Search for heavy diboson resonances in semileptonic final states

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Introduction

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  - Gravity
  - Hierarchy problem
  - Matter-antimatter asymmetry

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  - Heavy vector triplet (HVT) W', Z'
  - Randall–Sundrum model

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- Several **new physics models** suggest possible solutions:
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  - Randall–Sundrum model

→ Predict exsisting new heavy resonances that decay into a **pair of SM bosons**

VV or Vh

$V = Z, W$

Search for dibosons

- Looking for heavy resonances that decays into a pair of bosons: WW, WZ, ZZ, Wh and Zh

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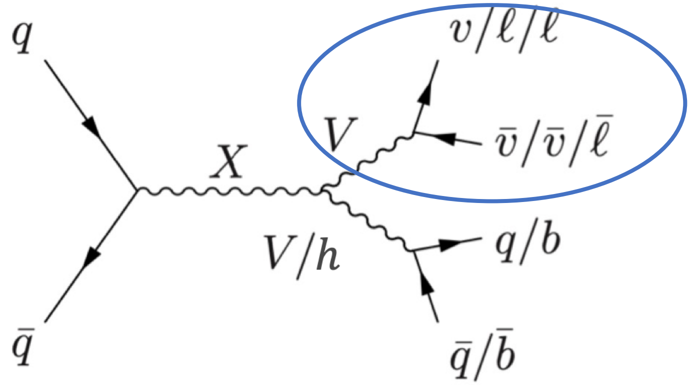
  1. $Z \rightarrow \nu\nu$ (0-lepton)
  2. $W \rightarrow l\nu$ (1-lepton)
  3. $Z \rightarrow ll$ (2-lepton)



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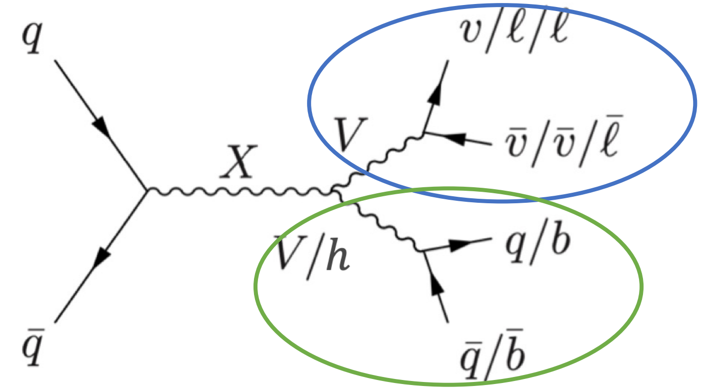
  2. $V/h \rightarrow$ 1 large-R jet (Merged)



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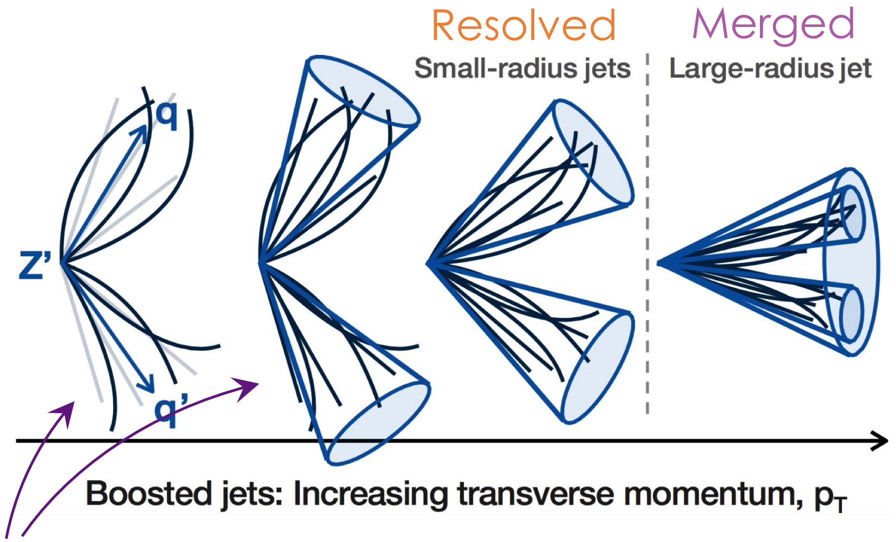

"**jet**" is a cluster of hadrons that originates from a quark or gluon

Search for dibosons

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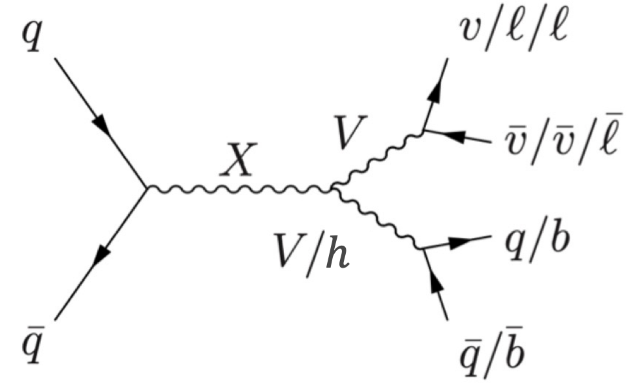
- The second round of the analysis that uses full Run-2 ATLAS data



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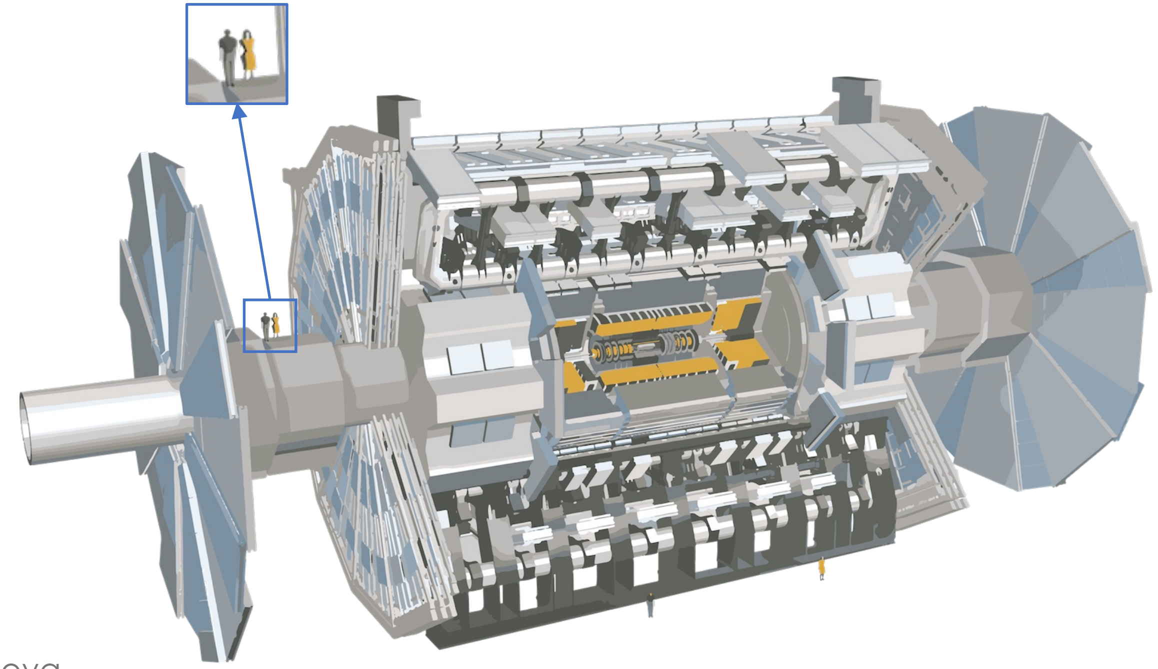
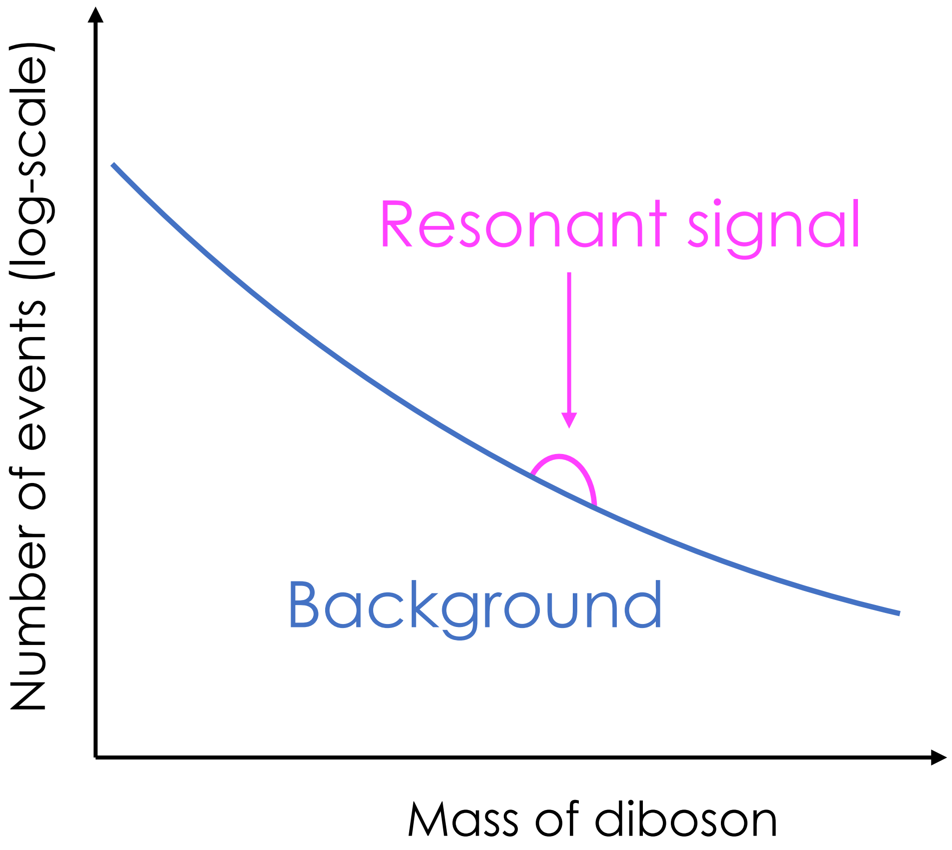


Signal and backgrounds

- Expect our signal to look like a resonance peak

Ideal situation



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- The signal has in the final states:
  - Electrons and/or muons
  - Missing energy (from un-detected neutrinos)
  - Jets

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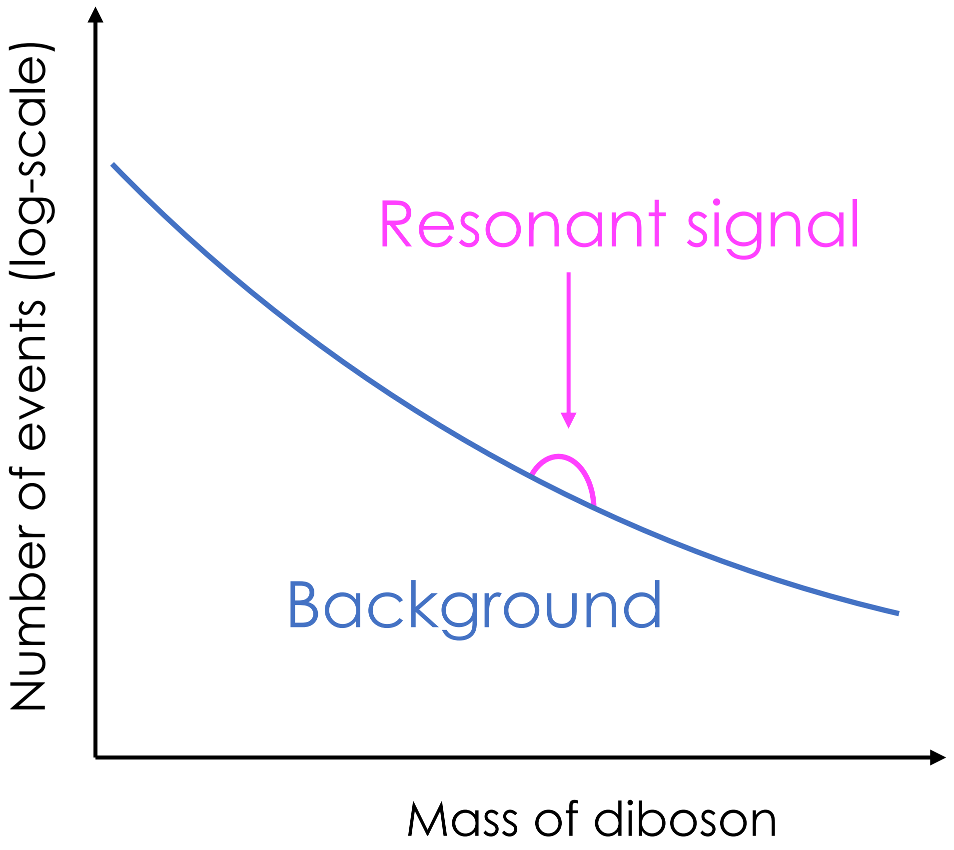
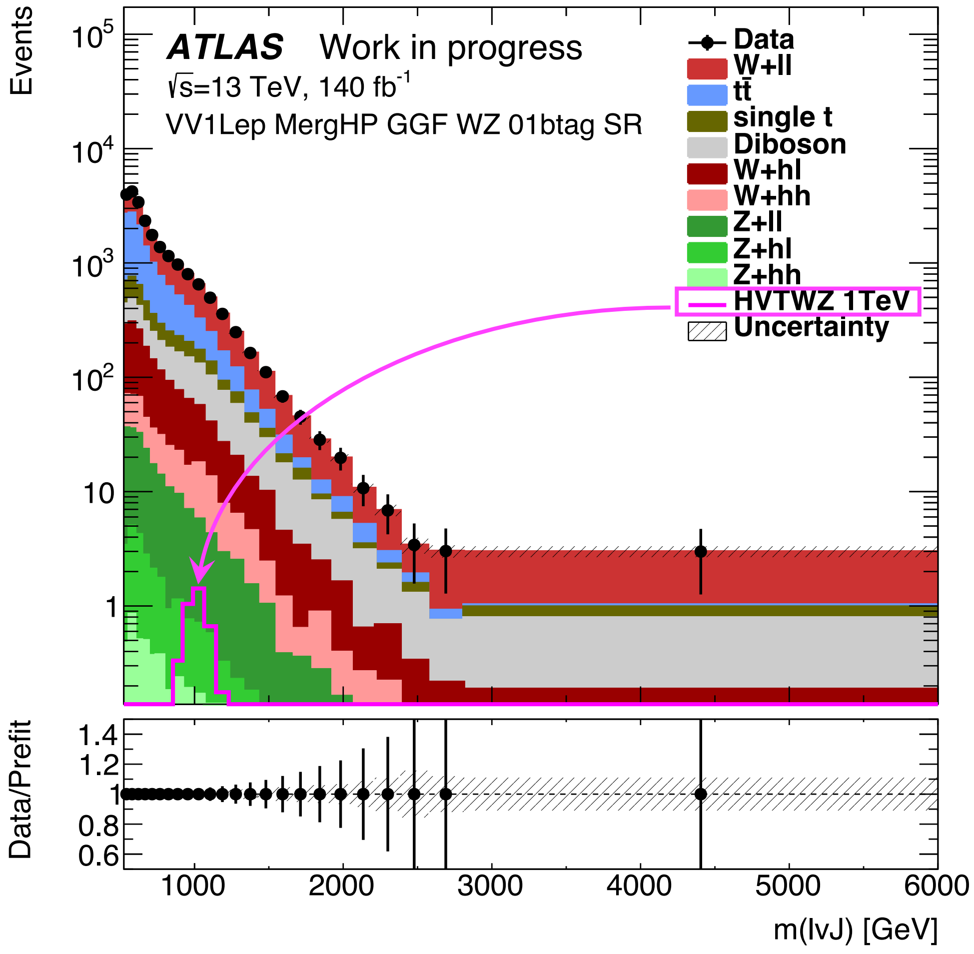


Signal and backgrounds

- Expect our signal to look like a resonance peak
- The signal has in the final states:
  - Electrons and/or muons
  - Missing energy (from un-detected neutrinos)
  - Jets
- Other processes have similar final states
- Need to efficiently reject background events:
  - Detailed event selection
  - Various techniques and algorithms

Real situation



Event selection

0, 1 or 2 leptons

↓

VV or Vh

↓

Production mode (GGF or VBF)

↓

Merged or Resolved

↓

Mass-window of a $W/Z/h$ boson

↓

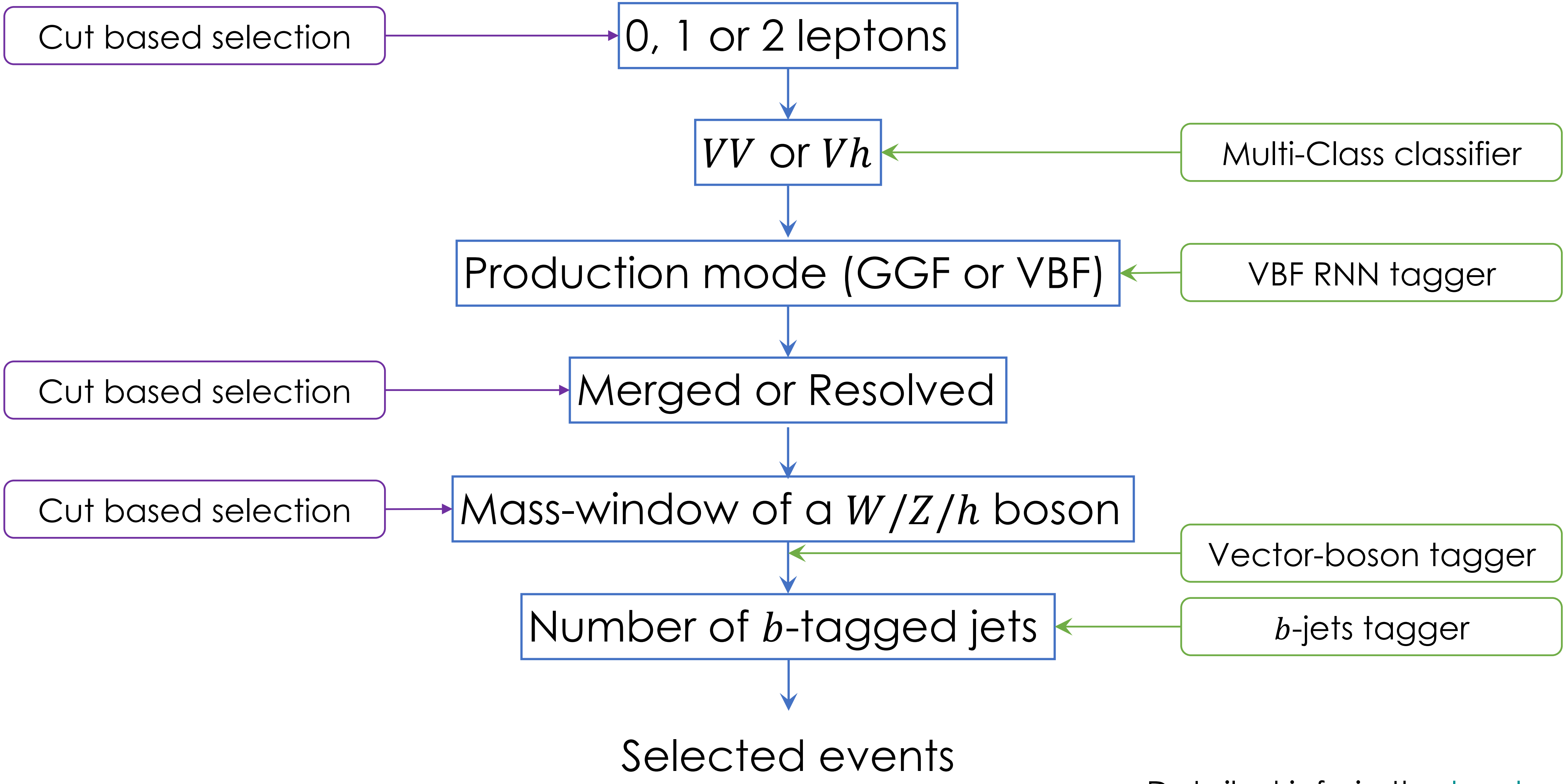
Number of b-tagged jets

↓

Selected events

Detailed info in the backup

Event selection



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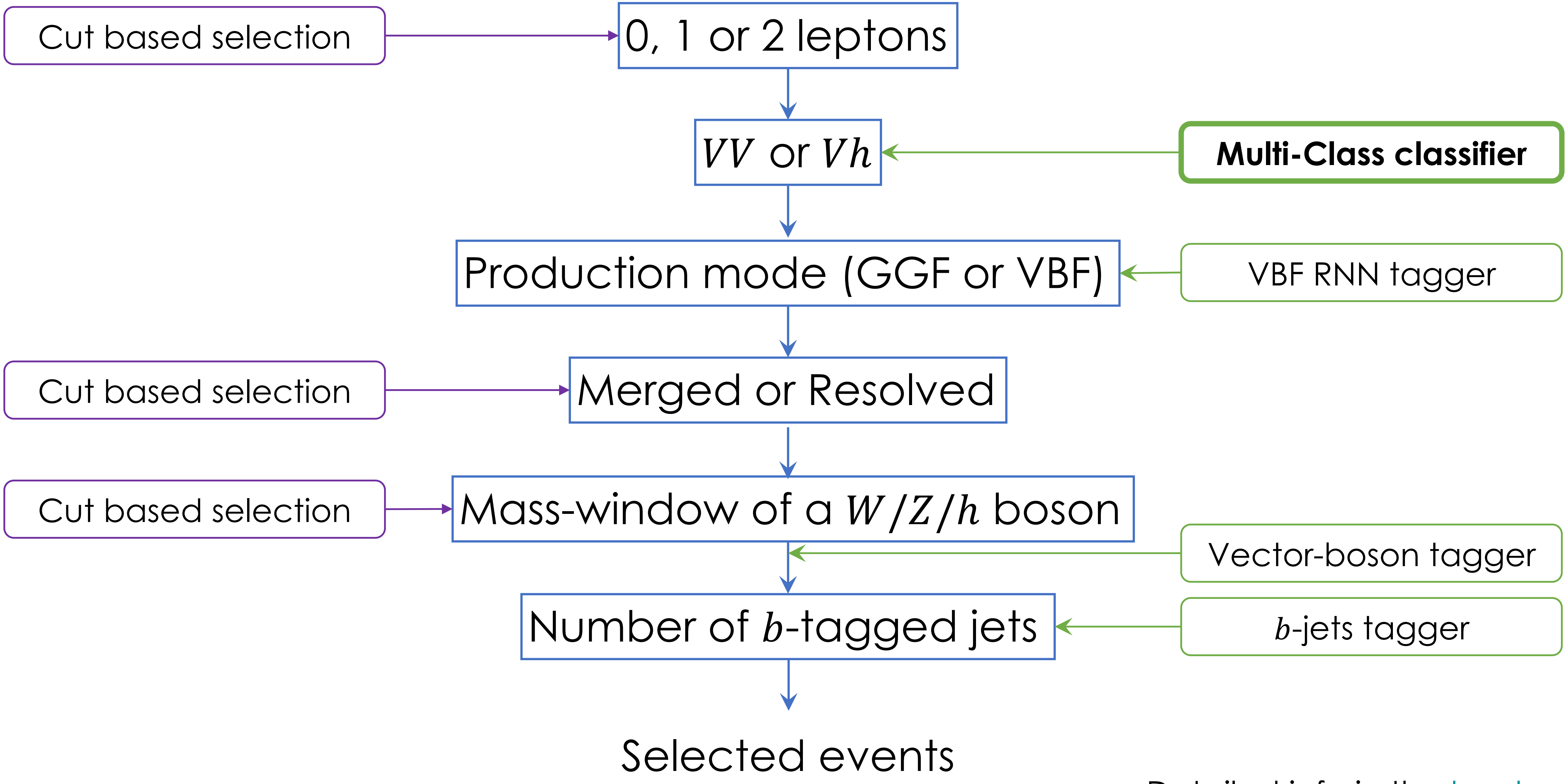

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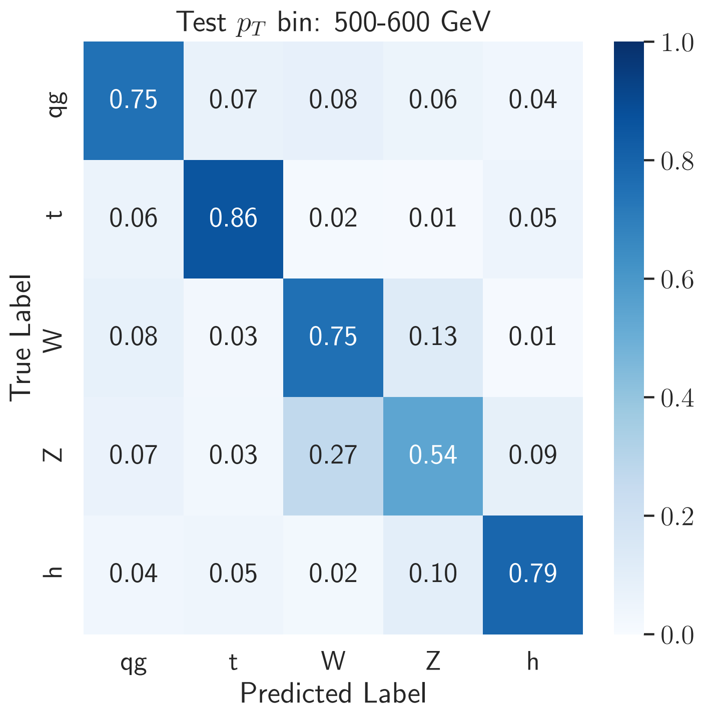
Multi-Class Classifier

➢DNN based classifier to orthogonalise VV and Vh channels
- Uses jet substructure and jet 4-momenta as input
- Outputs 5 classes: Higgs, W, Z, top, QCD
- Only applied on events that are selected in both VV and Vh

Good predictive power



Confusion matrix

Multi-Class Classifier

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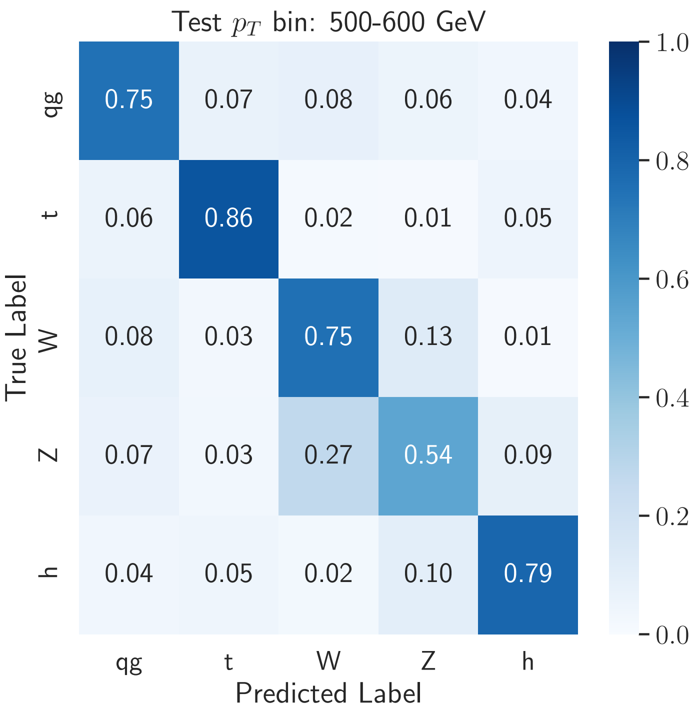
- Uses jet substructure and jet 4-momenta as input
- Outputs 5 classes: Higgs, W, Z, top, QCD
- Only applied on events that are selected in both VV and Vh
  - Uses the probability ratio as the discriminative variable

Good predictive power



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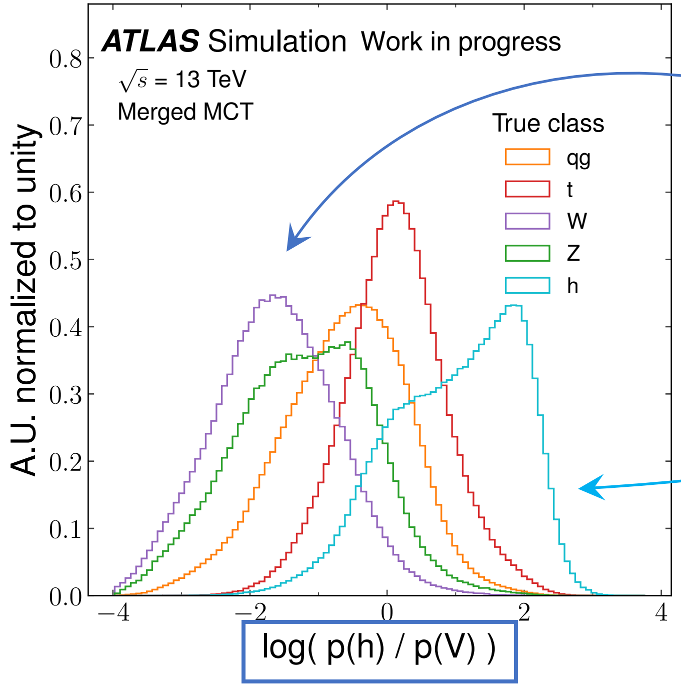
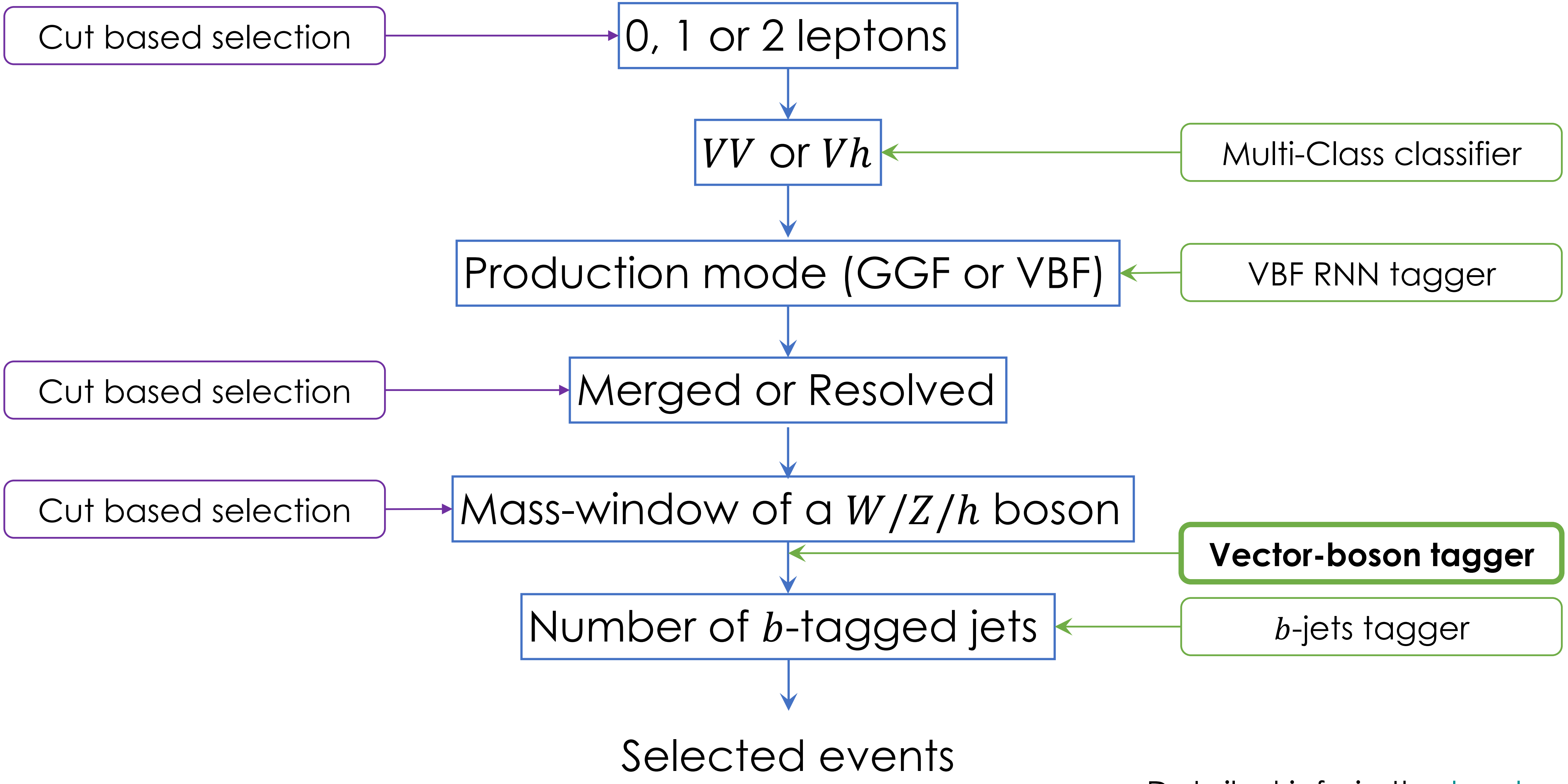


Good separation between W/Z and h

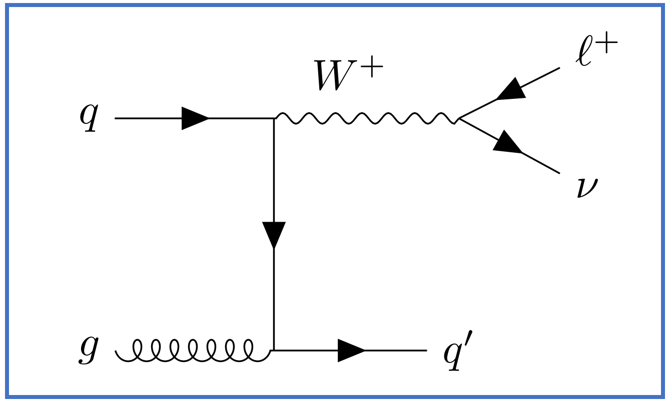
Event selection



Detailed info in the backup

Vector-boson tagger

- Targeted V(lep)$V(qq)$ final state has a lot of V+jets background



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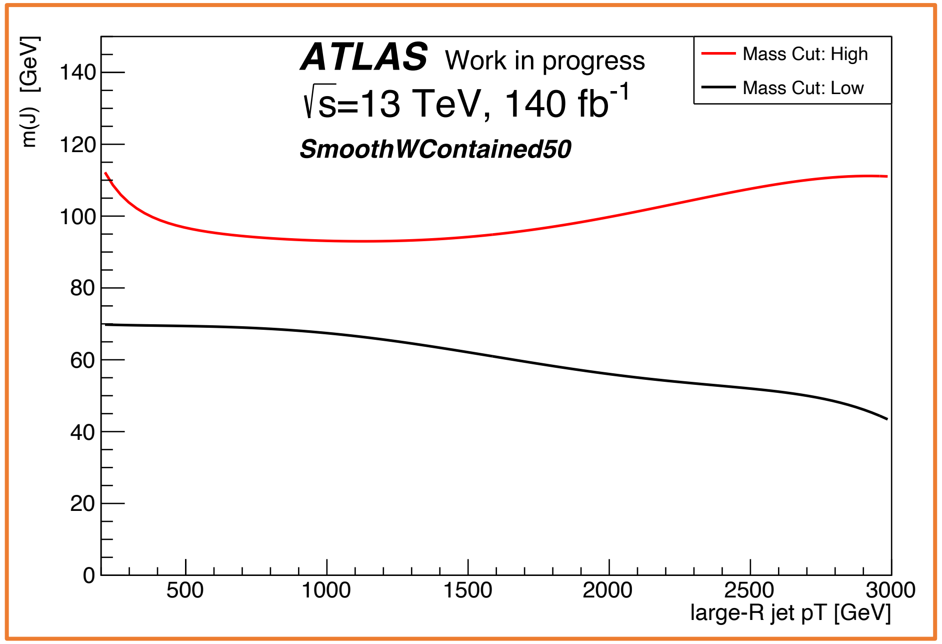
- Targeted $V(\text{lep})V(qq)$ final state has a lot of V+jets background

➢Cut-based tagger to reduce the V+jets background

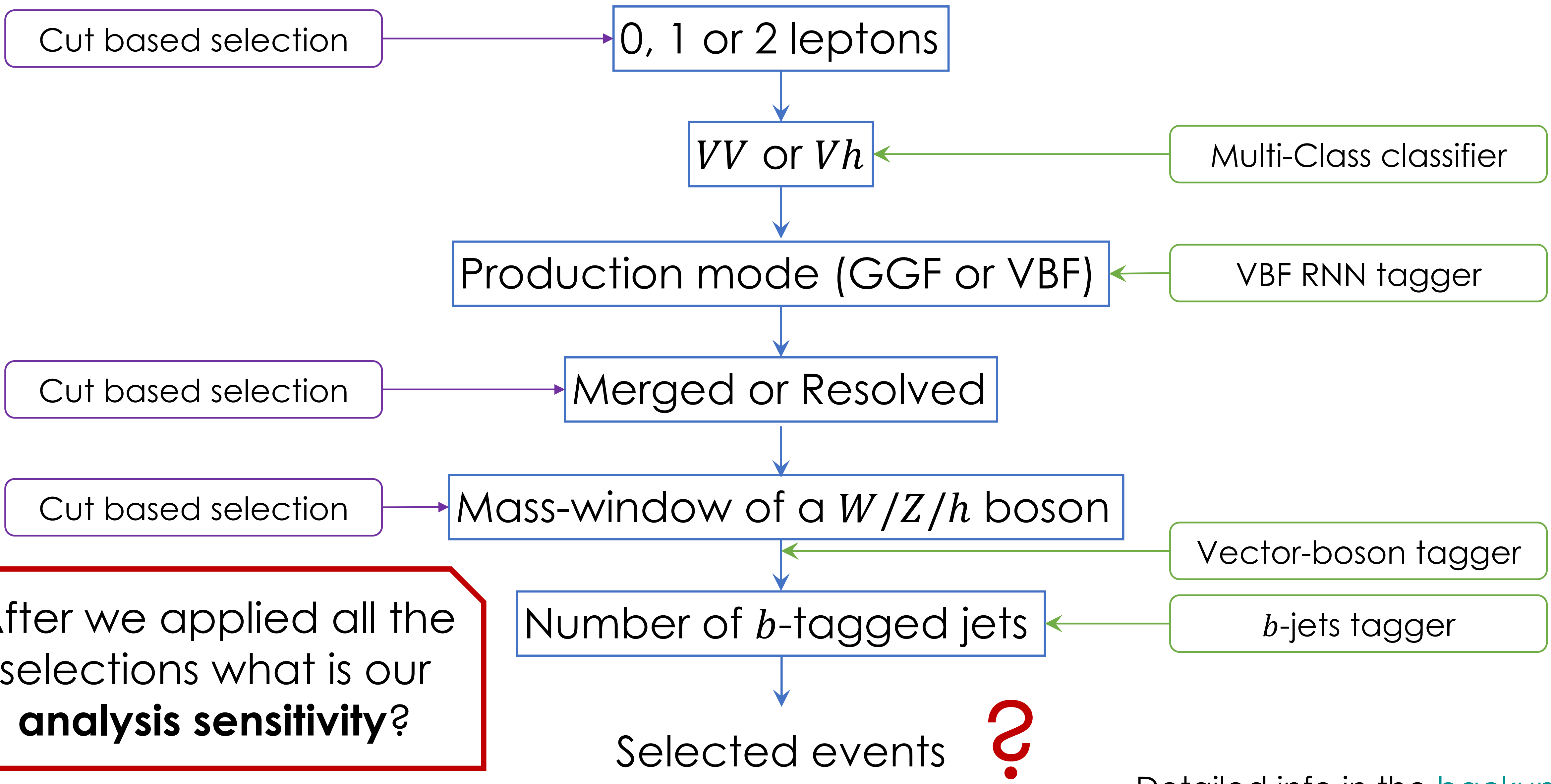
- Uses p_T-dependent variables:
  1. Large-R jet mass $m(J)$
  2. Jet substructure variable D_2
  3. Number of associated tracks to the jet



- Large-R jets are tagged if they pass 50% signal efficiency WP of the tagger

➢Removal of >60 % background events depending on a region

Event selection



After we applied all the selections what is our **analysis sensitivity**?

Detailed info in the backup

Expected sensitivity

- Simultaneous binned likelihood fit across all analysis regions
- Final observable:
  - 0-lepton: diboson transverse mass
  - 1-,2-lepton: diboson invariant mass
- Major backgrounds (V+jets, $t\bar{t}$) are freely floating
- Minor backgrounds use shape/normalisation from theory predictions

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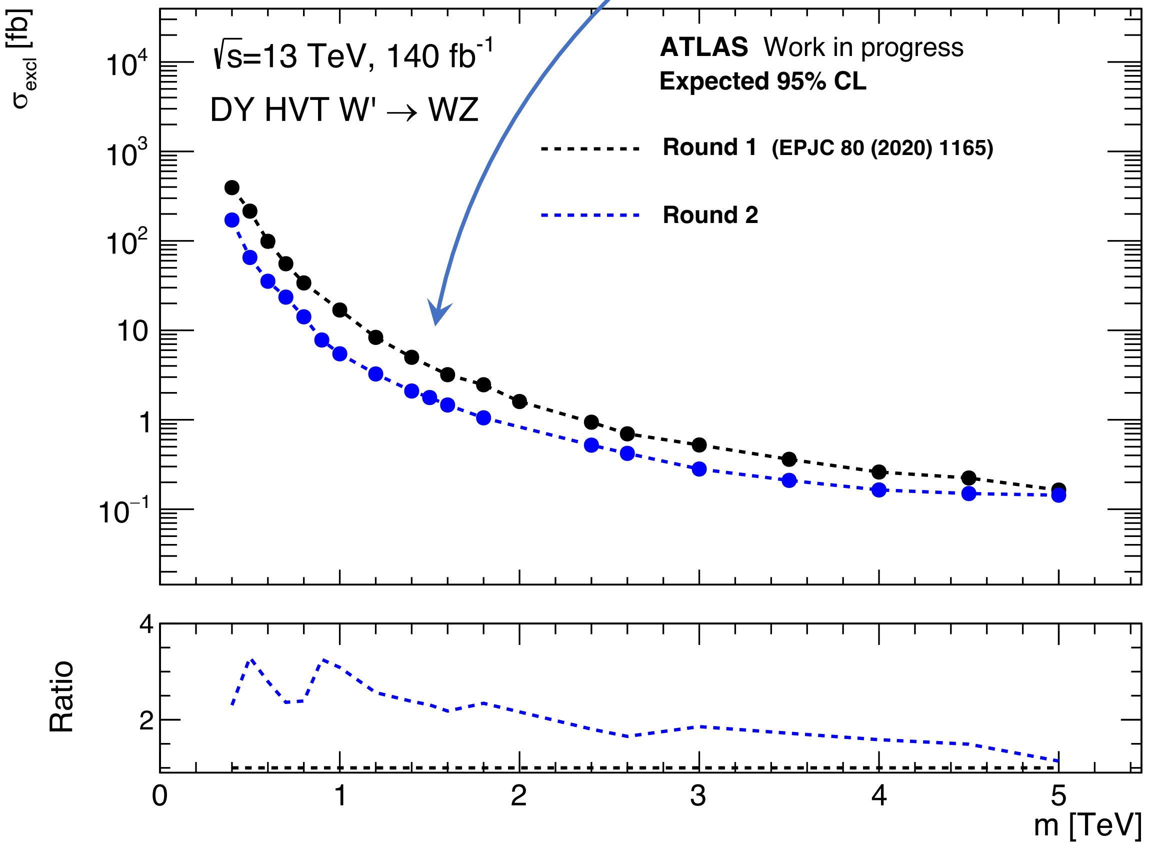
➢ Significant improvement wrt Round 1

Exclude the area above the line



Upper limit on diboson cross-section x BR

- Pseudo data used to estimate sensitivity
- Statistical + experimental systematic uncertainties are included

Summary

- Variety of models predict heavy new particles decaying to dibosons
- Search for their semileptonic decays is very complicated, but possible
- The 2^{nd} round of the analysis is presented
  - Many developments wrt the round 1
  - Expected sensitivity looks very promising
- Still some work to do:
  - Finalise fit strategy
  - Add missing uncertainties
  - When it is done → look at the real data!

Thank you for your attention!

Back up

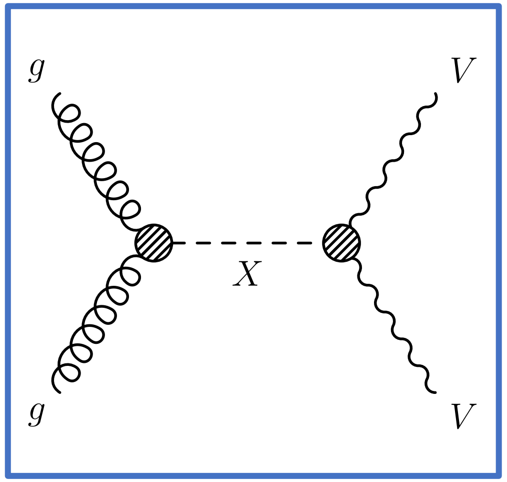
Analysis overview

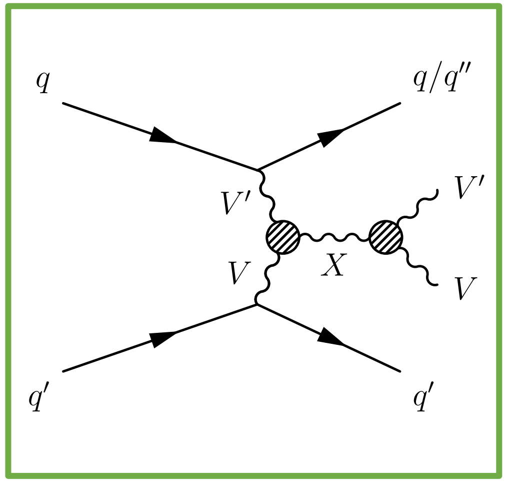
Benchmark models:

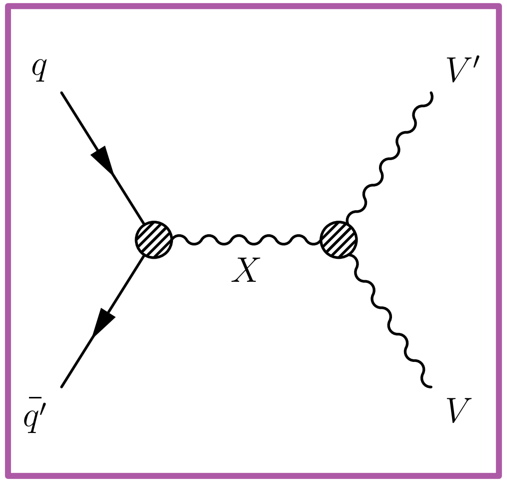
- Randall–Sundrum (RS) Radion (spin-0)
- 2HDM pseudoscalar A (spin-0)
- Heavy Vector Triplet (HVT) W'/Z' (spin-1)
- RS Graviton (spin-2)

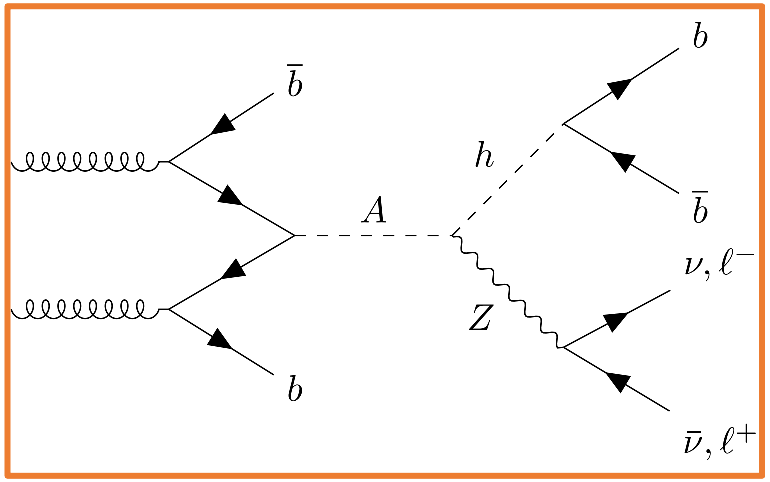
Production modes:

- Gluon-gluon fusion (ggF)
- Vector boson fusion (VBF)
- Drell-Yan (DY)
- b-associated production of A (bbA)

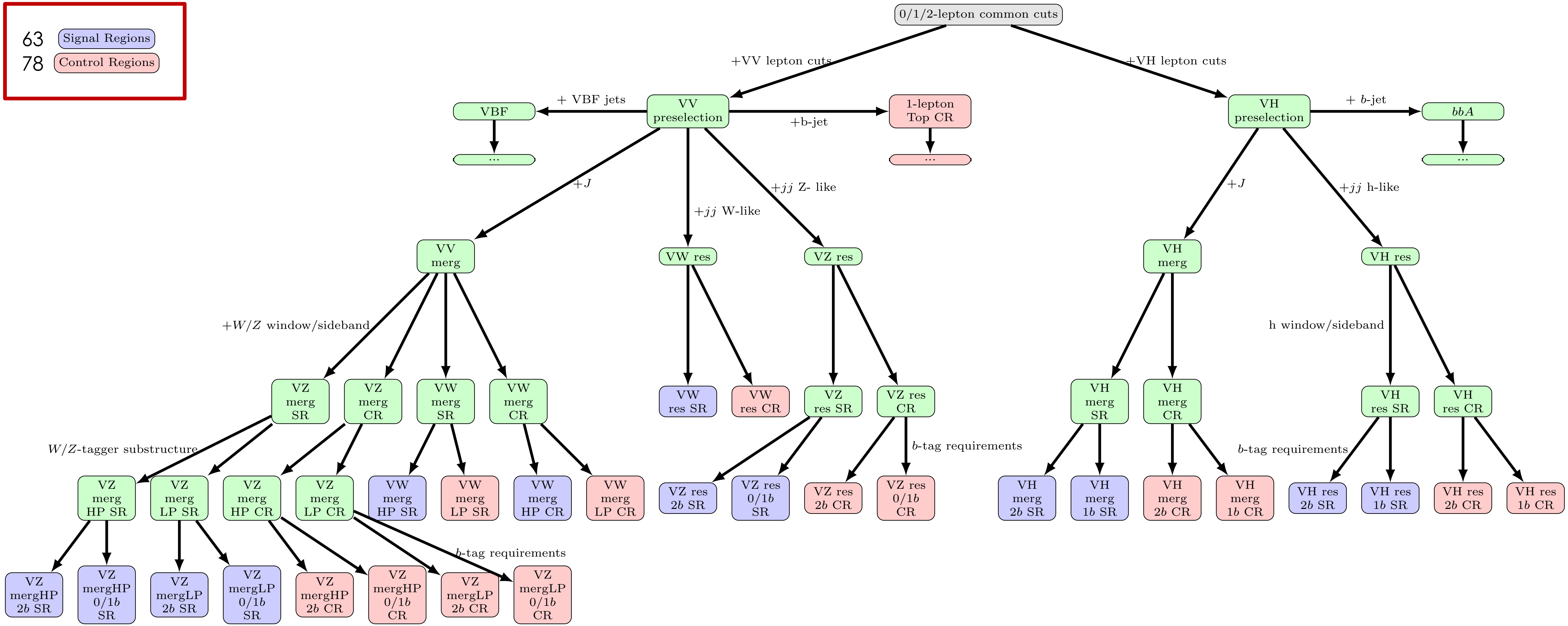








Analysis flow-chart

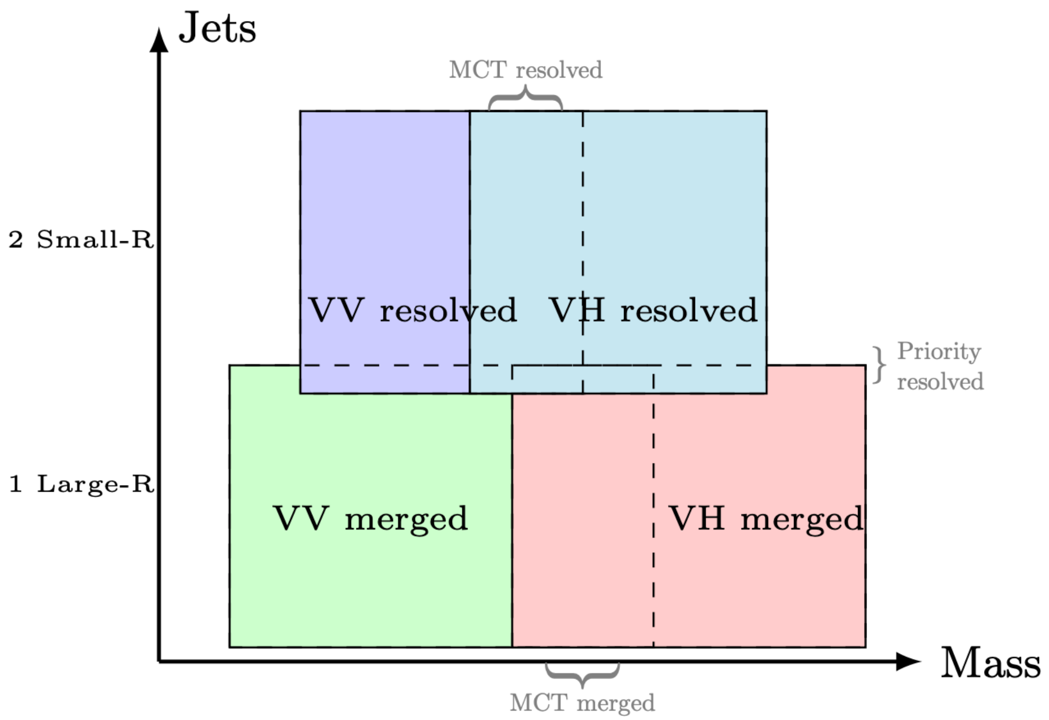


Region prioritization and orthogonalization

- Lepton channels are orthogonal by construction

But!

- Hadronic selection (merged/resolved) is not orthogonal
- VV and Vh SRs are not orthogonal: jet mass window overlap
- Merged (resolved) SRs can overlap with resilved (merged) CRs



Orthogonalisation procedure:

- Run analysis cutflows to find active SRs
- Remove any merged SR events from the resolved SR
- Remove and resolved/merged CR events which overlap with the opposite merged/resolved SR
- If remaining overlap, calculate the DNN MCT scores and classify the event into VV SR and remove from Vh SR and vice versa

Event selection

Event selection (simplified)

Jet requirements

Merged
- One large-R jet
- Vh: $p_T > 250\ GeV$
- VV: $p_T > 200\ GeV$

Resolved
- Two small-R jets
- h: 2 b-tagged or 1 b-tagged + 1 additional
- $p_T^{lead} > 45\ GeV$

Mass window
W: $62 < m_{jj} < 97\ GeV$

Z: $70 < m_{jj} < 105\ GeV$

h(0,1-lep): $110 < m_{jj} < 140\ GeV$

h(2-lep): $100 < m_{jj} < 145\ GeV$

Requirements per lepton channel

0-lep
- No leptons
- $E_T^{miss} > 200\ GeV$
- Anti-QCD cuts

$$\mathcal{R}_{p_T/m} = \frac{min(p_T^{V_l}, p_T^{V_h})}{m_{VV}}$$

1-lep
- Exactly 1 *Tight* lepton
- $p_T > 30\ GeV$
- $E_T^{miss} > 100\ GeV$ (Merg)
- $E_T^{miss} > 60\ GeV$ (Res)
- $\mathcal{R}_{p_T/m} > 0.35$ GGF
- $\mathcal{R}_{p_T/m} > 0.25$ VBF
- Anti-QCD cuts, b-veto

2-lep
- Exactly 2 *Loose* leptons
- Mass windows consistent with $Z \rightarrow ll$ decay
- $p_T^{lead} > 27\ GeV$
- $p_T^{sub} > 27(25) GeV$ Merg(Res)
- $\mathcal{R}_{p_T/m} > 0.35$ GGF
- $\mathcal{R}_{p_T/m} > 0.25$ VBF
- $METsig < 4$

Taggers

Together with the mass window cuts define SRs and CRs

Multi-class
Orthogonalizes VV and Vh regions

W/Z (3var)
In VV merged defines high/low purity regions, distinguishes W/Z from QCD

VBF RNN
Defines VBF regions

0-lepton channel

Selection	VV merged	Vh merged	VV resolved (not explored)	Vh resolved
	0-lepton Selection			
Trigger	MET Trigger			
Lepton Multiplicity	0 “loose" Leptons			
E_T^{miss}	> 200 GeV		> 150 GeV	
S	> 10			
$\min[\Delta\phi(\text{jets}, E_T^{miss})]$	> 0.2			
Jet Cleaning	Tight			
	Jet Selection			
Number of Jets	1 large-R jet		2 small-R jet	
Leading jet p_T	> 300 GeV	> 250 GeV	> 45 GeV	
$W/Z/h$ requirements	Tagger dependent mass and substructure cut	$75 < m(J) < 145$ GeV	W: $68 < m(jj) < 98$ Z: $78 < m(jj) < 105$	$110 < m(jj) < 140$

1-lepton channel

Selection	VV merged	Vh merged	VV resolved	Vh resolved
	1-lepton Selection			
Trigger	Single lepton or MET Trigger			
Lepton Multiplicity	1 "Tight" lepton and 0 "loose" leptons			
lepton p_T	> 30 GeV			
E_T^{miss}	> 100 GeV		> 60 GeV	
$p_T(W)$	> 200 GeV		> 75 GeV	
	Jet Selection			
Number of Jets	1 large-R jet		2 small-R jet	
Leading jet p_T	> 300 GeV	> 250 GeV	> 45 GeV	
$W/Z/h$ requirements	Tagger dependent mass and substructure cut	$75 < m(J) < 145$ GeV	W: $68 < m(jj) < 98$ Z: $78 < m(jj) < 105$	$110 < m(jj) < 140$
	Topology Requirements			
$E_T^{miss}/p_T(W)$	> 0.2 electron-only			
b-veto	No additional b-jet in event		No b-jet in $\Delta R(J, b) < 1.0$	
R	GGF:> 0.35 VBF: > 0.25			
$\Delta\phi(\ell, E_T^{miss})$	-		< 1.5	
$\Delta\phi(j_1, j_2)$	-		< 1.5	
$\Delta\phi(\ell, j_1/j_2)$	-		> 1.0	
$\Delta\phi(\ell, j_1/j_2)$	-		> 1.0	

$$R = \frac{\min(p_T(W_{lep}), p_T(W/Z/h_{had}))}{m(VV/Vh)}$$

2-lepton channel

Selection	VV merged	Vh merged	VV resolved	Vh resolved
	2-lepton Selection			
Trigger	Dilepton			
Lepton Multiplicity	2 "loose" lepton and no additional			
Leading lepton p_T	> 27 GeV			
Subleading lepton p_T	> 25 GeV		> 20 GeV	
$m(\ell\ell)$	$83 < m_{ee} < 99$ GeV $85.6 - 0.0117 p_T(\ell\ell) < m_{\mu\mu} < 94.0 + 0.0185 p_T(\ell\ell)$ GeV			
	Jet Selection			
Number of Jets	1 large-R jet		2 small-R jet	
Leading jet p_T	> 300 GeV	> 250 GeV	> 45 GeV	
$W/Z/h$ requirements	Tagger dependent mass and substructure cut	$75 < m(J) < 145$ GeV	W: $68 < m(jj) < 98$ Z: $78 < m(jj) < 105$	$100 < m(jj) < 145$
	Topology Requirements			
R	GGF:> 0.35 VBF: > 0.25			

$$R = \frac{p_T(\min(Z_{lep}), p_T(W/Z/h_{had}))}{m(VV/Vh)}$$

New developments

What is new wrt the round 1?

- Harmonisation between VV and Vh

- Improved physics object reconstruction:
  - New algorithms for Large-R and Small-R jets reconstruction
  - A new V-boson 3-variable tagger
  - Newer b-tadding algoritm
  - Improved V+jets modelling
  - Custom Multi-Class Classifier to enhance the separation between $V \to qq$ and $h \to bb$

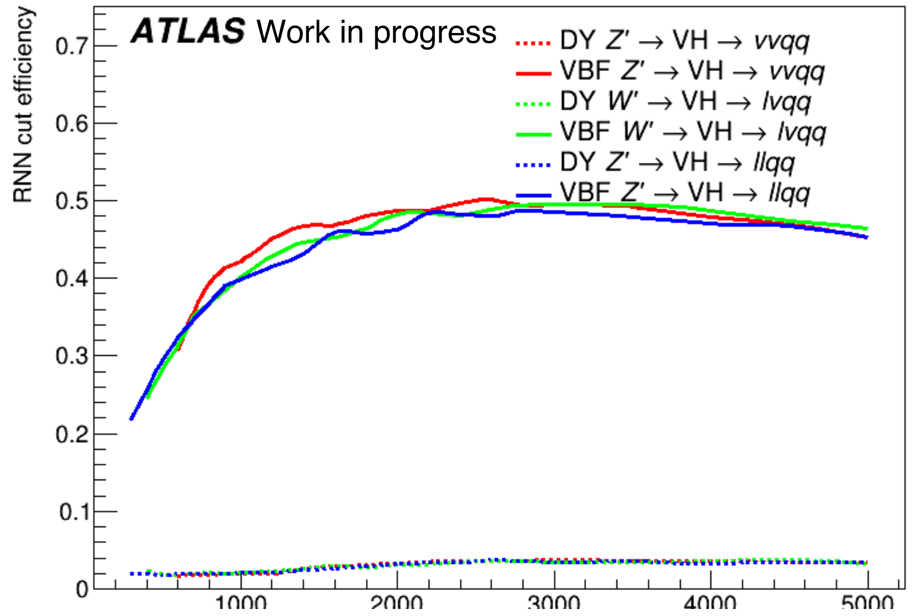
- Introduced a VBF category in Vh channel for the first time

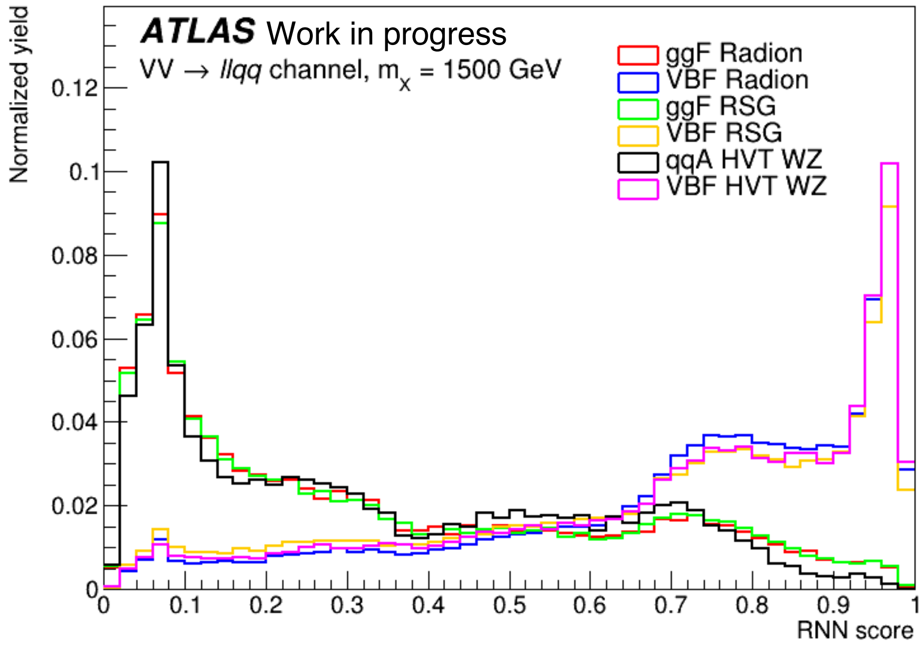
VBF RNN tagger

- ➢RNN tagger to classify VBF events from ggF/DY
- Was used in round 1 VV search, now extended to Vh channel

RNN

- Takes 4-momenta of the small-R jets
- Removes small-R jets from hadronic boson candidate
- Up to 2 remaining jets are chosen as input
- If no small-R jets left → ggF/DY region
- If RNN score < 0.8 → ggF/DY region otherwise VBF region



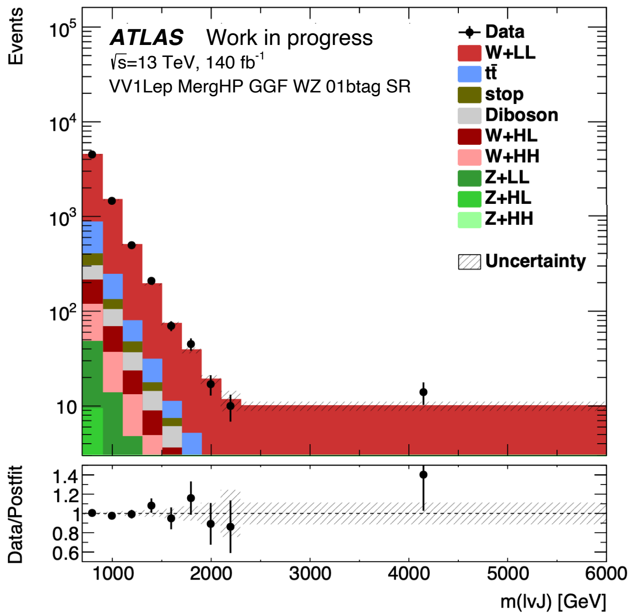


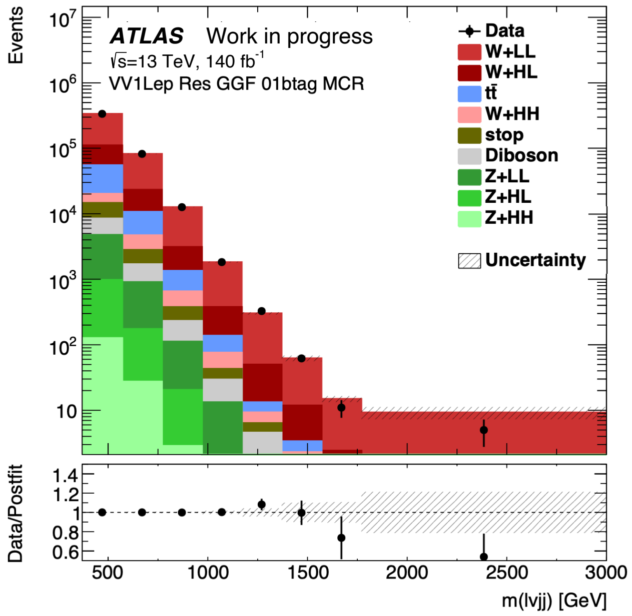
Expected sensitivity

Fit strategy

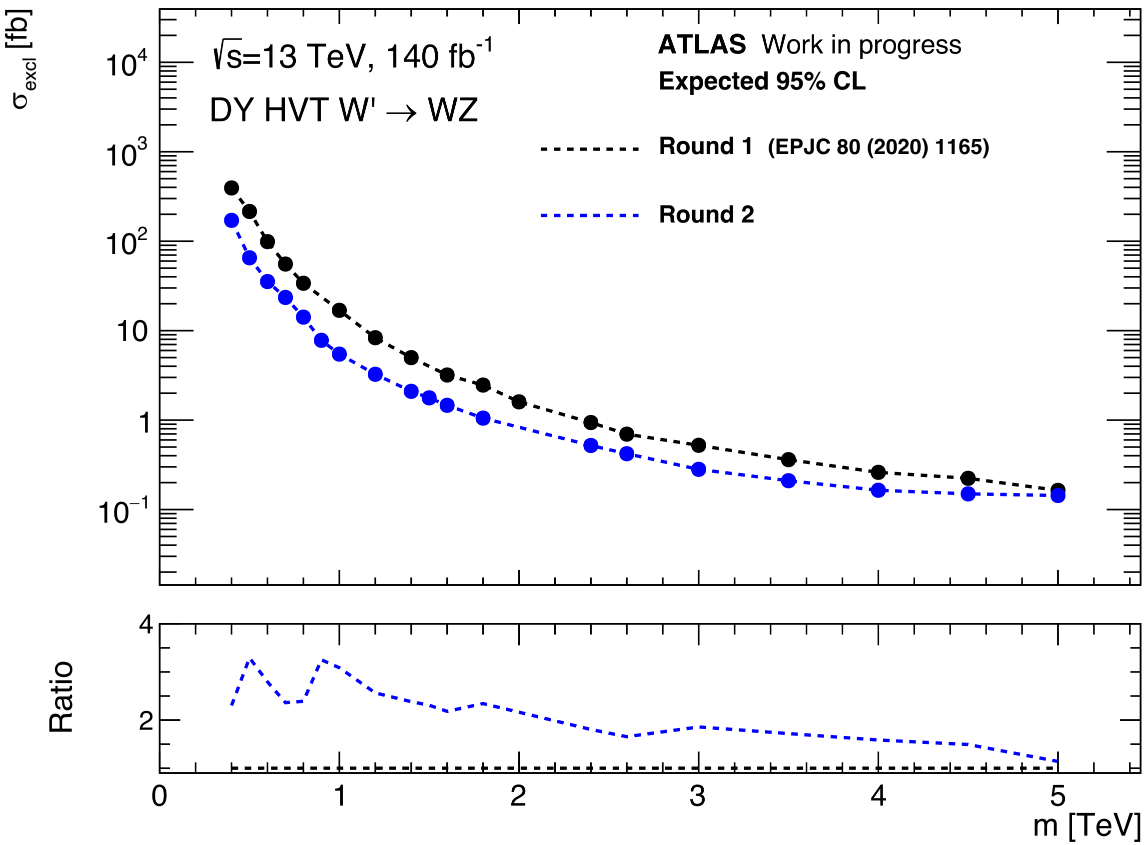
- Simultaneous binned likelihood fit across all signal and control regions
- 2 fit setups:
  - WZ+Vh
  - WW+ZZ+Vh
- Final observable:
  - 0-lepton: diboson transverse mass
  - 1-,2-lepton: diboson invariant mass
- Major backgrounds (W+jets, Z+jets, $t\bar{t}$) are freely floating:
  - Shape is from Monte-Carlo simulation
  - Normalisation is from data in CRs
- Minor backgrounds use shape/normalisation from theory predictions

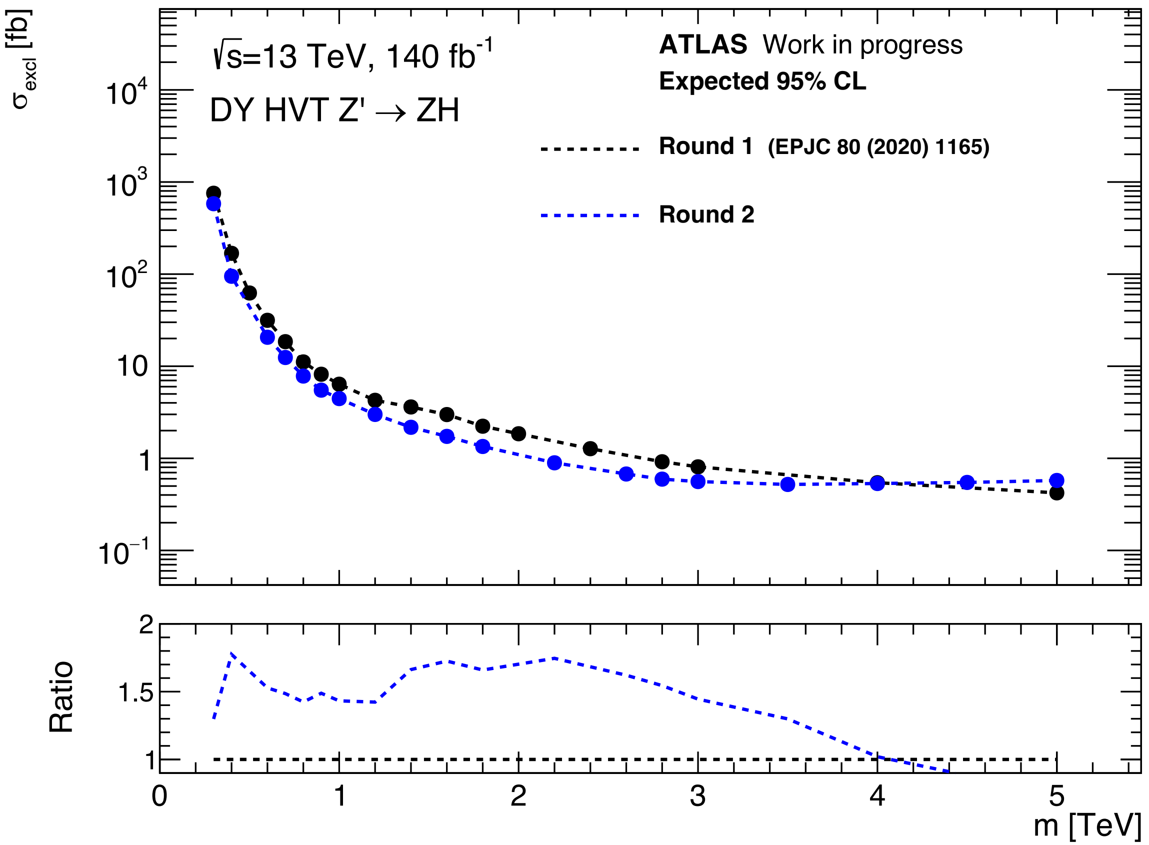
Post-fit distributions





Expected sensitivity





- ➢ Significant improvement wrt Round 1
- Pseudo data used to estimate sensitivity
- Statistical + experimental systematic uncertainties are included
- ➢ To do: add theory uncertainties and finalize fit strategy