Search for Resonant/Non-resonant VHH with the ATLAS Detector

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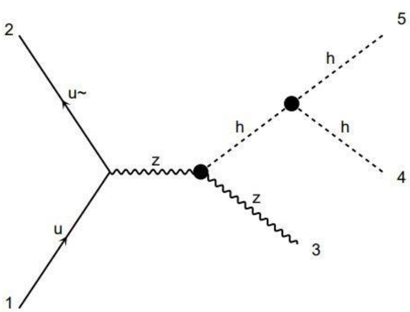
Overview

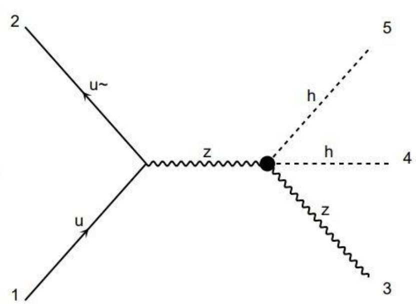
- Analysis targets either resonant or non-resonant models with a W/Z and two SM higgs bosons (hh) in the final state.
- Only h→bb is considered, for simplicity and for the sake of high statistics.
- Considering multiple final states(Zvv/Wlv/Zll) and multiple signal models
- Three signal models: Non-resonant production with varied hh and vvhh couplings, resonant VH(hh), and resonant A→ZH(hh)

Feynman diagram examples as below:

Non-resonant

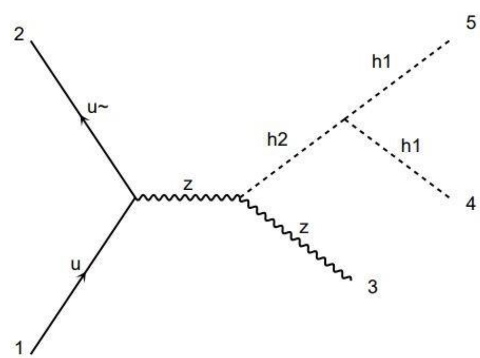


C3

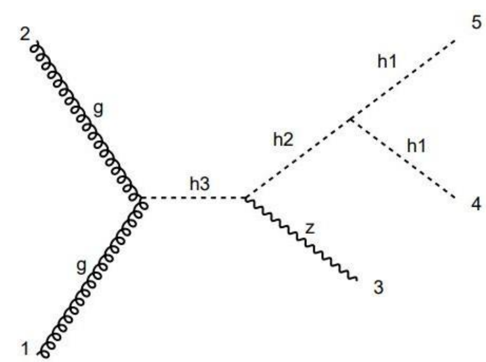


C2V

VH(hh)



A→ZH(hh)



Object selection

Signal object definitions:

Object	p_T	η	ID	Isolation
jets	> 20 GeV	< 4.5	Tight JVT	N
photon	> 150 GeV	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$	tight IsEM	FixedCutHighPtCaloOnly
electron	> 7 GeV	$\|\eta\| < 2.47$	Medium LLH	FCLoose
muon	> 7 GeV	$\|\eta\| < 2.5$	Loose ID	FCLoose
taus	> 20 GeV	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.5$	Medium RNN	

- Particle-flow jets, DL1r for b-tagging with 85% efficiency working point*
- Single lepton triggers used in 1/2-lepton channels
- MET triggers in 0-lepton channel
- Single photon trigger used in γ+jets control region

*corresponding c-jet rejection factor ~3, light-jet rejection factor ~60

Dataset

Background

MC-based:

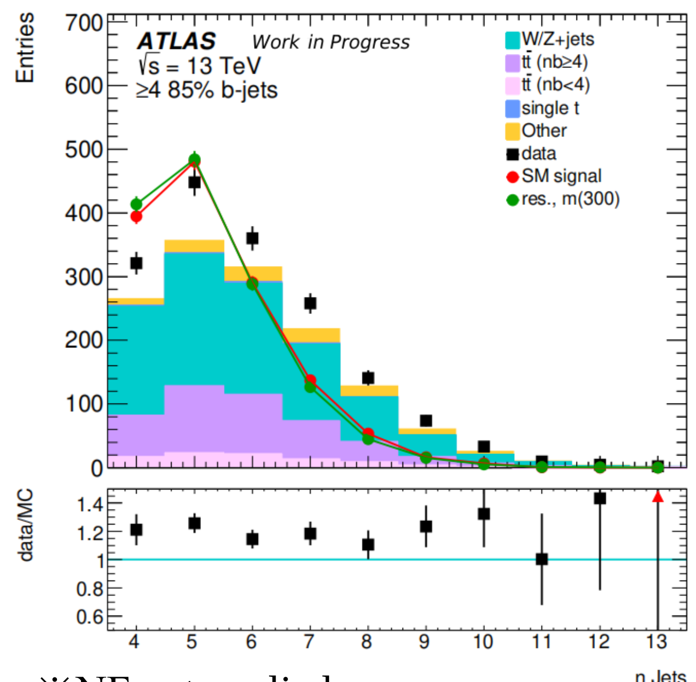
- W/Z+jets: Sherpa 2.2.1 NNLO with CRs
- ttbar: PowhegPythia8 with CRs
- Single top: PowhegPythia8 NLO
- Photon+jets: Sherpa 2.2.2 NNLO
- ttH: PowhegPythia8
- ttX: PowhegPythia8 NLO
- VVV: Sherpa 2.2.2/2.2.1 NNLO

Data-driven:

- Multi-jet: estimated by MJCR

Data: 2015-2018 140 fb^-1

Signal: MadgraphPythia 8 NLO



※NF not applied

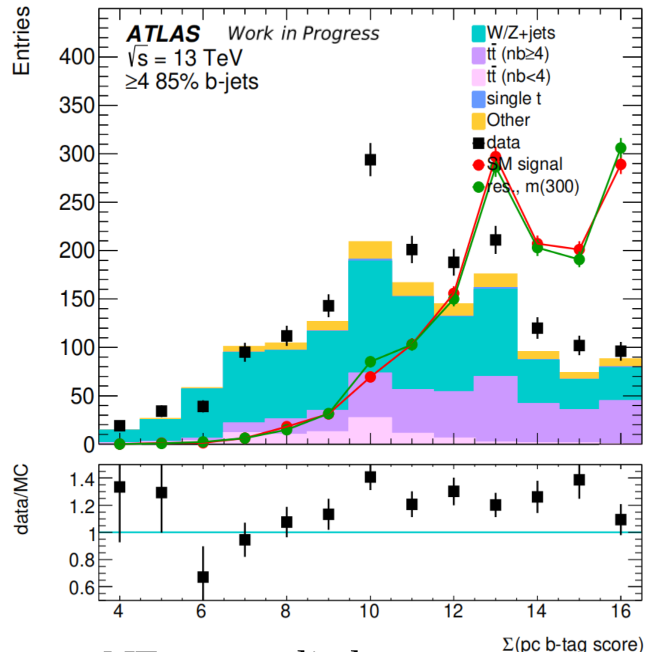
Event selection

Preselection:

- ≥ 4 85% b-jets with pT > 20 GeV and |η| < 2.5, tagged with DL1r
- 4 jets with leading pseudo continuous b-tagging scores are selected as signal jets.
- If jets have same pseudo continuous b-tagging scores, then four jets minimize |m(J1,J2) – 120 GeV| + | m(J3,J4) – 120 GeV| are selected

■ Pseudo continuous b-tagging score:

- 0 for jets failing the 85% WP
- 1 for jets passing the 85% WP but failing the 77% WP
- 2 for jets passing the 77% WP but failing the 70% WP
- 3 for jets passing the 70% WP but failing the 60% WP
- 4 for jets passing the 60% WP



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Event Categorization

- Signal Region(SR)
  - 0L SR(for ZvvHH signals)
  - 1L SR(for WlvHH signals)
  - 2L SR(for ZllHH signals)
- Control Region(CR)
  - e/mu CR (to constrain ttbar)
  - Photon CR (to constrain Vjets)

Used in final statistic fits

- Multi-jet(MJ) Region
  - 1L MJ (for MJ yield and shape in SR)
  - Photon+jets MJ (for MJ shape in CR)

Not included in fits, but used to extract yields or templates used in final fits

- Validation Region(VR)

BDT data/mc modeling

0/1/2 lepton signal region

Three orthogonal SRs for different lepton multiplicity

2 lepton

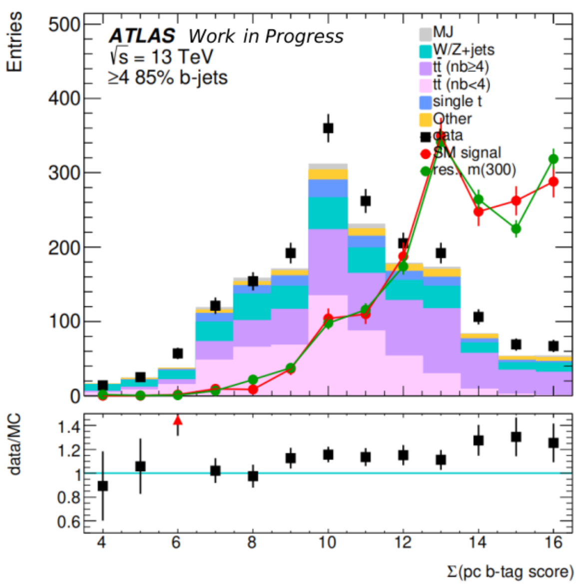
- Exactly 2 same-flavor opposite-sign baseline light, charged leptons (e^+e^- or $\mu^+\mu^-$)
- $81 < m_{ll} < 101$ GeV

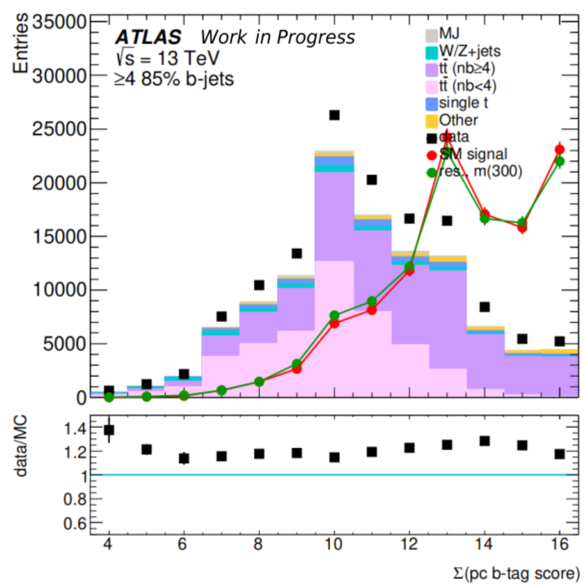
1 lepton

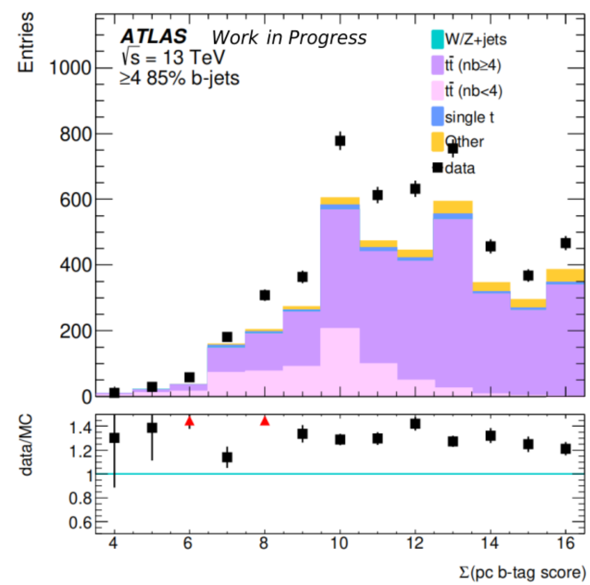
- Exactly 1 charged light leptons
- Exactly 0 taus
- $E_T^{miss} > 30$ GeV

0 lepton

- Exactly 0 charged leptons (including taus)
- $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
- $E_T^{miss,sig} > 12$
- $|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, h1)| > 1$
- $|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, h2)| > 1$







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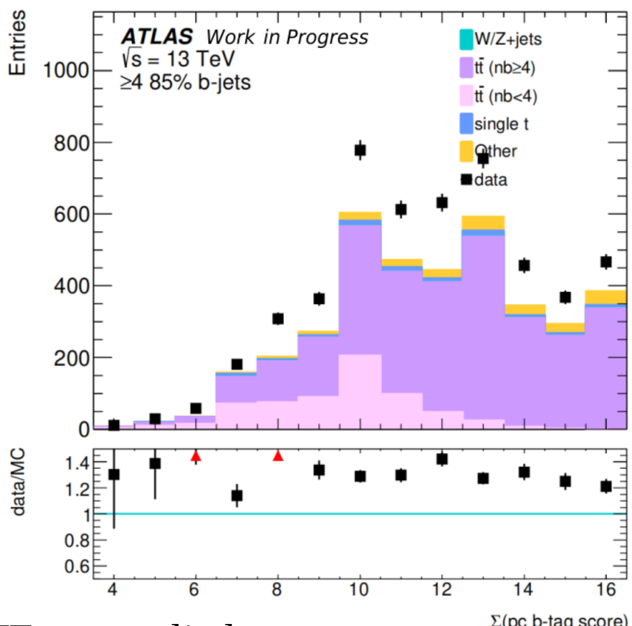
Control regions

- e/mu CR for constraining ttbar, γ+jets CR for constraining V+jets
- Only use b-tagging info in CRs, to constrain flavor composition uncertainties

e/μ CR

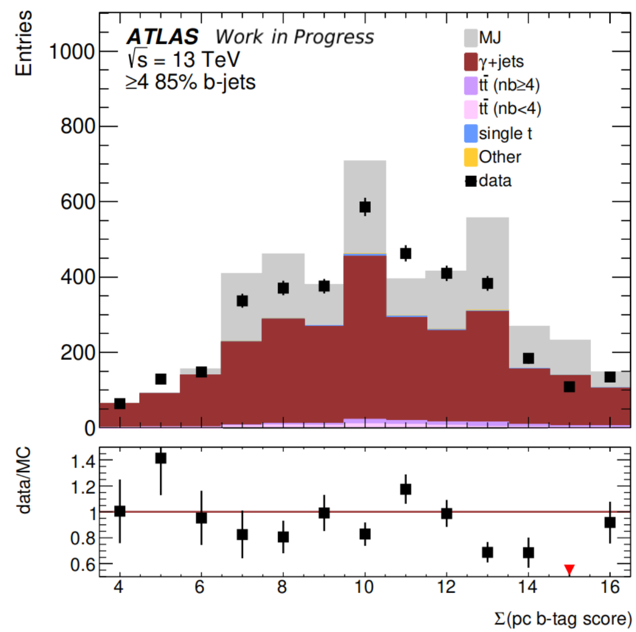
- Exactly 2 different-flavor opposite-sign baseline light, charged leptons ($e^{+}\mu^{-} or e^{-}\mu^{+}$)
- No requirement on m_{ll}



※NF not applied

γ+jets CR

- Exactly 0 charged leptons
- Exactly 1 photon
- $p_{T,\gamma} > 150$ GeV
- HLT_g140_loose



Multi-jet estimation

- Estimate Multi-jet in 0L, 1L, and γ+jets channels
- For 0L, Multi-jet is not explicitly included as a background in the 0L region in the fits, but it is implicitly included as an uncertainty, due to the validation region non-closure uncertainties.
- For 1L, Multi-jet CR provide both MJ yields and shape
- For γ+jets CR, Multi-jet CR provide a template which is float in fit.

0 lepton

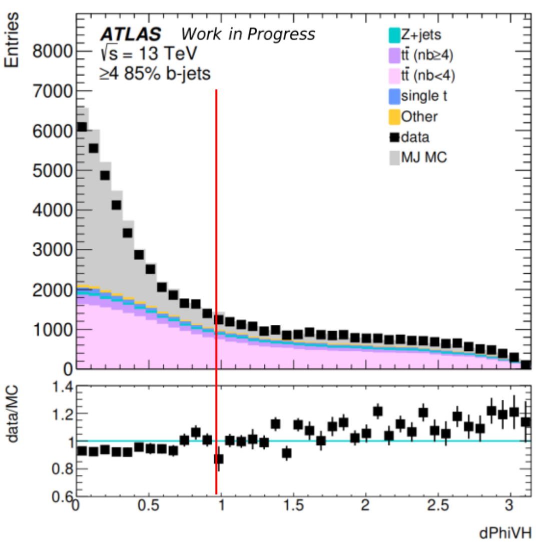
- Exactly 0 charged leptons (including taus)
- $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV

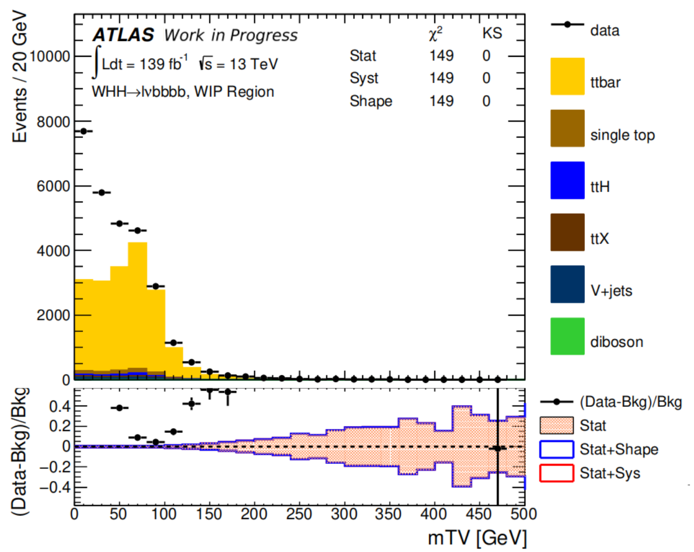
1 lepton

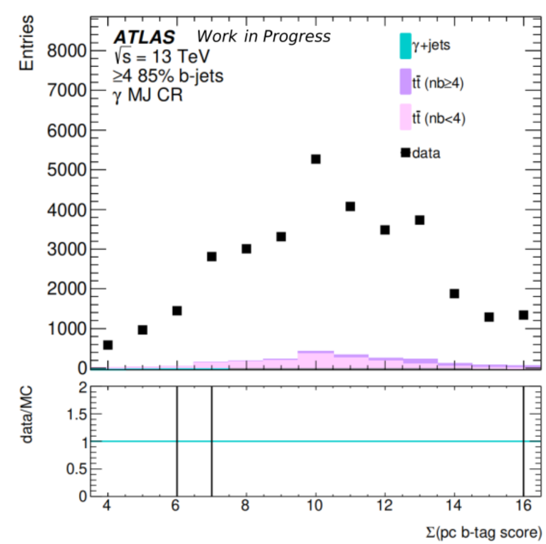
the same definition as the 1L SR, except inverting the isolation cut (requiring fail the isolation WP).

γ+jet

the same definition as the γ+jets CR, except inverting the isolation cut (requiring fail the isolation WP).





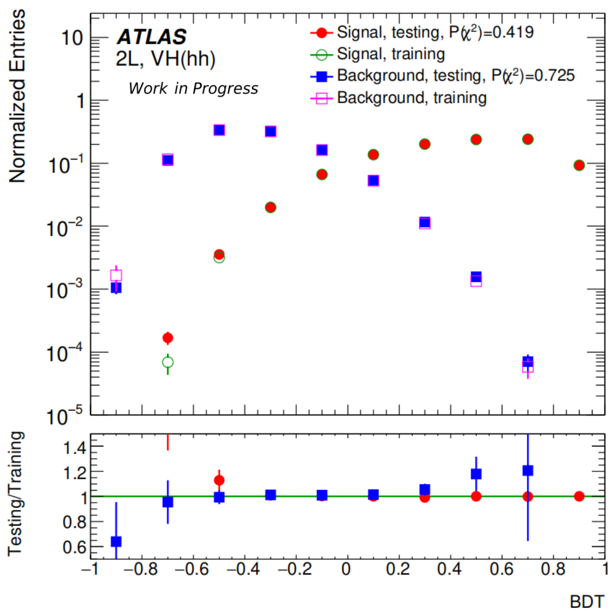


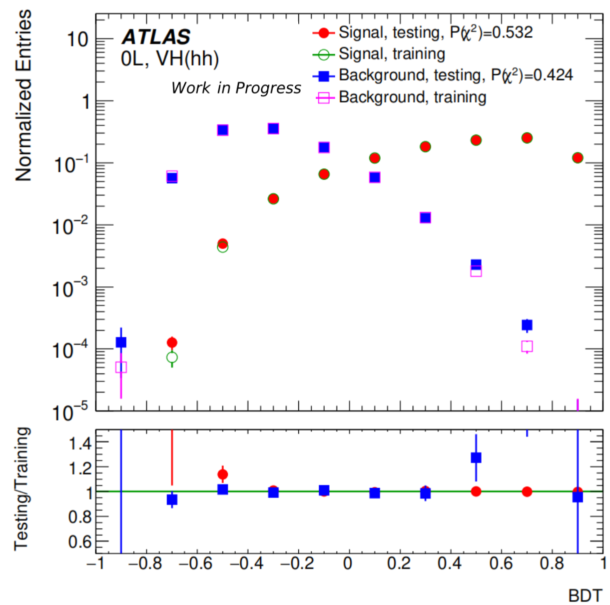
BDT

- BDTs as the final discriminant
- Variables used as listed:

Generally, all three channels use the same basic MVA strategy, with almost the same input variables.

	NR 0L	Hhh 0L	AZH 0L	NR 2L	VH(hh) 2L	AZH 2L	NR 1L	Hhh 1L
$mh1 + mh2$	X	X	X	X	X	X	X	X
$mh1 - mh2$	X	X	X	X	X	X	X	X
nJets	X	X	X	X	X	X	X	X
HT_Ex	X	X	X	X	X	X	X	X
Σ(b-tag scores)	X	X	X	X	X	X	X	X
p_T^V				X	X		X	X
p_T^{hh}	X	X		X	X		X	X
m^{hh}	X			X			X	
$cosh(\Delta\eta h1) - cos(\Delta\phi h1)$	X	X		X	X		X	X
$cosh(\Delta\eta h2) - cos(\Delta\phi h2)$	X	X		X	X		X	X
$\lvert\Delta y(h1, h2)$	X	X		X	X		X	X
$\lvert\Delta y(V, hh)$				X	X			
mh1_fsr8	X	X	X	X	X	X	X	X
mh2_fsr8	X	X	X	X	X	X	X	X
E_T^{miss}	X	X		X	X	X	X	X
mTVJ							X	

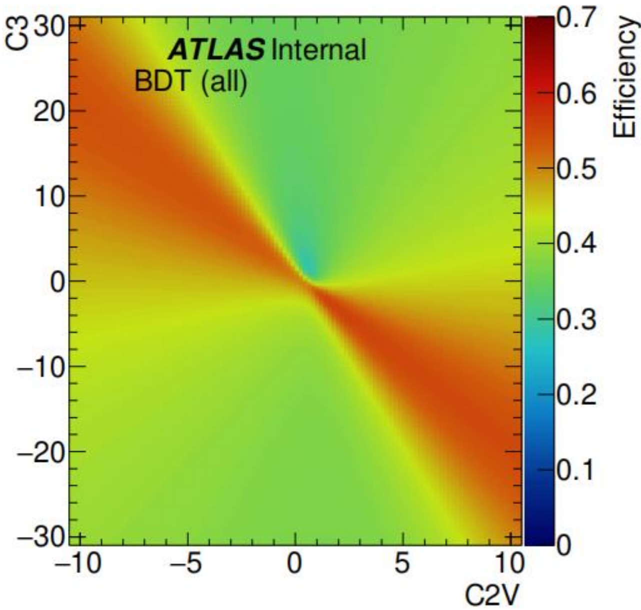




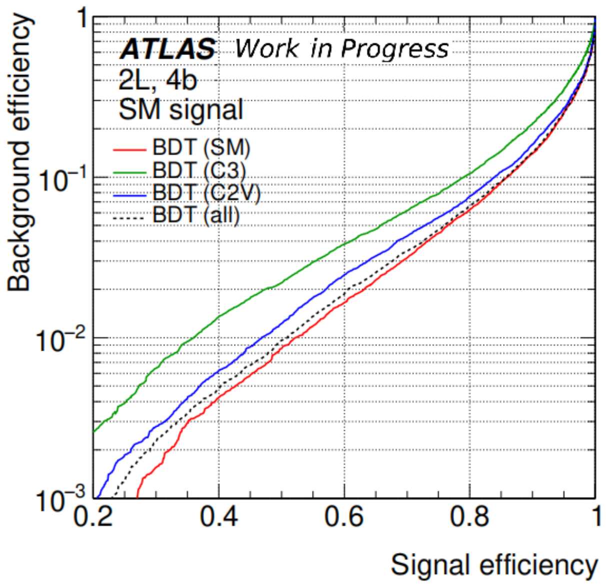
0L/1L BDT distribution, good separation and no overtraining

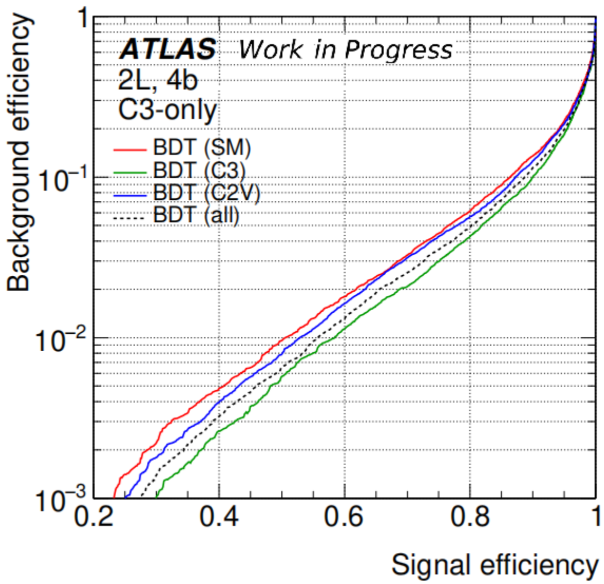
BDTs (Non-resonant)

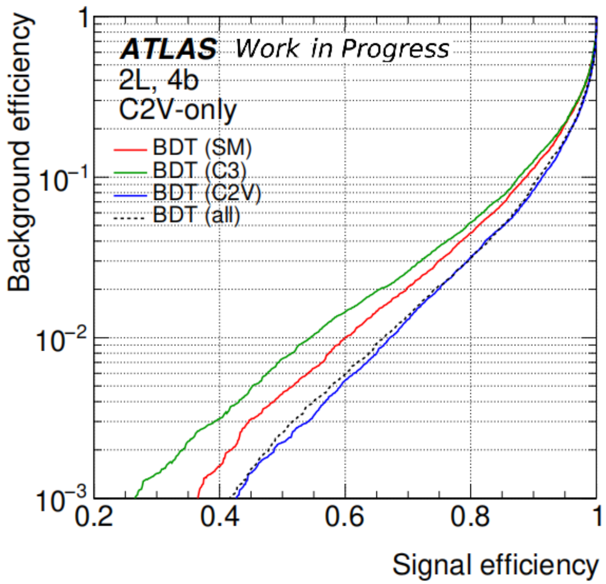
- One BDT per-channel
- For each BDT, train background against sum of SM-only, C3-only, and C2V-only signals
- Right plot shows signal efficiency for 98% background rejection
- Resonant BDT follows similar strategy.



ROC BDT curves shown below with different training

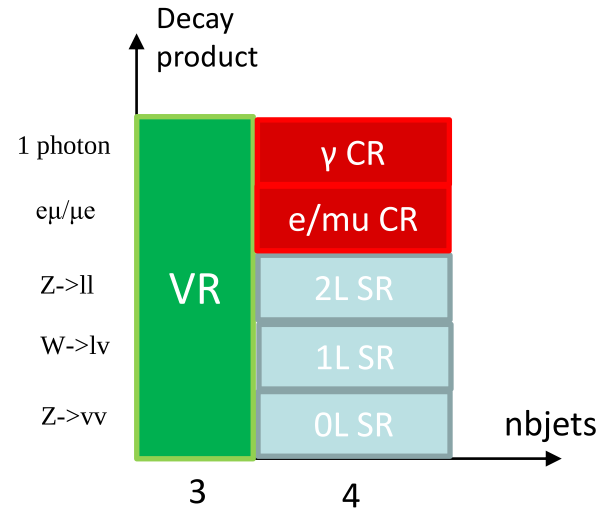


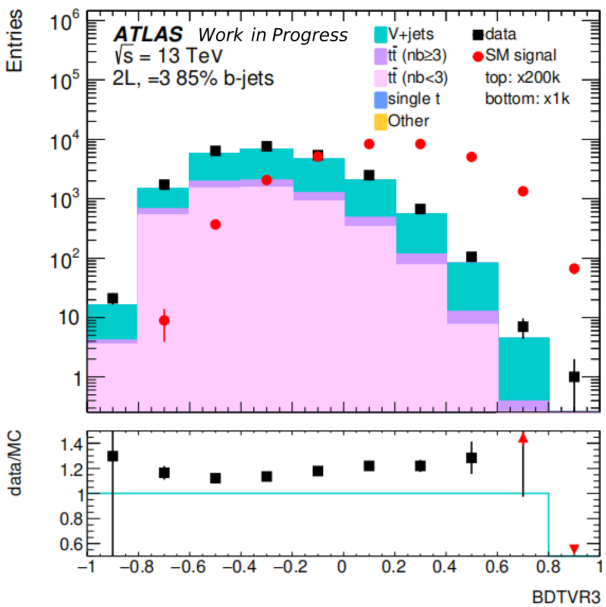


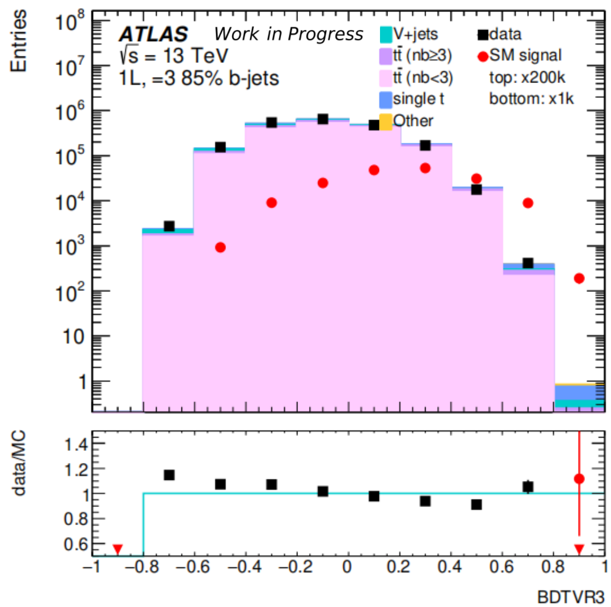


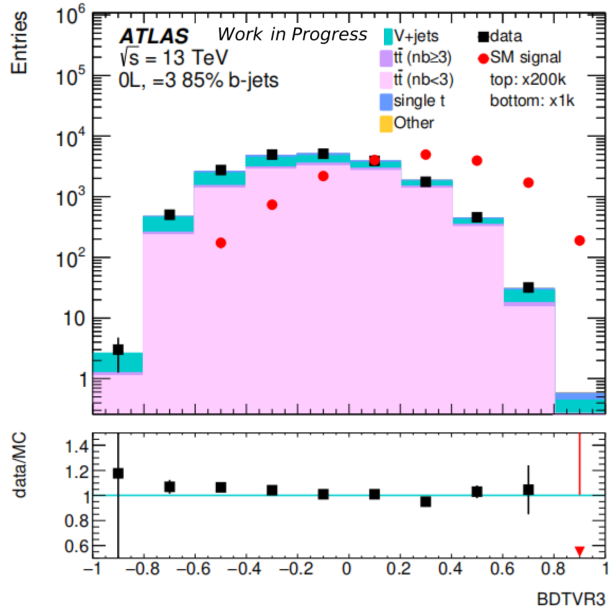
Validation Regions

- Five VRs corresponds to three SRs (0L, 1L, and 2L) and two CRs (e/μ and γ+jets), to validate the data/MC modeling on BDT distribution.
- VRs require at least 4 jets, only exactly 3 b-jets.
- Non-closure in VRs taken as uncertainty in the SRs
- BDT distributions shown below in VRs, for H(hh) BDTs



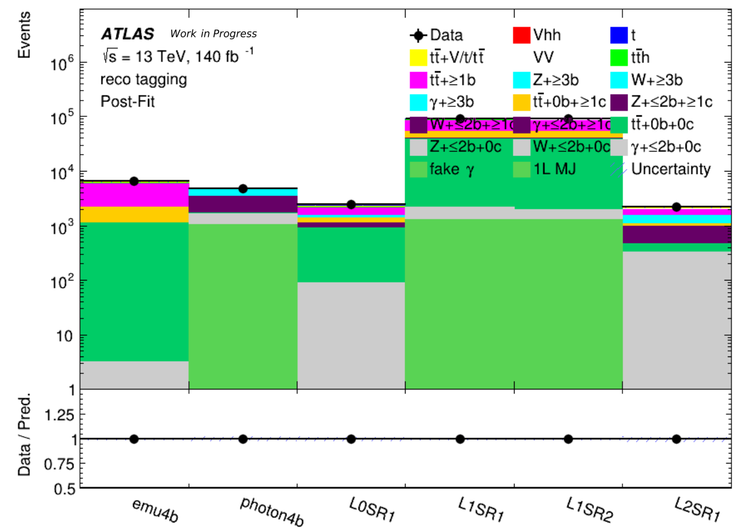




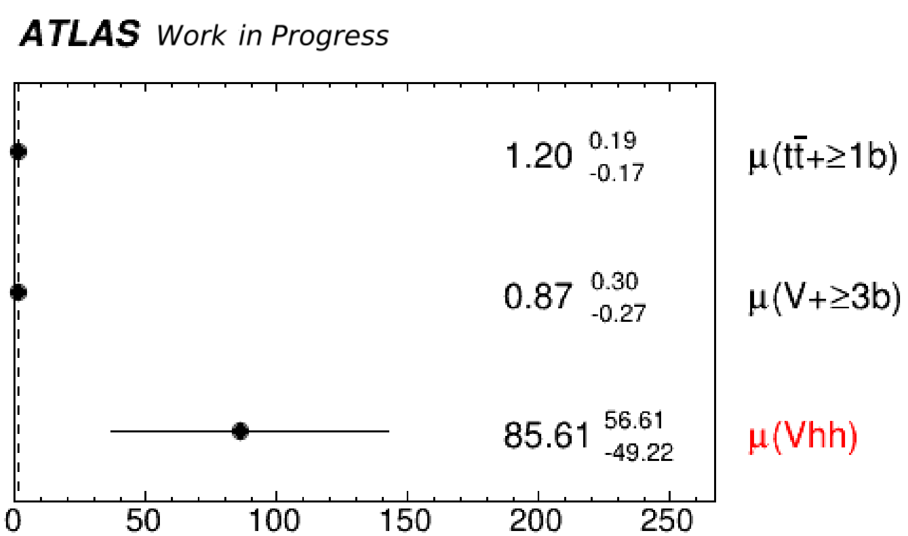


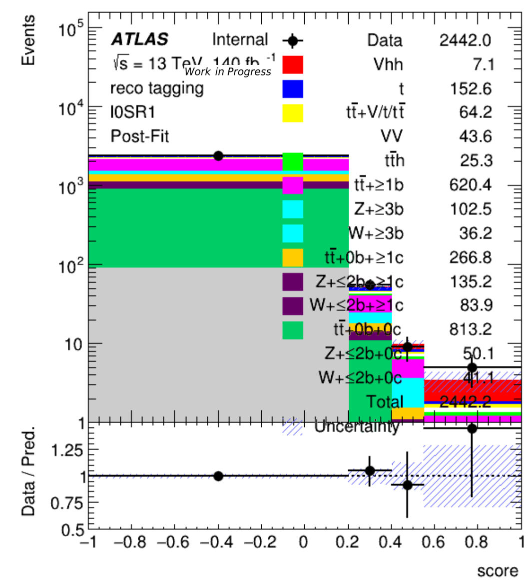
Fit Details

- Six regions total for all fits
- 1L channel is further split into W+/W- channels
- BDT score as final discriminant

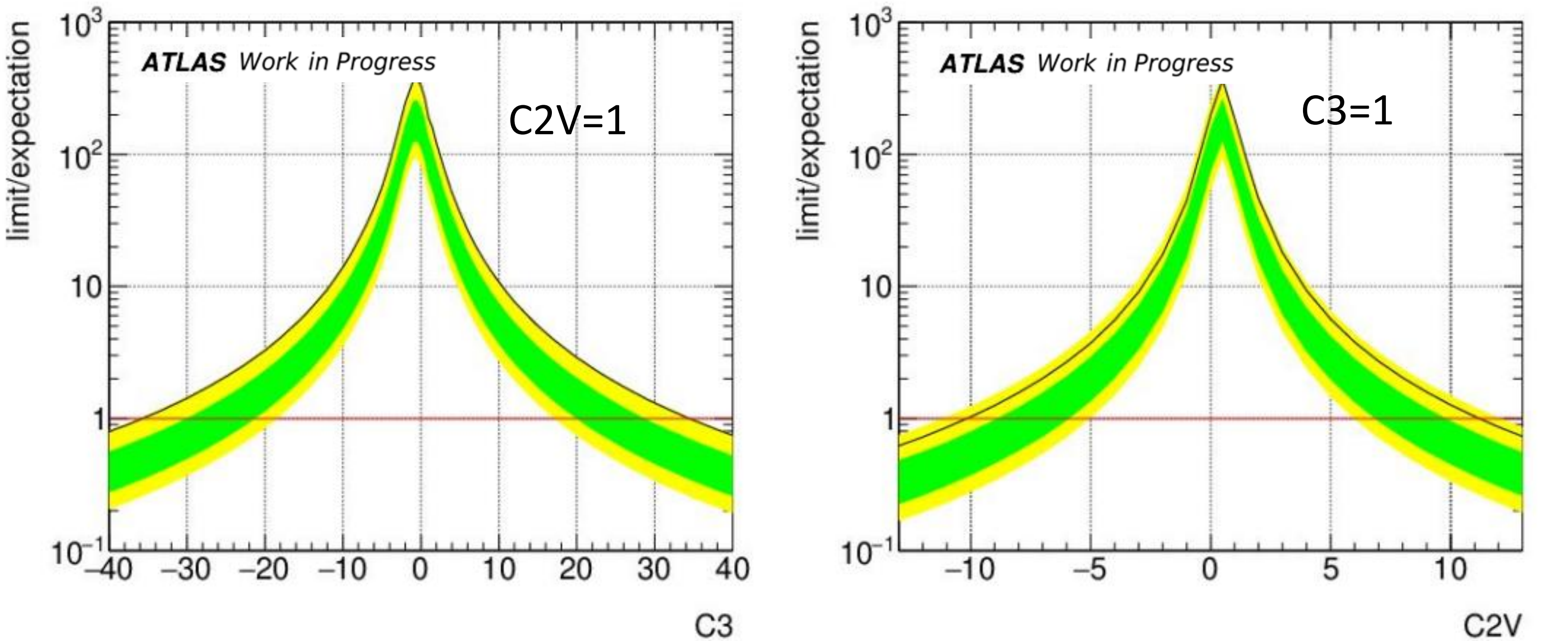


Plots show SM non-resonant fit result





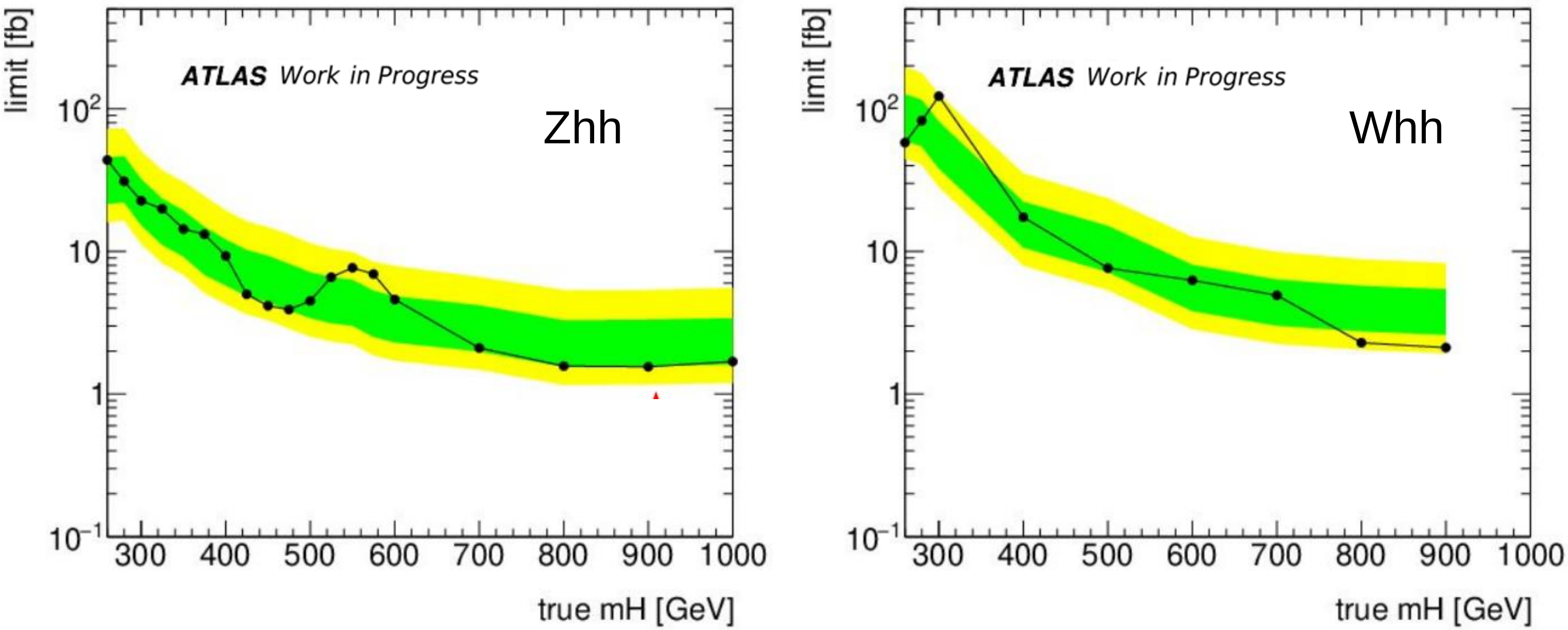
Observed signal strength(Non-resonant)



Observed signal strength as a function of each coupling parameter, fixing the other parameters to the SM expectation.

C3 is constrained in (-36,35), C2 in (-10,12.5)

Observed Limit(Resonant VH(hh))



Observed limits as a function of true mH mass, for resonant VH(hh) production (left: Zhh, right: Whh). Limit results from 260 GeV to 1 TeV, for each process separately comparison.

ZHH gives main contribution in the process.

Summary

- New search for Vhh final states with 0L/1L/2L. Three different models are considered, either non-resonant production, or resonant production in the form of either VH(hh) or A→ZH(hh).
- The analysis is just partially unblinded, expected to be published by early 2022.

Thank you

Backup

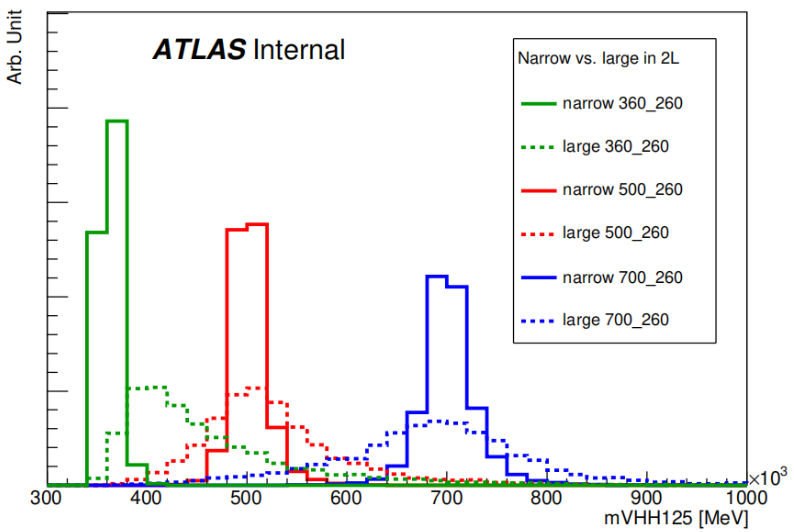
AZH large width signal interpolation

- For AZH large width signal , not all width (2%~20%) samples are available. Interpolation is needed to smear some width samples.
- Use Log-normal-Breit-Wigner function convolutes with narrow width signal to interpolate large width signal.

$$g_L = (f * g_N)(x)$$

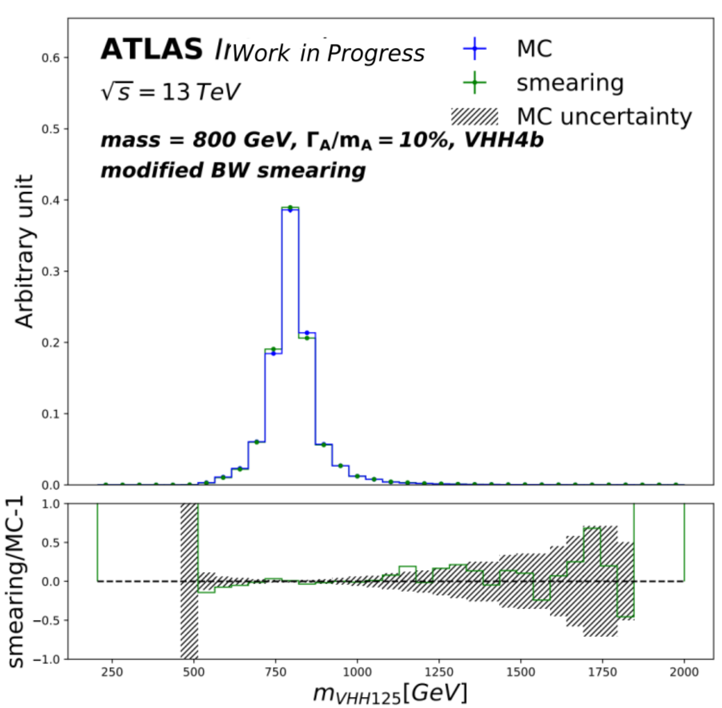
$$f = \frac{e^{\frac{-(\ln(x-x_0)-\ln(m)^2)}{2\times\ln(s)^2}}}{\sqrt{2\pi}(x-x_0)\ln(s)} \times \frac{1}{x^2+0.25w^2}$$

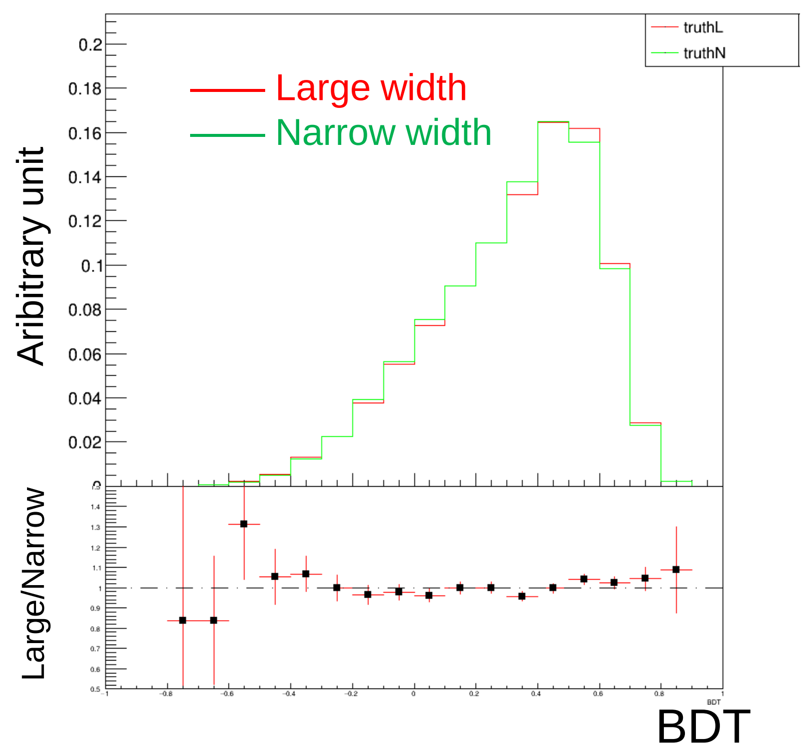
- The parameter x0,m,s is derived with 20% large width sample and convolution distribution by narrow width samples.
- Right plot shows large and narrow signal mVHH distribution comparison

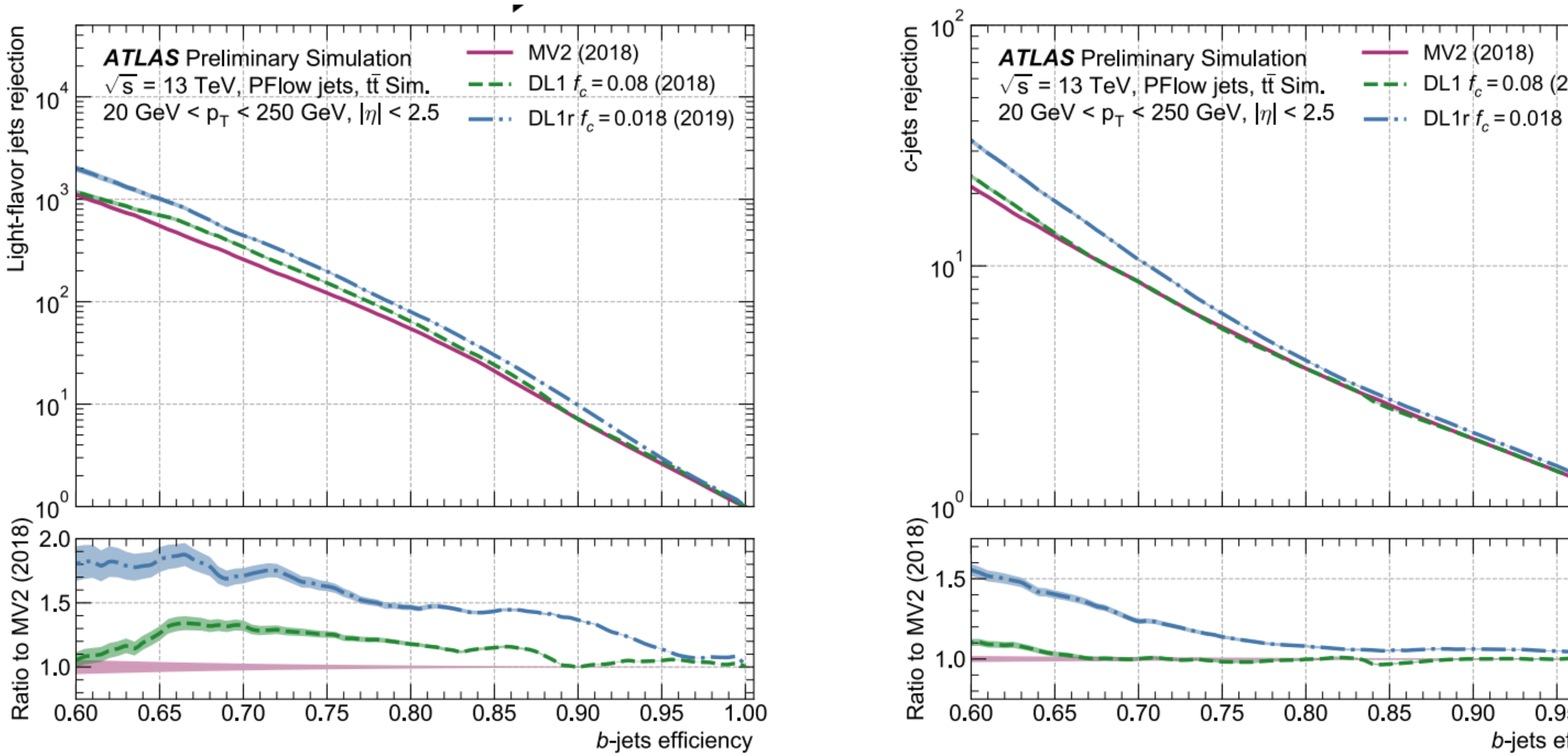


AZH large width signal interpolation

- The narrow convoluted distribution is consistent with the large width signal MC distribution (left plot)
- The BDT non-closure test show large width signal shares same distribution with narrow signal(right plot)

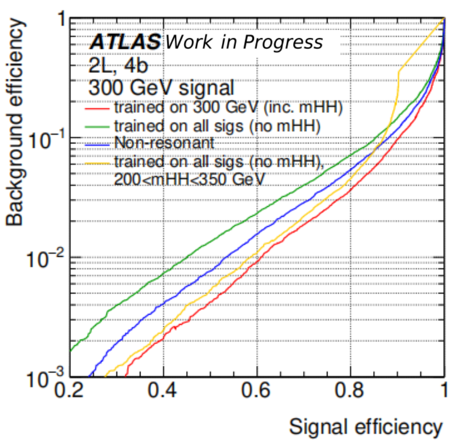


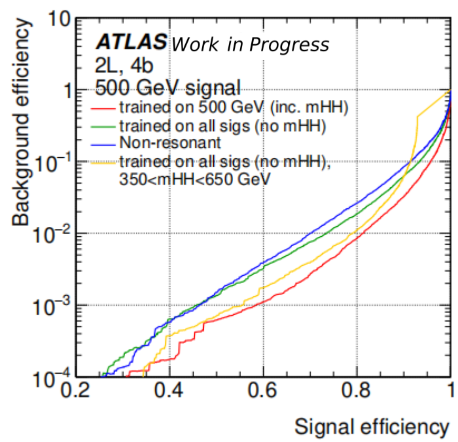


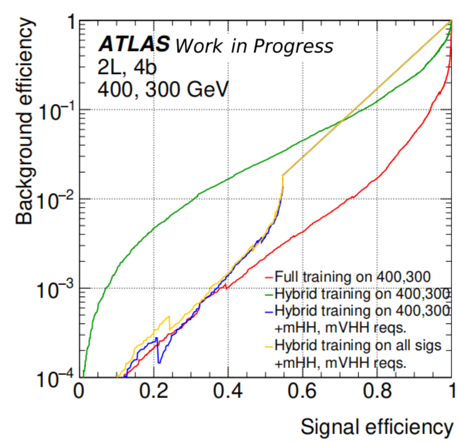

ATLAS Preliminary Simulation
√s = 13 TeV, PFlow jets, tt̄ Sim.
20 GeV < p_T < 250 GeV, |η| < 2.5
MV2 (2018)
DL1 f_c = 0.08 (2018)
DL1r f_c = 0.018 (2019)
Light-flavor jets rejection
c-jets rejection
Ratio to MV2 (2018)
b-jets efficiency

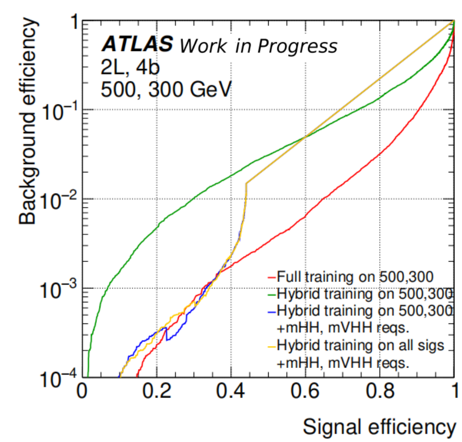
BDTs (Resonant)

- Have one BDT per-channel (so three BDTs total for A->ZH and VH(hh)), across all signal points
- For each BDT, train background against sum of all 10 signal points for that channel
- In fits, select events based on BDT as well as mhh (mass window cut on mH)
- Curves below compare BDTs trained on one signal point, vs. all of them vs. all of them with a mass window cut



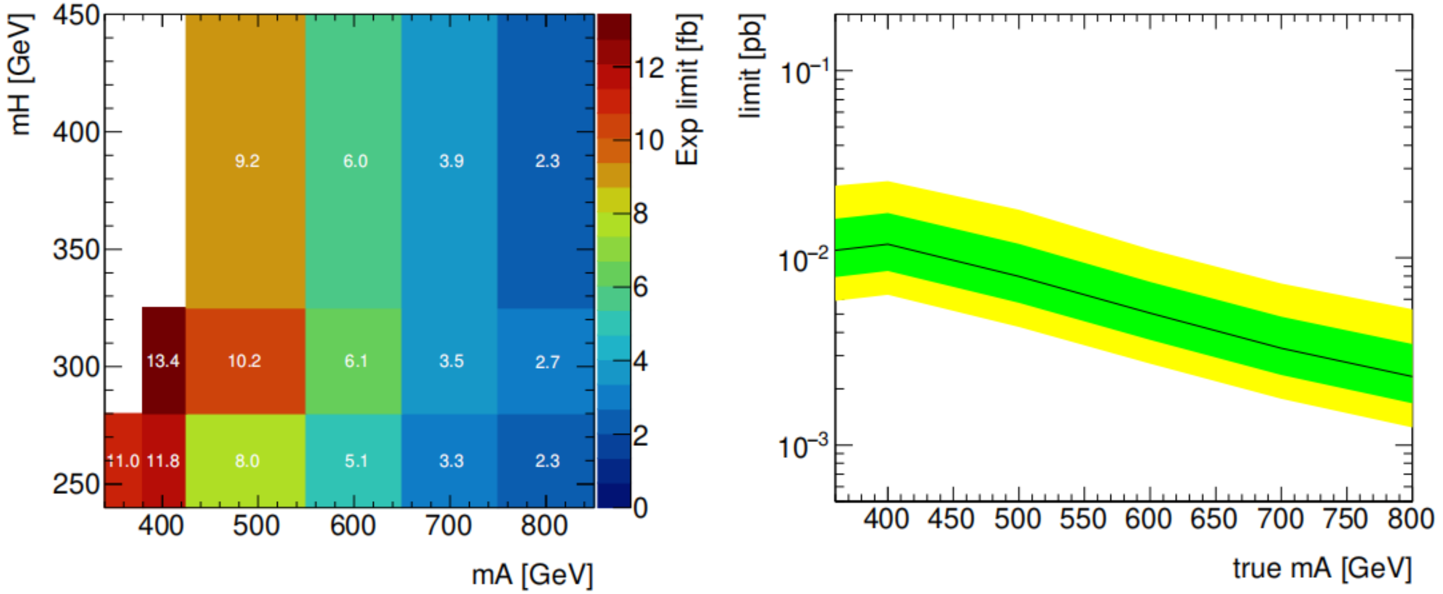






Expected Limit(Resonant AZH(hh))

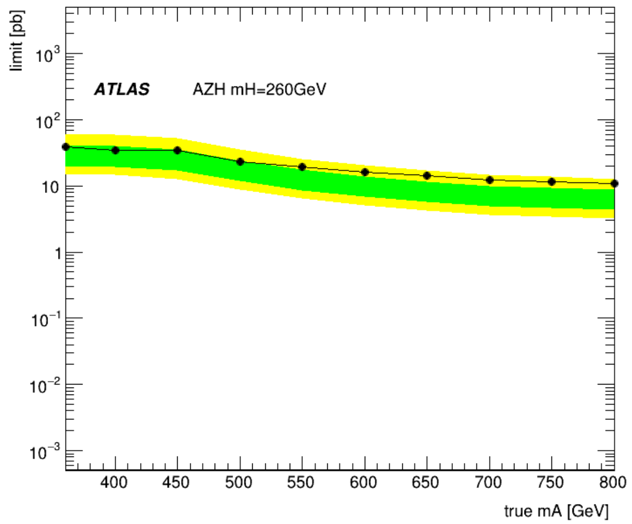
Resonant A->ZH(hh)

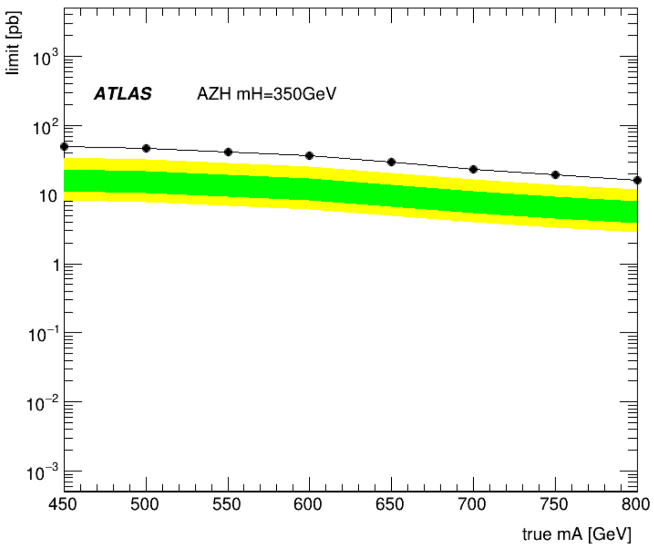


(a) 2D

(b) 1D, mH=260 GeV

Expected Limit(Resonant AZH)

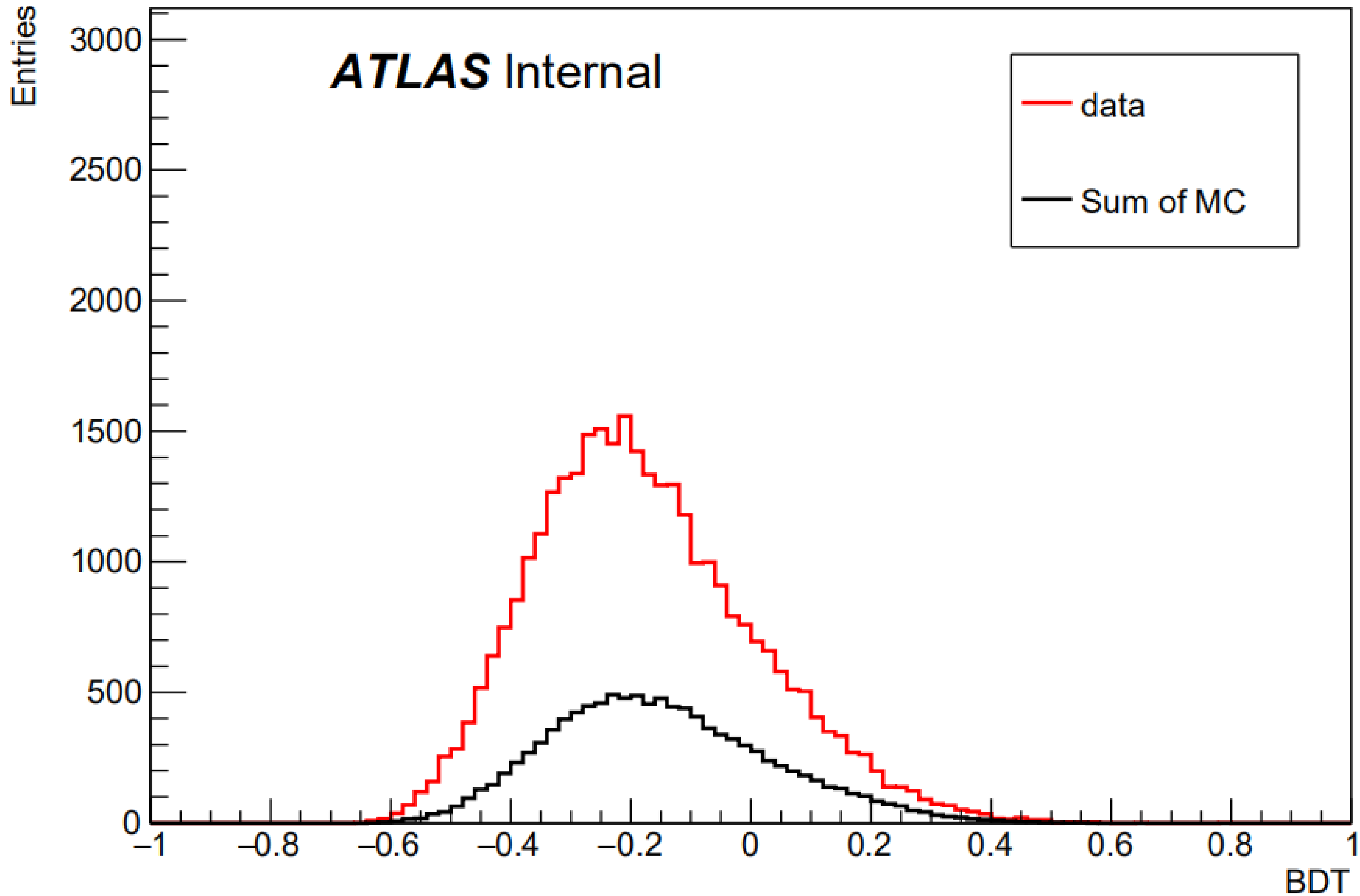




Whh

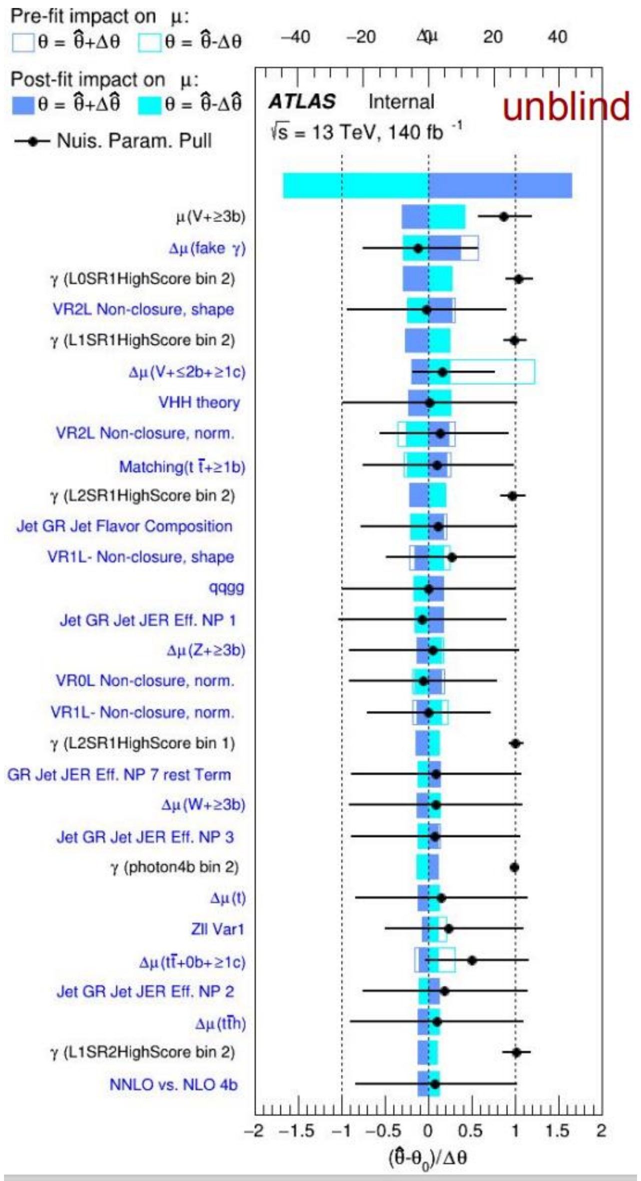
Expected limits as a function of true mH mass, for resonant AZHproduction (left: mH=260, right: mH=350). Limit results from mH=360GeV to 1TeV. The high mH result seems having excess, which is still under checking.

MJCR 1lep



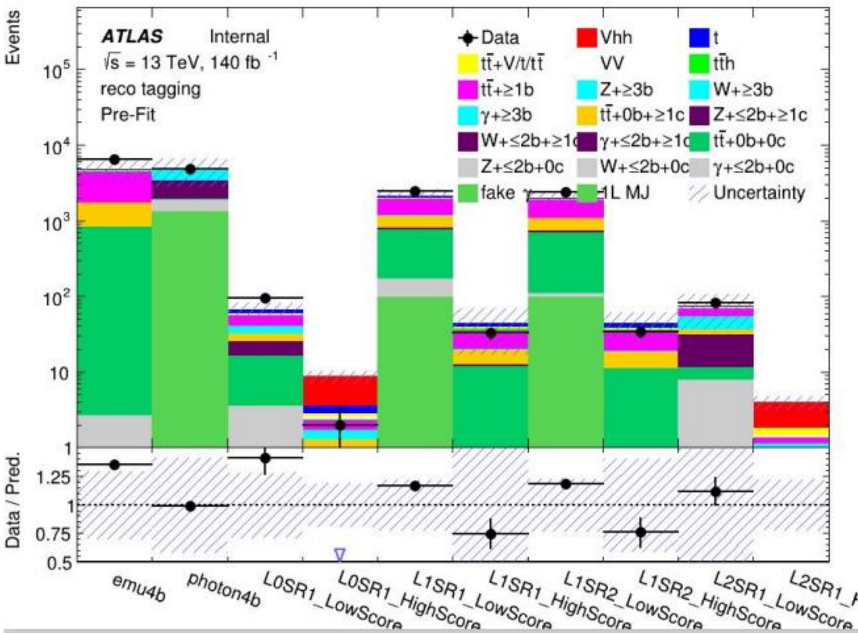
ATLAS Internal
data
Sum of MC
Entries
3000
2500
2000
1500
1000
500
0
–1
–0.8
–0.6
–0.4
–0.2
0
0.2
0.4
0.6
0.8
1
BDT

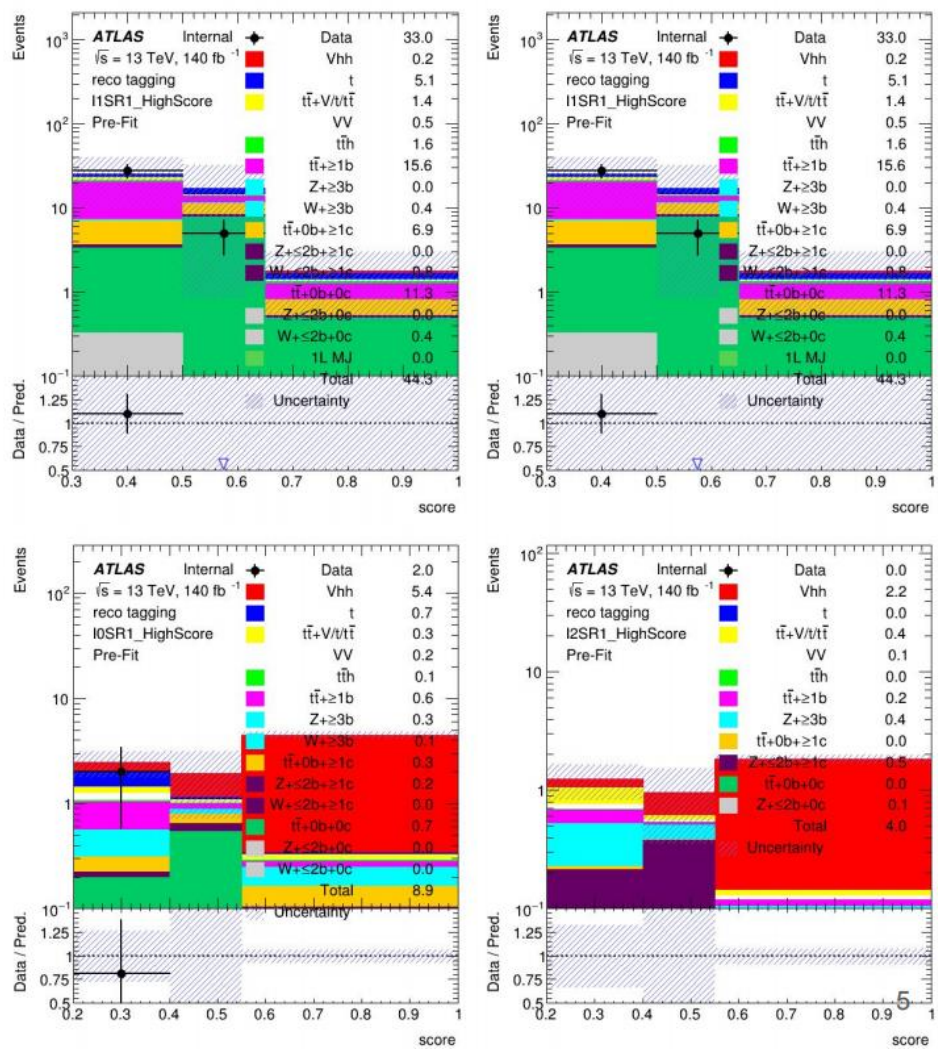
Non-Resonant Ranking



ZH(bb)

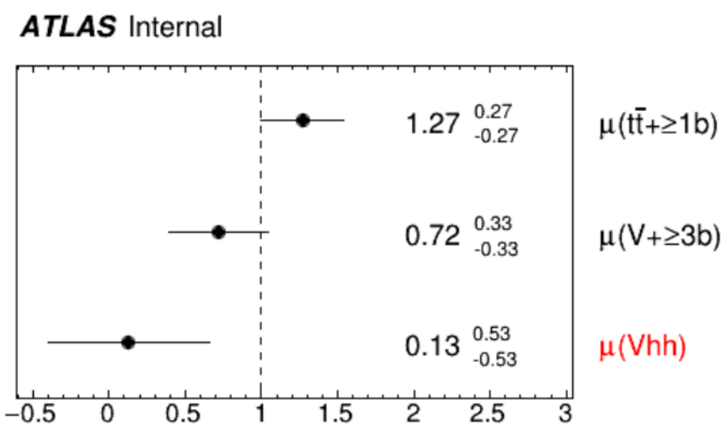
ZH(900) Pre-fit Plots

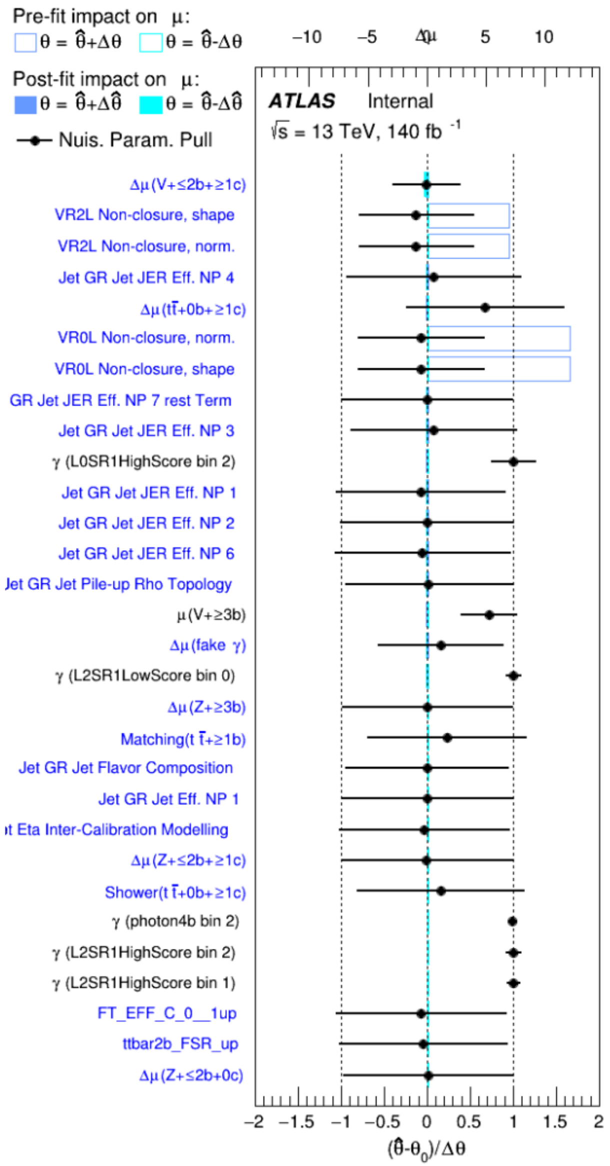




resonant AZH result

Results, A=600&H=300





Systematic (object)

Flavour-tagging

Muon uncertainty

Electron uncertainty

Jet uncertainty

MET uncertainty

Name	Number of parameters	notes
FT_EFF_B_[0-1]__1up	2	-
FT_EFF_C_[0-2]__1up	3	-
FT_EFF_Light_[0-3]__1up	4	-
Muon Eff. TTVA STAT	1	-
Muon Eff. Reco Syst. Low PT	1	-
Muon Eff. Reco Syst.	1	-
Muon Eff. Reco Stat. Low PT	1	-
Muon Eff. Reco Stat.	1	-
Muon Eff. TTVA Sys.	1	-
Muon Eff, ISO Sys.	1	-
Muon Eff. Iso Stat.	1	-
Muon ID	1	-
Muon Sagitta Rho	1	-
Muon MS	1	-
Muon Scale	1	-
Muon Sagitta Res Bias	1	-
EL Eff. Reco. Total 1 NP Corr + UnCorr	1	-
EL Eff. ID Total 1 NP Corr + UnCorr	1	-
EL Eff. Iso Tot. 1 NP Corr + UnCorr	1	-
EL Eff. Trigger Tot. 1 NP Corr + UnCorr	1	-
EG Scale All	1	-
EG Resolution All	1	-
PH Eff. ID Uncertainty	1	-
Jet JVT Eff.	1	-
Jet GR Jet Pile-up Offset Mu	1	-
Jet GR Jet Pile-up Offset NPV	1	-
Jet GR Jet Pile-up Rho Topology	1	-
Jet GR Jet Eff. NP [1-7]	7	-
Jet GR Jet Eff. NP 8 rest Term	1	-
Jet GR Jet Eta Inter-Calibration Modelling	1	-
Jet GR Jet Eta Inter-Calibration Tot. Stat.	1	-
Jet GR Jet Eta Inter-Calibration Non-Closure pos. Eta	1	-
Jet GR Jet Eta Inter-Calibration Non-Closure 2018 Data	1	-
Jet GR Jet Eta Inter-Calibration Non-Closure high-E	1	-
Jet GR Jet Eta Inter-Calibration Non-Closure neg-Eta	1	-
Jet GR Jet B-JES Response	1	-
Jet GR Jet Single Particle High PT	1	-
Jet GR Jet Flavor Composition	1	-
Jet GR Jet JER Eff. NP [1-6]	6	-
Jet GR Jet JER Eff. NP 7 rest Term	1	-
Jet GR Jet Pileup PT Term	1	-
Jet GR Jet Flavor Response	1	-
JET GR Jet Rel. NonClosure AFII	1	AFII samples only
Jet GR Jet JER Data vs. MC AFII	1	AFII samples only
Jet GR Jet Punch Through AFII	1	AFII samples only
MET Soft Trk Reso Perp	1	-
MET Soft Trk Reso Para	1	-
Lumi	1	-
PRW Data SF	1	-

Systematic(normalization)

Background normalization

Validation region uncertainty

Name	Shape or Norm.	Channels	Samples	Size
$\mu(t\bar{t}+\geq 1b)$	Norm	All	$t\bar{t}+\geq 1b$	floating
$\Delta\mu(t\bar{t}+0b+0c)$	Norm	All	$t\bar{t}+0b+0c$	10%
$\Delta\mu(t\bar{t}+0b+\geq 1c)$	Norm	All	$t\bar{t}+0b+\geq 1c$	100%
$\mu(V+\geq 3b)$	Norm	All	$Z/W/\gamma+\geq 3b$	floating
$\Delta\mu(V+\leq 2b+\geq 1c)$	Norm	All	$Z/W/\gamma+\leq 2b+\geq 1c$	100%
$\Delta\mu(V+\leq 2b+0c)$	Norm	All	$Z/W/\gamma+\leq 2b+0c$	10%
$\Delta\mu(Z+\geq 3b)$	Norm	All	$Z+\geq 3b$	20%
$\Delta\mu(Z+\leq 2b+\geq 1c)$	Norm	All	$Z+\leq 2b+\geq 1c$	20%
$\Delta\mu(Z+\leq 2b+0c)$	Norm	All	$Z+\leq 2b+0c$	20%
$\Delta\mu(W+\geq 3b)$	Norm	All	$W+\geq 3b$	30%
$\Delta\mu(W+\leq 2b+\geq 1c)$	Norm	All	$W+\leq 2b+\geq 1c$	30%
$\Delta\mu(W+\leq 2b+0c)$	Norm	All	$W+\leq 2b+0c$	30%
$\Delta\mu(t\bar{t}+V/t/t\bar{t})$	Norm	All	$t\bar{t}+V/t/t\bar{t}$	20%
$\Delta\mu(t)$	Norm	All	t	20%
$\Delta\mu(VV)$	Norm	All	VV	20%
$\Delta\mu(t\bar{t}h)$	Norm	All	$t\bar{t}h$	20%
$\Delta\mu(fakelepton)$	Norm	1L+,1L-	1L MJ	100%
$\Delta\mu(fake\gamma)$	Norm	γ	$fake\gamma$	100%
L0 trig eff.	Shape+Norm.	0L	All backgrounds	
L0_TT_up	Shape+Norm.	0L	$t\bar{t}/Z/W+0b+\geq 1c$,$t\bar{t}/Z/W+0b+0c$,t	
L1_TT_up	Shape+Norm.	1L+,1L-	$t\bar{t}/Z/W+0b+\geq 1c$,$t\bar{t}/Z/W+0b+0c$,t	
L2_TT_up	Shape+Norm.	2L	$t\bar{t}/Z/W+0b+\geq 1c$,$t\bar{t}/Z/W+0b+0c$,t	
HighPtExtrapB_up	Shape+Norm.	All	All	
VR0L Non-closure, norm.	Norm.	0L	All backgrounds	5.5%
VR0L Non-closure, shape	Shape.	0L	All backgrounds	
VR2L Non-closure, norm.	Norm.	2L	All backgrounds	41.6%
VR2L Non-closure, shape	Shape.	2L	All backgrounds	
VR1L+ Non-closure, norm.	Norm.	1L+	All backgrounds	11.7%
VR1L+ Non-closure, shape	Shape.	1L+	All backgrounds	
VR1L- Non-closure, norm.	Norm.	1L-	All backgrounds	11.4%
VR1L- Non-closure, shape	Shape.	1L-	All backgrounds	
VREMU Non-closure, norm.	Norm.	e/mu	All backgrounds	7.4%
VRGAMMA Non-closure, norm.	Norm.	gamma	All backgrounds	20.5%
$\Delta\mu$(fake lepton shape0)	Shape	1L+,1L-	1L MJ	
$\Delta\mu$(fake lepton shape1)	Shape	1L+,1L-	1L MJ	
$\Delta\mu$(fake γ contam)	Shape	γ	$fake\gamma$	

Systematic(theory)

Top (ttbar,s-top)

Z+jets

Name	Channels	Samples	Size
Matching($t\bar{t}+\geq 1b$)	All	$t\bar{t}+\geq 1b$	6.0%
Matching($t\bar{t}+0b+\geq 1c$)	All	$t\bar{t}+0b+\geq 1c$	7.3%
Matching($t\bar{t}+0b+0c$)	All	$t\bar{t}+0b+0c$	3.8%
Shower($t\bar{t}+\geq 1b$)	All	$t\bar{t}+\geq 1b$	16.7%
Shower($t\bar{t}+0b+\geq 1c$)	All	$t\bar{t}+0b+\geq 1c$	19.5%
Shower($t\bar{t}+0b+0c$)	All	$t\bar{t}+0b+0c$	0.3%
Matching(s-top)	All	t	5.4%
Shower(s-top)	All	t	27.4%
Interference(s-top)	All	t	12.0%
s-top_Scale	All	t	
ttbar2b_ISR_a_s_up	All	$t\bar{t}+0b+0c$	
ttbar2b_FSR_up	All	$t\bar{t}+0b+0c$	
ttbar2b1c_ISR_a_s_up	All	$t\bar{t}+0b+\geq 1c$	
ttbar2b1c_FSR_up	All	$t\bar{t}+0b+\geq 1c$	
ttbar4b_ISR_a_s_up	All	$t\bar{t}+\geq 1b$	
ttbar4b_FSR_up	All	$t\bar{t}+\geq 1b$	
ttbar2b_Scale_muRmuF_up	All	$t\bar{t}+0b+0c$	
ttbar2b1c_Scale_muRmuF_up	All	$t\bar{t}+0b+\geq 1c$	
ttbar4b_Scale_muRmuF_up	All	$t\bar{t}+\geq 1b$	
t_FSR	All	t	
t_ISR_alpha_s	All	t	
Z4b_Scale_muRmuF_up	All	$Z/W/\gamma+\geq 3b$	
Z2b1c_Scale_muRmuF_up	All	$Z/W/\gamma+\leq 2b+\geq 1c$	
Z2b_Scale_muRmuF_up	All	$Z/W/\gamma+\leq 2b+0c$	
vv_Scale_muRmuF_up	All	VV	
qqgg	All	Vhh	