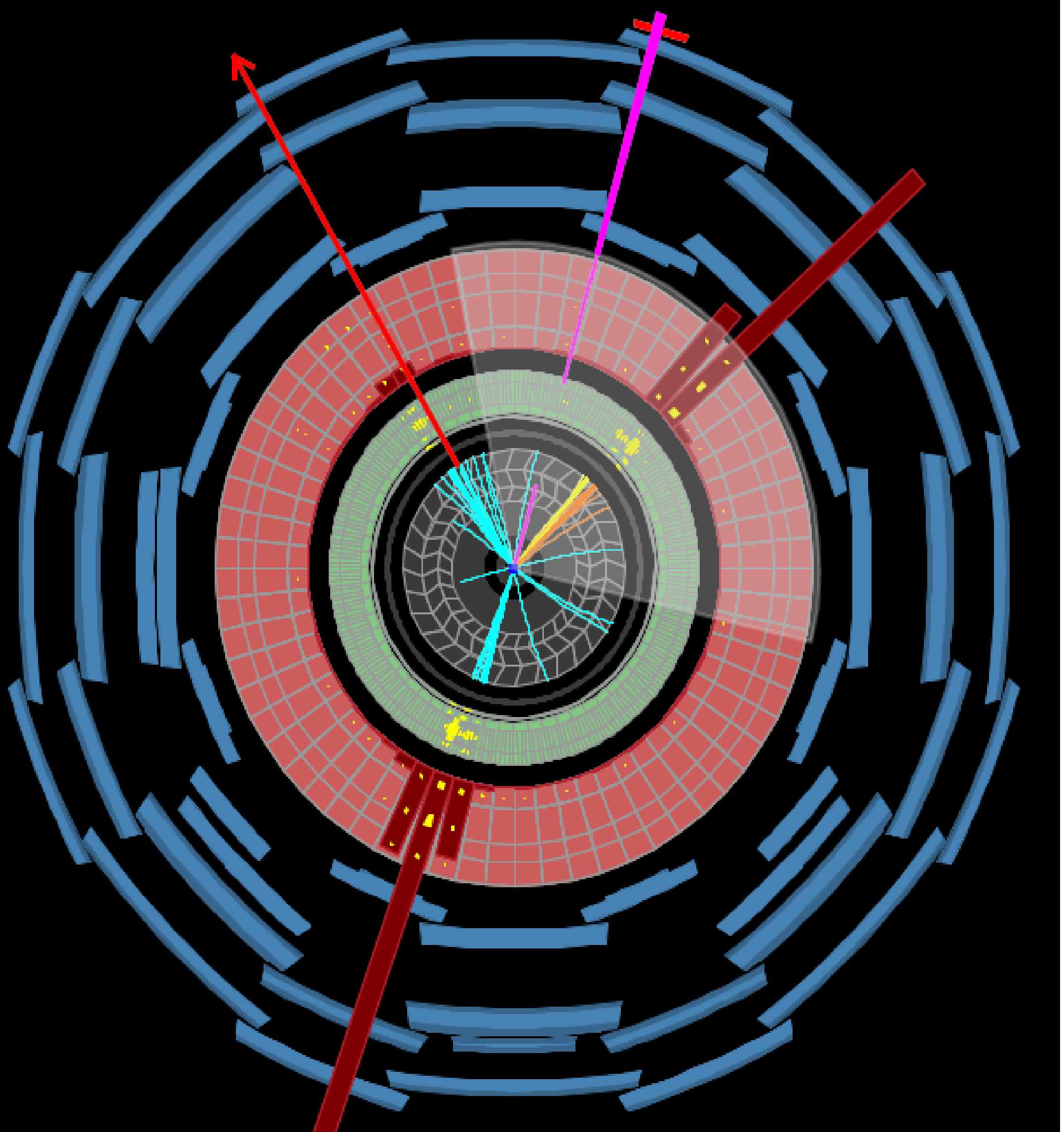
VH Resonances

Search for new resonances decaying to a W or Z boson & a Higgs in pp collisions at 13 TeV with the ATLAS Detector, using 3.21 ± 0.2 fb^{-1}.

UCL



Institute Of Physics

Joint Annual HEP and APP Conference 2016

Stephen Jiggins

University College London

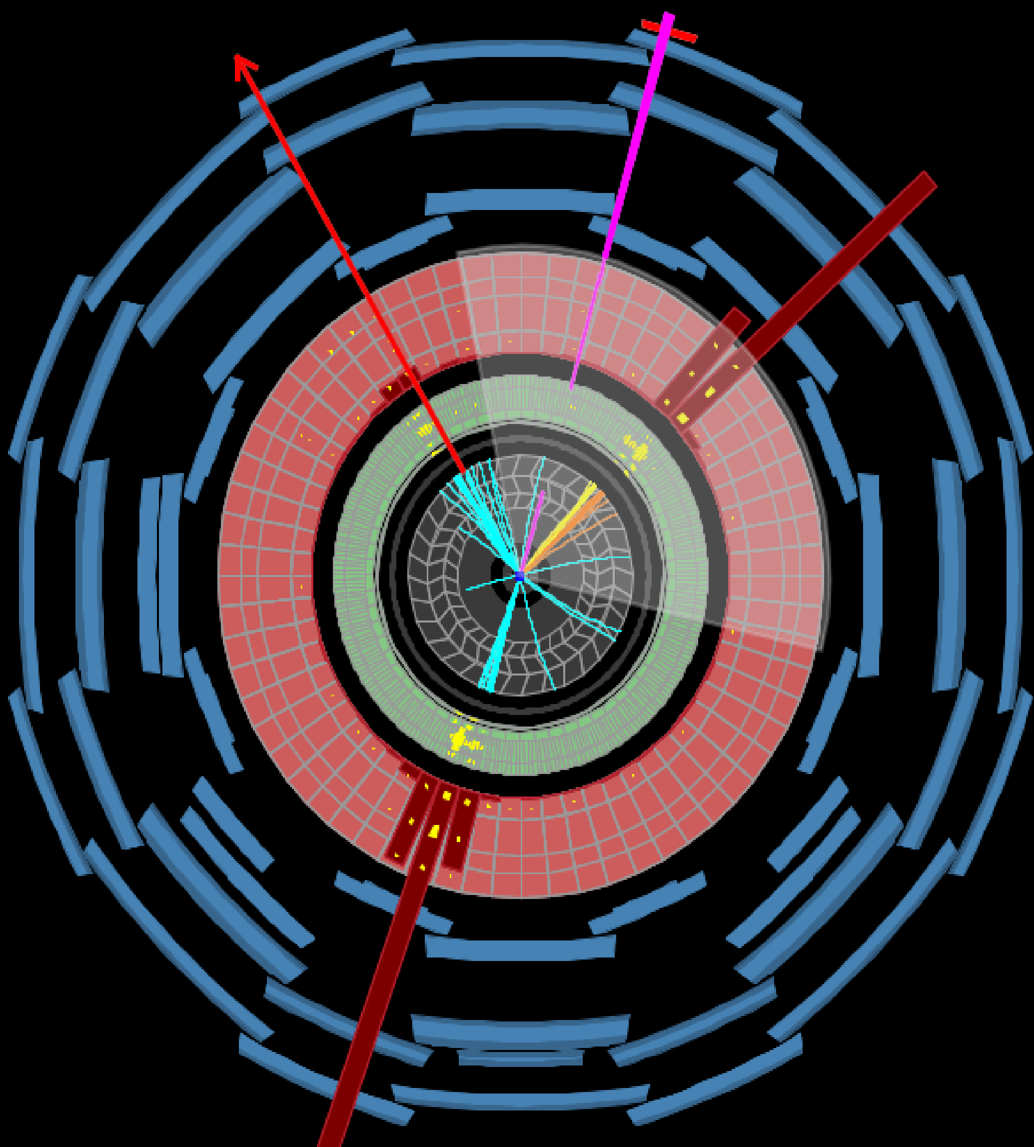
March 22nd 2016

Science & Technology Facilities Council

ATLAS EXPERIMENT

VH Resonances

Search for new resonances decaying to a W or Z boson & a Higgs in pp collisions at 13 TeV with the ATLAS Detector, using 3.21 ± 0.2 fb^{-1}.



Contents

Overview

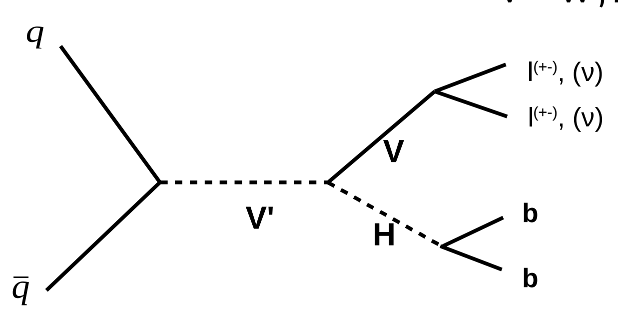
→ Higgs with mass @ 125GeV does not rule out its composite nature.

→ Naturalness & the Hierarchy Problem still persist.

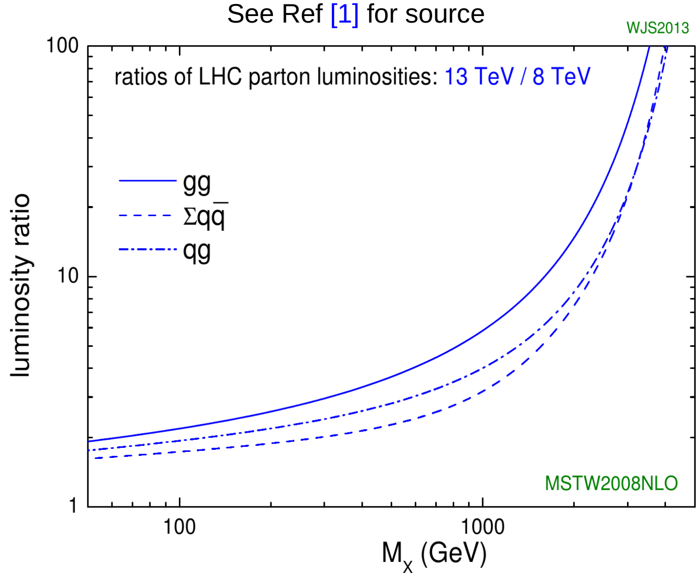
→ "Heavy Vector Triplet" (HVT) predicts new resonances decaying to a Higgs & SM Vector Boson:

$$\grave{V} \rightarrow V + H$$

Where:
V' = W', Z'



See Ref [1] for source



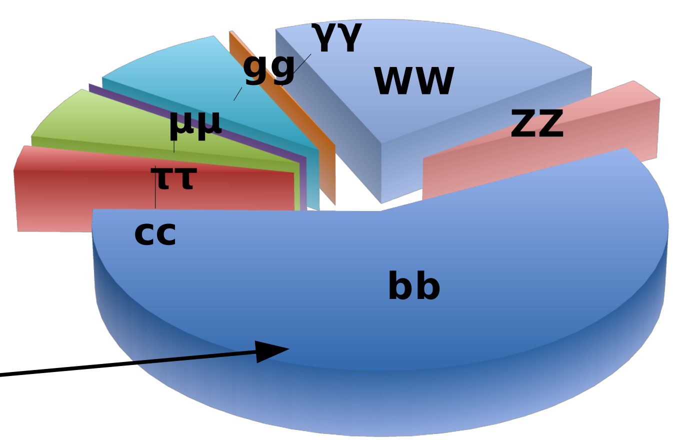
→ Run 1 yielded constraints:

→ ATLAS excluded @ 95% CL W' (Z') mass at 1.47 (1.36) TeV Ref [2]

→ CMS excluded V' → VH @ 1.7 TeV Ref [3]

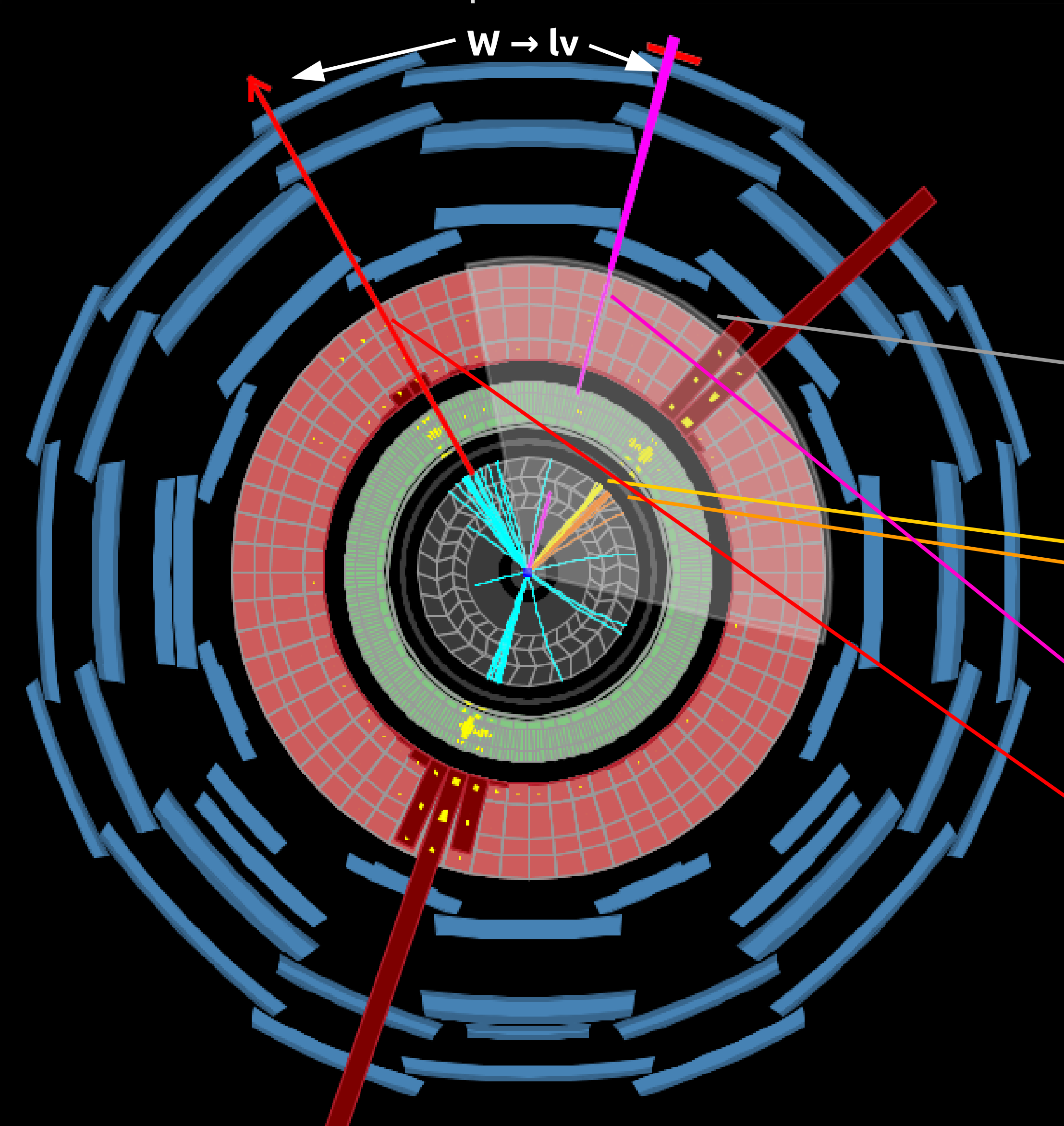
→ Run 2 increase in $\sqrt{s}$ from 8TeV → 13TeV leads to increase in parton luminosity

→ H → bb BR ~ 57.8% @ Higgs Mass



Higgs Branching Ratio Breakdown

Event Topology & Selection



→ Searching for m_{VH} system > 1.5 TeV

- **→ Boosted Topologies**
- **→ Use fat-jets with ΔR =1.0 & sub-structure techniques**

→ Leptonic decays of SM V used as topological trigger.

Anti-kT R = 1.0 "fat-jet":
p_T > 250GeV

Anti-kT R = 0.2 "track-jets":
p_T > 10 GeV
≥ 1 ghost associated b-jet

νν, lν, ll Vector Boson Decay:
Lepton P_T ≥ 60 GeV (25 GeV)
E^T_{miss} > 100 – 200 GeV

Search Strategy

→ Define the signal region as: $75\text{GeV} < m_J < 145\text{GeV}$ & b-tagged ghost associated track-jets ≥ 1

Where: m_J = invariant mass of Fat-Jet

Search Strategy

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→ Dominant backgrounds : V+jets & ttbar

Search Strategy

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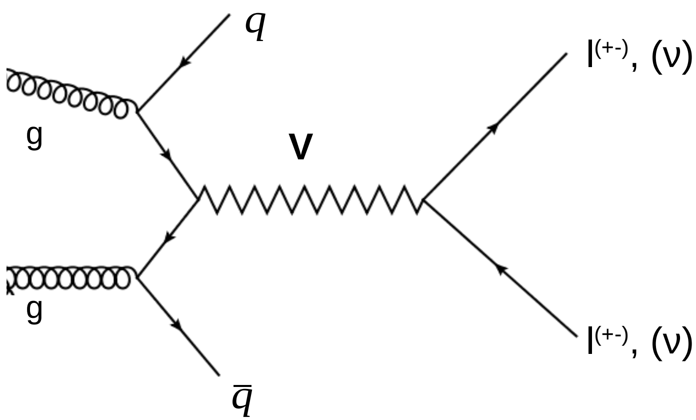
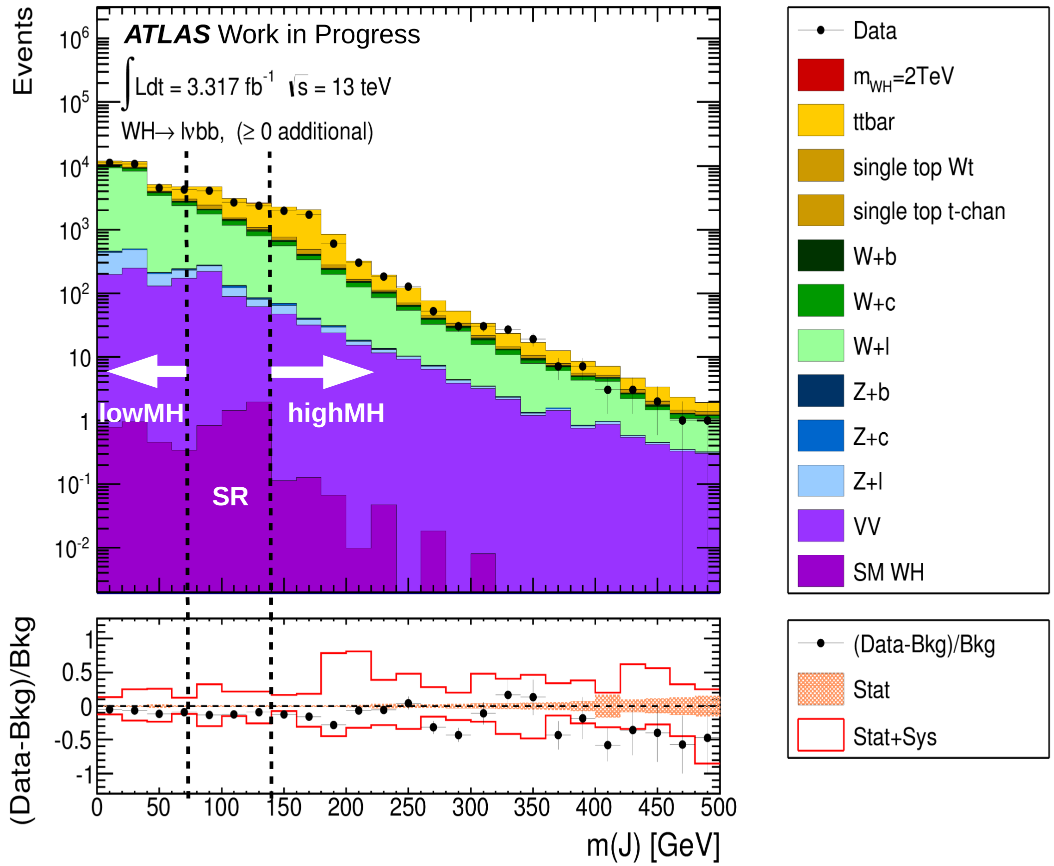
Dominant V+Jets Production





→ Divide V+jets into 3 flavour categories:

→ V+b : V+bb, V+bc, B+bl
→ V+c : V+cc
→ V+l : V+ll

Search Strategy

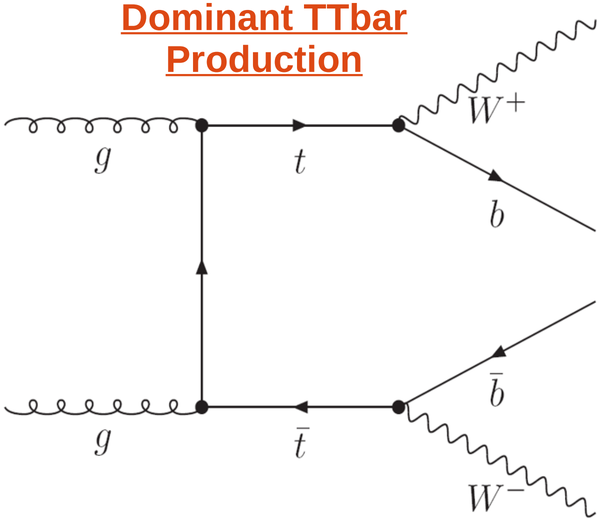
→ Define the signal region as: 75GeV < m_J < 145GeV & b-tagged ghost associated track-jets ≥ 1

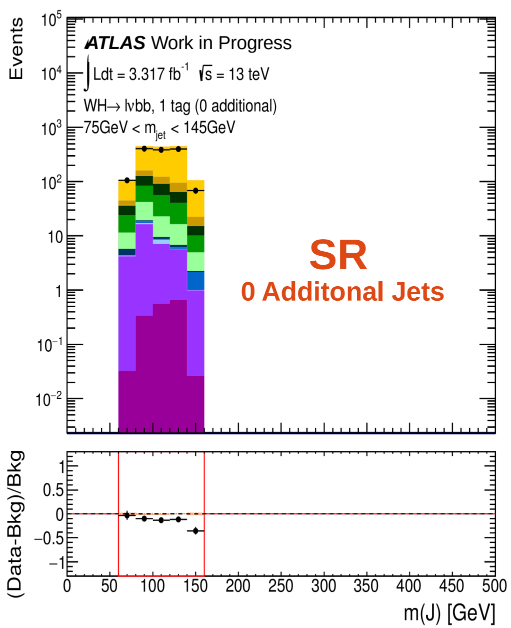
Where: m_J = invariant mass of Fat-Jet

→ Define series of control regions for background control & handling:

→ Dominant backgrounds : V+jets & ttbar

Dominant TTbar Production





Search Strategy

→ Define the signal region as: 75GeV < m_J < 145GeV & b-tagged ghost associated track-jets ≥ 1

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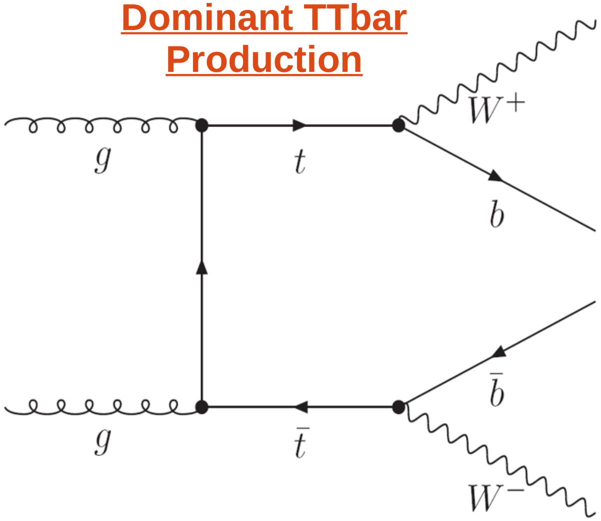
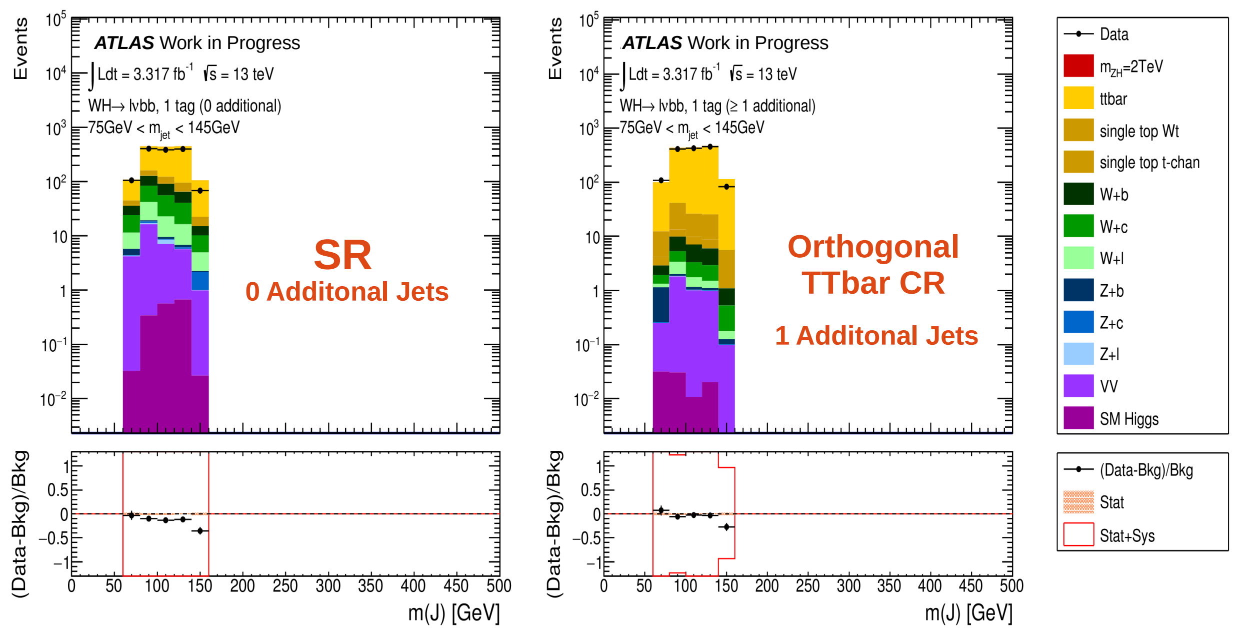
Dominant TTbar Production





→ 0 & 1-Lepton channel CR:

≥ 1 Additional B-tagged track jets not ghost associated to fat-jet

→ 2-Lepton channel CR:

eμ (different lepton flavours)

Search Strategy

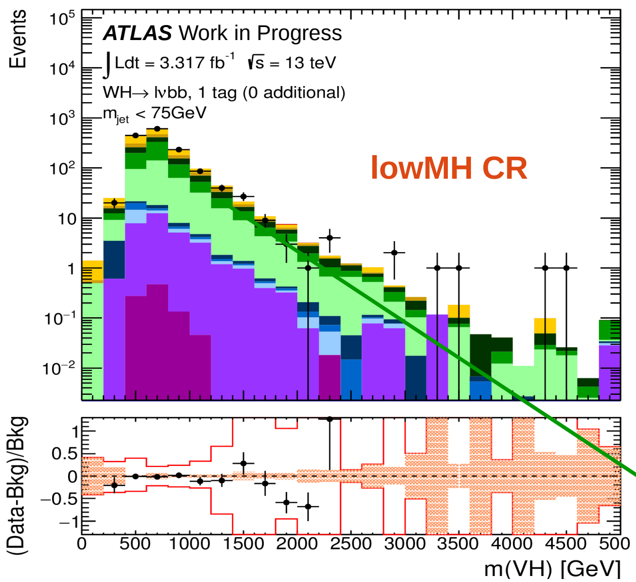
Resonance Finding:

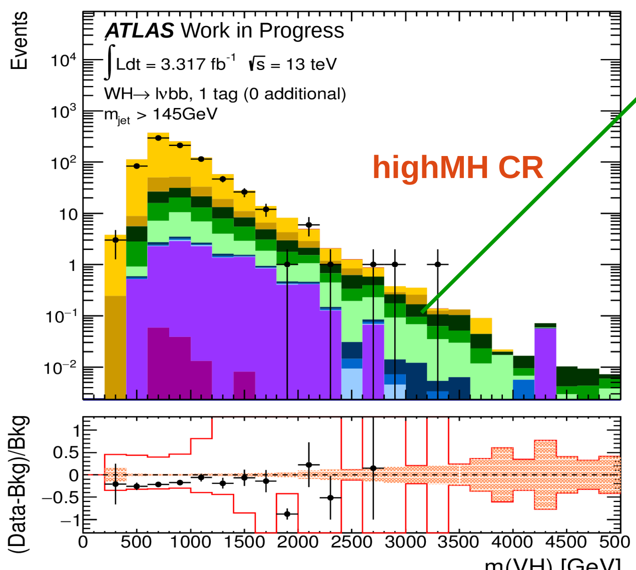
→ Using CR's & SR, a Binned Maximum Likelihood Fit is performed in the variable 'm_{VH}':

$$m^2_{VH} = (p^{\mu}_{J} + p^{\mu}_{\{ll,\, l\nu,\, \nu\nu\}})^2$$

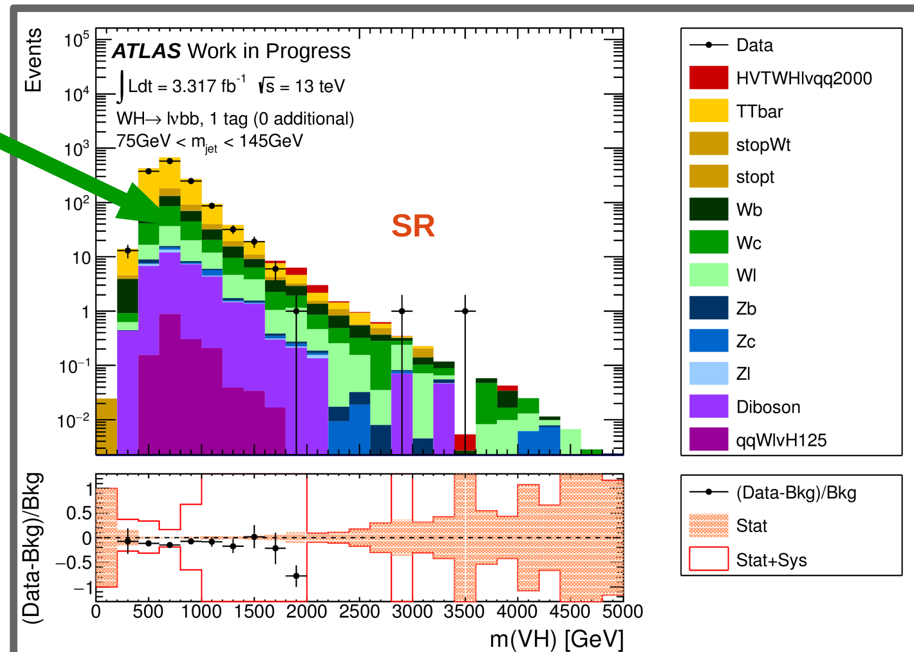
→ Performed simultaneously across lowMH, SR & highMH

→ And across number of b-tagged jets

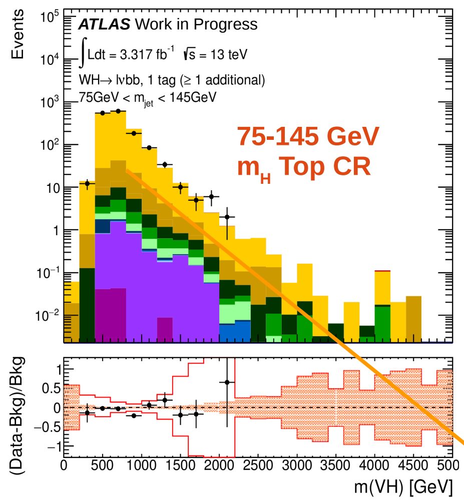


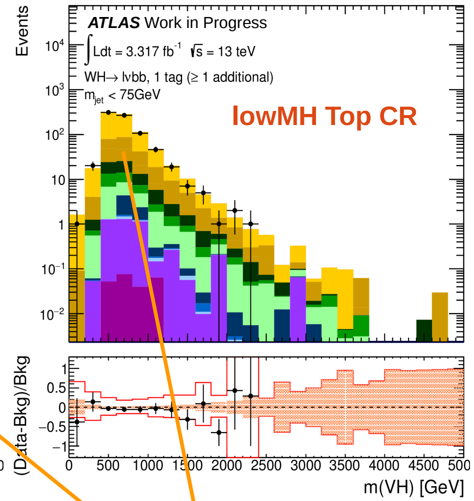


W+Jets



Search Strategy





Resonance Finding:

→ Using CR's & SR, a Binned Maximum Likelihood Fit is performed in the variable 'm_{VH}':

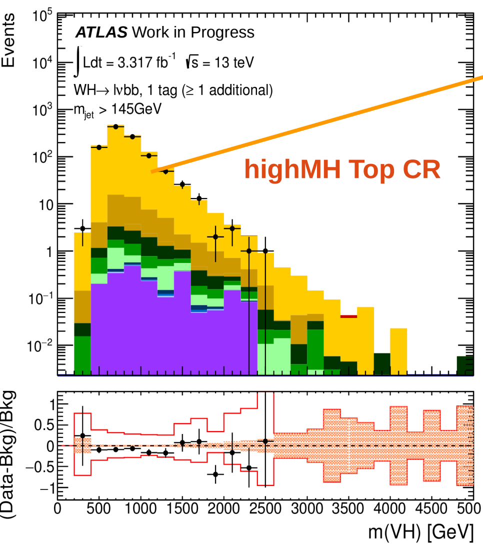
$$m^2_{VH} = (p^{\mu}_{J} + p^{\mu}_{\{ll,\, l\nu,\, \nu\nu\}})^2$$

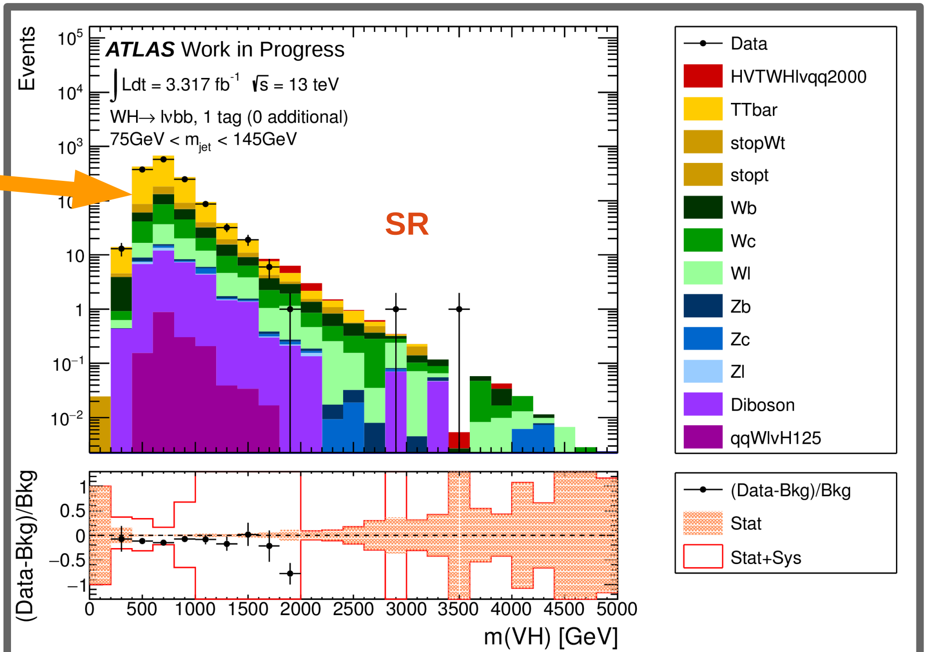
→ Performed simultaneously across lowMH, SR & highMH

→ And across number of b-tagged jets

→ And across N-additional b-tagged jets

TTbar



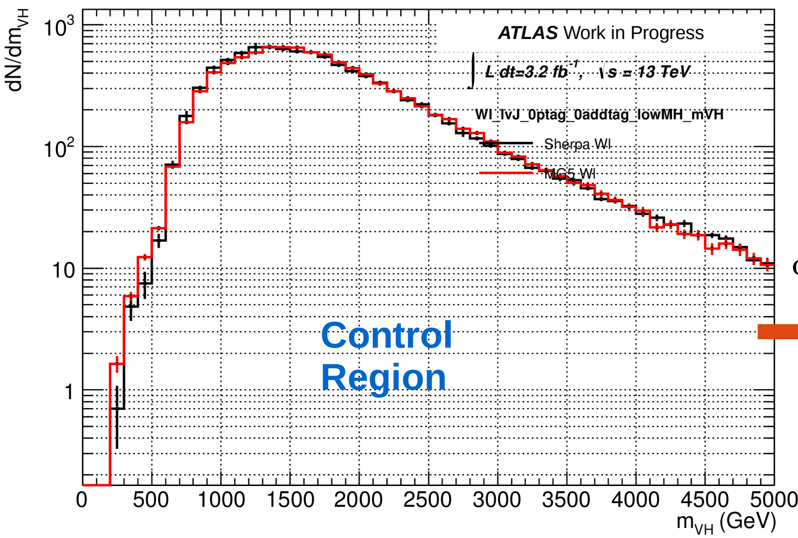


V+Jets Background & Deriving a Systematic

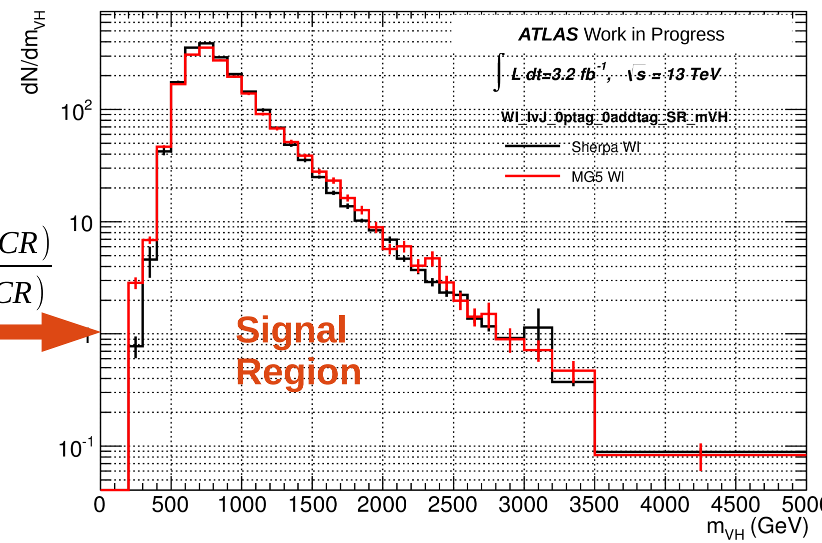
Sherpa W+l
MG5 W+l

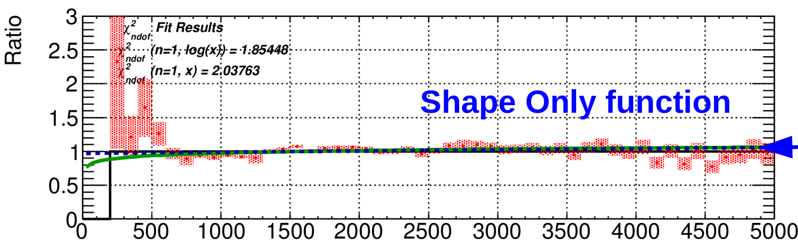
Derivation Methodology:

1) Calculate **α_{V+y} = Sherpa(V+y, low)/MG5(V+y, low)**
2) Normalise MG5 & Sherpa to same area, and fit 1st order polynomial to ratio
   → Shape variation only
3) Scale nominal SR V+Jets distribution by α_{V+y}
4) Fit polynomial to ratio:
   → shape variation + yield extrapolation

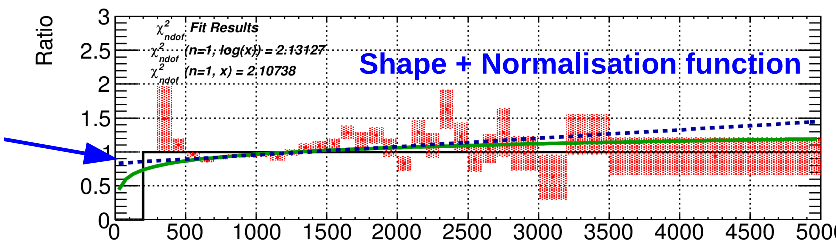


$$\alpha_{V+y} = \frac{N^{Sherpa}_{V+y}(CR)}{N^{MG5}_{V+y}(CR)}$$

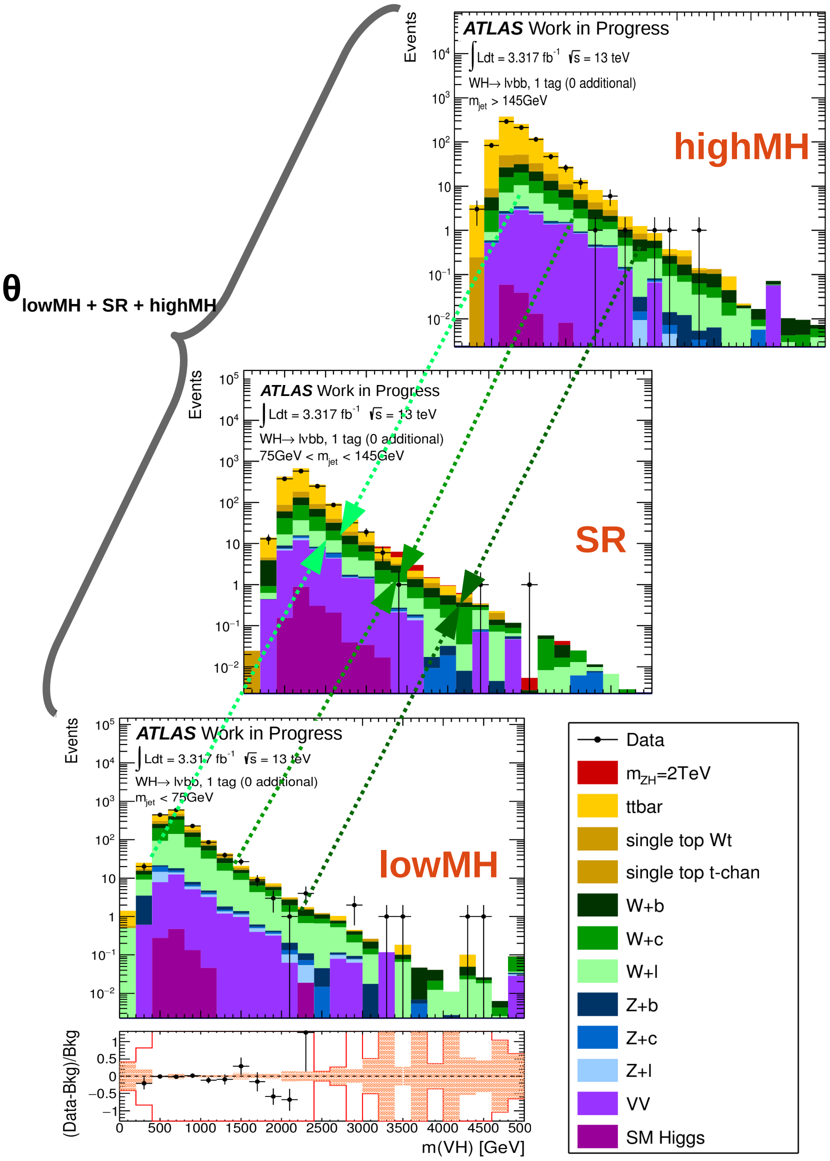




$$f^{syst}_{V+y}(x)$$



Nuisance Parameters & Fit Handling



Define a variation on the nominal (h^0) m_{VH} MC templates as:

$$h(x)=h^0(x)\pm\theta(h^{\pm var}(x)-h^0(x))$$

Where: θ = NP controlling a systematic variation on m_{VH}.

The variation h^{var} is derived by re-weighting the nominal histogram h^0 by the MadGraph/Sherpa ratio:

$$h^{\pm var}_{V+y}(x)=f^{syst}_{V+y}(x)\times h^0_{V+y}(x)$$

y = flavour

$$h^{post}_{V+b}(x)=h^0_{V+b}(x)\pm\theta(h^{\pm var}_{V+b}(x)-h^0_{V+b}(x))$$
$$h^{post}_{V+c}(x)=h^0_{V+c}(x)\pm\theta(h^{\pm var}_{V+c}(x)-h^0_{V+c}(x))$$
$$h^{post}_{V+l}(x)=h^0_{V+l}(x)\pm\theta(h^{\pm var}_{V+l}(x)-h^0_{V+l}(x))$$

} lowMH

....
....
....

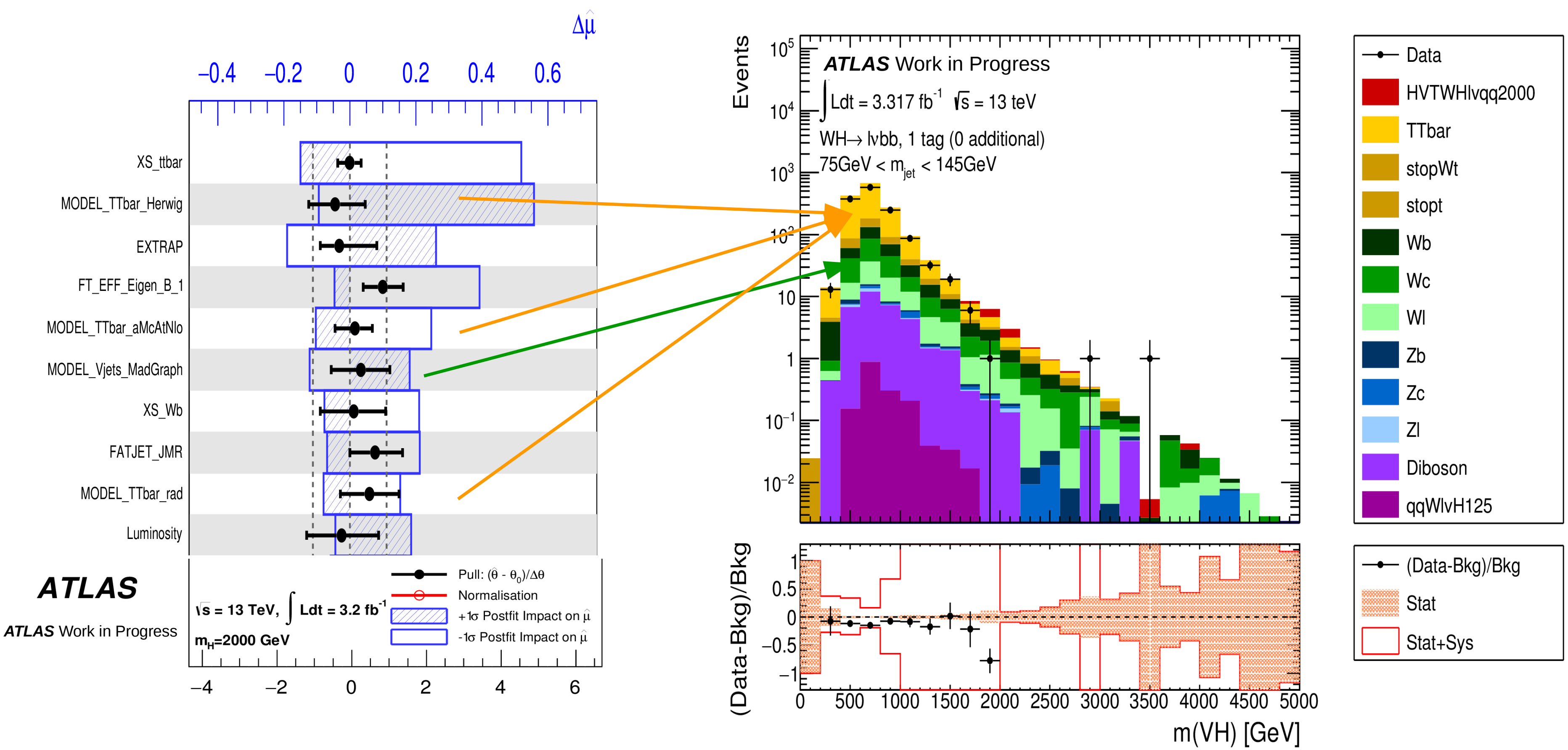
} SR & highMH

Nuisance Parameters & Fit Handling

→ Following fit procedure, the best fit results for the NP's can be summarised in 2 ways:

Ranking Plot : Quantifies the impact of a ±1σ variation in each NP on the best fit signal strength parameter

→ Ranking plot shows that in the 1-lepton channel, the V+Jets bkg is 6th most dominant systematic.



Conclusion

→ Search using a Phenomenological Lagrangian for Heavy Vector Resonances.

→ Boosted topologies resulting from heavy resonances: $500\text{GeV} < m_{V'} < 5\text{TeV}$

→ Substructure techniques open boosted topologies for investigation.

→ $H \rightarrow bb$ viable at high m_{VH} as backgrounds fall off

→ Possible reach due to substructure.

→ V+Jets & TTbar bkgs dominate

→ Derive systematic from MC modeling differences

→ Run 1 ~ 20 fb^{-1}, Run 2 ~ 3.2fb^{-1} – A competitive result already obtained

References:

[1] "W.J. Stirling, private communication"

[2] Aad et al., *Search for a new resonance decaying to a W or Z boson and a Higgs boson in the νν/lν/ll + bb final states with the ATLAS detector*, Eur. Phys. J. C75.6 (2015) 263, arXiv: 1503.08089 [hep-ex]

[3] V.Khachatryan et al., *Search for A Massive Resonance Decaying into a Higgs Boson and a W or Z Boson in Hadronic Final States in Proton-Proton Collisions at sqrt(s) = 8 TeV (2015)*, arXiv:1506.01443 [hep-ex]

[4] Glen Cowan et al, *Asymptotic formulae for likelihood-based tests of new physics*, arXiv:1007.1727 [physics.data-an]

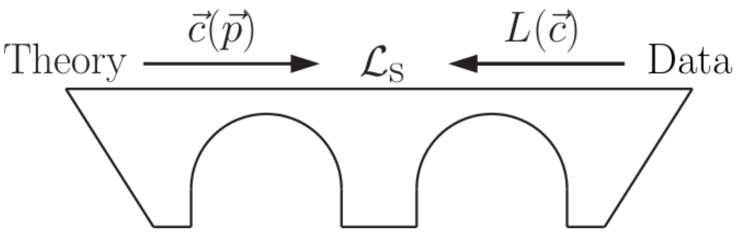
Back Up Slides

Overview

→ A theoretical paradigm is used called the "Heavy Vector Triplet" Model.
  → $SU(2)_L$ iso-triplet of fields: $W'^{\pm}$, Z'^{0}

→ "Simplified Strategy" Model, a simplified Lagrangian that retains the relevant mass & coupling parameters.

→ Limits can then be derived on "σ x BR"
  → Likelihood Function *'L'* in terms of phenomenological parameters $\vec{c}$
  → Relate $\vec{c}$ to $\vec{p}$ (explicit model parameters) to extract limits on the explicit parameters of a given theoretical model.



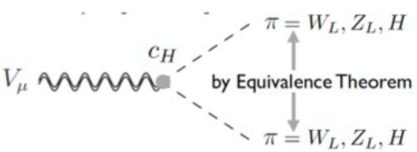
2 Benchmark Models:

→ Benchmark A:
  Weakly coupled vector resonances from extension of SM gauge group.
  $g_V = 1$
  Fermion & Vector Boson couplings equivalent

→ Benchmark B:
  Strongly coupled scenario,
  $g_V = 3$
  Suppressed fermionic couplings.

SM Vector Boson Coupling

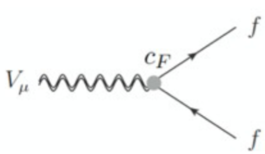
$i g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H$



SM Fermion Coupling

$\frac{g^2}{g_V} c_F V^a_\mu J^{\mu a}_F$

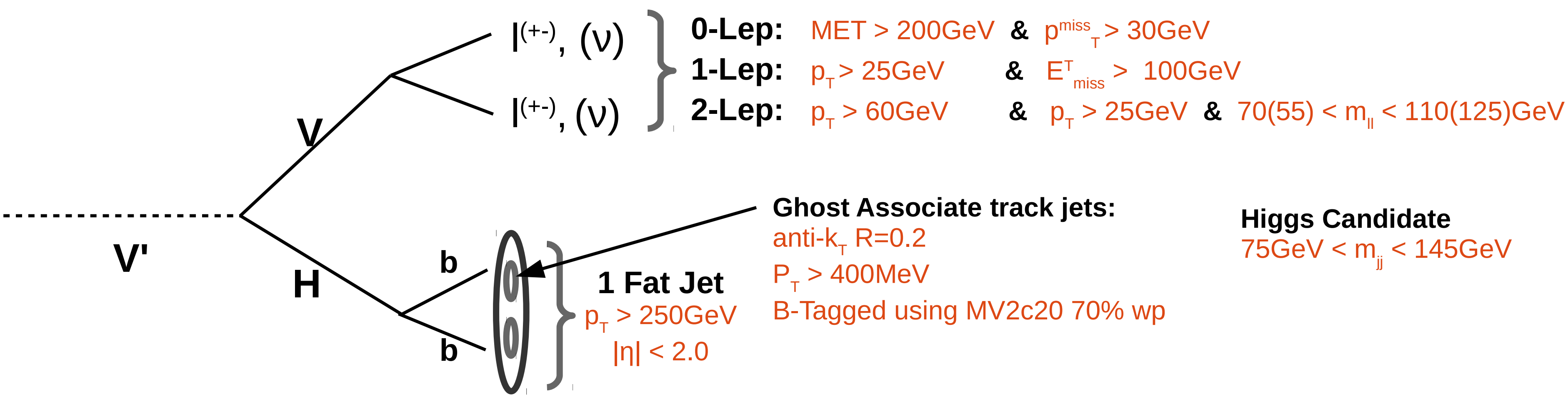
$c_F \rightarrow \{c_l, c_q, c_3\}$



Event Topology & Selection

→ Searching for m_{VH} system > 1.5 TeV will result in boosted topologies.

→ Use of fat-jets with ΔR =1.0 & sub-structure techniques



Event Topology & Selection

	0-lepton	**1-lepton**	**2-lepton**
# Leptons	Exactly 0	Exactly 1	Exactly 2
# Fat Jets (R=1.0)		≥1	
# Track-Jets		≥1	
Lepton p_T	N/A	> 25GeV	> {60, 25} GeV
Lepton η [e, μ]		< {2.47, 2.5}	
$E^T{}_{miss}$	> 200 GeV	> 100 GeV	N/A
$p^T{}_{miss}$	> 30 GeV	N/A	N/A
m_{ll}	N/A	N/A	70 < m_{ll} < 110 GeV (ee) 55 < m_{ll} < 125 GeV (μμ

Event Selection : 2-Lepton

Leptons e(μ):

Trigger:

trigger p_T > 7(7) GeV
trigger |η| < 2.47(2.5), crack region excluded

Quality Cuts:

$|d_0/\sigma(d_0)| < 3(5)$, d_0 defined wrt beam line
$|z_0 \sin\theta| < 0.5$mm

Muon Track Quality

min{1} pixel hit
min{5} SCT hits
} **Crossed dead pixel/SCT count**

Silicon holes < 3
Successful TRT extension

Preselection:

2 Lepton p_T > 25GeV
Isolation WP: **LooseTrackOnly**
} **Exactly 2 VHLoose**

1 Lepton p_T > 60GeV
ID WP: **Loose**
} **1 ZHTight**

Jets:

Fat Jets

1 Jet with:
- ΔR = 1.0 (anti-kT)
- p_T > 250GeV
- |η| < 2.0

} **Calorimeter Fat Jet**

Small R-Jets

1+ Track jets ghost associated to Fat Jet:
- ΔR = 0.2 (anti-kT)
- |η| < 2.5
- ID tracks p_T > 400MeV
- *Loose* criteria

} **MV2c20 b-tagged at 70% WP**

Triggers:

HLT_e24_lhmedium_iloose ← **L1 hadronic isolation & track isolation (ptcone20/pt) <0.2**
HLT_e60_lhmedium1
HLT_e120_lhloose
} **Electron Channel**

HLT_mu20_iloose_L1MU15
HLT_mu50
} **Muon Channel**

Miscellaneous

Overlap Removal

Large-R jet removed if ΔR(jet, e) < 1.2 ← **Remove 'e' if ΔR(jet, e) < 0.4 post overlap**

Variable Cone OR applied to Small-R jets

'e' does not share a track with 'Mu', else remove 'e'

Trigger match electron/muon to each fired trigger

Event Selection : 1-Lepton

Leptons e(μ):

Trigger:

trigger p_T > 7(7) GeV
trigger |η| < 2.47(2.5), crack region excluded

Quality Cuts:

$|d_0/\sigma(d_0)|$ < 3(5), d_0 defined wrt beam line
$|z_0 \sin\theta|$ < 0.5mm

Muon Track Quality

min{1} pixel hit
min{5} SCT hits
} **Crossed dead pixel/SCT count**
Silicon holes < 3
Successful TRT extension

Preselection:

1 Lepton p_T > 25GeV
Isolation WP: **Tight**
} **Exactly 1 WHTight Lepton**

Jets:

Fat Jets

1 Jet with:
- ΔR = 1.0 (anti-kT)
- p_T > 250GeV
- |η| < 2.0

} **Calorimeter Fat Jet**

Small R-Jets

1+ Track jets ghost associated to Fat Jet:
- ΔR = 0.2 (anti-kT)
- |η| < 2.5
- ID tracks p_T > 400MeV
- *Loose* criteria

} **MV2c20 b-tagged at 70% WP**

Triggers:

L1 hadronic isolation & track isolation (ptcone20/pt) <0.2 → HLT_e24_lhmedium_iloose

HLT_e24_lhmedium_iloose
HLT_e60_lhmedium1
HLT_e120_lhloose
} **Electron Channel**

HLT_mu20_iloose_L1MU15
HLT_mu50
} **Muon Channel**

Miscellaneous

MET

E^{miss}_T > 100GeV

Overlap Removal

Large-R jet removed if ΔR(jet, e) < 1.2 ← **Remove 'e' if ΔR(jet, e) < 0.4 post overlap**

Variable Cone OR applied to Small-R jets

'e' does not share a track with 'Mu', else remove 'e'

Search Strategy

→ Define the signal region as: $75GeV < m_J < 145GeV$

&

≥ 1B-tagged ghost associated track-jets

Where: m_J = invariant mass of Fat-Jet

→ Define series of control regions for background control & handling:

- → Dominant backgrounds : V+jets & ttbar
- → Sub-dominant backgrounds : Diboson & single top (+ associated production)

V+Jets:

→ Low & high m_J regions handle V+jets

- → lowMH : $m_J < 75GeV$
- → highMH : $m_J > 145GeV$

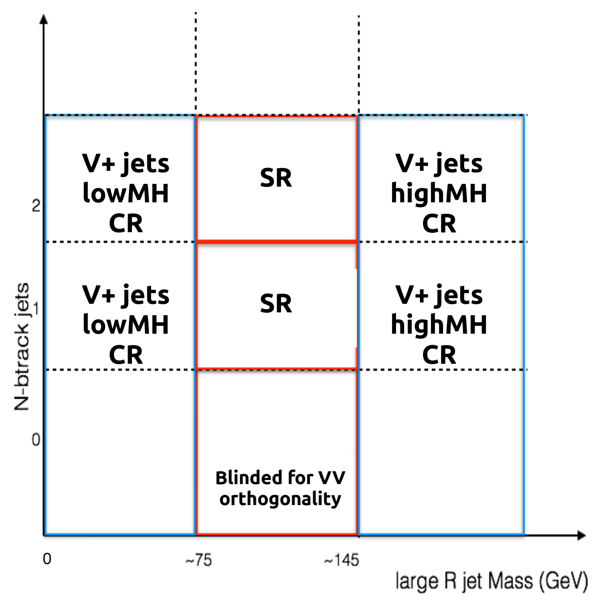
TTbar:

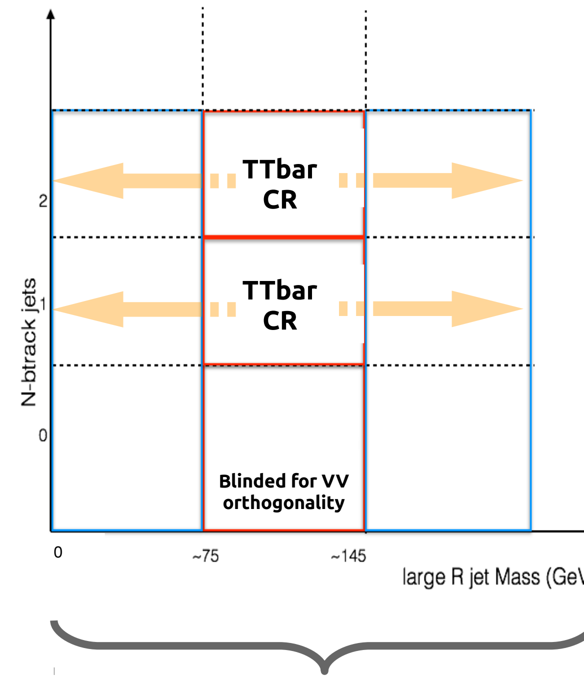
→ 0 & 1-Lepton channel CR:

≥ 1 Additional B-tagged track jets not ghost associated to fat-jet

→ 2-Lepton channel CR:

eμ (different lepton flavours)





≥ 1 Addional B-tagged Track jets

Search Strategy

Resonance Finding:

→ Using CR's & SR, a Binned Maximum Likelihood Fit is performed in the variable 'm_{VH}':

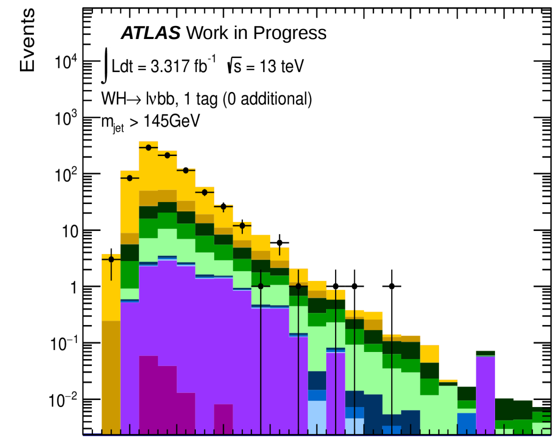
→ $m_{VH} = (p^{\mu}_{J} + p^{\mu}_{\{ll,\, l\nu,\, \nu\nu\}})^2$,

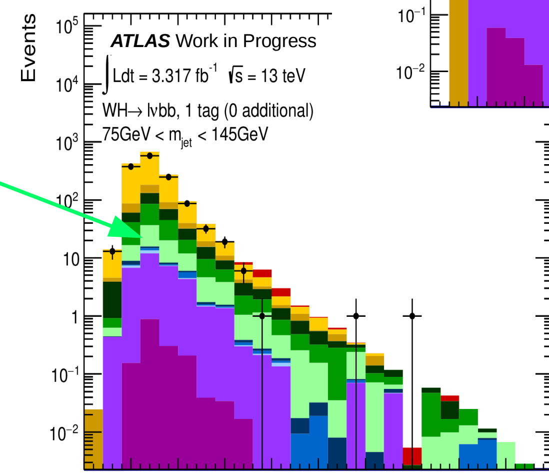
$$L(\mu_b,\mu_s)=\prod_{i=1}^{N_{chan}}\prod_{j=1}^{N_{bin}}\left[P\left(N_{ij}|\mu\, s(\vec{\theta})_{ij}+\sum_{k=1}^{N_{bkg}} b(\vec{\theta}_{ijk})\right)\right]\times\prod_{n=1}^{N_{\theta}} N(\hat{\theta}|\theta)$$

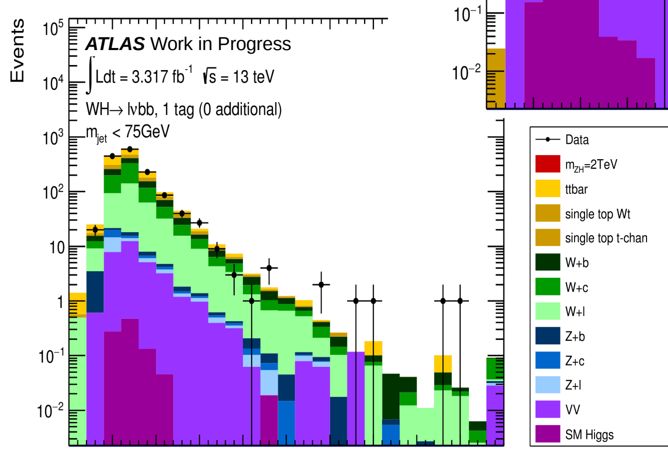
Ref [4]

- $b(\theta)$: Bkg from MC (forms templates)
- $s(\theta)$: Signal from MC
- Θ : Nuisance parameters
- N_{ij} : Number of events
- μ : Signal strength

→ Performed simultaneously across lowMH, SR & highMH





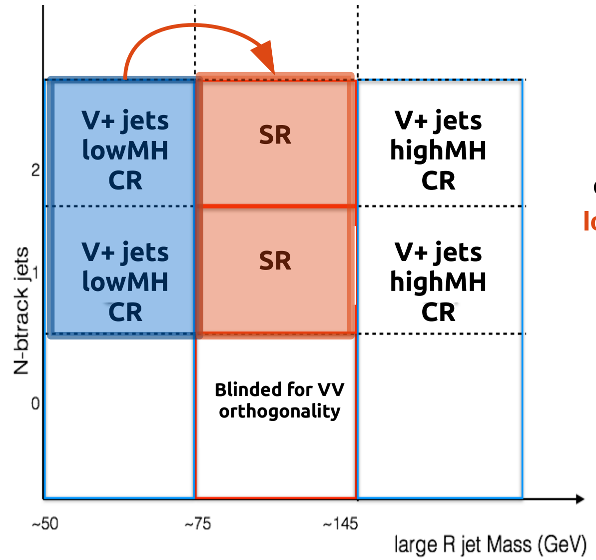


V+Jets Background & Deriving a Systematic

→ Define 3 categories of V+jet bkg:

- V+b : V+bb, V+bc V+bl
- V+c : V+cc, V+cl
- V+l : V+ll

→ These 3 categories go into the fit in each mass and tag region.



Apply Scale

a^{low}_{b} = Sherpa(b, lowMH)/MG5(b, lowMH) = 0.744691, to SR Sherpa.

Derivation Methodology:

1) Calculate **a_{V+y} = Sherpa(V+y, low)/MG5(V+y, low)**

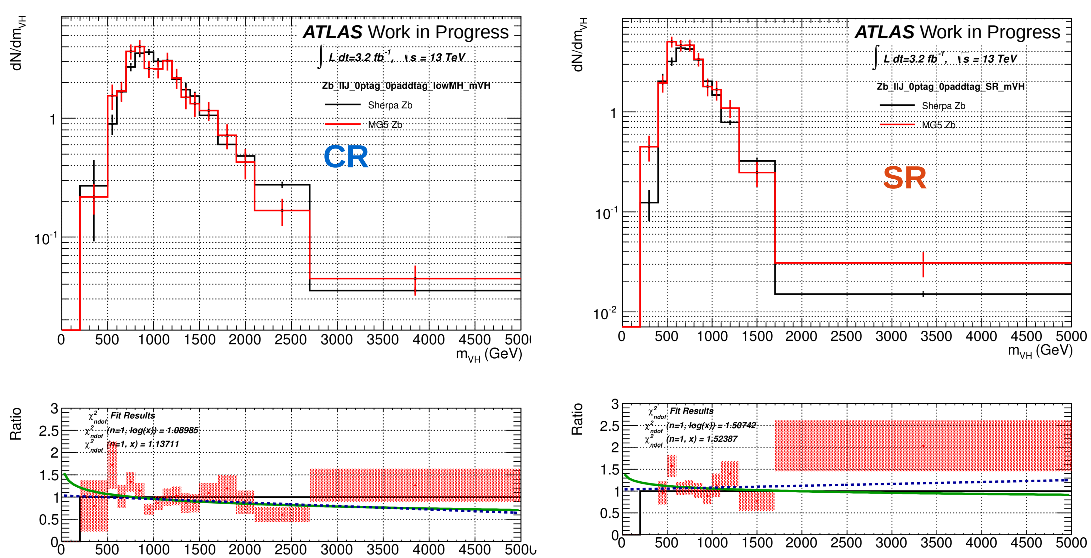
2) Normalise MG5 & Sherpa to same area, and fit 1st order polynomial to ratio → Shape variation only

3) Scale nominal SR V+Jets distribution by a_{V+y}

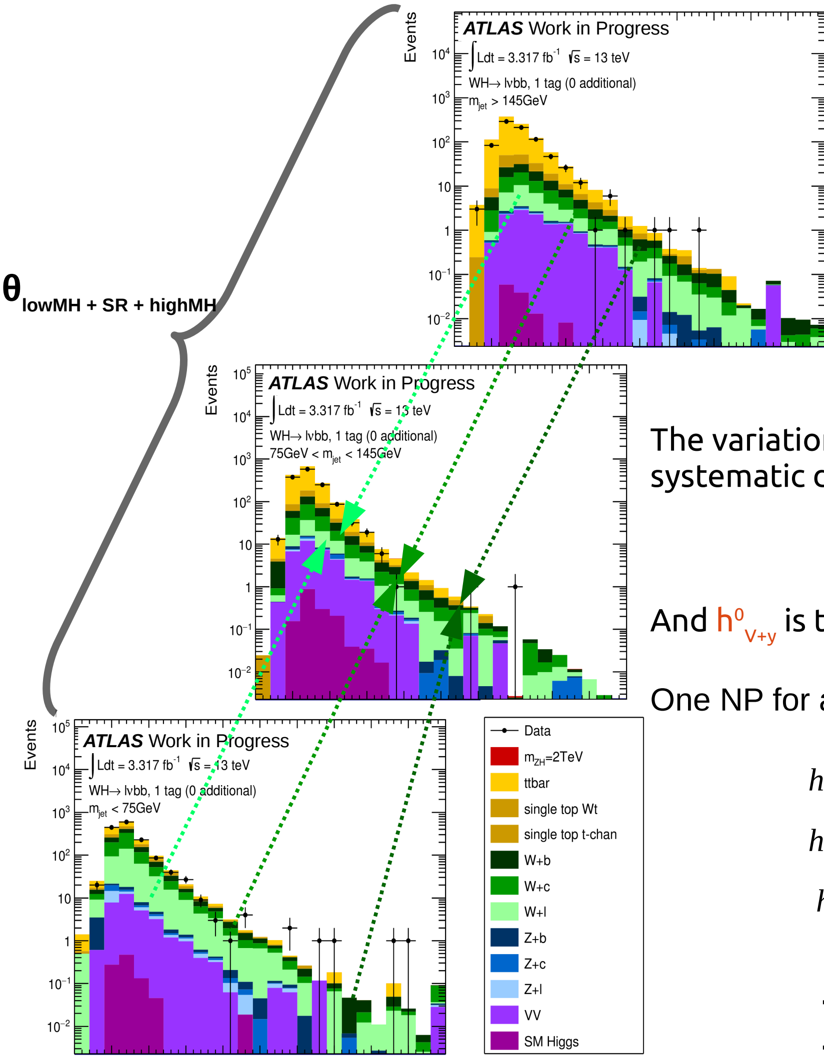
4) Fit 1st order polynomial to ratio:

$$f^{syst}_{V+y}(x) \rightarrow \frac{\alpha_{V+y}\times h^{MG5}_{V+y}(x|SR)}{h^{sherpa}_{V+y}(x|SR)} \rightarrow \frac{h^{Sherpa}_{V+y}(x|CR)}{h^{MG5}_{V+y}(x|CR)} \times \frac{h^{MG5}_{V+y}(x|SR)}{h^{sherpa}_{V+y}(x|SR)}$$

→ shape variation + yield extrapolation



Nuisance Parameters & Fit Handling



Perform a Maximum Likelihood fit (ML) to the $_{mVH}$ spectrum:

$$L(\mu_b,\mu_s)=\prod_{i=1}^{N_{chan}}\prod_{j=1}^{N_{bin}}[P(N_{ij}|\mu s(\vec{\theta})_{ij})+\sum_{k=1}^{N_{bkg}} b(\vec{\theta_{ijk}})]\times\prod_{n=1}^{N_{\theta}} N(\hat{\theta}|\theta)$$

Where θ represent the NP controlling a systematic variation on $m_{VH.}$

Define a variation on the m_{VH} MC templates as:

$$h(x)=h^0(x)\pm\theta(h^{\pm var}(x)-h^0(x))$$

The variation h^{var} is derived by re-weighting the nominal histogram h^0 via the systematic difference between MadGraph & Sherpa:

$$h^{\pm var}_{V+y}(x)=f^{syst}_{V+y}(x)\times h^0_{V+y}(x)$$

And h^0_{V+y} is the nominal MC template (histogram), y is the flavour of the event

One NP for all mass regions & all V+Jet flavours: $\theta = \theta_{V+b\,|\,lowMH}$, $\theta_{V+c\,|\,lowMH,}$ ...., $\theta_{V+b\,|\,SR}$

$$h^{post}_{V+b}(x)=h^0_{V+b}(x)\pm\theta(h^{\pm var}_{V+b}(x)-h^0_{V+b}(x))$$
$$h^{post}_{V+c}(x)=h^0_{V+c}(x)\pm\theta(h^{\pm var}_{V+c}(x)-h^0_{V+c}(x))$$
$$h^{post}_{V+l}(x)=h^0_{V+l}(x)\pm\theta(h^{\pm var}_{V+l}(x)-h^0_{V+l}(x))$$

lowMH

....

....

....

SR & highMH