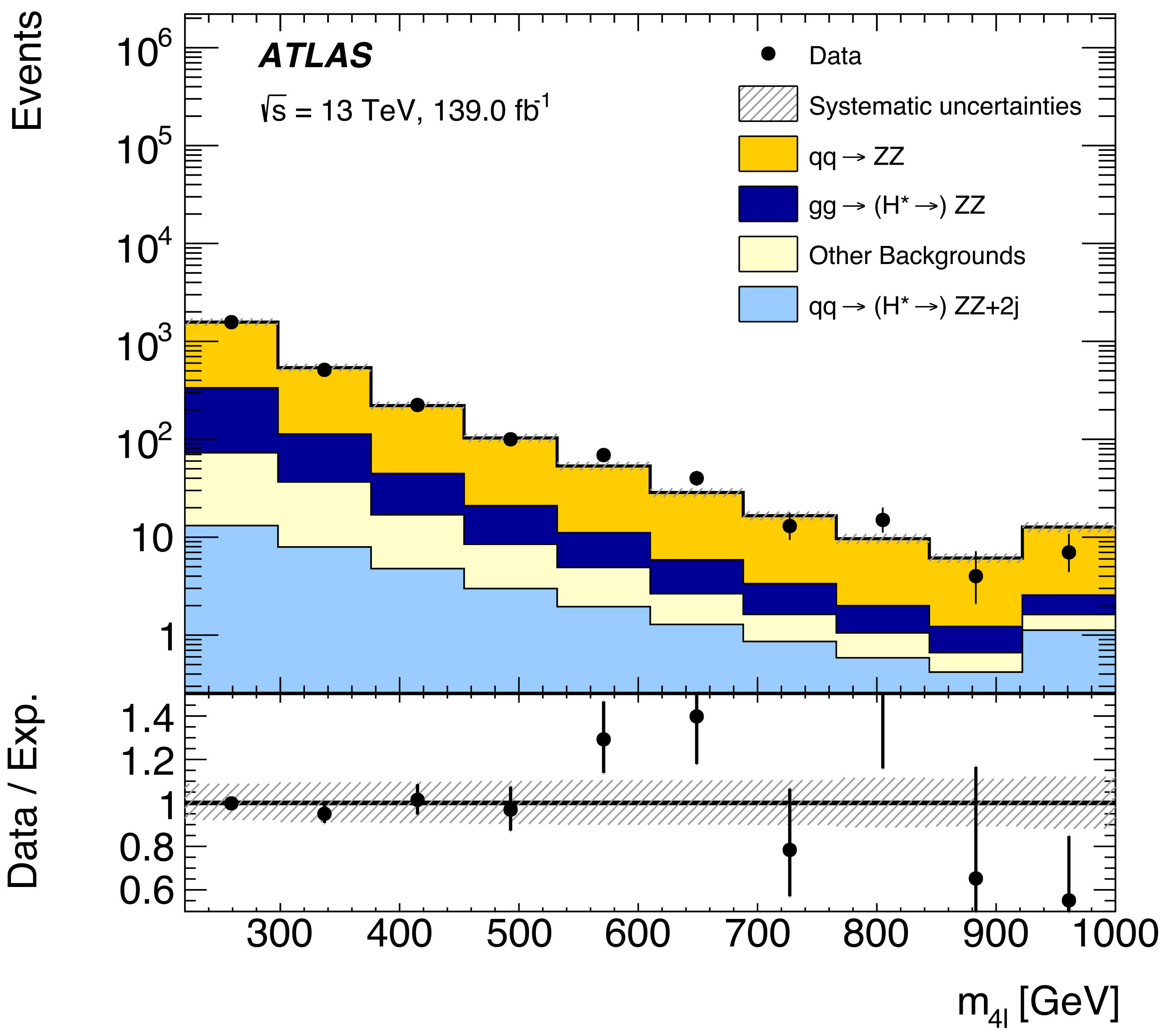
Systematic Uncertainty Fixed	$\mu_{\text{off-shell}}$ value at which $-2\ln\lambda(\mu_{\text{off-shell}}) = 4$
Parton shower uncertainty for $gg \to ZZ$ (normalisation)	2.26
Parton shower uncertainty for $gg \to ZZ$ (shape)	2.29
NLO EW uncertainty for $qq \to ZZ$	2.27
NLO QCD uncertainty for $gg \to ZZ$	2.29
Parton shower uncertainty for $qq \to ZZ$ (shape)	2.29
Jet energy scale and resolution uncertainty	2.26
None	2.30

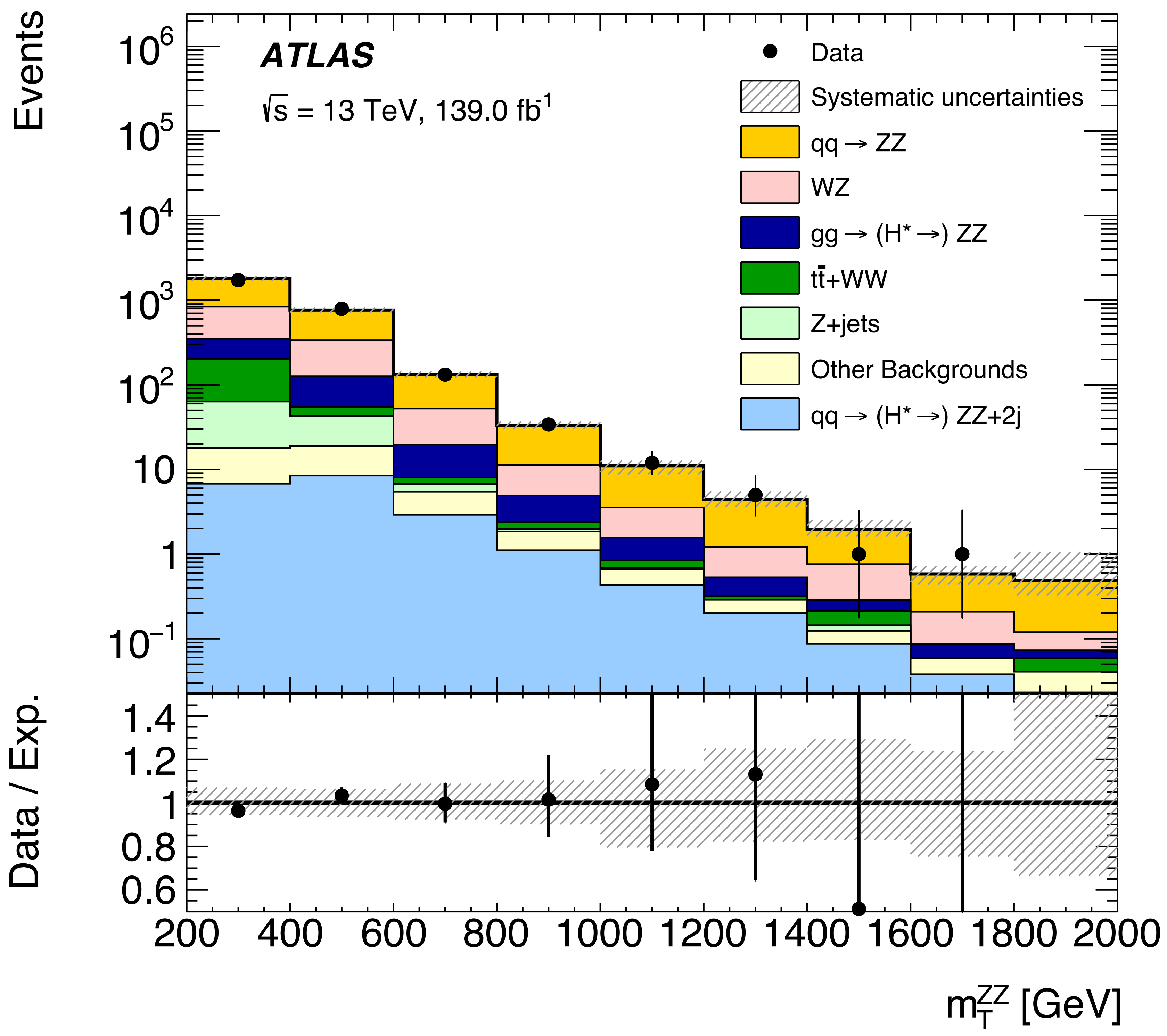
Yields

Process	ggF SR	Mixed SR	EW SR
$gg \to (H^* \to)ZZ$	341 ± 117	42.5 ± 14.9	11.8 ± 4.3
$gg \to H^* \to ZZ$	32.6 ± 9.07	3.68 ± 1.03	1.58 ± 0.47
$gg \to ZZ$	345 ± 119	43.0 ± 15.2	11.9 ± 4.4
$qq \to (H^* \to)ZZ + 2j$	23.2 ± 1.0	2.03 ± 0.16	9.89 ± 0.96
$qq \to ZZ$	1878 ± 151	135 ± 23	22.0 ± 8.3
Other backgrounds	50.6 ± 2.5	1.79 ± 0.16	1.65 ± 0.16
Total expected (SM)	2293 ± 209	181 ± 29	45.3 ± 10.0
Observed	2327	178	50

Process	ggF SR	Mixed SR	EW SR
$gg \to (H^* \to)ZZ$	210 ± 53	19.7 ± 4.9	4.29 ± 1.10
$gg \to H^* \to ZZ$	111 ± 26	10.9 ± 2.5	3.26 ± 0.82
$gg \to ZZ$	251 ± 66	23.4 ± 6.2	5.31 ± 1.46
$qq \to (H^* \to)ZZ + 2j$	14.0 ± 3.0	1.63 ± 0.17	4.46 ± 0.50
$qq \to ZZ$	1422 ± 112	80.4 ± 11.9	7.74 ± 2.99
WZ	678 ± 54	51.9 ± 6.9	7.89 ± 2.50
Z+jets	62.3 ± 24.3	7.51 ± 6.94	0.62 ± 0.54
Non-resonant-$\ell\ell$	106 ± 39	9.17 ± 2.73	1.55 ± 0.42
Other backgrounds	22.6 ± 5.2	1.62 ± 0.25	1.40 ± 0.10
Total expected (SM)	2515 ± 165	172 ± 17	28.0 ± 4.1
Observed	2496	181	27

Data-MC comparison in Inclusive SR





- Post-fit, with $\mu_{offshell}$=1 assumed in the fit