High mass X→WW→lνlν search

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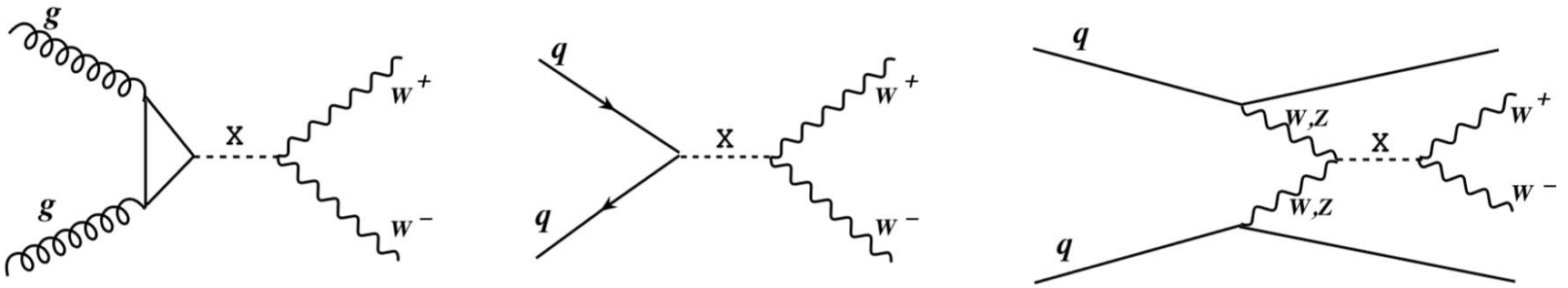
Outline

- Introduction
- Signal models
- Background estimation and event categorization
- Event selection and signal acceptance
- Dominant systematics
- Results
- Conclusion

Introduction

- **Motivation**: search for a heavy neutral Higgs boson and other resonances decaying via X→WW→eνμν



gluon-gluon fusion (ggF) quark-quark annihlation (qqA) vector boson fusion (VBF)

- **Data**: full Run-II 2015+2016 datasets (36.1 fb^{-1}) @ 13 TeV
- **Mass range**: [200 GeV, 5 TeV]
- **Paper status**: submitted to EPJC and accepted (arXiv:1710.01123)

Signal models

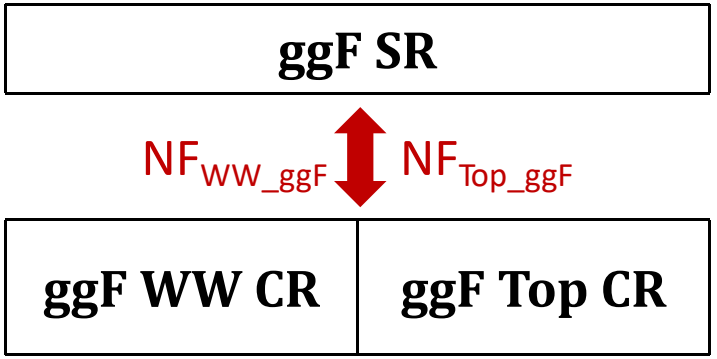
- Signal models considered in the analysis

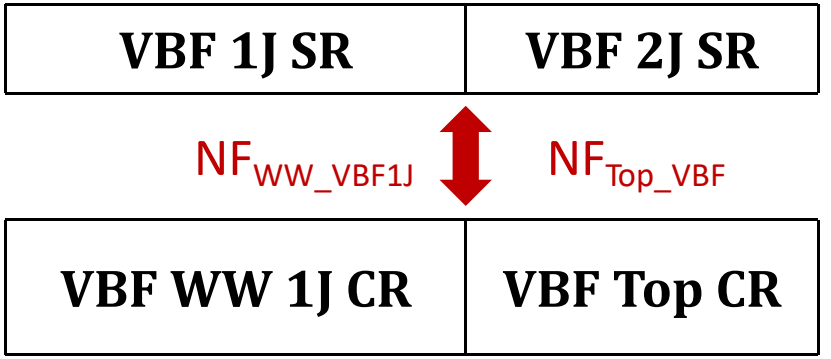
Model	Resonance spin	Production mode		
		ggF	qqA	VBF
Narrow width approximation (NWA)	Spin-0	x		x
Two Higgs doublet models(2HDM)		x		x
Large width assumption (LWA)		x		x
Georgi-Machacek model (GM)				x
Heavy vector triplet (HVT)	Spin-1		x	x
Bulk Randall-Sundrum (RS) graviton	Spin-2	x		
Effective Lagrangian model (ELM)				x

For LWA, widths of 5%, 10% and 15% * m_H are considered

Background estimation and event categorization

- Top (ttbar and single-top), WW (qq→WW and gg→WW) as dominant backgrounds, normalised to the data in control regions (CRs)
- W+jets is estimated with using fake-factor method (data-driven)
- Backgrounds with small contribution are estimated using MC prediction: Z+jets (NNLO), Non-WW diboson (NLO), H125
- Event categorization
  - **ggF** category (quasi-inclusive ggF, VBF phase spaces excluded)
  - **VBF** categories





* Physics results obtained finally from a simultaneous fit to the data in all SRs and CRs

Event selection

SRs

SR_{ggF}	SR_{VBF1J}	SR_{VBF2J}
Preselection: $p_T^{\ell,lead} > 25$ GeV, $p_T^{\ell,sublead} > 25$ GeV, $m_{\ell\ell} > 10$ GeV, veto if $p_T^{\ell,other} > 15$ GeV		
$N_{b\text{-jet}} = 0$ $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$ $m_{\ell\ell} > 55$ GeV $p_T^{\ell,lead} > 45$ GeV $p_T^{\ell,sublead} > 30$ GeV $\max(m_T^W) > 50$ GeV		
Inclusive in N_{jet} but excluding VBF1J and VBF2J phase space	$N_{jet} = 1$ $\lvert\eta_j\rvert > 2.4$, $\min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$	$N_{jet} \geq 2$ $m_{jj} > 500$ GeV, $\lvert\Delta y_{jj}\rvert > 4$

ggF phase space

VBF 1J phase space

VBF 2J phase space

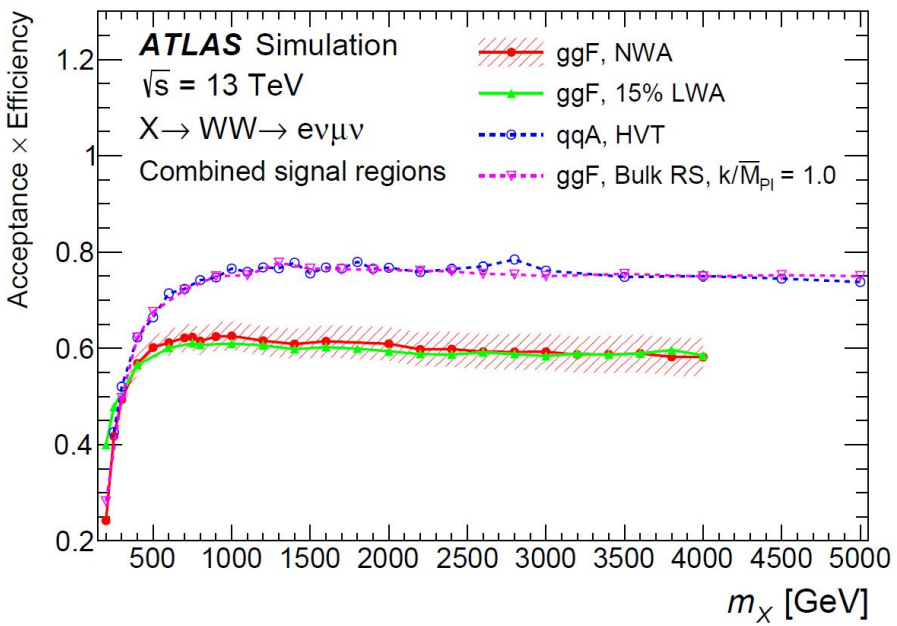
CRs

WW CR_{ggF}	Top CR_{ggF}	WW CR_{VBF1J}	Top CR_{VBF}
Preselection: $p_T^{\ell,lead} > 25$ GeV, $p_T^{\ell,sublead} > 25$ GeV, $m_{\ell\ell} > 10$ GeV, veto if $p_T^{\ell,other} > 15$ GeV			
$N_{b\text{-jet}} = 0$ $\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$	$N_{b\text{-jet}} = 1$ $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$	$N_{b\text{-jet}} = 0$ ($\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$ or $m_{\ell\ell} < 55$ GeV)	$N_{b\text{-jet}} \geq 1$
$m_{\ell\ell} > 55$ GeV		–	–
$p_T^{\ell,lead} > 45$ GeV		–	–
$p_T^{\ell,sublead} > 30$ GeV		$p_T^{\ell,lead} > 25$ GeV	$p_T^{\ell,lead} > 25$ GeV
$\max(m_T^W) > 50$ GeV		$p_T^{\ell,sublead} > 25$ GeV	$p_T^{\ell,sublead} > 25$ GeV
		–	–
Excluding VBF1J and VBF2J phase space		VBF1J phase space	VBF1J and VBF2J phase space

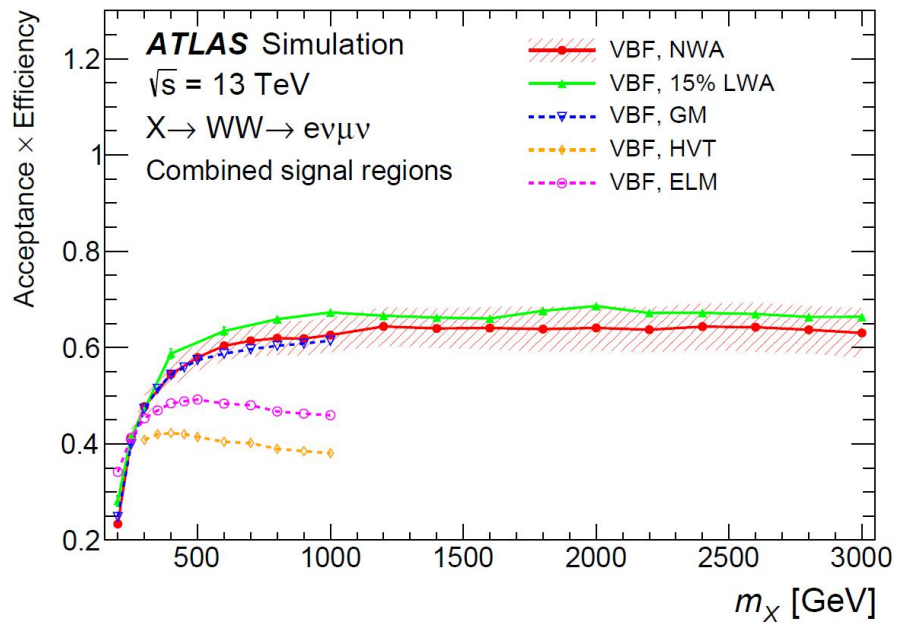
inversed cuts

Signal acceptance

- A simple and general event selection optimisation method developed for the analysis, divided mainly into 2 steps:
  - ① Choose most discriminating variables using BDT techniques
  - ② Optimise cut values based on maximisation of signal significance
  - ✓ ATLAS **internal** note: https://cds.cern.ch/record/2128947
- Signal selection acceptance * efficiency in combined 3 SRs



ggF (qqA) signals



VBF signals

Dominant systematics for backgrounds

- Top

Experimental | Theoretical

Source	Jet	b-tag	ME+PS	Scale	Single top	PDF	Total
SR_{ggF}	5.2	17	1.3	3.0	4.2	2.5	19
SR_{VBF1J}	9.6	7.8	1.0	1.6	5.9	2.6	15
SR_{VBF2J}	9.7	14	9.5	5.0	2.1	3.4	21
Top CR_{ggF}	2.2	4.8	0.34	0.21	2.6	3.0	6.6
WW CR_{ggF}	5.3	18	1.1	6.3	4.0	3.2	20
Top CR_{VBF}	8.2	3.5	10	1.5	1.3	3.7	14
WW CR_{VBF1J}	9.9	8.3	9.4	3.9	5.3	2.7	18

- WW

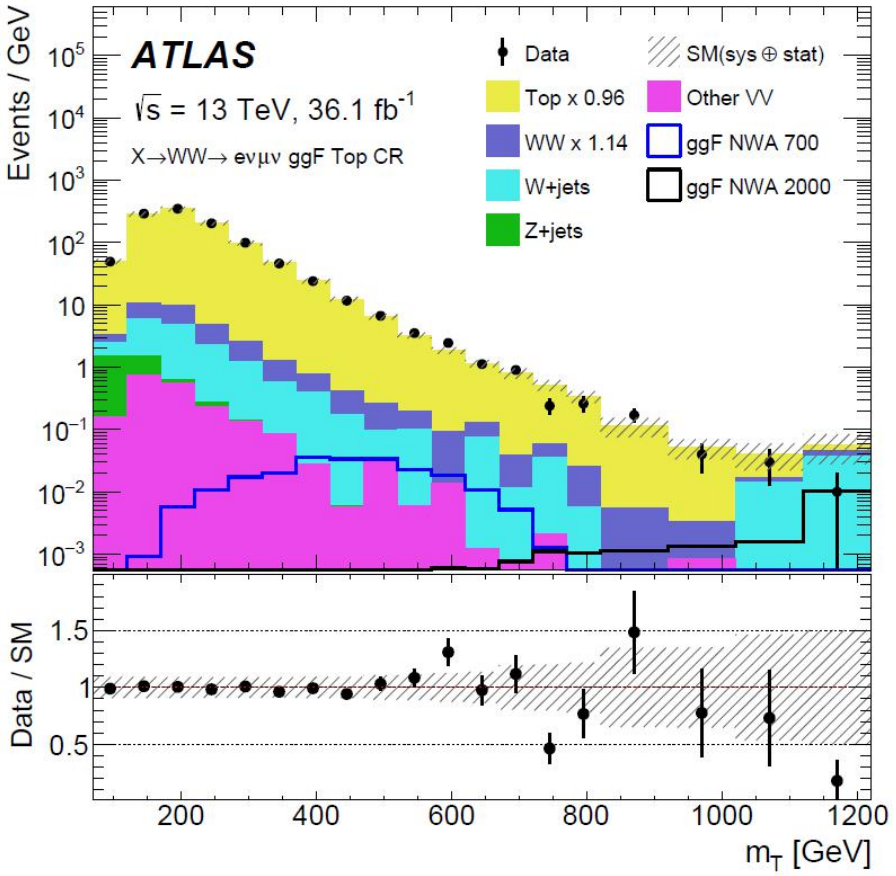
Source	Jet	Pile-up	ME+PS	μ_R	Resummation	PDF	Total
SR_{ggF}	1.2	1.8	2.4	1.7	3.1	2.7	5.5
SR_{VBF1J}	17	2.8	11	7.3	5.0	2.3	23
SR_{VBF2J}	18	3.1	38	18	1.4	2.1	47
WW CR_{ggF}	1.1	1.8	2.6	0.95	2.9	3.6	5.9
WW CR_{VBF1J}	16	4.5	12	11	2.3	2.8	23

- "Total" includes all systematics (not only the dominant ones in the tables)
- Systematics for signal in backup slides
- Shape uncertainties also considered in the analysis

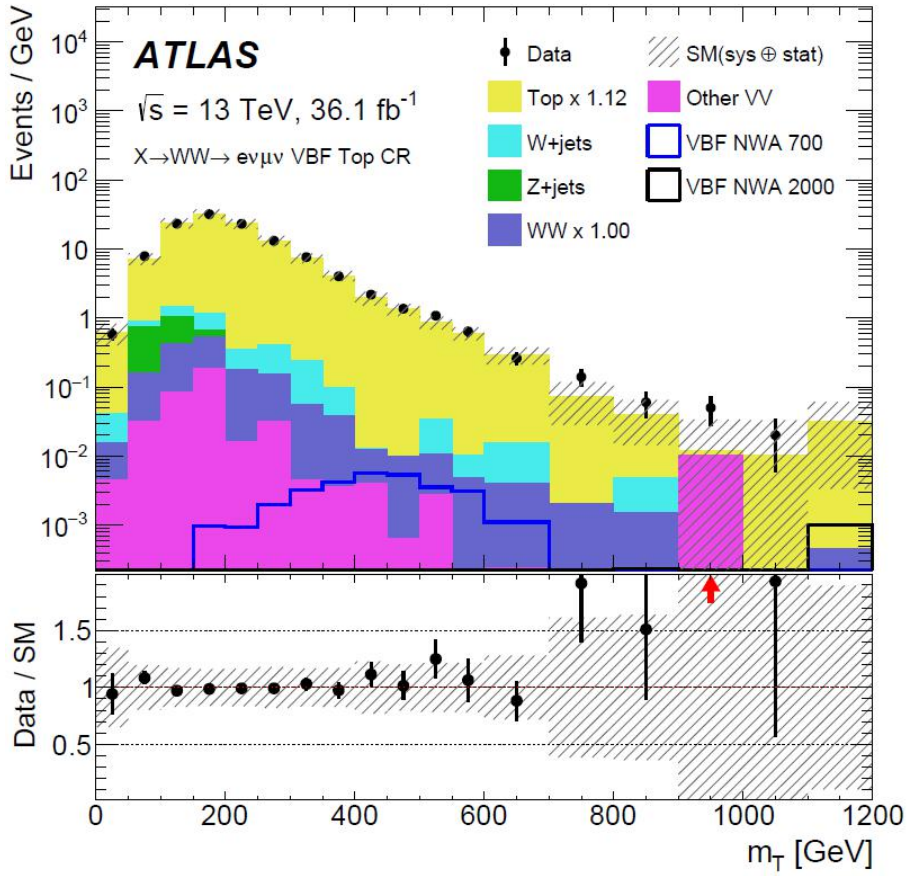
MT plots in Top CRs

- Backgrounds event yields scaled to the post-fit
- Signals scaled to expected limits in the plots

ggF Top CR $NF_{ggF}^{top} = 0.96 \pm 0.05$



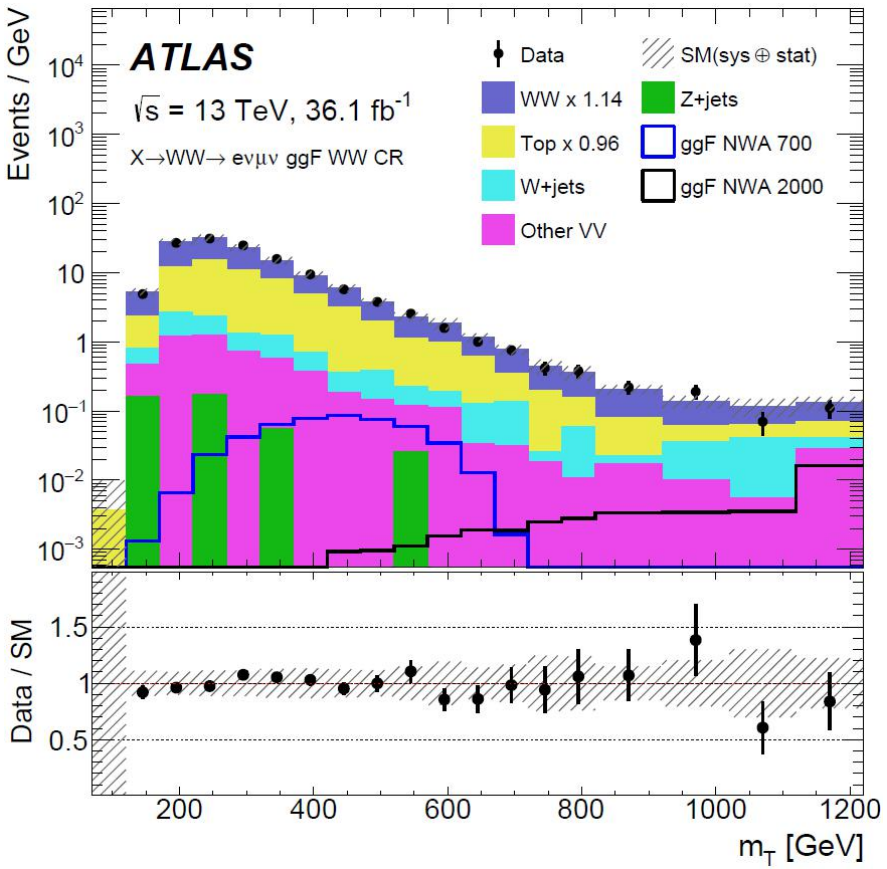
VBF Top CR $NF_{VBF}^{top} = 1.12 \pm 0.1$



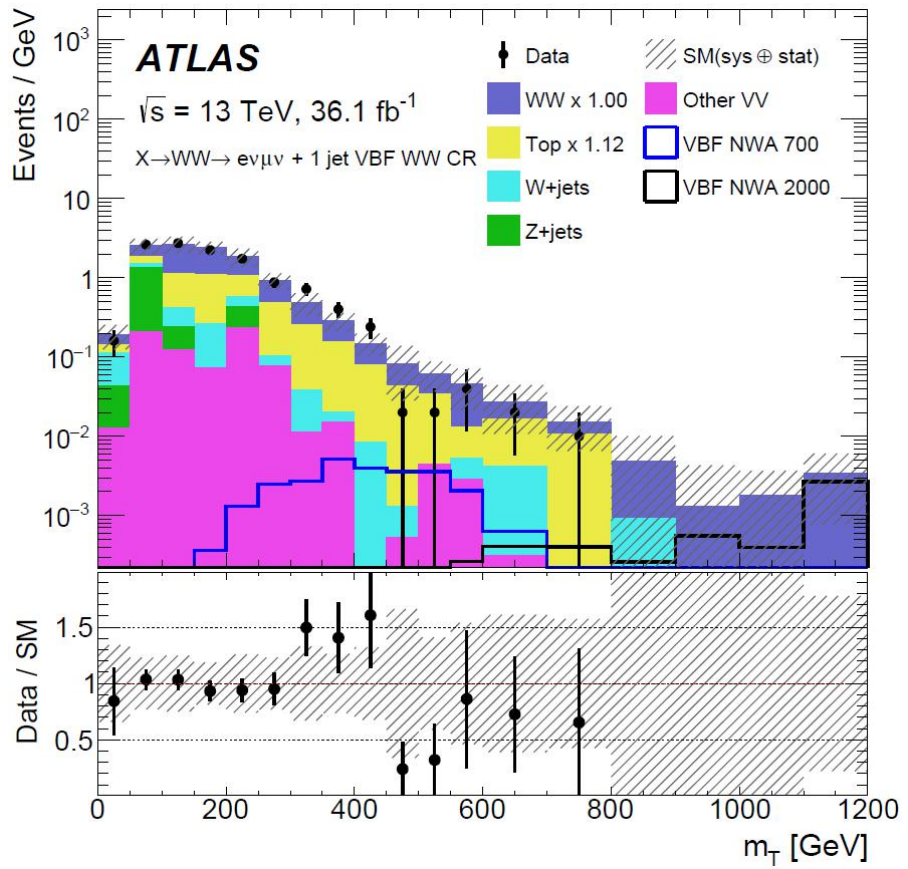
MT plots in WW CRs

- Backgrounds event yields scaled to the post-fit
- Signals scaled to expected limits in the plots

ggF WW CR $NF_{ggF}^{WW} = 1.14 \pm 0.09$



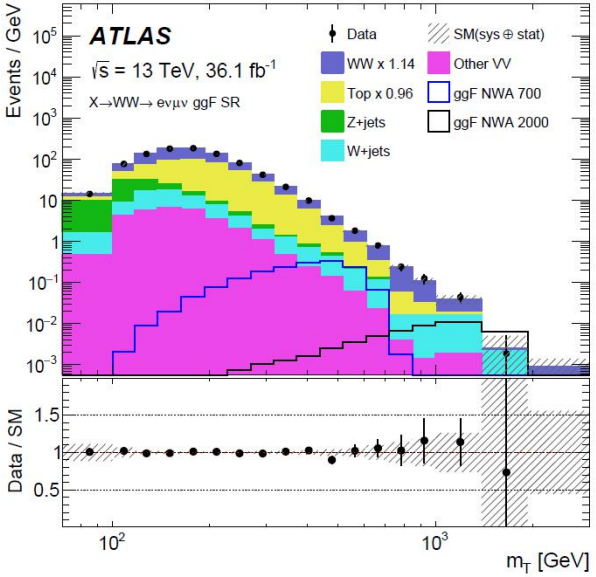
VBF 1J WW CR $NF_{VBF,1J}^{WW} = 1.00 \pm 0.2$



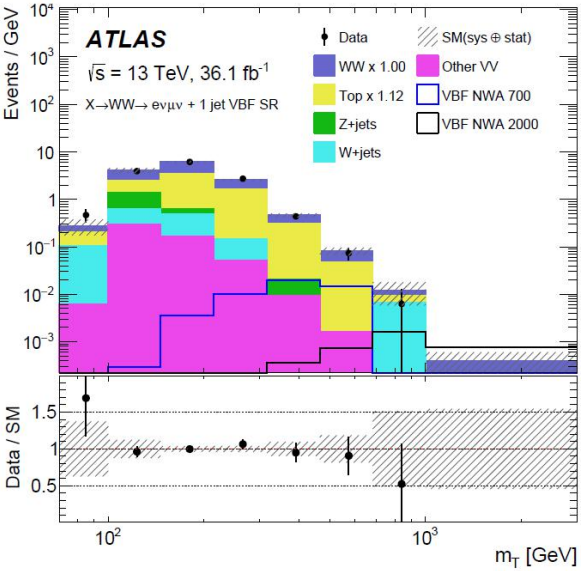
MT plots in SRs

- Post-fit plots
- Signals scaled to expected limits in the plots

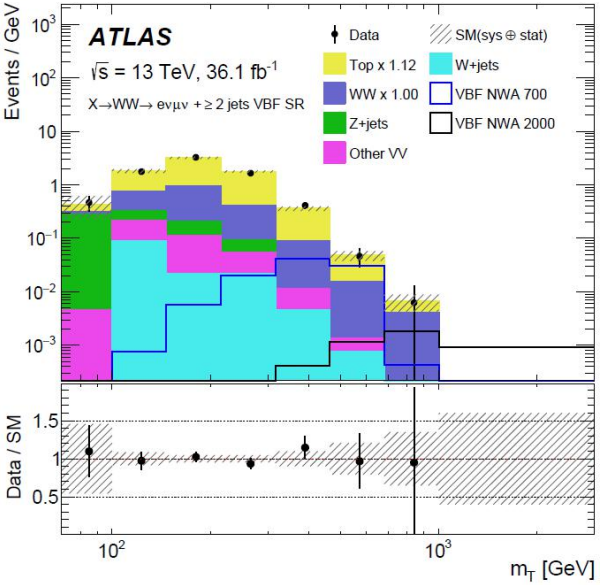
ggF SR



VBF 1J SR



VBF 2J SR



Post-fit NFs

$$NF_{ggF}^{top} = 0.96 \pm 0.05$$

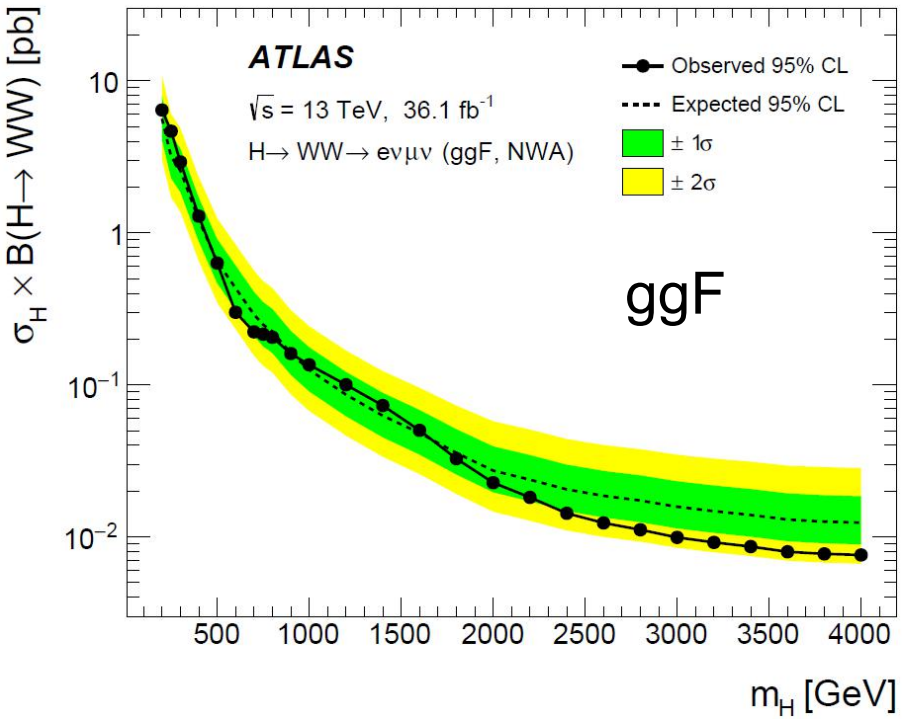
$$NF_{ggF}^{WW} = 1.14 \pm 0.09$$

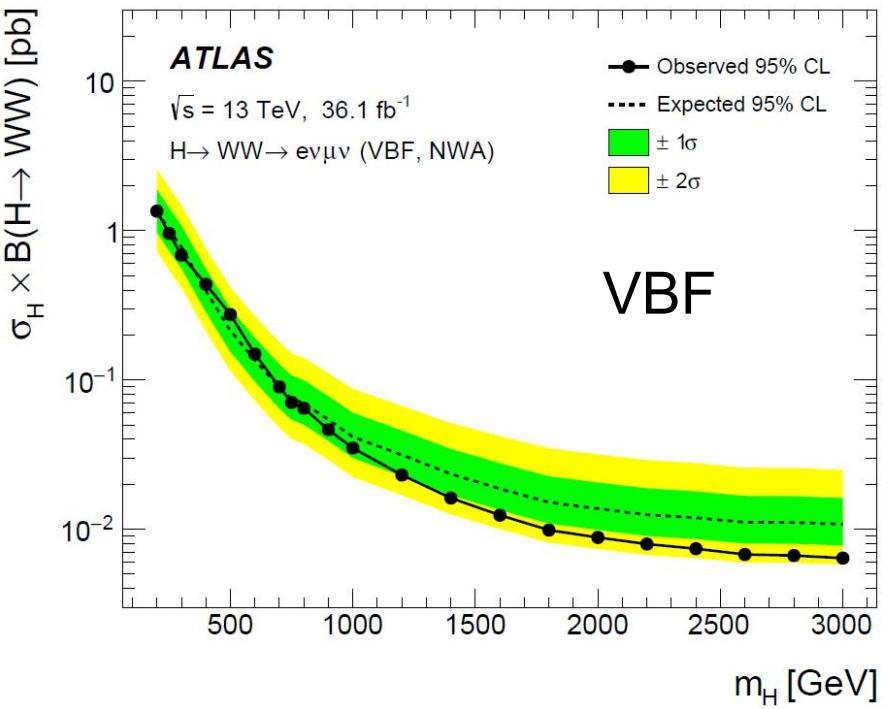
$$NF_{VBF}^{top} = 1.12 \pm 0.1$$

$$NF_{VBF,1J}^{WW} = 1.00 \pm 0.2$$

(stat. ⊕ sys.)

Limits for NWA



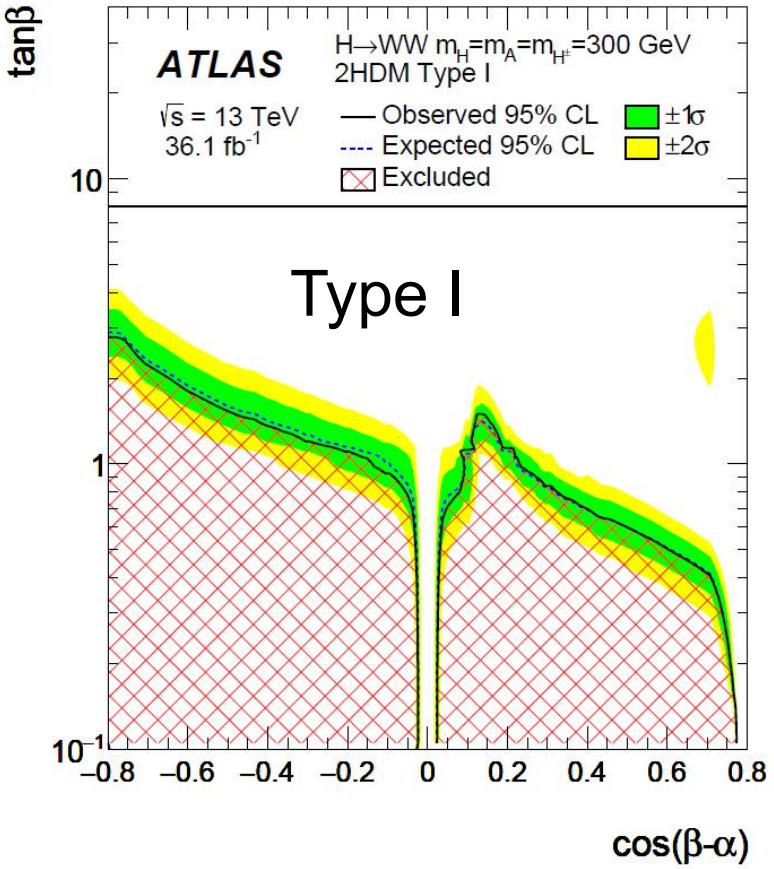


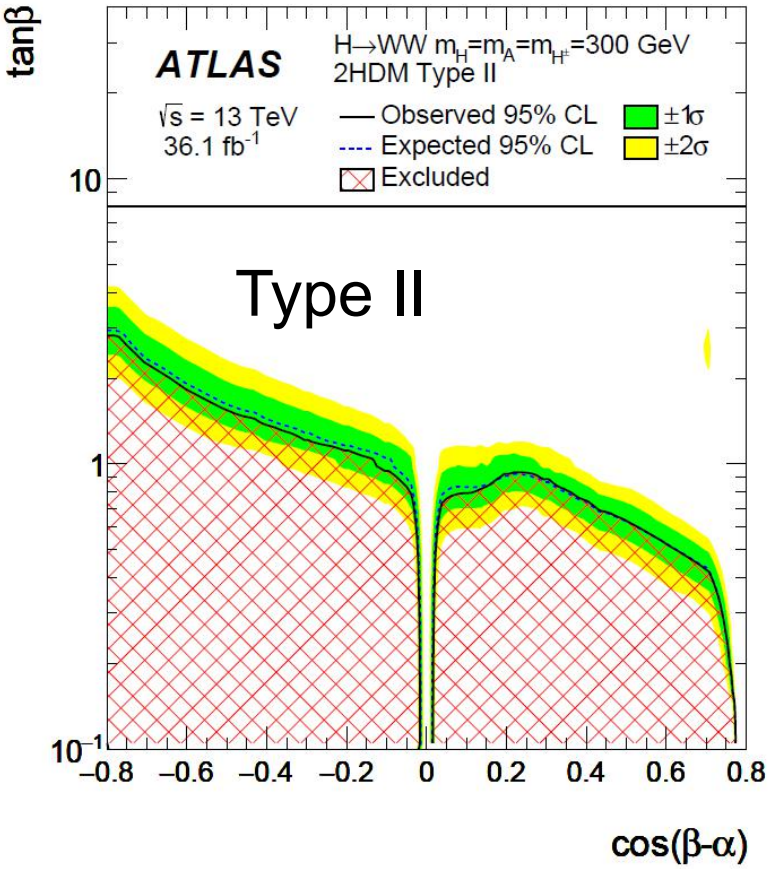
Limits [pb]	ggF	VBF
Lowest mass (200 GeV)	6.4	1.3
Highest mass	0.008 (4 TeV)	0.006 (3TeV)

2HDM interpretation

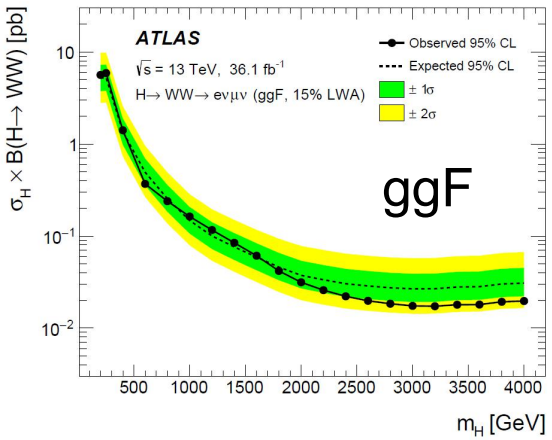
- The limits for NWA are further translated to exclusion contours in the 2HDM model for the phase space where NWA is valid

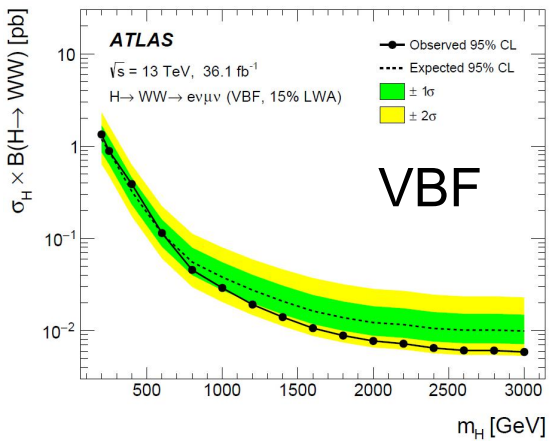
$$m_H = 300\ \mathrm{GeV}$$



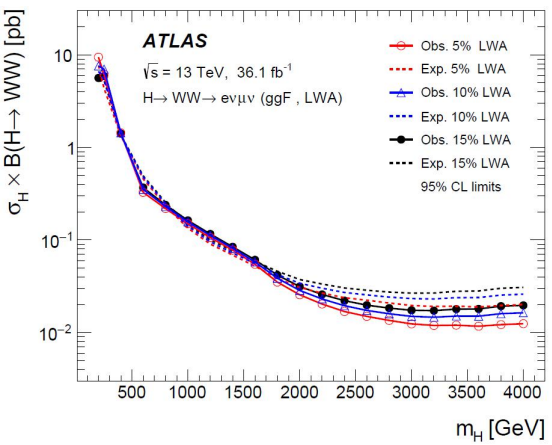


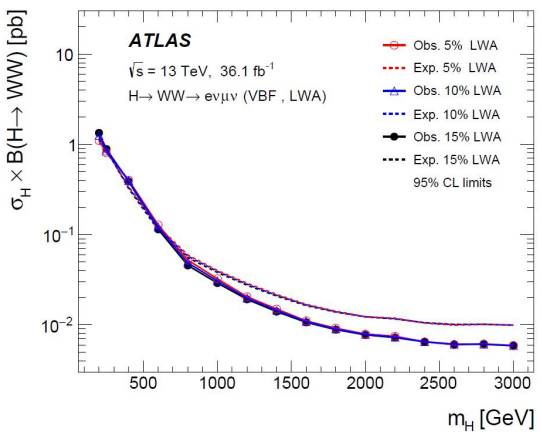
Limits for LWA





→ Width: 15%*m_H





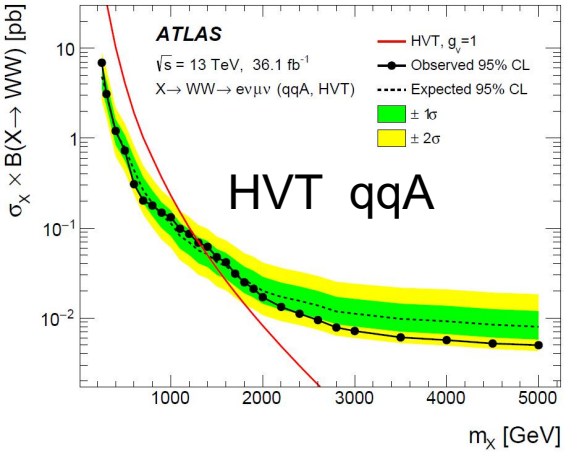
→ Widths:

15%*m_H, 10%*m_H, 5%*m_H

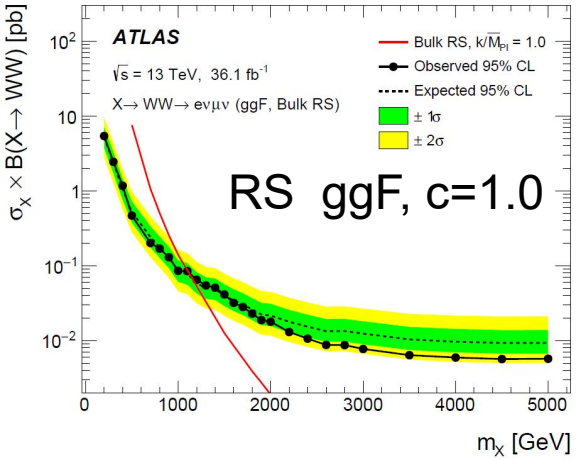
Limits (width = 15%*m_H) [pb]	**ggF**	**VBF**
Lowest mass (200 GeV)	5.2	1.3
Highest mass	0.02 (4 TeV)	0.006 (3TeV)

- Interference effects between signals and backgrounds also studied and found to be negligible

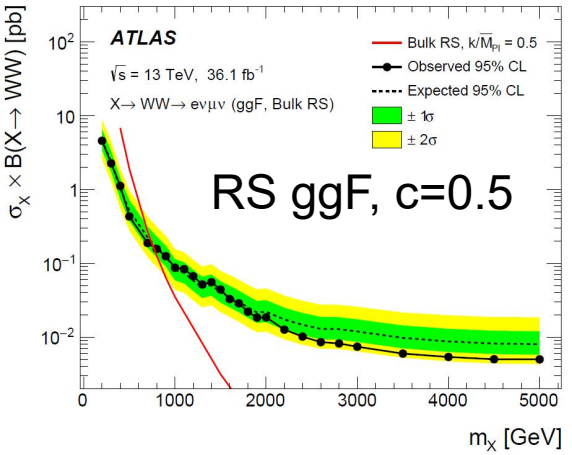
Limits for other models



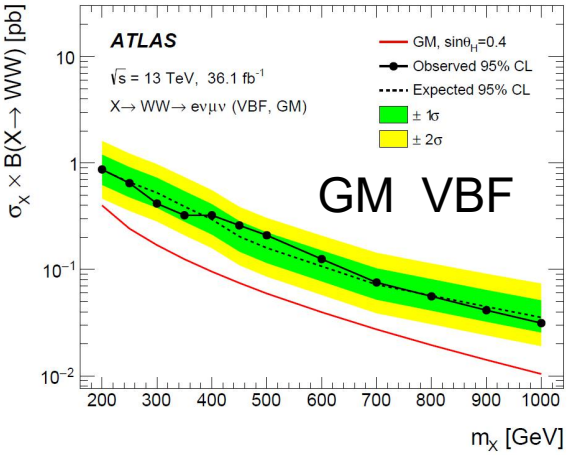
below 1.3 TeV excluded

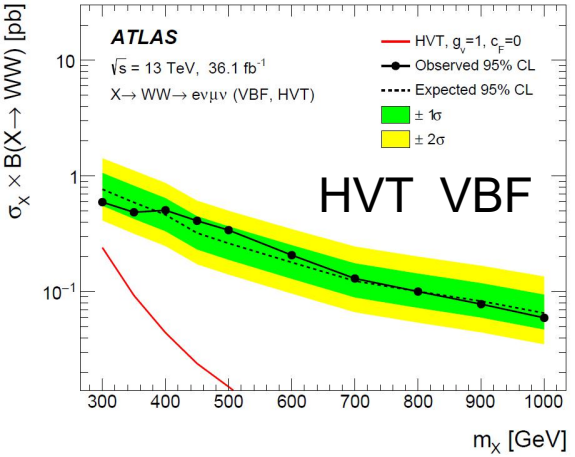


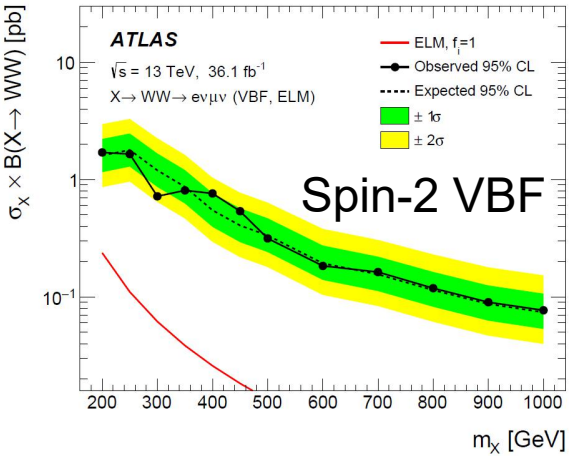
below 1.1 TeV excluded



below 750 GeV excluded







Conclusion

- A search for heavy resonance performed in the X→WW→eνμν decay channels at 13 TeV with Run 2 data at 36.1 fb^{-1}
- Results interpreted by several signal models, e.g. NWA, LWA, 2HDM, HVT, etc., covering a mass range of [200 GeV, 5 TeV]
- No significant excess or evidence of new heavy resonance found
- Upper limits given for different signal models

Thanks for your attention!

BACKUP

Dominant systematics for signals

- QCD scale, PDF and PS uncertainties on signal acceptance
  - The uncertainties have some dependences on the masses
  - Only overall results shown below
  - PS shower tune uncertainties also evaluated, but the the PS shower model uncertainties are significantly larger

ggF induced signals

Sources(%)	ggF SR	VBF 1J SR	VBF 2J SR
Scale	-	-	0.2 ~ 2.5
PDF	< 0.4	< 1.5	< 1.6
PS model	1.3 ~ 3.1	13 ~ 28	2.3 ~ 15

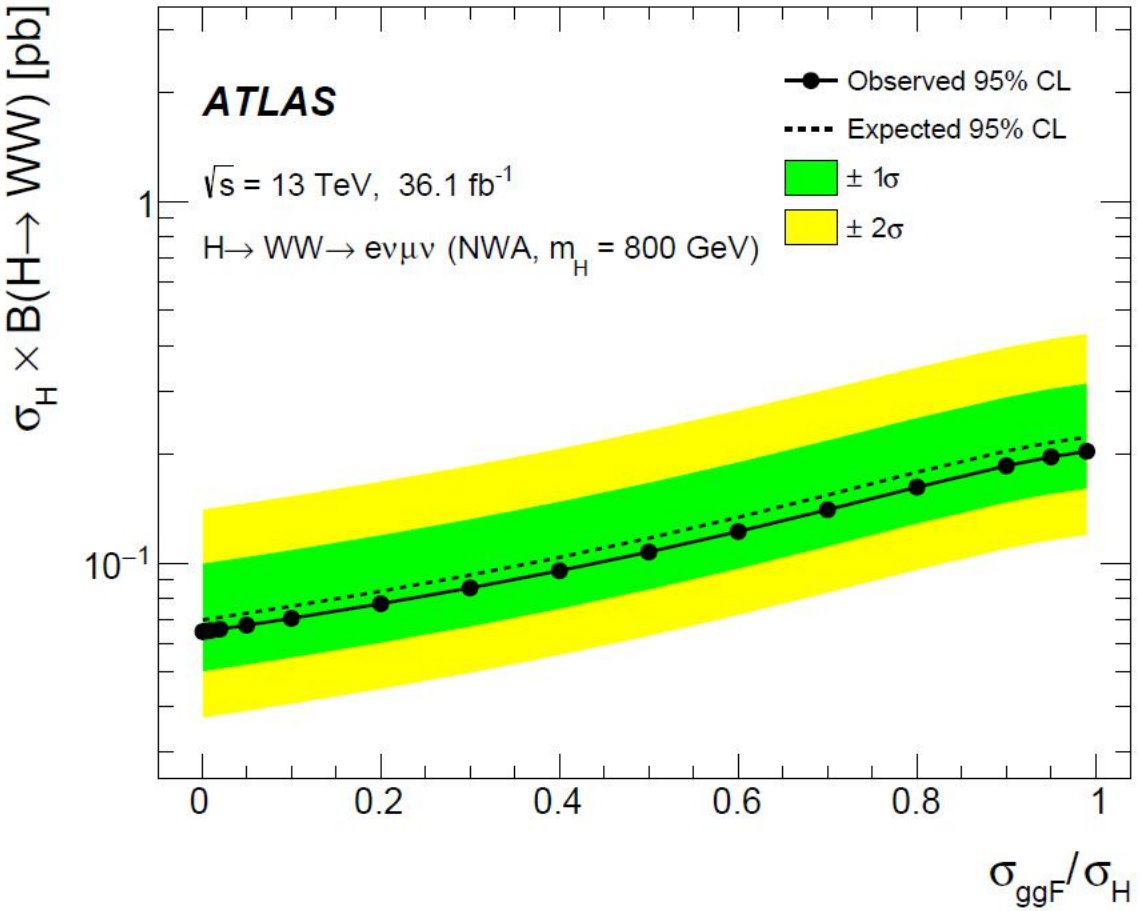
VBF induced signals

Sources(%)	ggF SR	VBF 1J SR	VBF 2J SR
Scale	0.9 ~ 2.8	1.9 ~ 3.6	1.0 ~ 7.3
PDF	< 1.7	< 1.2	< 1.5
PS model	4.3 ~ 19	5.1 ~ 9.0	3.3 ~ 8.0

- QCD scale uncertainties on event category migration
  - 3% - 10% for ggF SR, 4% - 30% (30% - 60%) for VBF 1J (2J) SRs

Limits extension for NWA

- Limits on "σ_{total} (ggF + VBF) * BR", as a function of "σ_{ggF} / σ_{total}"



2HDM interpretation

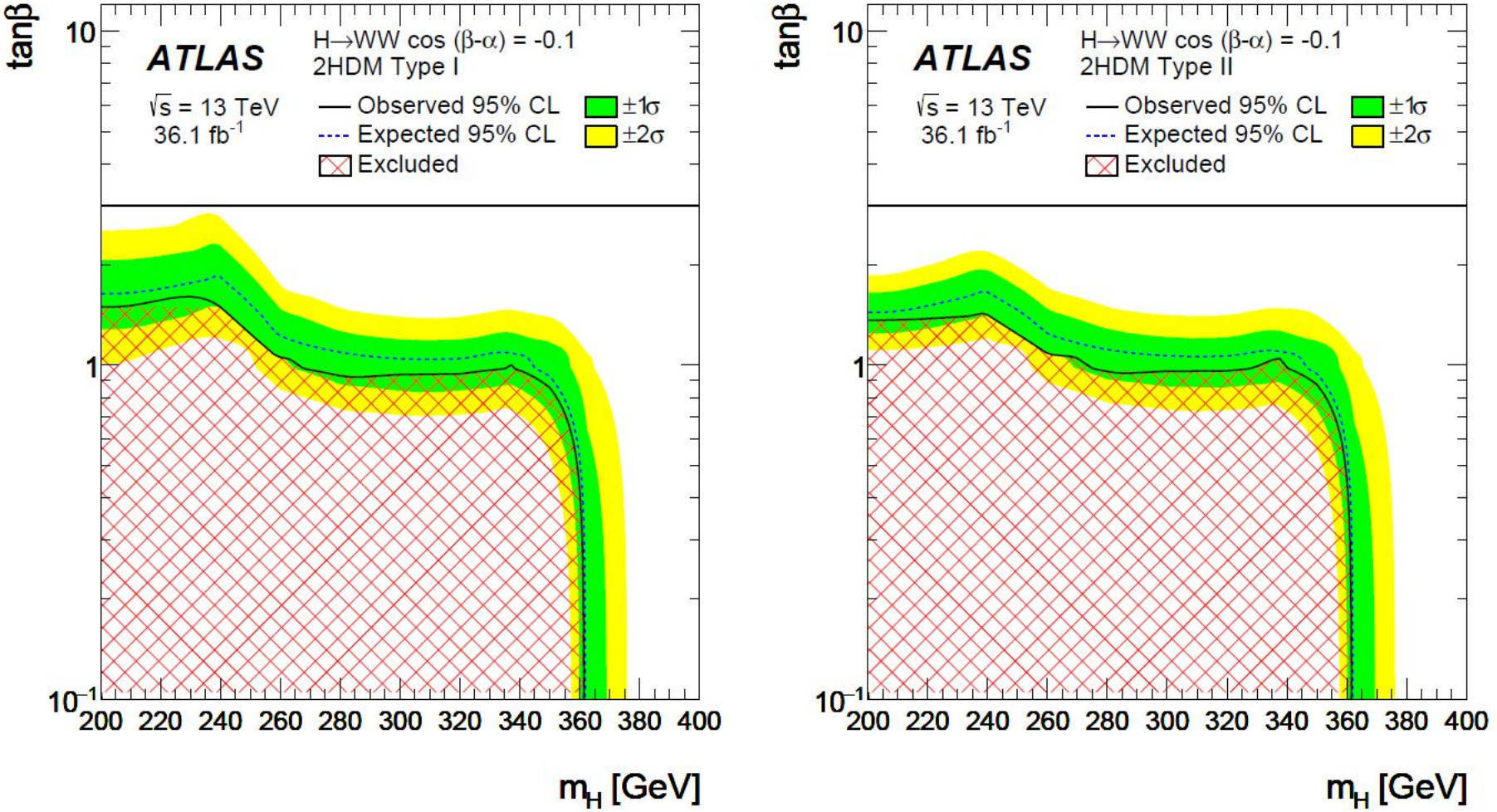


Figure 8: Exclusion contours at 95% CL in the plane of $\tan\beta$ and m_H for Type I (left) and Type II (right) 2HDM signals with $\cos(\beta - \alpha) = -0.1$. The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit and the hatched regions are excluded. The other heavy Higgs boson states A and $H^{\pm}$ are assumed to have the same mass as H.

Limits for other models

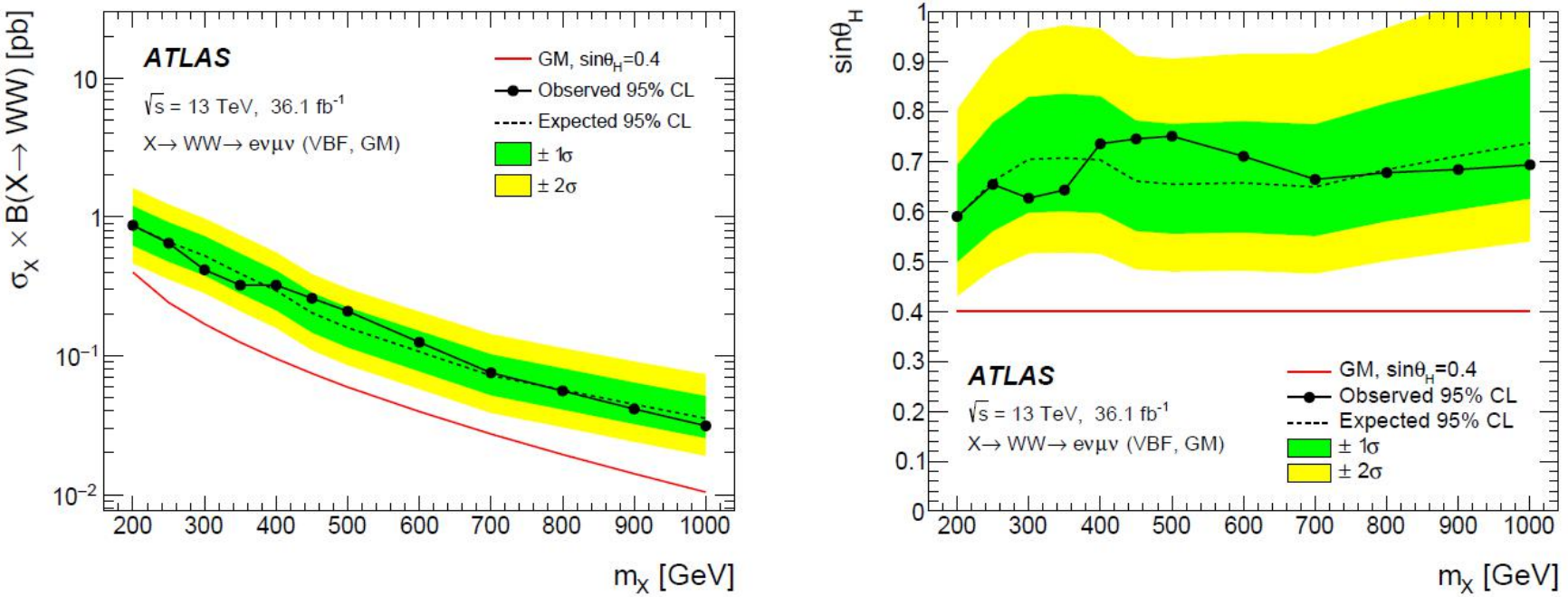


Figure 10: Upper limits at 95% CL on the resonance production cross section times branching fraction $\sigma_X \times B(X \rightarrow WW)$ (left) and on $\sin\theta_H$ (right) in the $e\nu\mu\nu$ channel, for a GM signal. The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit. The full curves without dots correspond to the predicted theoretical cross section and the model parameter used in the benchmark model, respectively.

Event yields in ggF regions

- Post-fit event yields
- Numbers are rounded by PDG rules

	SR_{ggF}	Top CR_{ggF}	WW CR_{ggF}
WW	11 500 ± 800	820 ± 120	3 360 ± 220
Top quark	11 800 ± 600	52 550 ± 330	2 610 ± 180
Z/γ^*	1 420 ± 110	111 ± 20	20.9 ± 2.0
W+jets	1 180 ± 320	710 ± 190	280 ± 70
VV	866 ± 34	101 ± 12	250 ± 11
Background	26 740 ± 170	54 290 ± 250	6 510 ± 80
Data	26 739	54 295	6 515

Uncertainties including both statistical and systematic uncertainties

Good agreement found between data and backgrounds

Event yields in VBF regions

- Post-fit event yields
- Numbers are rounded by PDG rules

	SR_{VBF1J}	SR_{VBF2J}	Top CR_{VBF}	WW CR_{VBF1J}
WW	390 ± 50	120 ± 26	61 ± 11	265 ± 32
Top quark	450 ± 50	391 ± 24	$5\,650 \pm 90$	167 ± 18
Z/γ^*	45 ± 11	24 ± 6	68 ± 19	74 ± 12
W+jets	52 ± 13	8.9 ± 2.5	91 ± 24	43 ± 11
VV	32 ± 7	16.6 ± 1.9	20 ± 9	38 ± 4
Background	972 ± 29	563 ± 22	$5\,890 \pm 80$	596 ± 22
Data	978	560	5 889	594

Uncertainties including both statistical and systematic uncertainties

Good agreement found between data and backgrounds

Event selection

SRs

SR_{ggF}	SR_{VBF1J}	SR_{VBF2J}
Preselection: $p_T^{\ell,lead} > 25$ GeV, $p_T^{\ell,sublead} > 25$ GeV, $m_{\ell\ell} > 10$ GeV, veto if $p_T^{\ell,other} > 15$ GeV		
$N_{b\text{-jet}} = 0$		
$\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$		
$m_{\ell\ell} > 55$ GeV		
$p_T^{\ell,lead} > 45$ GeV		
$p_T^{\ell,sublead} > 30$ GeV		
$\max(m_T^W) > 50$ GeV		
Inclusive in N_{jet} but excluding VBF1J and VBF2J phase space	$N_{jet} = 1$ $\lvert\eta_j\rvert > 2.4$, $\min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$	$N_{jet} \geq 2$ $m_{jj} > 500$ GeV, $\lvert\Delta y_{jj}\rvert > 4$

optimized to improve WW purity and reduce Z+jets, W+jets in CRs

optimized to improve sensitivity in SRs

CRs

WW CR_{ggF}	Top CR_{ggF}	WW CR_{VBF1J}	Top CR_{VBF}
Preselection: $p_T^{\ell,lead} > 25$ GeV, $p_T^{\ell,sublead} > 25$ GeV, $m_{\ell\ell} > 10$ GeV, veto if $p_T^{\ell,other} > 15$ GeV			
$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} \geq 1$
$\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$	$\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$	($\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$ or	–
$m_{\ell\ell} > 55$ GeV		$m_{\ell\ell} < 55$ GeV)	–
$p_T^{\ell,lead} > 45$ GeV		$p_T^{\ell,lead} > 25$ GeV	$p_T^{\ell,lead} > 25$ GeV
$p_T^{\ell,sublead} > 30$ GeV		$p_T^{\ell,sublead} > 25$ GeV	$p_T^{\ell,sublead} > 25$ GeV
$\max(m_T^W) > 50$ GeV		–	–
Excluding VBF1J and VBF2J phase space		VBF1J phase space	VBF1J and VBF2J phase space

Event selection

SRs

SR_{ggF}	SR_{VBF1J}	SR_{VBF2J}
Preselection: $p_T^{\ell,lead} > 25$ GeV, $p_T^{\ell,sublead} > 25$ GeV, $m_{\ell\ell} > 10$ GeV, veto if $p_T^{\ell,other} > 15$ GeV		
$N_{b\text{-jet}} = 0$ $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$ $m_{\ell\ell} > 55$ GeV $p_T^{\ell,lead} > 45$ GeV $p_T^{\ell,sublead} > 30$ GeV $\max(m_T^W) > 50$ GeV		
Inclusive in N_{jet} but excluding VBF1J and VBF2J phase space	$N_{jet} = 1$ $\lvert\eta_j\rvert > 2.4$, $\min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$	$N_{jet} \geq 2$ $m_{jj} > 500$ GeV, $\lvert\Delta y_{jj}\rvert > 4$

VBF 1J phase space

VBF 2J phase space

CRs

WW CR_{ggF}	Top CR_{ggF}	WW CR_{VBF1J}	Top CR_{VBF}
Preselection: $p_T^{\ell,lead} > 25$ GeV, $p_T^{\ell,sublead} > 25$ GeV, $m_{\ell\ell} > 10$ GeV, veto if $p_T^{\ell,other} > 15$ GeV			
$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} \geq 1$
$\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$	$\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$	($\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$ or $m_{\ell\ell} < 55$ GeV)	–
$m_{\ell\ell} > 55$ GeV			–
$p_T^{\ell,lead} > 45$ GeV		$p_T^{\ell,lead} > 25$ GeV	$p_T^{\ell,lead} > 25$ GeV
$p_T^{\ell,sublead} > 30$ GeV		$p_T^{\ell,sublead} > 25$ GeV	$p_T^{\ell,sublead} > 25$ GeV
$\max(m_T^W) > 50$ GeV		–	–
Excluding VBF1J and VBF2J phase space		VBF1J phase space	VBF1J and VBF2J phase space

inversed cuts

loose cuts

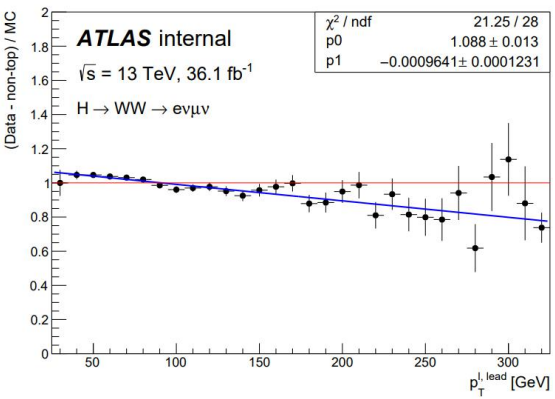
MC corrections

- All corrections to MC samples that considered in the analysis are shown below:
  - top leading lepton pt (in-situ) reweighting in ggF SR and CRs
  - qq→WW Sherpa-to-Matrix correction applied in ggF SR and WW CR
  - gg→WW NLO k-factor: 1.7 (60% uncertainty quoted)
  - ggF NWA signal Powheg-to-MadGraph reweighting in VBF SRs

- More details in backup slides

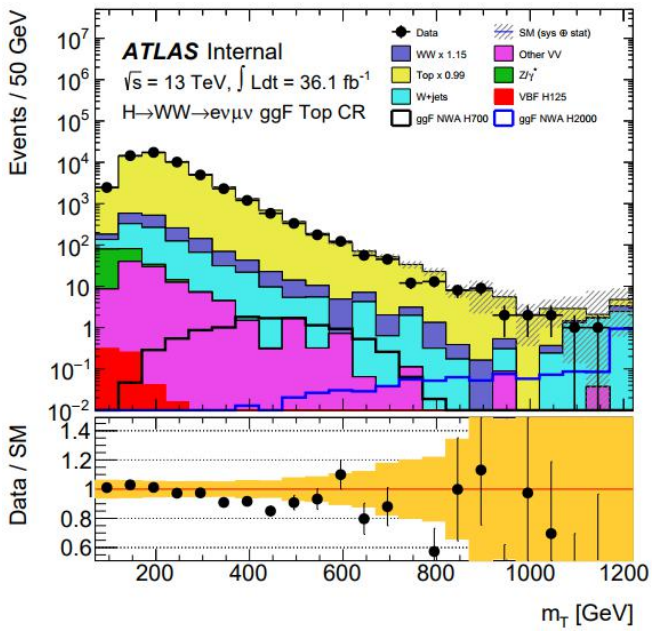
Top leading lepton pt reweighting

- The reweighting was applied only for ggF category

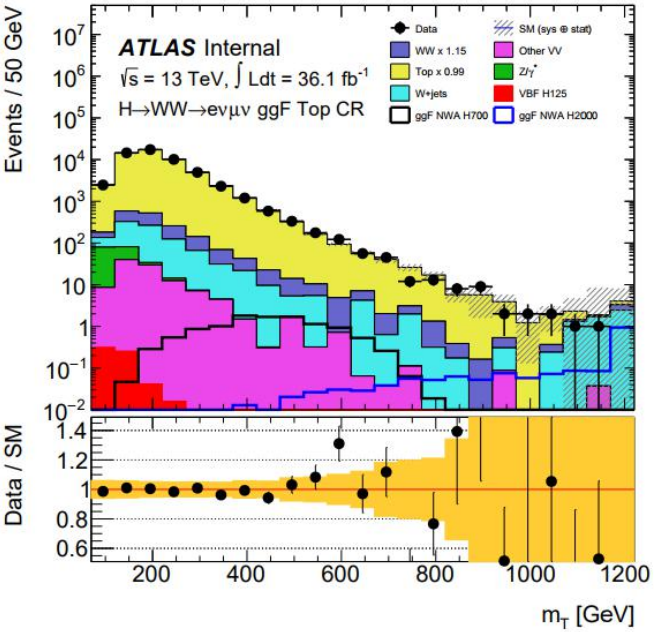


reweighting fit function

Before reweighting



After reweighting

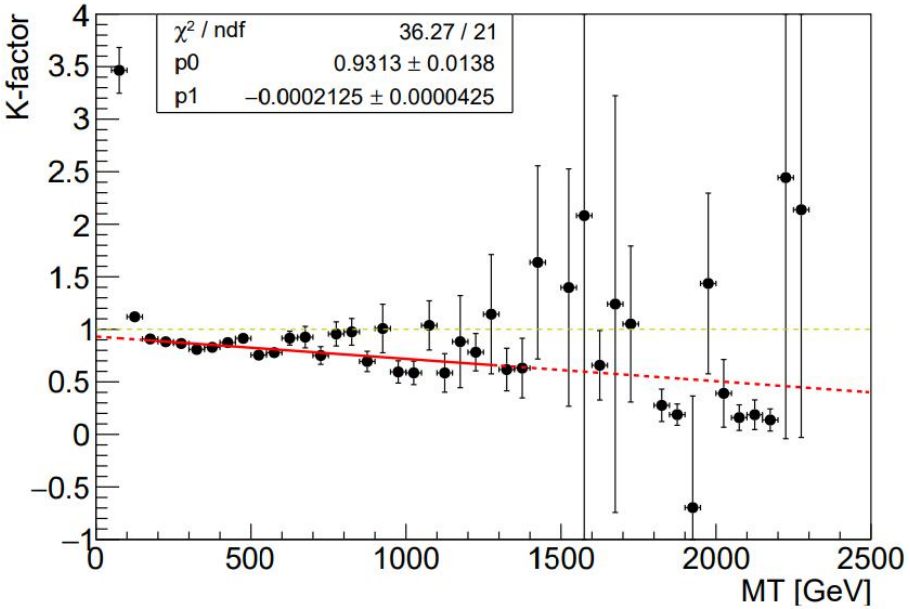


m_T in ggF Top CR

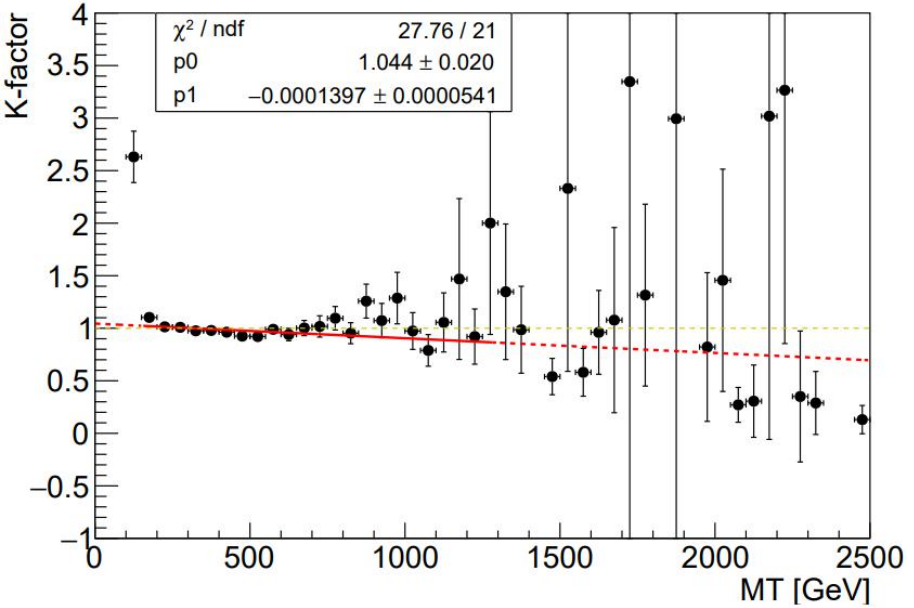
All other distributions also checked and found to have better agreement between data and MC after reweighting

WW Sherpa-to-Matrix correction

- Sherpa 2.2.1 (currently used) qq→WW is not fully a NLO sample
- A reweighting to Matrix NNLO calculation + NLO EW correction is applied to improve the prediction
  - fit performed only in the bulk m_T range
- The total uncertainty on the correction considered to be the 100% of the correction (±50% assigned for up and down)



ggF SR



ggF WW CR

W+jets estimation

- Using data-driven method based on "fake-factor" (FF), same as SM HWW coupling analysis. Fake-factors derived using di-jets samples.

$$
\begin{aligned}
N_{\text{id+id}}^{W+\text{jets}} &= N_{\text{id+anti-id}}^{W+\text{jets}} \times \text{FF} \\
&= (N_{\text{id+anti-id}} - N_{\text{id+anti-id}}^{\text{EW}}) \times \frac{N_{\text{id}}}{N_{\text{anti-id}}}
\end{aligned}
$$

- FFs are dependent on lepton flavour, pt and eta. FFs shown below as an example