Recent VH, $H \to b\bar{b}$ Analysis Results

Jeff Hetherly on behalf of the ATLAS Collaboration

Higgs Hunting 2016 YSF

ATLAS-CONF-2016-091

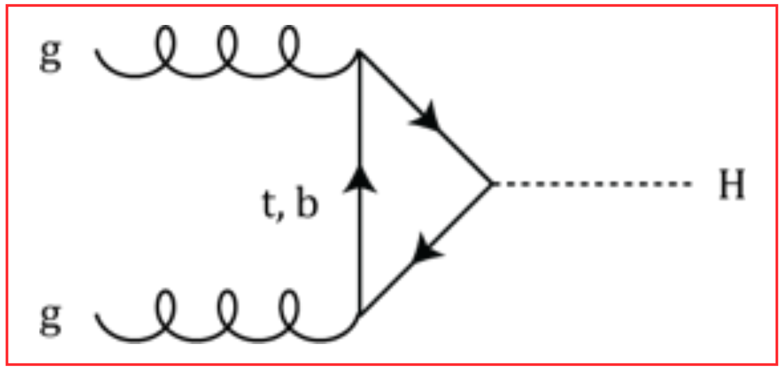
Overview

- VH, $H \rightarrow b\bar{b}$ (V = W/Z) Physics at the LHC
- Analysis Details
- Systematics Uncertainties
- Statistical Treatment & Measurement
- Summary

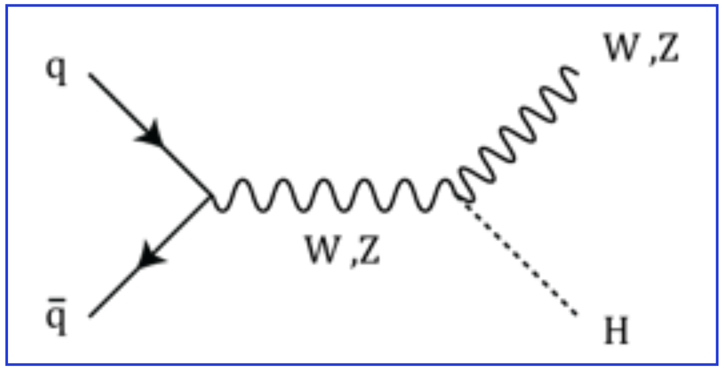
VH, $H \rightarrow b\bar{b}$ Physics

- $H \rightarrow b\bar{b}$ has the largest predicted branching ratio out of all the possible Higgs decays
  - ✓ Test of Yukawa coupling between b-quarks and Higgs boson (yet to be directly observed)
  - – Jets in the final state introduces potential for large background contamination

ggF (48 pb @ 13 TeV LHC)



"Higgsstrahlung" (2.25 pb @ 13 TeV LHC)*



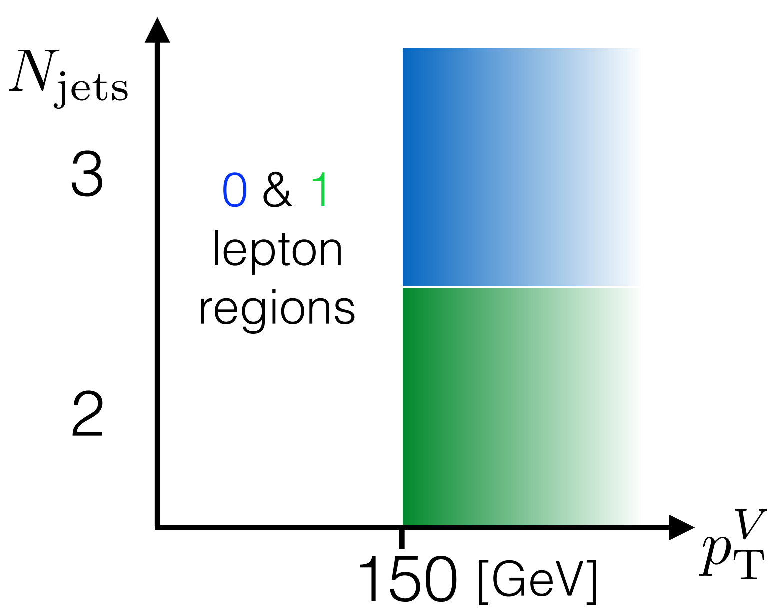
$WH \rightarrow 1.37$pb
$ZH \rightarrow 0.88$pb

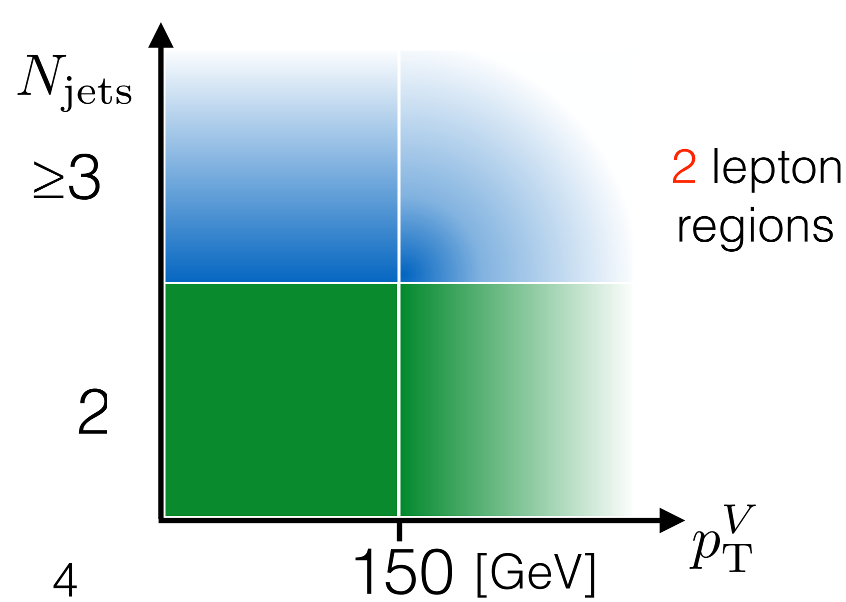
*includes $gg \rightarrow ZH$

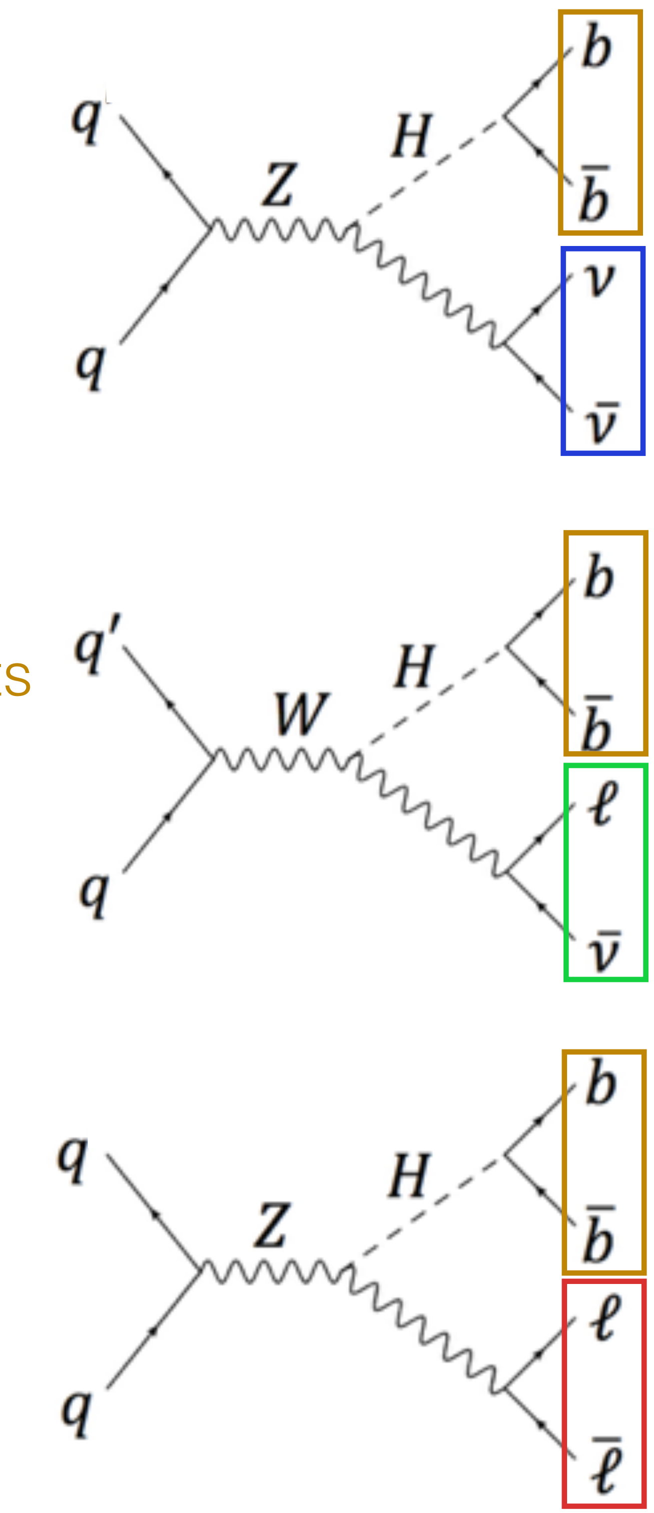
- Vector boson-associated Higgs (@125 GeV) production at the LHC provides a convenient mechanism to search for the Higgs boson
  - – Cross-section is much lower than gluon-gluon fusion (ggF)
  - ✓ Leptonic decays of vector boson allow for triggering and reduction of multi-jet backgrounds

VH Analysis Overview

- Events are classified by:
  - exclusive number of (non-τ) leptons: 0, 1, & 2
  - vector boson transverse momentum
  - jet multiplicity
- Flavor tagging of calorimeter jets is used to distinguish “Higgs” jets from backgrounds largely comprised of non-b-quark initiated jets
- Uses both 2015 (3.2 fb^{-1}) and 2016 (10 fb^{-1}) datasets







0-lepton Channel

Selection	0-lepton
Trigger	$E_T^{miss} > 70$ GeV for data15 (90 GeV for data16)
Number of Leptons	0
Number of Jets	2 or 3
b-jets	exactly 2 b-tagged jets
Leading Jet p_T	> 45 GeV
E_T^{miss}	> 150 GeV
S_T	> 120 GeV for 2 jets (> 150 GeV for 3 jets)
p_T^V regions	$[150, \infty]$ GeV
Multi-jet Suppression	
$\Delta\Phi(E_T^{miss}, E_{T,trk}^{miss})$	$< 90°$
$\Delta\Phi(jet_1, jet_2)$	$< 140°$
$\Delta\Phi(E_T^{miss}, Higgs)$	$> 120°$
$\min[\Delta\Phi(E_T^{miss}, jets)]$	$> 20°$

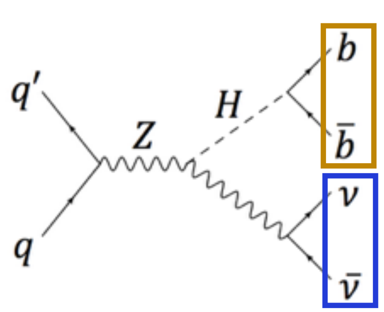
S_T is the scalar sum of the transverse momentum of available jets (2 or 3)

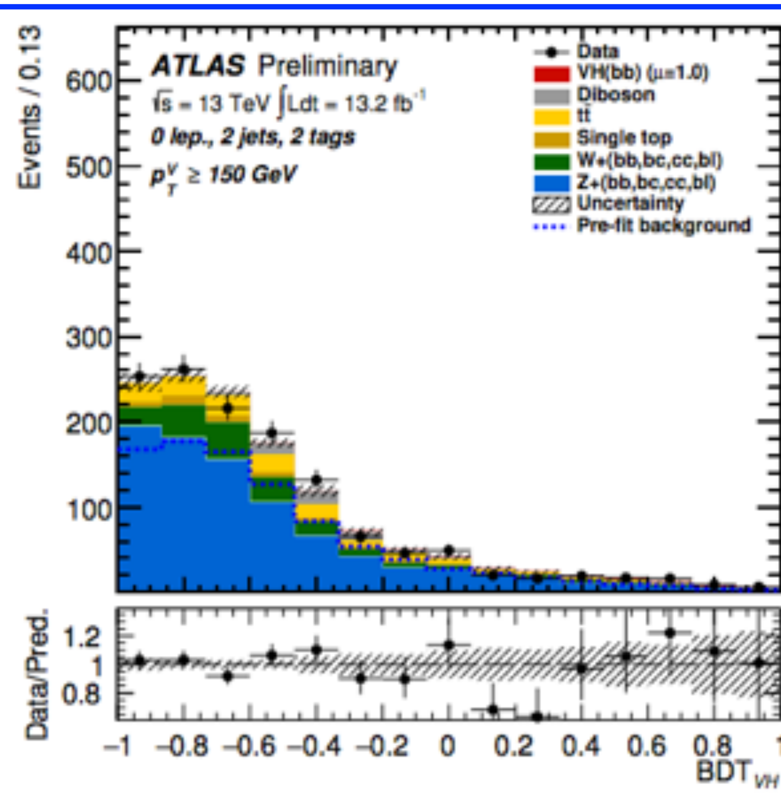
BDT Inputs
E_T^{miss}
$p_T^{b_1}$
$p_T^{b_2}$
m_{bb}
$\Delta R(b_1, b_2)$
$\lvert\Delta\eta(b_1, b_2)\rvert$
$\Delta\phi(V, bb)$
H_T
$p_T^{jet_3}$
m_{bbj}

BDT = Boosted Decision Tree

← only for 3 jets

H_T is the scalar sum of the transverse momenta of all jets and E_T^{miss}





Dominant Backgrounds

- V+heavy flavor (Z mostly)
- $t\bar{t}$
- Diboson
- Single top
- Negligible multi-jet
    - from MC, checked with data
    - after anti-multi-jet selection

b-jet energy corrections: μ-in-jet, PtReco

1-lepton Channel

Selection	1-lepton
Trigger	μ-sub-channel: same $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger as 0-lepton e-sub-channel: lowest unprescaled single e trigger
Number of Leptons	exactly 1 “high quality” lepton
Number of Jets	2 or 3
b-jets	exactly 2 b-tagged jets
Leading Jet p_{T}	$> 45\,\mathrm{GeV}$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 30\,\mathrm{GeV}$ (e-sub-channel only)
p_{T}^{V} regions	$[150, \infty]\,\mathrm{GeV}$

$p_{\mathrm{T}}^{l} > 25\,\mathrm{GeV}$ for “high quality” leptons (in addition to other requirements)

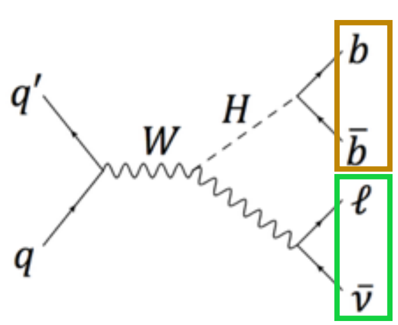
BDT Inputs
p_{T}^{V}
$E_{\mathrm{T}}^{\mathrm{miss}}$
$p_{\mathrm{T}}^{b_1}$
$p_{\mathrm{T}}^{b_2}$
m_{bb}
$\Delta R(b_1, b_2)$
$\Delta\phi(V, bb)$
$\min[\Delta\phi(l, b)]$
m_{T}^{W}
m_{Top}
$\lvert\Delta Y(V, bb)\rvert$
$p_{\mathrm{T}}^{\mathrm{jet}_3}$
m_{bbj}

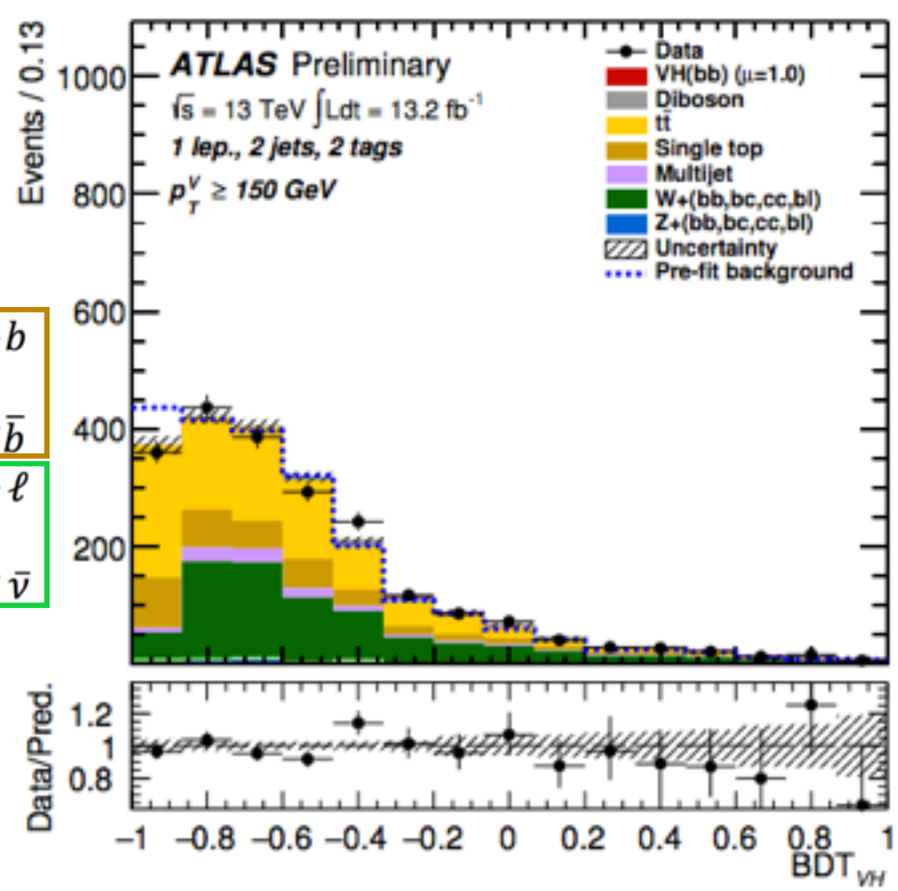
$$m_{\mathrm{T}}^{W} = \sqrt{2 p_{\mathrm{T}}^{l} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos(\Delta\phi(l, E_{\mathrm{T}}^{\mathrm{miss}})))}$$

minimum t-quark mass under $t\bar{t}$ hypothesis (m_{Top})

rapidity difference between the W and Higgs boson ($\lvert\Delta Y(V, bb)\rvert$)

only for 3 jets ($p_{\mathrm{T}}^{\mathrm{jet}_3}$, m_{bbj})





Dominant Backgrounds

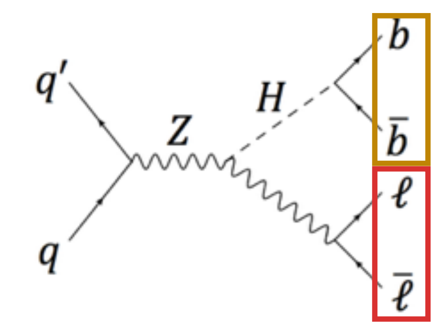
- $t\bar{t}$
- W+heavy flavor
- Single top
- Multi-jet

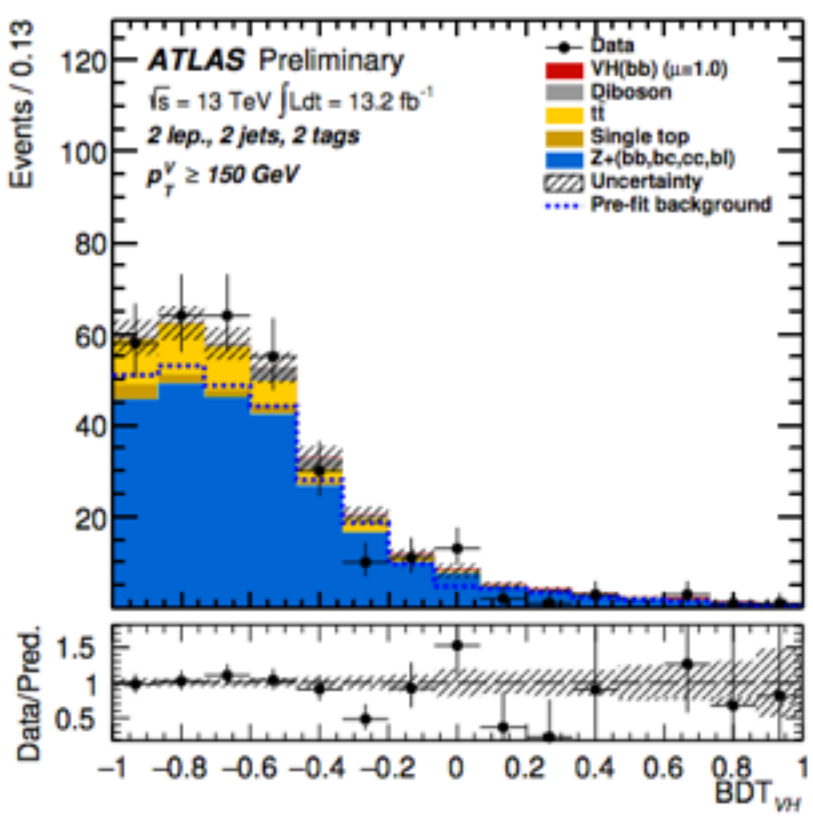
  - b-jet energy corrections: μ-in-jet, PtReco
  - Data-driven multi-jet estimate (fake factor method)

2-lepton Channel

Selection	2-lepton
Trigger	μ-sub-channel: lowest unprescaled single μ trigger e-sub-channel: lowest unprescaled single e trigger
Number of Leptons	exactly 1 “low quality” lepton and 1 “medium quality” lepton of the same flavor
Lepton Charge	opposite charge in μ-sub-channel
m_{ll}	$71 < m_{ll} < 121\,\text{GeV}$
Number of Jets	2 or ≥ 3
b-jets	exactly 2 b-tagged jets
Leading Jet p_{T}	$> 45\,\text{GeV}$
p_{T}^{V} regions	$[0, 150]$ and $[150, \infty]$ GeV

$p_{\text{T}}^{l} > 25\,\text{GeV}/7\,\text{GeV}$ for “medium/low quality” leptons





Dominant Backgrounds

- Z+heavy flavor
- $t\bar{t}$
- Diboson
- Single top
- Negligible multi-jet
    - checked with data
    - after m_{ll} cut

- b-jet energy correction: μ-in-jet
- Event-level kinematic fit using fully reconstructed Zh system

BDT Inputs
p_{T}^{V}
$E_{\text{T}}^{\text{miss}}$
$p_{\text{T}}^{b_1}$
$p_{\text{T}}^{b_2}$
m_{bb}
$\Delta R(b_1, b_2)$
$\lvert\Delta\eta(b_1, b_2)\rvert$
$\Delta\phi(V, bb)$
$\lvert\Delta\eta(V, bb)\rvert$
m_{ll}
$p_{\text{T}}^{\text{jet}_3}$
m_{bbj}

only for 3 jets

Systematics

flavor-tagging has largest impact of the experimental systematics

Z+heavy flavor normalization has largest impact of the modeling systematics

Source	Impact on Error +	Impact on Error -
DataStat	0.361	0.346
MC Stat.	0.208	0.215
Flavor Tagging	0.162	0.19
Z+jets	0.118	0.179
Floating Normalizations	0.0985	0.15
W+jets	0.097	0.136
Model $t\bar{t}$	0.09	0.145
Signal	0.081	0.028
Jets + MET	0.0504	0.0462
Model Single Top	0.042	0.031
Diboson	0.0225	0.0217
Luminosity	0.0173	0.011
Model Multi-Jet	0.016	0.017
Leptons	0.01	0.0105
FullSyst	0.358	0.36
Total	0.508	0.499

(Not a quadrature sum)

Notable Background Systematics:

- V+jets:
  - Relative normalization ratios of the heavy flavor components
  - Normalization uncertainties for the V+cl and V+l components
  - Relative acceptance ratios between the lepton and N_{jets} channels
- $t\bar{t}$
  - Relative acceptance ratios between the lepton and N_{jets} channels
- Single top
  - Cross section uncertainties broken down by t, s, and Wt channels
  - Relative acceptance ratios between the lepton channels

Dominant Experimental Systematics:

- Flavor Tagging = 3 b-jet + 4 c-jet + 5 light-jet + 2 “extrapolation”
- Jet Energy Scale and Resolution = 19

Notable Signal Systematics:

- Cross section uncertainties for $q\bar{q}$ and gg production
- Branching ratio
- Acceptance variations (parton shower, etc.)

Statistical Treatment

- BDT output is used as the final discriminant
- Parameter of interest is μ (signal yield over Standard Model expectation)
- Binned-Likelihood model
    - Poisson terms for bin contents
    - Constraint terms for various systematics, etc.
    - Total of a 8 regions (N_{jets}: 2 & 3*, p^{V}_{T} regions: [0,150] GeV in 2-lepton & [150,∞] GeV in all lepton channels)
    - Floating Normalizations: $t\bar{t}$ (separately for 0+1 lepton and 2 lepton), W/Z+heavy flavor

Sample	Scale factor
$t\bar{t}$ 0+1-lepton	0.86 ± 0.13
$t\bar{t}$ 2-lepton	0.94 ± 0.09
W + HF	1.59 ± 0.39
Z + HF	1.04 ± 0.11

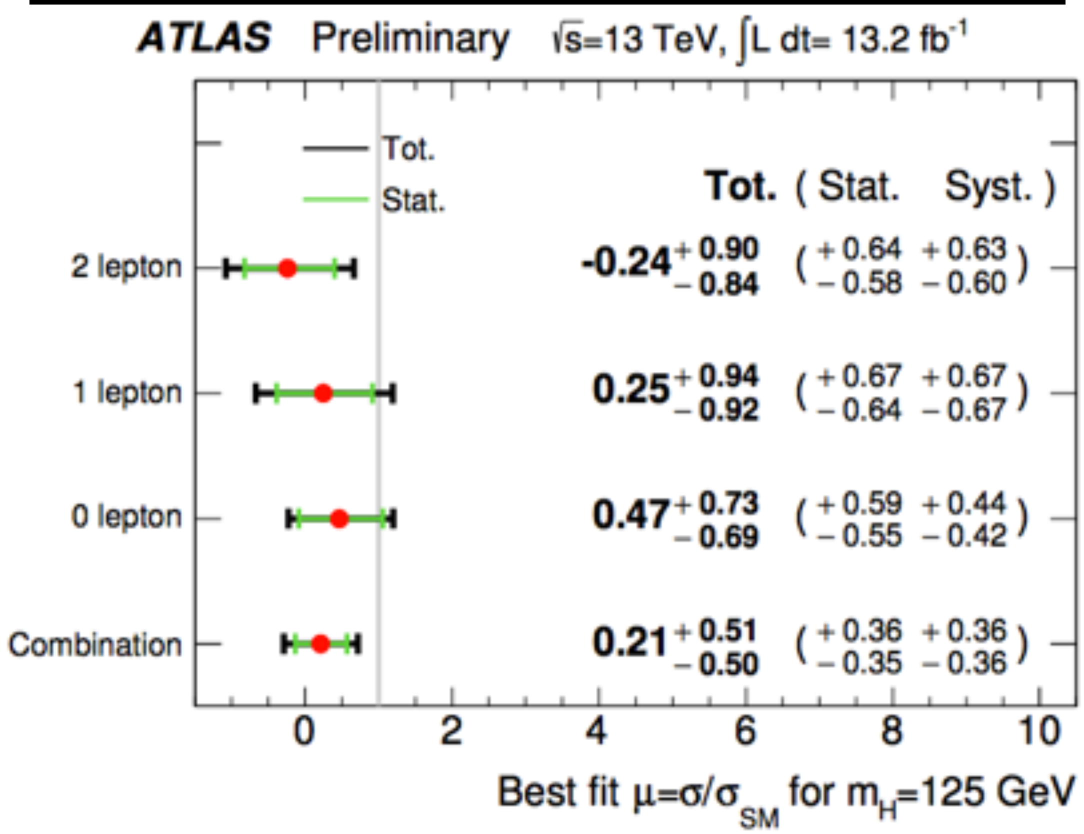
Postfit

Dominant Background Systematics (description: correlated regions)
V+jets
V+hf norm: all, Vbl/Vbb acc. ratio: all, Vcc/Vbb acc. ratio: all, Vbc/Vbb acc. ratio: all Vbb 2-3 jets acc. ratio: 2 jets, Zbb 0-2 lep. acc. ratio: 0-lepton, Wbb 0-1 lep. acc. ratio: 0-lepton Vl norm: all, Vcl norm: all, p_T^V shape: all, m_{bb} shape: all
$t\bar{t}$
$t\bar{t}$ norm: 0+1 lepton and 2-lepton, $t\bar{t}$ 2-3 jets acc. ratio: 0+1 lepton and 2-lepton p_T^V shape: 0+1 lepton and 2-lepton, m_{bb} shape: 0+1 lepton and 2-lepton

* ≥ 3 jets in 2-lepton

Results

Best Fit Signal Strength



Limits, p-values, & significance

Dataset	Limit		p_0		Significance	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
0-lepton	$1.4^{+0.6}_{-0.4}$	2.0	0.07	0.15	1.45	1.02
1-lepton	$2.0^{+0.8}_{-0.6}$	2.1	0.15	0.46	1.04	0.10
2-lepton	$1.8^{+0.7}_{-0.5}$	1.7	0.13	0.57	1.14	–0.17
Combined	$1.0^{+0.4}_{-0.3}$	1.2	0.03	0.34	1.94	0.42

Table 8: The expected and observed 95% CL limits on the ratio of the cross-section times branching ratio with respect to the SM expectation and p_0 and significance values for the individual lepton channels and their combination. The expected limits are evaluated assuming the absence of signal and the expected p_0 and significance assuming a Higgs boson of 125 GeV mass with the SM signal strength.

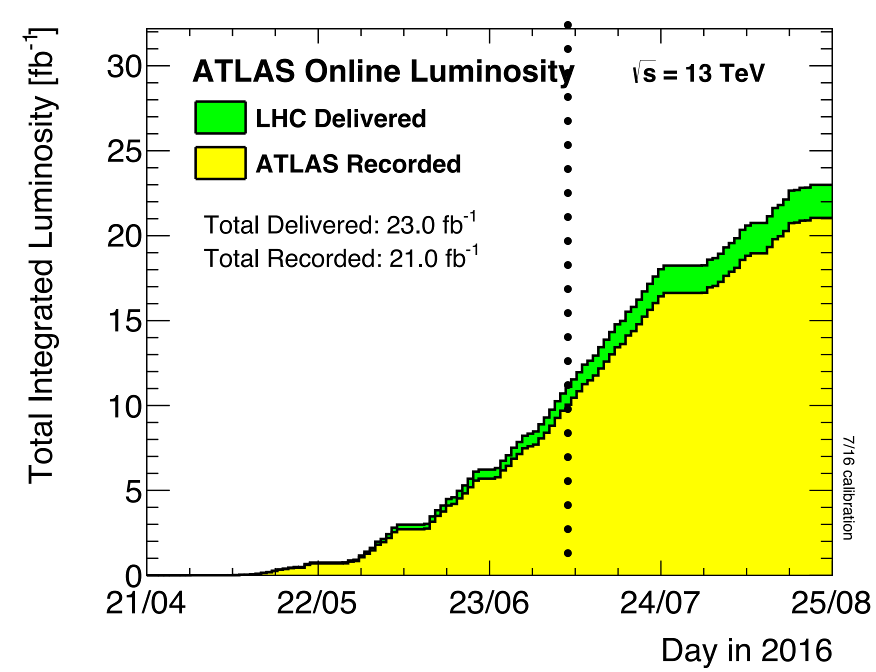
Di-boson cross-check: 3.21σ (3.0σ) exp. (obs.) significance

$$\mu_{VZ} = 0.91 \pm 0.17(\text{stat.})^{+0.32}_{-0.27}(\text{syst.})$$

Summary & Outlook

- ATLAS' first SM VH, $H \rightarrow b\bar{b}$ results for Run 2 appear promising and consistent with SM
  - statistical and systematic contributions to error are currently equal
- Important decay channel that has yet to be observed
  - Looking forward to more luminosity

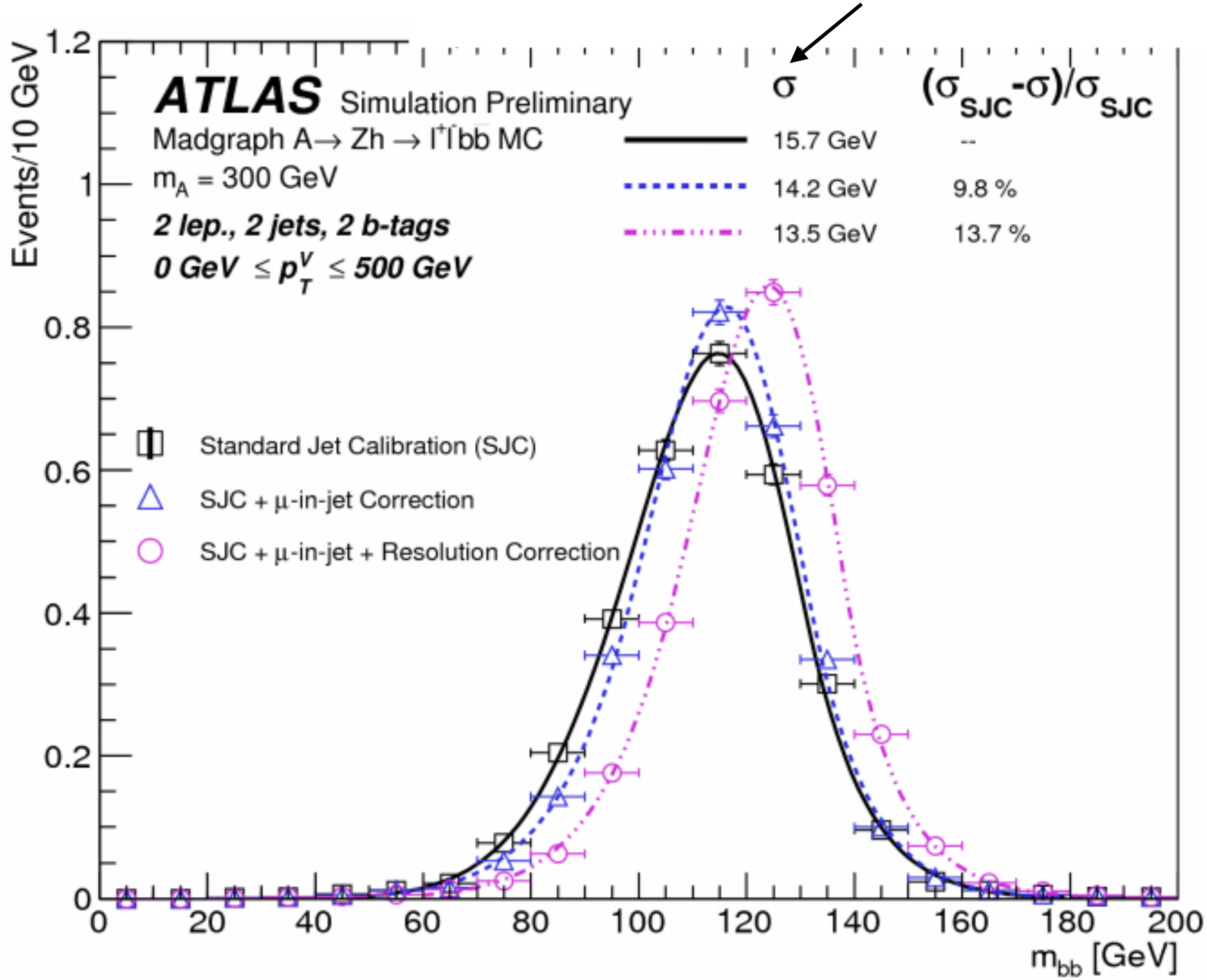
Run	Signal Strength	Observed (Expected) Significance
I	$0.52 \pm 0.32(\text{stat.}) \pm 0.24(\text{syst.})$	$1.4\sigma(2.6\sigma)$
II	$0.21 \pm 0.36(\text{stat.}) \pm 0.36(\text{syst.})$	$0.42\sigma(1.94\sigma)$



Backup

b-Jet Energy Correction

standard deviation



https://cds.cern.ch/record/2207283/files/ATL-PHYS-SLIDE-2016-465.pdf

Object Selection

Electron Selection	p_T	η	ID	d_0^{sig}	$\|\Delta z_0^{BL} \sin\theta\|$	Isolation
$VH-loose$	>7 GeV	$\|\eta\| < 2.47$	LH Loose + B-layer cut	< 5	< 0.5 mm	LooseTrackOnly
$ZH-signal$	>25 GeV	$\|\eta\| < 2.47$	LH Loose + B-layer cut	< 5	< 0.5 mm	LooseTrackOnly
$WH-signal$	>25 GeV	$\|\eta\| < 2.47$	LH Tight	< 5	< 0.5 mm	FixedCutTight

Table 4: Electron selection requirements.

Muon Selection	p_T	η	ID	d_0^{sig}	$\|\Delta z_0^{BL} \sin\theta\|$	Isolation
VH-Loose	>7 GeV	$\|\eta\| < 2.7$	Loose quality	< 3	< 0.5 mm	LooseTrackOnly
ZH-Signal	>25 GeV	$\|\eta\| < 2.5$	Loose quality	< 3	< 0.5 mm	LooseTrackOnly
WH-Signal	>25 GeV	$\|\eta\| < 2.5$	Medium quality	< 3	< 0.5 mm	FixedCutTightTrackOnly

Table 5: Muon selection requirements.

Jet Category	Selection Requirements
Forward Jets	jet cleaning $p_T > 30$ GeV $2.5 \leq \|\eta\| < 4.5$
Signal Jets	$p_T > 20$ GeV and $\|\eta\| < 2.5$ jet cleaning JVT ≥ 0.64 if ($p_T < 60$ GeV and $\|\eta\| < 2.4$)

Table 6: `AntiKt4EMTopoJets` selection requirements. The jet cleaning is applied via the JetCleaningTool, that removes events in regions corresponding to hot calorimeter cells.

70% b-tagging MV2c10 working point

Systematics

Systematics

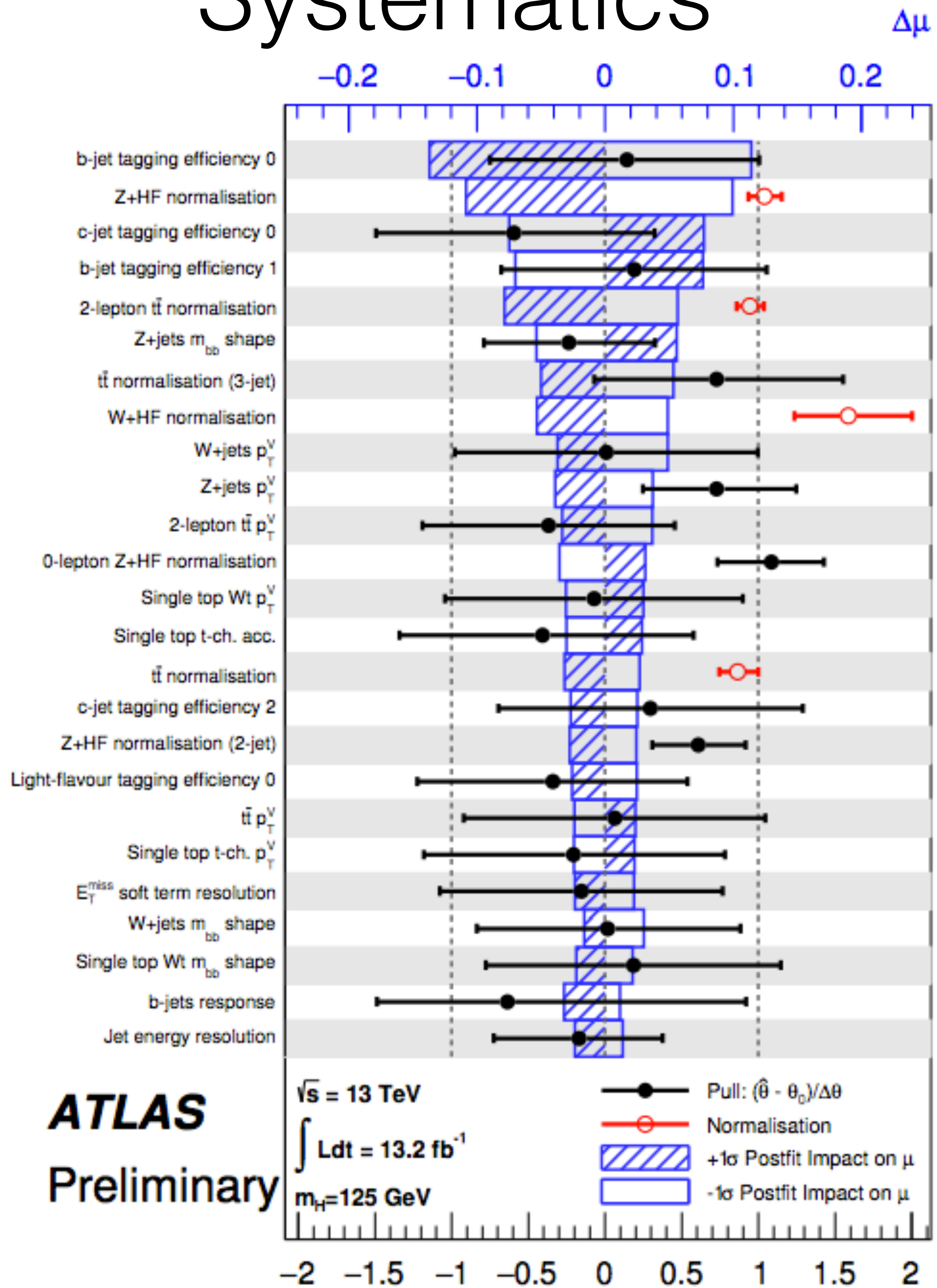
Z+jets	
Zl normalisation	18%
Zcl normalisation	23%
Zbb normalisation	Floating
Zbc-to-Zbb ratio	14-27%
Zcc-to-Zbb ratio	7-31%
Zbl-to-Zbb ratio	15-38%
0-to-2 lepton ratio	26%
2-to-3 jet ratio	28% (0-lepton) and 25% (2-lepton)
p_T^V, m_{bb}	S
W+jets	
Wl normalisation	32%
Wcl normalisation	37%
Wbb normalisation	Floating
Wbl-to-Wbb ratio	17% (0-lepton) and 31% (1-lepton)
Wbc-to-Wbb ratio	42% (0-lepton) and 21% (1-lepton)
Wcc-to-Wbb ratio	17% (0-lepton) and 31% (1-lepton)
2-to-3 jet ratio	23%
0-to-1 lepton ratio	17%
p_T^V, m_{bb}	S
$t\bar{t}$ (all are decorrelated between the 0+1 and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating
2-to-3-jet ratio	9% (0+1-lepton) and 24% (2-lepton)
p_T^V, m_{bb}	S
Single top	
Cross section	4.4% (s-channel), 4.6% (t-channel), 6% (Wt)
Acceptance 2-jet	16% (t-channel), 25% (Wt)
Acceptance 3-jet	19% (t-channel), 32% (Wt)
m_{bb}, p_T^V	S (p_T^V uncorrelated between 2 and 3-jet channels Wt)

ZZ	
Normalisation	20%
0-to-2 lepton ratio	30%
2-to-3 jet ratio	19 %
m_{bb}, p_T^V	S (correlated with WZ uncertainties)
WZ	
Normalisation	26%
2-to-3 jet ratio	14% (0-lepton) and 11% (1-lepton)
0-to-1 lepton ratio	12%
m_{bb}, p_T^V	S (correlated with ZZ uncertainties)
WW	
Normalisation	25%
Multi-jet (1-lepton)	
Normalisation	14-81% (electron), 5-50%(muon)
Template variations	S

Signal	
Cross section (scale)	0.7% ($q\bar{q}$), 27% (gg)
Cross section (PDF)	1.9% ($q\bar{q} \to WH$), 1.6% ($q\bar{q} \to ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance (scale)	1.4%–5%
3-jet acceptance (scale)	1.4%–4.7%
p_T^V shape (scale)	S
Acceptance (PDF)	0.3%–0.7%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	4%–7.5%

S denotes shape systematics

Systematics



S/B yield plot

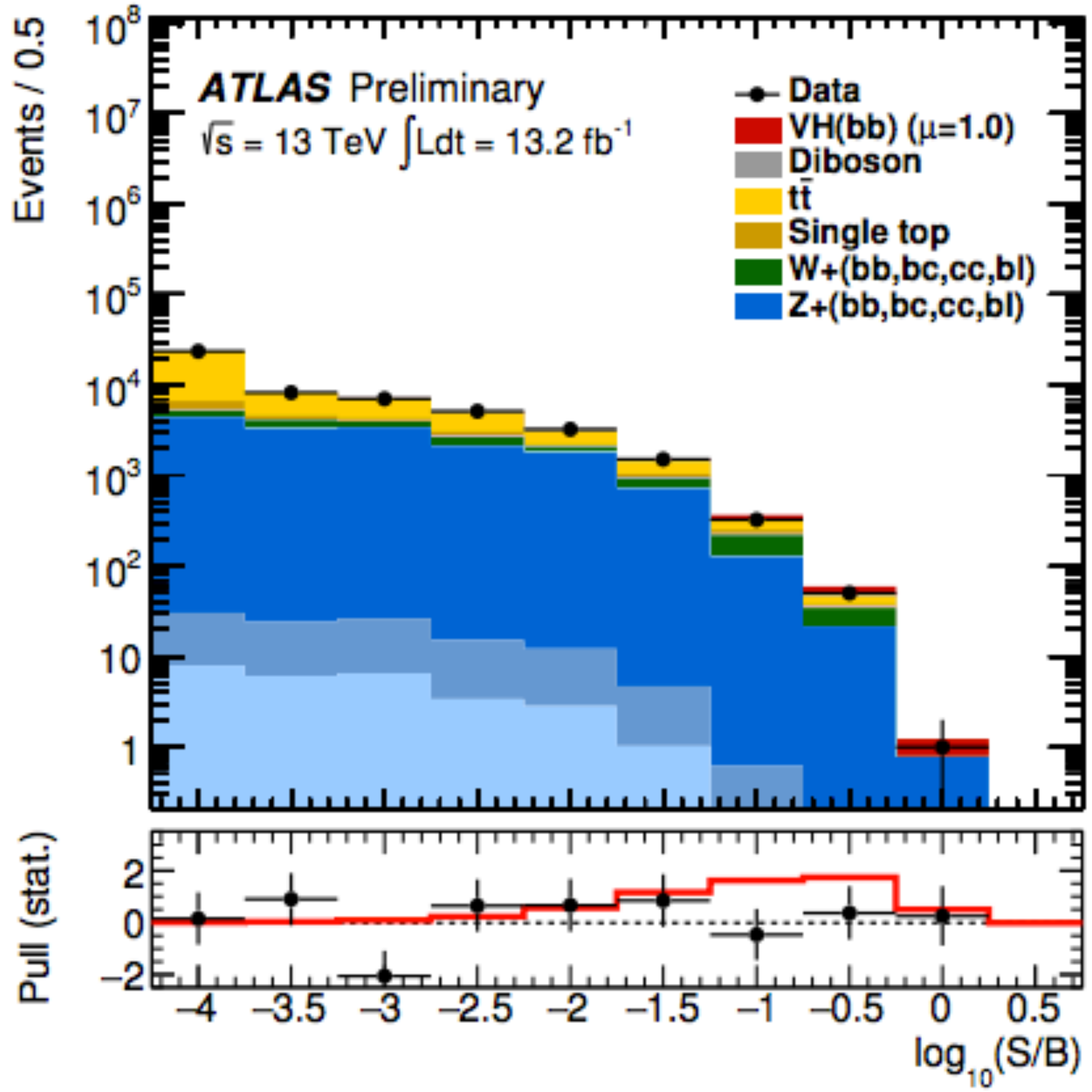
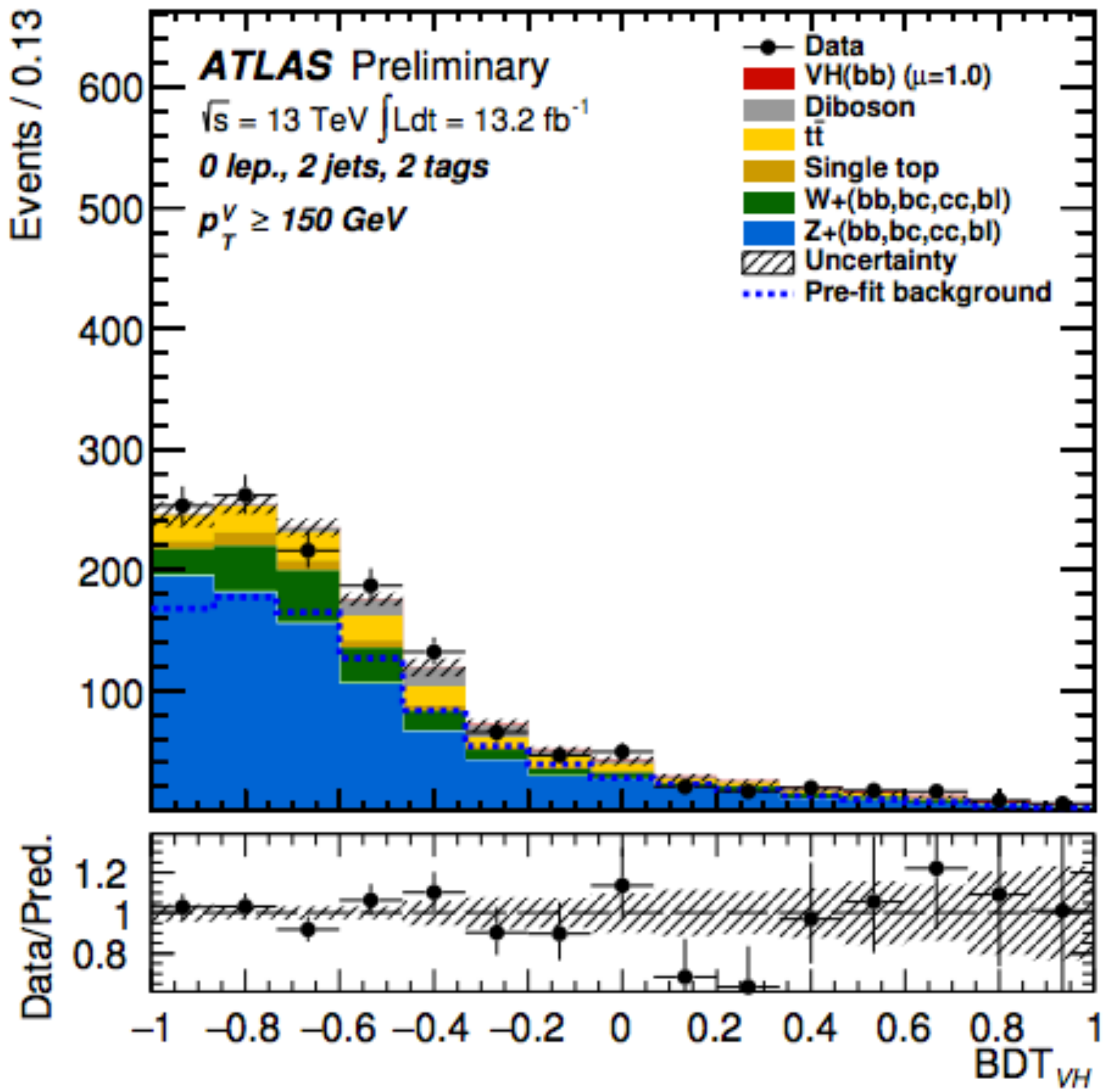


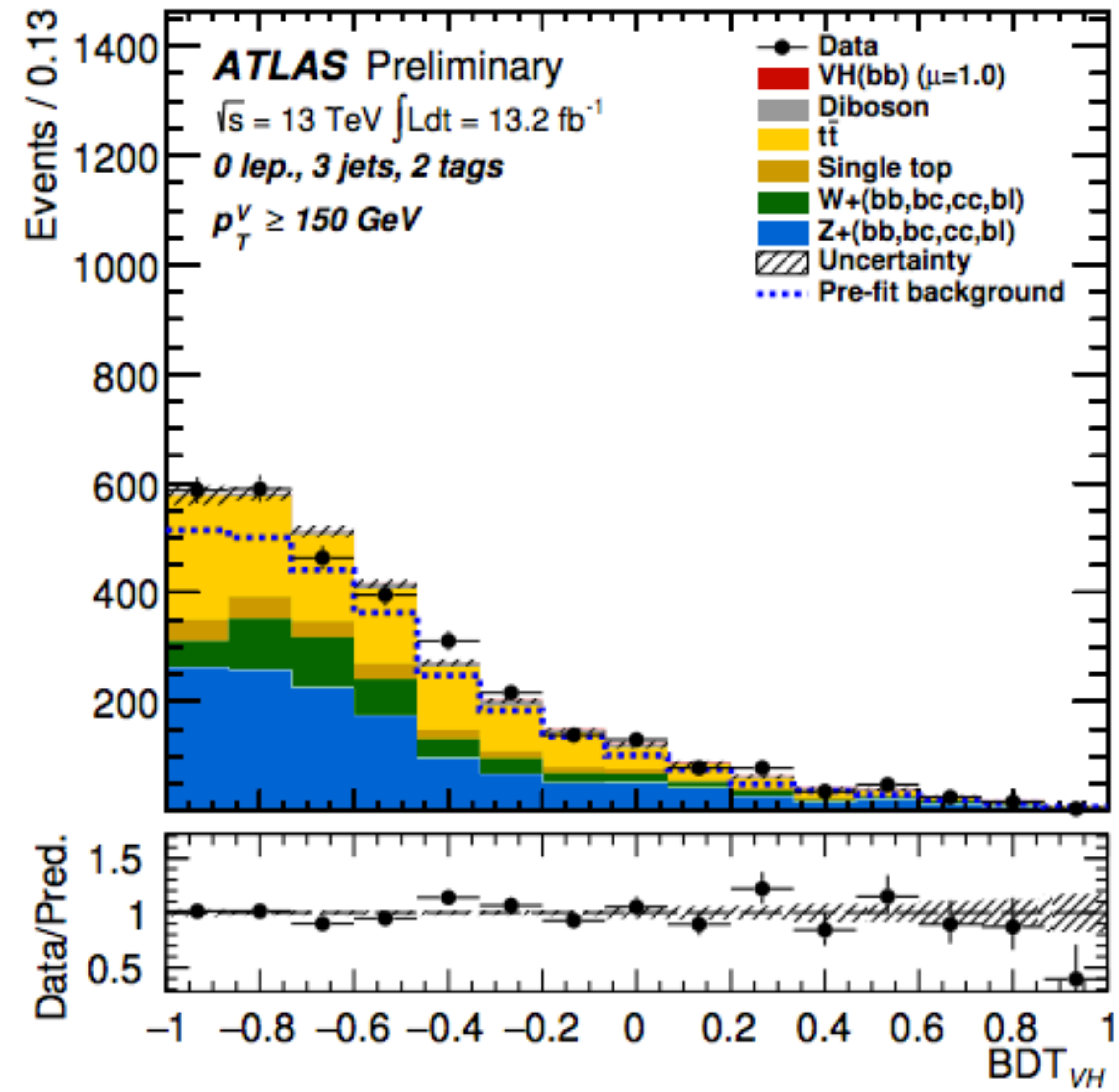
Figure 4: Event yields as a function of $\log(S/B)$ for data, background and Higgs boson signal with $m_H = 125$ GeV. Final-discriminant bins in all signal regions are combined into bins of $\log(S/B)$. The signal S and background B yields are the expected and fitted values, respectively. The Higgs boson signal contribution is shown as expected for the SM cross section (indicated as $\mu = 1.0$). The pull of the data with respect to the background-only prediction is shown without systematic uncertainties. The solid red line indicates the pull of the prediction for signal ($\mu = 1.0$) and background with respect to the background-only prediction.

Postfit Plots

0-Lepton



ATLAS Preliminary
√s = 13 TeV ∫Ldt = 13.2 fb⁻¹
0 lep., 2 jets, 2 tags
p_T^V ≥ 150 GeV
Data
VH(bb) (μ=1.0)
Diboson
tt̄
Single top
W+(bb,bc,cc,bl)
Z+(bb,bc,cc,bl)
Uncertainty
Pre-fit background
Events / 0.13
Data/Pred.
BDT_VH



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Uncertainty
Pre-fit background
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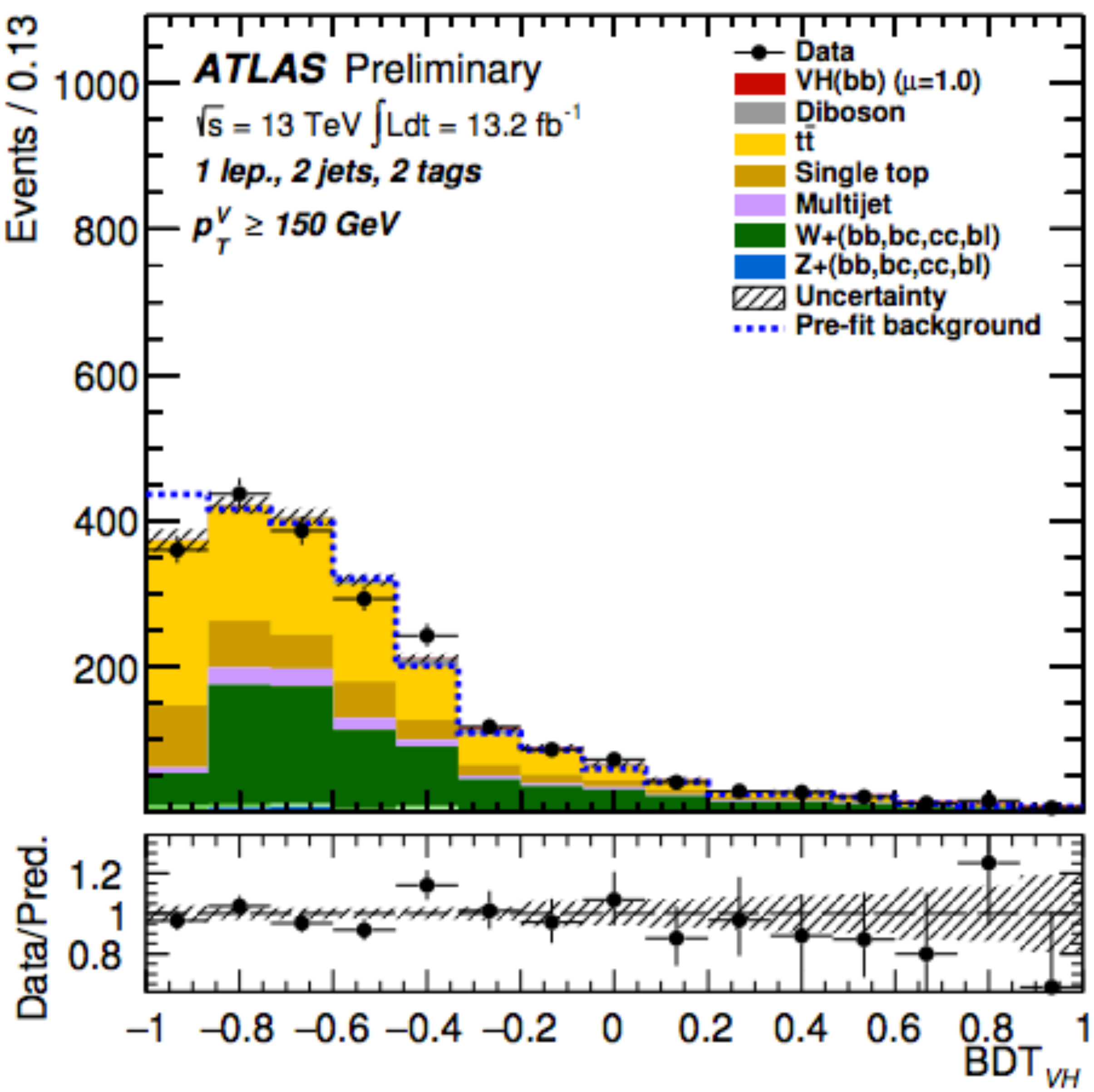
BDT_VH

1-Lepton



ATLAS Preliminary
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p_T^V ≥ 150 GeV
Data
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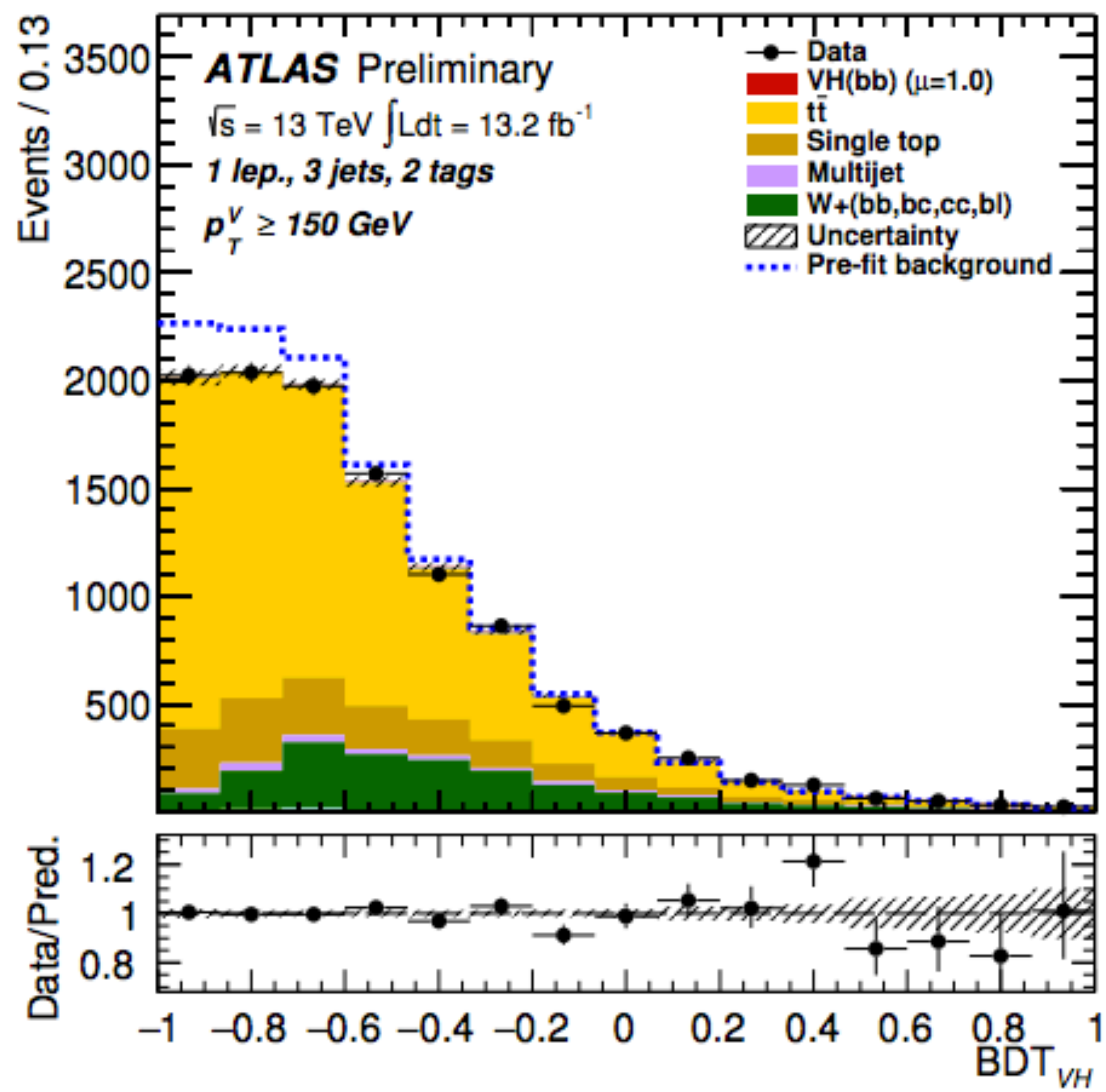
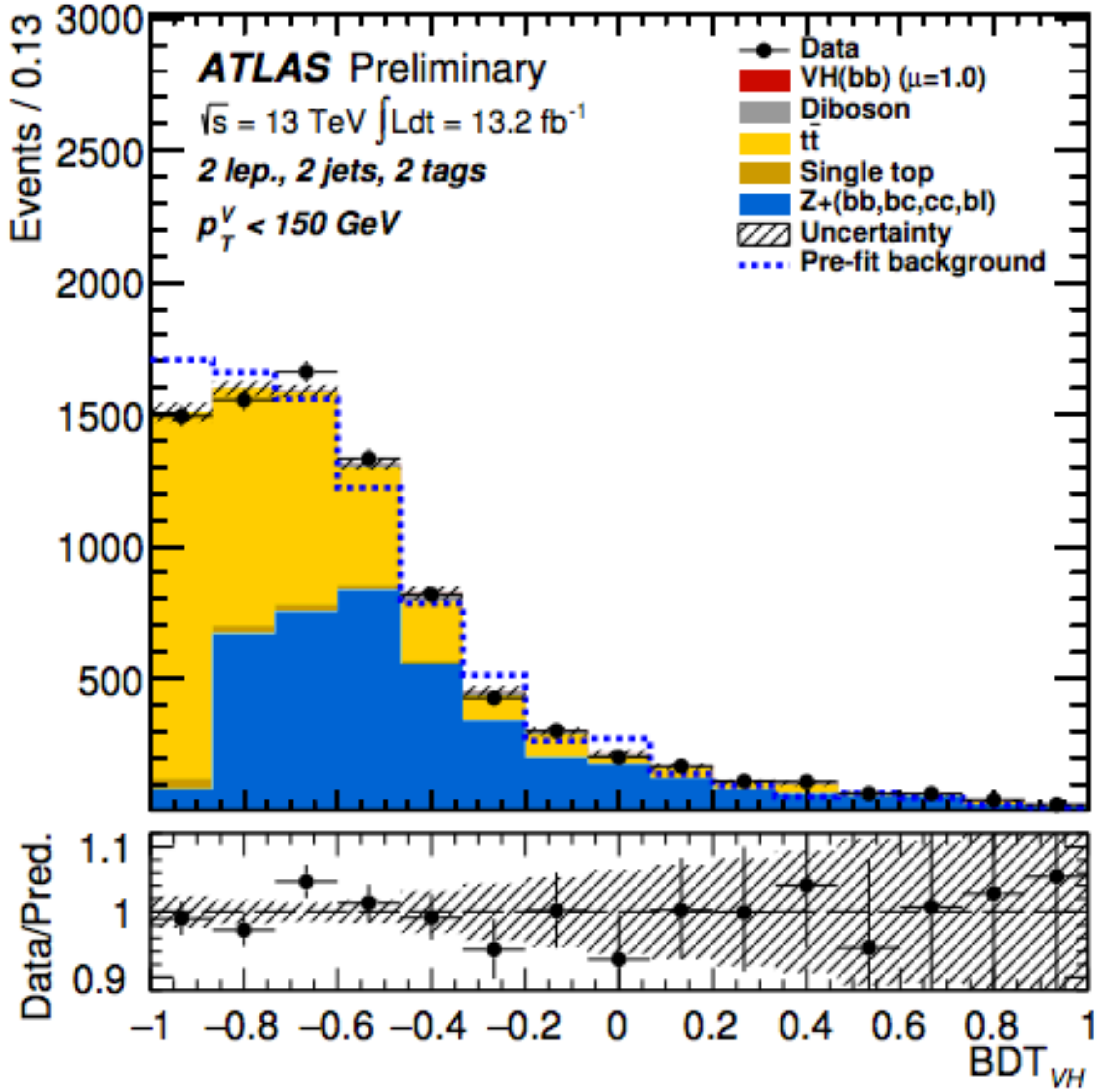
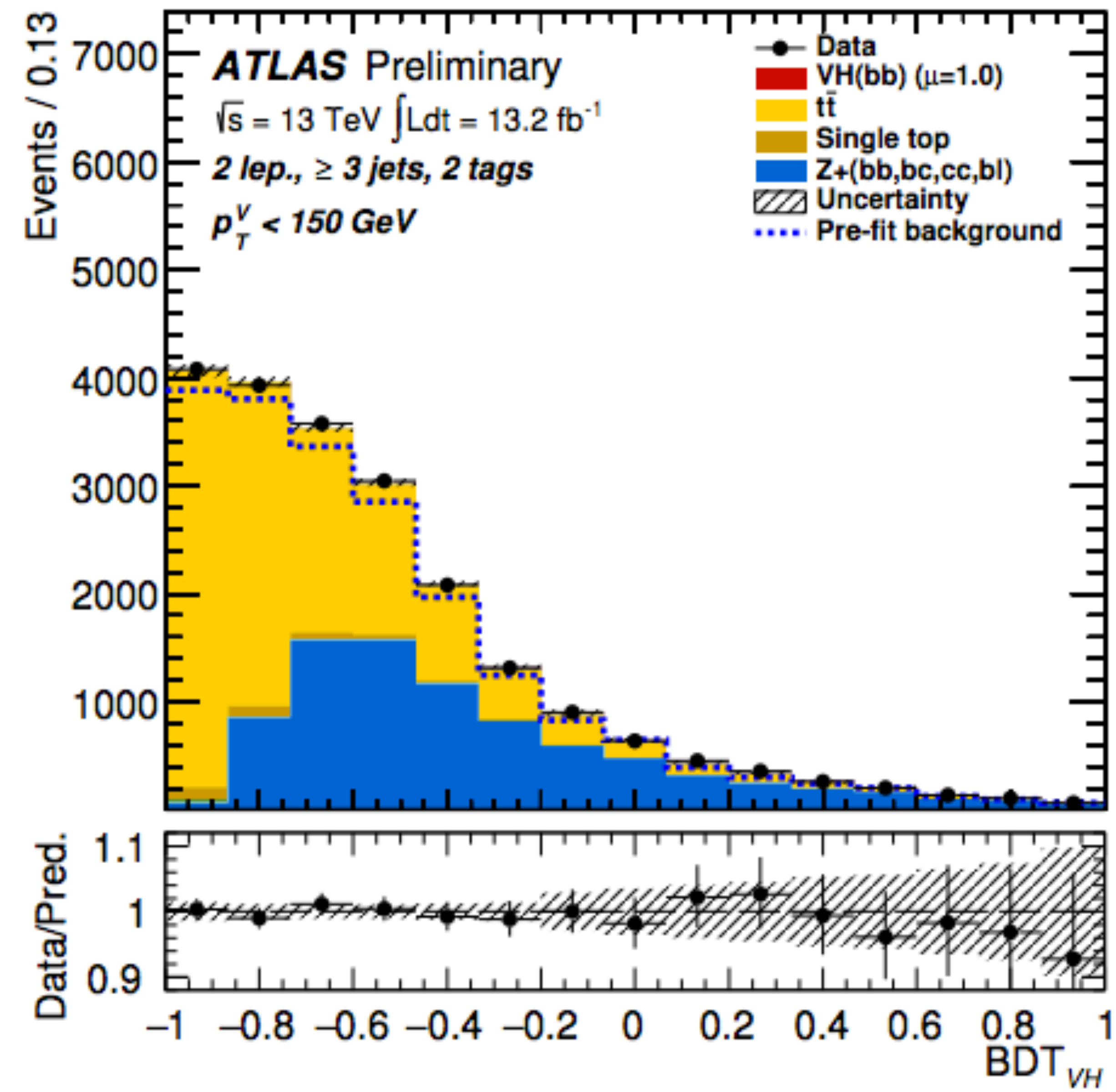
Diboson
tt̄
Single top
Multijet
W+(bb,bc,cc,bl)
Z+(bb,bc,cc,bl)
Uncertainty
Pre-fit background
Events / 0.13
Data/Pred.
BDT_VH



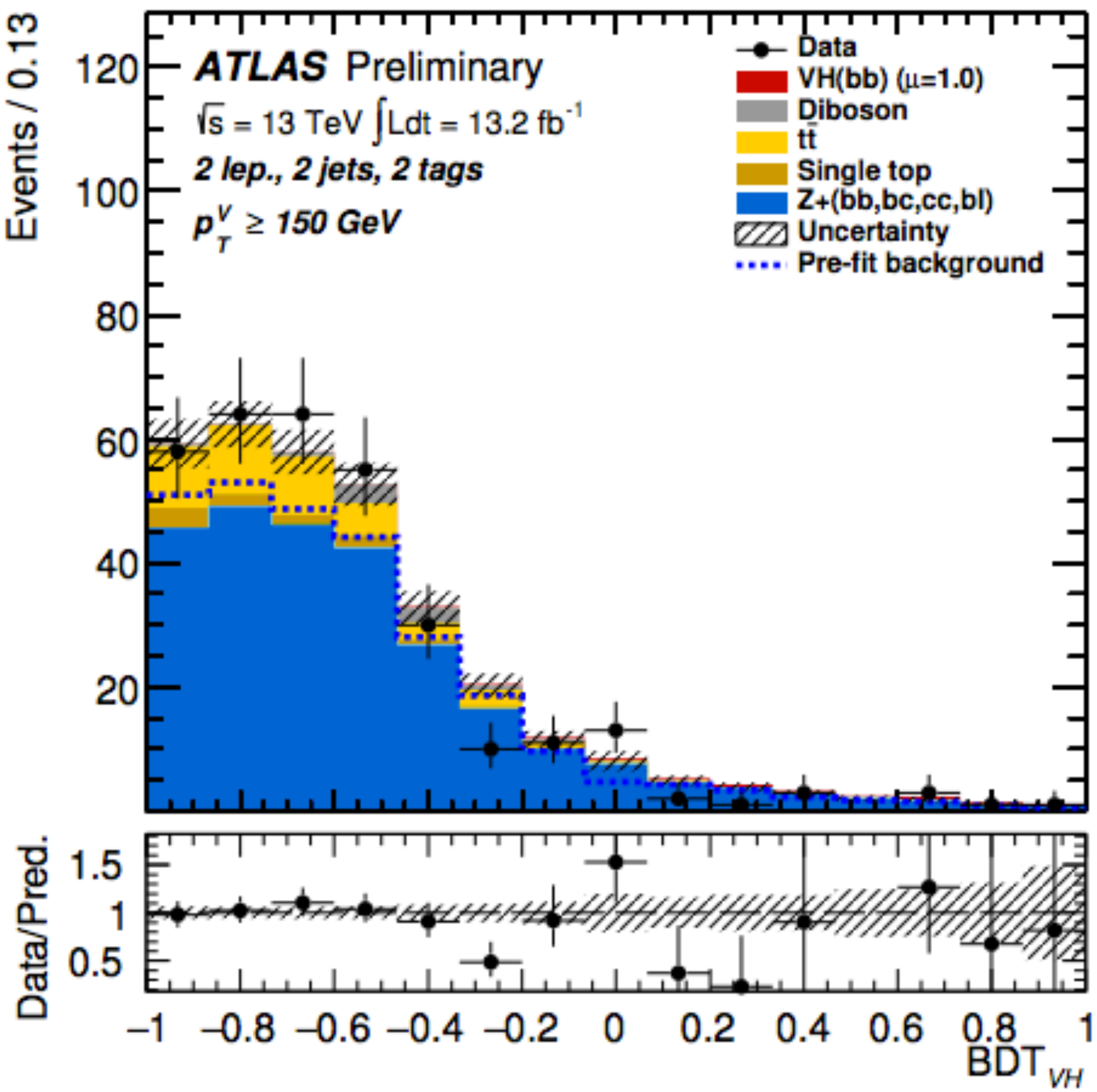
ATLAS Preliminary
√s = 13 TeV ∫Ldt = 13.2 fb⁻¹
1 lep., 3 jets, 2 tags
p_T^V ≥ 150 GeV
Data
VH(bb) (μ=1.0)
tt̄
Single top
Multijet
W+(bb,bc,cc,bl)
Uncertainty
Pre-fit background
Events / 0.13
Data/Pred.
BDT_VH

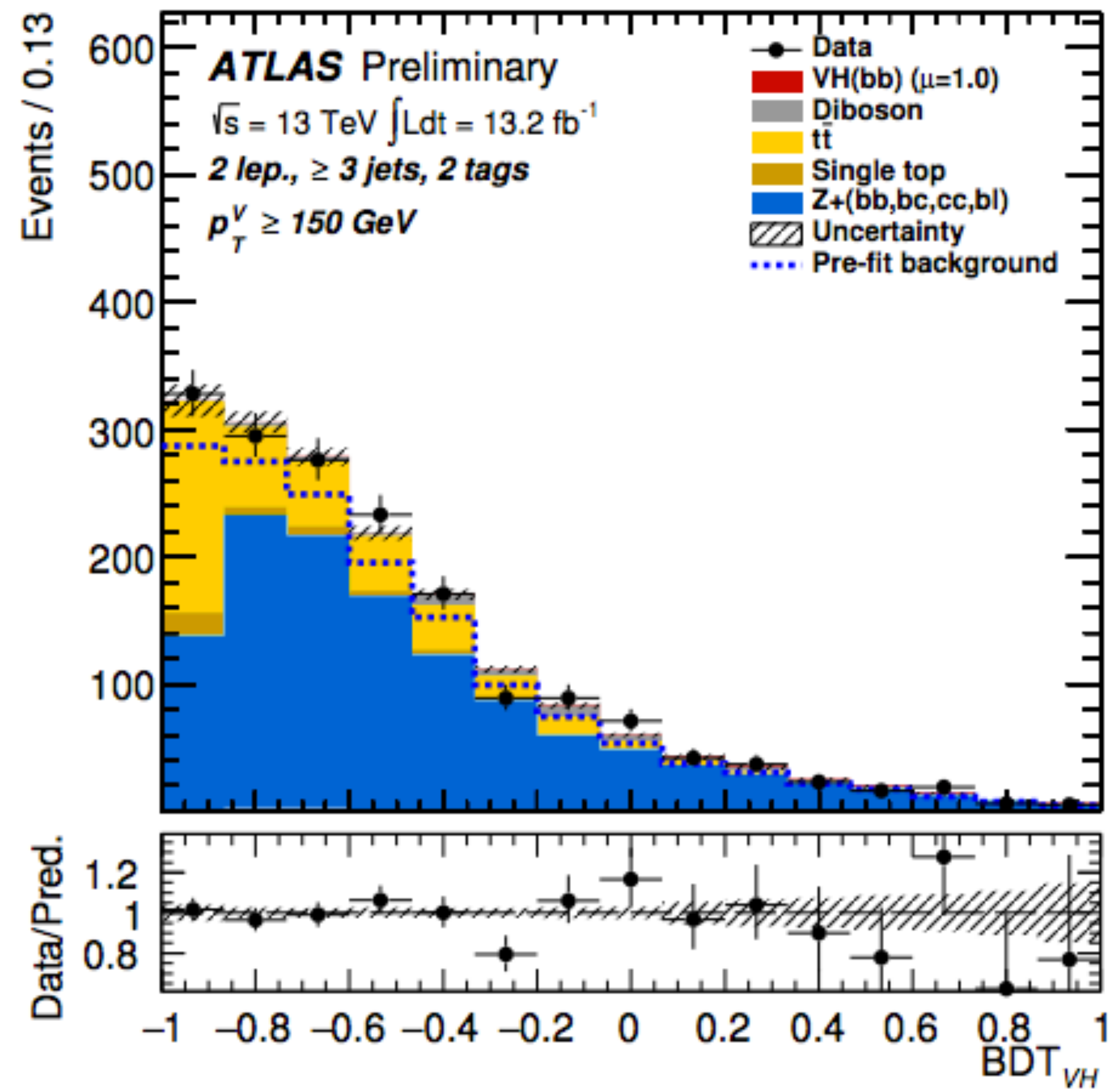
2-Lepton: Low p^V_T





2-Lepton: High p^V_T





Postfit Yields Table

Sample	0-lepton		1-lepton		2-lepton			
	p_T^V > 150 GeV, 2-tag		p_T^V > 150 GeV, 2-tag		p_T^V < 150 GeV, 2-tag		p_T^V > 150 GeV, 2-tag	
	2-jet	3-jet	2-jet	3-jet	2-jet	3-jet	2-jet	3-jet
$Z + l$	1.5±0.1	3.3±2.2	–	–	4.6±0.1	15.4±0.5	0.4±0.0	2.9±0.1
$Z + cl$	4.2±1.8	6.7±2.6	0.9±0.6	–	13.9±5.9	49±21	1.0±0.4	10.0±4.3
Z + HF	864±49	1300±90	29.0±3.0	65.7±3.7	4000±120	8250±300	260±14	1192±49
$W + l$	2.3±1.5	3.8±2.2	4.3±0.1	9.6±0.3	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
$W + cl$	3.7±1.8	7.4±3.5	20±11	33±17	0.0±0.0	0.5±0.0	0.0±0.0	0.0±0.0
W + HF	184±37	440±96	741±114	1610±300	1.2±0.3	42±10	0.4±0.1	1.3±0.3
Single-top	45.5±7.7	204±39	331±55	1590±300	139±39	400±130	10.5±3.0	44±14
Multi-jet	–	–	101±63	210±140	–	–	–	–
$t\bar{t}$	136±14	1081±67	886±82	7520±360	4080±120	12210±340	42.3±4.3	402±36
Diboson	56±17	65±16	39±10	68±16	121±32	190±36	8.3±2.3	46.6±8.4
Total bkg.	1297±35	3110±52	2152±48	11120±110	8358±92	21150±150	322±13	1698±38
$VH(bb)$ (fit)	3.7±8.7	4.3±10.3	4.2±10.1	5.0±12.0	4.2±10.0	6.2±14.9	0.9±2.2	2.5±5.9
Data	1313	3120	2145	11124	8365	21163	316	1700

Table 7: The data, background and signal yields along with the total uncertainty. All the background and signal values are evaluated according to the results of the global fit. The V + HF yields includes events from the $V + bb$, $V + bc$, $V + bl$ and $V + cc$ categories.