Search for non-resonant $HH(\to 2b + 2l + E_T^{miss})$ with the ATLAS experiment

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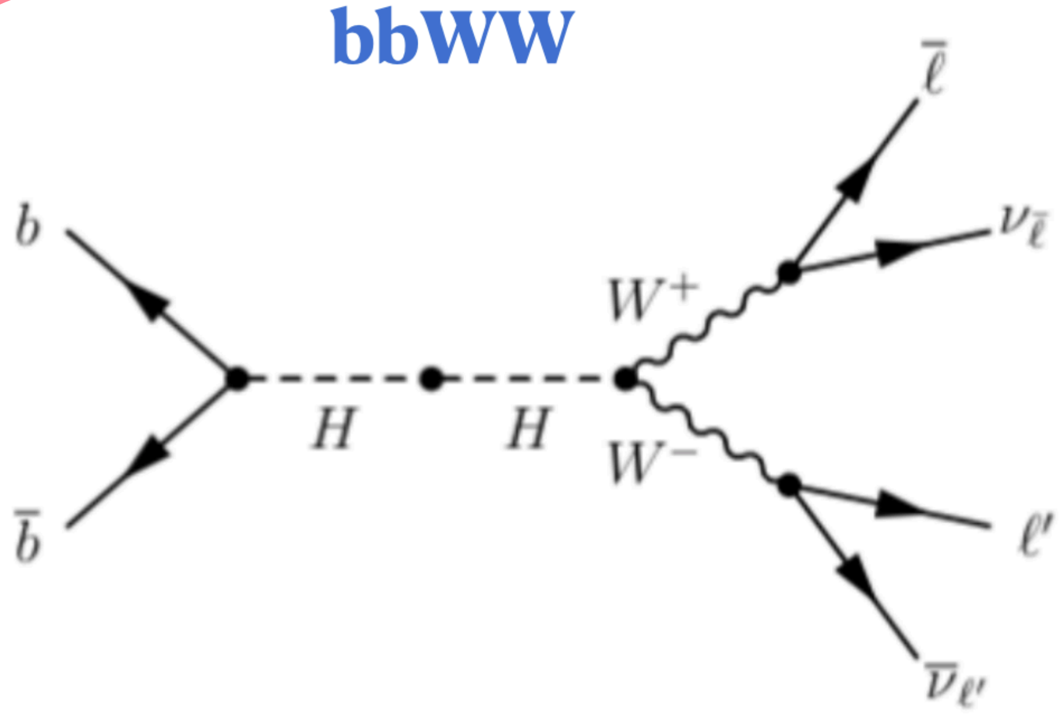
Introduction

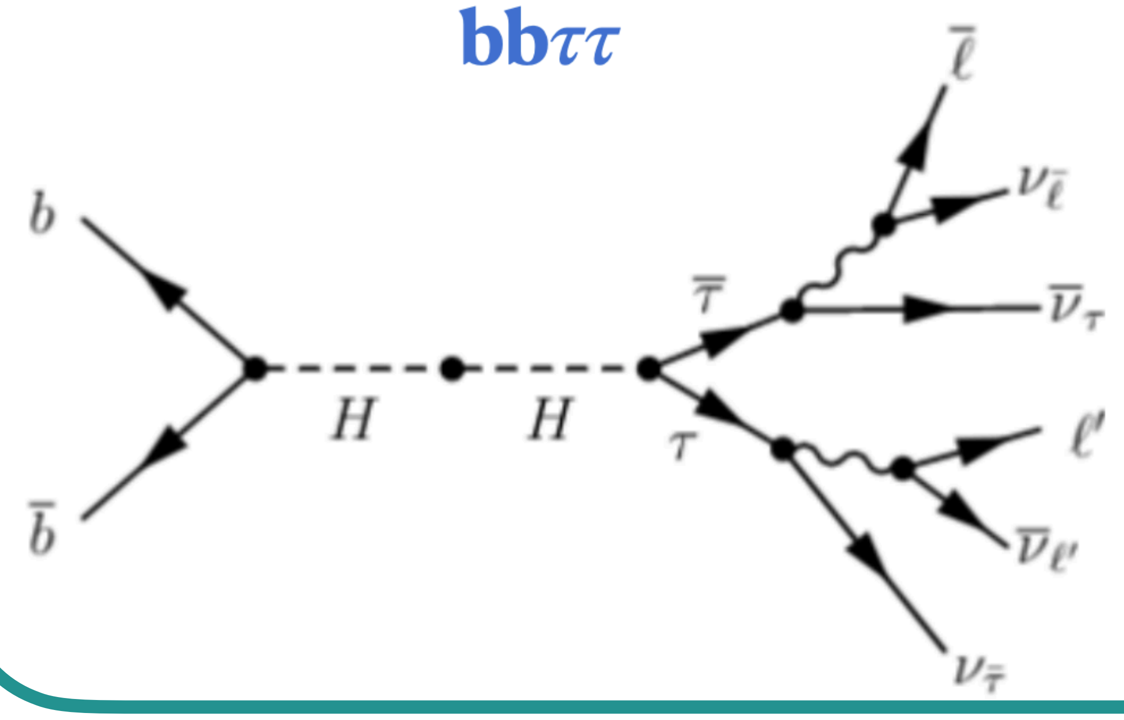
- **Search for non-resonant HH production in 2l+2b+MET final state:**
  - Processes considered **bbWW**, **bb$\tau\tau$** and **bbZZ**
  - ***Experimental signature:*** 2b (close to m_H, 2l (OS), MET from neutrinos)
  - Constrain HH production through ggF and VBF processes
  - Constrain κ_λ and κ_{2V} (coupling modifiers to Higgs boson self-coupling and two vector bosons, respectively)
    - Shape of the Higgs boson potential and SM validity
    - Additional validity test for the SM

bbWW



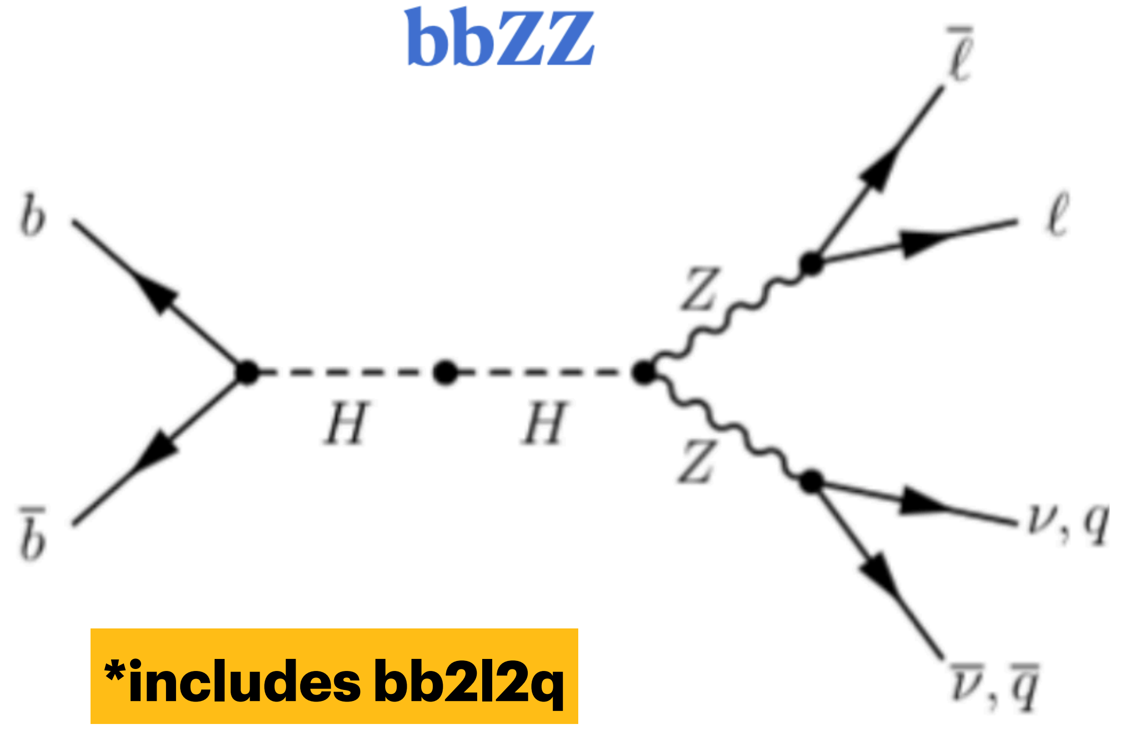
- $BR_{HH\rightarrow bbll+MET} = 1.62\,\%$
- W-pair has spin correlation
- small m_{ll} and $\Delta\Phi_{ll}$

bb$\tau\tau$



- $BR_{HH\rightarrow bbll+MET} = 0.91\,\%$
- Light leptons are collinear to τ-lepton ($m_{\tau\tau}^{coll}$)

bbZZ



- $BR_{HH\rightarrow bbll+MET} = 0.095\,\%$
- m_{ll} close to Z peak or small for offshell Z
- Only same flavour leptons

***includes bb2l2q**

Simulated samples

Process	ME Generator	ME PDF	PS/UE model	UE Tune
SM HH (ggF)	POWHEG BOX v2	PDF4LHC15NLO	PYTHIA 8.244	A14
SM HH (VBF)	MADGRAPH5_AMC@NLO 2.7.3	NNPDF3.0NLO	PYTHIA 8.244	A14
$t\bar{t}$	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14
Single-top	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14
$t\bar{t}+W/Z$	MADGRAPH5_AMC@NLO 2.3.3	NNPDF3.0NLO	PYTHIA 8.210	A14
$W/Z+$jets	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	SHERPA default
WW, WZ, ZZ	SHERPA 2.2.1/SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.1/SHERPA 2.2.2	SHERPA default
ggF, H	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.212	AZNLO
VBF, H	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.230	AZNLO
WH, ZH	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.230/PYTHIA 8.186	AZNLO
$t\bar{t}H$	POWHEG BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14

SM HH signals

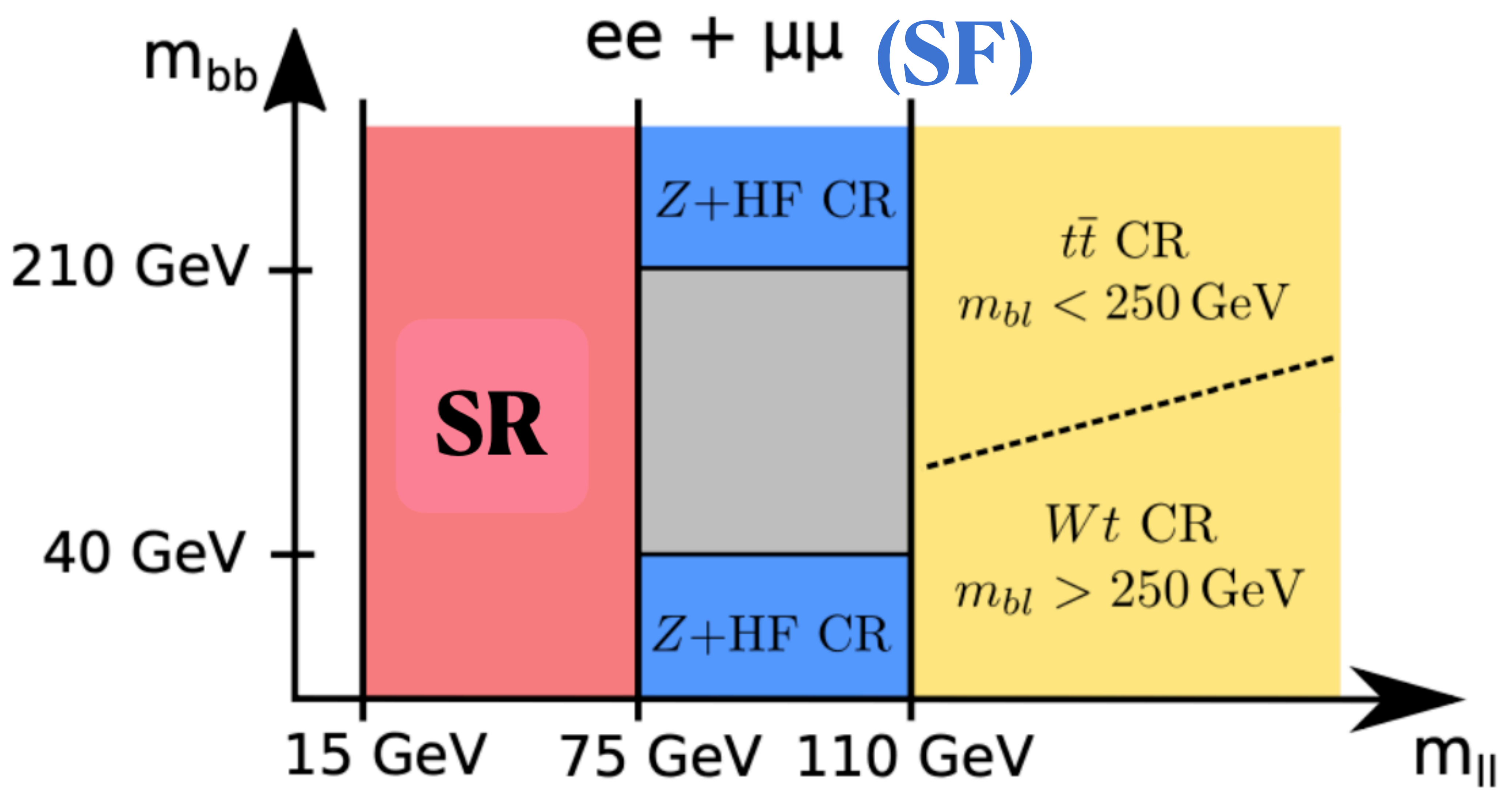
SM background processes

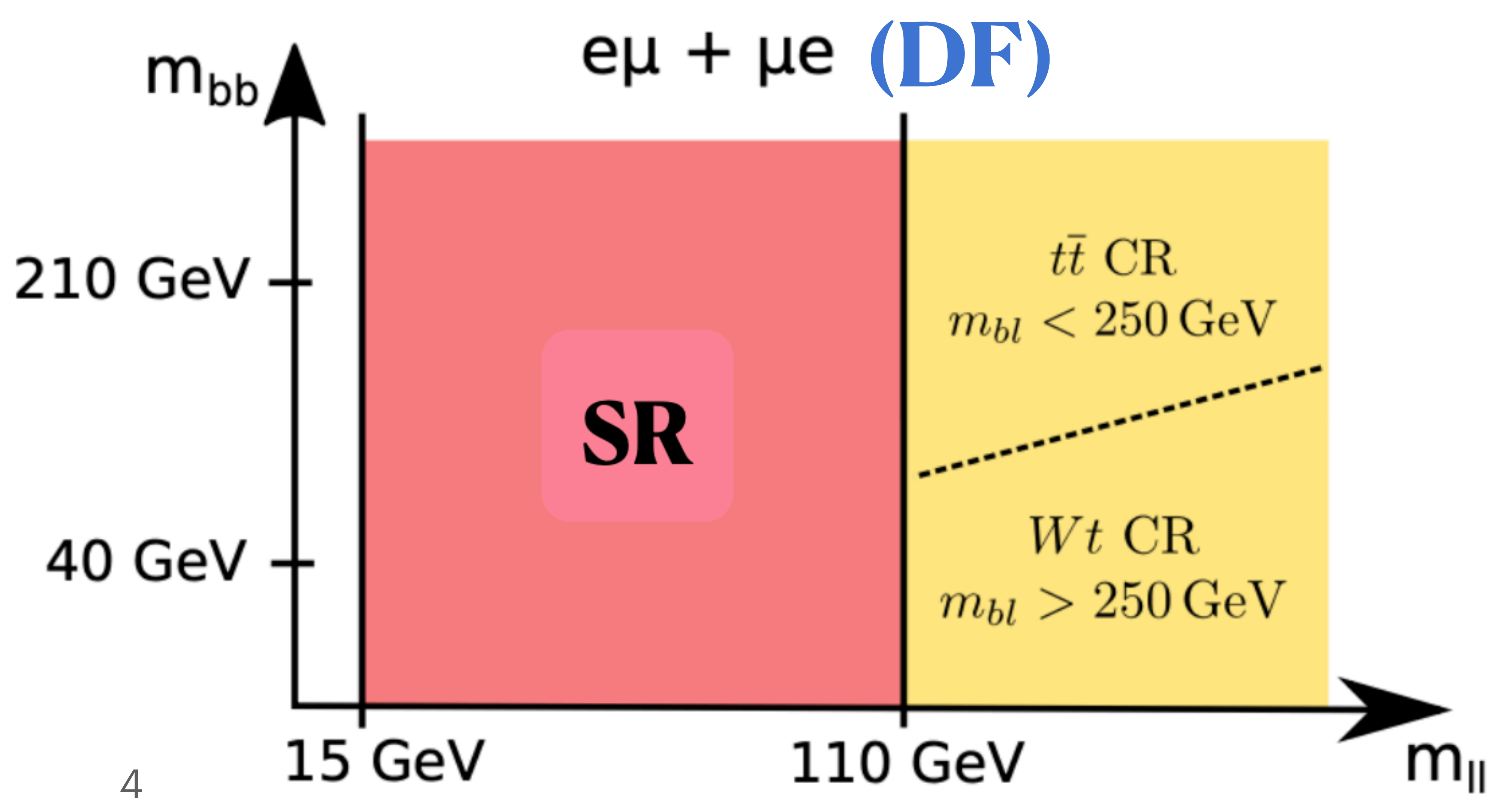
- **Non SM HH signal samples ($\kappa_\lambda \neq 1, \kappa_{2V} \neq 1$):**
  - **ggF:** simulated samples at different values of κ_λ and combined using morphing techniques
  - **VBF:** linear combination of six samples with different values for the κ_λ and κ_{2V} parameters

Event selection

- **Pre-selection:**
  - Single and di-lepton triggers
  - Exactly two light leptons OS charge with pT > 9 GeV
  - Exactly two b-tagged jets with pT > 20 GeV and satisfying DL1r (77% WP)

- **ggF Signal Region:**
  - Veto VBF selection in SR
- **VBF Signal Region:**
  - At least 2 additional jets with pT > 30 GeV with
    - $\max(\Delta\eta_{jj}) > 4$
    - $\max(m_{jj}) > 600$ GeV





Multivariate Analysis (ggF region)

Event classification (optmise signal and background separation)

- **DNN (ggF category):**
  - Classifier based on Keras+TensorFlow
  - Optmize separation between ggF HH signal and tt, tW and other backgrounds
  - Finally, model is trained with 50%/50% split, 0.3 dropout rate to avoid overfitting
  - 95%CL upper limits on μ_{HH} is used as metric
  - Signal output node score is binned -> background uncertainties < 30%

List of Input Features

Input feature	Description
same flavour	unity if final state leptons are ee or $\mu\mu$, zero otherwise
p_{T}^{ℓ}, p_{T}^{b}	transverse momenta of the leptons, b-tagged jets
$m_{\ell\ell}$, $p_{\mathrm{T}}^{\ell\ell}$	invariant mass and the transverse momentum of the di-lepton system
m_{bb}, p_{T}^{bb}	invariant mass and the transverse momentum of the b-tagged jet pair system
m_{T2}^{bb}	stransverse mass of the two b-tagged jets [125, 126]
$\Delta R_{\ell\ell}$, ΔR_{bb}	ΔR between the two leptons and two b-tagged jets
$m_{b\ell}$	$\min\{\max(m_{b_0\ell_0}, m_{b_1\ell_1}), \max(m_{b_0\ell_1}, m_{b_1\ell_0})\}$ [54]
$\min \Delta R_{b\ell}$	minimum ΔR of all b-tagged jet and lepton combinations
$m_{bb\ell\ell}$	invariant mass of the $bb\ell\ell$ system
$E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$-sig	missing transverse energy and its significance [127]
$m_{\mathrm{T}}(\ell_0, E_{\mathrm{T}}^{\mathrm{miss}})$	transverse mass of the p_{T}-leading lepton with respect to $E_{\mathrm{T}}^{\mathrm{miss}}$
$\min m_{\mathrm{T},\ell}$	minimum value of $m_{\mathrm{T}}(\ell_0, E_{\mathrm{T}}^{\mathrm{miss}})$ and $m_{\mathrm{T}}(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}})$
$H_{\mathrm{T2}}^{\mathrm{R}}$	measure for boostedness[6] of the two Higgs bosons

- **Final SRs: 7 bins with highest DNN output score (max $O(10^2)$ background events in a bin)**
- **DNN output score as final discriminant**

Multivariate Analysis (VBF region)

Event classification (optmise signal and background separation)

- **BDT (VBF category):**
  - Classifier trained based on Adaptive Boosting (AdaBoost) + TMVA framework
  - Two-fold cross-validation with 50%/50% train/test split
  - Trained on VBF HH signal, with ggF HH events classified as background to maximize VBF sensitivity
  - VBF sample $\kappa_\lambda = 0$ used for training: best performance in SM and BSM scenarios
- **Final SRs: 5 bins with highest BDT output score (max $O(10^3)$ background events in a bin)**
- **BDT output score as final discriminant**

List of Input Features

Input feature	Description
$\eta_{\ell_0}, \eta_{\ell_1}, \phi_{\ell_0}, \phi_{\ell_1}, p_T^{\ell_0}, p_T^{\ell_1}$	η, ϕ, p_T of the p_T-(sub)leading lepton
$\eta_{b_0}, \eta_{b_1}, \phi_{b_0}, \phi_{b_1}, p_T^{b_0}, p_T^{b_1}$	η, ϕ, p_T of the p_T-(sub)leading b-tagged jet
$\eta_{j_0}, \eta_{j_1}, \phi_{j_0}, \phi_{j_1}, p_T^{j_0}, p_T^{j_1}$	ϕ, η, p_T of the p_T-(sub)leading non b-tagged jet
E_T^{miss}, $\phi^{E_T^{miss}}$, E_T^{miss}-sig	missing transverse energy, its ϕ and significance [127]
$p_T^{bb}, \Delta R_{bb}, \Delta\phi_{bb}, m_{bb}$	p_T, ΔR, $\Delta\phi$ and invariant mass of di-b-jet system
$p_T^{\ell\ell}, \Delta R_{\ell\ell}, \Delta\phi_{\ell\ell}, m_{\ell\ell}, \phi^{\ell\ell}_{\text{centrality}}$	p_T, ΔR, $\Delta\phi$, p_T and centrality[7] of di-leptons system
$p_T^{bb\ell\ell}, m_{bb\ell\ell}$	p_T and invariant mass of the $bb\ell\ell$ system
$p_T^{bb\ell\ell+E_T^{miss}}, m_{bb\ell\ell+E_T^{miss}}$	p_T and invariant mass of $bb\ell\ell + E_T^{miss}$ system
$m_{\ell\ell+E_T^{miss}}$	invariant mass of di-lepton + E_T^{miss} system
$p_T^{E_T^{miss}+\ell\ell}, \Delta\phi_{E_T^{miss},\ell\ell}$	p_T of and $\Delta\phi$ between E_T^{miss} and di-lepton system
p_T^{tot}	p_T of $bb\ell\ell+E_T^{miss}+$ p_T-leading and -sub-leading jet
m_{tot}	invariant mass of $bb\ell\ell+E_T^{miss}+$ p_T-leading and -sub-leading jet
m_t^{KLF}	Kalman fitter top-quark mass [129]
$\min\Delta R_{\ell_0 j}, \min\Delta R_{\ell_1 j}$	minimum ΔR between p_T-(sub)leading ℓ-j couples
$\sum m_{\ell j}$	sum of the invariant masses of all ℓ+jet combinations
$\max p_T^{jj}, \max m_{jj}$	maximum p_T and invariant mass of any two non b-tagged jets
$\max\Delta\eta_{jj}, \max\Delta\phi_{jj}$	maximum $\Delta\eta$ and $\Delta\phi$ between any two non b-tagged jets
$\min\Delta R_{b\ell}$	minimum ΔR of all b-tagged jet and lepton combinations
$N_{\text{forward jets}}, N_j$	number of forward jets, number of non b-tagged jets
m_{T2}^{bb}	stransverse mass of the two b-tagged jets [125, 126]
m_{coll}	collinear mass (reconstruction of $m_{\tau\tau}$) [130]
m_{MMC}	value of the MMC algorithm (reconstruction of $m_{\tau\tau}$) [130]

Background estimation

Leading backgrounds

- Top quark pair production ($t\bar{t}$), single top-quark in association with W boson (Wt) and Z/γ^* production in association with heavy-flavour (b,c) jets
- **$t\bar{t}$ CR:** $m_{ll} > 110$ GeV and $m_{bl} \leq 250$ GeV
- **Wt CR:** $m_{ll} > 110$ GeV and $m_{bl} > 250$ GeV
- **Z+HF CR:**
  - Consider only SF events
  - $75 \text{ GeV} < m_{ll} < 110 \text{ GeV}$
  - $m_{bb} < 40$ GeV or $m_{bb} > 210$ GeV
- **Normalization is constrained from data and shape is taken from MC simulation**

Fake-lepton background

- Photons or jets mis-ID as leptons as well as lepton from hadronic decays of HF quarks
- $f_{SS\to OS} = \frac{N^{fake}_{MC,OS}}{N^{fake}_{MC,SS}}$ (transfer factors, TF)
- $N^{fake}_{OS} = f_{SS\to OS} \times (N_{data,SS} - N^{prompt}_{MC,SS})$
- TF ranges from 1.2 to 1.9 (binned in pT of sub-leading lepton)
- **Estimated by data-driven approach**

Minor backgrounds

- **Normalization and shape estimated from MC Simulation**

Signal and Control Region yields

Process	ggF-SR	VBF-SR	$t\bar{t}$-CR	Wt-CR	Z+HF-CR
			SM background		
$t\bar{t}$	561220 ± 150	52670 ± 50	436840 ± 130	2270 ± 10	34700 ± 40
$t\bar{t}+V$	1121 ± 4	194.7 ± 1.9	1133 ± 5	97.0 ± 1.1	440.1 ± 1.9
Single top (Wt)	16260 ± 50	1165 ± 12	14100 ± 40	2901 ± 20	1237 ± 13
Single top (s/t-channel)	12.7 ± 0.8	2.48 ± 0.35	1.21 ± 0.28	0.35 ± 0.14	0.25 ± 0.11
$Z \to \ell\ell$ (HF)	16090 ± 180	1178 ± 34	3610 ± 70	525 ± 11	43390 ± 260
$Z \to \ell\ell$ (LF)	2720 ± 170	260 ± 40	600 ± 90	55 ± 8	5470 ± 190
$Z \to \tau\tau$ (HF)	2200 ± 40	154 ± 13	3 ± 7	1.9 ± 0.5	4 ± 6
$Z \to \tau\tau$ (LF)	370 ± 50	24 ± 4	-1.3 ± 1.5	0.11 ± 0.06	0.8 ± 0.5
W+jets	0.7 ± 0.5	0.09 ± 0.08	-0.2 ± 0.4	—	—
Diboson	288 ± 4	32.6 ± 0.8	159.0 ± 2.8	39.0 ± 0.9	226.8 ± 3.3
Single Higgs	601.0 ± 1.1	105.1 ± 0.4	336.5 ± 0.5	22.06 ± 0.12	48.28 ± 0.29
Fakes	18510 ± 170	2390 ± 60	10020 ± 140	529 ± 35	1360 ± 50
Total SM bkg.	619390 ± 350	58170 ± 100	466810 ± 230	6440 ± 40	86890 ± 330
			HH signal, ggF		
ggF $HH \to bbWW$	8.318 ± 0.016	0.857 ± 0.005	0.00113 ± 0.00019	0.00033 ± 0.00010	0.0014 ± 0.0002
ggF $HH \to bb\tau\tau$	3.138 ± 0.009	0.3284 ± 0.0029	0.00332 ± 0.00029	0.00068 ± 0.00015	0.0047 ± 0.0004
ggF $HH \to bbZZ$	0.633 ± 0.005	0.0873 ± 0.0018	0.00083 ± 0.00018	0.00020 ± 0.00009	0.0442 ± 0.0013
$\sum$ ggF HH	12.088 ± 0.019	1.272 ± 0.006	0.0053 ± 0.0004	0.00121 ± 0.00020	0.0504 ± 0.0014
			HH signal, VBF		
VBF $HH \to bbWW$	0.1518 ± 0.0014	0.2138 ± 0.0017	0.00013 ± 0.00004	—	0.00009 ± 0.00004
VBF $HH \to bb\tau\tau$	0.0537 ± 0.0006	0.0769 ± 0.0007	0.000086 ± 0.000022	0.000048 ± 0.000018	0.00024 ± 0.00004
VBF $HH \to bbZZ$	0.0097 ± 0.0004	0.0184 ± 0.0006	0.000040 ± 0.000024	0.0000029 ± 0.0000016	0.00236 ± 0.00023
$\sum$ VBF HH	0.2152 ± 0.0016	0.3091 ± 0.0019	0.00026 ± 0.00005	0.000051 ± 0.000018	0.00269 ± 0.00024
			HH signal, ggF+VBF		
$\sum$ ggF+VBF HH	12.303 ± 0.019	1.582 ± 0.006	0.0055 ± 0.0004	0.00126 ± 0.00020	0.0531 ± 0.0014

- Pre-fit yields (Uncertainty from MC statistics and template statistics only)

Z+jets split into heavy (HF) and light (LF) flavours

Fakes (fake-lepton from data driven estimation)

No events from given MC sample process in the respective region

Systematic uncertainties

- **Different sources of systematic uncertanties accounted for:**
- ***Experimental sources:***
  - Jets: JES/JER and b-tagging
  - Leptons: Momentum and ID efficiencies
  - Luminosity (0.83%), PU, trigger efficiency
- ***Background modelling:***
  - Top-quark processes: scale variations, ISF/FSR, PDF and interference uncertainties
  - Z+jets: evaluated by variating merging/resummation scales and PDFs
- ***Signal modelling:***
  - Scale and PDF uncertainties, as well as PS (Herwig7 vs Pythia 8)
  - Production cross-section uncertainties: $\pm 3\ \%$ (PDF+α_S), $+6\ \% / -23\ \%$ (ggF scale)
- **Dominant systematics :**
  - In the ggF and VBF SRs: background modelling, experimental, signal normalization
    - Most sensitive bins: ggF-SR 1 to ggF-SR3 and VBF-SR 1 and VBF-SR 2
  - In the CRs: background modelling and normalization

Statistical uncertainty also becomes dominant source

Statistical results

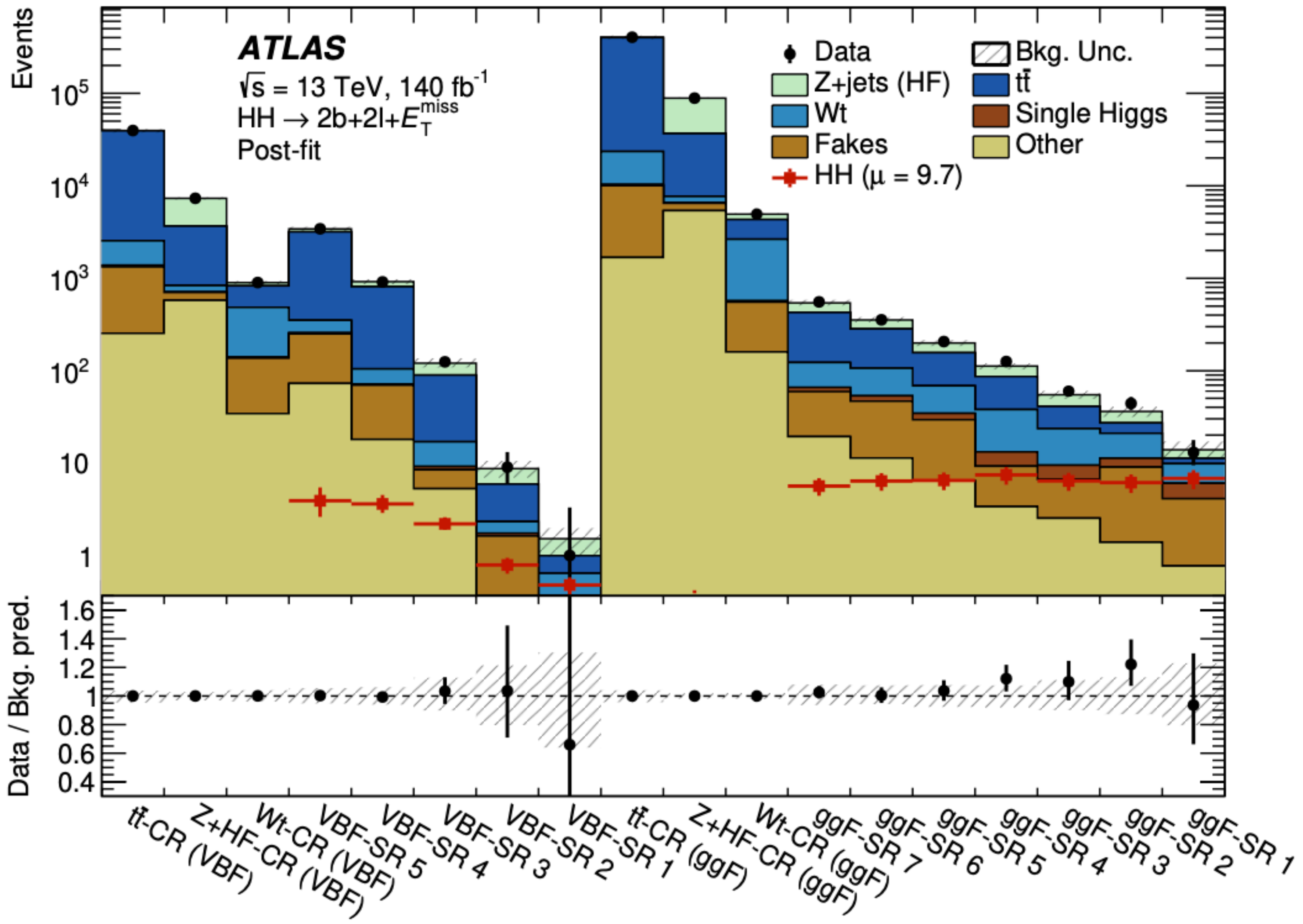
- **Model to fit to data:**
  - A likelihood function is built as a product of Poisson distributions

$$L(\text{data}|\mu,\boldsymbol{\theta}) = \prod_{i=1}^{N} \text{Poisson}(\text{data}_i|\mu \cdot s_i(\boldsymbol{\theta}) + \mu_b b_i(\boldsymbol{\theta})) \times \text{G}(\tilde{\boldsymbol{\theta}}|\boldsymbol{\theta})$$

- s_i and b_i: signal and background contributions in i-th of fitted variable
- μ (signal strength) (**POI**) and μ_b (background NF)
- θ (nuisance parameters)

- **Test statics for setting upper limit:**

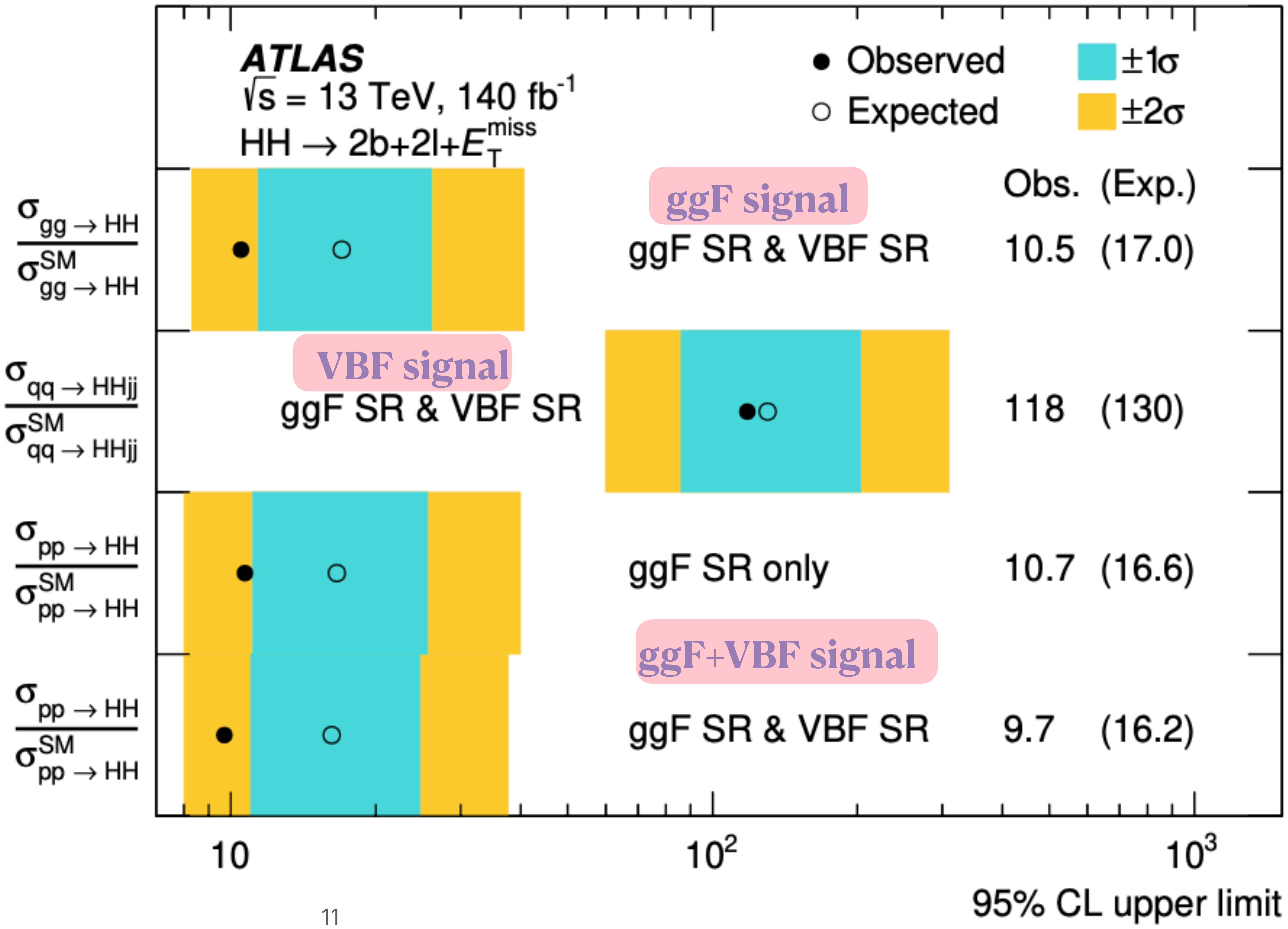
$$q_\mu = \begin{cases} -2\ln\frac{L(\text{data}|\mu,\hat{\hat{\boldsymbol{\theta}}}_\mu)}{L(\text{data}|0,\hat{\boldsymbol{\theta}}_0)} & \hat{\mu} < 0 \\ -2\ln\frac{L(\text{data}|\mu,\hat{\hat{\boldsymbol{\theta}}}_\mu)}{L(\text{data}|\hat{\mu},\hat{\boldsymbol{\theta}})} & 0 \leq \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$



- **Overview of the signal and control regions used in the analysis after the signal+background fit to data**
  - **The fit is a conditional fit with the signal strength fixed to the observed upper limit of $\mu_{HH} = 9.7$**
- **Numbering High (VBF-SR 1 and ggF-SR 1) to Low score (VBF-SR 5 and ggF-SR 7) for the bins used in the final fit**

Upper limit on μ_{HH}

- **Upper limits on μ_{HH}** with consideration of both the ggF and VBF signals are set:
  - $\mu_{HH} = 9.7$ @ 95%CL

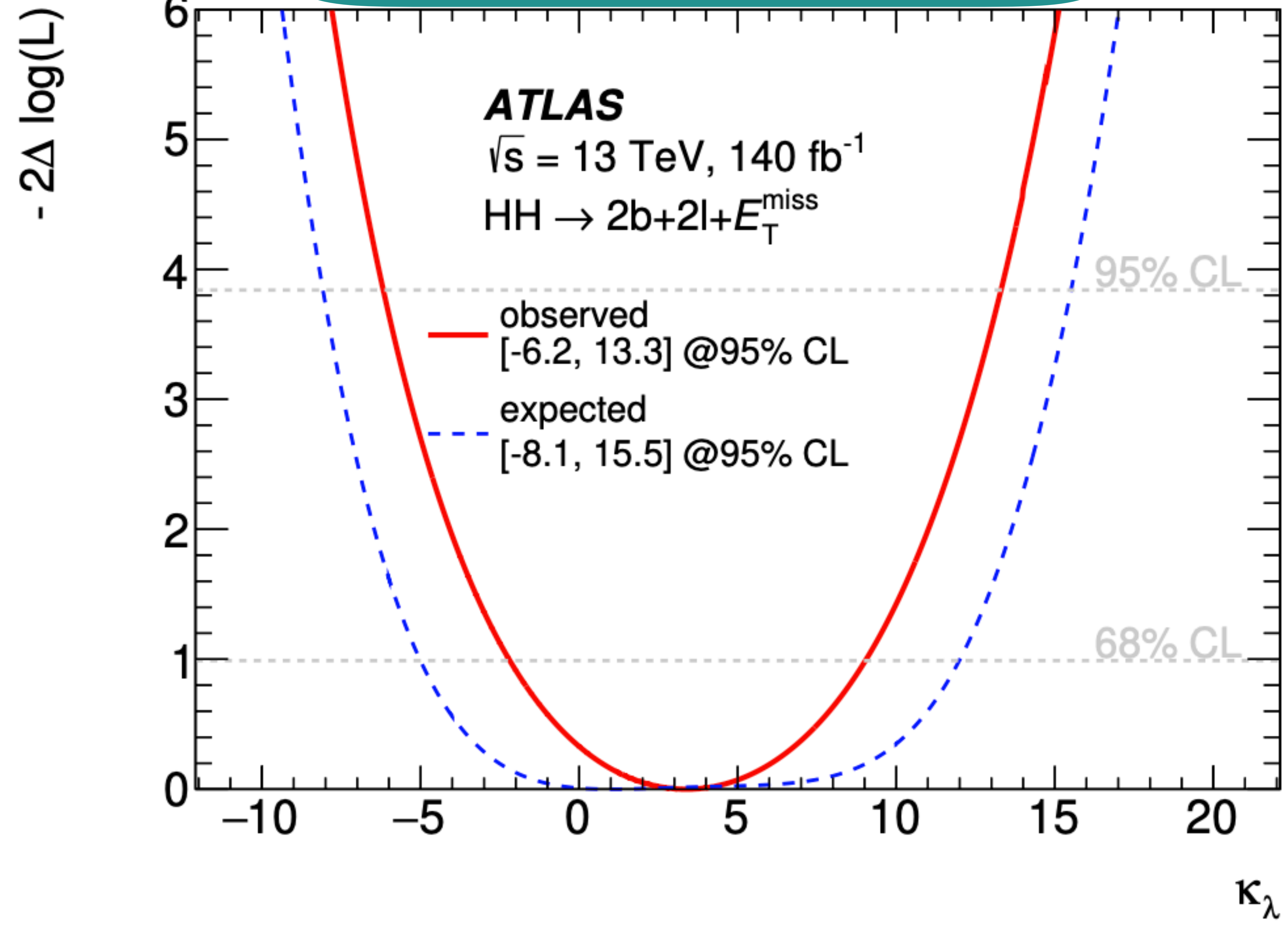


Constraints on κ_λ and κ_{2V}

- **Likelihood scans on κ_λ and κ_{2V}**
  - Both ggF and VBF SRs are included
  - Other κ-modifiers are fixed to the SM predictions

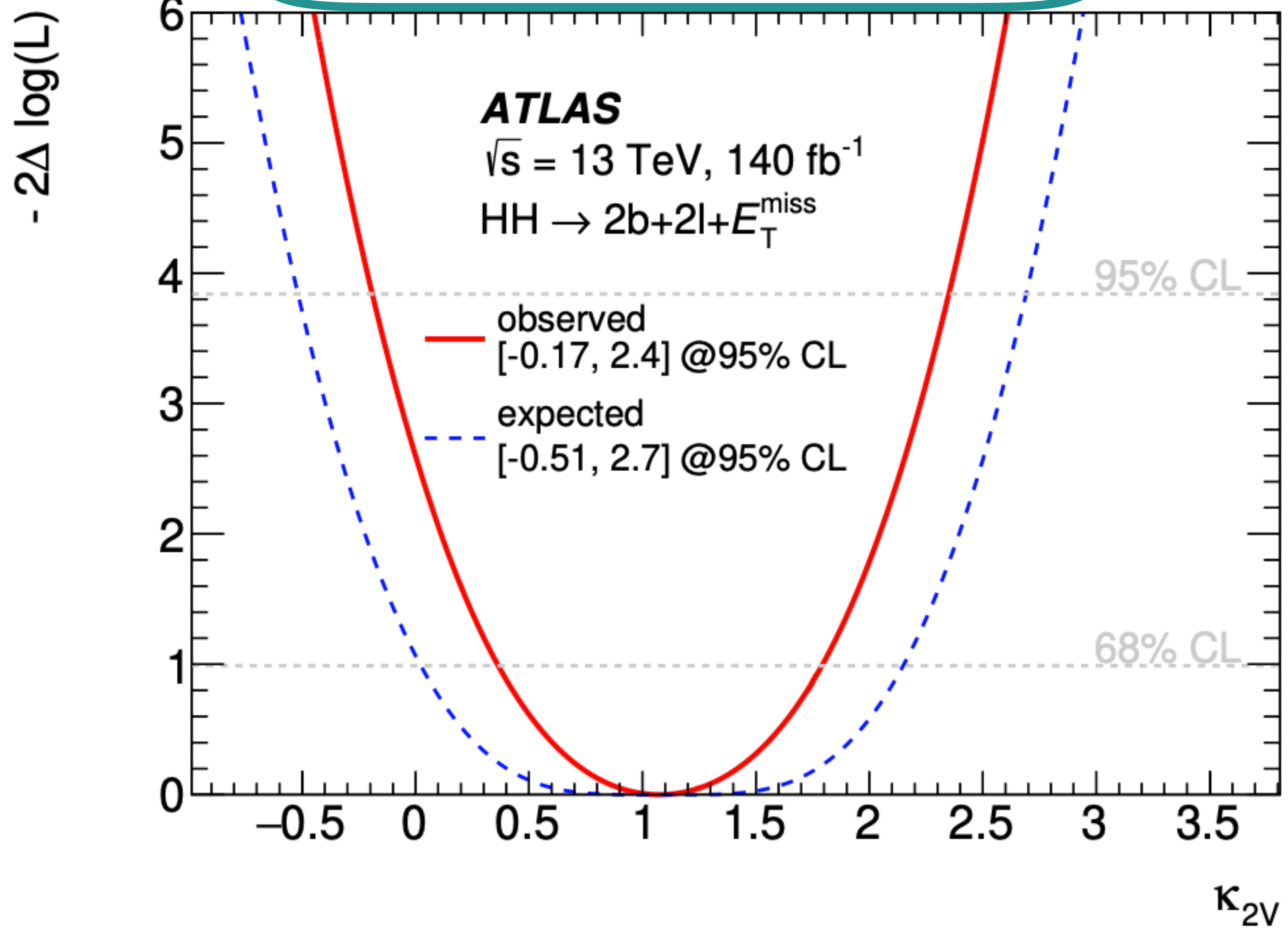
κ_λ in $[-6.2, 13.3]$ @ 95 % CL (obs)

κ_λ in $[-8.1, 15.5]$ @ 95 % CL (exp)



κ_{2V} in $[-0.17, 2.4]$ @ 95 % CL (obs)

κ_{2V} in $[-0.51, 2.7]$ @ 95 % CL (exp)



Summary

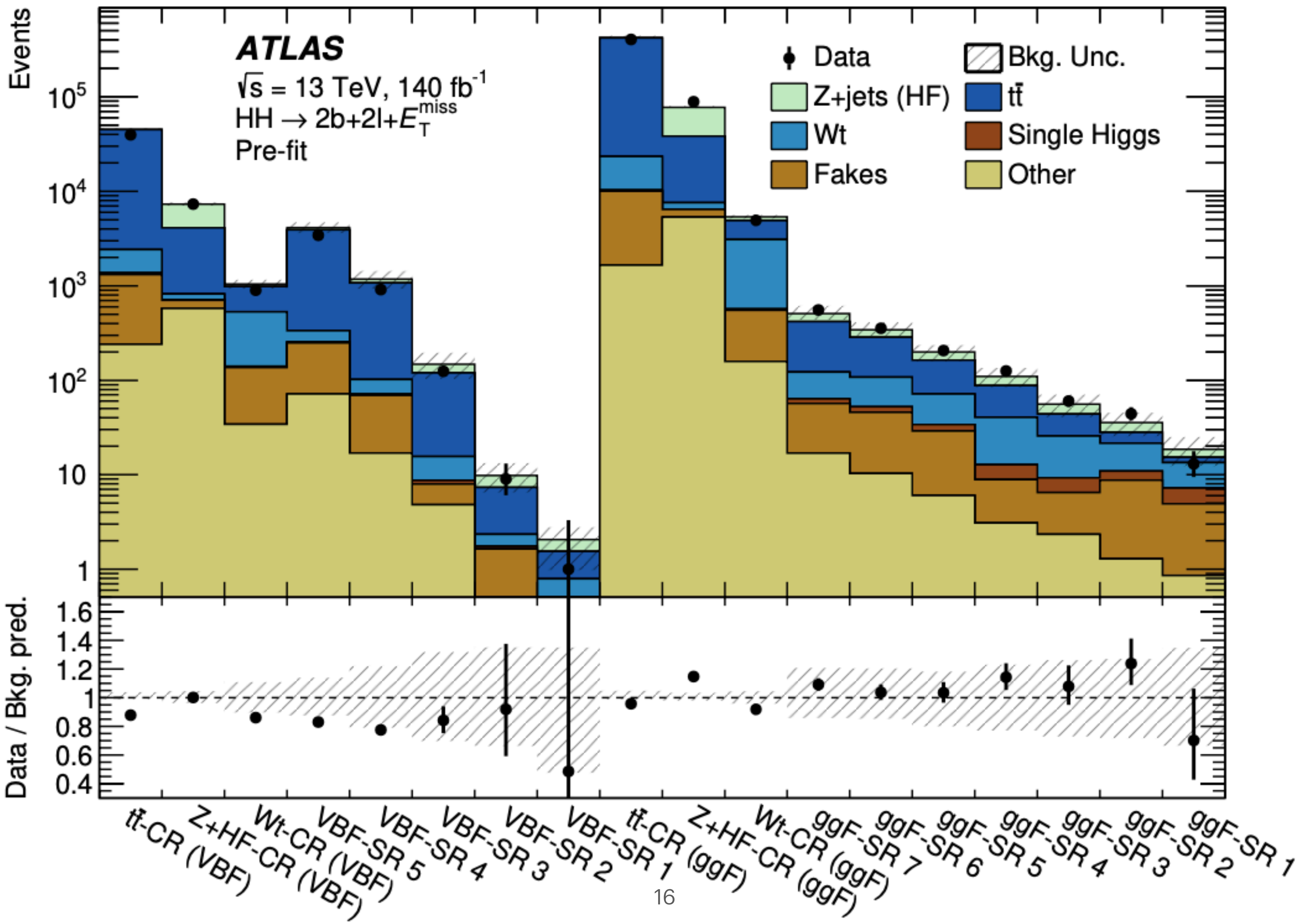
- **Search for non-resonant HH production in $2b + 2l + E_T^{\text{miss}}$ final state using Full Run2 dataset:**
  - HH pair production via ggF and VBF production modes
  - Contributions from bbWW, bb$\tau\tau$ and bbZZ channels
  - No deviation wrt SM background processes is observed
  - **Upper limit on** μ_{HH} = 9.7 (observed), 16.2 (expected)
    - Significant improvement with respect to previous iteration of this analysis (optimized for bbWW only)
  - **Constraints on** κ_λ **and** κ_{2V}:
    - κ_λ in $[-6.2, 13.3]$ @ 95 % CL (obs)
    - κ_{2V} in $[-0.17, 2.4]$ @ 95 % CL (obs)

Back-up slides

Overlap removal

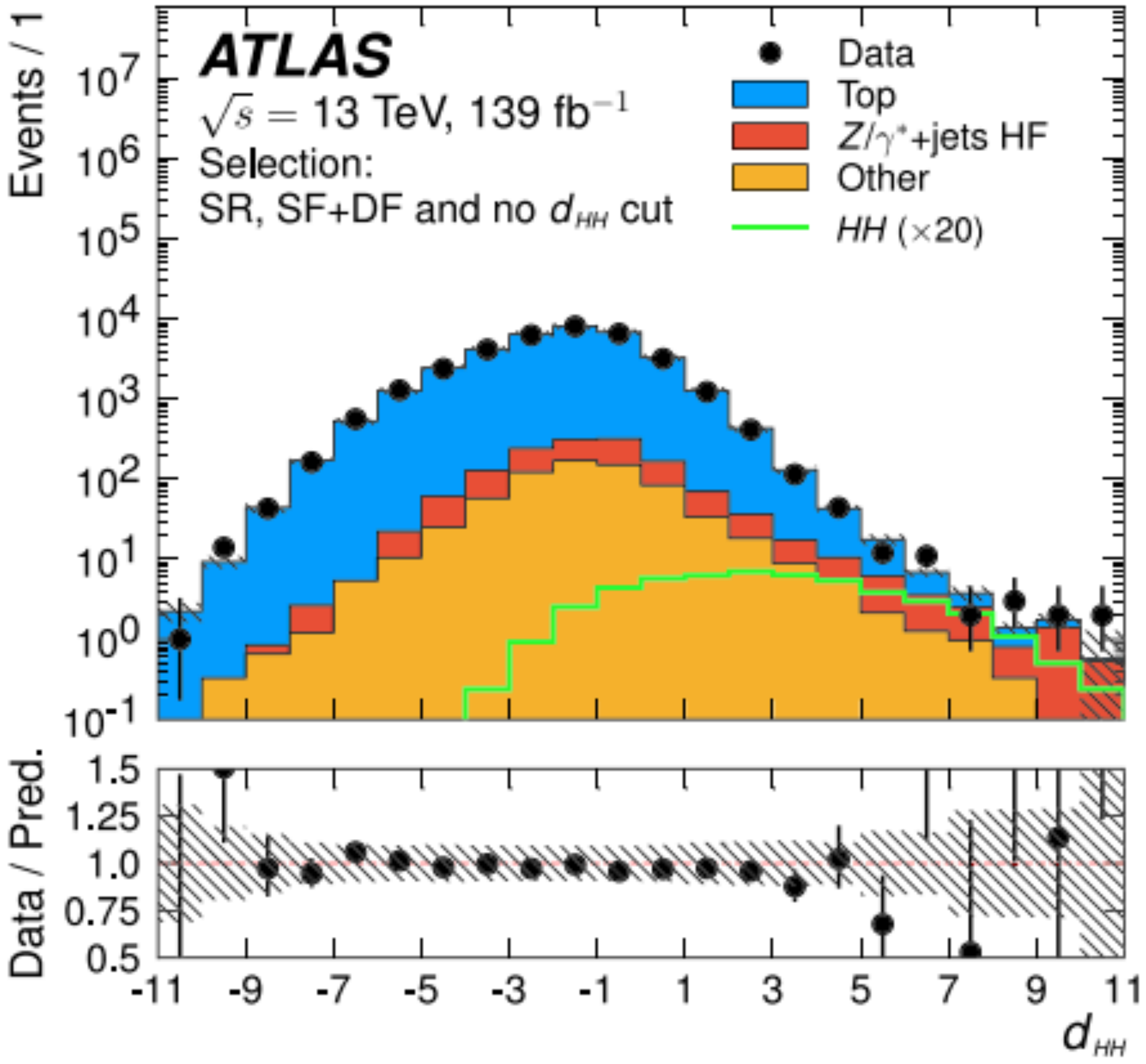
- **It follows the following steps:**
  - if any electrons share a track, only electron with highest pT is kept;
  - If a hadronically decaying τ-lepton candidate is within ΔR_y= 0.2 of any electron or muon, it is removed;
  - If an electron and a muon share a track, the muon is kept only if it is associated with a signature in the MS;
  - Any jet within ΔR_y = 0.2 of an electron and subsequent any electron within ΔR_y = 0.4 of any jet is removed. Any jet within ΔR_y = 0.2 of a muon, or having an inner detector track ghost-matched to a muon within ΔR_y = 0.2 of the jet, is removed if it has fewer then three associated tracks;
  - Any muon within ΔR_y = 0.4 of a jet is removed as well as any jet within ΔR_y= 0.2 of a hadronically decaying τ-lepton candidate.

Pre-fit yields



Run2 Analysis optimized to bbWW

Run2 analysis



Breakdown of the main different sources of uncertainties

Uncertainty [%]	SR-SF				SR-DF			
	Top	Z/γ^*+ HF	Other	Total Bkg.	Top	Z/γ^*+ HF	Other	Total Bkg.
Total uncertainty	28	18	20	14	30	26	41	25
Theoretical	21	15	17	11	20	15	40	17
Experimental	12	< 5	8	< 5	15	17	8	12
MC statistics	8	8	6	8	13	13	7	11
μ_{Top}, $\mu_{Z/\gamma^*\text{+ HF}}$	13	5	n/a	5	13	5	n/a	10

Observed and expected upper limits on HH pair production

	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$	Observed
$\sigma\,(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma\,(gg \to HH)\,/\sigma^{\text{SM}}\,(gg \to HH)$	14	20	29	43	62	40