Measurement of boosted $VH(H \to b\bar{b})$ process with the ATLAS experiment

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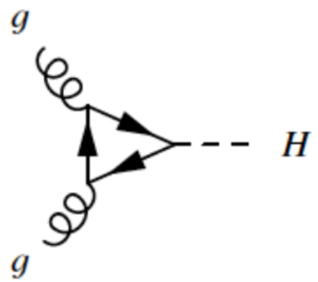
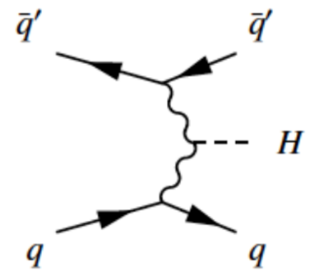
Introduction

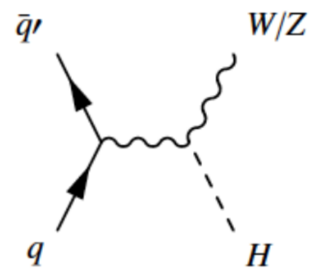
- Higgs boson: discovered in 2012 by the ATLAS and the CMS experiments.
- SM predicted Higgs boson: spin-0, $J^P = 0^+$, with a free parameter in its mass.
  - Measured mass: 125.09 ± 0.24 GeV Phys. Rev. Lett. 114 (2015) 191803
- Major Higgs production modes at the Large Hadron Collider (LHC)



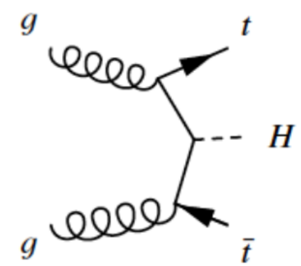
ggF production 88%



VBF production 6.8%

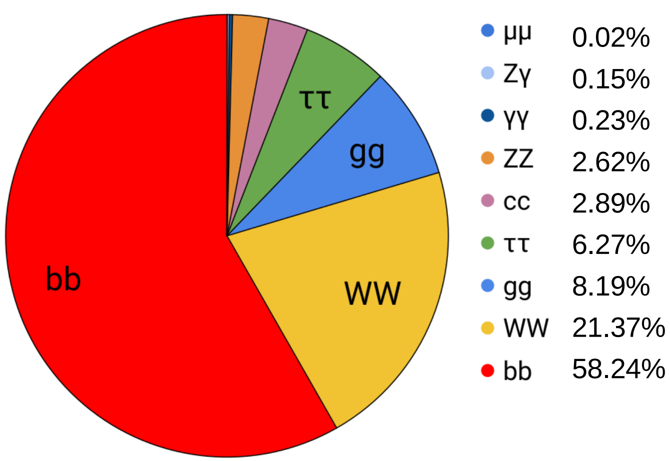


VH production 4.0%



ttH production 0.9%

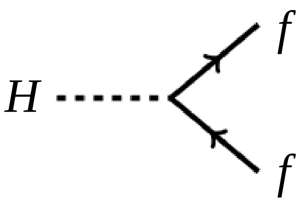
- Decay channels of the Higgs boson
  - Largest branching ratio (BR): $H \rightarrow b\bar{b}$
  - Second largest BR: $H \rightarrow WW^*$
  - Cleanest: $H \rightarrow ZZ^*$, $H \rightarrow \gamma\gamma$



$H \rightarrow b\bar{b}$ decay

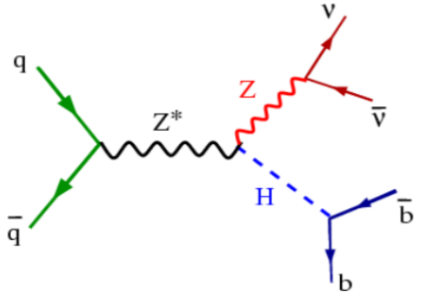
- $H \rightarrow b\bar{b}$ was not observed in Run 1 (all hadronic final state through ggF).
- Best channel to study the Yukawa nature of Higgs coupling to fermions directly.
  - largest BR: 58.2% for m_H = 125 GeV.

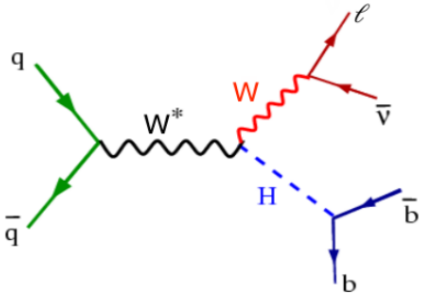
$$\mathcal{L}_{\text{Yukawa}} = y_{ij}\psi_i\phi\psi_j + \text{h.c.}$$

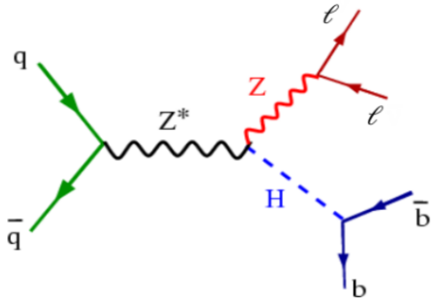


$g \propto m_f$

- The most sensitive production modes for detecting $H \rightarrow b\bar{b}$: VH production





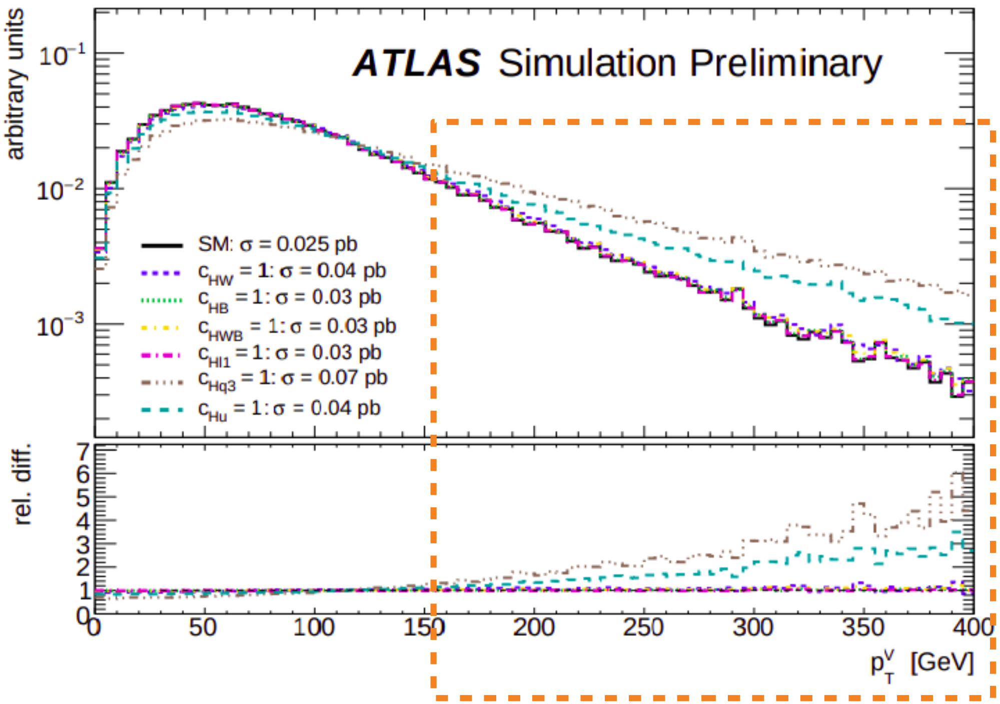


  - W/Z boson decays leptonically
  - Three channels, 0-lepton, 1-lepton, 2-lepton
- Increased energy of LHC Run 2 enabled sufficient VH statistics.
  - Full Run 2 data, 139 fb^{-1} integrated luminosity

High energy phase space

- Two keys to look for potential anomalous couplings:
  - Precision
  - High energy

ATL-PHYS-PUB-2019-042



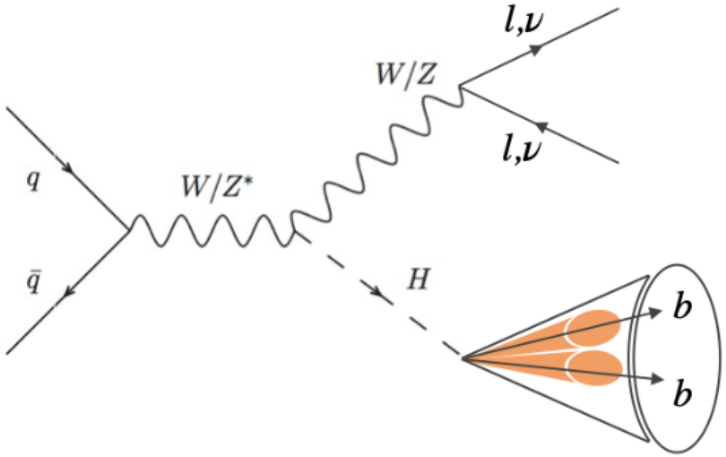
Use energy growth to probe regimes comparable to the ones accessible in experiments with much higher precision level.

Impacts of D-6 operators on leptonic *ZH* production

- $VH(H \rightarrow b\bar{b})$ produced at high transverse momentum phase space

$VH(bb)$ boosted overview

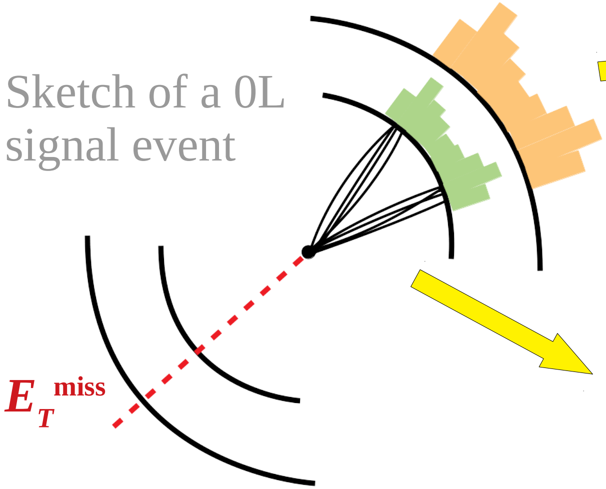
- Strategy of the $VH(bb)$ boosted analysis



$$\Delta R(b_1, b_2) \sim \frac{2m^{\mathrm{Higgs}}}{p_T^{\mathrm{Higgs}}}$$

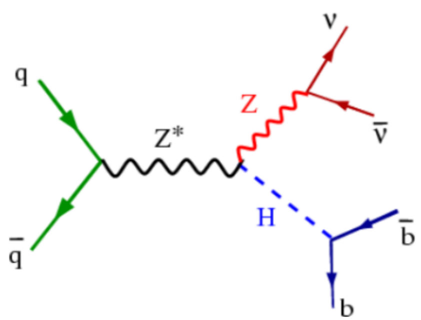
  - Two b-jets merge into a large-R jet.
  - Medium to high $p_{\mathrm{T}}^{\mathrm{V}}$ region.
- For $VH(bb)$ boosted analysis
  - Reconstruct Higgs decay products as a large-R jet.
  - At least two track jets matched to the large-R jet.
  - Two matched track jets being b-tagged

Baseline event selection



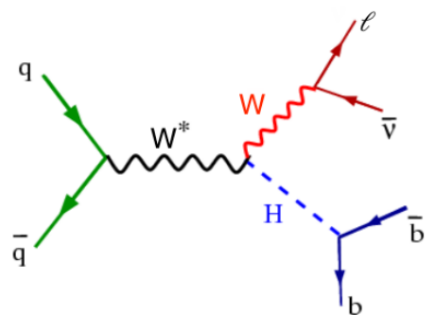
large-R jets (LCTopo trimmed, $R = 1.0$),
$p_T > 250$ GeV, $|\eta| < 2.0$, $m_J > 50$ GeV

track jets (variable radius $R = 30/p_T$ [GeV])
$R \in [0.002, 0.4]$, $p_T > 10$ GeV, $|\eta| < 2.5$

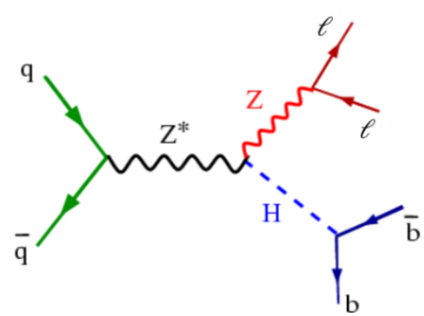


- E_T^{miss} trigger
- 0 *VH*-loose lepton

$p_T^V > 250$ GeV for all three channels



- **Single electron trigger (*e* channel)**
  E_T^{miss} trigger (*μ* channel)
- 1 *WH*-signal lepton, no 2nd *VH*-loose lepton, $p_T > 27$ (25) GeV (*μ* channel)
- $E_T^{miss} > 50$ GeV



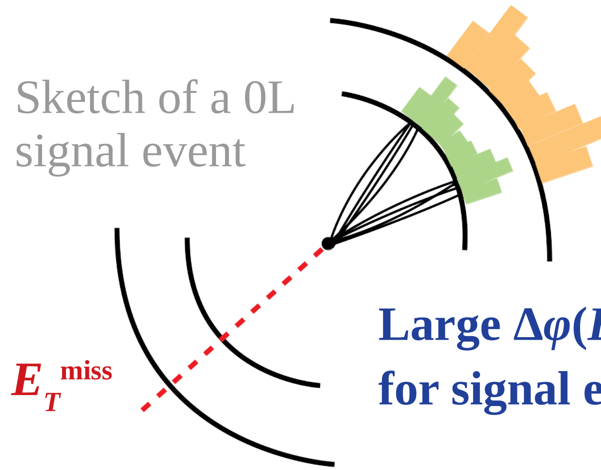
- 2 *VH*-loose leptons, at least 1 *ZH*-signal lepton, $p_T > 27$ GeV
- Opposite sign required for *μ* channel

Baseline event selection

Suppress multijets in 0L channel:

- $\Delta\varphi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{large-}R \text{ jet}) > 120°$
- $\Delta\varphi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) < 90°$
- $\min[\Delta\varphi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{calo jets*})] > 30°$

*small-R calo. jets (PFlow or Topo, R = 0.4),
p_T > 70 GeV, $|\eta|$ < 4.5, not matched to leading fat jet



Large $\Delta\varphi(E_{\mathrm{T}}^{\mathrm{miss}}$, large-$R$ jet) for signal event

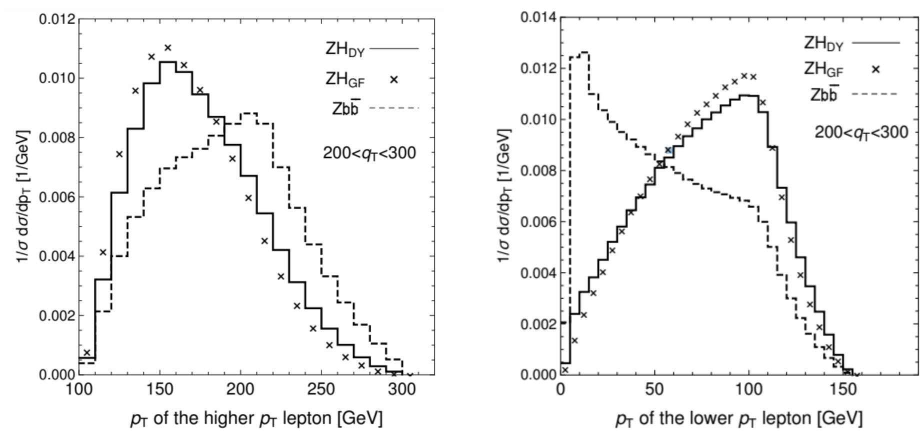
Suppress V+jets in 1L and 2L channel:

- $\Delta Y(V, \text{large-}R \text{ jet}) < 1.4$

Further suppress Z+jets in 2L channel:

- $[p_{\mathrm{T}}(l_1)\text{-}p_{\mathrm{T}}(l_2)]/p_{\mathrm{T}}(Z) < 0.8$
- Z-mass window: 66-116 GeV

Z boson polarization is different between *VH* and *Z*+jets

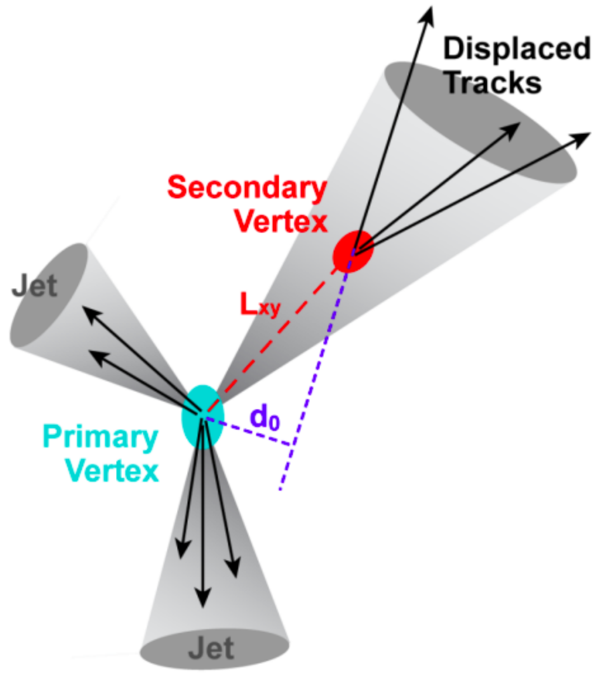


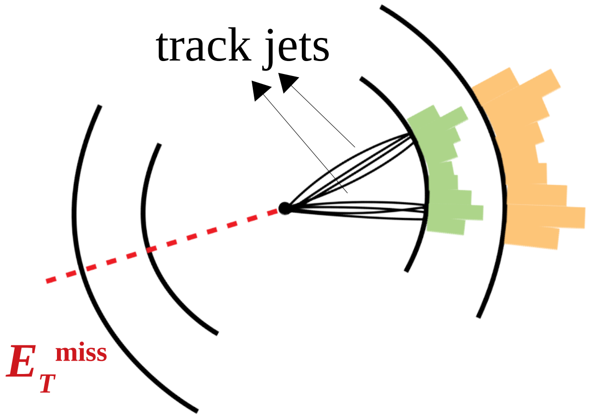
Phys. Rev. D98 (2018) 093005

Selection of Higgs candidate

B-tagging: identifying jets originating from *b*-hadrons

- B-hadron lifetime $\tau \sim 1.5$ ps, $L = \beta\gamma c\tau \sim 450\ \mu$m
- Algorithms: ATL-PHYS-PUB-2017-013
  - Low level: reconstruct tracks associated to jets and find secondary vertices
  - High level: combine low level results using multivariate classifiers
- MV2 tagger at 70% *b*-tagging efficiency





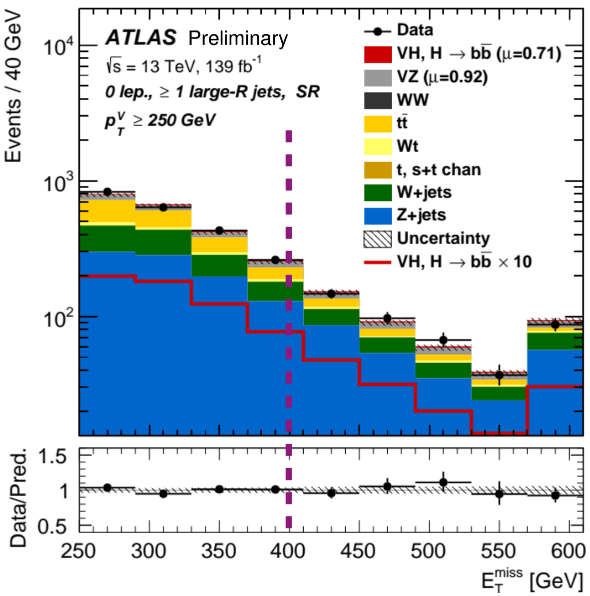
- At least 1 large-*R* jet
- At least 2 track jets being associated to the leading large-*R* jet
- B-tagging strategy
  - The 2 leading track jets being *b*-tagged

Event categorization

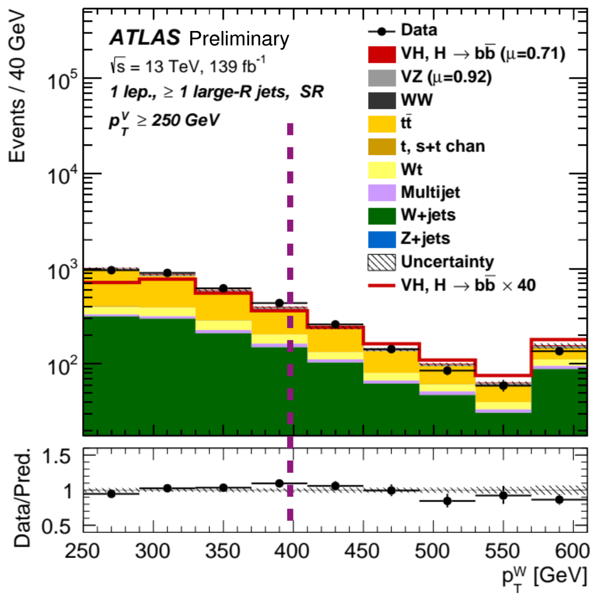
The events are categorized to further increase sensitivity.

p_T^V categorization

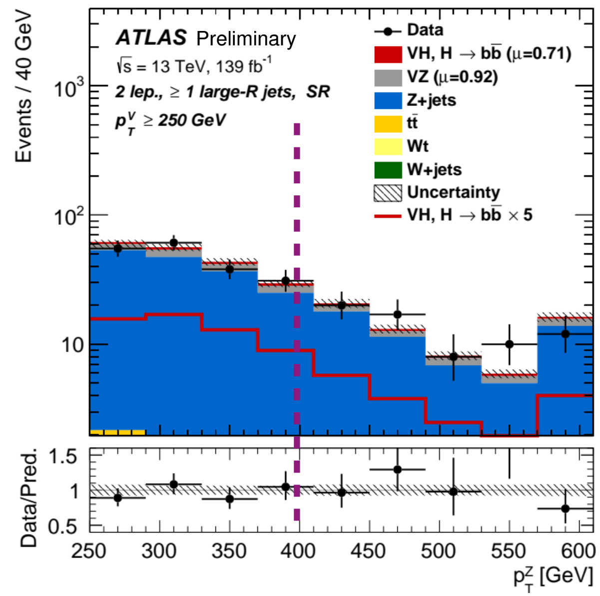
- $250 < p_T^V < 400$ GeV
- $p_T^V > 400$ GeV



0-lepton



1-lepton

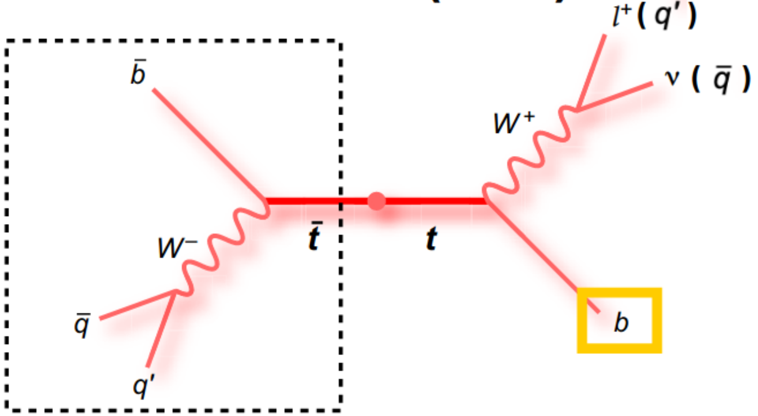


2-lepton

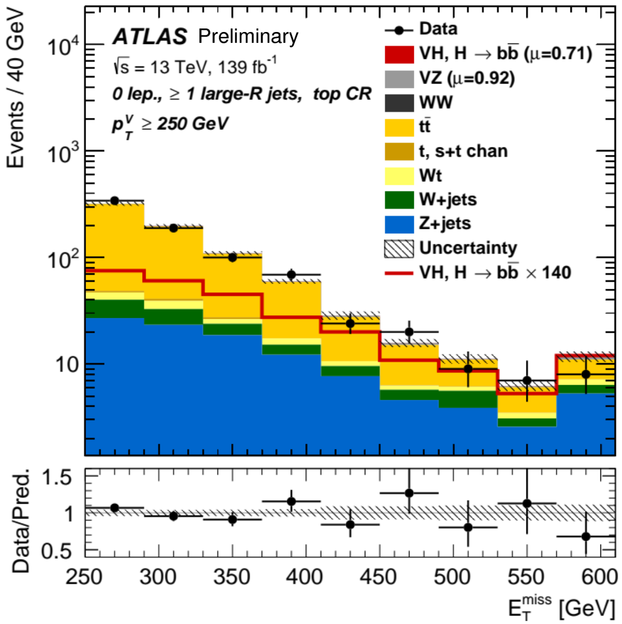
Event categorization

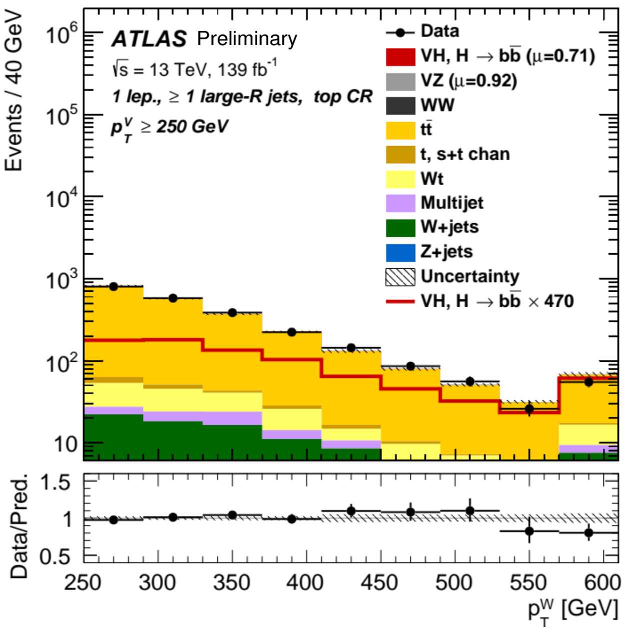
Only in 0/1L channel:

- **B-tag categories**
  - Signal region: no *b*-tagged track jet outside the large-*R* jet.
  - top control region: at least 1 *b*-tagged track jets outside the large-*R* jet.



0L top CR





1L top CR

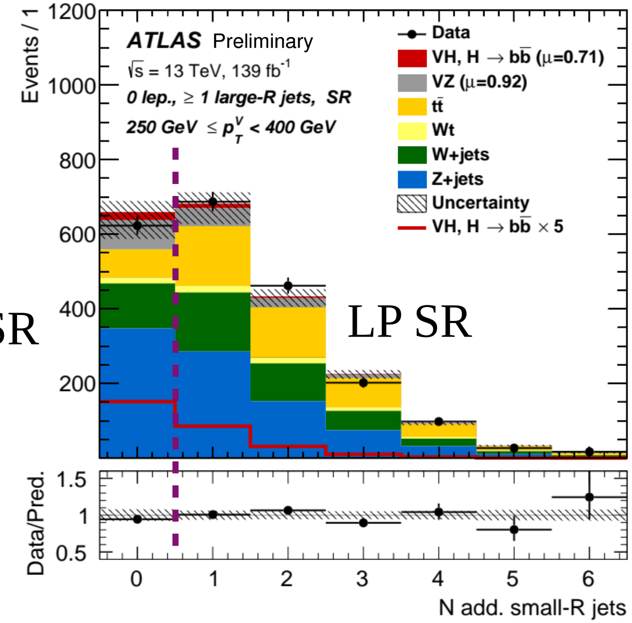
Event categorization

Only in 0/1L channel:

- **Calo-jets multiplicity categories**
  - high purity SR: 0 add. small-*R* jet
  - low purity SR: ≥ 1 add. small-*R* jets

  "additional small-*R* jets": p_T > 30 GeV small-*R* jets not matched to the leading large-*R* jet.

HP SR



Channel	Categories					
	250 GeV < p_T^V < 400 GeV			p_T^V > 400 GeV		
	0 add. *b*-tagged track-jet		≥ 1 add. *b*-tagged track-jets	0 add. *b*-tagged track-jet		≥ 1 add. *b*-tagged track-jets
	0 add. small-*R* jet	≥ 1 add. small-*R* jets		0 add. small-*R* jet	≥ 1 add. small-*R* jets	
0L	HP SR	LP SR	top CR	HP SR	LP SR	top CR
1L	HP SR	LP SR	top CR	HP SR	LP SR	top CR
2L	SR			SR		

Statistical analysis

Binned profile likelihood fit to m_J in all the SRs and CRs.

$$L(\mu, \boldsymbol{\theta}, \boldsymbol{\gamma}) = \prod_{i=1}^{n_{\text{bins}}} \text{Pois}\left(N_i | \mu \cdot s_i \cdot \nu_s(\boldsymbol{\theta}) + \gamma_i b_i \cdot \nu_b(\boldsymbol{\theta})\right)$$

Poisson likelihood

$$\cdot \prod_{j=1}^{n_{\text{syst}}} \text{Gauss}(\theta_j | 0, 1) \cdot \prod_{i=1}^{n_{\text{bins}}} \text{Gauss}\left(\beta_i | \gamma_i \beta_i, \sqrt{\gamma_i \beta_i}\right)$$

Constraint exp/modeling unc.

Constraint MC stat. unc.

- μ – signal strength
- $\boldsymbol{\gamma}$ – NPs for uncertainties due to limited MC statistics
- $\boldsymbol{\theta}$ – NPs for experimental and modeling uncertainties

2 parameters of interest (POI): Signal strengths of *VH* (μ_{VH}) and *VZ* (μ_{VZ})

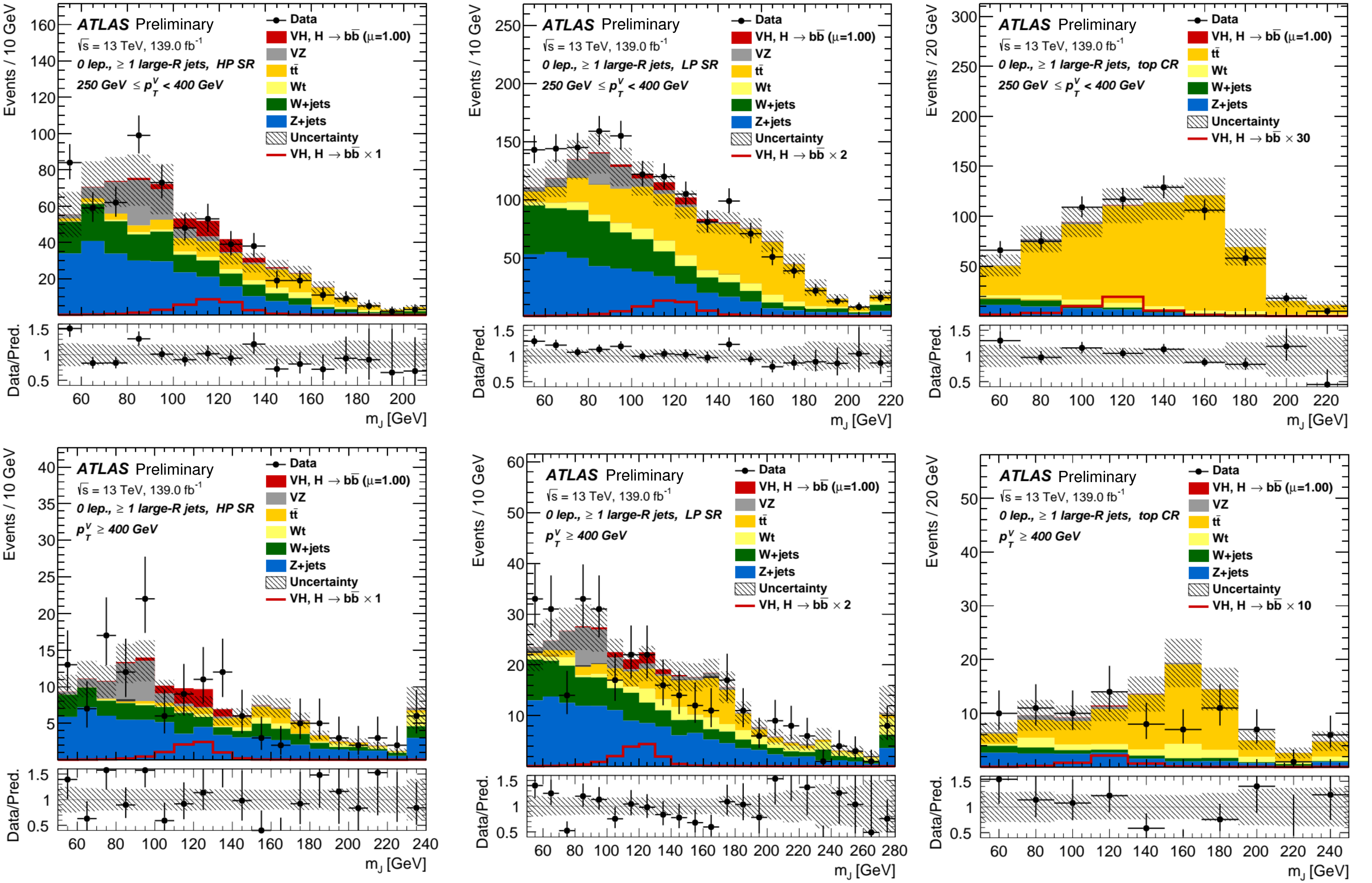
- Systematic uncertainties:
  - Experimental: large-*R* / small-*R* jet scale, resolution, leptons, E_T^{miss}, *b*-tagging …
  - Modeling: normalization, acceptance, shape …
    - Main backgrounds $t\bar{t}$, *V*+heavy flavor, free floated in the fit

large-*R* jet mass: 0L

0L: high purity SR | **low purity SR** | **top CR**

$250 < p_T^V < 400$ GeV

$p_T^V > 400$ GeV

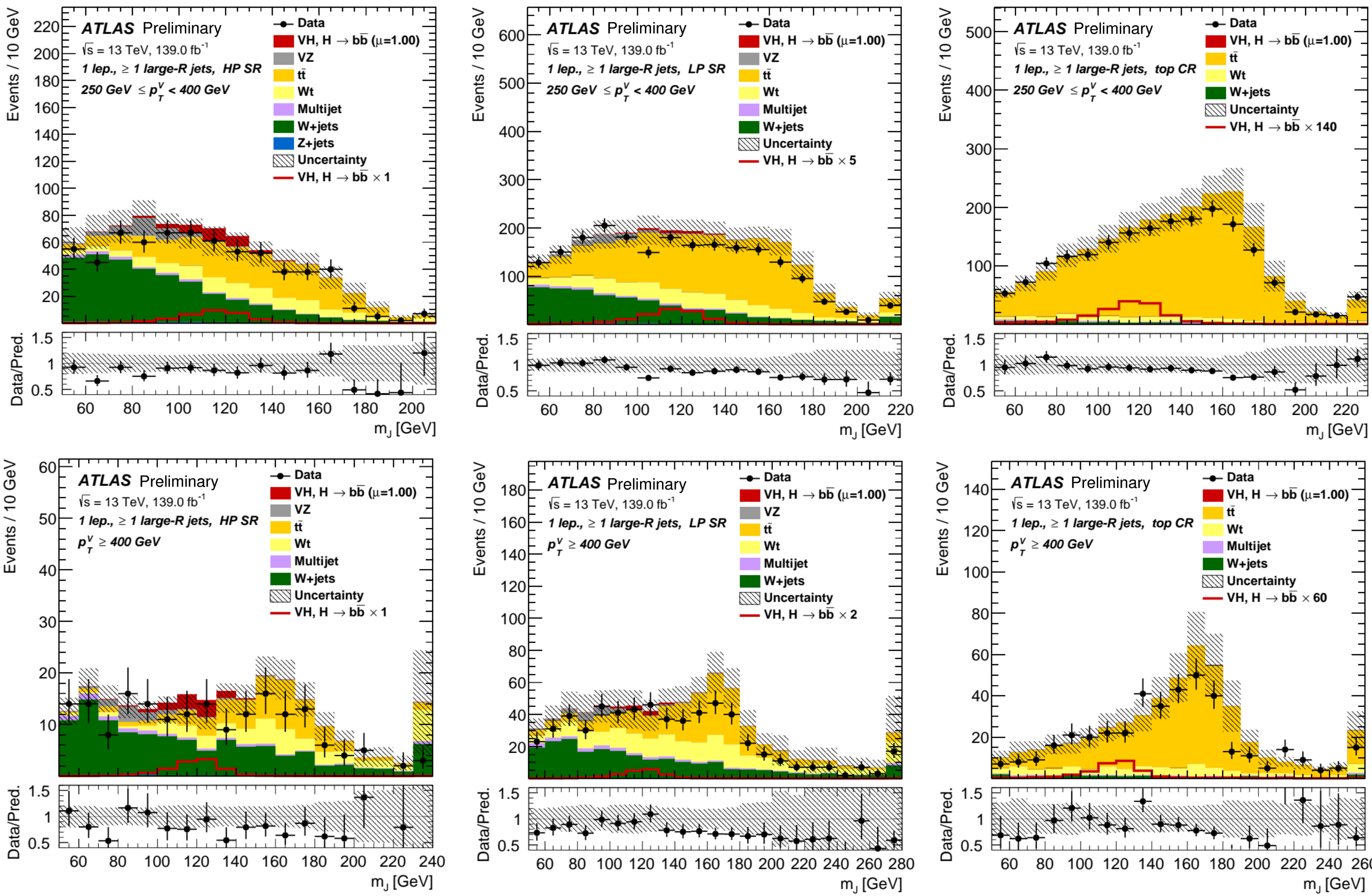


large-R jet mass: 1L

1L: high purity SR | **low purity SR** | **top CR**

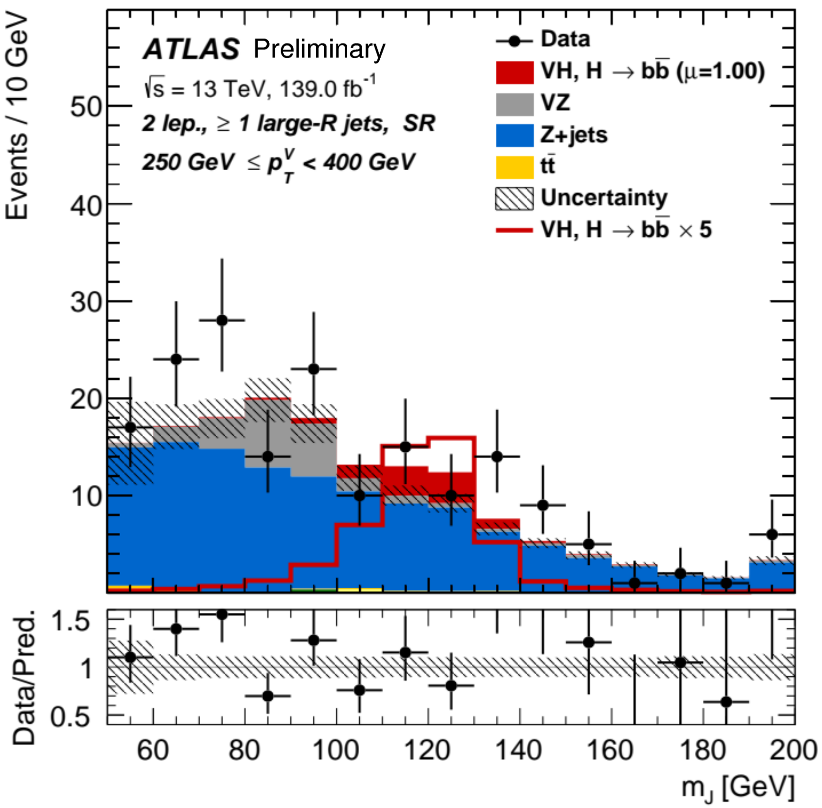
$250 < p_T^V < 400$ GeV

$p_T^V > 400$ GeV

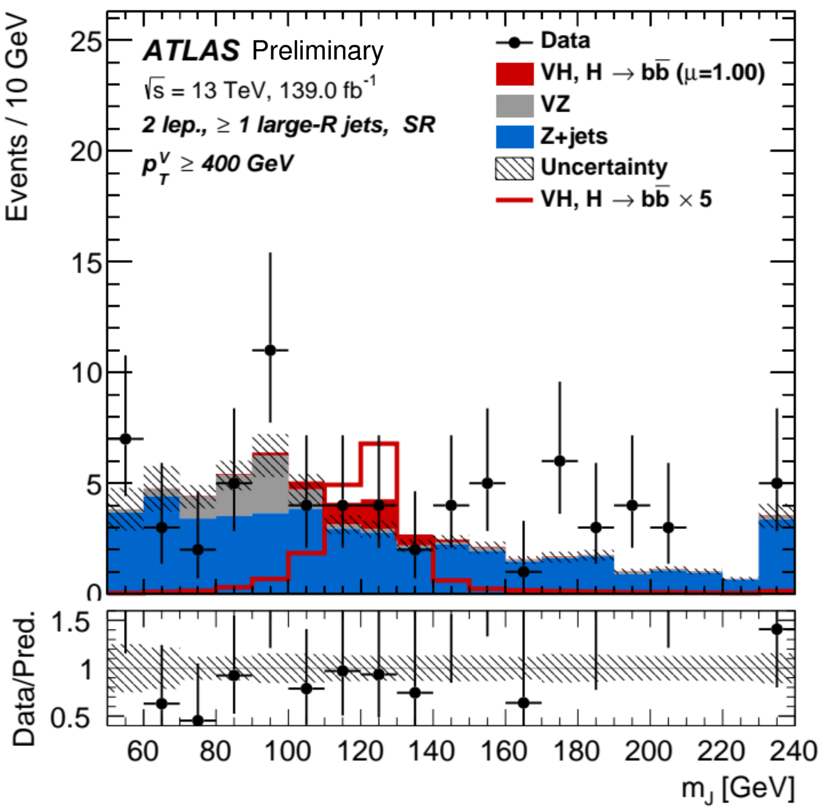


large-R jet mass: 2L

2L: 250 < p_T^V < 400 GeV



p_T^V > 400 GeV



Main background after event selection:

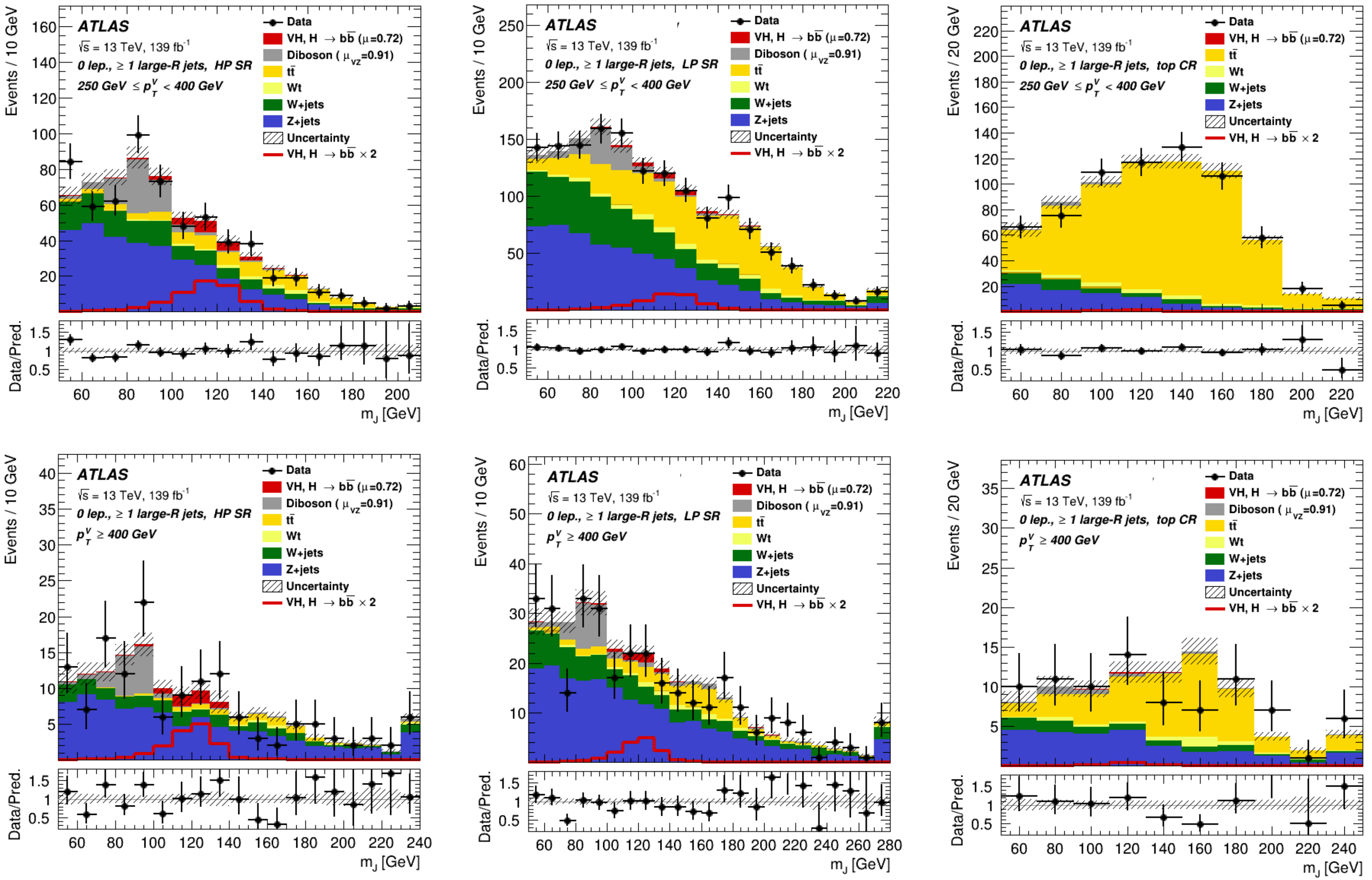
0L: ***Z*+jets**, ***W*+jets**, ***$t\bar{t}$*** 1L: ***$t\bar{t}$***, ***W*+jets**, **single top** 2L: ***Z*+jets**, **diboson**

0L post-fit results

0L: high purity SR | low purity SR | top CR

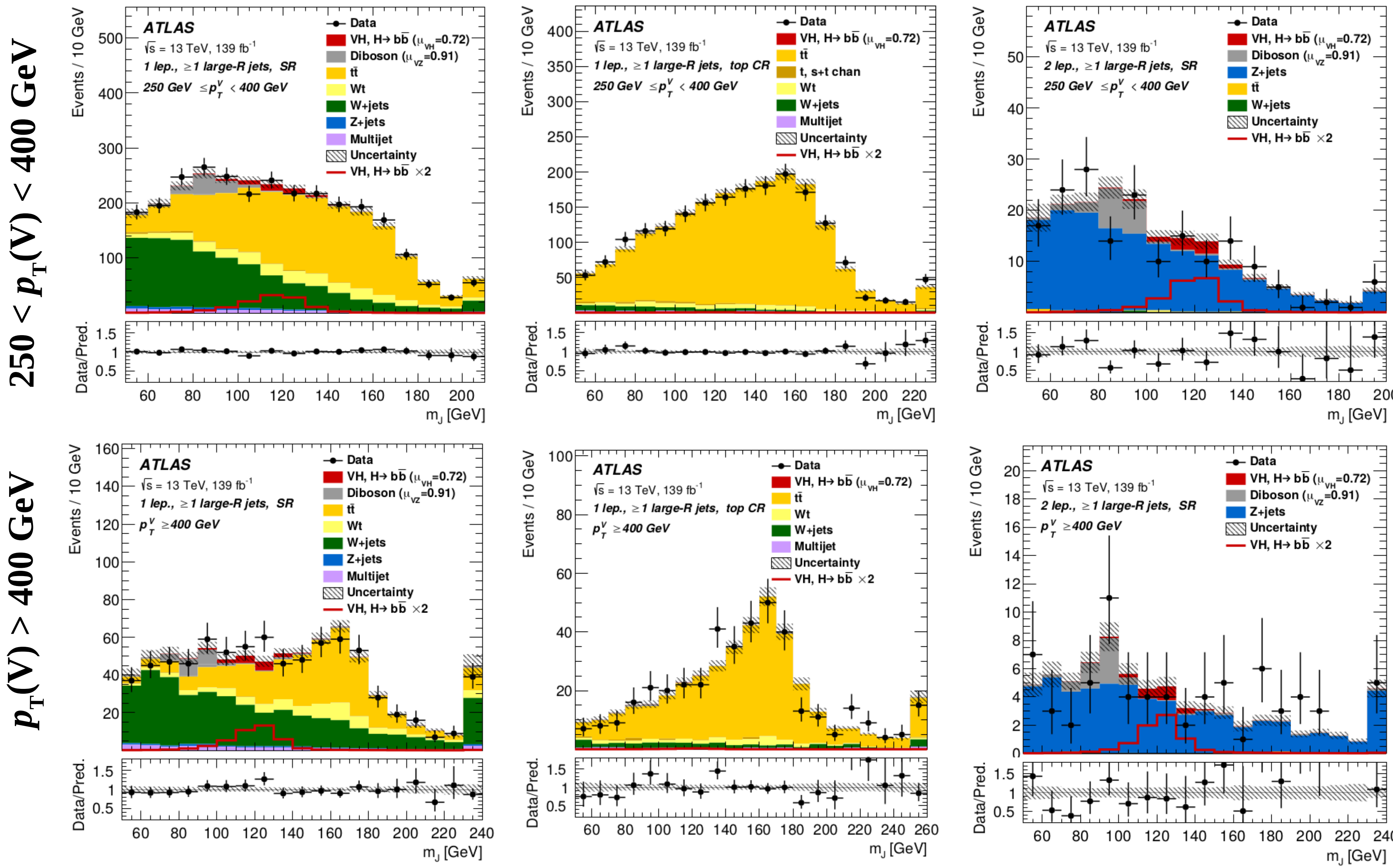
$250 < p_T(V) < 400$ GeV

$p_T(V) > 400$ GeV



1L and 2L post-fit results

1L: merged HP and LP SR | **1L: top CR** | **2L**



$VH(bb)$ boosted results

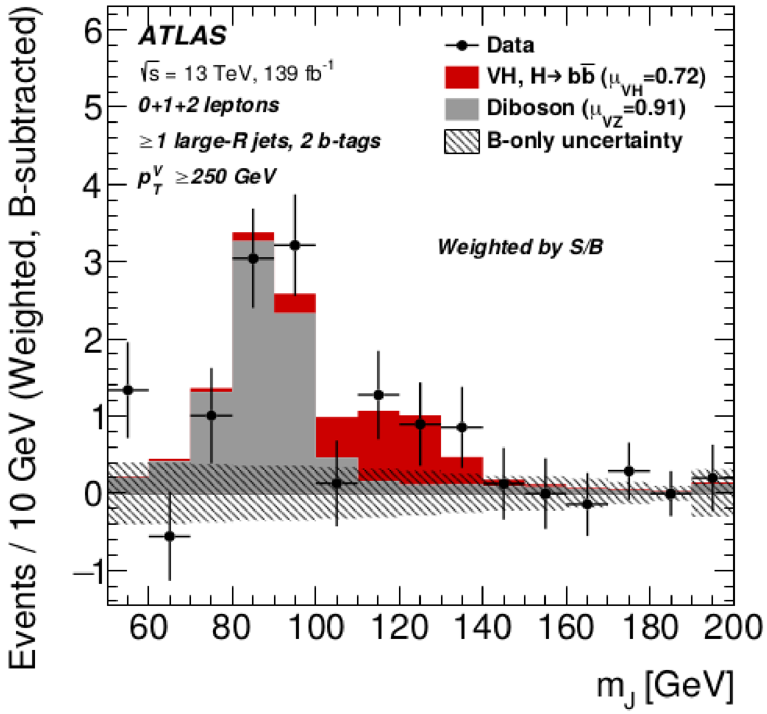
Fitted value of VH (VZ) signal strength

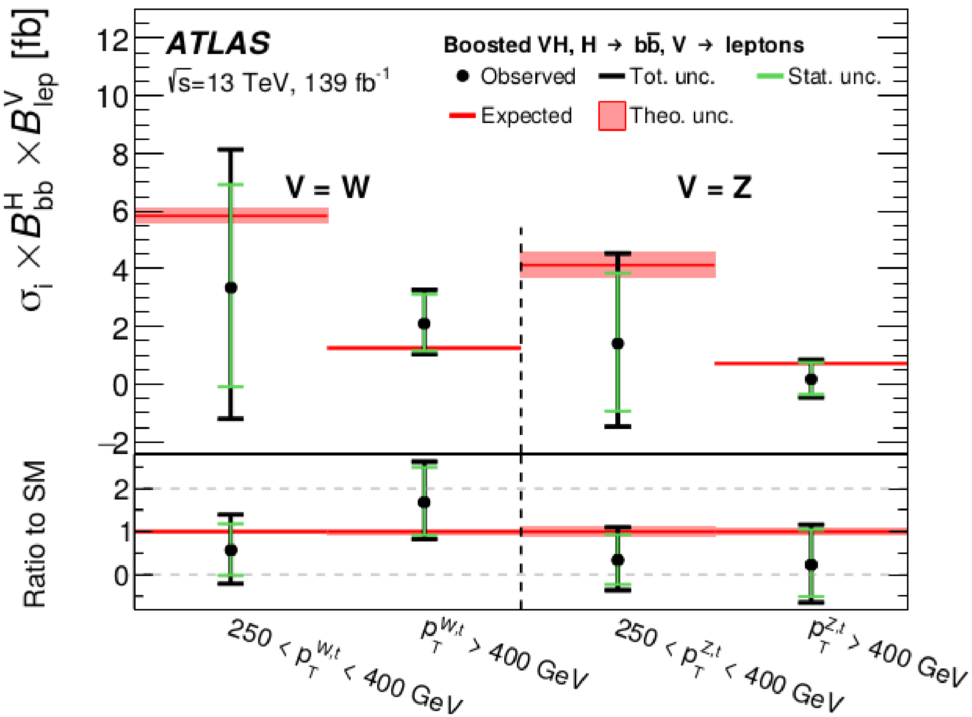
$$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$$

$$\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.25}_{-0.17}(\text{syst.})$$

Significance of VH signal: 2.1 σ (observed), 2.7 σ (expected)

Significance of VZ: 5.4 σ (observed), 5.7 σ (expected)





Conclusion

- First measurement of Higgs decays using large-*R* jet.
  - Nice sensitivity in high transverse momentum phase space.
  - Analysis strategy suitable for p_T > 400 GeV particularly.
  - All results are compatible with the SM predictions.

Backup

Beyond the Standard Model

- Model-independent approach: Effective Field Theory (EFT)
  - The SM: low energy approximation of a more generic model
  - Effects of new physics show up at energy scale Λ

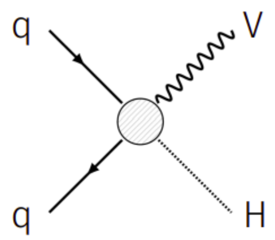
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \boxed{\frac{1}{\Lambda^2}\mathcal{L}_6} + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

$$\sum_i \frac{\boxed{c_i^{(6)}}}{\Lambda^2}\boxed{\mathcal{O}_i^{(6)}}$$

Wilson coefficients
0 in the SM

Dimension-6 operators

17 operators have effects on VH or $\mathrm{H} \rightarrow b\bar{b}$ process



- Cross sections interpreted in the EFT approach

$$\frac{\sigma_{\mathrm{EFT}}}{\sigma_{\mathrm{SM}}} = 1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_i c_j\,, \quad \frac{\Gamma_{\mathrm{EFT}}}{\Gamma_{\mathrm{SM}}} = 1 + \sum_i \alpha_i c_i + \sum_{ij} \beta_{ij} c_i c_j$$

  - A_i, B_{ij}, α_i, β_{ij} can be calculated from Monte-Carlo simulation.
  - Wilson coefficients need to be constrained in experiment.