Higgs Decays to Third-Generation Fermions at ATLAS

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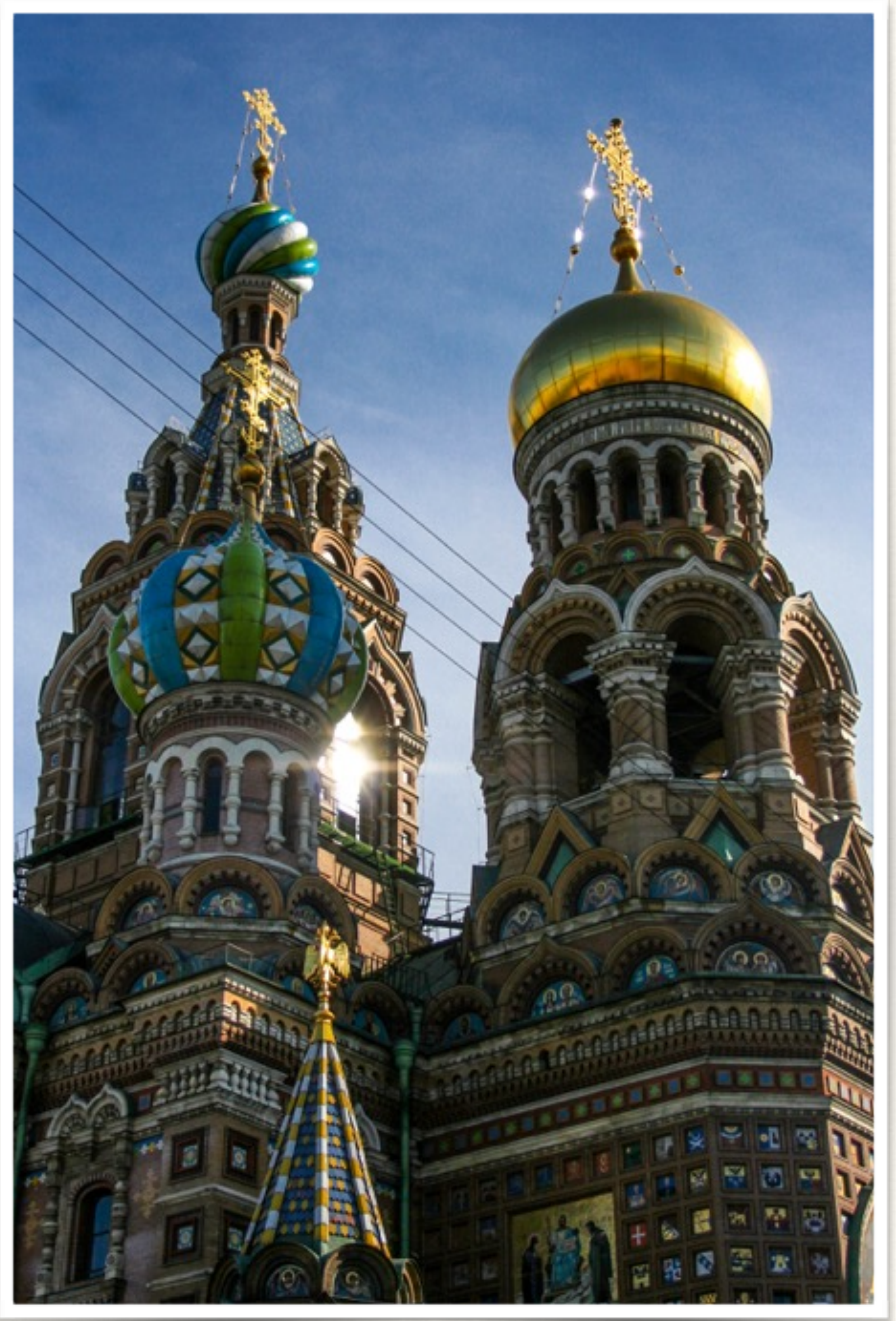
[CERN]

October 1st 2019
Higgs Couplings
Oxford



Motivation

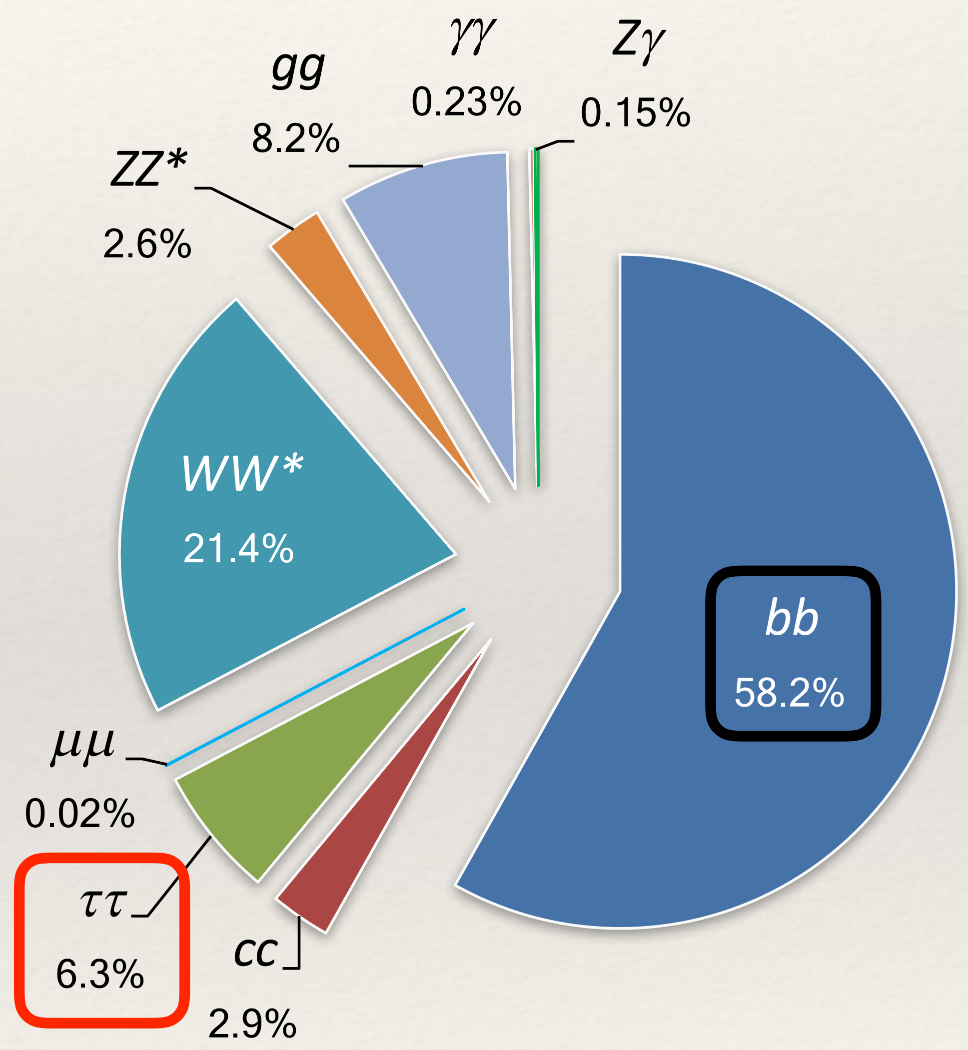
CP Properties in VBF production ($\tau\tau$ final state) covered in Alena Loesle's talk tomorrow afternoon!

- Higgs Boson properties (mass, production rates, spin/CP) are predominantly constrained by measurements of the bosonic decay modes
- However, Higgs decays to third generation fermions (taus, b-quarks), while experimentally more challenging, offer a unique opportunity to **directly probe the Standard Model Yukawa couplings**
  - Such measurements are highly complementary, as they provide important inputs to the global Higgs fits and allow to constrain Beyond the Standard Model phenomena
  - Both b-jets and hadronically-decaying taus are **complex physics objects** which require an **excellent understanding** of both tracking and calorimeter observables, and their combination through the use of **multivariate techniques**
- The large dataset provided by Run-II means these measurements are transitioning from the *'observation'* regime to *'precision measurements'*

Third Generation Decays

2nd generation decays covered in Jan Kretzschmar's talk this afternoon!

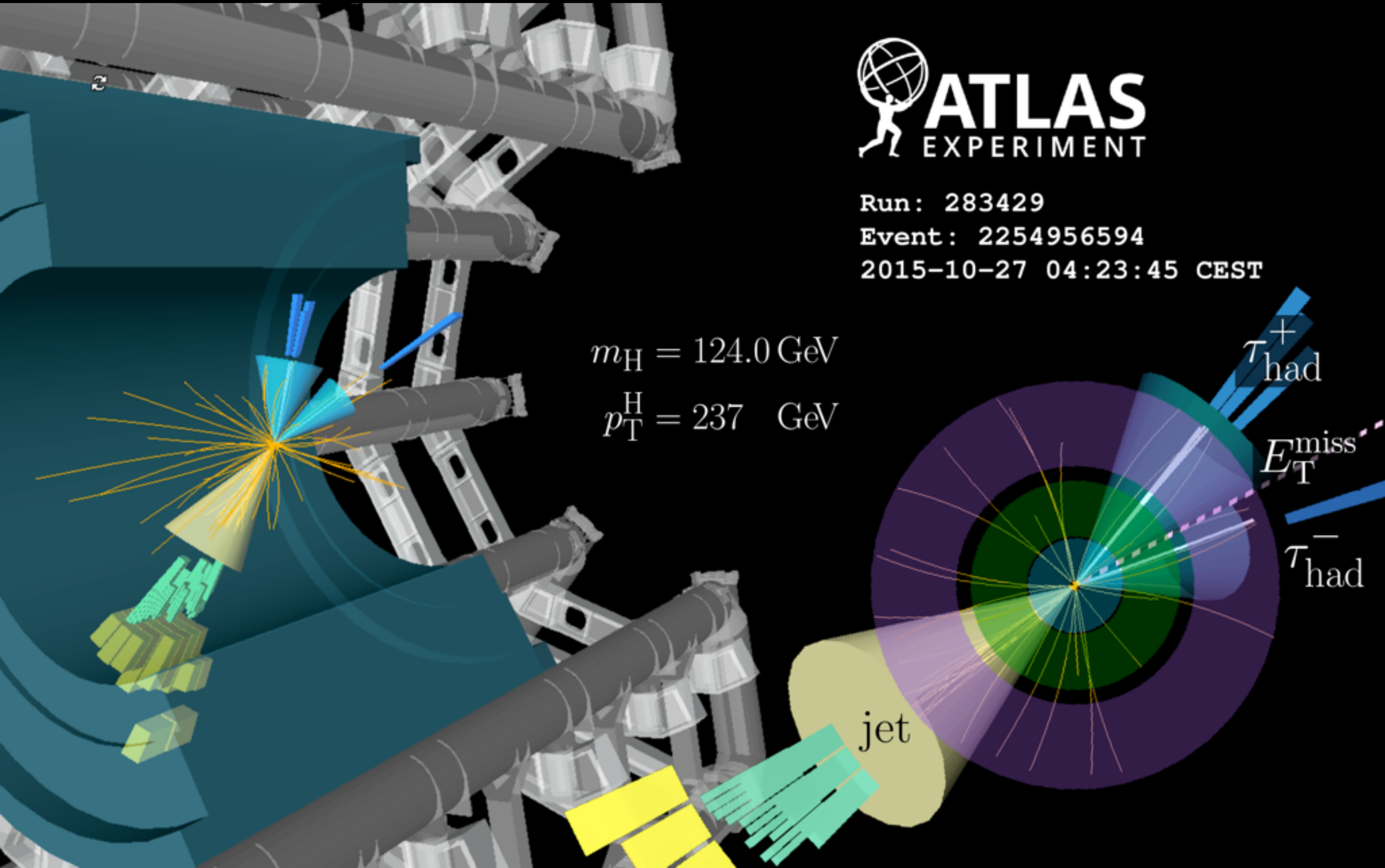
- **Covered in this talk:**
  - $H \to \tau\tau$ (BR ~ 6.3%)
    - Presence of neutrinos in the tau decays leads to a degradation in the mass resolution which leads to significant backgrounds from Z sources
    - Large multi-jet induced backgrounds in all channels containing hadronically-decaying taus
  - $H \to bb$ (BR ~ 58%)
    - Significant multi-jet induced background means that the predominant gluon-gluon fusion production mode cannot be exploited
    - Requires excellent performance for the identification of b-jets, and precise determination of the associated systematics



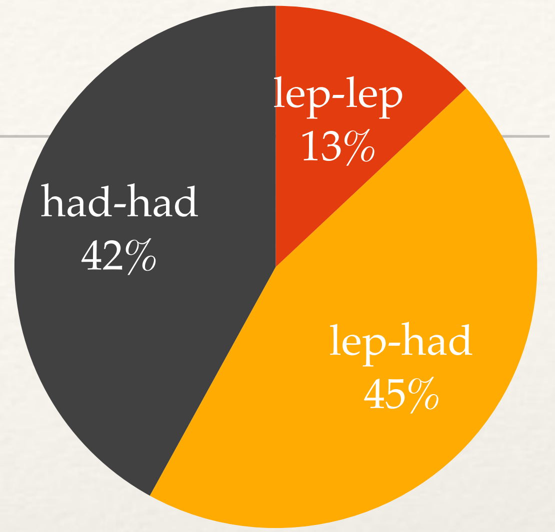
The Measurements

$H \to \tau\tau$ (36 fb^{-1})

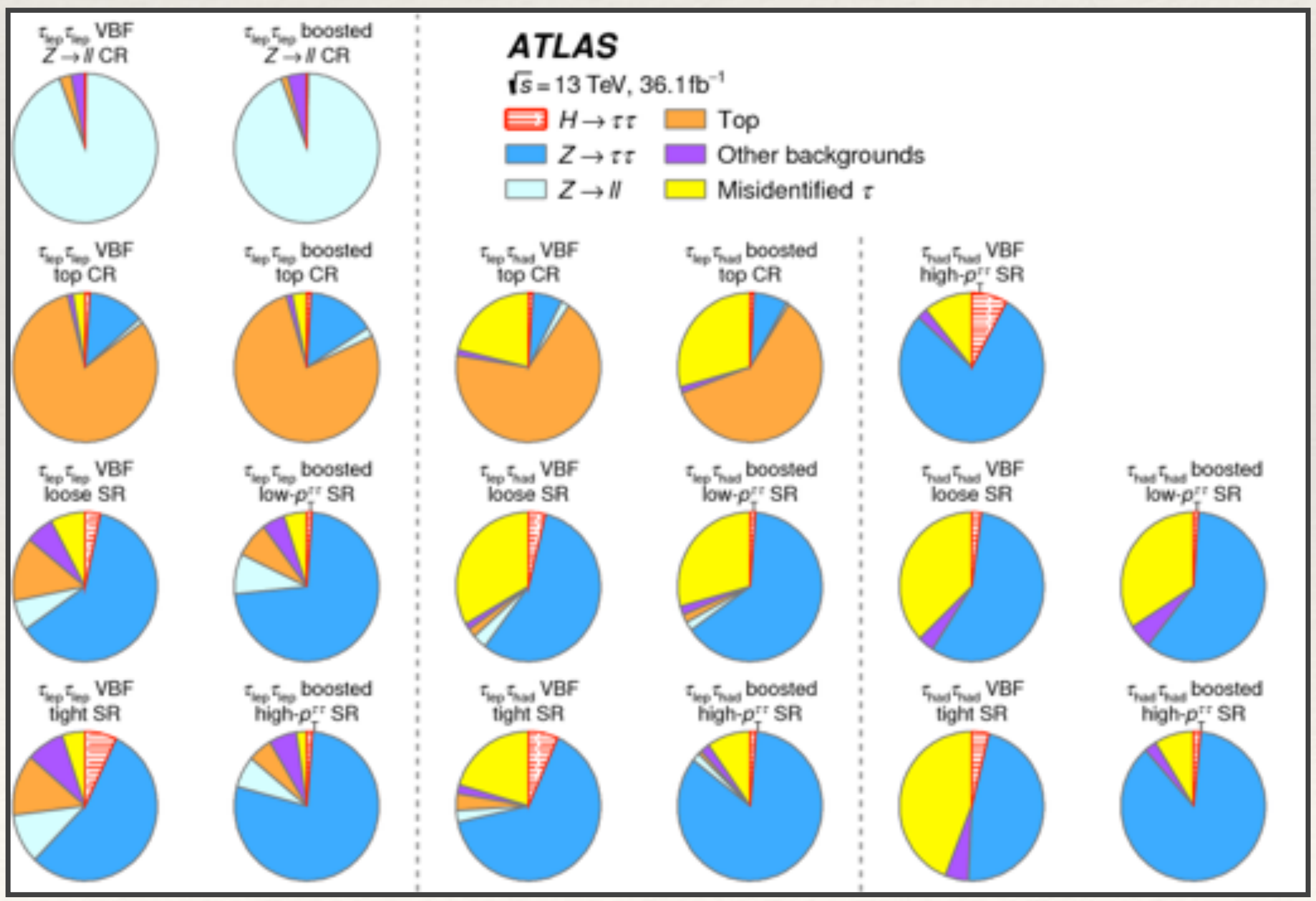
[Phys. Rev. D 99 (2019) 072001]

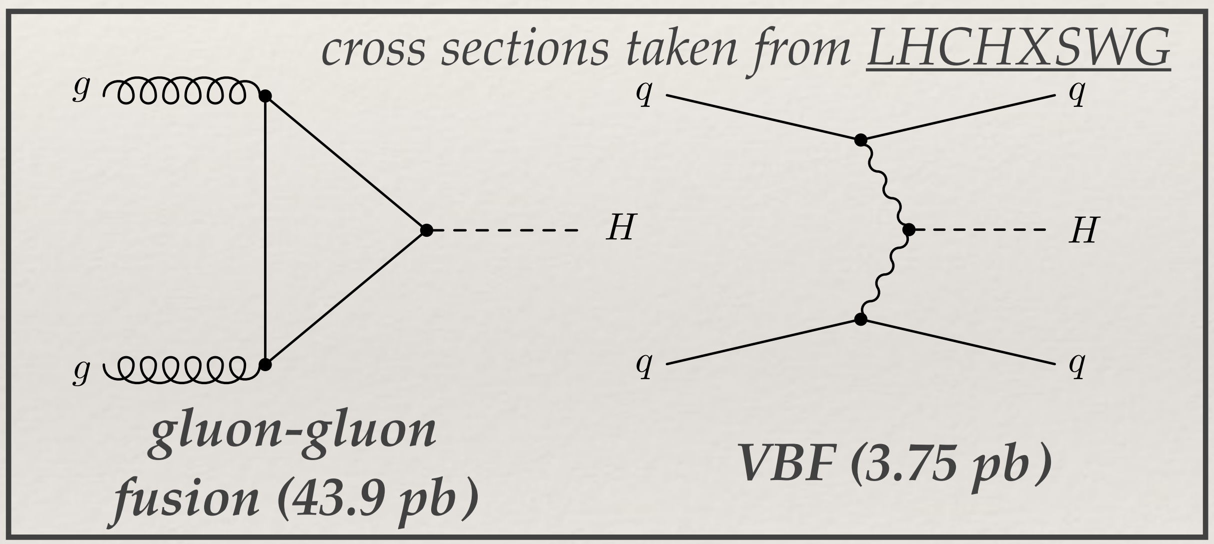


Measurement Strategy



- All tau decay combinations are exploited, giving rise to three channels ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$)
- Analysis targets both *gluon-gluon fusion* and *VBF production* modes through dedicated signal region (SRs) selections



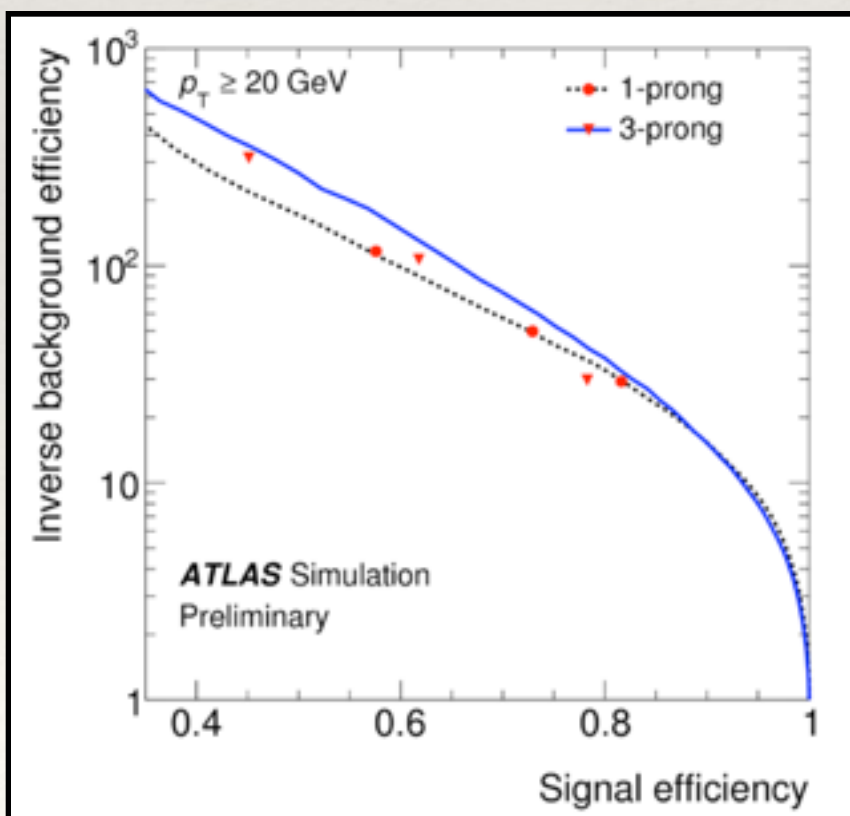


- Dedicated Control Regions (CRs) are defined to control $Z \to ll$ and Top contributions
- **In total: 13 SRs and 6 CRs**

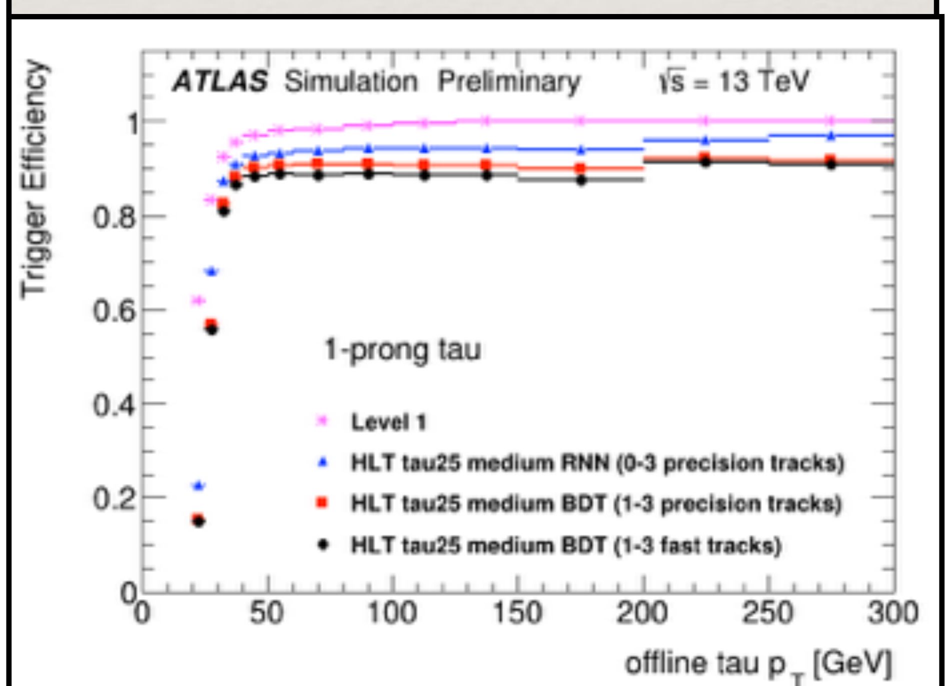
Interlude: ATLAS Tau Performance

- High jet and light-lepton induced **background rejection**, **low p_T thresholds**, and good **energy resolution** are crucial ingredients in maximizing sensitivity in channels with hadronically-decaying taus

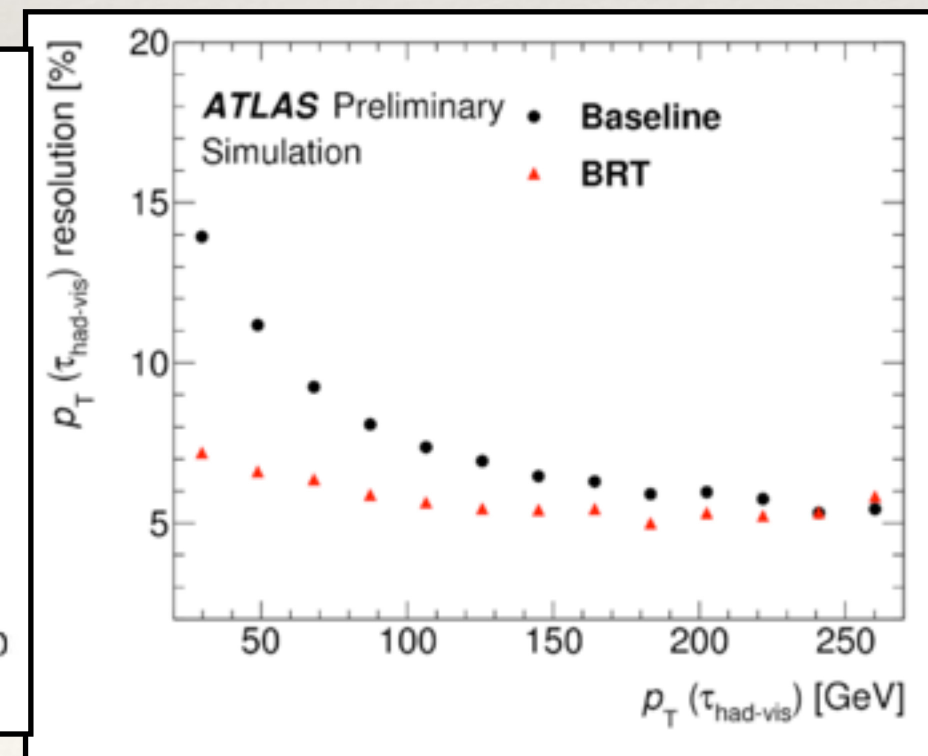
BDT-based tau identification algorithm



Di-hadronic Tau Trigger
With ~40 and 30 GeV offline thresholds
Uses topology requirements to control rates

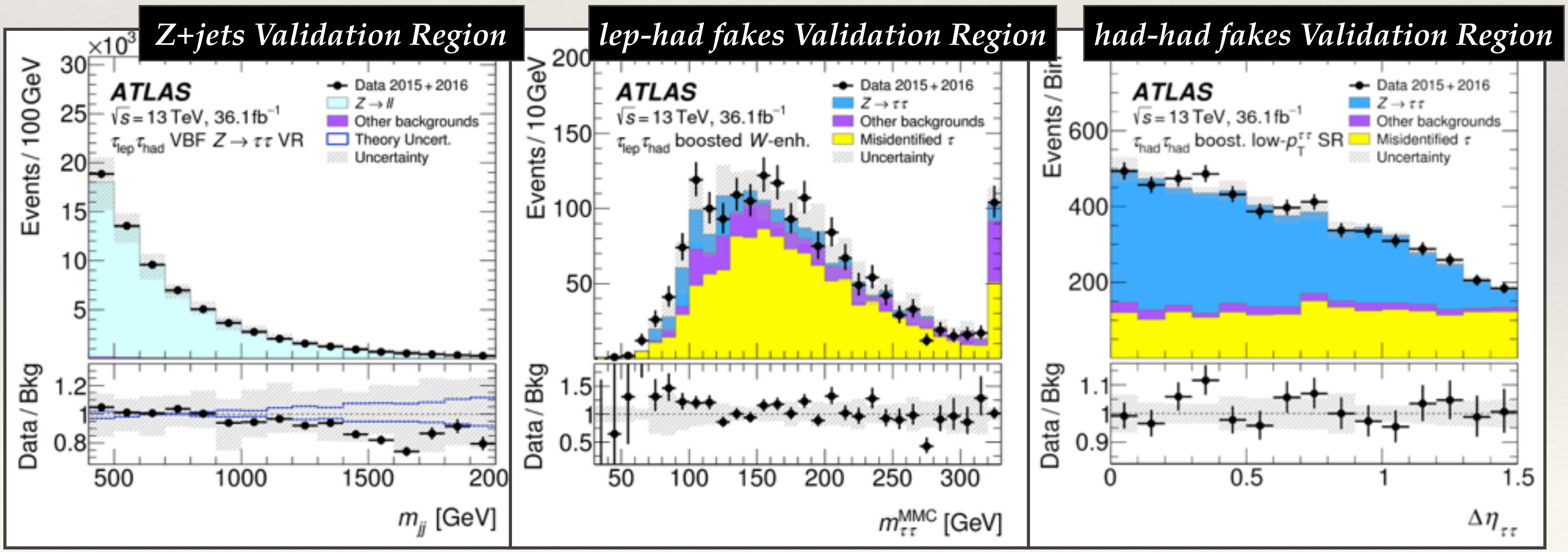


Multivariate Energy Calibration
(Particle Flow Inputs)



Dominant Backgrounds

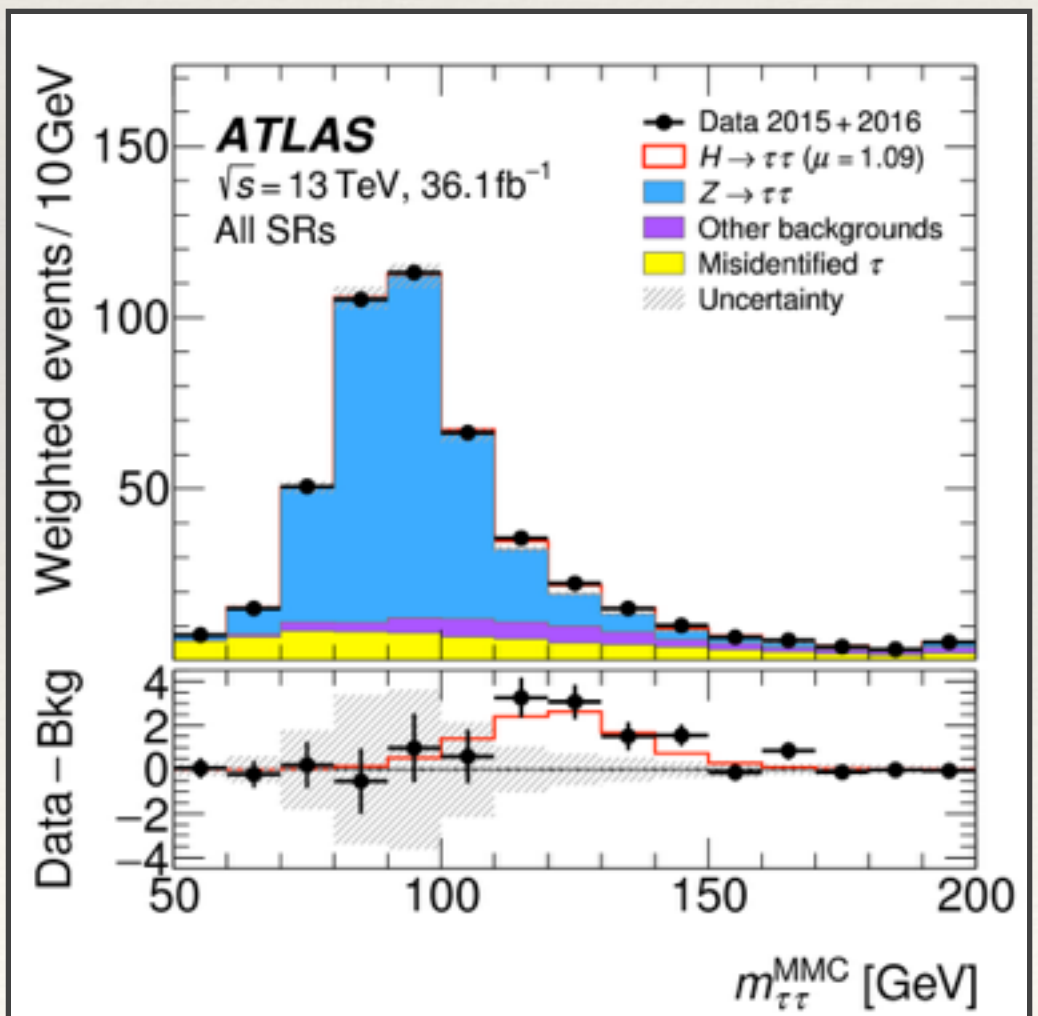
- **Z+jets production:** Estimated from Sherpa NLO MC simulations (normalization floated in the fit, decorrelated in VBF and boosted phase spaces)
  Main challenge: *Ensuring proper modelling of the recoiling jet system in both high boost and high di-jet mass phase space [in-depth scrutiny in dedicated Validation Regions]*
- **Misidentified ('fake') taus:** Estimated using data-driven methods
  Main challenge: *Ensuring the phase space dependencies are well taken into account [Fake-factor & ABCD extrapolation methods]*

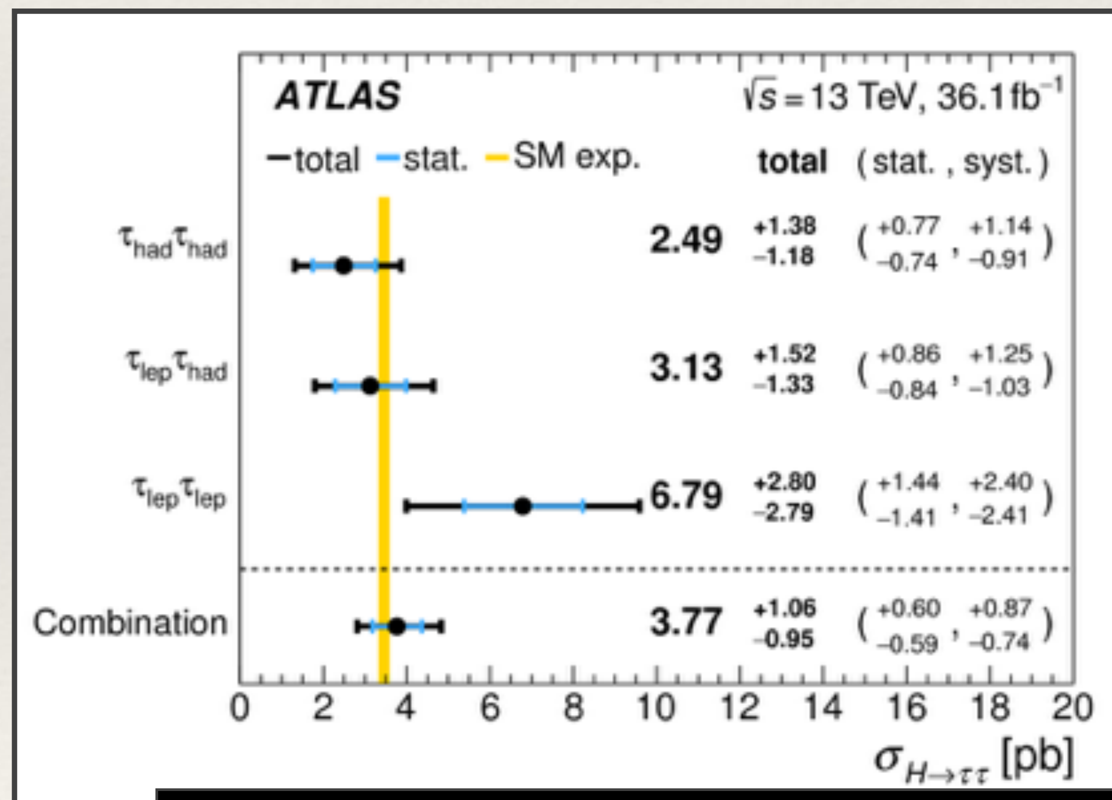


Fit & Results

Recent MMC studies covered in Krystsina Petukhova's talk this afternoon!

- Simultaneous likelihood fit in all SRs and CRs with both Higgs signal strength and individual gluon-gluon fusion and VBF production rates as Parameters of Interest
- Missing Mass Calculator distribution ($m_{\tau\tau}^{MMC}$) used as the fit variable (uses E_T^{miss} and tau mass/decay kinematics to form neutrino hypotheses [ref.])
- Combination with Run-I result adds up to single experiment observation (significance of 6.4σ [5.4 exp.])





Results are in agreement with the SM predictions with relative uncertainties of ~16% (stat.) and ~23% (syst.) [~28% total]

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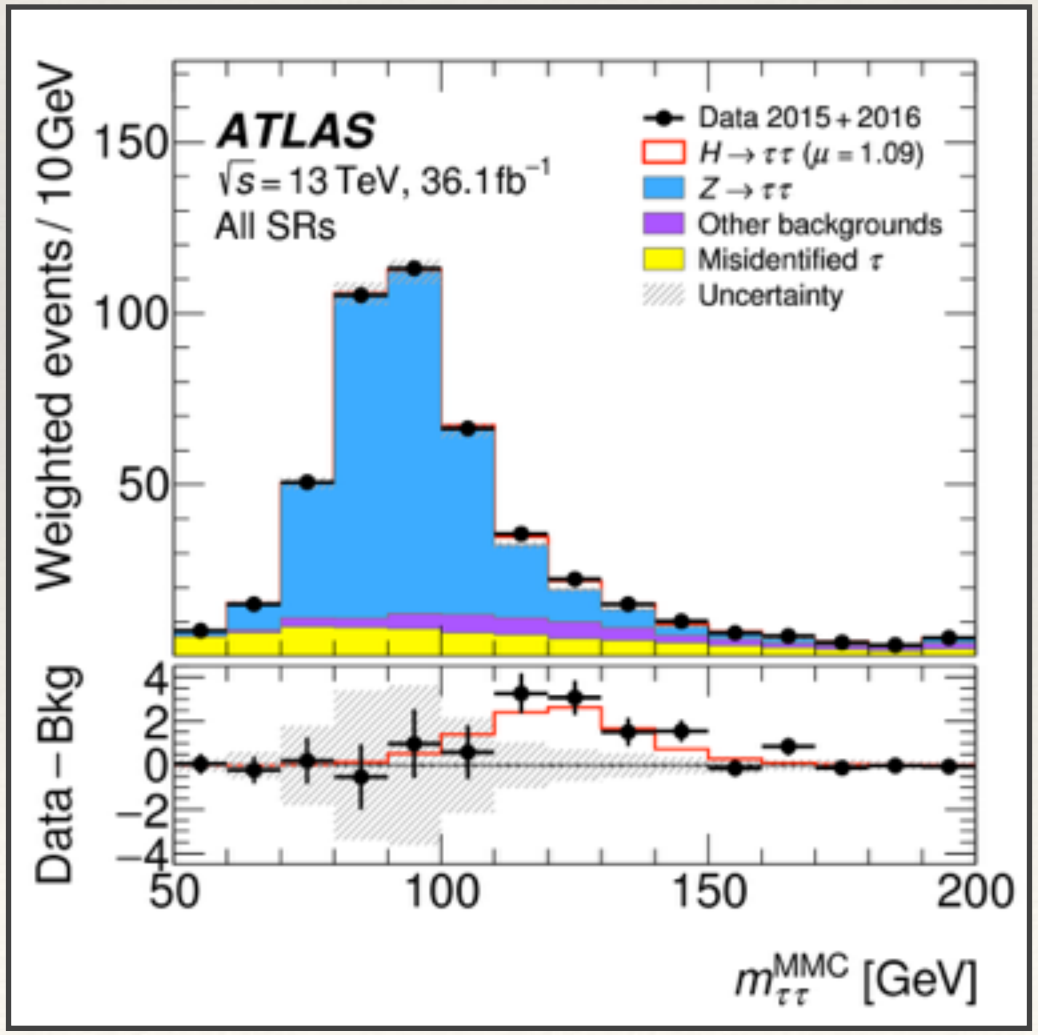
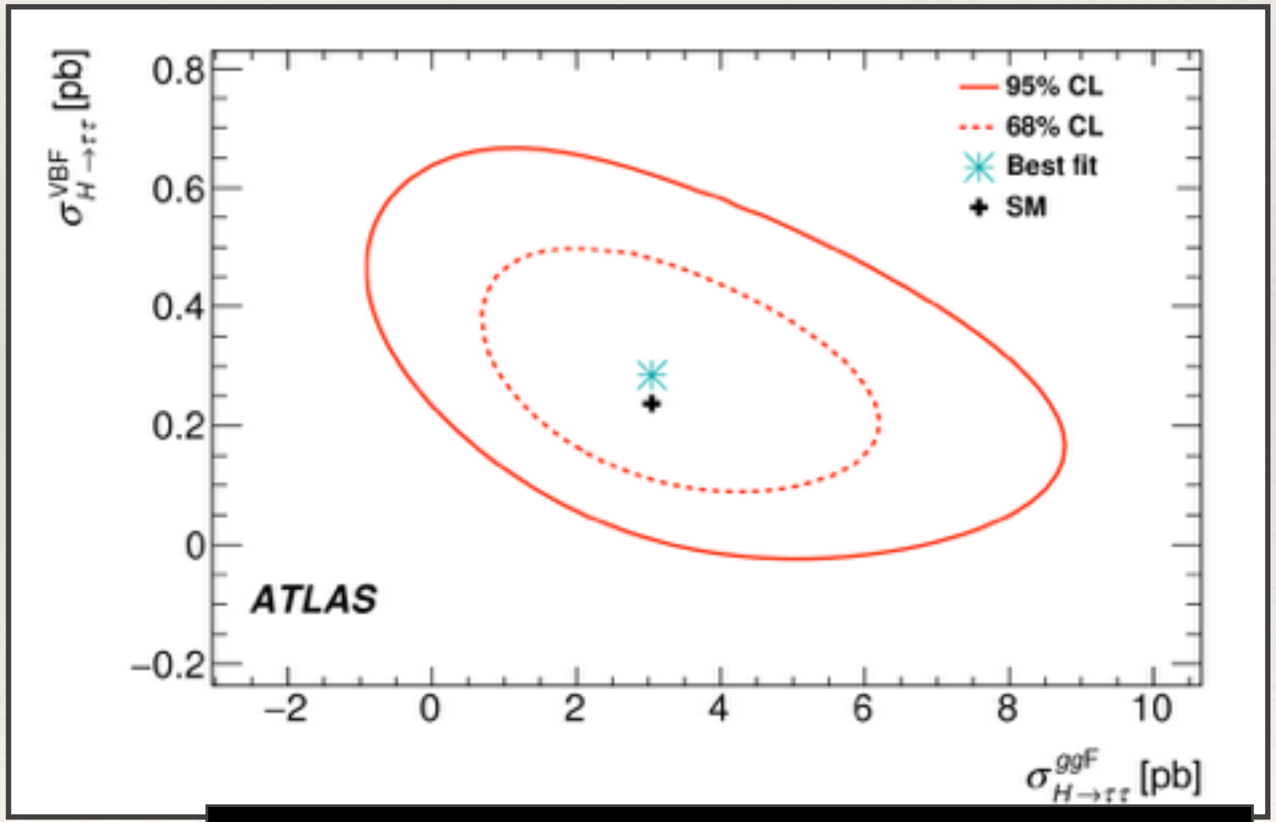
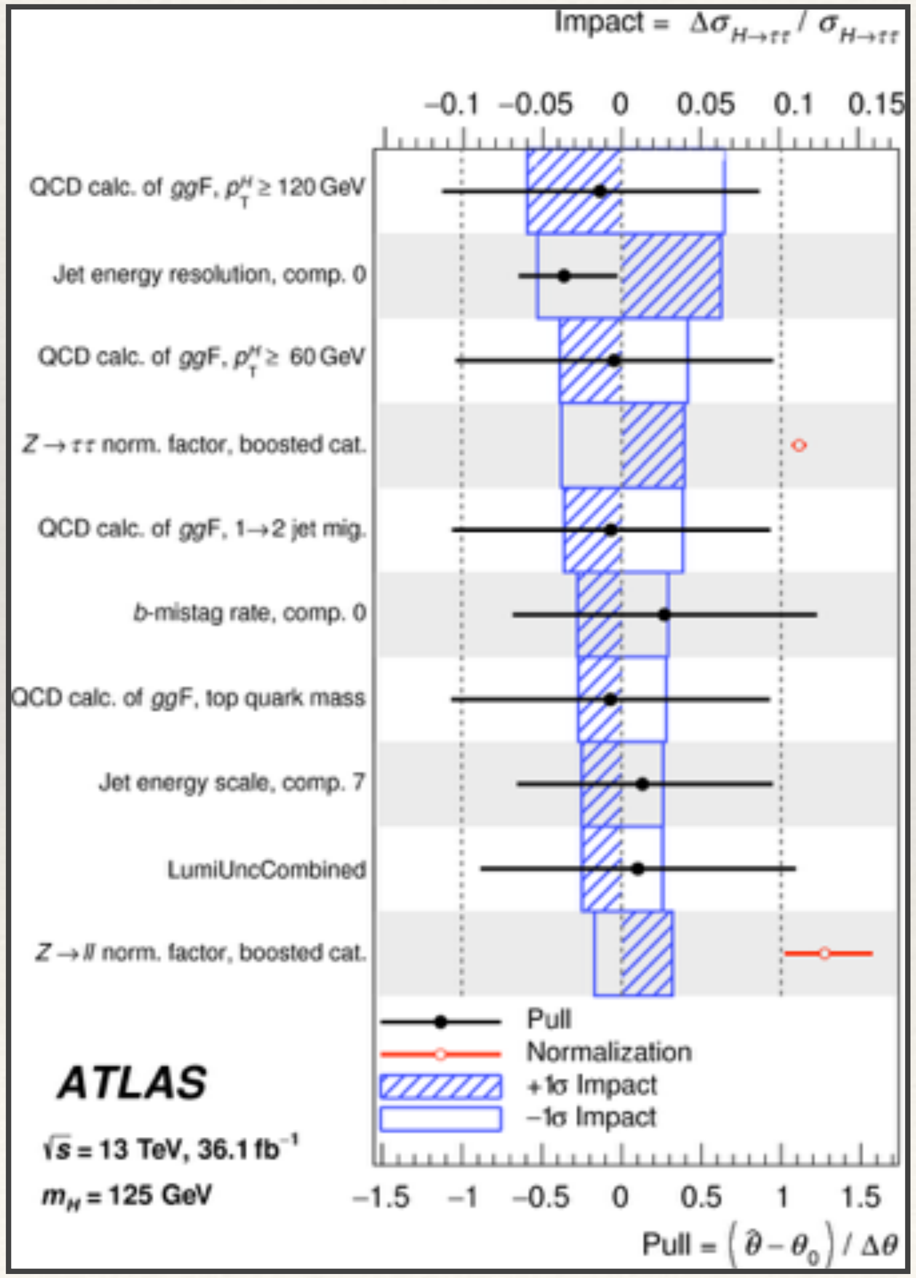




Results are in agreement with the SM predictions with relative uncertainties of ~51% (VBF) and ~61% (ggF)

Uncertainties

- Systematic uncertainties are a significant component of the total uncertainty



Source of uncertainty	Impact $\Delta\sigma/\sigma_{H\to\tau\tau}$ [%] Observed	Expected
Theoretical uncert. in signal	+13.4 / −8.7	+12.0 / −7.8
Background statistics	+10.8 / −9.9	+10.1 / −9.7
Jets and E_T^{miss}	+11.2 / −9.1	+10.4 / −8.4
Background normalization	+6.3 / −4.4	+6.3 / −4.4
Misidentified τ	+4.5 / −4.2	+3.4 / −3.2
Theoretical uncert. in background	+4.6 / −3.6	+5.0 / −4.0
Hadronic τ decays	+4.4 / −2.9	+5.5 / −4.0
Flavor tagging	+3.4 / −3.4	+3.0 / −2.3
Luminosity	+3.3 / −2.4	+3.1 / −2.2
Electrons and muons	+1.2 / −0.9	+1.1 / −0.8
Total systematic uncert.	+23 / −20	+22 / −19
Data statistics	±16	±15
Total	+28 / −25	+27 / −24

Dominant Effects:

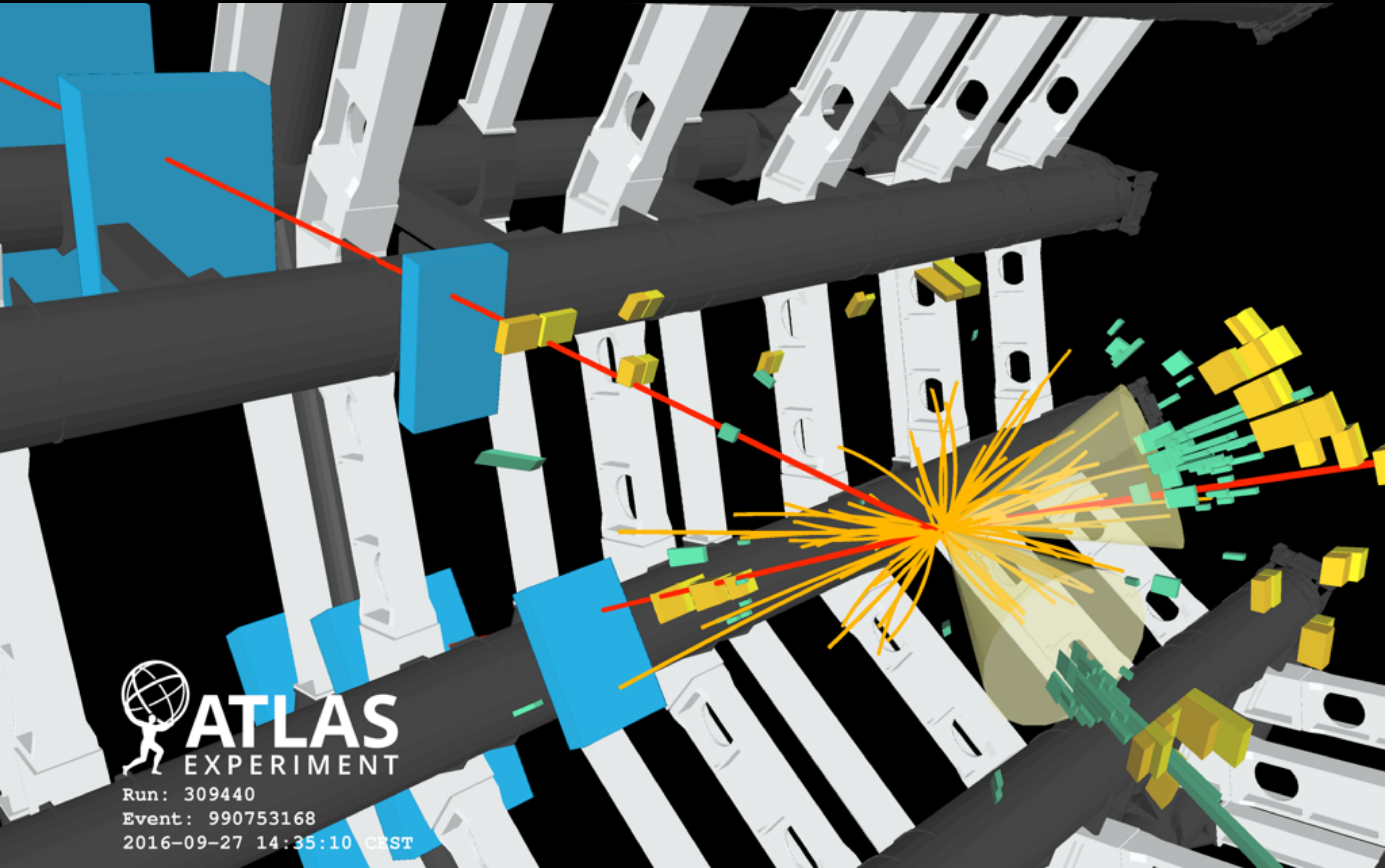
ggF Higgs production rate in boosted regime

Statistics of MC Samples

Effect of JES/JER on acceptance and MMC shape

$H \rightarrow bb$ (80 fb^{-1})

[Phys. Lett. B 786 (2018) 59]
[JHEP 05 (2019) 141]
[Phys. Rev. D 98 (2018) 052003]

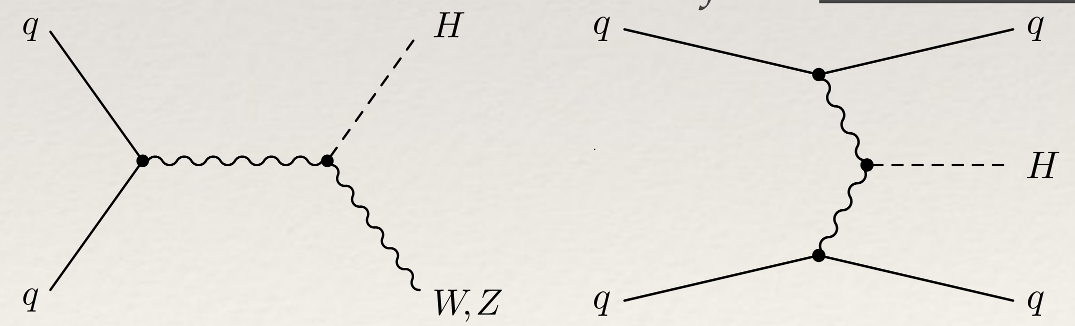


Measurement Strategy

More details in Giulia Di Gregorio's presentation this afternoon!

- Focus on VH production mode to control backgrounds
  - Dedicated VBF search released in 2018 with 30 fb^{-1} [*Phys. Rev. D 98 (2018) 052003*]
- Analysis is split into 3 channels based on the number of light leptons: **ZH→ννbb (0-lepton), WH→lνbb (1-lepton), ZH→llbb (2-leptons)**
  - Additional separation based on number of additional non-b-jets (0, 1+)
- Template fit in multivariate discriminant distribution is used to extract VH signal
  - Fit using alternative discriminant also used to extract VZ(→bb) contribution
- Event selection relies on large p_T^V requirement to improve signal to background ratio
  $p_T^V > 150$ GeV *(all channels)*
  75 GeV $< p_T^V <$ 150 GeV
  (extra bin for the 2-lepton channel)

cross sections taken from LHCHXSWG



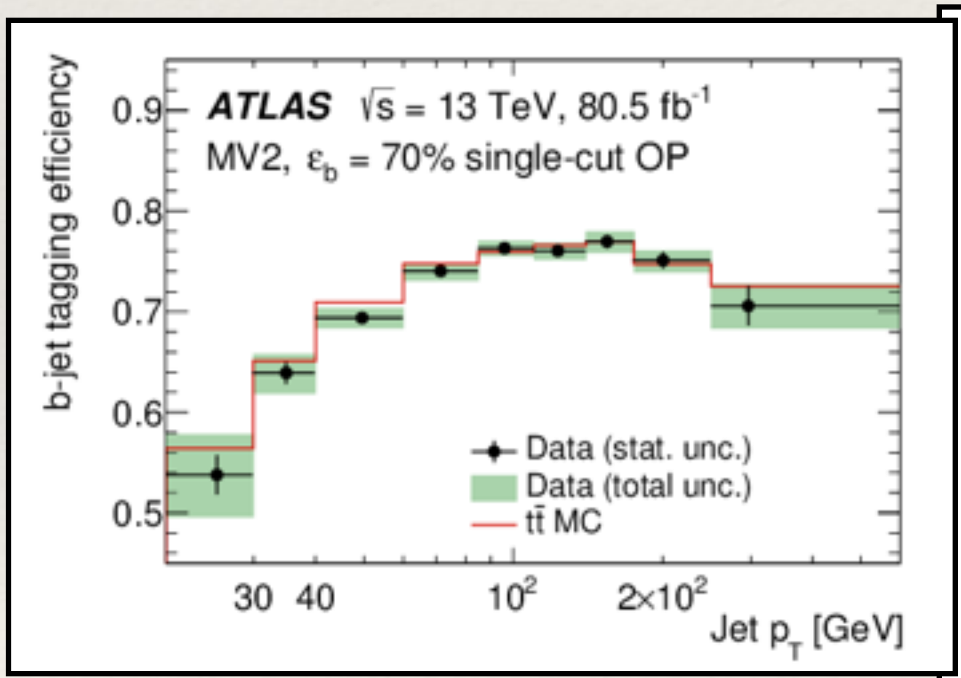
WH (1.4 pb) & ZH (0.87 pb)

VBF (3.75 pb)

Interlude: ATLAS B-Tagging Performance

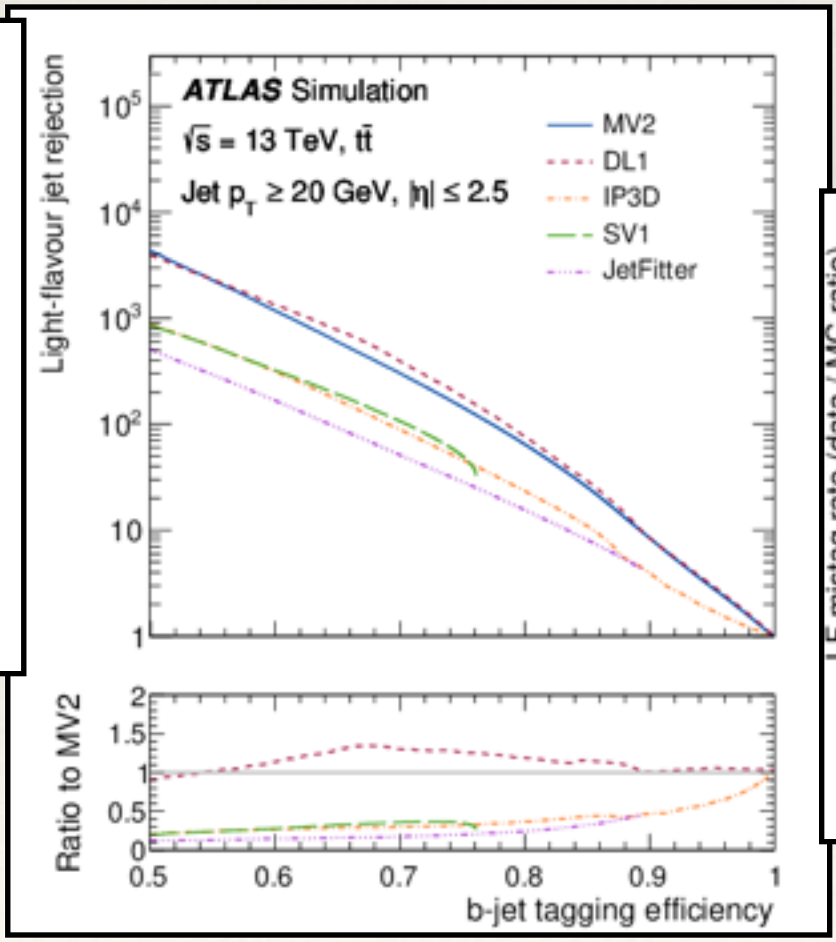
- **Rejection of light-flavour and c-jets** and precise **measurements** of the tagging algorithm performance are the crucial ingredients for this analysis

Tagging efficiency measurement in tt events

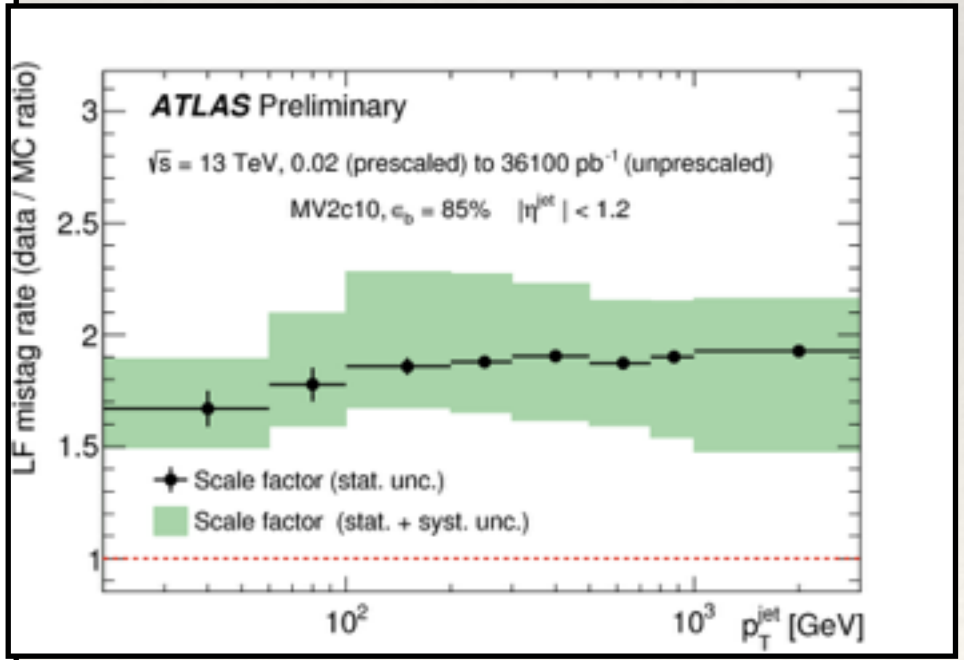


Working point used in analysis:
b-jet efficiency: ~70%
c-jet mis-ID efficiency: ~12.5%
light-flavour mis-ID efficiency: ~0.3%

BDT-based b-tagger light-flavour jet rejection



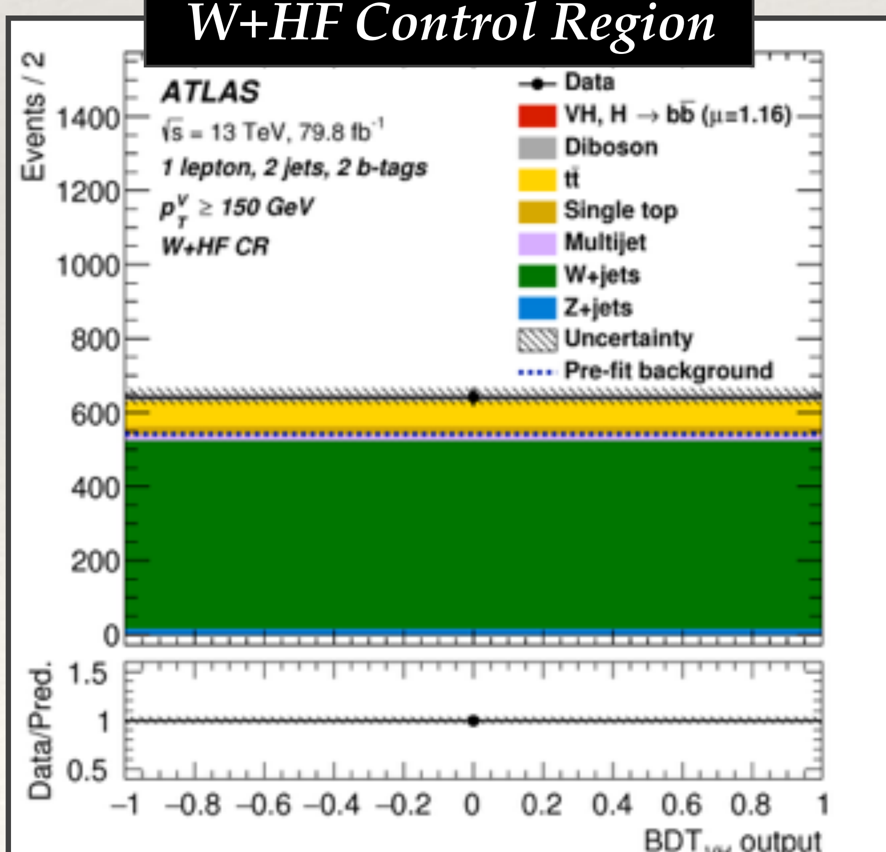
Light flavour mistag rate measurement in data



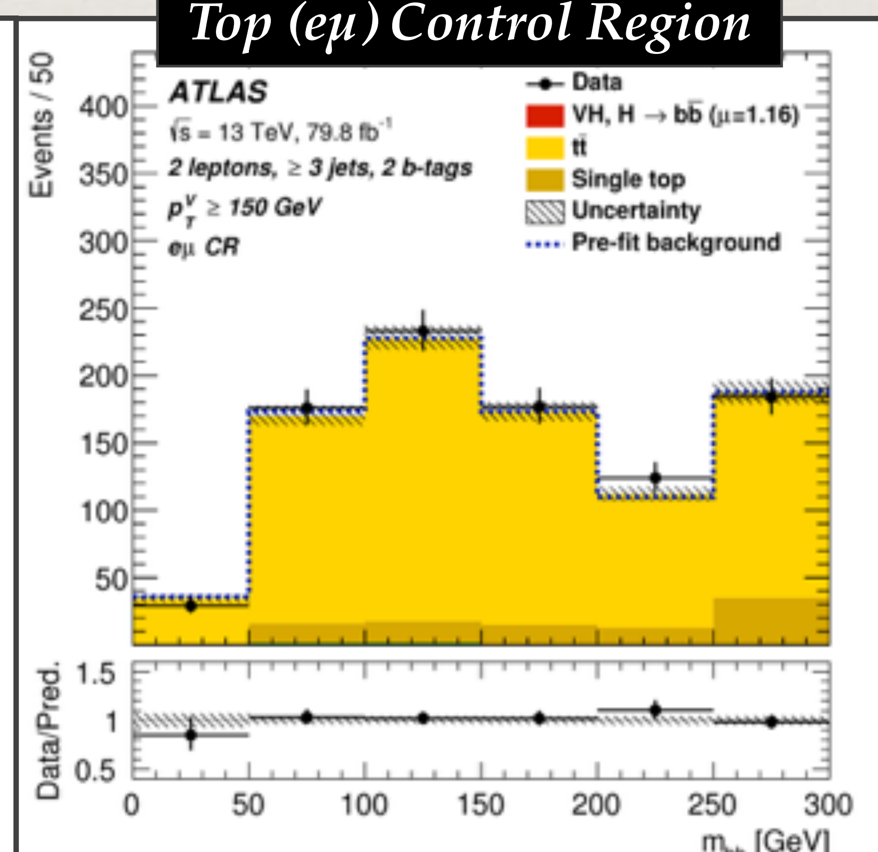
Dominant Backgrounds

- Main backgrounds from processes involving W and Z bosons decaying to leptons (di-bosons, V+jets, top quark processes):
  - Templates taken from MC simulation at NLO
  - Dedicated Control Regions established to isolate **W+heavy flavour** (1-lepton with $m_{bb} < 75$ GeV & $m_{Top} > 225$ GeV) and **Top** processes (2-lepton eμ)
- Multijet background (1-lepton region only, negligible otherwise):
  - **Data-driven:** Fit to $m_T(W)$ distribution, multi-jet template from an inverted lepton isolation region

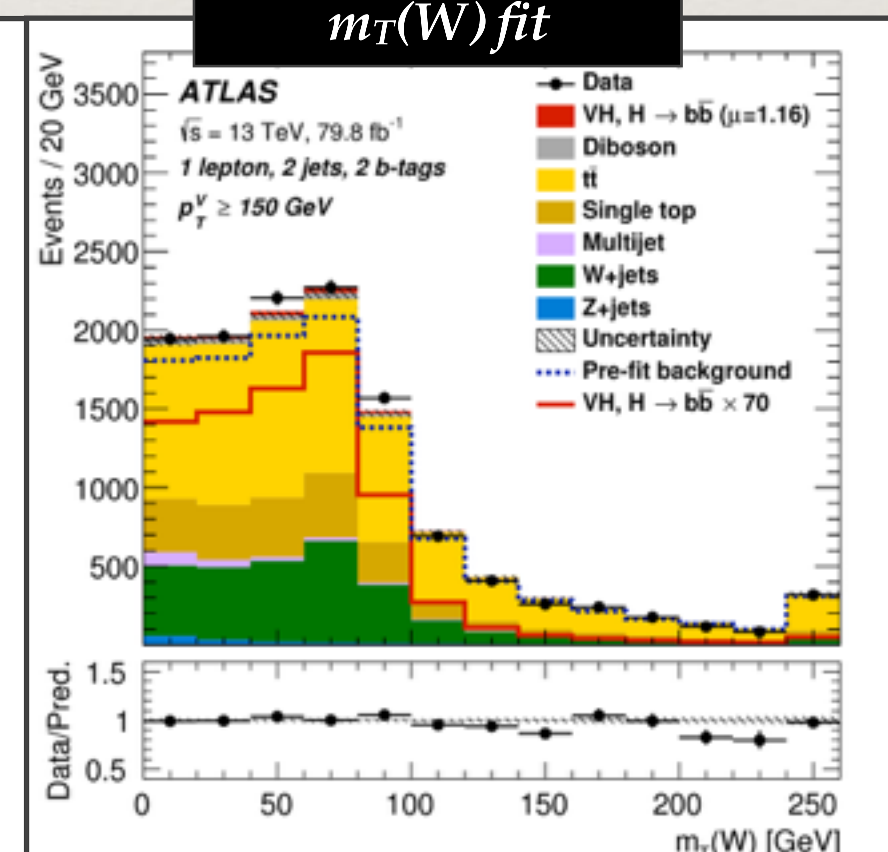
W+HF Control Region



Top (eμ) Control Region

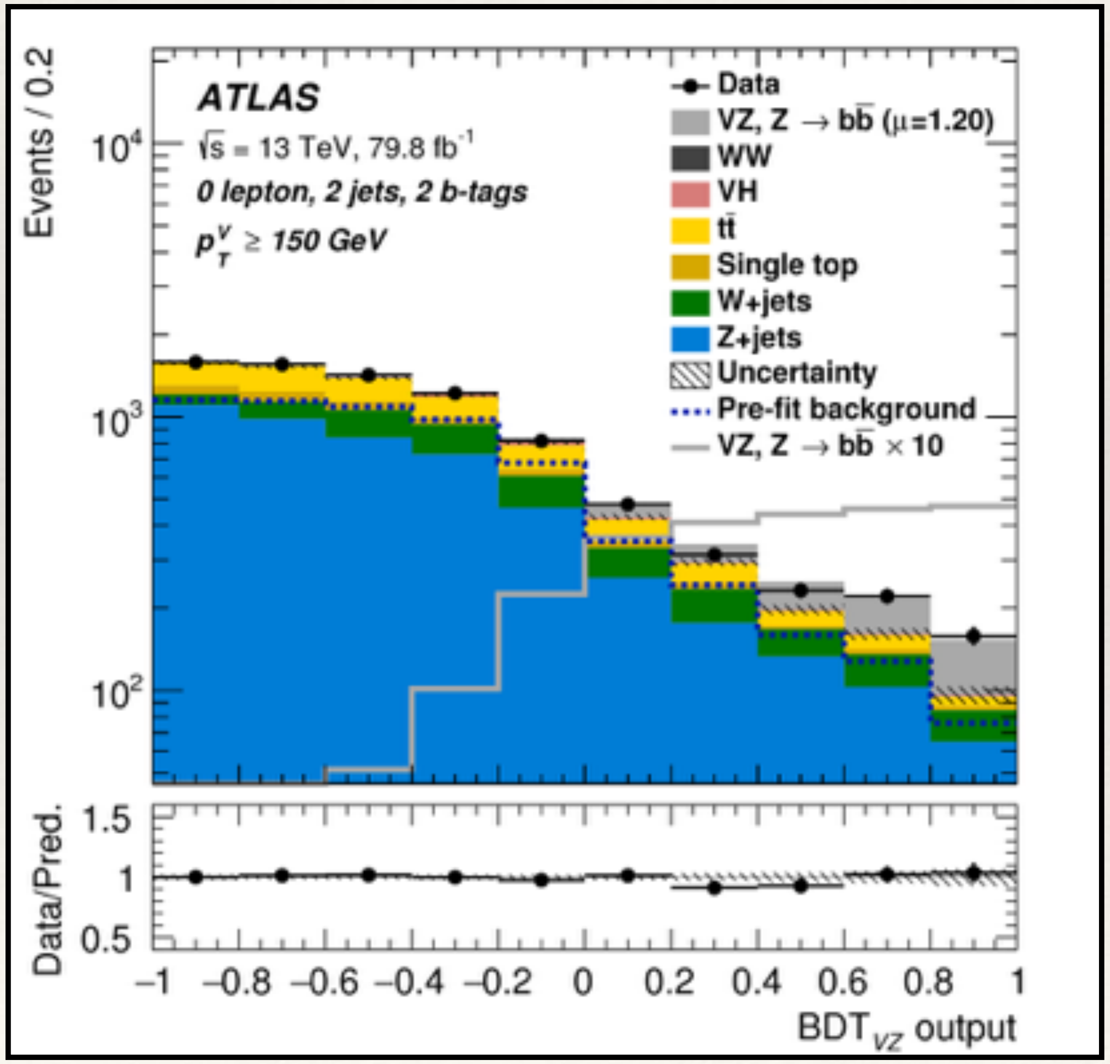


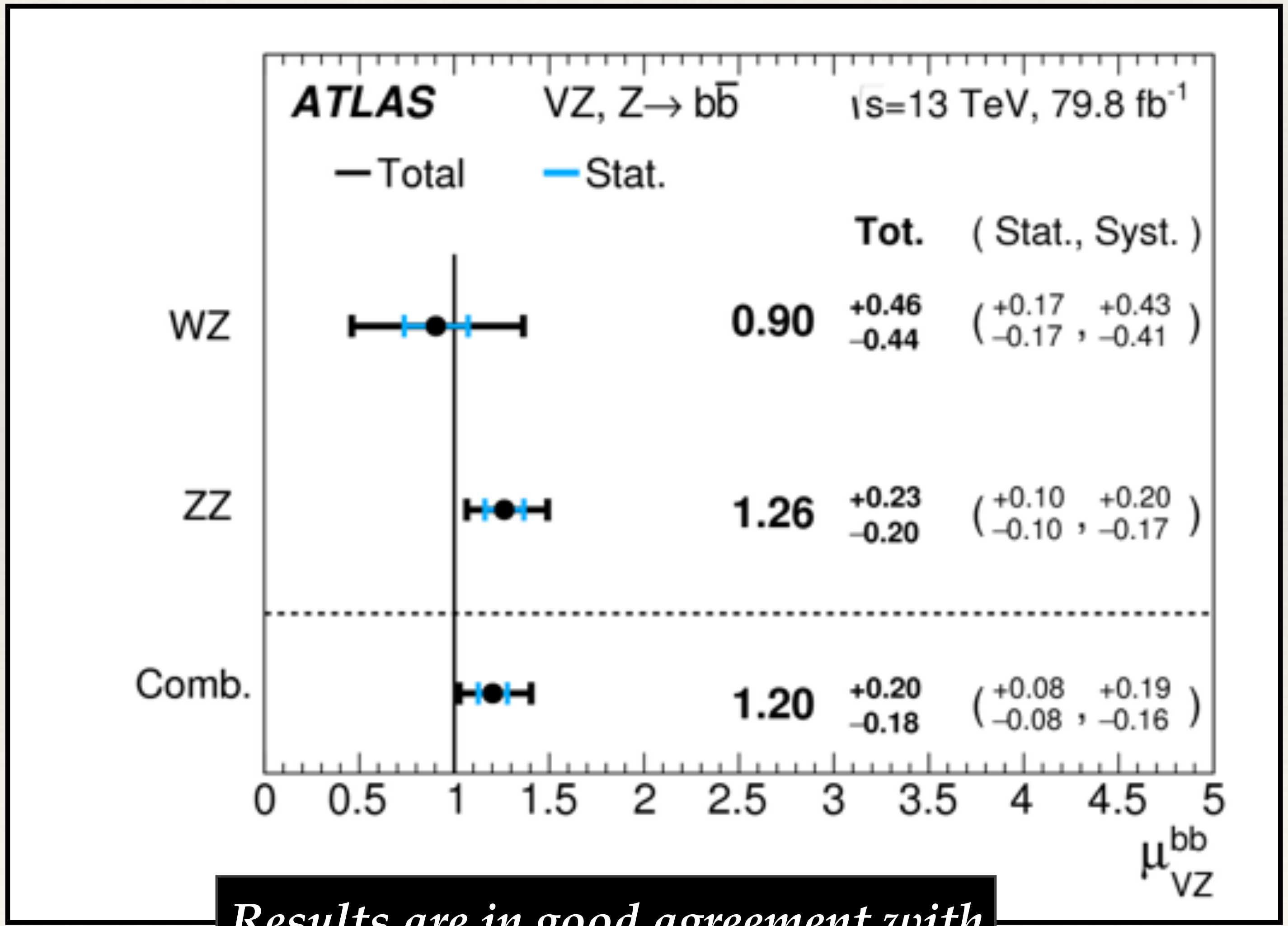
$m_T(W)$ fit



Bonus: WZ & ZZ

- Full fit is performed, using the alternative discriminant trained to identify VZ(→bb)
  - Offers an extra handle in validating the results of the main analysis!





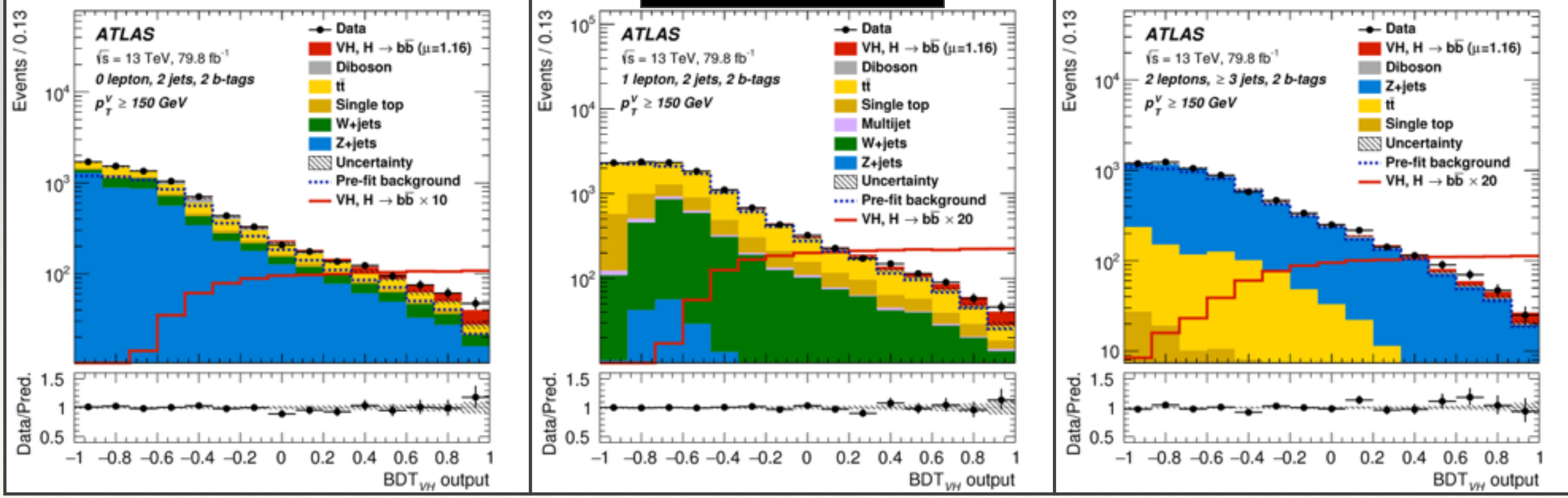
Results are in good agreement with the SM predictions!

Fit & Results

ttH results covered in Peter Onyisi's talk this afternoon!

- Simultaneous fit to all SRs and CRs to extract H→bb signal strength
- Combination performed with Run-I and ttH/VBF H→bb yields a single experiment observation at an observed (expected) significance of 5.4σ (5.5σ)
- Combination with VH→γγ and VH→ZZ also yields an observation of VH production at 5.3σ [4.8σ exp.]

Fit distributions



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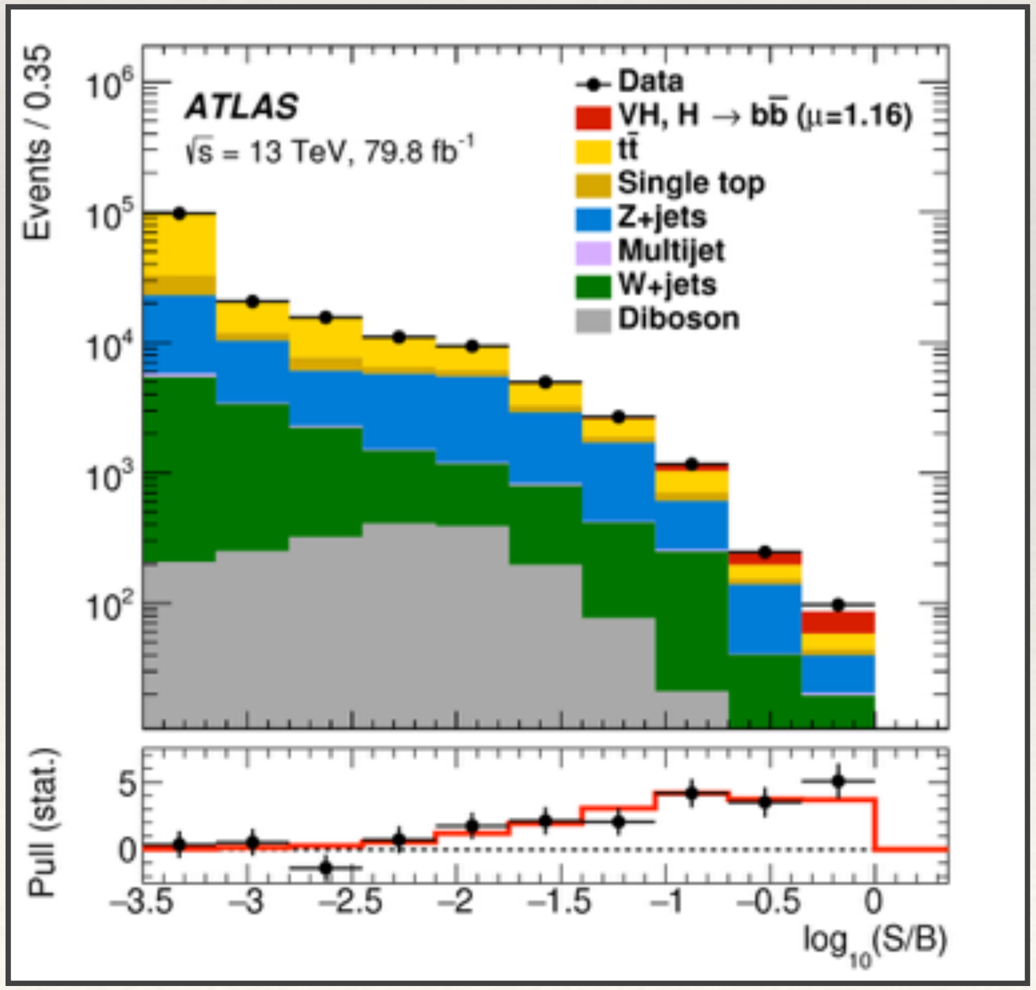
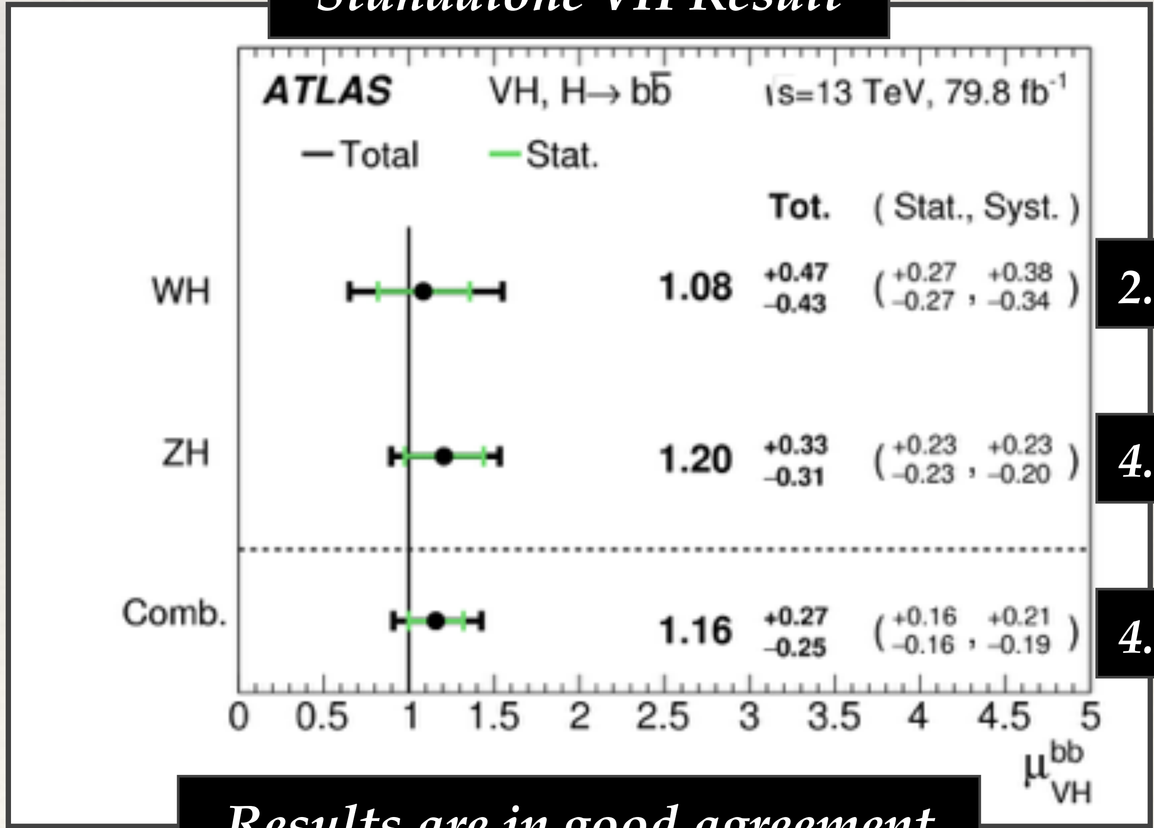


Standalone VH Result



2.5σ (2.3σ exp)

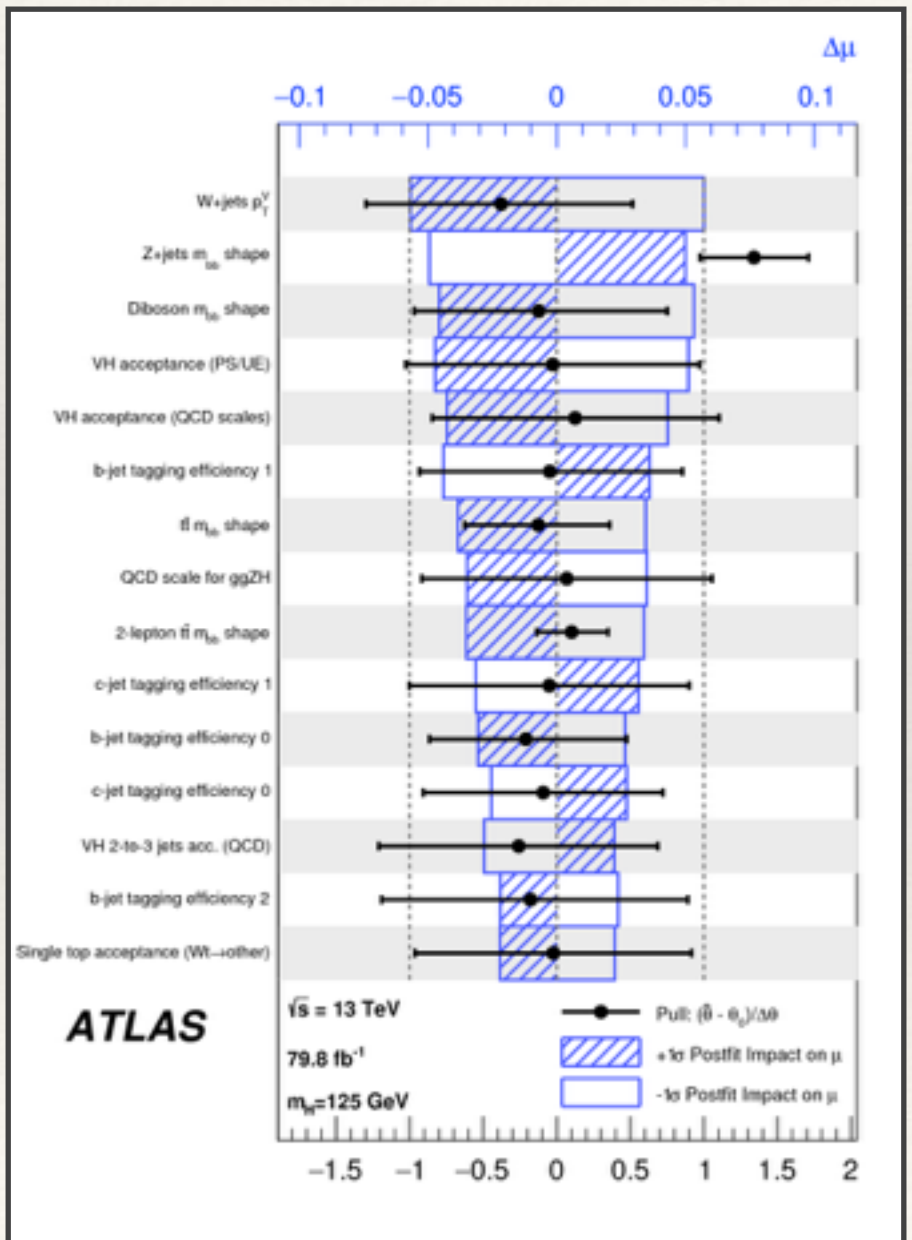
4.0σ (3.5σ exp)

4.9σ (4.3σ exp)

Results are in good agreement with the SM predictions!

Uncertainties

- H→bb analysis in a regime where systematic uncertainties are becoming dominant…



Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
	b-jets	0.061
b-tagging	*c*-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Dominant Effects:

b-tagging performance measurements

Signal Acceptance Uncertainties

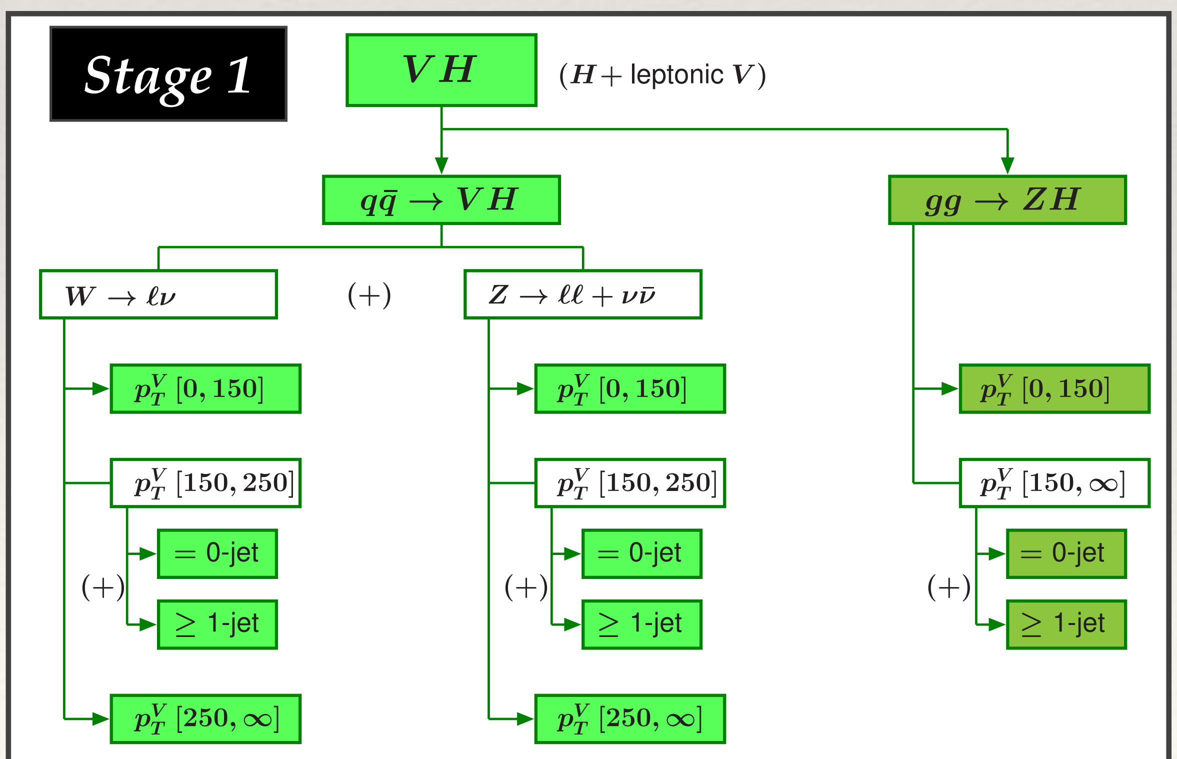
Background Modelling

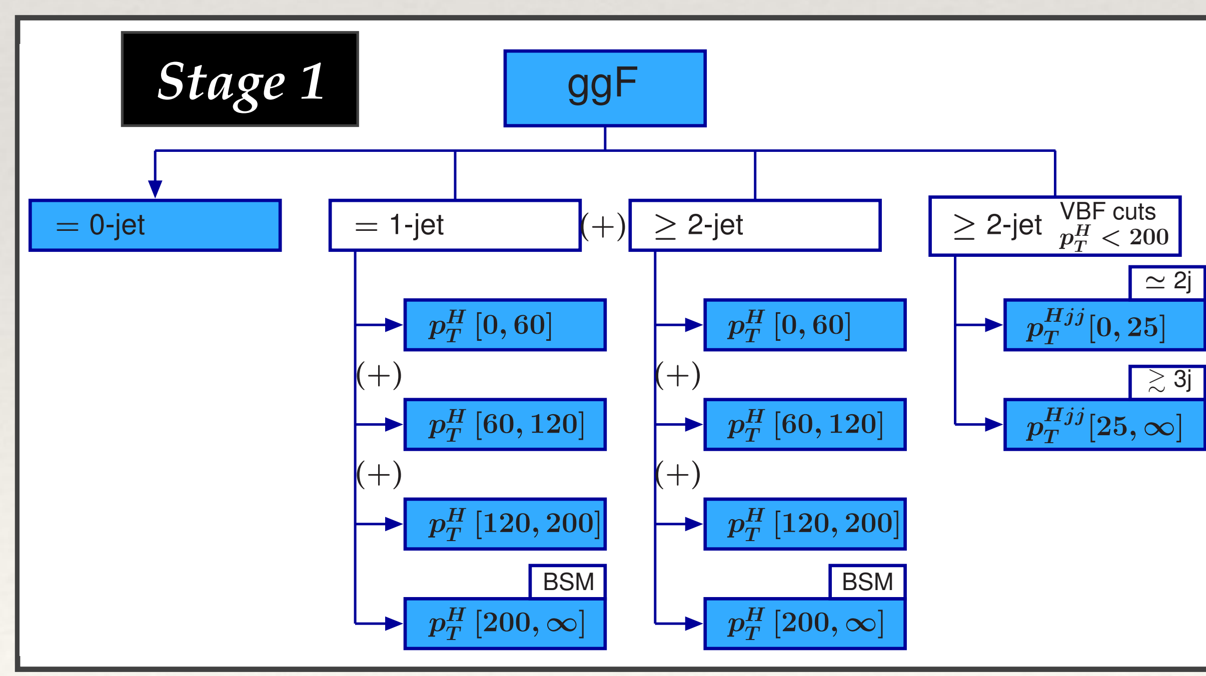
Statistics of MC Samples

The Interpretations

Simplified Template Cross Sections

- The Simplified Template Cross Section (STXS) framework offers a **unified methodology** to perform fiducial/differential cross section measurements
  - Bins in phase space defined in a consistent manner across all channels, simplifies combinations and theory interpretations significantly
- **Stage 0:** Per production mode cross sections (with ~detector acceptance)
- **Stage 1:** Targeting specific areas of phase space (reduce theory dependences)





STXS in H→ττ

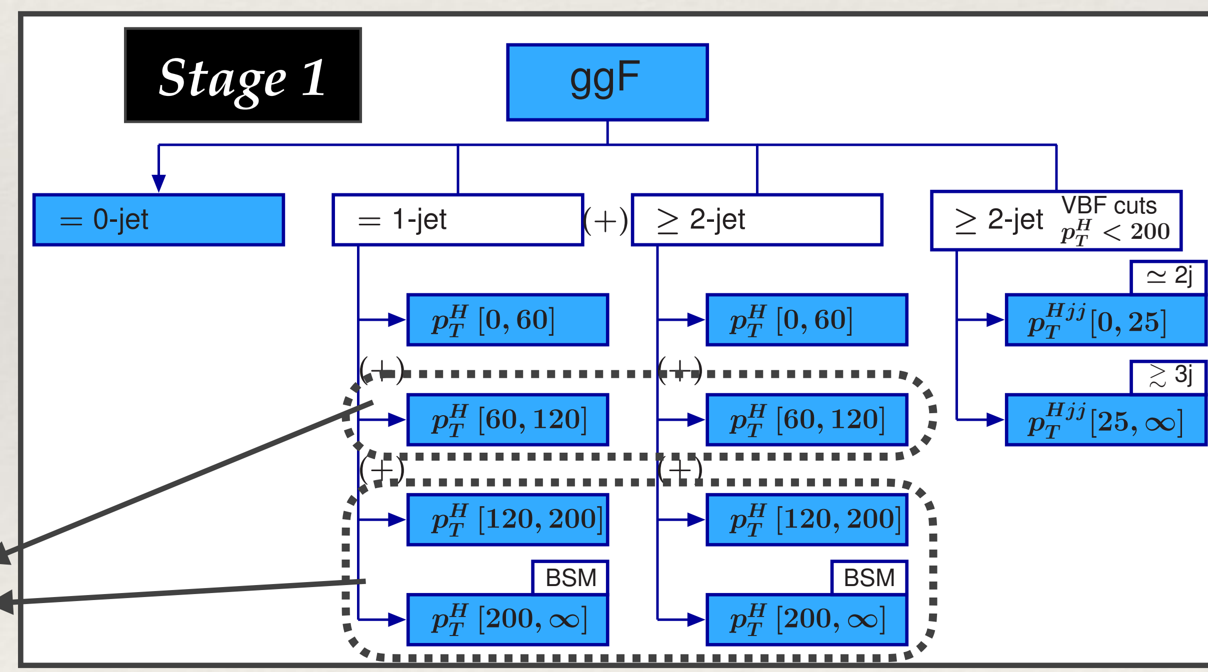
- The precision level of the analysis is only sufficient to extract results in a few bins (multiple Stage 1 bins merged together)
  - …but this is still a very useful exercise in understanding the available sensitivity!
  - Unfortunate mismatch between STXS and analysis binning in Higgs p_T artificially reduces sensitivity

Boosted SR selection

Boosted	High-$p_T^{\tau\tau}$	Not VBF $p_T^{\tau\tau} > 100$ GeV	$p_T^{\tau\tau} > 140$ GeV $\Delta R_{\tau\tau} < 1.5$
	Low-$p_T^{\tau\tau}$		Not boosted high-$p_T^{\tau\tau}$

STXS results

Process	Particle-level selection	σ [pb]	σ^{SM} [pb]
ggF	$N_{jets} \geq 1$, $60 < p_T^H < 120$ GeV, $\lvert y_H \rvert < 2.5$	1.79 ± 0.53 (stat.) ± 0.74 (syst.)	0.40 ± 0.05
ggF	$N_{jets} \geq 1$, $p_T^H > 120$ GeV, $\lvert y_H \rvert < 2.5$	0.12 ± 0.05 (stat.) ± 0.05 (syst.)	0.14 ± 0.03
VBF	$\lvert y_H \rvert < 2.5$	0.25 ± 0.08 (stat.) ± 0.08 (syst.)	0.22 ± 0.01

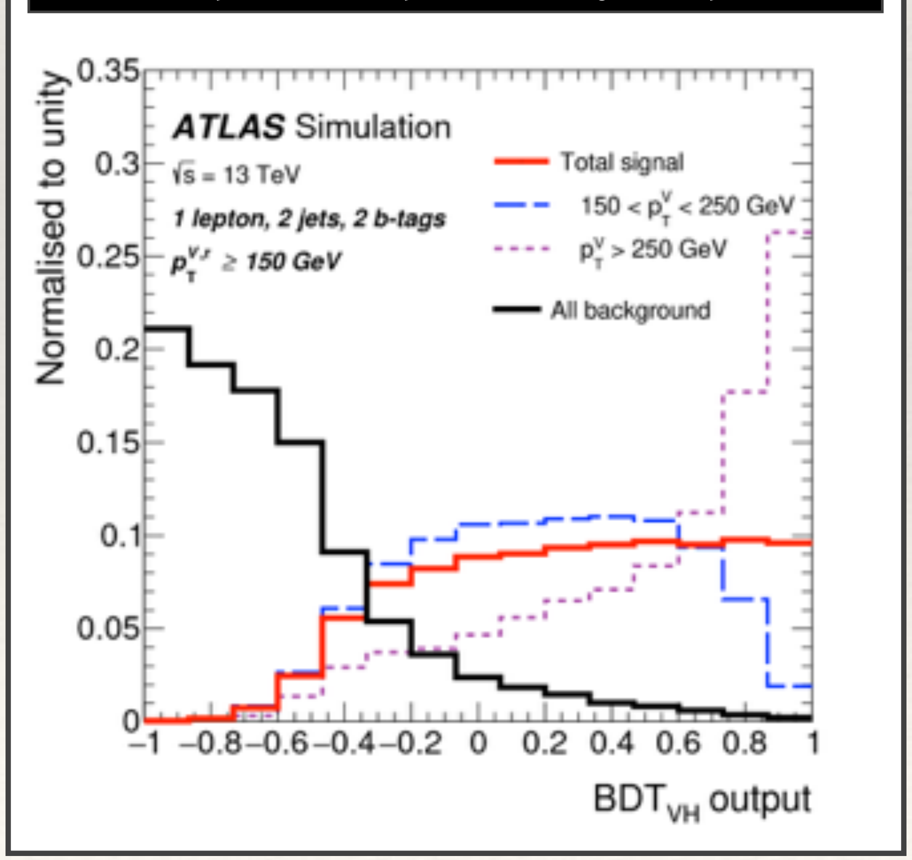


This is still one of the more precise measurements of the very high Higgs p_T regime (>120 GeV) (~60% relative total uncertainty)

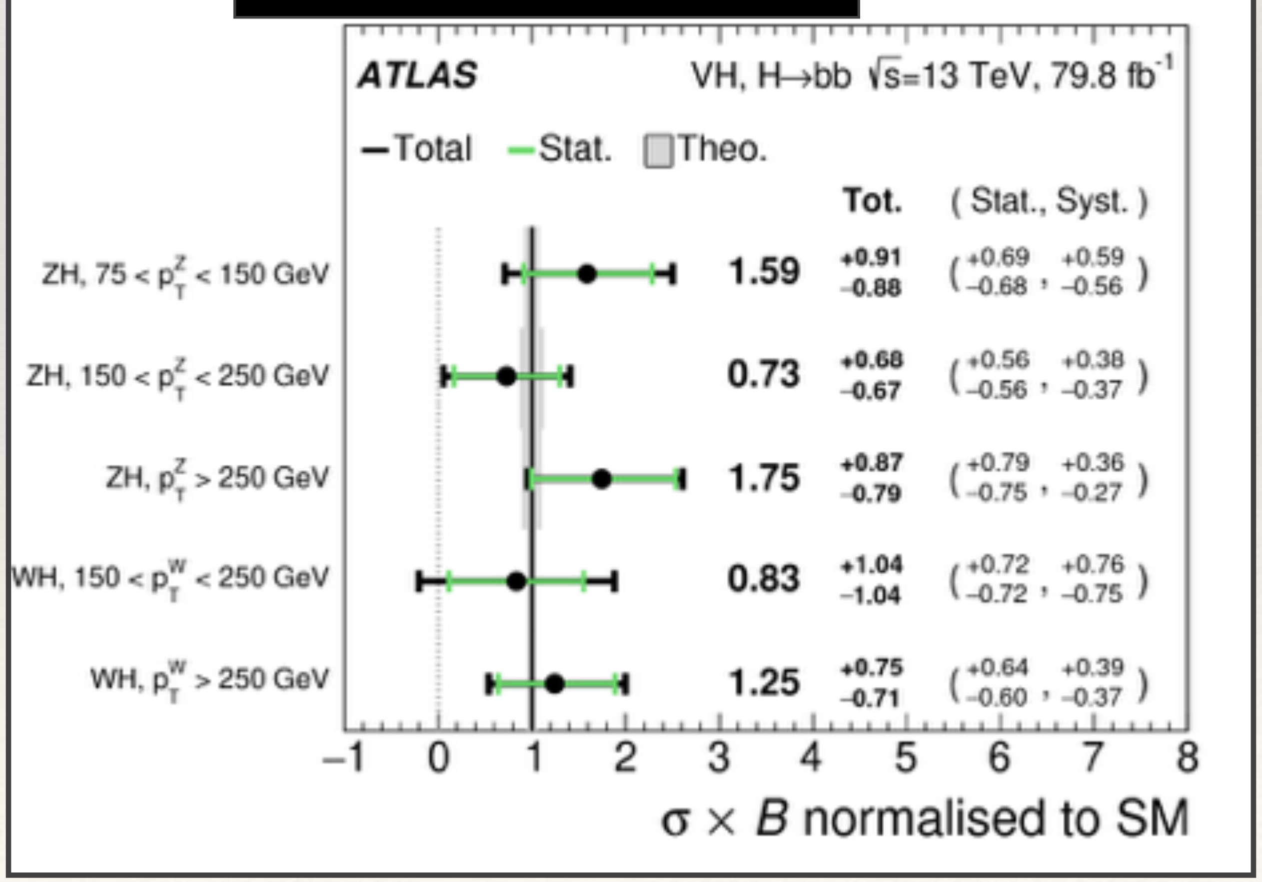
STXS in H→bb

- STXS interpretation in H→bb is more complex: multi-variate discriminant shape depends strongly on the Higgs kinematics (new templates introduced)
  - Binning defined based on p_T^V (2 schemes considered, 3 & 5 bins)
  - Extra granularity not originally included in STXS proposal used here to reduce extrapolation uncertainties (introduction of a bin starting at $p_T^V > 75$ GeV)

Template dependency on p_T^V



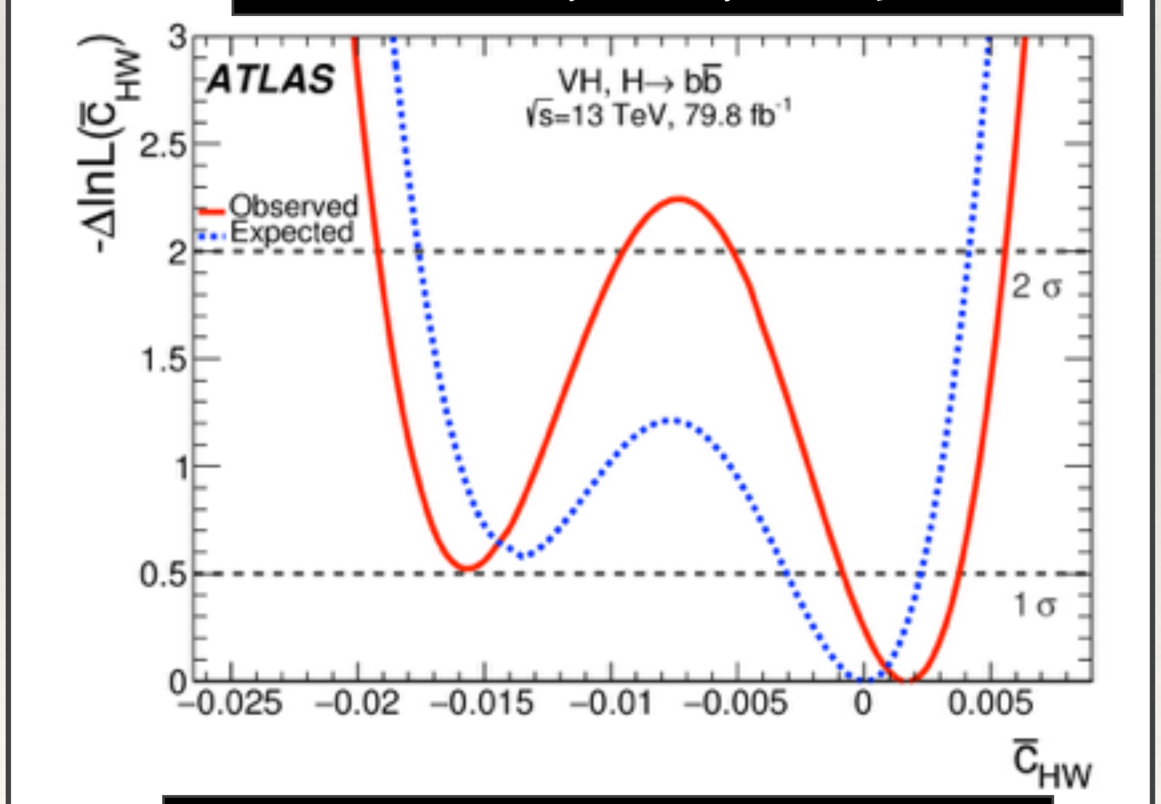
5 bin scheme



EFT in H→bb

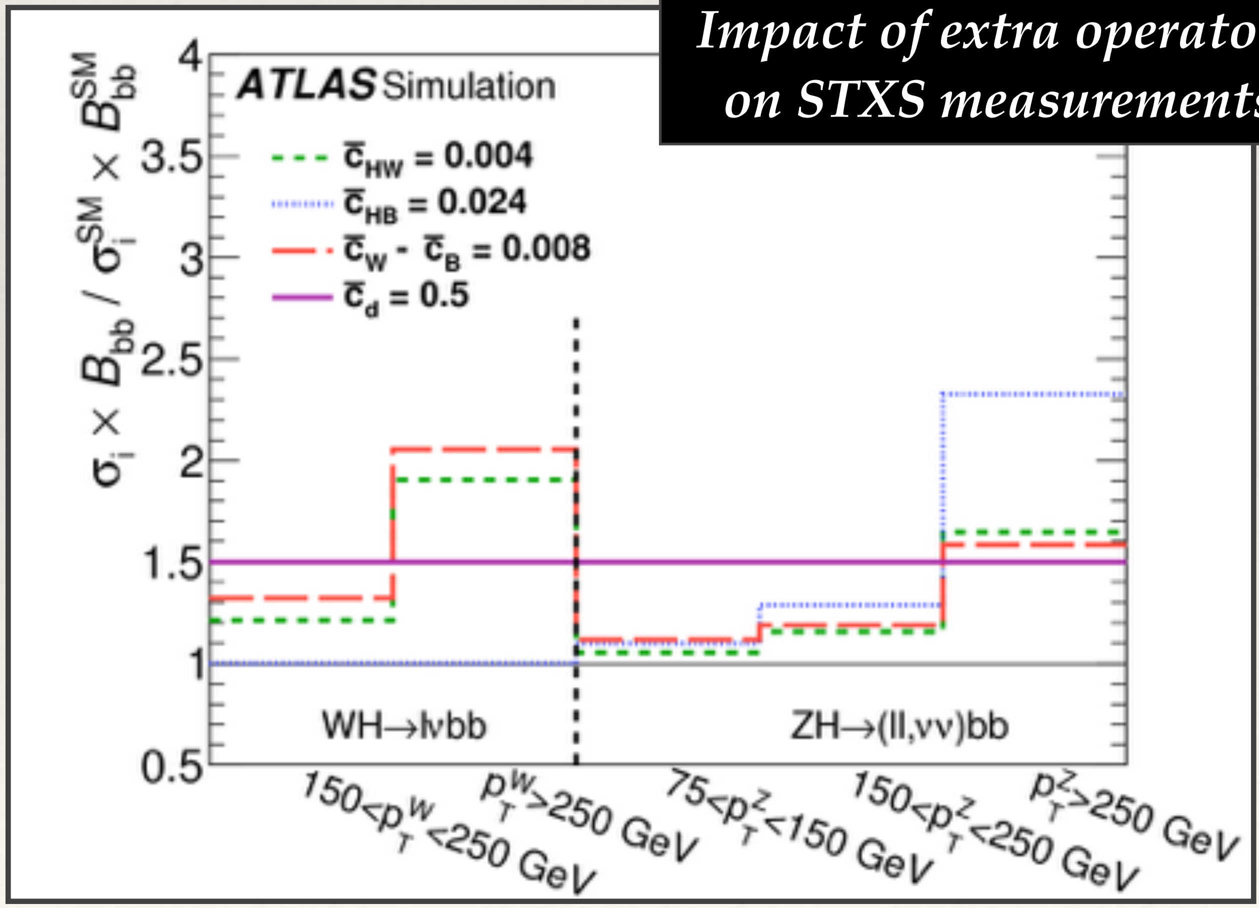
- The STXS results of the H→bb measurement can also be re-interpreted in a generic Effective Field Theory (EFT) framework, to set limits on BSM interactions
- Probe all dimension 6 operators which would affect the analysis results
    - Either through modifications to WH/ZH couplings, or in down-quark Yukawa interactions

Likelihood for W-field operator



Some interactions constrained at the few percent level!

Impact of extra operators on STXS measurements



Conclusions

- Higgs decays into both 3rd generation fermions have now been observed in ATLAS (>5σ in both cases)
    - Measurements are in good agreement with the Standard Model predictions!
- Both channels have begun extracting *fiducial cross-sections* through the STXS framework, providing sensitivity in the parts of phase space they are uniquely sensitive to
- Still a significant fraction of the Run-II luminosity not included in these measurements - stay tuned!

The impact of these measurements on the full ATLAS Higgs combination will be shown in Nicolas Berger's presentation tomorrow morning!