Determination of Higgs boson properties and searches for new resonances using highly boosted objects with the ATLAS experiment

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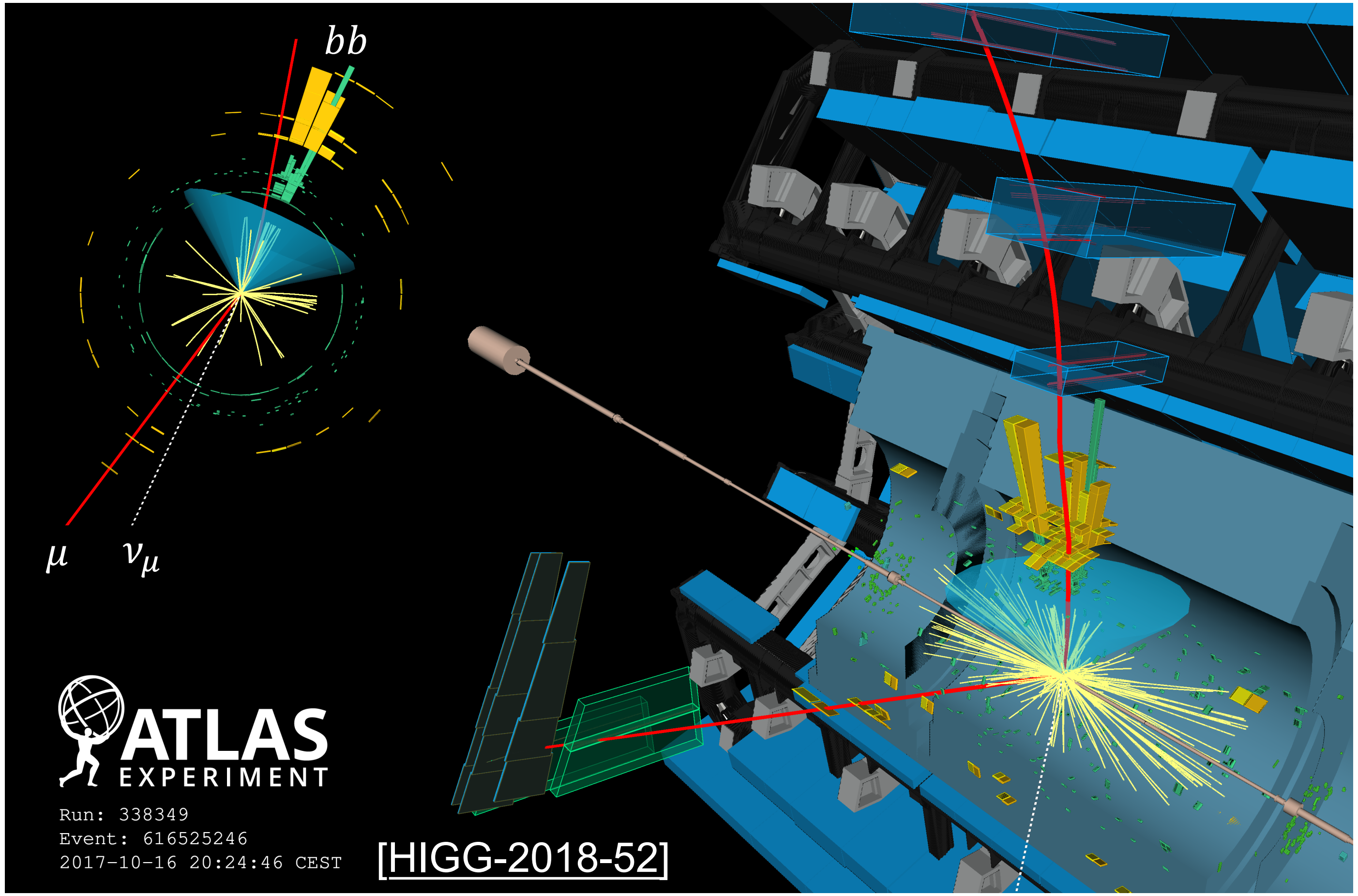
Introduction

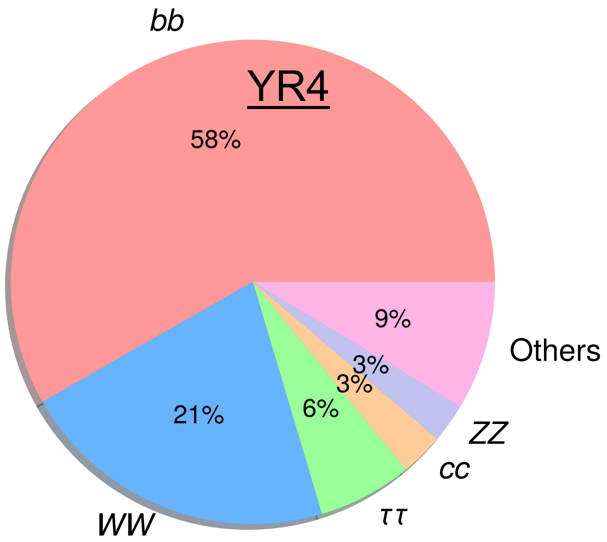
- In pp collision events, two or more object signatures may be overlapped in the detector due to extremely high momenta
- Usually in the boosted region, BSM theory effects become more and more significant

➢ **Important to test the validity of the SM or to discover new physics there!**

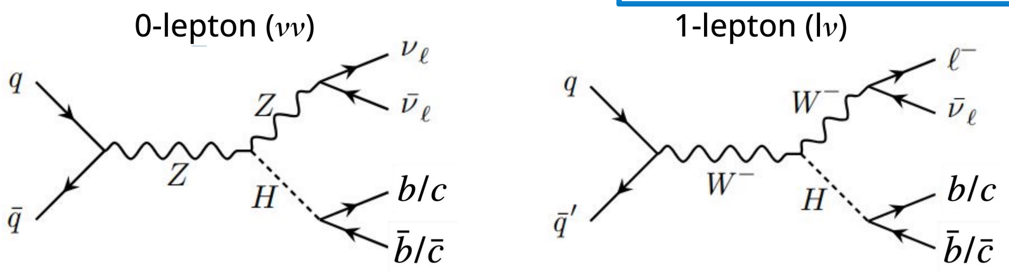


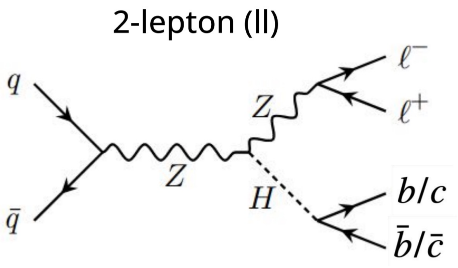
- Using highly boosted objects, the Higgs boson properties are studied in details with Run 2 datasets in the ATLAS experiment
  - $V(\rightarrow \mathrm{lep})H(\rightarrow bb/cc)$ analysis [ATLAS-CONF-2024-010]
  - $V(\rightarrow qq)H(\rightarrow bb)$ analysis [HIGG-2021-11]
  - $ttH(\rightarrow bb)$ analysis [HIGG-2020-24]
  - CP properties of the top Yukawa coupling in the $ttH/tH\ (\rightarrow bb)$ processes [HIGG-2020-03]
  - High mass Higgs-like resonances to $Z\gamma$ search [HIGG-2018-44]

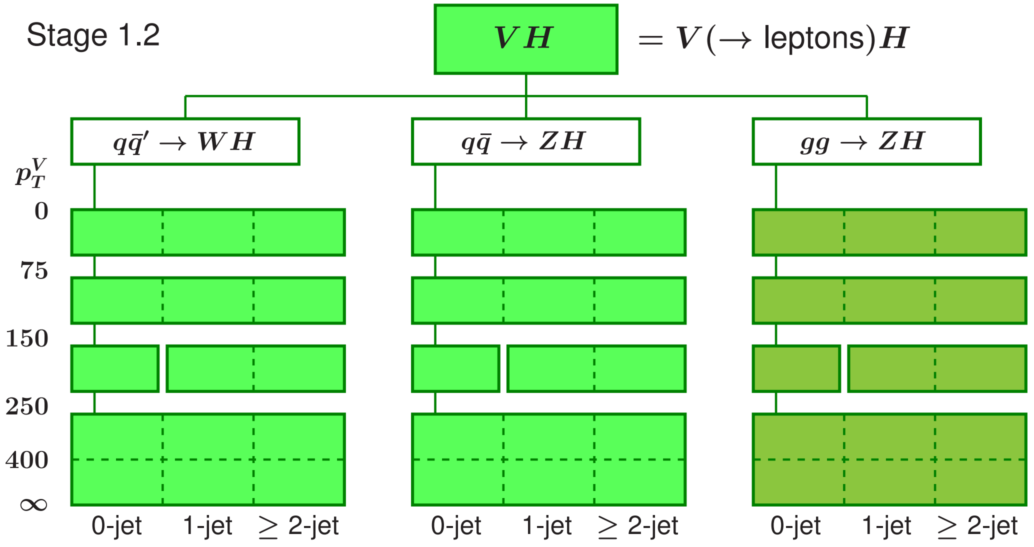
$VH(\rightarrow bb/cc)$



- $H-b$ **Yukawa coupling: largest impact on the Higgs width** → crucial to constrain new physics
- $H \rightarrow bb$: H can be reconstructed from decay products
  - **Most sensitive to measure rarer Higgs prods (ie VH, ttH)**
  - Probe kinematic properties in the VH STXS framework
- $H \rightarrow cc$: **small BR;** c quark: smaller life time → much more challenging
- $V(\rightarrow \text{lep})H$: clean signal with leptonic decays → separate $H \rightarrow bb/cc$ from large jet bkg

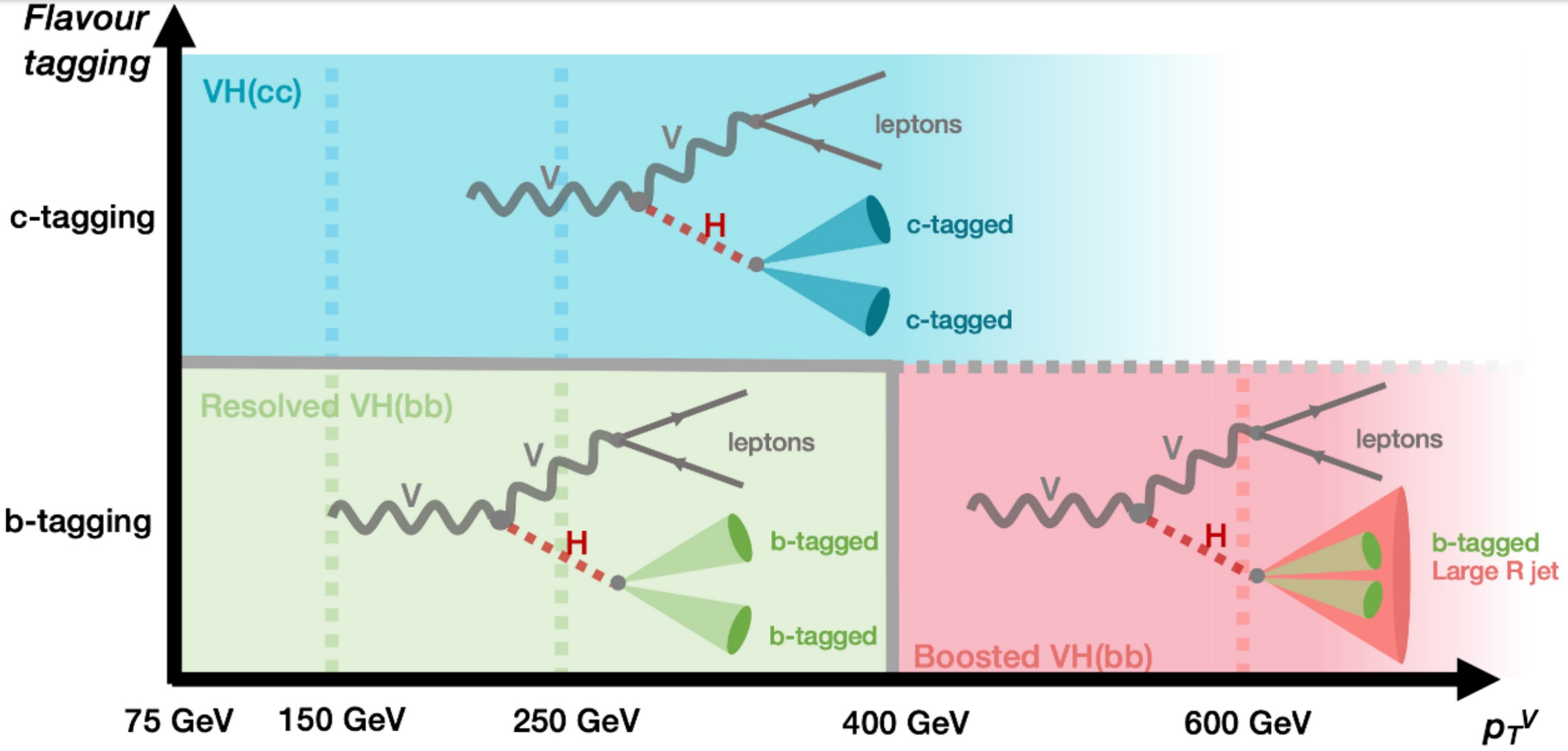




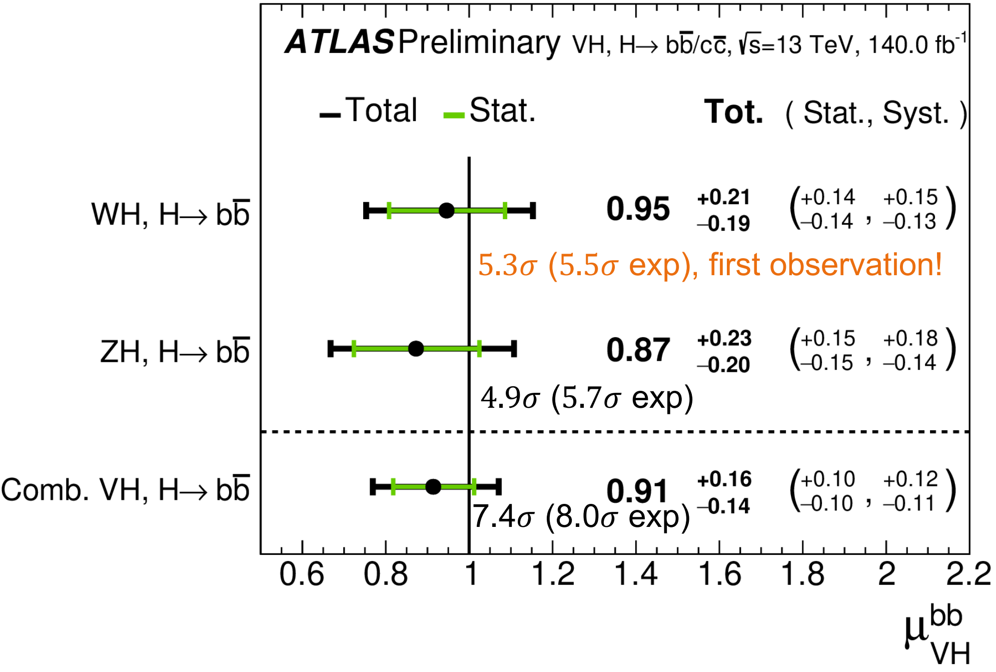


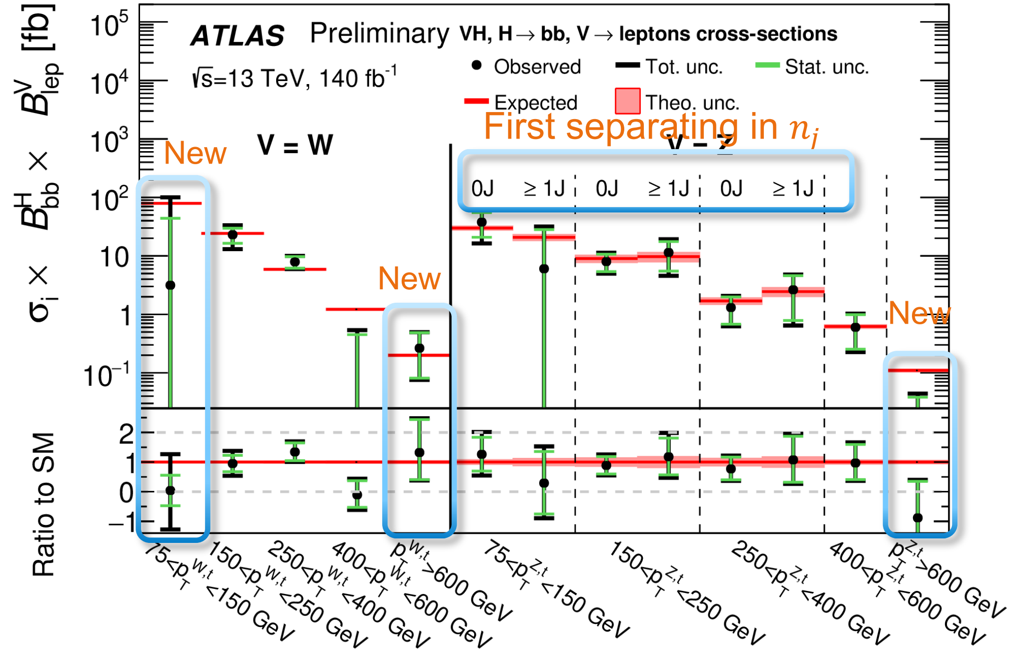
Run 2 $V(\rightarrow \mathrm{lep})H(\rightarrow bb/cc)$ analysis [ATLAS-CONF-2024-010]

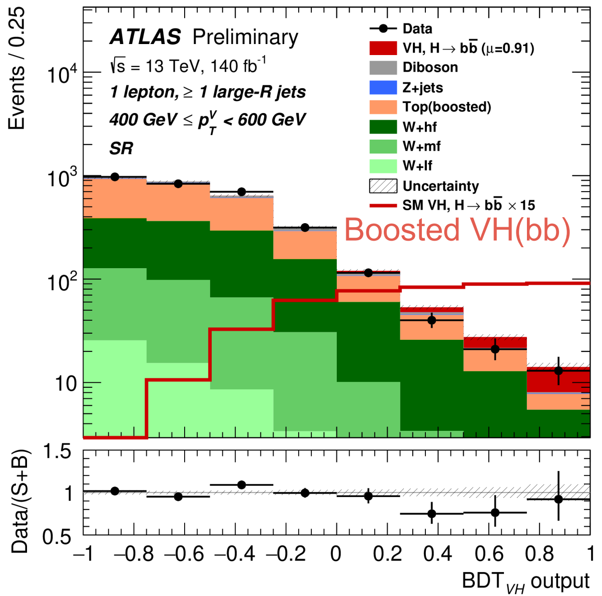
- **Large-R (R = 1.0) jet:** formed from topological clusters of energy depositions with anti-kt algorithms, **used for $p_T^V > 400$ GeV in the $VH(\rightarrow bb)$ channel**
  - To identify $H \rightarrow bb$ decay, DL1r b-tagger applied to p_T-dependent radius (VR) track jets within large-R jet
  - ➢ **Good sensitivity across full range!**



BDT distributions and results [ATLAS-CONF-2024-010]



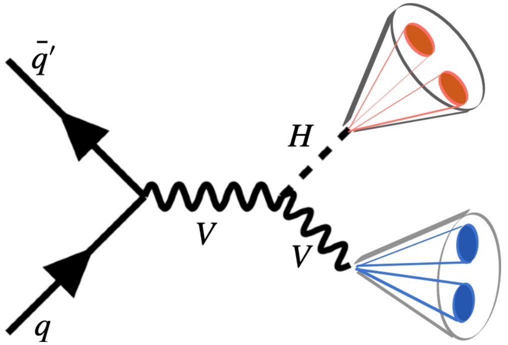


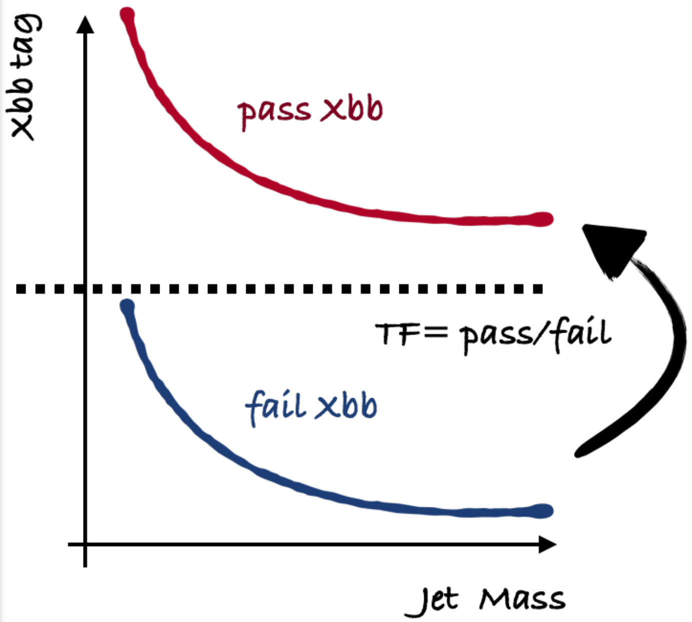


- BDTs used to maximize signal sensitivity in every category, firstly applied to boosted VH(bb), VH(cc) channels
- **15% better precision of μ_{VH}^{bb} wrt previous <u>resolved</u>, <u>boosted VH(bb)</u> results**
    - Better object reconstructions/calibrations, improved analysis strategies, etc
- **First time exploring $\sigma(p_T^V > 600\ \mathrm{GeV})$, contributed by the boosted channel!**
- **$\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2}$; < 11.3 (< 10.4 exp assuming $\mu_{VH}^{cc} = 0$) at 95% CL**
    - **Factor of 3 improvement wrt previous <u>VH(cc)</u> search**
- **All results agree with SM**

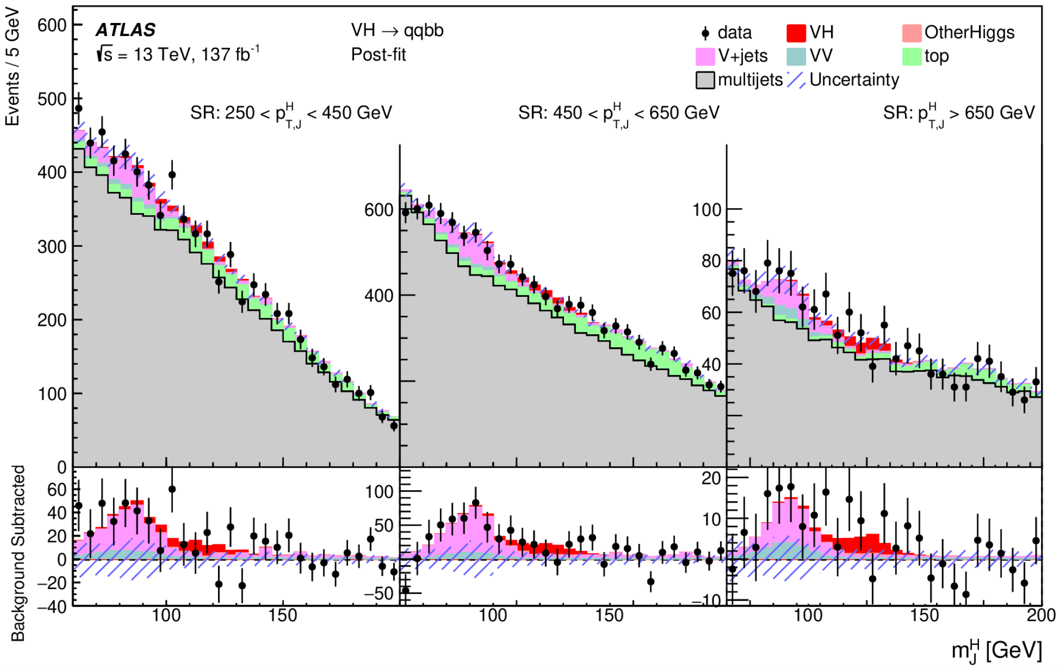
$V(\rightarrow qq)H(\rightarrow bb)$ [HIGG-2021-11]

- **VH(bb) in highly boosted topology**
  - Sensitive to higher-order effective operators in high p_T, important to test new physics
- **Run 2 $V(\rightarrow qq)H(\rightarrow bb)$ analysis: first study in two large-R topology in ATLAS!**
  - Greater BR than $V(\rightarrow \text{lep})H(\rightarrow bb)$ → **potential to probe Higgs properties in higher p_T to TeV scale!**
- **Large-R jets used to identify/reconstruct high p_T hadronic V, H**
  - **W/Z tagger**: optimized using m_J, $D_2^{\beta=1}$, N_{trk}, as a function of p_T^J
  - **Dedicated Hbb tagger (Xbb)**: discriminate $H \rightarrow bb$ decay from gluon, light or top quark jets
- Dominant multijet background modeled by the data-driven method





Results [HIGG-2021-11]



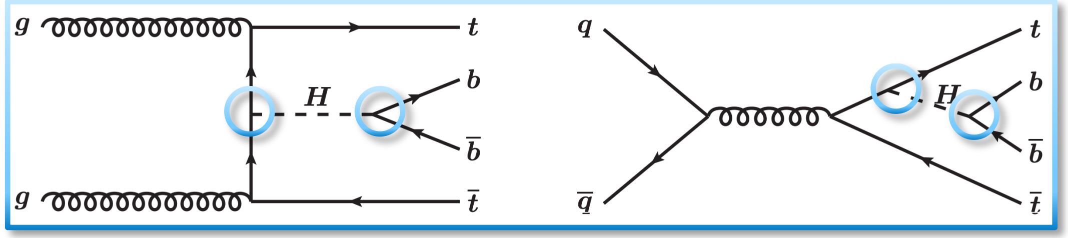
- **$\mu_{VH} = 1.4^{+1.0}_{-0.9}$, with 1.7$\sigma$ significance**; $\sigma_{VH} = 3.1 \pm 1.3(stat.)^{+1.8}_{-1.4}(syst.)$ pb

Kinematic region	Observed μ	Observed σ [fb]	Expected σ [fb]
$250 \leq p_T^H < 450$ GeV, $\lvert y_H \rvert < 2$	$0.8^{+2.2}_{-1.9}$	47^{+125}_{-109}	57.0
$450 \leq p_T^H < 650$ GeV, $\lvert y_H \rvert < 2$	$0.4^{+1.7}_{-1.5}$	2^{+10}_{-9}	5.9
$p_T^H \geq 650$ GeV, $\lvert y_H \rvert < 2$	$5.3^{+11.3}_{-3.2}$	6^{+13}_{-4} (<43)	1.2

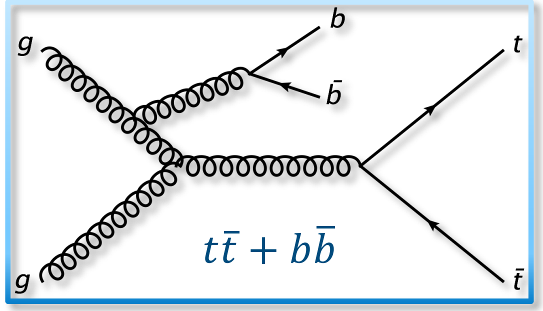
- Though limited by large uncertainties atm, **the analysis opens a fully hadronic region with high sensitivity to new physics in the future!**

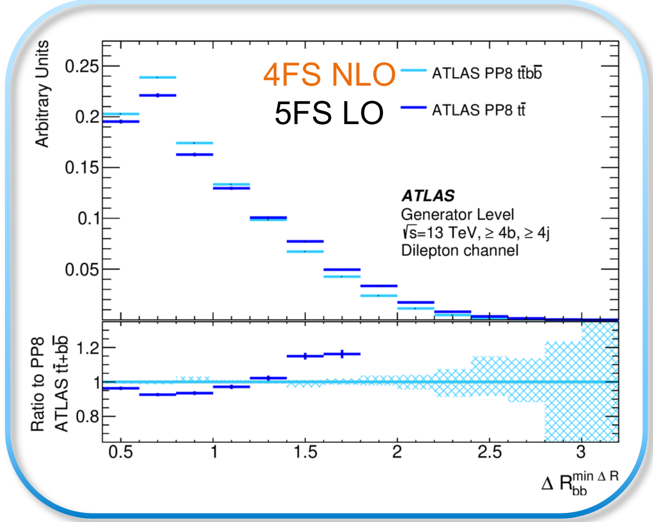
$ttH(\to bb)$

- ttH: **direct constraint on $H-t$ (heaviest SM particle) Yukawa coupling at tree level** → very sensitive to BSM effects
  - **Observed by ATLAS/CMS using several decay modes**
- $ttH(\to bb)$: **involves only $H-f$ couplings → sensitivity enhanced!**



- While with large irreducible background: $t\bar{t}+jets$ (originates from b/c) → challenging to predict theoretically
  - **Dominant modelling systematics in the previous Run 2 analysis**

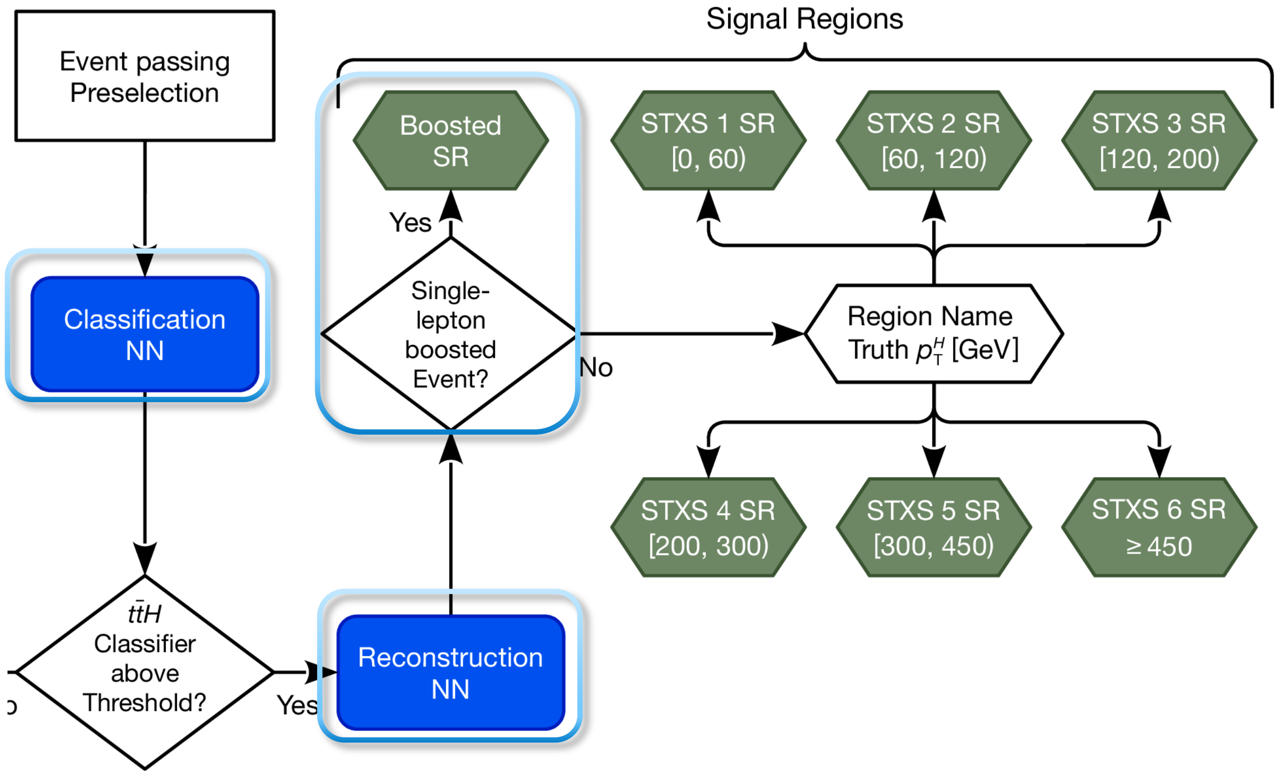




- In ATL−PHYS−PUB−2022−026, MC generators of dominant backgrounds compared at particle level in the similar phase spaces of the previous ttH(bb), ttH(ML) analyses
- **Smaller scale uncertainties for the 4FS NLO generators, used for the new ttH(bb) analysis**
- Starting point to develop common theory uncertainty strategies for the ATLAS/CMS combination

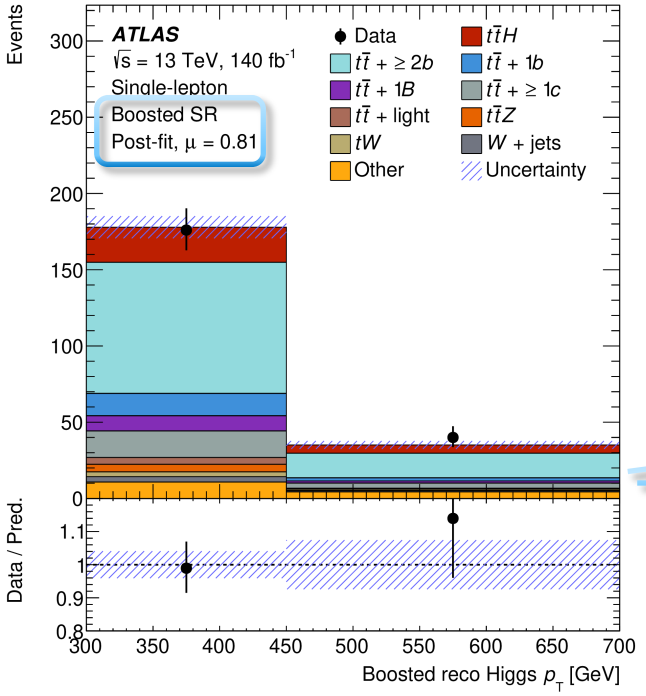
Legacy ttH(bb) analysis [HIGG-2020-24]

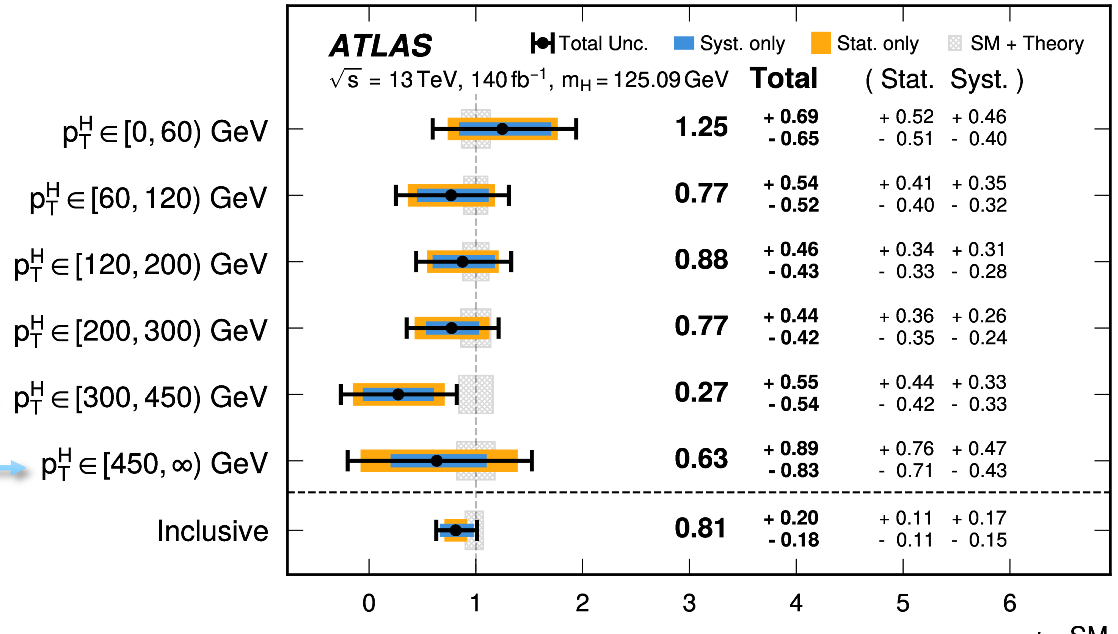
- **Re-analyze Run 2 data in single-/di-lepton channels**
  - Improved b-tagging algorithms; NN techniques for categorizations and p_T^H reconstruction → **sensitivity increased!**
- **Boosted category in single-lepton: reclustered (RC) anti-kt jet (R = 1.0) for high p_T H,** identified by DNN
  - DL1r b-tagger applied to two small-R (R=0.4) particle flow jets inside RC jet



Results [HIGG-2020-24]

- $\mu_{ttH} = 0.81^{+0.22}_{-0.19} = 0.81 \pm 0.11(stat.)^{+0.20}_{-0.16}(syst.)$, **significance: 4.6$\sigma$ (5.4σ exp)**
  - **Improved $tt + jets$ background modellings**, systematics updated → **better control over background**
- **Exclusive boosted regions: improve sensitivity by ~15% for measuring $\sigma_{ttH}(p_T^H > 450\ \mathrm{GeV})$**, compared with the scenario w/o introducing boosted regions





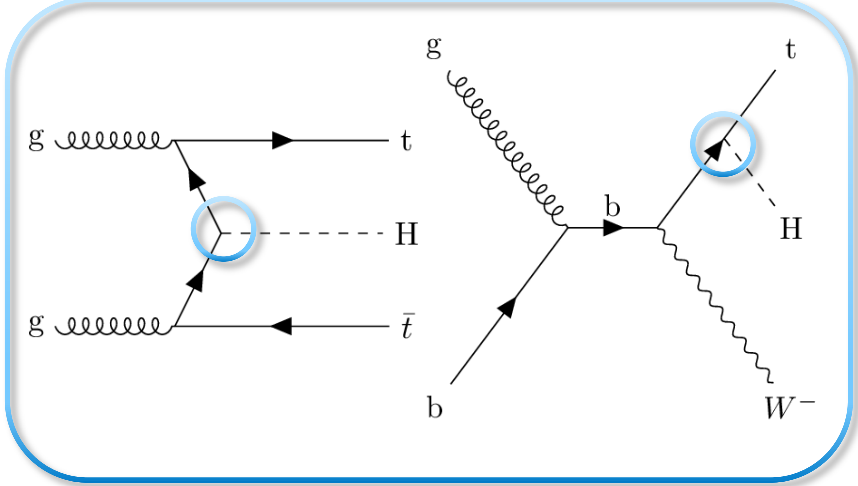
Most precise and full ttH STXS measurement!

- 50% better overall sensitivity wrt previous analysis, particularly 70% better for $\sigma_{ttH}(p_T^H > 450\ \mathrm{GeV})$, all consistent with SM

CP properties of $H - t$ coupling

- **SM Higgs: $J^{CP} = 0^{++}$**
- In BSM, CP-odd $H - f$ couplings won't be suppressed by the new physics scale → maybe significant at tree level
  - $J^P = 0^-$ excluded by more than 95% CL (ATLAS, CMS)
  - Pure CP-odd $H - t$ coupling excluded by more than 3σ significance in $ttH(\gamma\gamma)$ (ATLAS, CMS) and multilepton analyses
- CP-odd/-even mixture states not ruled out → **CP-odd components observation will open up CP-violation possibility in the Higgs sector**
  - **Play a fundamental role in explaining the matter–antimatter asymmetry of the universe**

- **ttH/tH: sensitive to potential CP-mixing at tree level, especially in the boosted topology**
- $\mathcal{L}_{ttH} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$
  - $i\gamma_5 \sin\alpha$: pseudoscalar coupling ($J^{CP} = 0^{+-}$), change σ differentially; κ_t': inclusive impact to σ
  - $\sigma_{tH} > \sigma_{ttH}$ if there're significant CP-odd components



Run 2 ttH/tH(bb) analysis to study CP properties [HIGG-2020-03]

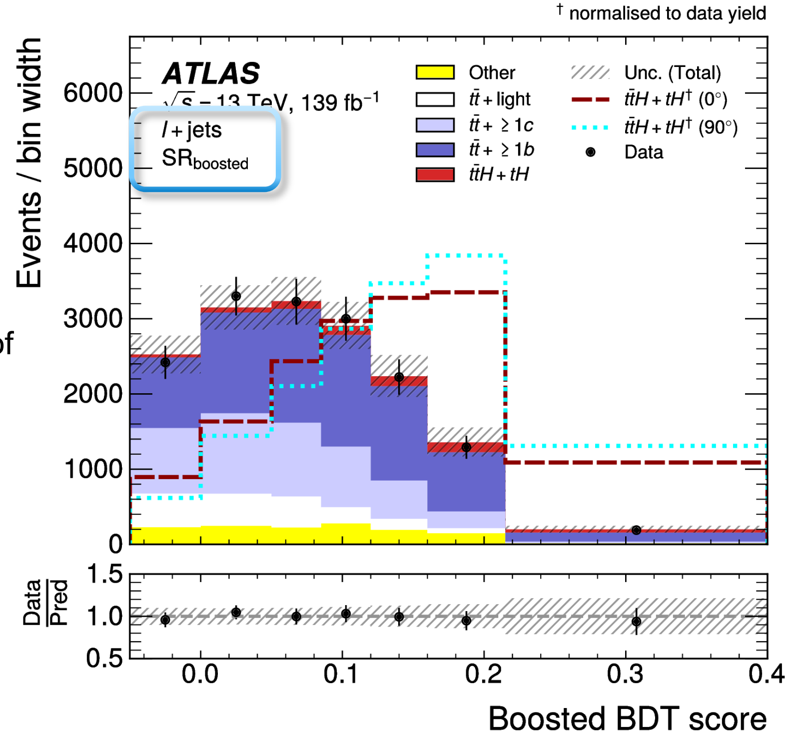
- **Run 2 ttH or $tH(\rightarrow bb)$ analysis**: **firstly used for CP properties of $H-t$ coupling**
  - Based on previous coupling analysis, re-optimized for the CP sensitivities
- ML used for H/top reconstruction and event categorization
- **$\mathrm{SR_{boosted}}$: RC jet (R = 1.0) for high p_T H**, identified by DNN
- In the region $N_{tH}^{odd} \approx N_{ttH} \rightarrow N_{ttH/tH}^{odd} \approx 1.5N_{ttH/tH}^{even}$ → **substantial sensitivities, no need b_2, b_4 observables!**

Channel (TR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($\mathrm{TR}^{\geq 4j,\geq 4b}$)	$\mathrm{CR}_{\text{no-reco}}^{\geq 4j,\geq 4b}$	–	$\Delta\eta_{\ell\ell}$
	$\mathrm{CR}^{\geq 4j,\geq 4b}$	$\mathrm{BDT}^{\geq 4j,\geq 4b} \in [-1,-0.086)$	b_4
	$\mathrm{SR}_1^{\geq 4j,\geq 4b}$	$\mathrm{BDT}^{\geq 4j,\geq 4b} \in [-0.086,0.186)$	b_4
	$\mathrm{SR}_2^{\geq 4j,\geq 4b}$	$\mathrm{BDT}^{\geq 4j,\geq 4b} \in [0.186,1]$	b_4
ℓ+jets ($\mathrm{TR}^{\geq 6j,\geq 4b}$)	$\mathrm{CR}_1^{\geq 6j,\geq 4b}$	$\mathrm{BDT}^{\geq 6j,\geq 4b} \in [-1,-0.128)$	b_2
	$\mathrm{CR}_2^{\geq 6j,\geq 4b}$	$\mathrm{BDT}^{\geq 6j,\geq 4b} \in [-0.128,0.249)$	b_2
	$\mathrm{SR}^{\geq 6j,\geq 4b}$	$\mathrm{BDT}^{\geq 6j,\geq 4b} \in [0.249,1]$	b_2
ℓ+jets ($\mathrm{TR_{boosted}}$)	$\mathrm{SR_{boosted}}$	$\mathrm{BDT^{boosted}} \in [-0.05,1]$	$\mathrm{BDT^{boosted}}$

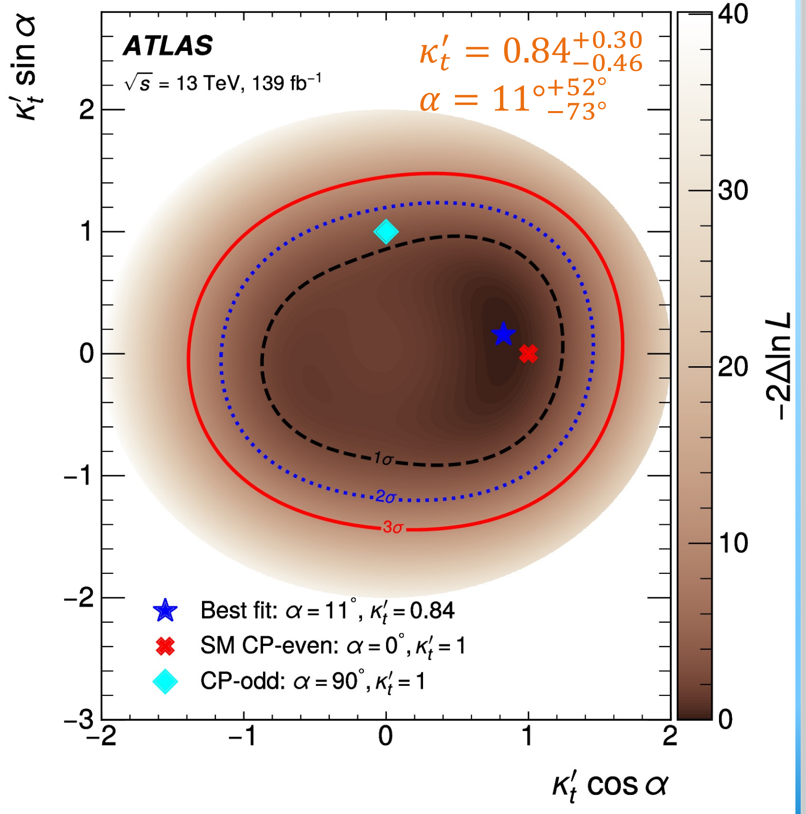
b_4: $\dfrac{(\vec{p}_1\cdot\hat{z})(\vec{p}_2\cdot\hat{z})}{|\vec{p}_1||\vec{p}_2|}$

b_2: $\dfrac{(\vec{p}_1\times\hat{z})\cdot(\vec{p}_2\times\hat{z})}{|\vec{p}_1||\vec{p}_2|}$

$\vec{p}_i$: momentum of top quark; CP sensitive



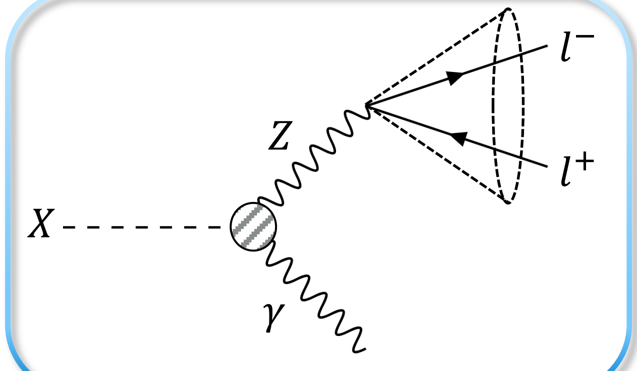
Results [HIGG-2020-03]



- Expectations
  - CP-even: $\kappa_t' = 1.00^{+0.29}_{-0.27}$, $\alpha \in [-180°, -173°] \cup [-50°, 52°] \cup [171°, 180°]$
  - CP-odd: $\kappa_t' = 1.00^{+0.22}_{-0.33}$, $\alpha \in [-157°, -41°] \cup [43°, 157°]$
- $tt + \geq 1b$ modelling uncertainties dominate, impact to α: ${}^{+37°}_{-51°}$
  - **Better modelling of $ttbb$ background will be the essential ingredient in the future!**
- **Compatible with pure CP-even or CP-odd (1.2σ interval) assumptions**
- **Complement to HGam analysis, allow for future combination**
- This channel will become quite sensitive for the CP studies in the future due to the tree-level sensitivity and high BR_{bb}

High mass $Z\gamma$ [HIGG-2018-44]

- **Search for spin-0/spin-2 $pp \rightarrow X \rightarrow Z\gamma$ from 220 to 3400 GeV using Run 2 data**
  - Test wide range of BSM scenarios
- **Final states: $Z(\rightarrow ll)\gamma$** → powerful experimental signature!
  - High reconstruction efficiency; $m_{ll\gamma}$: good resolution
  - Leptonic and photon signatures → relatively small backgrounds

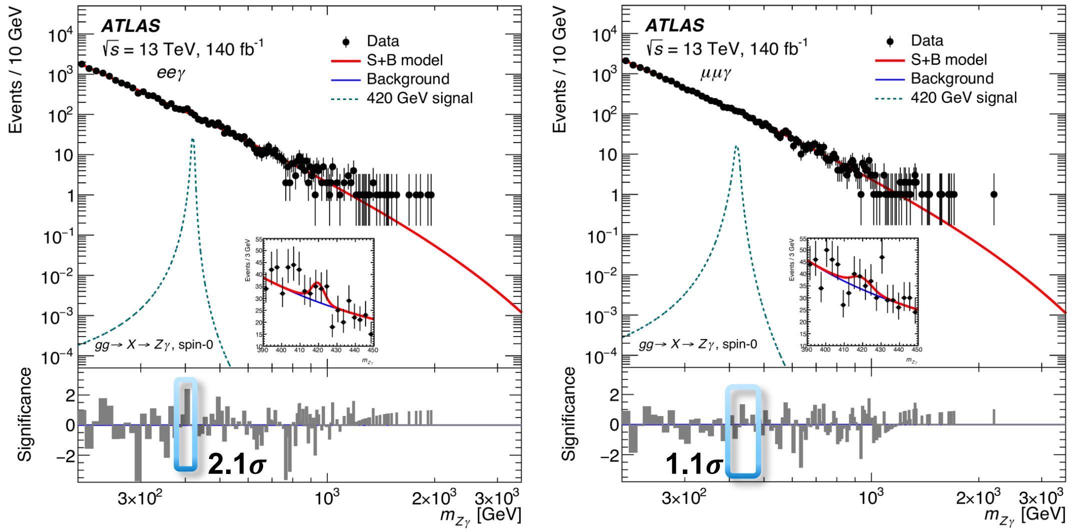


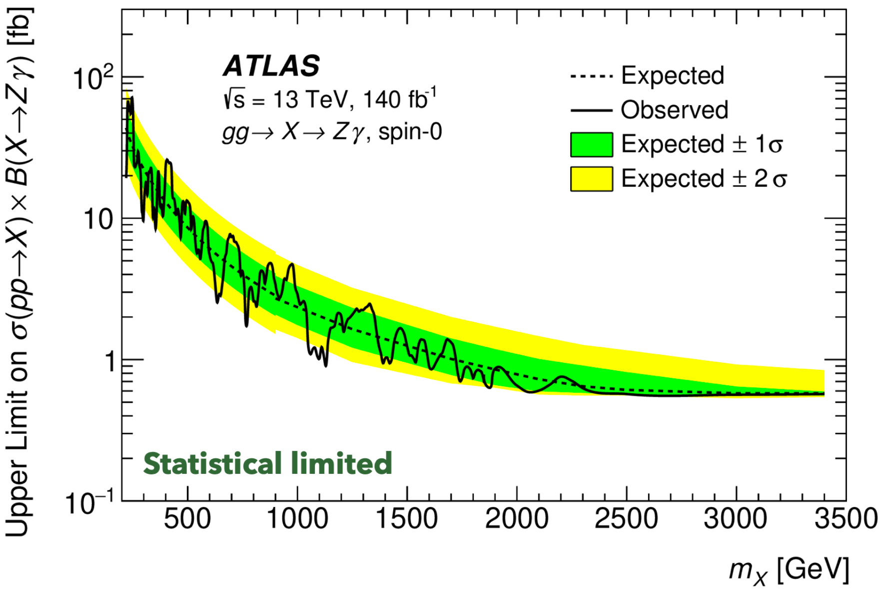
- **High mass $X \rightarrow$ boosted $Z \rightarrow$ collimated electrons, $\Delta R(e,e)\sim 0.2$ at 3400 GeV**
- Low ID efficiencies with the Loose criterion (~15-20% loss for higher masses)
- **Developed dedicated electron ID with MVA method**

Selection	Electron	Electron as photon
p_T	> 10 GeV	> 50 GeV
$\lvert\eta\rvert$	< 2.47 Exclude [1.37, 1.52]	< 2.47 Exclude [1.37, 1.52]
$\lvert d_0\rvert/\sigma_{d_0}$	< 5	
$\lvert z_0 \sin\theta\rvert$	< 0.5 mm	
Identification	Mixed	MVA
Isolation	Track-based *Tight*	

- Combine Loose and MVA ID (**Mixed ID**) results in 6% (13%) efficiency improvement for $m_X = 200$ GeV (3400 GeV) wrt Loose ID
- Due to the same reason, ~20% of sub-leading electrons mis-reconstructed as photons for higher m_X
- **Define/optimize selections for electrons mis-reconstructed as photons**: **$e\gamma$ channel**
  - **10% efficiency improvement wrt ee only**

Results [HIGG-2018-44]





- **Discriminant variable: $m_{ll\gamma}$**; Parametric signal/background models used
- Largest significance (spin 0): 2.3σ at 420 GeV
- **No significant excess wrt the background-only hypothesis**

- **Due to the increased Run 2 dataset and the use of an ML electron ID technique**
  - Expected upper limit improved by a factor of 1.9 to 4 for m_X in [250 - 2400] GeV wrt previous partial Run 2 analysis
  - Search range extended to 3.4 TeV
  - Better expected upper limits for $m_X < 2.3$ TeV wrt $Z(\rightarrow qq)\gamma$ analysis

Summary

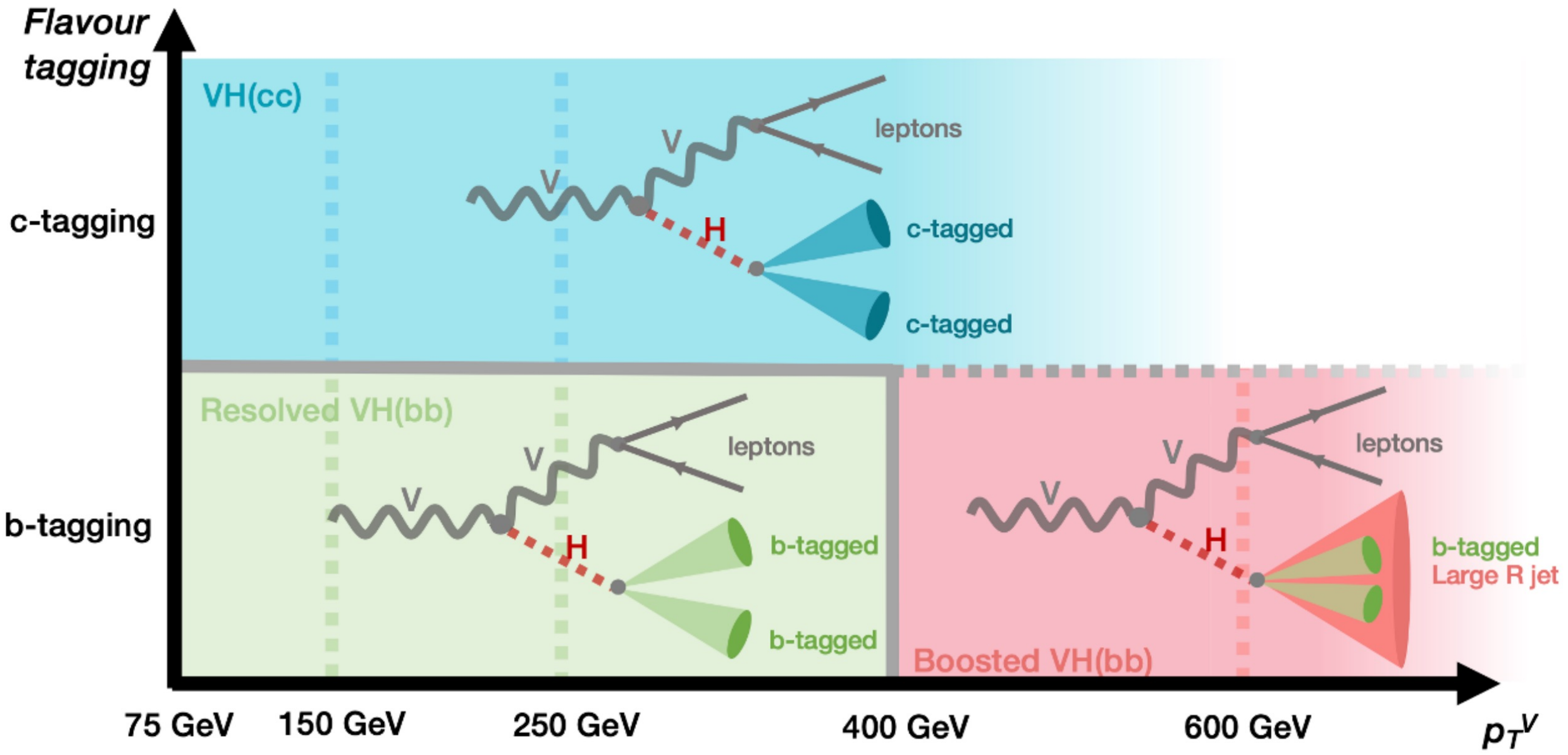
- Using Run 2 datasets, the Higgs boson properties are studied in various aspects using highly boosted objects

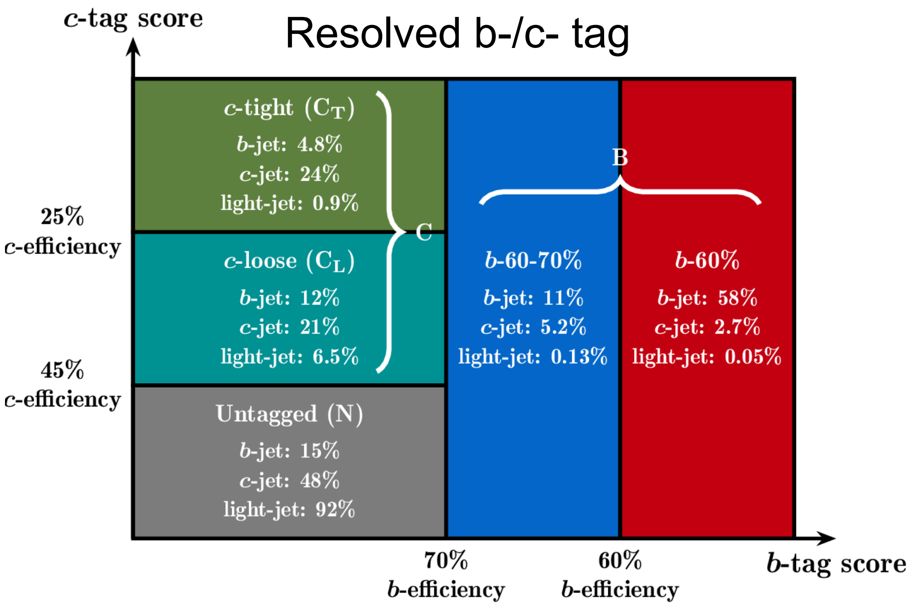
- **$V(\rightarrow lep)H(\rightarrow bb/cc)$ analysis** [ATLAS-CONF-2024-010]
  - Large-R jet used for $p_T^V > 400$ GeV in the $VH(\rightarrow bb)$ channel → good sensitivity achieved!
- **$V(\rightarrow qq)H(\rightarrow bb)$ analysis** [HIGG-2021-11]
  - First study in two large-R topology in ATLAS!
  - Open a fully hadronic region with high sensitivity to new physics when larger data collected
- **$ttH(\rightarrow bb)$ analysis** [HIGG-2020-24]
  - Boosted category defined using RC jet → improve sensitivity by ~15% for measuring σ_{ttH} in high p_T^H
- **CP properties of the top Yukawa coupling in the $ttH/tH\,(\rightarrow bb)$ processes** [HIGG-2020-03]
  - CP-odd sensitive boosted SR defined using RC jet
- **High mass Higgs-like resonances to $Z\gamma$ search** [HIGG-2018-44]
  - Developed merged electron ID and identified electrons mis-reconstructed as photons for the decay products from the boosted Z → improved efficiencies!

Backup

Run 2 $V(\rightarrow \text{lep})H(\rightarrow bb/cc)$ analysis [ATLAS-CONF-2024-010]

- **Large-R (R = 1.0) jet:** formed from topological energy deposition anti-kt algorithm, **used for $p_T^V > 400$ GeV in the $VH(\rightarrow bb)$ channel**
  - To identify $H \rightarrow bb$ decay, DL1r b-tagger applied to p_T-dependent radius (VR) track jets within large-R jet
  - **Good sensitivity across full range!**
- Updates wrt previous resolved, boosted VH(bb), VH(cc) analyses
  - Better lepton, jet reconstruction/calibration; Improved FT algorithm combining b-/c- jet ID, more precise calibration
  - Improved SR/CR definitions as a function of n_l, n_j, p_T^V (harmonized with STXS), background predictions and estimations





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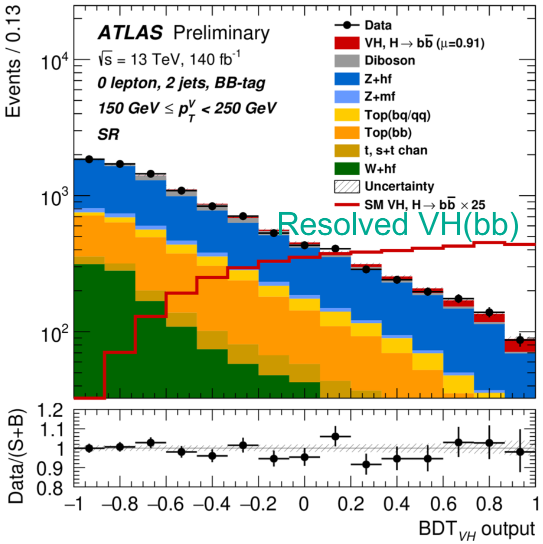
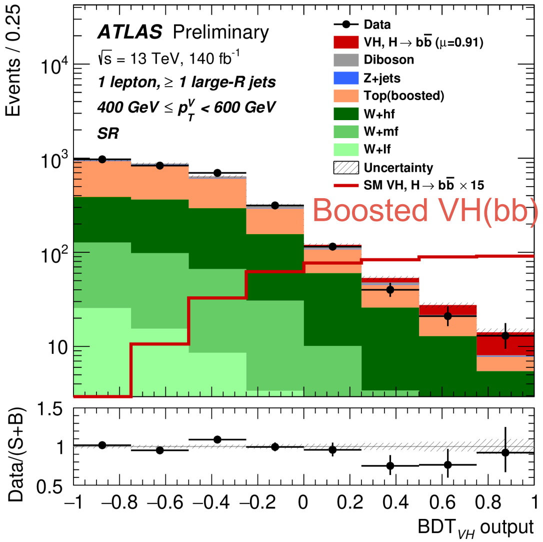
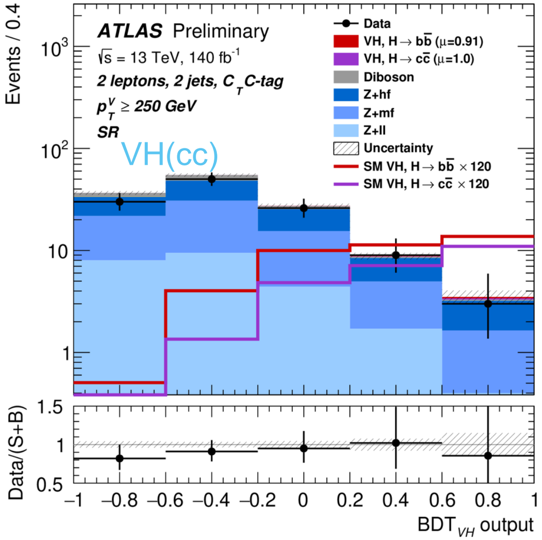
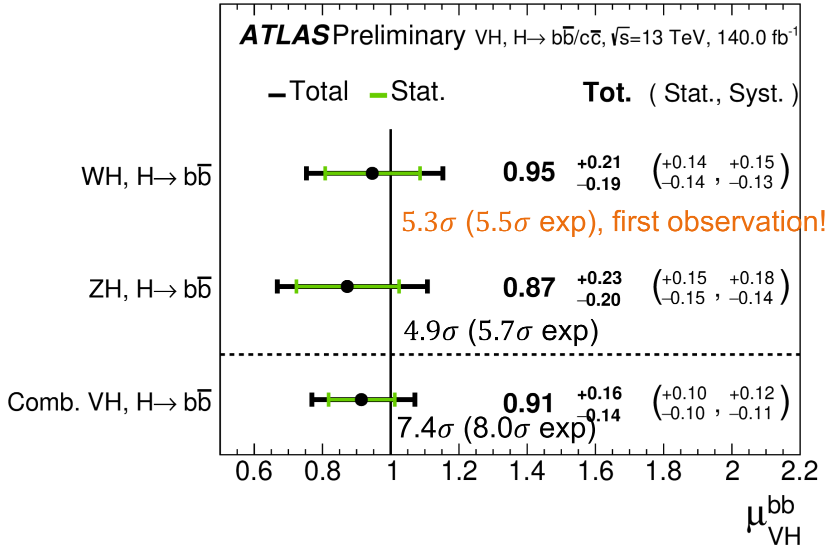
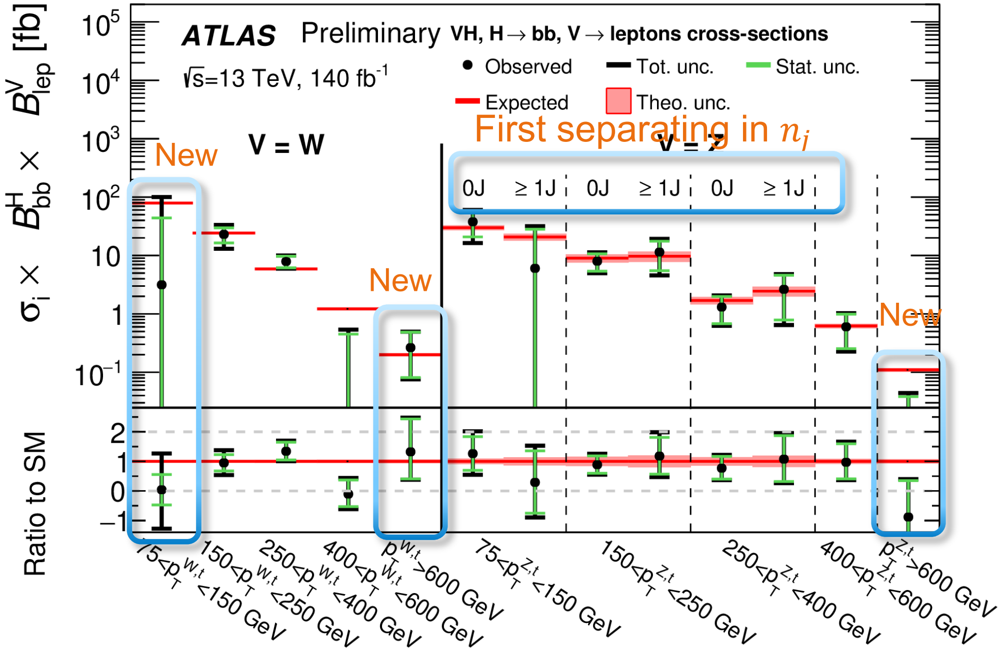










- BDTs used to maximize signal sensitivity in every category, firstly applied to boosted VH(bb), VH(cc) channels
- **15% better precision of μ_{VH}^{bb} wrt previous resolved, boosted VH(bb) results**
- **Granularity in STXS increased wrt previous results**
- $\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2}$; **< 11.3 (< 10.4 exp assuming $\mu_{VH}^{cc} = 0$) at 95% CL**
  - **Factor of 3 improvement wrt previous VH(cc) search**
- $|\kappa_c| < 4.2$ at 95% CL assuming $\kappa_b = 1$
- $|\kappa_c/\kappa_b| < 3.5$ at 95% CL, smaller than $m_b/m_c = 4.578 \pm 0.008$ (Phys. Rev. D 98, 054517 (2018)) → $H - c$ coupling strength < $H - b$ coupling strength
- **All results agree with SM**

$ttbb$ and ttW modellings for the ttH(bb/ML) analyses

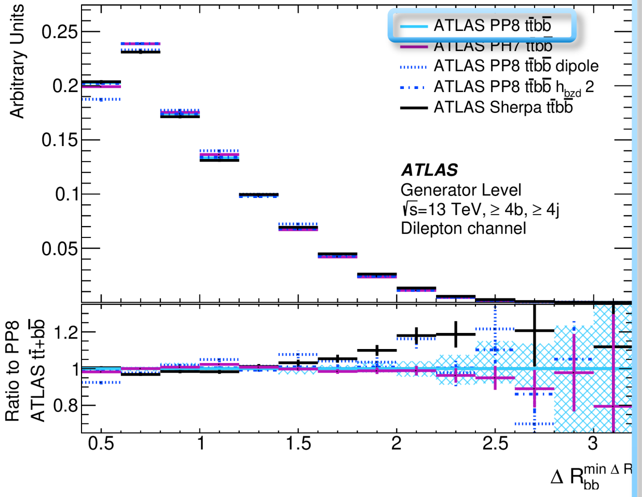
- In ATL-PHYS-PUB-2022-026, MC generators of dominant backgrounds compared at particle level in the similar phase spaces of the previous ttH(bb), ttH(ML) analyses

- $t\bar{t}b\bar{b}$

4FS NLO

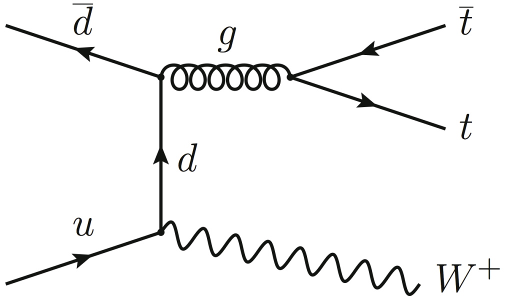
5FS LO

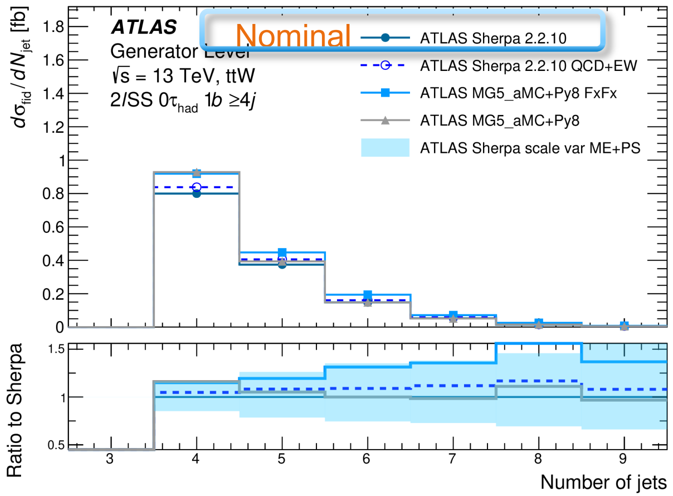
ttbb and ttW modellings for the ttH(bb/ML) analyses



- **Smaller scale uncertainties for the 4FS NLO generators, used for the new ttH(bb) analysis**
- Starting point to develop common theory uncertainty strategies for the ATLAS/CMS combination

- $t\bar{t}W$

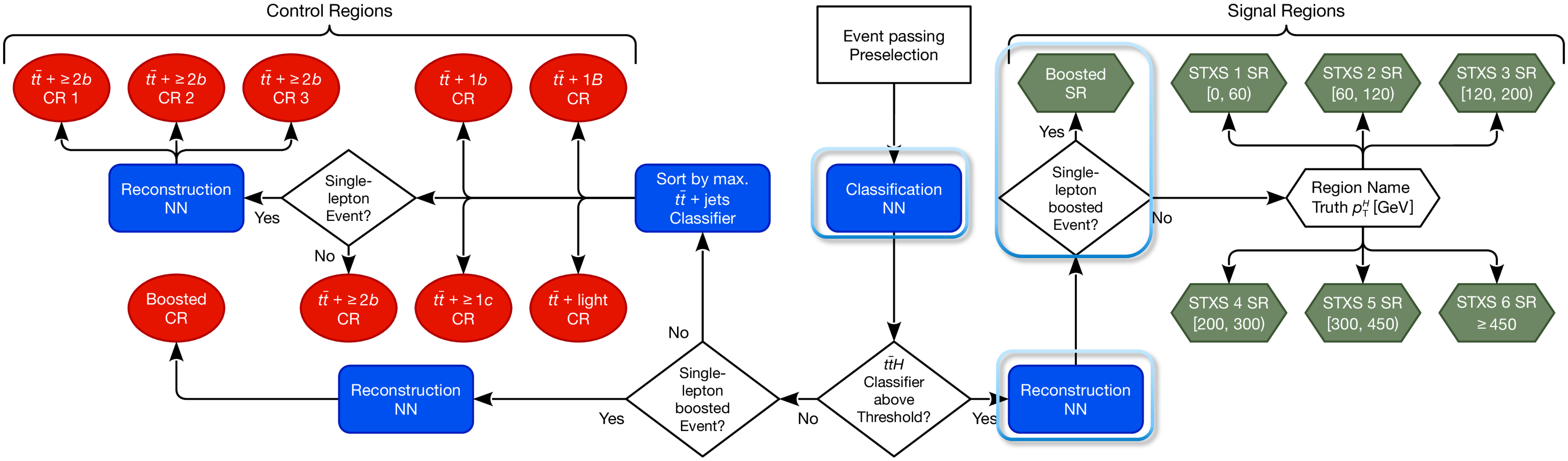




- Overall differences mostly within the scale uncertainty bands
- Small shape effects of scale uncertainties (<10%), while significant impacts to acceptances
- Tree-level EW effects → minor shape impacts, up to 20% on σ at high N_j
- Significant effects for MG5_aMC@NLO+Pythia8 FxFx

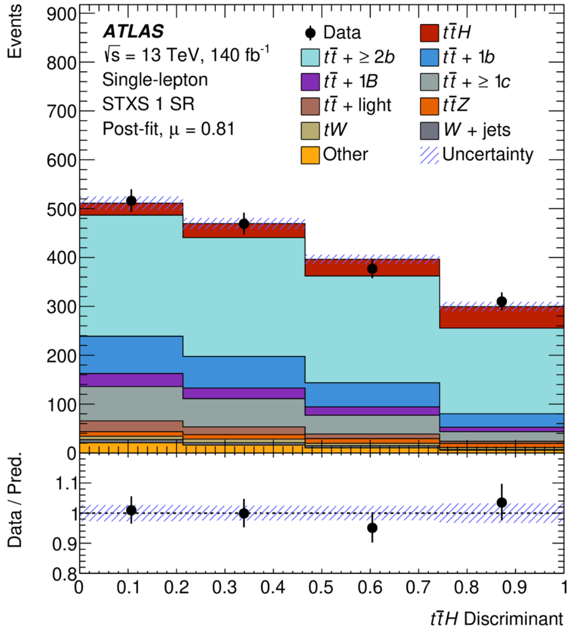
Legacy ttH(bb) analysis [HIGG-2020-24]

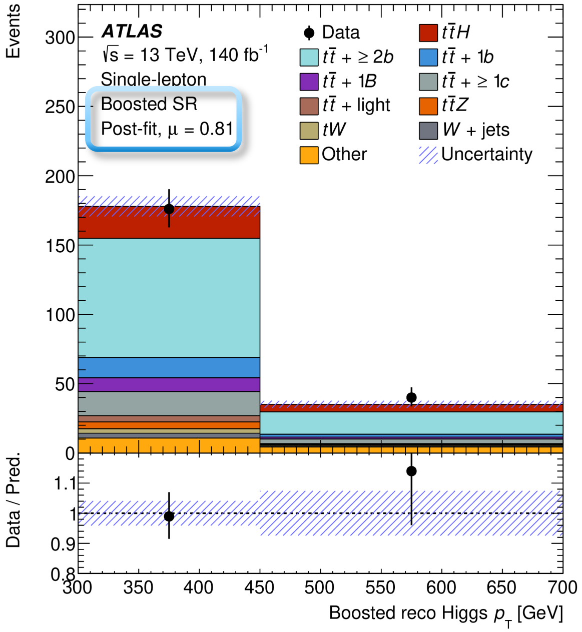
- **Re-analyze Run 2 data in single-/di-lepton channels**
  - Improved b-tagging algorithm; less requirements on N_b → **increased acceptance and efficiency**
  - Advanced NN techniques (transformer) used to categorize events and to reconstruct p_T^H → **sensitivity increased!**
- **Boosted category in single-lepton: reclustered (RC) antikt jet (R = 1.0) for high p_T H**

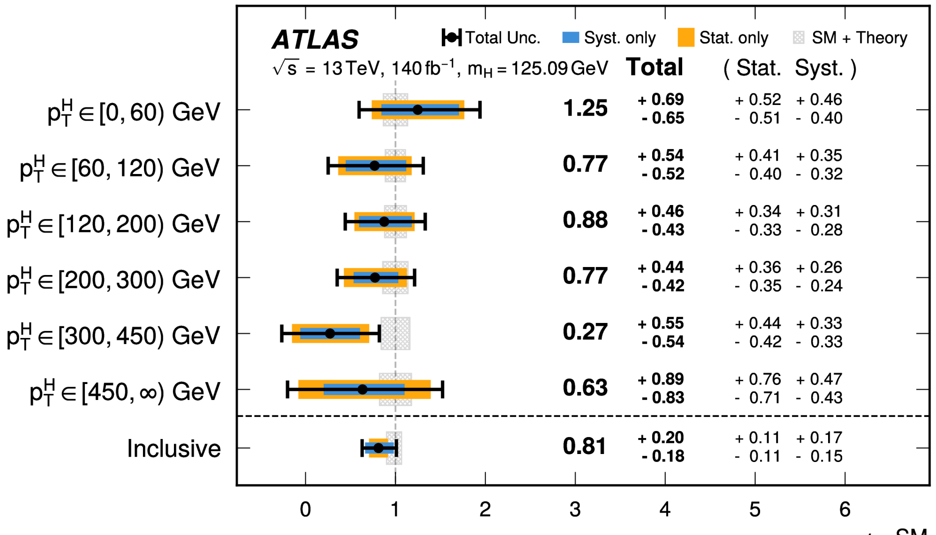


Results [HIGG-2020-24]

- $\mu_{ttH} = 0.81^{+0.22}_{-0.19} = 0.81 \pm 0.11(stat.)^{+0.20}_{-0.16}(syst.)$, **significance: 4.6$\sigma$ (5.4σ exp)**
  - ttH modelling uncertainties dominated
- **Improved $tt + jets$ background modellings**, systematics updated → **better control over background**
- **Exclusive boosted regions: improve sensitivity by ~15% for measuring $\sigma_{ttH}(p_T^H > 450\ \mathrm{GeV})$**, compared with the scenario where the events are selected in the resolved regions







Most precise and full ttH STXS measurement!

- **Better overall sensitivity wrt previous analysis, all consistent with SM**

Run 2 ttH/tH(bb) analysis to study CP properties [HIGG-2020-03]

- **Run 2 ttH or $tH(\to bb)$ in single-/di-lepton channels: firstly used for CP properties of $H-t$ coupling**
- ML used for H/top reconstruction and event categorization
- **$\mathrm{SR_{boosted}}$: RC jet (R = 1.0) for high p_T H**, identified by DNN
  - In the region $N_{tH}^{odd} \approx N_{ttH} \to N_{ttH/tH}^{odd} \approx 1.5 N_{ttH/tH}^{even}$ → substantial sensitivities, no need b_2, b_4 observables!

Channel (TR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($\mathrm{TR}^{\geq 4j, \geq 4b}$)	$\mathrm{CR}_{\text{no-reco}}^{\geq 4j, \geq 4b}$	–	$\Delta\eta_{\ell\ell}$
	$\mathrm{CR}^{\geq 4j, \geq 4b}$	$\mathrm{BDT}^{\geq 4j, \geq 4b} \in [-1, -0.086)$	b_4
	$\mathrm{SR}_1^{\geq 4j, \geq 4b}$	$\mathrm{BDT}^{\geq 4j, \geq 4b} \in [-0.086, 0.186)$	b_4
	$\mathrm{SR}_2^{\geq 4j, \geq 4b}$	$\mathrm{BDT}^{\geq 4j, \geq 4b} \in [0.186, 1]$	b_4
ℓ+jets ($\mathrm{TR}^{\geq 6j, \geq 4b}$)	$\mathrm{CR}_1^{\geq 6j, \geq 4b}$	$\mathrm{BDT}^{\geq 6j, \geq 4b} \in [-1, -0.128)$	b_2
	$\mathrm{CR}_2^{\geq 6j, \geq 4b}$	$\mathrm{BDT}^{\geq 6j, \geq 4b} \in [-0.128, 0.249)$	b_2
	$\mathrm{SR}^{\geq 6j, \geq 4b}$	$\mathrm{BDT}^{\geq 6j, \geq 4b} \in [0.249, 1]$	b_2
ℓ+jets ($\mathrm{TR_{boosted}}$)	$\mathrm{SR_{boosted}}$	$\mathrm{BDT^{boosted}} \in [-0.05, 1]$	$\mathrm{BDT^{boosted}}$

$$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

$\vec{p}_i$: momentum of top quark; CP sensitive