Search for Higgs pair production in association with a vector boson with ATLAS

Tong Li, Zhongyukun Xu, Lianliang Ma

Shandong University

Higgs Potential 2022 @ Peking University, 26 July 2022

ATLAS-CONF-2022-043

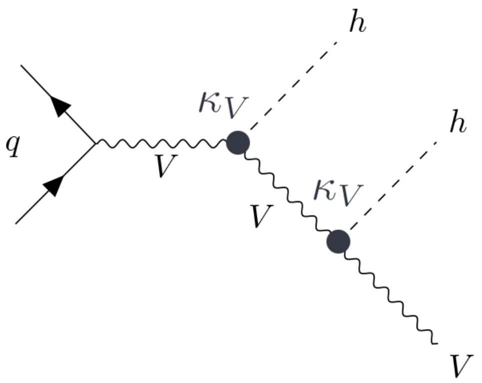
Contents

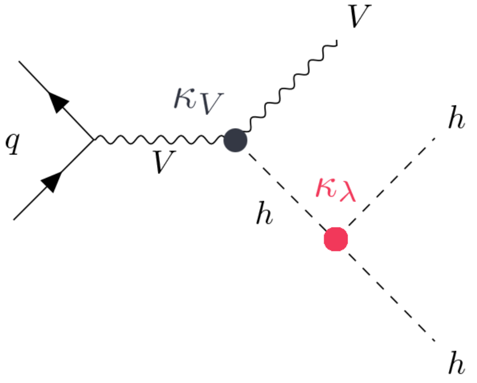
ATLAS-CONF-2022-043

Introduction

SM predicts Higgs trilinear coupling (hhh) and quartic couplings with itself and vector boson (VVhh)

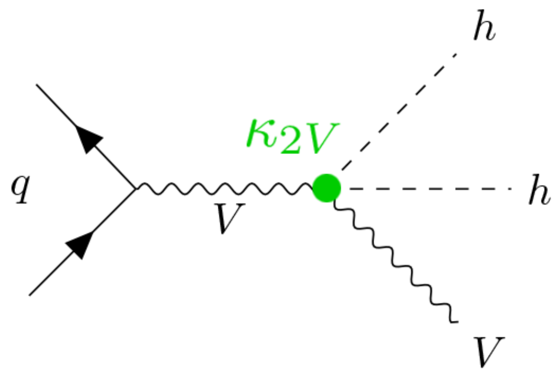
- Not confirmed yet experimentally
- Can be probed via Higgs pair production in association with a vector boson (Vhh)





Non-resonant Vhh production with κ_λ, κ_V and κ_{2V} vertices

- For SM case, $\kappa_\lambda = \kappa_V = \kappa_{2V} = 1$



Non-resonant Vhh

First search with Vhh final state with ATLAS

- V → νν / lν / ll, h → bb

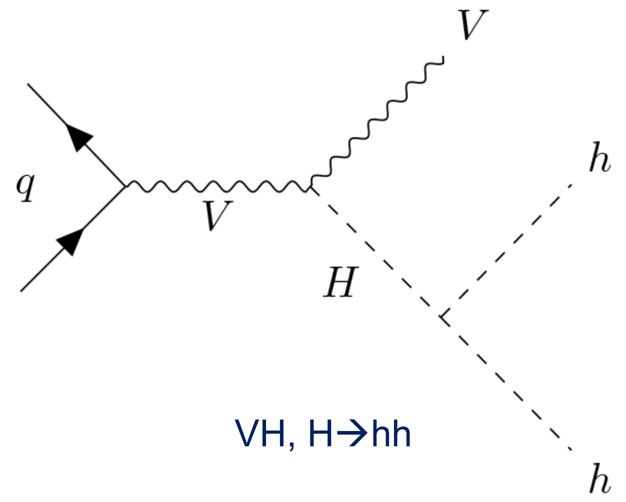
Full Run 2 dataset used

Introduction

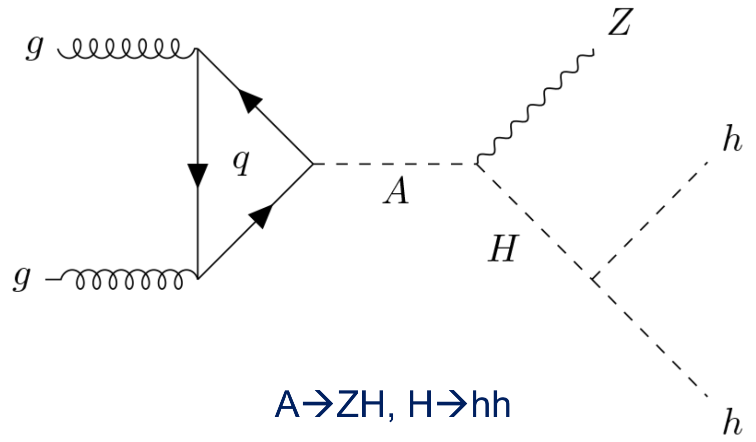
BSM models predict the existences of the heavy neutral scalar H and heavy pseudoscalar A

- H produced in association with a vector boson
- A produced via gluon-gluon fusion, and decays into ZH
- H decays into a pair of SM Higgs (H→hh)
- The same final state with non-resonant production
  - V → νν / lν / ll, h → bb

- Resonant Vhh production
- First search with Vhh final state in ATLAS
- Full Run 2 dataset used



VH, H→hh



A→ZH, H→hh

ATLAS detector

- A Toroidal LHC ApparatuS (ATLAS), located at the Point 1 of the LHC
- World's largest particle detector with diameter of 25 m and length of 44 m
- General-purpose detector designed mainly to search for Higgs and new physics

Inner detector

- Tracks and transverse momentum of charged particles

EM Calorimeter

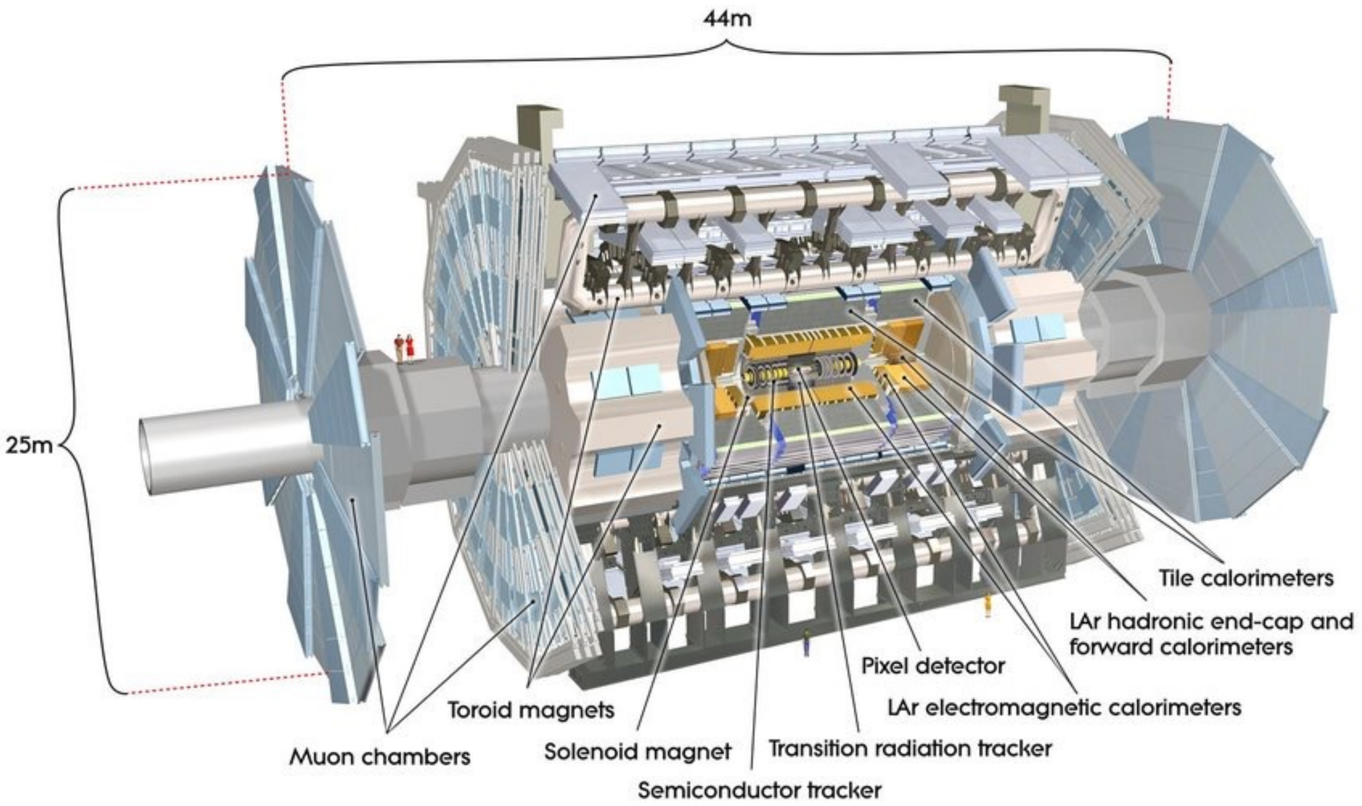
- Energy of electrons and photons

Hadronic Calorimeter

- Energy of hadrons

Muon spectrometer

- Momentum of muons



MC samples

List of MC event generators, PDFs, parton shower, hadronization and UE models used to simulate signal and background processes

The last column shows the calculation orders of cross-sections used

The mass of the Higgs boson h is set to 125 GeV in the simulation

Process	Matrix element generator	order	PDF	Parton shower	UE model	Cross-section order
Signal samples						
Non-resonant Vhh	MadGraph5_aMC@NLO	LO	NNPDF2.3LO	PYTHIA 8.244	A14	NNLO
Resonant VH	MadGraph5_aMC@NLO	LO	NNPDF2.3LO	PYTHIA 8.244	A14	LO
Resonant $A \to ZH$	MadGraph5_aMC@NLO	LO	NNPDF2.3LO	PYTHIA 8.244	A14	LO
Top quark processes						
$t\bar{t}$	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NNLO +NNLL
Single-t: s-channel	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO
Single-t: t-channel	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO
Single-t: Wt	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NNLO
ttH	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO (QCD+EW)
ttV	MadGraph5_aMC@NLO	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO (QCD+EW)
$tt\ell\ell^{\S}$	MadGraph5_aMC@NLO	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO
$tttt$	MadGraph5_aMC@NLO	NLO	NNPDF3.1LO	PYTHIA 8.230	A14	NLO (QCD+EW)
ttt	MadGraph5_aMC@NLO	LO	NNPDF2.3LO	PYTHIA 8.230	A14	LO
$ttWW$	MadGraph5_aMC@NLO	LO	NNPDF2.3LO	PYTHIA 8.230	A14	LO
tWZ	MadGraph5_aMC@NLO	NLO	NNPDF2.3LO	PYTHIA 8.212	A14	NLO
tZ	MadGraph5_aMC@NLO	LO	NNPDF2.3LO	PYTHIA 8.212	A14	LO
Single- and multi-boson production						
V + jets	SHERPA 2.2.1	NLO†	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
γ + jets	SHERPA 2.2.2	NLO†	NNPDF3.0NNLO	SHERPA 2.2.2	Default	NNLO
$qq \to V_\ell V_{\ell \text{ or } h}$	SHERPA 2.2.1	NLO	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO‡
$gg \to V_\ell V_{\ell \text{ or } h}$	SHERPA 2.2.2	NLO	NNPFD3.0NNLO	SHERPA 2.2.2	Default	NLO‡
$V_\ell V_\ell V$	SHERPA 2.2.2	NLO	NNPDF3.0NNLO	SHERPA 2.2.2	Default	LO
$V_\ell V_h V_h$	MadGraph5_aMC@NLO	LO	NNPDF2.3LO	PYTHIA 8.243	A14	LO
$qq \to VH$	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	NNLO(QCD) +NLO(EW)
$gg \to ZH$	POWHEG-BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	NLO+NLL

§ Here $\ell\ell$'s are from $Z^*/\gamma^* \to \ell\ell$.
† Produced with up to two extra jets at NLO and up to four extra jets at LO.
‡ For the diboson samples the cross-sections are calculated by the Monte Carlo generator at NLO accuracy in QCD.

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
- Three channels according to the decays of vector bosons (0L, 1L, and 2L)
  - Missing-E_T triggers used in 0L channel
  - Single lepton triggers used in 1L / 2L channel, and eμ CR
  - Single gamma triggers used in γ+jets CR

Event selections

	Signal regions			Control regions	
	0L	1L (1L+/1L−)	2L	$t\bar{t}$	V + jets
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	single-lepton	single-lepton	single-lepton	single-photon
Lepton or photon	0 *loose* leptons	= 1 *tight* electron with $p_{\mathrm{T}} > 27$ GeV OR 1 *medium* muon with $p_{\mathrm{T}} > 25$ GeV, 0 additional *loose* leptons	= 2 *loose* leptons (e^+e^- or $\mu^+\mu^-$), $\geq$ 1 lepton with $p_{\mathrm{T}} > 27$ GeV, 81 GeV $< m_{\ell\ell} <$ 101 GeV	= 2 *loose* leptons ($e^{\pm}\mu^{\mp}$), $\geq$ 1 lepton with $p_{\mathrm{T}} > 27$ GeV	= 1 photon with $p_{\mathrm{T}} > 150$ GeV, 0 *loose* leptons
$\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, $\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}}) > 12$, $\lvert\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}, h)\rvert > 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV	—	—	—
Jets	$\geq$ 4 jets with $p_{\mathrm{T}} > 20$ GeV and passing the 85% b-tagging WP				

- At least four 85% b-tagged jets
- 1L channel split into 1L+ and 1L- according to the W boson charge
- Z boson mass window applied in 2L channel
- eμ CR for constraining ttbar, γ+jets CR for constraining V+jets
- Loose selection criteria, due to the low expected signal cross-sections

CRs

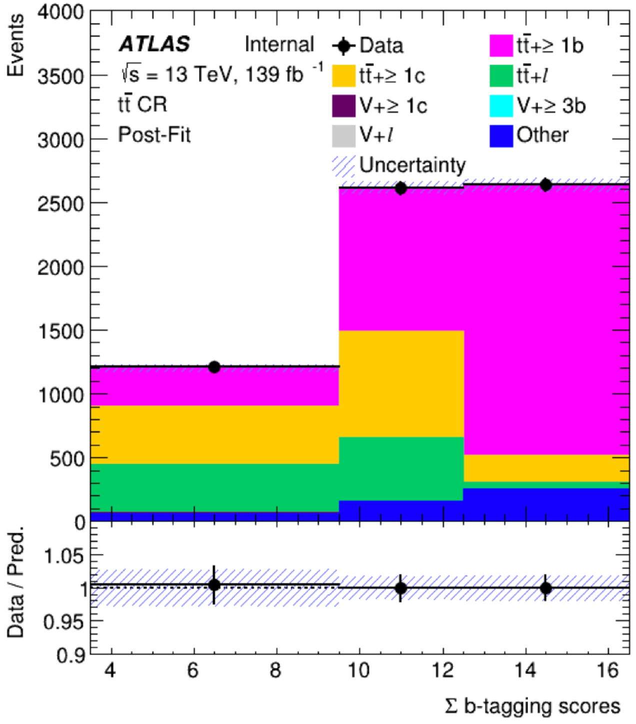
Two non-MJ CRs, to constrain main background

- eμ CR for constraining *ttbar*
- γ+jets CR for constraining *V*+jets

eμ CR

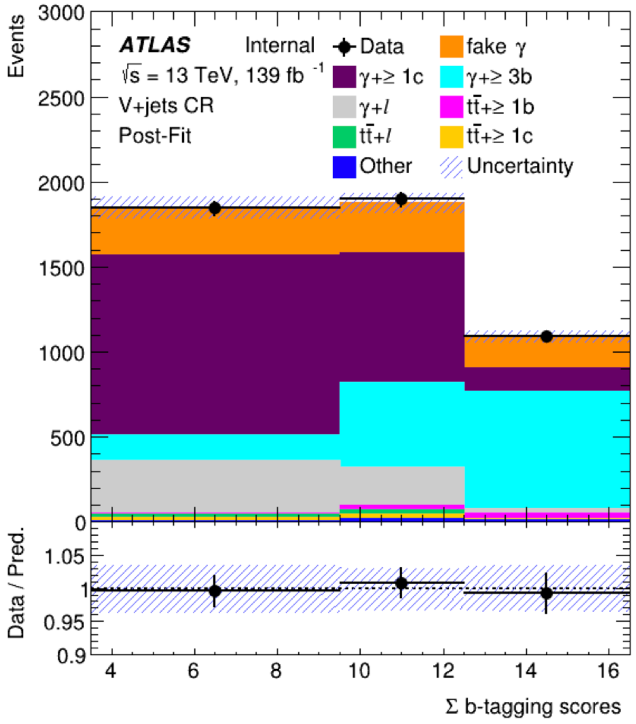
Exactly 2 different-flavor-opposite-sign (DFOS) light leptons

(e+μ- or e-μ+)



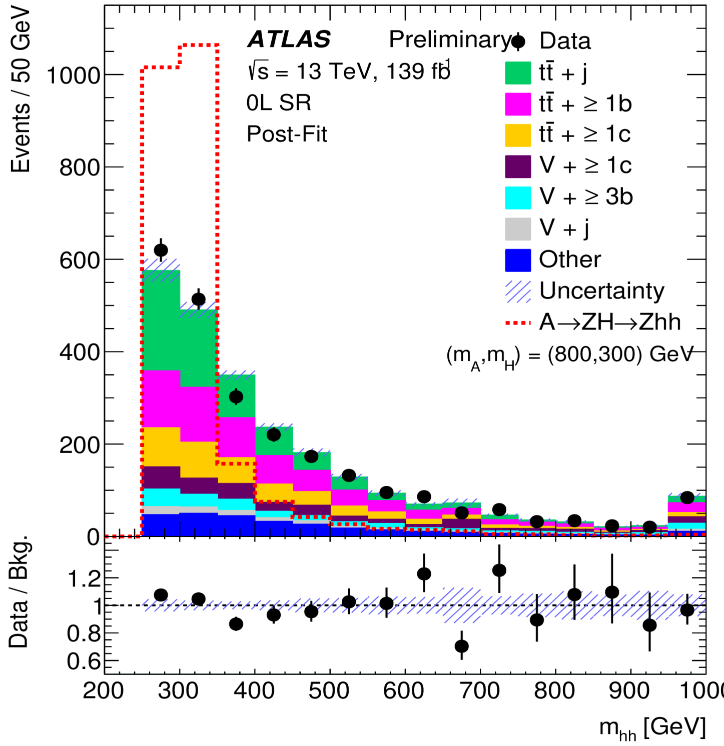
γ+jets CR

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

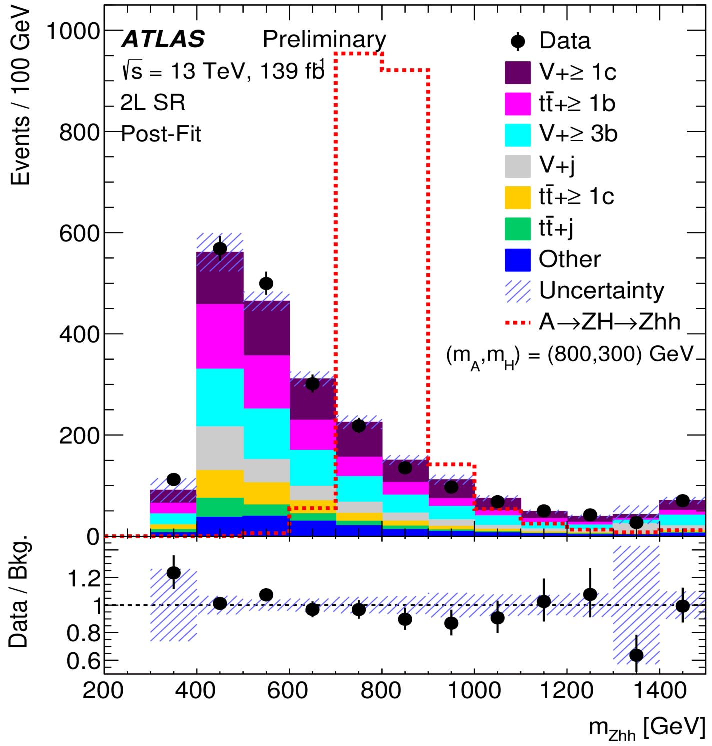


SRs

- All masses calculated after rescaling the measured Higgs candidate mass to 125 GeV
- The NFs of backgrounds obtained from the background-only fits to the control and signal regions
- A → ZH signal distributions at (m_A, m_H) = (800, 300) GeV normalized to the total background expectations overlaid (red dashed histograms)

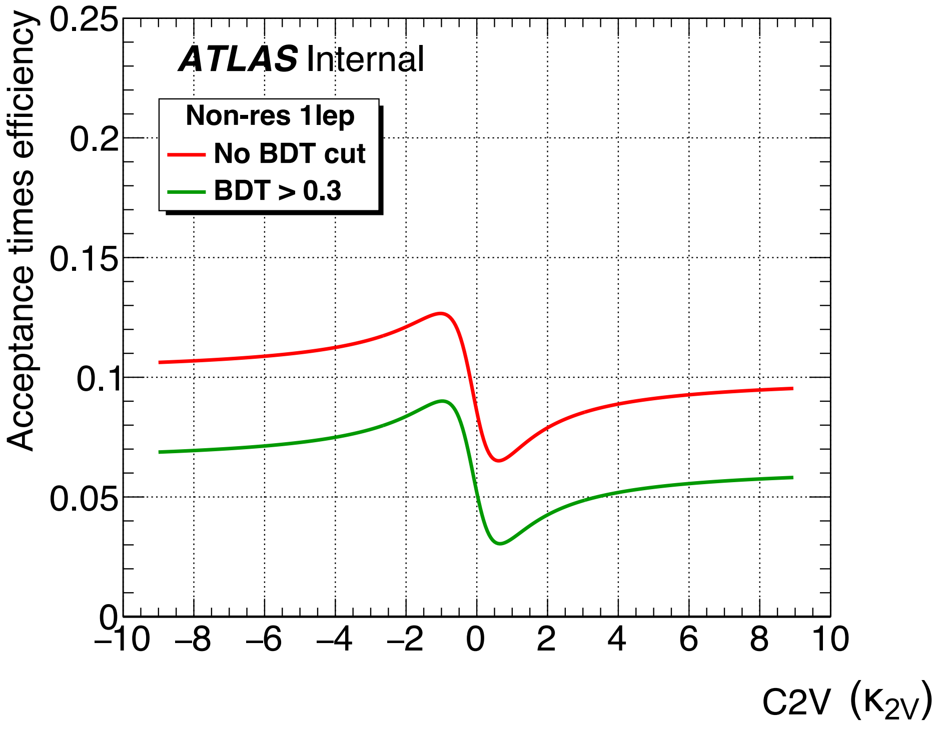


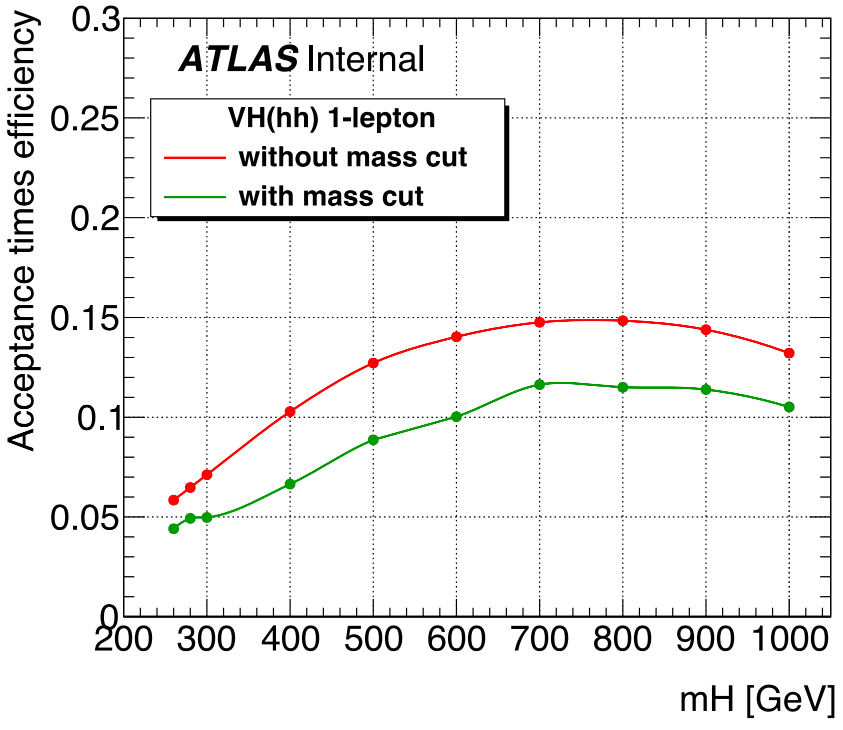
m_{hh} in 0L SR



m_{Zhh} in 2L SR

Signal selection performance





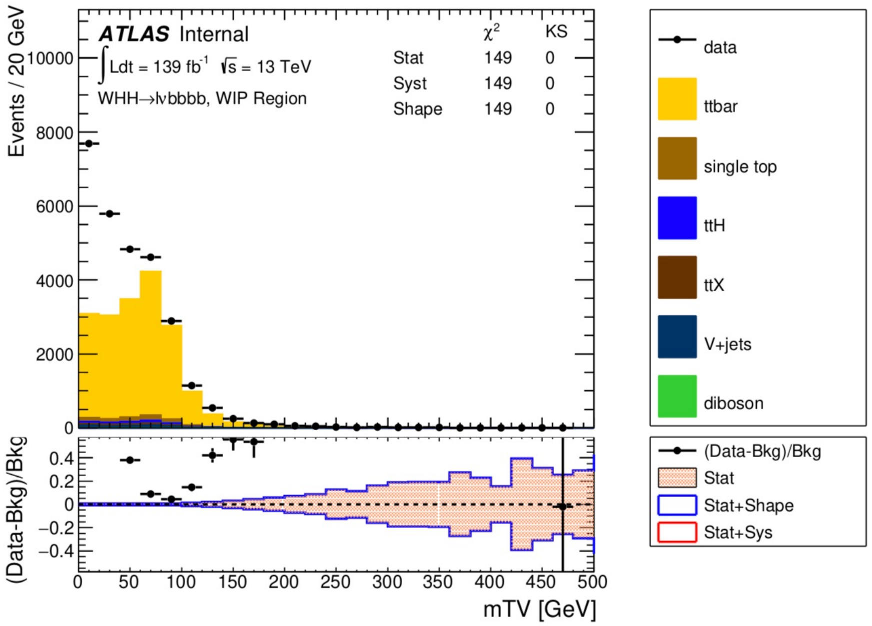
- Products of signal acceptance and efficiency shown as functions of κ_{2V} and mass of *H*, for non-resonant *Vhh* and resonant *VH*, *H*→*hh* signal in 1L channel
- Structure in left plot reflects changes in event kinematic
- Small decreases in right plot for high m_H values due to the highly boosted $h \rightarrow bb$ decays

MJ background estimation

- ➢ Data-driven method to estimate the MJ background
- ➢ MJ CRs defined for 1L SR and γ+jets CR
  - ➢ Same selection but with inverted isolation

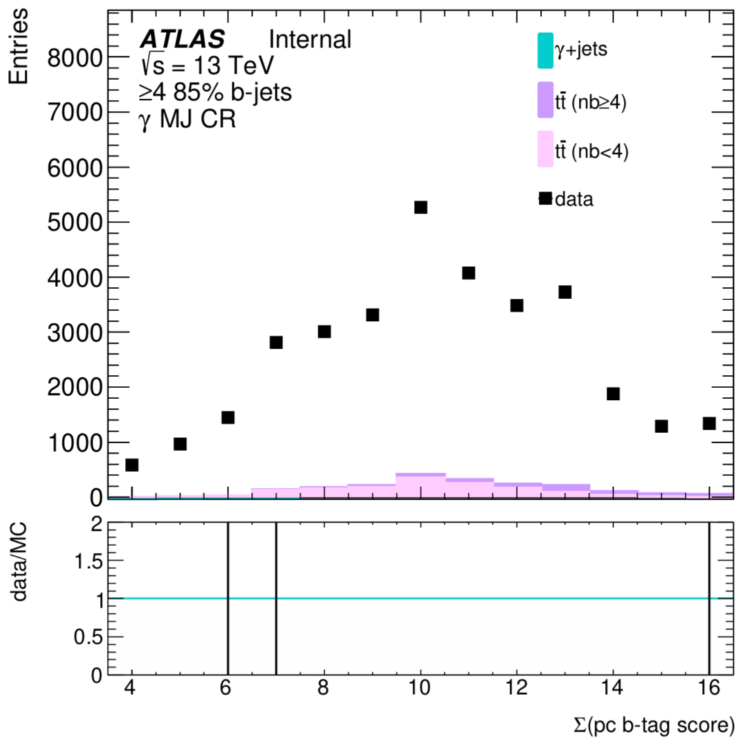
➢ MJ CR

- Extract MJ shape
- Obtain MJ yields

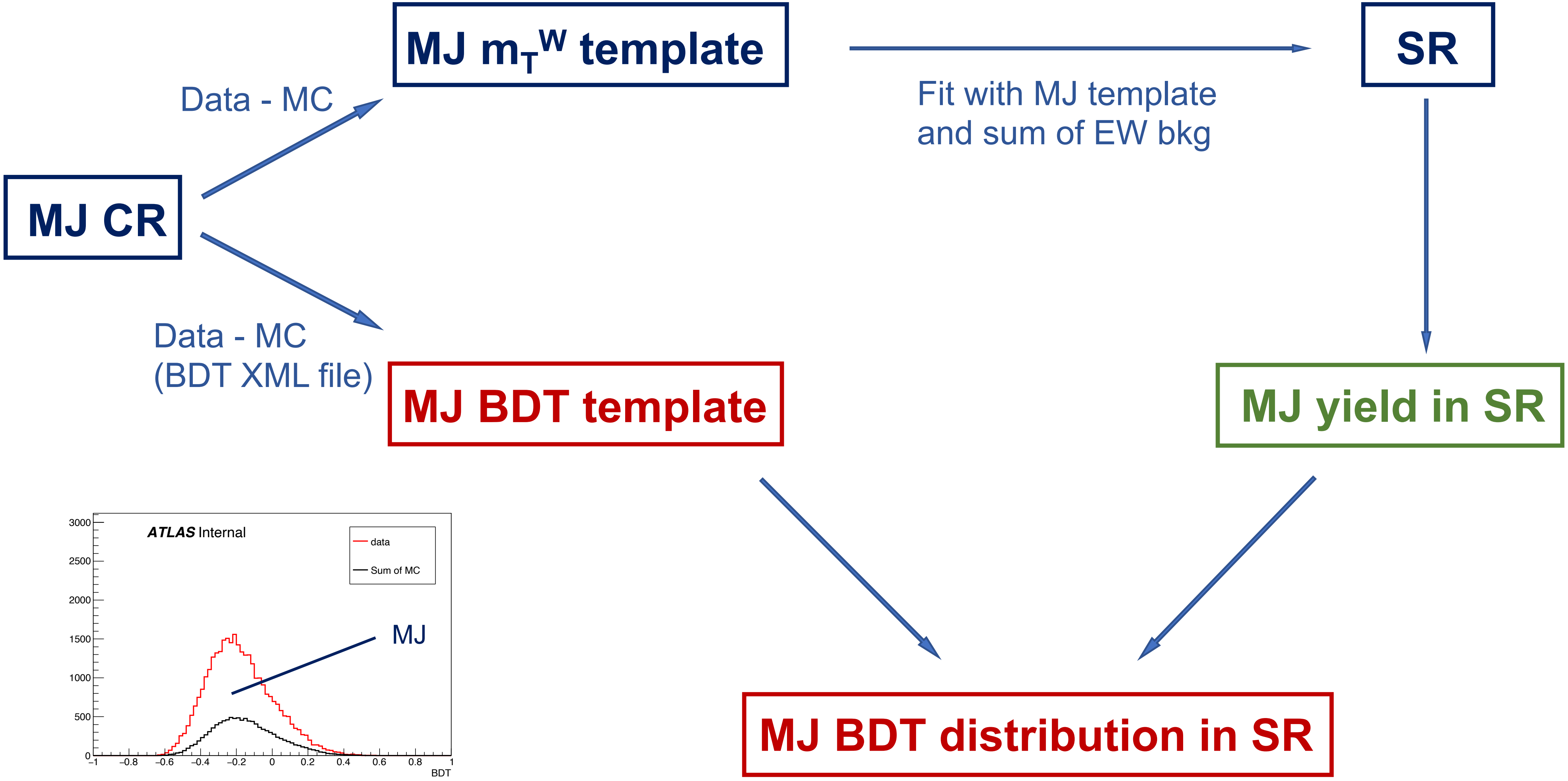


➢ γ+jets MJ CR

- Extract MJ shape
- Float it in fits



Workflow of MJ estimation in 1L SR

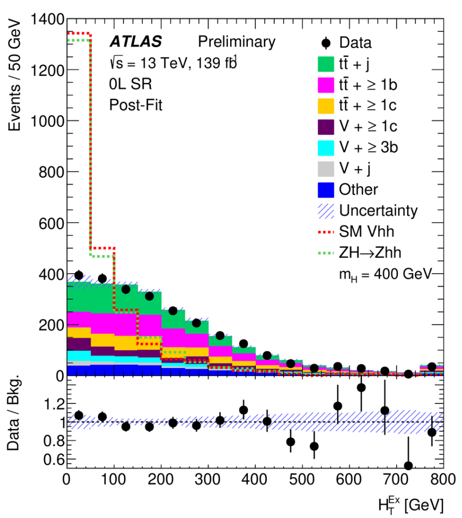


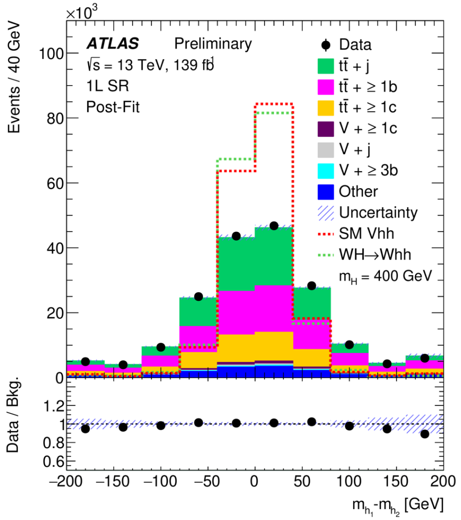
BDT of data and sum of MC in MJ CR

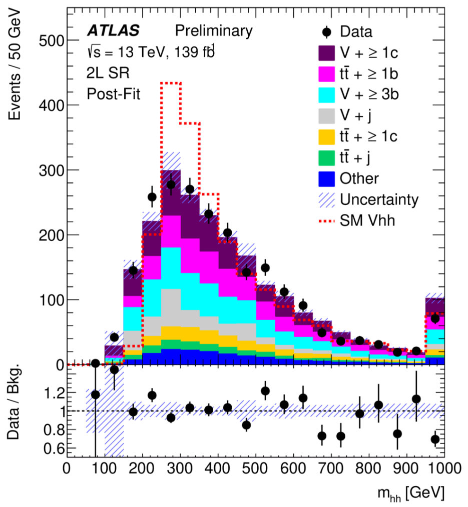
BDT training

- ~15 variables based on kinematics and *b*-tagging information

Variable	0L			1L		2L		
	Vhh	VH	$A \to ZH$	Vhh	VH	Vhh	VH	$A \to ZH$
$m_{h_1} + m_{h_2}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_1} - m_{h_2}$	✓	✓	✓	✓	✓	✓	✓	✓
N_{jets}	✓	✓	✓	✓	✓	✓	✓	✓
H_{T}^{ex}	✓	✓	✓	✓	✓	✓	✓	✓
$\sum pc$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_1}^{\text{FSR}}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_2}^{\text{FSR}}$	✓	✓	✓	✓	✓	✓	✓	✓
m_{hh}	✓			✓		✓		
p_{T}^{hh}	✓	✓		✓	✓	✓	✓	
$E_{\text{T}}^{\text{miss}}$	✓	✓		✓	✓	✓	✓	✓
p_{T}^{V}				✓	✓	✓	✓	
m_{T}^{W}				✓				
$\cosh(\Delta\eta)_1 - \cos(\Delta\phi)_1$	✓	✓		✓	✓	✓	✓	
$\cosh(\Delta\eta)_2 - \cos(\Delta\phi)_2$	✓	✓		✓	✓	✓	✓	
$\lvert y_{h_1} - y_{h_2}\rvert$	✓	✓		✓	✓	✓	✓	
$\lvert y_V - y_{hh}\rvert$						✓	✓	



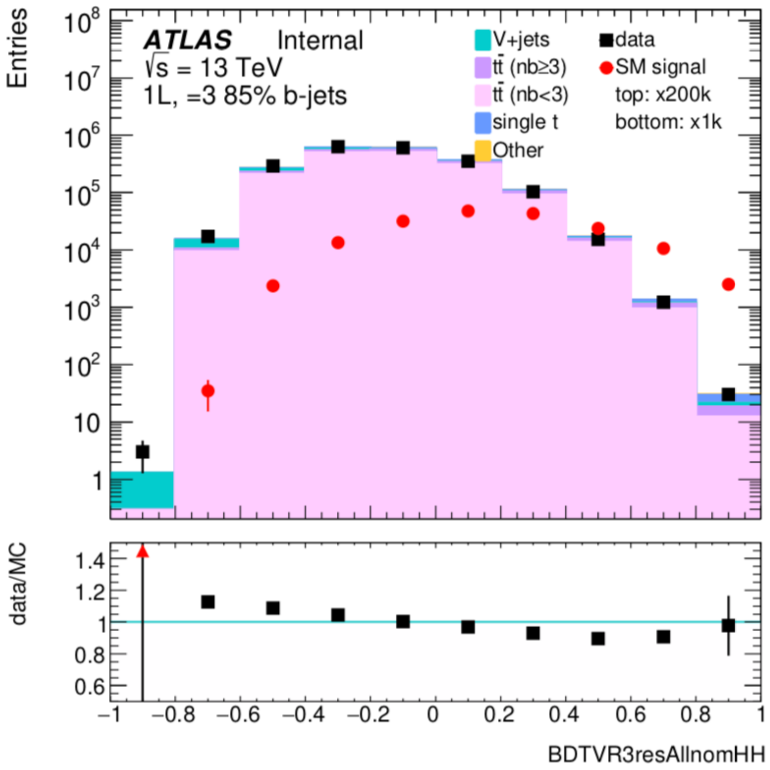


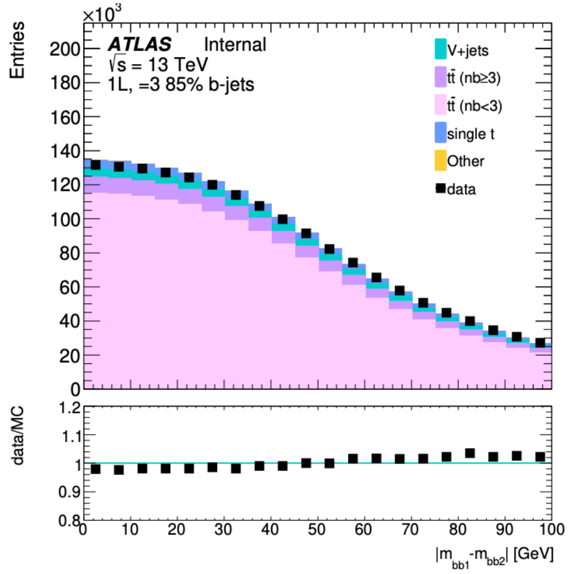


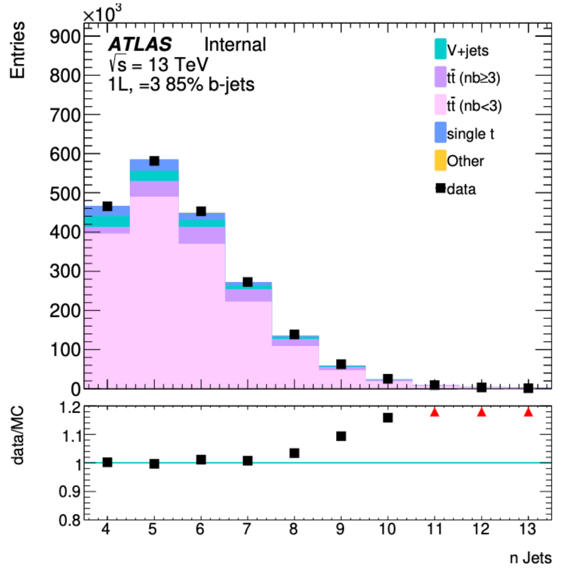
Distributions of kinematic variables used in BDT

Validation regions

- Exact 3 *b*-tagged jets instead of ≥ 4 *b*-tagged jets
- Non-closure in VRs taken as systematic uncertainties
- BDT and kinematic distributions in VRs shown







Statistical analysis

- SRs
  - 0L (for Zvvhh signals)
  - 1L (for Wlvhh signals)
  - 2L (for Zllhh signals)
- CRs (non-MJ)
  - eμ (to constrain *ttbar*)
  - γ+jets (to constrain *V*+jets)

→ Participate in fits

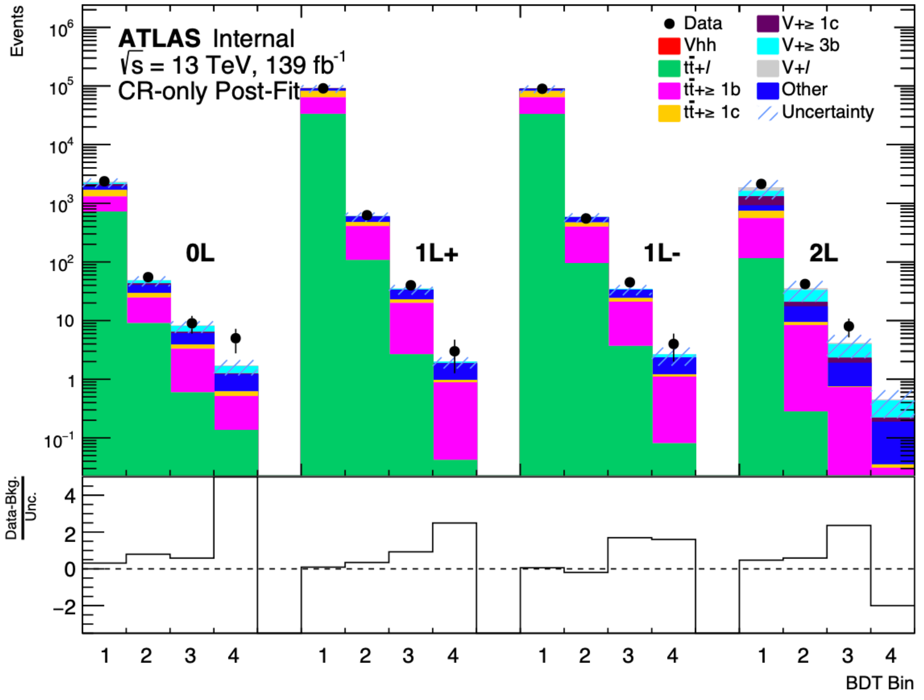
- CRs (MJ)
  - 1L MJ (for MJ yield in SR)
  - γ+jets MJ (for MJ shape in CR)

→ Extract MJ templates

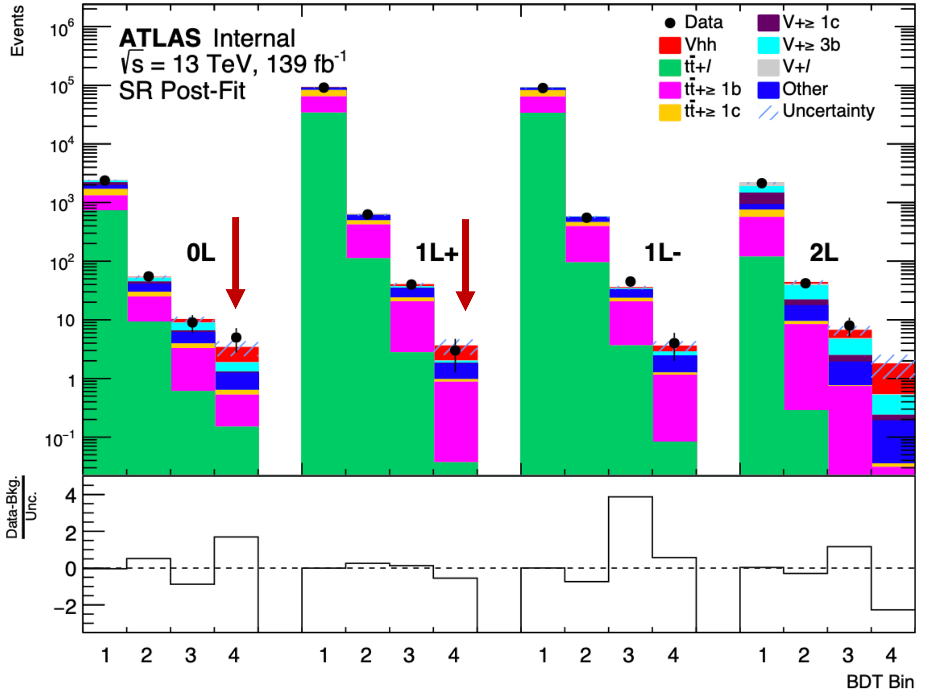
- VRs
  - 0L (to validate BDT modeling)
  - 1L (to validate BDT modeling)
  - 2L (to validate BDT modeling)
  - eμ
  - γ+jets

→ Extract uncertainties

Non-resonant Vhh



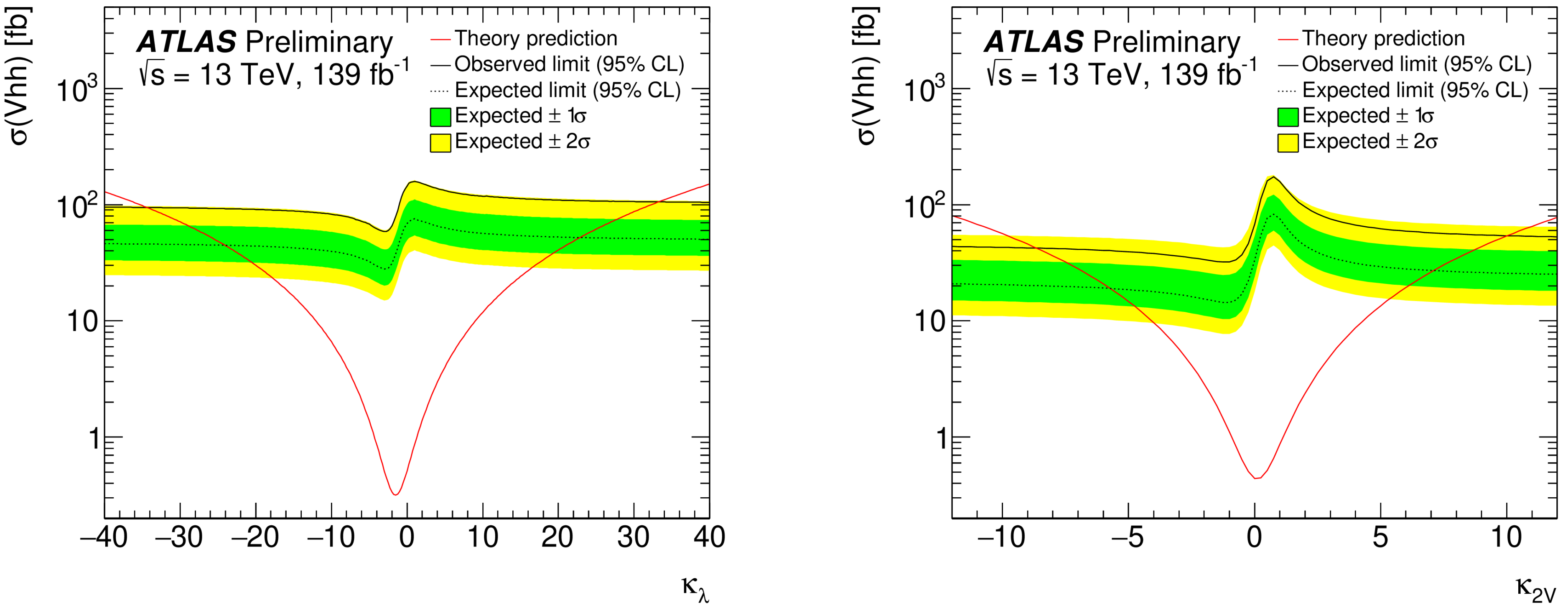
Post CR-only fit



Post CR+SR fit

- Results mainly driven by the last bins with the highest BDT scores

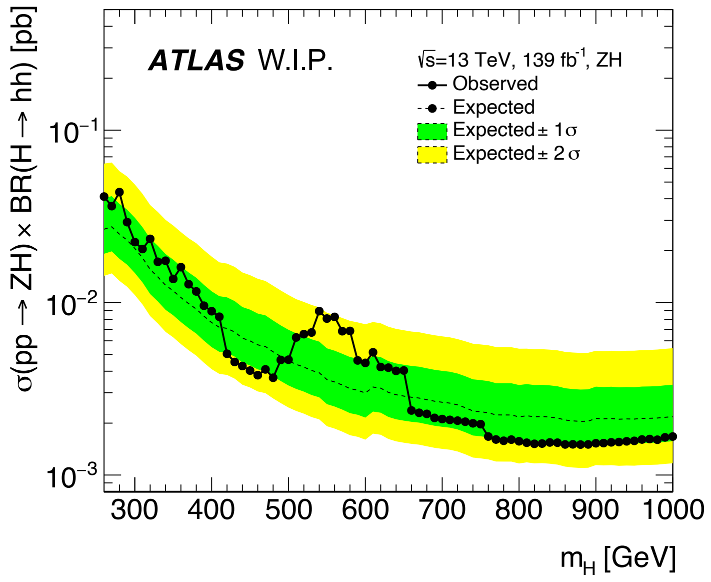
Limits on non-resonant Vhh

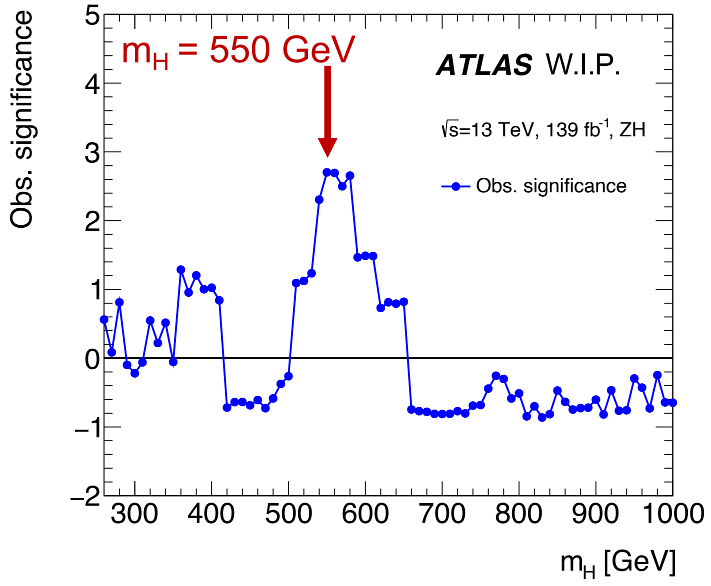


- Upper limits set on Vhh cross-section as functions of κ_λ and κ_{2V}
- 95% CL upper limit of 183 (87) is observed (expected) on the Vhh cross-section relative to SM
- The observed (expected) 95% CL intervals of κ_λ and κ_{2V} are $-34.4 < \kappa_\lambda < 33.3$ ($-24.1 < \kappa_\lambda < 22.9$), and $-8.6 < \kappa_{2V} < 10.0$ ($-5.7 < \kappa_{2V} < 7.1$)

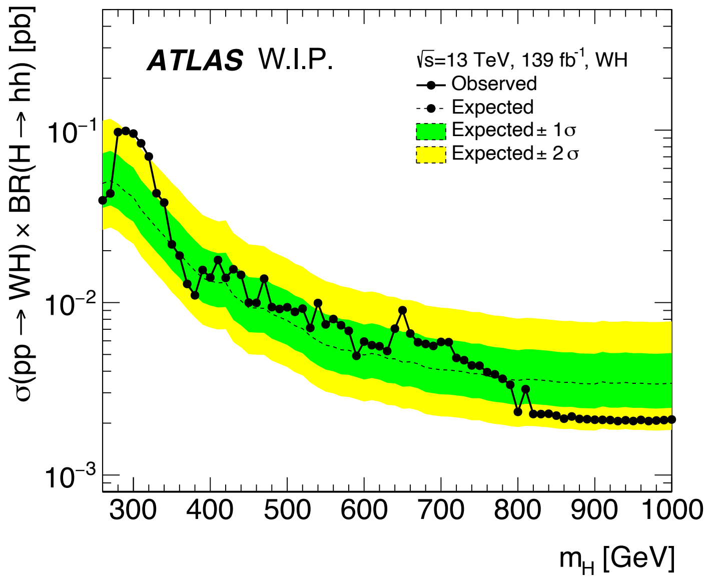
Resonant VH, H→hh

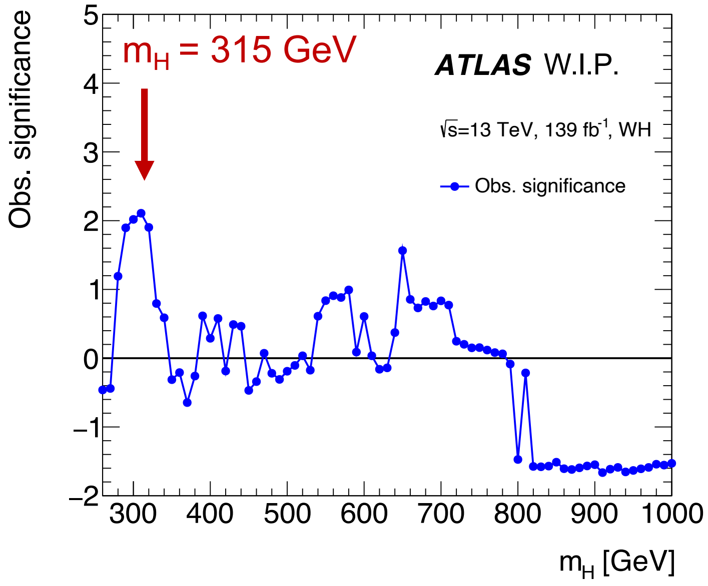
ZH, H→hh



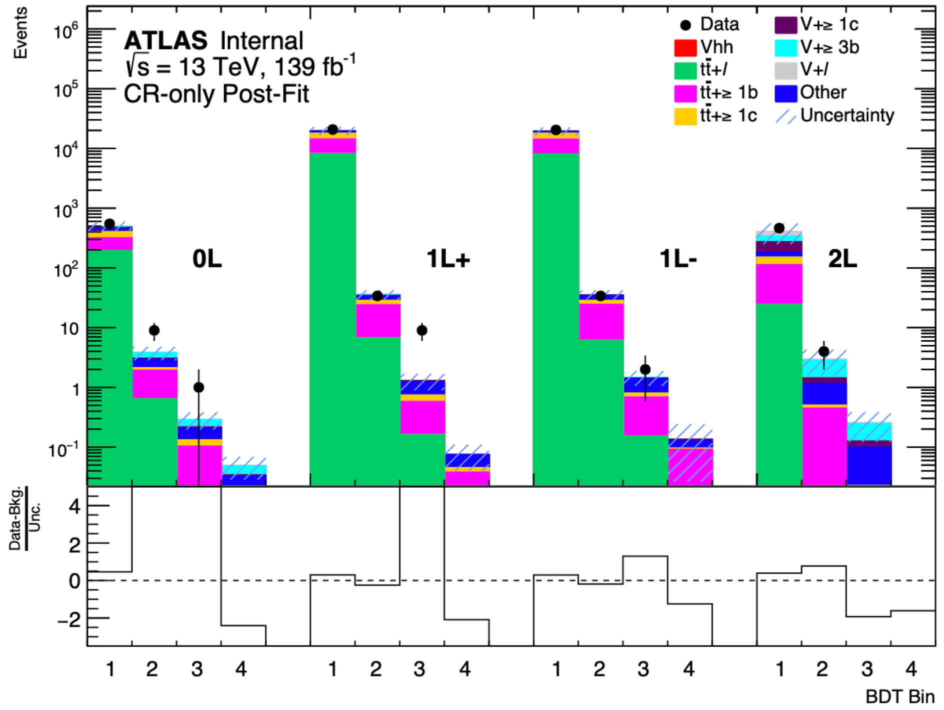


WH, H→hh

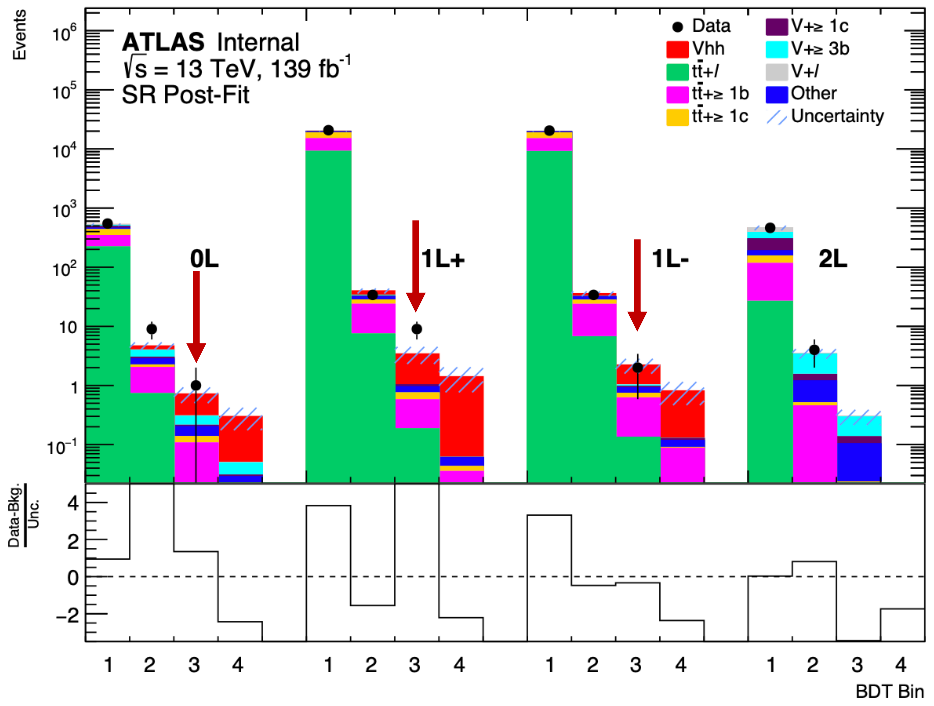




WH, H→hh, m_H=315 GeV



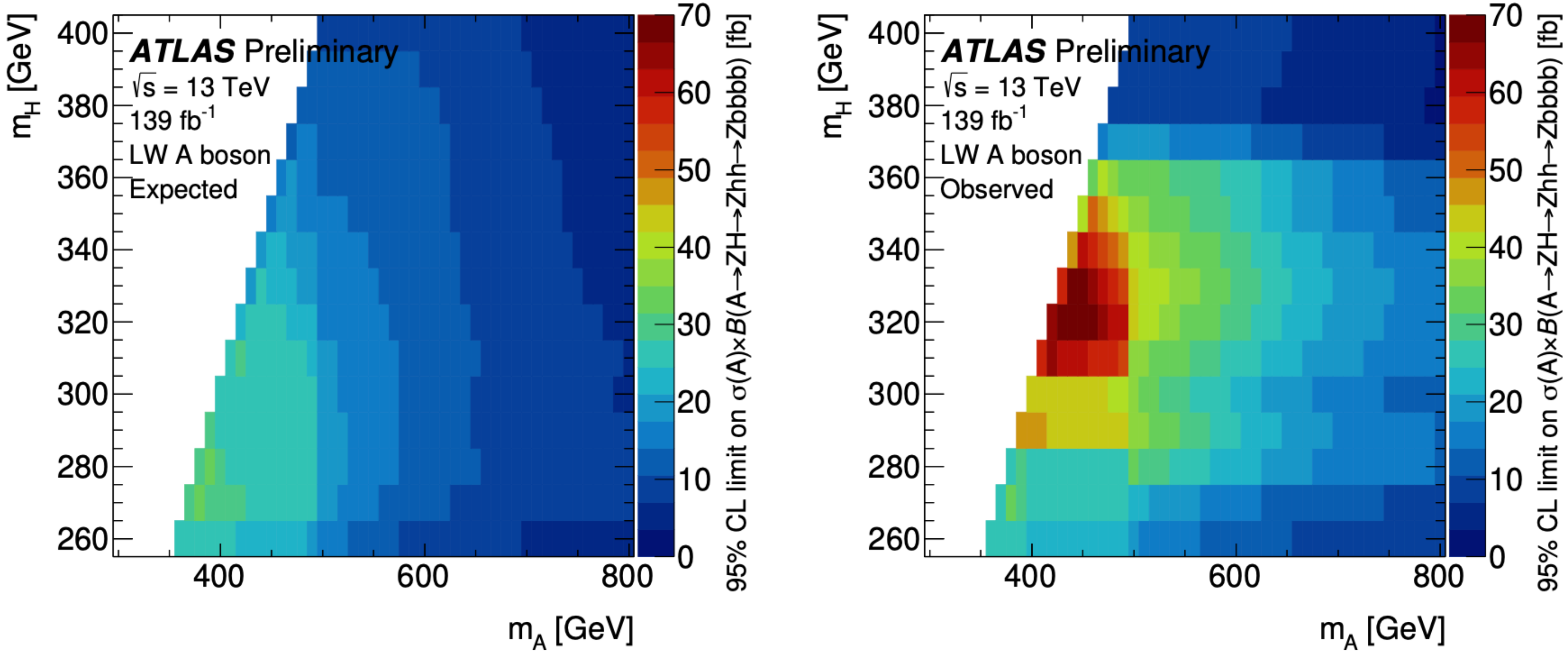
Post CR-only fit



Post CR+SR fit

- Results mainly driven by the third bins with high BDT scores
- Local (global) significance: 2.5 (1.3) σ

Resonant A → ZH, H → hh



- The most significant excess observed in the large-width (20%) A→ZH search at (m_A, m_H) = (420, 320) GeV with a local (global) significance of 3.8 (2.8) σ
- More data needed to ascertain this excess!

Summary

- Search for non-resonant and resonant Vhh production presented using full Run 2 dataset collected by the ATLAS detector

- In the non-resonant search,
  - Upper limit of 183 (87) on μ observed (expected) for SM-like Vhh production

- In the resonant VH, H → hh search,
  - Excess in ZH search at m_H = 550 GeV with local (global) significance of 2.7 (1.3) σ
  - Excess in WH search at m_H = 315 GeV with local (global) significance of 2.5 (1.3) σ

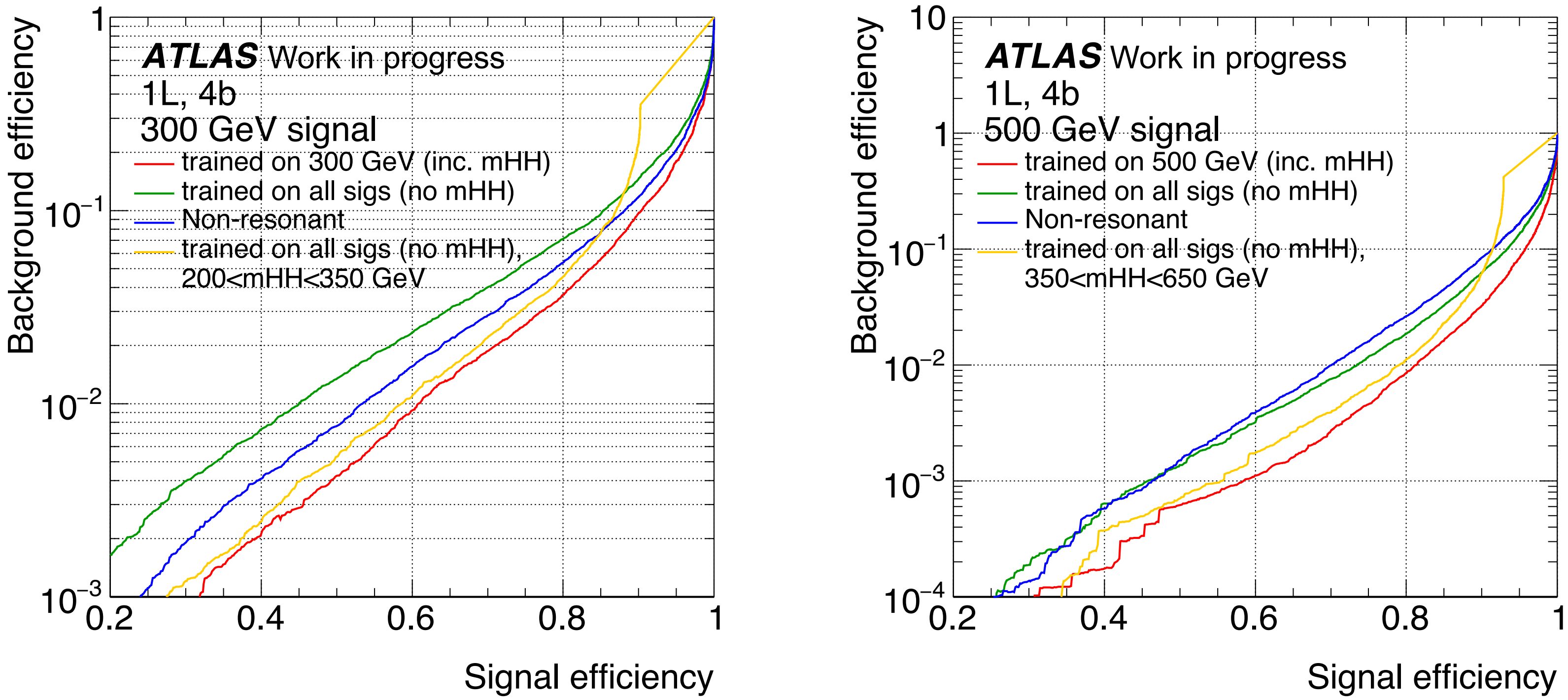
- In the resonant A → ZH, H → hh search,
  - The most significant excess observed in the large-width (20%) A→ZH search at (m_A, m_H) = (420, 320) GeV with a local (global) significance of 3.8 (2.8) σ

- More data needed to ascertain excesses!
- Looking forward to Run 3 and HL-LHC!

Back Up

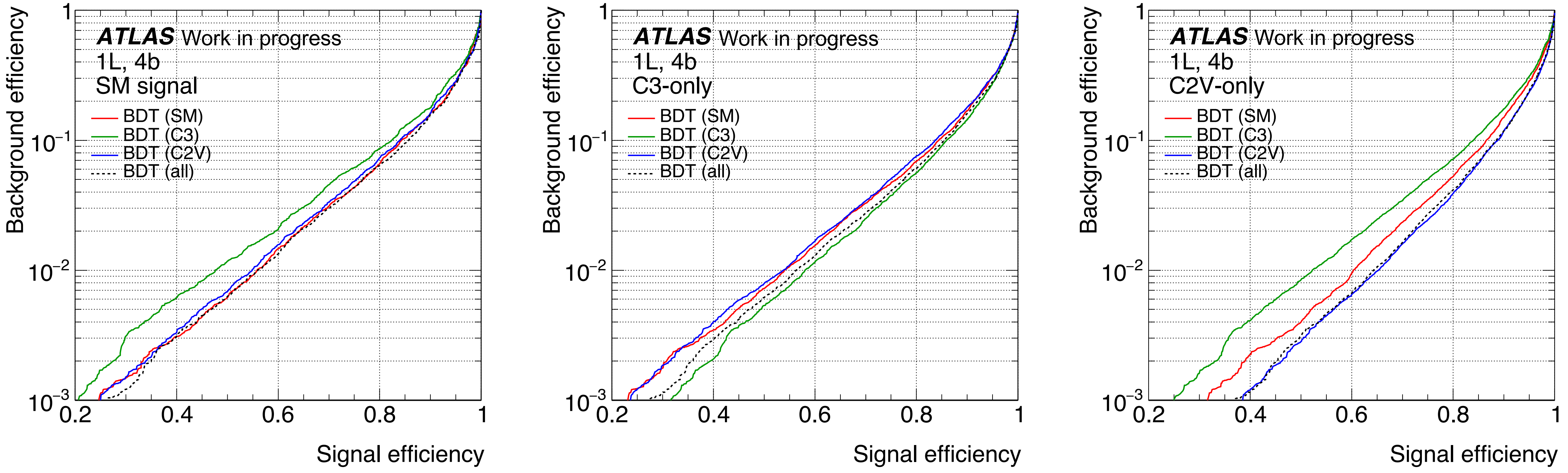
BDTs for resonant signals

- MC samples with different resonant masses are combined to form a signal sample for BDT training
- Curves below compare BDTs trained on one specific mass point vs. sum of all mass points vs. sum of all mass points with mass window cut
- Training on sum of all mass points with mass window cut (yellow) has similar performance with it on specific mass point (red)
- In the fits, select events based on BDTs as well as m_{hh} windows, for different mass points



BDTs for non-resonant signals

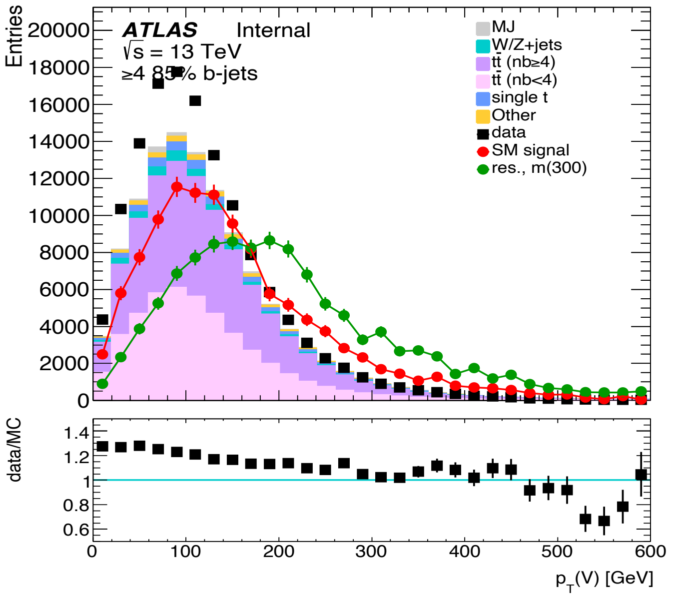
- The SM, κ_λ-, and κ_{2V}-only signal samples with equal statistics are added together to form a combined signal sample for BDT training
- Curves below compare BDTs trained on specific signal vs. combined signal (all)
- Training on combined signal (dashed line) has similar performance with it on specific signal

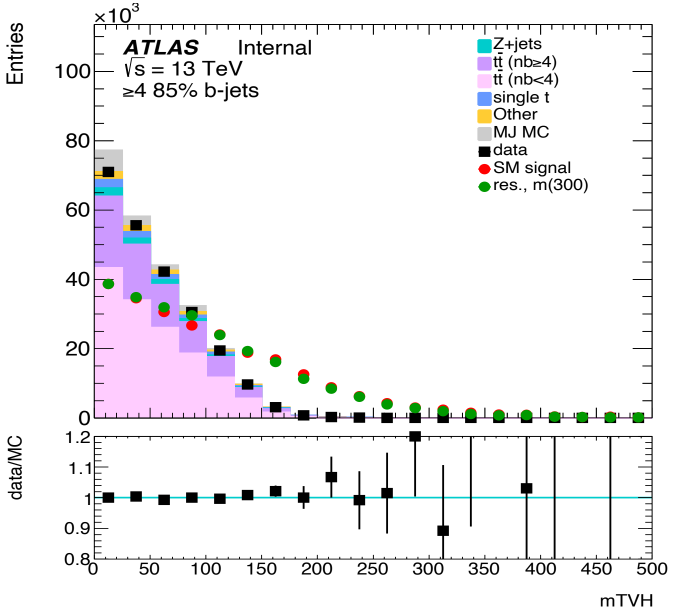


Event pre-selection for SR

- At least four 85% DL1r *b*-jets
- Exactly one charged light lepton (e or μ)
- Exactly no tau
- E_T^{miss} > 30 GeV

Pre-fit distributions at pre-selection level (without NFs)

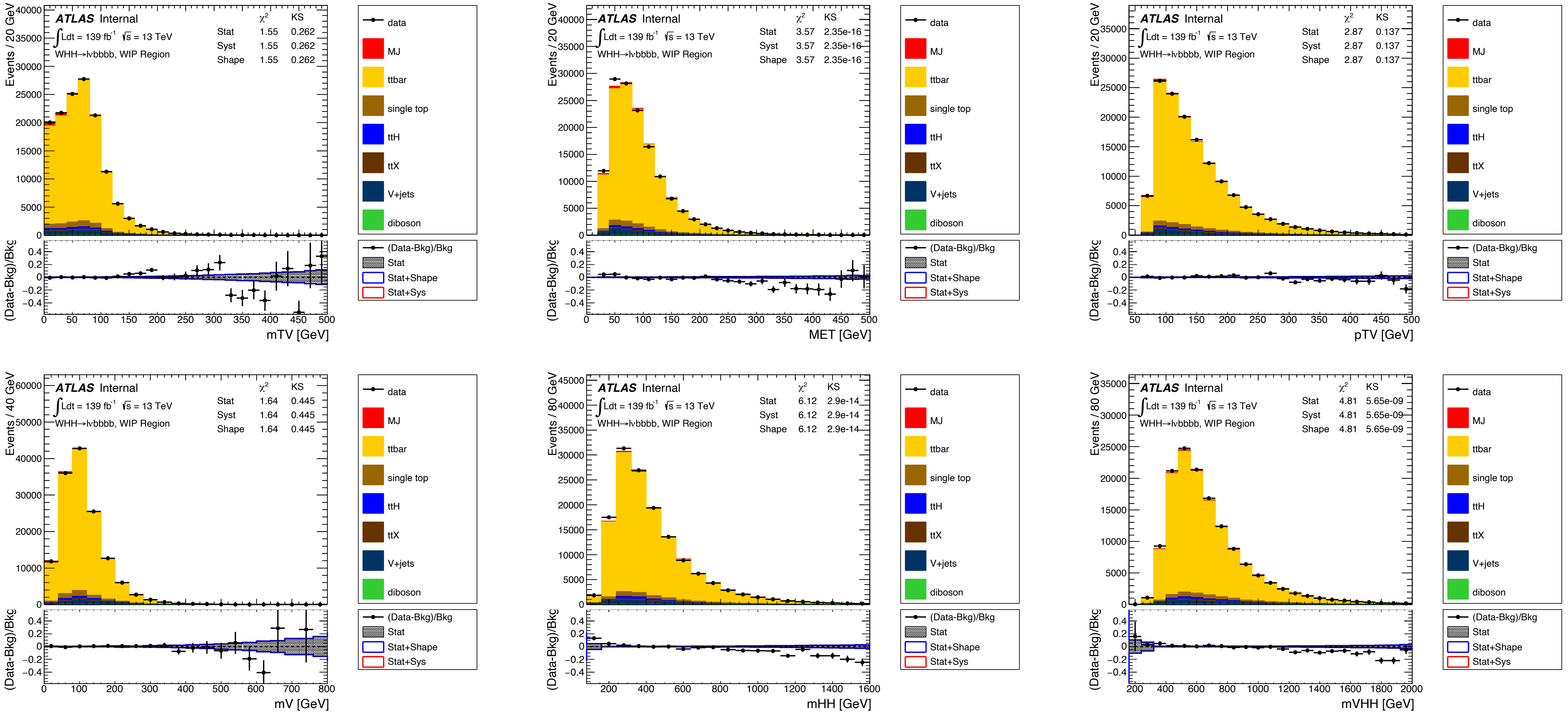




- mH=260 GeV: 250<mhh<280 GeV
- mH=280 GeV: 260<mhh<300 GeV
- mH=300 GeV: 280<mhh<320 GeV
- mH=400 GeV: 375<mhh<425 GeV
- mH=500 GeV: 465<mhh<535 GeV
- mH=600 GeV: 555<mhh<645 GeV
- mH=700 GeV: 630<mhh<770 GeV
- mH=800 GeV: 725<mhh<875 GeV
- mH=900 GeV: 805<mhh<995 GeV
- mH=1000 GeV: 890<mhh<1110 GeV

- *H* mass windows for different mass points of resonant *VH, H→hh* production
- Optimization shown in backup slides

Post-fit distributions with MJ contribution



- MJ events presented as red histograms
- Good agreement between data and MC observed

Systematic uncertainties

- Object uncertainties (A) and conventional theory uncertainties (B) generally have little impact
- Main impact from VR non-closure uncertainties, normalization uncertainties of *V*+jets and *ttbar* (C), as well as MC statistical uncertainties

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

A

Name
Matching($t\bar{t}+\geq 1b$)
Matching($t\bar{t}+0b+\geq 1c$)
Matching($t\bar{t}+0b+0c$)
Shower($t\bar{t}+\geq 1b$)
Shower($t\bar{t}+0b+\geq 1c$)
Shower($t\bar{t}+0b+0c$)
Matching(s-top)
Shower(s-top)
Interference(s-top)
s-top_Scale_muR
s-top_Scale_muF
ttbar2b_ISR_a_s_up
ttbar2b_FSR_up
ttbar2b_NNLO
ttbar2b1c_ISR_a_s_up
ttbar2b1c_FSR_up
ttbar2b1c_NNLO
ttbar4b_ISR_a_s_up
ttbar4b_FSR_up
ttbar4b_NNLO
ttbar2b_Scale_muRmuF_up
ttbar2b_Scale_muR_up
ttbar2b_Scale_muF_up
ttbar2b1c_Scale_muRmuF_up
ttbar2b1c_Scale_muR_up
ttbar2b1c_Scale_muF_up
ttbar4b_Scale_muRmuF_up
ttbar4b_Scale_muR_up
ttbar4b_Scale_muF_up
t_FSR
t_ISR_alpha_s
Z4b_Scale_muRmuF_up
Z4b_Scale_muR_up
Z4b_Scale_muF_up
Z2b1c_Scale_muRmuF_up
Z2b1c_Scale_muR_up
Z2b1c_Scale_muF_up
Z2b_Scale_muRmuF_up
Z2b_Scale_muR_up
Z2b_Scale_muF_up
zll_var1
qqgg

B

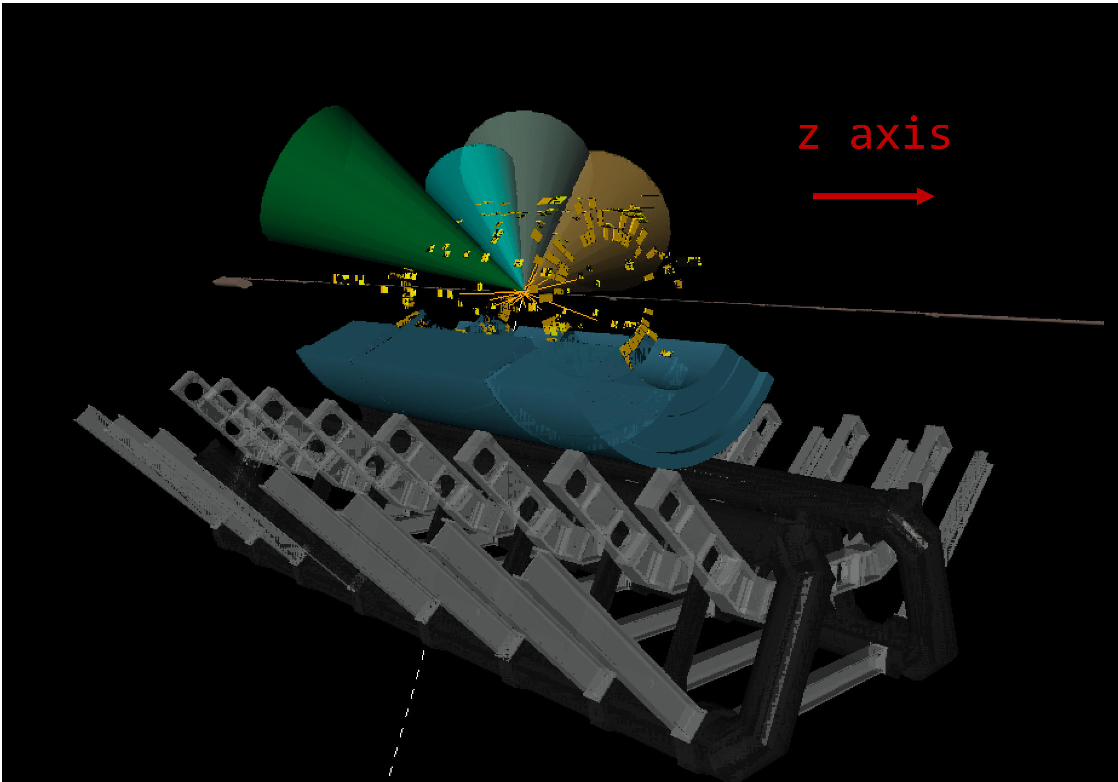
Name	Shape or Norm.
$\mu(t\bar{t}+\geq 1b)$	Norm
$\Delta\mu(t\bar{t}+0b+0c)$	Norm
$\Delta\mu(t\bar{t}+0b+\geq 1c)$	Norm
$\mu(V+\geq 3b)$	Norm
$\Delta\mu(V+\leq 2b+\geq 1c)$	Norm
$\Delta\mu(V+\leq 2b+0c)$	Norm
$\Delta\mu(Z+\geq 3b)$	Norm
$\Delta\mu(Z+\leq 2b+\geq 1c)$	Norm
$\Delta\mu(Z+\leq 2b+0c)$	Norm
$\Delta\mu(W+\geq 3b)$	Norm
$\Delta\mu(W+\leq 2b+\geq 1c)$	Norm
$\Delta\mu(W+\leq 2b+0c)$	Norm
$\Delta\mu(t\bar{t}+V/t/t\bar{t})$	Norm
$\Delta\mu(t)$	Norm
$\Delta\mu(VV)$	Norm
$\Delta\mu(t\bar{t}h)$	Norm
$\Delta\mu(fakelepton)$	Norm
$\Delta\mu(fake\gamma)$	Norm
L0 trig eff.	Shape+Norm.
L0_TT_up	Shape+Norm.
L1_TT_up	Shape+Norm.
L2_TT_up	Shape+Norm.
HighPtExtrapB_up	Shape+Norm.
VR0L Non-closure, norm.	Norm.
VR0L Non-closure, shape	Shape.
VR2L Non-closure, norm.	Norm.
VR2L Non-closure, shape	Shape.
VR1L+ Non-closure, norm.	Norm.
VR1L+ Non-closure, shape	Shape.
VR1L- Non-closure, norm.	Norm.
VR1L- Non-closure, shape	Shape.
VREMU Non-closure, norm.	Norm.
$\Delta\mu$(fake lepton shape0)	Shape
$\Delta\mu$(fake lepton shape1)	Shape
$\Delta\mu$(fake γ contam)	Shape

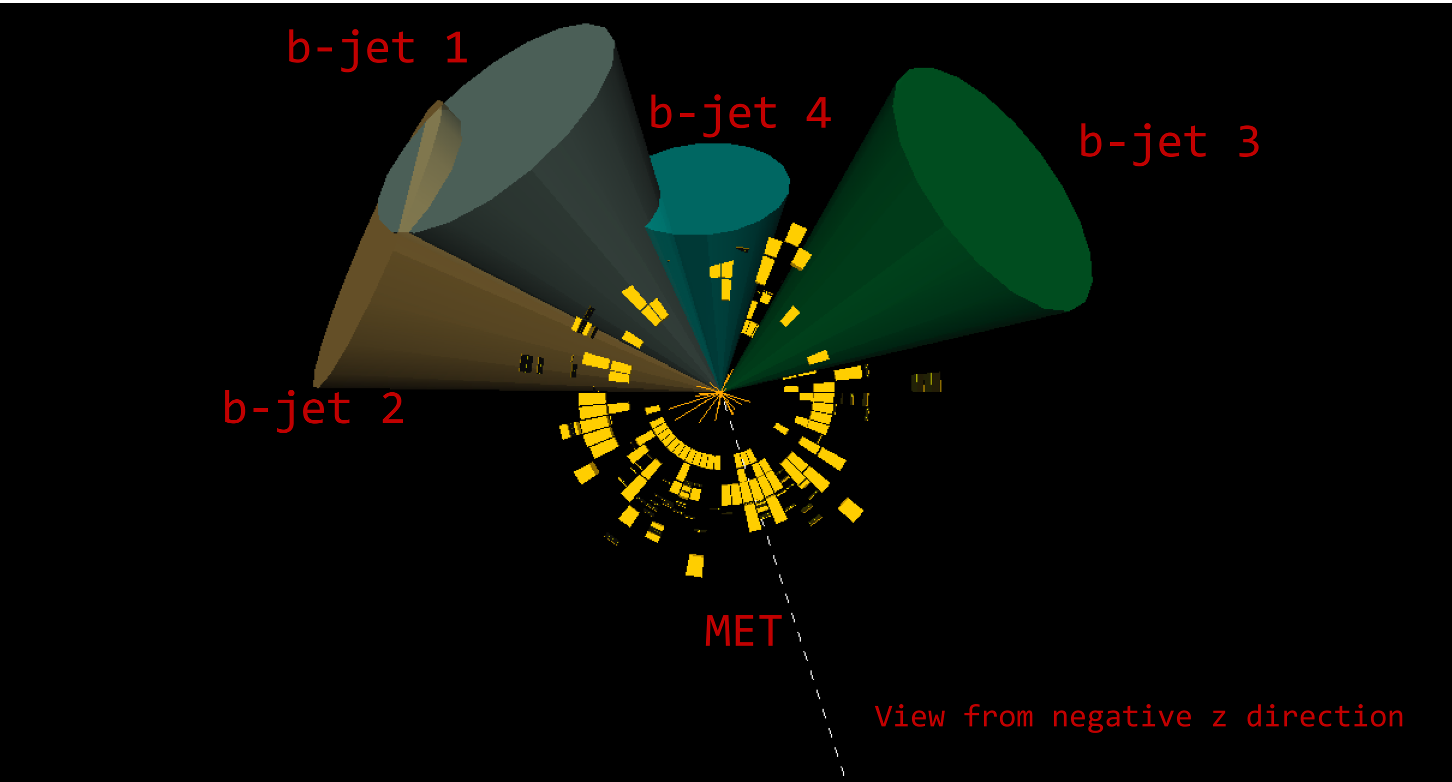
C

Display of 0L candidate event

- Run number: 350121
- Event number: 876442950
- E_T^{miss} = 556.845 GeV

	b-jet 1	b-jet 2	b-jet 3	b-jet 4
pT (GeV)	394.555	111.069	191.720	58.895
eta	-0.759	-0.491	-0.813	-0.841
phi	0.869	0.408	2.497	1.485





Display of 1L candidate event

- Run number: 355754
- Event number: 1008833929
- Exact 1 good electron
- E_T^{miss} = 64.898 GeV

	electron	b-jet 1	b-jet 2	b-jet 3	b-jet 4
pT (GeV)	326.610	257.846	49.554	98.075	52.136
eta	1.831	0.107	-0.237	-0.571	-1.791
phi	-1.639	1.292	2.193	1.812	1.607