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

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Higgs potential and BSM opportunity
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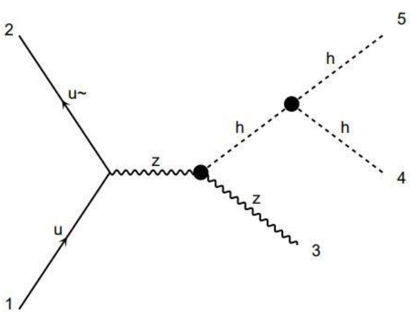
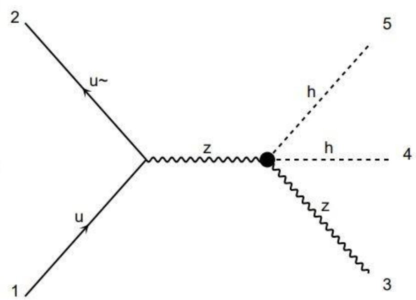
Overview

- 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.
- Relatively broad strategy, considering multiple final states(Zvv/Wlv/Zll) and multiple resonant and non-resonant 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

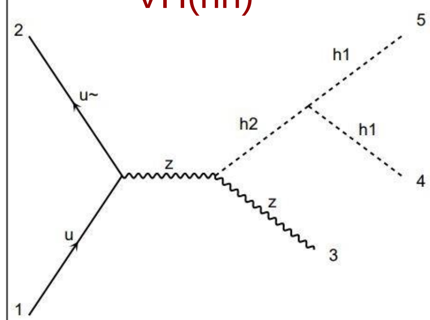


C3



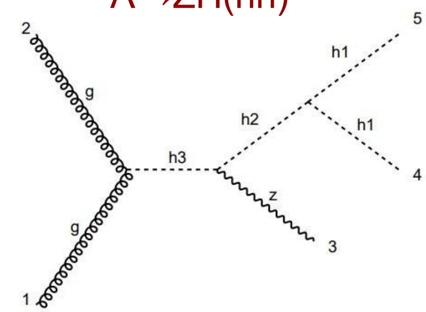
C2V

VH(hh)



mH = 260, 280. 300, 400, 500, 600, 700, 800, 900, 1000

A→ZH(hh)



	A=360	A=400	A=500	A=600	A=700	A=800
H=260	X	X	X	X	X	X
H=300		X	X	X	X	X
H=400			X	X	X	X

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 channels
- Single photon trigger used in photon+jets control region

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

Dataset

Background

Data: 2015-2018 140 fb^-1

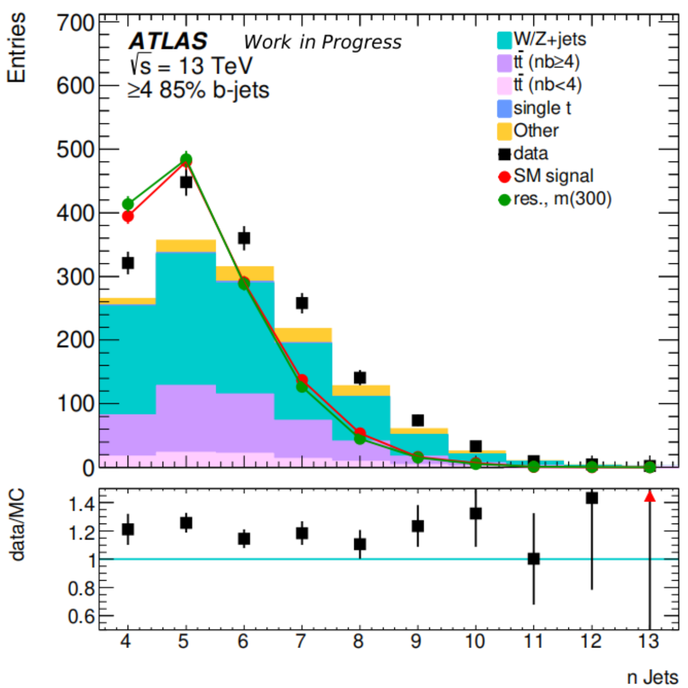
Signal: MadgraphPythia 8 NLO

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

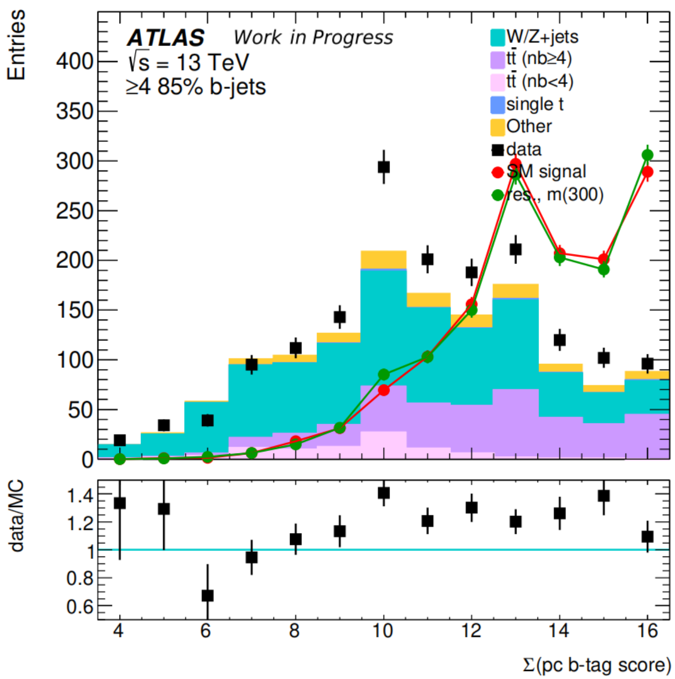


Event selection

Preselection:

- ≥ 4 jets, pT > 20 GeV and |η| < 2.5
- ≥ 4 85% b-jets with pT > 20 GeV and |η| < 2.5, tagged with DL1r
- Higgs candidate jets required to be 4 jet candidates with leading pseudo continuous b-tagging scores.
- If four more jets satisfy, then four Higgs candidate jets minimize |m(J1,J2) − 120 GeV| + | m(J3,J4) − 120 GeV| is selected
- leading higgs candidate chosen as jet pair with leading pT

- 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



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)
  - 0L (validate BDT modeling in SR)
  - 1L (validate BDT modeling in SR)
  - 2L (validate BDT modeling in SR)
  - e/mu

Provide uncertainties to be used in SR fits

0/1/2 lepton signal region

Three SRs, orthogonally with different lepton multiplicity

2 lepton

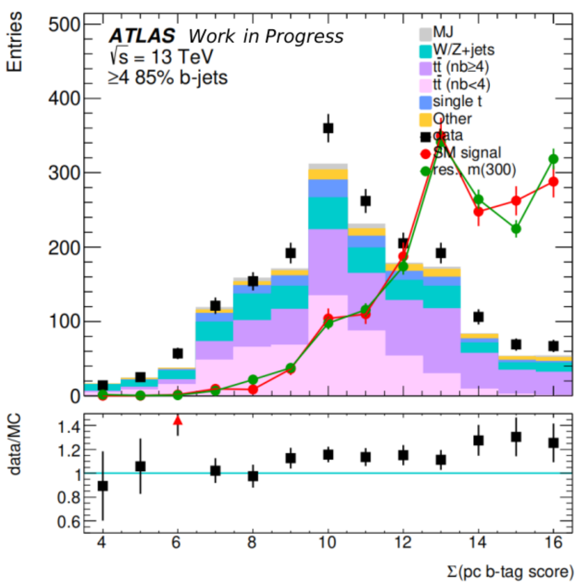
- Exactly 2 same-flavor opposite-sign baseline light, charged leptons ($e^+e^-\, or\, \mu^+\mu^-$)
- $81 < m_{ll} < 101$ GeV

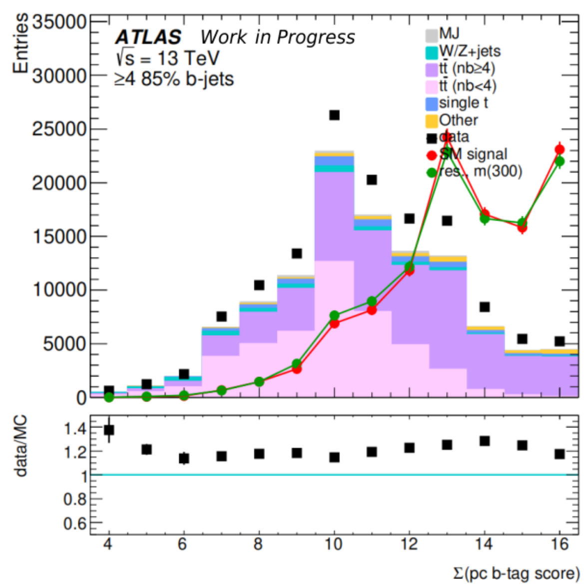
1 lepton

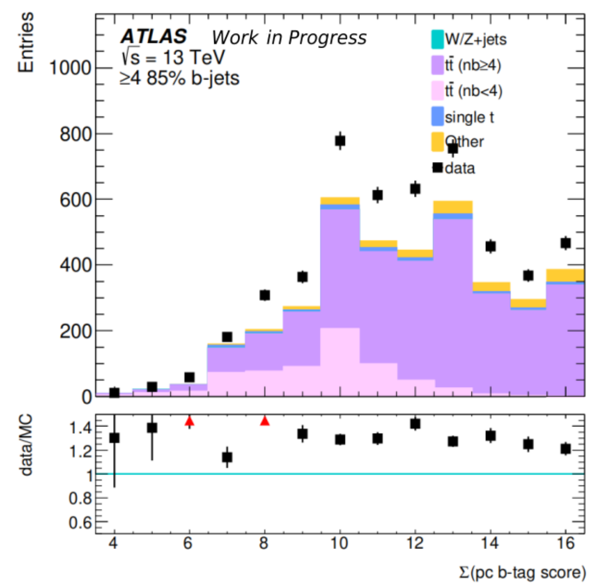
- Exactly 1 charged light leptons
- Exactly 0 taus
- $E_T^{miss} > 30$ GeV

0 lepton

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





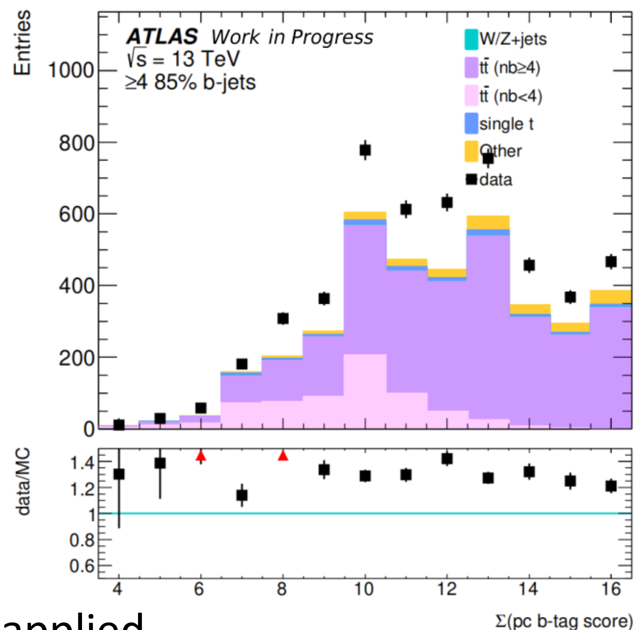


Control regions

- Two CRs (not including MJ CRs), for constraining main analysis backgrounds
- 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

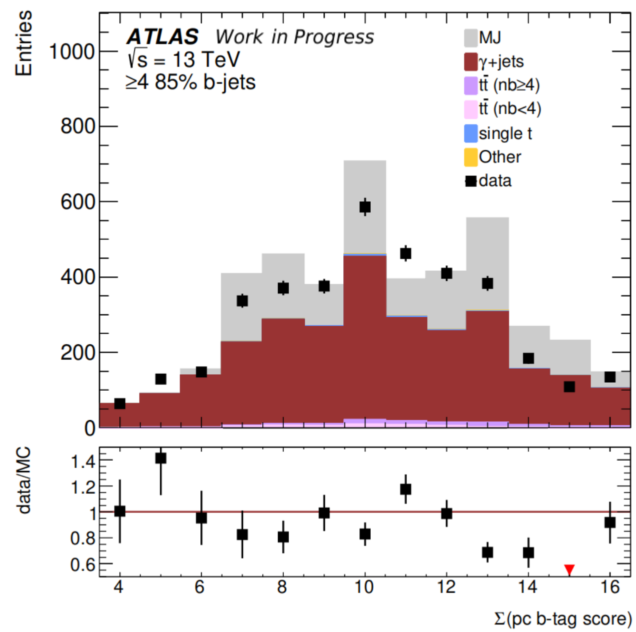
- Exactly 2 different-flavor opposite-sign baseline light, charged leptons ($e^+\mu^- or e^-\mu^+$)
- No requirement on m_{ll}



NF not applied

γ+jets CR

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

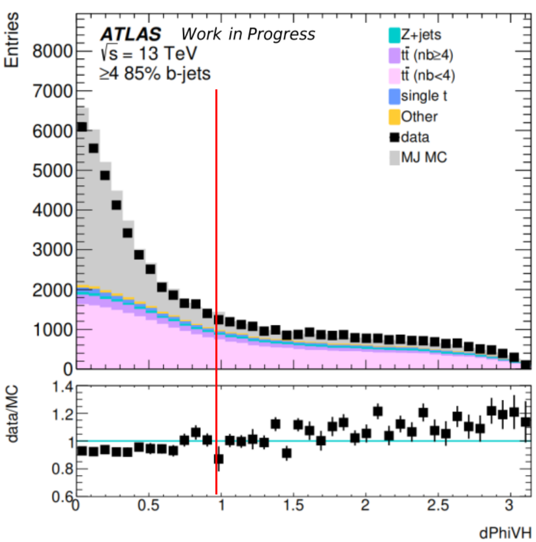


Multi-jet estimation

- 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.

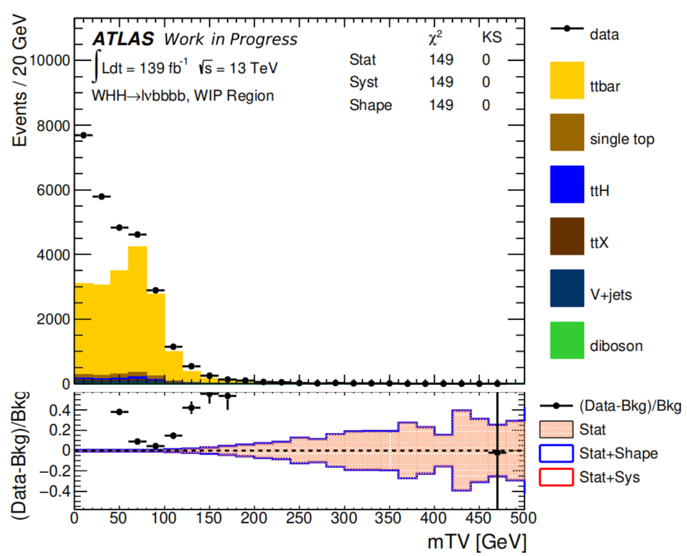
0 lepton

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



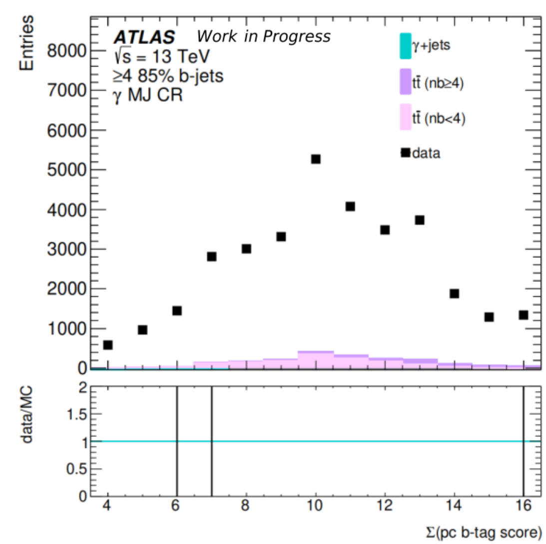
1 lepton

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



γ+jet

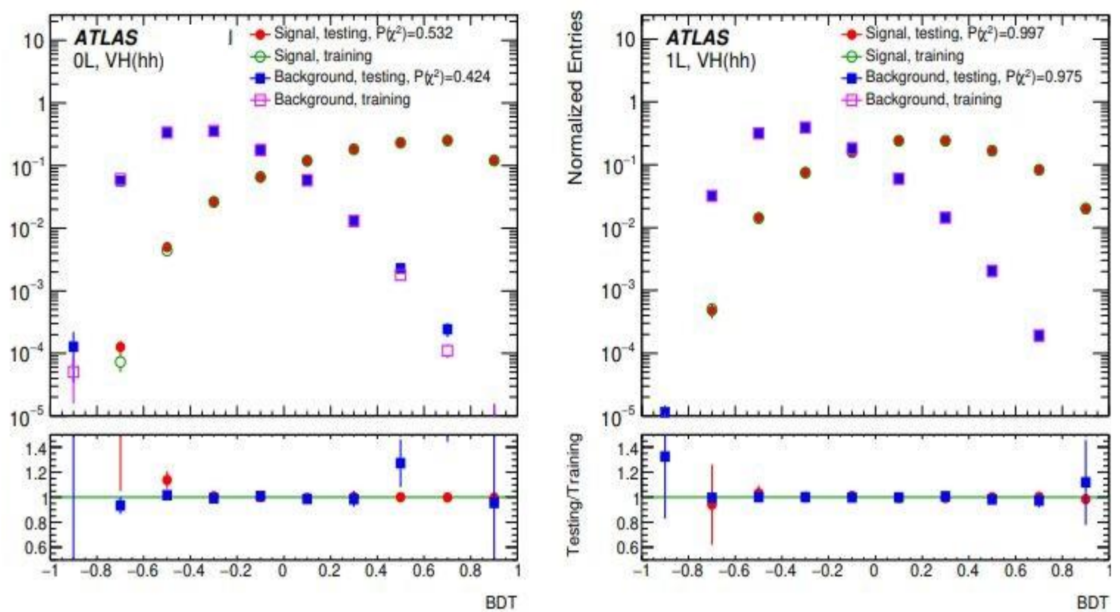
the same definition as the γ+jets CR, except inverting the isolation cut (requiring fail the isolation WP).



BDT

- BDTs for discriminating background and signal in each channel
- ~15 variables per channel as listed

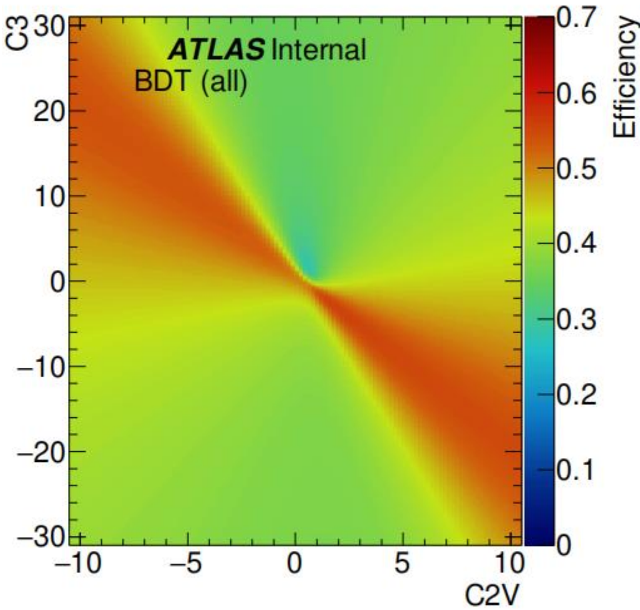
	NR 0L	Hhh 0L	AZH 0L	NR 2L	VH(hh) 2L	AZH 2L	NR 1L	Hhh 1L
$mh1 + mh2$	X	X	X	X	X	X	X	X
$mh1 - mh2$	X	X	X	X	X	X	X	X
nJets	X	X	X	X	X	X	X	X
HT_Ex	X	X	X	X	X	X	X	X
Σ(b-tag scores)	X	X	X	X	X	X	X	X
p_T^V				X	X		X	X
p_T^{hh}	X	X		X	X		X	X
m^{hh}	X			X			X	
$cosh(\Delta\eta h1) - cos(\Delta\phi h1)$	X	X		X	X		X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

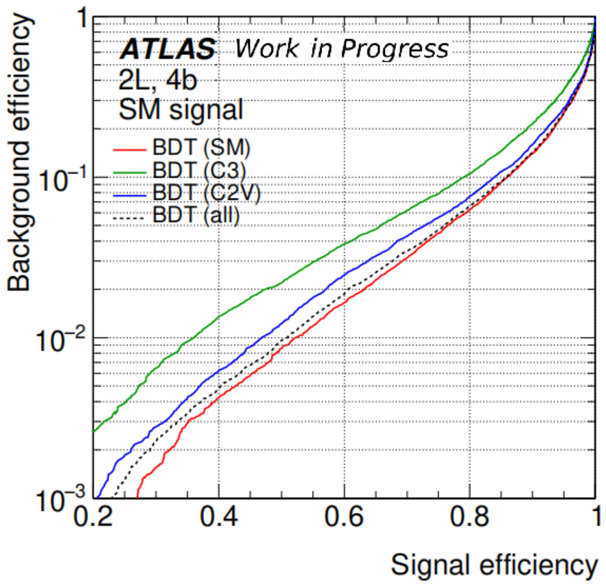


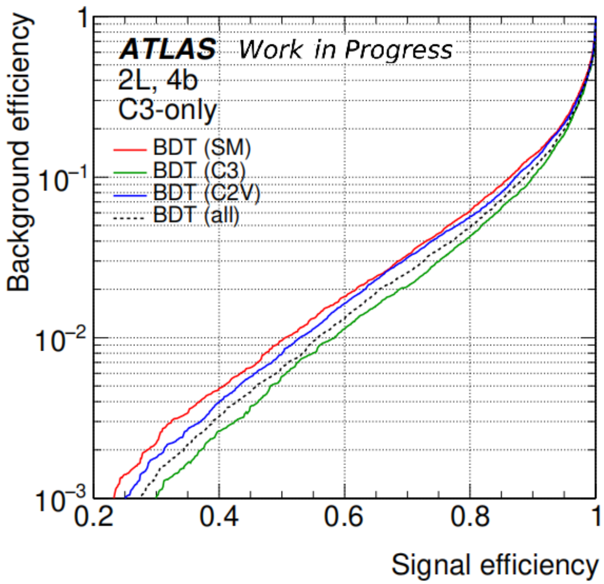
0L/1L BDT distribution, good separation and no overtraining

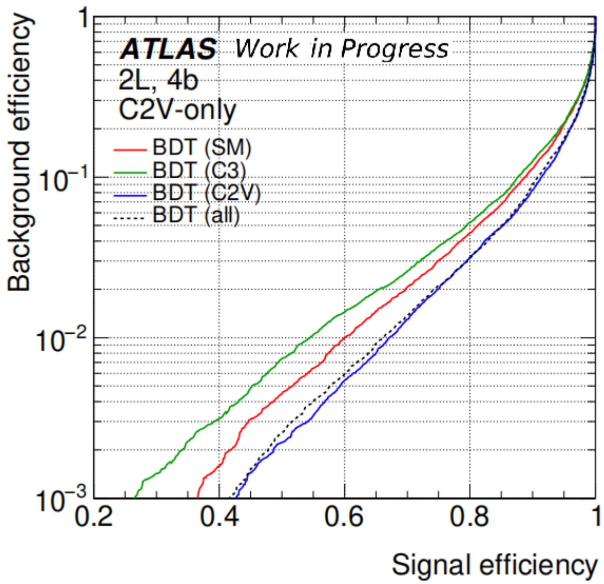
BDTs (Non-resonant)

- 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
- ROC BDT curves shown below with different training
- Resonant BDT follows similar strategy.



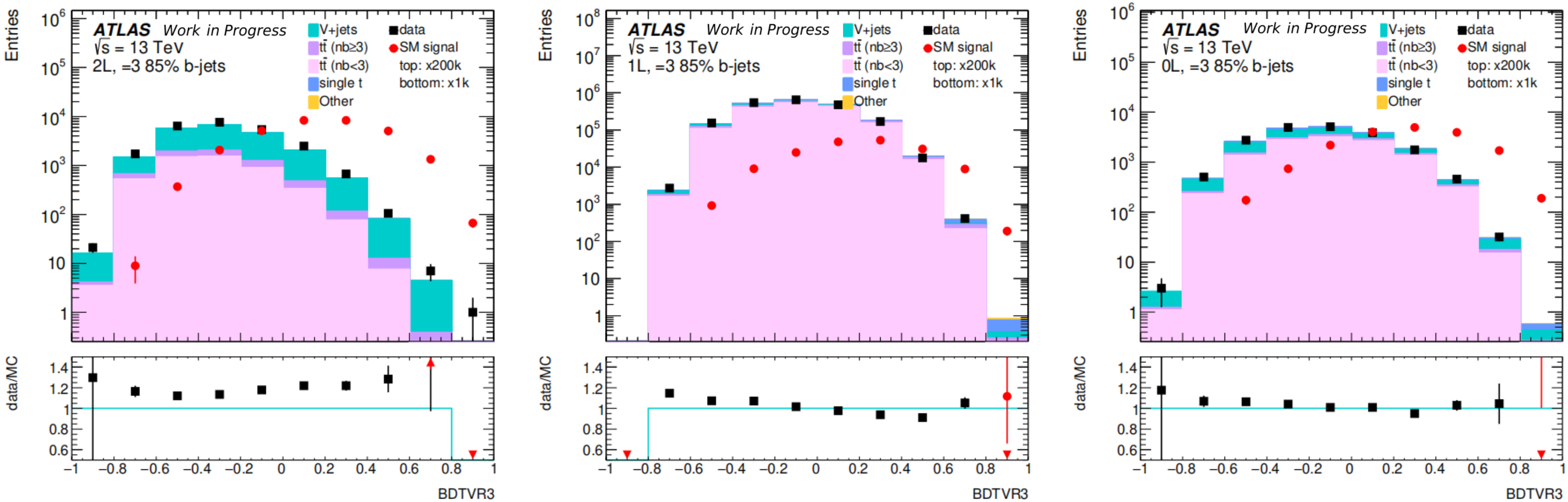






Validation Regions

- Each of the three SRs (0L, 1L, and 2L) and each of the CRs (e/μ and γ+jets), not including the MJCR, has a corresponding VR, to validate the data/MC modeling in the SRs).
- VRs require at least 4 jets, exactly 3 of which are b-tagged with the 85% WP (instead of the usual 4). The fourth signal jet (used to build all the kinematic variables) is taken to be the highest *p*T central non-b-jet in the event.
- Non-closure in VRs taken as uncertainty in the SRs
- BDT distributions shown below in VRs, for H(hh) BDTs

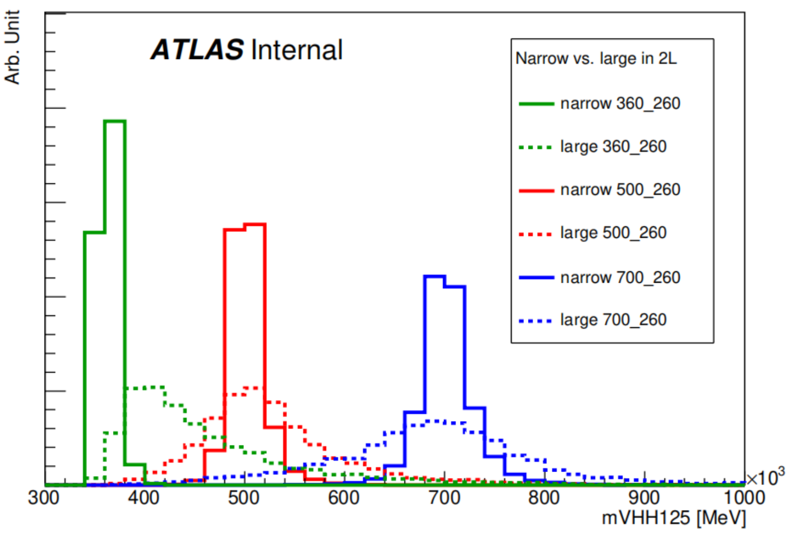


AZH large width signal interpolation

- 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.

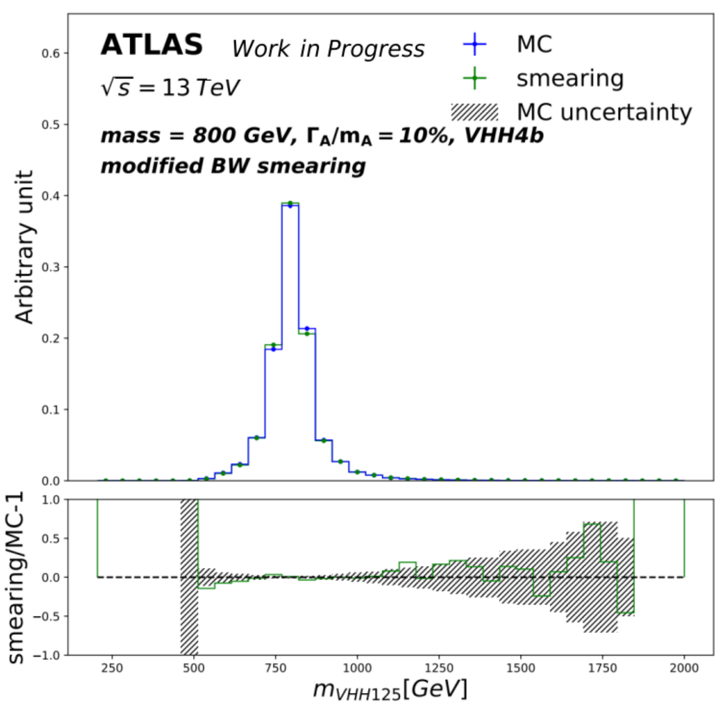
$$g_L = (f * g_N)(x) \qquad f = \frac{e^{\frac{-(\ln(x-x_0)-\ln(m)^2)}{2\times\ln(s)^2}}}{\sqrt{2\pi}(x-x_0)\ln(s)} \times \frac{1}{x^2+0.25w^2}$$

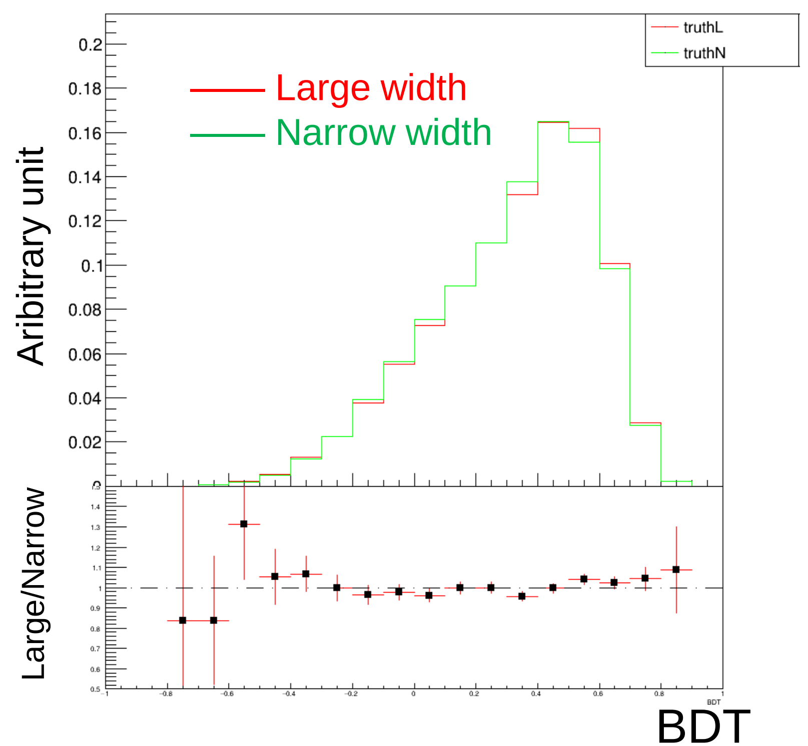
- The parameter x0,m,s is derived with 20% large width sample and convolution distribution by narrow width samples.
- Right plot shows large and narrow signal mVHH distribution comparison



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)





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)

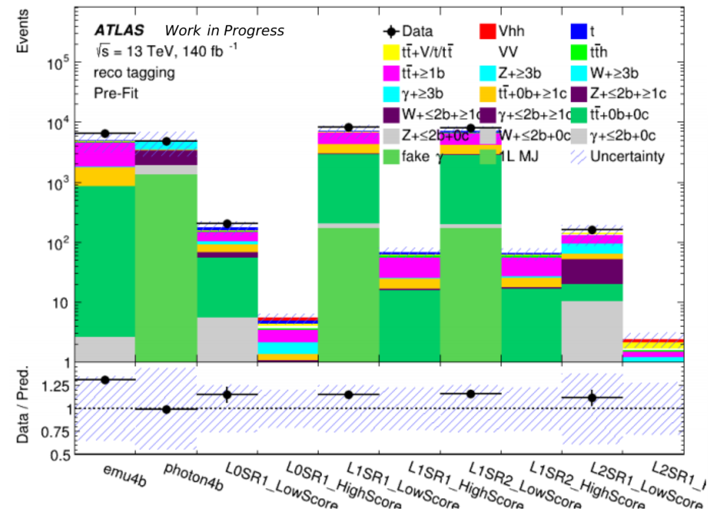
Top
(ttbar,s-top)

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	

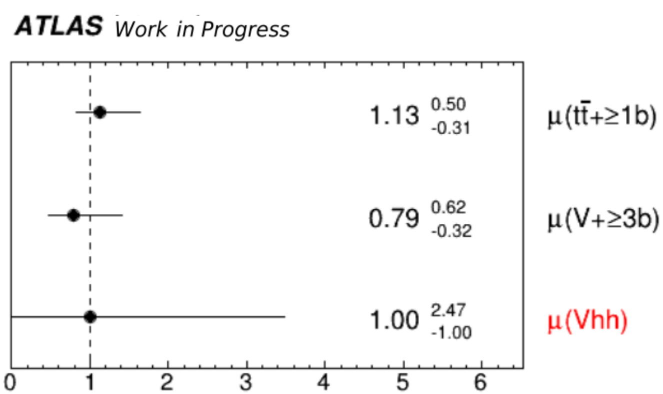
Fit Details

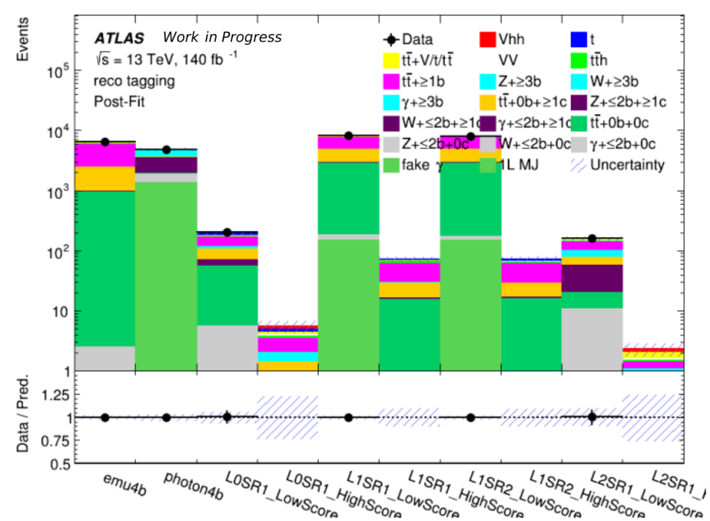
- Ten regions total for all fits
- SRs are further divided into Lowscore (BDT<0.3) and HighScore(BDT>0.3), Lowscore uses real data, HighScore is bilnded
- For 1L channel, split into W+/W- channels



(a)

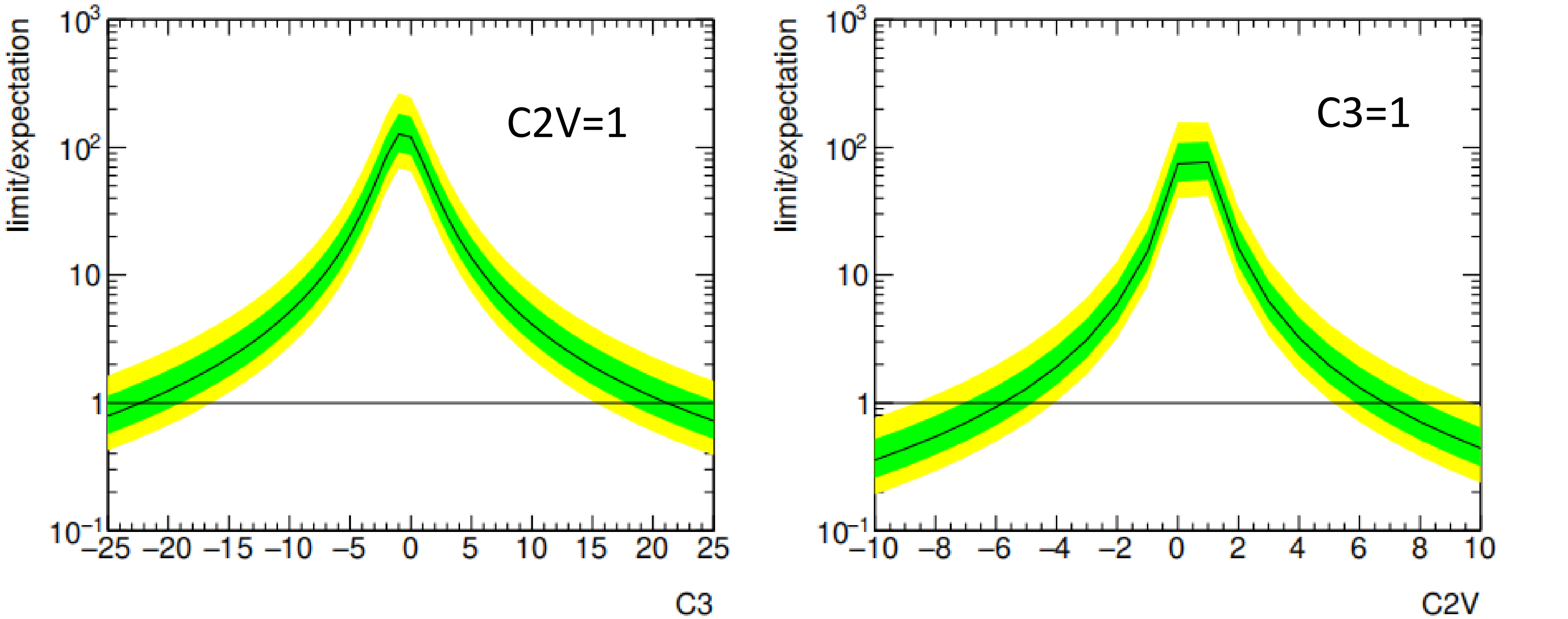
Plots show mH=500GeV VH(hh) fit result





(d)

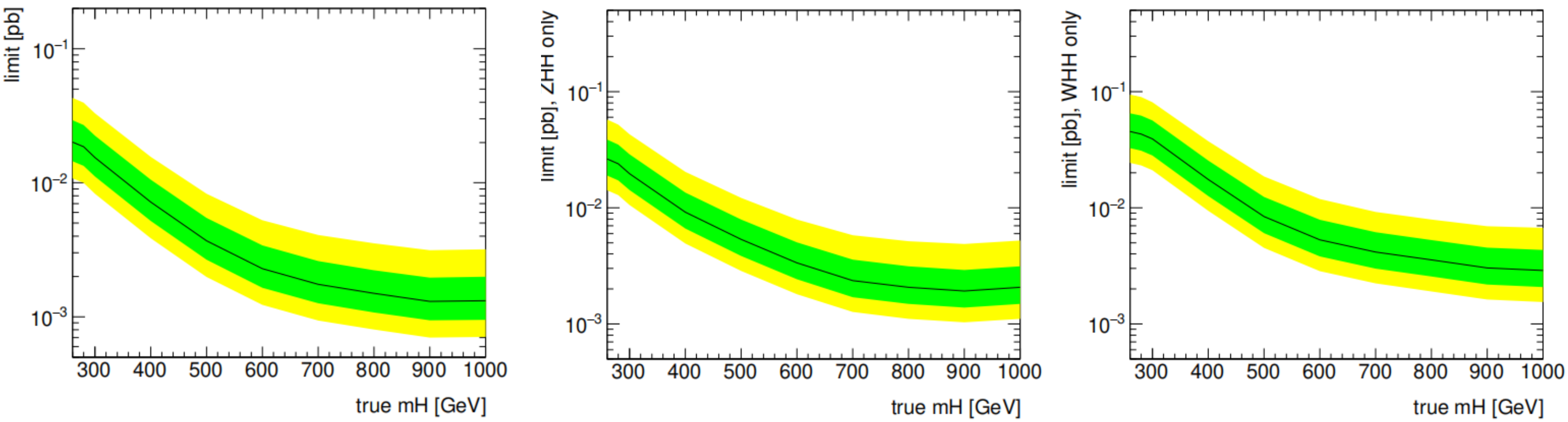
Expected signal strength(Non-resonant)



(a) C3 (b) C2V

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

Expected Limit(Resonant VH(hh))



(a) Zhh+Whh (b) Zhh only (c) Whh only

Expected limits as a function of true mH mass, for resonant VH(hh) production. Limit results from mH=260GeV to 1TeV, for the combination and for each process separately. 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 in the ATLAS internal review, expected to be published by early 2022.

Thank you