Measurement of high-momentum Higgs boson production in association with a vector boson in the *qq bb* final state with the ATLAS detector

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Higgs Hunting 2023
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ATLAS EXPERIMENT

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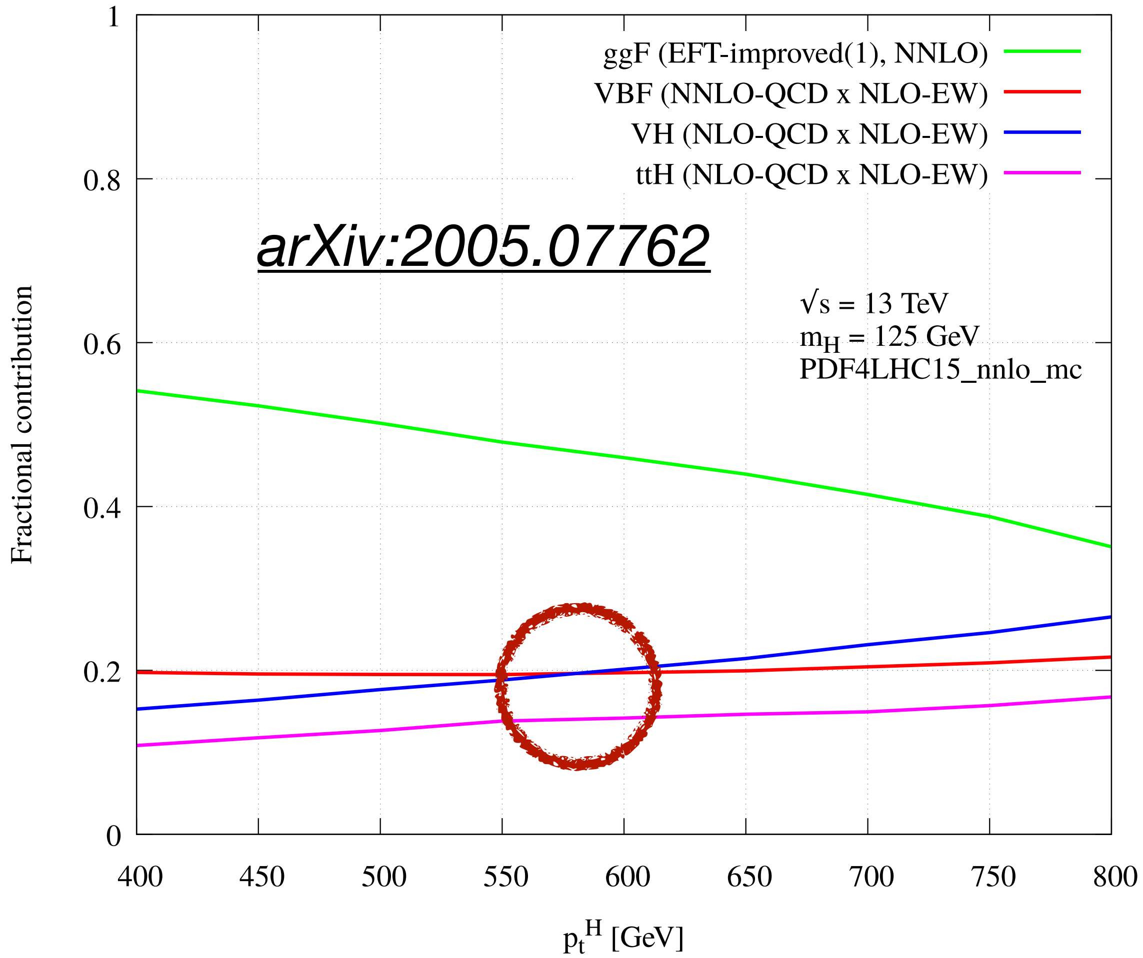
Motivation for Boosted All-Hadronic Higgs-Boson Searches

- Shifting interest from static to **dynamic** properties of the **Higgs** boson
  - All production modes contribute similarly towards p_T^H ~ 1 TeV
- Increased impact expected from new physics
  - Probe BSM, especially EFTs: **effects enhanced by powers of E/Λ**
- Main experimental challenges: flavour-tagging in boosted/busy environment, background modelling, jet-tagging & resolution



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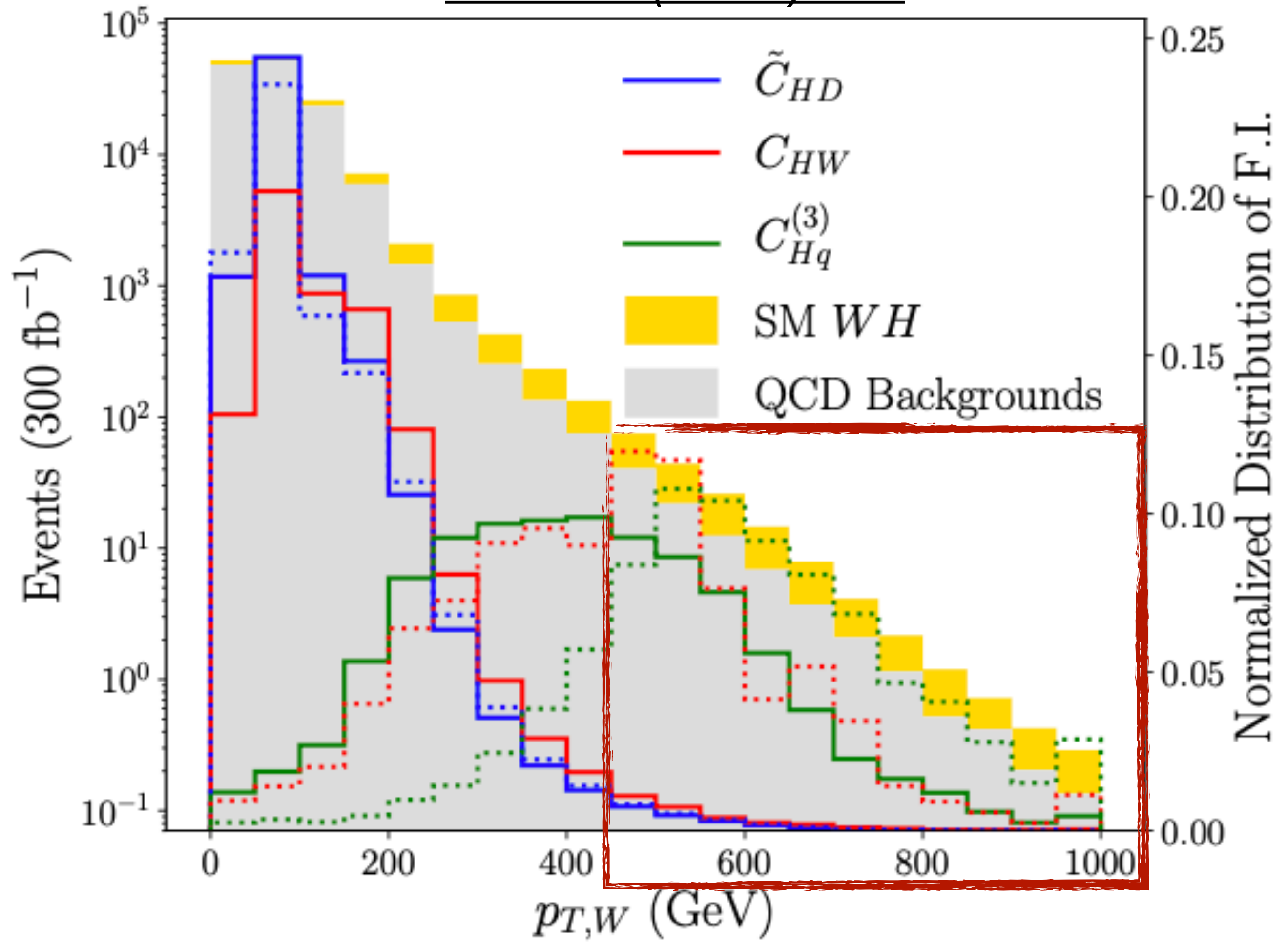
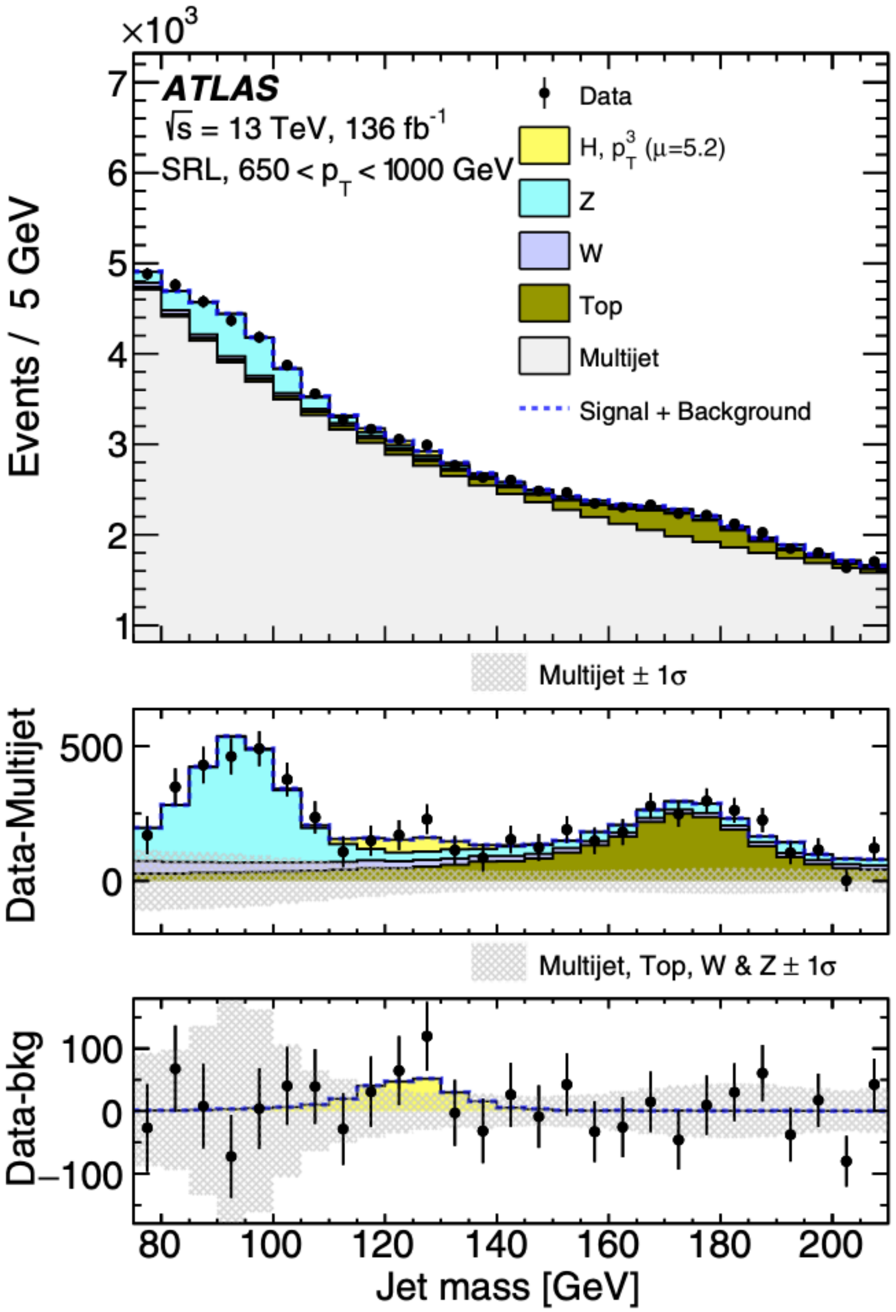
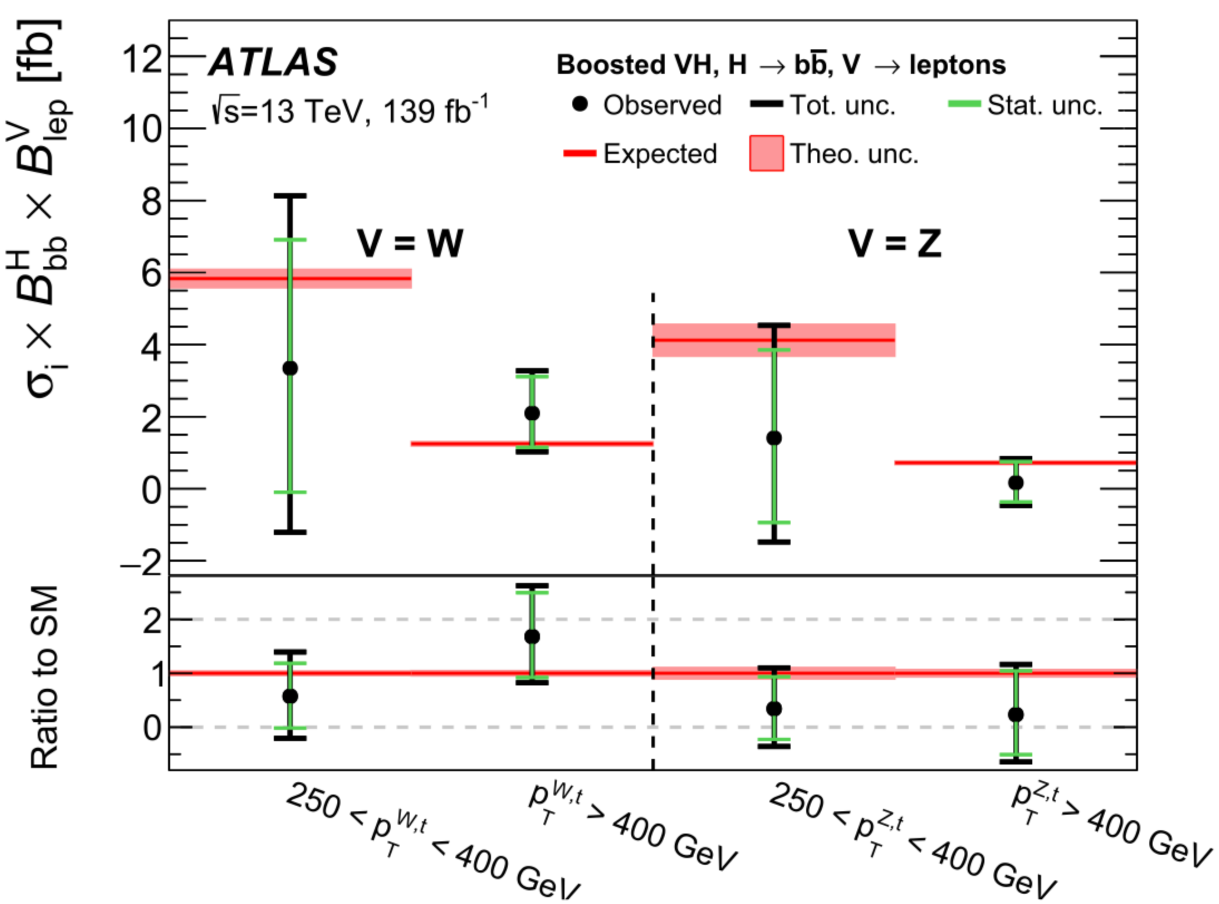


Boosted Inclusive & *VH* Semileptonic Results

- All-hadronic production of Higgs boson in *bb* decay channel
  - First ATLAS **p_T^H-differential results in all-had** phase space *Phys. Rev. D 105, 092003*
    - Inclusive in Higgs-boson production modes
  - Recent result by CMS focused on ***VBF*** *CMS-PAS-HIG-21-020*
- ATLAS boosted semilep *VH(bb)* *Phys. Lett. B 816 (2021) 136204*
  - Observed (expected) significance for p_T^V >250 GeV: **2.1**(2.7)**σ**
  - Signal events increase by a factor of two in all-hadronic channel

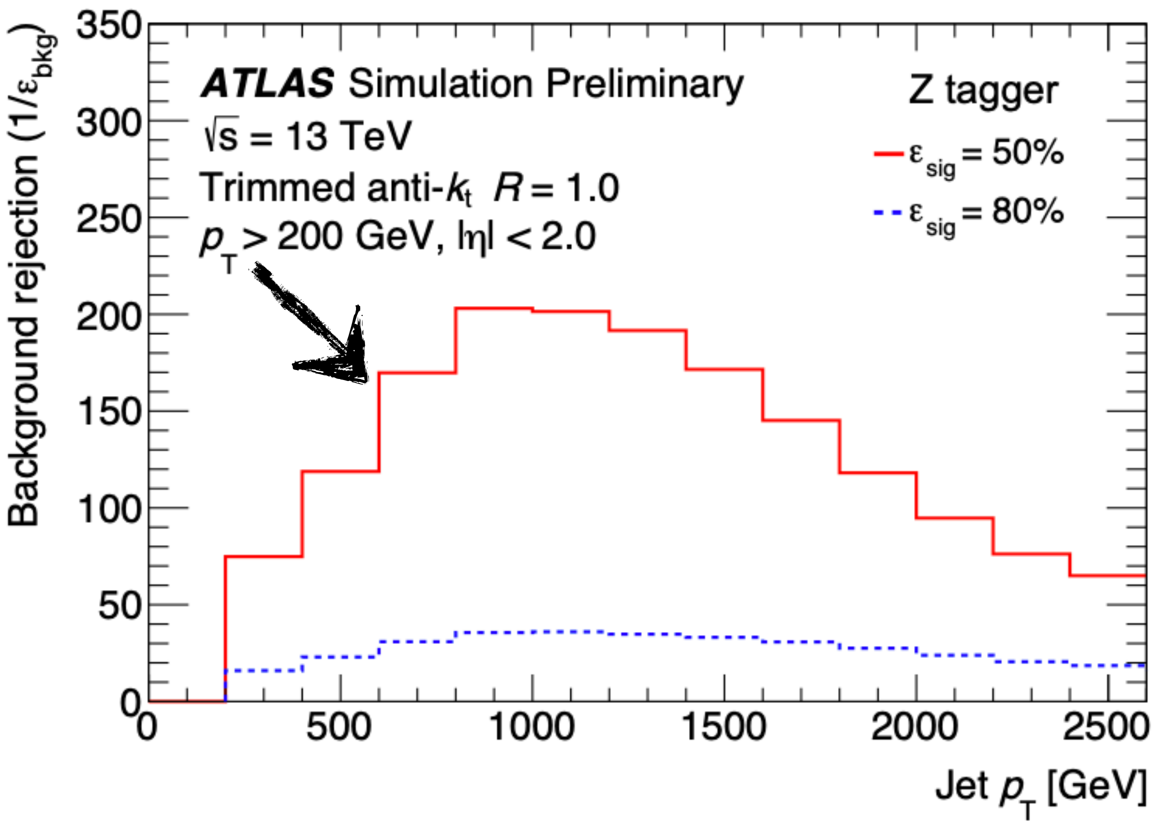
Exclusively probe *VH* production mode in *qq bb* decay mode

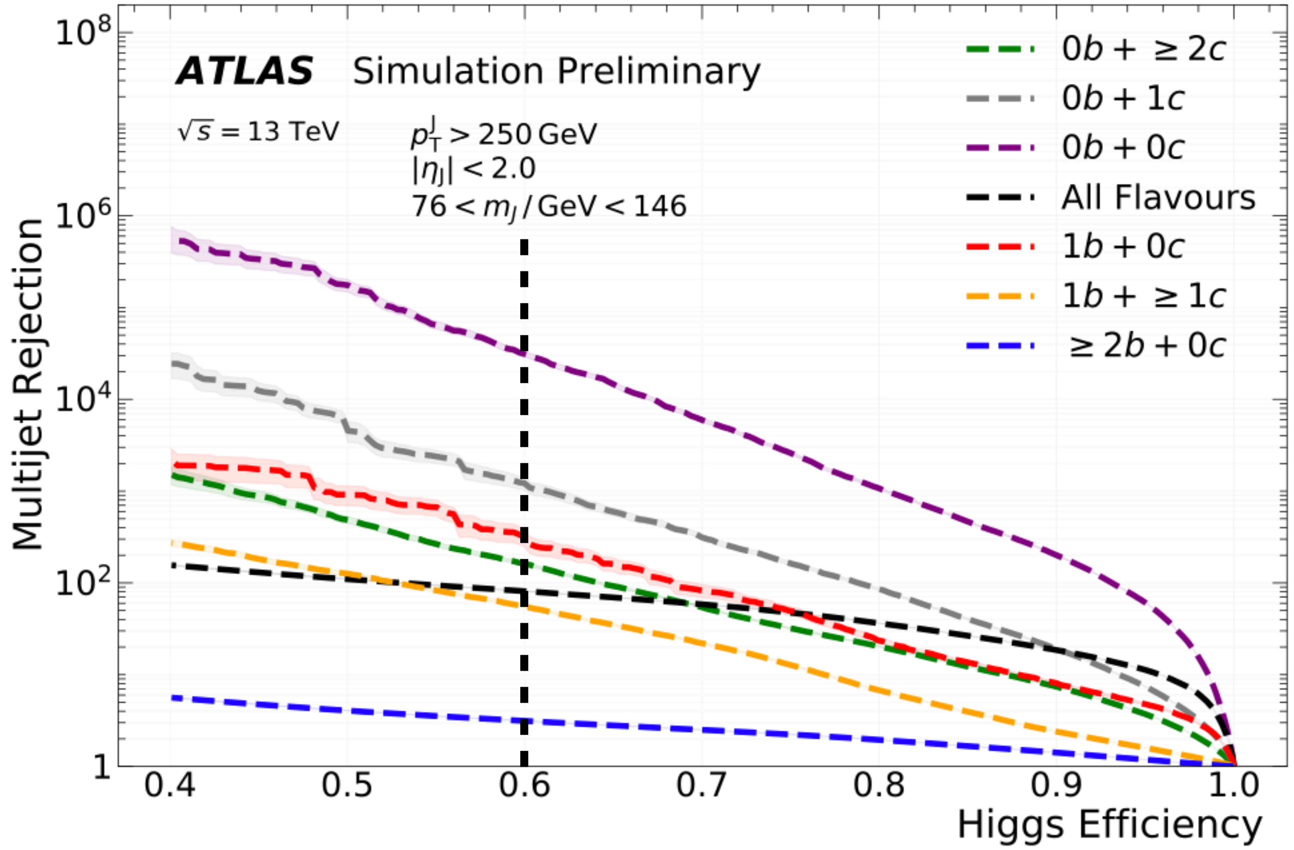




Dedicated Techniques for Boosted Topologies

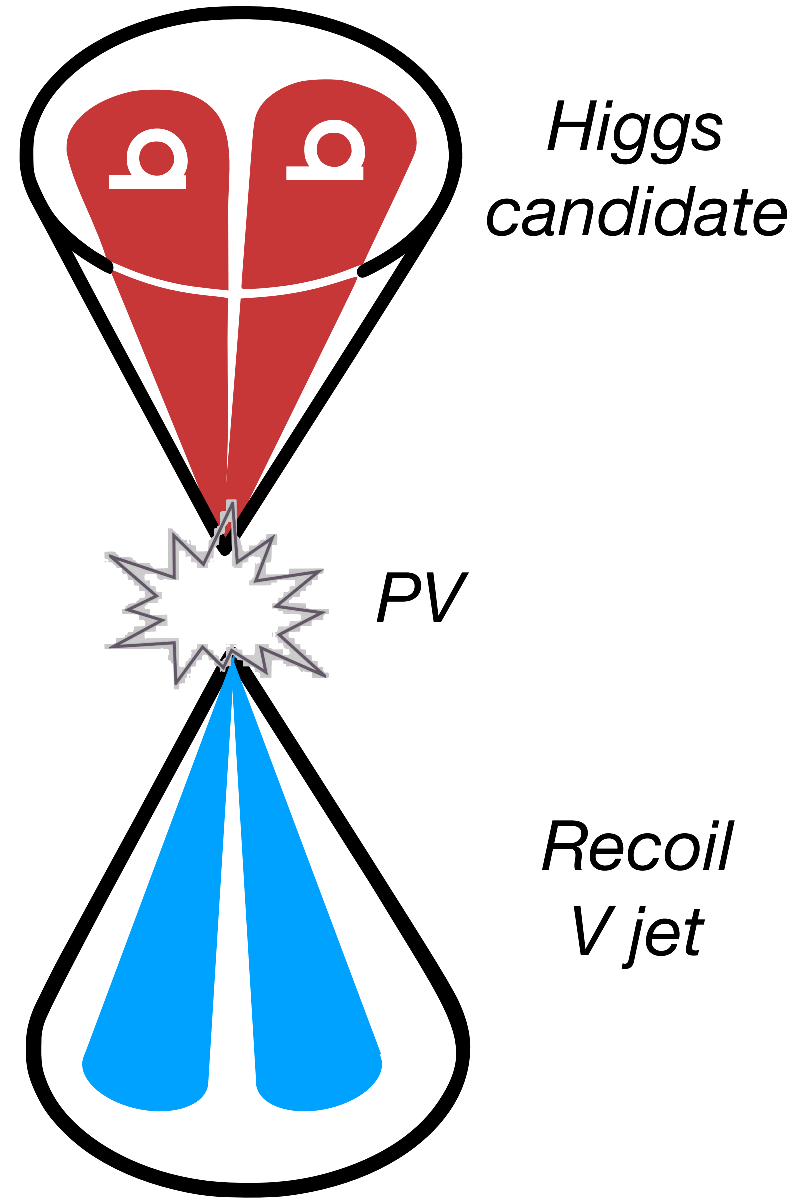
- Advancement of **novel jet substructure** techniques & **background estimation** methods enabled searches for *H->bb* in all-hadronic final states
  - Reduce & describe large irreducible **multi-jet background**
- ***V-tagger*** : tag jets likely coming from *V*-boson decay
  - Requirements on jet mass, two-prongness & number of tracks yielding a signal efficiency of 50%
- ***Hbb tagger :*** tag jets likely resulting from Higgs-boson decay to *b*-quark pair
  - Neural Network using track & vertex info associated to variable-radius track-jets
  - Fixed 60% *H->bb* efficiency used





Dataset & Event Selection

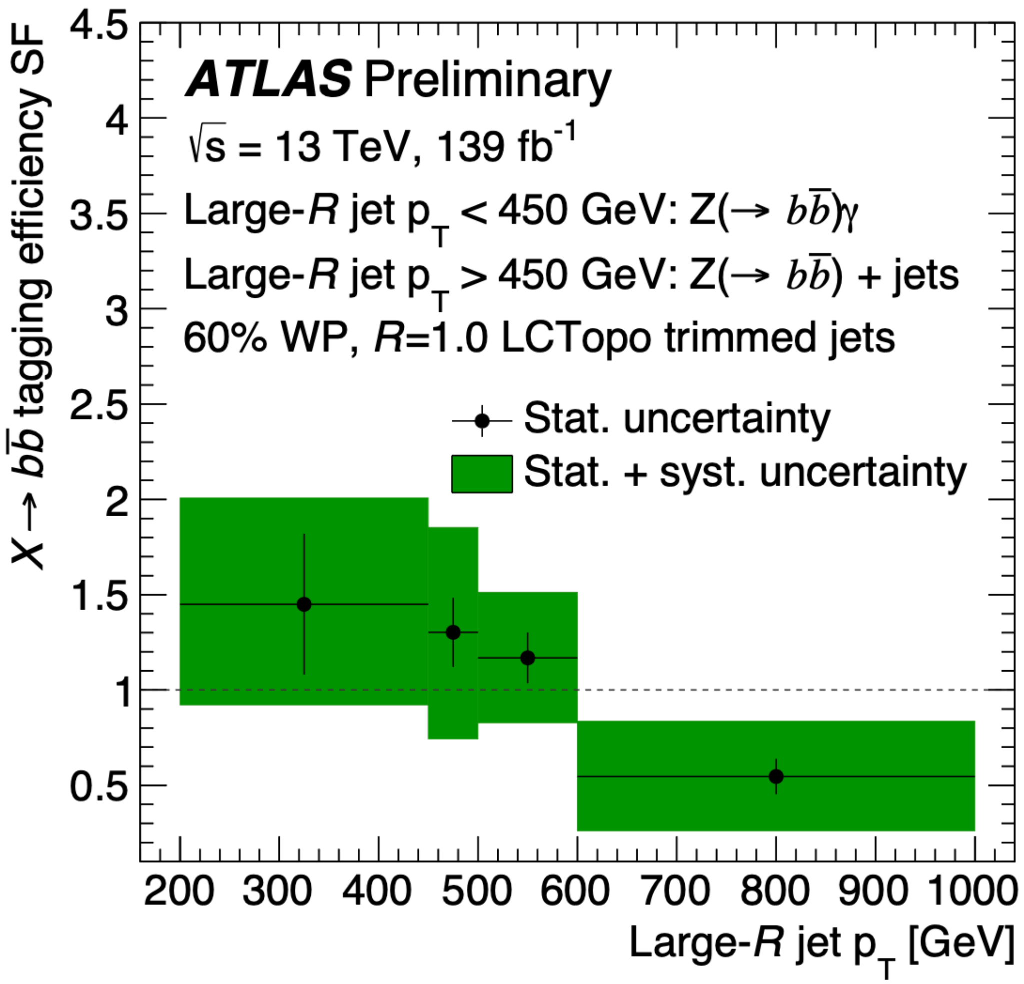
- Proton-proton collision data collected by ATLAS detector from 2015 to 2018
  - Integrated luminosity of **137 fb^{-1}** at 13 TeV
- Event selection:
  - **Single large-R** (R=1.0 anti-k_t) **jet triggers** with mass (M_J) and p_T thresholds
  - **At least two large-R jets** $p_T > 200$ GeV & $|\eta|<2$
    - p_T-leading : $\boldsymbol{p_T > 450}$ **& $\boldsymbol{M_J > 50}$ GeV**
    - Second p_T-leading $M_J > 40$ GeV
  - Events with isolated charged leptons are rejected



Event Selection (cont'd)

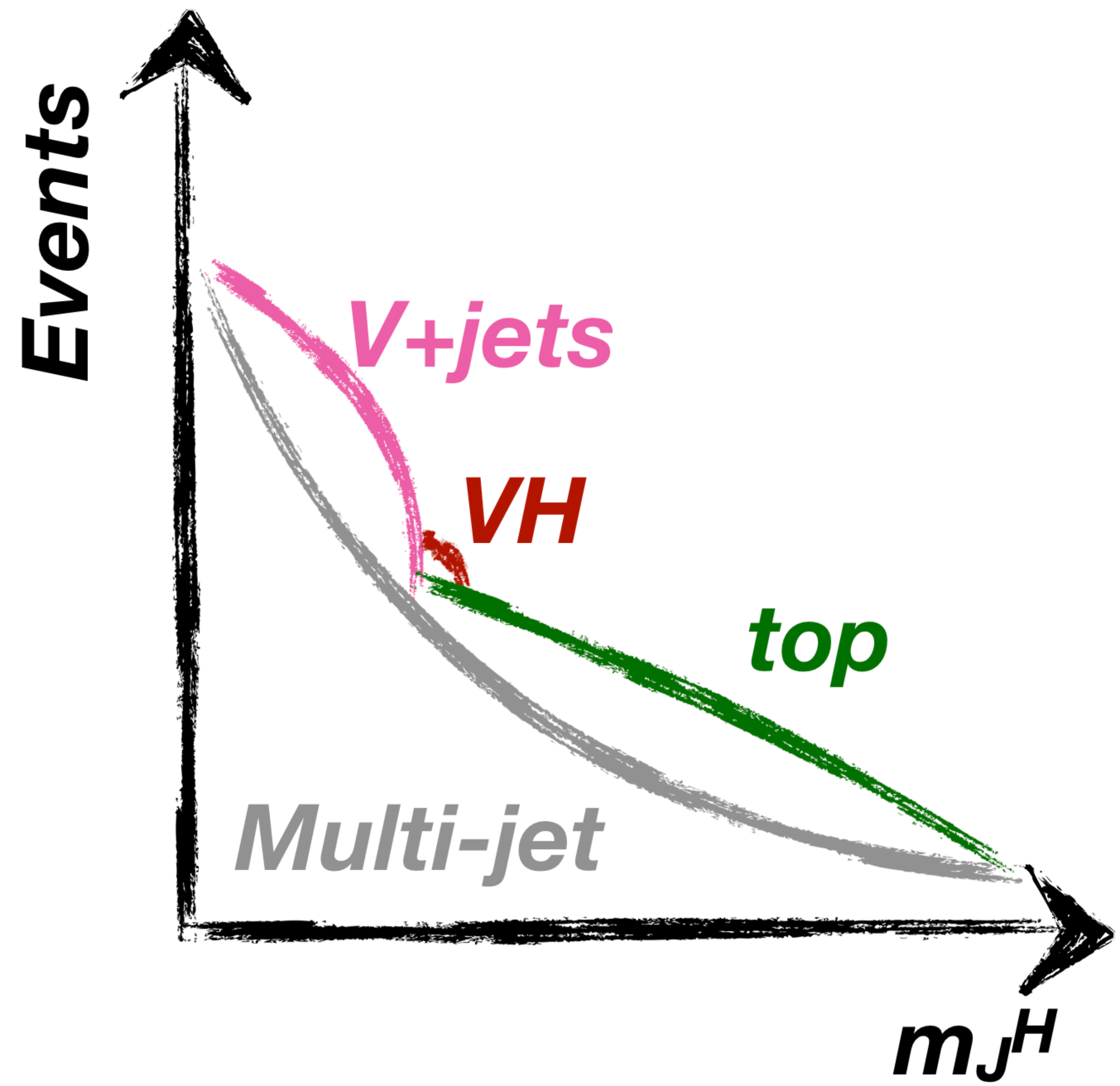
- In region of interest (**SR**):
  - At least one of the two p_T-leading jets must pass *Hbb*-tagger requirements
    - If both, jet with larger mass is **Higgs candidate** & is required to fulfill $\boldsymbol{p_T > 250}$ **GeV**
    - Other jet must satisfy ***V*-tagger** requirements
- Events are split according to Higgs-candidate p_T: **[250,450)**, **[450,650)**, **≥650 GeV**

- Dedicated *Hbb*-tagger calibration with independent boosted *Z->bb* events
  - Inverted *V*-tagger on recoil jet



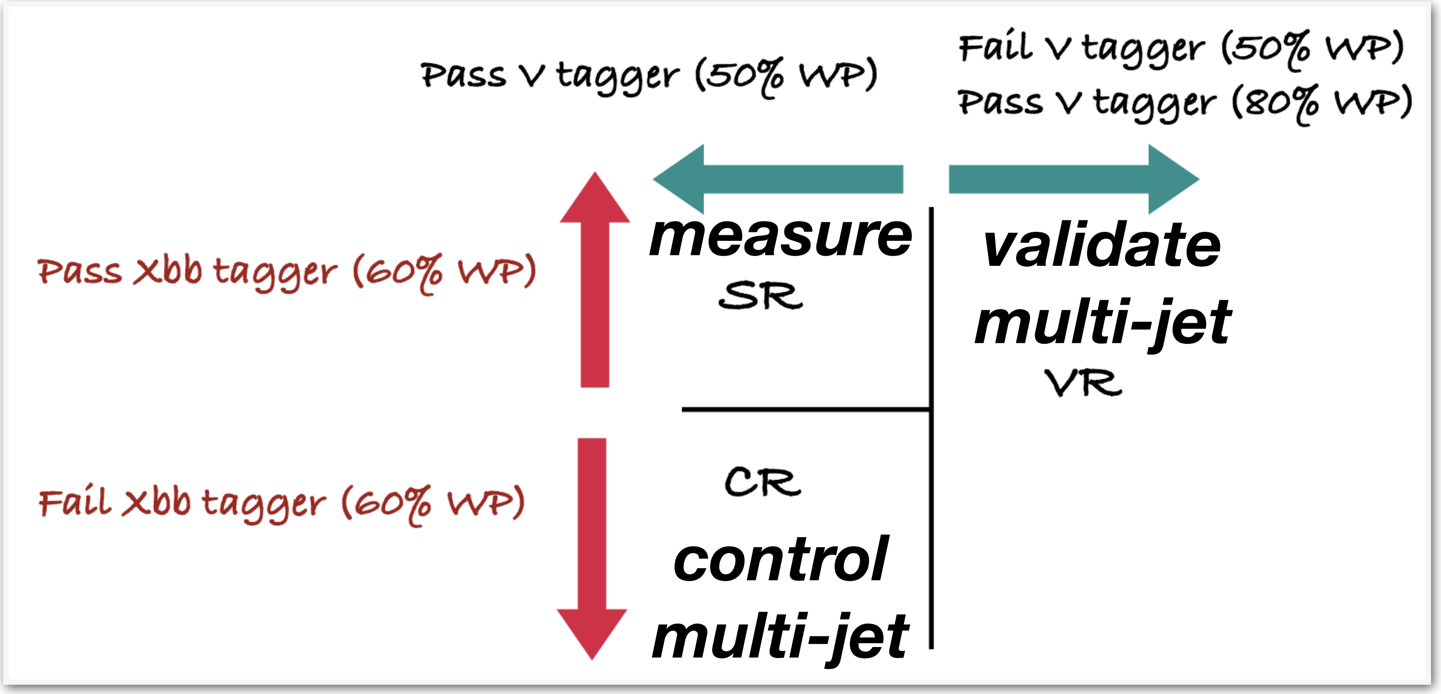
Inclusive Signal & Background Composition

- In SR, ***VH*** production mechanism **dominates: ~85%**
  - *ttH* (8%), *ggF* (6%), *VBF* (1.4%)
- Background by far dominated by **multi-jet** production (90%); followed by:
  - ***ttbar*** (5%)
  - ***V*+jets** (3.6%)
  - *VV* (0.7%)
- Key to have full control of multi-jet background estimation
  - Two **data-driven** estimations in place



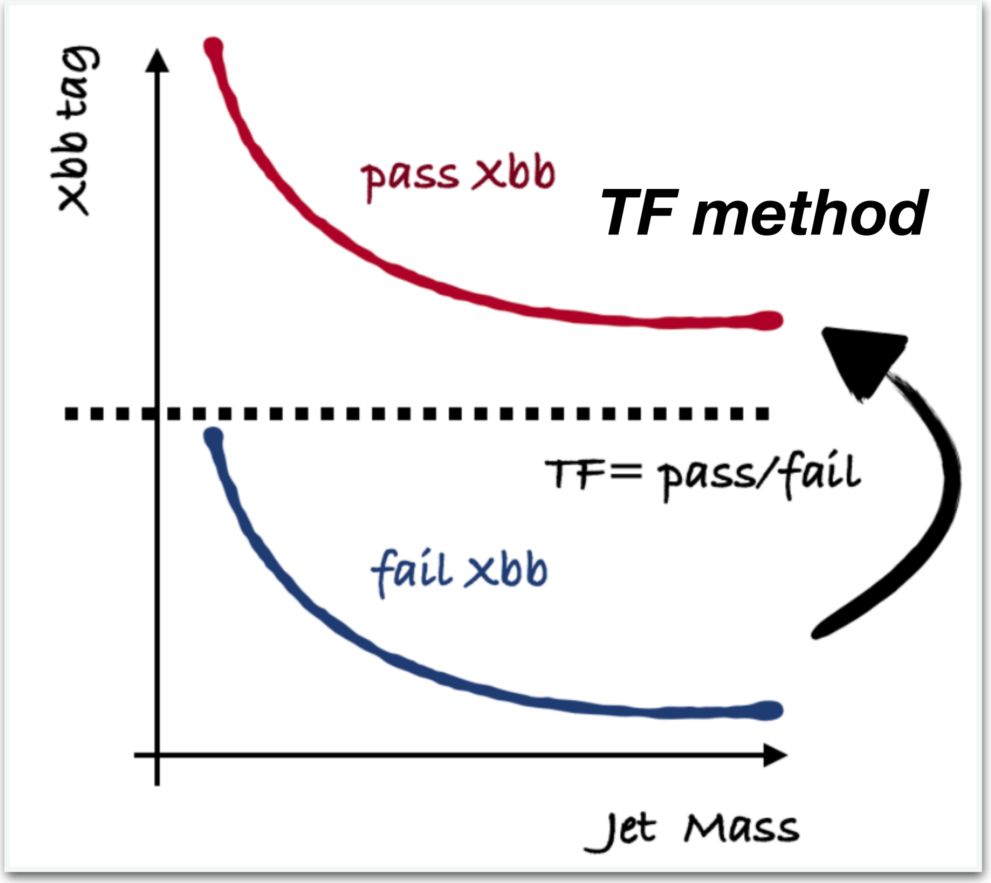
Analysis Strategy & Region Definitions

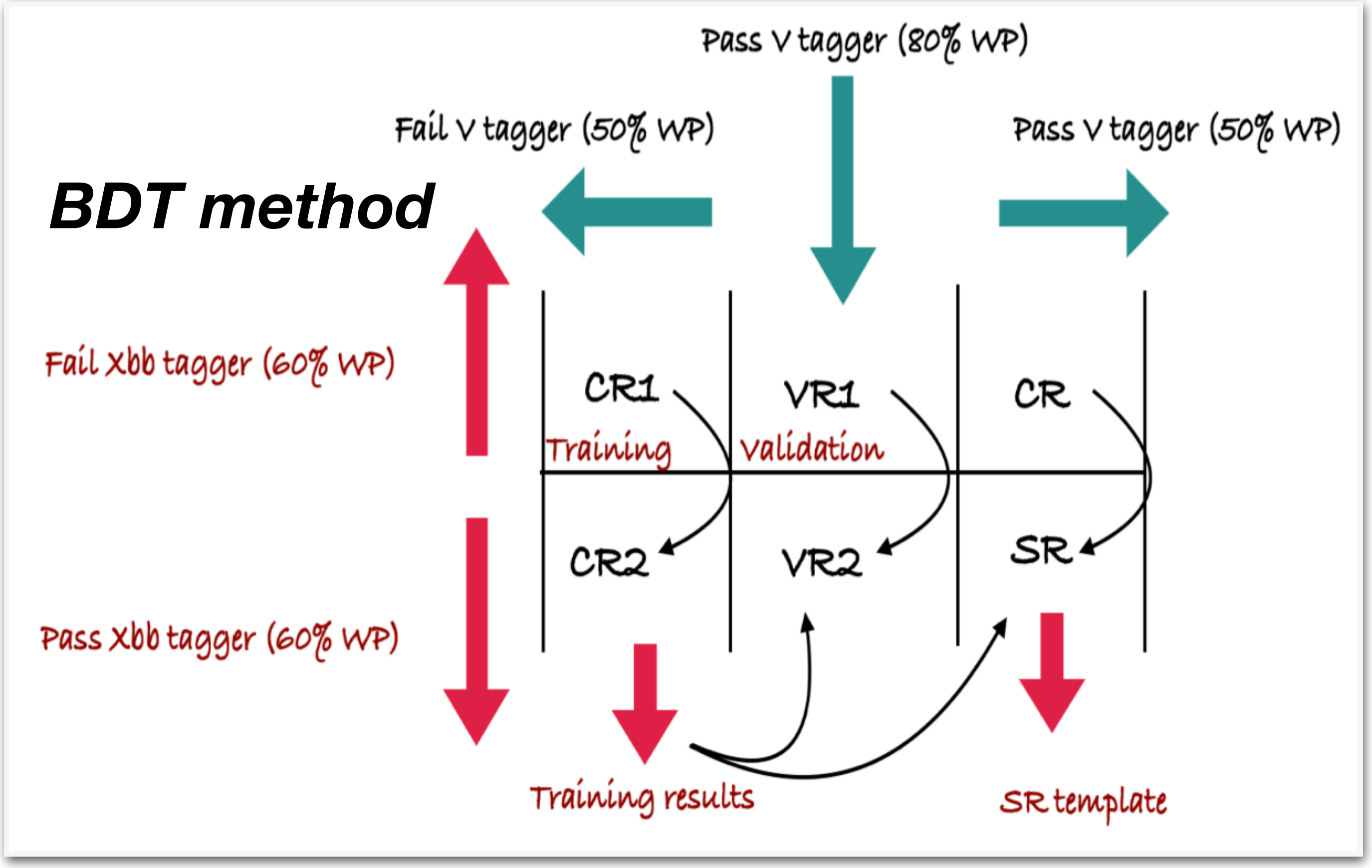
- **Higgs-candidate jet mass** fit (m_J^H) to extract signal in SR
  - Reconstructed combining calorimeter & tracking measurements
  - Corrected to account for **muons** from semileptonic *b*-hadron decays
- Control Region (**CR**):
  - Events fail *Hbb*-tagger requirements
  - **Derive** multi-jets background
- Three Validation Regions (**VR**):
  - Pass looser (80% eff) *V*-tagger, but fail one of three nominal (50% eff) requirements
  - **Validate** multi-jet background estimation method



Multi-Jet Background Estimation

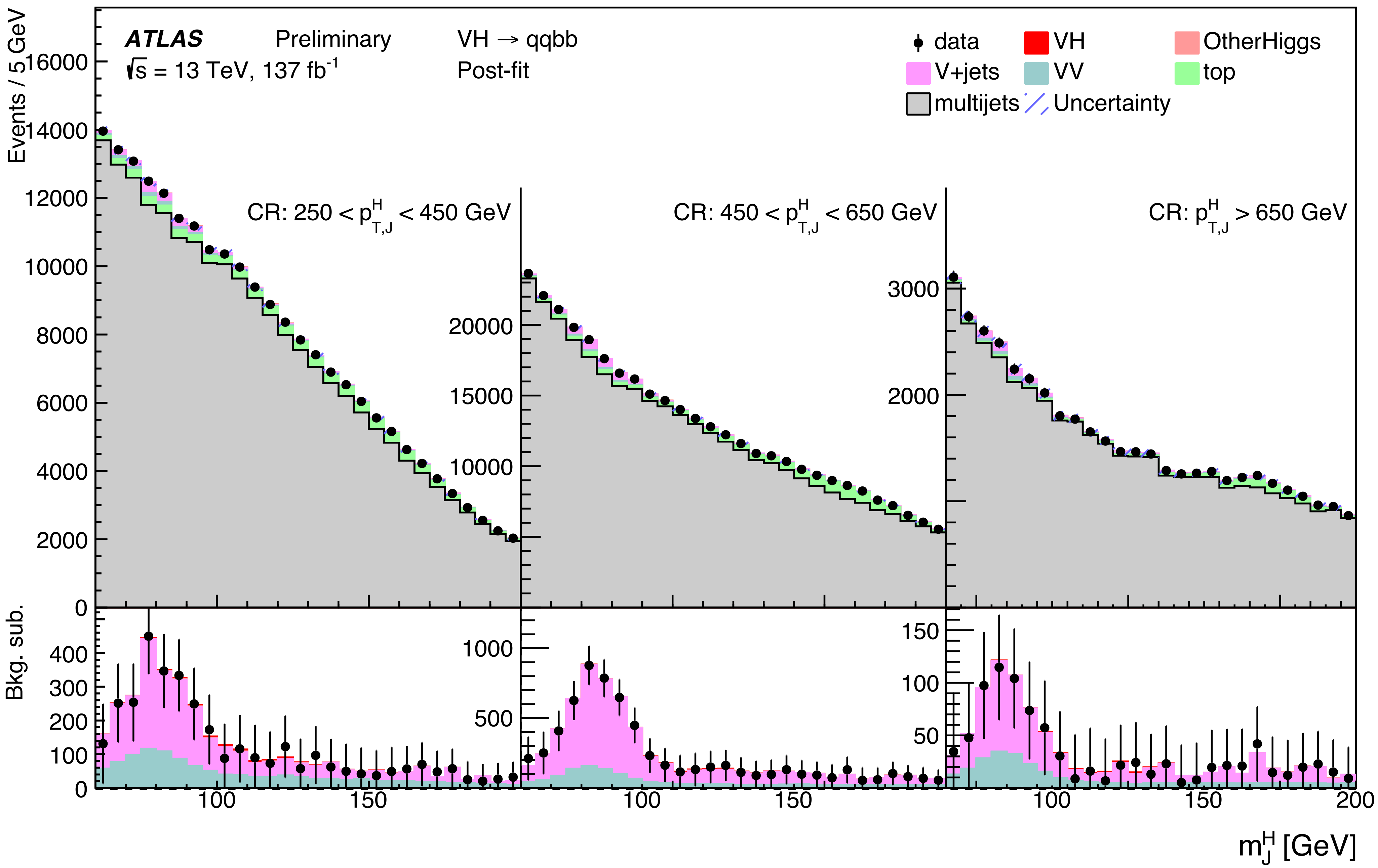
- Multi-jet background modelled from CR with **Transfer Factor** (TF) dependent on **candidate-jet p_T** & **$\rho=\log(m_J^2/p_T^2)$**:
  - $\mathrm{TF}(p_\mathrm{T}, \rho) = \sum_{k,l} \alpha_{kl}\, \rho^k\, p_\mathrm{T}^l$, where α_{kl} are polynomial coefficients
- **TF scales CR events to yield number of multi-jet events in SR**
- Polynomial order determined via Fisher F-tests in data
  - **First order in both p_T & ρ** proves to be sufficient, without inducing significant spurious signal
- Alternate method: **BDT** exploiting kinematics of two leading jets to predict SR from CR
  - Consistent results between the two methods





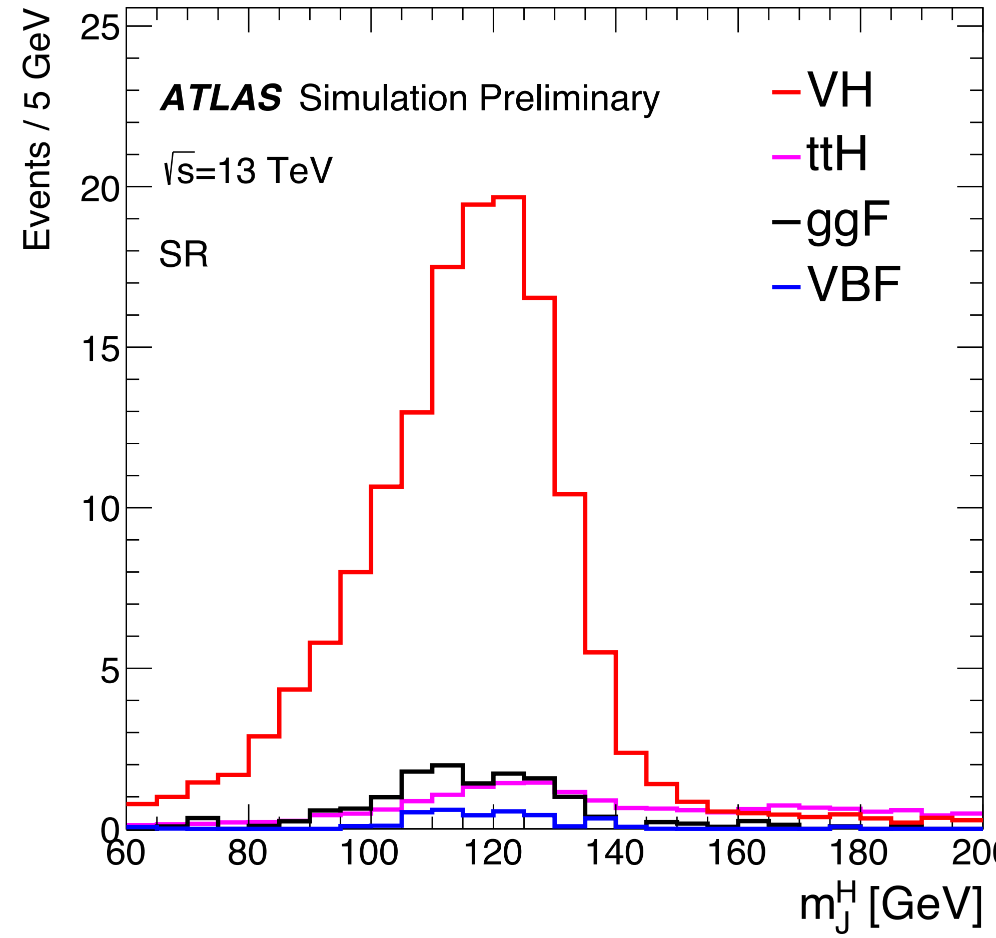
Control Region - Post-Fit Plots

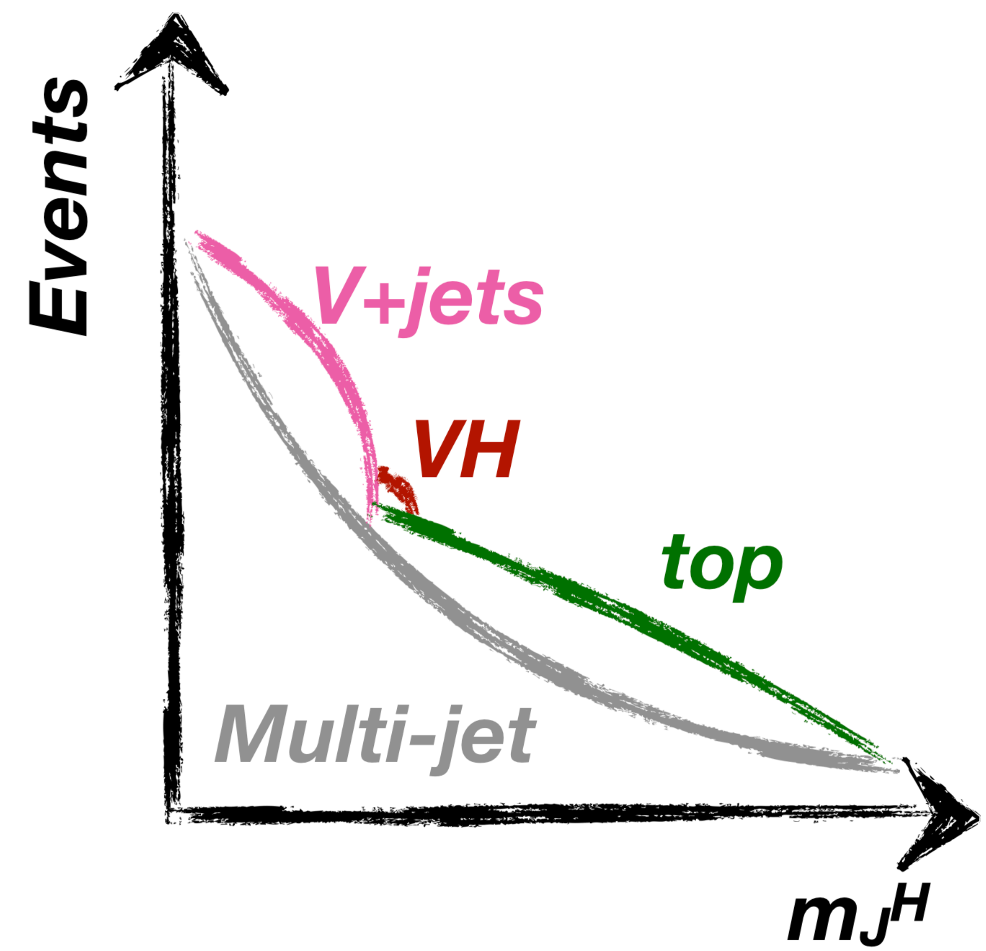
- Good desciption observed in VRs: **no additional non-closure uncertainty** necessary
- Significant constraining power from **CR**, shown in combined fit with SR
  - Great handle on description of non-resonant processes
- *How are resonant contributions estimated?*



Simulation-based Estimations

- **Signal** & **smaller backgrounds** (*ttbar*, *V*+jets, & *VV* production) are modeled using **simulation**
- Modelling of ***VH*** production:
  - *qq/qg* production @NNLO QCD & NLO EW
    - Differential NLO EW corrections computed with <u>*HAWK*</u>
    - *gg->ZH* production @NLO+NLL QCD
- ***ttbar***: generated with NLO accuracy
- ***V*+jets**: NLO QCD + EW predictions
- *VV*: (N)LO QCD accuracy up to three(one) additional partons





Uncertainties & Fit Setup

- Three main sources of systematic uncertainties: **data-driven multi-jet** models, **signal theoretical** predictions & **experimental reconstruction**
  - Difference between TF & BDT multi-jet estimates
  - Large-R jet energy & mass resolution & scale
  - *V*-tagger uncertainties from independent semilep *ttbar*-enriched events
  - *Hbb*-tagger efficiency, further constrained due to *Z->bb* resonance
- ***Z*+jets normalisation determined by fit to data**
  - Shape effects from scale variations
- Scale variations, alternative event generators & **normalisation** uncertainties for other subdominant backgrounds:
  - *ttbar*: 12%
    - p_T-dependent norm from semileptonic events in pure CR (*Phys. Rev. D 105, 092003*)
  - *VV*: 80%
- **Simultaneous binned maximum-likelihood fit to m_J^H in SR & CR** in range 60 to 200 GeV

Inclusive Results

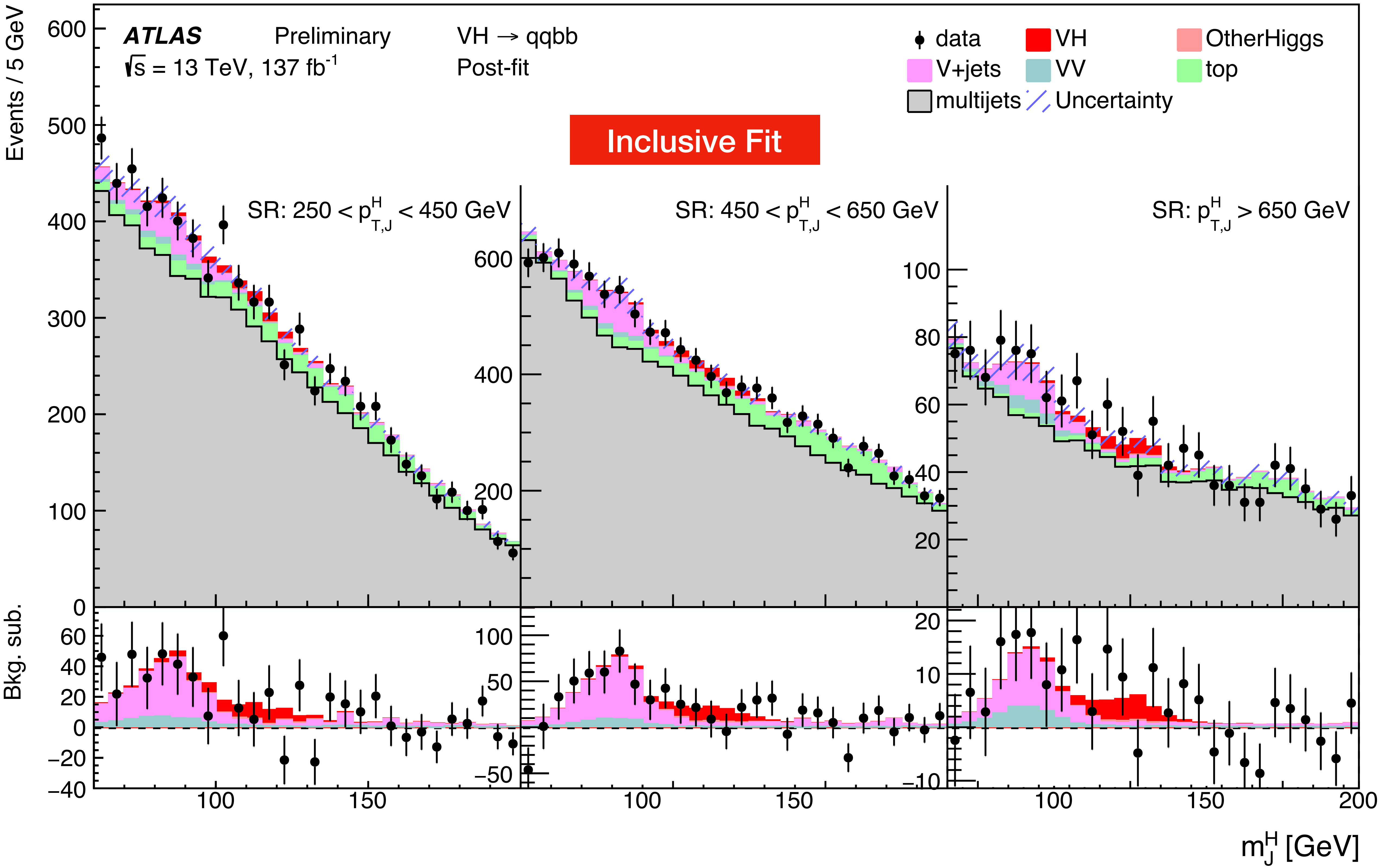
NEW RESULTS!

- Observed *Z*+jets normalisation: $\mu_Z = 1.41^{+0.80}_{-0.58}$
- Observed *V(qq)H(bb)* best-fit value: **$\mu = 1.39^{+1.02}_{-0.88}$ (±0.63 stat. $^{+0.80}_{-0.61}$ syst.)**
  - Observed significance for rejection of null-signal hypothesis: **1.7σ** (1.2σ expected)
  - Corresponding to an observed cross-section: **$3.3 \pm 1.5(\text{stat})^{+1.9}_{-1.5}(\text{syst})$ pb**
- Systematic uncertainties dominated by shape of **multi-jet data-driven estimate** & ***Hbb*-tagger scale factors**

Uncertainty source	$\delta\mu$
Signal modeling	$^{+0.10}_{-0.02}$
MC statistical uncertainty	$^{+0.13}_{-0.13}$
Instrumental (pileup, luminosity)	$^{+0.012}_{-0.004}$
Large-R jet	$^{+0.13}_{-0.14}$
Top-quark modeling	$^{+0.14}_{-0.15}$
Other theory modeling	$^{+0.050}_{-0.031}$
$H \to b\bar{b}$ tagging	$^{+0.52}_{-0.23}$
Multijet estimate (TF uncertainty)	$^{+0.52}_{-0.41}$
Multijet modeling (TF vs. BDT)	$^{+0.14}_{-0.18}$
Total systematic uncertainty	$^{+0.80}_{-0.61}$
Signal statistical uncertainty	$^{+0.60}_{-0.60}$
Z+jets normalization	$^{+0.42}_{-0.20}$
Total statistical uncertainty	$^{+0.63}_{-0.63}$
Total uncertainty	$^{+1.02}_{-0.88}$

Inclusive Results - Post-Fit Plots

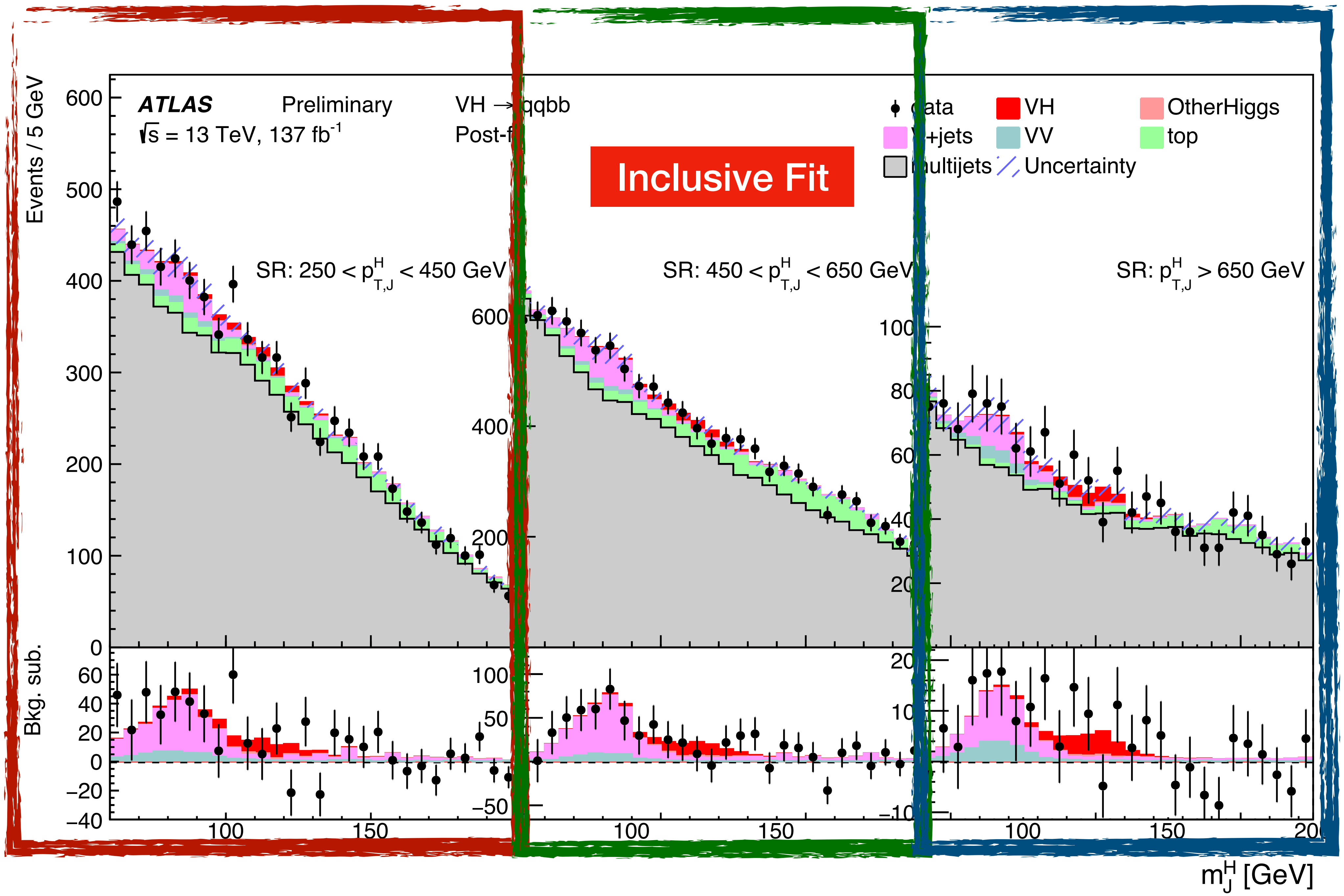
NEW RESULTS!



Differential Results

NEW RESULTS!

- Signal strengths resulting from fit to each of the three p_T categories
  - $p_T \in [250, 450)$ GeV $\mu = 0.6^{+1.8}_{-1.7}$
  - $p_T \in [450, 650)$ GeV $\mu = 0.6^{+1.3}_{-1.2}$
  - $p_T \geq 650$ GeV $\mu = 4.5^{+8.8}_{-2.7}$



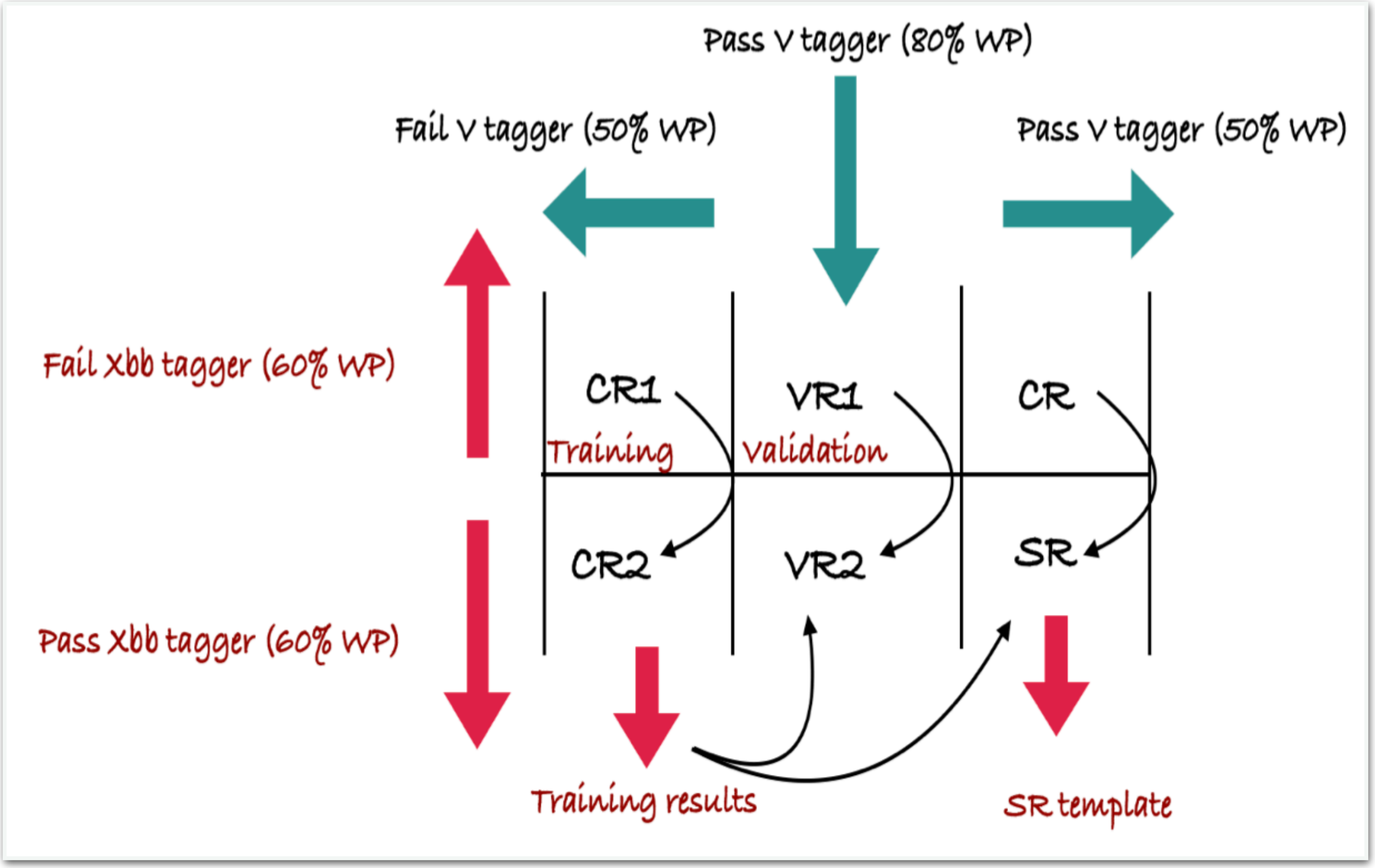
Summary & Conclusion

- Performed a **first dedicated search for production of *VH* associated production in boosted fully hadronic** final state
  - Higgs-boson transverse momenta towards TeV scale start to be at reach!
- Mass distribution of Higgs-candidate large-R jet fit to extract *VH* rate, both **inclusively** & **differentially in p_T**
  - Overall observed *VH* significance of **1.7σ**
  - Rates extracted in three p_T ranges: [250,450), [450,650), **≥650 GeV**
- **Paving the road for more & more dedicated searches for Higgs-boson production in the boosted all-hadronic phase space… stay tuned!**

BACKUP

The BDT Method

- BDT method: extract background templates from events failing both *V*- and *Hbb*-tagger requirements
  - MVA used to perform **kinematic reweighting**, by predicting event weights needed to bring shapes of kinematic distributions in CRs and SRs into agreement



Transfer Factor & BDT Methods

- Consistent multi-jet predictions between the two methods
  - Difference assumed as **alternative shape systematics**