Associated production of H($b\bar{b}$,$c\bar{c}$) with a W or a Z in ATLAS

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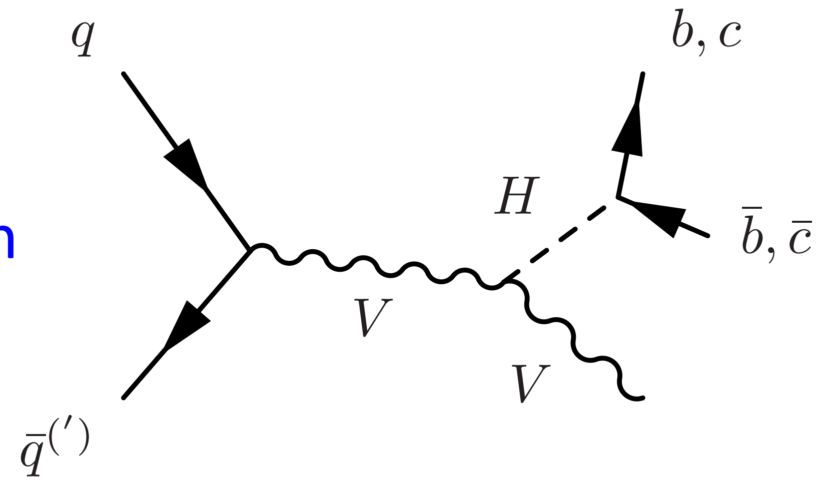
Introduction and Outline

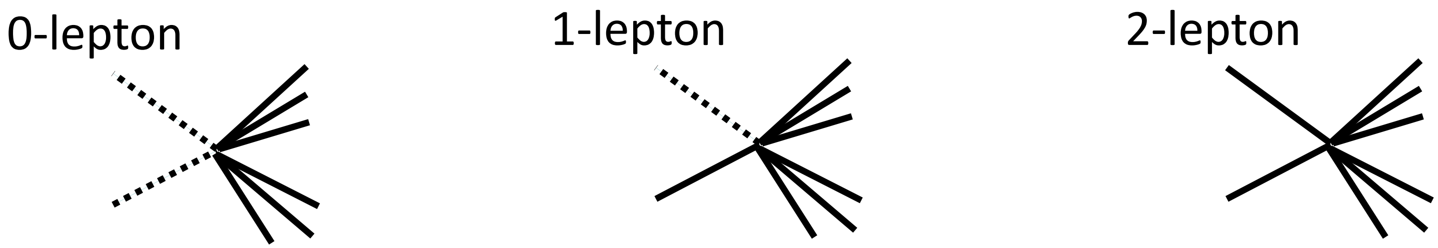
- Measurement of Hbb (& Hcc) couplings is a long-standing challenge
- Associated Higgs boson production with W or Z vector boson
  - Calculated at NNLO (QCD) + NLO (EW)
  - Clean signature to reject background
  - But 20x smaller cross sect. than gluon fusion



In this talk

- Overview of VH($b\bar{b}$) measurement strategy
- Multivariate event selection and background rejection
- Results for VH($b\bar{b}$) production, and combination with Run-1 data
- Results for benchmark VZ($b\bar{b}$) production
- Search for related ZH($c\bar{c}$) production in 13 TeV data

Measurement Strategy for VH($b\bar{b}$)



- Capture WH and ZH through 0-, 1-, and 2- charged lepton channels
  - Each channel divided into 2- and 3-jet categories to improve sensitivity
  - Focus on boosted V production: p_T > 150 GeV (75 GeV for 2-lepton)
- Tag b-jets to reconstruct Higgs boson candidate
  - Multivariate method based on impact parameter, vertexing, decay length
  - Dedicated b-jet energy corrections for energy losses from muons and neutrinos (plus kinematic fit in 2-lepton)
- Fits to data to determine Higgs vs. non-resonant background
  - Discriminating variable is output of kinematic Boosted Decision Tree
  - Floating normalizations in signal/control region channels and categories

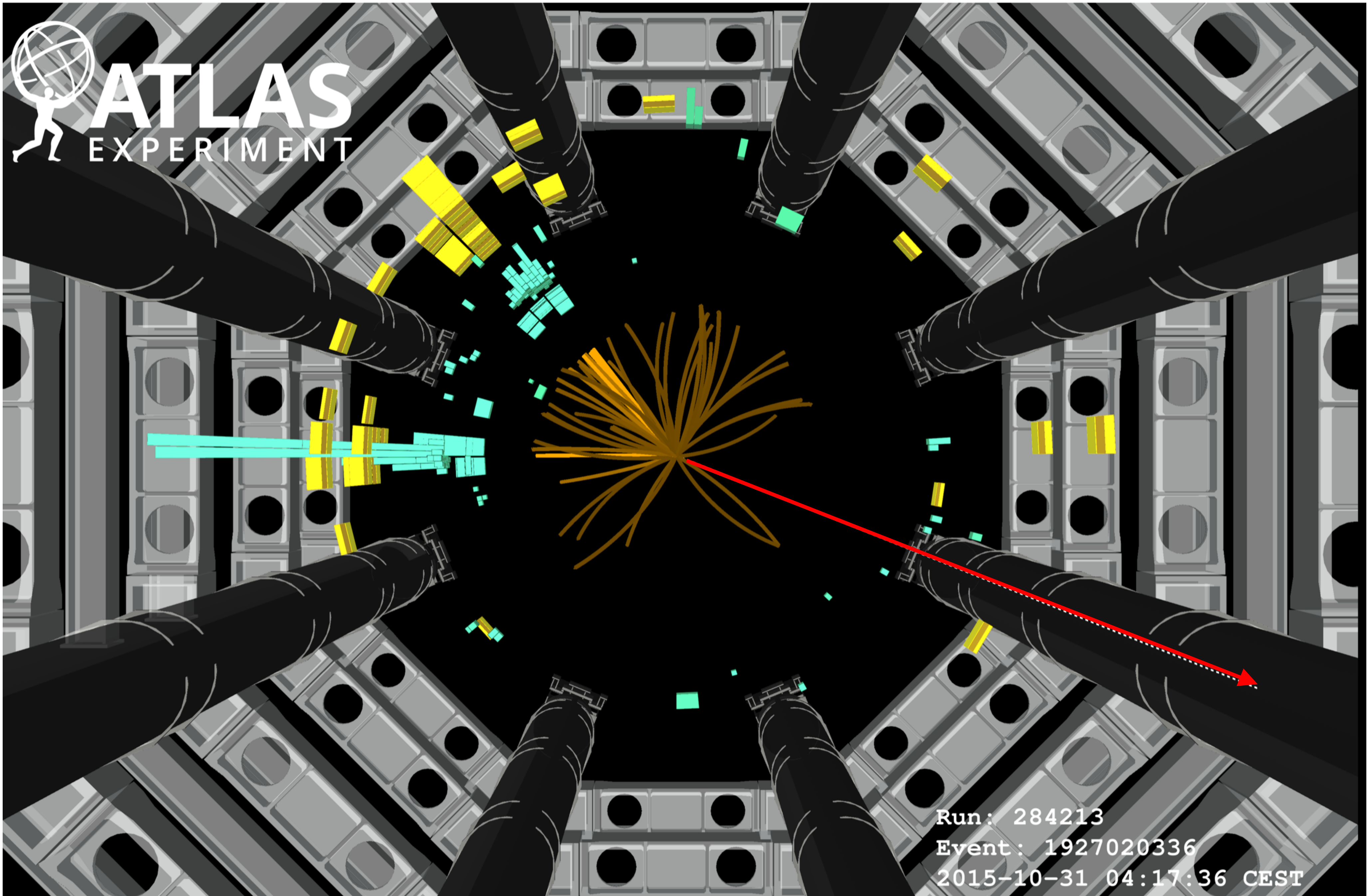
Event Selection & Background Rejection

- Basic event requirements:
  - 2 b-tagged jets with $p_T > 20$ GeV (lead jet $p_T > 45$ GeV)
  - Split into 2- and 3-jet samples
  - $E_T^{miss} > 150$ (0-lep), 30 GeV (1-ele)
  - p_T^V ranges vary by channel
    - $p_T^V > 150$ GeV for 0,1-lep
    - $75 > p_T^V > 150$ GeV or > 150 GeV for 2-lep
- Boosted Decision Tree trained in each signal region
  - Use event-level BDT variables, including m_{bb}, in TMVA

Event kinematic variables used in BDT training

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	$\times$	$\times$
E_T^{miss}	$\times$	$\times$	$\times$
$p_T^{b_1}$	$\times$	$\times$	$\times$
$p_T^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\vec{b}_1, \vec{b}_2)$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\vec{b}_1, \vec{b}_2)\rvert$	$\times$		
$\Delta\phi(\vec{V}, \vec{bb})$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			$\times$
m_{eff}	$\times$		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		$\times$	
m_T^W		$\times$	
$m_{\ell\ell}$			$\times$
m_{top}		$\times$	
$\lvert\Delta Y(\vec{V}, \vec{bb})\rvert$		$\times$	
	Only in 3-jet events		
$p_T^{\mathrm{jet}_3}$	$\times$	$\times$	$\times$
m_{bbj}	$\times$	$\times$	$\times$

2-b-tag 2-jet 0-lepton Candidate Event



Strategies for Estimating Background

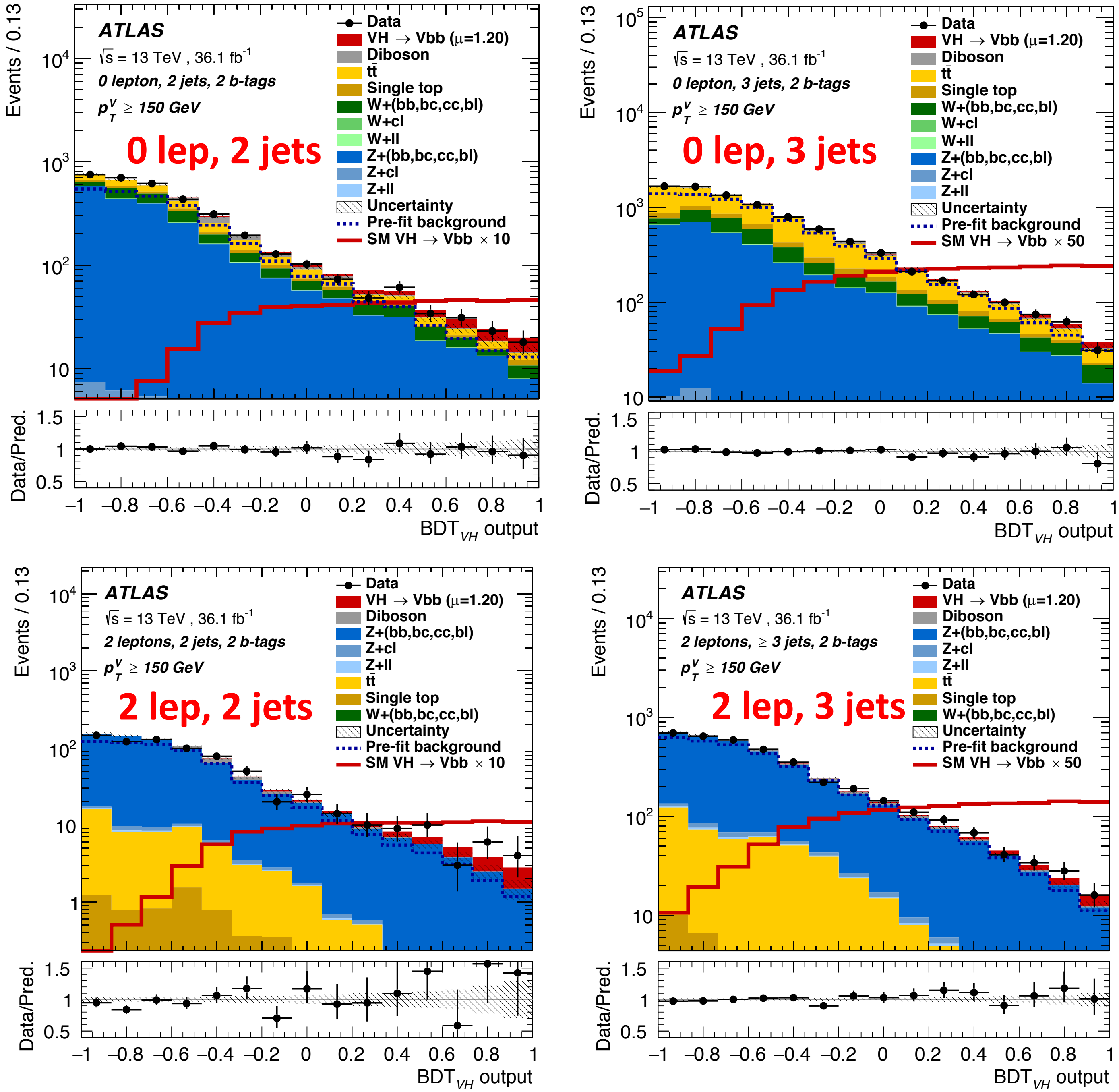
- Background fractions differ between signal regions
  - Fit templates from simulation to find floating normalization factors, especially for W/Z+heavy flavor and $t\bar{t}$ backgrounds

Combine for Z+HF norm.

	2-jet	3-jet	Control regions	
0-lepton	Z+HF, $t\bar{t}$	$t\bar{t}$, Z+HF		
1-lepton	$t\bar{t}$, W+HF	$t\bar{t}$	W+HF	$m_{bb} < 75$ $m_{top} > 225$
2-lepton	Z+HF, $t\bar{t}$	Z+HF, $t\bar{t}$	$t\bar{t}$	$e\mu$ pair

Separate to fit all normalization factors

Example: Z+Heavy Flavor Backgrounds



Post-fit results with all normalization factors applied

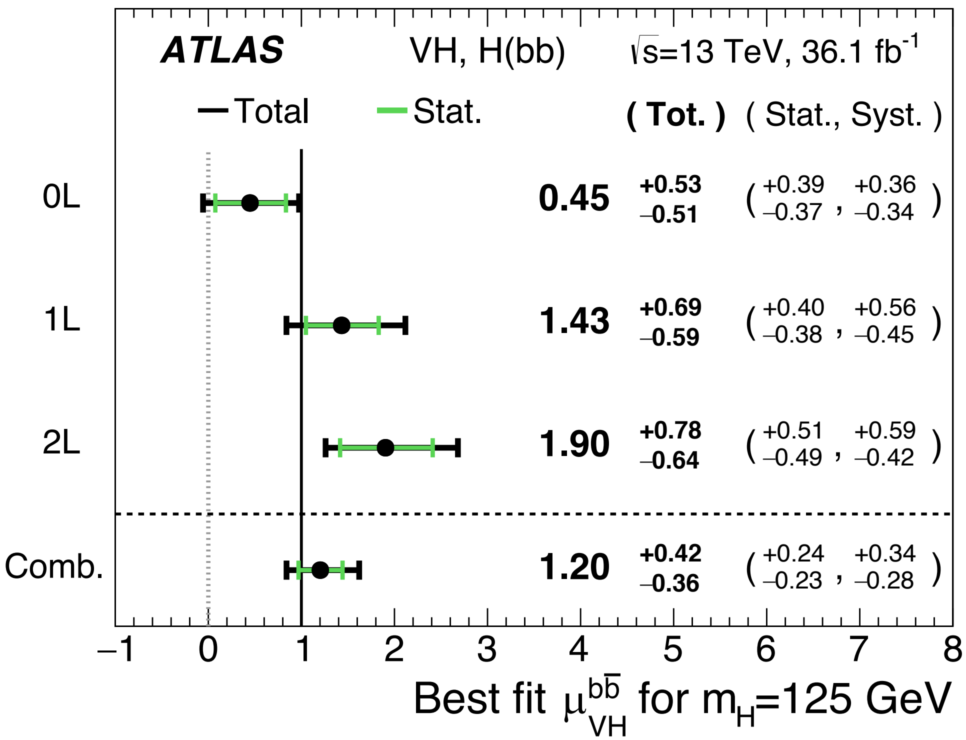
- Enough data to constrain Z+HF & W+HF separately in 2- & 3-jet events

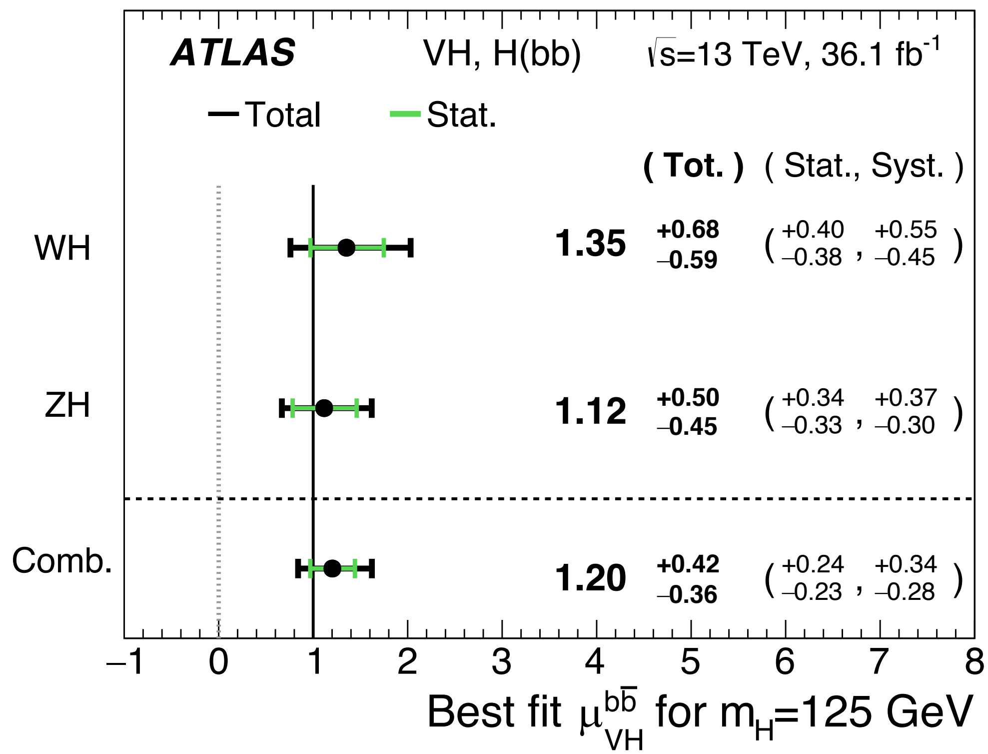
Process	Normalization
W + HF 2-jet	1.22 ± 0.14
W + HF 3-jet	1.27 ± 0.14
Z + HF 2-jet	1.30 ± 0.10
Z + HF 3-jet	1.22 ± 0.09

- Top is constrained in 0- & 1-lep combined, plus separate 2-lep 2- and 3-jet categories

VH Measurement Results @ 13 TeV

- Overall fitted signal strength $\mu = 1.20^{+0.24}_{-0.23}\,(\text{stat.})^{+0.34}_{-0.28}\,(\text{syst.})$
  - Observed excess 3.5σ significance (3.0σ expected)



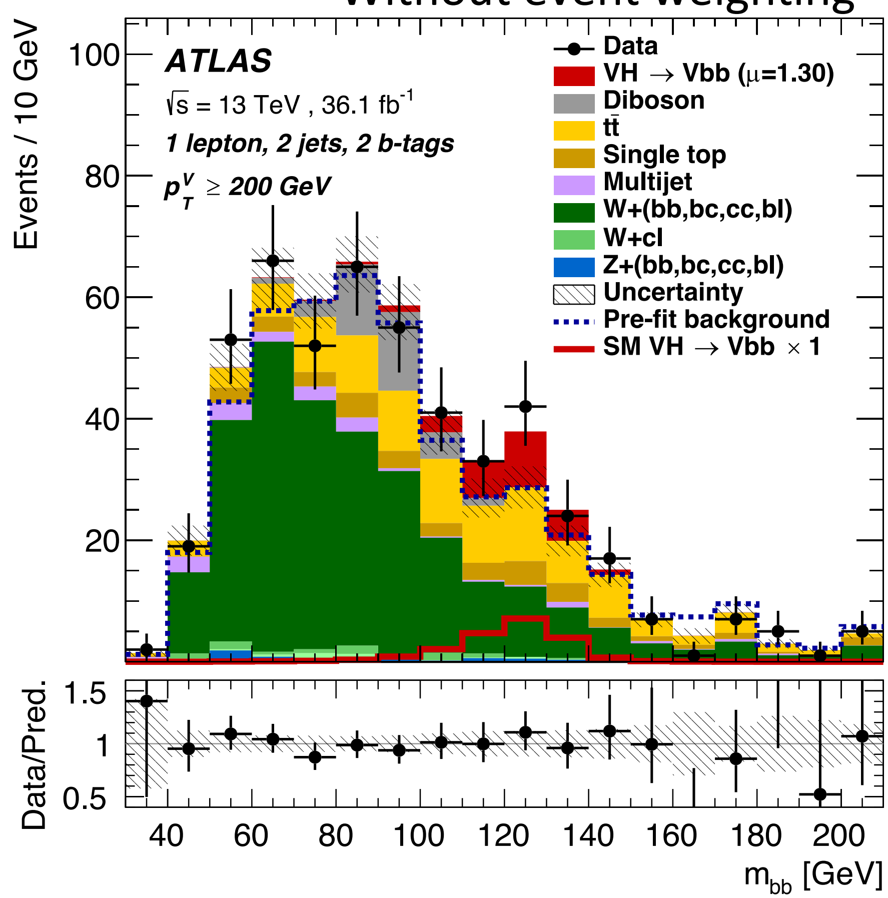


- Measurements of WH and ZH rates consistent with SM
  - $\sigma(WH) \times B(H \to b\bar{b}) = 1.08^{+0.54}_{-0.47}$ pb
  - $\sigma(ZH) \times B(H \to b\bar{b}) = 0.57^{+0.26}_{-0.23}$ pb

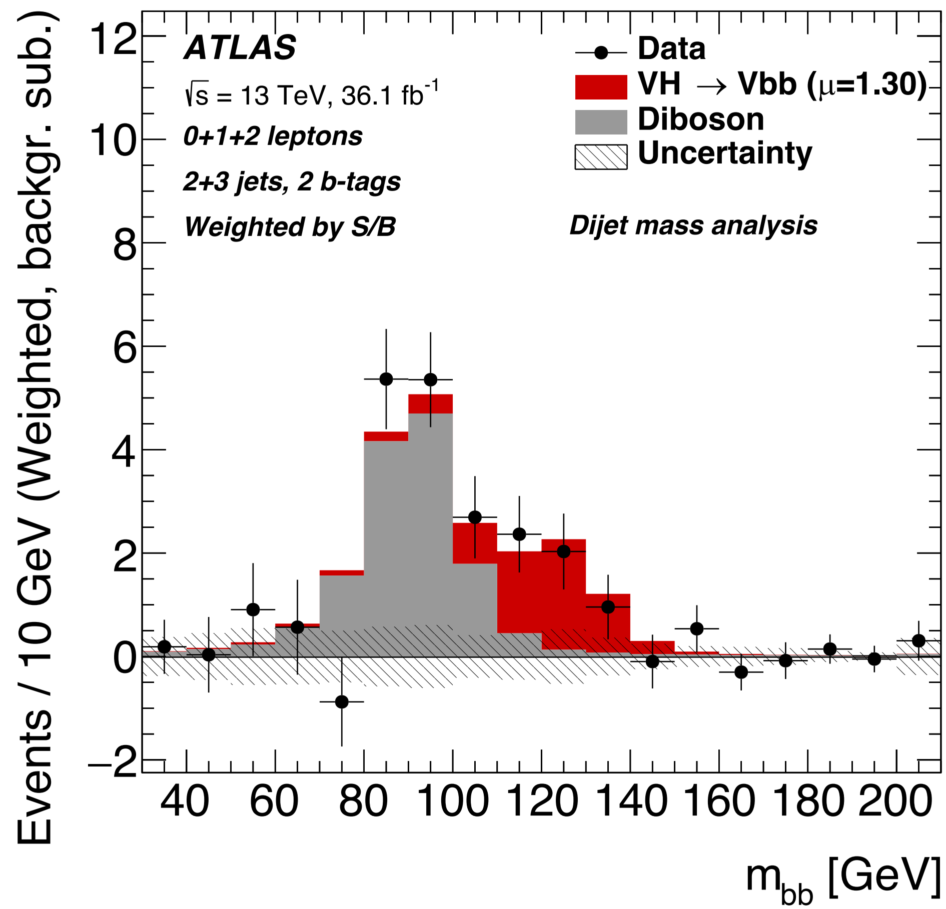
Cross-Check Measurement with mbb

- Alternative fit to m_{bb} with tighter selection, more regions
- Irreducible $VZ(b\bar{b})$ background kinematically similar to VH

Without event weighting

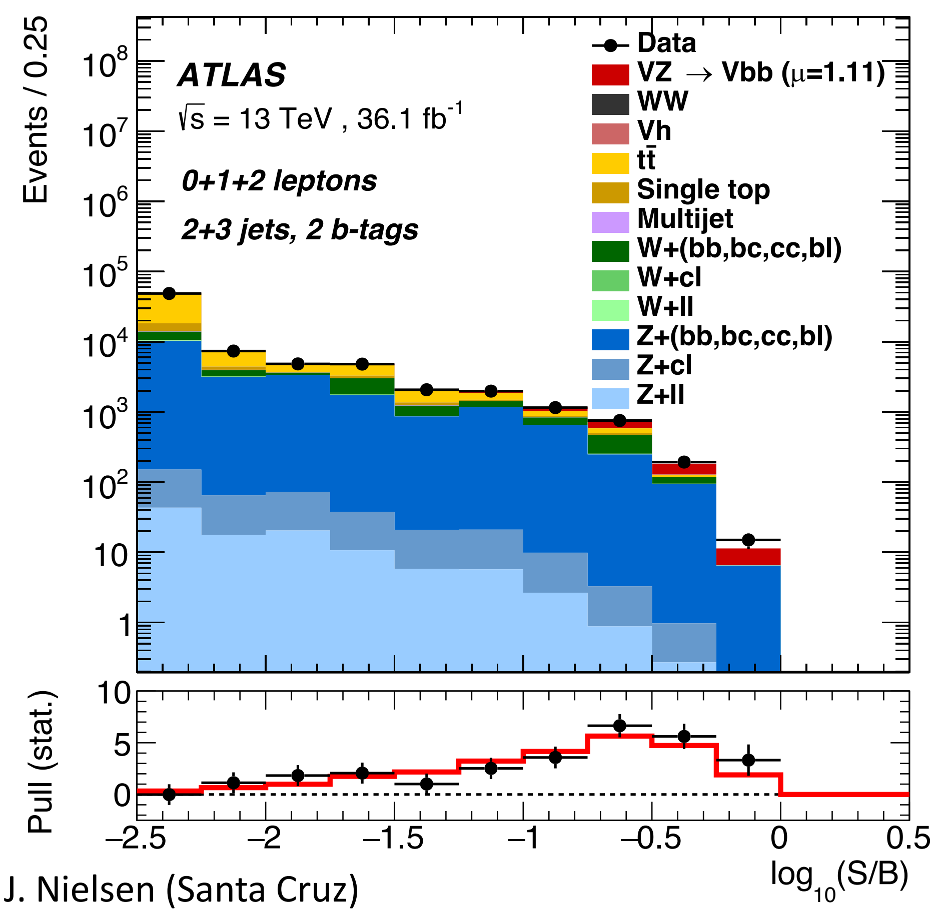


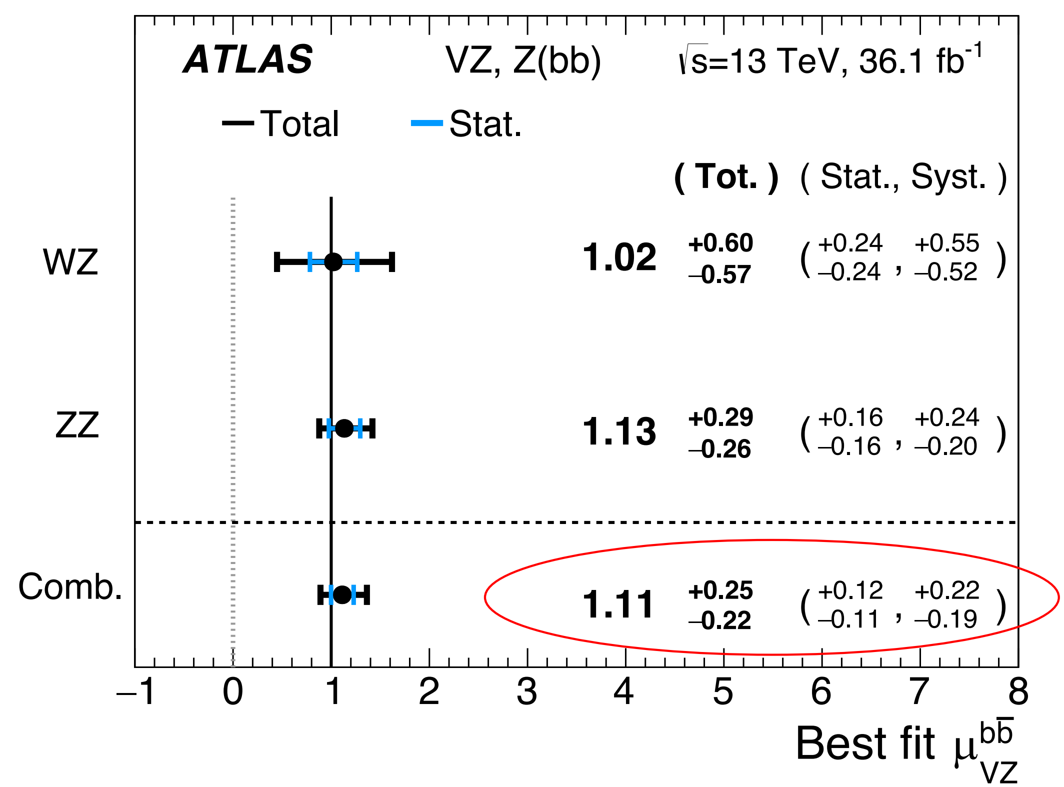
With S/B event weighting



VZ Result from Diboson Analysis

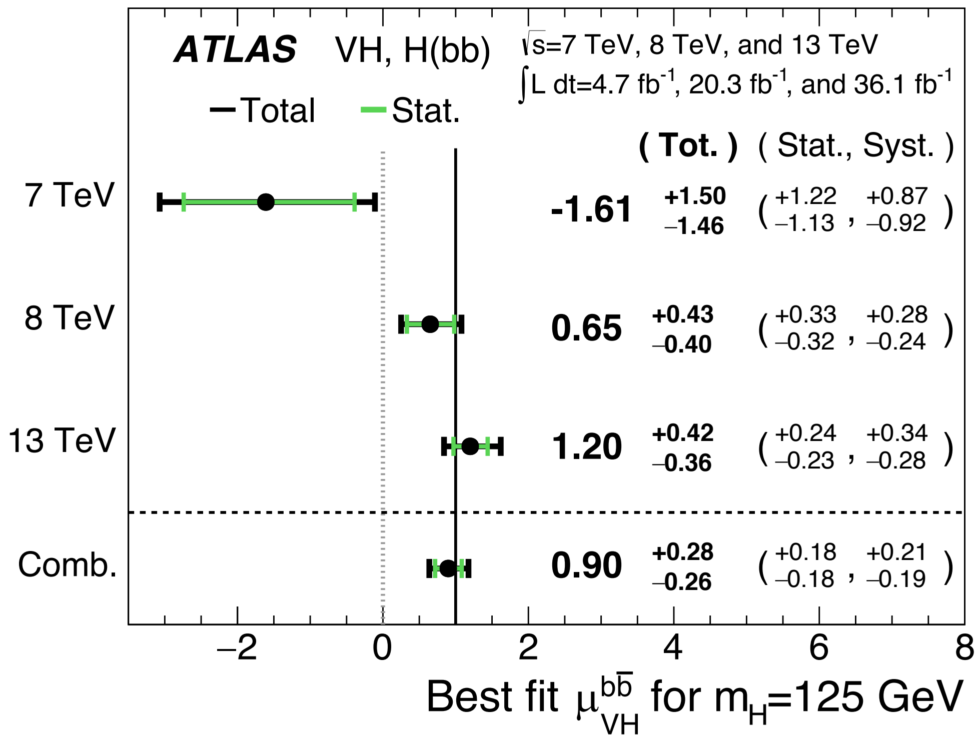
- Train a separate BDT_{VZ} adapted for softer m_{bb}, p_T spectra
  - In this fit, Higgs VH production is treated as a background!
  - Result is a $VZ(b\bar{b})$ measurement with 5.8σ significance
  - This is a very good validation of the Higgs boson analysis

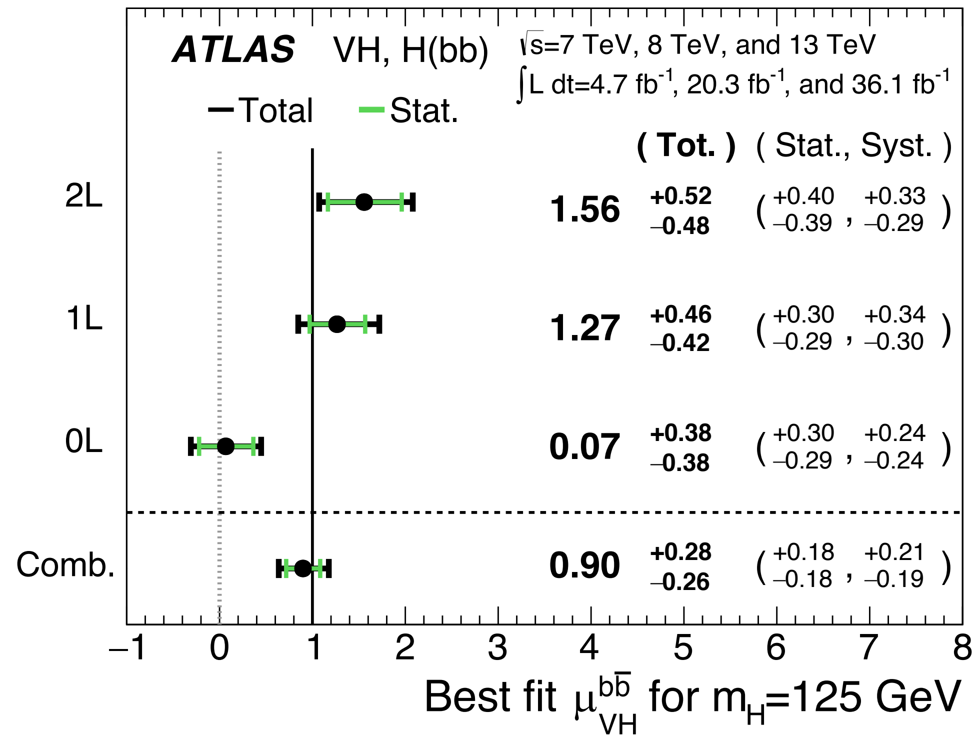




Combined ATLAS VH($b\bar{b}$) Results

- Comparison with 7 & 8 TeV results from LHC Run 1
  - Use the signal strength μ_{VH} for different values of √s
  - Combined observed significance 3.6σ (4.0σ expected)





- Consistent with Standard Model, so far…

Focus on Dominant Uncertainties

- WH and ZH signal acceptance:
  - Uncertainties in V p_T and m_{bb} due to missing higher orders, PS tune
- Monte Carlo statistics:
  - Few events with high-p_T, 2-b-tags, and high BDT values
- Background normalizations
  - Control of backgrounds will improve with more data in CRs
- B-tagging efficiency:
  - MC-to-data correction factors, parameterized in p_T, $|\eta|$

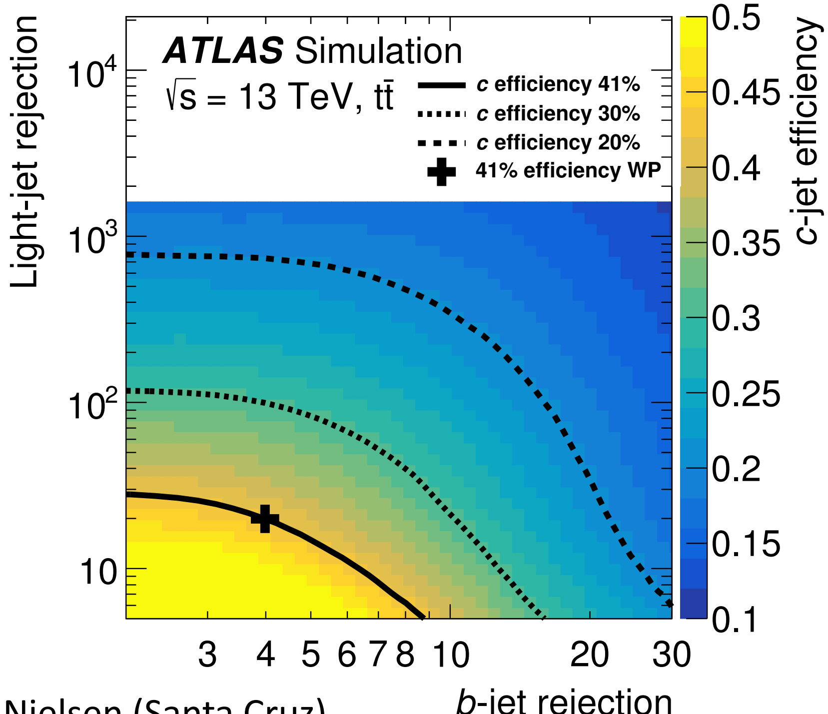
Prospects for improvements!

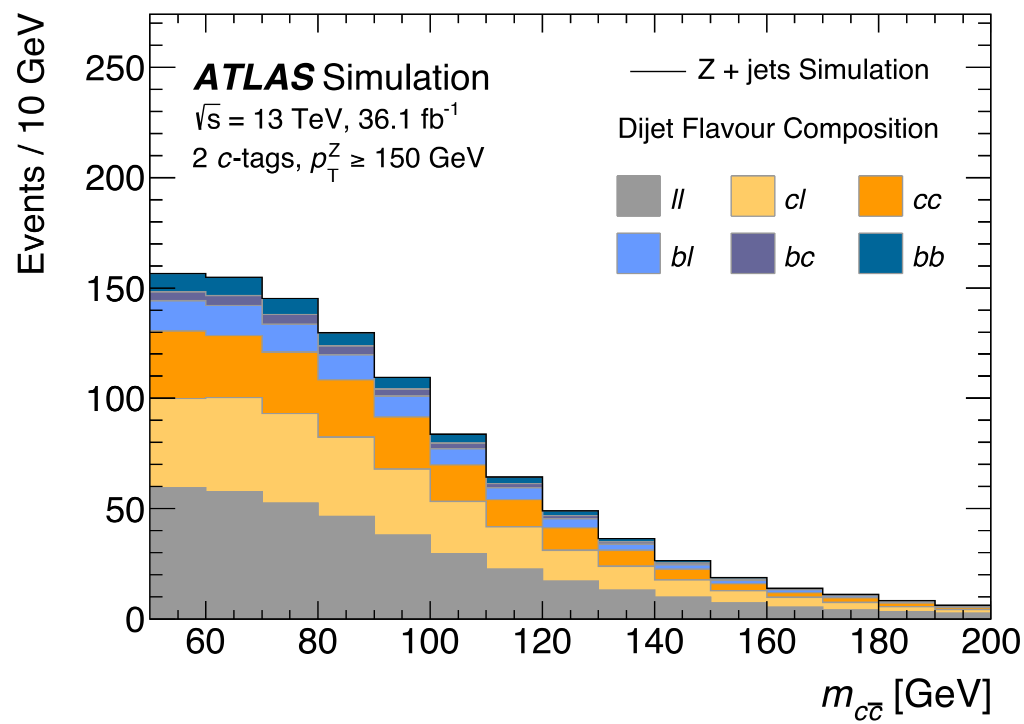
From 13 TeV results only

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z + jets		0.07
W + jets		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

Search for ZH($c\bar{c}$) Production

- New inclusive approach to constrain Hcc coupling
  - Focus on 2-lepton channel for simpler background composition
- Dedicated multivariate discriminants similar to b-tagger:
  - Separate c-jets from light-jets and c-jets from b-jets
  - Challenges of short τ_c , low track multiplicity in c-hadron decays
  - Both 1 c-tag and 2 c-tag events are used to keep efficiency high

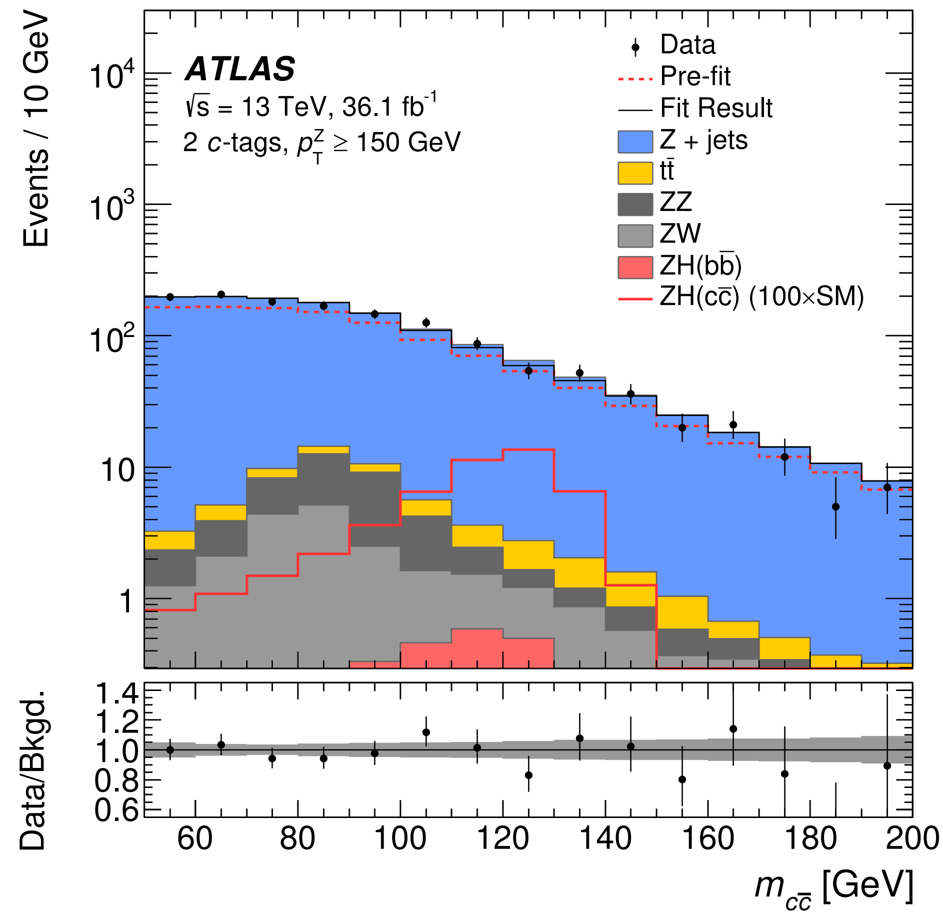




Results for ZH($c\bar{c}$) and ZZ/ZW

Cut-based event selection with fit to m_{cc}

- Target $c\bar{c}$ resonances
  - Requirement on ΔR_{cc} varies from 2.2 at low p_T^Z to 1.3 at high p_T^Z (>200 GeV)
  - p_T^Z ranges 75-150, >150 GeV
- Simultaneous fit of signal and Z+jets background
  - Flavor tagging uncertainty is dominant limitation on uncert.



Validation: $\mu_{ZV} = 0.6^{+0.5}_{-0.4}$
(1.4σ observed, 2.2σ expected)

Observed upper limit of 2.7 pb on $\sigma(ZH) \times B(H \to c\bar{c})$
(SM predicts 26 fb at 13 TeV)

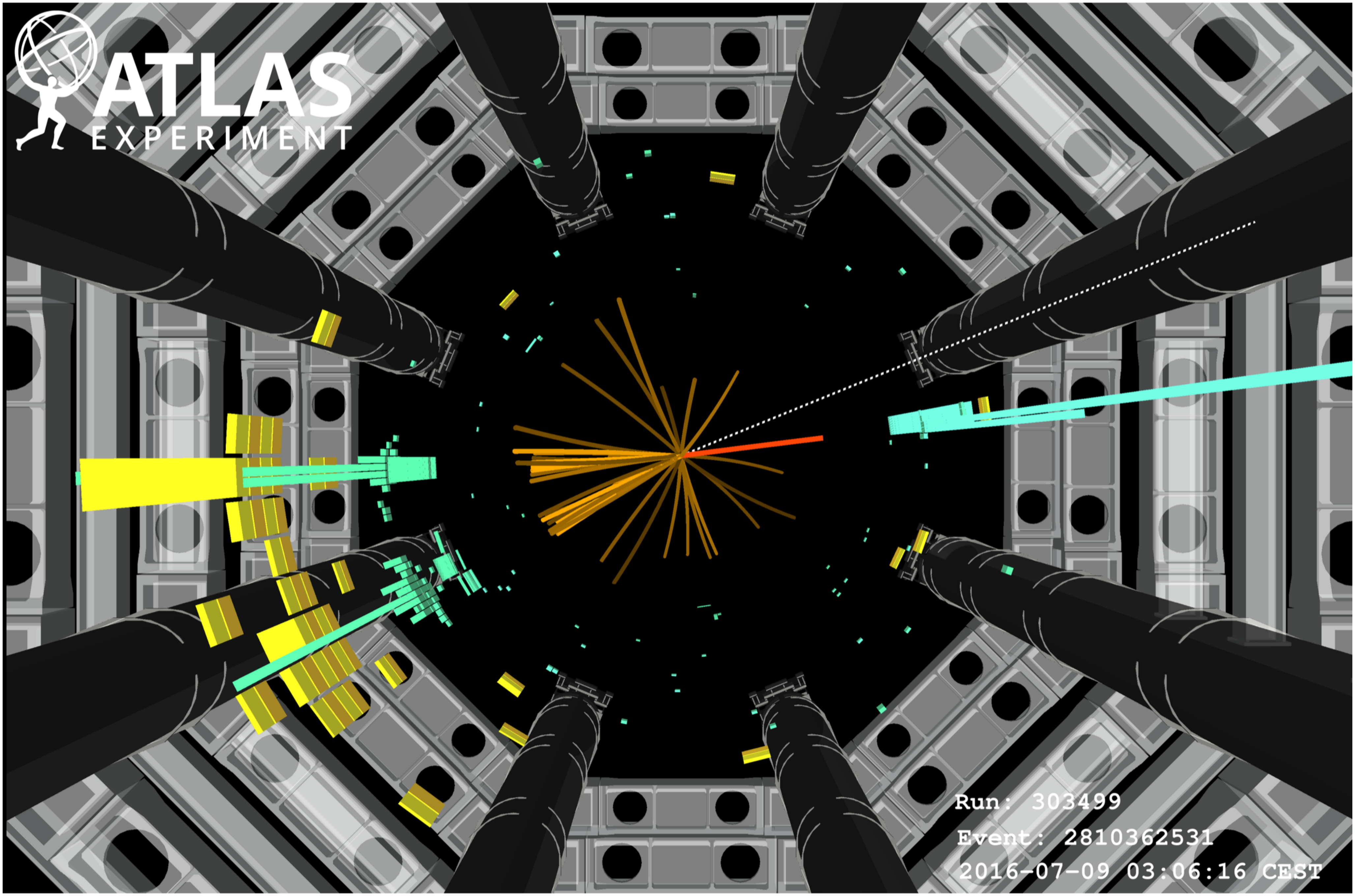
Summary and Conclusions

- Updated Run-2 ATLAS evidence for $H(b\bar{b})$ in VH production
  - 3.5σ observed significance in 13 TeV result: σ(VH) x BR($b\bar{b}$) = $1.58^{+0.55}_{-0.47}$ pb
  - Combination with Run-1 results: $\mu = 0.90 \pm 0.18\,(\text{stat.})^{+0.21}_{-0.19}\,(\text{syst.})$

- New ATLAS limit on Higgs ZH production and decay to $c\bar{c}$
  - σ x BR limit of 2.7 pb is most stringent yet in direct searches for $H(c\bar{c})$

- For further details on the published results:
  - $VH(b\bar{b})$ result with 36.1 fb^{-1} at 13 TeV & combination: JHEP 12 (2017) 024
  - $ZH(c\bar{c})$ result with 36.1 fb^{-1} at 13 TeV: arXiv:1802.04329 (submitted to PRL)

Looking forward to more 13 TeV data and improved measurements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