Indirect measurements of the Higgs Boson natural width with the ATLAS detector

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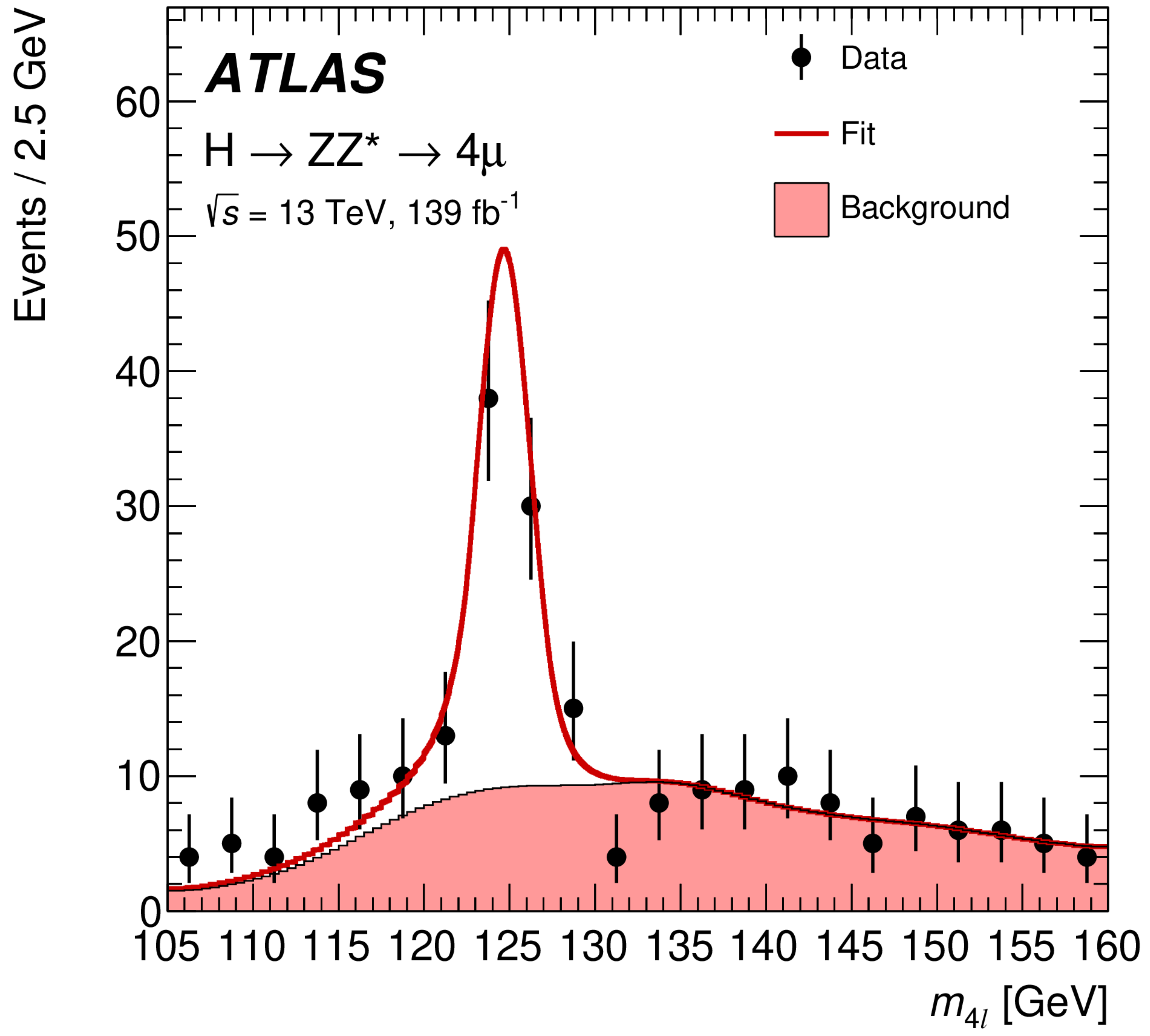
HIGGS2024, Uppsala, Sweden

Off-shell Production and the Higgs Boson Width

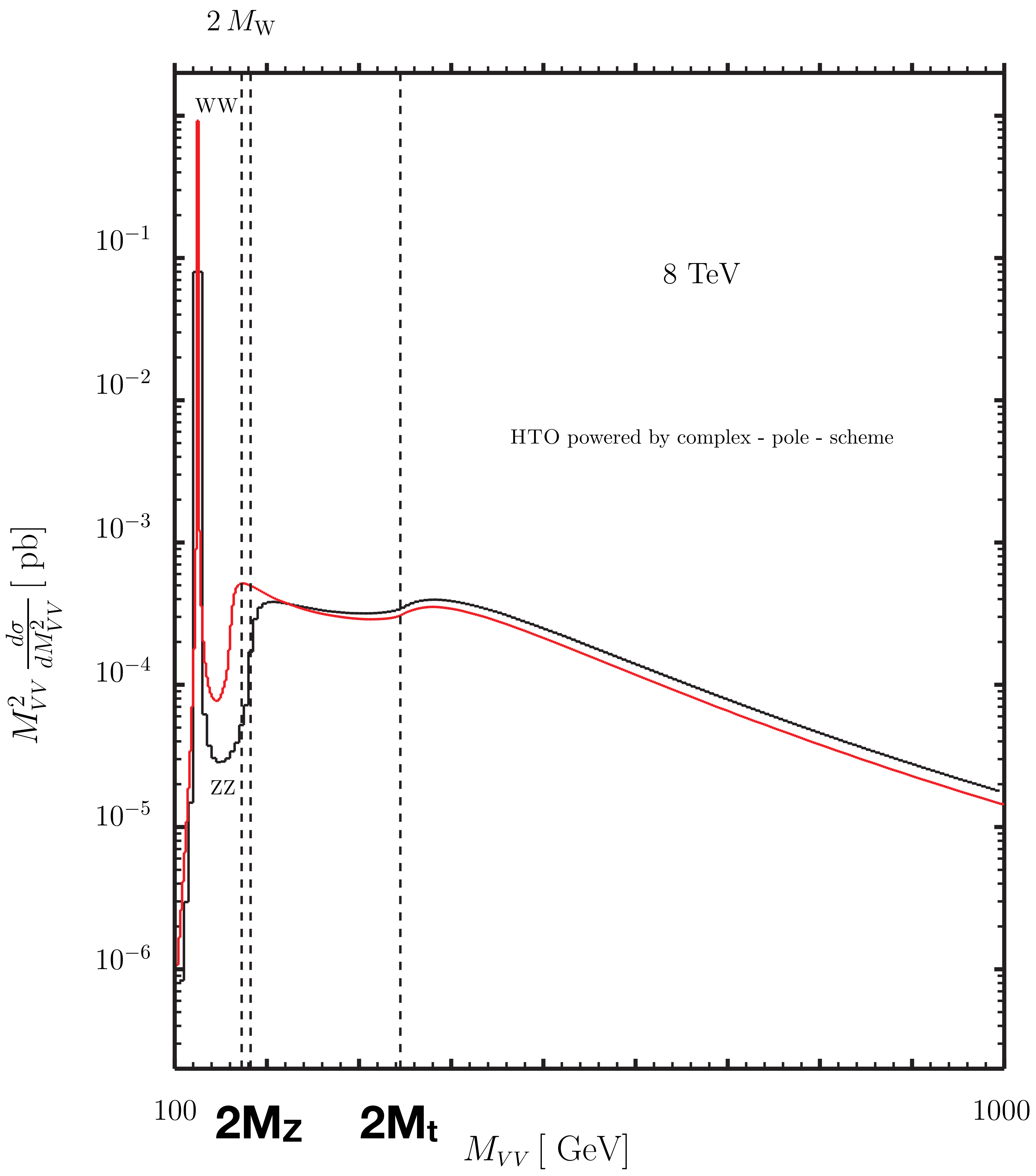
Phys. Lett. B 843 (2023) 137880



- Higgs peak in the H→ZZ→4μ channel
- Best achievable resolution is still >1 GeV
- It is challenging to measure Γ_H of 4.1 MeV at ATLAS from the on-shell lineshape
- But it can be measured using off-shell production, which does not depend on Γ_H

Off-shell Production in H→ZZ

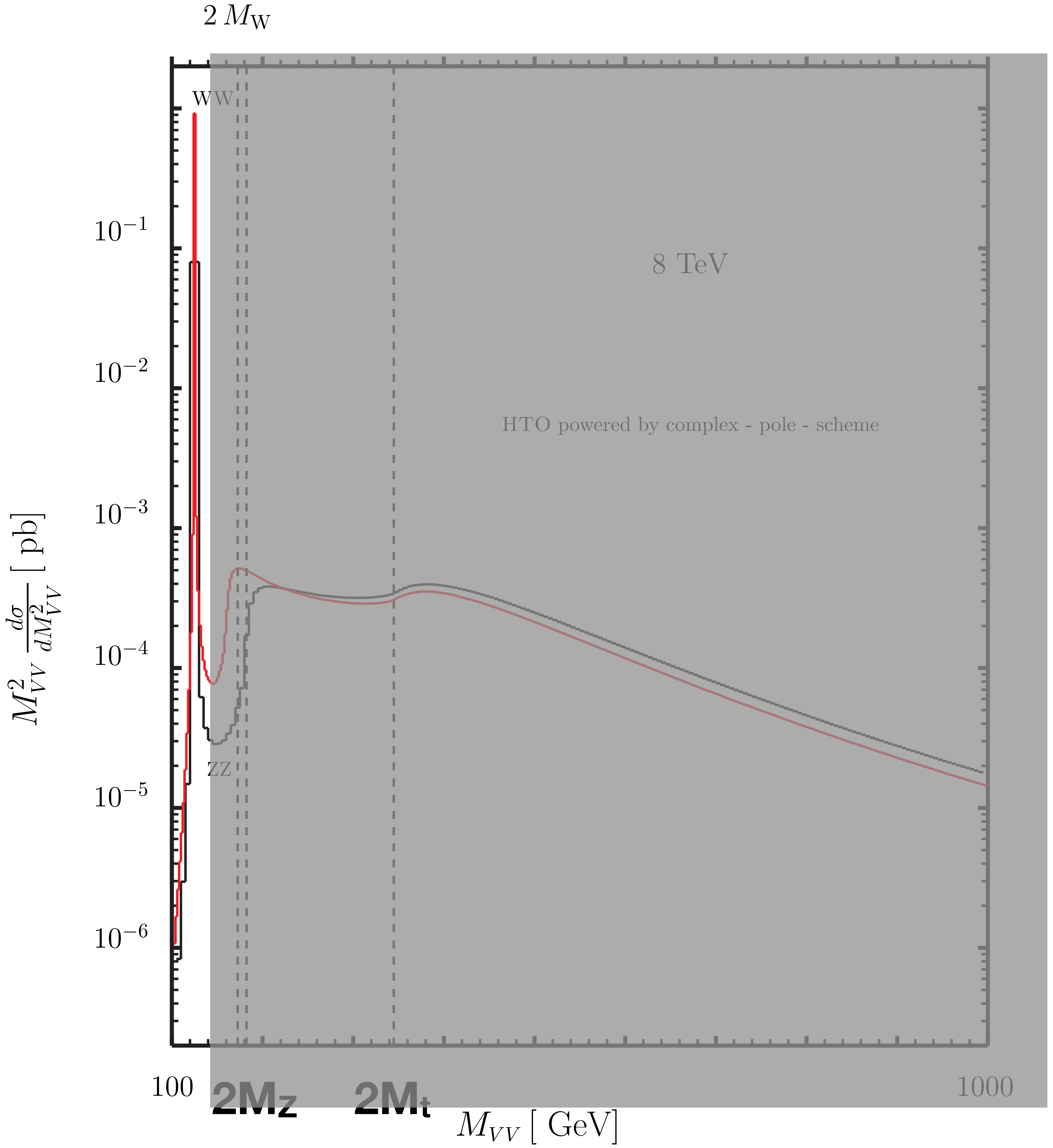
Kauer & Passarino, JHEP 2012, 116



- The H→ZZ channel is a good candidate for measuring the width using off-shell production
  - Decays in this channel are enhanced when both Z bosons are on-shell

Off-shell Production in H→ZZ

Kauer & Passarino, JHEP 2012, 116

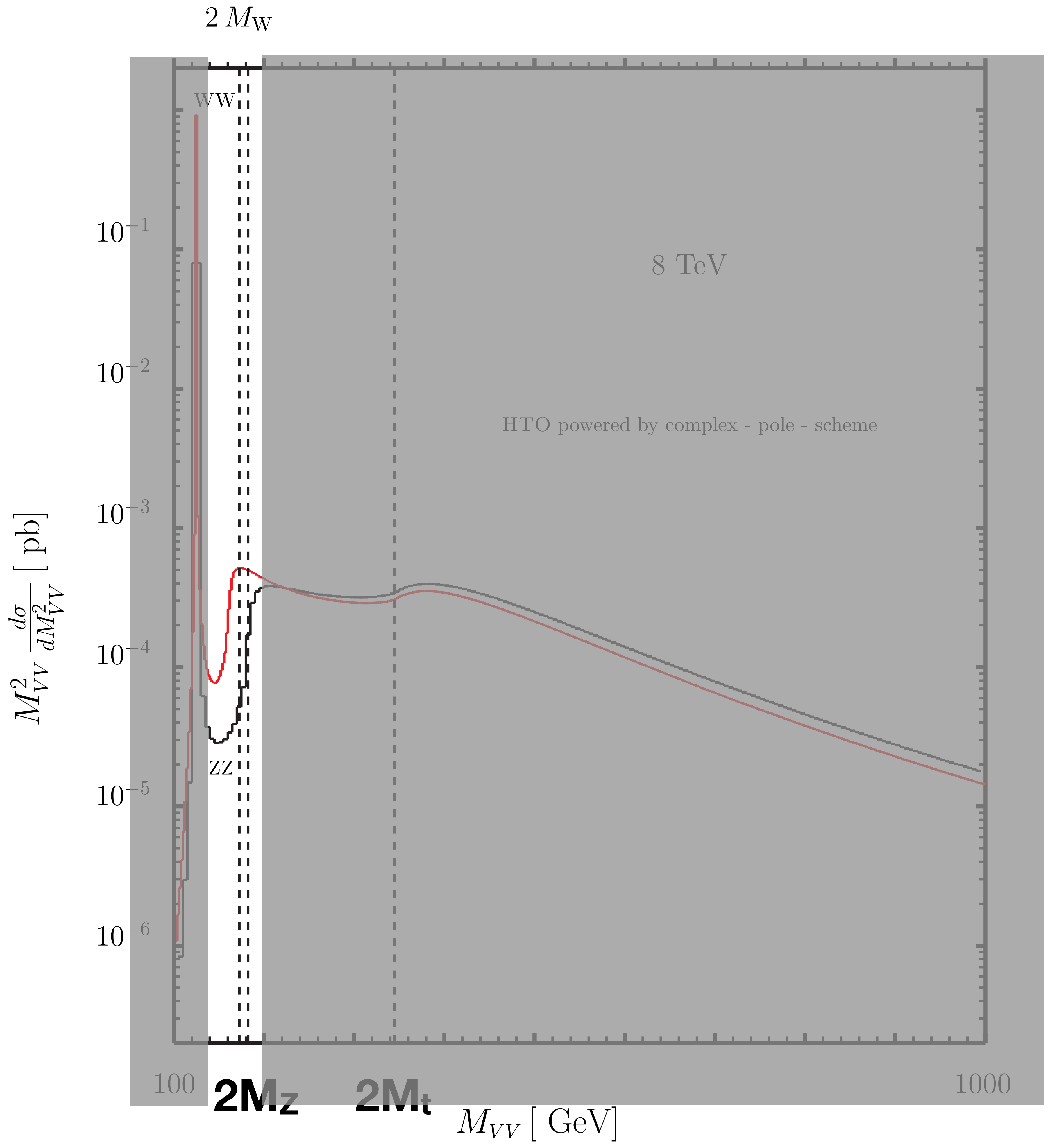


- On-shell, lineshape is Breit-Wigner, hence $\sigma_{\text{on-shell}} \sim 1/\Gamma_H$

$$\frac{1}{\left(q^2 - M_H^2\right)^2 + \Gamma_H^2\, M_H^2}$$

Off-shell Production in H→ZZ

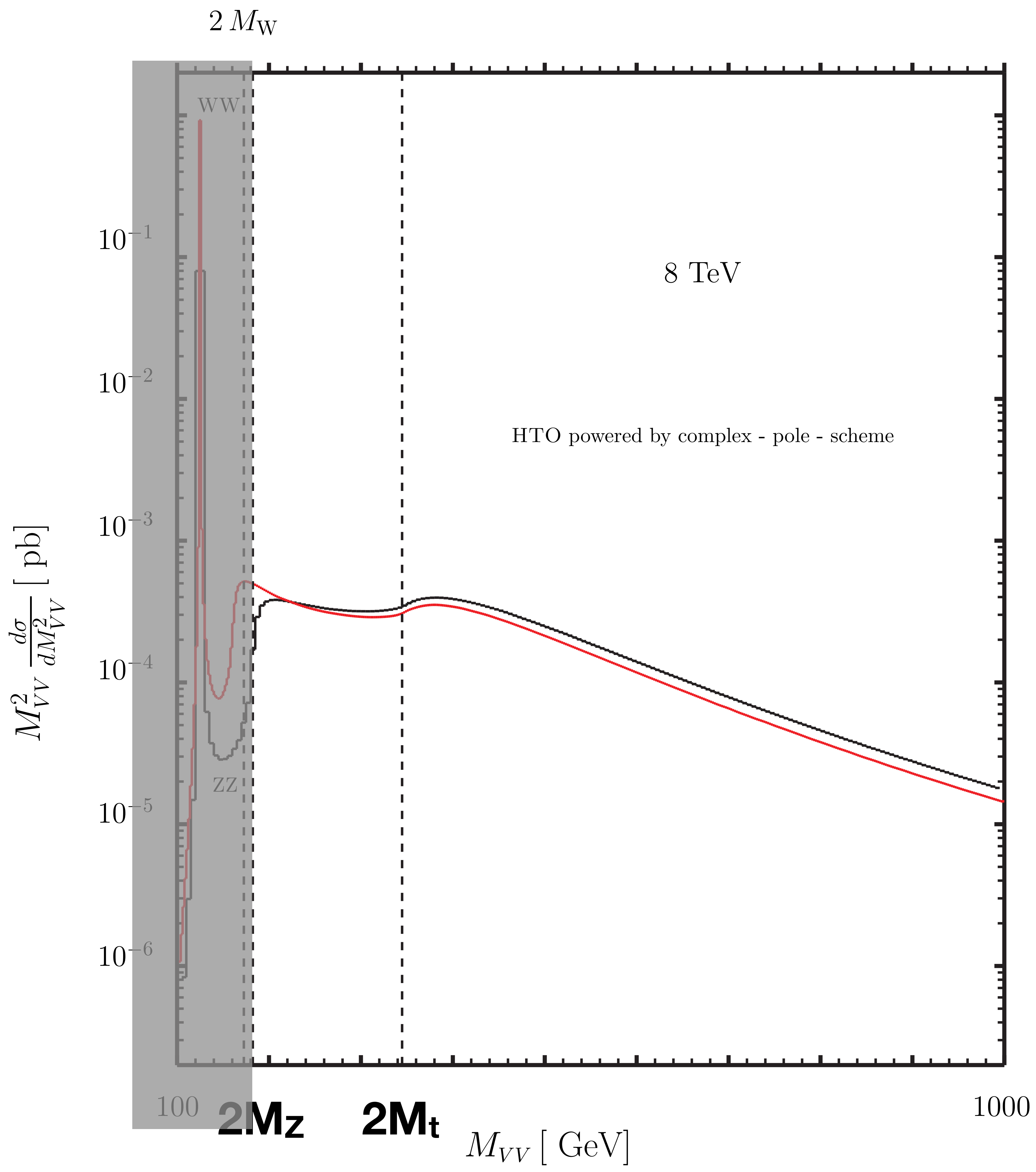
Kauer & Passarino, JHEP 2012, 116



- But at higher masses, this is no longer the case
- In the ZZ channel, there is an increase in the cross-section as m_{ZZ} approaches $2m_Z$
  - There is a dropoff due to the q^2 dependence of the propagator
  - But the increase in decay phase space is much larger

Off-shell Production in H→ZZ

Kauer & Passarino, JHEP 2012, 116

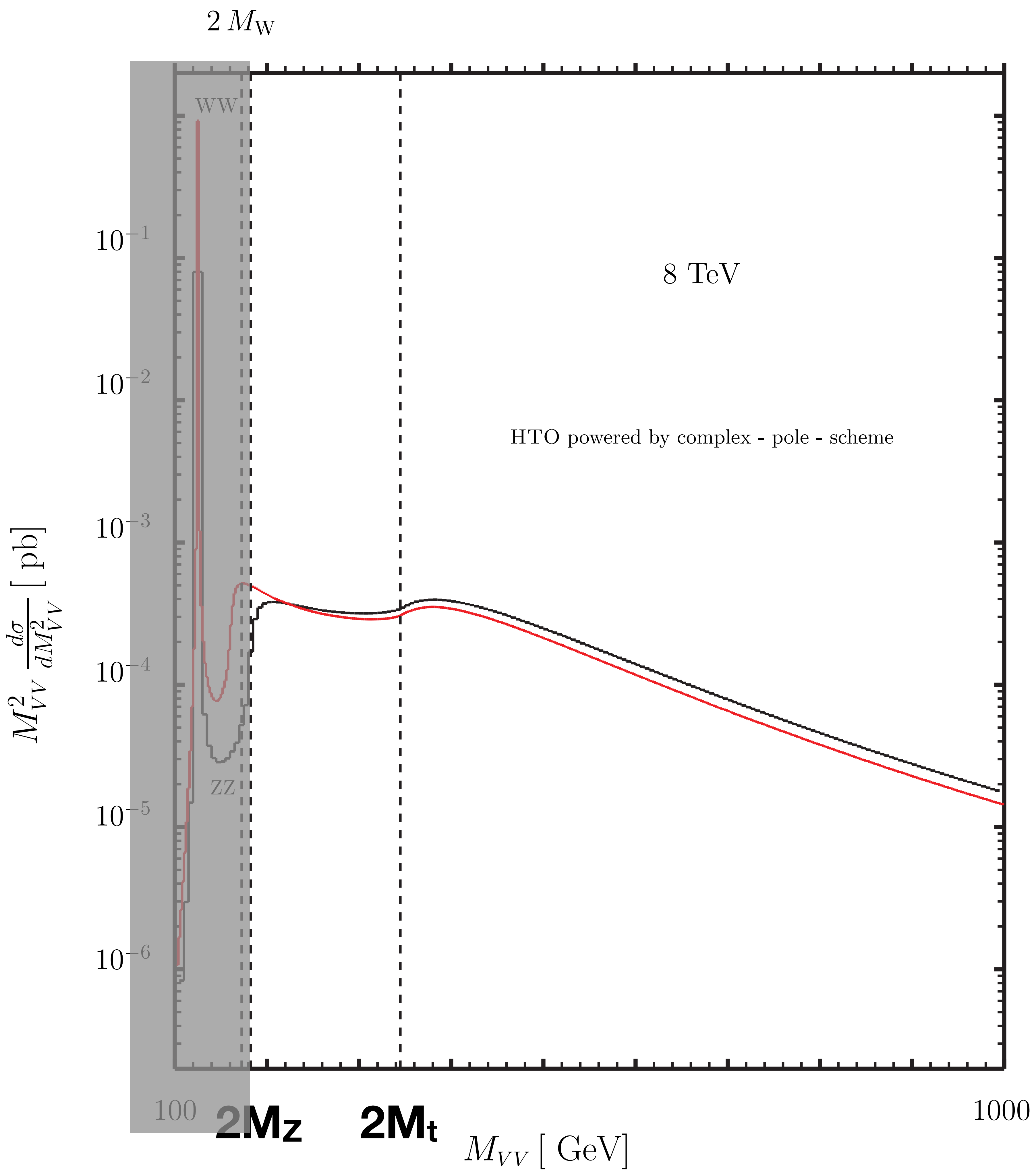


- Above 2m$_Z$, the production cross-section is no longer dependent on the width

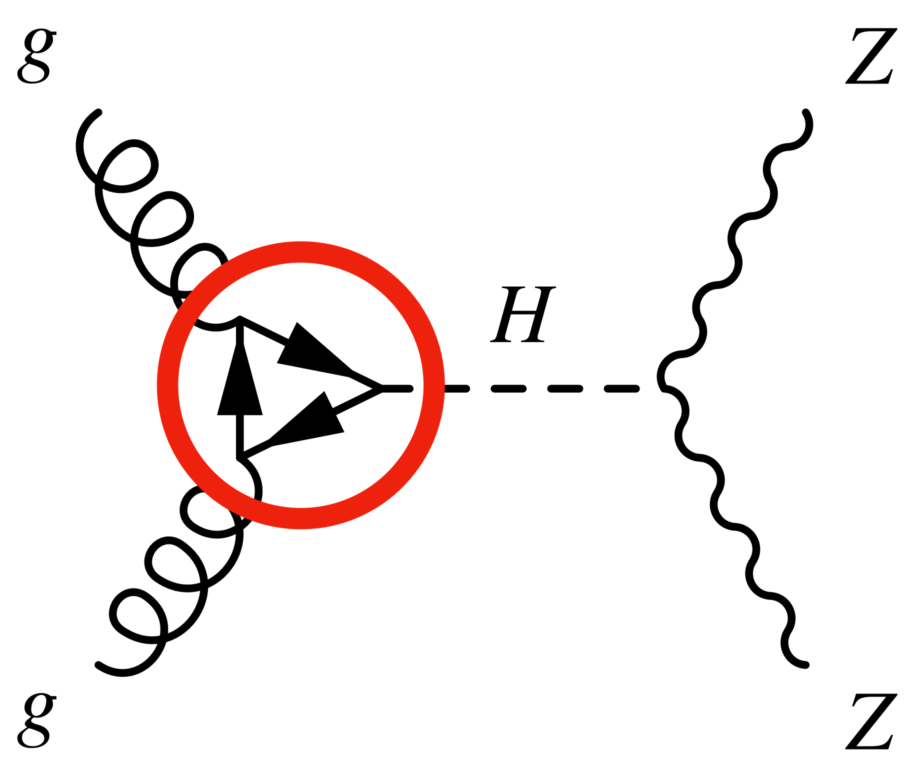
- Therefore Γ_H can be obtained from a ratio of on-shell and off-shell production

Off-shell Production in H→ZZ

Kauer & Passarino, JHEP 2012, 116



- **Requires the assumption that all couplings follow SM predictions**
- **In particular, the effective coupling g_{ggH}**
- **→ No new particles enter the quark loop, so on-shell and off-shell production are the same**



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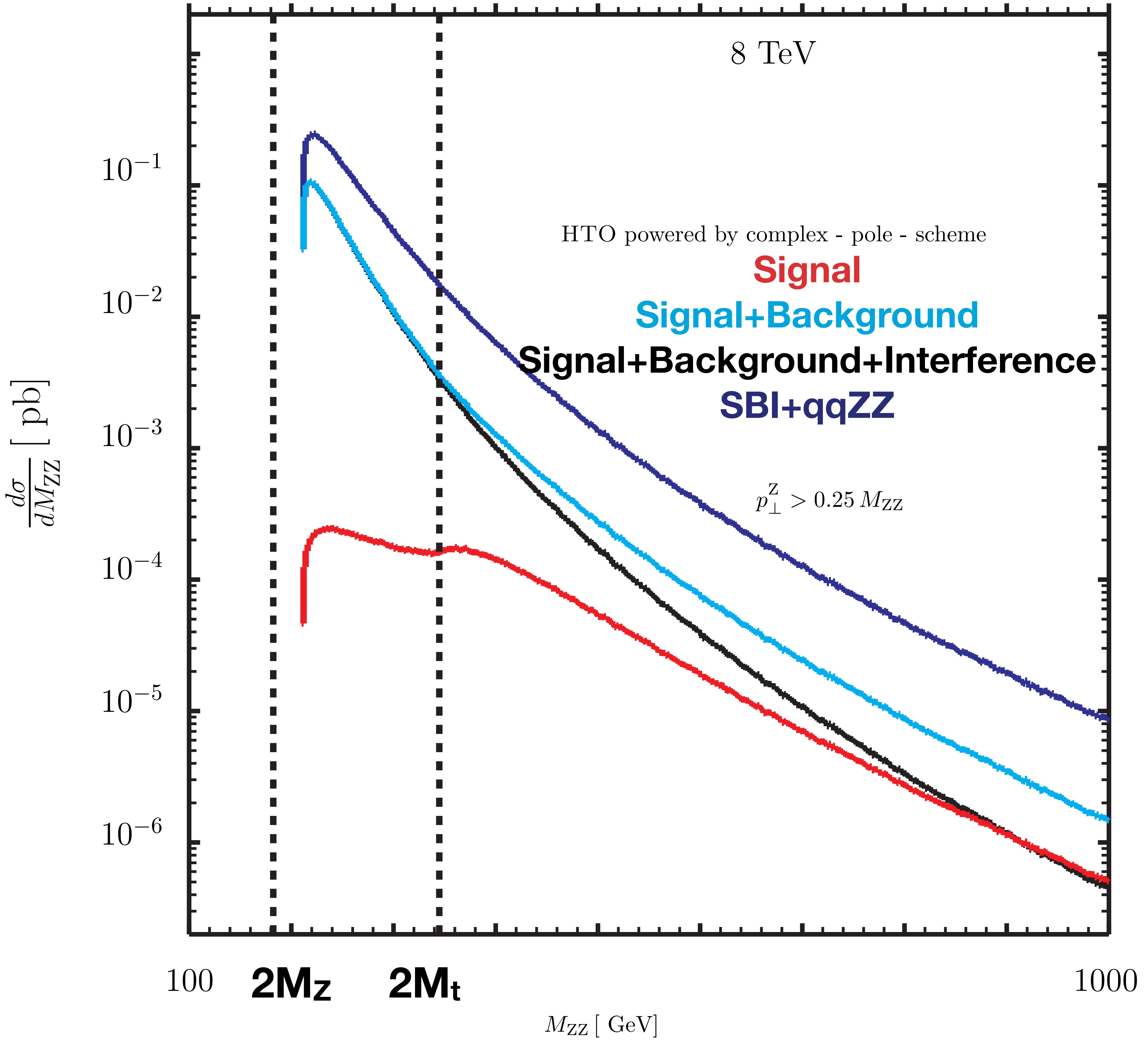
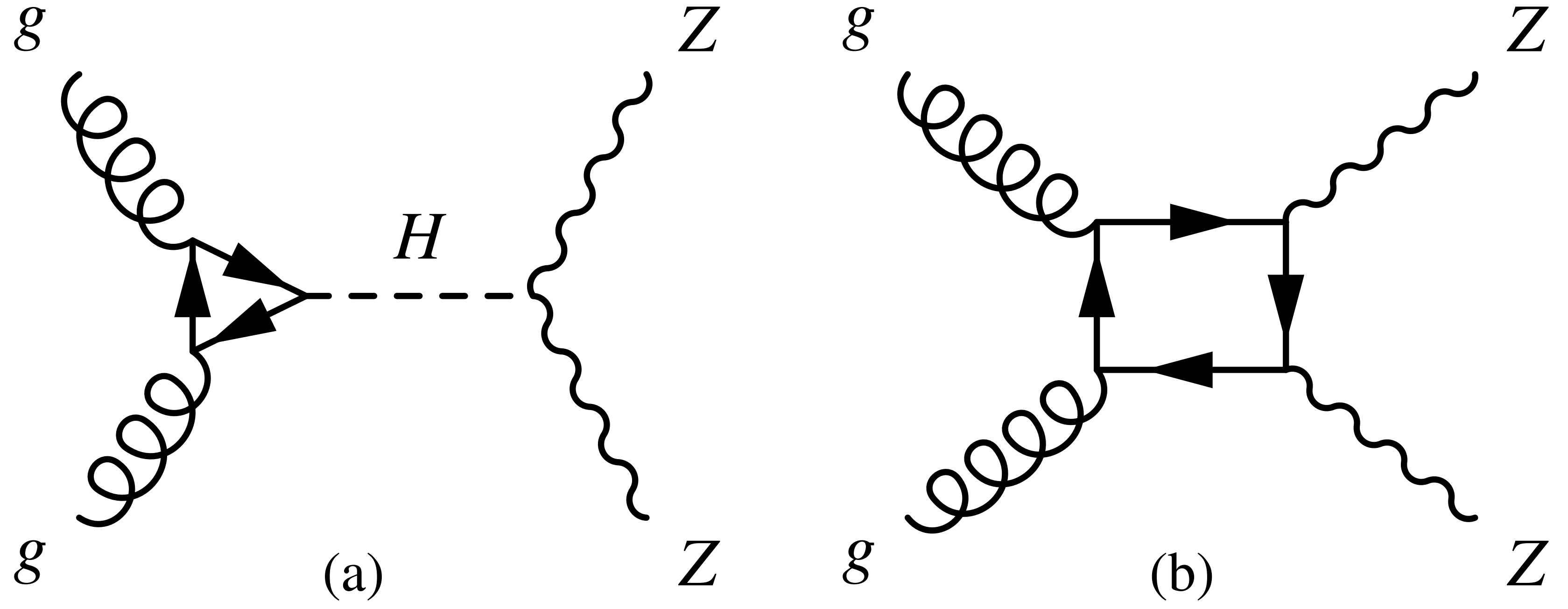
Signal-Background Interference in H→ZZ

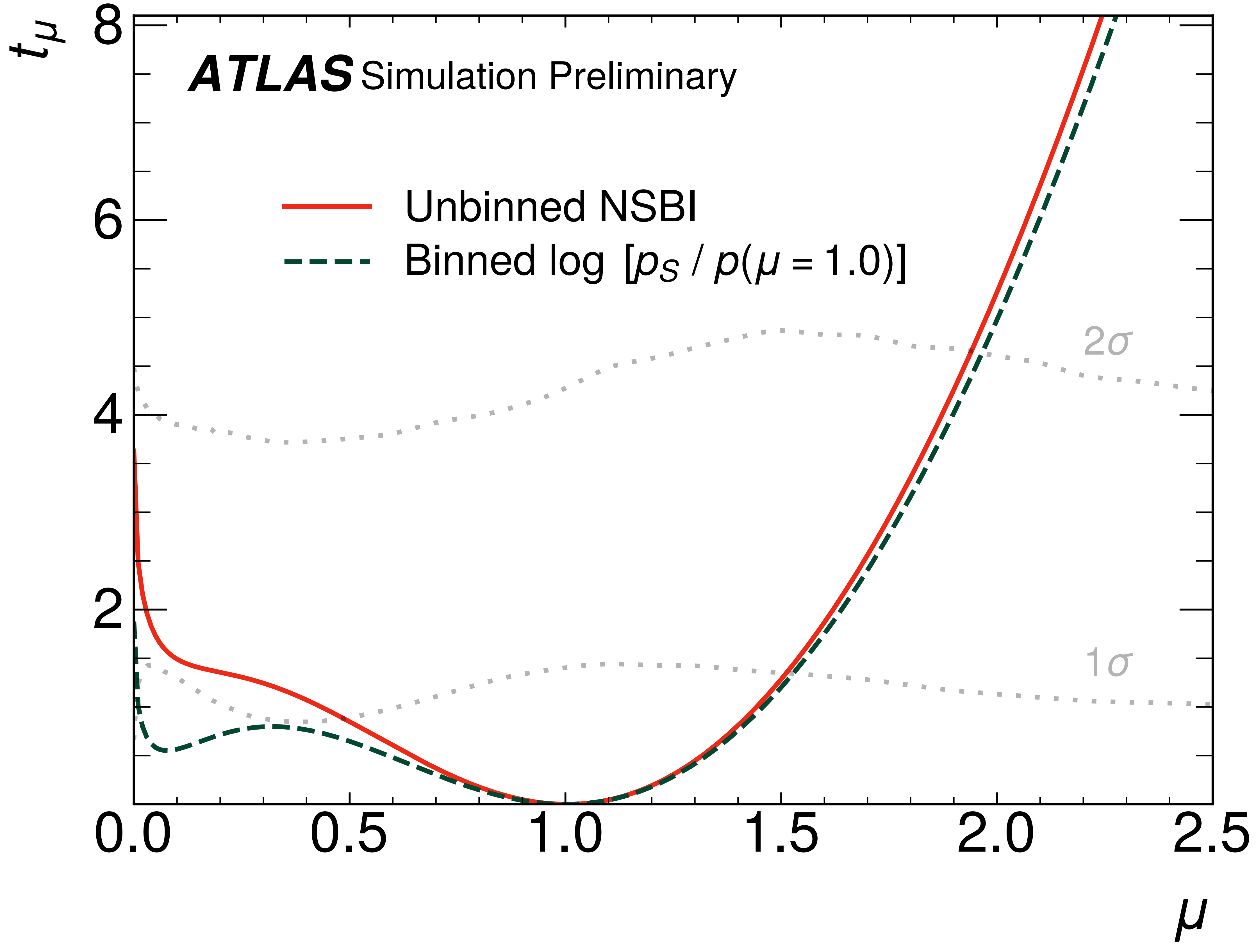
Kauer & Passarino, JHEP 2012, 116

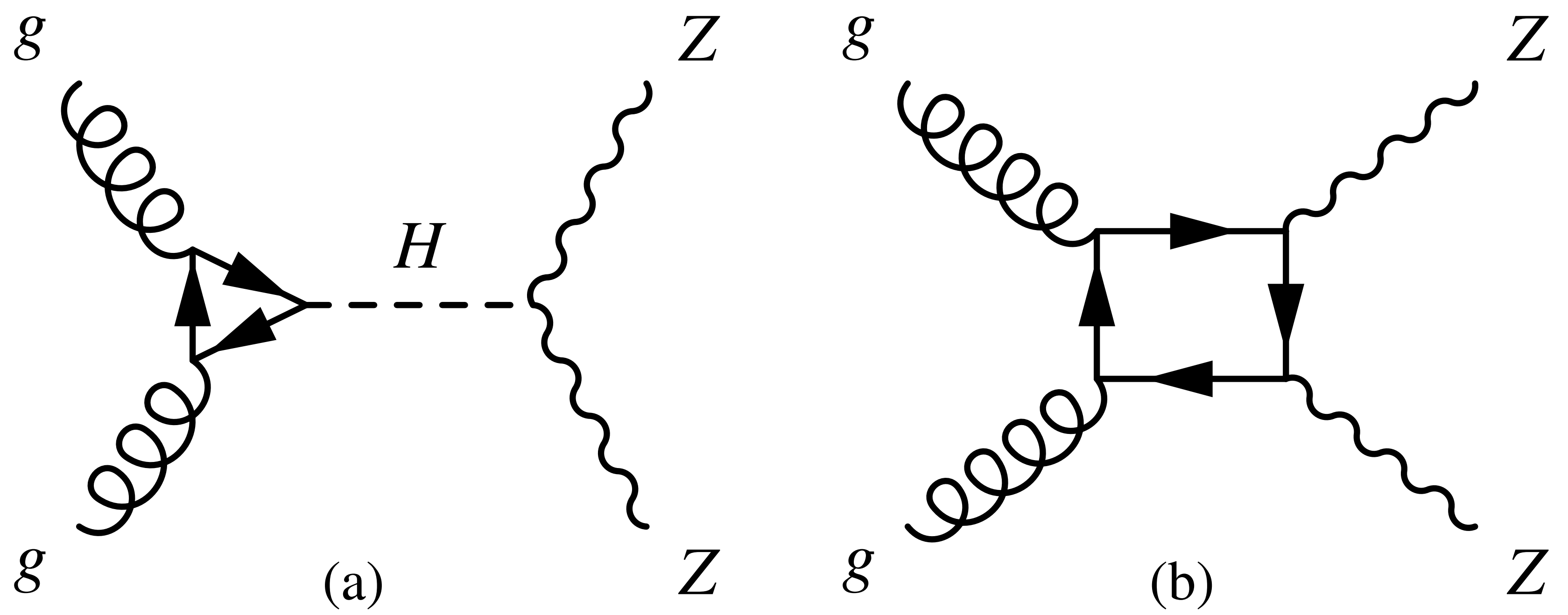




- The signal gg→H*→ZZ and background gg→ZZ process interfere
    - We measure a deficit wrt the background, not a signal
- Signal scales with μ_{offshell} but the interference goes as $\sqrt{\mu_{\text{offshell}}}$

Signal-Background Interference in H→ZZ



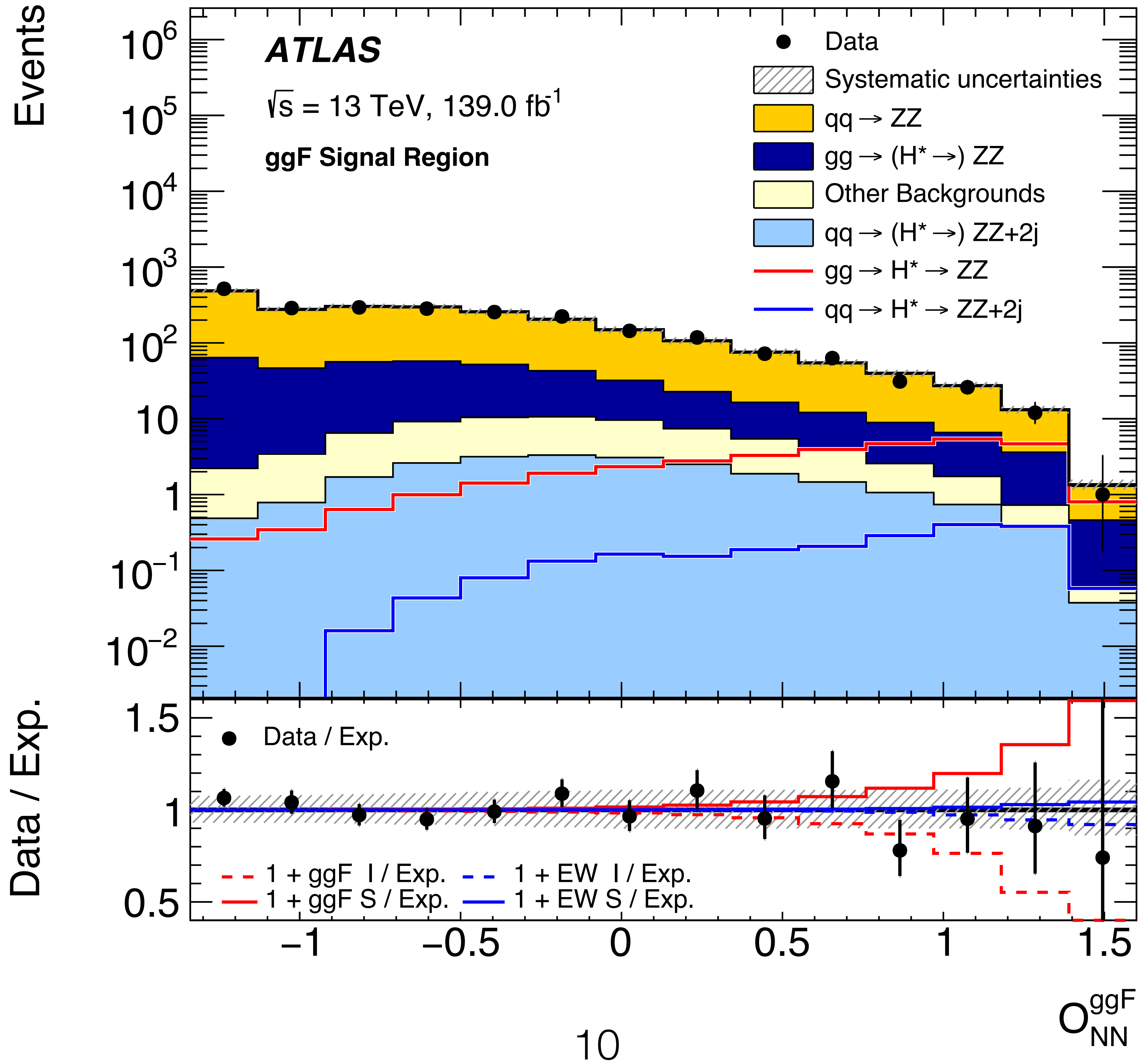


- $\sqrt{\mu_{\text{off-shell}}}$ dependence means that asymptotic approximation does not hold
  - Introduces double minimum
  - Requires cutoff at $\mu_{\text{off-shell}}=0$
  - → Confidence intervals have to be derived using the Neyman construction

See talk by J. Sandesara

Neural Simulation Based Inference

- Standard approach uses histograms of kinematic observables to approximate density ratio
  - As done in the previous ATLAS result, Phys. Lett. B 846 (2023) 138223
  - NN trained to distinguish between signal and background



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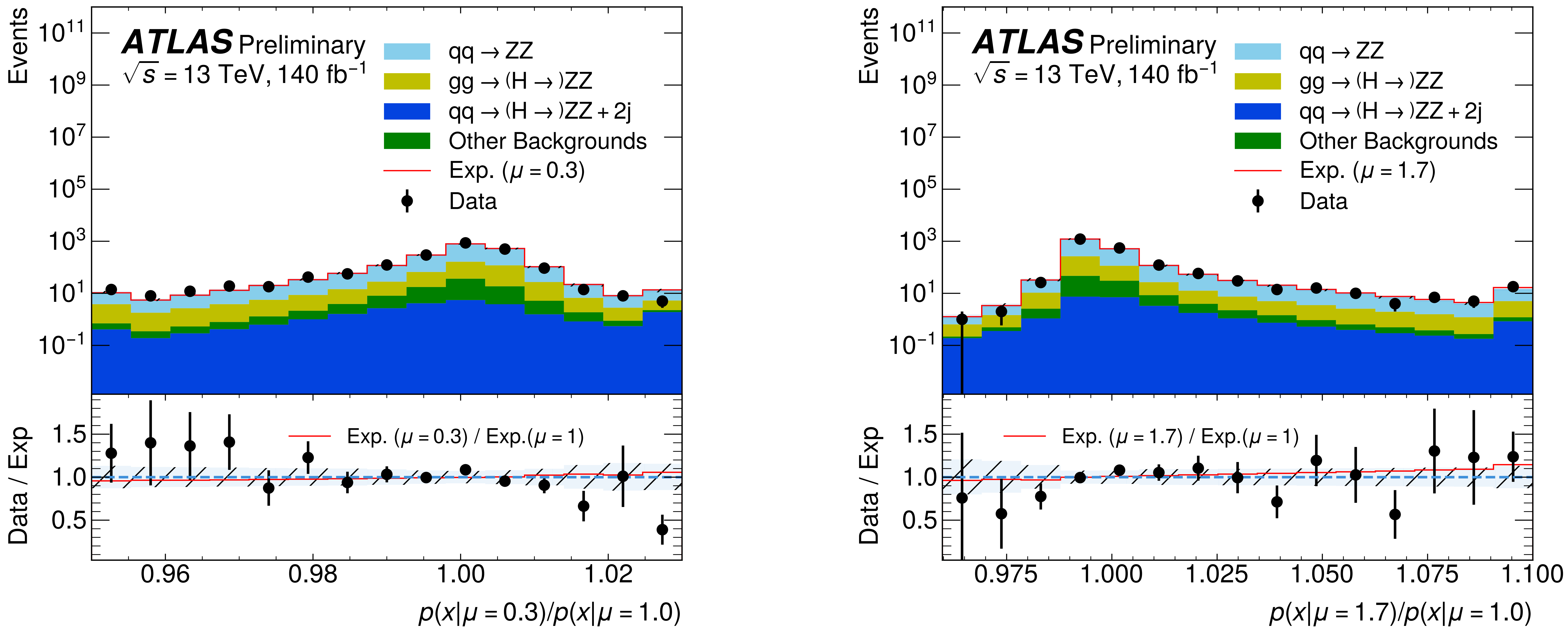
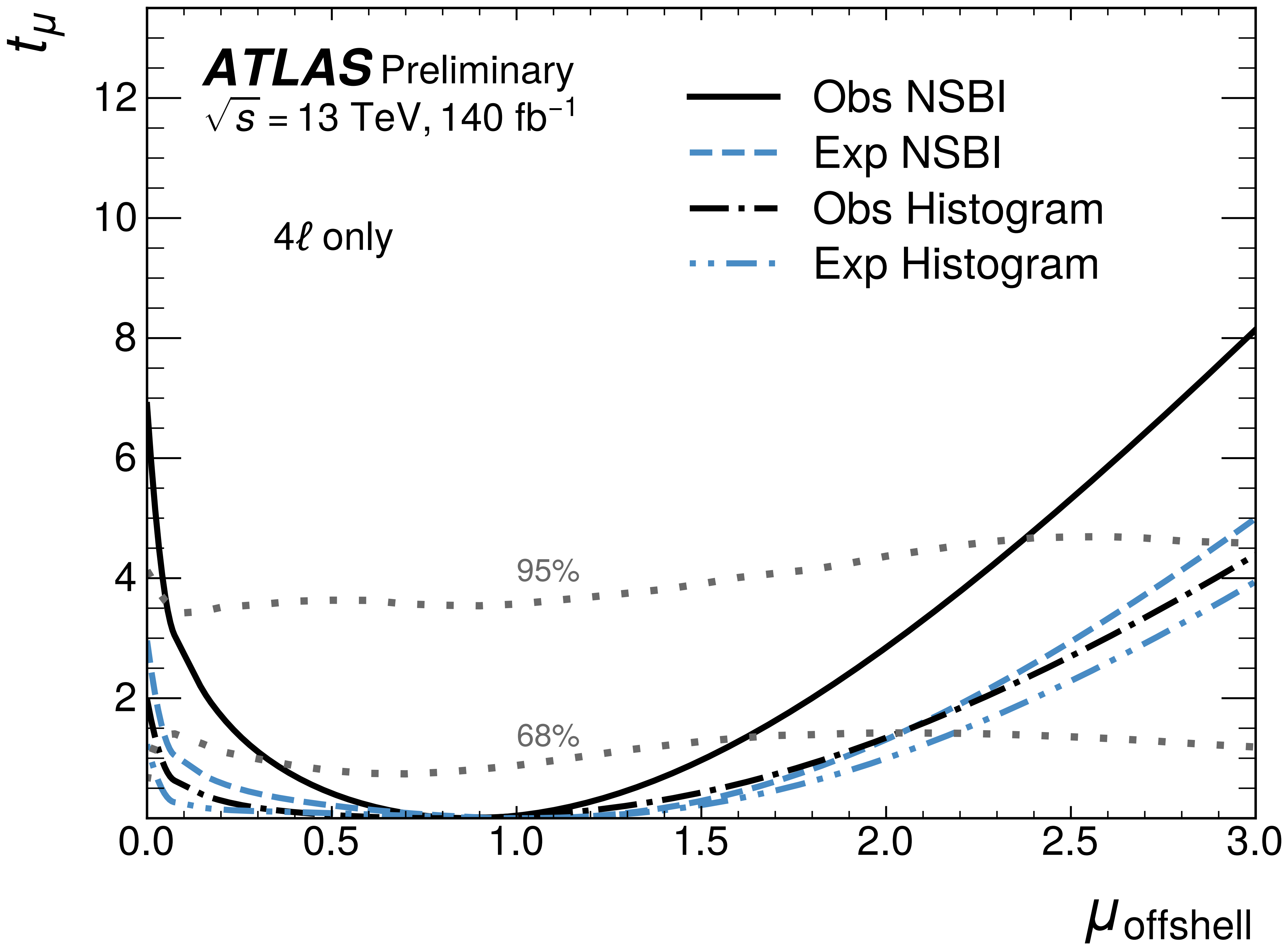
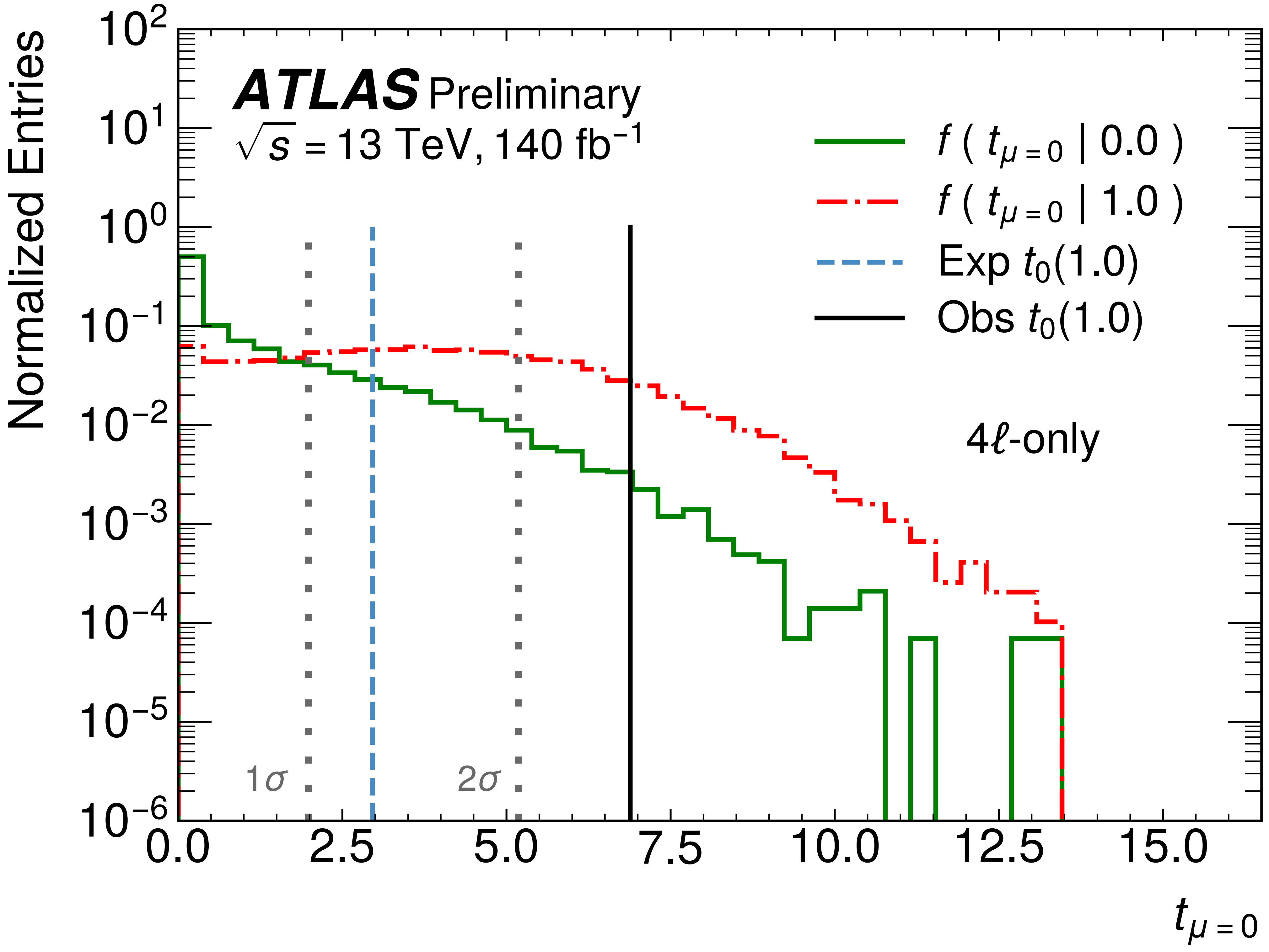
Neural Simulation Based-Inference



- Event-by-event approximation of probability density ratios using NSBI offers potential for improvement
  - Allows building an optimal observable for any value of $\mu_{\text{off-shell}}$

Results in the 4l Final State





- Improvement compared to histogram analysis
- Observe off-shell Higgs boson production with significance 2.3σ using only the ZZ→4l channel

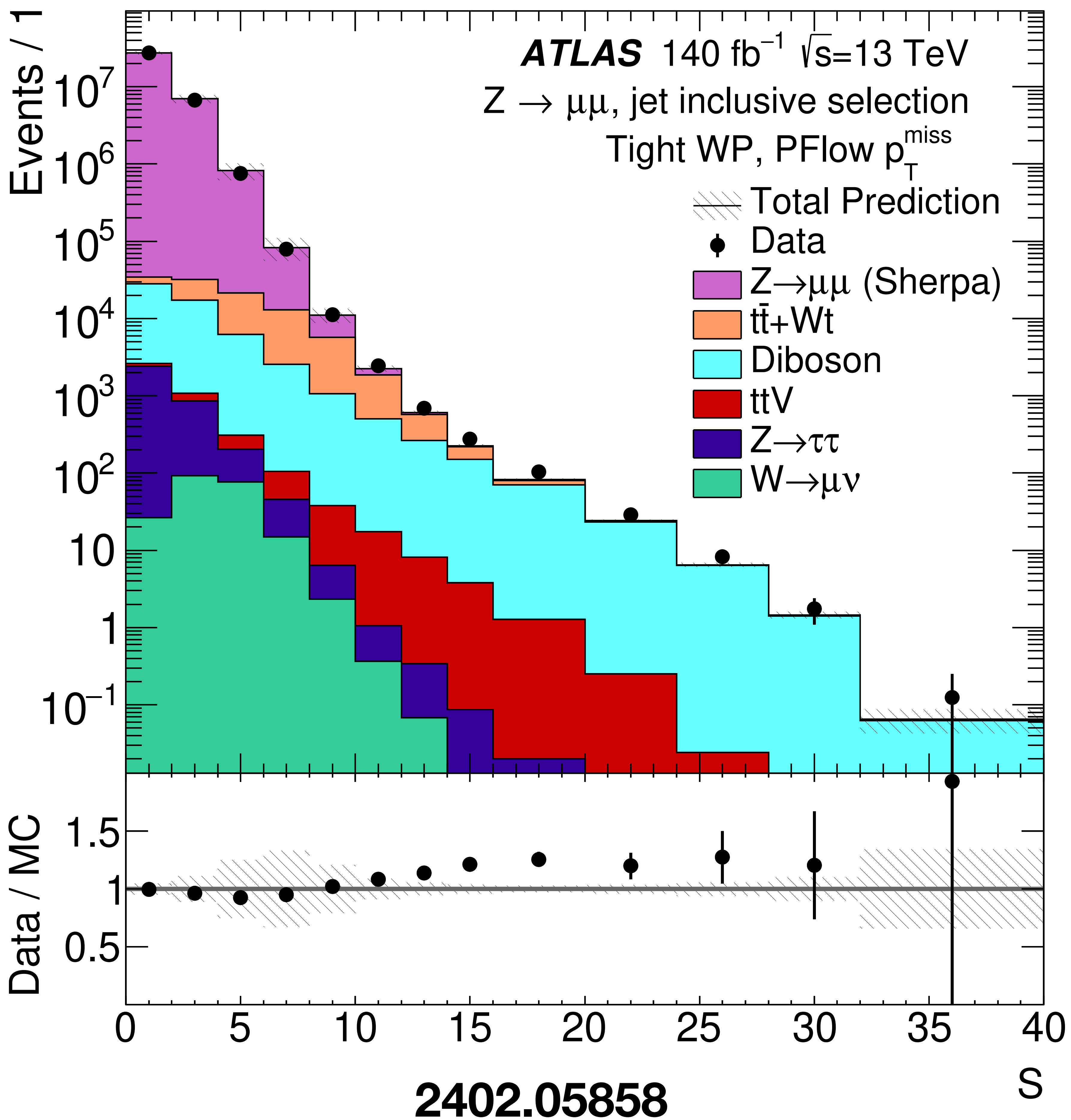
Phys. Lett. B 846 (2023) 138223

2l2ν Final State

- The analysis in this final state is not changed, it remains a histogram analysis
- Observable is transverse mass m_T^{ZZ}

$$m_T^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\,\right]^2 - \left|\vec{p}_T^{\;\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2}$$

  - The off-shell signal is more significant at higher m, m_T^{ZZ} is a useful proxy
- Much larger background than 4l, mainly from Z+jets events
  - These are suppressed by cutting on the E_T^{miss} significance



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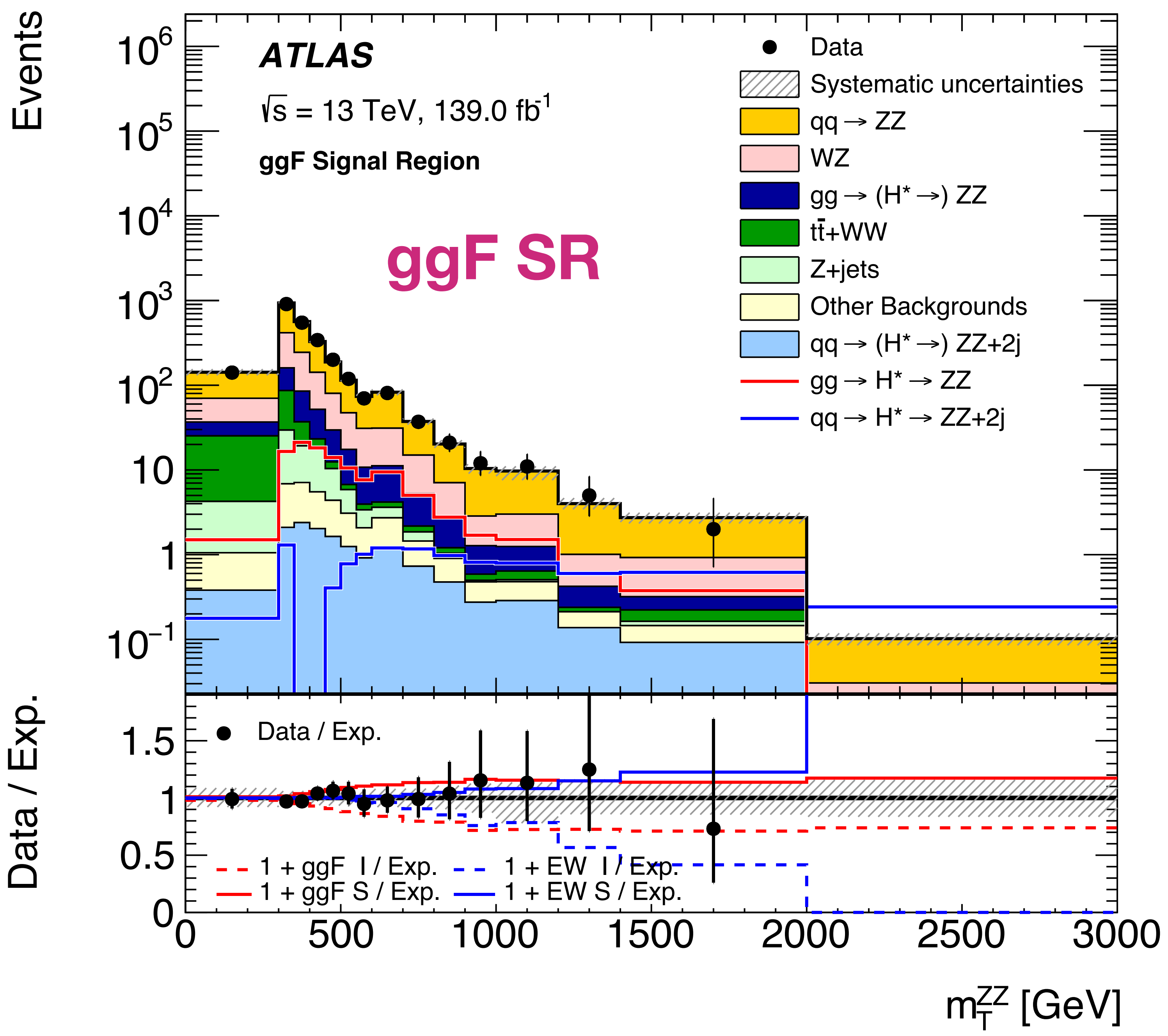
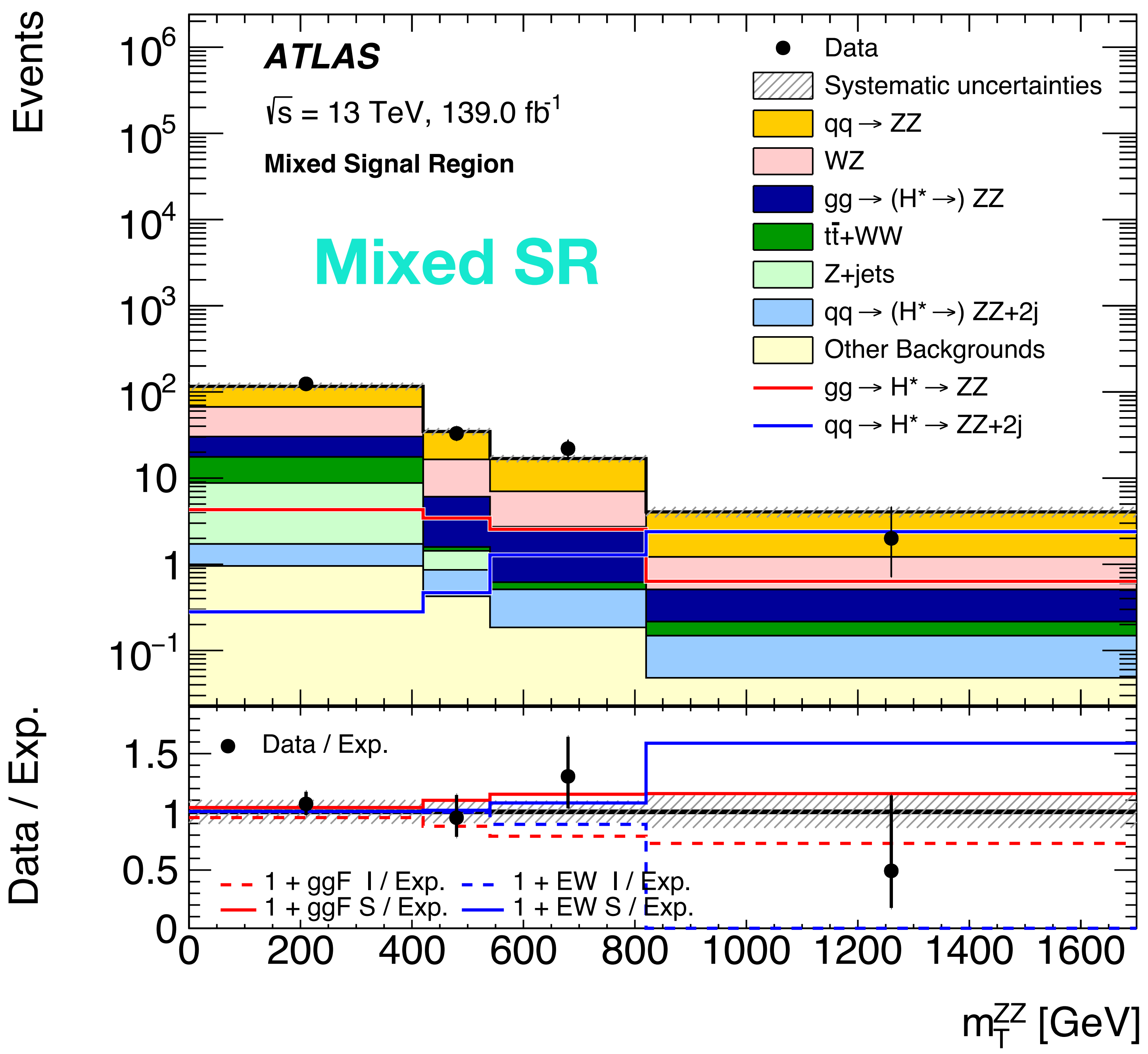
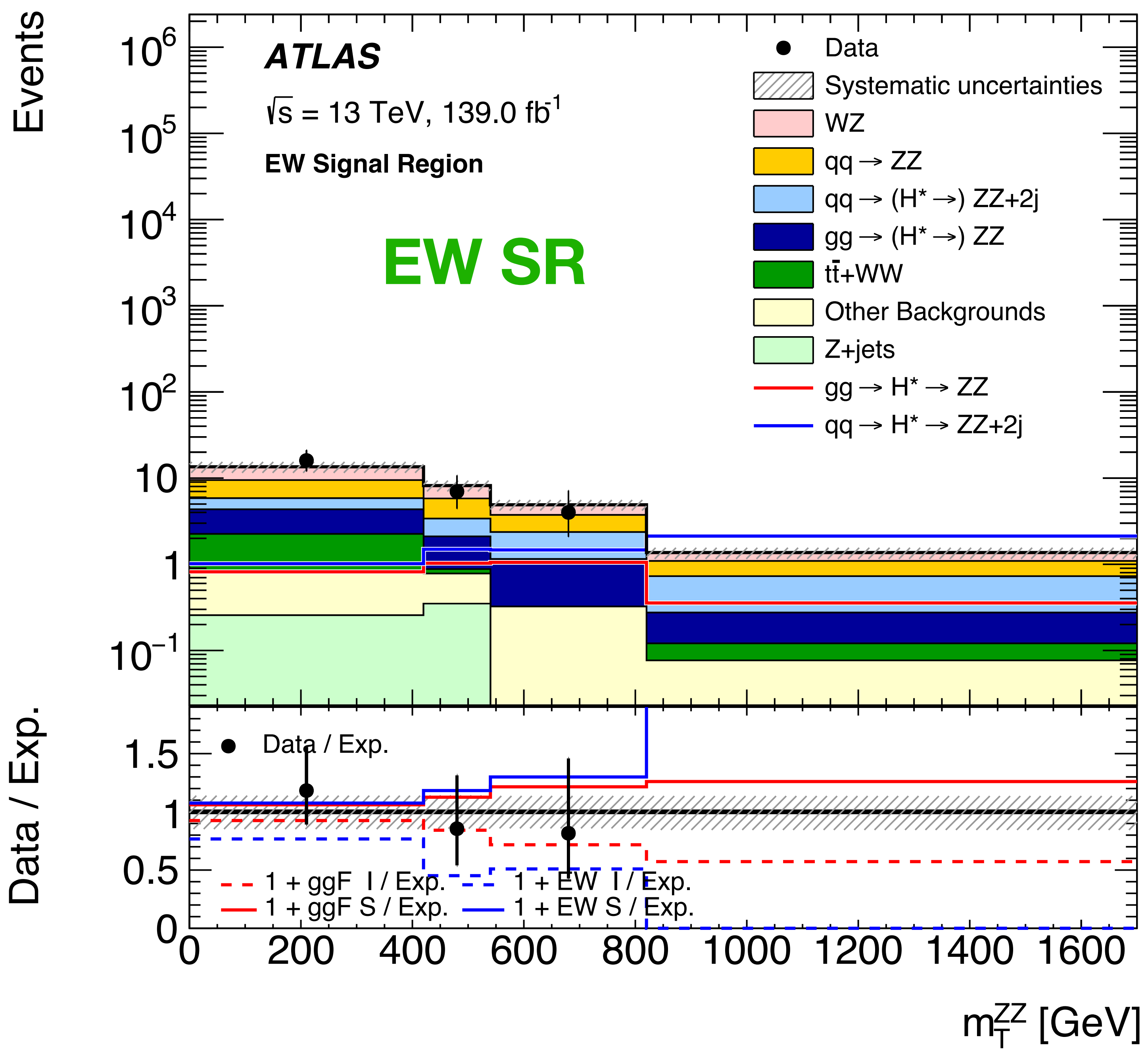
$2l2\nu$ Final State

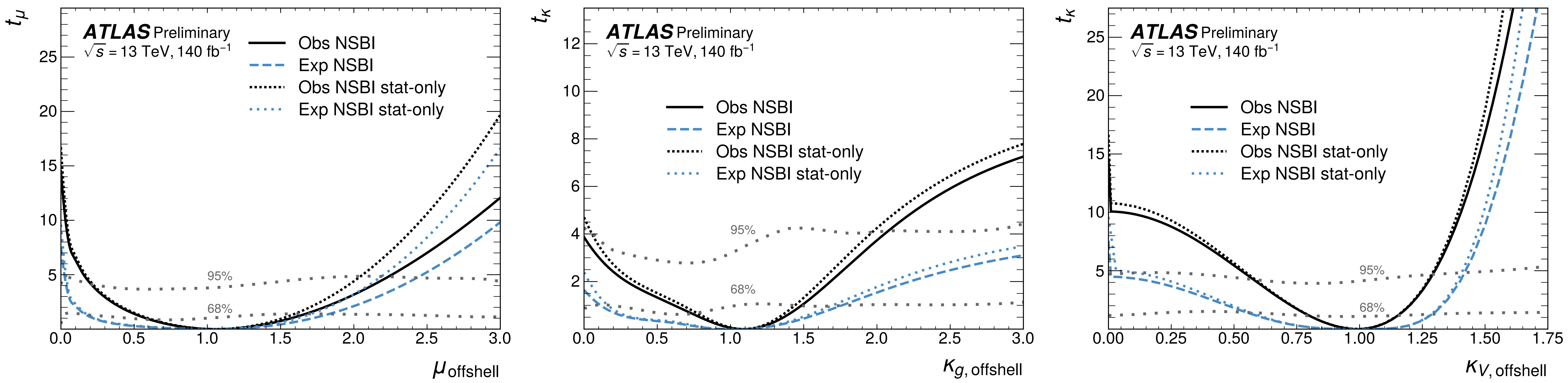






- SR further divided by N_{jets}, 2-jet SR targets EW (VBF+VH) production, others ggF
- qqZZ production is the dominant background
  - Constrained using 4l CRs, 1 per jet bin
  - Separate CRs constructed to constrain WZ, Z+jets, and non-resonant backgrounds

Combined HZZ Off-Shell Analysis

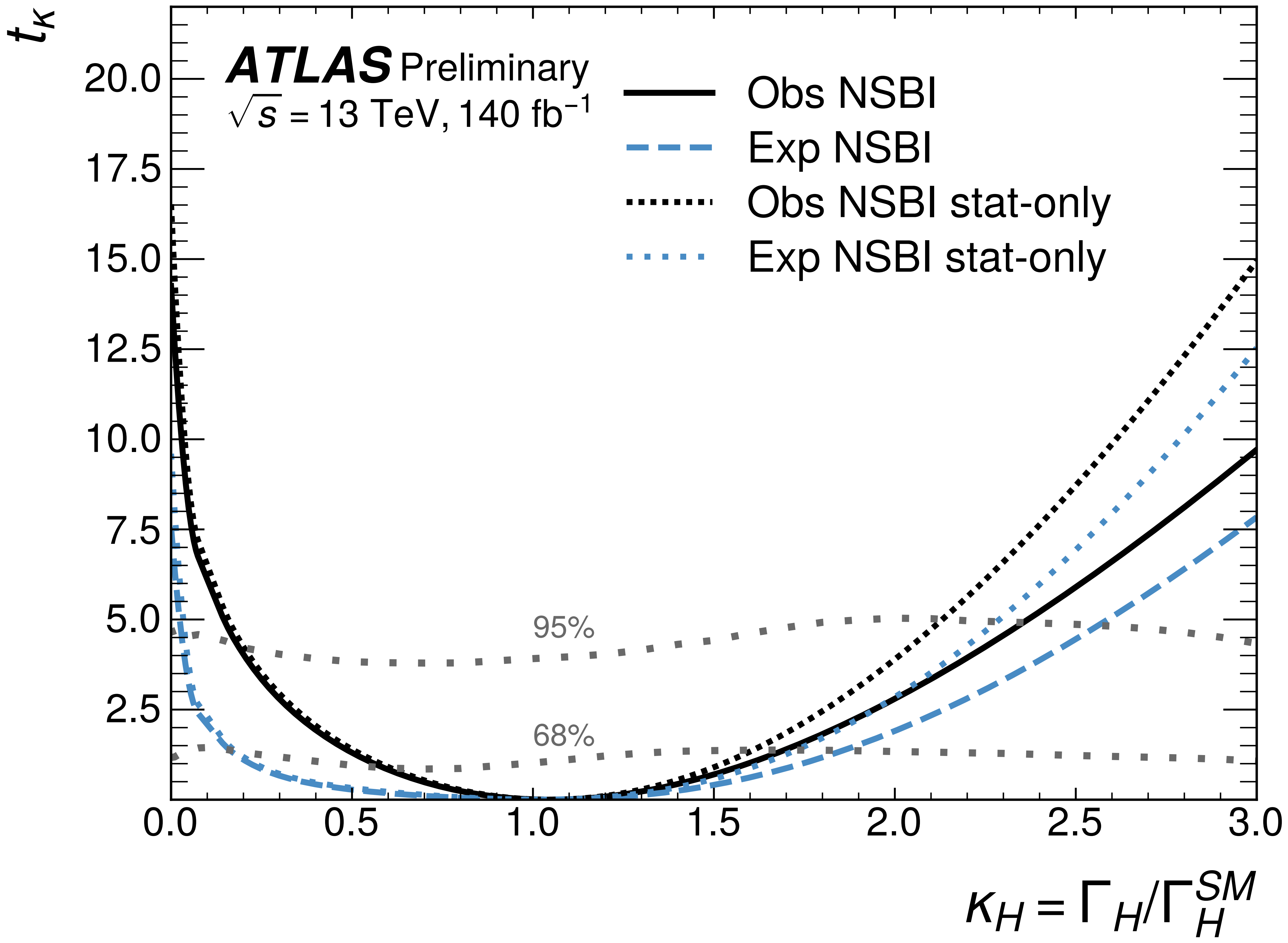


- Evidence for off-shell Higgs boson production with 3.7 σ significance

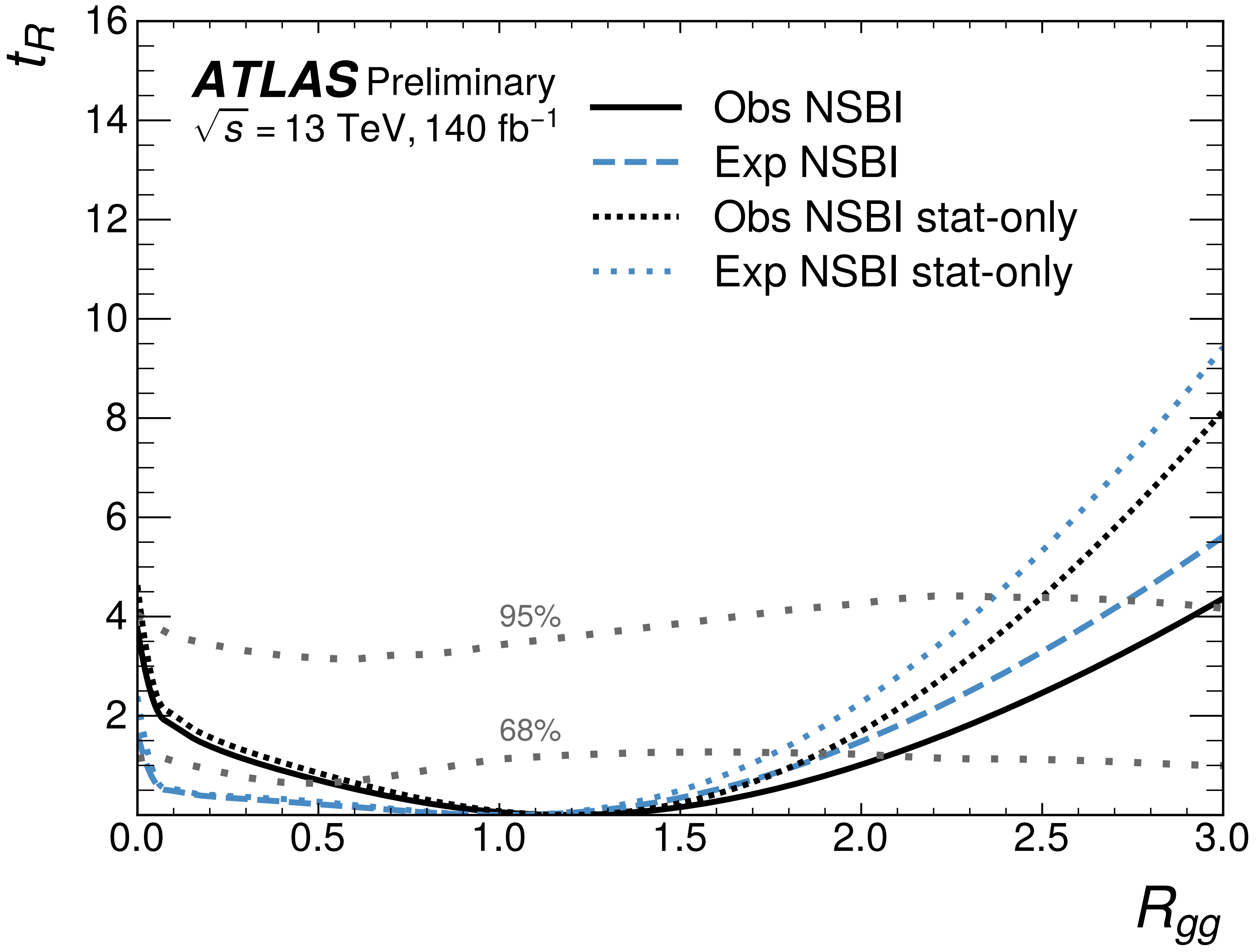
- Can also constrain Higgs-gluon and Higgs-vector boson couplings
  - Without any assumption on the total Higgs width
  - Precision on $\kappa_{V,\text{off-shell}}=0.99^{+.016}_{-0.19}$ approaches on-shell measurement of 1.02±0.06

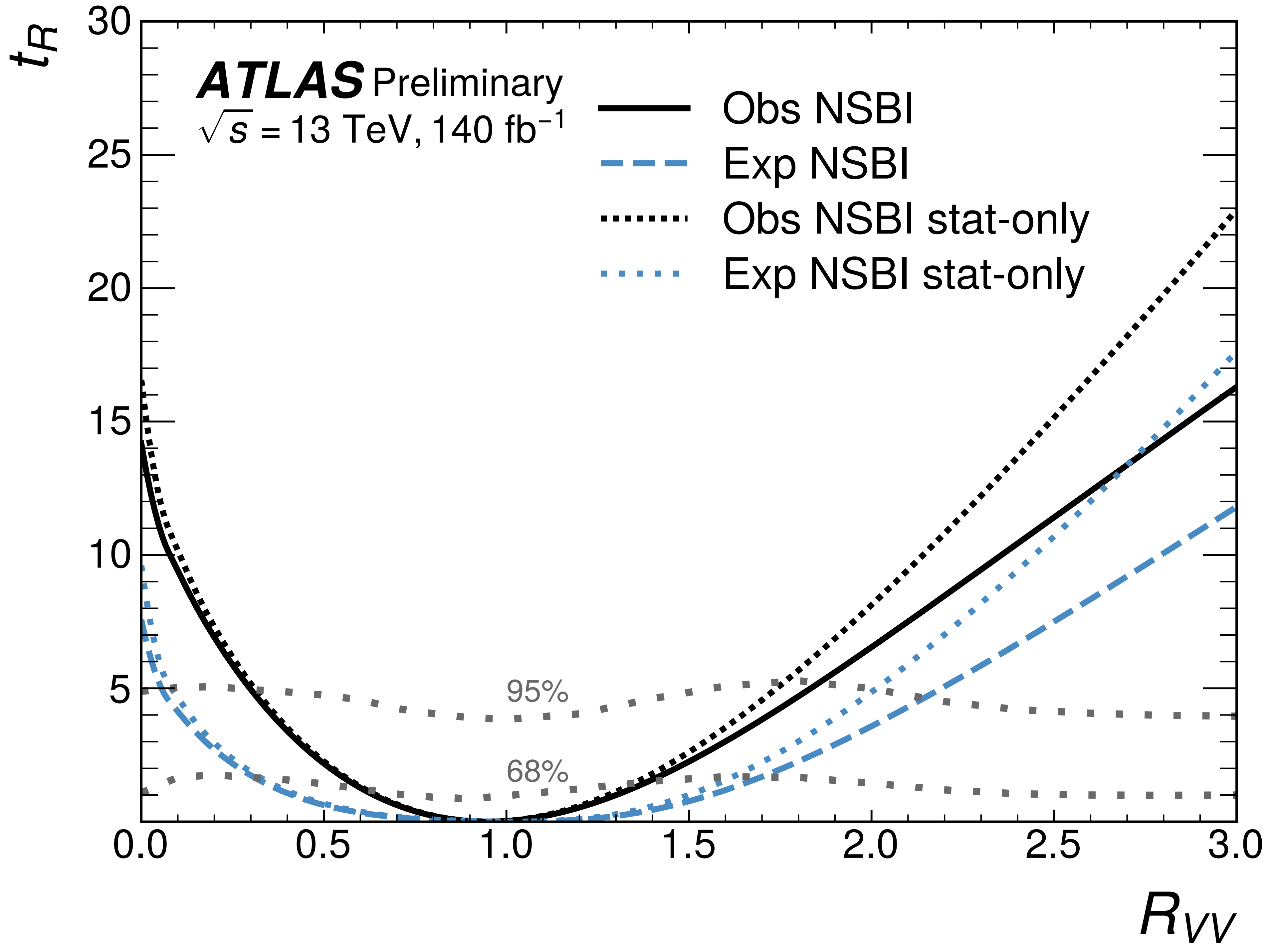
Width Interpretation

- Combine with previous HZZ on-shell analysis to constrain Γ_H
- $\Gamma_H = 4.3^{+2.7}_{-1.9}$ MeV, with 95% CL limits of [0.8, 9.8] MeV
  - Compare to previous result of $4.5^{+3.0}_{-2.5}$ and [0.1, 10.2] MeV
  - The 2l2v channel provides ~ half of the sensitivity here



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, verify that on-shell and off-shell couplings to vector bosons/ gluons agree: $R_{VV}=0.95^{+0.44}_{-0.34}$, $R_{gg}=1.19^{+0.89}_{-0.66}$

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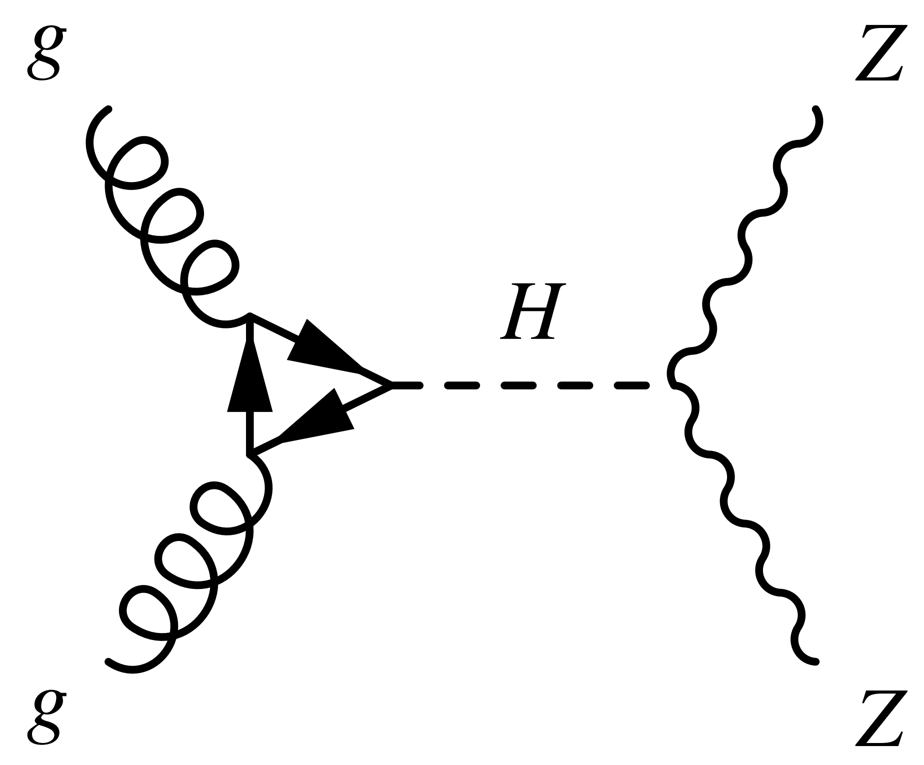
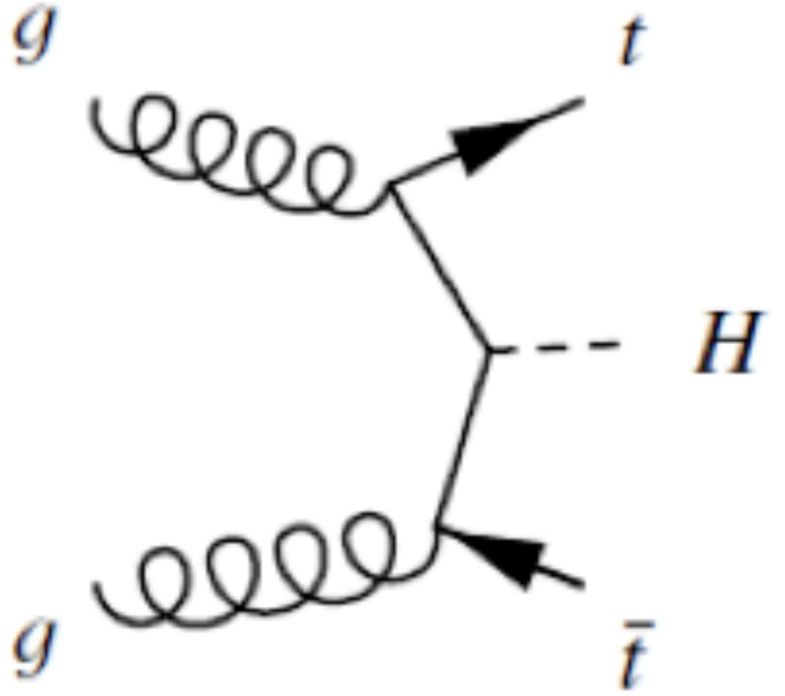
A Complementary Approach

- The analysis in the HZZ channel requires assuming no changes to the ggH or HVV couplings
  - Especially problematic for ggH production which requires assuming no new particles that could enter into the quark loop

- Important to try to constrain the width using other processes to avoid relying on the same assumptions

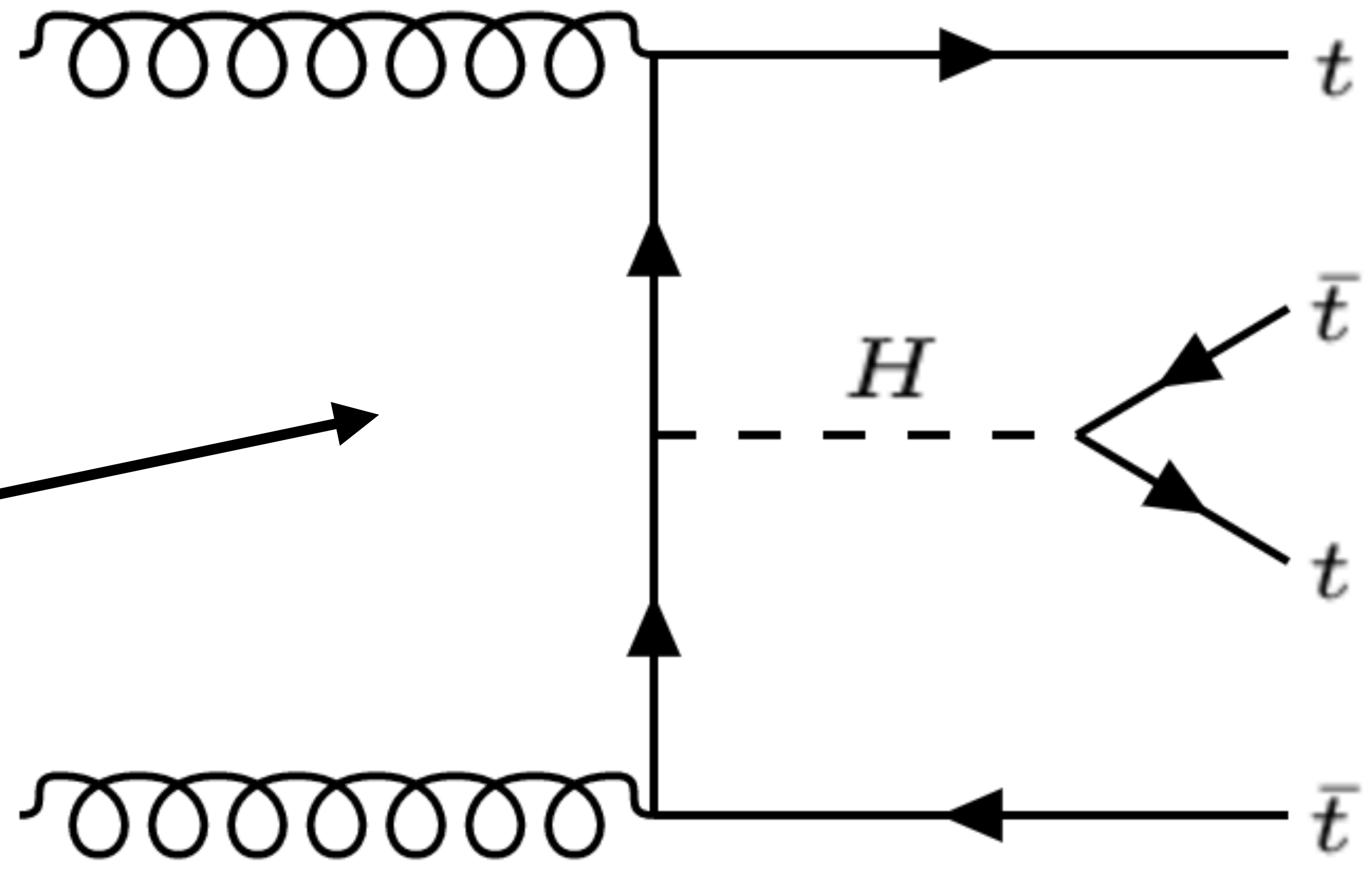
- ttH production is the largest cross-section Higgs production method that does not involve g or V couplings
  - Measurements of off-shell ttH could then be used to constrain Γ_H without overlapping assumptions
  - Use 4t production, recently observed by ATLAS, Eur. Phys. J C 83 (2023) 496

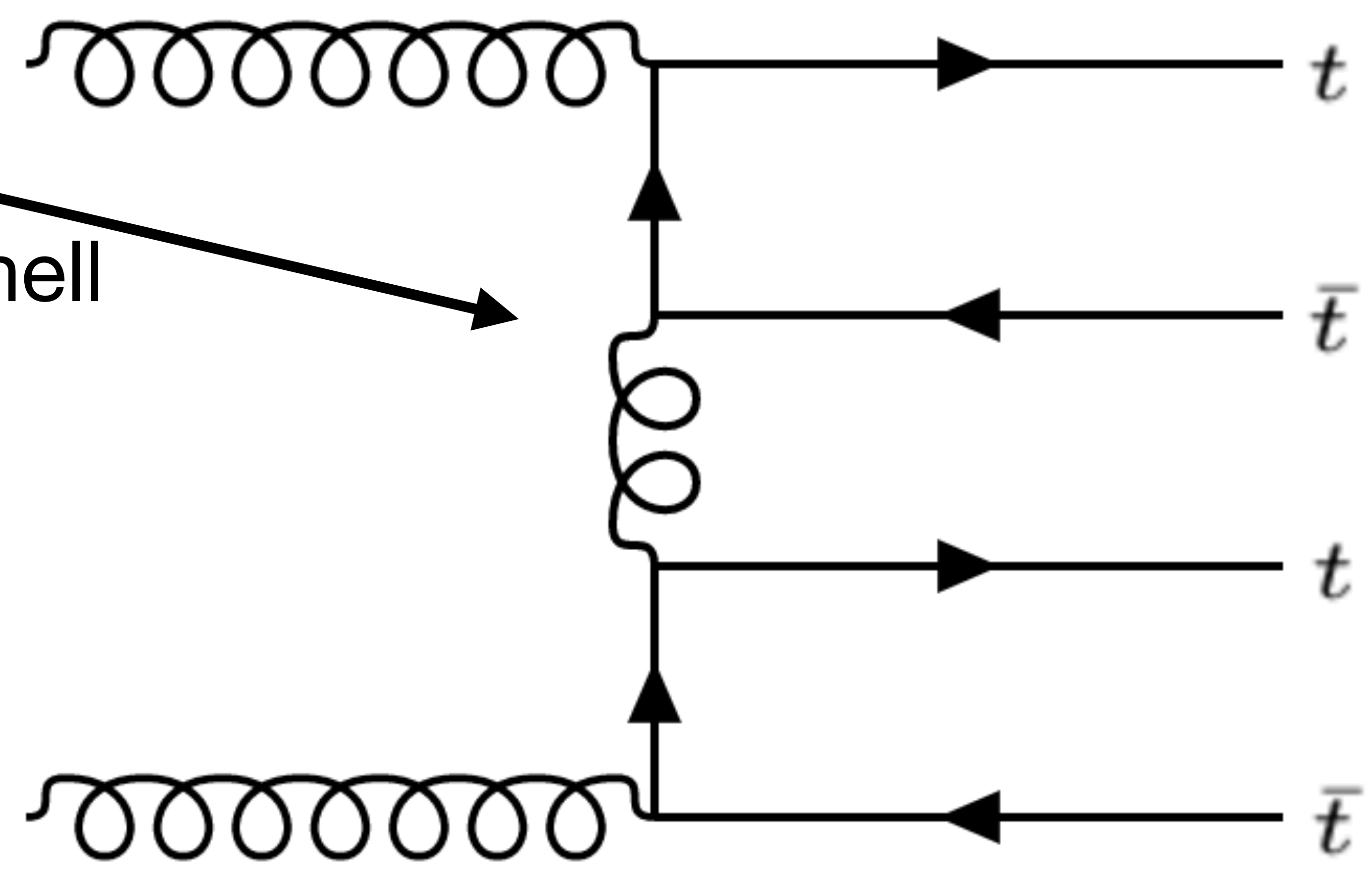




A Complementary Approach

- 4top production is a combined signal + background + interference process, analogous to the combined HZZ off-shell process
    - The mediator in 4t production can be a Higgs: signal
    - Or g/Z/ɣ*: background
    - And the two interfere, of course

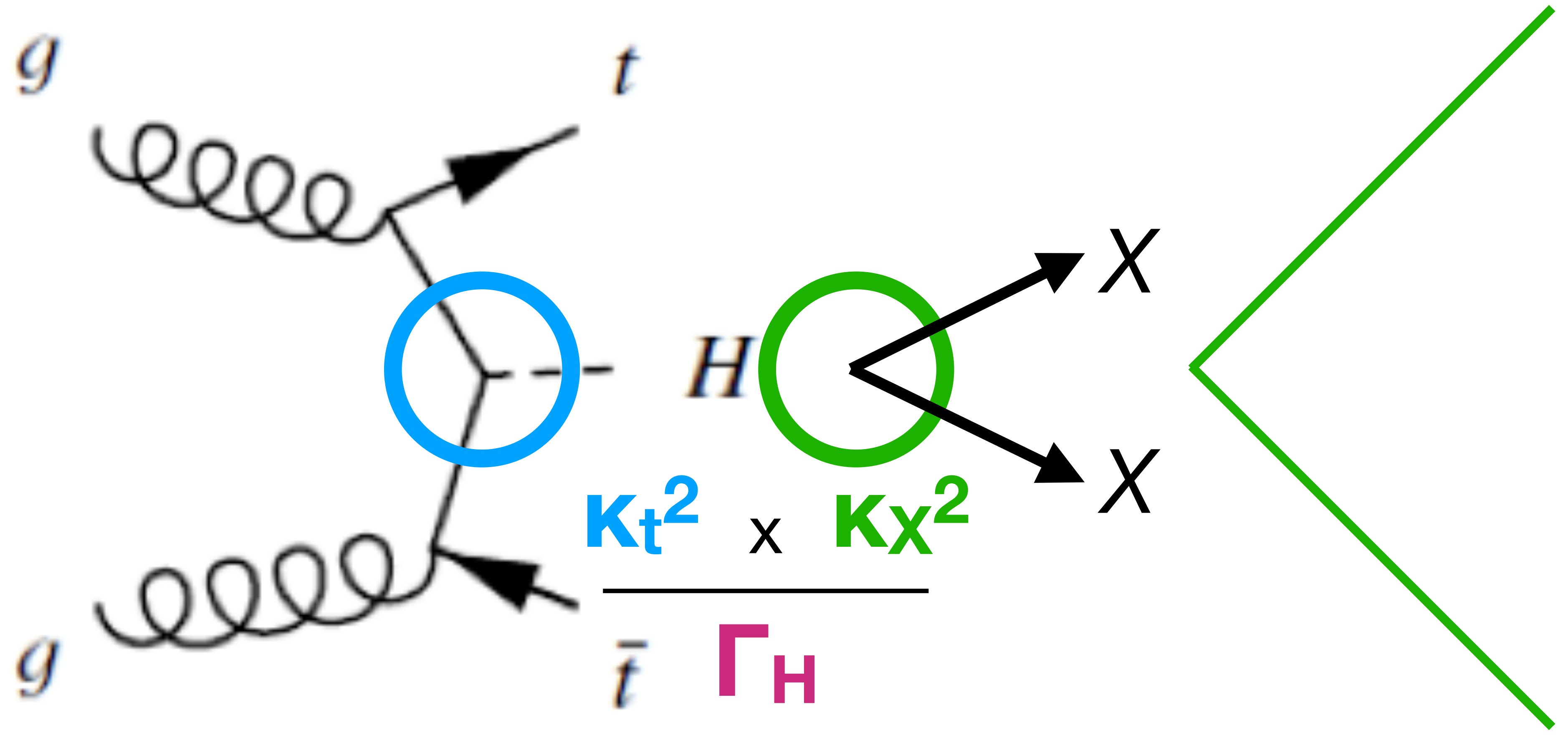


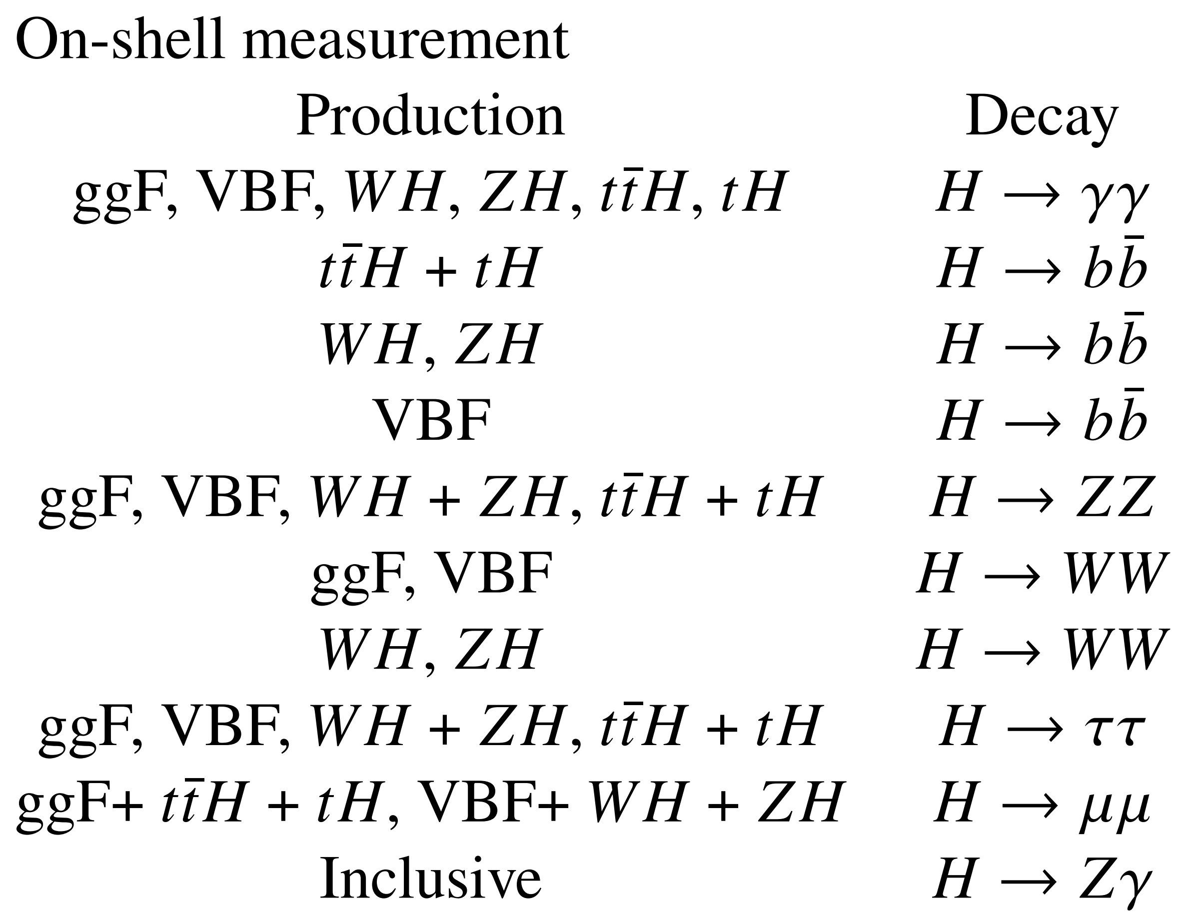


- Quartic dependence on κ_t instead of quadratic on $\mu_{\text{off-shell}}$
    - Signal ~ κ_t^4, interference ~ κ_t^2, background is constant

- 2L and 3L final states used for the measurement

On-Shell Analysis



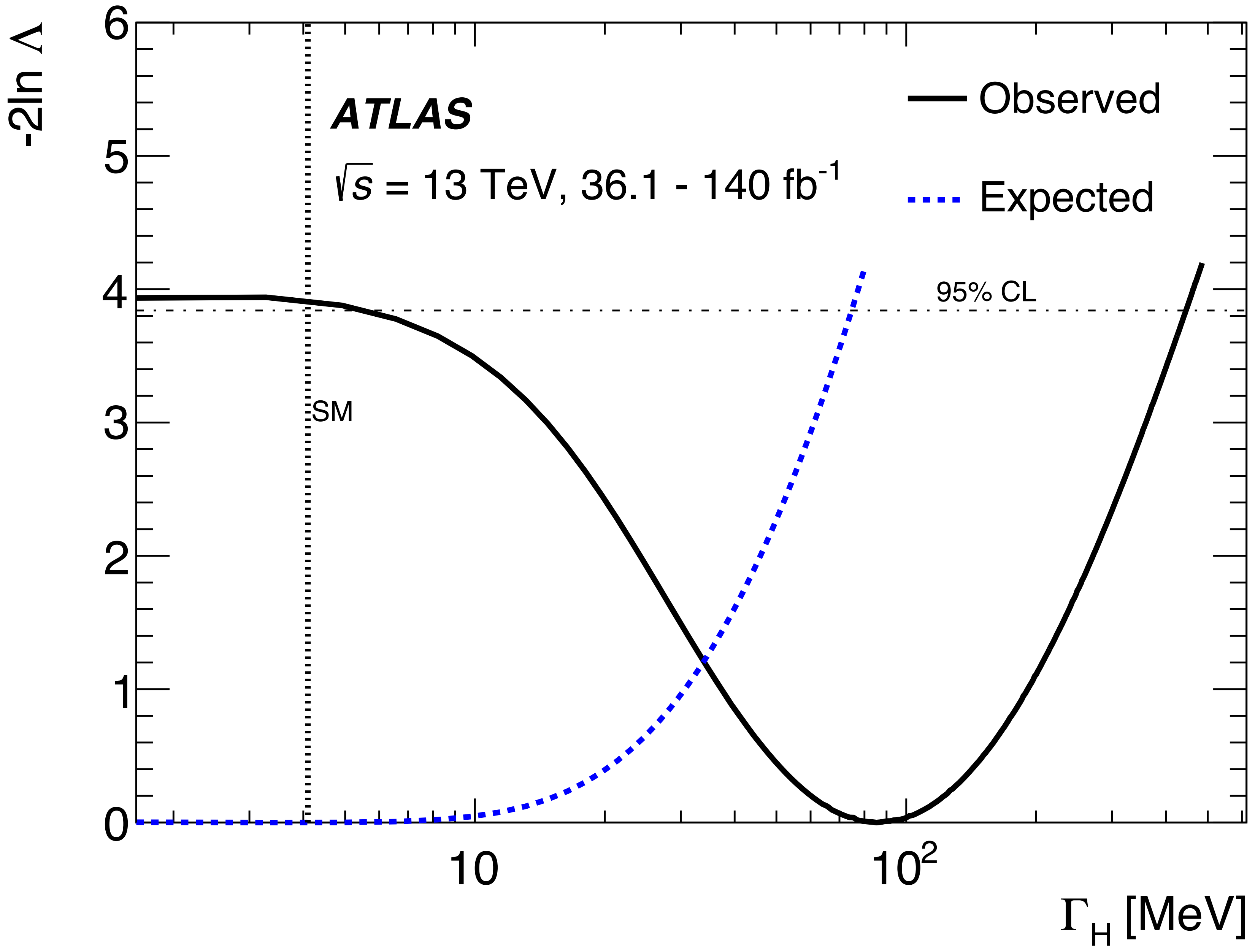


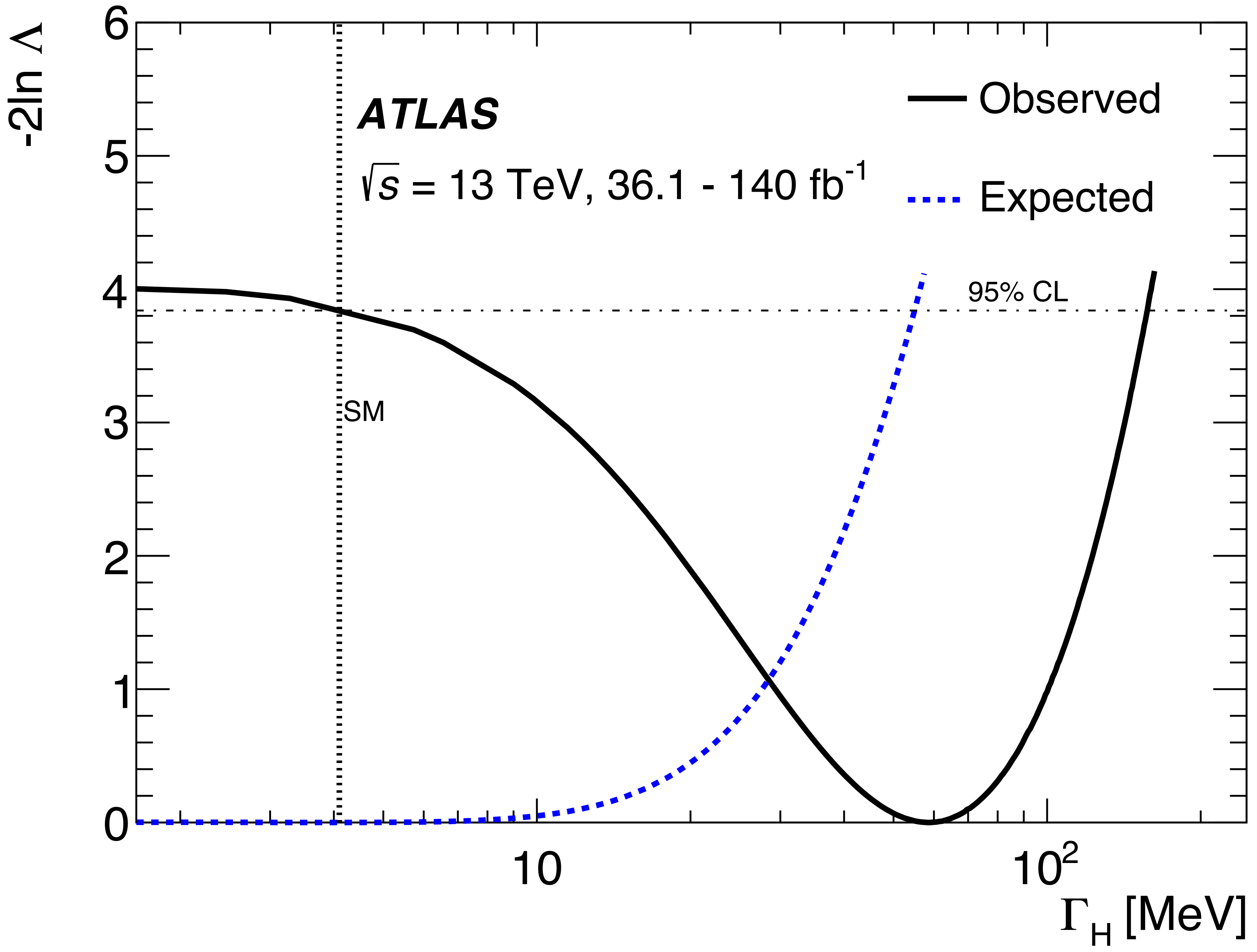
On-shell measurement	
Production	Decay
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \to \gamma\gamma$
$t\bar{t}H + tH$	$H \to b\bar{b}$
WH, ZH	$H \to b\bar{b}$
VBF	$H \to b\bar{b}$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to ZZ$
ggF, VBF	$H \to WW$
WH, ZH	$H \to WW$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to \tau\tau$
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \to \mu\mu$
Inclusive	$H \to Z\gamma$

- Only κ_t is present in the off-shell production, but other couplings are involved on-shell, depending on the decay
- Use other on-shell Higgs measurements to constrain them
  - Strength of constraint depends on whether ggH is treated as an effective coupling to gluons or as a quark loop
- Analyses not designed to avoid overlap, so some off-shell contamination in on-shell and vice versa
  - Drop ttH multilepton final state to try to minimize this

Width From ttH

- Observed 95% CL upper limit for Γ_H is 450 MeV, with $\Gamma_H=86^{+110}_{-49}$ MeV
  - 2σ tension with SM due to measured 4t cross-section being larger than SM prediction
    - $\sigma_{4t}=22.5^{+6.6}_{-5.5}$ pb, compared to SM 12 pb
  - Stronger limits from parameterizing κ_g as a function of κ_t
    - 95% CL upper limit of 160 MeV in this case





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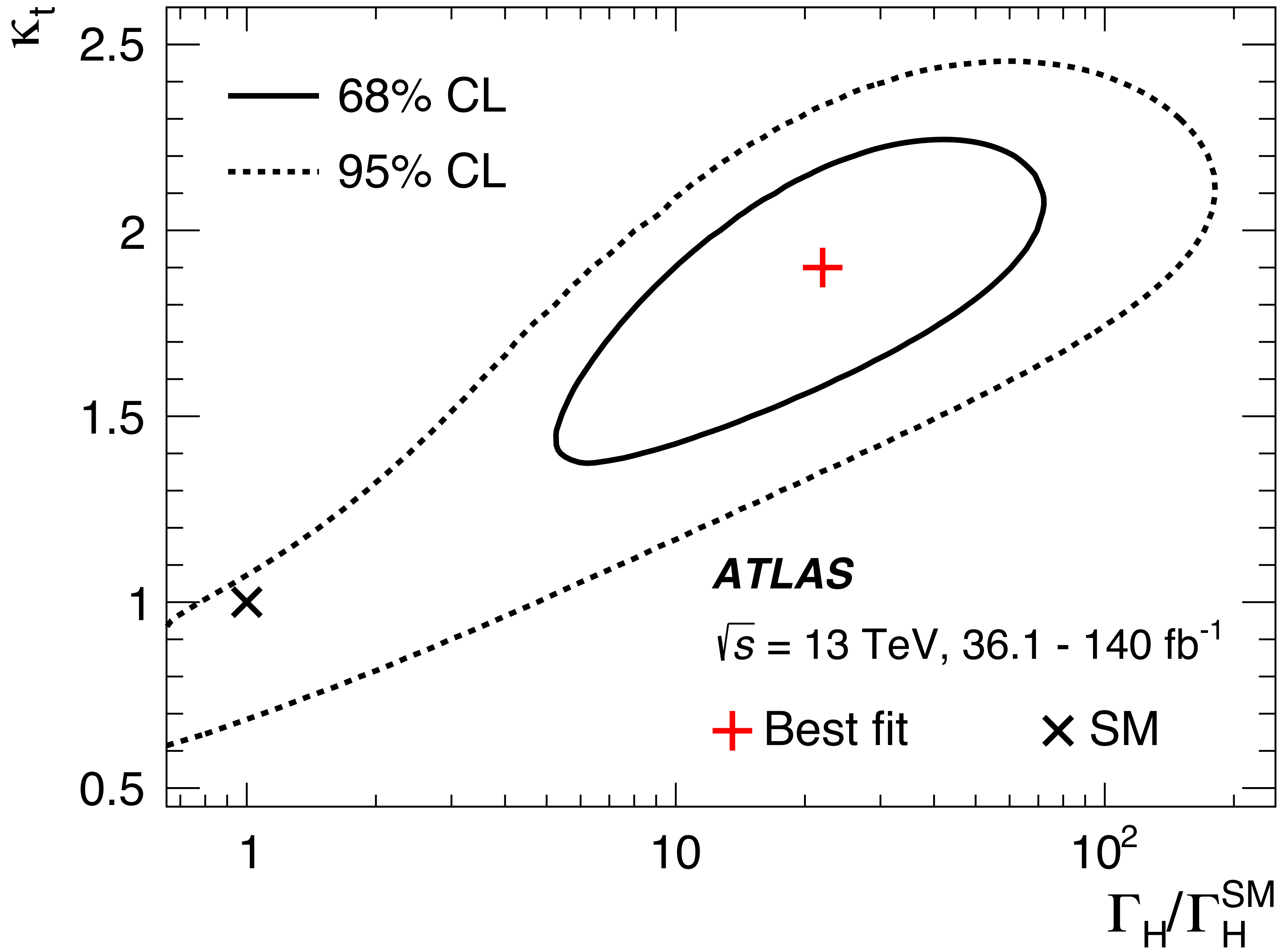
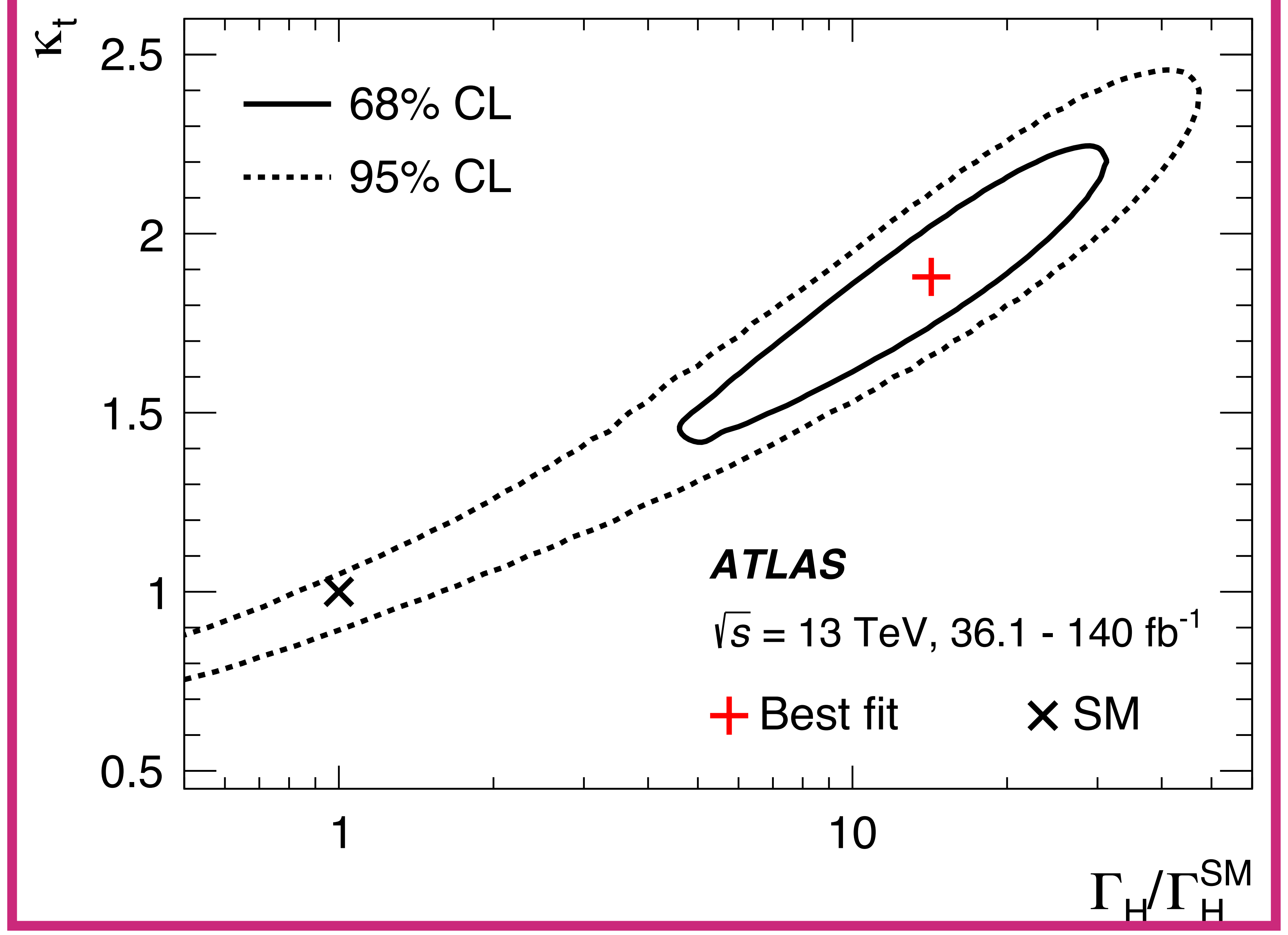




Summary and Outlook

- Direct measurement of Γ_H is very difficult but indirect measurements using off-shell Higgs boson production have been quite successful
- The H→ZZ channel is good for this measurement due to the relatively large off-shell cross-section
- New statistical techniques allow us to make the best possible use of our limited dataset
- Using 4t provides a complementary measurement reliant on different assumptions
- Stay tuned, more results are coming!

Backup

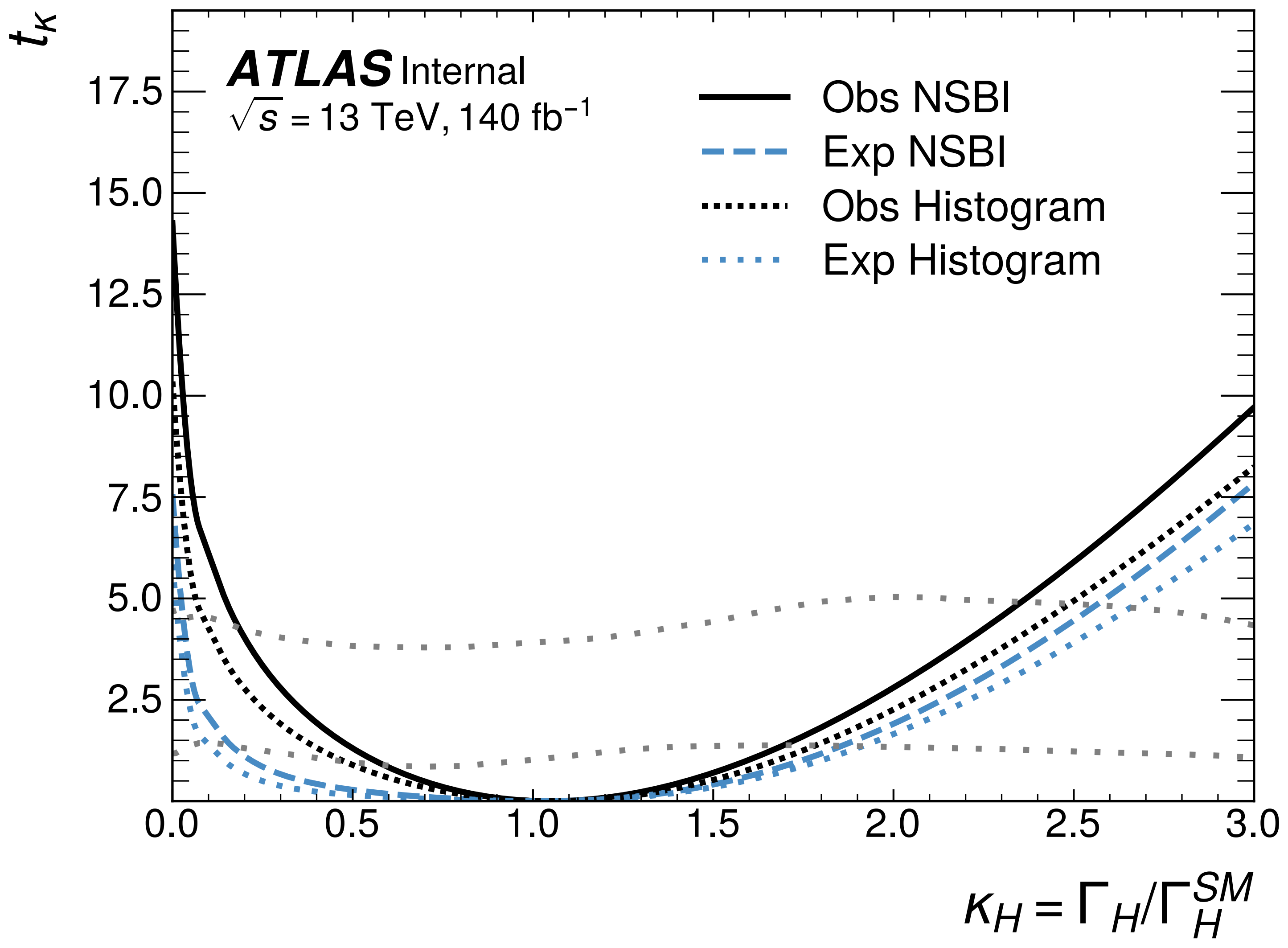
ttH+4t Systematic Uncertainty Impacts

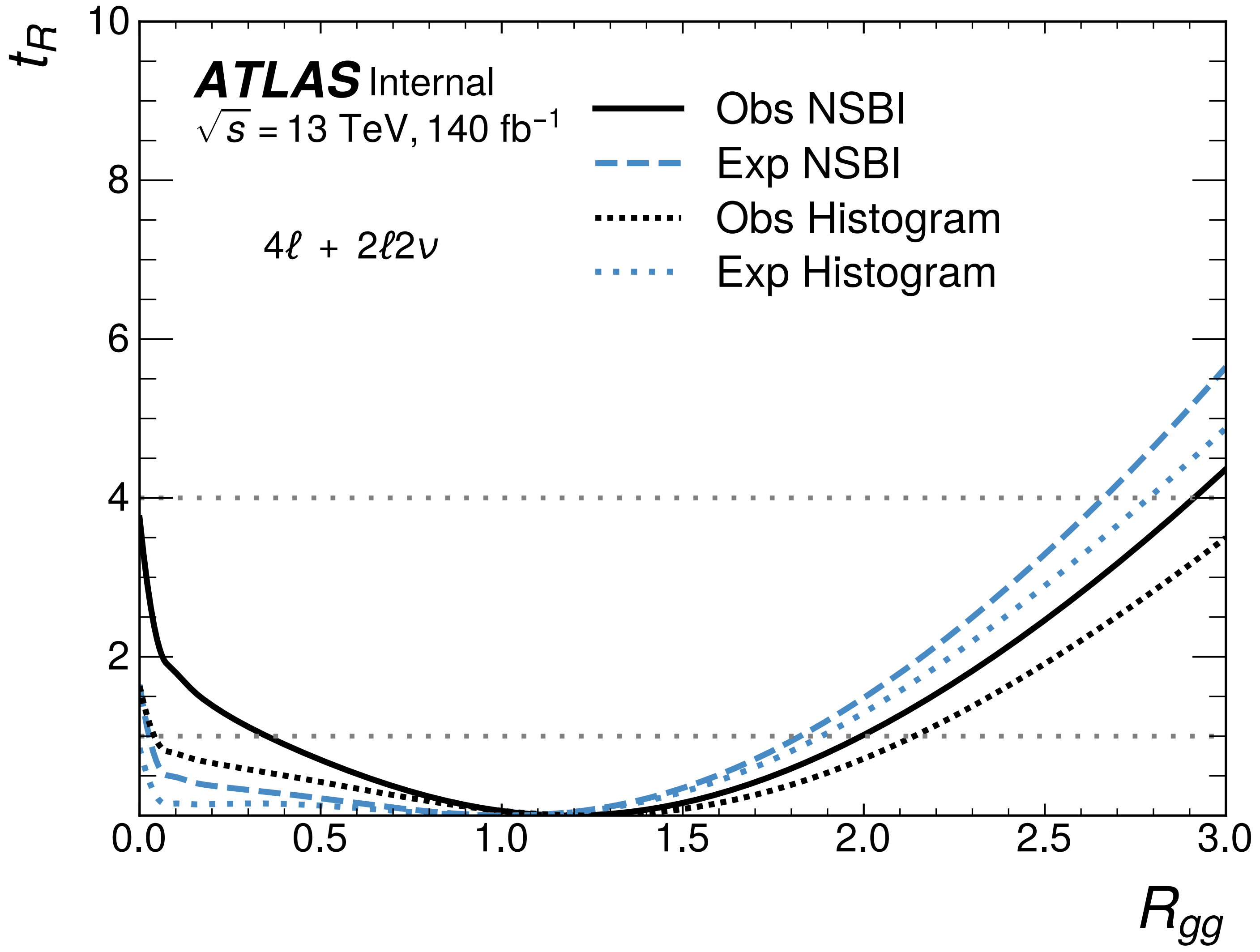
Systematic uncertainty	Impact on 95% CL upper limit on Γ_H	
	Expected [%]	Observed [%]
Theory	37	33
$t\bar{t}t\bar{t}$ production	25	13
Higgs boson production/decay	5	6
Other processes	10	16
Experimental	2	2
Jet flavour tagging	2	1
Jet and missing transverse energy	< 1	< 1
Leptons and photons	< 1	< 1
All other systematic uncertainties	< 1	< 1

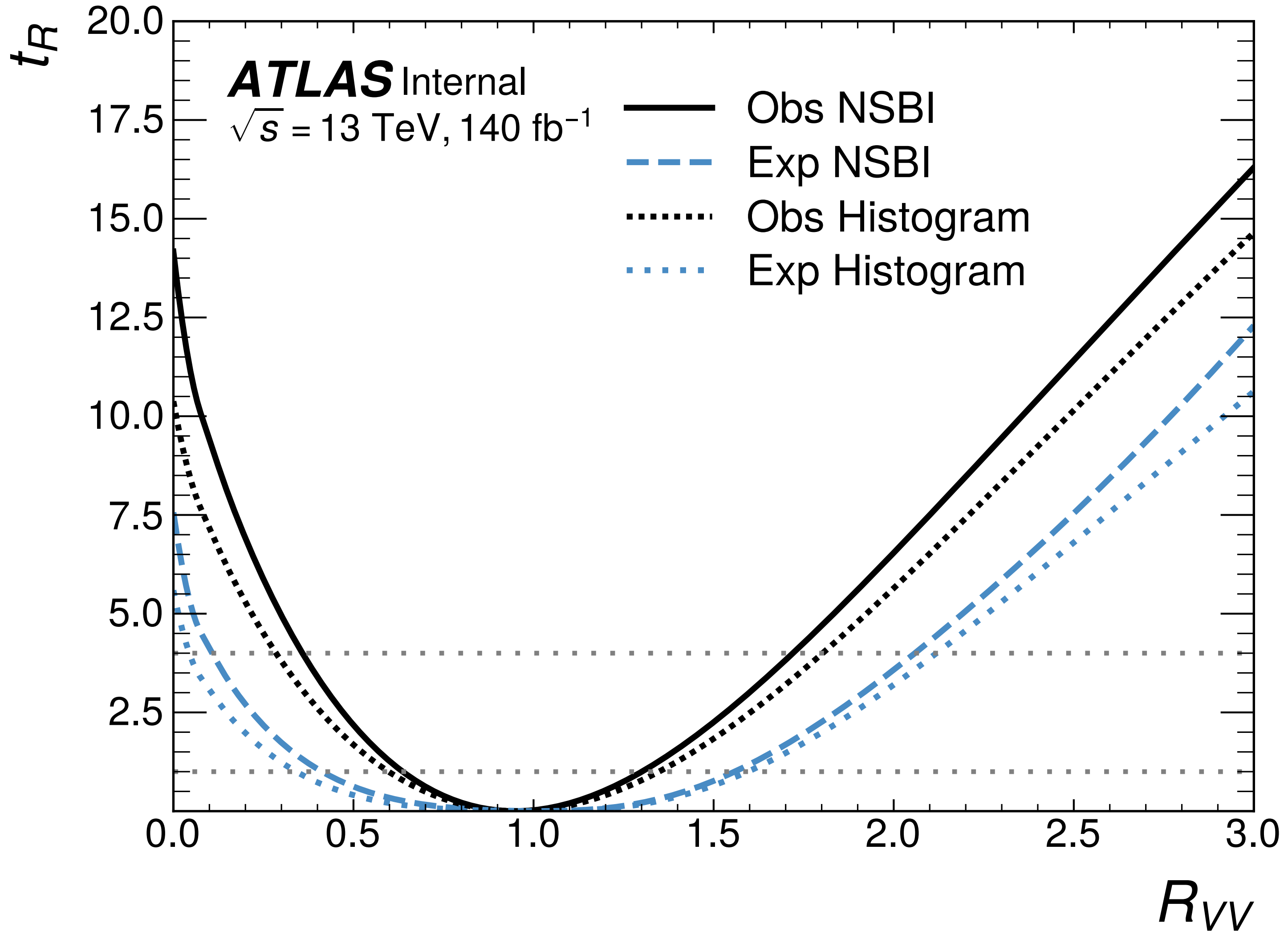
HZZ Systematic Uncertainty Impacts

Uncertainty source	**Absolute impact on $\mu_{\text{off-shell}}$**	
	Nuisance Parameter	**Global Observable**
Electron uncertainties	$(-5\%, +6\%)$	$(-5\%, +6\%)$
Muon uncertainties	$(-3\%, +3\%)$	$(-2\%, +3\%)$
Jet uncertainties	$(-10\%, +10\%)$	$(-9\%, +11\%)$
Luminosity	$(-1\%, +1\%)$	$(-1\%, +1\%)$
Total experimental	-	$(-11\%, +12\%)$
$q\bar{q} \to ZZ$ modeling	$(-6\%, +7\%)$	$(-6\%, +7\%)$
$gg \to ZZ$ modeling	$(-8\%, +13\%)$	$(-7\%, +9\%)$
EW $q\bar{q} \to ZZ + 2j$ modeling	$(-1\%, +1\%)$	$(-1\%, +1\%)$
Total modeling	-	$(-9\%, +12\%)$
Systematic uncertainty	-	$(-14\%, +17\%)$
Statistical uncertainty	-	$(-51\%, +73\%)$
Total uncertainty	$(-53\%, +75\%)$	

Comparison With Histogram Analysis

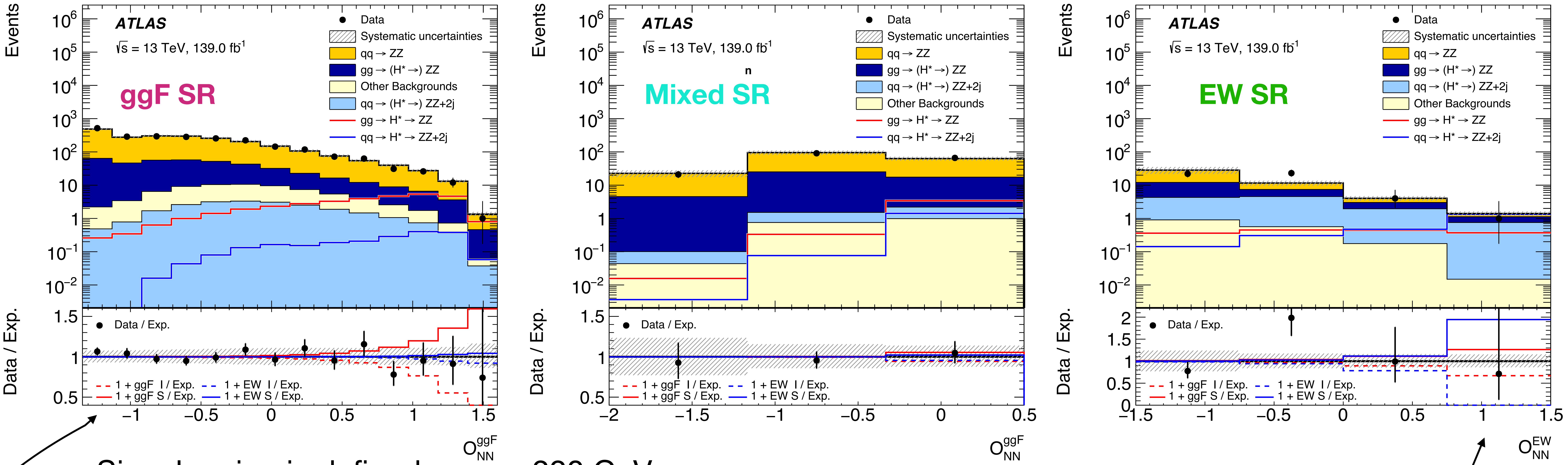






Parameter	**Observed (expected)**	
	NSBI analysis	**histogram-based analysis**
Γ_H [MeV] (4ℓ only)	$3.5^{+2.7}_{-2.2}$ $(4.1^{+3.6}_{-3.8})$	$3.4^{+4.4}_{-3.4}$ $(4.1^{+4.2}_{-4.1})$
Γ_H [MeV]	$4.3^{+2.7}_{-1.9}$ $(4.1^{+3.6}_{-3.8})$	$4.3^{+3.0}_{-2.3}$ $(4.1^{+3.7}_{-3.7})$
R_{gg}	$1.2^{+0.8}_{-0.8}$ $(1.0^{+0.8}_{-1.0})$	$1.2^{+0.9}_{-1.1}$ $(1.0^{+0.8}_{-1.0})$
R_{VV}	$0.95^{+0.35}_{-0.31}$ $(1.00^{+0.54}_{-0.60})$	$0.95^{+0.40}_{-0.36}$ $(1.00^{+0.60}_{-0.66})$

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

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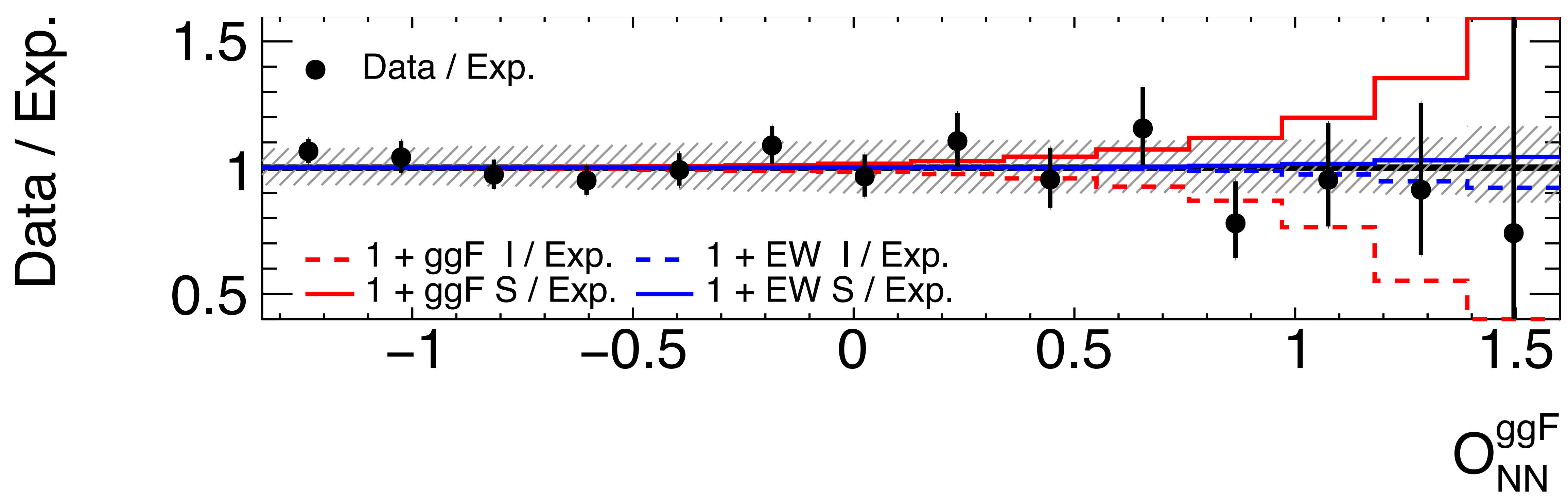
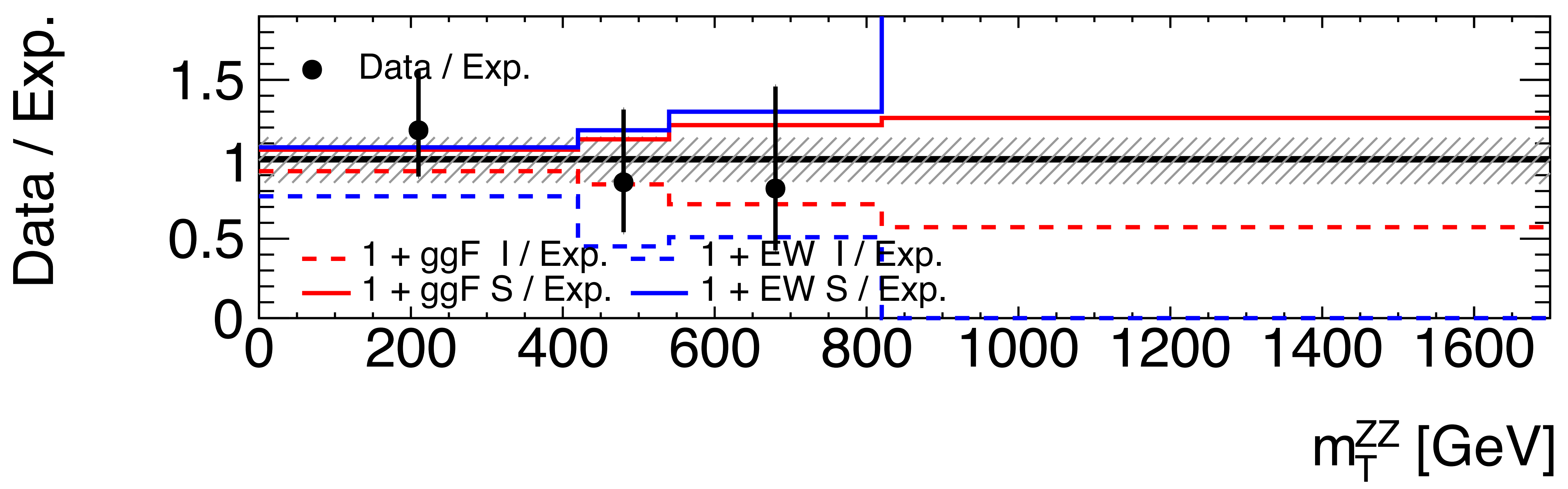
Observables

4l ggF SR



2l2ν 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)

4l SR and CR Definitions

EW SR	Mixed SR	ggH SR	0-jet 4l CR	1-jet 4l CR	2-jet 4l CR
$N_{jets}\geq2$	$N_{jets}=1$	$N_{jets}=0$ or ($N_{jets}=1$ and $\lvert\eta_j\rvert<2.2$) or ($N_{jets}\geq2$ and $\Delta\eta_{jj}<4$)	$N_{jets}=0$	$N_{jets}=1$	$N_{jets}\geq2$
$\Delta\eta_{jj}>4$	$\lvert\eta_j\rvert>2.2$		$180<m_{4l}<220$ 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
$N_{jets}\geq2$	$N_{jets}=1$	$N_{jets}=0$ OR	$N_{jets}=0$	$N_{jets}=1$	$N_{jets}\geq2$	OFOS pair	
$\Delta\eta_{jj}>4$	$\lvert\eta_j\rvert>2.2$	$(N_{jets}=1, \lvert\eta_j\rvert<2.2)$ OR $(N_{jets}\geq2, \Delta\eta_{jj}<4)$	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

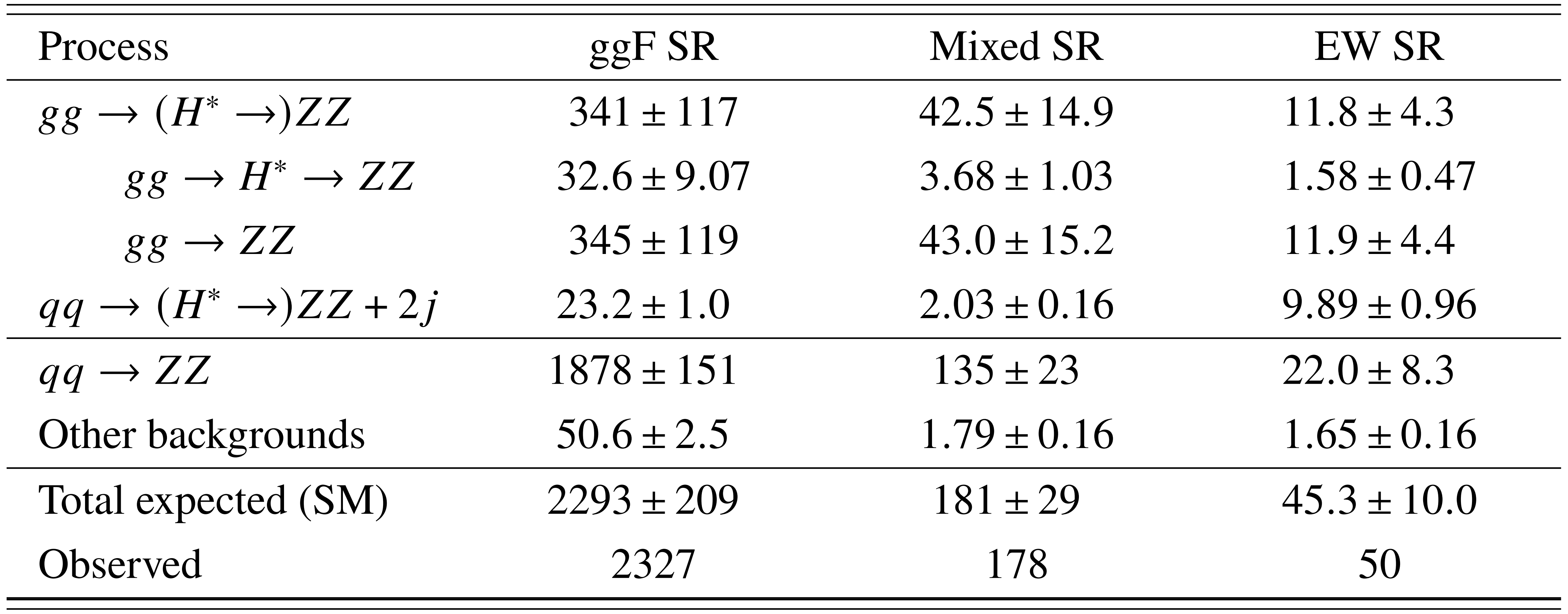
- Unprescaled single-lepton triggers
- Lepton $p_T>20$ GeV
- $76<m_{ll}<106$ GeV

Leading Systematic Uncertainties

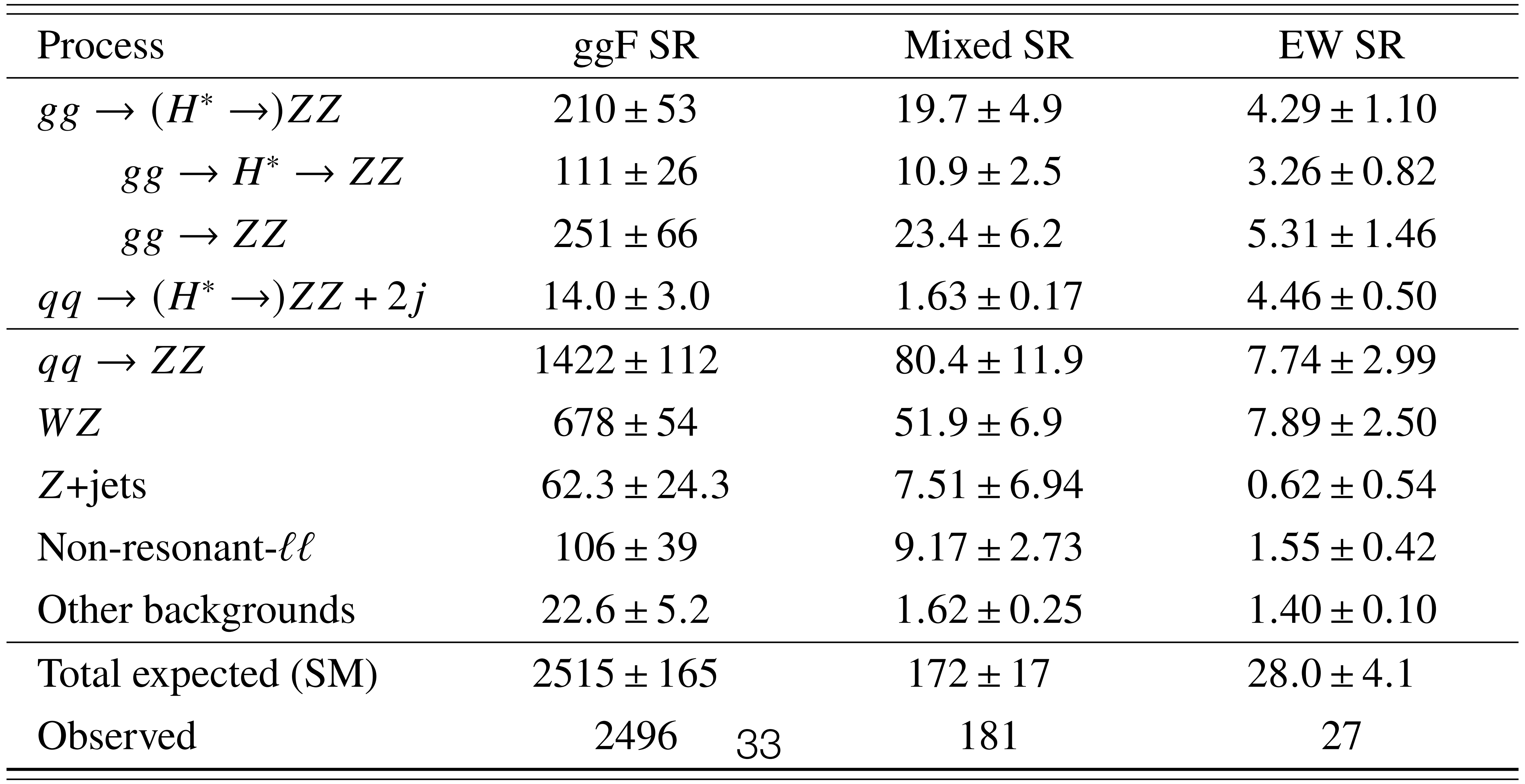
Process	Uncertainty	Final State	Value (%)
ggF Signal Region			
$qq \to ZZ$	QCD Scale	$2\ell 2\nu$	4–40
$qq \to ZZ + 2j$	QCD Scale	4ℓ	21–28
$qq \to ZZ + 2j$	QCD Scale	$2\ell 2\nu$	22–37
$qq \to ZZ + 2j$	Parton Shower	$2\ell 2\nu$	1–67
$gg \to H^* \to ZZ$	Parton Shower	4ℓ	27
$gg \to H^* \to ZZ$	Parton 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
$gg \rightarrow (H^* \rightarrow) ZZ$	341 ± 117	42.5 ± 14.9	11.8 ± 4.3
$gg \rightarrow H^* \rightarrow ZZ$	32.6 ± 9.07	3.68 ± 1.03	1.58 ± 0.47
$gg \rightarrow ZZ$	345 ± 119	43.0 ± 15.2	11.9 ± 4.4
$qq \rightarrow (H^* \rightarrow) ZZ + 2j$	23.2 ± 1.0	2.03 ± 0.16	9.89 ± 0.96
$qq \rightarrow ZZ$	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
$gg \rightarrow (H^* \rightarrow) ZZ$	210 ± 53	19.7 ± 4.9	4.29 ± 1.10
$gg \rightarrow H^* \rightarrow ZZ$	111 ± 26	10.9 ± 2.5	3.26 ± 0.82
$gg \rightarrow ZZ$	251 ± 66	23.4 ± 6.2	5.31 ± 1.46
$qq \rightarrow (H^* \rightarrow) ZZ + 2j$	14.0 ± 3.0	1.63 ± 0.17	4.46 ± 0.50
$qq \rightarrow ZZ$	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