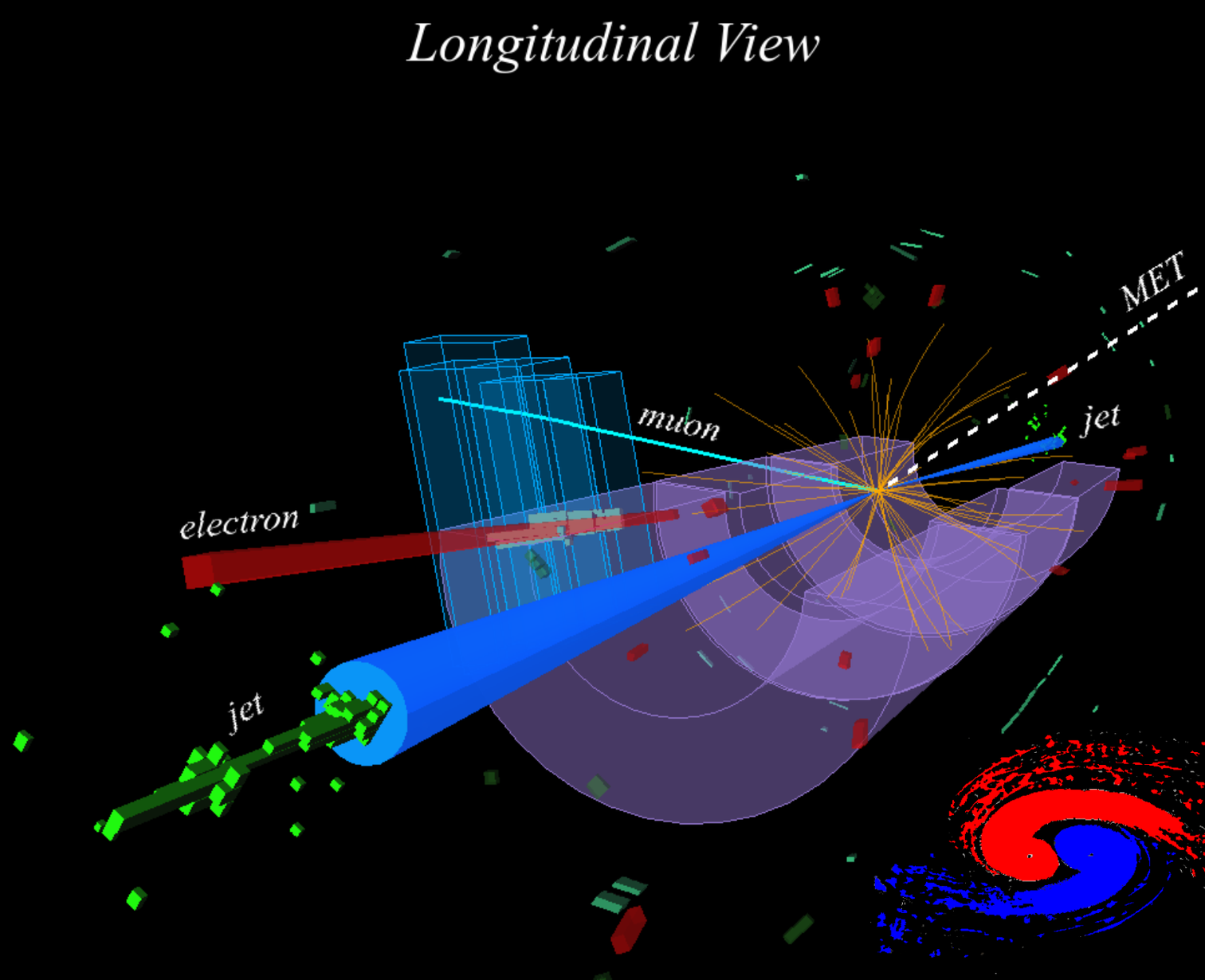
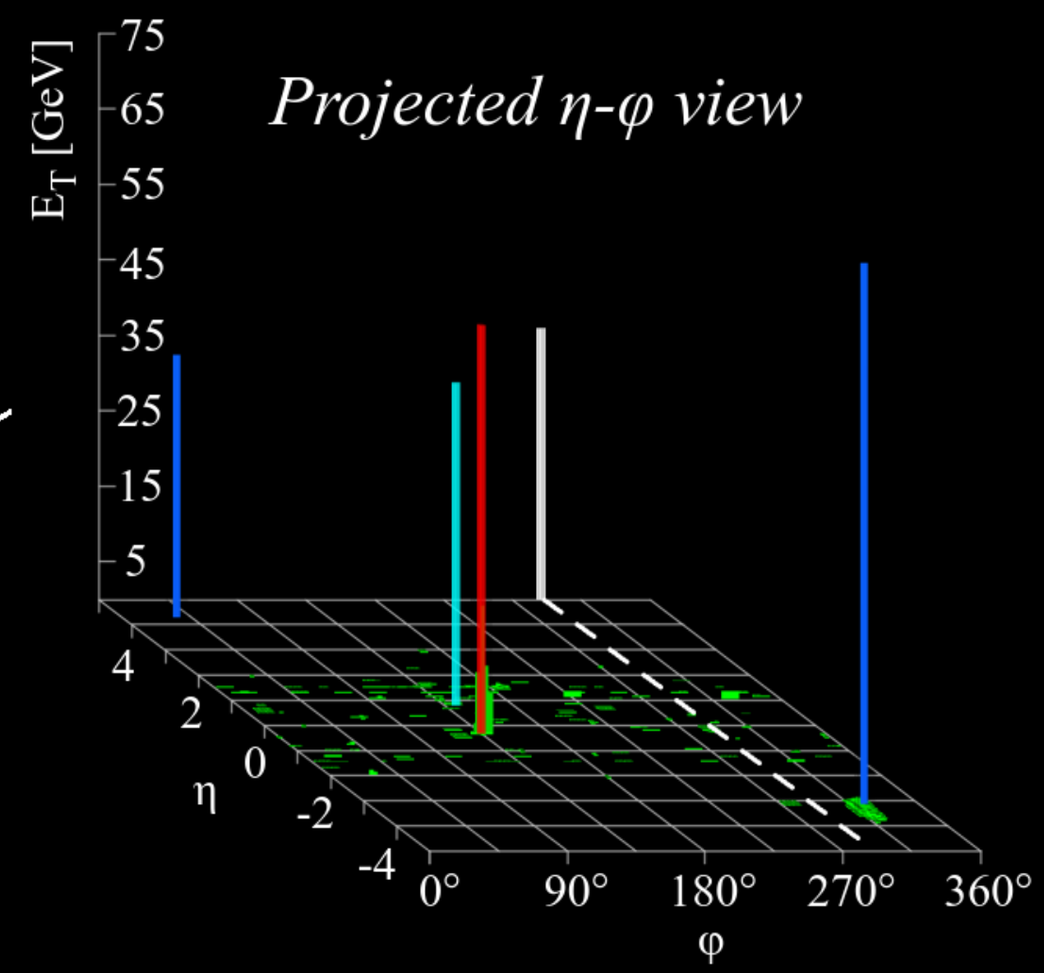
Latest results on the SM Higgs boson in the WW decay channel using the ATLAS detector

ATLAS-CONF-2016-112



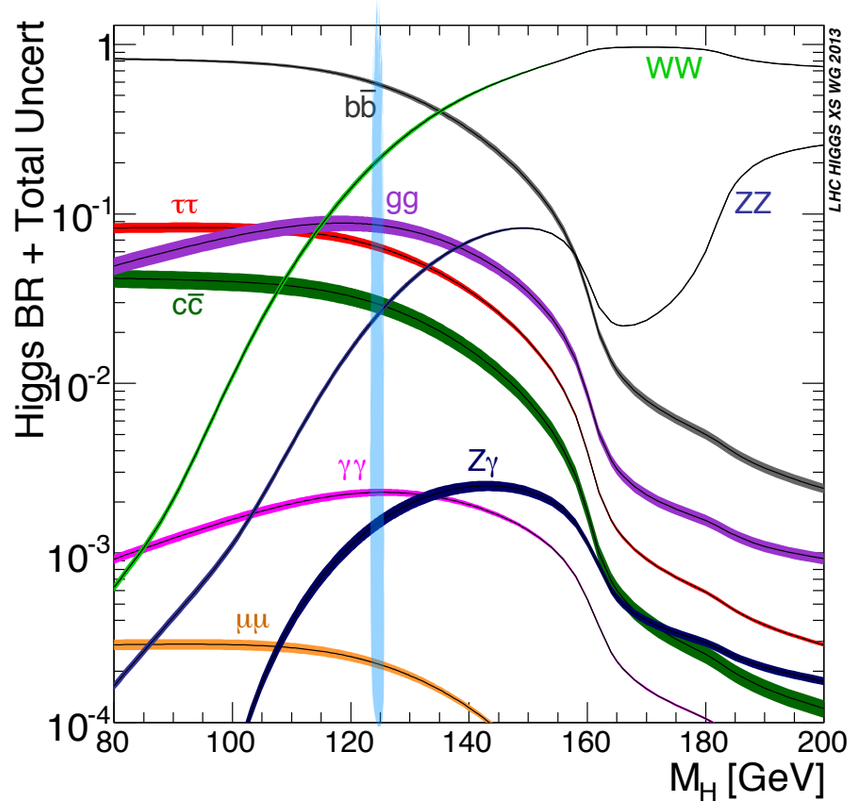


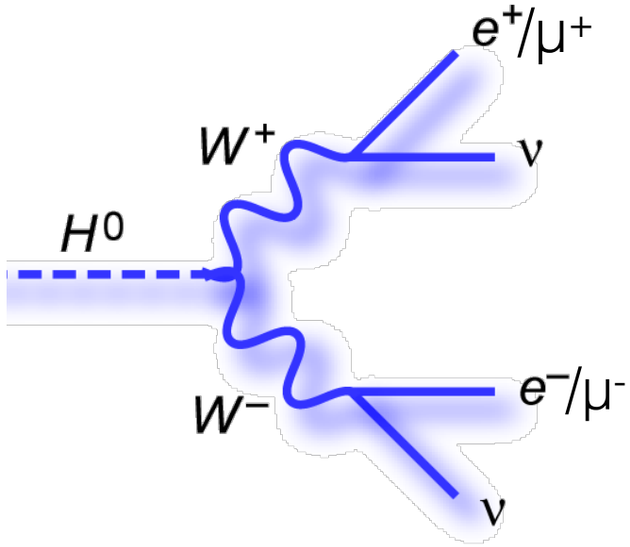
C. Bertella

Second China LHC Physics Workshop: CLHCP 2016

H→WW*→lνlν

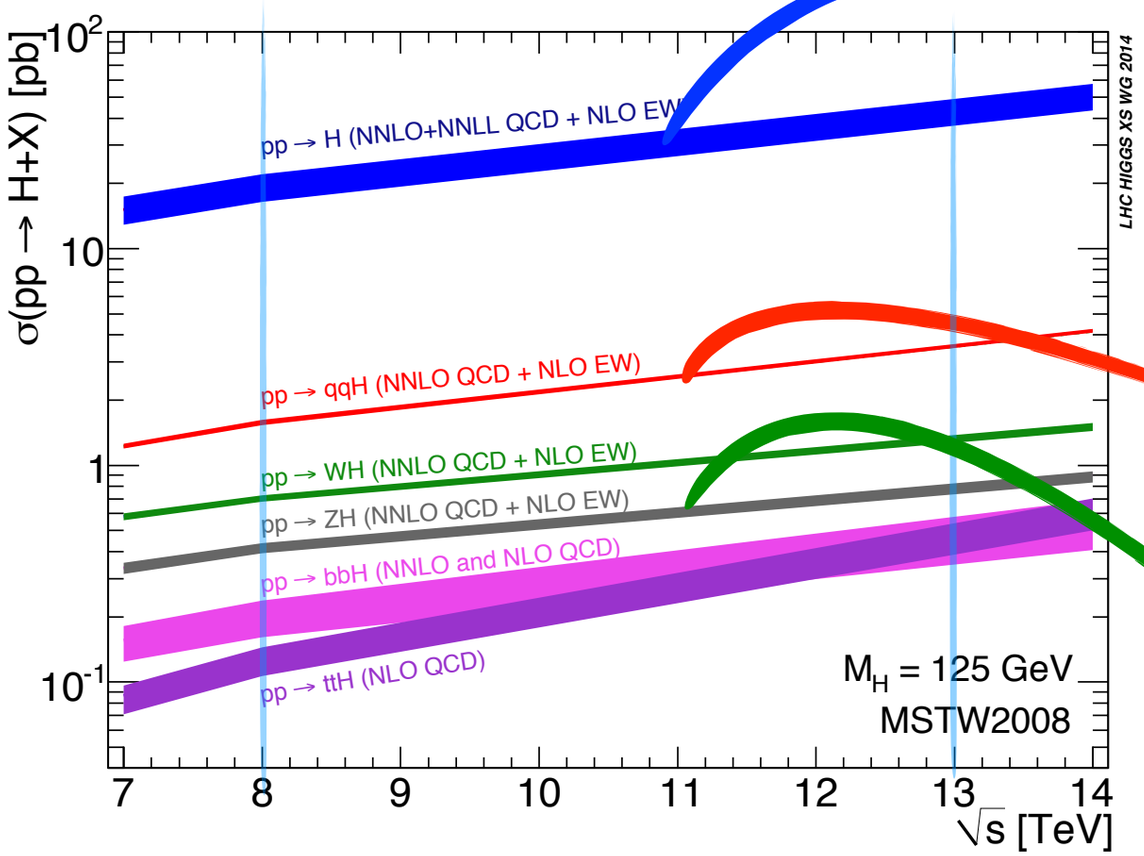
- WW channel well-suited to exploring rare production modes and searching at highness
- Large branching ratio: 22 %
- Good S/B from a clean dilepton signature

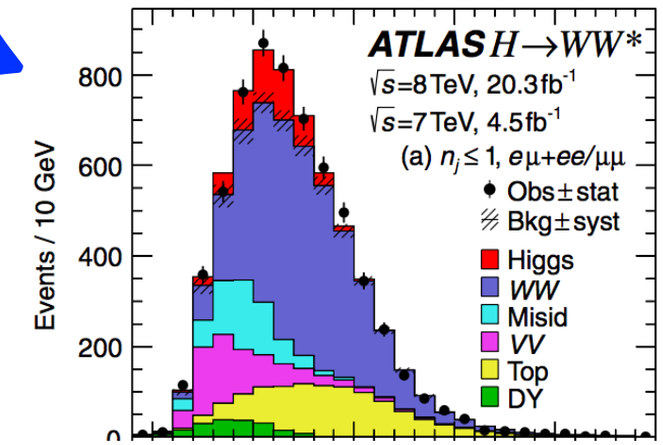




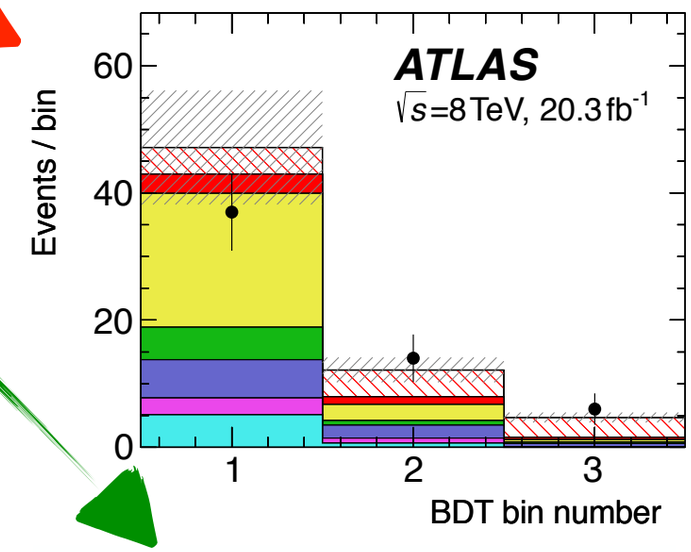
- Higgs boson couplings measurement essential SM consistency test
- Search for rare production modes
- Provide a template for searching additional states at high mass
  - More detail in Weimin SONG's talk on Sunday

H→WW*→lνlν @ RunI



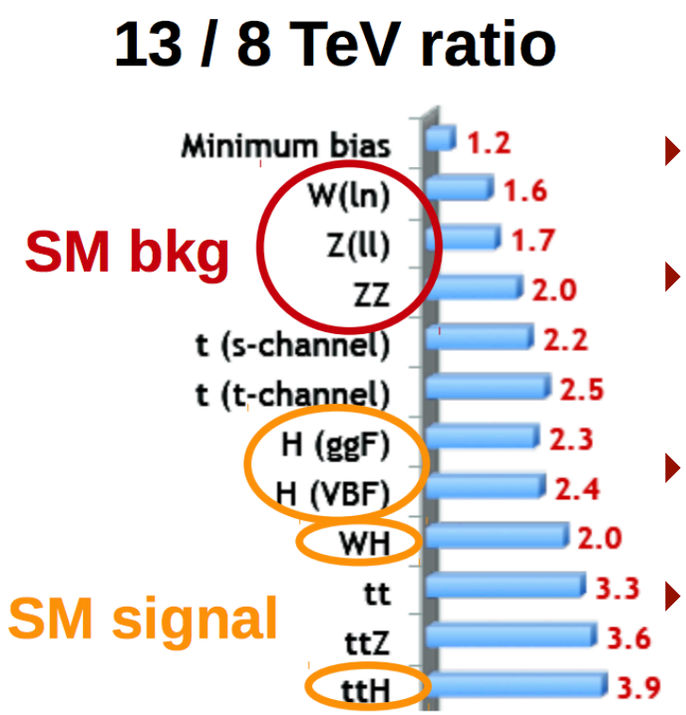


Confirmed:
5.8 σ
μ_{ggF}=1.02

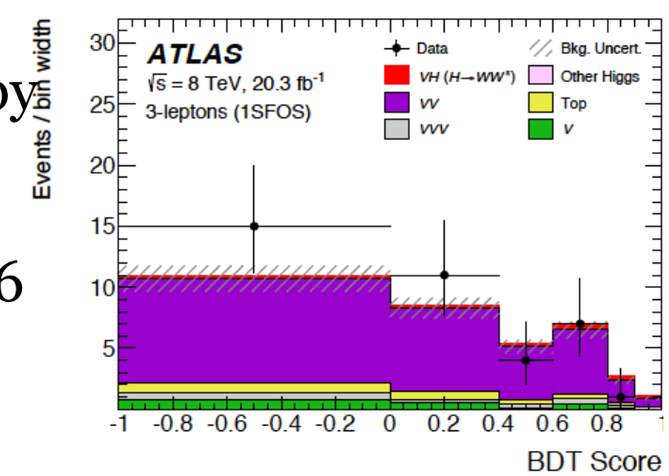


Evidence:
3.2 σ
μ_{VBF}=1.27

Phys. Rev. D 92, 012006 (2015)



- Higgs XS increases by factor 2.3
- Background typically increases by factor 1.9 (3.3 for tt)
- Significance scales as S/√B → 1.6
- Sensitivity for 10/fb @ 13 TeV corresponds to full Run 1 dataset

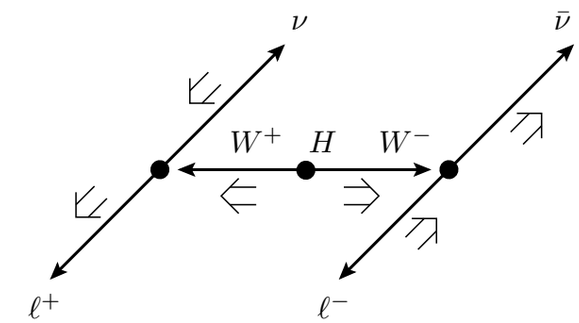


Search:
2.5 σ
μ_{VH}=3

JHEP08 (2015) 137

H→WW*→lνlν: Signal Topology

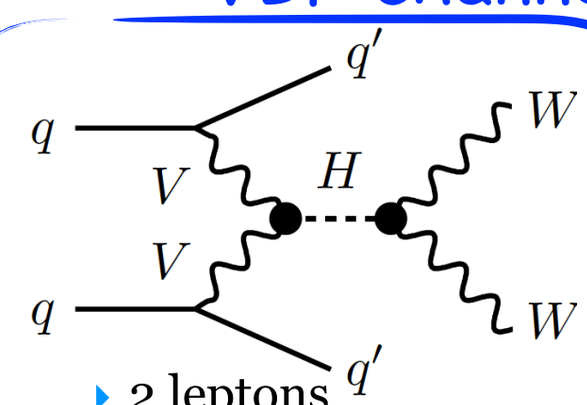
- Higgs boson final state: $H \rightarrow WW^* \rightarrow l\nu l\nu$
  - 2 leptons from Higgs tend to have small angular separation due to the spin 0
  - Final state can not be fully reconstructed due to the presence of neutrinos
    - A transverse mass m_T can be calculated without the unknown longitudinal neutrino momenta



$$m_T = \sqrt{\left(E_T^{\ell\ell} + p_T^{\nu\nu}\right)^2 - \left|\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{p}_T^{\nu\nu}\right|^2}$$

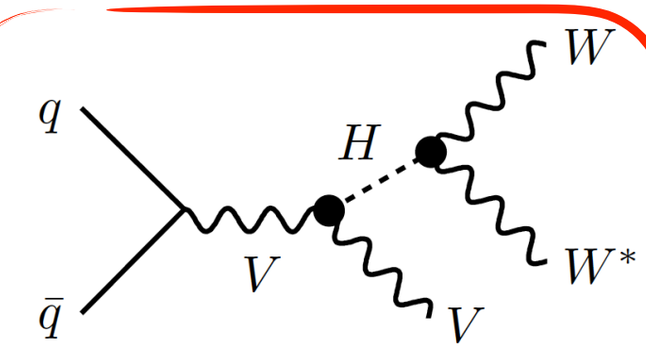
- Production modes investigated @ 13 TeV with 5.8 fb^{-1}: VBF and WH
  - Direct access to the Higgs boson couplings to gauge bosons

VBF channel



- 2 leptons
- E_T^{miss}
- 2 forward jets

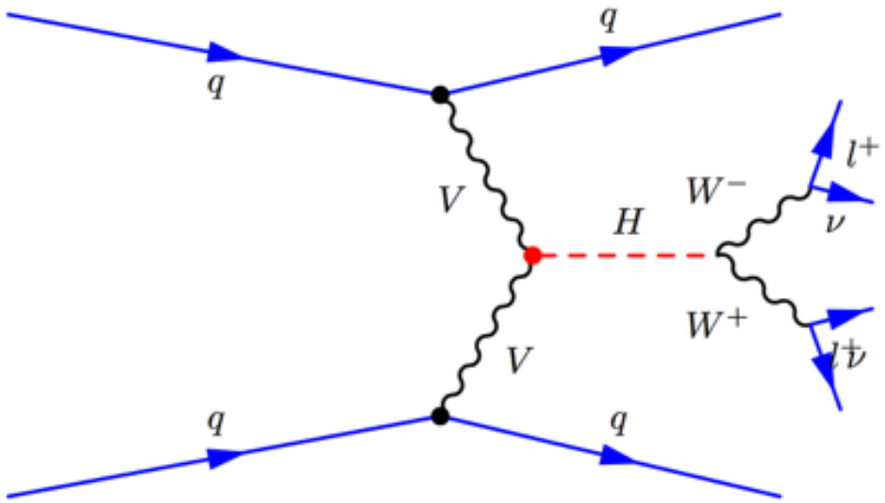
WH channel



- 2 leptons
- Large E_T^{miss}
- Low jet multiplicity

VBF channel

VBF $H \rightarrow WW \rightarrow l\nu l\nu$



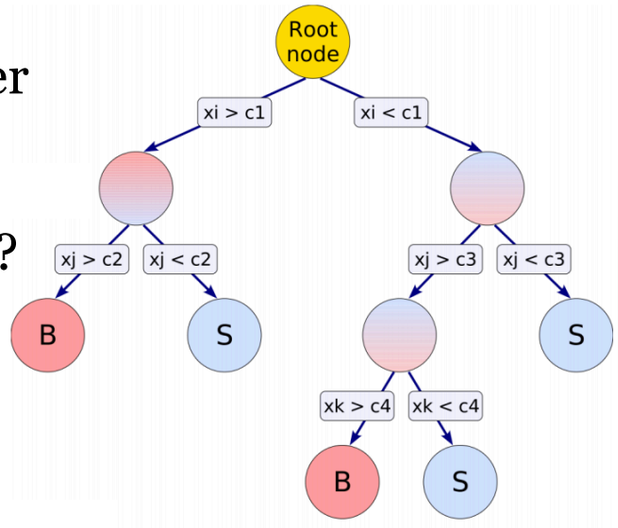
- Electro-weak process with small theoretical uncertainty
  - No color flow between the two partons, unique topology of two energetic jets with large rapidity separation

Analysis Strategy:

- Only the different flavour channels: eμ , μe
- Selection criteria are applied on: m_{ll}, $m_{\tau\tau}$, lepton and jet centrality
- Multivariate technique (BoostDecisionTree) is used to separate the signal from the main background processes
  - BDT distribution used to extract the signal strength

Bonus

- Why a MVA? Allows to combine several discriminating variables into one final discriminant —> Better separation
- What is Decision Tree? Consecutive set of questions (nodes)
- Why Boosting? Misclassified events are weighted higher so that future learners concentrate on these



Event Selection

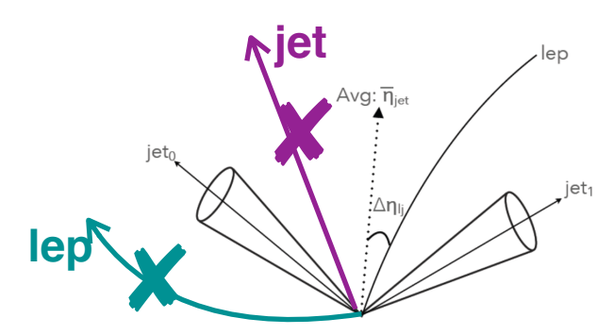
Main backgrounds:

- **ggF** estimated with MC simulation
- **WW**: estimated with MC simulation
- ➡ **Top** and **Z→ττ**: shape form MC simulation, NF estimated with data
- **W+jets**: data-driven from events with one lepton satisfying only loose but failing tight ID criteria; fake factors measured in a di-jet sample

Cuts	SR	Top CR	Z→ττ
Njets	>1	>1	>1
b-jets	0	1	0
$m_{\tau\tau}$	<66.2 GeV	<66.2 GeV	$\lvert m_{\tau\tau}-m_Z\rvert$<25 GeV
m_{ll}	-	-	<80 GeV
OLV	✓	✓	✓
CJV	✓	✓	✓
MVA>-0.8	✓	✓	✓

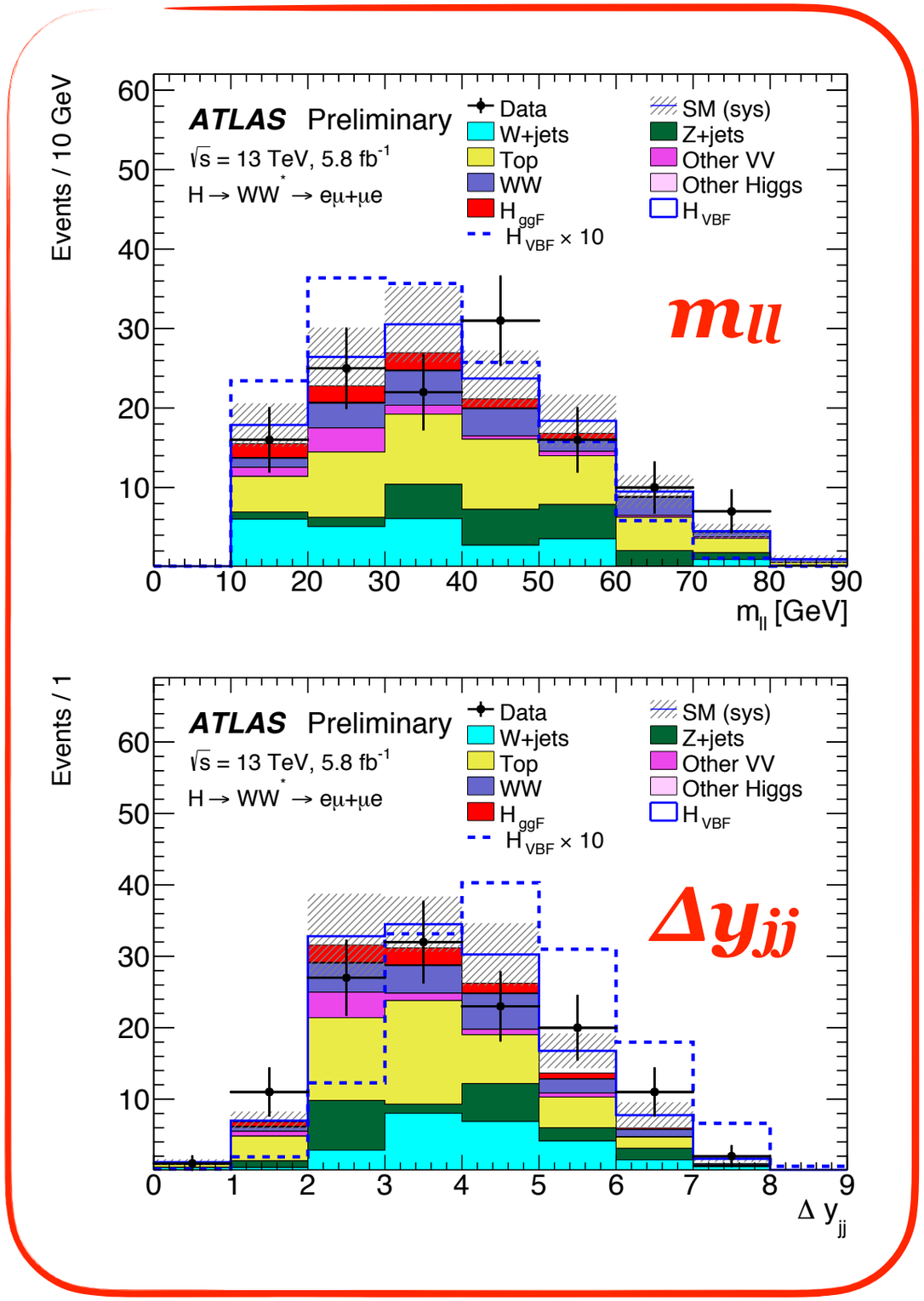
reject Top/select

reject/select Z+jet



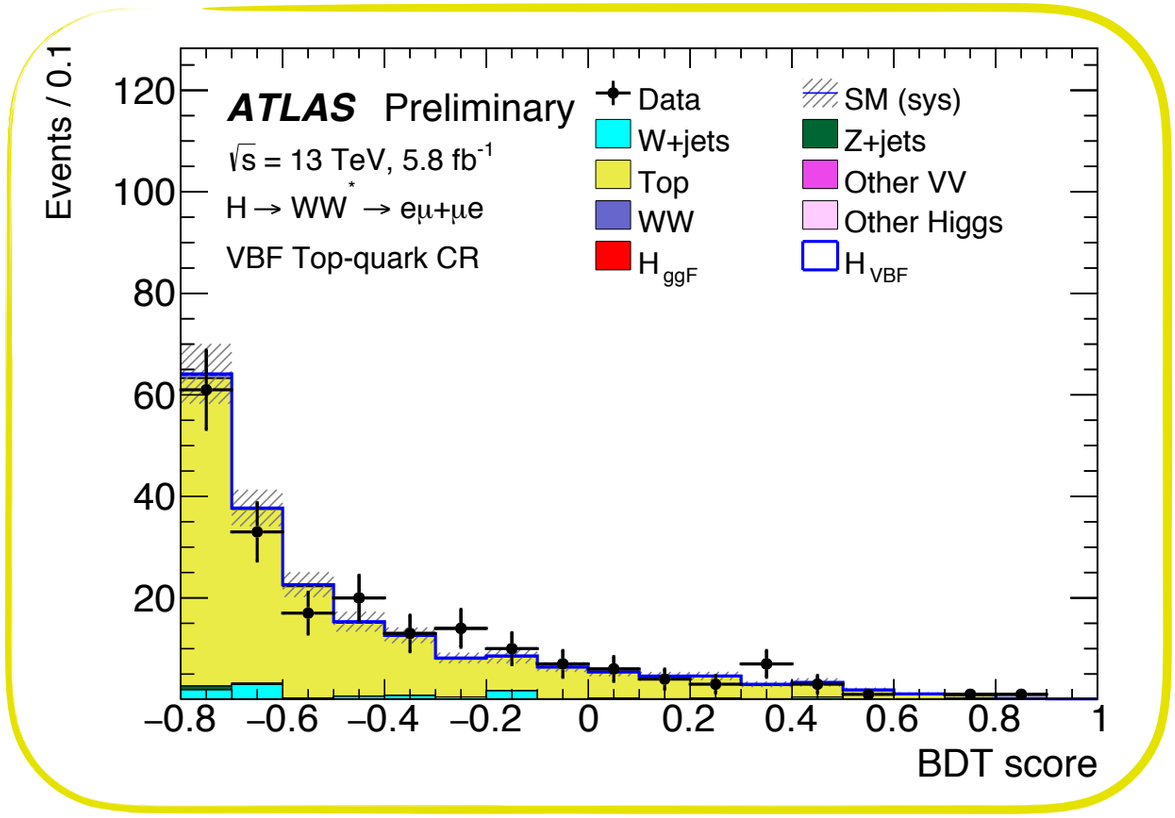
MVA Analysis

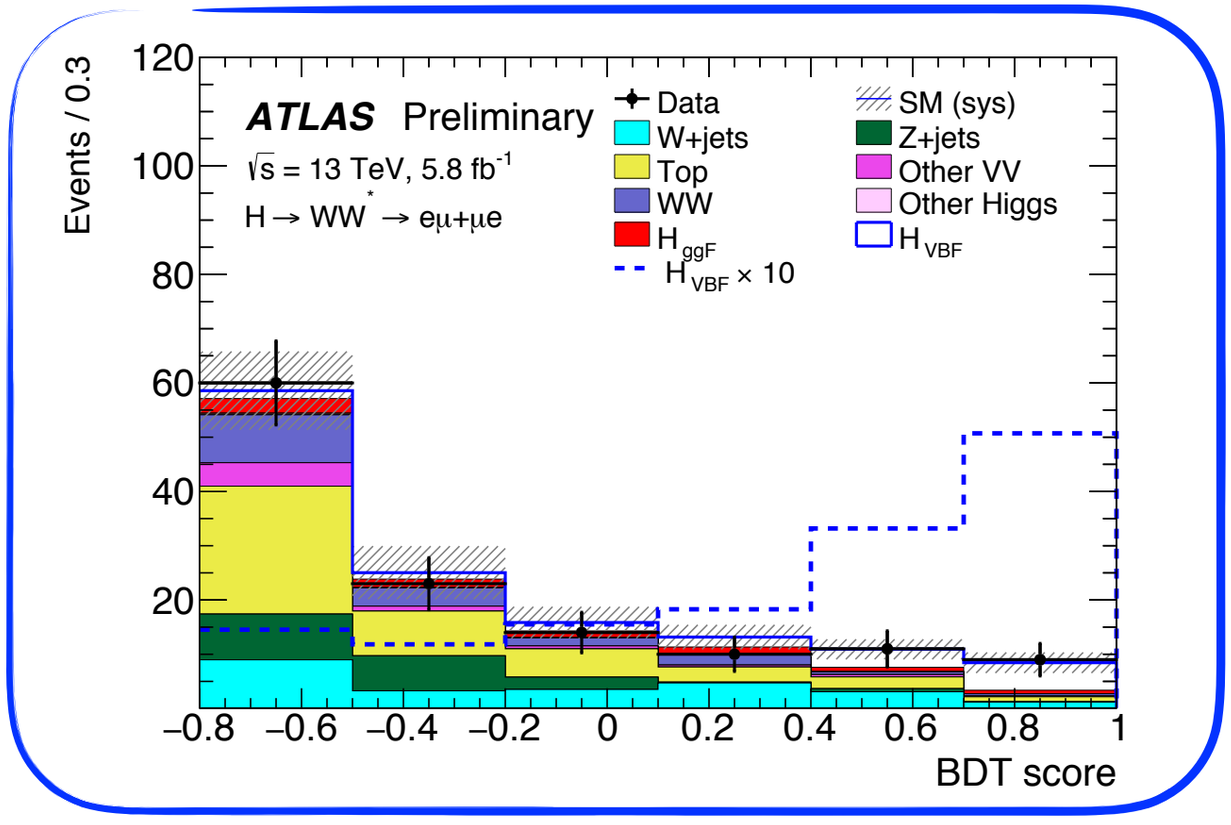
- The analysis uses a MVA to classify an event as signal- or background-like:
  - Signal: VBF
  - Bkg: Top,VV, Z+jets and ggF
- The training is performed after $N_{b\text{-}jet}=0$
- It uses information related to the production and decay topology
  - Leptons: m_{ll}, $\Delta\phi_{ll}$, m_T
  - Jets: m_{jj}, Δy_{jj}
  - Jets/Leptons: $\eta_{centrality}$, $\sum M_{lj}$, p_T^{tot}

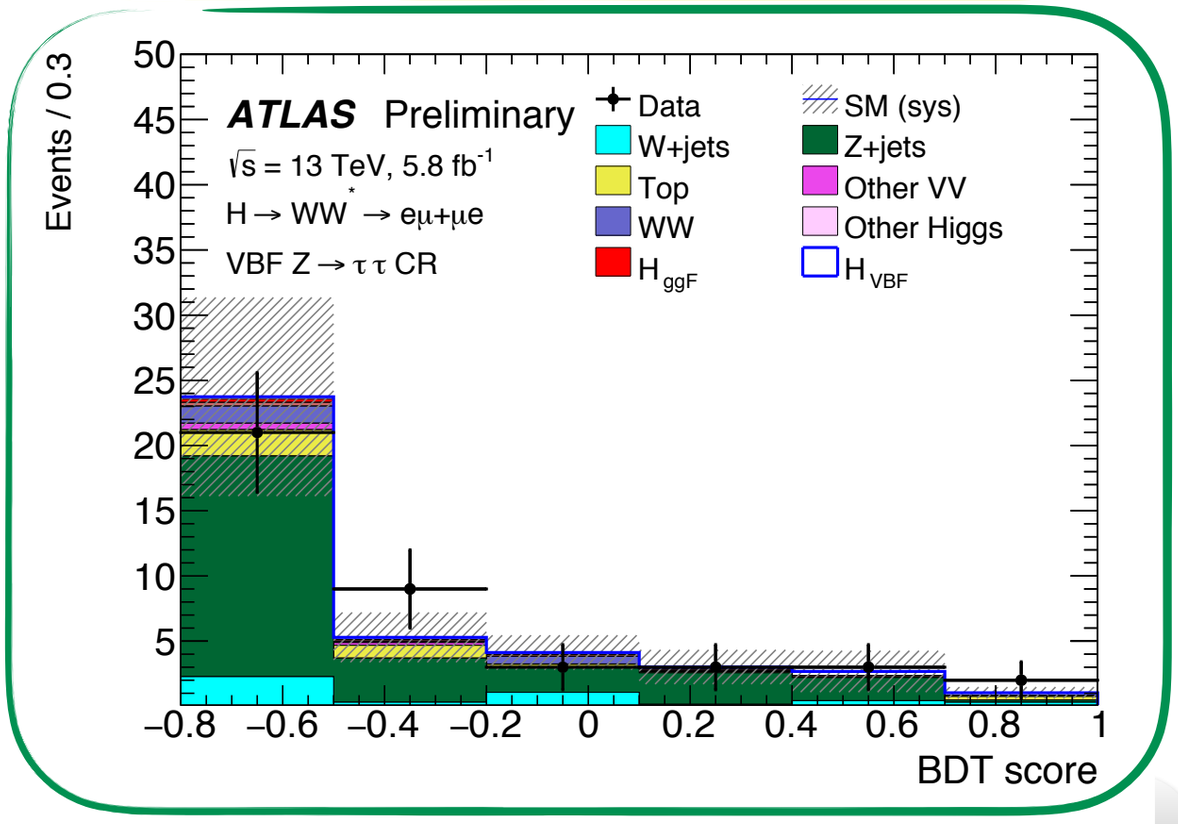


BDT Modelling

- BDT modelling has been checked in the **Top** and **Z→ττ** CRs and **SR**
  - Good data/MC region in all the regions
- Important shape different between signal and background in SR

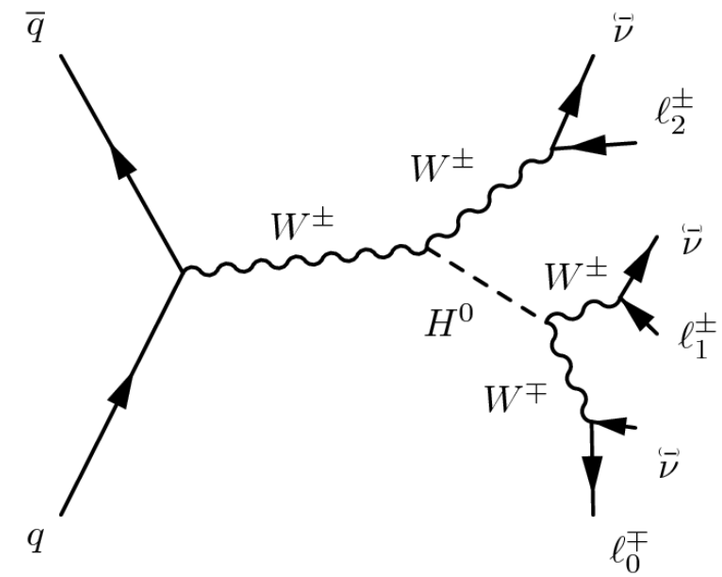






WH channel

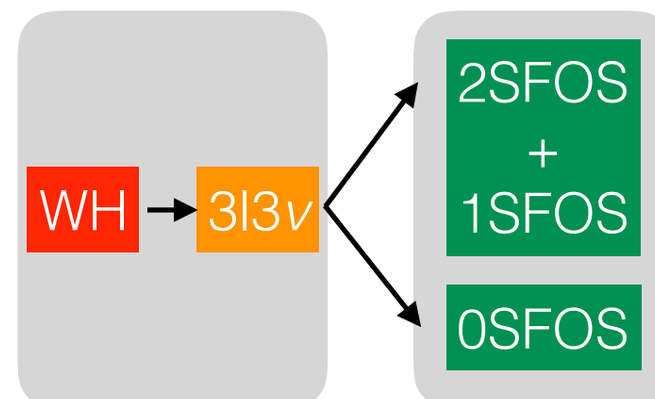
WH → WWW→ lvlvlvlv



- Test of the WH production
- Direct access to the Higgs boson couplings to W boson

Analysis Strategy

- Final state: 3 leptons (e/μ) with charge ±1 and E_T^{miss}
  - Origin of lepton with unique charge: Higgs decay
- Cut-Based Analysis:
  - Selection criteria are applied on: m_{ll}, m_{lll}, E_T^{miss} and ΔR
- 2 signal regions:
  - Z-dominated: at least one Z-candidate, 75% of the signal
  - Z-depleted: no Z-candidate, 25% of the signal



Nomenclature

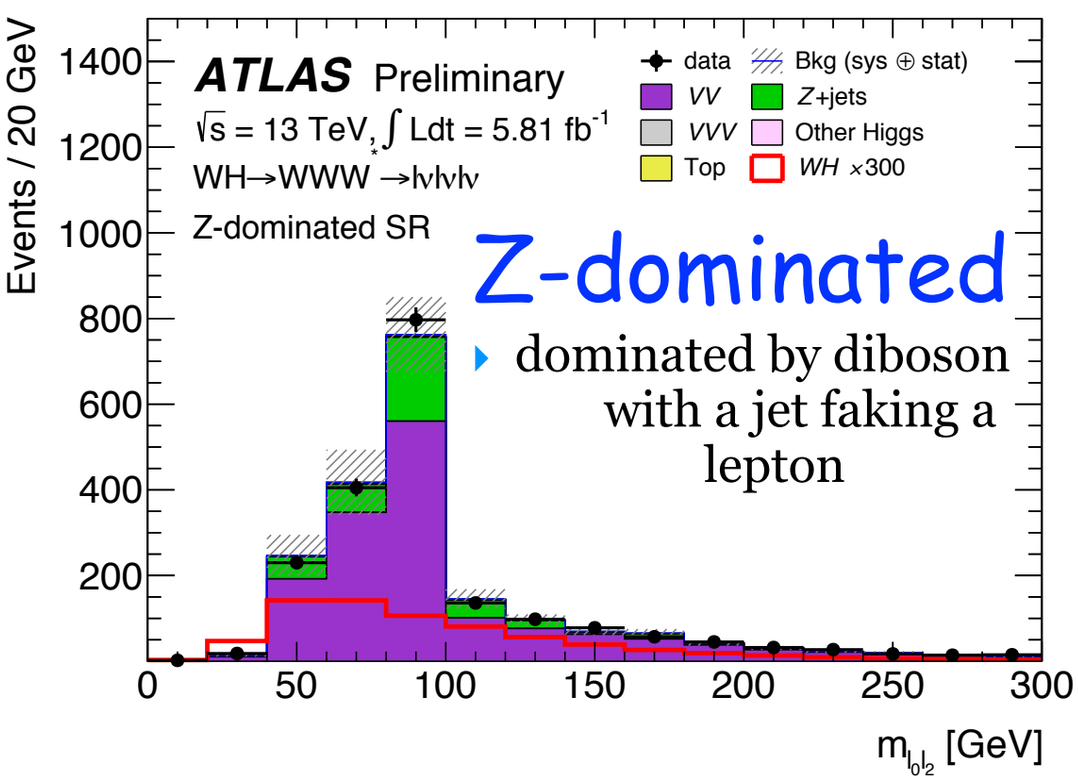
- l_0: lepton with unique charge
- l_1: lepton closest in ΔR to l_0
- l_2: remaining one
- SF: Same Flavour
- OS:Opposite Sign

Event Selection: Signal regions

Category	Z-dominated SR ≥ 1 SFOS pair	Z-depleted SR no SFOS pair
Preselection	Three isolated leptons (p_{T} >15 GeV) total charge $= \pm 1$ ≥ 1 lepton matches to the trigger	
Background Rejection	$N_{\mathrm{jet}} \leq 1$, $N_{b\text{-jet}} = 0$	reject Top
	$E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV	– reject Z+jet
reject WZ, ZZ and Z+jets	$\lvert m_{\ell^+\ell^-} - m_Z \rvert > 25$ GeV	$Z/\gamma^* \to ee$ veto
reject WZ/Wγ*	$m_{\ell^+\ell^-}^{\mathrm{max}} < 200$ GeV	
reject non prompt leptons	$m_{\ell^+\ell^-}^{\mathrm{min}} > 12$ GeV	$m_{\ell^+\ell^-}^{\mathrm{min}} > 6$ GeV
$H \to WW^* \to \ell\nu\ell\nu$ topology	$\Delta R_{\ell_0\ell_1} < 2.0$	Higgs Spin 0

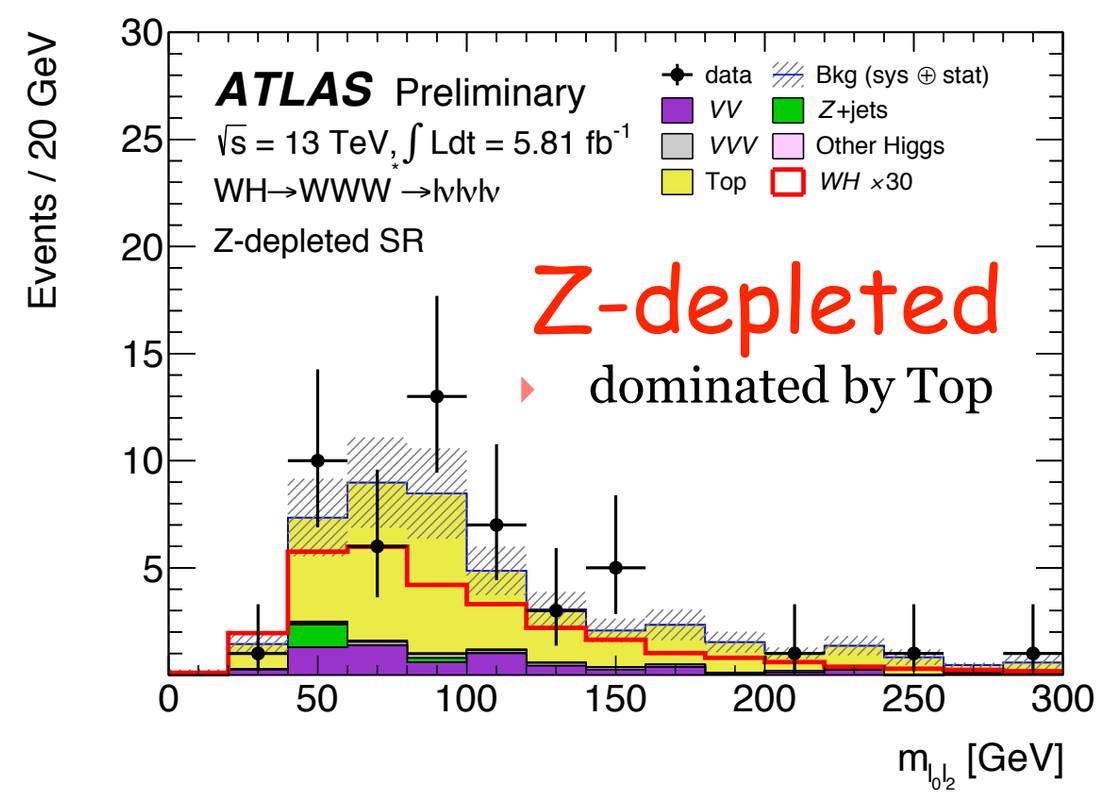
Main backgrounds:

- **VV:** WZ/Wγ*, ZZ*, Zγ
- **VVV**
- **Top:** mainly ttbar
- **Z+jets**



Z-dominated

- dominated by diboson with a jet faking a lepton

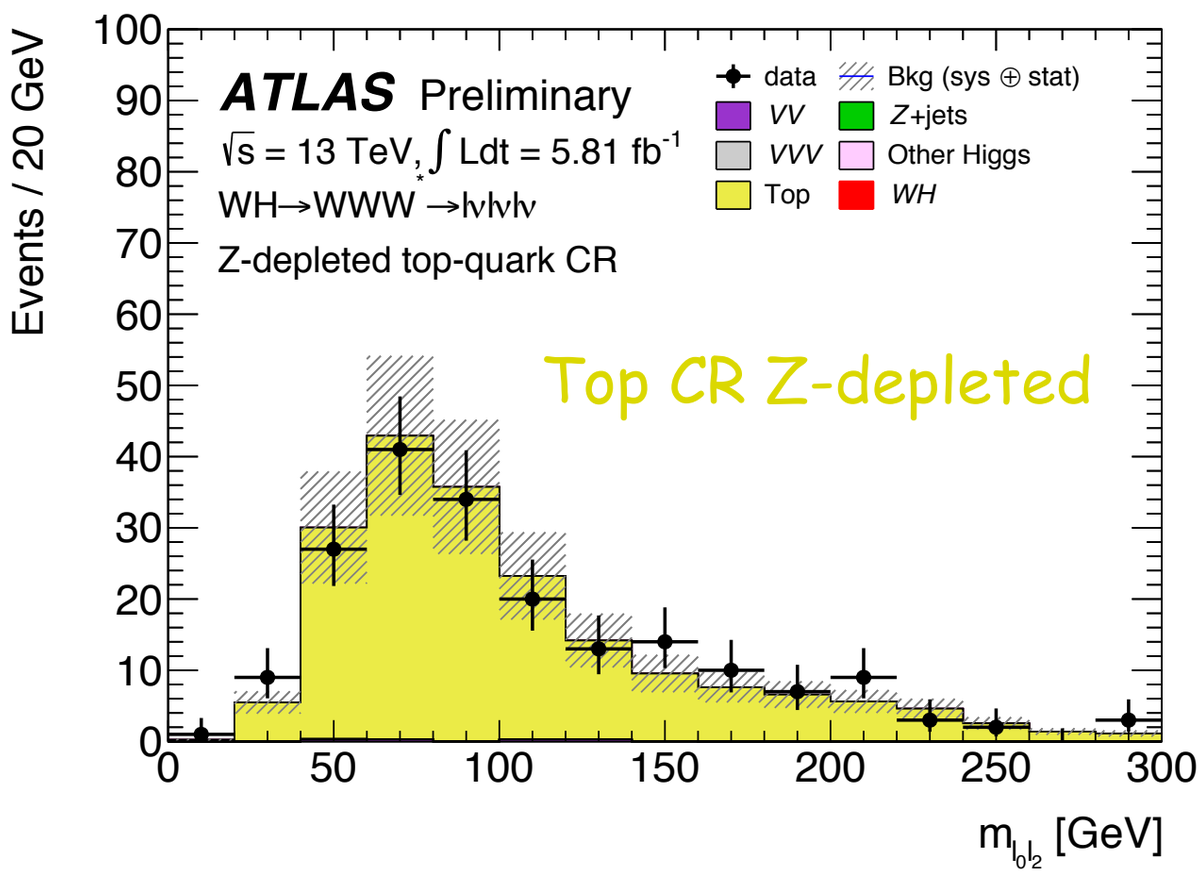


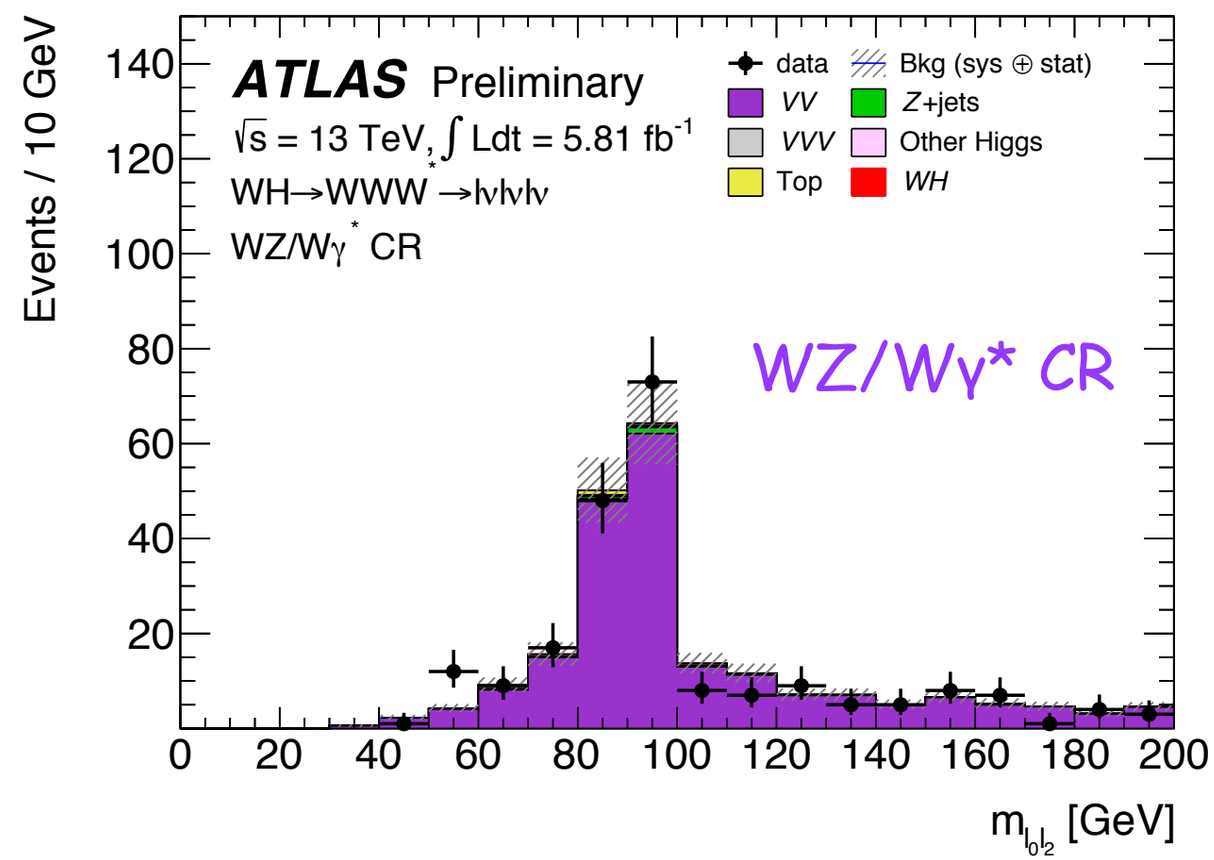
Z-depleted

- dominated by Top

Event Selection: Control regions

Process	Reference SR	Cut
Top quark	Z-depleted	at least 1 jet one b-jet one lepton without an isolation requirement
WZ/Wγ*	Z-dominated	≥1 SFOS pair with $\lvert m_{ll} - m_Z \rvert < 25$ GeV

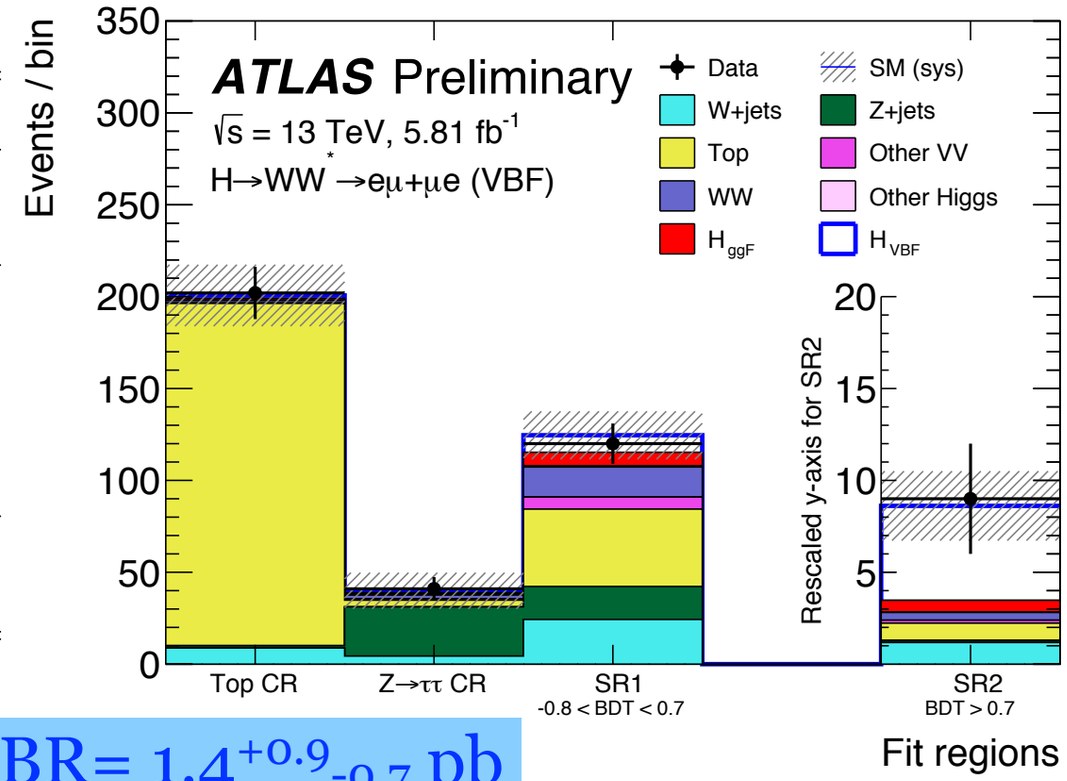




- Additional CRs defined for for Zγ, Z+jet used to extract Normalisation Factors

Results

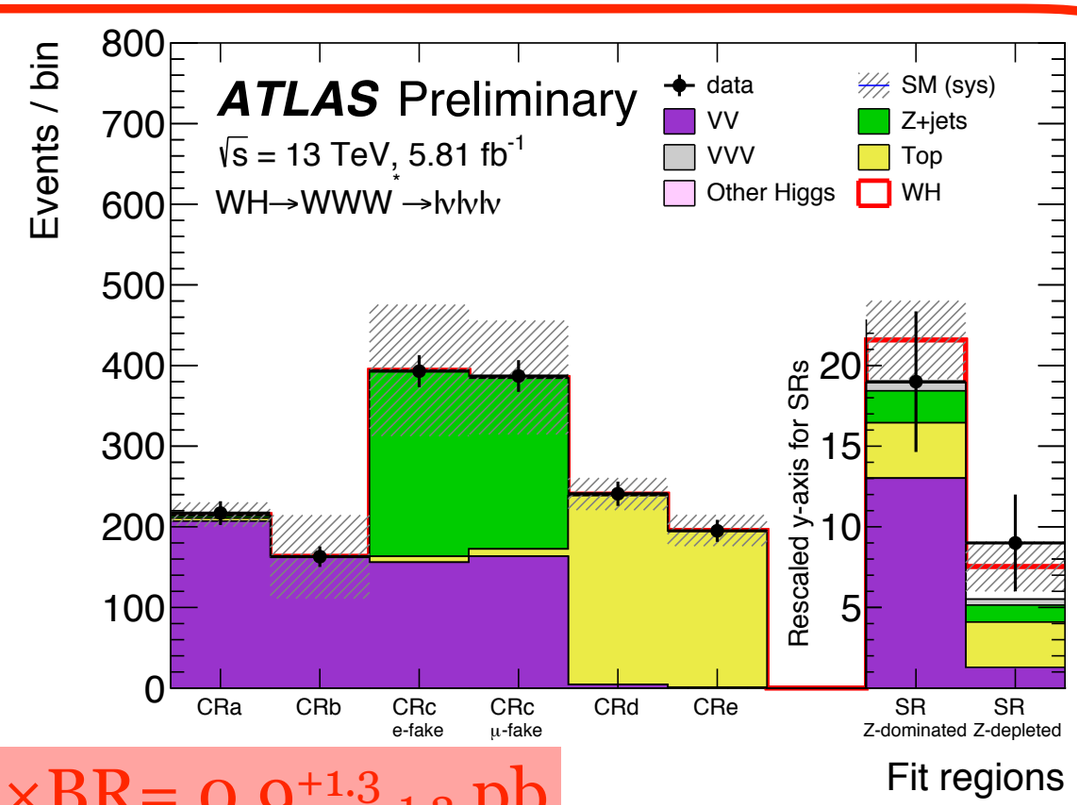
Category	SR1	SR2	Top CR	Z+jets CR
VBF	9.3 ± 3.6	5.1 ± 1.8	1.7 ± 0.6	1.1 ± 0.4
Other Higgs	8.0 ± 4.0	0.7 ± 0.4	1.1 ± 0.2	1.2 ± 0.0
WW	13.0 ± 8.0	0.4 ± 0.2	1.4 ± 0.5	2.0 ± 0.9
Other VV	6.6 ± 2.6	0.2 ± 0.1	0.2 ± 0.0	0.8 ± 0.2
Top quark	42.2 ± 7.6	0.9 ± 0.7	186 ± 17	3.6 ± 1.6
W+jets	24.3 ± 9.2	1.2 ± 0.7	8.8 ± 4.0	4.4 ± 2.2
Z+jets	18.0 ± 9.9	0.1 ± 0.1	1.3 ± 1.0	27 ± 10
Total background	115 ± 13	3.5 ± 1.9	199 ± 17	38.8 ± 9.8
Observed	120	9	202	41



- SR with 2 bins
- CRs with 1 bin

$\mu_{VBF}=1.7^{+1.1}_{-0.9} \rightarrow \sigma_{VBF}\times BR= 1.4^{+0.9}_{-0.7}$ pb

Category	Z-dominated	Z-depleted
WH	2.6 ± 1.0	2.0 ± 0.8
Other Higgs	0.1 ± 0.0	0.1 ± 0.0
VV	13.0 ± 1.6	1.3 ± 0.4
VVV	0.5 ± 0.1	0.4 ± 0.1
Top quark	3.4 ± 0.9	2.8 ± 0.8
Z+jets	2.0 ± 1.6	1.1 ± 1.1
Total background	19.1 ± 2.4	5.6 ± 1.5
Observed	19	9



- 2 SR with 1 bin
- 6 CRs with 1 bin

$\mu_{WH}=3.2^{+4.4}_{-4.2} \rightarrow \sigma_{WH}\times BR= 0.9^{+1.3}_{-1.2}$ pb

Systematic Uncertainties

- Leading sources of uncertainties on the measured signal strength, μ_{VBF} and μ_{WH}
  - Analyses limited by the data statistic
  - Important impact of the MC statistic

Source	$\Delta\mu_{\mathrm{VBF}}/\mu_{\mathrm{VBF}}$ [%]
Statistical	+60 / -50
Fake factor, sample composition	+18 / -15
MC statistical	±15
VBF generator	+14 / -5
WW generator	+11 / -7
QCD scale for ggF signal for $N_{\mathrm{jet}} \geq 3$	+8 / -7
Jet energy resolution	+8 / -7
b-tagging	+8 / -6
Pile-up	+8 / -6
QCD scale for ggF signal for $N_{\mathrm{jet}} \geq 2$	±6
JES flavour composition	+6 / -4
WW renormalisation scale	±5
Total systematic	+33 / -26
Total uncertainty	+70 / -50

Source	$\Delta\mu_{WH}/\mu_{WH}$ [%]
Statistical	+120 / -100
MC statistical	+60 / -70
Pile-up	+22 / -26
Jet energy resolution	+22 / -23
Top-quark generator	+17 / -20
b-tagging	+10 / -11
Top-quark PS/UE	+7 / -8
JES flavour comp.	+8 / -5
JES η intercalibration	+7 / -6
$WZ/W\gamma^*$ generator	+7 / -6
Top-quark QCD scales	+6 / -7
$WZ/W\gamma^*$ resum. scale	±5
Total systematic	+70 / -80
Total uncertainty	+140 / -130

Summary

- VBF and WH $H \rightarrow WW^* \rightarrow l\nu l\nu$ analyses performed using the 5.8 fb^{-1} of 2015+2016 data
- The observed (expected) signal significance at m_H= 125.0 GeV is 1.9σ (1.2σ) for VBF and 0.77σ (0.24σ) for W H
- The signal strengths are $\mu_{VBF}=1.7^{+1.1}_{-0.9}$ and $\mu_{WH}=3.2^{+4.4}_{-4.2}$
- Corresponding cross section times branching ratio are
  - $\sigma_{VBF}\times BR= 1.4^{+0.9}_{-0.7}$ pb —> 95% CL upper limit 3.0 pb
  - $\sigma_{WH}\times BR= 0.9^{+1.3}_{-1.2}$ pb —> 95% CL upper limit 3.3 pb
- **Future steps:**
  - Analyse the full 2015+2016 dataset ~36/fb
  - Perform the inclusive XS measurement of gluon fusion and VBF
  - Working on fiducial and differential measurements

Thanks for the attention!

MC Samples

- Monte Carlo generators used to model the signal and background processes with the corresponding product of cross section and the branching ratio for the Higgs boson production ar 13 TeV

Mode	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
ggF	POWHEG [13,14,15]+PYTHIA 8 [19]	$10.38^{+0.58}_{-0.77}$
VBF	POWHEG +PYTHIA 8	0.808 ± 0.021
WH	POWHEG +PYTHIA 8 (MiNLO [25])	0.293 ± 0.007
ZH	POWHEG +PYTHIA 8 (MiNLO)	$0.189^{+0.008}_{-0.007}$

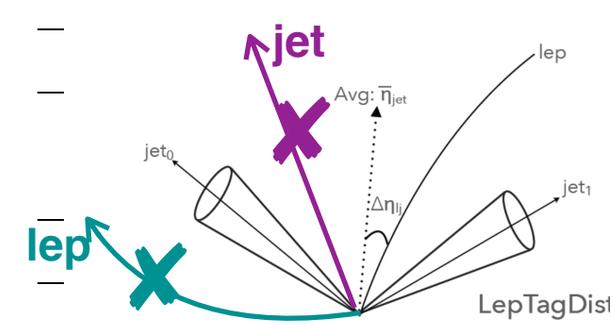
Background	MC generator
$q\bar{q}/g \to \ell\ell\ell\ell, \ell\nu\ell\ell, \ell\nu\ell\nu$	SHERPA [16]
$gg \to \ell\ell\ell\ell, \ell\nu\ell\nu$	SHERPA
EW $\ell\ell\ell\ell, \ell\nu\ell\ell, \ell\nu\ell\nu$	SHERPA
$q\bar{q}/g \to WW, Z^{(*)}Z^{(*)} \to \ell\nu\ell\nu$	POWHEG +PYTHIA 8
$t\bar{t}$, tW	POWHEG +PYTHIA 6 [38]
$t\bar{t}W/Z$, tZ	MADGRAPH 5 [17]
$W\gamma$, $Z\gamma$	SHERPA
Z+jets	MADGRAPH 5
VBF $q\bar{q} \to (Z \to \tau\tau)q\bar{q}$	SHERPA
WWW, WWZ, ZZW, ZZZ	SHERPA

Event Selection

Main backgrounds:

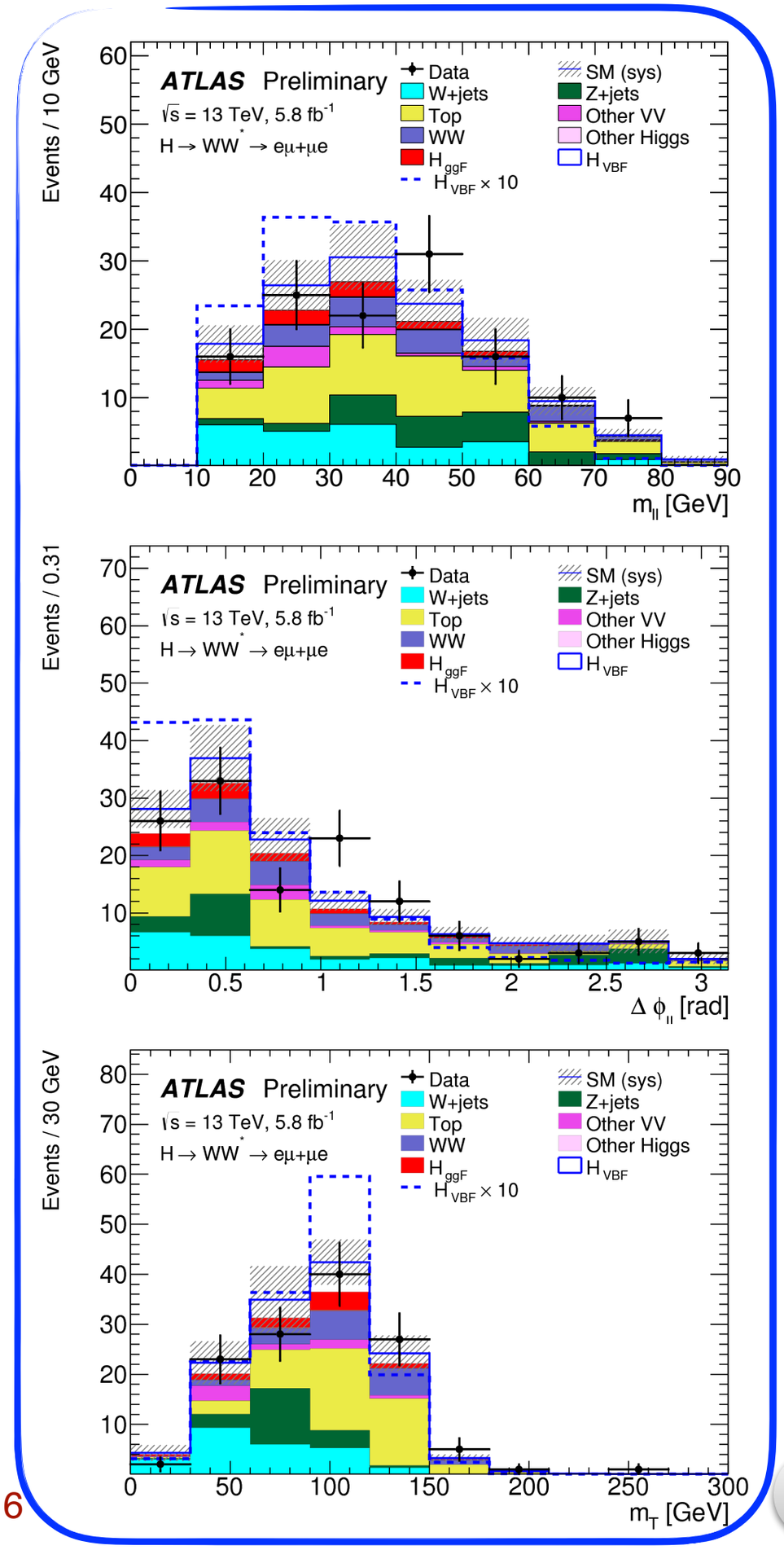
- **ggF** estimated with MC simulation
- **WW**: estimated with MC simulation
- **Top** and **Z→ττ**: shape form MC simulation, NF estimated with data
- **W+jets**: data-driven from events with one lepton satisfying only loose but failing tight ID criteria; fake factors measured in a di-jet sample

	Signal region	$Z \to \tau\tau$ CR	Top-quark CR
Preselection	Two isolated leptons ($\ell = e, \mu$) with opposite charge $p_{\mathrm{T}}^{\mathrm{lead}} > 25GeV$ ($p_{\mathrm{T}}^{\mathrm{lead}} > 22GeV$ for muons in 2015), $p_{\mathrm{T}}^{\mathrm{sublead}} > 15GeV$ $m_{\ell\ell} > 10GeV$, $N_{\mathrm{jet}} \geq 2$		
	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$
A BDT is trained at this level. Eight discriminant variables are used: $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, m_{T}, Δy_{jj}, m_{jj}, $p_{\mathrm{T}}^{\mathrm{tot}}$, $\sum_{\ell,j} m_{\ell j}$, and $\eta_{\ell}^{\mathrm{centrality}}$			
Selection	$m_{\tau\tau} < 66.2GeV$	$\lvert m_{\tau\tau} - m_Z \rvert < 25GeV$	–
	–	$m_{\ell\ell} < 80GeV$	–
	OLV applied	CJV applied, BDT > -0.8	
	SR1: $-0.8 < \mathrm{BDT} \leq 0.7$	–	–
	SR2: $0.7 < \mathrm{BDT} \leq 1$	–	–



MVA Analysis

- The analysis uses a BDT to classify an event as signal- or background-like:
  - Signal: VBF
  - Bkg: Top,VV, Z+jets and ggF
- The training is performed after $N_{b\text{-jet}}=0$
- It uses information related to the production and decay topology
  - ➡ Leptons: m_{ll}, $\Delta\phi_{ll}$,m_T
  - Jets: m_{jj}, Δy_{jj}
  - Jets/Leptons: $\eta_{centrality}$, $\sum M_{lj}$, p_T^{tot}



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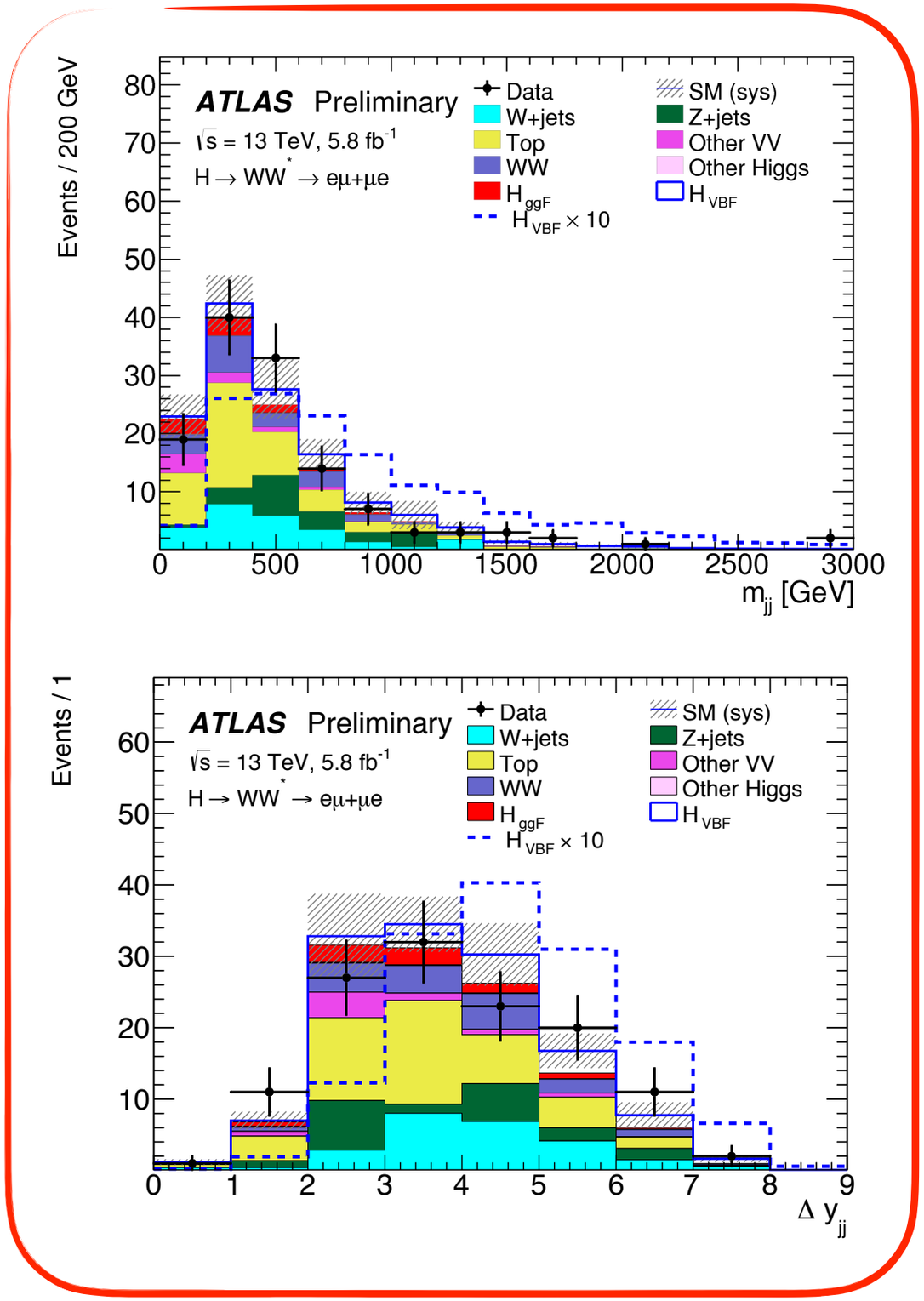
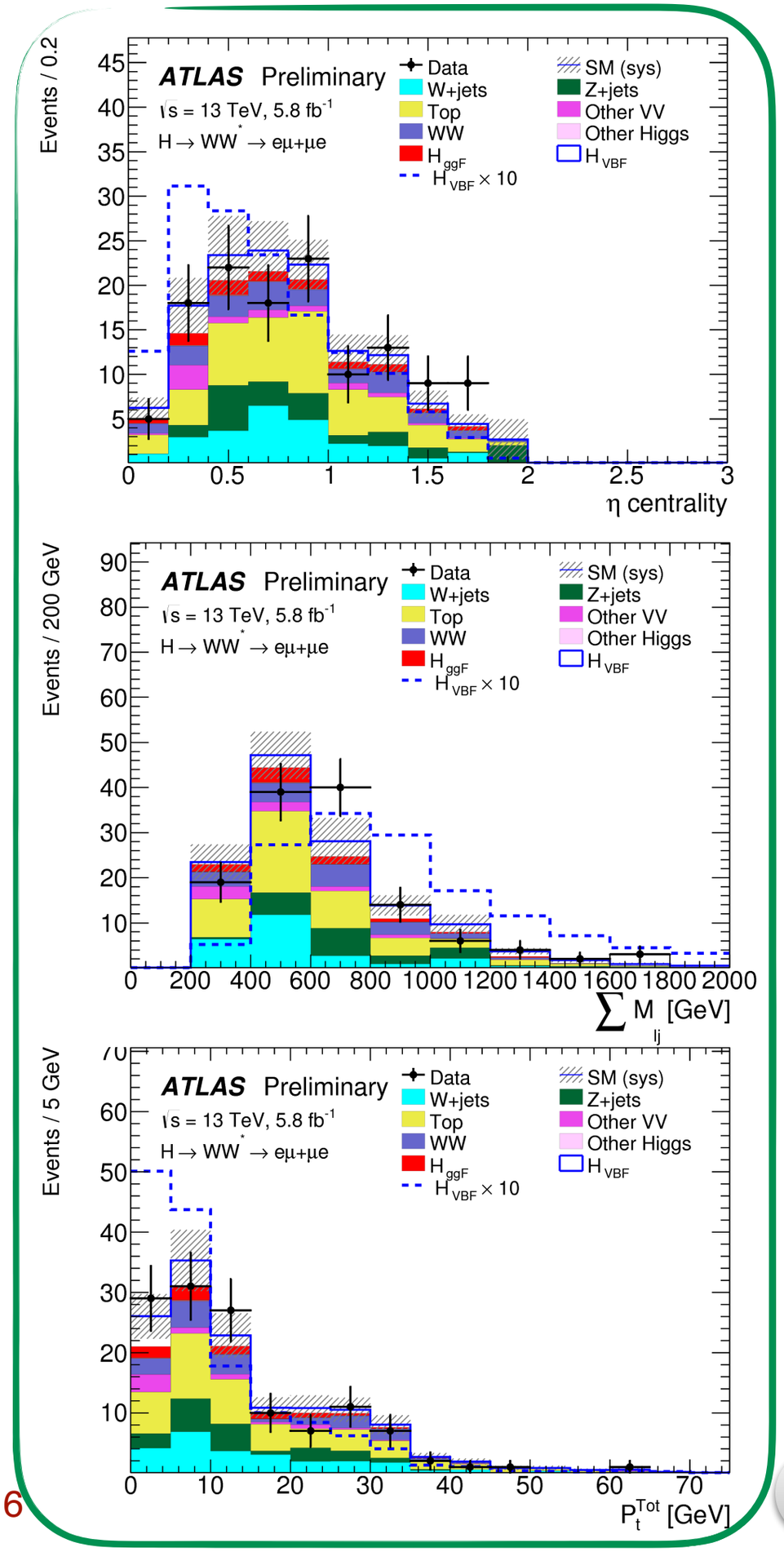
  - ➡ Jets: m_{jj}, Δy_{jj}
  - Jets/Leptons: $\eta_{centrality}$, $\sum M_{lj}$, p_T^{tot}



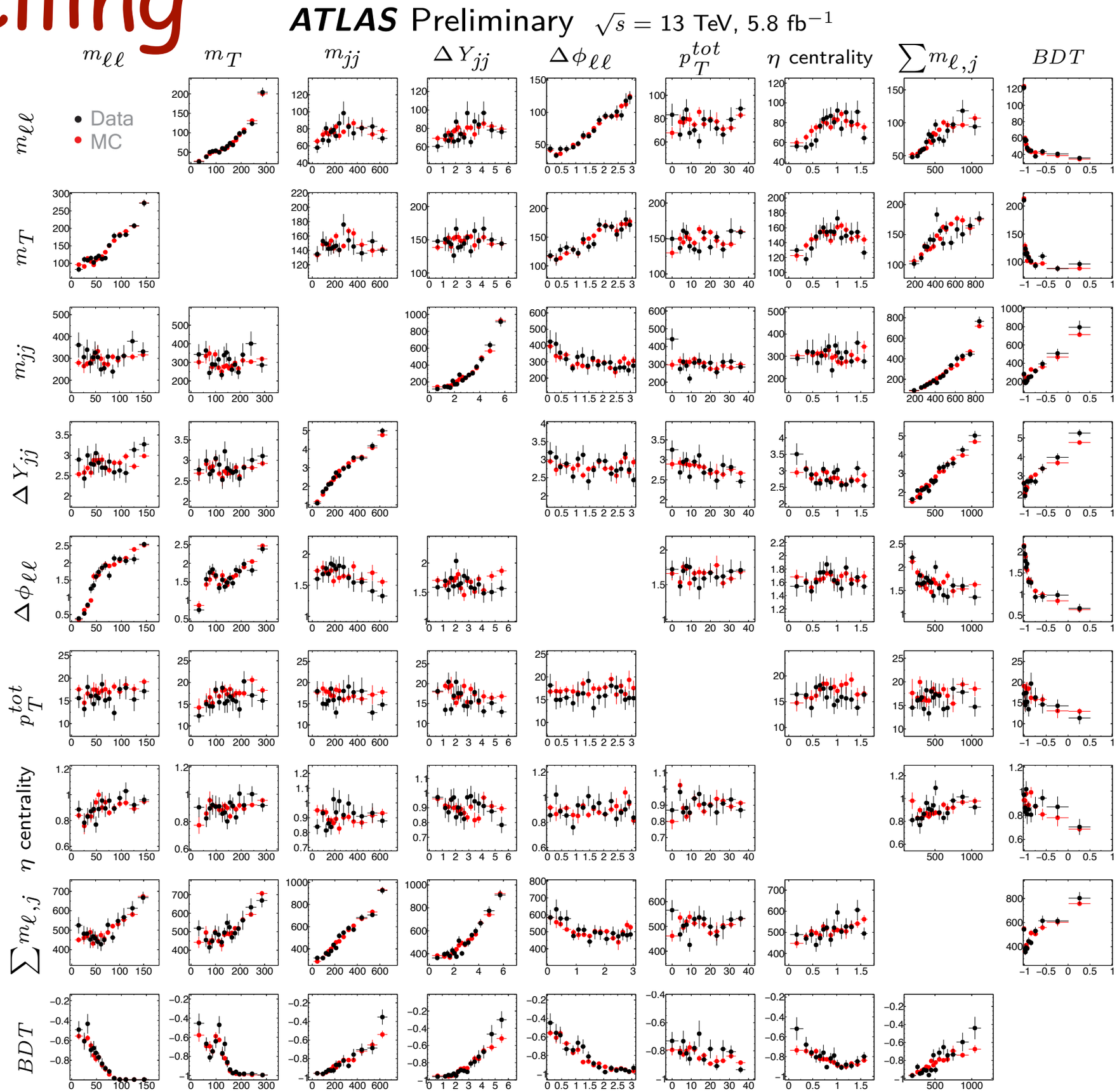
MVA Analysis

- The analysis uses a BDT to classify an event as signal- or background-like:
  - Signal: VBF
  - Bkg: Top,VV, Z+jets and ggF
- The training is performed after $N_{b\text{-}jet}=0$
- It uses information related to the production and decay topology
  - Leptons: m_{ll}, $\Delta\phi_{ll}$,m_T
  - Jets: m_{jj}, Δy_{jj}
  - ➡ Jets/Leptons: $\eta_{centrality}$, $\sum M_{lj}$, p_T^{tot}



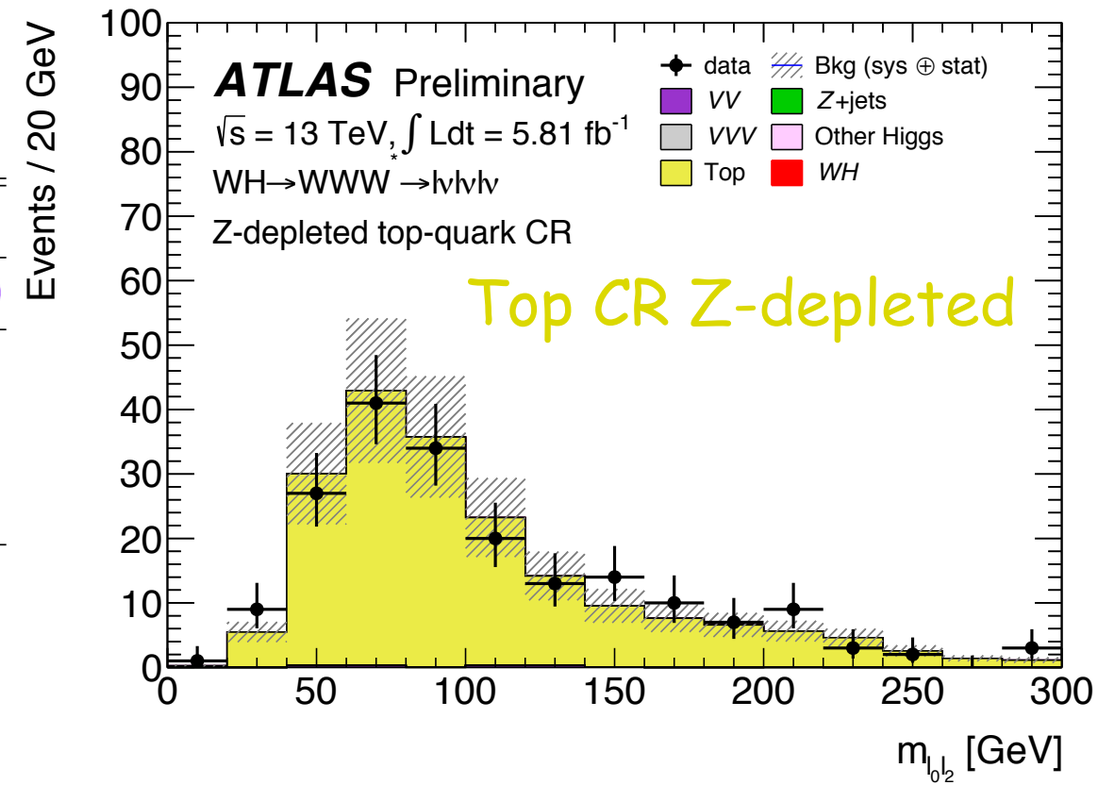
BDT Modelling

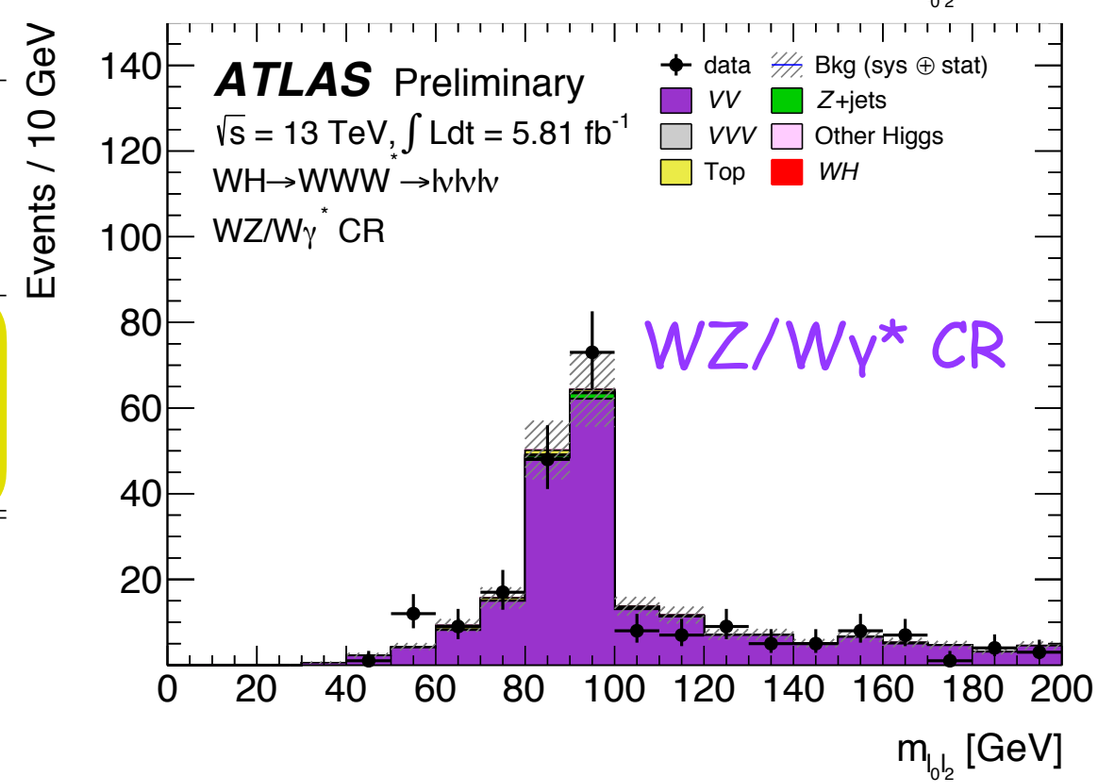
- Correlation plots of BDT classification variables in the signal region of BDT
- For variable v_X and v_Y in row x and column y, the distributions of $< v_X >$ versus $< v_Y >$, and vice versa, are shown for each pair of training variable in the BDT as well as the correlation of each training variable with BDT



Event Selection: Control regions

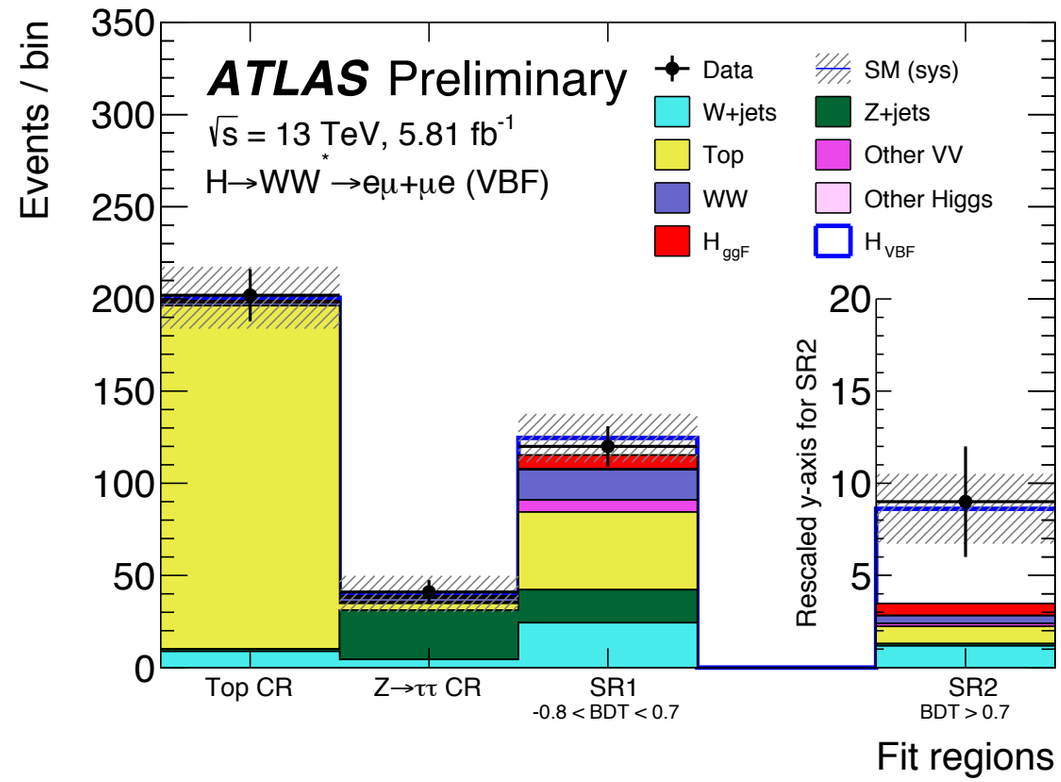
CR	Process	Reference SR	Changes w.r.t. reference SR
CRa	$WZ/W\gamma^*$	Z-dominated	≥ 1 SFOS pair with $\lvert m_{\ell\ell} - m_Z \rvert < 25$ GeV
CRb	$Z\gamma$	Z-dominated	no Z-mass veto $\lvert m_{\ell\ell\ell} - m_Z \rvert < 15$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV only $eee, \mu\mu e$
CRc	Z+jets	Z-dominated	≥ 1 SFOS pair with $\lvert m_{\ell\ell} - m_Z \rvert < 25$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV $\lvert m_{\ell\ell\ell} - m_Z \rvert > 15$ GeV one lepton without an isolation requirement (NFs are derived for e-fake sample and μ-fake sample separately)
CRd	Top quark	Z-dominated	no $m_{\ell^+\ell^-}^{\max}$ and $\Delta R_{\ell_0\ell_1}$ cuts at least 1 jet one b-jet one lepton without an isolation requirement
CRe	Top quark	Z-depleted	no $m_{\ell^+\ell^-}^{\max}$ and $\Delta R_{\ell_0\ell_1}$ cuts at least 1 jet one b-jet one lepton without an isolation requirement





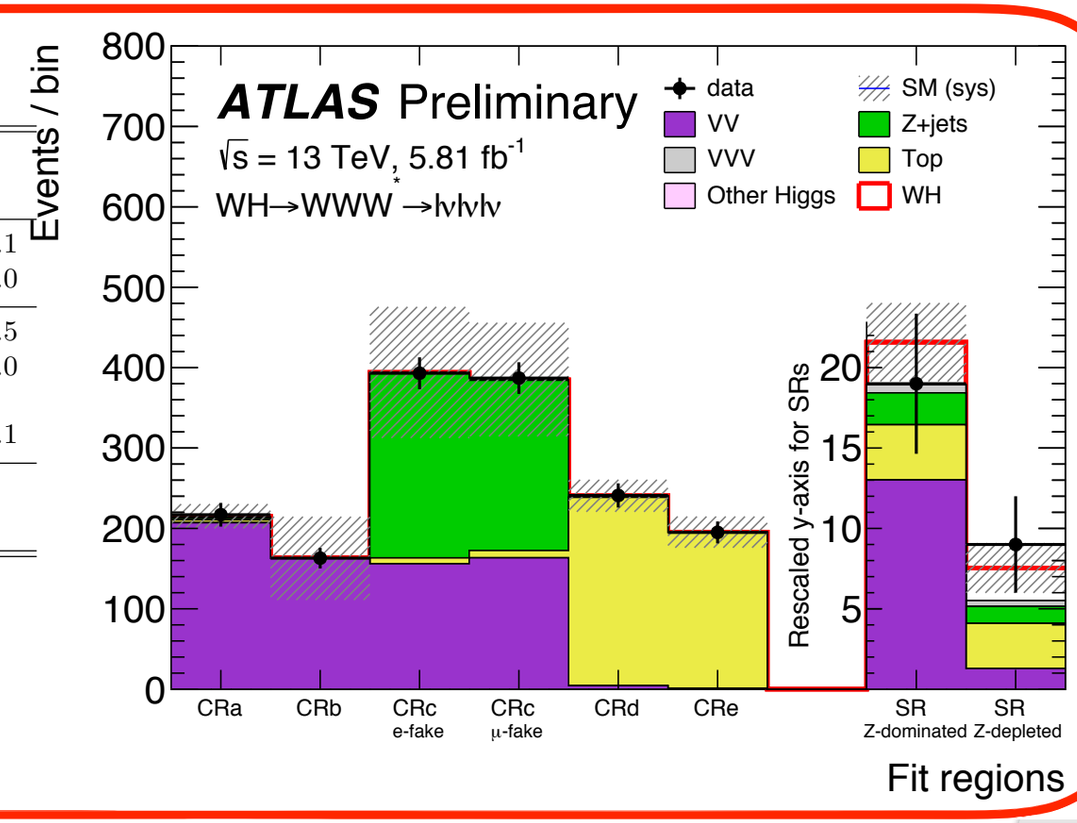
Results

Category	SR1	SR2	Top CR	Z+jets CR
VBF	9.3 ± 3.6	5.1 ± 1.8	1.7 ± 0.6	1.1 ± 0.4
Other Higgs	8.0 ± 4.0	0.7 ± 0.4	1.1 ± 0.2	1.2 ± 0.0
WW	13.0 ± 8.0	0.4 ± 0.2	1.4 ± 0.5	2.0 ± 0.9
Other VV	6.6 ± 2.6	0.2 ± 0.1	0.2 ± 0.0	0.8 ± 0.2
Top quark	42.2 ± 7.6	0.9 ± 0.7	186 ± 17	3.6 ± 1.6
W+jets	24.3 ± 9.2	1.2 ± 0.7	8.8 ± 4.0	4.4 ± 2.2
Z+jets	18.0 ± 9.9	0.1 ± 0.1	1.3 ± 1.0	27 ± 10
Total background	115 ± 13	3.5 ± 1.9	199 ± 17	38.8 ± 9.8
Observed	120	9	202	41



- SR with 2 bins
- CRs with 1 bin

Category	CRa	CRb	CRc e-fake	CRc μ-fake	CRd	CRe
WH	1.0 ± 0.4	0.3 ± 0.0	0.4 ± 0.1	0.5 ± 0.0	0.2 ± 0.1	0.1 ± 0.1
Other Higgs	0.8 ± 0.0	0.0 ± 0.0	0.4 ± 0.0	0.4 ± 0.0	0.1 ± 0.0	0.0 ± 0.0
VV	207 ± 15	163 ± 53	156 ± 13	163 ± 14	4.4 ± 0.8	1.0 ± 0.5
VVV	0.9 ± 0.2	0.0 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.1	0.2 ± 0.0
Top quark	3.7 ± 0.6	0.4 ± 0.2	7.3 ± 0.9	9.1 ± 1.2	234 ± 19	194 ± 19
Z+jets	2.5 ± 1.2	0.0 ± 0.0	230 ± 83	212 ± 73	2 ± 0.7	0.1 ± 0.1
Total background	215 ± 15	163 ± 52	394 ± 82	385 ± 71	240 ± 20	195 ± 19
Observed	217	163	393	387	241	195



- 2 SR with 1 bin
- 6 CRs with 1 bin