Search for heavy resonances in the $X \to WW \to e\nu\mu\nu$ channel with the ATLAS detector at the LHC

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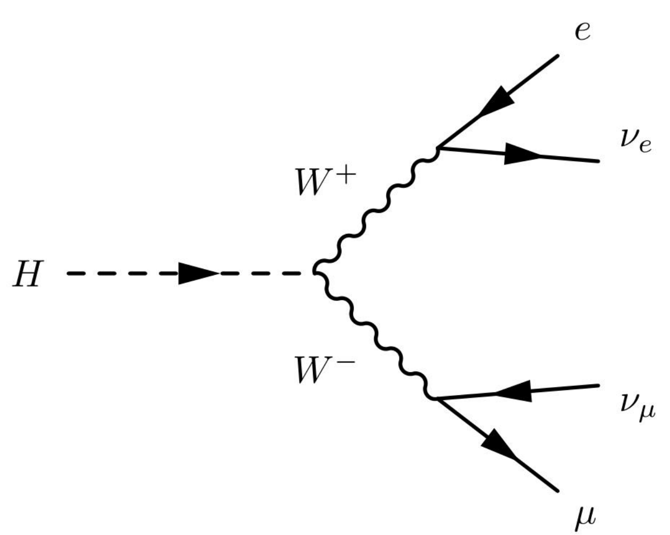
Outline

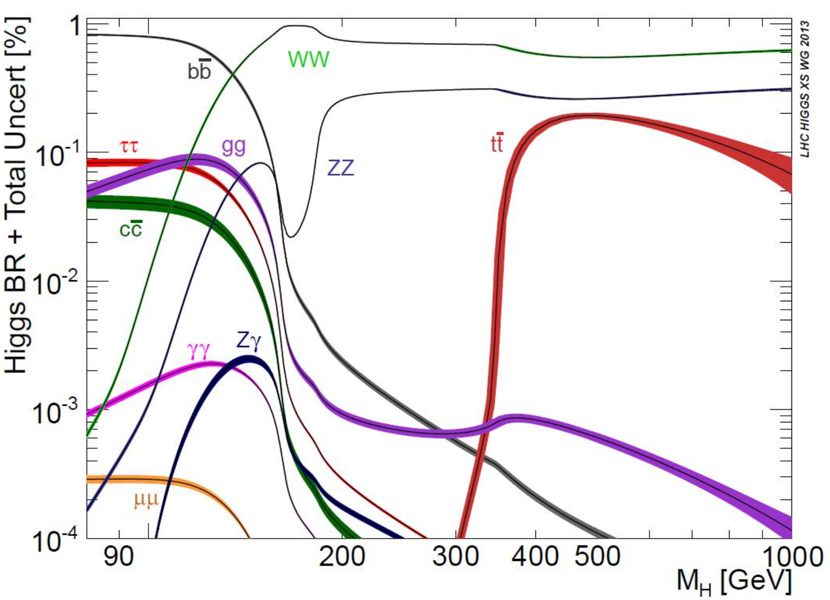
- Introduction
- Signal models
- Event selection optimisation strategy
- The $X \rightarrow WW \rightarrow e\nu\mu\nu$ analysis
- Results
- Conclusion

Introduction

- Full 2015+2016 datasets (36.1 fb^{-1}) @ 13 TeV used
- The anaysis used the $X \rightarrow WW \rightarrow e\nu\mu\nu$ channel to search for a heavy resonance *X* for the reasons:
  - The *WW* decay channel is generally very sensitive to various models for its high branching ratio
  - The eμ final state provides most of the sensitivity of the search, whilst in the ee and μμ final states, there is significantly larger Drell-Yan background

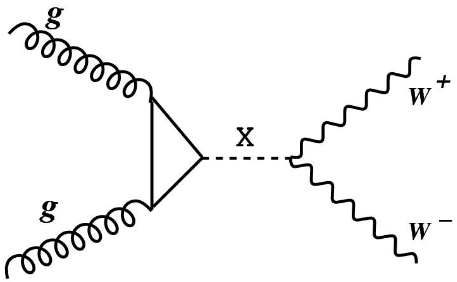


SM-like Higgs decay branching ratio

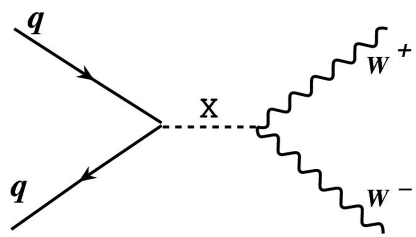


Benchmark signal models

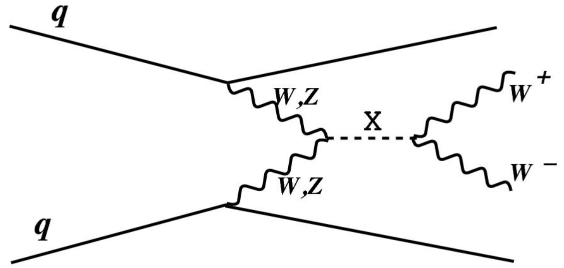
- Production modes considered for signals in the search



gluon-gluon fusion (ggF)



quark-antiquark annihilation (qqA)



vector-boson fusion (VBF)

- Benchmark signal models considered for interpretations

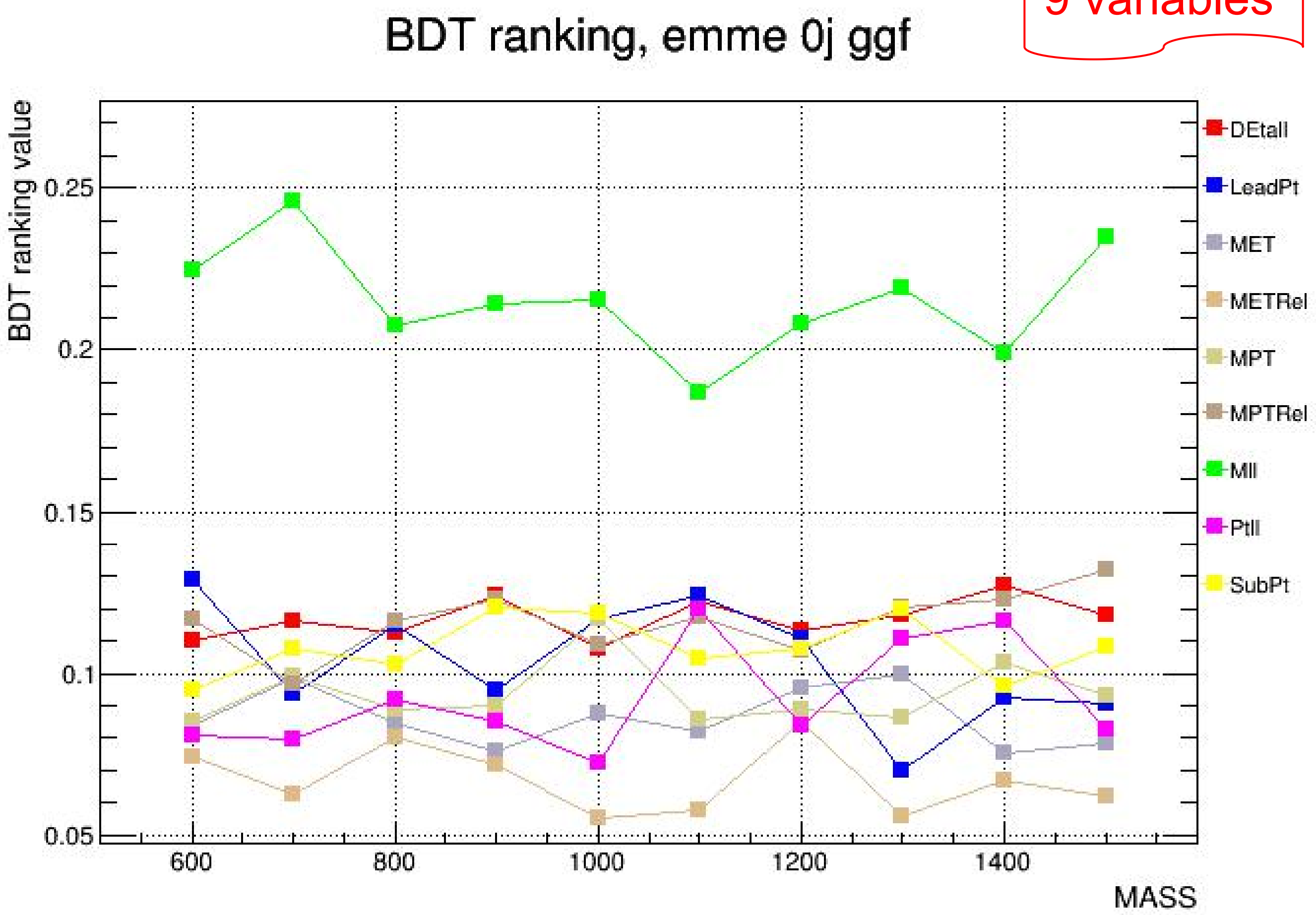
Model	Resonance spin	Production mode		
		ggF	qqA	VBF
Narrow Width Approximation (NWA)	Spin-0	x		x
Two Higgs Doublet Models (2HDM)	Spin-0	x		x
Large Width Assumption (LWA)	Spin-0	x		x
Georgi-Machacek model (GM)	Spin-0			x
Heavy Vector Triplet (HVT)	Spin-1		x	x
Bulk Randall-Sundrum (RS) graviton	Spin-2	x		
Effective Lagrangian Model (ELM)	Spin-2			x

Event selection optimisation

- A simple and general optimisation method developed

Step 1: Select the most discriminant variables based on the BDT training

9 variables



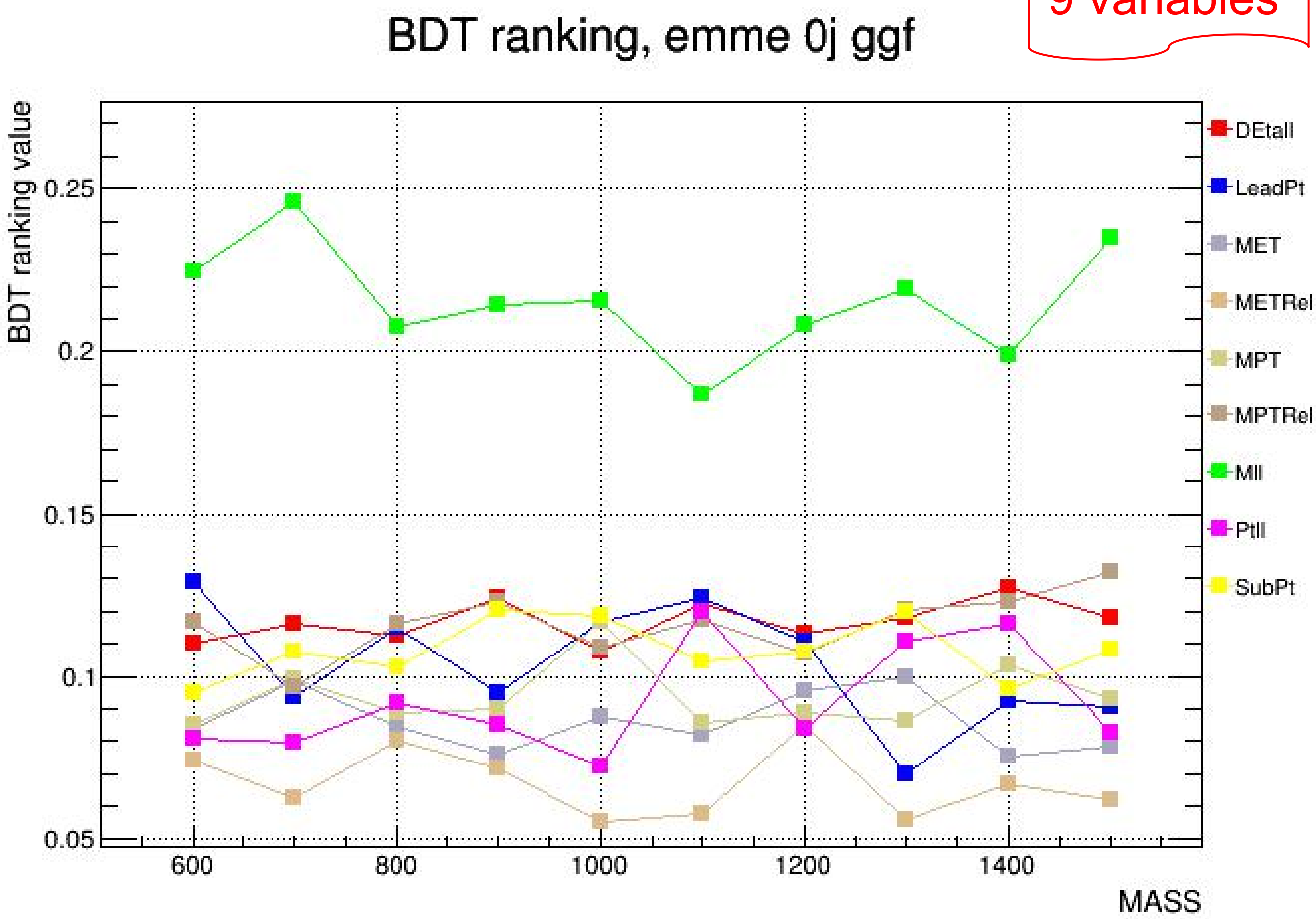
Event selection optimisation

- A simple and general optimisation method developed

Step 1: Select the most discriminant variables based on the BDT training

9 variables

Average ranking		
Var.	Value	Rel.
Mll	0.216	100%
DEtall	0.117	54%
MPTRel	0.116	54%
SubPt	0.108	50%
LeadPt	0.104	48%
MPT	0.094	43%
Ptll	0.092	43%
MET	0.086	40%
METRel	0.067	31%



Event selection optimisation

- A simple and general optimisation method developed

Step 1: Select the most discriminant variables based on the BDT training (Rel. ≥ 40%)

8 variables

Average ranking		
Var.	Value	Rel.
Mll	0.216	100%
DEtall	0.117	54%
MPTRel	0.116	54%
SubPt	0.108	50%
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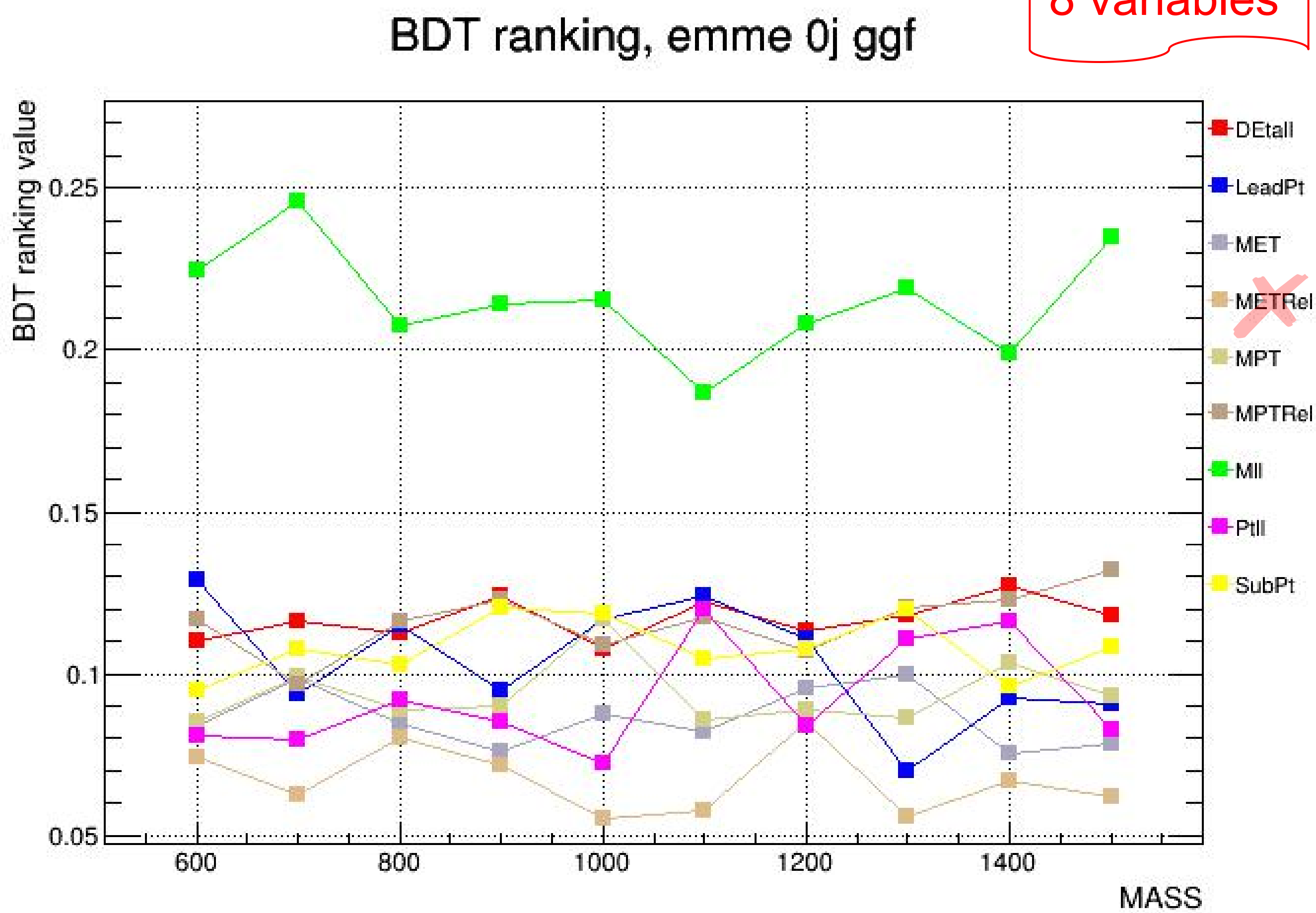
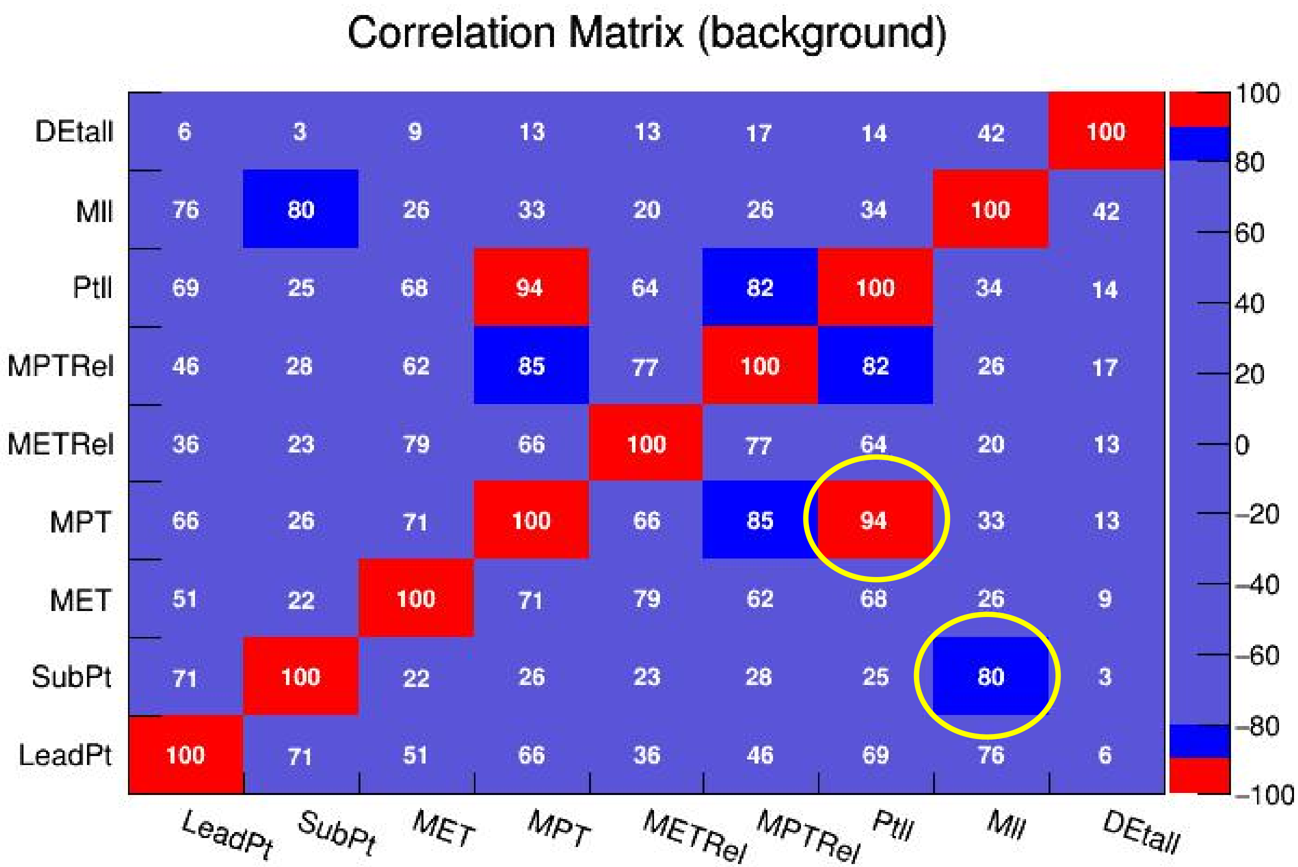


Event selection optimisation

Remove the less discriminant variables if they are highly correlated with the others

8 variables



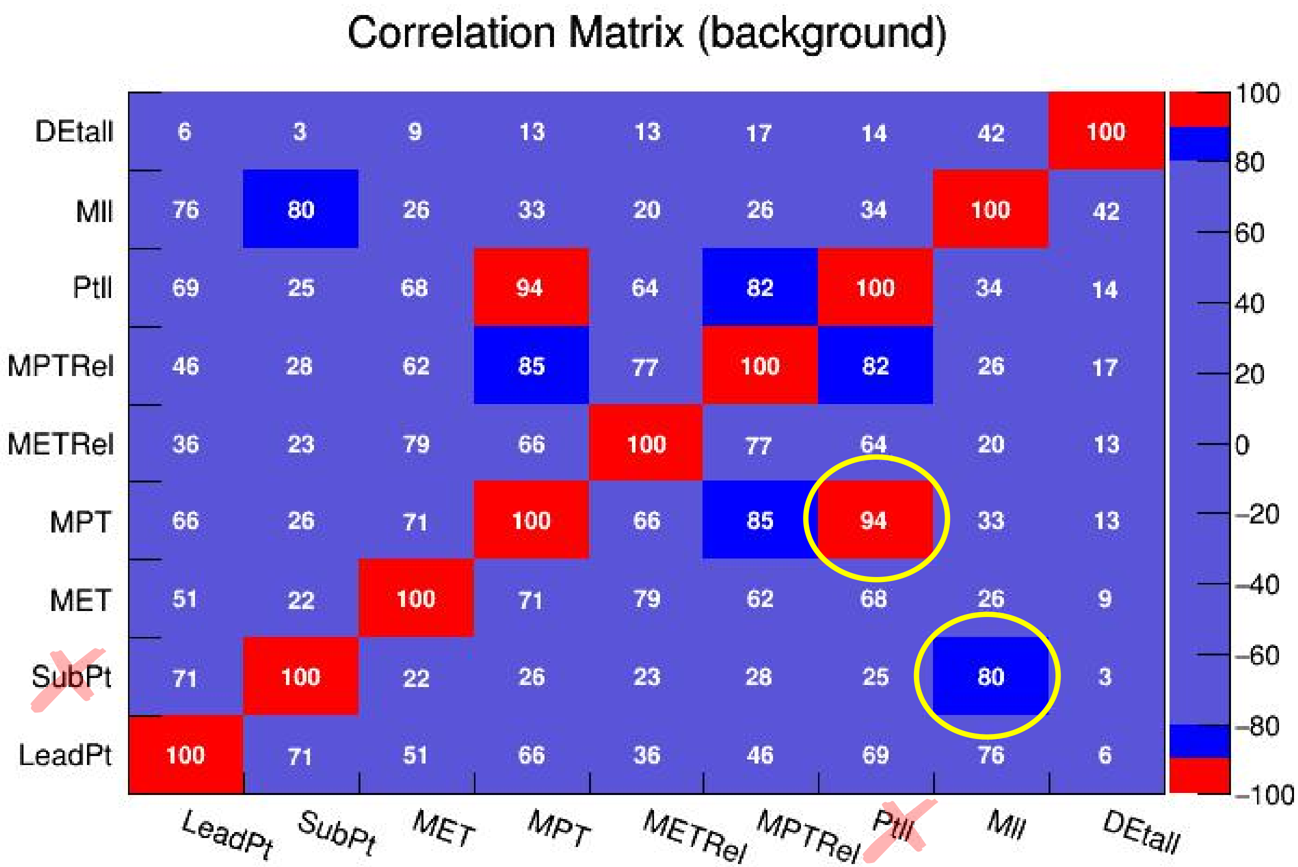
Highly correlated (in both signal and background):

- **MPT - Ptll**
- **Mll - SubPt**

Event selection optimisation

Remove the less discriminant variables if they are highly correlated with the others (Corr. ≥ 80%)

6 variables



Highly correlated (in both signal and background):

- **MPT** - Ptll
- **Mll** - SubPt

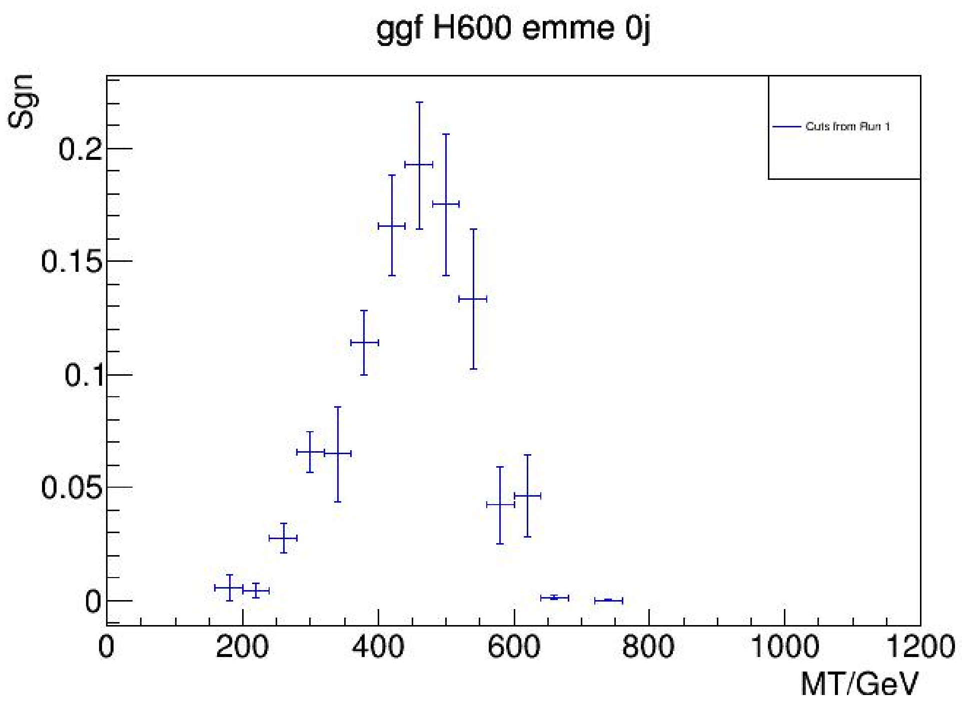
Event selection optimisation

Step 2: Choose cut values by maximising the signal significance

- Significance calculation

$$Sgn = \sqrt{2\left[(n_S + n_B)\ln(1+\frac{n_S}{n_B}) - n_S\right]}$$

$$RSS = \sqrt{\sum_{i}^{N_{bins}} Sgn_i^2}$$

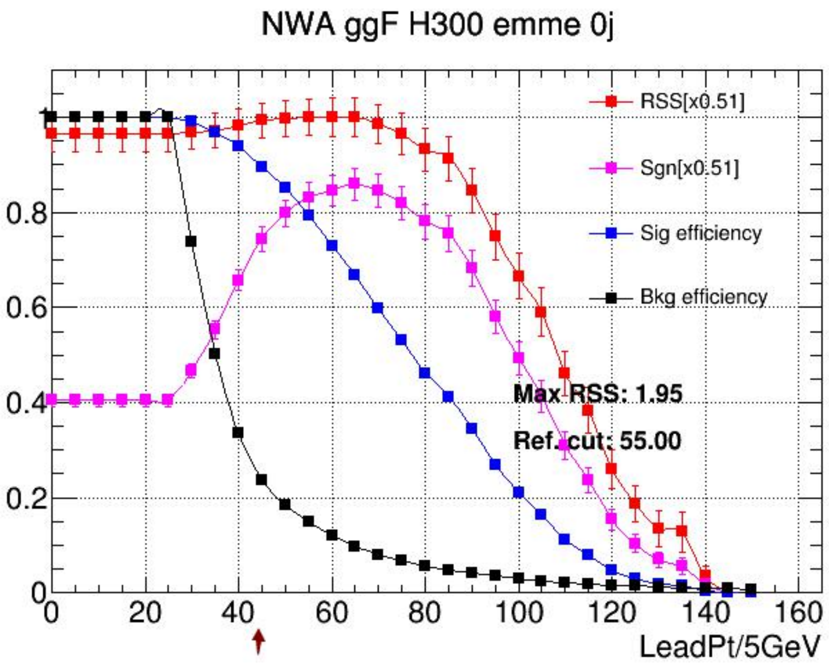


Sgn (Significance): a general definition (suits low statistics)

RSS (Root Squared Significance): defined using MT distribution (by default 1-D)

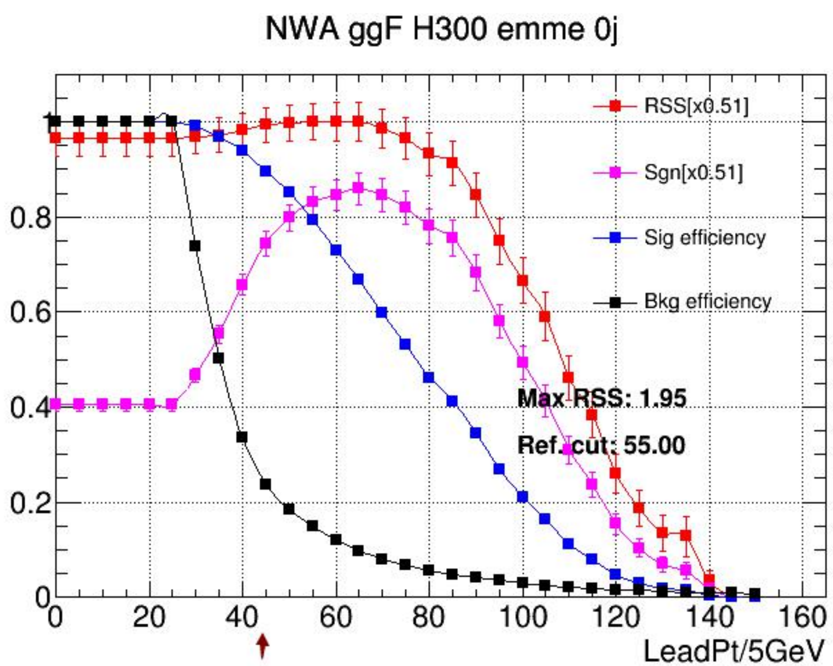
Event selection optimisation

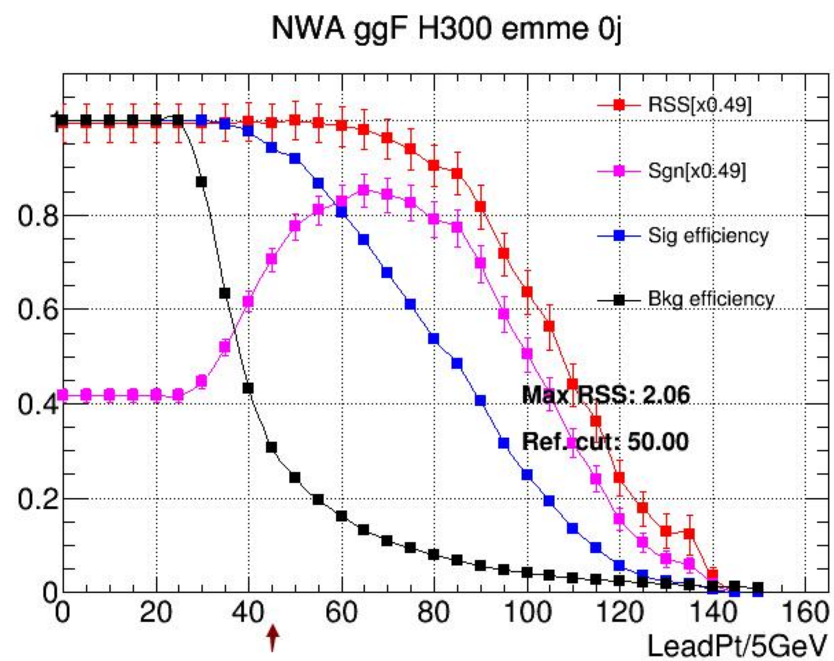
- Scanning on cut values (**LeadPt** plots shown only as an **example**)
    1. Individual scan (plot on the left): other optimised cuts **not** applied



Event selection optimisation

- Scanning on cut values (**LeadPt** plots shown only as an **example**)
  1. Individual scan (plot on the left): other optimised cuts **not** applied
  2. N-1 scan (plot on the right): other optimised cuts applied

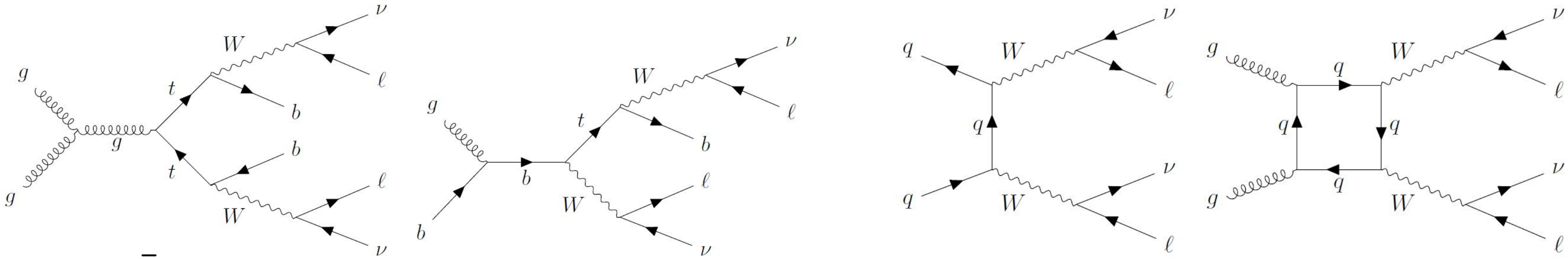




➢ Need also an iteration of the N-1 scan (usually repeat 1~2 times until cuts fixed)

Background estimation

- Top and WW, the dominant backgrounds, MC (shape and normalisation) determined from the simultaneous fit to data



$t\bar{t}$ tW $qq \to WW$ $gg \to WW$

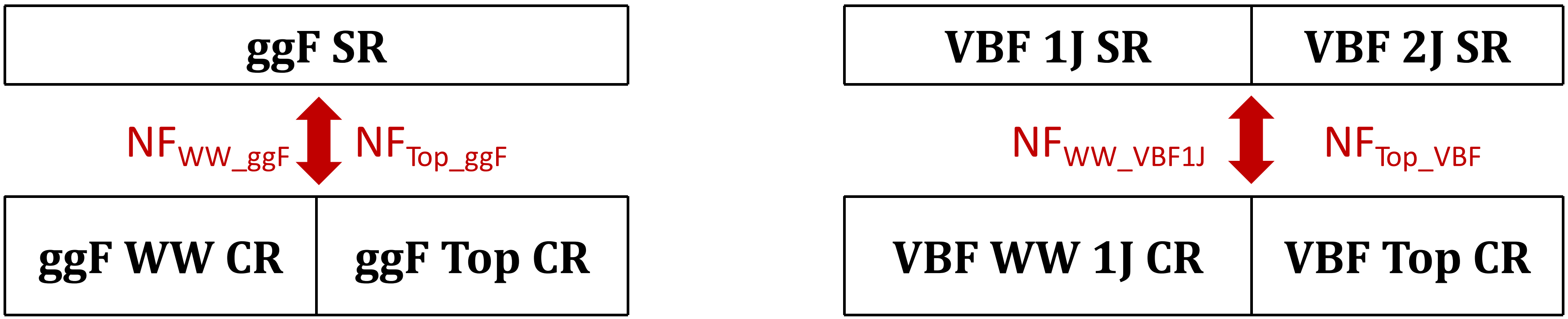
- Z+jets, non-WW diboson and H125, with small contributions, using MC prediction

- W+jets, estimated using data-driven method based on “fake-factor” (FF)

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

Event categorisation

- Event categorization
  - **ggF** category (quasi-inclusive ggF, VBF phase spaces excluded)
  - **VBF** categories



Physics results obtained from a simultaneous fit to all SRs and CRs

- The categorisation is defined due to the special topology of the VBF signal production
- 1J requires exactly 1 jet, while 2J requires at least 2 jets
- NF denoted normalisation factor for MC
- No VBF 2J CR for WW, due to limited statistics

Event selection

SRs

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

ggF phase space

VBF 1J phase space

VBF 2J phase space

CRs

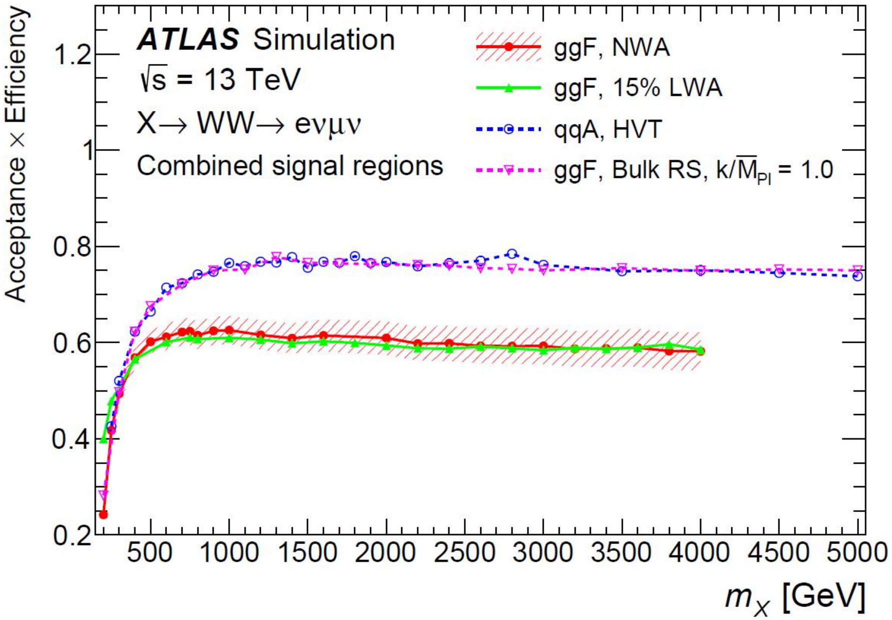
WW CR_{ggF}	Top CR_{ggF}	WW CR_{VBF1J}	Top CR_{VBF}
Preselection: $p_T^{\ell,\text{lead}} > 25$ GeV, $p_T^{\ell,\text{sublead}} > 25$ GeV, $m_{\ell\ell} > 10$ GeV, veto if $p_T^{\ell,\text{other}} > 15$ GeV			
$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} \geq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

inversed cuts

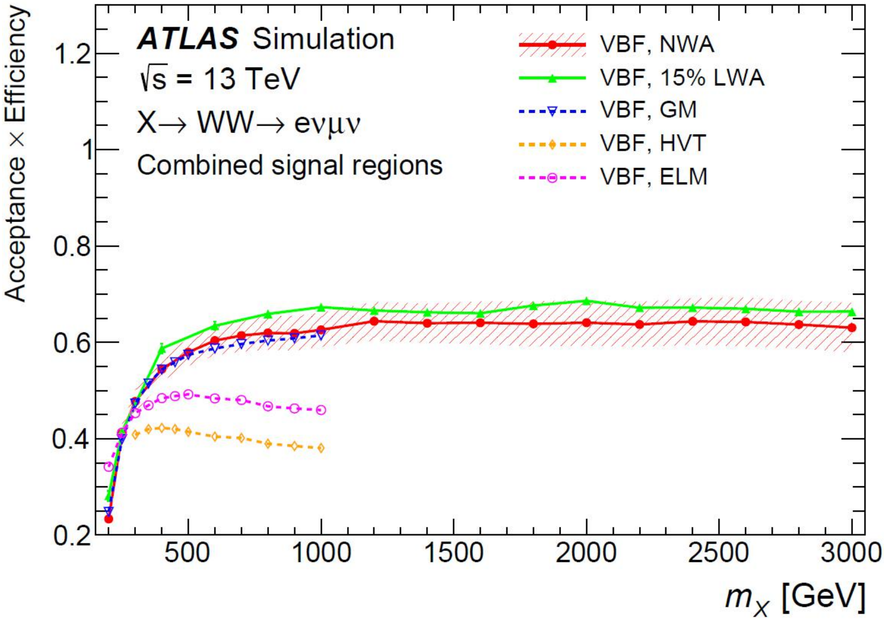
Signal acceptance

- To simplify the analysis, the event selection is based on the optimisation for the NWA and LWA signals around m_H = 600 GeV. The same selection applied to the other mass points and other signal models.
- Signal selection acceptance * efficiency in combined 3 SRs

Similar plots for separated 3 SRs could be found in the backup slides



ggF (qqA) signals

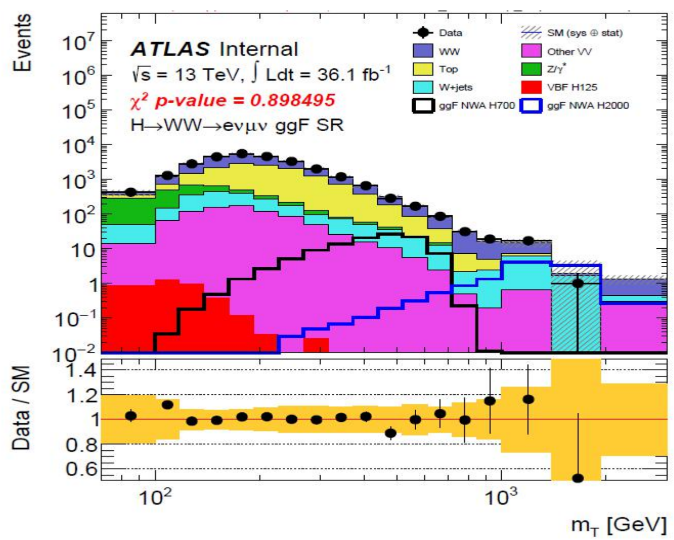


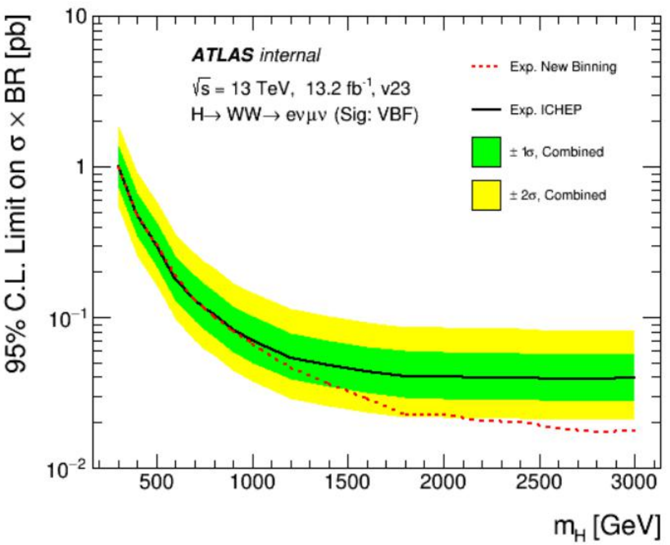
VBF signals

The difference between the models is expected, due to the different $|\Delta\eta_{ll}|$ distributions for the different spin states.

MT binning optimisation

- The old m_T binnings were not optimal,therefore the binning was optimized to maximise the signal sensitivity for all signals in the full mass range, in a similar way as in the event selection optimisation
- The new binning is mass-independent, defined to give a logMT distribution with the same bin size (except for the tails beyond [100 GeV, 1000 GeV] which have twice bin size)

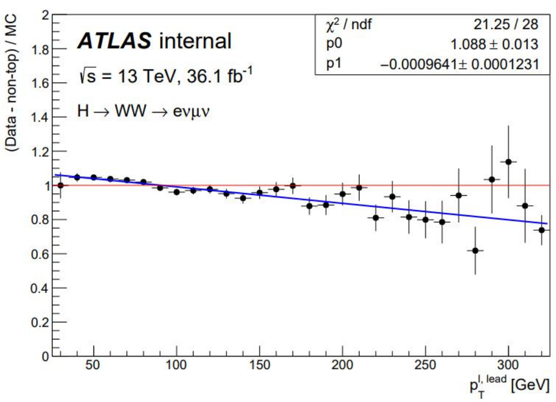




- The optimisation makes small difference at low masses, but improved the results at high masses significantly
- A cross-check with completely different optimisation method and mass-dependent binning shows similar results

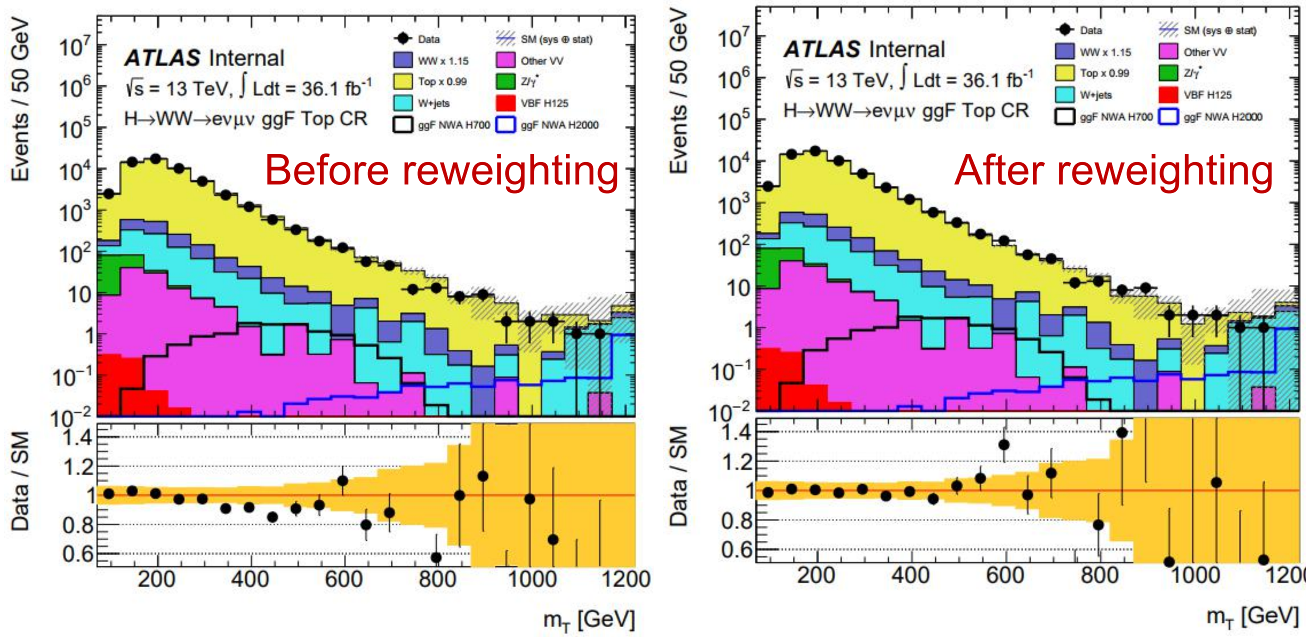
Top leading lepton pt reweighting

- A mismodelling found in the p_T^{lead} distribution in the ggF Top CR
- Thus an in-situ correction applied on top background



reweighting fit function

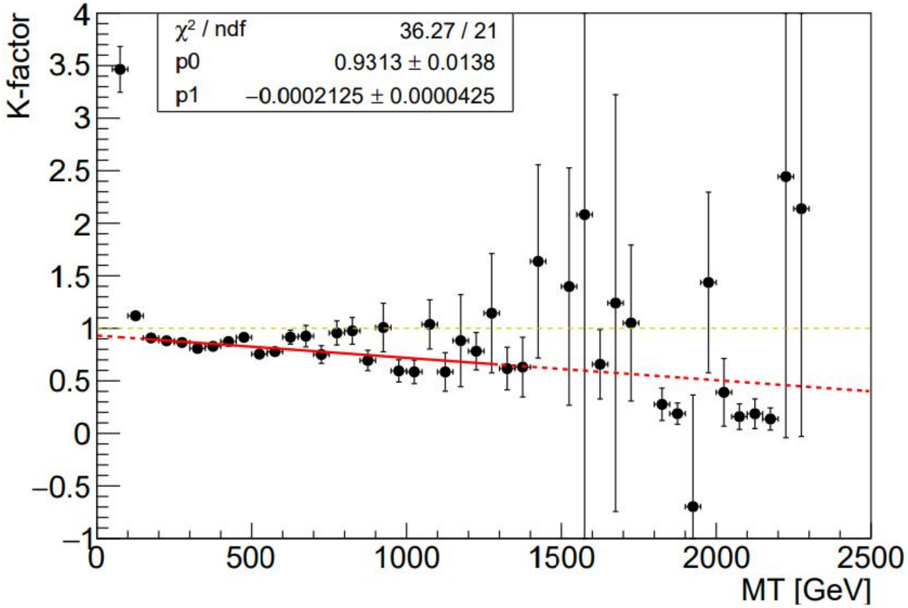
m_T in ggF Top CR



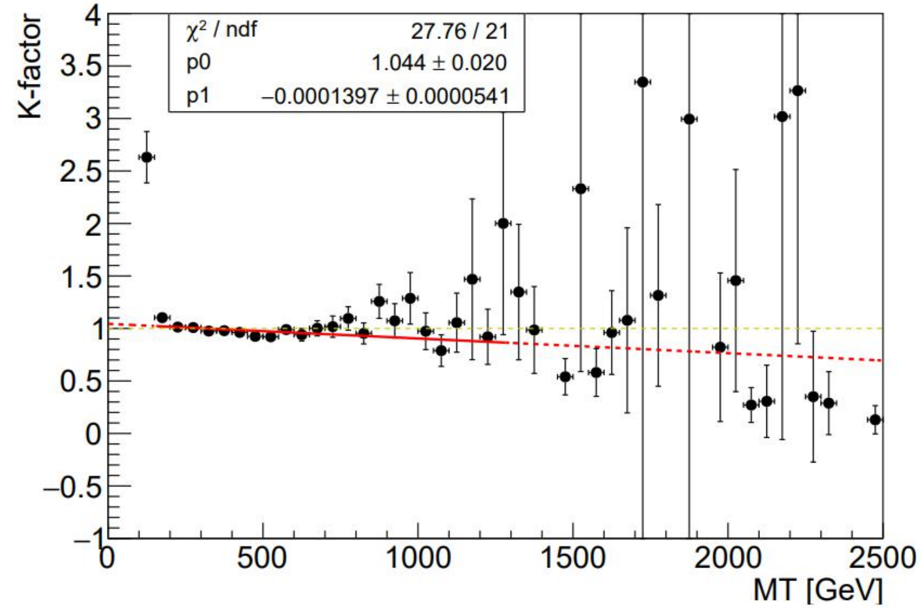
- The reweighting was applied only for ggF category
- All other distributions also checked and found to have better agreement between data and MC after reweighting

WW Sherpa-to-Matrix correction

- Sherpa 2.2.1 (used in the analysis) $qq \rightarrow WW$ 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

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

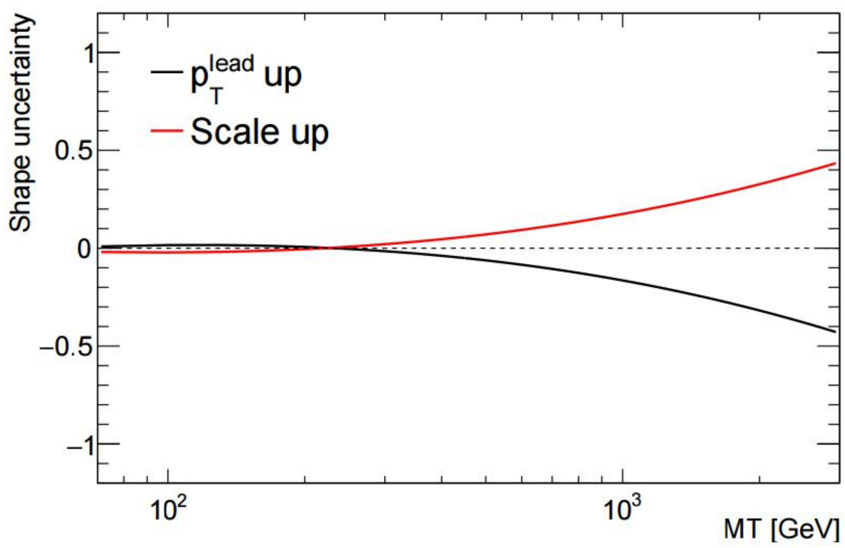
- WW

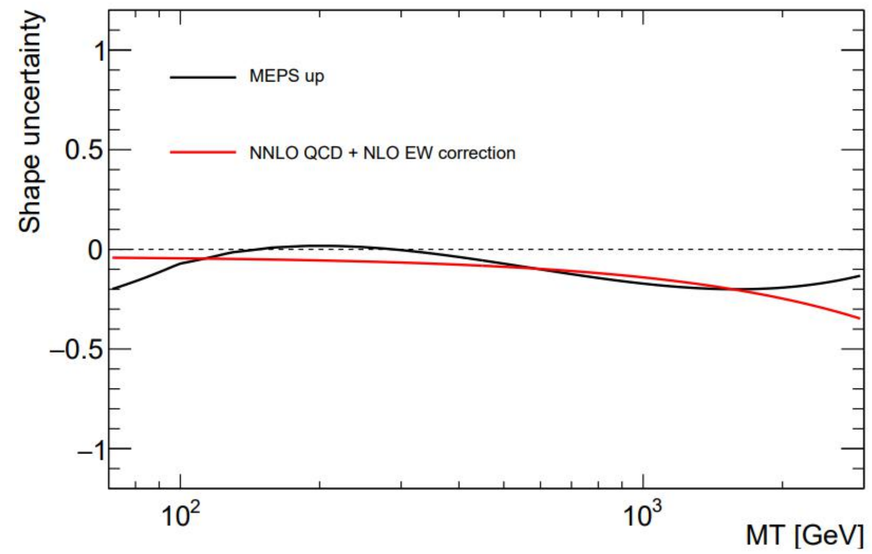
Source	Jet	Pile-up	ME+PS	μ_R	Resummation	PDF	Total
SR_{ggF}	1.2	1.8	2.4	1.7	3.1	2.7	5.5
SR_{VBF1J}	17	2.8	11	7.3	5.0	2.3	23
SR_{VBF2J}	18	3.1	38	18	1.4	2.1	47
WW CR_{ggF}	1.1	1.8	2.6	0.95	2.9	3.6	5.9
WW CR_{VBF1J}	16	4.5	12	11	2.3	2.8	23

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

Shape uncertainties

- All shape uncertainties that are considered in the analysis
  - Except for PDF uncertainties, shown in backup slides



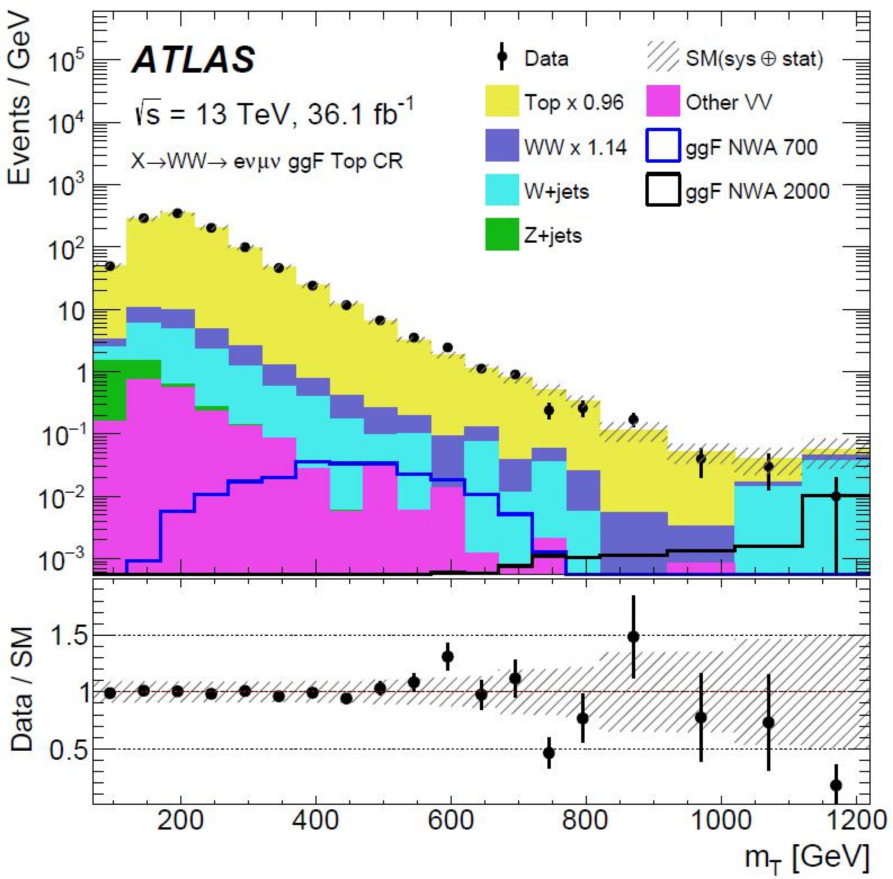


- Experimental shape uncertainties have been checked and found to be small and negligible

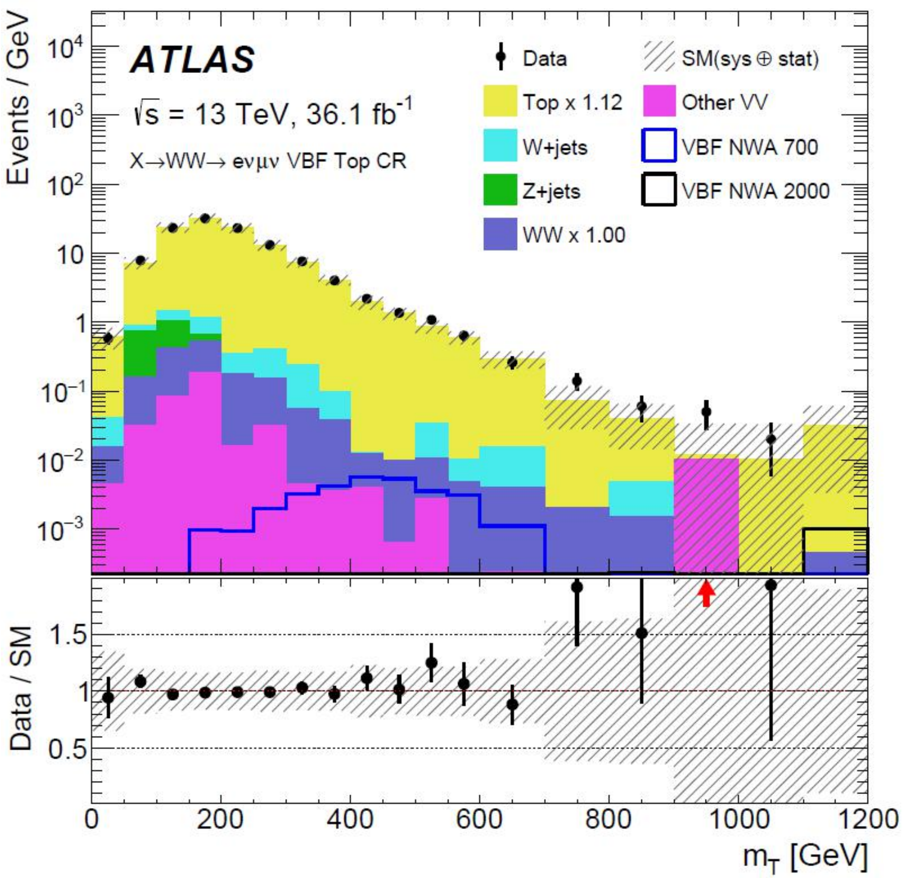
MT plots in Top CRs

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

ggF Top CR $\mathrm{NF}_{\mathrm{ggF}}^{\mathrm{top}} = 0.96 \pm 0.05$



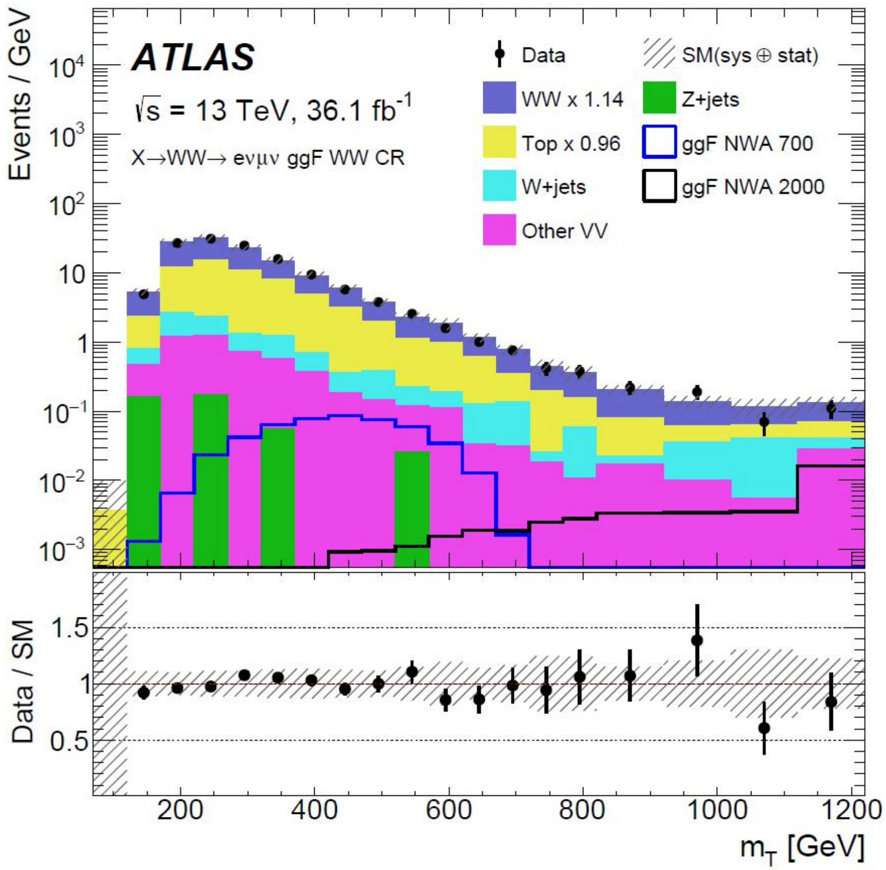
VBF Top CR $\mathrm{NF}_{\mathrm{VBF}}^{\mathrm{top}} = 1.12 \pm 0.1$



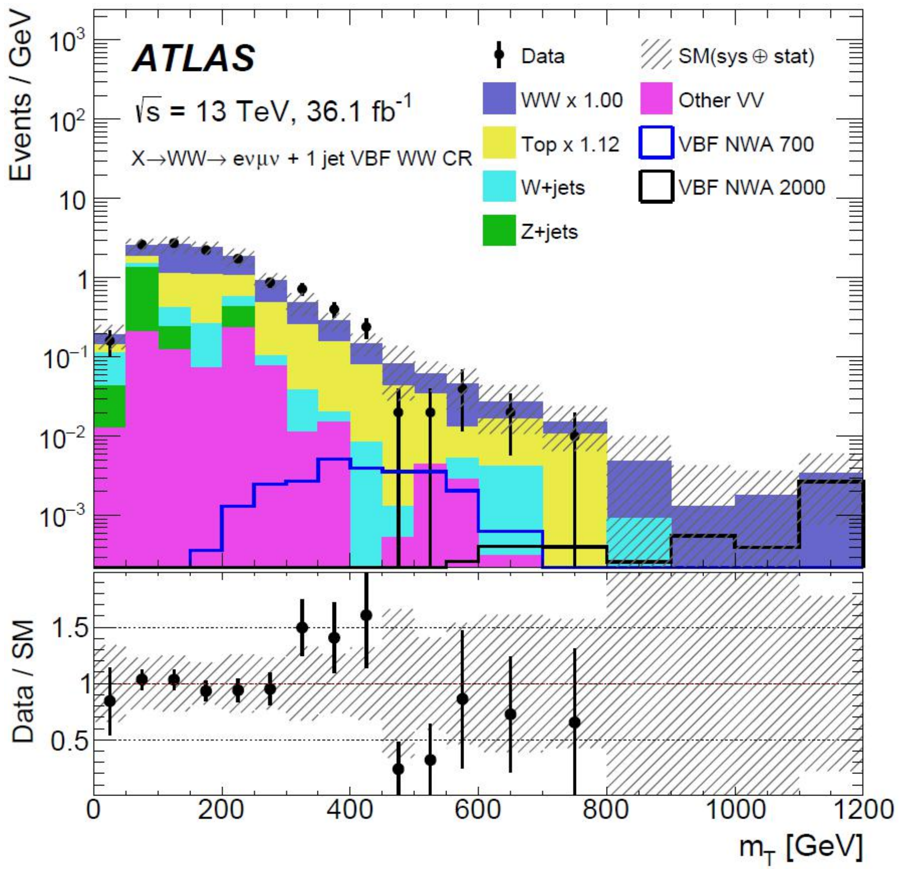
MT plots in WW CRs

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

ggF WW CR $\mathrm{NF}_{\mathrm{ggF}}^{\mathrm{WW}} = 1.14 \pm 0.09$



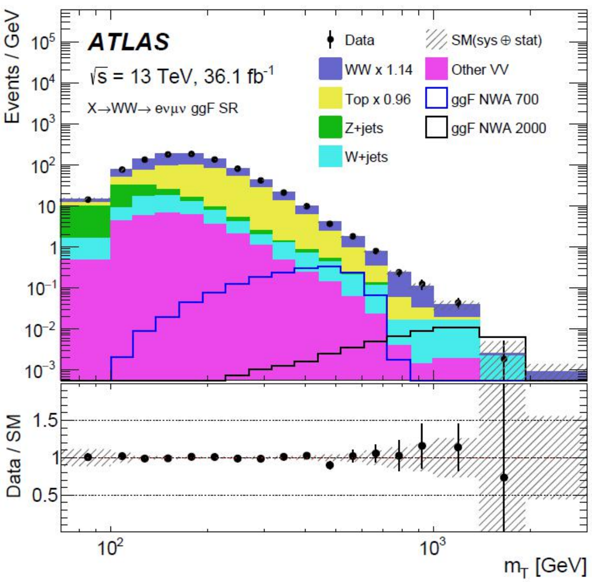
VBF 1J WW CR $\mathrm{NF}_{\mathrm{VBF,1J}}^{\mathrm{WW}} = 1.00 \pm 0.2$



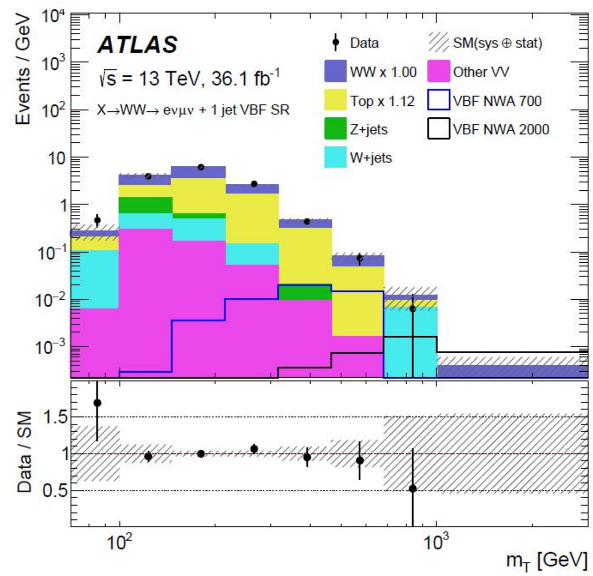
MT plots in SRs

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

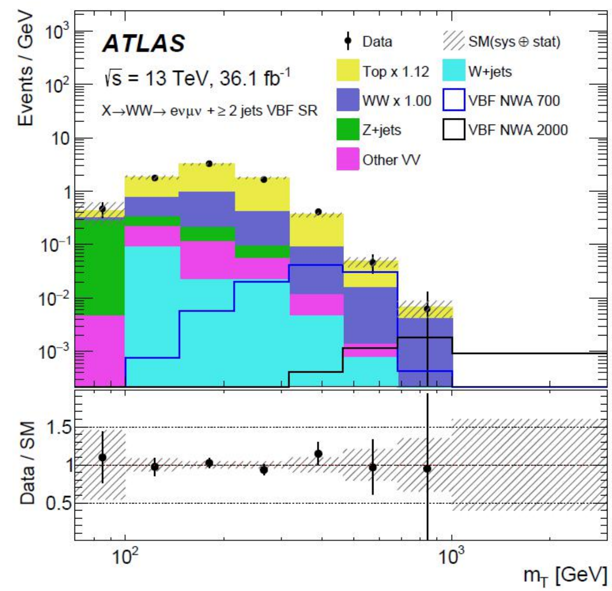
ggF SR



VBF 1J SR



VBF 2J SR



Post-fit NFs

$$\mathrm{NF}^{\mathrm{top}}_{\mathrm{ggF}} = 0.96 \pm 0.05$$

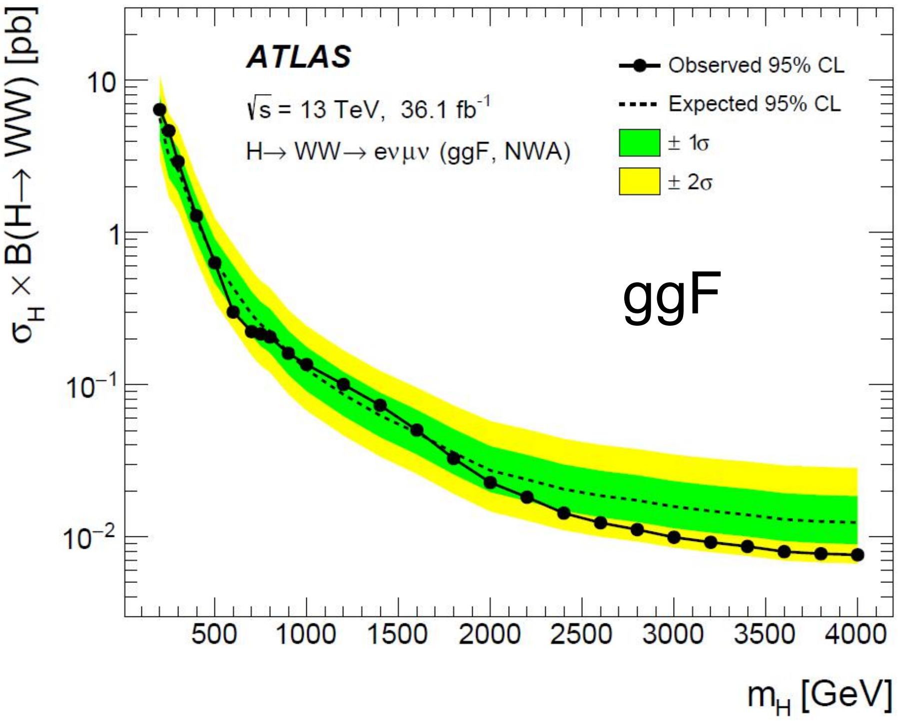
$$\mathrm{NF}^{\mathrm{WW}}_{\mathrm{ggF}} = 1.14 \pm 0.09$$

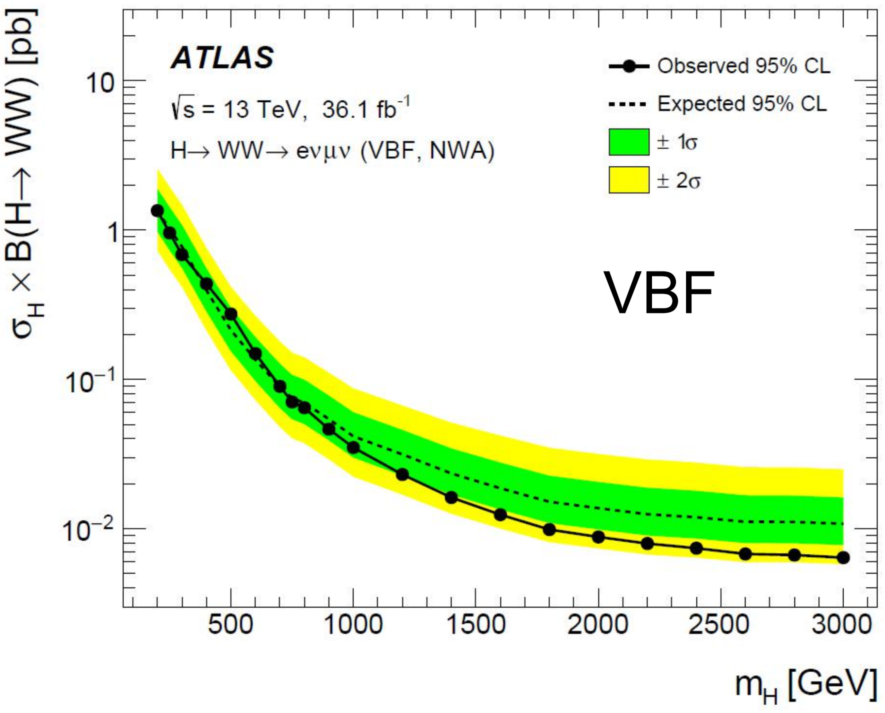
$$\mathrm{NF}^{\mathrm{top}}_{\mathrm{VBF}} = 1.12 \pm 0.1$$

$$\mathrm{NF}^{\mathrm{WW}}_{\mathrm{VBF,1J}} = 1.00 \pm 0.2$$

(stat. ⊕ sys.)

Limits for NWA

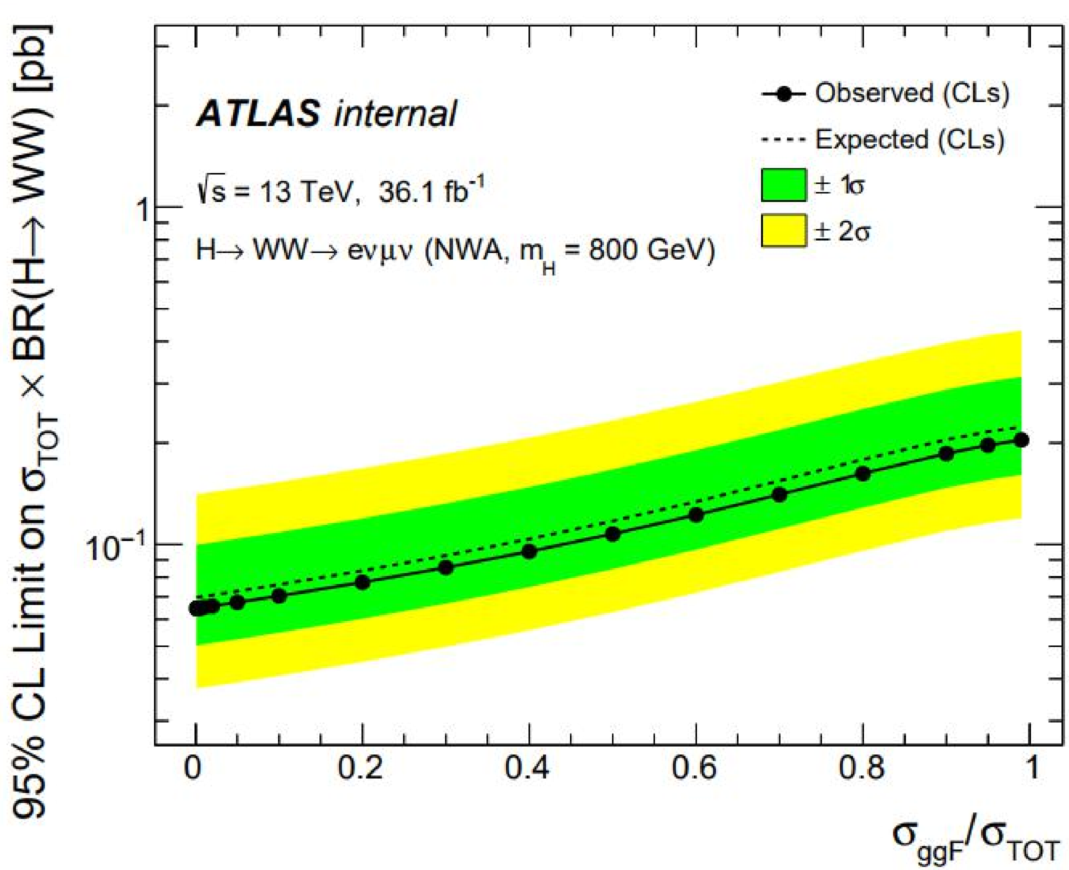




Limits [pb]	ggF	VBF
Lowest mass (200 GeV)	6.4	1.3
Highest mass	0.008 (4 TeV)	0.006 (3TeV)

Limits extension for NWA

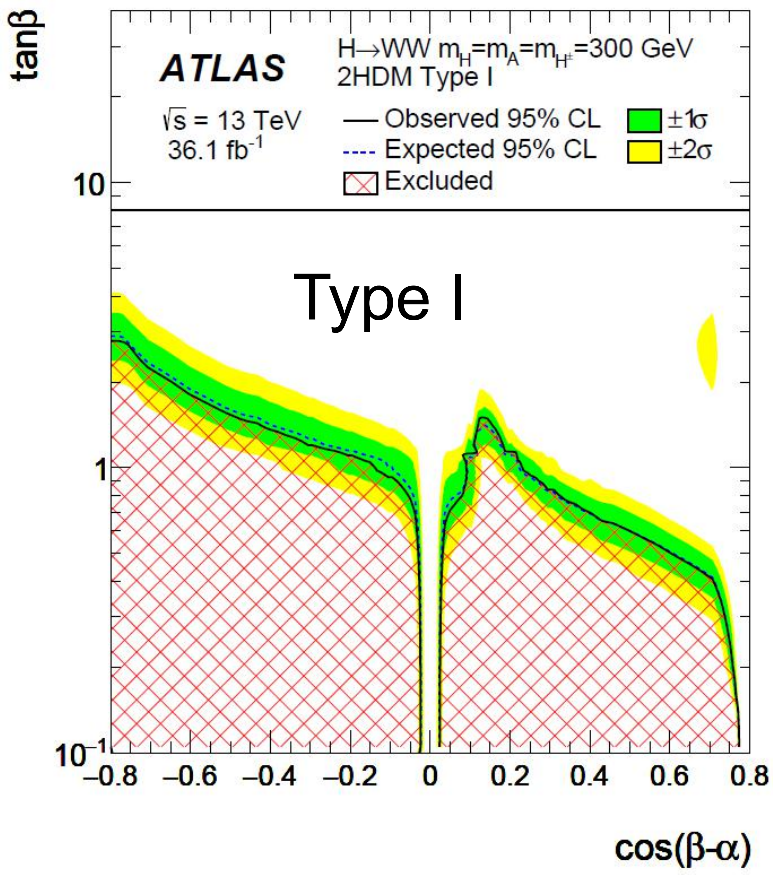
- Limits on "σ_{total} (ggF + VBF) * BR", as a function of "σ_{ggF} / σ_{total}"

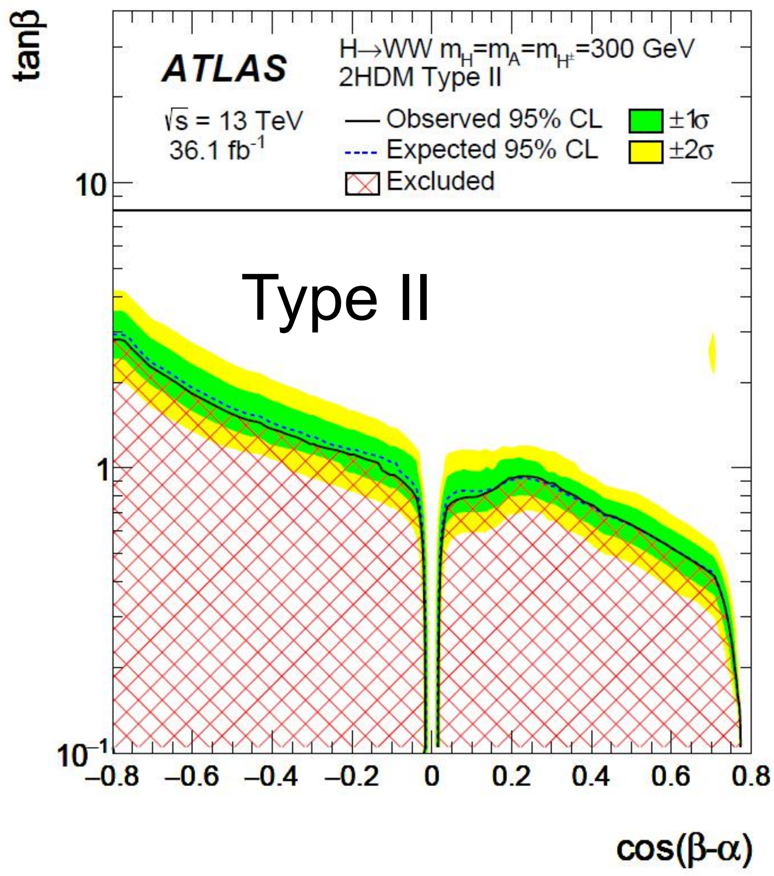


2HDM interpretation

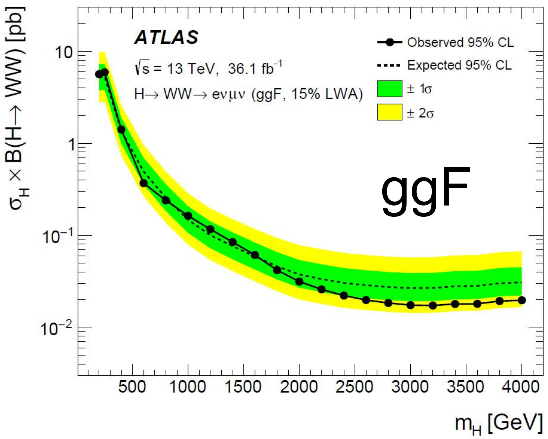
- The limits for NWA are further translated to exclusion contours in the 2HDM model for the phase space where NWA is valid

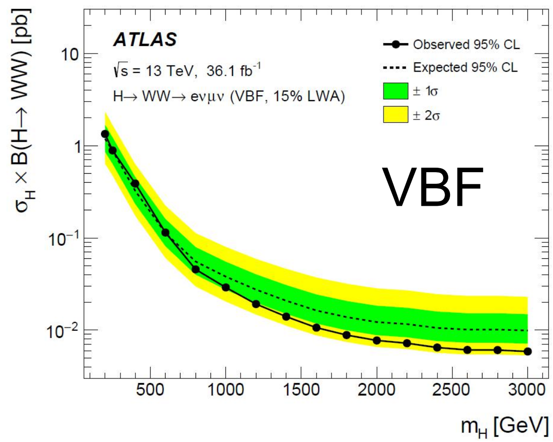
$$m_H = 300\,\mathrm{GeV}$$



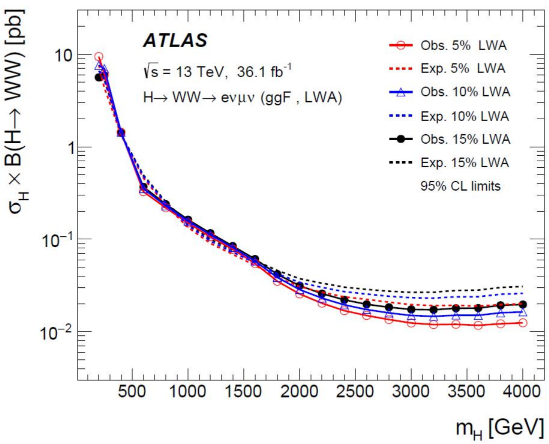


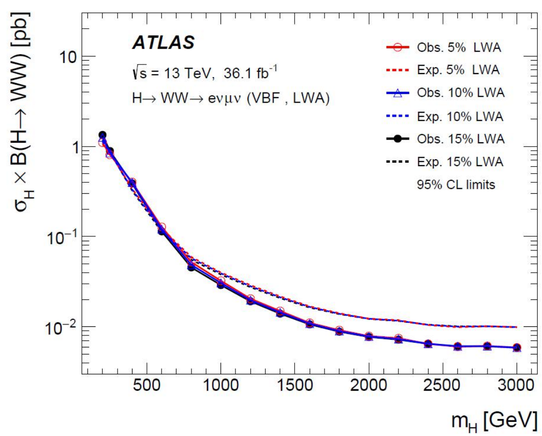
Limits for LWA





→ Width: 15%*m_H





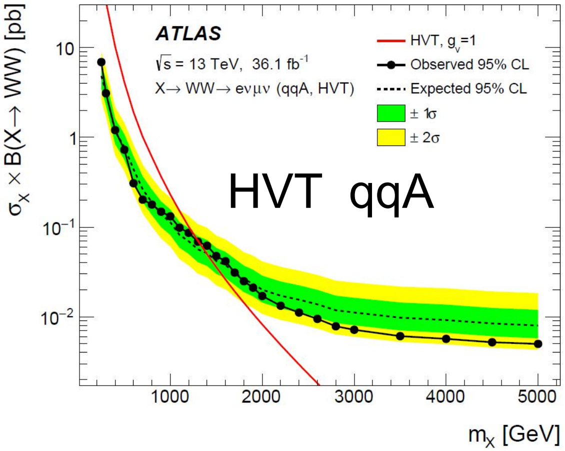
→ Widths:

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

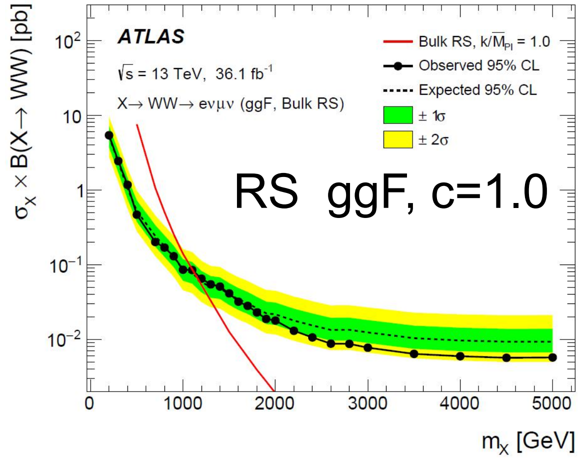
Limits (width = 15%*m_H) [pb]	**ggF**	**VBF**
Lowest mass (200 GeV)	5.2	1.3
Highest mass	0.02 (4 TeV)	0.006 (3TeV)

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

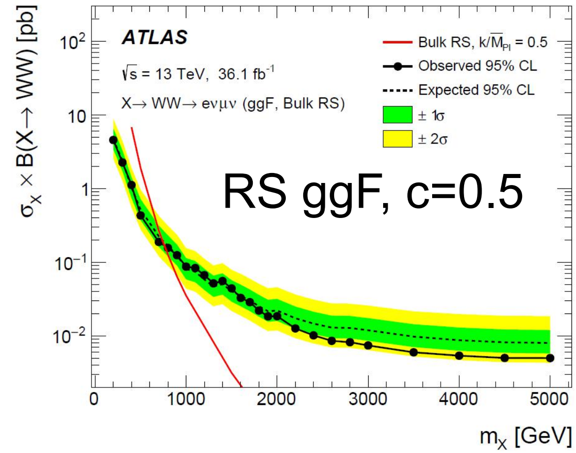
Limits for other models



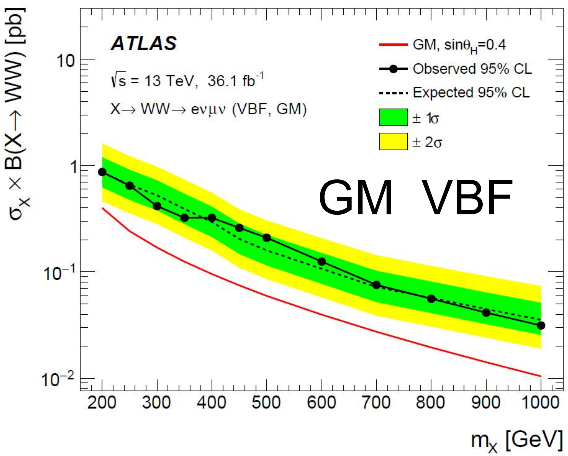
below 1.3 TeV excluded

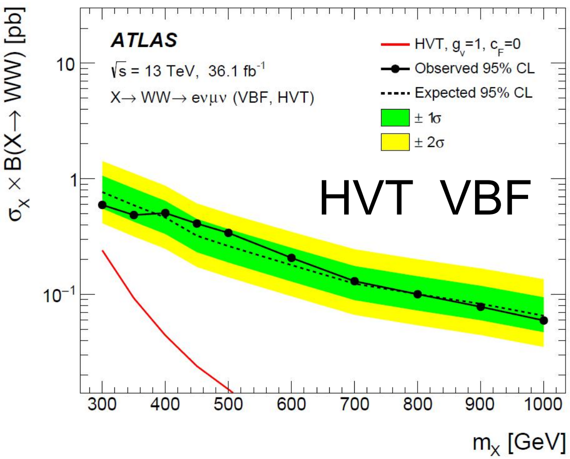


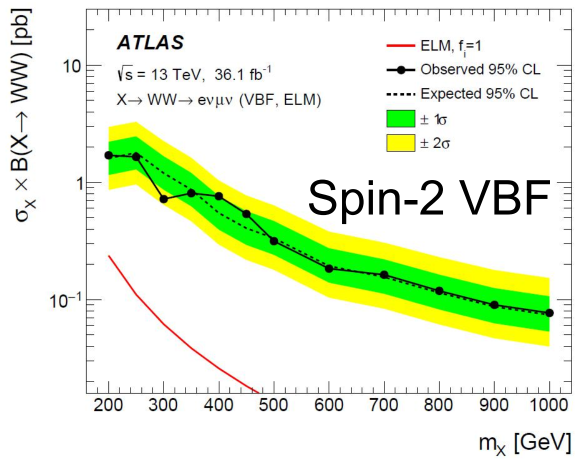
below 1.1 TeV excluded



below 750 GeV excluded







Conclusion

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

Thanks for your attention!

BACKUP

Benchmark signal models

- SM-like Higgs with a Narrow Width Approximation (NWA)
- Two-Higgs-doublet models (2HDM)
  - Type I and Type II
- SM-like Higgs with a Large Width Assumption (LWA)
  - width: 5%, 10% and 15% of m_H
- Georgi-Machacek (GM) model
  - single parameter: $\sin^2\theta_H$
- Heavy vector triplet (HVT) model
  - coupling strength: $c_h g_V$ (bosons) and $g^2 c_F/g_V$ (fermions)
- A bulk Randall-Sundrum (RS) graviton model with a spin-2 Graviton
  - coupling constant: $k/\bar{M}_{\mathrm{Pl}}$
- Effective Lagrangian model (ELM) with a spin-2 tensor resonance in the VBF production

Event selection

SRs

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

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

VBF 1J phase space

VBF 2J phase space

CRs

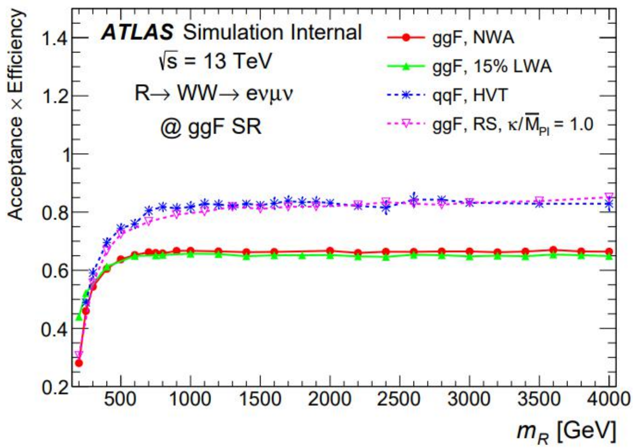
WW CR_{ggF}	Top CR_{ggF}	WW CR_{VBF1J}	Top CR_{VBF}
Preselection: $p_T^{\ell,\text{lead}} > 25$ GeV, $p_T^{\ell,\text{sublead}} > 25$ GeV, $m_{\ell\ell} > 10$ GeV, veto if $p_T^{\ell,\text{other}} > 15$ GeV			
$N_{b\text{-jet}} = 0$ $\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$	$N_{b\text{-jet}} = 1$ $\lvert\Delta\eta_{\ell\ell}\rvert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

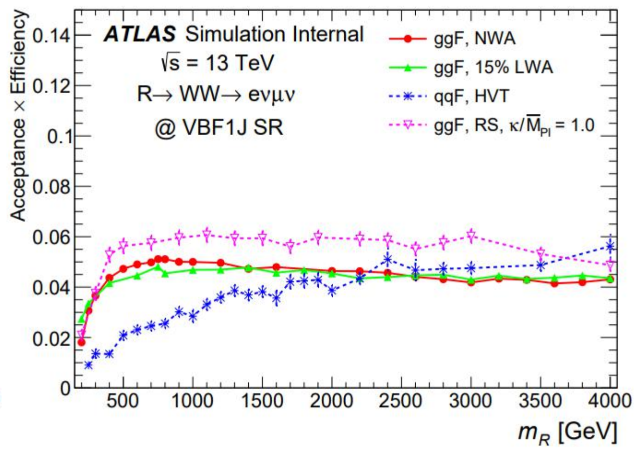
inversed cuts

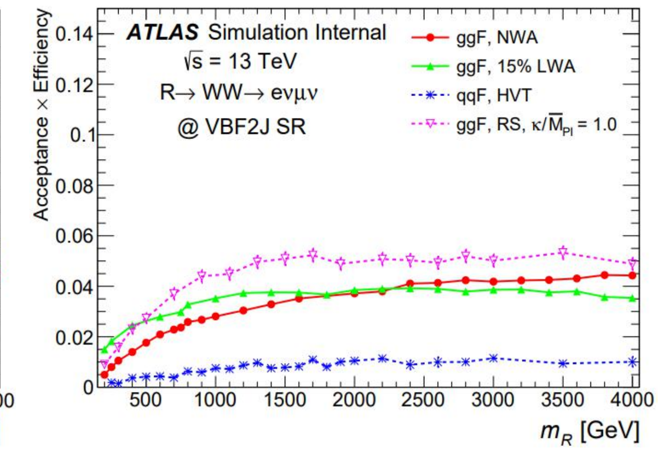
loose cuts

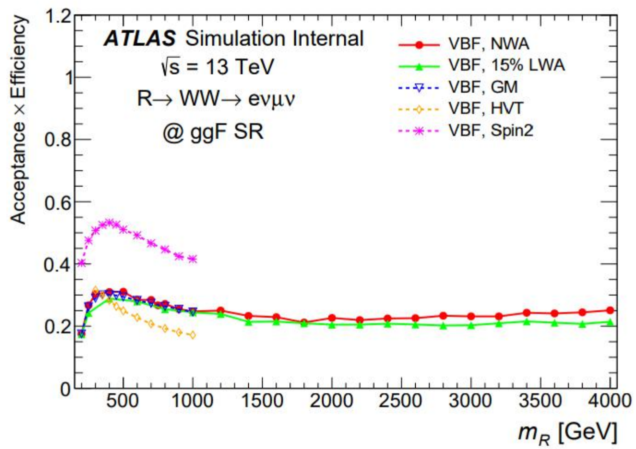
Signal acceptance

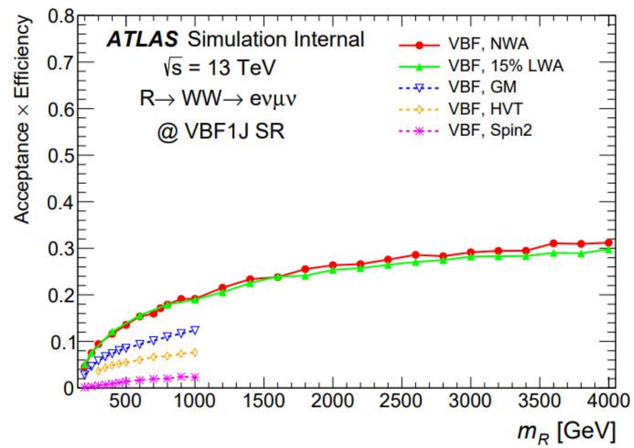
- Signal acceptance * efficiency

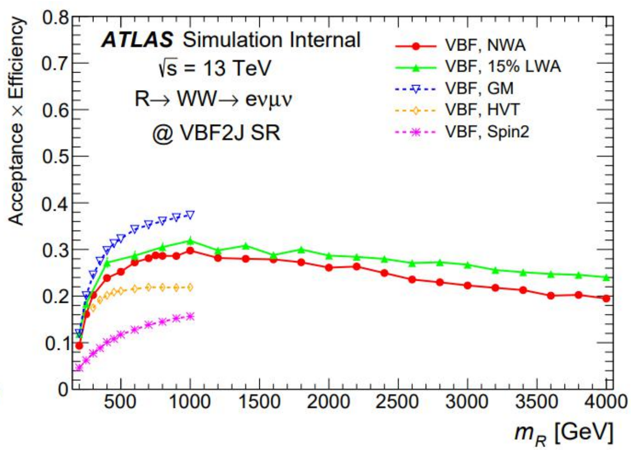












Transverse mass

- The transverse mass of resonance system, which is the discriminating variable, m_T, defined as:

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}\,,$$

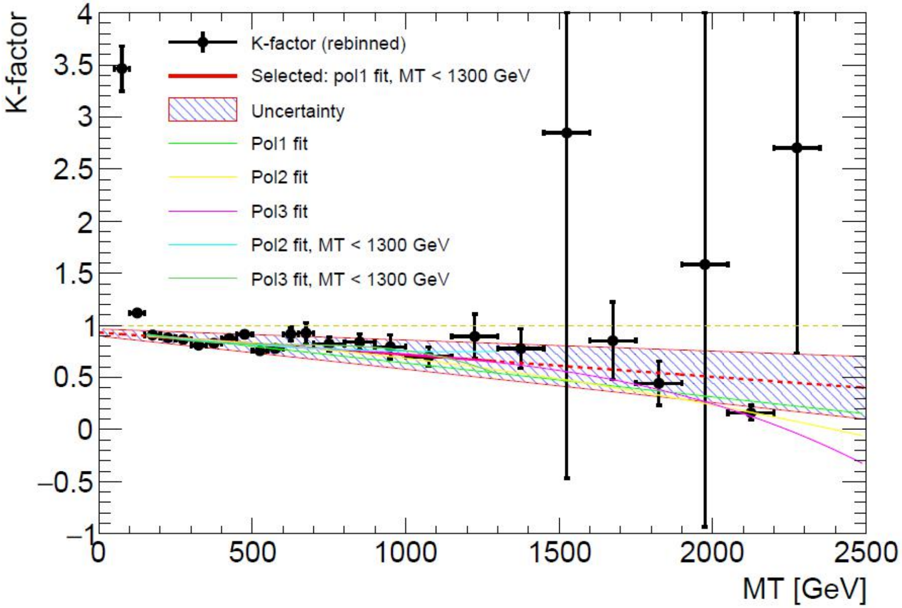
$$E_{\mathrm{T}}^{\ell\ell} = \sqrt{|\mathbf{p}_{\mathrm{T}}^{\ell\ell}|^2 + m_{\ell\ell}^2}\,,$$

where, MET is defined as the negative vectorial sum of the momenta of the calibrated objects in the detector:

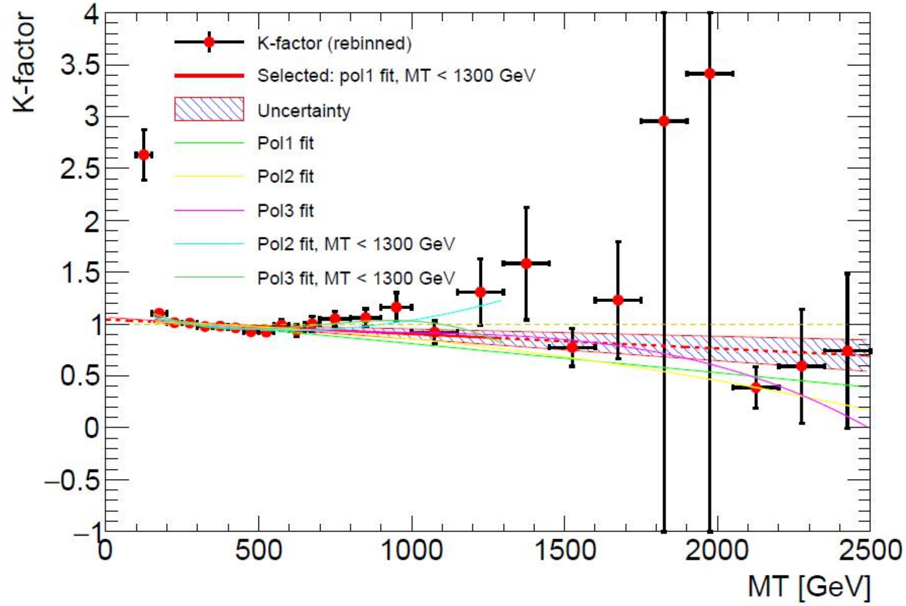
$$E_{x(y)}^{\mathrm{miss}} = E_{x(y)}^{\mathrm{miss},e} + E_{x(y)}^{\mathrm{miss},\gamma} + E_{x(y)}^{\mathrm{miss},\tau} + E_{x(y)}^{\mathrm{miss,jets}} + E_{x(y)}^{\mathrm{miss},\mu} + E_{x(y)}^{\mathrm{miss,soft}}$$

WW Sherpa-to-Matrix correction

- The fit function for this correction was also checked to avoid bias from statistical fluctuation
- All the fit functions that are tried can be covered by the uncertainty band



ggF SR

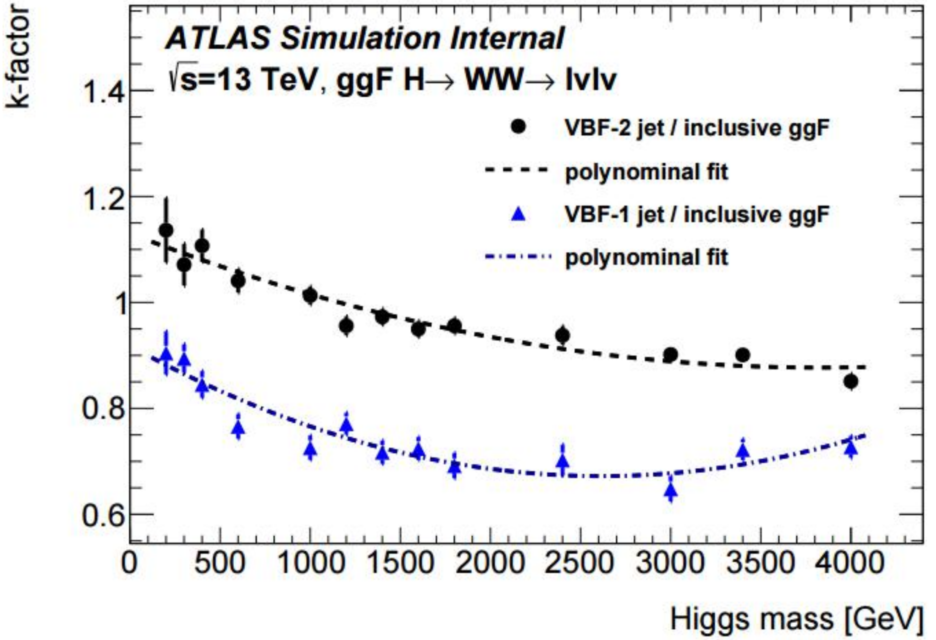


ggF WW CR

Powheg-to-MadGraph correction

- Powheg (ggF NWA signals) provides only events with only up-to-one jet at the ME, therefore higher jet multiplicities are expected to be insufficiently described
- Scale factor for 2J (similar for 1J):

$$k = \frac{N^{\text{2-jet VBF}}_{\textsc{MadGraph5}} / N^{\text{inclusive ggF}}_{\textsc{MadGraph5}}}{N^{\text{2-jet VBF}}_{\textsc{Powheg}} / N^{\text{inclusive ggF}}_{\textsc{Powheg}}}$$

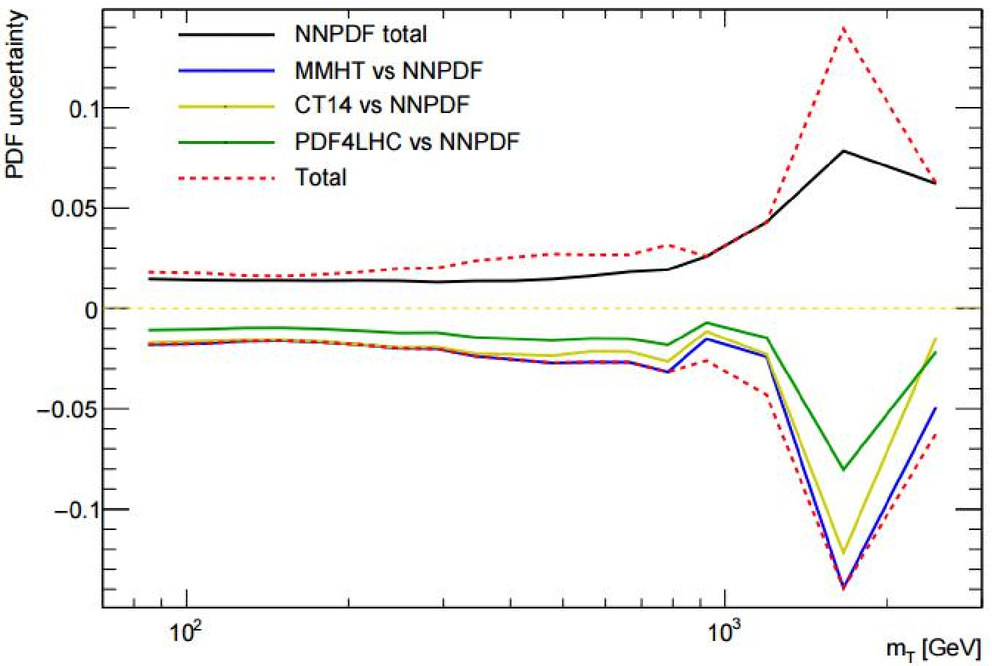


PDF uncertainty

- PDF uncertainties for are actually applied as a function of m_T
- For NNPDF, standard deviation is used to estimate the uncertainty
- The envelope of the different PDF sets is taken as the total PDF uncertainty

More plots in backup slides

Top @ GGFSR



top PDF uncertainty in ggF SR

Standard deviation:

$$\Delta X = \sqrt{\frac{1}{N}\sum_i (X_i - X_0)^2}$$

where X_0 is the central value or the mean value, and N, the number of ensembles, is usually 100 for NNPDF.

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

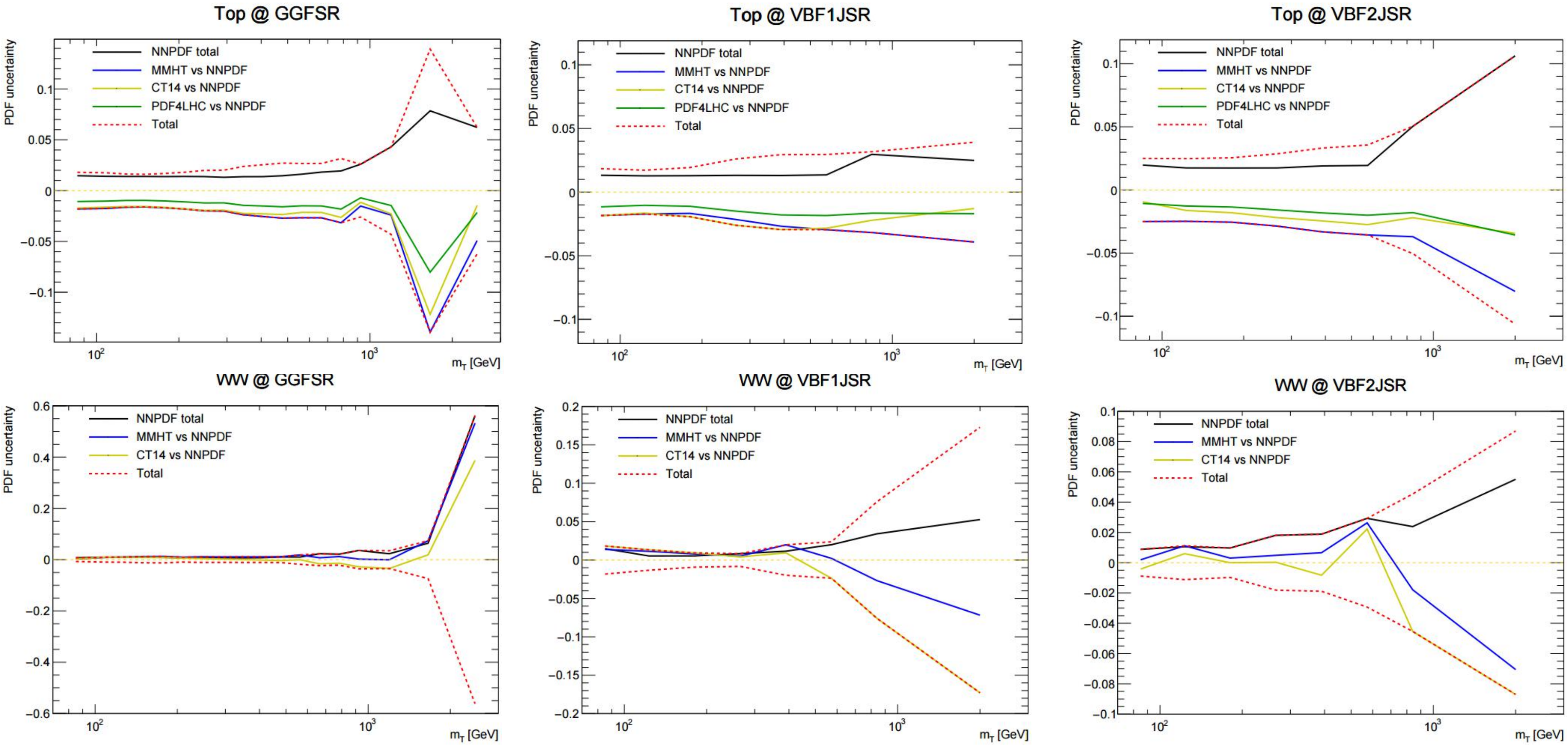
VBF induced signals

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

Top and WW PDF uncertainties in SRs



- Following PMG recommendations for NNPDF PDF set

https://twiki.cern.ch/twiki/bin/view/AtlasProtected/PdfRecommendations#Standard_deviation

- Envelope of different PDF sets taken as total uncertainty as a function of MT in 3 SRs (overall uncertainty used in CRs)

Event yields in ggF regions

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

	SR_{ggF}	Top CR_{ggF}	WW CR_{ggF}
WW	11500 ± 800	810 ± 110	3350 ± 220
Top-quark	11800 ± 600	52550 ± 330	2610 ± 180
Z/γ^*	1420 ± 110	111 ± 20	21.0 ± 2.0
W+jets	1180 ± 320	710 ± 190	280 ± 70
VV	866 ± 34	101 ± 12	250 ± 11
Backgrounds	26740 ± 170	54290 ± 250	6510 ± 80
Data	26739	54295	6515

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 ± 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
Backgrounds	972 ± 29	563 ± 22	5 890 ± 80	596 ± 22
Data	978	560	5 889	594

Uncertainties including both statistical and systematic uncertainties

Good agreement found between data and backgrounds

MT binning optimization

- ICHEP m_T binning
  - ggF SR:
    [0,100,120,140,160,180,200,220,240,260,280,300,320,340,360,380,400,450,500,550,600,650,700,800,900,1000,3000]
  - VBF SRs:
    [0,100,150,200,250,300,350,400,500,600,3000]
- New m_T binning (optimized)
  - ggF SR:
    [70, 100, 117, 138, 163, 193, 227, 268, 316, 372, 439, 517, 610, 719, 848, 1000, 1389, 1930, 3000]
  - VBF SRs:
    [70, 100, 146, 215, 316, 464, 681, 1000, 3000]
- New m_T binning (optimized, in log scale)

Table 32: Bin boundaries in log [linear] scale of the m_T distributions used in the fit for the three signal regions are shown.

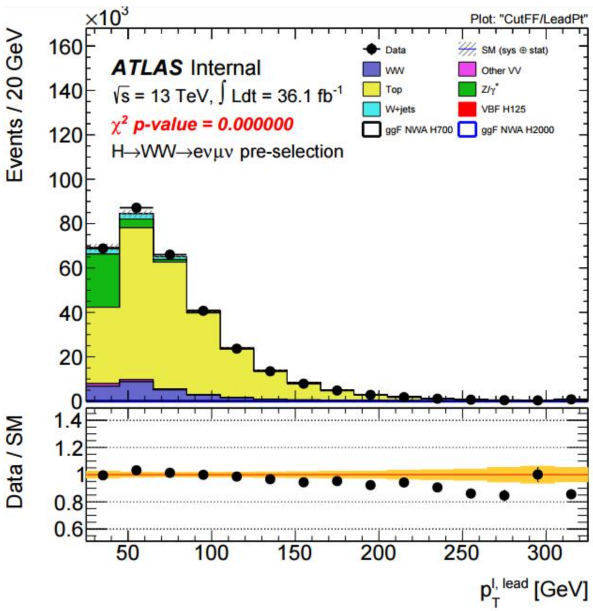
Inclusive ggF SR									
~ 1.8 [70]	2.0 [100]	2.07 [120]	2.14 [140]	2.21 [160]	2.28 [190]	2.36 [230]	2.43 [270]	2.5 [315]	2.57 [370]
2.64 [440]	2.71 [510]	2.78 [600]	2.86 [725]	2.93 [850]	3.0 [1000]	3.14 [1380]	3.28 [1900]	3.48 [3000]	

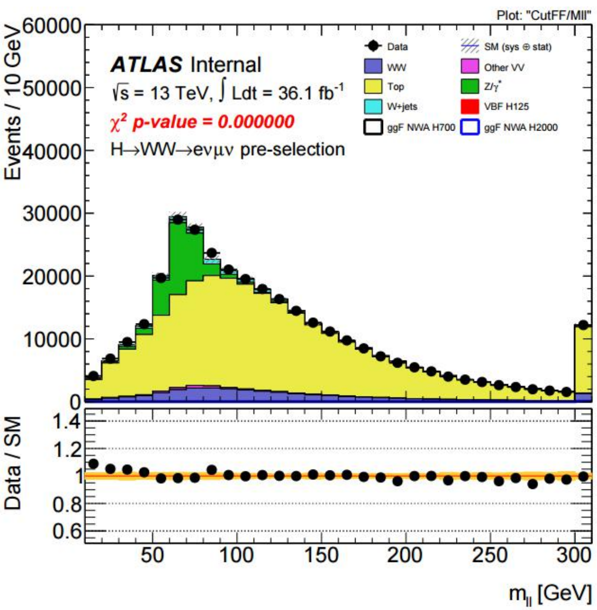
$N_{\text{jet}} = 1$ and ≥ 2 VBF SRs								
~ 1.8 [70]	2.0 [100]	2.17 [150]	2.33 [215]	2.5 [315]	2.67 [470]	2.83 [680]	3.0 [1000]	3.48 [3000]

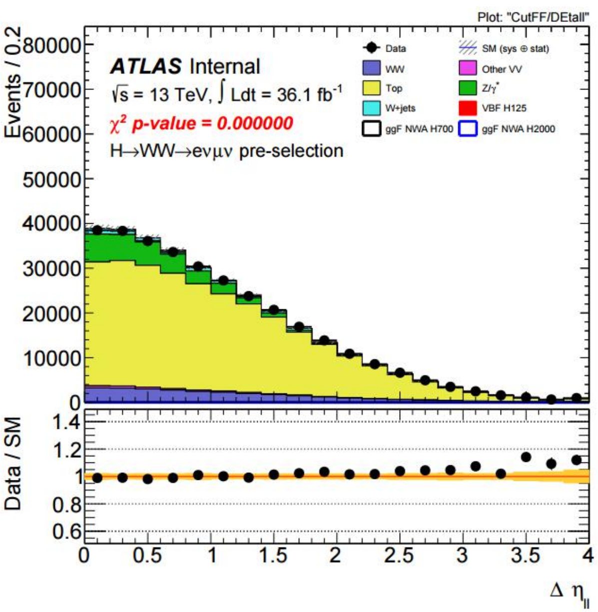
Plots after pre-section

- Signals are normalized to expected limits

Pre-fit







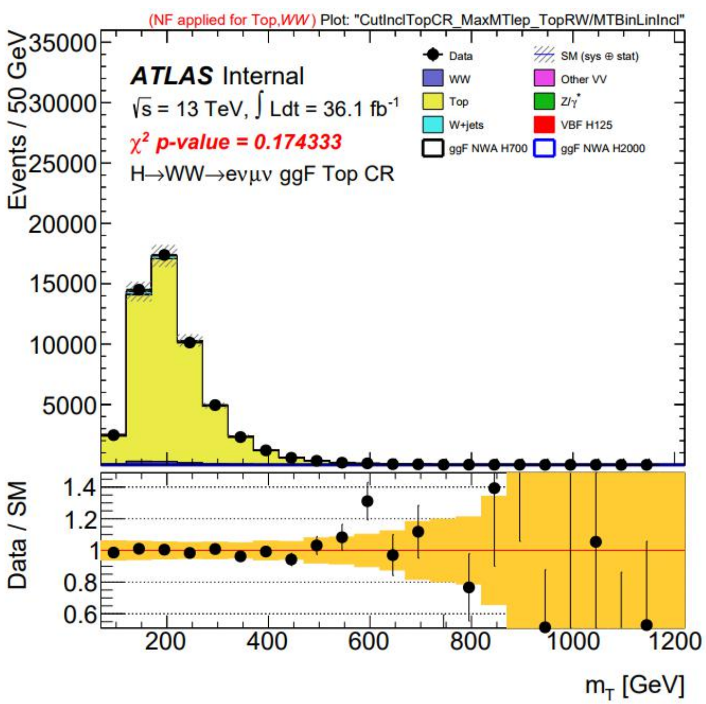
$p_T^{l,lead}$ $\quad$ $m_{\ell\ell}$ $\quad$ $|\Delta\eta_{\ell\ell}|$

MT plots in top CRs

Pre-fit

- Top and WW NFs applied
- Top leadlep pt reweighting applied
- Signals are normalized to expected limits

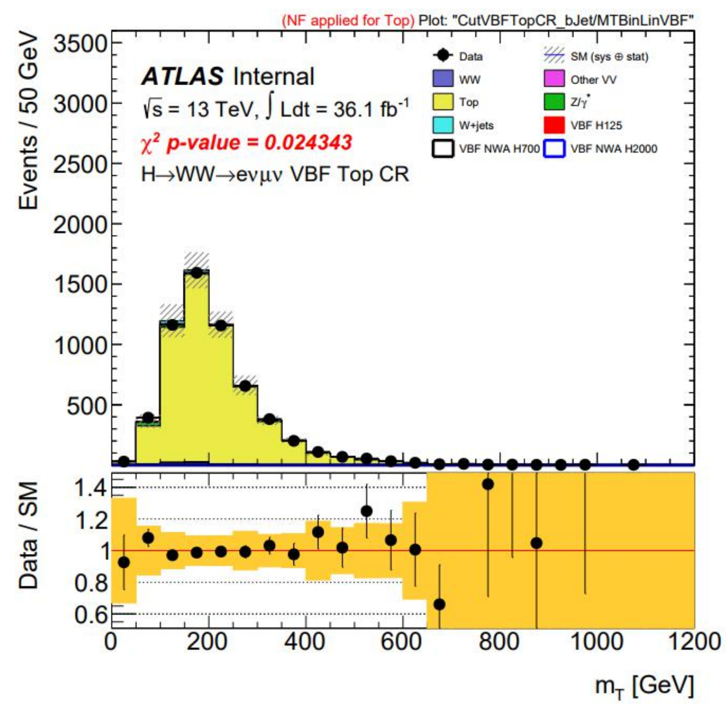
ggF Top CR



$$NF_{ggF}^{top} = 0.99 \pm 0.01$$

$$NF_{ggF}^{WW} = 1.15 \pm 0.03$$

VBF Top CR



$$NF_{VBF}^{top} = 0.98 \pm 0.02$$

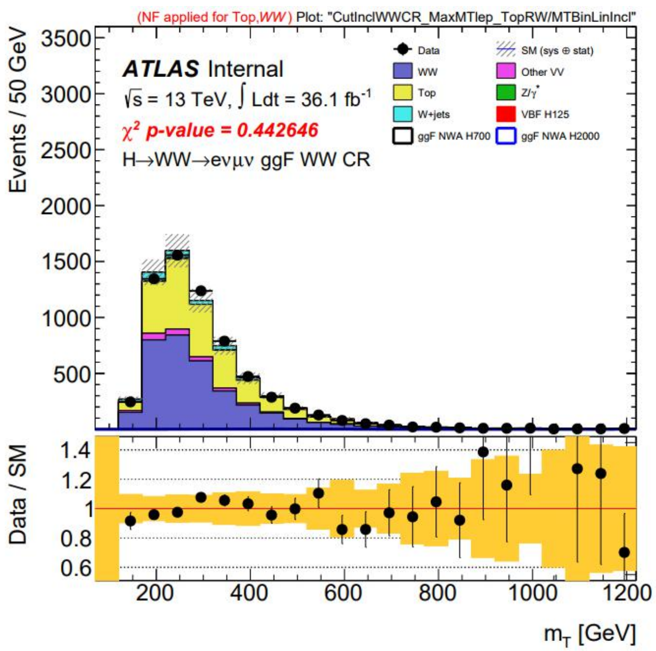
$$NF_{VBF,1J}^{WW} = 0.92 \pm 0.13$$

MT plots in WW CRs

Pre-fit

- Top and WW NFs applied
- Sherpa-to-Matrix correction applied on qq→WW
- Top leadlep pt reweighting applied
- Signals are normalized to expected limits

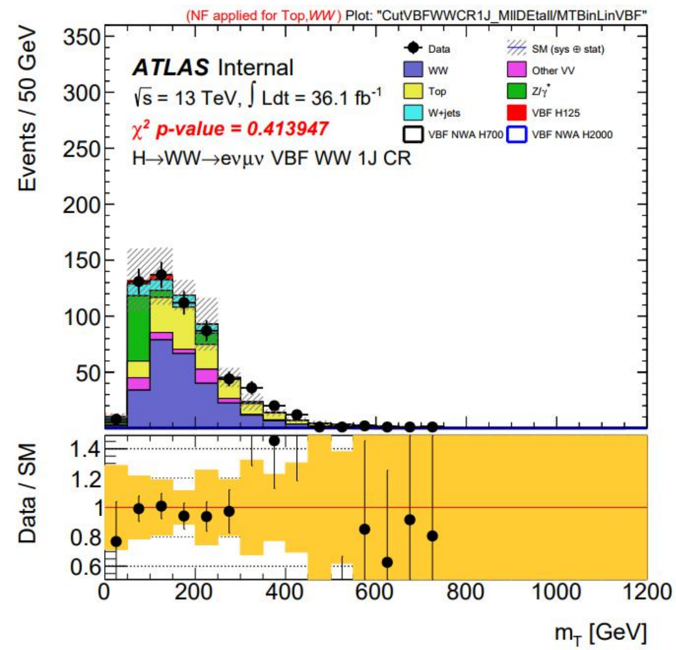
ggF WW CR



$$\mathrm{NF}_{\mathrm{ggF}}^{\mathrm{top}} = 0.99 \pm 0.01$$

$$\mathrm{NF}_{\mathrm{ggF}}^{\mathrm{WW}} = 1.15 \pm 0.03$$

VBF WW 1J CR



$$\mathrm{NF}_{\mathrm{VBF}}^{\mathrm{top}} = 0.98 \pm 0.02$$

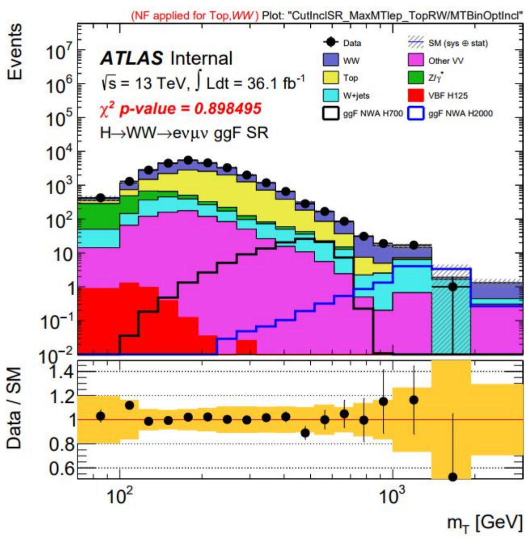
$$\mathrm{NF}_{\mathrm{VBF,1J}}^{\mathrm{WW}} = 0.92 \pm 0.13$$

MT plots in SRs

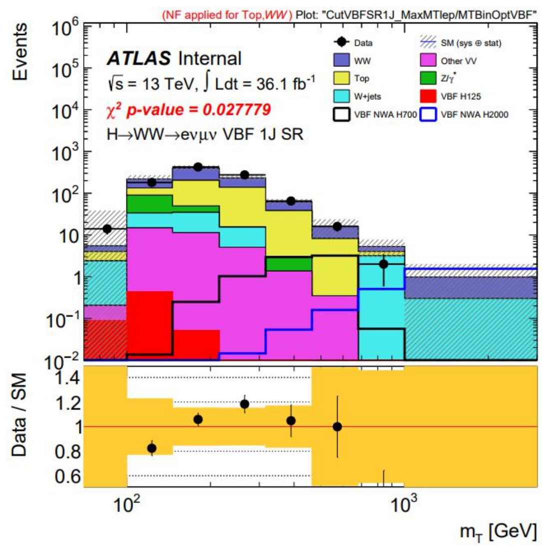
- Top and WW NFs applied
- Sherpa-to-Matrix correction applied on qq→WW
- Top leadlep pt reweighting applied
- Signals are normalized to expected limits
- Using the optimized MT binning for the fit

Pre-fit

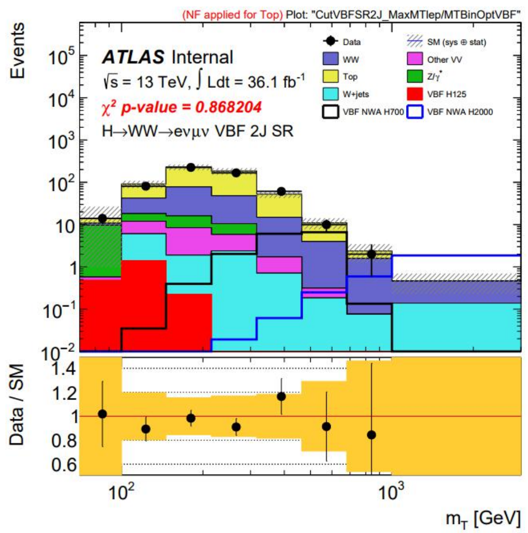
ggF SR



VBF 1J SR



VBF 2J SR



$$NF^{top}_{ggF} = 0.99 \pm 0.01$$

$$NF^{WW}_{ggF} = 1.06 \pm 0.03$$

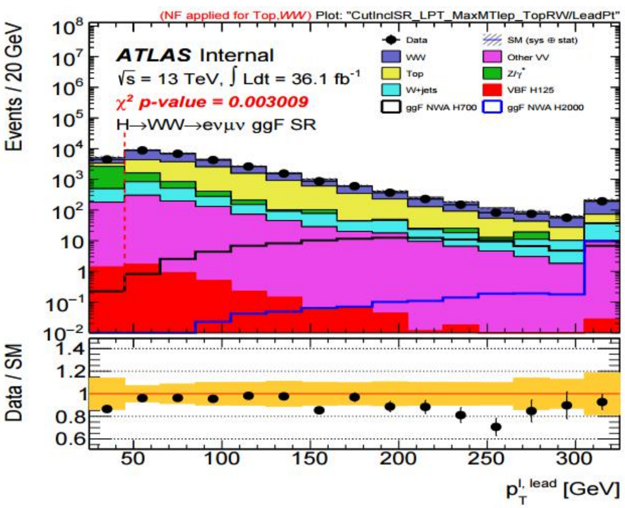
$$NF^{top}_{VBF} = 0.98 \pm 0.02$$

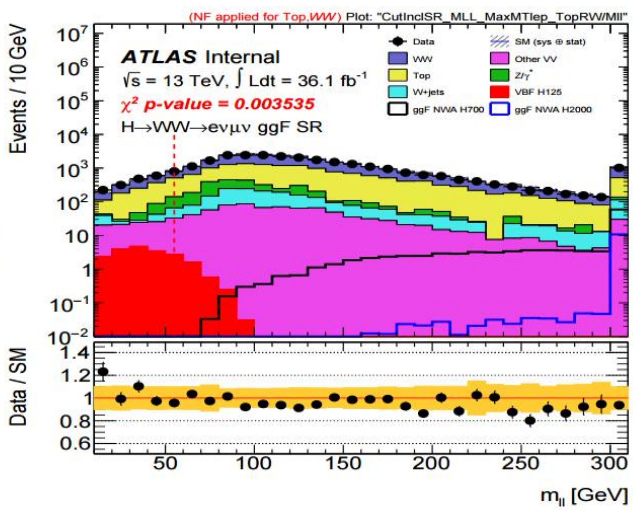
$$NF^{WW}_{VBF,1J} = 0.92 \pm 0.13$$

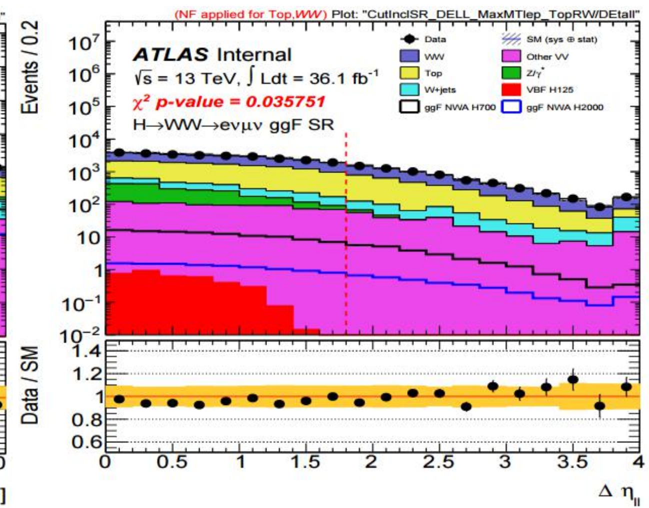
N-1 plots in ggF SR

- Top and WW NFs applied
- Top leadlep pt reweighting applied
- Signals are normalized to expected limits

Pre-fit





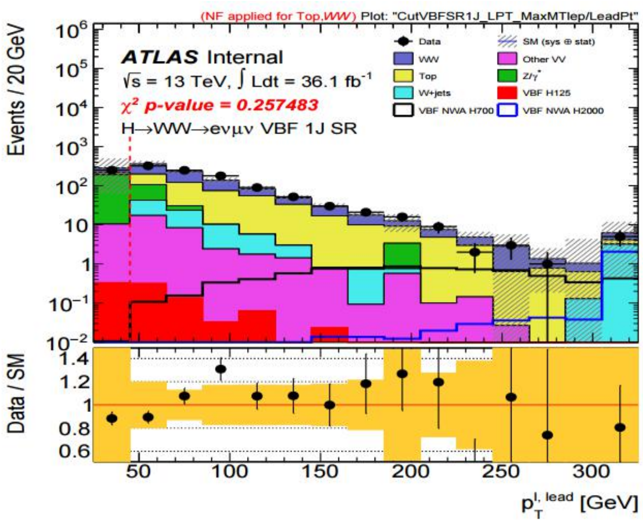


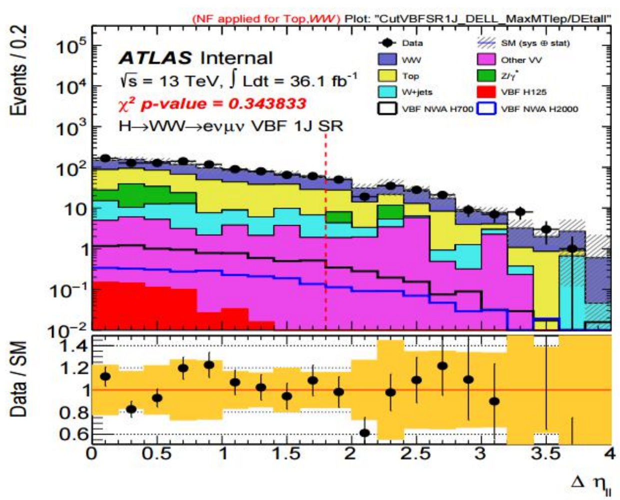
$p_T^{l,lead}$ $m_{\ell\ell}$ $|\Delta\eta_{\ell\ell}|$

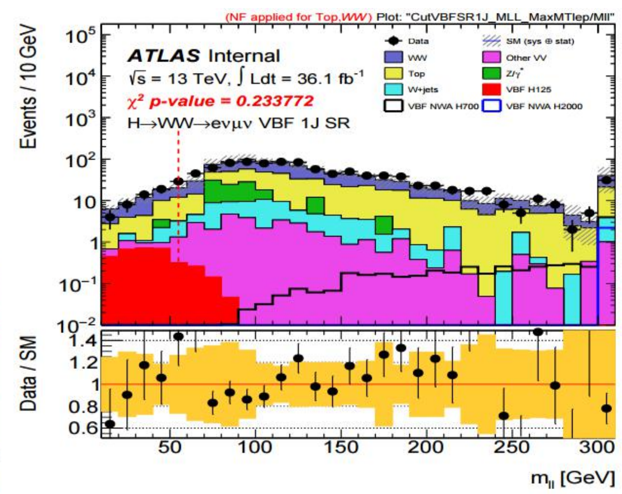
N-1 plots in VBF 1J SR

Pre-fit

- Top and WW NFs applied
- Signals are normalized to expected limits





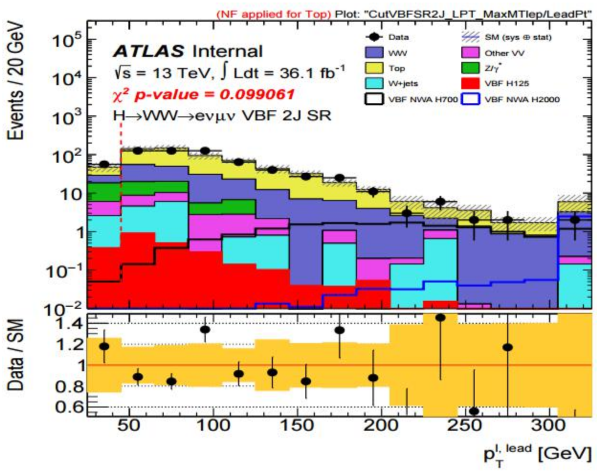


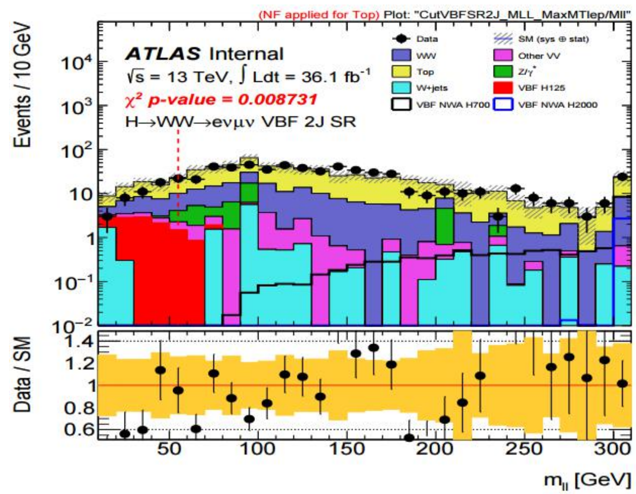
$p_T^{l,lead}$ $m_{\ell\ell}$ $|\Delta\eta_{\ell\ell}|$

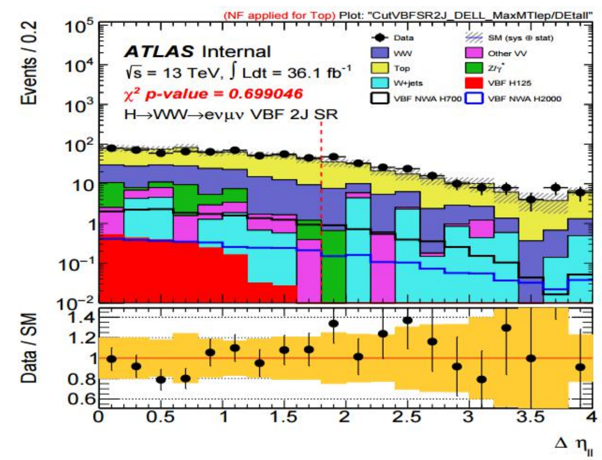
N-1 plots in VBF 2J SR

- Top and WW NFs applied
- Signals are normalized to expected limits

Pre-fit

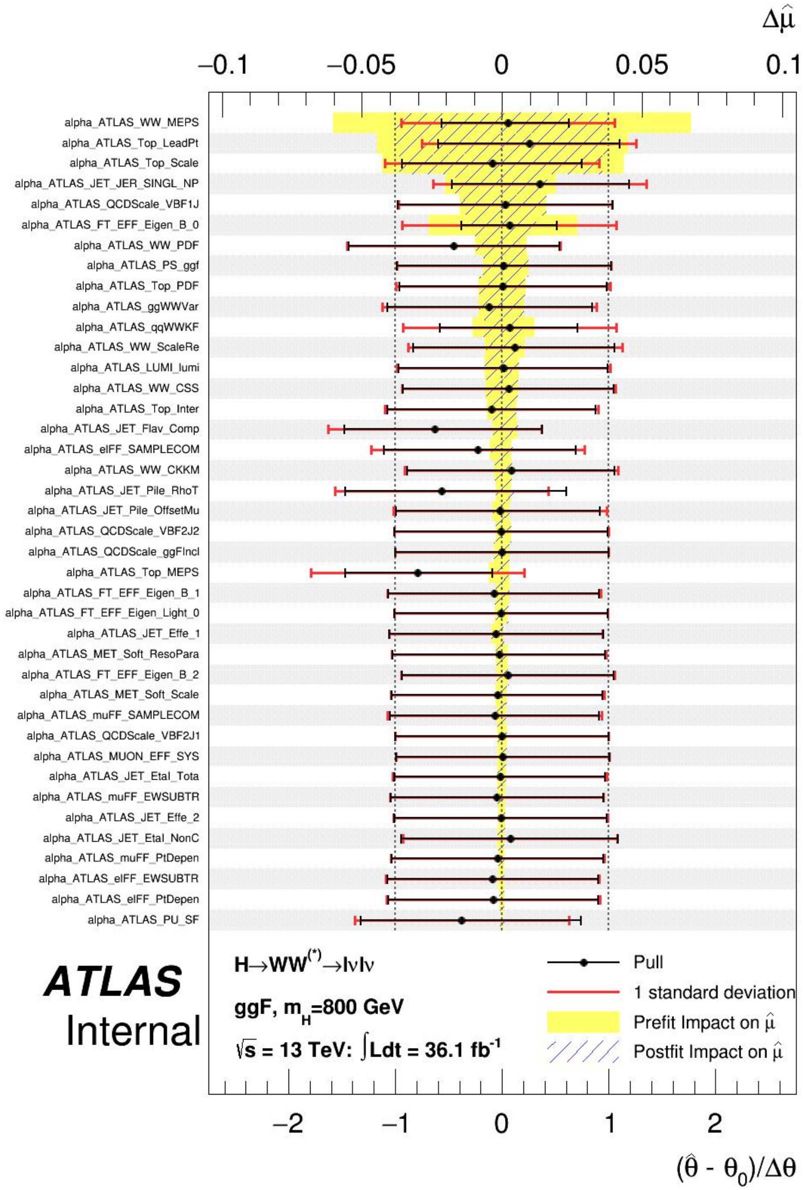






$p_T^{l,\mathrm{lead}}$ $m_{\ell\ell}$ $|\Delta\eta_{\ell\ell}|$

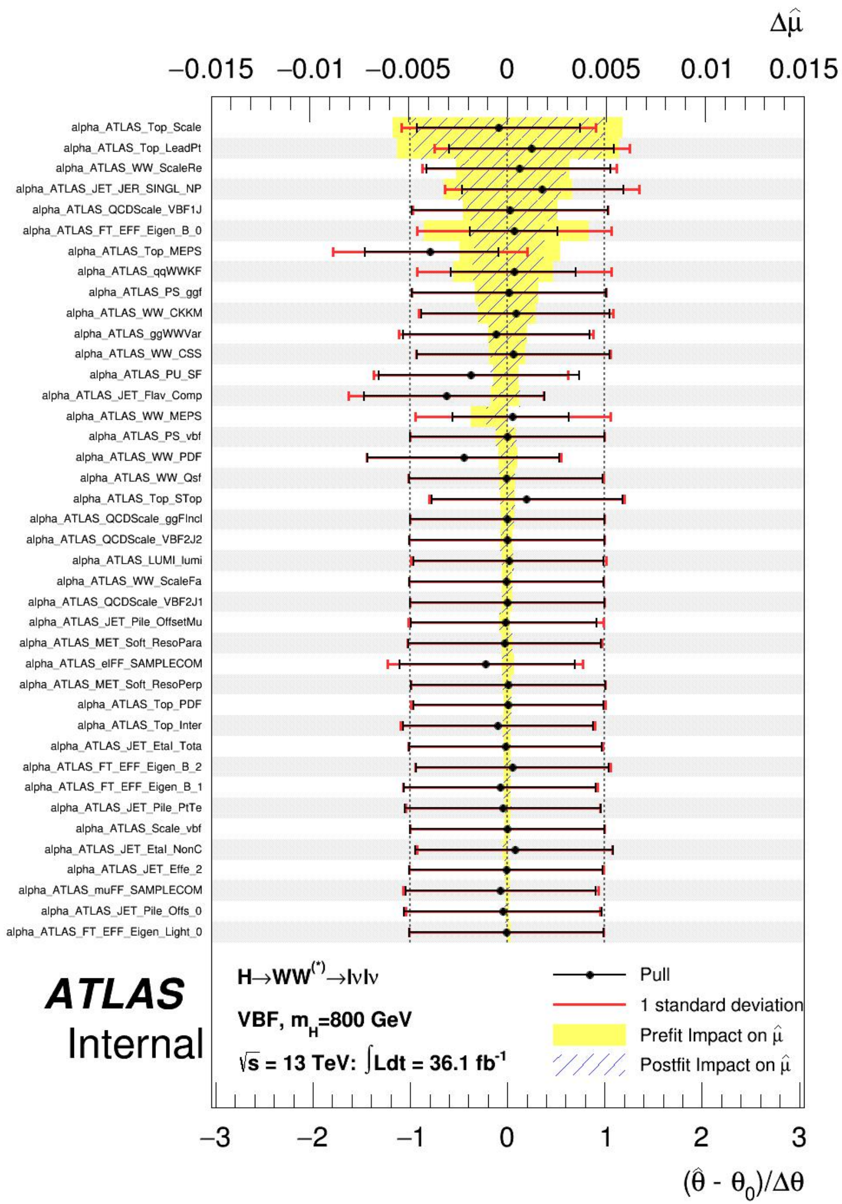
Pull plots for NWA H800 (ggF)



- Dominant sources:
  - WW ME+PS
  - Top leading lepton pt reweighting shape uncertainty
  - Top radiation (QCD scale)
  - JER
  - Signal QCD scale in VBF 1J SR
  - B-tagging efficiency
  - WW PDF uncertainty

More in supp. note

Pull plots for NWA H800 (VBF)



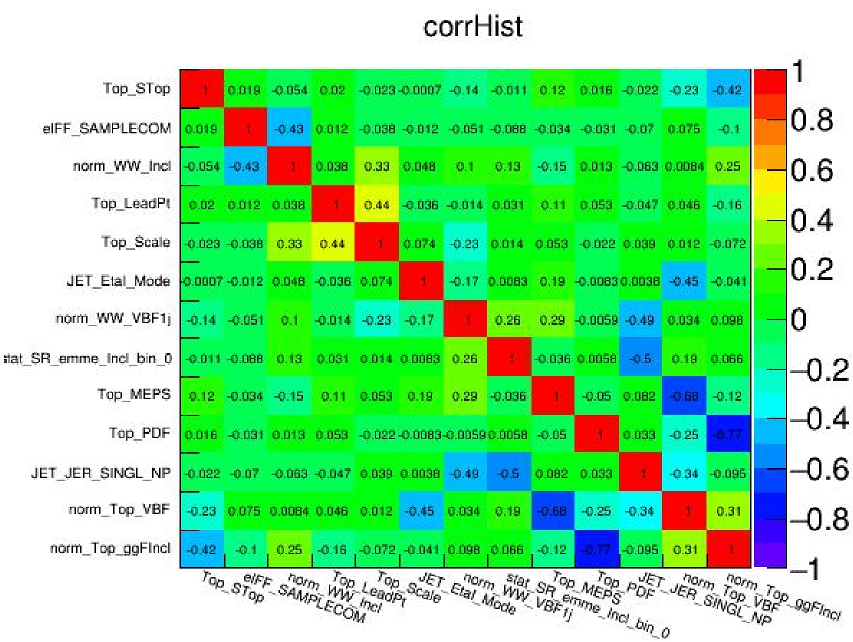
■ Dominant sources:

- ➢ Top radiation (QCD scale)
- ➢ Top leading lepton pt reweighting shape uncertainty
- ➢ WW renormalisation scale
- ➢ JER
- ➢ Signal QCD scale in VBF 1J SR
- ➢ B-tagging efficiency
- ➢ Top MEPS
- ➢ WW k-factor uncertainty

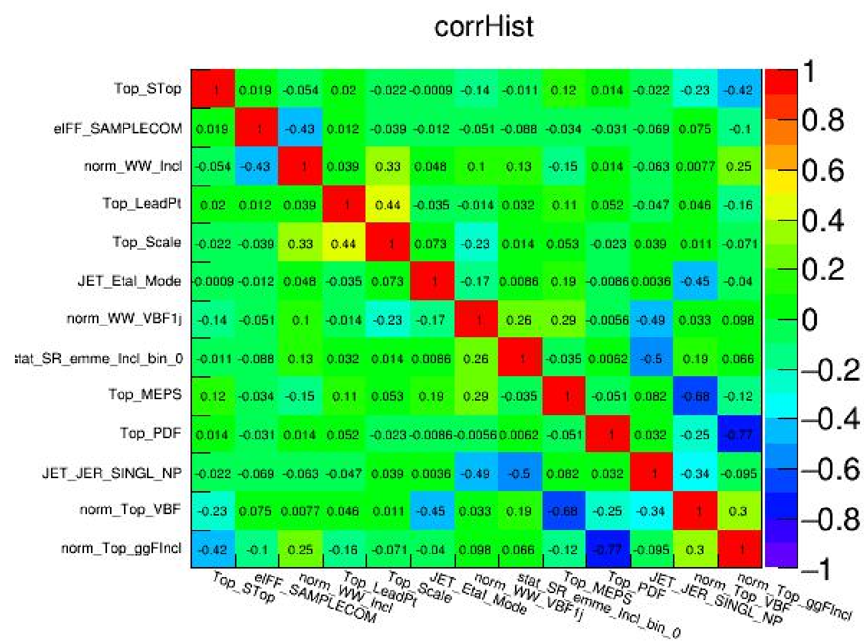
More in supp. note

Correlation plots for NWA H800

- Only NPs with coefficient > 0.4 are shown
- Correlation as expected
- Very similar plots for other mass points (more in backup slides)



ggF

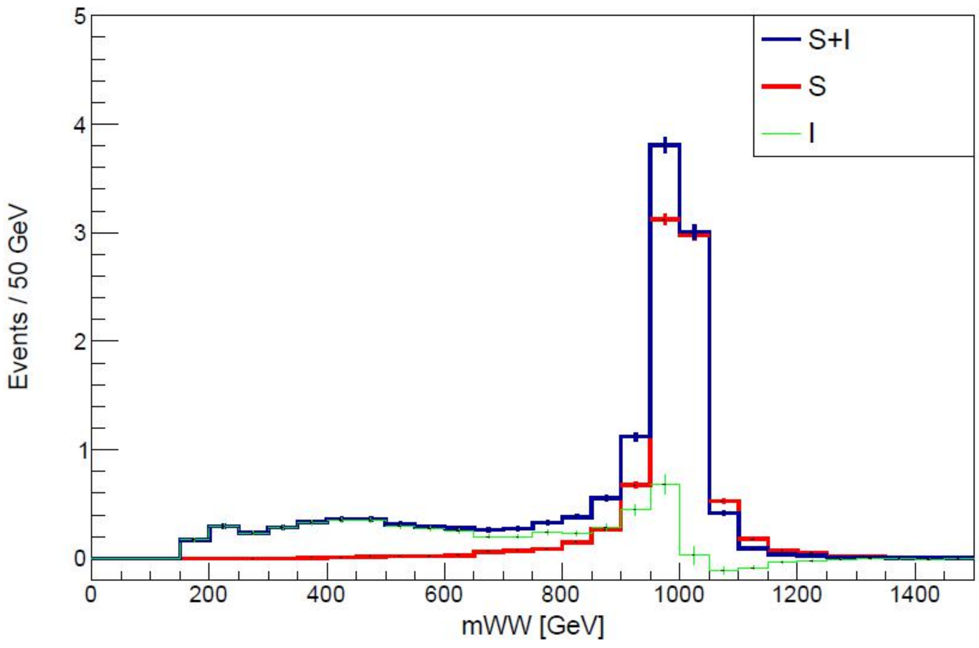


VBF

More in supp. note

Interference effects

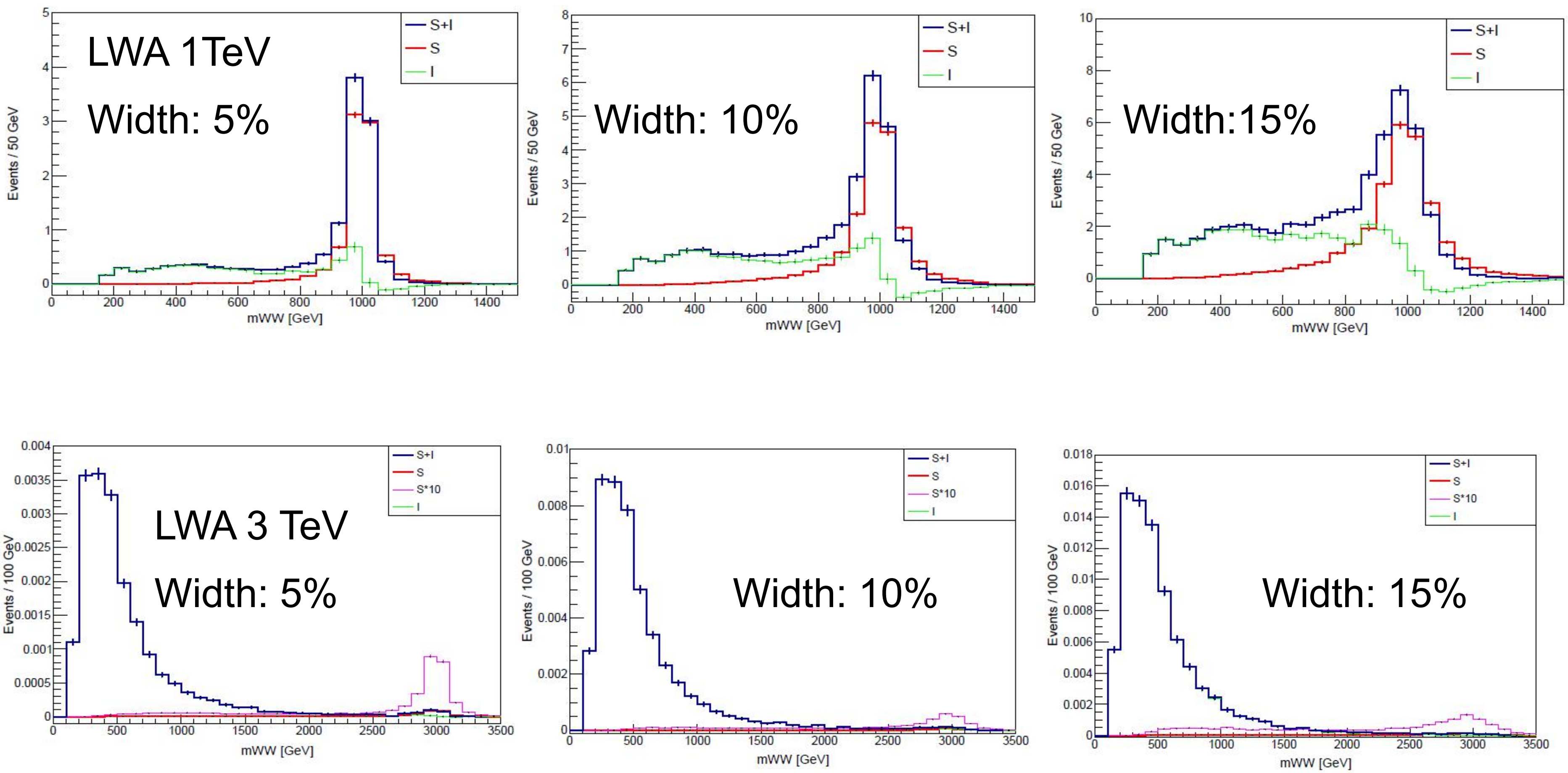
- Generator: gg2VV
- The interference effects considered here include the interference effects between a heavy resonance and the SM WW continuum and the SM Higgs boson at 125 GeV
- The lineshape has been compared with MadGraph5_aMc@Nlo for SM-like heavy Higgs and good agreement observed



The yields are normalised to the integrated luminosity of the data 2015 and 2016 (36.1 fb^{-1})

Interference effects

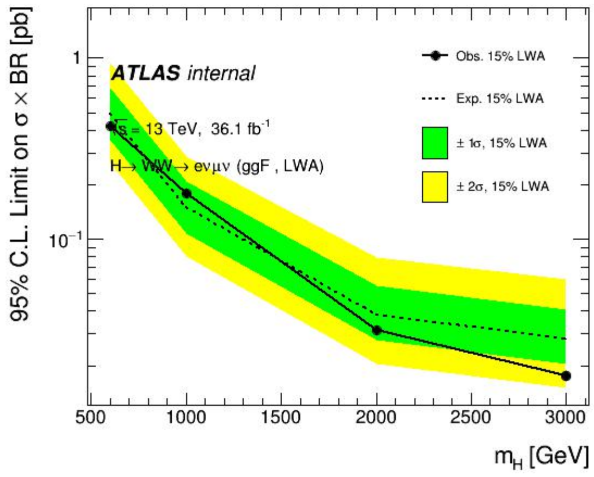
- Interference effects increase with larger masses and widths



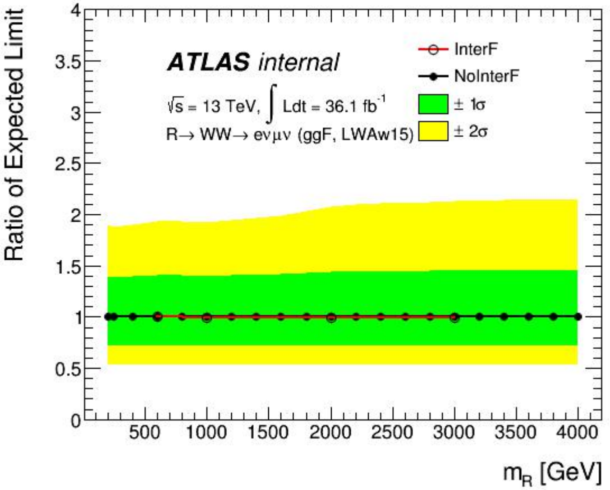
Interference effects

■ Expected limits for LWA (width: 15%·m_H) [pb]

- Only a few mass points have been studied
- Signal cross section scaled to $\sigma_{H\rightarrow WW}$ = 1 pb in the input



Limits with interference



Compared to expected limits without interference

The effects for ggF LWA are negligible

The interference effects for VBF are smaller than ggF, and neglected