Observation of Higgs Boson Decays to bb with the ATLAS Detector

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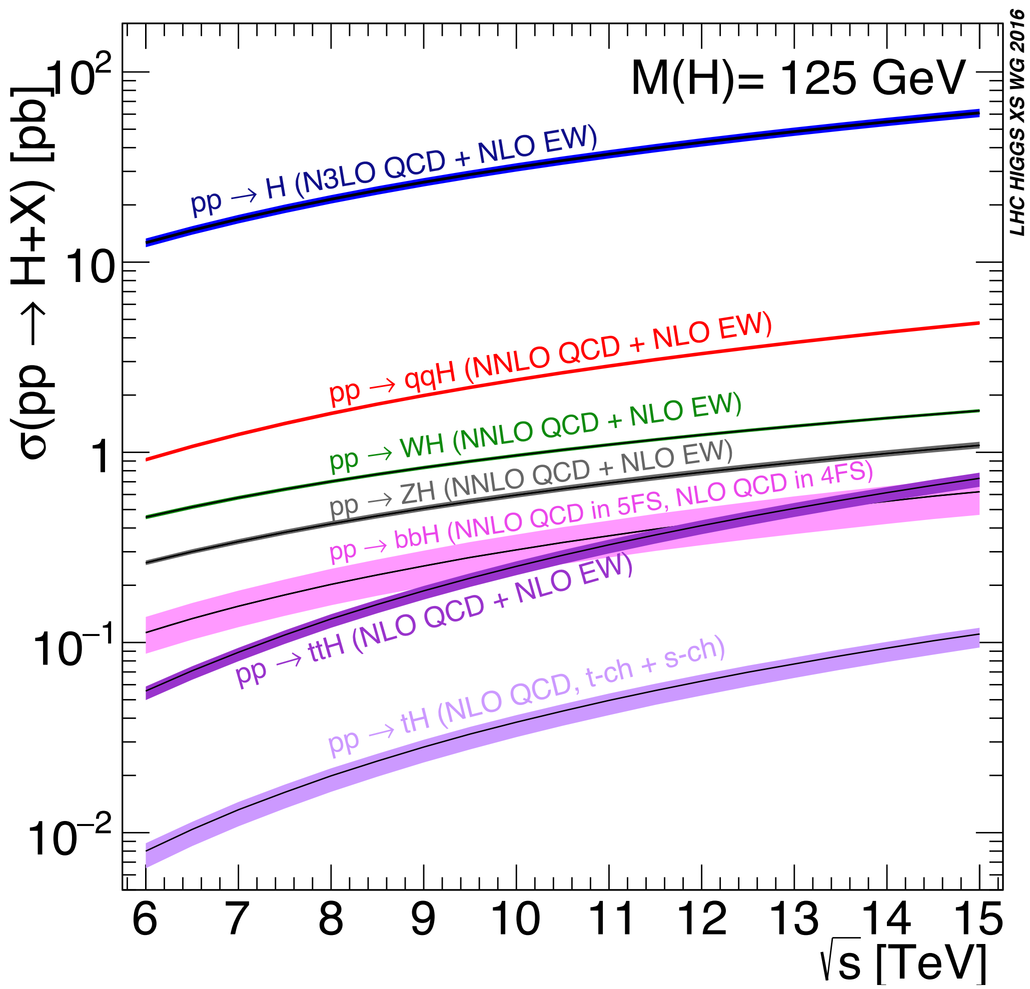
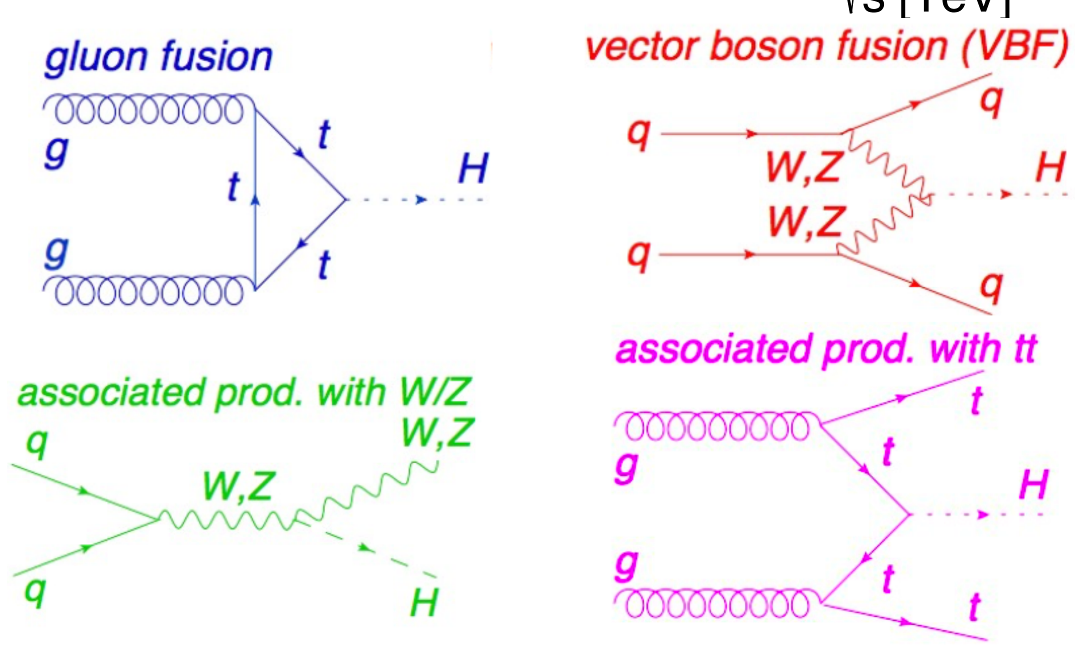
Outline

- Standard Model (SM) Higgs Boson
  - Search for $H \rightarrow b\bar{b}$ at colliders
  - LHC and ATLAS
- Search for VH, $H \rightarrow b\bar{b}$ production with ATLAS data
  - Evidence of VH, $H \rightarrow b\bar{b}$ production with 36 fb^{-1} *JHEP 12 (2017) 024*
  - Observation of $H \rightarrow b\bar{b}$ decays and VH production with 80 fb^{-1} *PLB 786 (2018) 59*
- Future prospects
  - VH simplified template cross section (STXS) measurement *submitted to JHEP arXiv:1903.04618*

Higgs boson phenomenology at the LHC

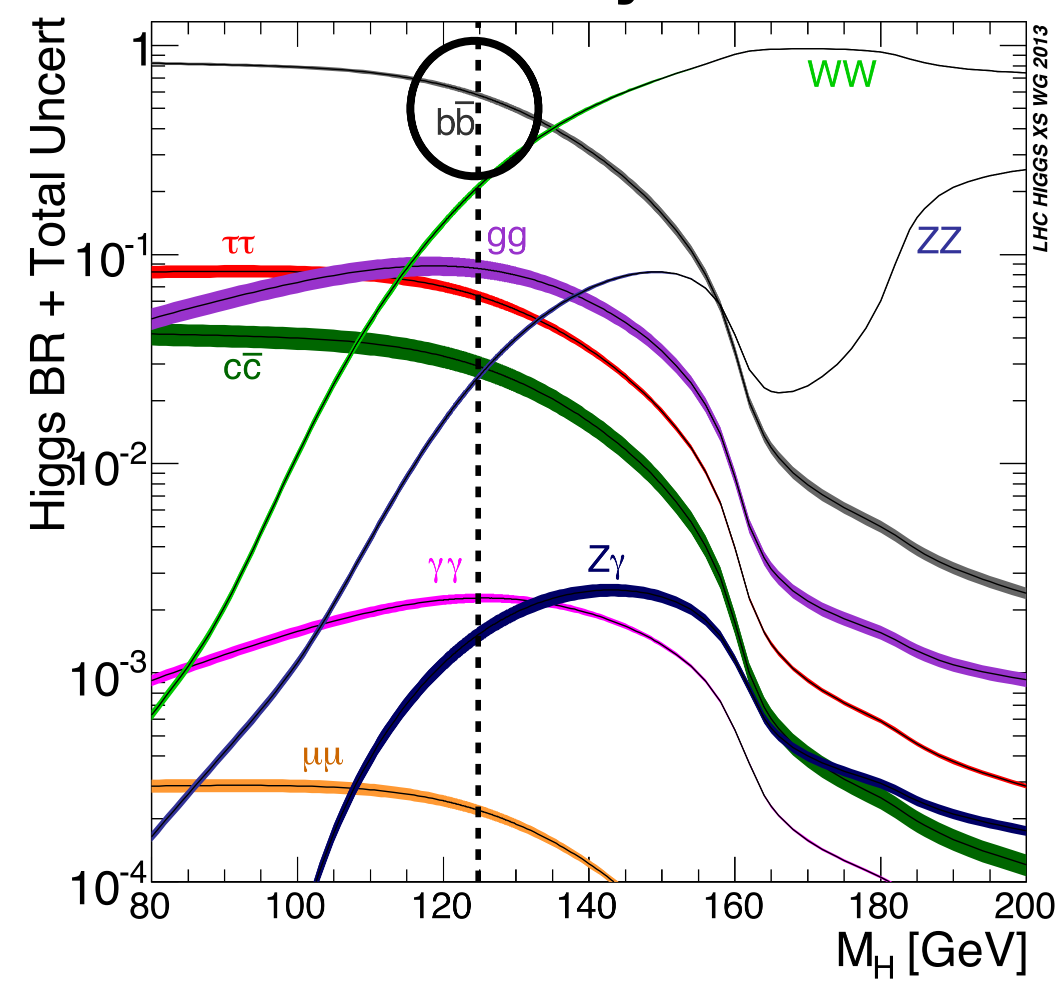
Production





- at 13 TeV: σ_{tot} ~ 56 pb, σ_{VH} ~ 2.2 pb

Decay



- **ZZ**, **γγ**: small BR, high resolution, good S/B
- **WW**: large BR, poor resolution
- **μμ**: very small BR, access to coupling to 2nd generation fermions
- **tt**: forbidden (but Htt coupling can be studied with ttH production)
- **bb**, **ττ**: large BR, poor resolution, low S/B, probe couplings to 3rd generation fermions

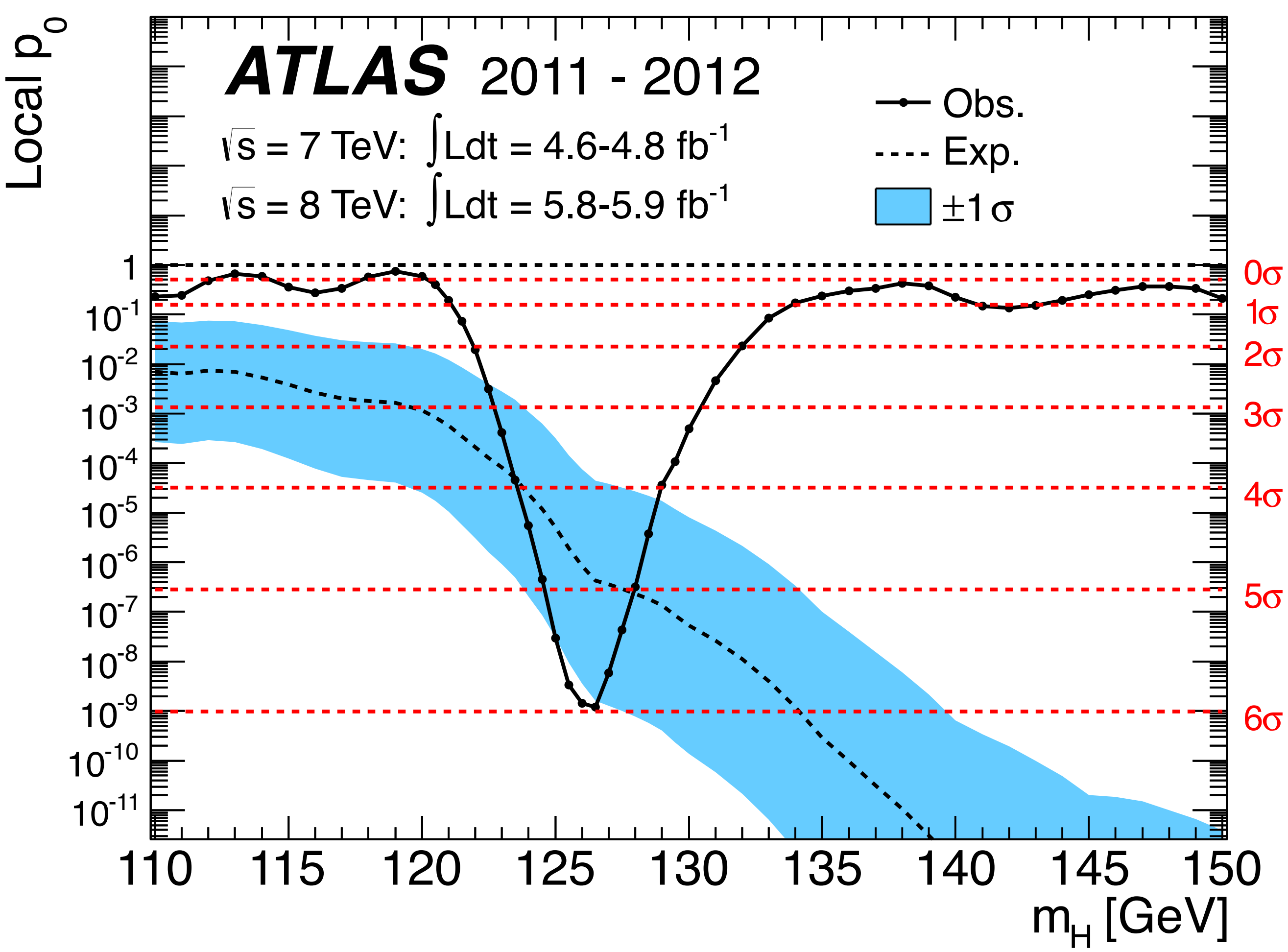
Higgs boson discovery and measurements in Run-1

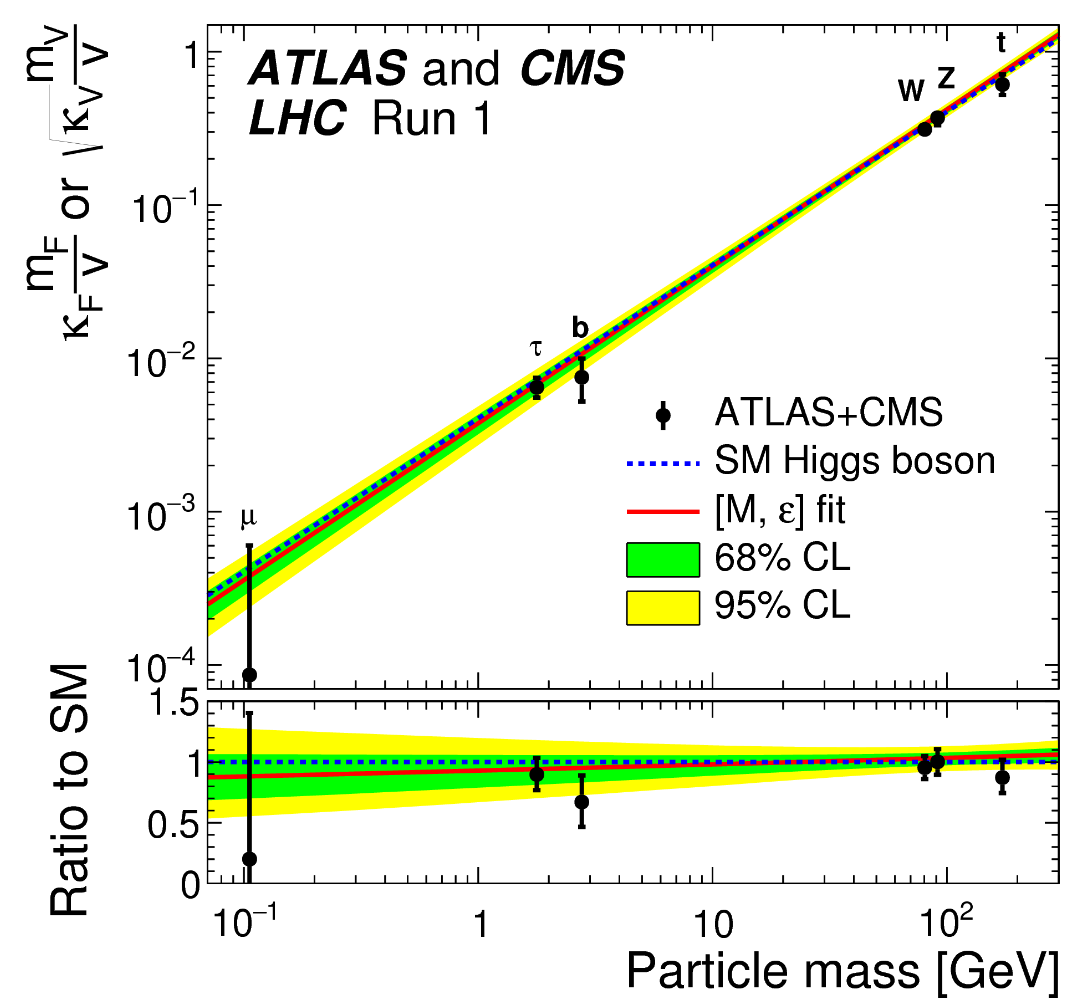
- Higgs boson was discovered in 2012 by ATLAS and CMS from the combination of the decays to
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ^*$
  - $H \rightarrow WW^*$

Phys. Lett. B716 (2012) 1

Phys. Lett. B716 (2012) 30

- Run-1 measurements:
  - mass = 125.09 ± 0.24 GeV *Phys. Rev. Lett. 114, 191803 (2015)*
  - Properties in agreement with SM predictions for m_H~125 GeV
    - Spin-0, CP-even *Eur. Phys. J. C 75 (2015) 476*
    - SM-like couplings *JHEP 08 (2016) 045*



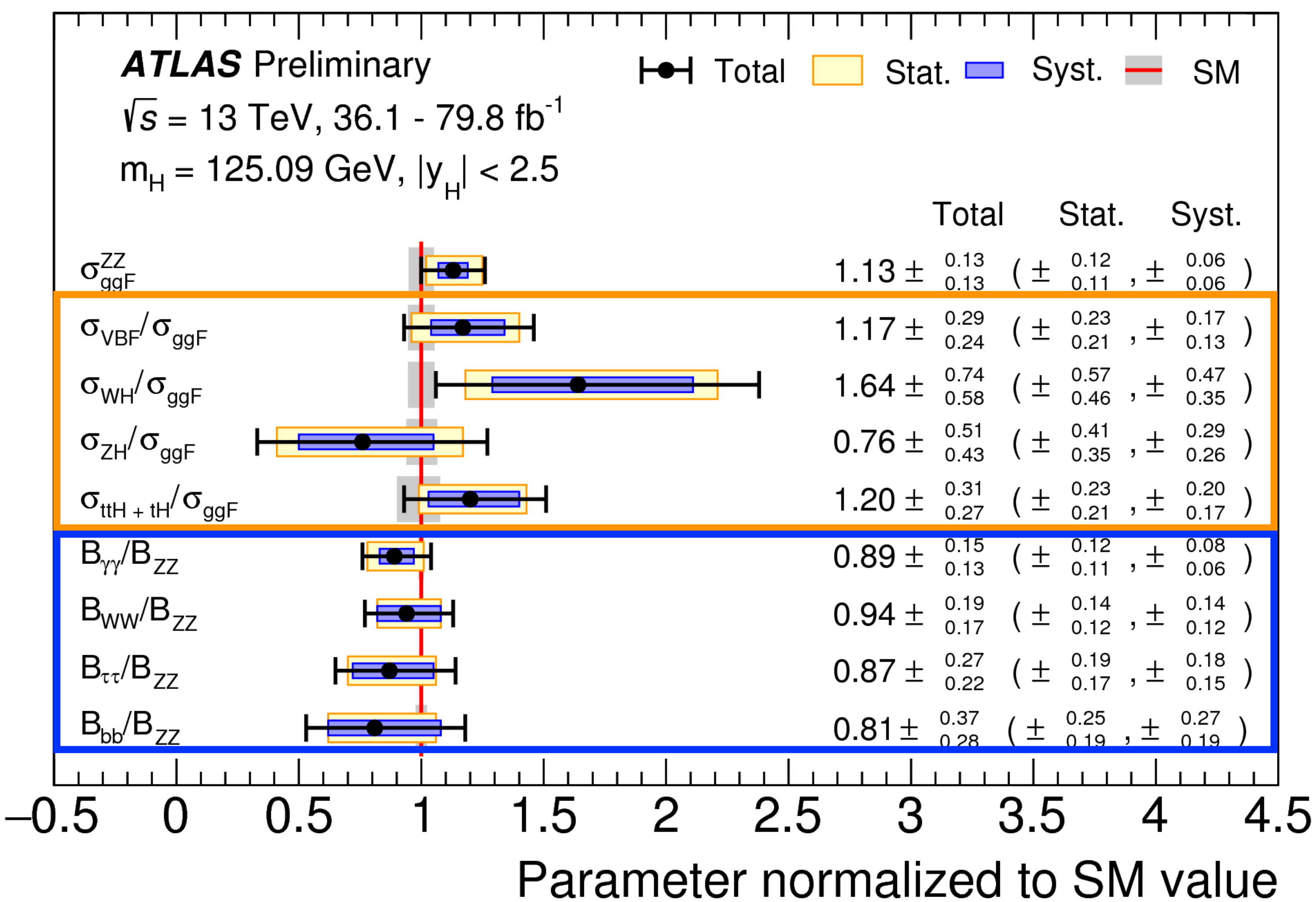


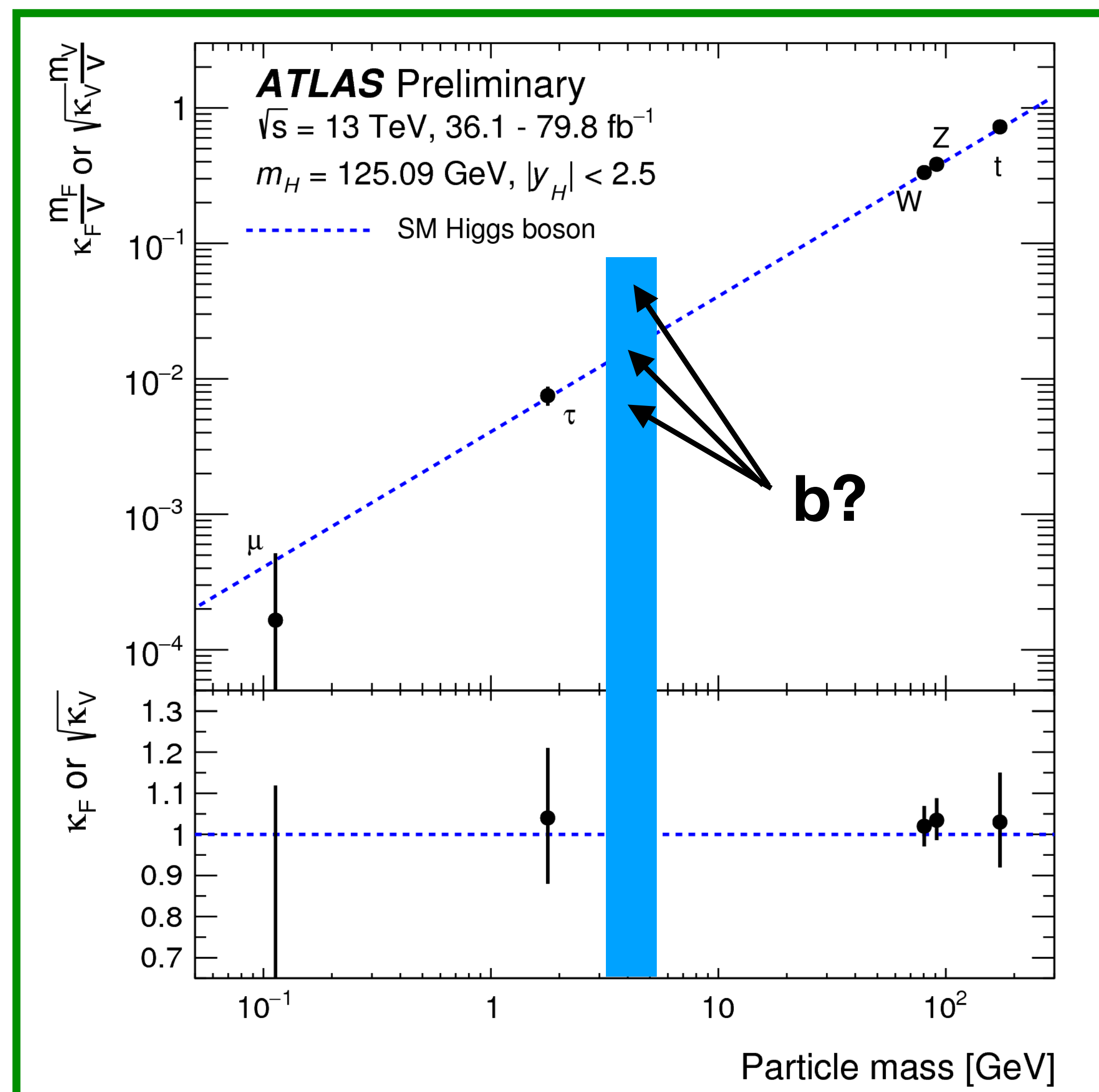
Recent results from ATLAS Run-2 data

- Several production and decay modes measured with 36-80 fb^{-1} of 13 TeV data
- Good agreement with SM for
  - global signal strength μ (= measured σ*BR / SM prediction)
  - ratios of cross sections of various production modes
  - ratios of branching ratios to different decay modes
  - couplings

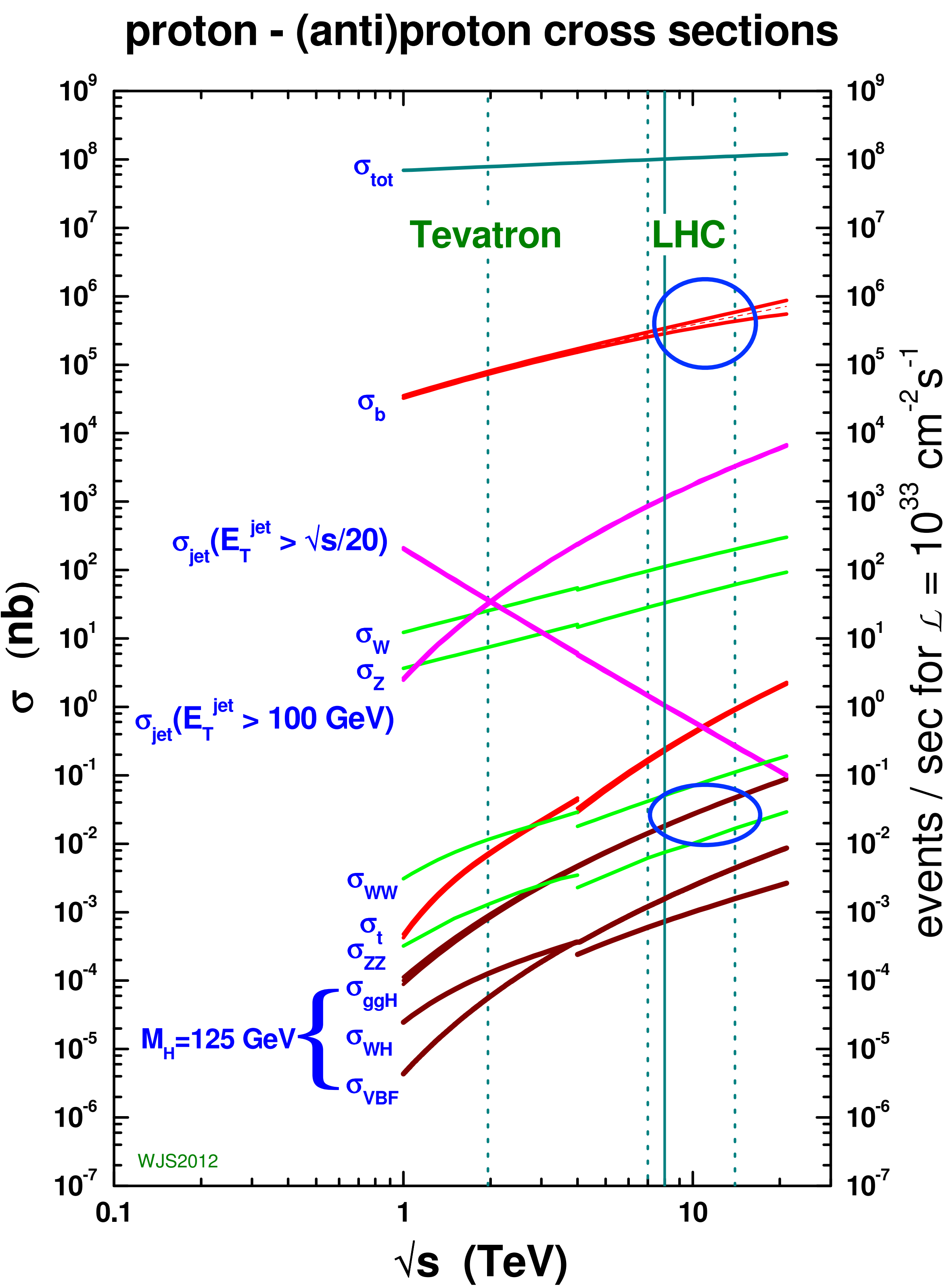
$$\mu = 1.13^{+0.09}_{-0.08}$$

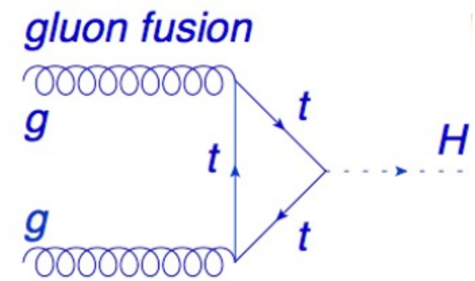
ATLAS-CONF-2018-031



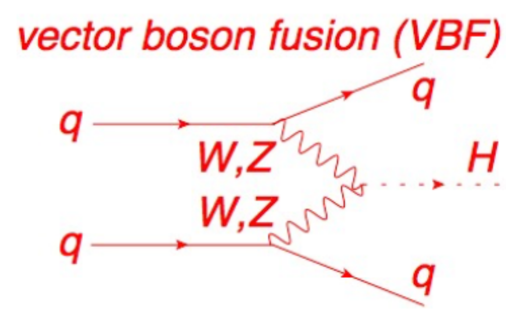


Searches for H→$b\bar{b}$ at hadron colliders

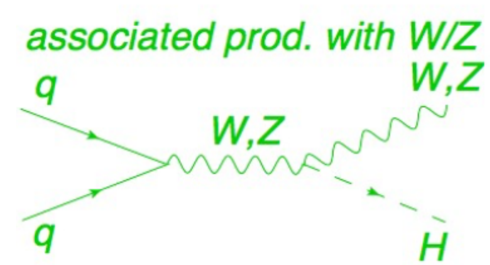




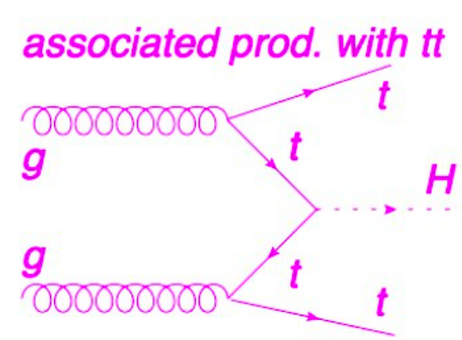
- Largest cross section
- Huge multi-jet (MJ) background



- Two forward jets
- Large MJ



- Leptonic signature
- Better triggering
- Better MJ suppression



- Leptonic signature
- Also top quark coupling

VH, $H \to b\bar{b}$: previous results (before Run-2)

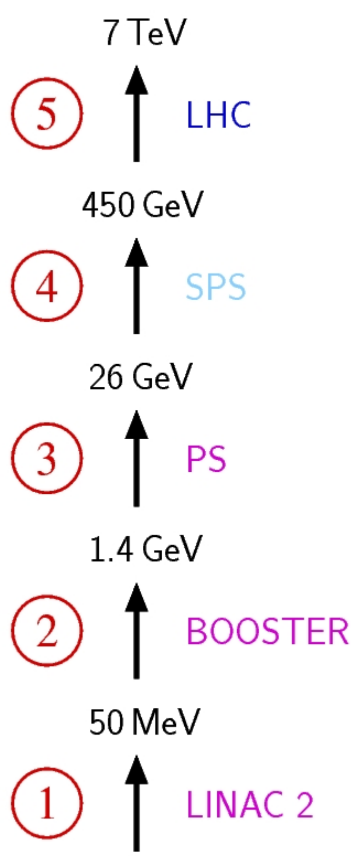
	Signal strength $\mu = \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}}$	Significance (expected)	Significance (observed)
CDF+DØ combination [1]	$1.9^{+0.8}_{-0.7}$	1.5σ	2.8σ (3.1σ global)
ATLAS Run-I [2]	$0.52^{+0.40}_{-0.37}$	2.6σ	1.4σ
CMS Run-I [3]	$0.89^{+0.47}_{-0.44}$	2.5σ	2.1σ
ATLAS+CMS Run-I* [4]	$0.70^{+0.29}_{-0.27}$	3.7σ	2.6σ

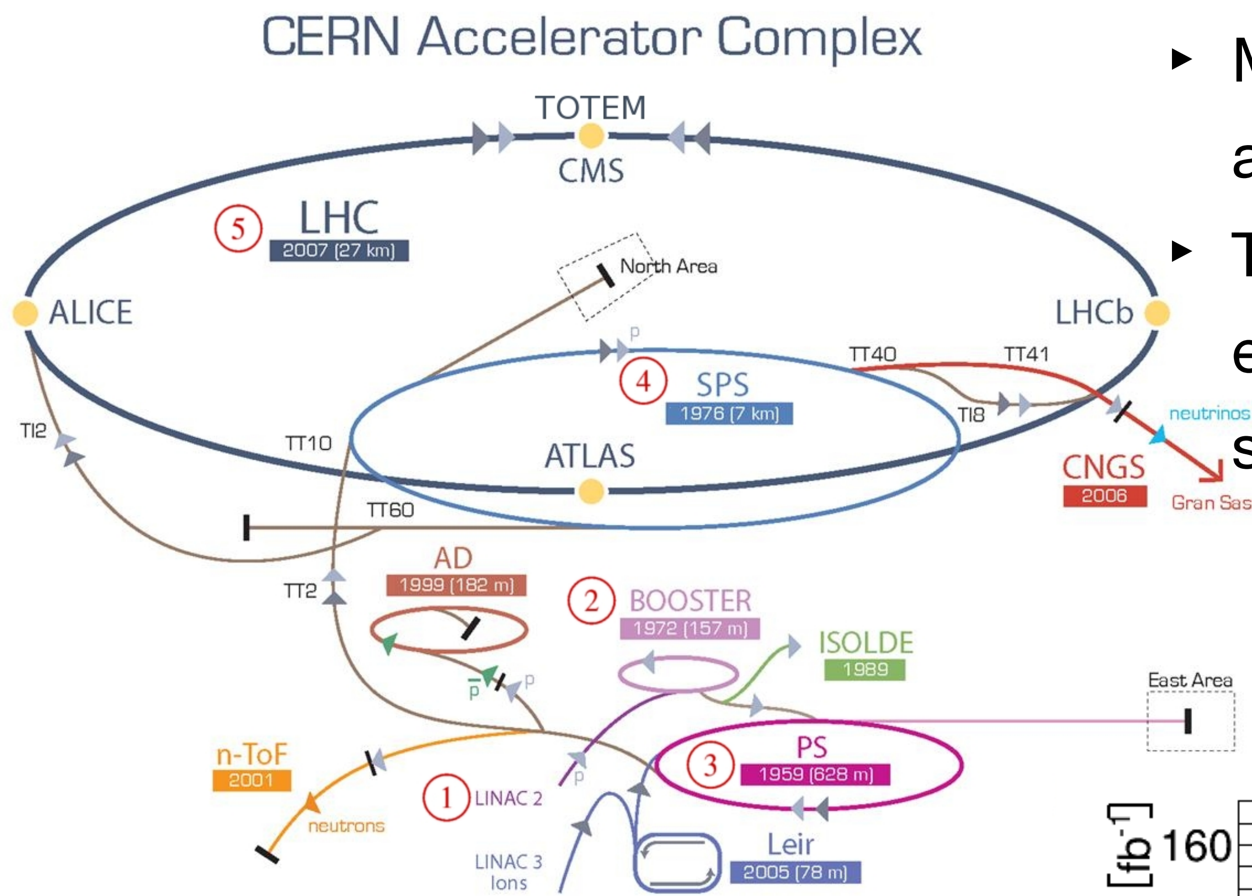
*with sub-leading contribution from ttH, $H \to bb$

[1] Phys. Rev. Lett. **109** (2012) 071804
[2] JHEP01(2015)069
[3] Eur.Phys.J. C75(5), 212 (2015) + twiki
[4] JHEP08(2016)045

- Before LHC Run-2, no observation of VH, $H \to b\bar{b}$
- Identification of b-jet is crucial from Run-1 experience
  - Efficiency plays a key role in sensitivity
  - Large impact on relative uncertainty on μ (13% in ATLAS Run-1)

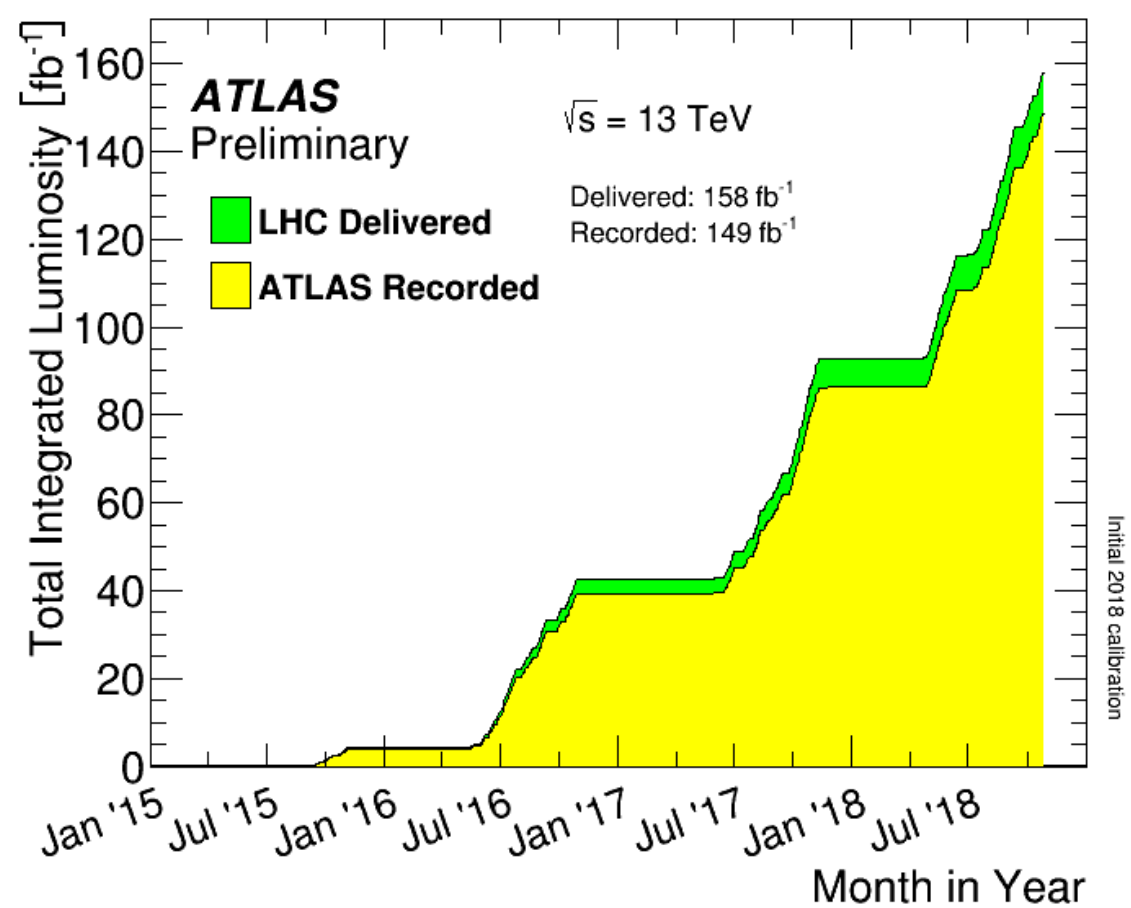
Large Hadron Collider @ CERN





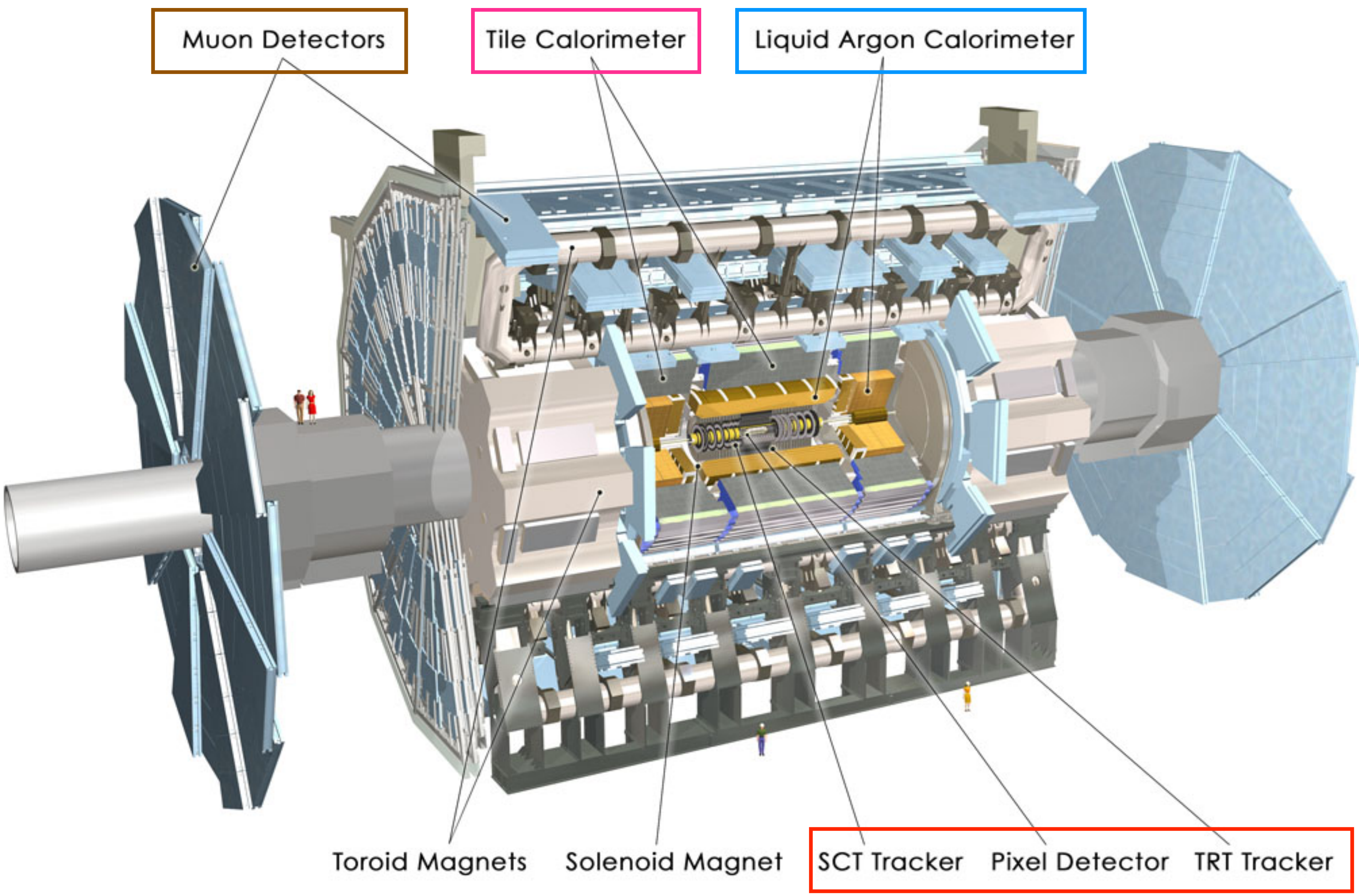
- Most powerful pp and heavy ion accelerator and collider
- Two main multi-purpose experiments (ATLAS, CMS) out of several experiments
  - test SM and search for new phenomena at the ~TeV scale

Beam condition pp collision	Design	Run-1 (2011-2012)	Run-2 (2015-2018)
Beam energy [GeV]	7.0	3.5~4.0	6.5
Bunching space [ns]	25	50	25
Max peak luminosity [10^{34} cm-2 s-1]	1.0	0.36~0.77	0.47~2.14



ATLAS Experiment @ LHC

General-purpose, ~ 4π detector for multi-TeV pp collisions



0.5-1T **2T**

Inner detector:

- charged particle tracks

EM calorimeter:

- e/γ energy/direction

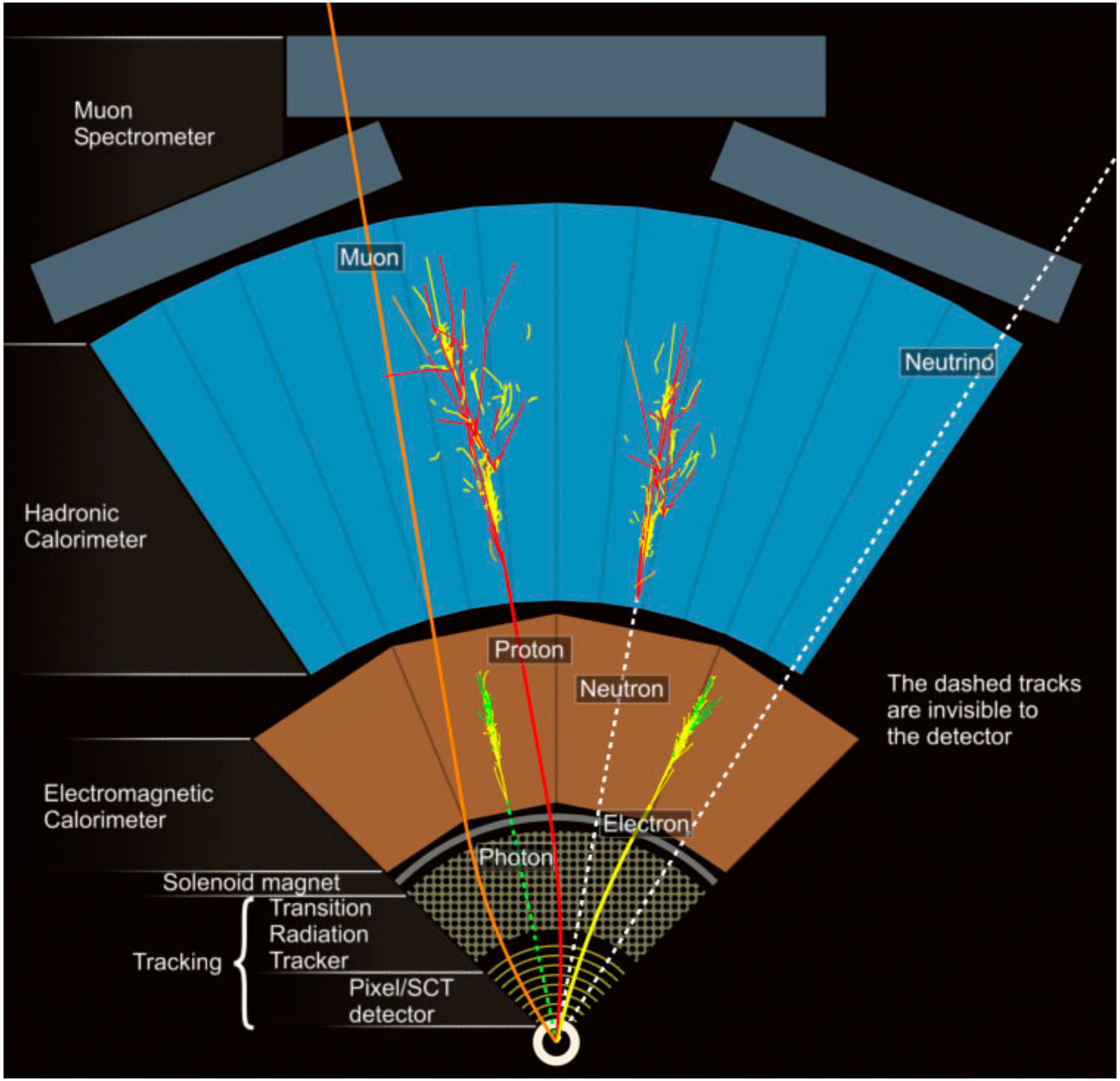
Hadronic calorimeter:

- hadron energy/direction

Muon spectrometer:

- Muon tracks

Object reconstruction in ATLAS



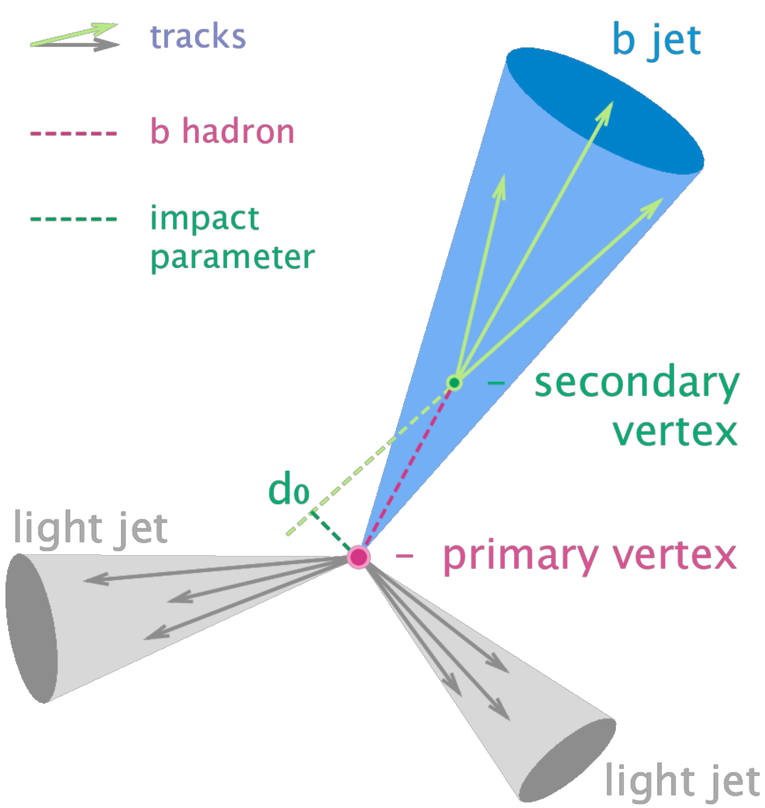
- Hadrons are clustered → jets
  - Anti-k_t clustering algorithm (R=0.4)
  - MC-based calibration + in-situ correction (Z+jet, γ+jet, multijets)

- Weakly interacting particles → transverse momentum imbalance (MET)

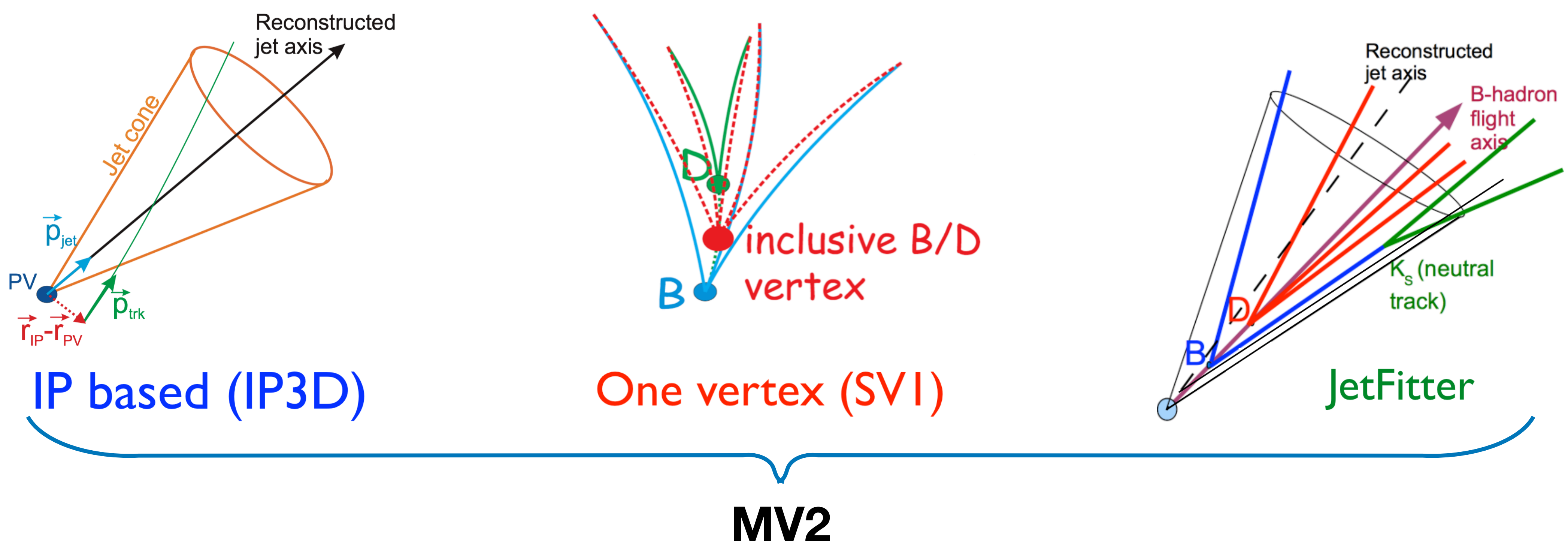
$$\vec{E}_T^{\text{miss}} = - \sum_{\text{observable}} \vec{p}_i$$

  - use calibrated identified particles + “soft term” from unassociated charged particle tracks

b-jet identification in ATLAS



- b-jets: jets containing b hadrons
- Identification ("tagging") of b-jets fundamental for:
  - Precision measurements in the top quark sector
  - Higgs boson decays to b quarks
  - New phenomena producing b quarks
- Three basic algorithms exploiting long lifetime of b-hadrons:
  - Tracks with large impact parameters (IP)
  - Inclusive secondary vertices (SV)
  - Eventual tertiary vertices
- Output combined into Boosted Decisions Tree (BDT): **MV2**



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- Future prospects
  - VH simplified template cross section (STXS) measurement *submitted to JHEP arXiv:1903.04618*

VH, $H \to b\bar{b}$ search with ATLAS Run-2 data

Published for SISSA by Springer

Received: *August 11, 2017*
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Published: *December 6, 2017*

JHEP12(2017)024

data 2015-2016: 36 fb^{-1}

Evidence for the $H \to b\bar{b}$ decay with the ATLAS detector

Physics Letters B 786 (2018) 59–86

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

data 2015-2017: 80 fb^{-1}

Observation of $H \to b\bar{b}$ decays and VH production with the ATLAS detector

Simulated event samples

- State-of-the-art NLO Monte Carlo generators normalised to higher-order calculations for the description of all backgrounds (except for multi-jet that is data-driven) and signals

Background

Process	Generator (PDF set)
Vector boson + jets	
$Z \to \nu\nu$	SHERPA 2.2.1 (NNPDF3.0NNLO)
$W \to \ell\nu$	SHERPA 2.2.1 (NNPDF3.0NNLO)
$Z\gamma^* \to \ell\ell$	SHERPA 2.2.1 (NNPDF3.0NNLO)
Top-quark	
$t\bar{t}$	POWHEG v2 + PYTHIA 8 (NNPDF3.0NNLO)
t, s-channel	POWHEG v1 + PYTHIA 6 (CT10)
t, t-channel	POWHEG v1 + PYTHIA 6 (CT10)
t, Wt-channel	POWHEG v1 + PYTHIA 6 (CT10)
Diboson	
WW	SHERPA 2.2.1 (CT10)
WZ	SHERPA 2.2.1 (NNPDF3.0NNLO)
ZZ	SHERPA 2.2.1 (NNPDF3.0NNLO)

Main background processes:

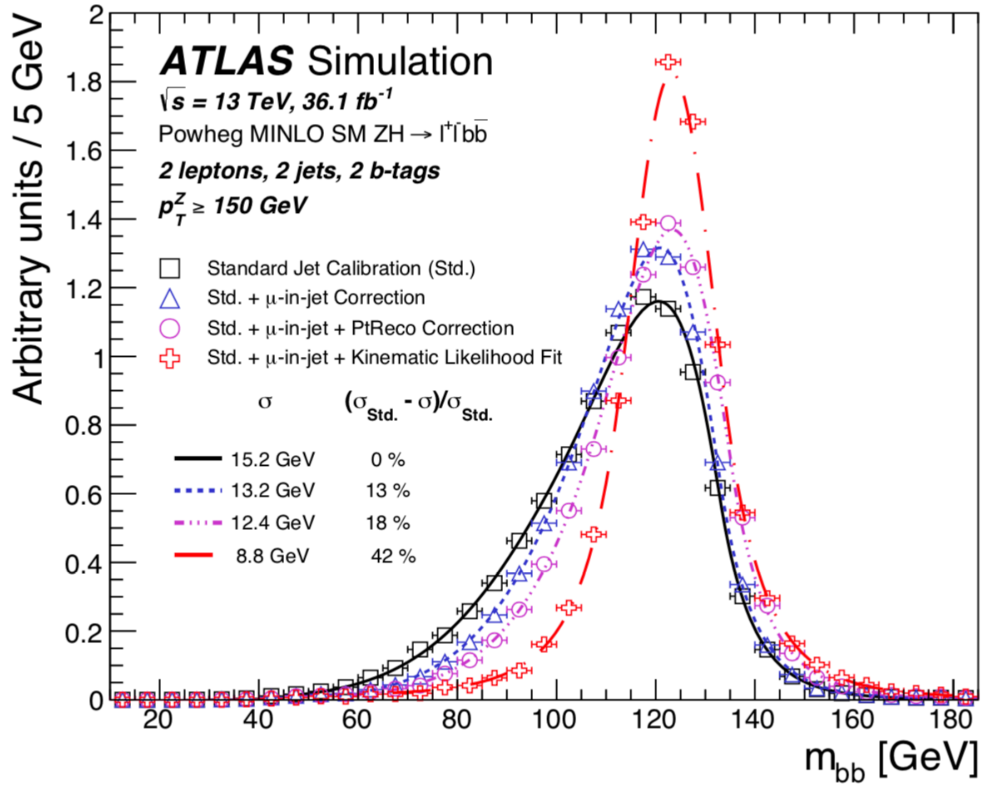
- Top-quark production
- Z+jets (heavy-flavours)
- W+jets (heavy-flavours)
- Diboson

Signal

Process	Generator (PDF set)
$qq \to ZH \to \nu\nu b\bar{b}$	POWHEG v2 + MINLO + PYTHIA 8 (PDF4LHC15)
$qq \to W^+H \to \ell^+\nu b\bar{b}$	POWHEG v2 + MINLO + PYTHIA 8 (PDF4LHC15)
$qq \to W^-H \to \ell^-\nu b\bar{b}$	POWHEG v2 + MINLO + PYTHIA 8 (PDF4LHC15)
$qq \to ZH \to \ell\ell b\bar{b}$	POWHEG v2 + MINLO + PYTHIA 8 (PDF4LHC15)
$gg \to ZH \to \nu\nu b\bar{b}$	POWHEG v2 + PYTHIA 8 (PDF4LHC15)
$gg \to ZH \to \ell\ell b\bar{b}$	POWHEG v2 + PYTHIA 8 (PDF4LHC15)

Signal signature and basic selection

- **H** (→ b$\bar{b}$) recoiling against **V** (→leptons)



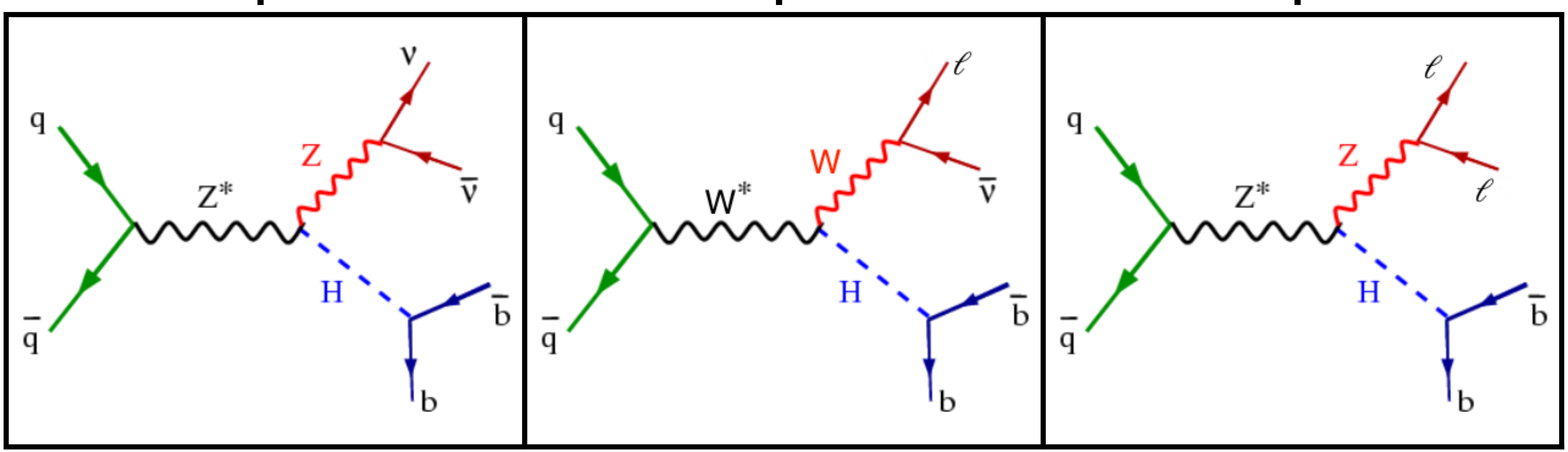
H → b$\bar{b}$

- 2 high-p_T b-jets, not from pile-up, b-tagged
- Kinematic properties consistent with VH production, e.g. m_{bb}~125 GeV

V→leptons

- 1 or 2 isolated charged leptons (W→lν, Z→ll) and/or large MET (Z→νν, W→μν)
  - also useful for triggering purposes
  - Z→ll: same flavour, m_{ll}~m_Z
- Channels denoted by the number of reconstructed charged leptons (e or μ)

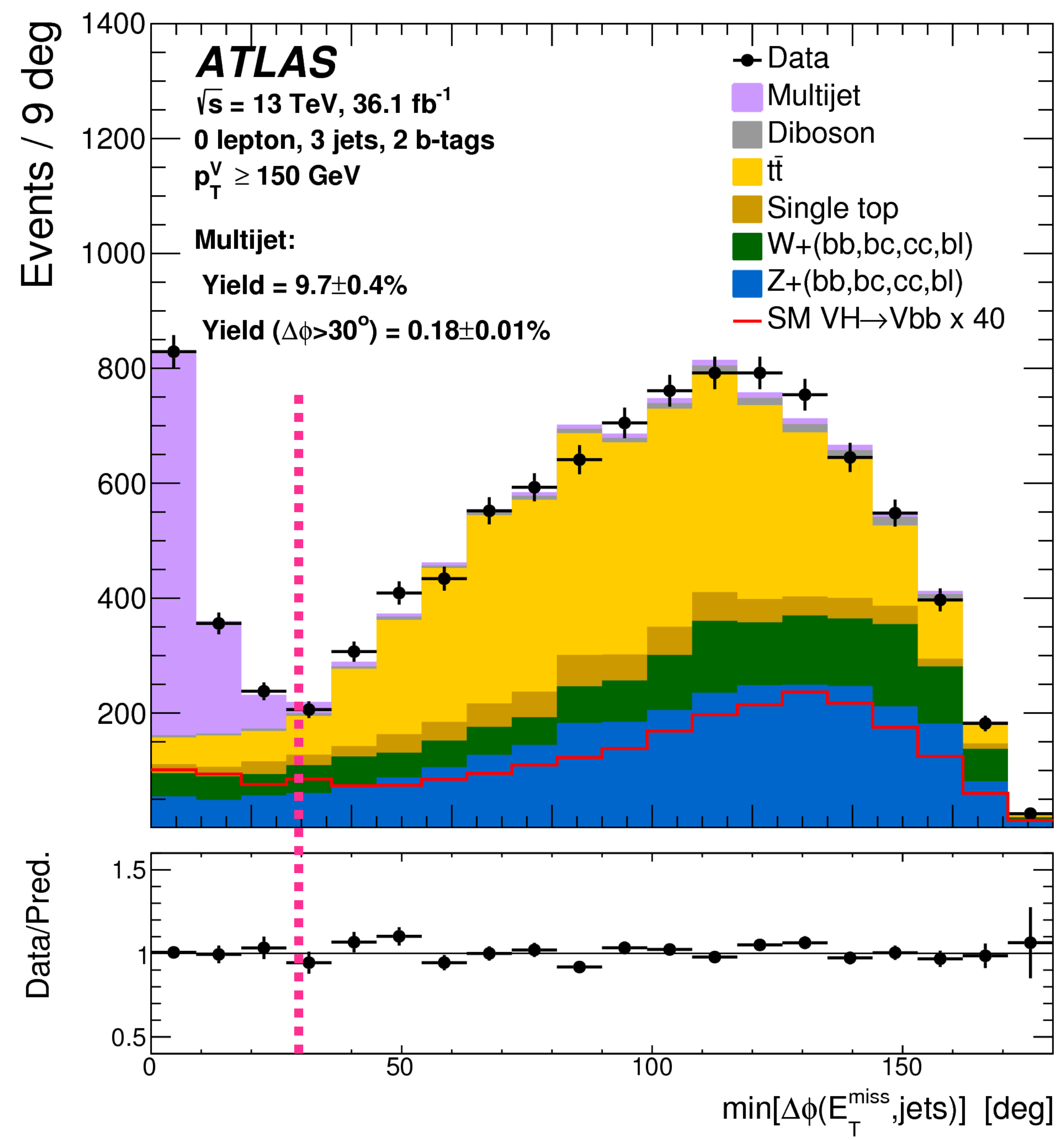
0-lepton **1-lepton** **2-lepton**



Specific selection vs lepton channel

- Additional selection criteria to suppress processes hard to model and estimate: QCD multi-jet
  - Take the 0-lepton as an example

Variable	Selection
MET	>150 GeV
$H_T = \Sigma\, p_T$ jets	>120 GeV for 2-jet events >150 GeV for 3-jet events
$\Delta\phi(E_T^{miss}, p_T^{miss})$	< 90°
$\Delta\phi(b,b)$	< 140°
$\Delta\phi(E_T^{miss}, bb)$	> 120°
$\min[\Delta\phi(E_T^{miss}, jet)]$	> 20° for 2-jet events > 30° for 3-jet events



- H_T cut to avoid trigger turn-on mis-modelling
- Angular cuts to reject QCD multi-jet

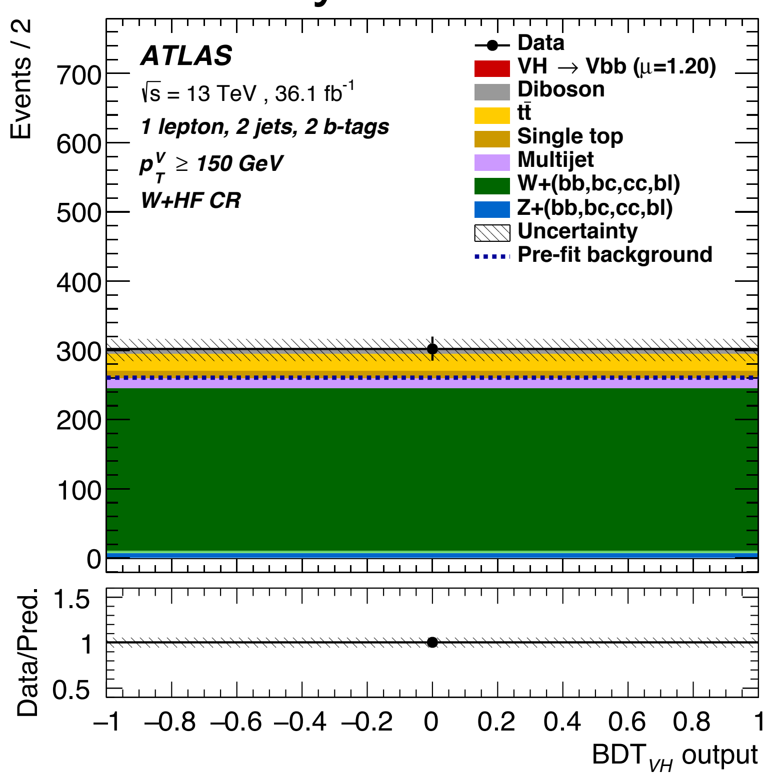
Control regions and event categories

- **Control regions** (CR) to constrain main backgrounds:

W+HF CR

1-lepton selection, $m_{b\bar{b}}$ < 75 GeV, m_{top} > 225 GeV

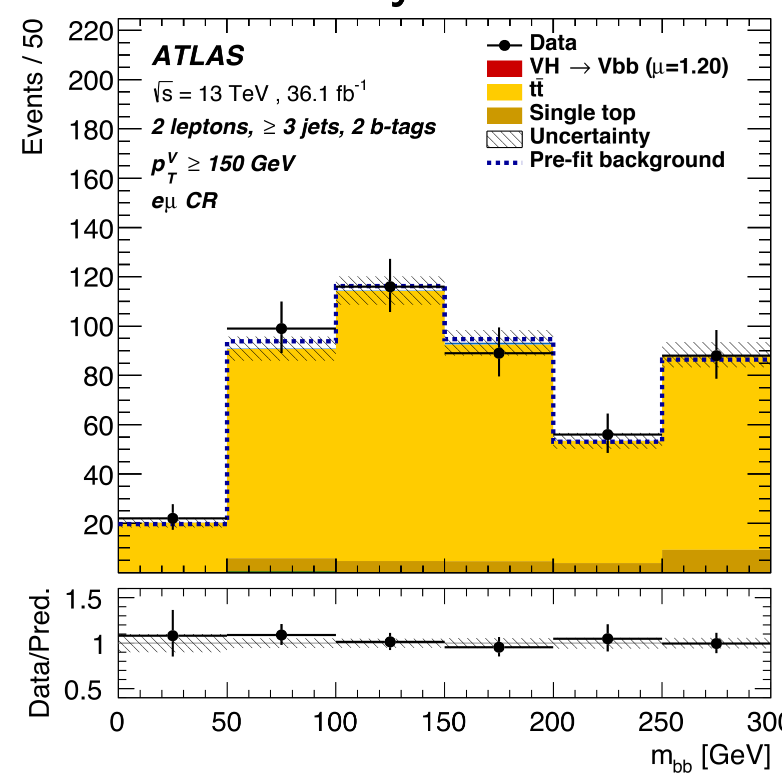
Purity 75~80%



$t\bar{t}$ eμ CR

2-lepton selection but require eμ final state

Purity > 99%



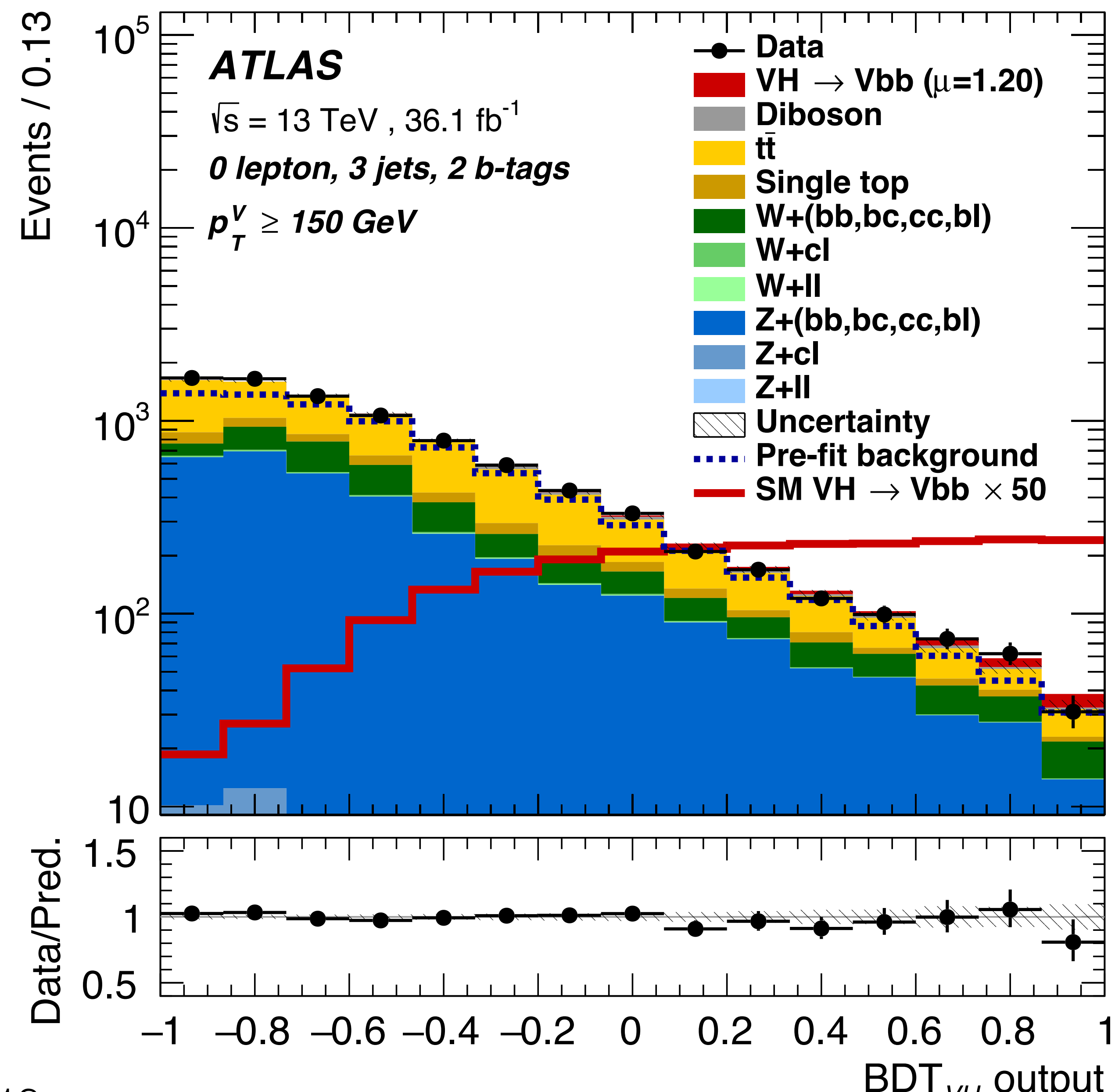
- **Event categories** with different S/B to increase sensitivity:

		2 regions in V transverse momentum (p_T^V)		2 bins in jet multiplicity
signal region (SR)	⊗	75 < p_T^V < 150 GeV (only for 2-lepton)	⊗	2-jet
W+HF CR (1-lepton)		150 GeV < p_T^V		3-jet (≥3-jet for 2lepton)
$t\bar{t}$ eμ CR (2-lepton)				

The analysis strategy: Multivariate approach

- Final S/B discrimination from fit to score of BDT combining several input variables
  - Start from a minimal set of variables with largest S/B separation [m_{bb}, ΔR_{bb}]
  - Test additional variables one-by-one, keep variable providing maximum sensitivity
  - Iterate the procedure until the sensitivity improvement is negligible
- Separate training for lepton/p_T^V/N_{jet} regions

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\boldsymbol{b}_1, \boldsymbol{b}_2)$	×	×	×
$\|\Delta\eta(\boldsymbol{b}_1, \boldsymbol{b}_2)\|$	×		
$\Delta\phi(\boldsymbol{V}, \boldsymbol{bb})$	×	×	×
$\|\Delta\eta(\boldsymbol{V}, \boldsymbol{bb})\|$			×
m_{eff}	×		
$\min[\Delta\phi(\boldsymbol{\ell}, \boldsymbol{b})]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
m_{top}		×	
$\|\Delta y(\boldsymbol{V}, \boldsymbol{bb})\|$		×	
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×



The Fit Model

- Combined Likelihood fit is built across channels and multiple analysis regions

Channel	SR/CR	Categories			
		$75\,\text{GeV} < p_T^V < 150\,\text{GeV}$		$p_T^V > 150\,\text{GeV}$	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	—	—	BDT	BDT
1-lepton	SR	—	—	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	—	—	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

- Each bin contributes with a Poisson term

$$\mathcal{L}(\mu, \boldsymbol{\theta}) = \left[\prod_{i \in \text{bins}} \text{Pois}\left(n^i | \mu \nu_s^i(\boldsymbol{\theta}) + \nu_b^i(\boldsymbol{\theta}) \right) \right]$$

Parameter of interest

$$\mu = \frac{\sigma \cdot \text{BR}}{\sigma_{\text{SM}} \cdot \text{BR}_{\text{SM}}}$$

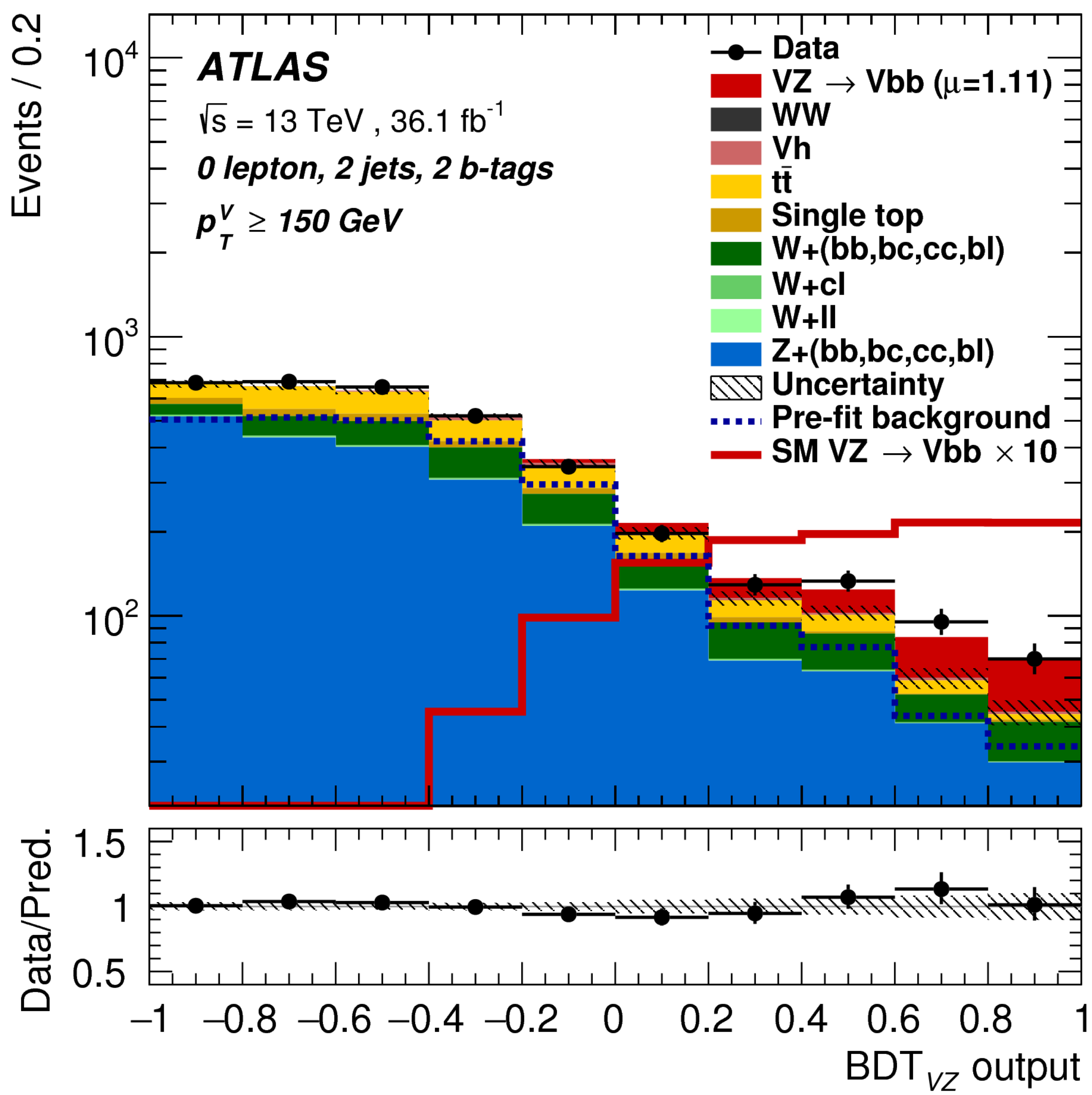
Nuisance parameters (NPs) $\boldsymbol{\theta}$:

- Uncertainties from performance:
  - Lepton / Jet / MET / b-tagging
- Parametrized shapes and relative normalisations across regions

Cross-checks

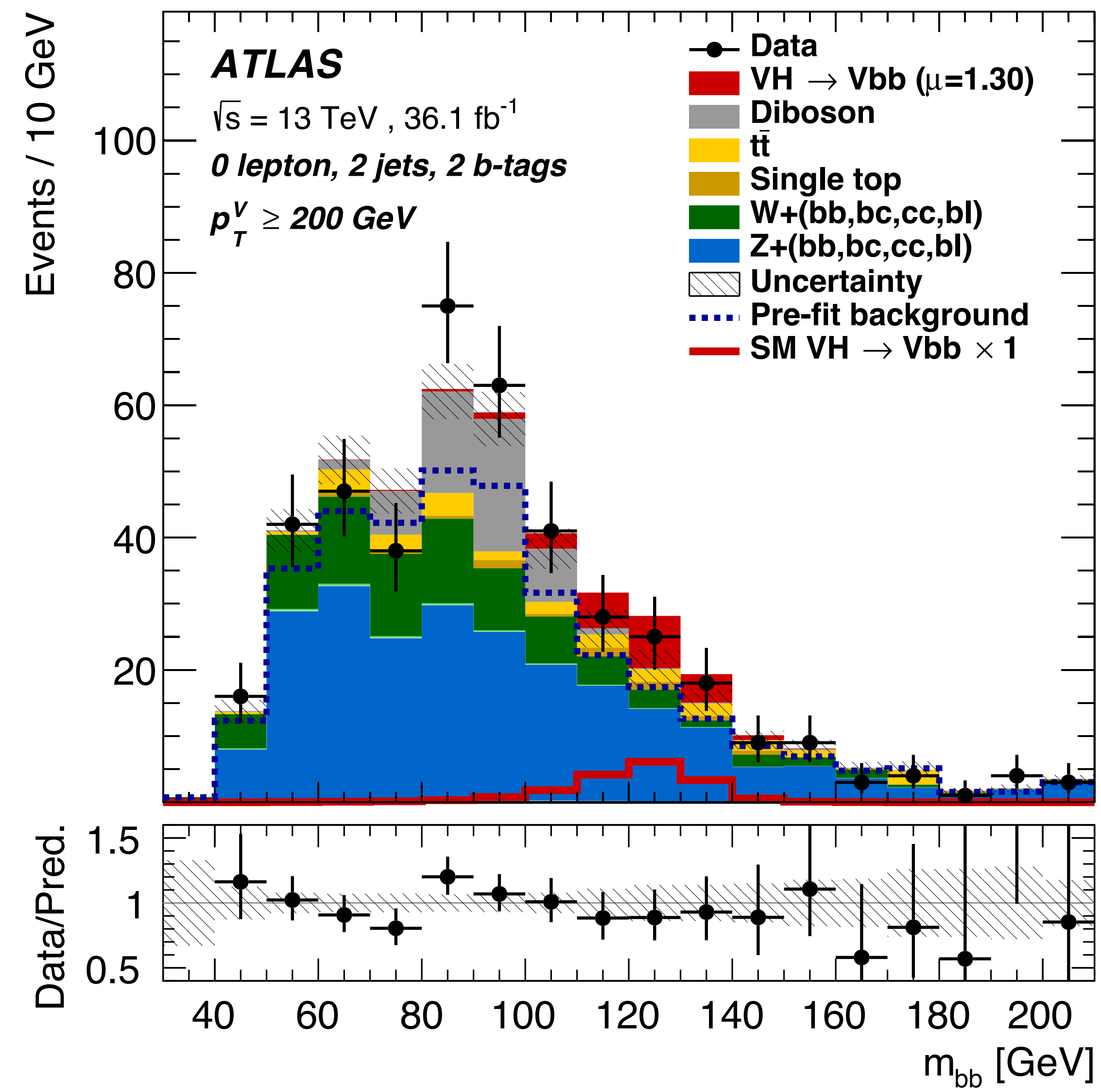
Diboson cross-check

- VZ, Z → $b\bar{b}$ same final states as VH, H → $b\bar{b}$
- Same analysis, but with VZ, Z → $b\bar{b}$ as signal
- BDT re-trained with VZ as signal (BDT_{VZ})
- Fit BDT_{VZ} distribution to extract μ_{VZ}

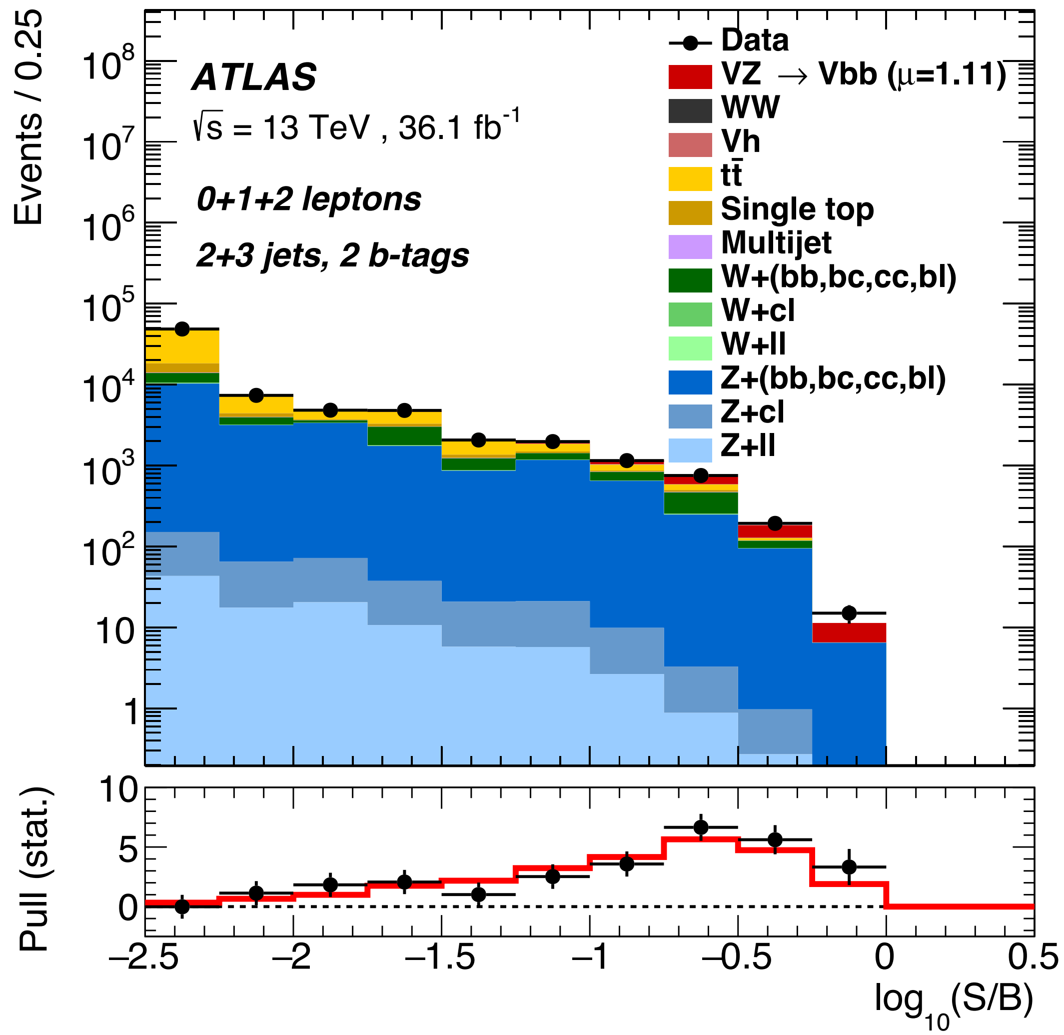


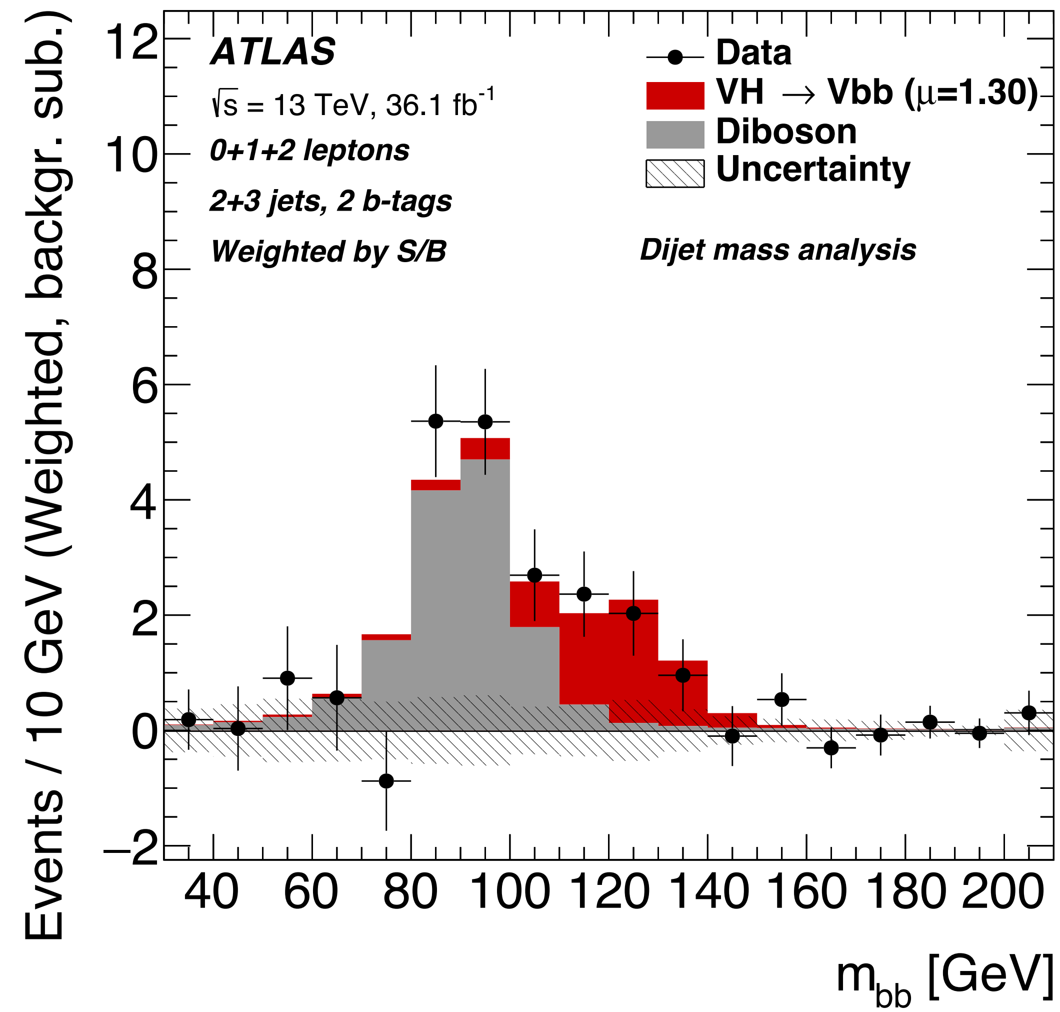
Dijet mass cross-check

- VH, H → $b\bar{b}$ as the signal
- Fit m_{bb} distribution instead of BDT_{VH}
- Additional selections to compensate for sensitivity loss due to simpler fit discriminant



Cross-checks: Results with 36 fb^{-1}





- Signal strength

$$\mu_{VZ} = 1.11^{+0.12}_{-0.11}(\text{stat.})^{+0.22}_{-0.19}(\text{syst.})$$

- Expected significance: 5.3σ
- Observed significance: 5.8σ

VZ, Z → $b\bar{b}$

- Signal strength

$$\mu = 1.30^{+0.28}_{-0.27}(\text{stat.})^{+0.37}_{-0.29}(\text{syst.})$$

- Expected significance: 2.8σ
- Observed significance: 3.5σ

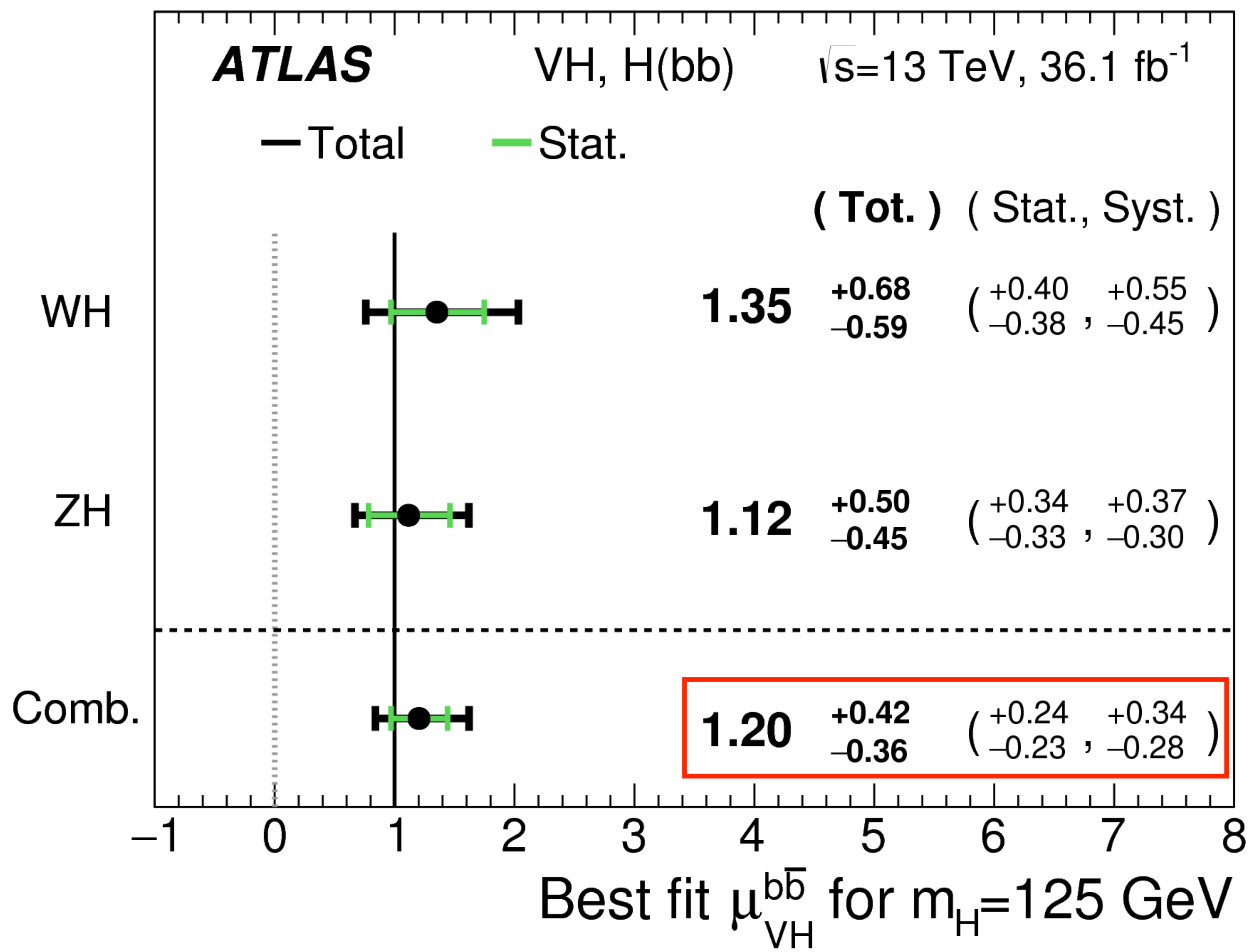
VH, H → $b\bar{b}$
Dijet mass

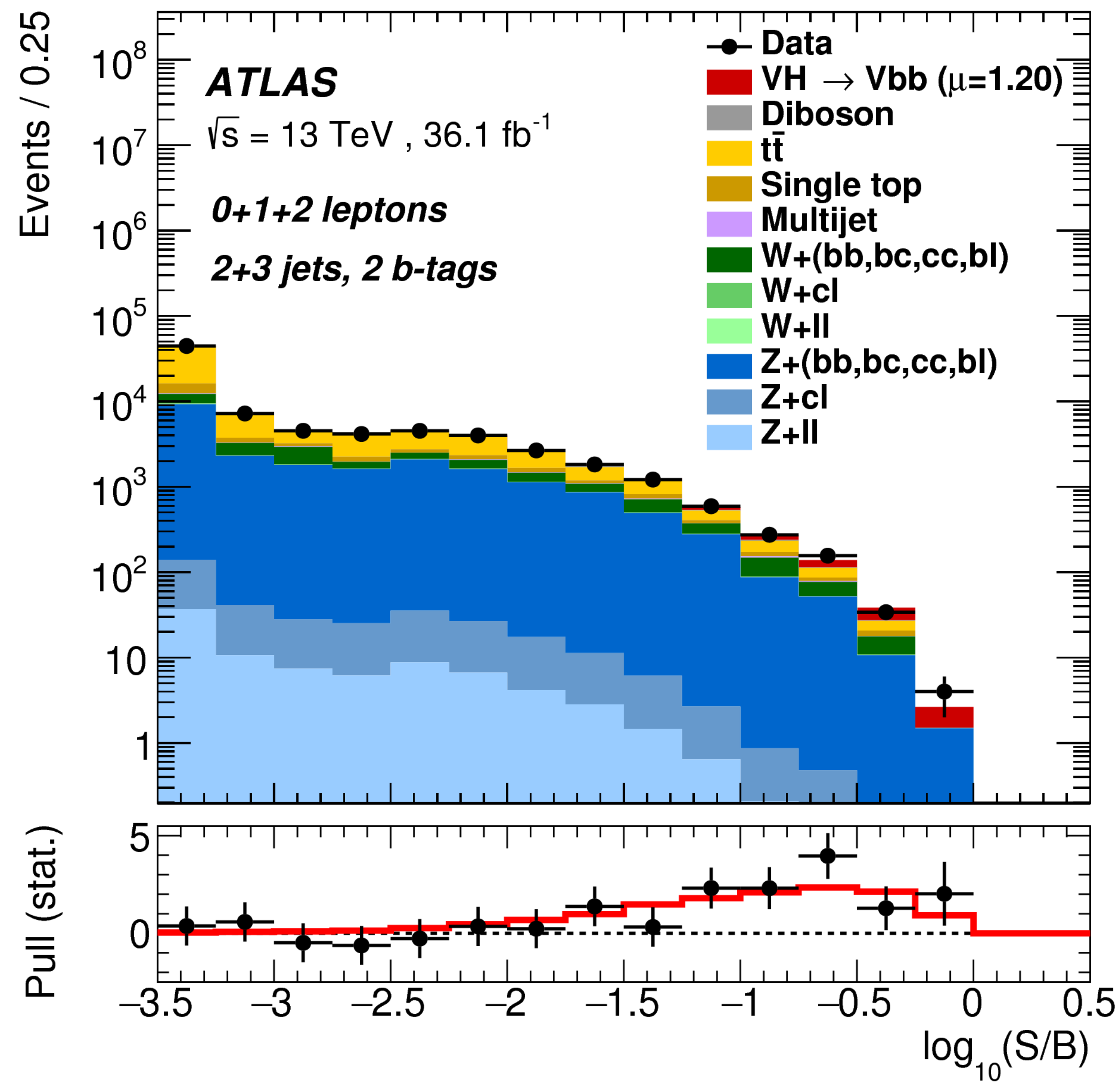
Impact of systematic uncertainties on μ_{VH}

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
Multi-jet		0.02
MC statistical		0.13

- Dominant effects:
  - Signal Modelling
  - Background Modelling
    - W+jet
    - Single top Wt
    - Z+jets
    - $t\bar{t}$
  - b-tagging calibration
  - Limited Monte Carlo statistics

VH, H → $b\bar{b}$ results with 36 fb^{-1}





2 signal strengths (μ_{WH}, μ_{ZH}) and the inclusive signal strength μ_{VH}

- Expected significance: 3.0σ
- Observed significance: 3.5σ

Updates in the “Observation” Analysis

“Evidence” Analysis

Source of uncertainty		σ_μ
Total		0.39
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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
Multi-jet		0.02
MC statistical		0.13

“Observation” Analysis

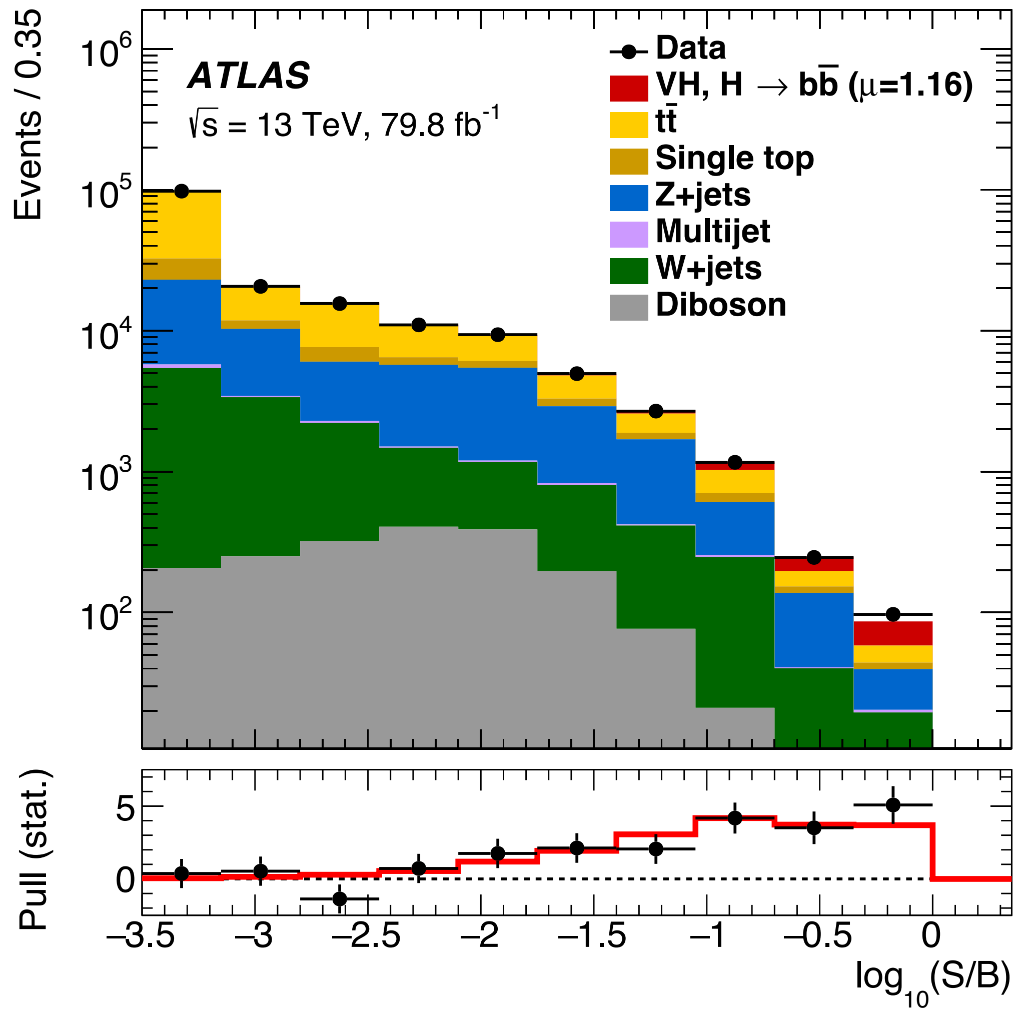
Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	*b*-jets	0.061
	c-jets	0.042
	light jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
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

- Main updates from “evidence”:
  - More data: 80 fb^{-1} vs. 36 fb^{-1}
  - Larger MC samples
  - Improved reconstruction algorithms
  - Better evaluation of systematic uncertainties

Lead to a more accurate measurement

Uncertainty	Reduction [%]
Signal Modelling	45
Bkg. Modelling	max 65
b-tagging (b-jets)	32
MC stat.	46
Systematics	35
Statistical	33
Total	34

VH, H → $b\bar{b}$ results with 80 fb^{-1}



Signal strength
$\mu_{\mathrm{WH}} = 1.08^{+0.27}_{-0.27}(\mathrm{stat.})^{+0.38}_{-0.34}(\mathrm{syst.})$
$\mu_{\mathrm{ZH}} = 1.20^{+0.23}_{-0.23}(\mathrm{stat.})^{+0.23}_{-0.20}(\mathrm{syst.})$
$\mu_{\mathrm{VH}} = 1.16^{+0.16}_{-0.16}(\mathrm{stat.})^{+0.21}_{-0.19}(\mathrm{syst.})$

- Expected significance: 4.3 σ
- Observed significance: 4.9 σ

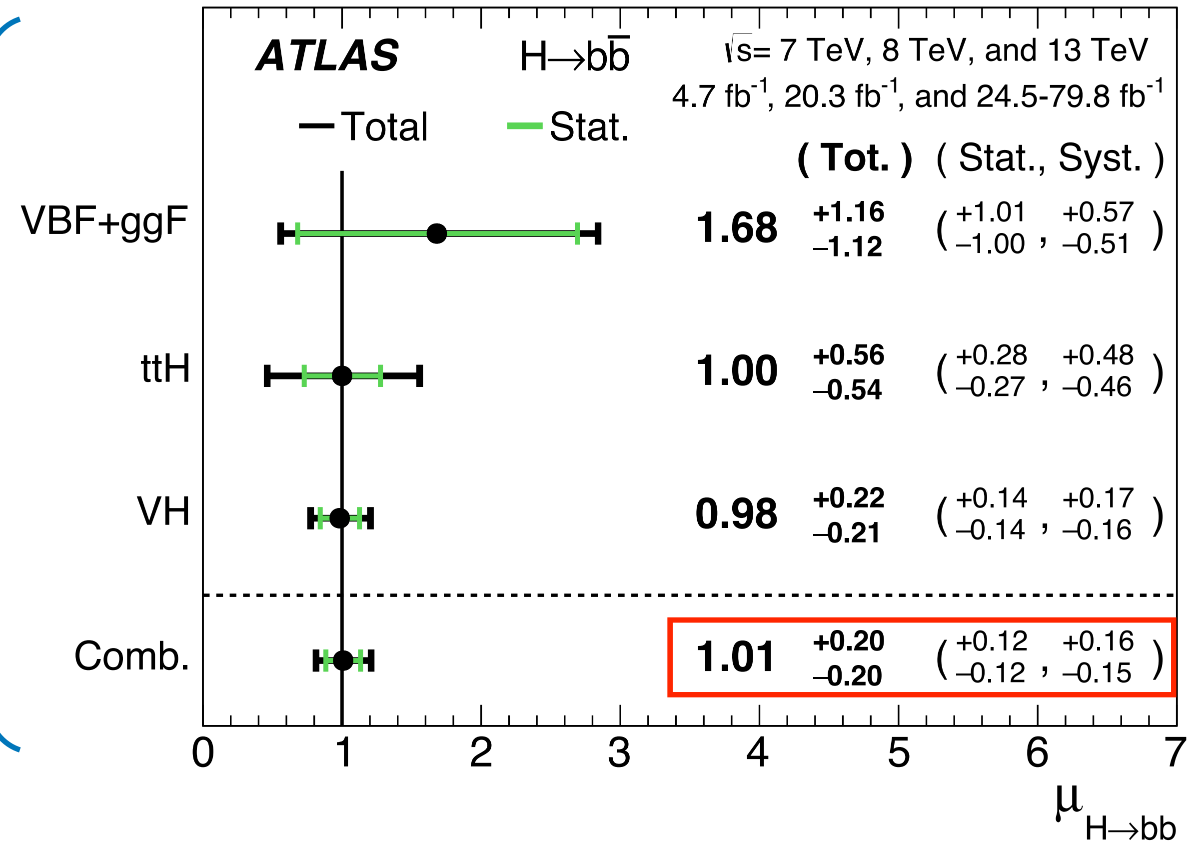
Combination with Run-1 Analysis:
(correlate signal theory and b-jets)

- Expected significance: 5.1 σ
- Observed significance: 4.9 σ

$\mu_{\mathrm{WH}} = 1.08^{+0.24}_{-0.23}(\mathrm{stat.})^{+0.29}_{-0.27}(\mathrm{syst.})$
$\mu_{\mathrm{ZH}} = 0.92^{+0.21}_{-0.20}(\mathrm{stat.})^{+0.19}_{-0.17}(\mathrm{syst.})$
$\mu_{\mathrm{VH}} = 0.98^{+0.14}_{-0.14}(\mathrm{stat.})^{+0.17}_{-0.16}(\mathrm{syst.})$

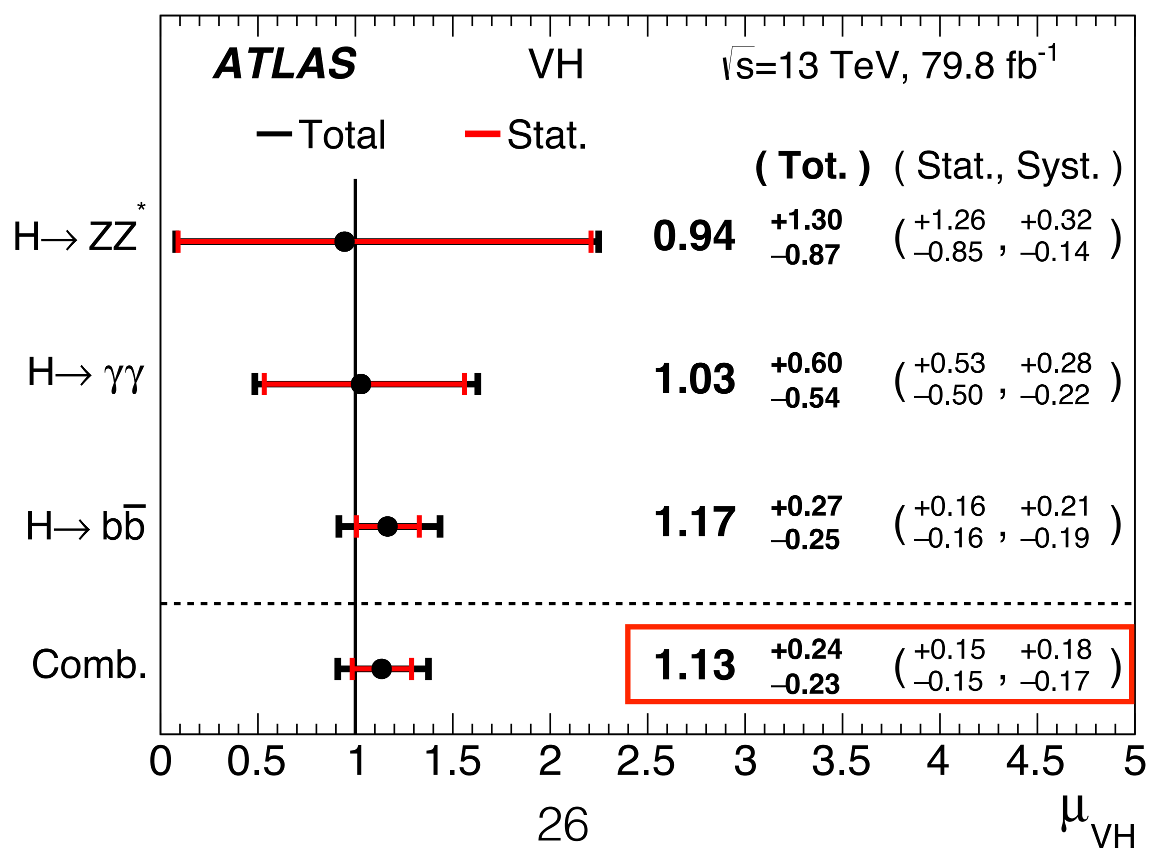
Observation of $H \rightarrow b\bar{b}$ decay and VH production

Combination of production modes with cross sections predicted by SM



- Exp. significance = 5.5σ
- Obs. significance = 5.4σ
- $H \rightarrow b\bar{b}$ observed

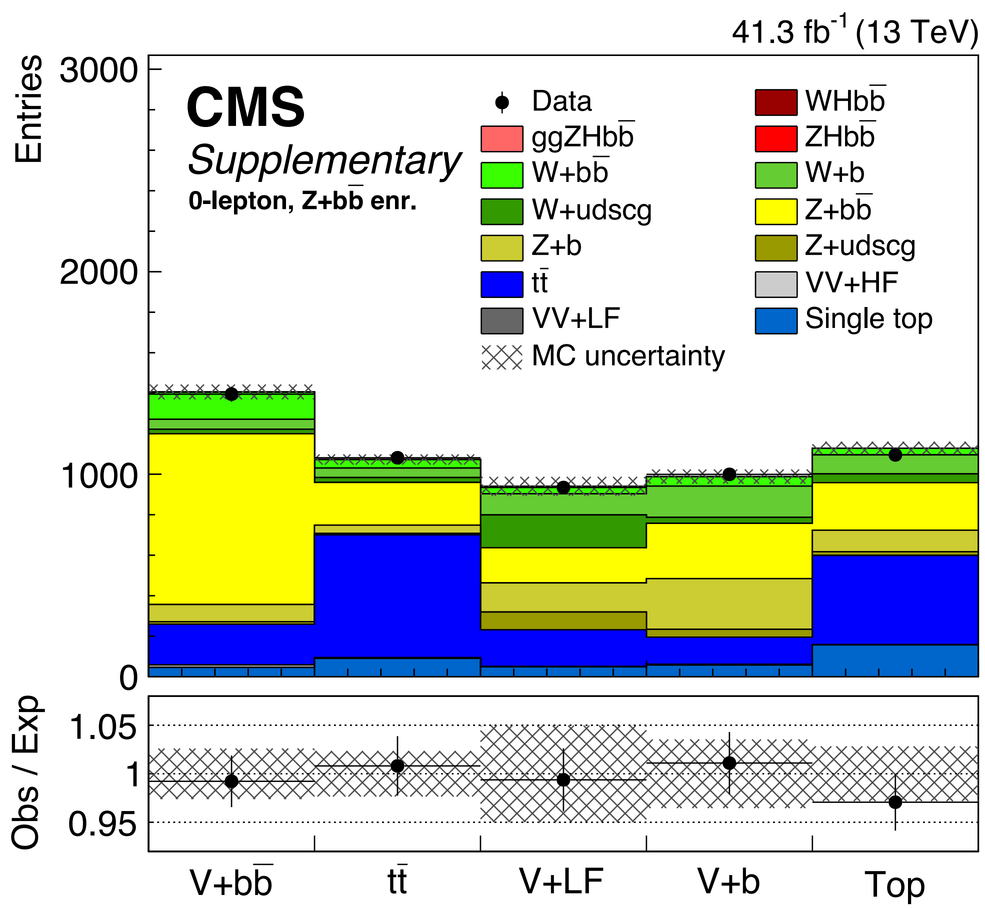
Combination of decay modes with branching ratios predicted by SM



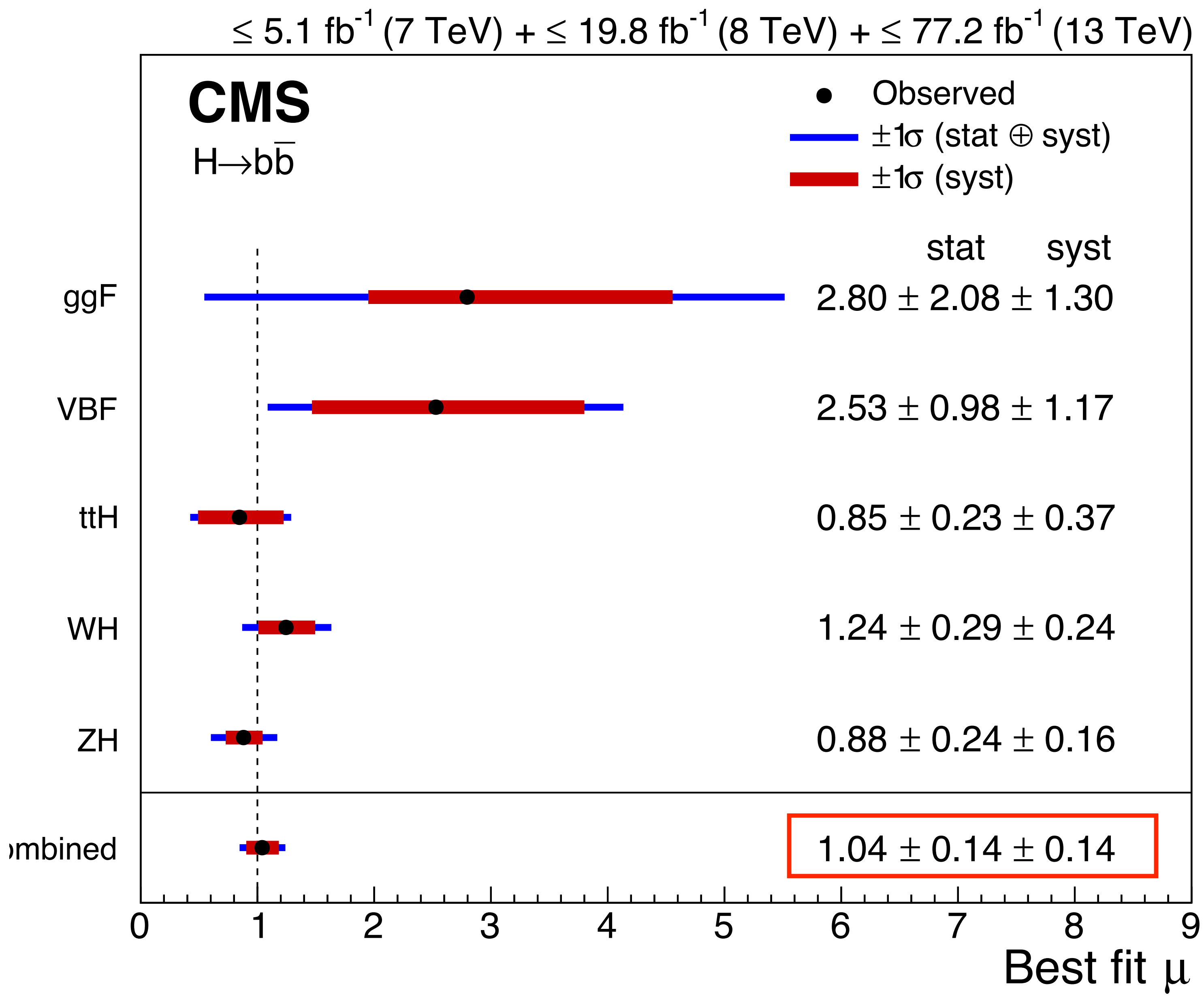
- Exp. significance = 4.8σ
- Obs. significance = 5.3σ
- VH observed

Observation of H → b$\bar{b}$ decay by CMS

- Main differences from ATLAS analysis
  - SR and CR divided by the m_{jj}
    - 0L SR 60 < m_{jj} <160 GeV
    - 1/2L SR 90 < m_{jj} <150 GeV
  - Deep Neural Network (DNN) used
    - SR: score as the fit variable
    - CR: multiclassifier defines the background categories



PRL 121 (2018) 121801



- Exp. significance = 5.6σ
- Obs. significance = 5.5σ
- H → b$\bar{b}$ observed by CMS

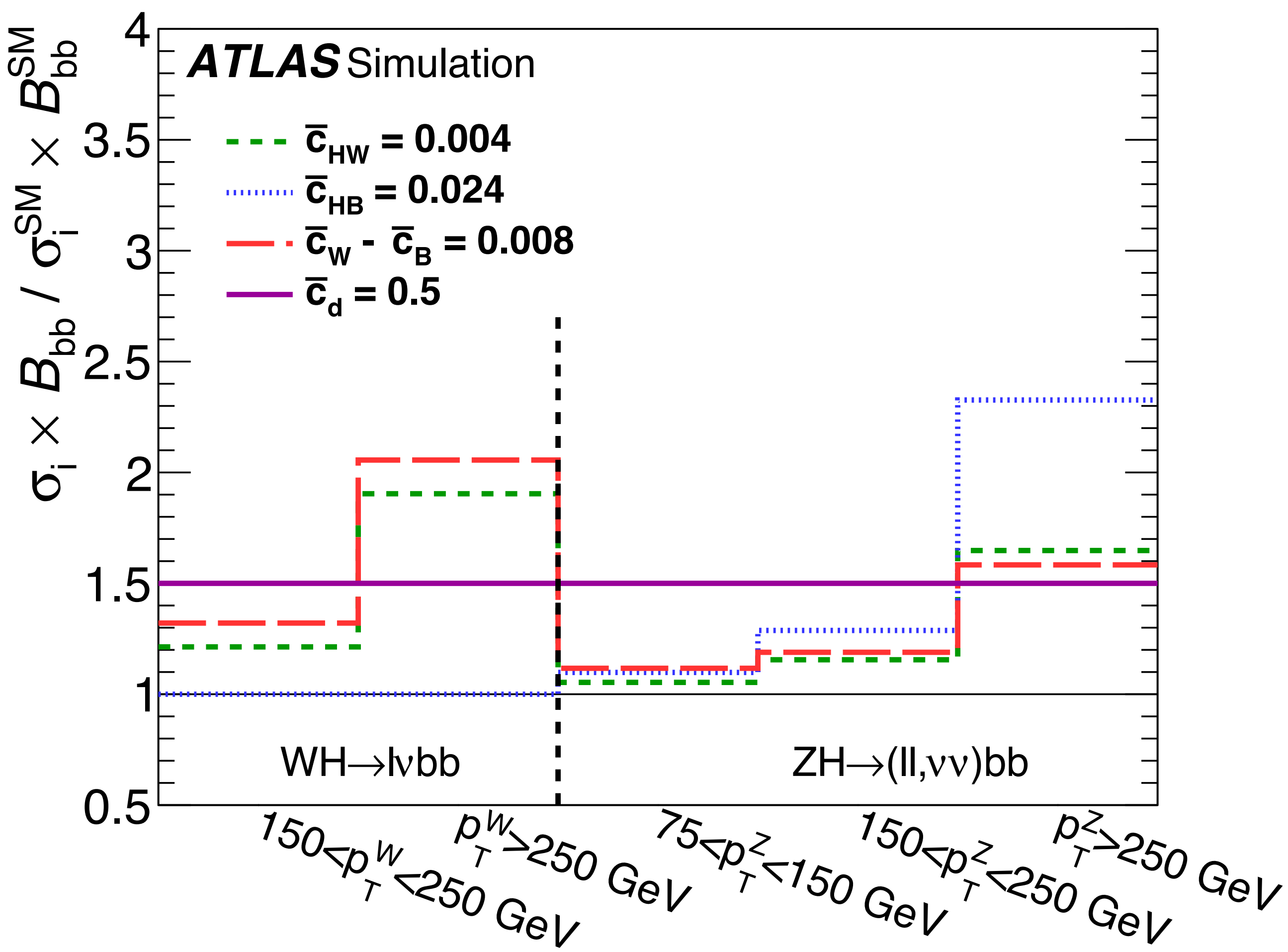
Outline

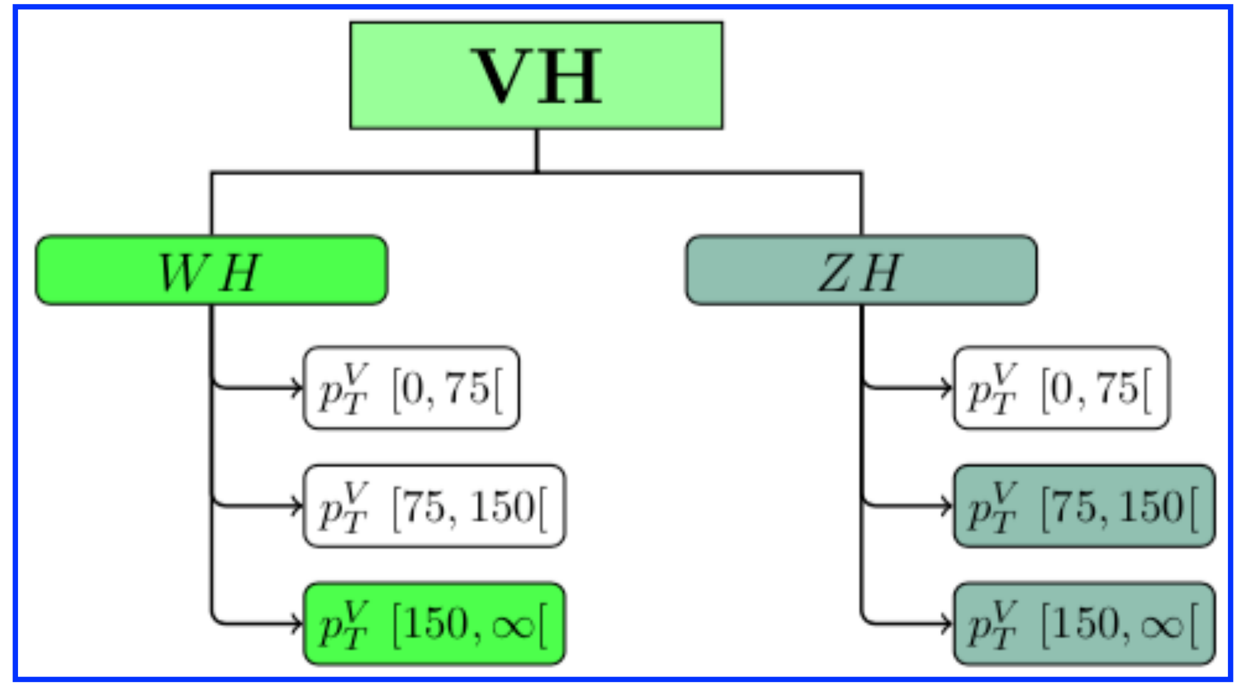
- Standard Model (SM) Higgs Boson
  - Search for $H \rightarrow b\bar{b}$ at colliders
  - LHC and ATLAS
- Search for VH, $H \rightarrow b\bar{b}$ production with ATLAS data
  - Evidence of VH, $H \rightarrow b\bar{b}$ production with 36 fb^{-1} *JHEP 12 (2017) 024*
  - Observation of $H \rightarrow b\bar{b}$ decays and VH production with 80 fb^{-1} *PLB 786 (2018) 59*
- Future prospects
  - VH simplified template cross section (STXS) measurement

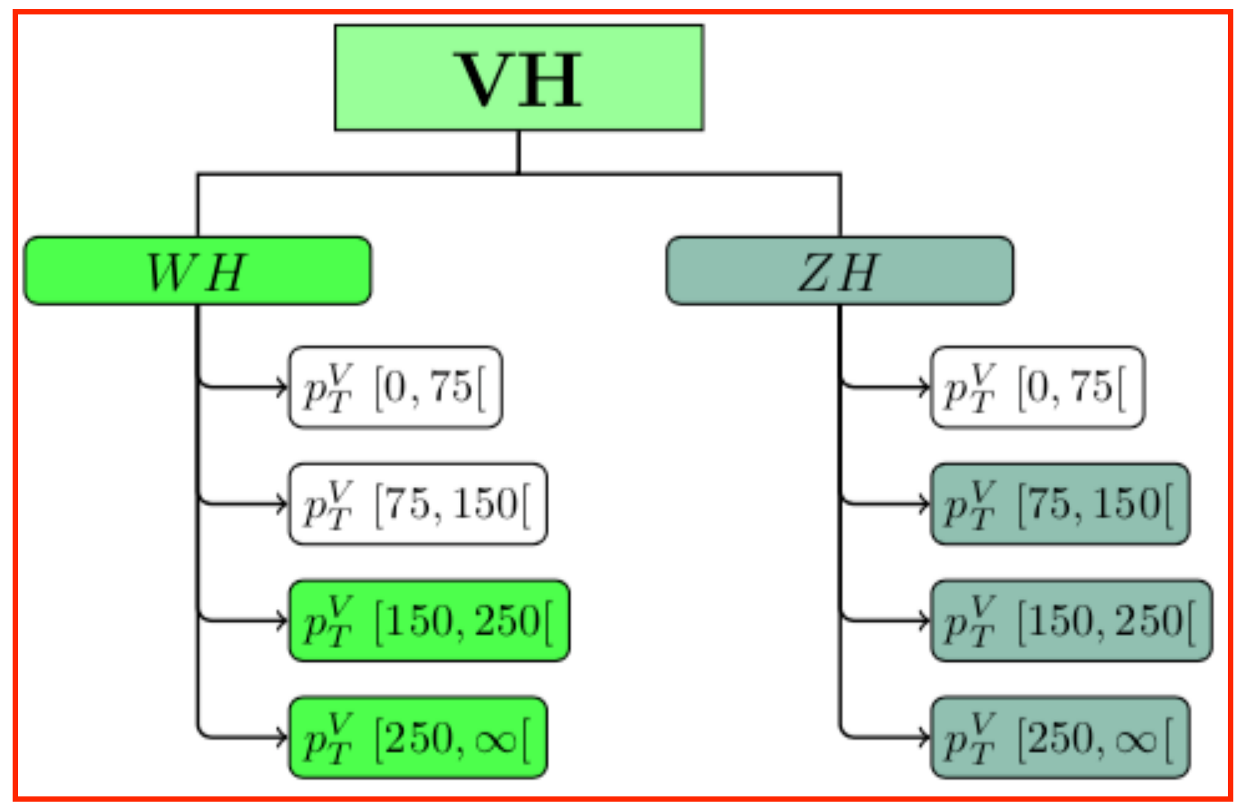
submitted to JHEP
arXiv:1903.04618

VH stage-1 STXS measurement with $H \rightarrow b\bar{b}$

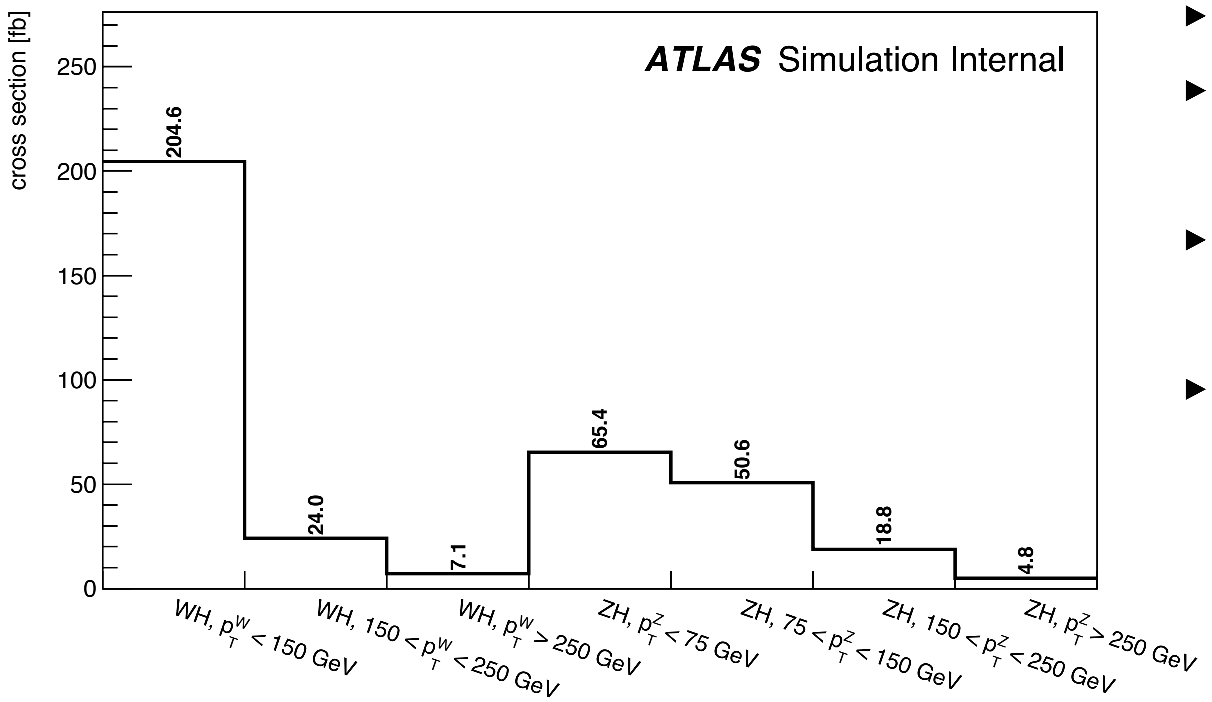
- Template XS instead of inclusive signal strength
    - Same analysis strategy:
        - Classification for the events
        - Same discriminant variables for fit
    - Signal theory uncertainties re-evaluated
- Two templates defined:
    - **3 XS** denoted as **3-POI** in the following
    - **5 XS** denoted as **5-POI** in the following



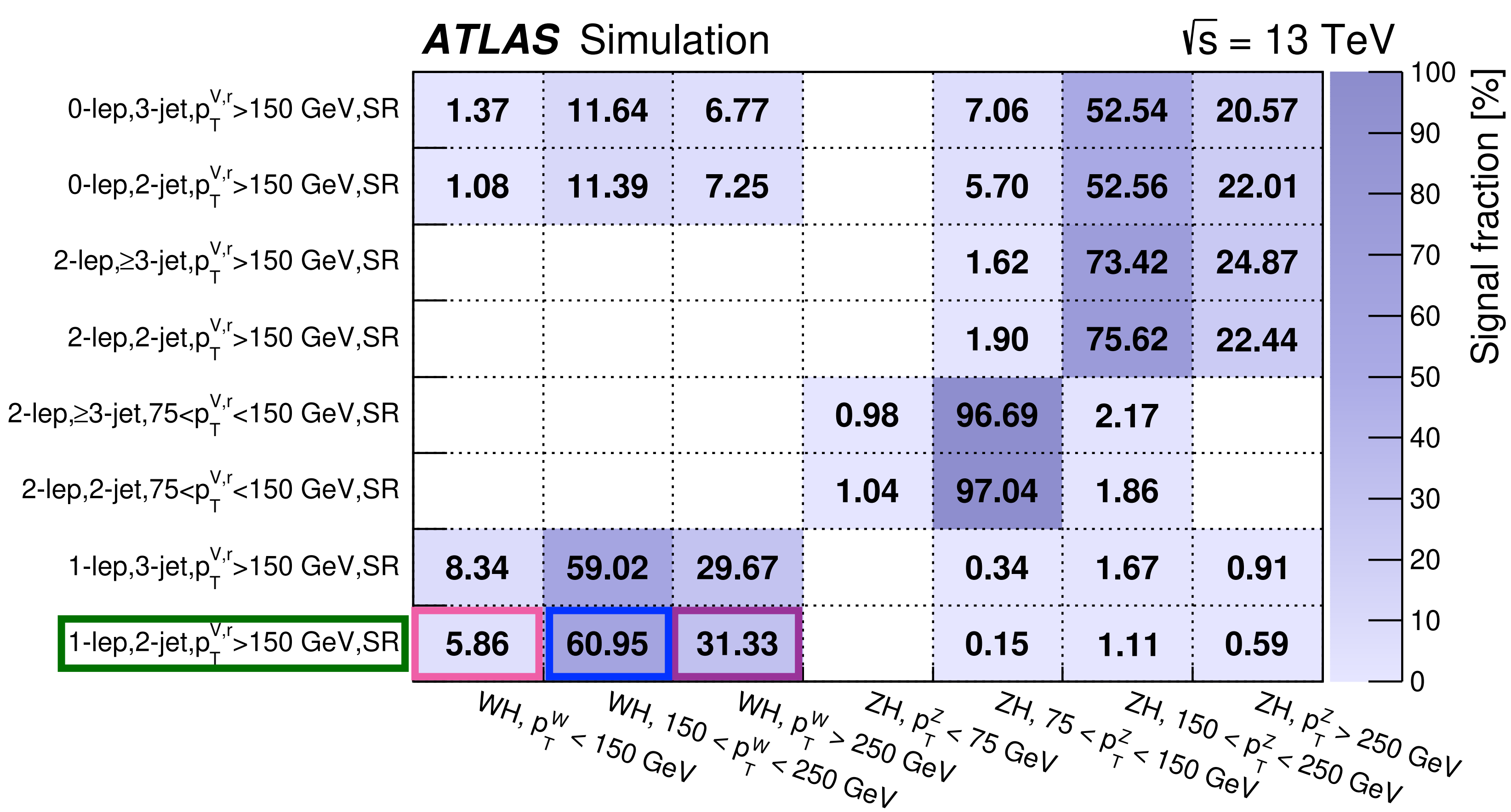


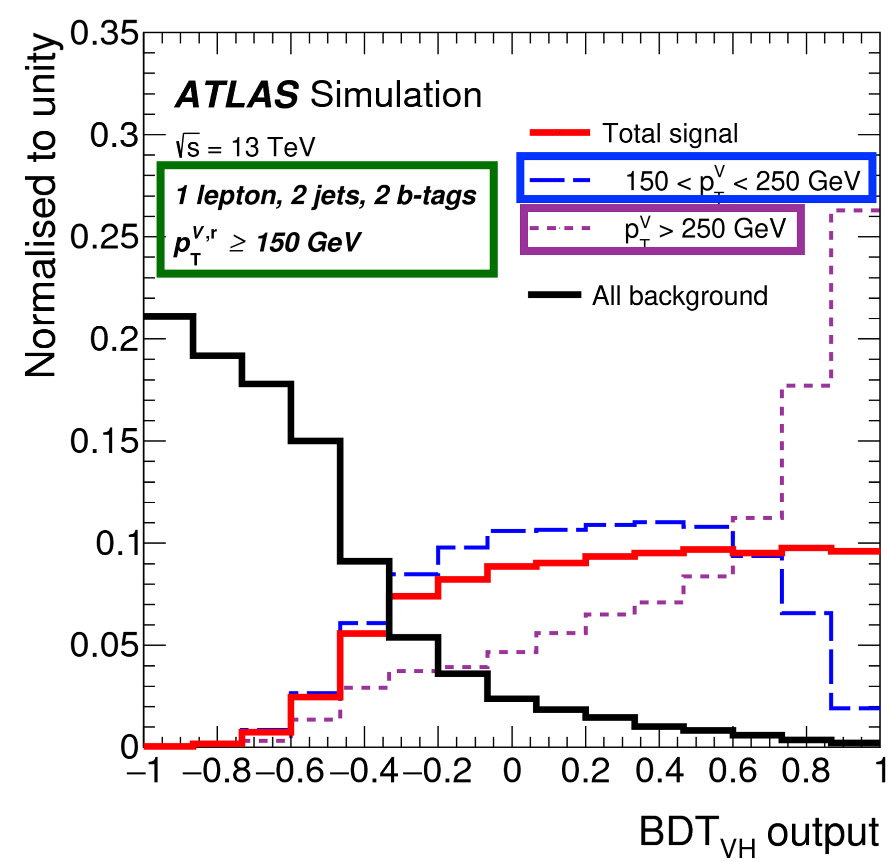


Expected signal yield in each SR



- XS for template bins predicted by SM
- Signal with different p_T^V survived mainly in the corresponding $p_T^{V,r}$ region
- **Small migration** with p_T^V to $p_T^{V,r}$ due to the resolution
- **p_T^V 150-250** and **>250** survived in the same region **$p_T^{V,r}$ >150**
  - Separated by BDT classifier ($p_T^{V,r}$ used in training)

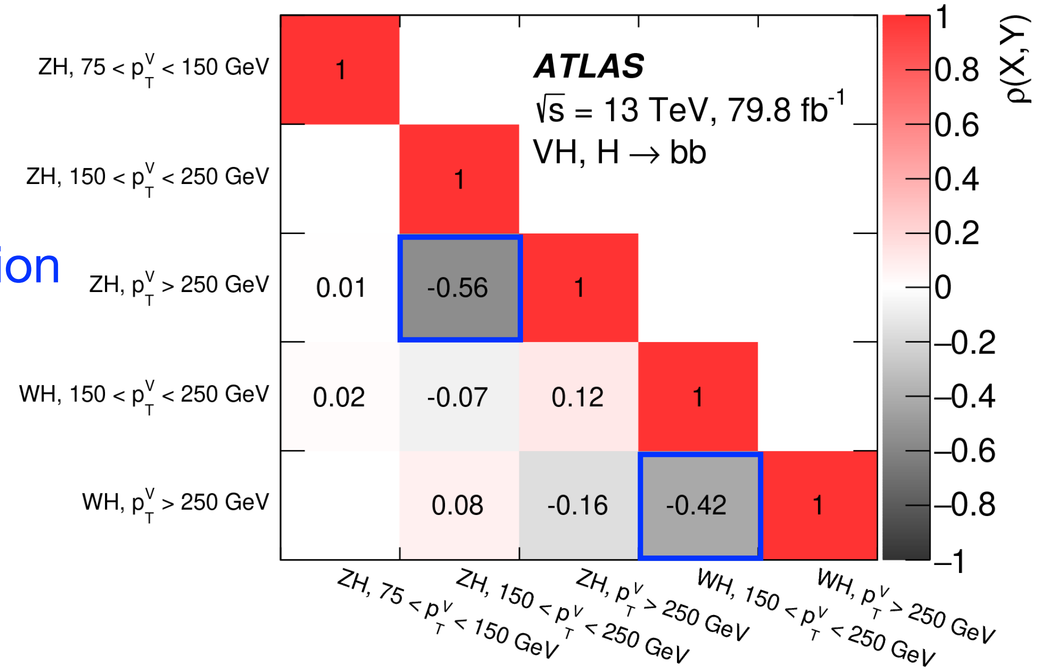


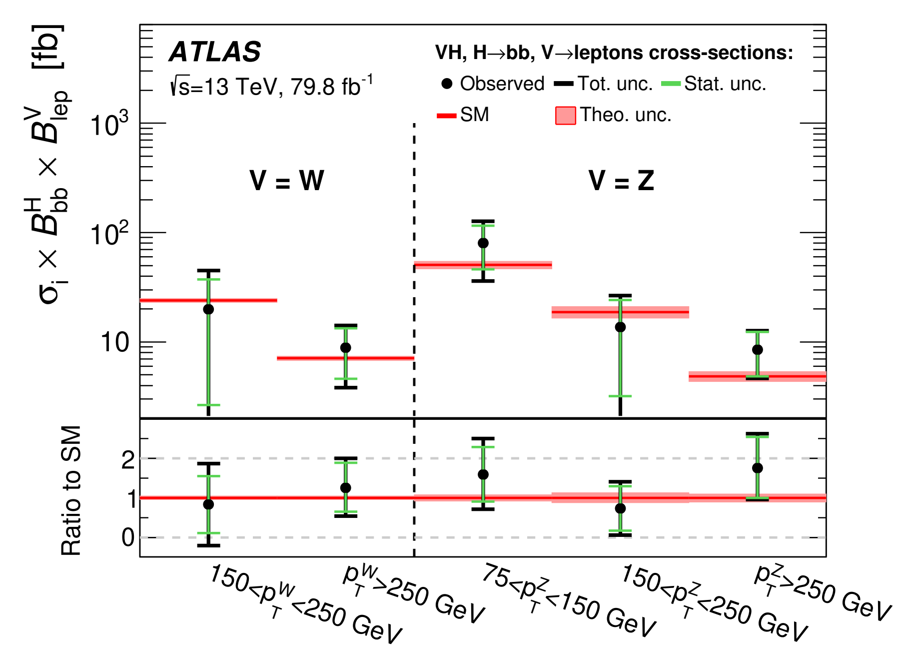


Measurement of 5XS

- Theory prediction uncertainty on XS of measure bins removed
- Systematics from high-granularity regions merged to 5-POI
- 5-POI (each XS normalised to SM prediction) simultaneous measured

Strong anti-correlation
p_T^V in [150,250]
p_T^V > 250

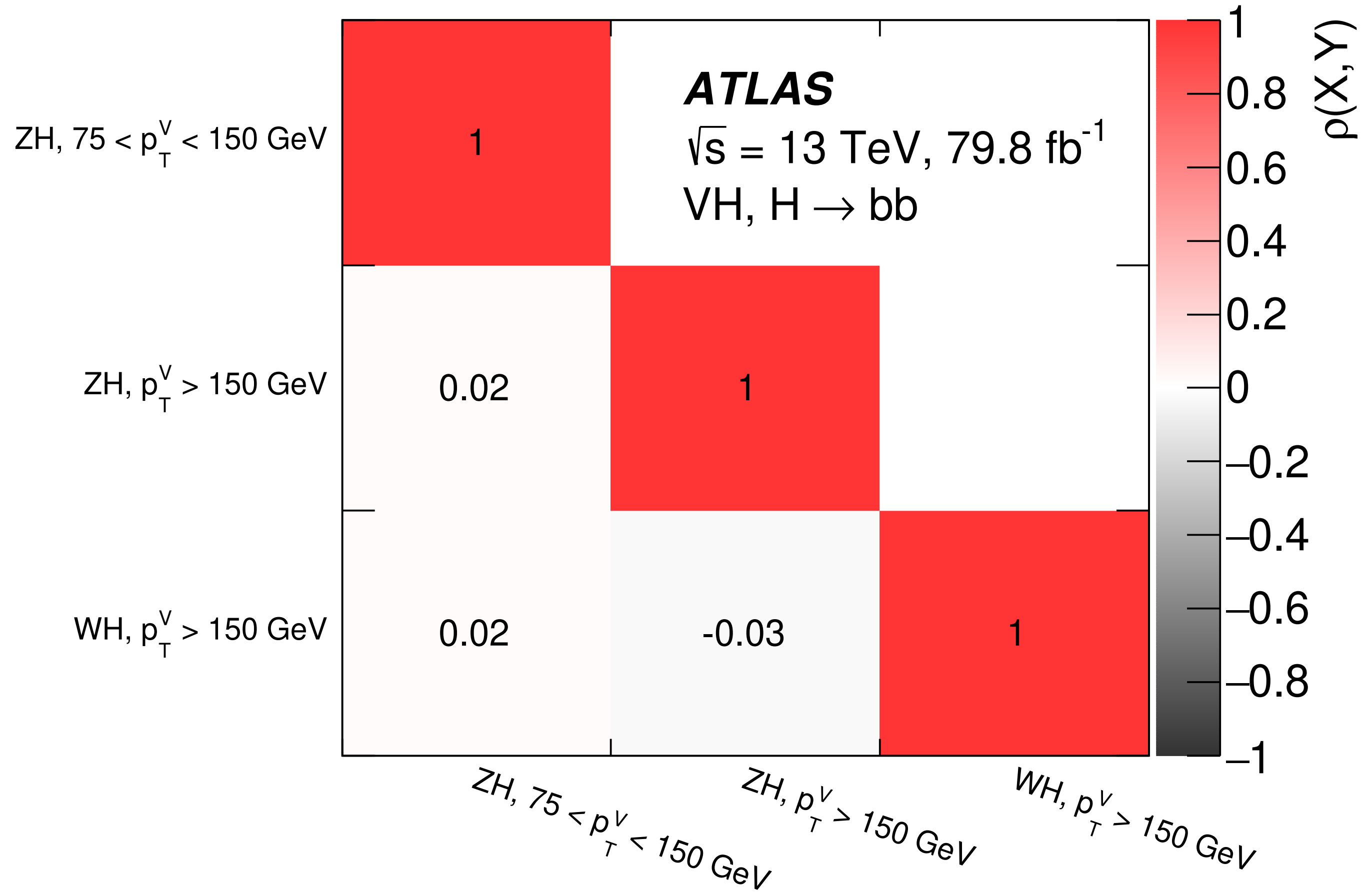




Measurement region ($\lvert y_H \rvert < 2.5$, $H \to b\bar{b}$)	SM prediction [fb]	Result [fb]	Stat. Unc. [fb]	Syst. Unc. [fb] Th. Sig.	Th. Bkg.	Exp.
$W \to l\nu$, $150 < p_T^V < 250$ GeV	24.00 ± 1.06	19.9 ± 25.0	± 17.3	± 1.6	± 13.2	± 9.4
$W \to l\nu$, $p_T^V > 250$ GeV	7.08 ± 0.34	8.8 ± 5.2	± 4.4	± 0.5	± 2.5	± 0.9
$Z \to ll, \nu\nu$, $75 < p_T^V < 150$ GeV	50.61 ± 4.09	80.5 ± 45.2	± 34.7	± 10.1	± 20.8	± 19.3
$Z \to ll, \nu\nu$, $150 < p_T^V < 250$ GeV	18.80 ± 2.37	13.7 ± 12.7	± 10.6	± 1.4	± 6.1	± 3.3
$Z \to ll, \nu\nu$, $p_T^V > 250$ GeV	4.85 ± 0.50	8.5 ± 4.0	± 3.7	± 0.8	± 1.2	± 0.6

- Most of measurement limited by statistics

Measurement of 3XS



- No strong correlation observed

Measurement region ($\|y_H\| < 2.5$, $H \to b\bar{b}$)	SM prediction [fb]	Result [fb]	Stat. Unc. [fb]	Syst. Unc. [fb] Th. Sig.	Syst. Unc. [fb] Th. Bkg.	Syst. Unc. [fb] Exp.
$W \to l\nu$, $p_T^V > 150$ GeV	31.08 ± 1.37	34.5 ± 14.0	± 9.2	± 1.8	± 8.5	± 4.3
$Z \to ll, \nu\nu$, $75 < p_T^V < 150$ GeV	50.61 ± 4.09	80.5 ± 45.0	± 34.5	± 10.0	± 20.9	± 19.2
$Z \to ll, \nu\nu$, $p_T^V > 150$ GeV	23.65 ± 2.97	28.4 ± 8.1	± 6.4	± 2.4	± 3.6	± 2.3

EFT interpretation

- Beyond Standard Model (BSM) prediction constrained by the STXS measurement
- Effective Field Theory (EFT) parametrising the effects from BSM
- Leading effect on BSM from Dimension 6 operators $\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} O_i^{(6)} / \Lambda^2$
- Focus on four operators affecting Higgs interaction with W (O_{HW}, O_W) and Z (all four)

$$O_{HW} = i\,(D^\mu H)^\dagger\, \sigma^a\, (D^\nu H)\, W^a_{\mu\nu},$$

$$O_{HB} = i\,(D^\mu H)^\dagger\, (D^\nu H)\, B_{\mu\nu},$$

$$O_W = \frac{i}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu},$$

$$O_B = \frac{i}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) D^\nu B_{\mu\nu},$$

Dimensionless coefficients

$$\mathrm{cHW} = \frac{m_W^2}{g}\frac{c_{HW}}{\Lambda^2},\quad \mathrm{cHB} = \frac{m_W^2}{g'}\frac{c_{HB}}{\Lambda^2},\quad \mathrm{cWW} = \frac{m_W^2}{g}\frac{c_W}{\Lambda^2},\quad \mathrm{cB} = \frac{m_W^2}{g'}\frac{c_B}{\Lambda^2},$$

- The impact on the XS include
  - Interference between SM and BSM (linear terms)
  - BSM only (quadratic terms)

$$\frac{\sigma_{EFT}}{\sigma_{SM}} = 1 + \sum_i A_i \bar{c}_i + \sum_{ij} B_{ij} \bar{c}_i \bar{c}_j$$

- Relationship between 5 XS and coefficients

Cross section region	$\sum_i A_i \bar{c}_i$
$q\bar{q} \to Hl\nu$ $(150 \le p_T^V \le 250)$ GeV	50cHW + 74cWW
$q\bar{q} \to Hl\nu$ $(p_T^V \ge 250)$ GeV	170cHW + 200cWW
$q\bar{q} \to Hll$ $(75 \le p_T^V \le 150)$ GeV	13cHW + 38cWW + 3.9cHB + 10.5cB
$q\bar{q} \to Hll$ $(150 \le p_T^V \le 250)$ GeV	37cHW + 61cWW + 11cHB + 18cB
$q\bar{q} \to Hll$ $(p_T^V \ge 250)$ GeV	130cHW + 150cWW + 38cHB + 46cB

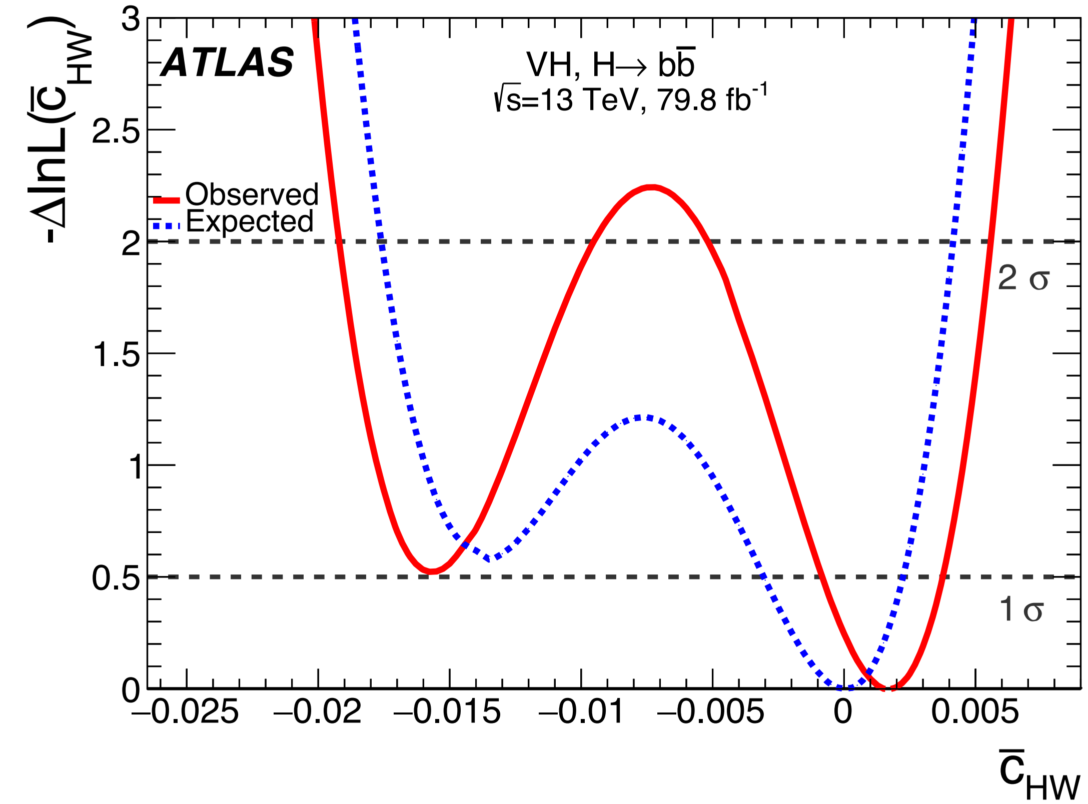
Strongly Interacting Light Higgs formulation

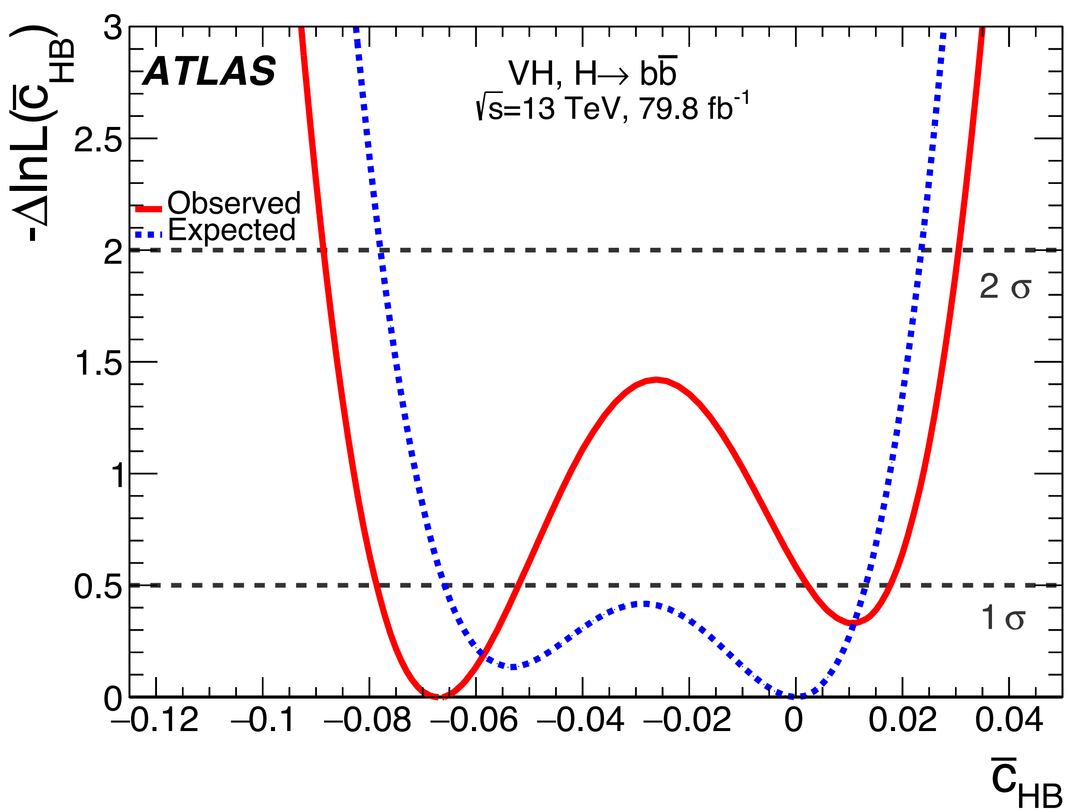
Cross section region	$\sum_{ij} B_{ij} \bar{c}_i \bar{c}_j$
$q\bar{q} \to Hl\nu$ $(150 \le p_T^V \le 250)$ GeV	$839\mathrm{cHW}^2 + 1555\mathrm{cWW}^2 + \mathrm{cHW}(900\mathrm{cWW})$
$q\bar{q} \to Hl\nu$ $(p_T^V \ge 250)$ GeV	$14000\mathrm{cHW}^2 + 16000\mathrm{cWW}^2 + \mathrm{cHW}(30000\mathrm{cWW})$
$q\bar{q} \to Hll$ $(75 \le p_T^V \le 150)$ GeV	$85\mathrm{cHW}^2 + 400\mathrm{cWW}^2 + 8\mathrm{cHB}^2 + 35\mathrm{cB}^2$ $+\mathrm{cHW}(150\mathrm{cWW} + 20\mathrm{cHB} + 42\mathrm{cB})$ $+\mathrm{cHB}(44\mathrm{cWW} + 12\mathrm{cB}) + \mathrm{cWW}(140\mathrm{cB})$
$q\bar{q} \to Hll$ $(150 \le p_T^V \le 250)$ GeV	$462\mathrm{cHW}^2 + 982\mathrm{cWW}^2 + 41\mathrm{cHB}^2 + 86\mathrm{cB}^2$ $+\mathrm{cHW}(1255\mathrm{cWW} + 277\mathrm{cHB} + 358\mathrm{cB})$ $+\mathrm{cHB}(373\mathrm{cWW} + 105\mathrm{cB}) + \mathrm{cWW}(587\mathrm{cB})$
$q\bar{q} \to Hll$ $(p_T^V \ge 250)$ GeV	$8000\mathrm{cHW}^2 + 9600\mathrm{cWW}^2 + 720\mathrm{cHB}^2 + 850\mathrm{cB}^2$ $+\mathrm{cHW}(17000\mathrm{cWW} + 4800\mathrm{cHB} + 5100\mathrm{cB})$ $+\mathrm{cHB}(5100\mathrm{cWW} + 1500\mathrm{cB}) + \mathrm{cWW}(5700\mathrm{cB})$

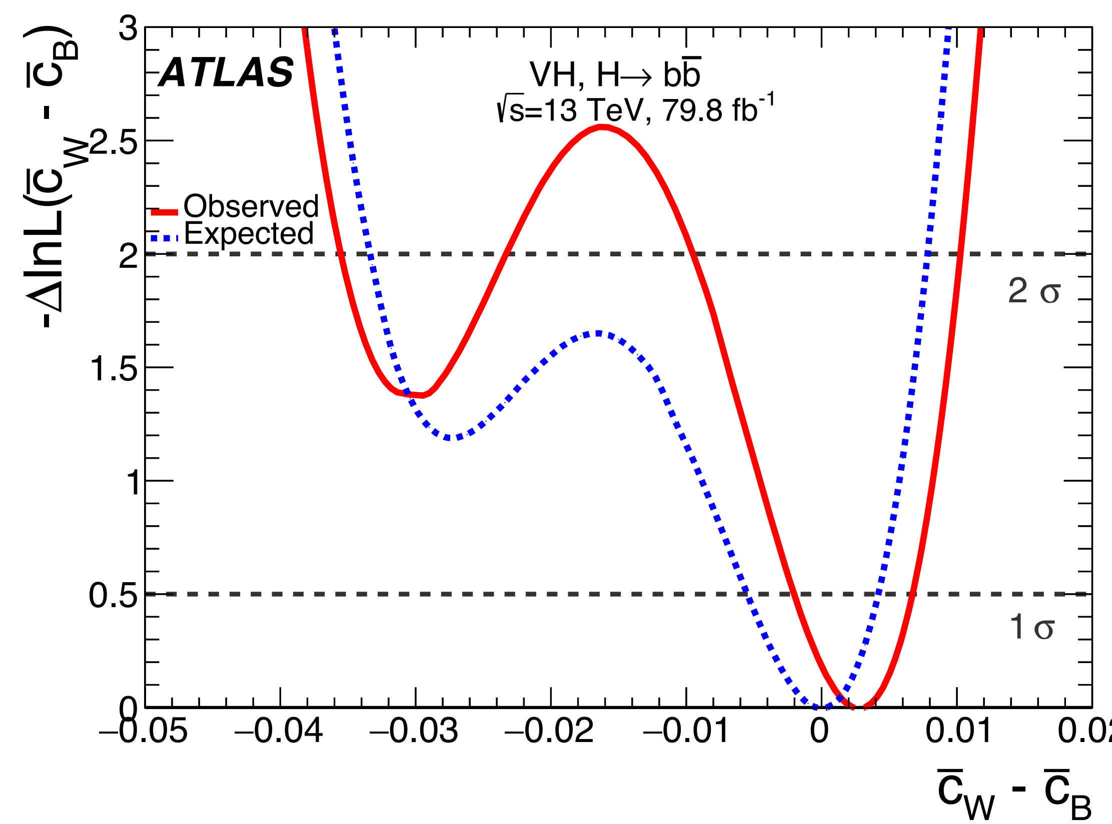
"Higgs Effective Lagrangian" implementation

5-POI → coefficients

- Strong constrain on S = cWW + cB from precise electroweak data, S assumed as 0
- Thus constrain set on the coefficients: cHW, cHB, cWW-cB
- 5-POI parametrised with the above coefficients in linear and quadrature terms
- Maximum likelihood fits with POIs as cHW, cHB, cWW-cB
- One-dimensional fit performed







Constrains on coefficients

Coefficient	Expected interval	Observed interval
	Results at 68% confidence level	
$\bar{c}_{HW}$	[−0.003, 0.002]	[−0.001, 0.004]
(interference only	[−0.002, 0.003]	[−0.001, 0.005])
$\bar{c}_{HB}$	[−0.066, 0.013]	[−0.078, −0.055] ⋃ [0.005, 0.019]
(interference only	[−0.016, 0.016]	[−0.005, 0.030])
$\bar{c}_W - \bar{c}_B$	[−0.006, 0.005]	[−0.002, 0.007]
(interference only	[−0.005, 0.005]	[−0.002, 0.008])
$\bar{c}_d$	[−1.5, 0.3]	[−1.6, −0.9] ⋃ [−0.3, 0.4]
(interference only	[−0.4, 0.4]	[−0.2, 0.7])
	Results at 95% confidence level	
$\bar{c}_{HW}$	[−0.018, 0.004]	[−0.019,−0.010] ⋃ [−0.005, 0.006]
(interference only	[−0.005, 0.005]	[−0.003, 0.008])
$\bar{c}_{HB}$	[−0.078, 0.024]	[−0.090, 0.032]
(interference only	[−0.033, 0.033]	[−0.022, 0.049])
$\bar{c}_W - \bar{c}_B$	[−0.034, 0.008]	[−0.036,−0.024] ⋃ [−0.009, 0.010]
(interference only	[−0.009, 0.010]	[−0.006, 0.014])
$\bar{c}_d$	[−1.7, 0.5]	[−1.9, 0.7]
(interference only	[−0.8, 0.8]	[−0.6, 1.1])

- The 68% and 95% confidence level intervals obtained from 1-D scan
- Currently, no results to have a fair comparison with

Conclusion

- Standard Model (SM) Higgs Boson
    - Search for $H \rightarrow b\bar{b}$ at colliders
    - LHC and ATLAS
- Search for VH, $H \rightarrow b\bar{b}$ production with ATLAS data
    - Evidence of VH, $H \rightarrow b\bar{b}$ production with 36 fb^{-1} *JHEP 12 (2017) 024*
    - Observation of $H \rightarrow b\bar{b}$ decays and VH production with 80 fb^{-1} *PLB 786 (2018) 59*
- Future prospects
    - VH simplified template cross section (STXS) measurement

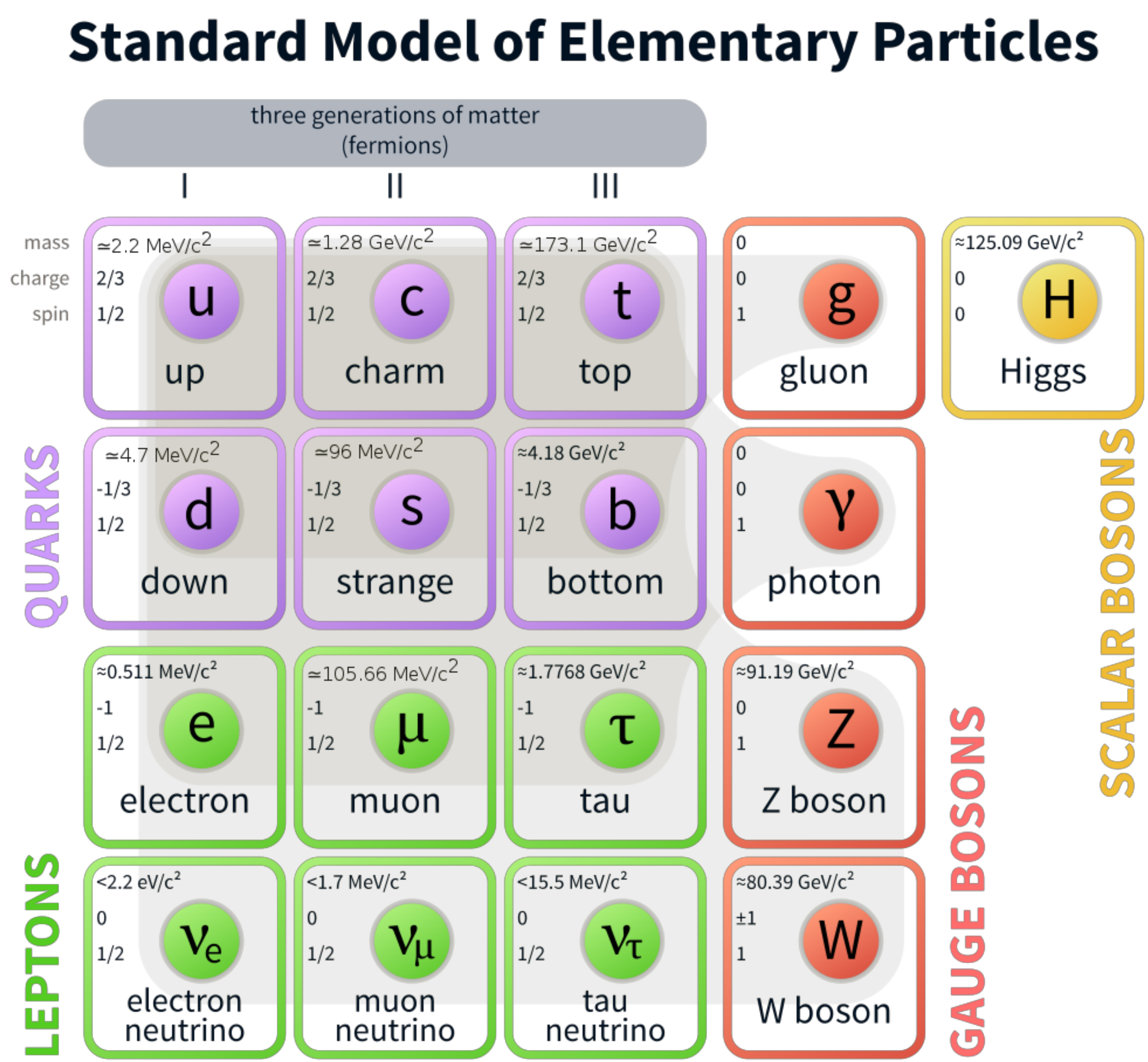
submitted to JHEP
arXiv:1903.04618

Backup

Standard Model (SM) of particle physics

A renormalisable quantum field theory based on the local gauge invariance under the SU(3)xSU(2)xU(1) group

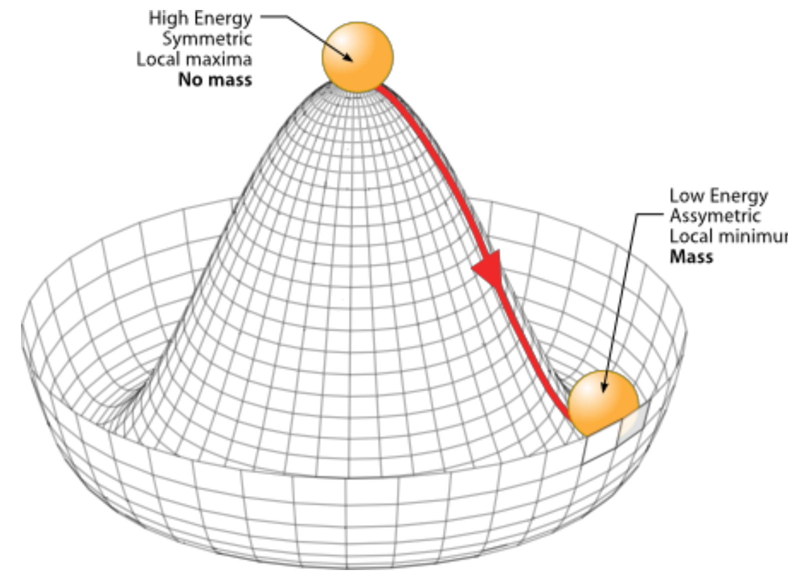
- Matter is made of fermions (spin 1/2)
  - quarks
  - leptons
- Forces are carried by the gauge bosons (spin 1)
- The Higgs boson is responsible for the particle masses



Higgs boson theory

- Explicit mass terms of fermions and bosons in the SM Lagrangian are not gauge invariant
- Introducing in the Lagrangian a scalar field with non trivial vacuum can solve this problem:

field $\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ potential $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2.$



v = vacuum expectation value of field ϕ

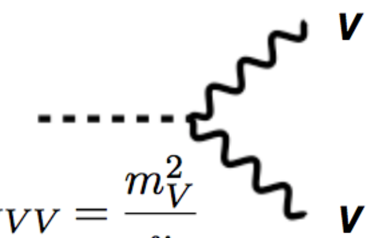
- After spontaneous symmetry breaking, vector bosons acquire masses

$$\frac{1}{2}\partial_\mu H \partial^\mu H + \mu^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

mass terms ⟵
$$+ \frac{g^2 v^2}{4} W_\mu^+ W^{-\mu} + \frac{1}{2} \frac{(g^2 + g'^2)\, v^2}{4} Z_\mu Z^\mu$$

$$+ \frac{g^2 v}{2} W_\mu^+ W^{-\mu} H + \frac{1}{2} \frac{(g^2 + g'^2)\, v}{2} Z_\mu Z^\mu H$$ ⟶

$$+ \frac{g^2}{4} W_\mu^+ W^{-\mu} H^2 + \frac{1}{2} \frac{g^2 + g'^2}{4} Z_\mu Z^\mu H^2.$$

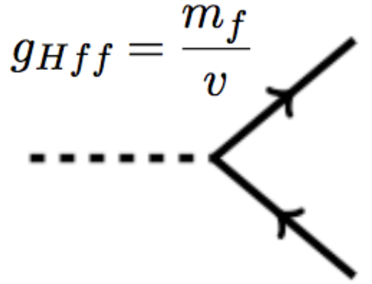


$$g_{HVV} = \frac{m_V^2}{v}$$

- Gauge invariant and renormalisable Yukawa extra terms

$$\mathcal{L}_{\text{Yukawa}} = y^l_{\alpha\beta} \bar{L}_\alpha l_\beta H + y^d_{\alpha\beta} \bar{Q}_\alpha D_\beta H + y^u_{\alpha\beta} \bar{Q}_\alpha U_\beta \tilde{H} + \text{hermitian conjugate}$$ ⟶

$$g_{Hff} = \frac{m_f}{v}$$



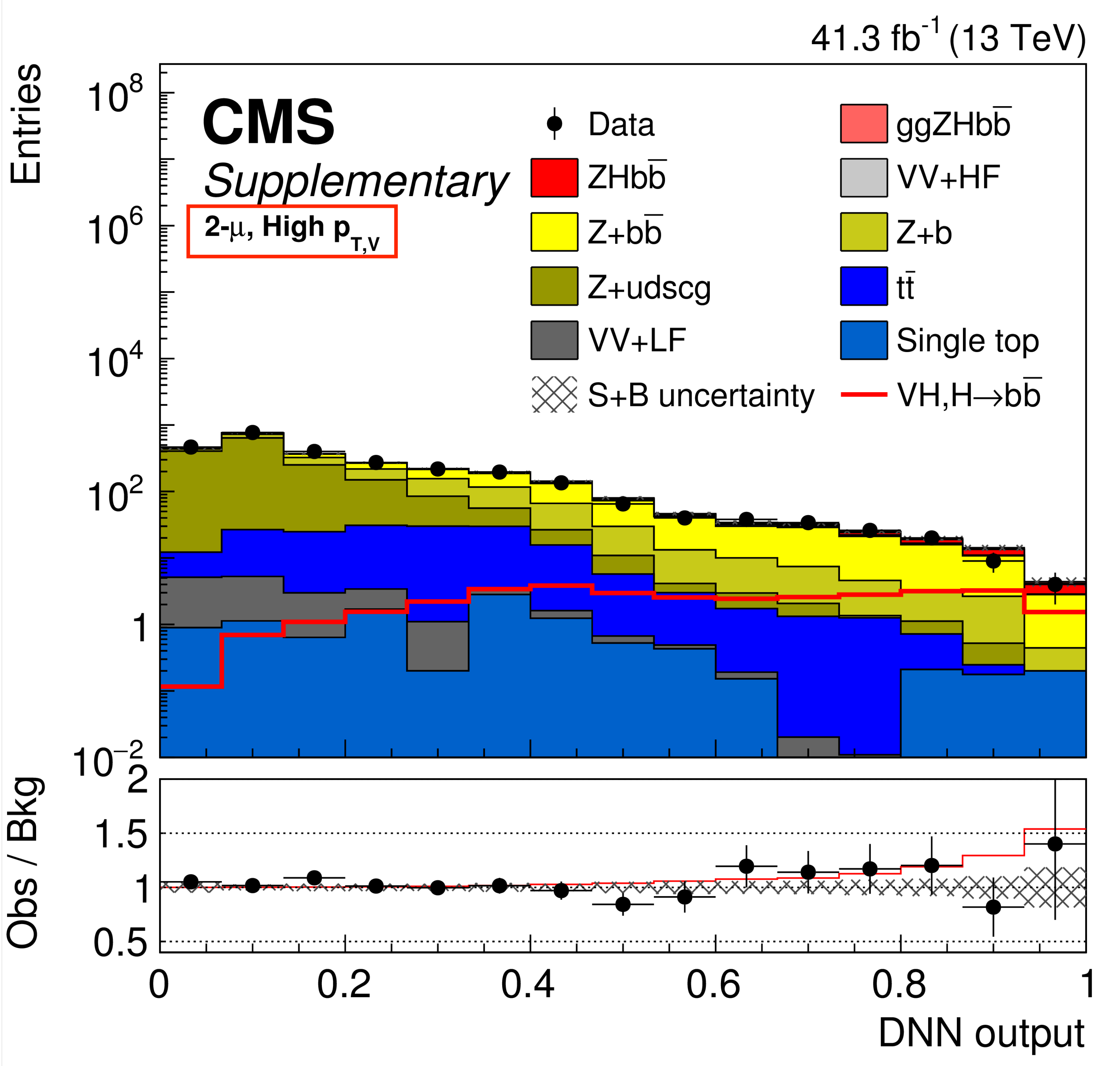
give rise to fermion mass terms as well fermion-Higgs couplings

Signal background generators

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal					
$qq \to WH$ $\to \ell\nu b\bar{b}$	Powheg-Box v2 [38] + GoSam [41] + MiNLO [42, 43]	NNPDF3.0NLO$^{(\star)}$ [39]	Pythia8.212 [32]	AZNLO [40]	NNLO(QCD)+ NLO(EW) [44–50]
$qq \to ZH$ $\to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2 + GoSam + MiNLO	NNPDF3.0NLO$^{(\star)}$	Pythia8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)
$gg \to ZH$ $\to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2	NNPDF3.0NLO$^{(\star)}$	Pythia8.212	AZNLO	NLO+ NLL [51–55]
Top quark					
$t\bar{t}$	Powheg-Box v2 [56]	NNPDF3.0NLO	Pythia8.212	A14 [57]	NNLO+NNLL [58]
s-channel	Powheg-Box v1 [59]	CT10 [60]	Pythia6.428 [61]	P2012 [62]	NLO [63]
t-channel	Powheg-Box v1 [59]	CT10f4	Pythia6.428	P2012	NLO [64]
Wt	Powheg-Box v1 [65]	CT10	Pythia6.428	P2012	NLO [66]
Vector boson + jets					
$W \to \ell\nu$	Sherpa 2.2.1 [35, 67, 68]	NNPDF3.0NNLO	Sherpa 2.2.1 [69, 70]	Default	NNLO [71]
$Z/\gamma^* \to \ell\ell$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
$Z \to \nu\nu$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
Diboson					
WW	Sherpa 2.1.1	CT10	Sherpa 2.1.1	Default	NLO
WZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
ZZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO

Table 1. The generators used for the simulation of the signal and background processes. If not specified, the order of the cross-section calculation refers to the expansion in the strong coupling constant (α_S). The acronyms ME, PS and UE stand for matrix element, parton shower and underlying event, respectively. ($\star$) The events were generated using the first PDF in the NNPDF3.0NLO set and subsequently reweighted to PDF4LHC15NLO set [37] using the internal algorithm in Powheg-Box v2. ($\dagger$) The NNLO(QCD)+NLO(EW) cross-section calculation for the $pp \to ZH$ process already includes the $gg \to ZH$ contribution. The $qq \to ZH$ process is normalised using the NNLO(QCD)+NLO(EW) cross-section for the $pp \to ZH$ process, after subtracting the $gg \to ZH$ contribution.

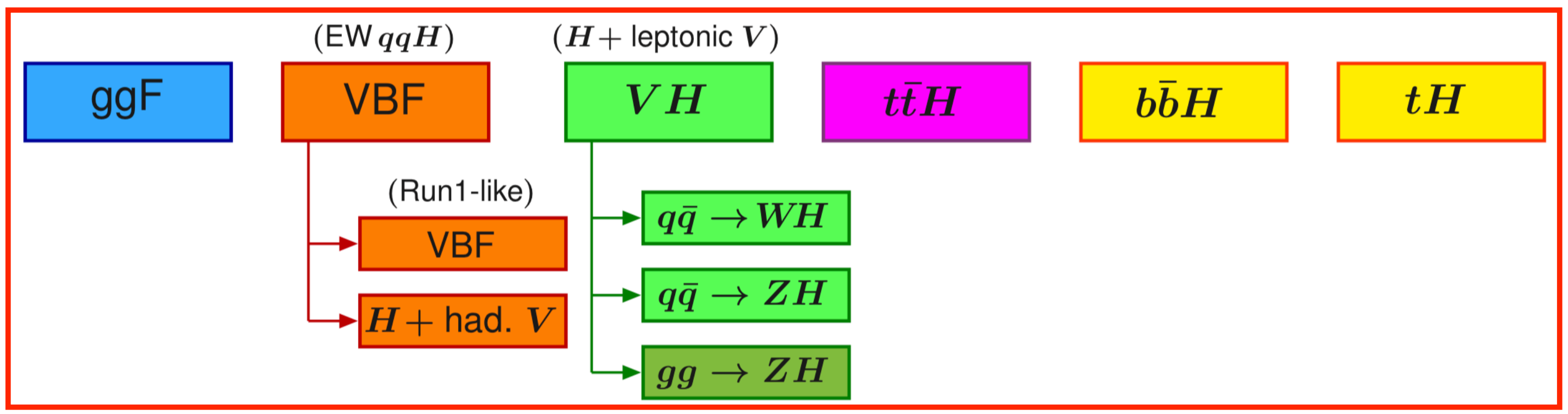
Post fit plots for CMS VHbb



Backup
STXS

Simplified Template Cross Section (STXS)

- XS for Higgs boson production measured in template bins
  - Defined with kinematic properties of the Higgs boson production
  - Maximising the experimental sensitivity
  - Minimizing the dependence on the theory uncertainties
  - The region with high sensitivity to BSM isolated

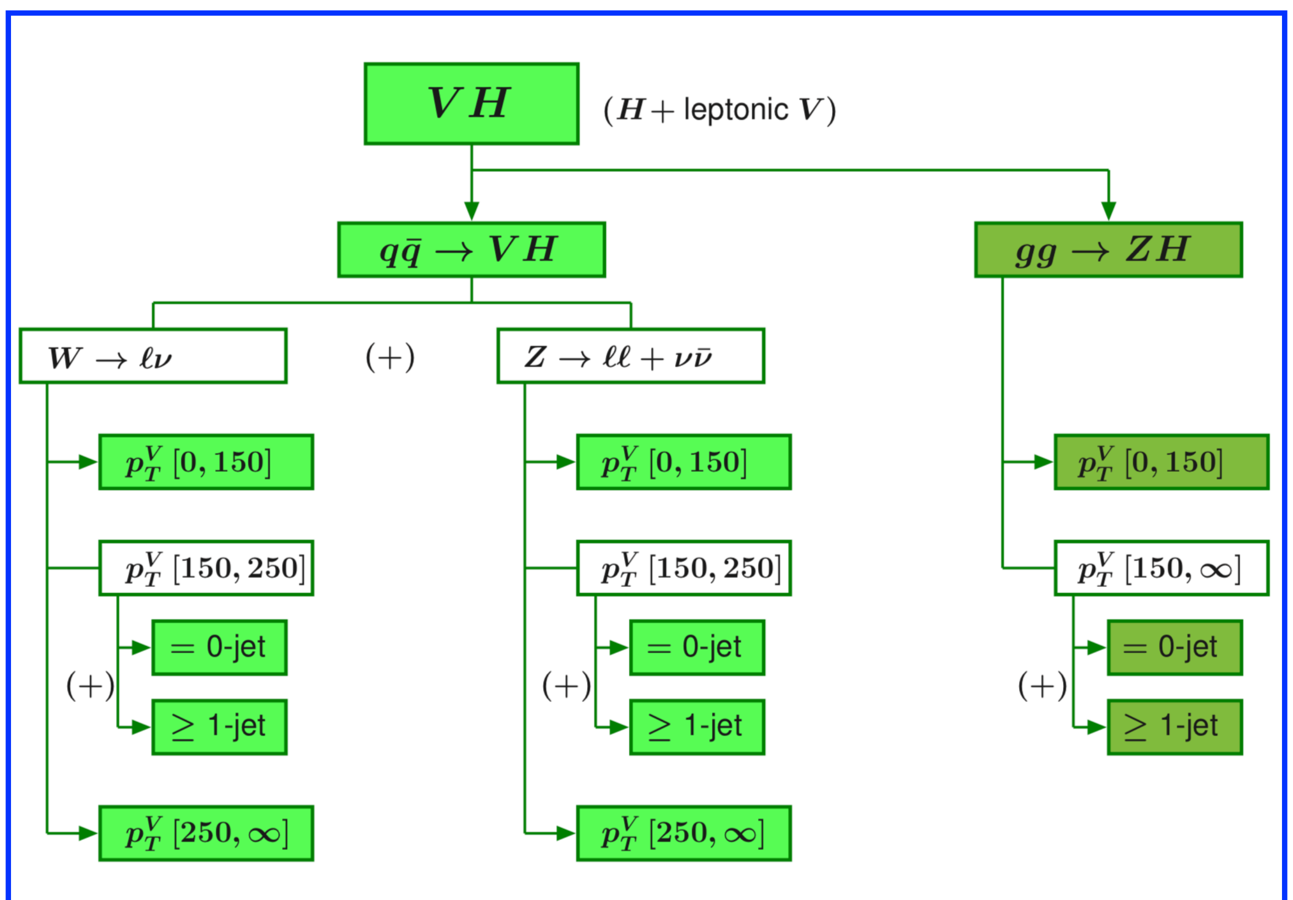


Stage-0

- Split by production mode
- Measured with 36.1 fb^{-1} of data

***ATLAS-CONF-2018-018* (H → ZZ* → 4 ℓ)**

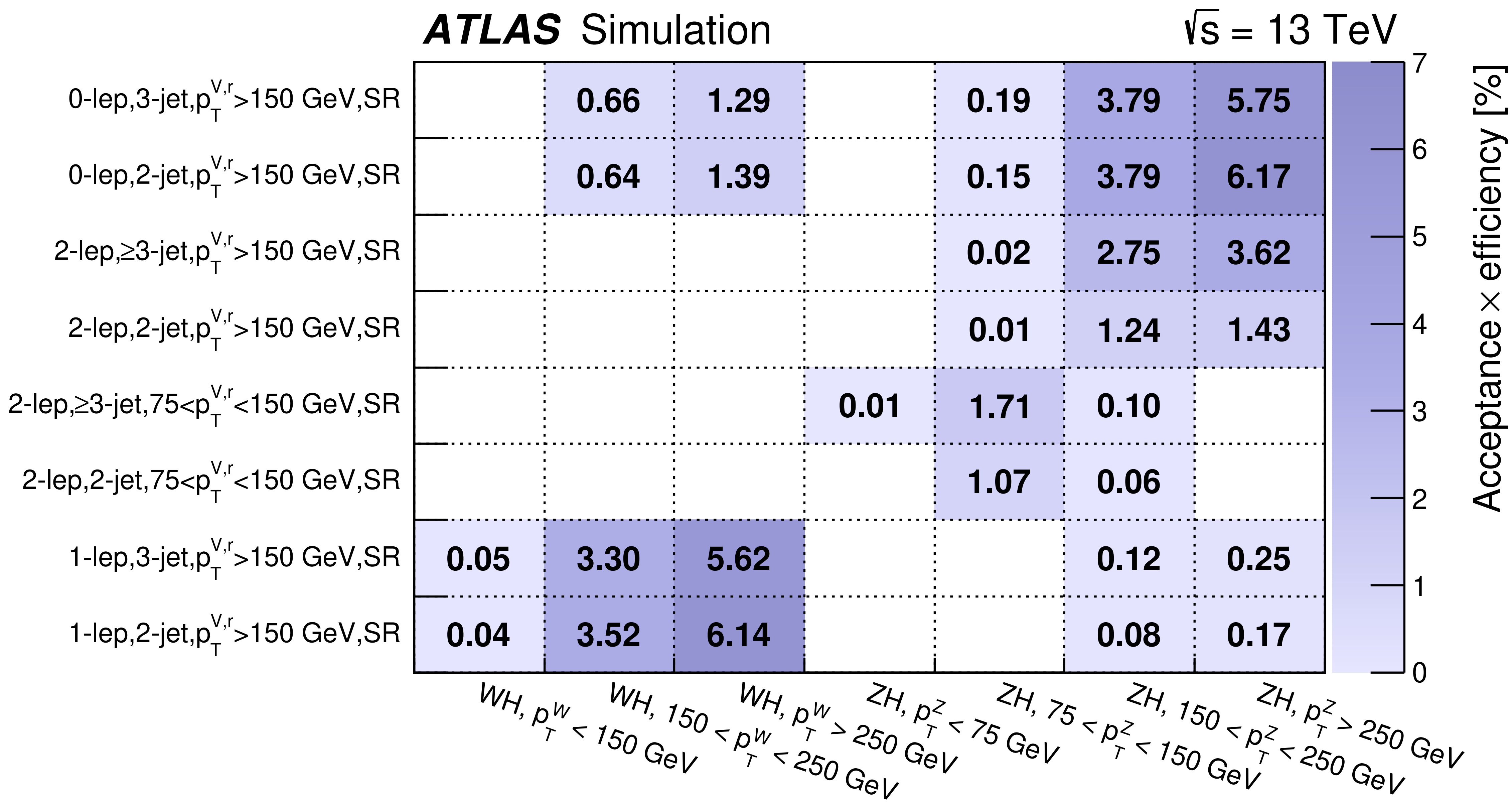
***ATLAS-CONF-2018-031* (H → $\gamma\gamma$)**



Stage-1 (for VH)

- Further split into 11 regions according to
  - Production mode (qqVH / ggZH)
  - Number of jets (not from Higgs decay)
  - p_T^V
- Only $|y_{Higgs}| < 2.5$ measured (detector acc.)
- H → $b\bar{b}$ decay mode chosen for the sake of sensitivity
- Thus ICHEP VH, H → $b\bar{b}$ analysis as a good choice as the fundament of the measurement

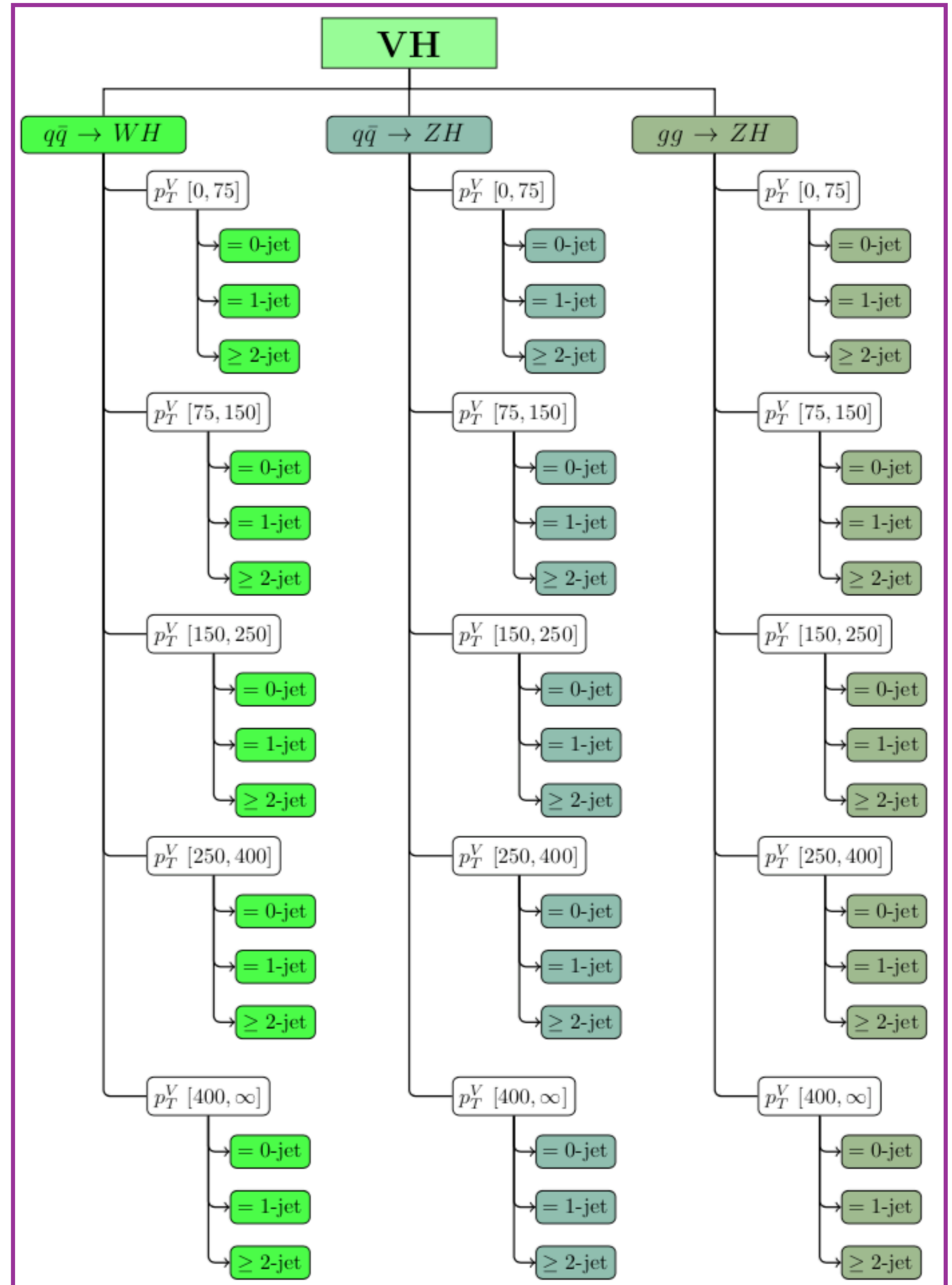
Simplified Template Cross Section (STXS)



Theory Systematics

- The systematics kept same as "ICHEP" VH, H → $b\bar{b}$ analysis except the signal systematics
- The signal systematics re-evaluated for:
  - Factorisation and renormalisation QCD scale uncertainties
  - PDF and alphaS variations
  - PS and UE uncertainties
  - **The scheme decided from the interaction with theorist**
  - **Details openly discussed in a <u>PUB note</u> (LHCHiggsXS WG)**
- Evaluated for the **high-granularity regions** to have the best flexibility (for need in future)
- Merged into 3-POI or 5-POI template bins for the practical measurement

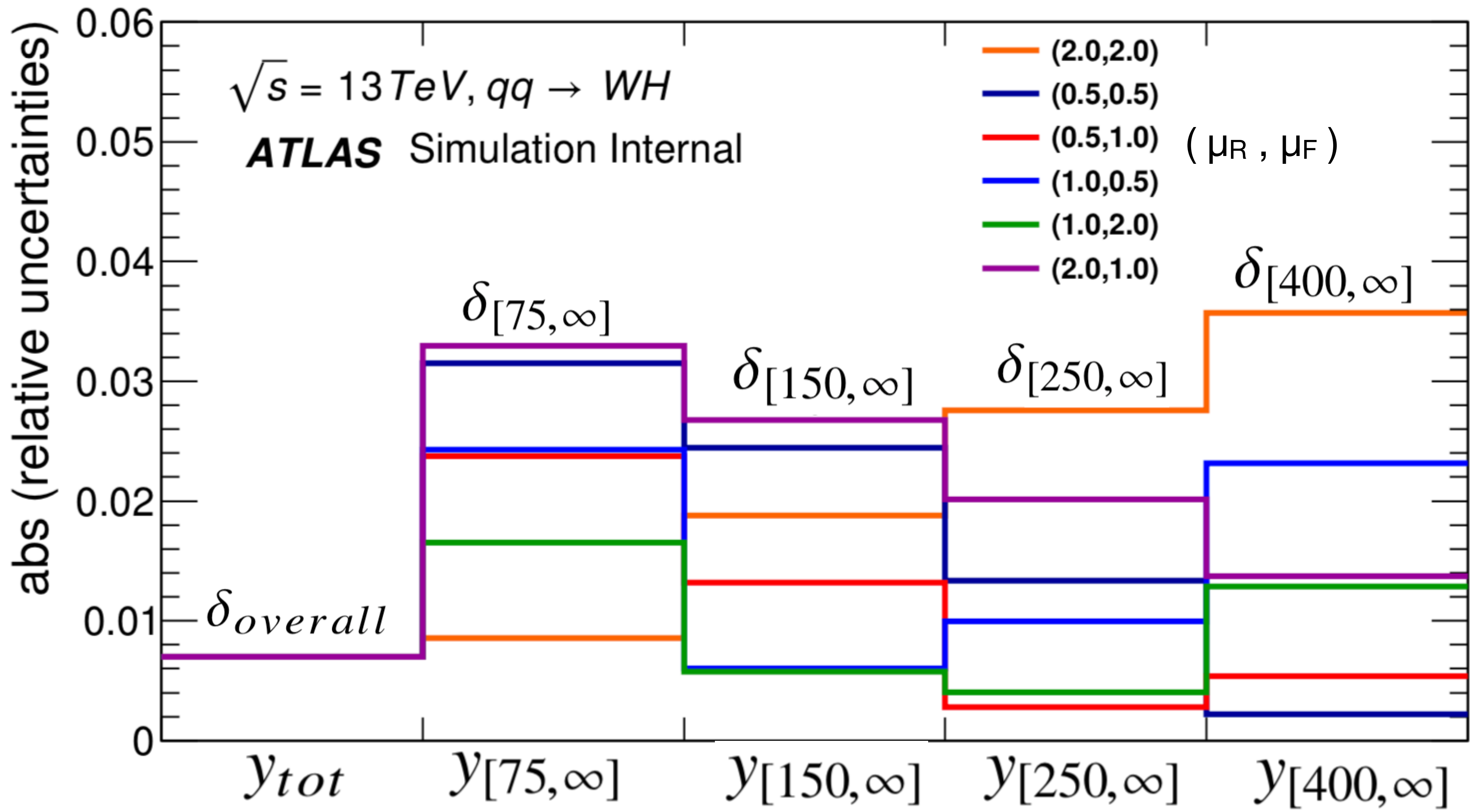
ATL-PHYS-PUB-2018-035



QCD scale uncertainties

prod. mode	$\delta_{overall}$
WH	0.7 %
qqZH	0.6 %
ggZH	25 %

From the most updated computations (YR4)



XS above the p_T^V boundary

- Uncertainty for the missing higher-order terms in the QCD perturbative expansion
- ICHEP inclusive measurement accounts the overall impact on XS
- Besides the overall impact, the migration effects should be considered for STXS template
- Varying (μ_R , μ_F) to evaluate
  - maximum relative uncertainties ($\delta[p_T^V,\infty]$) on $y[p_T^V,\infty]$
  - maximum relative uncertainties on the XS for the jet multiplicity bin in each p_T^V bin

Parametrisation of the QCD impact on migration

- Performed following the StewartTackmann method
- Parametrisation (Δ) accounts for the migration across p_T^V
- Opposite impact of Δ for on signal below / above p_T^V boundary

	sum	$\sigma_{0,75}$	$\sigma_{75,150}$	$\sigma_{150,250}$	$\sigma_{250,400}$	$\sigma_{400,\infty}$
Overall	overall XS unc.	+				
Δ_{75}	0	−	+			
Δ_{150}	0	−		+		
Δ_{250}	0	−			+	
Δ_{400}	0	−				+

- Performed from low p_T^V boundary to high boundary
- Effect from lower subtracted ($\delta_{[150,\infty]}$ already covered by $\delta_{[75,\infty]}$)
  - otherwise overestimation exists
  - subtract by multiplying a correction factor (K = 0.5)

$$\Delta_{75} = y_{[75,\infty]} \times \delta_{[75,\infty]}$$

$$\Delta_{150} = y_{[150,\infty]} \times \delta_{[150,\infty]} \times K$$

$$\Delta_{250} = y_{[250,\infty]} \times \delta_{[250,\infty]} \times K$$

$$\Delta_{400} = y_{[400,\infty]} \times \delta_{[400,\infty]} \times K$$

Migration impact in each p_T^V bin

p_T^V bin [GeV]	Δ_{75}	Δ_{150}	Δ_{250}	Δ_{400}
p_T^V [0, 75[	$-\Delta_{75}/\sigma_{[0,75[}$	$-\Delta_{150}/\sigma_{[0,150[}$	$-\Delta_{250}/\sigma_{[0,250[}$	$-\Delta_{400}/\sigma_{[0,400[}$
p_T^V [75, 150[	$+\Delta_{75}/\sigma_{[75,\infty[}$	$-\Delta_{150}/\sigma_{[0,150[}$	$-\Delta_{250}/\sigma_{[0,250[}$	$-\Delta_{400}/\sigma_{[0,400[}$
p_T^V [150, 250[	$+\Delta_{75}/\sigma_{[75,\infty[}$	$+\Delta_{150}/\sigma_{[150,\infty[}$	$-\Delta_{250}/\sigma_{[0,250[}$	$-\Delta_{400}/\sigma_{[0,400[}$
p_T^V [250, 400[	$+\Delta_{75}/\sigma_{[75,\infty[}$	$+\Delta_{150}/\sigma_{[150,\infty[}$	$+\Delta_{250}/\sigma_{[250,\infty[}$	$-\Delta_{400}/\sigma_{[0,400[}$
p_T^V [400, ∞[	$+\Delta_{75}/\sigma_{[75,\infty[}$	$+\Delta_{150}/\sigma_{[150,\infty[}$	$+\Delta_{250}/\sigma_{[250,\infty[}$	$+\Delta_{400}/\sigma_{[400,\infty[}$

p_T^V bin [GeV]	Δ_{75}	Δ_{150}	Δ_{250}	Δ_{400}
p_T^V [0, 75[	$-\Delta_{75}/\sigma_{[0,75[}$	0	0	0
p_T^V [75, 150[	$+\Delta_{75}/\sigma_{[75,\infty[}$	$-\Delta_{150}/\sigma_{[75,150[}$	0	0
p_T^V [150, 250[	$+\Delta_{75}/\sigma_{[75,\infty[}$	$+\Delta_{150}/\sigma_{[150,\infty[}$	$-\Delta_{250}/\sigma_{[150,250[}$	0
p_T^V [250, 400[	$+\Delta_{75}/\sigma_{[75,\infty[}$	$+\Delta_{150}/\sigma_{[150,\infty[}$	$+\Delta_{250}/\sigma_{[250,\infty[}$	$-\Delta_{400}/\sigma_{[250,400[}$
p_T^V [400, ∞[	$+\Delta_{75}/\sigma_{[75,\infty[}$	$+\Delta_{150}/\sigma_{[150,\infty[}$	$+\Delta_{250}/\sigma_{[250,\infty[}$	$+\Delta_{400}/\sigma_{[400,\infty[}$

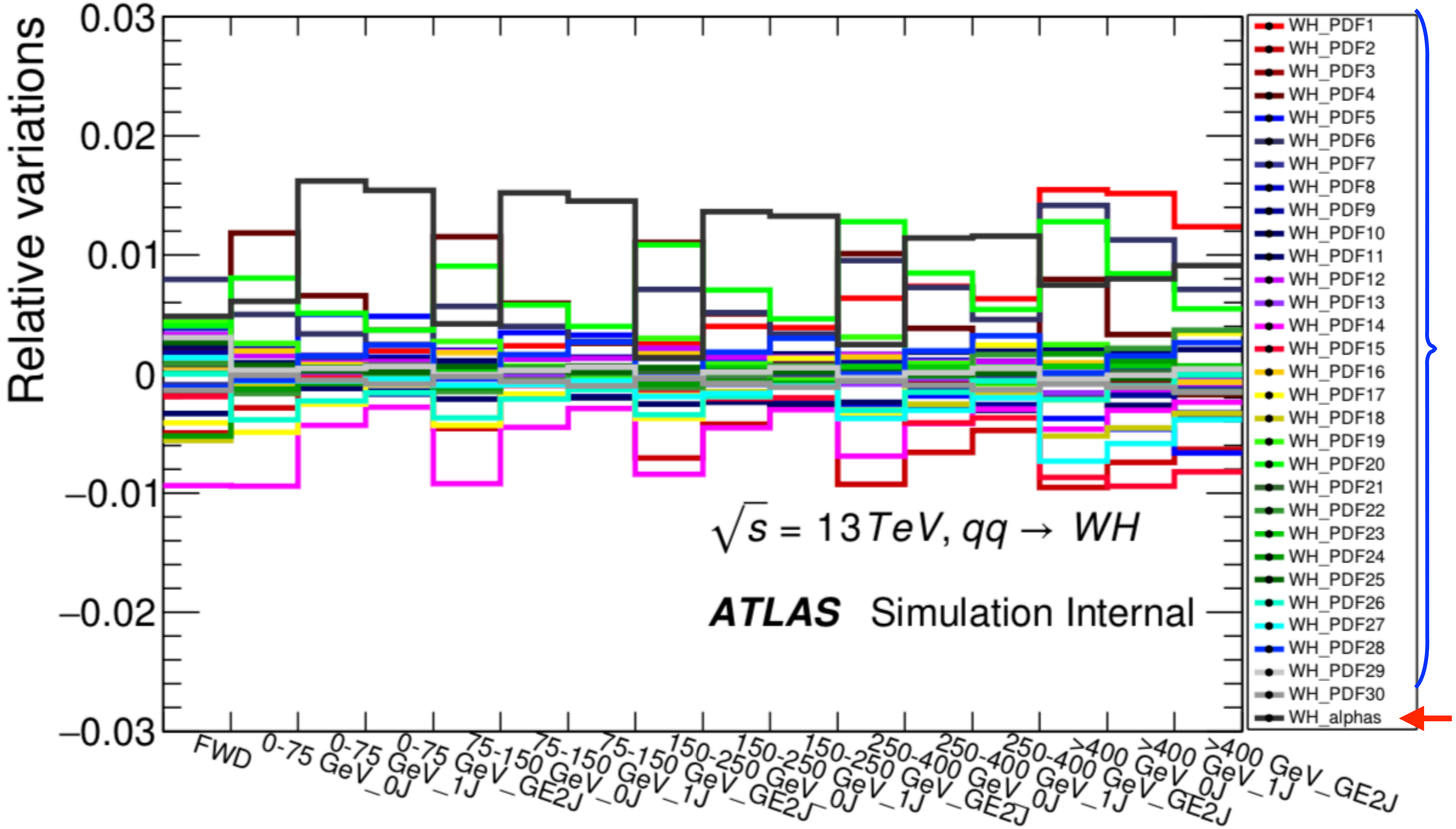
Two schemes for implementation of impact from Δ

- Impact on relative uncertainty on σ (XS) above **p_T^V boundary** anti-correlated with:
  - all σ below p_T^V boundary (scheme-1, used for circulation)
  - bin of p_T^V just lower than the boundary (scheme-2)
- Tiny difference on the results between two schemes (Milene's talk)

Agreed upon to change to scheme-2 during circulation

PDF and alphaS variation

- Uncertainties from the choice of the PDF and alphaS
- ICHEP inclusive measurement: 30 PDF4LHC15 + 2 alphaS weight variation enveloped
- STXS:
  - each of 30 PDF variations as an individual uncertainty
  - one uncertainty accounts for the alphaS
  - 31 uncertainties evaluated in each of high-granularity regions
  - The impacts are small (< 2% for qqWH)



Parton Shower / Underlying Events uncertainty

- Inclusive measurement in ICHEP
- STXS:
  - individual uncertainties for 4 Pythia-8 AZNLO tunes
  - one dedicated uncertainty for the difference between Pythia-8 and Herwig-7
  - uncertainty on the acceptance evaluated in each STXS bin
  - fully correlated across all STXS bins

Tune variation	1L: $WH \to \ell\nu bb$		
	2j	3j	2/3j
Ren	0.27%	0.32%	0.05%
MPI	−0.42%	−0.24%	0.18%
Var1	0.06%	−0.25%	−0.31%
Var2	0.17%	0.11%	−0.05%
Tot PStune	0.53%	0.49%	0.37%
Herwig7	2.90%	1.21%	−1.64%
Tot PS/UE	2.95%	1.30%	1.68%

- Stewart-Tackman like in ICHEP:
  - overall acceptance uncertainty
  - 2/3j acceptance ratio as the migration effect