Latest ATLAS results on H→bb decays and Interpretation of Combined Higgs Measurements

Matt Klein (University of Michigan) on behalf of the ATLAS Collaboration

2020 November 3

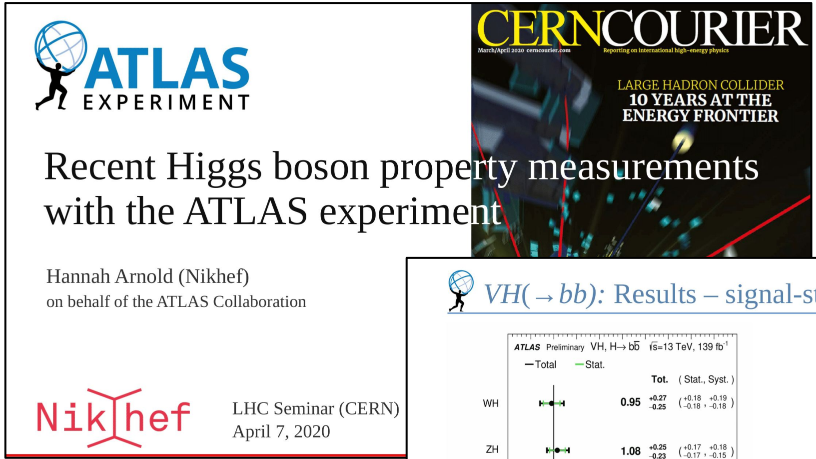
UNIVERSITY OF MICHIGAN

ATLAS EXPERIMENT

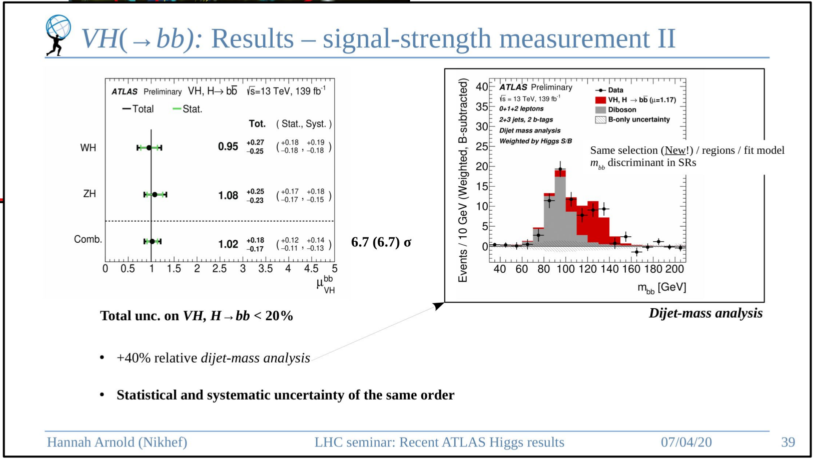
Recent H→bb History

- H→bb observed by ATLAS and CMS in 2018, mostly with V(lep)H(bb)

- H→bb and VH measurements performed with unprecedented precision with the full Run 2 dataset - see LHC seminar in April



VH is the most sensitive H→bb production mode
→*Relatively* high signal relative to background
→Relative ease to trigger

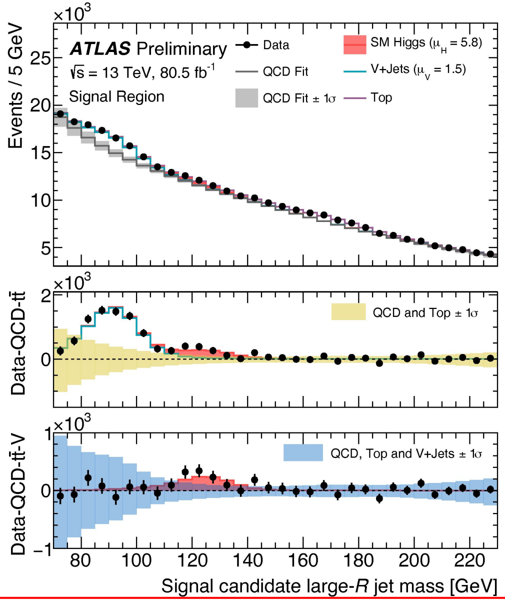


H→bb History

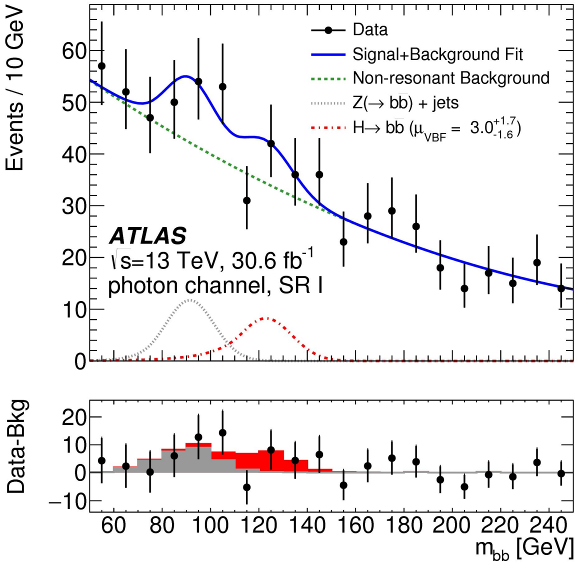
- **However -** VH is not the only production mode

- Other production modes allow for increased precision of Higgs coupling measurements, Higgs measurements at high p_T, and H→bb measurement not explicitly correlated with VH

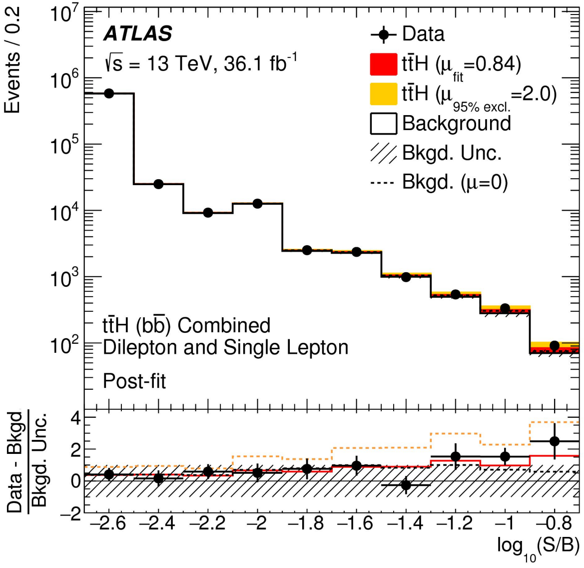
ggF: ATLAS-CONF-2018-052



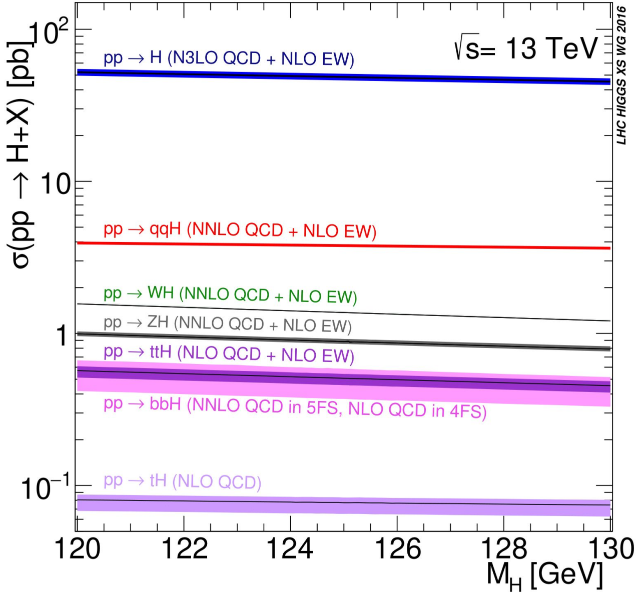
VBF: arXiv:1807.08639



ttH: arXiv:1712.08895

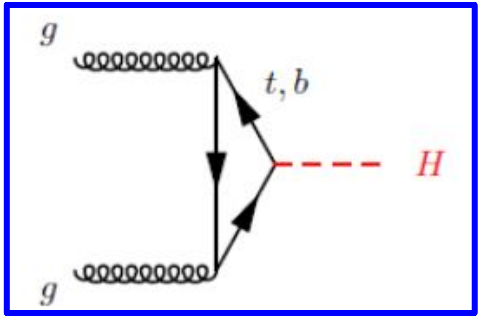


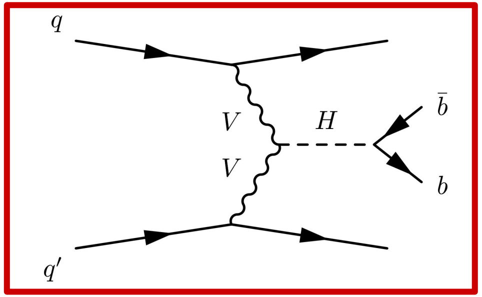
Higgs Production Modes

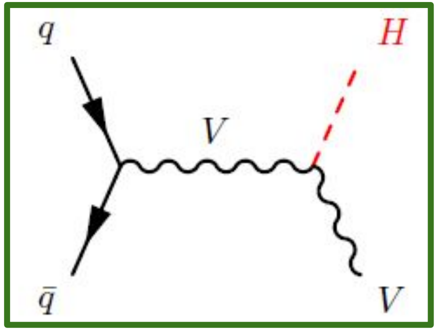


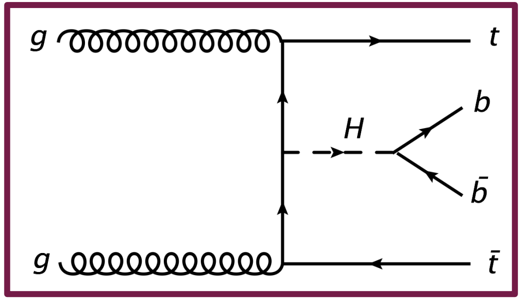
Expect H→bb 58% of time

Decreasing cross-section







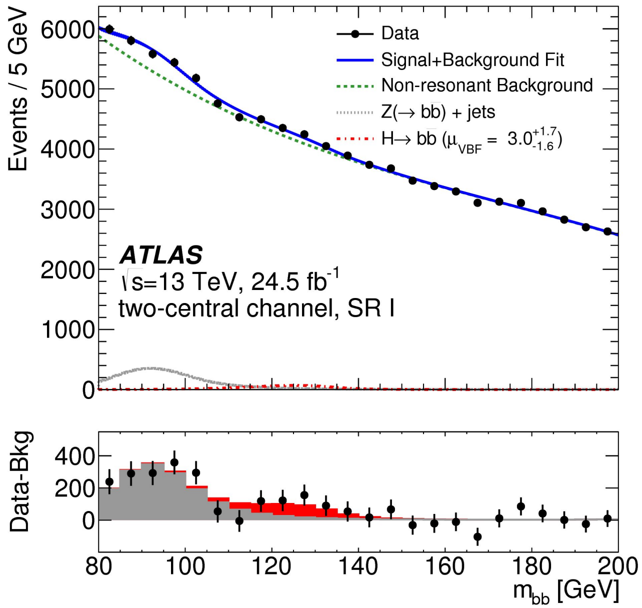


Decreasing background

arXiv:1807.08639

History: VBF Hbb and VBF Hbb+γ

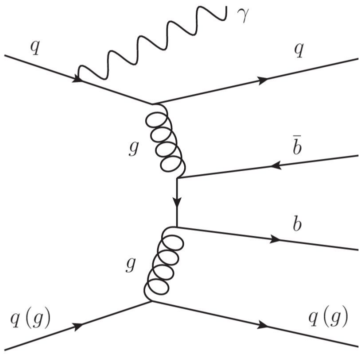
Large, difficult to model multijet background
Smaller, peaked Z→bb background near signal
Trigger on jets

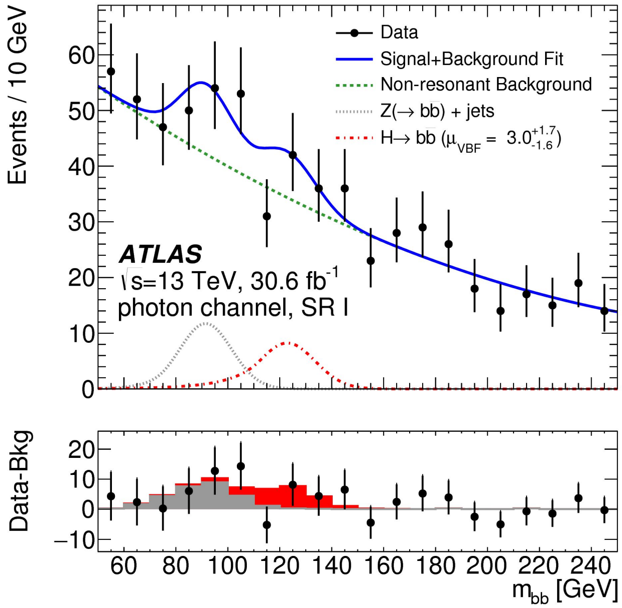


Larger Z→bb background

Mainly γ+jets background - gg-initiated diagrams suppressed

Trigger on γ+jets

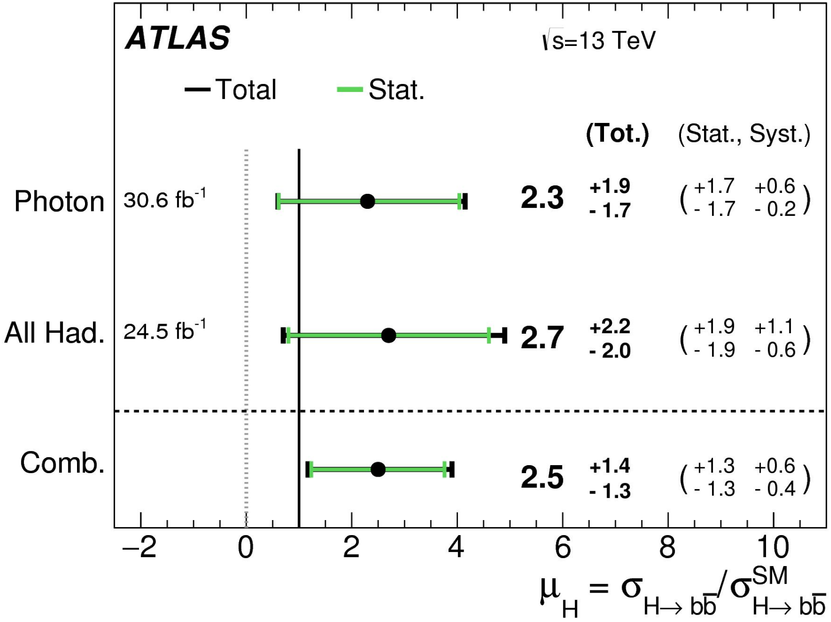




arXiv:1807.08639

History: VBF H→bb

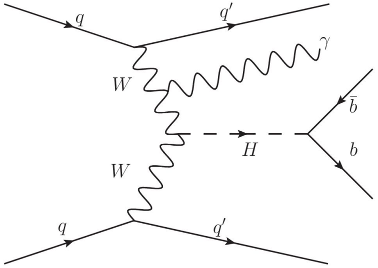
Results	Inclusive production		
	All-hadronic	*Photon*	Combined
Expected significance	0.5σ	0.6σ	0.8σ
Observed significance	1.4σ	1.3σ	1.9σ



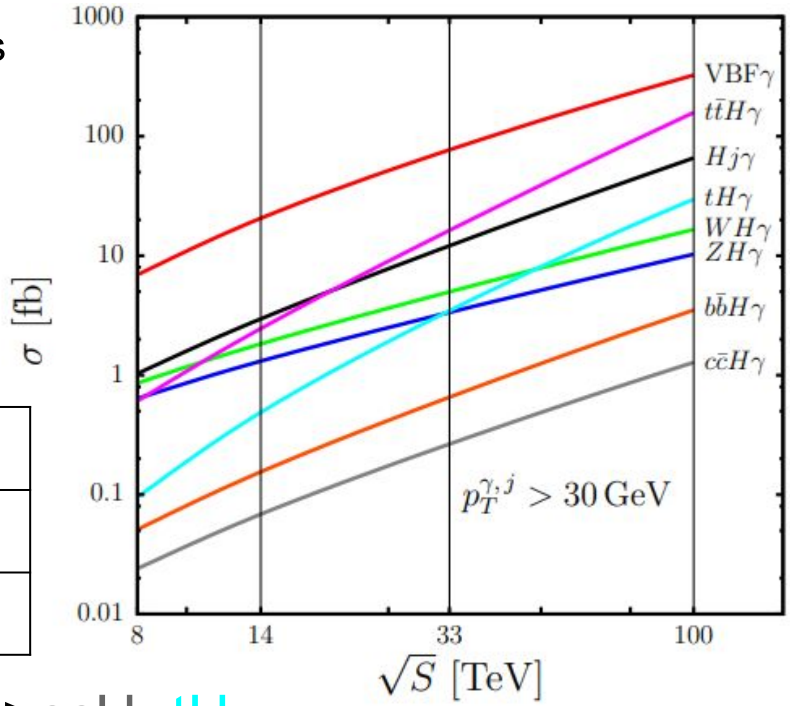
https://doi.org/10.1007/JHEP07(2016)003

VBF+ɣ

- ɣ decreases cross-section, but dramatically increases VBF yield relative to background
- ɣ from internal W: sizeable cross-section
- Enriched WW fusion compared to ZZ fusion



	Inclusive	+ɣ (LO, 30 GeV)
ggF	49 pb	3 fb
VBF	3.8 pb	19 fb



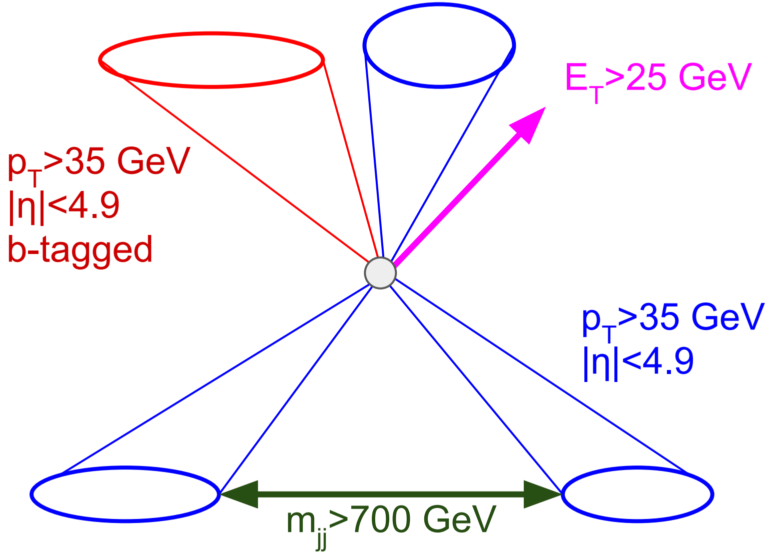
Without ɣ: ggF>>VBF>WH>ZH>ttH~bbH>>ccH~tH

With ɣ: VBF>>ggF>ttH>WH>ZH>tH>bbH>ccH
at 13 TeV

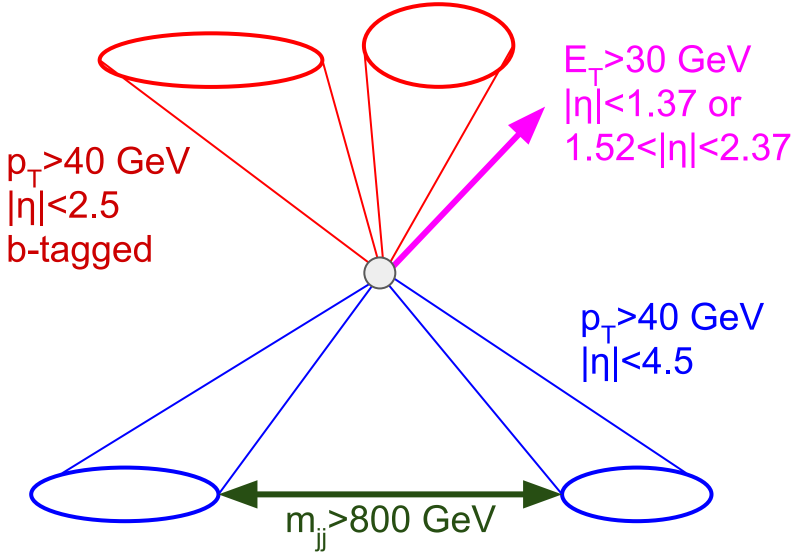
VBF+γ: Event Selection

arXiv:2010.13651

Trigger (HLT) Selection

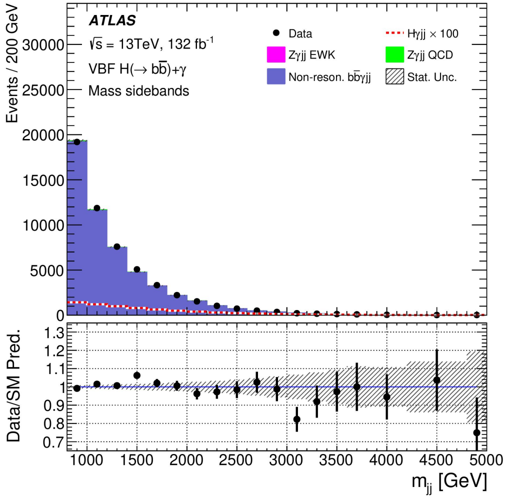


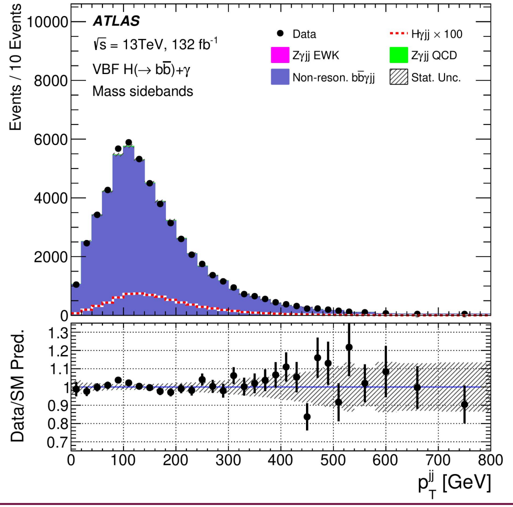
Offline Selection



arXiv:2010.13651

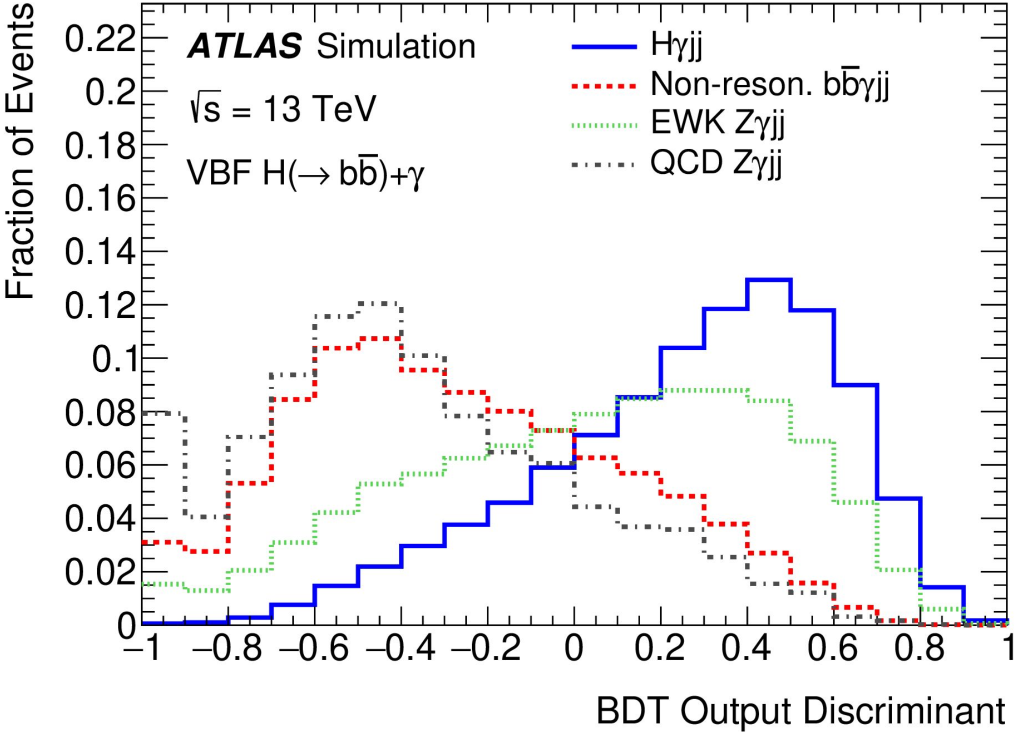
Categorization



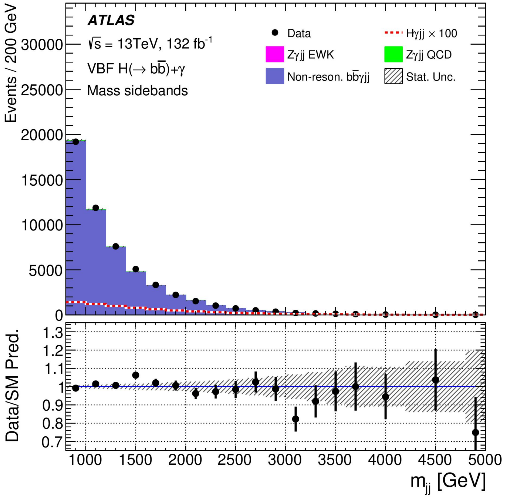


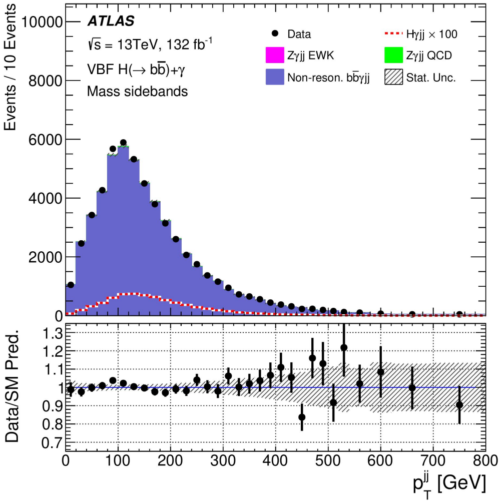
Train BDT to discriminate signal and background

Exclude variables m_{bb}-correlated, to avoid sculpting background



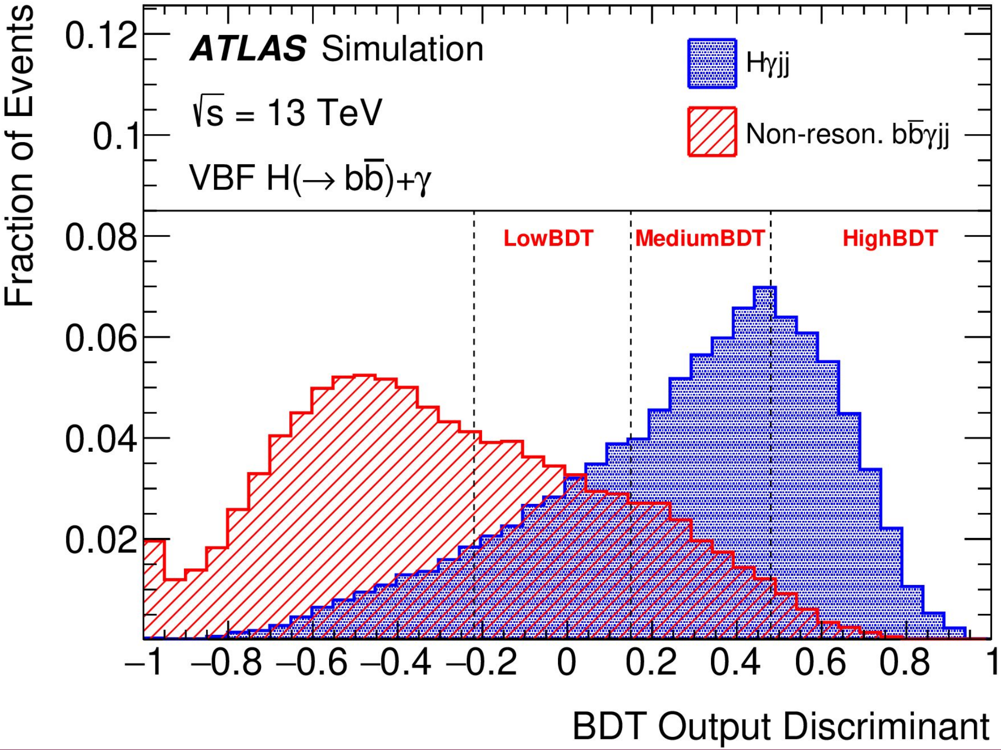
Categorization





Categorize based on score, maximizing combined significance

Fit m_{bb} distribution in each region



Model and Spurious Signal

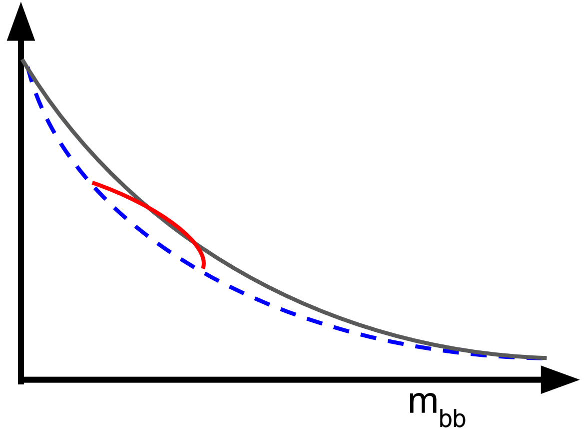
Fit data as sum of polynomial term (for non-resonant background) and peaks (Z and H)

1st order polynomial used in highest score region; 2nd order used in other regions

Primary systematic uncertainty is spurious signal - measures the potential inability of the background fit function to correctly fit the continuous background in data

Fit functions chosen to maximize sensitivity, subject to requirements on spurious signal uncertainties

Spurious signal estimated by fitting signal+background to large simulated background samples

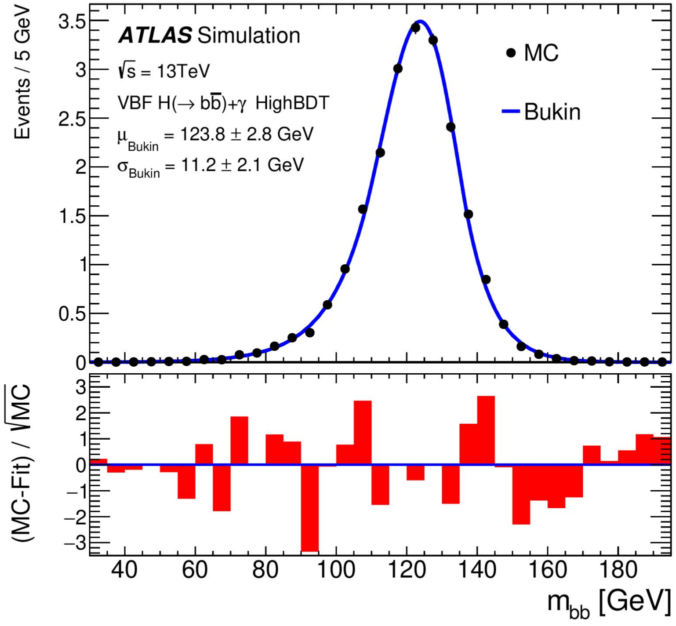


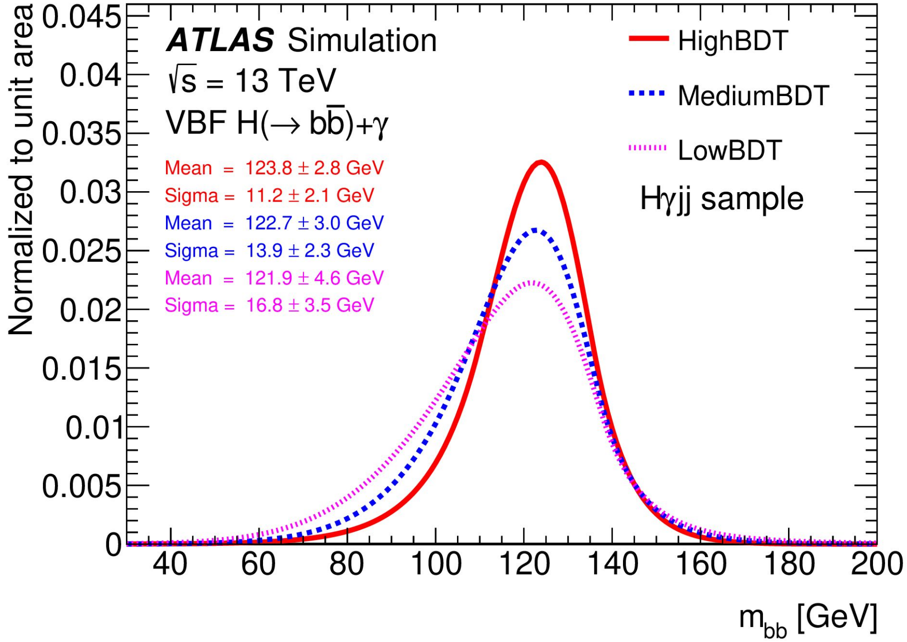
Signal and Fits

Uses b-jet energy corrections, derived in VH→bb

Signal fit of m_{bb} distribution

Parameterize Z and H with Bukin functions



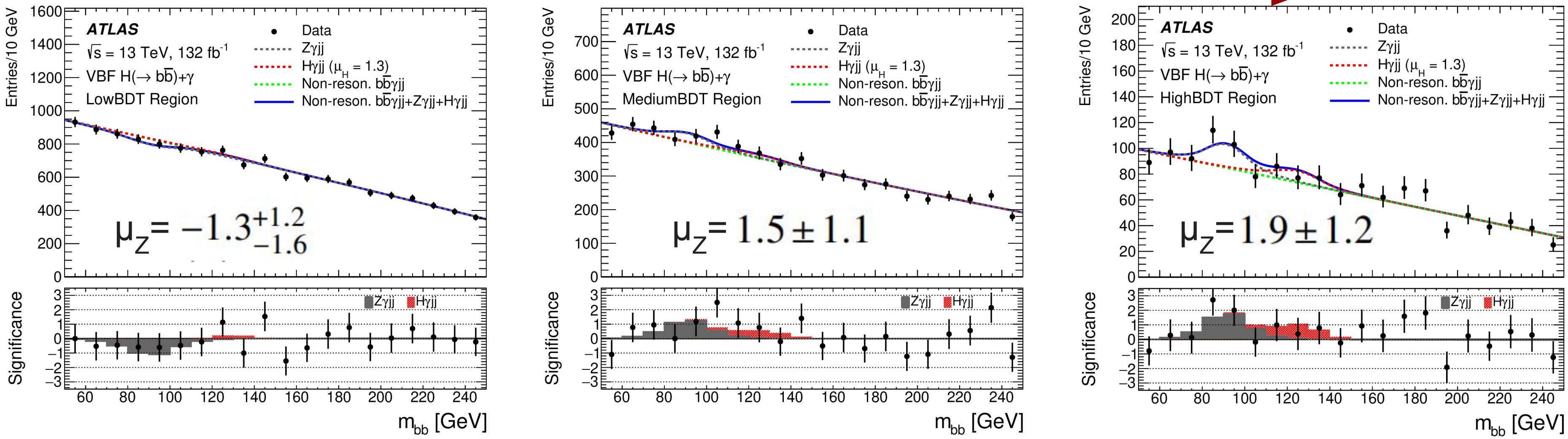


Signal+Background Fits

Signal+background fits in each region

Float both Z and H components' normalizations, uncorrelating Z yields between regions

Increasing score



Uncertainties

arXiv:2010.13651

Source of absolute uncertainty	$\sigma(\mu_H)$ down	$\sigma(\mu_H)$ up
Statistical		
Data statistical	−0.78	+0.80
Bkg. fit shapes	−0.19	+0.22
Bkg. fit normalizations	−0.51	+0.52
Z boson normalizations	−0.15	+0.14
Systematic		
Spurious signal	−0.24	+0.21
Theoretical	−0.01	+0.08
Photon	−0.01	+0.03
Jet	−0.06	+0.20
b-tagging	−0.02	+0.11
Auxiliary	−0.01	+0.04
Total	−0.99	+1.04
Total statistical	−0.96	+0.99
Total systematic	−0.25	+0.32

Statistical uncertainties dominant

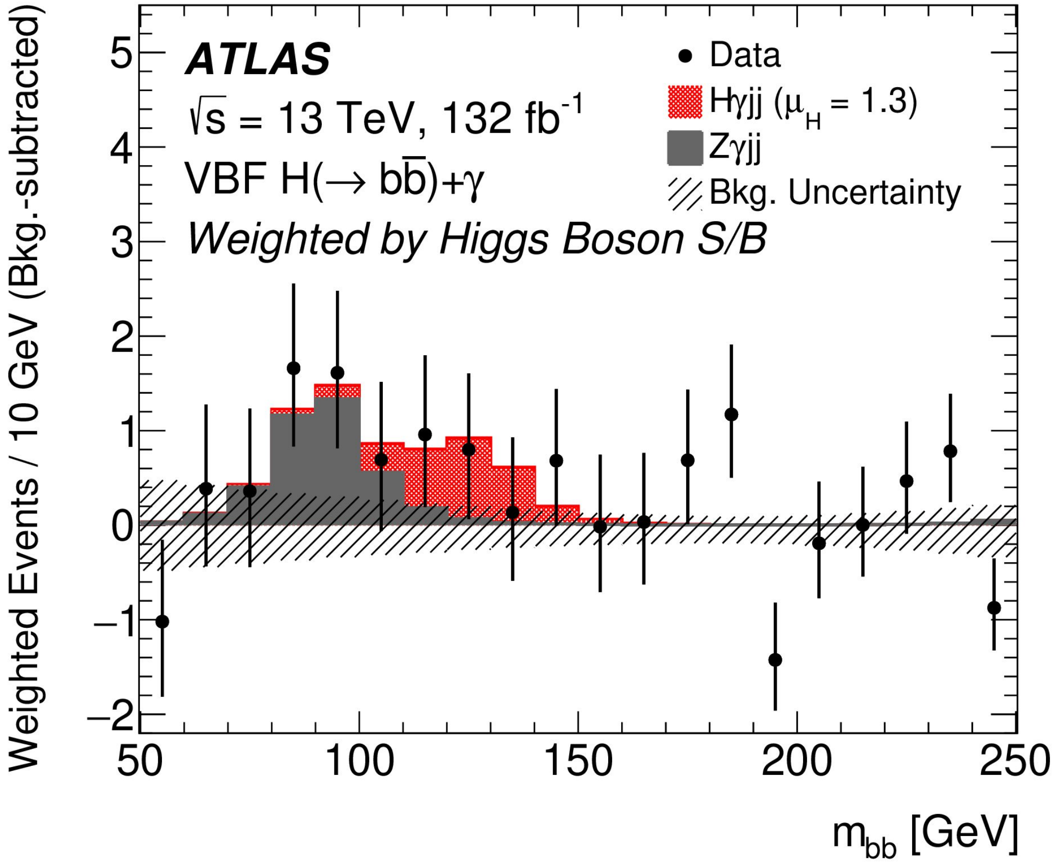
Systematics on multijet background

Signal uncertainties (theory + object)

Results

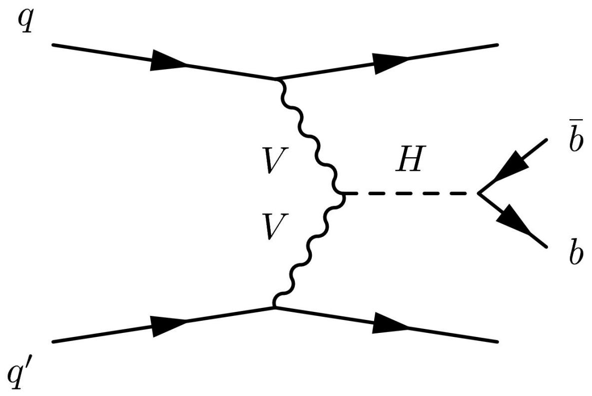
Observe (expect)

- 1.3σ (1.0σ)
- $\mu_{H\rightarrow bb}$= 1.3±1.0 (1.0±1.0)
- $\mu_{VBF\ H\rightarrow bb}$= 1.3±1.0 (1.0±1.0)



Fully Hadronic VBF H→bb

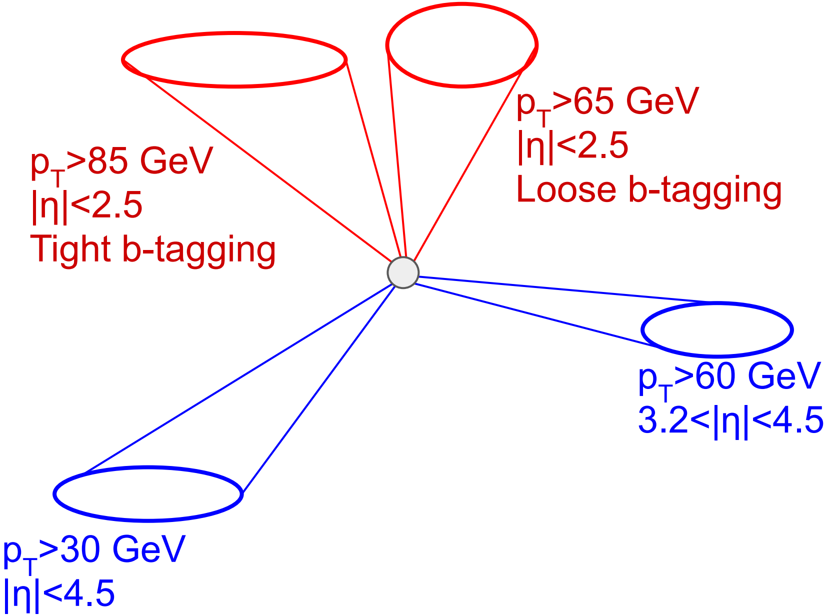
- Search for VBF H→bb in a fully hadronic final state
- MVA approach to categorize events
- Fit signal and background on m_{bb} distribution
- Analysis dramatically different from 2016 result, resulting in significant improvement to sensitivity (beyond improvement in statistics)
- Expected 0.5σ with 2016 data -
  extrapolating to Run 2 dataset, would expect 1.1σ



Analysis Channels and Selection

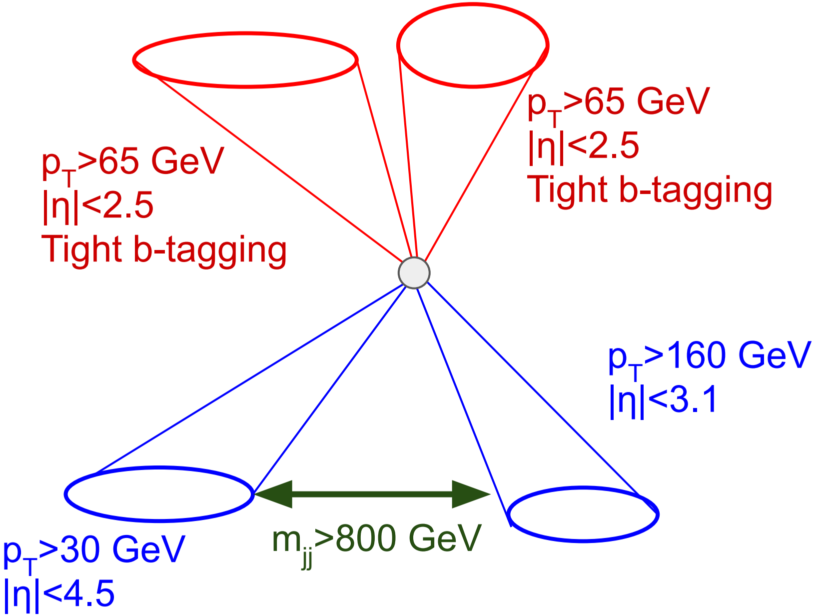
Forward Channel

Events contain a high p_T forward jet



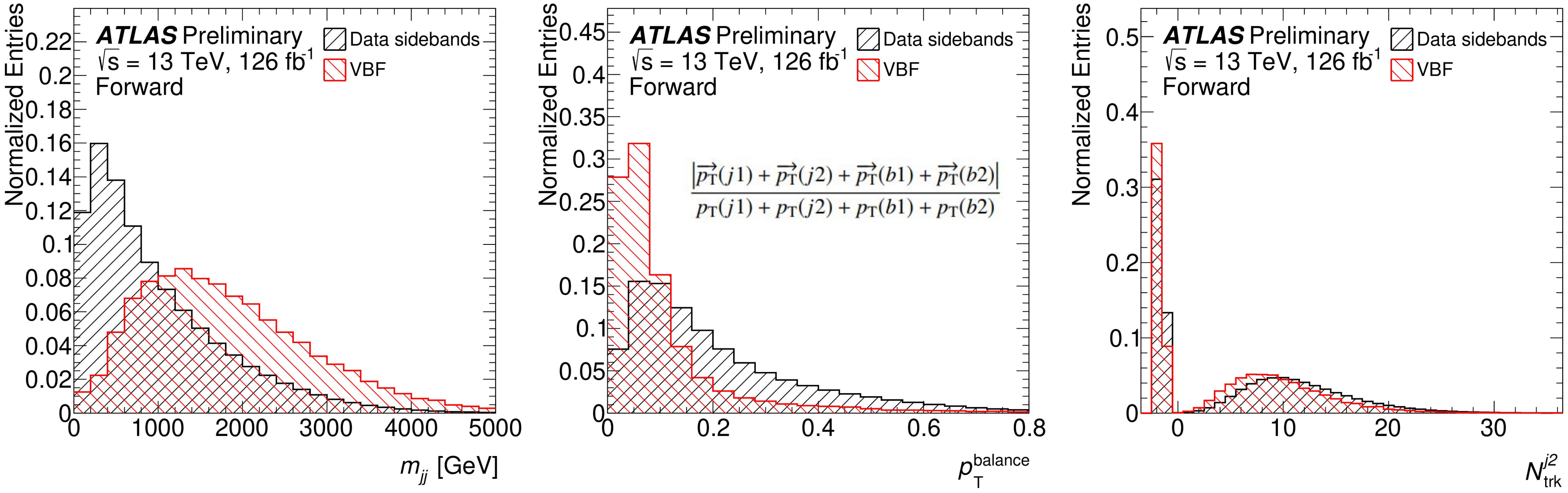
Central Channel

Events do not contain a high p_T forward jet



Signal/Background Discrimination

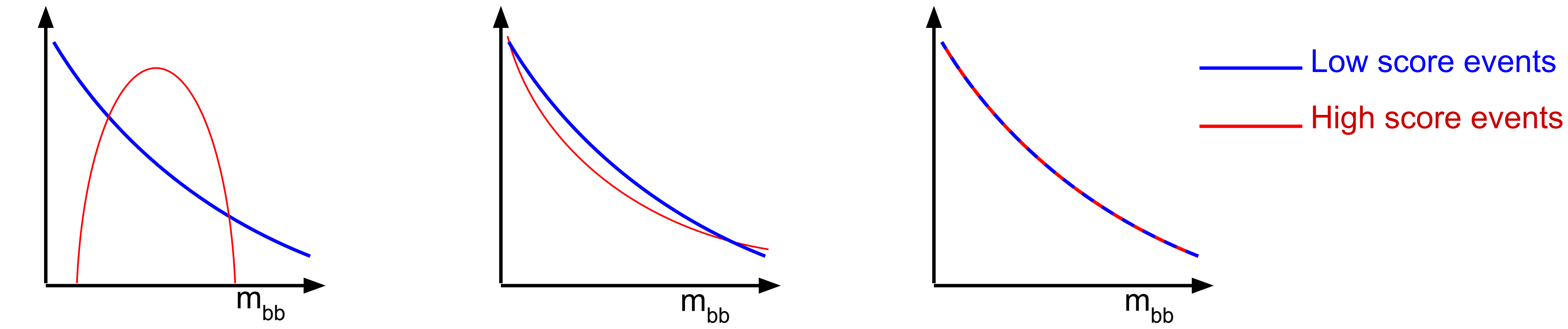
- MVA to categorize events, based on set of input kinematic variables
- Strongest discriminants based on angular separation of jets or on the presence of extra jets or soft emissions
- Extra discrimination comes from, for example, quark/gluon tagging



Adversarial Neural Network

- MVA variables chosen to be largely uncorrelated with m_{bb}
- Residual correlations still possible, particularly when combining variables in MVA
- Train an **adversarial neural network** in each channel, effectively adding a term to the loss function to explicitly penalize a network that correlates m_{bb} and score
- Training performed between signal and data sidebands

All variables | m_{bb}-independent variables | ANN with m_{bb}-independent variables



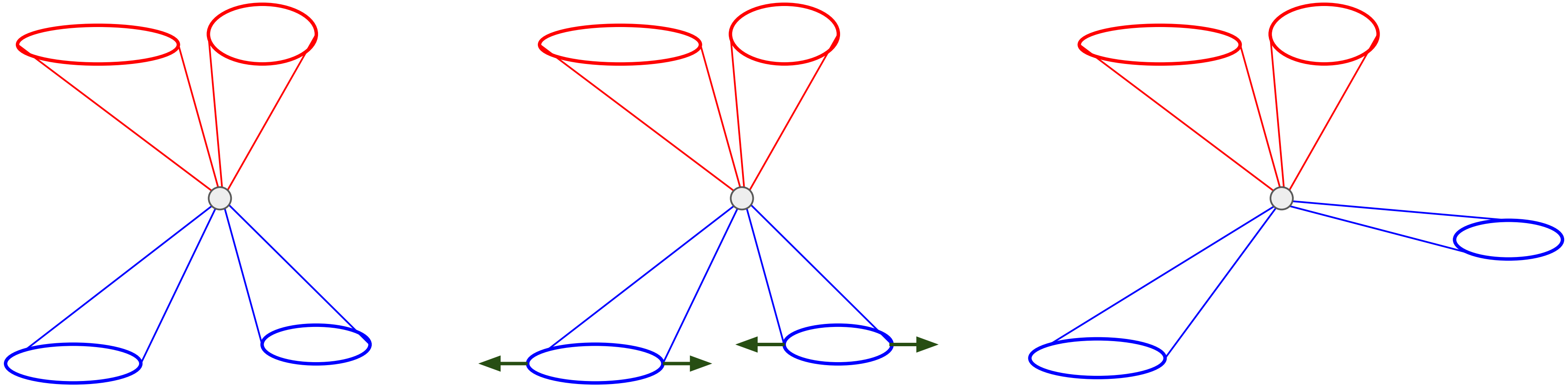
Background Uncertainties

Define CRs to measure any potential bias induced by excluding Higgs mass window

Select events with low m_{jj} and no forward jets

Smear VBF jet η to mimic SR kinematics

Reweight event-kinematics to remove residual SR-CR differences



Fit signal+background to CRs to measure maximum possible bias

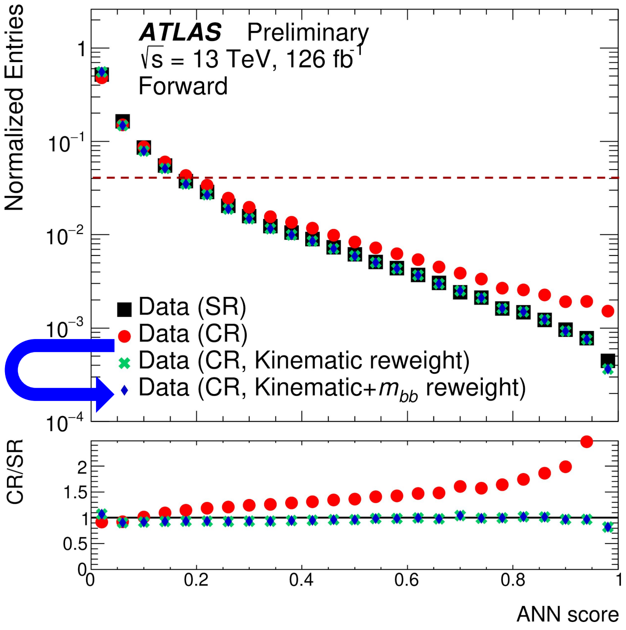
Classifier and CRs

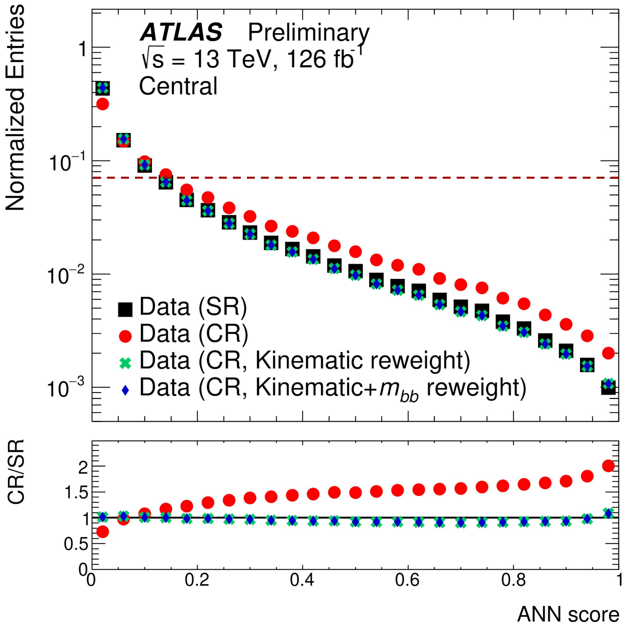
Score distributions shown in SR, for each ANN

Score distribution shown for CR, before kinematic CR→SR reweighting, after reweighting (except m_{bb}), and after reweighting m_{bb}

VBF distribution flat from 0 to 1(at 0.04 in these figures)

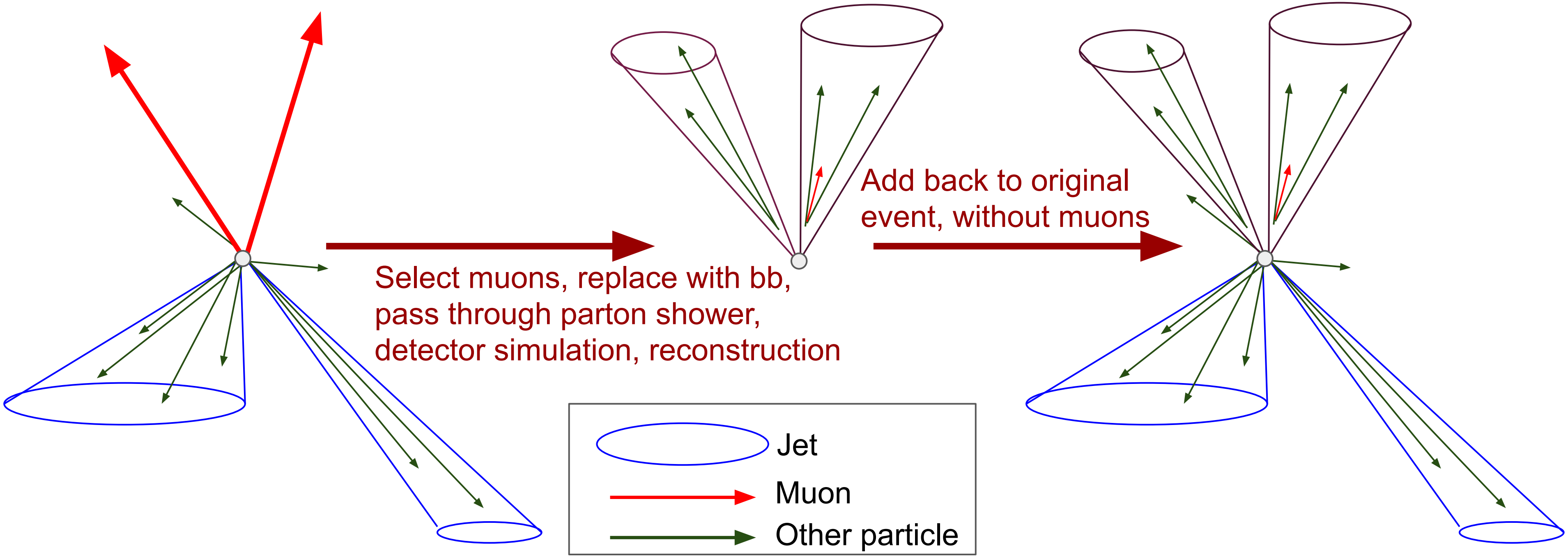
Reweight variables in CR to match SR





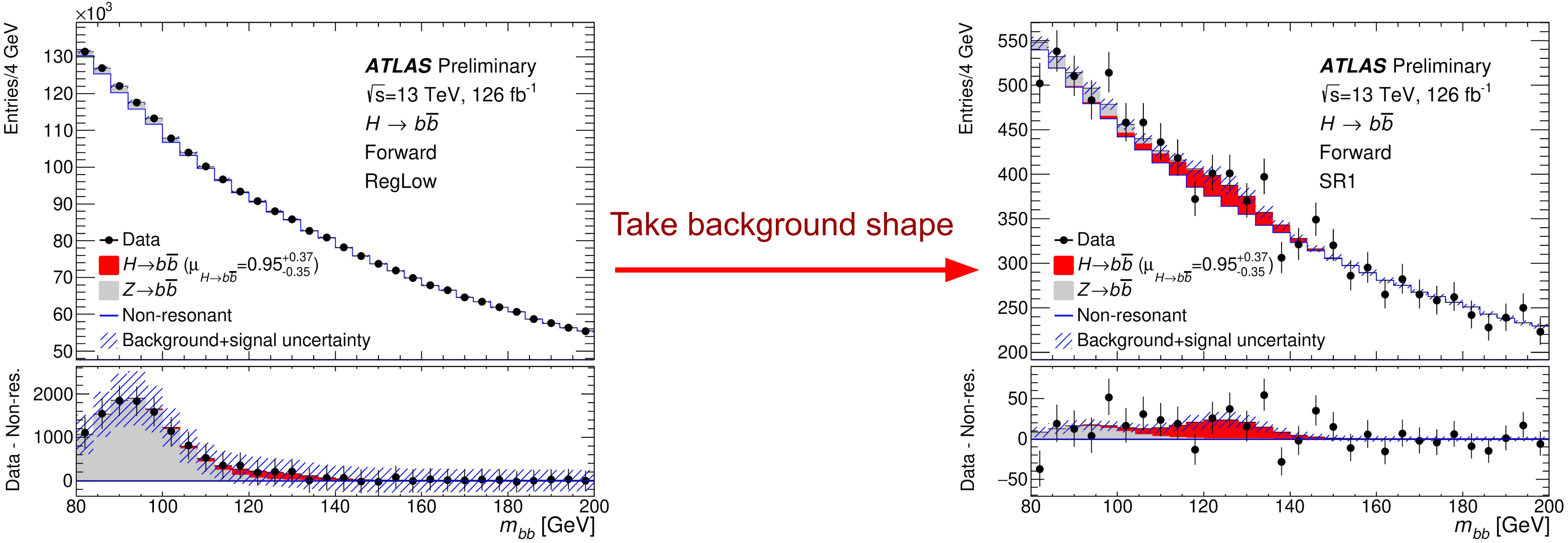
Z→bb Background

- Potentially significant mismodeling and systematic uncertainties
- Due to trigger limitations, cannot constrain Z in fits
  →Data-driven approach: estimate Z→bb from Z→μμ (embedding)



Fits (Forward Channel)

- Fit 4 high score regions + one low score region in each channel (10 regions total)
- Score and m_{bb} uncorrelated → constrain background template in high score signal regions using high-statistic low score control region



Uncertainties

Uncertainty	$\sigma(\mu_{H\to bb})$
Statistical	±0.31
Background shape	±0.15
Resonant background	±0.05
Theory	+0.06, -0.03
Object	+0.10, -0.05

Statistical uncertainties dominate

Uncertainties from CRs

Uncertainties from data-driven $Z\to bb$ estimate

Theory uncertainties, signal only

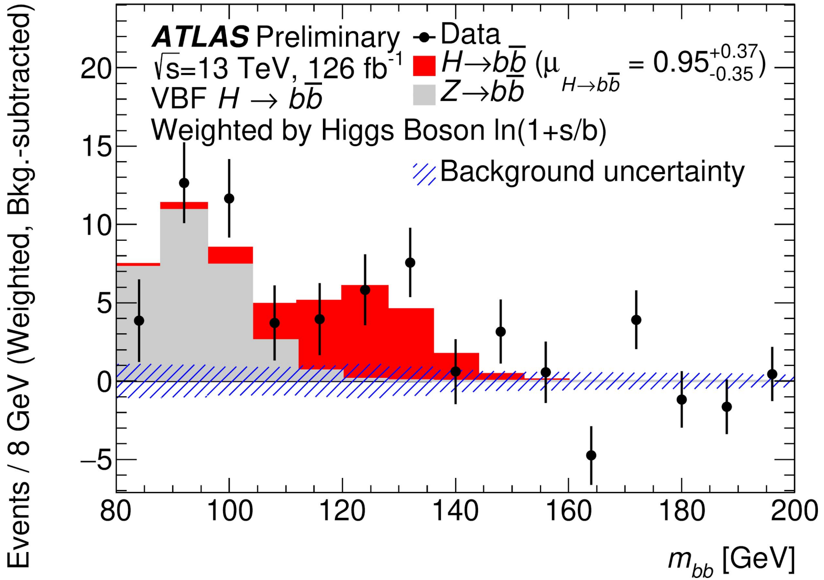
Other uncertainties, signal only
(trigger, jet energy, b-tagging, etc.)

CERN-EP-2020-195

Results

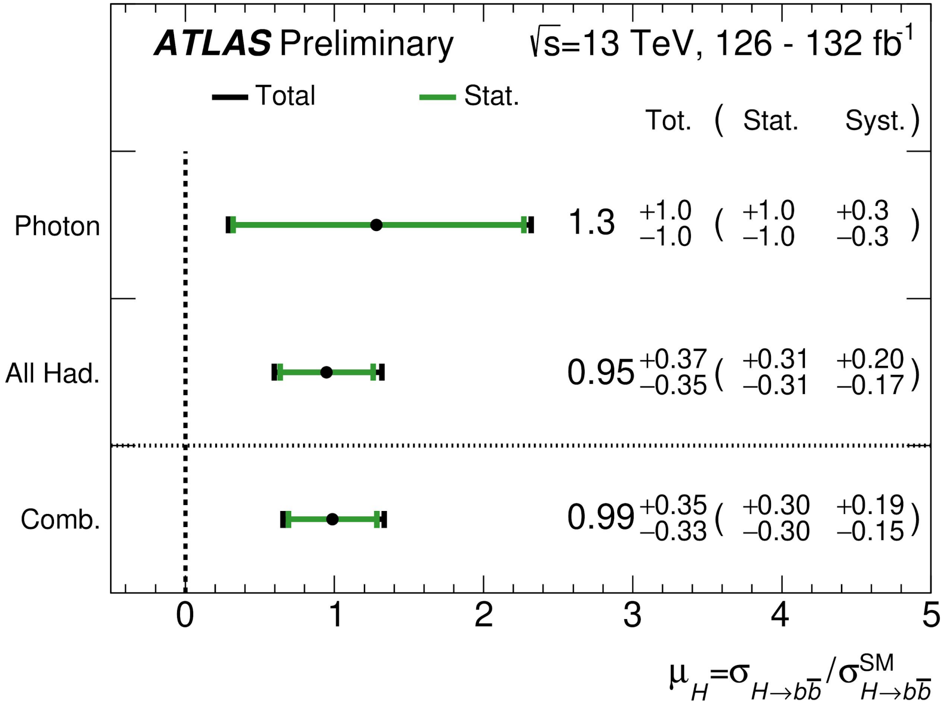
Observe (expect):

Inclusive H→bb production	2.7σ (2.9σ)	$\mu = 0.95^{+0.37}_{-0.35}\ (1.00^{+0.37}_{-0.36})$
VBF H→bb production	2.6σ (2.8σ)	$\mu = 0.95^{+0.38}_{-0.36}\ (1.00^{+0.38}_{-0.37})$
Inclusive H→bb production for p_T^H > 200 GeV	2.2σ (2.3σ)	$\mu = 0.93^{+0.45}_{-0.43}\ (1.00^{+0.45}_{-0.43})$



Combination

- Combination of all-hadronic VBF H→bb and VBF H+γ results
- Statistical uncertainties dominant
- Observe (expect) 3.0σ (3.0σ) for H→bb production and 2.9σ (2.9σ) for VBF H→bb



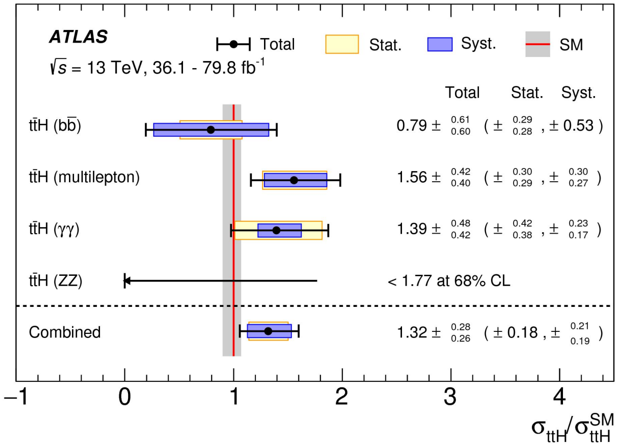
ttH: History

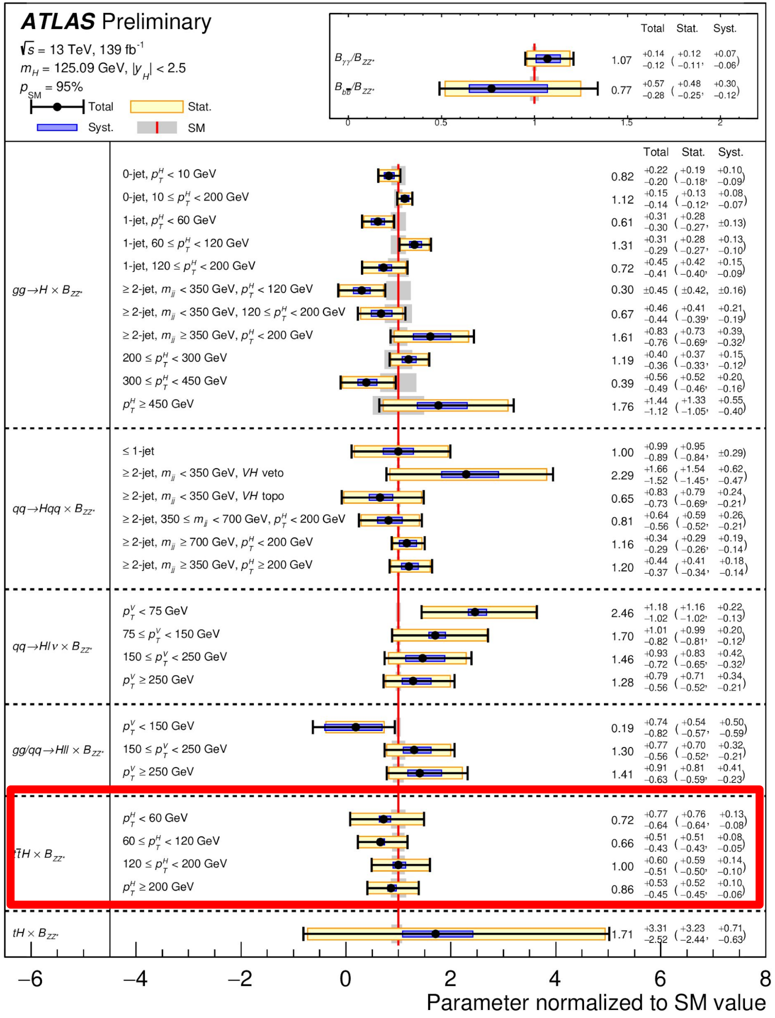
ttH is sensitive to many BSM effects, but precise measurement is difficult due to small cross-section (0.5 pb)

ttH observed by CMS and ATLAS with 2015-2016 or 2015-2017 data, combining ttH(bb), ttH(γγ), ttH(4l), and ttH(multilepton)

Updated measurements include full Run 2 dataset for ttH(γγ)

Low ttH(γγ) statistics at high p_T^H→make high p_T^H measurements with ttH(bb)





[arXiv:1806.00425]

[ATLAS-CONF-2020-027]

ttH→bb

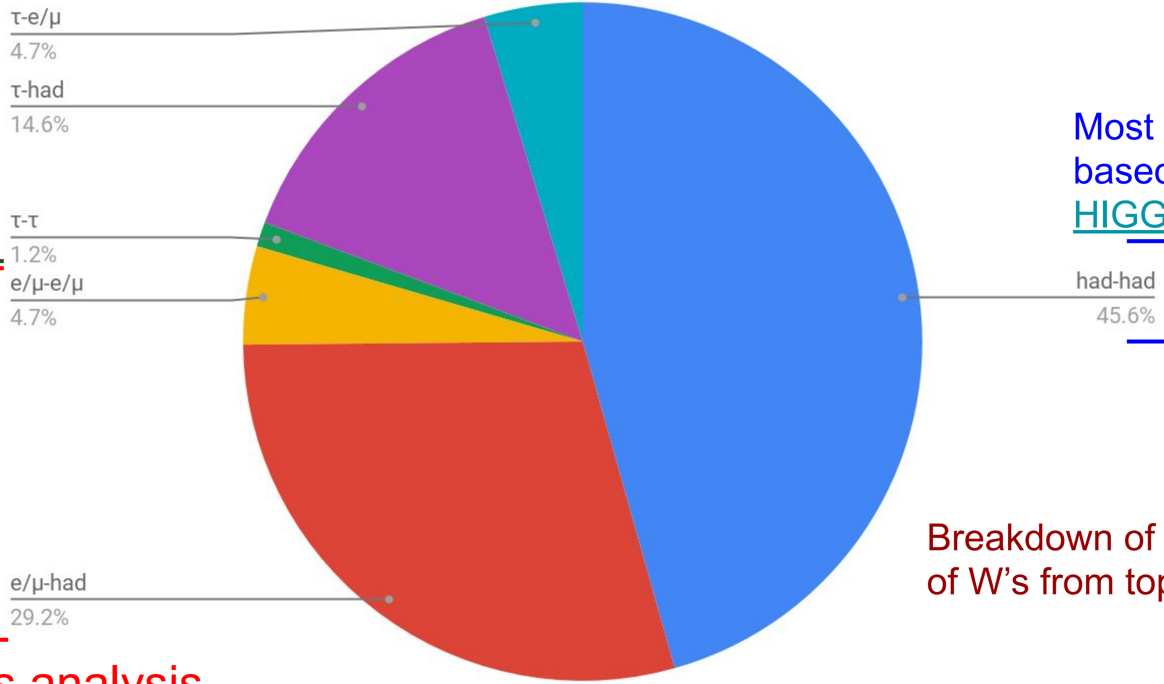
Events categorized based on lepton multiplicity into 1-lepton and 2-lepton channels

Hadronic τ decays not included, for orthogonality with other channels

2-lepton channel

1-lepton channel

Included in this analysis



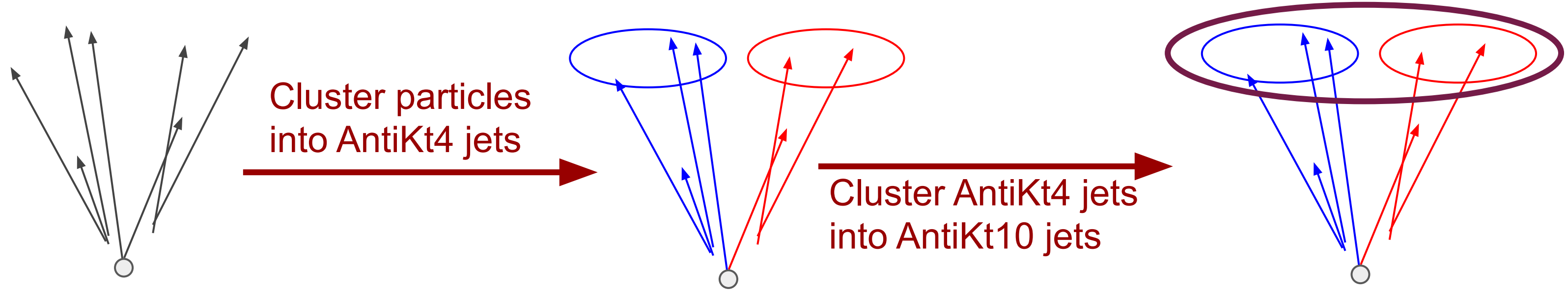
Most recent result, based on Run 1 data [HIGG-2015-05]

Breakdown of branching fractions of W's from top decays

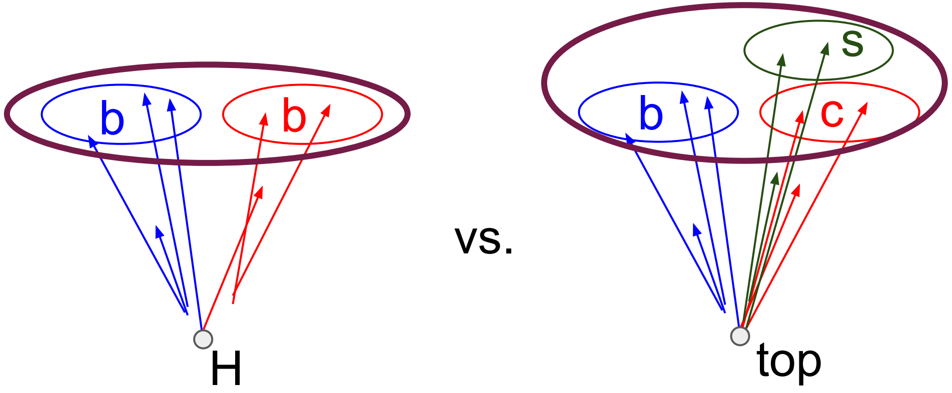
Boosted vs. Resolved Channels

ttH→bb 1-lepton channel split into boosted and resolved channels

Remove events from resolved channel that contain large-R jet passing selection



DNN to discriminate H→bb from tt or other backgrounds:



Largely relies on b-tagging and mass information

ATLAS-CONF-2020-058

ATLAS-CONF-2020-058

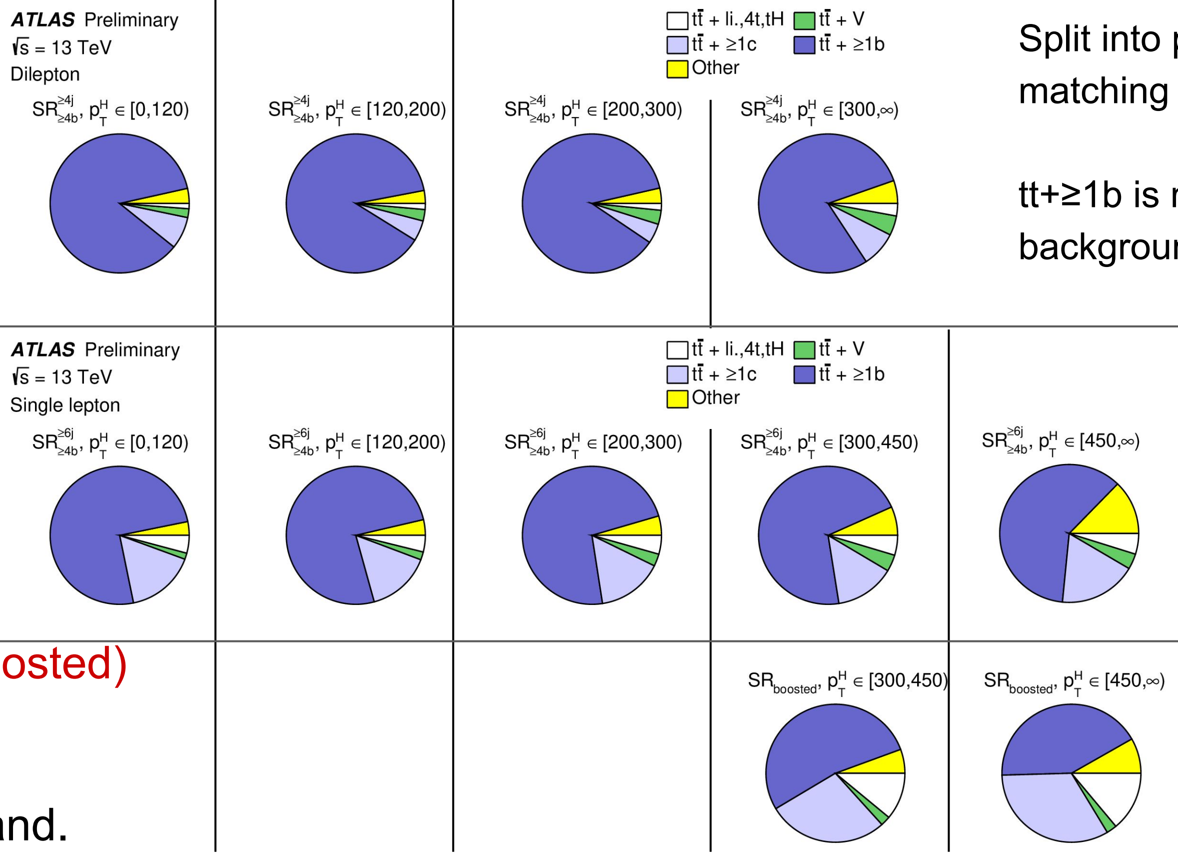
Regions and Backgrounds

0-120 GeV | 120-200 GeV | 200-300 GeV | 300-(450 GeV) | 450- GeV

2-lepton
≥4 b-jets
≥4 jets

1-lepton (resolved)
≥4 b-jets
≥6 jets

1-lepton (boosted)
≥2 b-jets
≥4 jets
≥boosted cand.

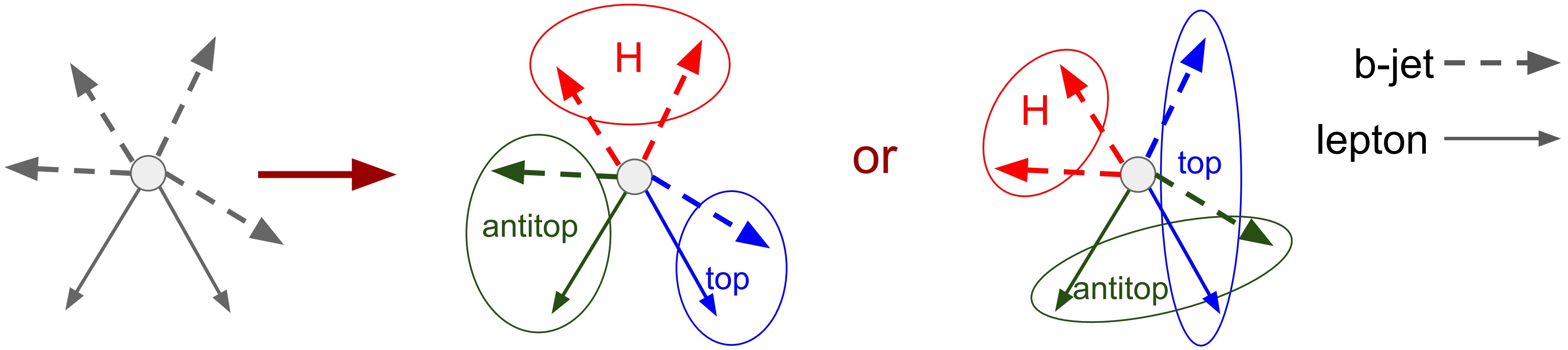


Split into pTH bins, matching STXS pTH bins

tt+≥1b is main background in all regions

BDTs

Reconstruction BDTs: In non-boosted channels, group jets, leptons, and E_T^{miss} into H, W, top, and antitop candidates to calculate input variables and p_T^{bb}



Classification BDTs: discriminate signal from background, using as input kinematic properties of input objects, as well as reconstruction BDTs

Classification BDTs used in signal+background fits in signal regions

Background Estimate Overview

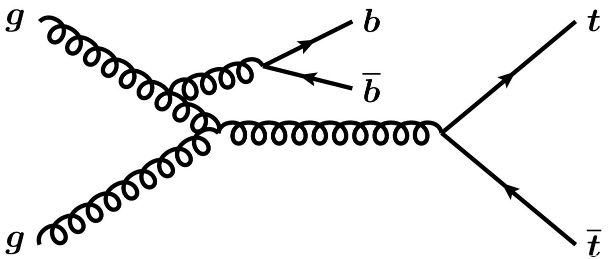
tt+light jets is small, due to tightened and simplified b-jet requirements

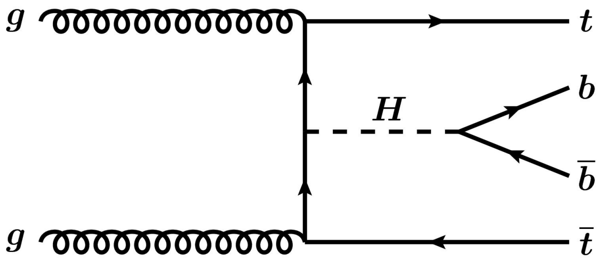
→little overall impact from modeling uncertainties

tt+≥1b largest background in all regions

New: ttbb Powheg+Pythia8 4FS used in analysis as nominal tt+≥1b estimate

Define CRs to constrain tt+≥1b and tt+≥1c





Rely on presence of fewer b-tagged jets in tt+≥1c and lower jet multiplicity (above p_T thresholds) in tt+jets than ttH

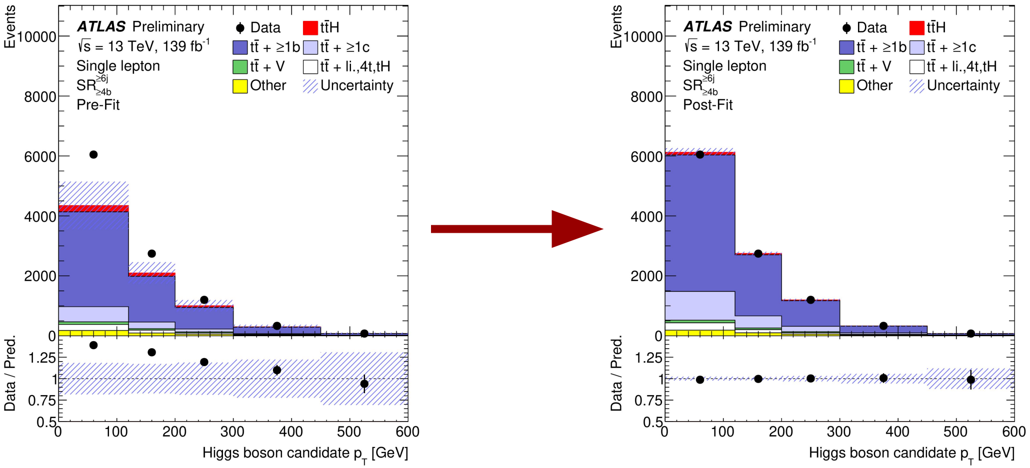
Background Modeling

- Extra parameters to account for potential mis-modeling in analysis phase space
- Dominant background normalization k(tt+≥1b) is floated in fit (but not tt+≥1c)
- Other notable changes compared to 2016 analysis
  - 2-point systematic 4FS-vs-5FS removed from the analysis model
  - Effective statistics of alternative simulated samples dramatically increased

Uncertainty source	Description		Components
$t\bar{t}$ cross-section	$\pm 6\%$		$t\bar{t}$ + light
$t\bar{t} + \geq 1b$ normalisation	Free-floating		$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1c$ normalisation	$\pm 100\%$		$t\bar{t} + \geq 1c$
NLO matching	MadGraph5_aMC@NLO+Pythia8 vs. PowhegBox+Pythia8		All
PS & hadronisation	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		All
ISR	Varying α_S^{ISR} (PS), μ_{R}&μ_{F} (ME)	in PowhegBoxRes+Pythia8	$t\bar{t} + \geq 1b$
		in PowhegBox+Pythia8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
FSR	Varying α_S^{FSR} (PS)	in PowhegBoxRes+Pythia8	$t\bar{t} + \geq 1b$
		in PowhegBox+Pythia8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
$t\bar{t} + \geq 1b$ fractions	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		$t\bar{t} + 1b/1B$, $t\bar{t} + \geq 2b$
p_{T}^{bb} shape	Shape mismodelling measured from data		$t\bar{t} + \geq 1b$

Background Modeling: p_T^{bb}

Shape parameter introduced to account for potential shape differences between data and MC

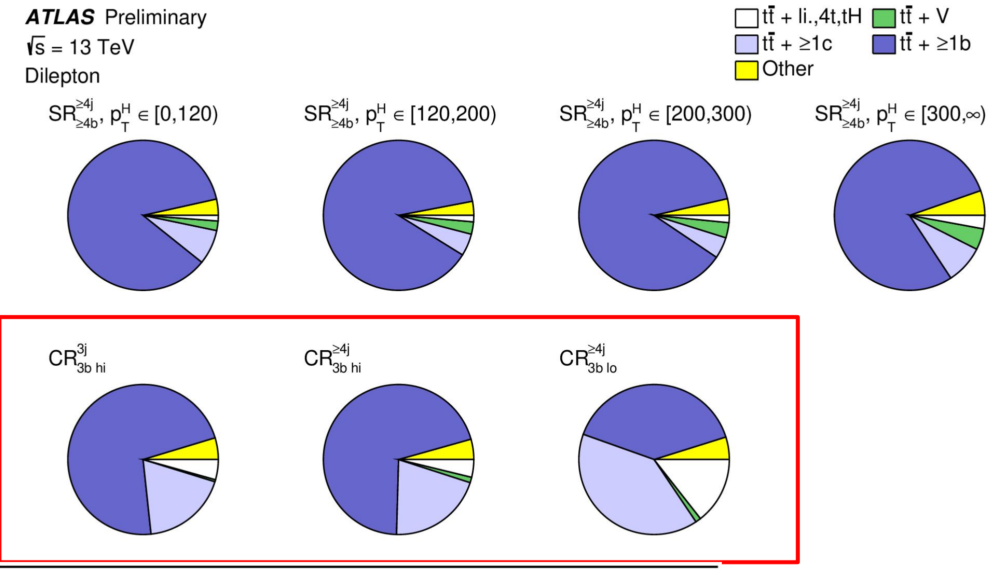


Uncertainty source	Description		Components
$t\bar{t}$ cross-section	$\pm 6\%$		$t\bar{t}$ + light
$t\bar{t} + \geq 1b$ normalisation	Free-floating		$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1c$ normalisation	$\pm 100\%$		$t\bar{t} + \geq 1c$
NLO matching	MadGraph5_aMC@NLO+Pythia8 vs. PowhegBox+Pythia8		All
PS & hadronisation	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		All
ISR	Varying α_S^{ISR} (PS), $\mu_{\mathrm{R}} \& \mu_{\mathrm{F}}$ (ME)	in PowhegBoxRes+Pythia8	$t\bar{t} + \geq 1b$
		in PowhegBox+Pythia8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
FSR	Varying α_S^{FSR} (PS)	in PowhegBoxRes+Pythia8	$t\bar{t} + \geq 1b$
		in PowhegBox+Pythia8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
$t\bar{t} + \geq 1b$ fractions	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		$t\bar{t} + 1b/1B$, $t\bar{t} + \geq 2b$
p_{T}^{bb} shape	Shape mismodelling measured from data		$t\bar{t} + \geq 1b$

Background Modeling: Dilepton

Dilepton CRs with loosened b-tagging and also including 3j events

Constrain relative normalization of each tt background

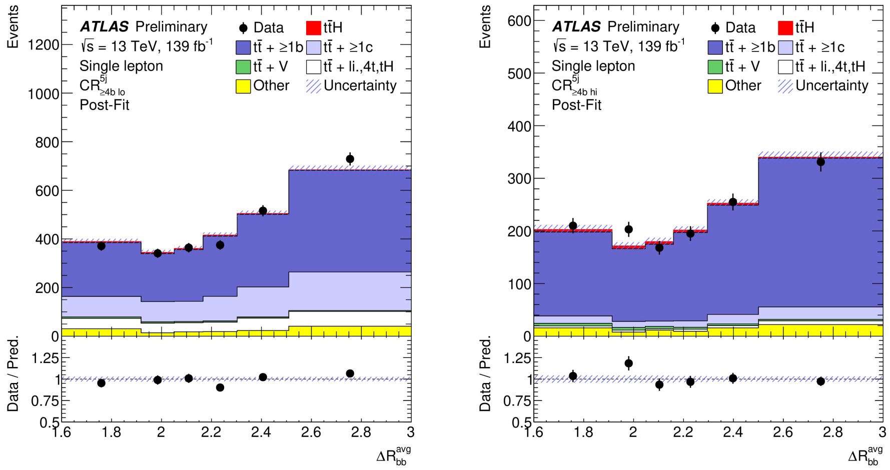


Uncertainty source	Description		Components
$t\bar{t}$ cross-section	±6%		$t\bar{t}$ + light
$t\bar{t} + \geq 1b$ normalisation	Free-floating		$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1c$ normalisation	±100%		$t\bar{t} + \geq 1c$
NLO matching	MadGraph5_aMC@NLO+Pythia8 vs. PowhegBox+Pythia8		All
PS & hadronisation	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		All
ISR	Varying α_S^{ISR} (PS), μ_R&μ_F (ME)	in PowhegBoxRes+Pythia8	$t\bar{t} + \geq 1b$
		in PowhegBox+Pythia8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
FSR	Varying α_S^{FSR} (PS)	in PowhegBoxRes+Pythia8	$t\bar{t} + \geq 1b$
		in PowhegBox+Pythia8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
$t\bar{t} + \geq 1b$ fractions	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		$t\bar{t} + 1b/1B$, $t\bar{t} + \geq 2b$
p_T^{bb} shape	Shape mismodelling measured from data		$t\bar{t} + \geq 1b$

Background Modeling: Single Lepton

Single lepton CRs with low n-jets

Constrain kinematic variable shape and constrain relative normalization of each tt background

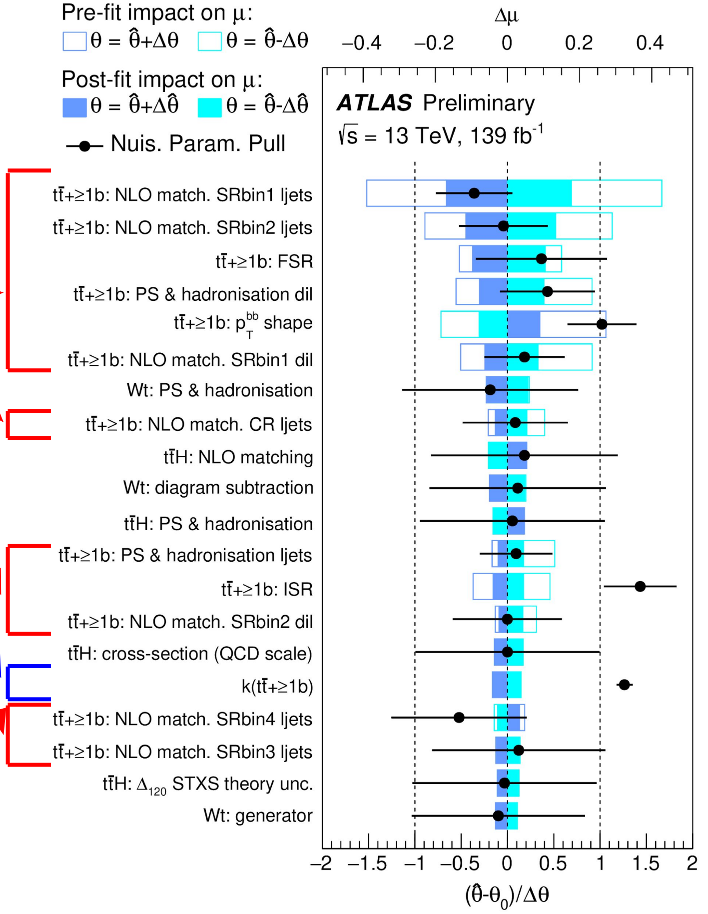


Uncertainty source	Description		Components
$t\bar{t}$ cross-section	$\pm 6\%$		$t\bar{t}$ + light
$t\bar{t} + \geq 1b$ normalisation	Free-floating		$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1c$ normalisation	$\pm 100\%$		$t\bar{t} + \geq 1c$
NLO matching	MadGraph5_aMC@NLO+Pythia8 vs. PowhegBox+Pythia8		All
PS & hadronisation	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		All
ISR	Varying α_S^{ISR} (PS), μ_{R}&μ_{F} (ME)	in PowhegBoxRes+Pythia8	$t\bar{t} + \geq 1b$
		in PowhegBox+Pythia8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
FSR	Varying α_S^{FSR} (PS)	in PowhegBoxRes+Pythia8	$t\bar{t} + \geq 1b$
		in PowhegBox+Pythia8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
$t\bar{t} + \geq 1b$ fractions	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		$t\bar{t} + 1b/1B$, $t\bar{t} + \geq 2b$
p_{T}^{bb} shape	Shape mismodelling measured from data		$t\bar{t} + \geq 1b$

ATLAS-CONF-2020-058

Uncertainty Breakdown

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.25	−0.24
Total systematic uncertainty	+0.30	−0.27
$t\bar{t}+\geq 1b$ normalisation	+0.03	−0.05
Total statistical uncertainty	+0.20	−0.19
Total uncertainty	+0.36	−0.33



Dominant uncertainties relate to tt+≥1b modeling

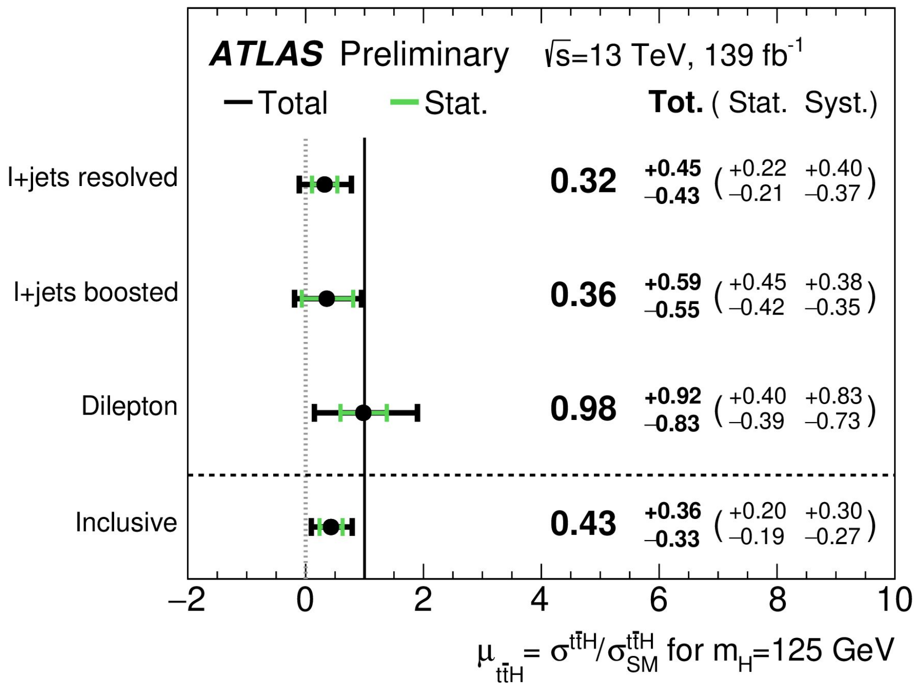
k(tt+≥1b) has deviation from the expectation ($1.25^{+0.09}_{-0.08}$)

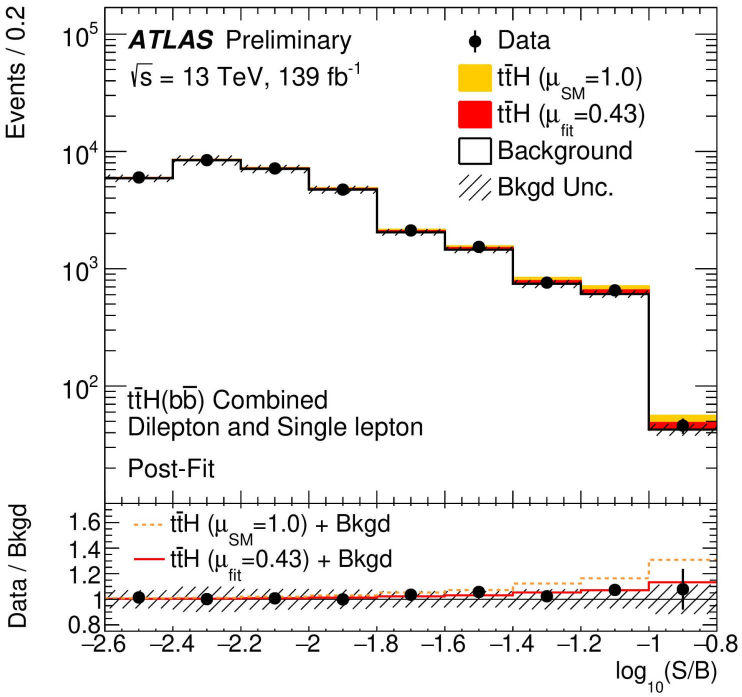
Better understanding of tt+≥1b processes will be key to further improvements of this measurement

Total Signal Strength

Inclusive measurement of ttH signal-strength:

$$\mu = 0.43^{+0.20}_{-0.19}\,(\text{stat.})\,^{+0.30}_{-0.27}\,(\text{syst.}) = 0.43^{+0.36}_{-0.33}$$

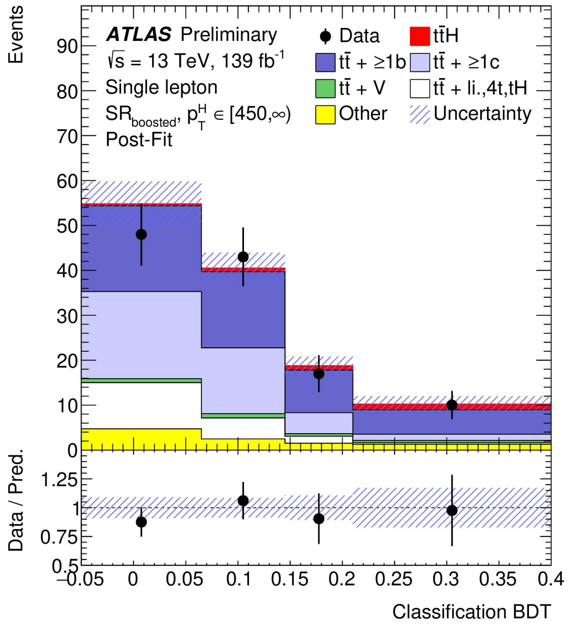


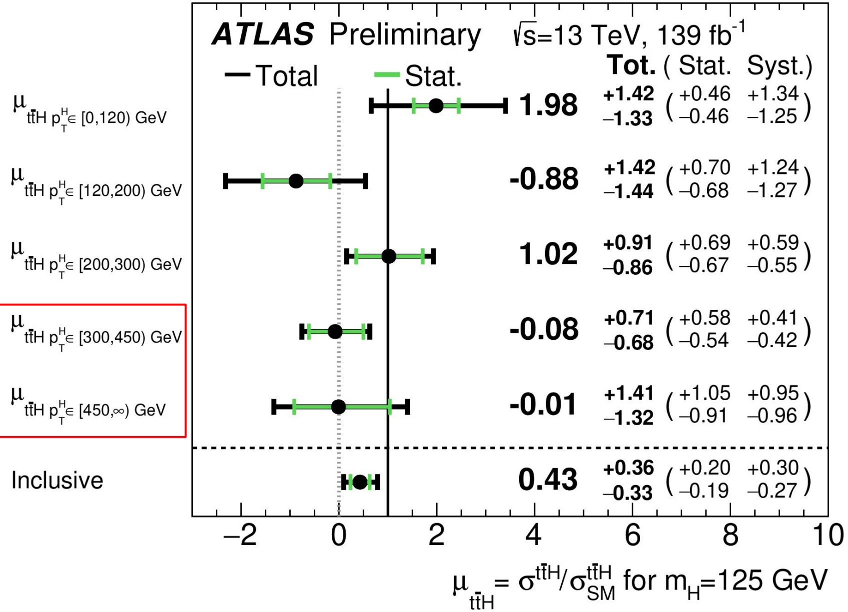


ATLAS-CONF-2020-058

Results for p_T^H Measurement

Highest ttH p_T^H constraint ever with ATLAS!





ATLAS-CONF-2020-052

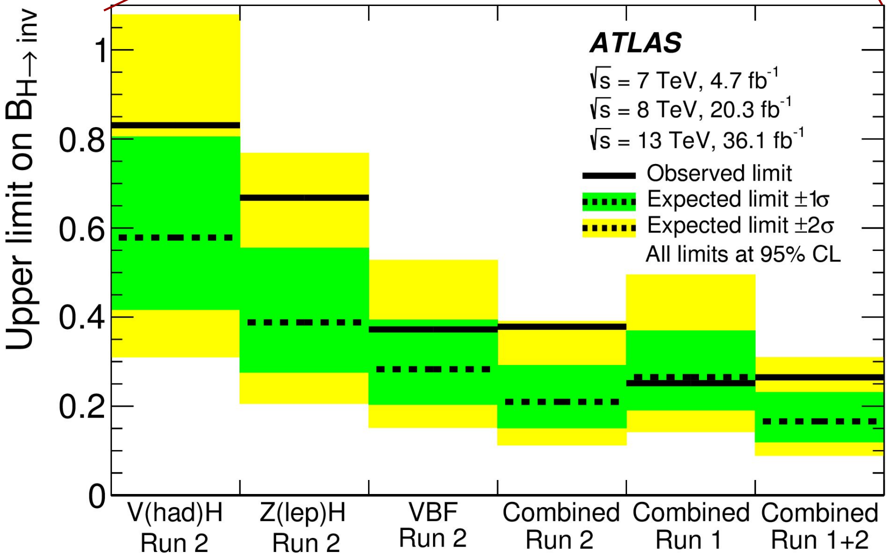
H→Invisible: History

Run 1
VBF, Z(lep)H, V(had)H
$\mathcal{B}_{H\to\text{inv}} < 0.25\ (0.27^{+0.10}_{-0.08})$

Run 1 + 2015-2016
VBF, Z(lep)H, V(had)H
$\mathcal{B}_{H\to\text{inv}} < 0.26\ (0.17^{+0.07}_{-0.05})$

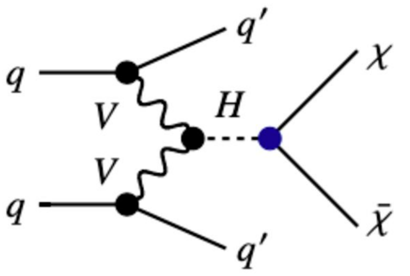
Run 1 + Run 2
Run 1: VBF, Z(lep)H, V(had)H
Run 2: VBF, ttH

New result

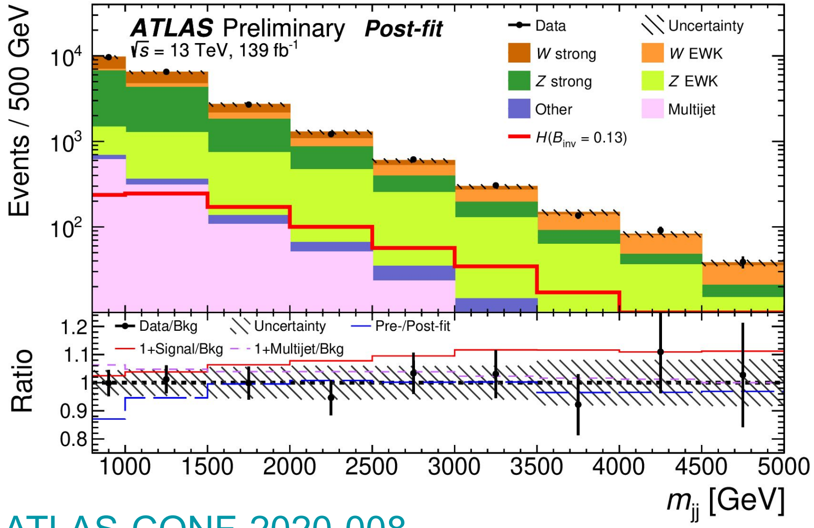


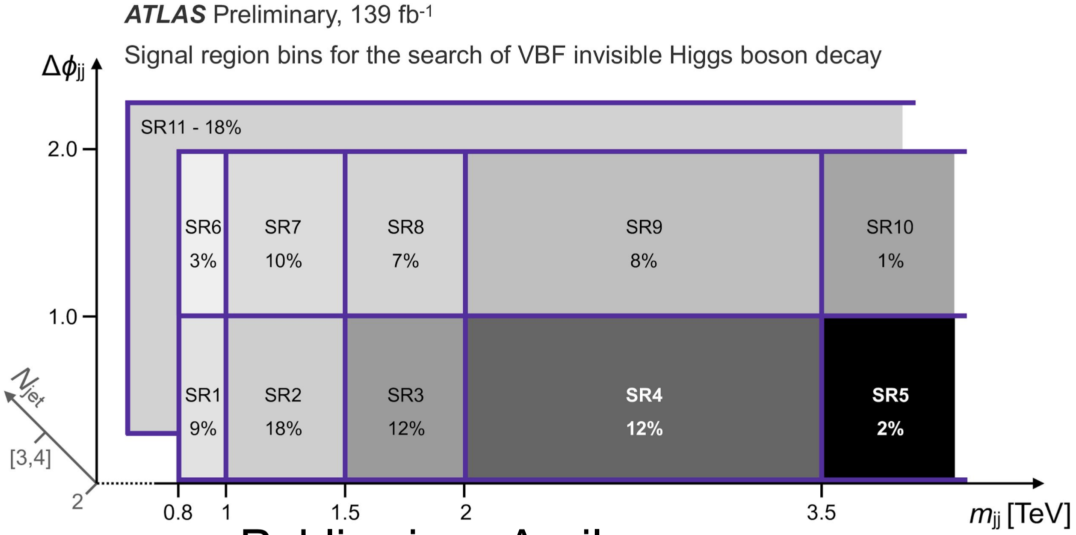
VBF H→Invisible

Require high E_T^{miss}, with VBF-like topology



Divide events into SRs based on m_{jj} and $\Delta\phi$, with CRs to constrain normalization

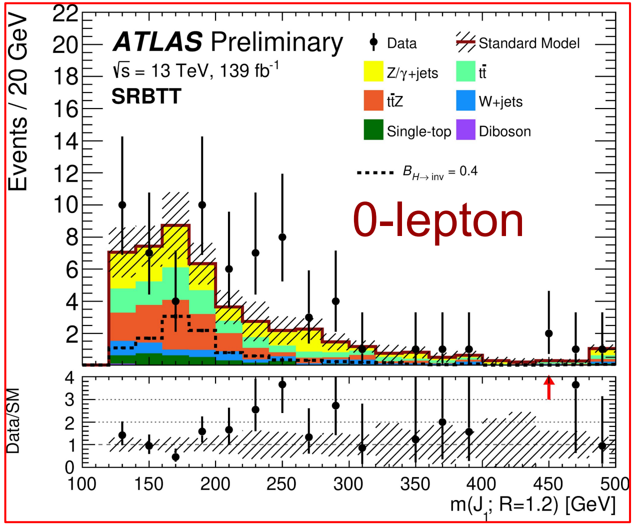


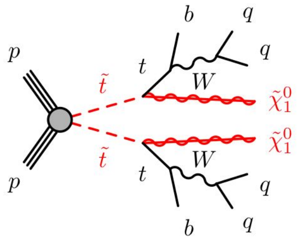


[ATLAS-CONF-2020-008]

Public since April, discussed in [seminar]

ttH→Invisible

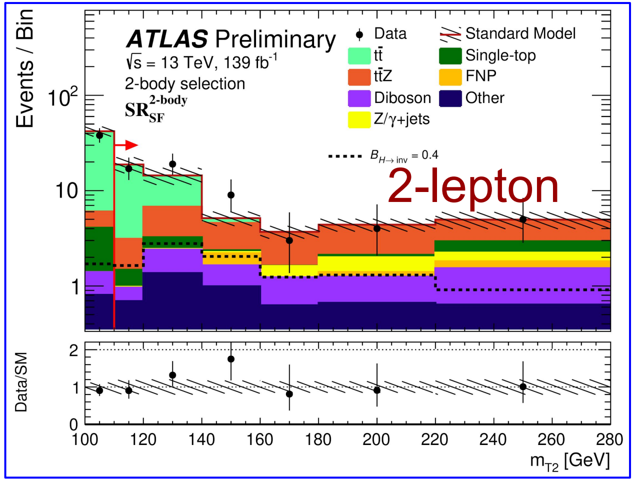


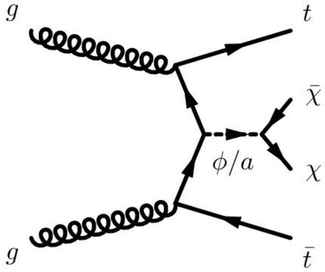


Originally designed for high mass stop squarks

2 b-jets, E_T^{miss}>250 GeV, recluster jets into large-R jets representing top quarks

Reinterpretation of existing SUSY analyses, which targeted for example models given by these diagrams

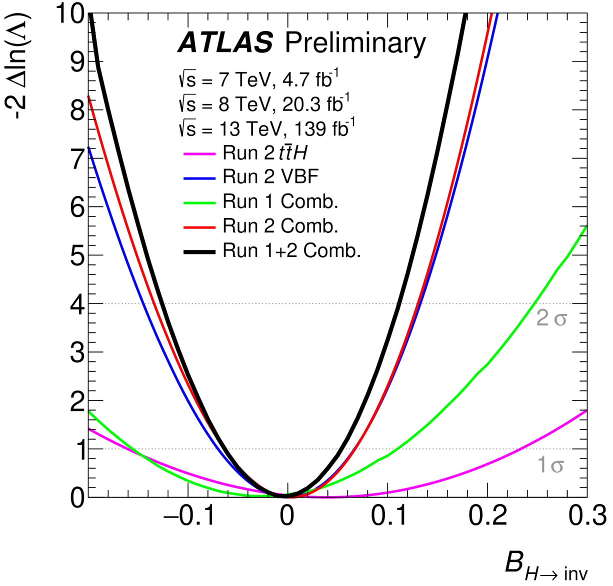




Selection designed for dark matter models

Requires ≥1 b-jet, with requirements placed on $E_T^{miss,significance}$ and m_{T2}

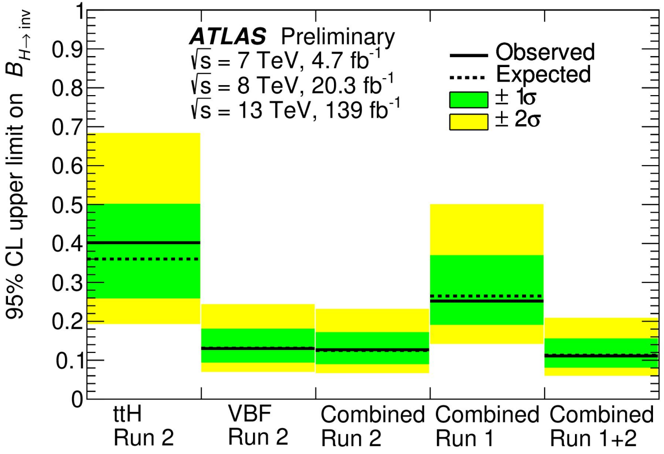
2L: ATLAS-CONF-2020-046
0L: **arXiv:2004.14060**



Combined H→Invisible

95% CL

Analysis	$\sqrt{s}$ [TeV]	Int. luminosity [fb^{-1}]	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
Run 2 VBF	13	139	$0.00^{+0.07}_{-0.07}$	0.13	$0.13^{+0.05}_{-0.04}$
Run 2 $t\bar{t}H$	13	139	$0.04^{+0.20}_{-0.20}$	0.40	$0.36^{+0.15}_{-0.10}$
Run 2 Comb.	13	139	$0.00^{+0.06}_{-0.07}$	0.13	$0.12^{+0.05}_{-0.04}$
Run 1 Comb.	7, 8	4.7, 20.3	$-0.02^{+0.14}_{-0.13}$	0.25	$0.27^{+0.10}_{-0.08}$
Run 1+2 Comb.	7, 8, 13	4.7, 20.3, 139	$0.00^{+0.06}_{-0.06}$	0.11	$0.11^{+0.04}_{-0.03}$



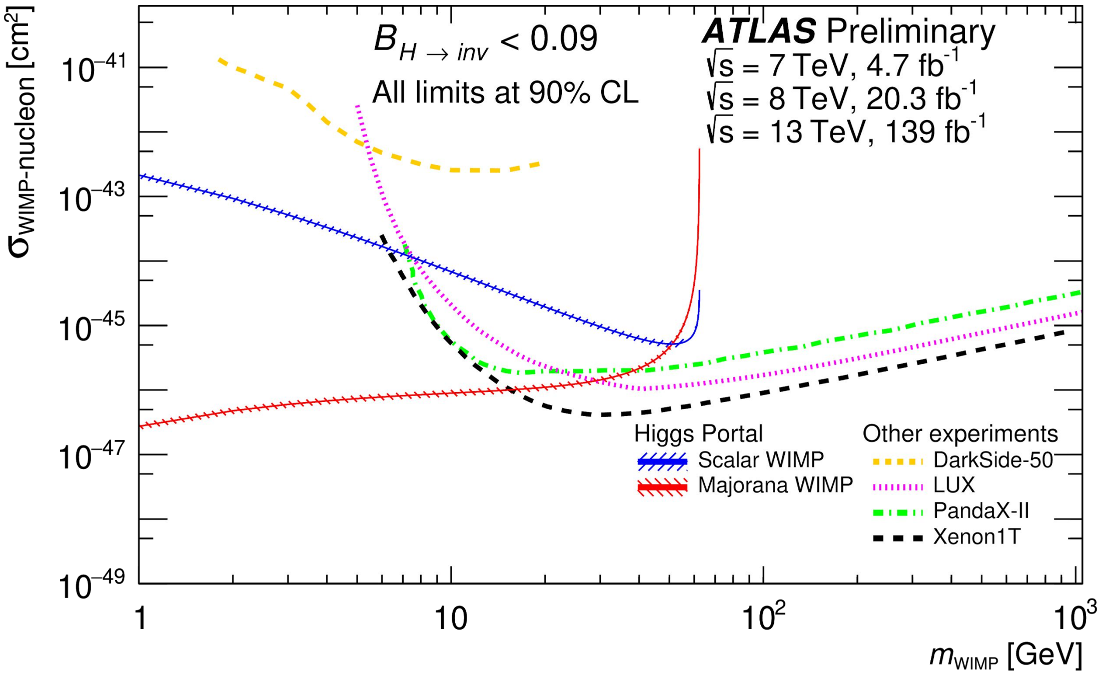
Limit largely driven by VBF channel, with extra sensitivity contributed by ttH and full set of Run 1 measurements

ATLAS-CONF-2020-052

H→Invisible in Context

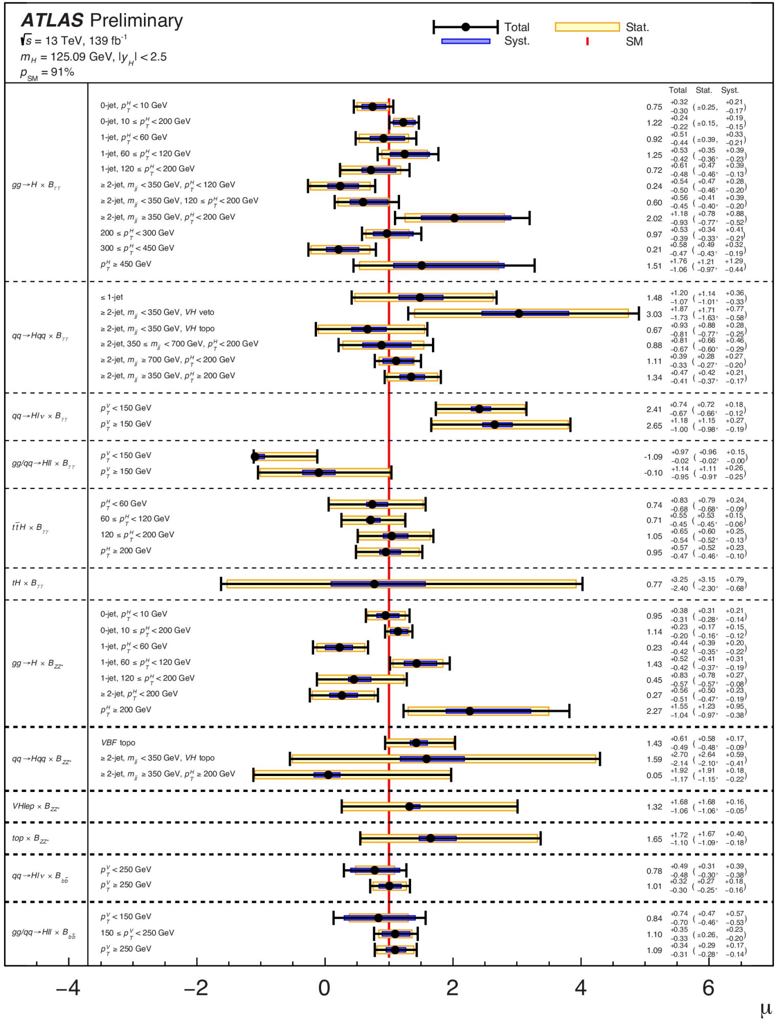
Comparison to direct detection experiments

The Higgs is assumed to decay to a pair of dark matter particles, either scalars or Majorana fermions



Higgs Properties: History

- Summer 2020 combination produced precise set of Higgs property measurements
- Result included coupling measurements and 2HDM interpretation
- Extended interpretation to MSSM and SMEFT



ATLAS-CONF-2020-053

MSSM Interpretation

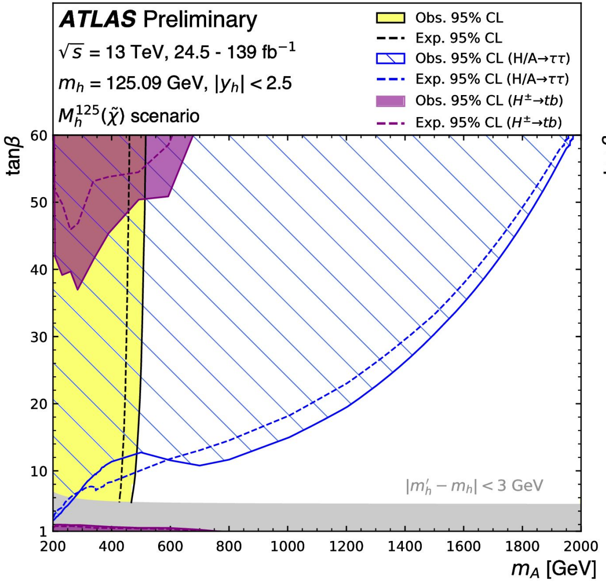
Interpretations for multiple different MSSM scenarios

Examples given below, with comparison to direct searches

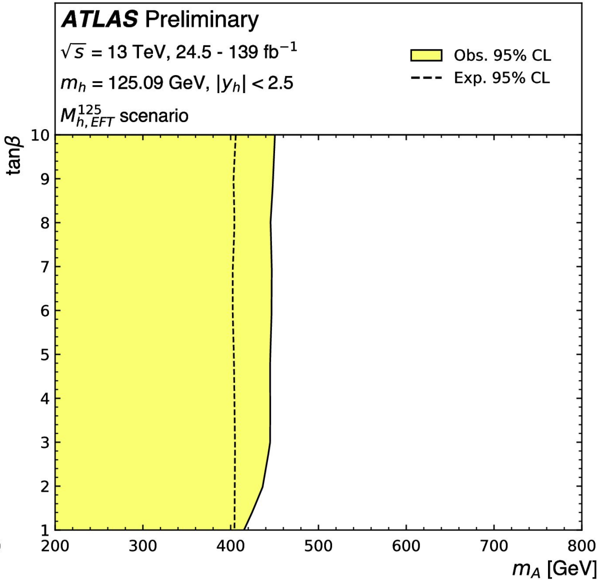
Includes cross-section measurements in all channels given in the table

Analysis	
$H \to \gamma\gamma$	(all production modes)
$H \to ZZ^* \to 4\ell$	(all production modes)
$H \to b\bar{b}$	(VH)
$H \to WW^*$	(ggH, VBF)
$H \to \tau\tau$	(ggH, VBF)
$H \to b\bar{b}$	(VBF)
$H \to b\bar{b}$	$(t\bar{t}H)$
$H \to$ multilepton	$(t\bar{t}H)$
$H \to \mu\mu$	(all production modes)

$M_h^{125}(\tilde{\chi})$ scenario



$M_{h,\mathrm{EFT}}^{125}$ scenario



SMEFT Interpretation

- Includes full Run 2 dataset analyses with differential STXS measurements

Analysis		Integrated lumi (fb^{-1})
$H \to \gamma\gamma$	(all production modes)	139
$H \to ZZ^* \to 4\ell$	(all production modes)	139
$H \to b\bar{b}$	(VH)	139

- In practice, introduce set of operators to the SM Lagrangian:

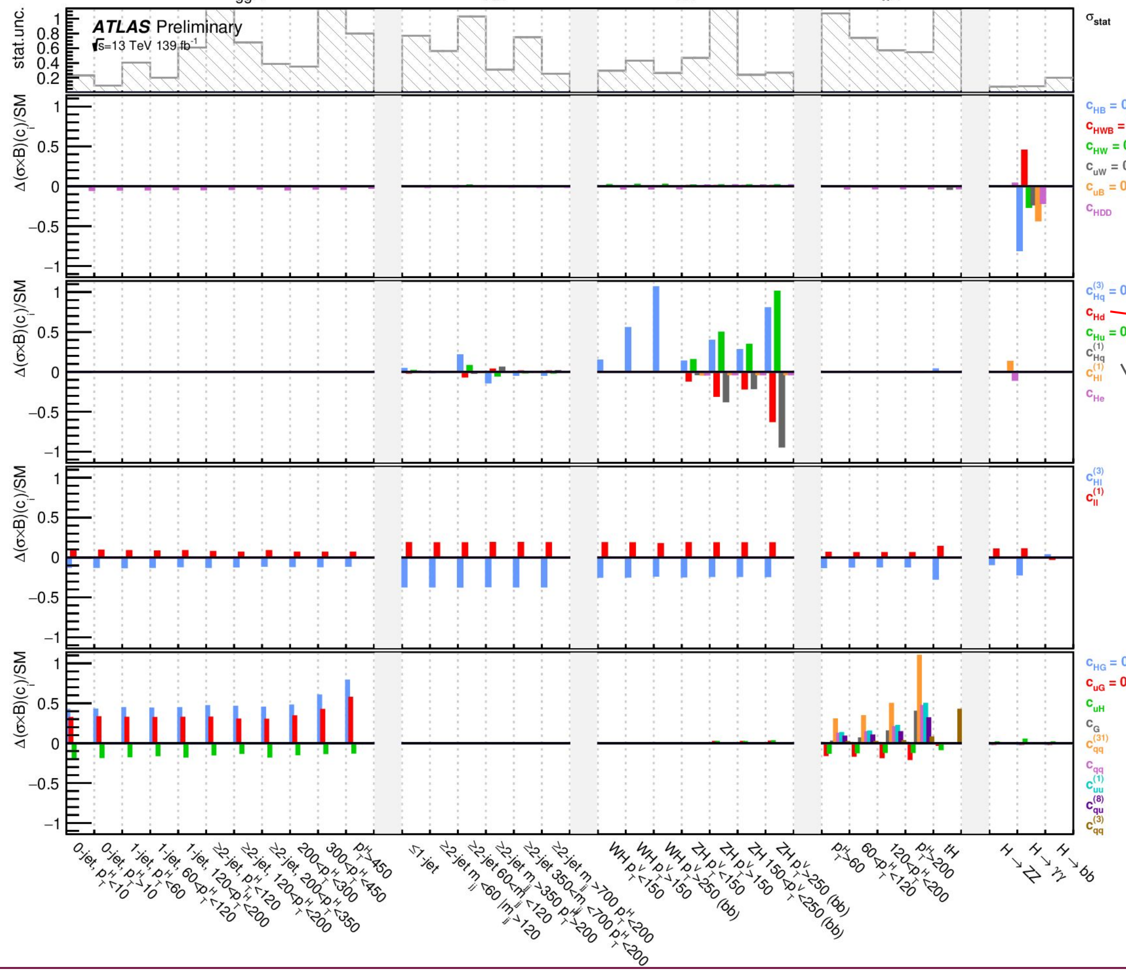
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots$$

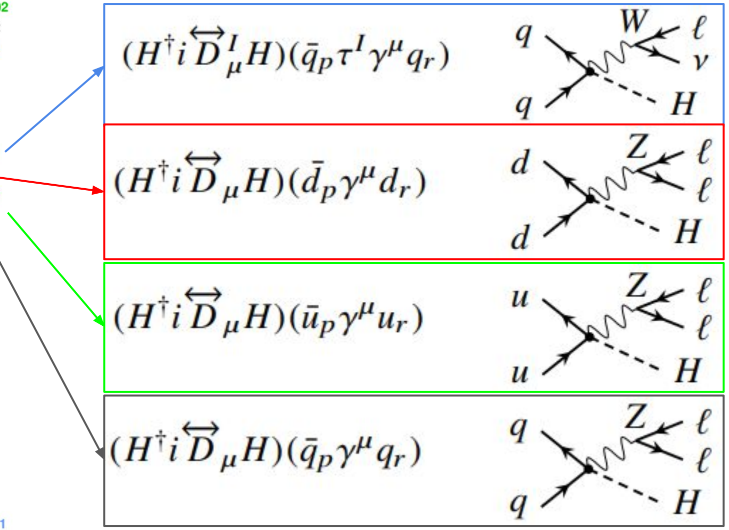
  Considering $O_i^{(6)}$ operators, evaluate the expected effect of nonzero values of each parameter c_i on measurable Higgs kinematics, and constrain parameters based on combination of Higgs measurements

- Interpretations for linear (interference terms) and linear+quadratic (interference+pure BSM terms) dependence on d=6 SMEFT operators

SMEFT Interpretation

Λ = 1 TeV





Many parameters: for illustration, focus on a set that largely affects VH

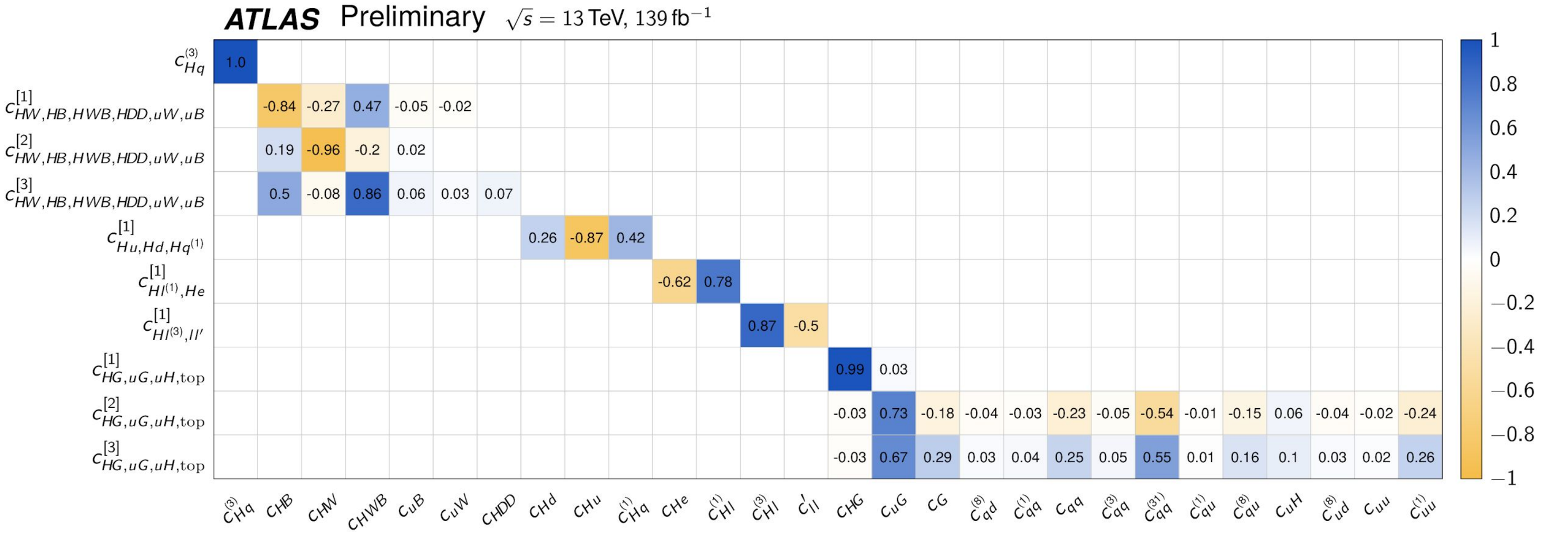
Only linear terms in model in figure: model with quadratic terms also included in result

SMEFT Interpretation

Due to large number of parameters with complicated correlation, Cannot separately constrain all parameters

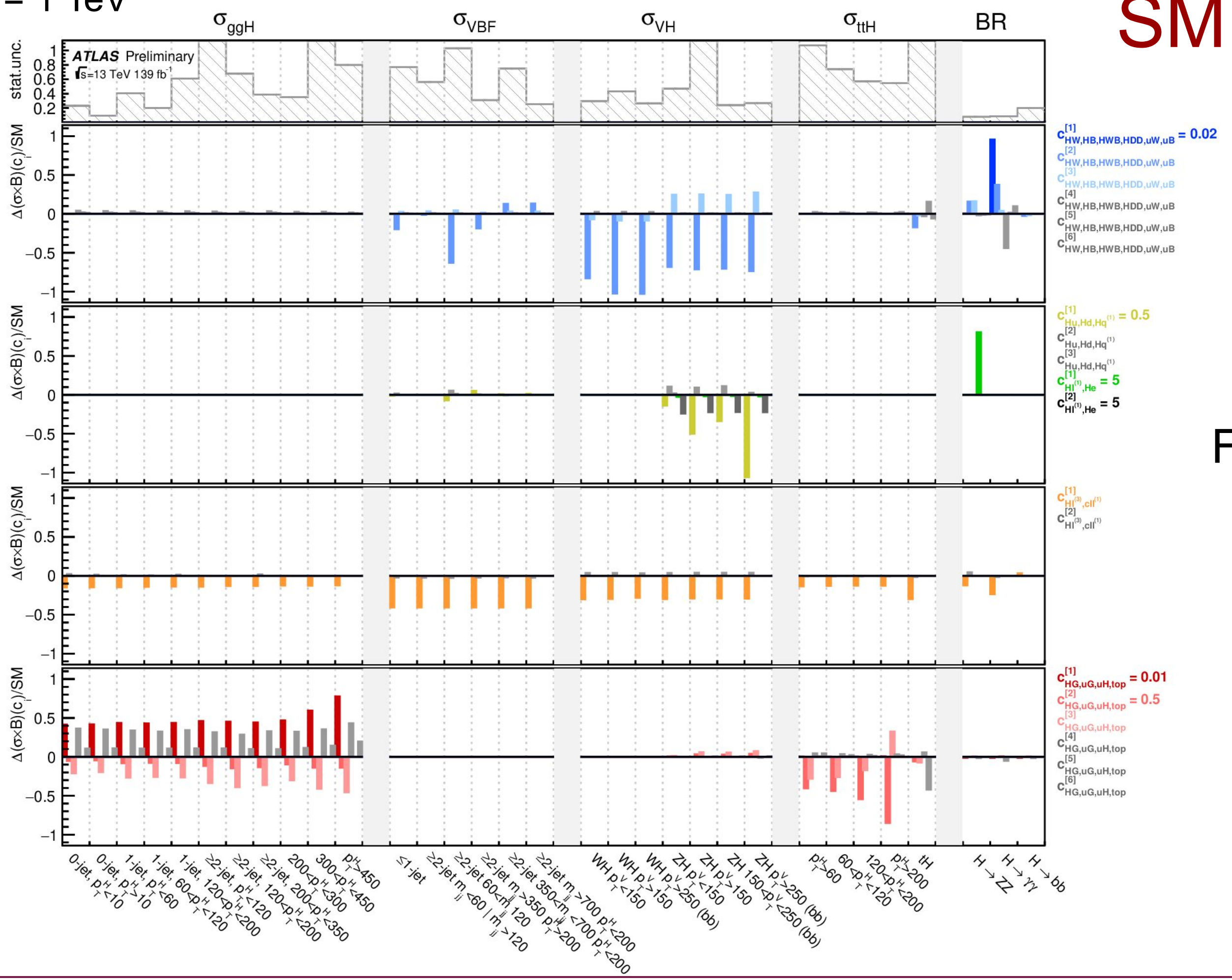
Decompose into subspaces, motivated by correlations and physics concerns

Set parameters with weak eigenvalues to 0 and fit resulting parameter set



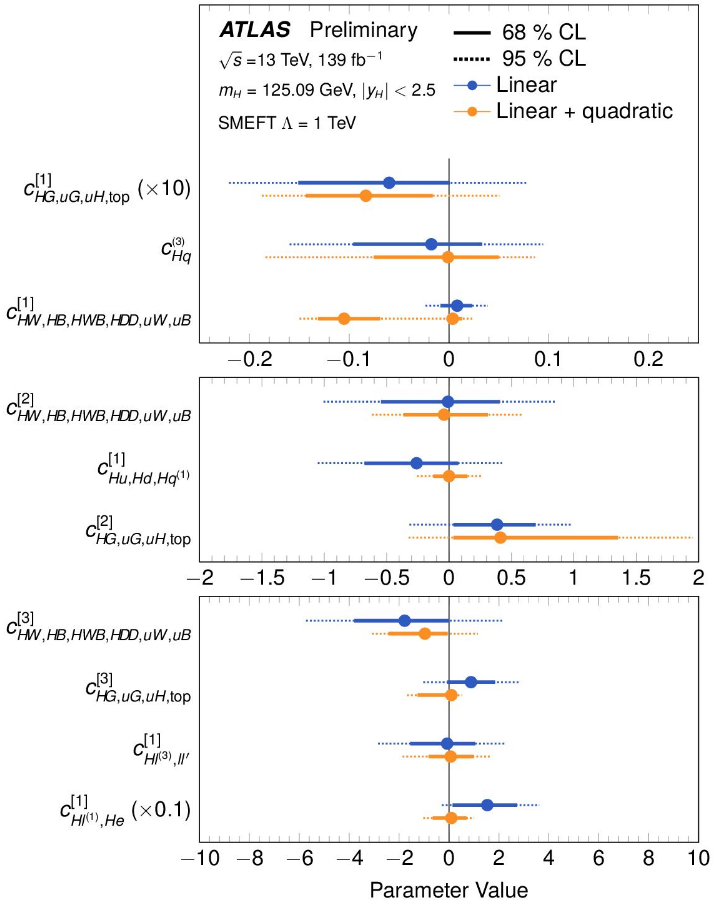
Λ = 1 TeV

SMEFT Interpretation



Fit resulting parameter set

SMEFT Results



Parameter measurements and correlations

ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 139 fb^{-1}
m_H = 125.09 GeV, $|y_H| < 2.5$

$\rho(X,Y)$

	$c_{Hq}^{(3)}$	$c^{[1]}_{Hl^{(1)},He}$	$c^{[1]}_{Hl^{(3)},ll'}$	$c^{[1]}_{Hd,Hq^{(1)},Hu}$	$c^{[1]}_{HG,uG,uH,top}$	$c^{[2]}_{HG,uG,uH,top}$	$c^{[3]}_{HG,uG,uH,top}$	$c^{[1]}_{HW,HB,HWB,HDD,uB,uW}$	$c^{[2]}_{HW,HB,HWB,HDD,uB,uW}$	$c^{[3]}_{HW,HB,HWB,HDD,uB,uW}$
$c_{Hq}^{(3)}$	1	−0.74	0.28	0.75	−0.38	0.24	0.07	0.12	0.64	0.70
$c^{[1]}_{Hl^{(1)},He}$	−0.74	1	−0.19	−0.91	0.19	−0.05	0.05	0.00	−0.44	−0.95
$c^{[1]}_{Hl^{(3)},ll'}$	0.28	−0.19	1	0.25	−0.54	0.47	0.05	0.95	−0.40	0.44
$c^{[1]}_{Hd,Hq^{(1)},Hu}$	0.75	−0.91	0.25	1	−0.24	0.12	0.06	0.09	0.30	0.90
$c^{[1]}_{HG,uG,uH,top}$	−0.38	0.19	−0.54	−0.24	1	−0.69	−0.20	−0.66	−0.09	−0.33
$c^{[2]}_{HG,uG,uH,top}$	0.24	−0.05	0.47	0.12	−0.69	1	0.19	0.58	0.00	0.18
$c^{[3]}_{HG,uG,uH,top}$	0.07	0.05	0.05	0.06	−0.20	0.19	1	0.11	0.09	−0.03
$c^{[1]}_{HW,HB,HWB,HDD,uB,uW}$	0.12	0.00	0.95	0.09	−0.66	0.58	0.11	1	−0.49	0.27
$c^{[2]}_{HW,HB,HWB,HDD,uB,uW}$	0.64	−0.44	−0.40	0.30	−0.09	0.00	0.09	−0.49	1	0.21
$c^{[3]}_{HW,HB,HWB,HDD,uB,uW}$	0.70	−0.95	0.44	0.90	−0.33	0.18	−0.03	0.27	0.21	1

- Inclusion of quadratic terms→tighter constraints
- Suggests a non-negligible influence of d = 6 operator terms suppressed by power Λ^{-4}

Conclusion

New results presented for VBF and ttH(bb)
→expect ~3σ for both

For VBF, measured 3σ for H→bb production

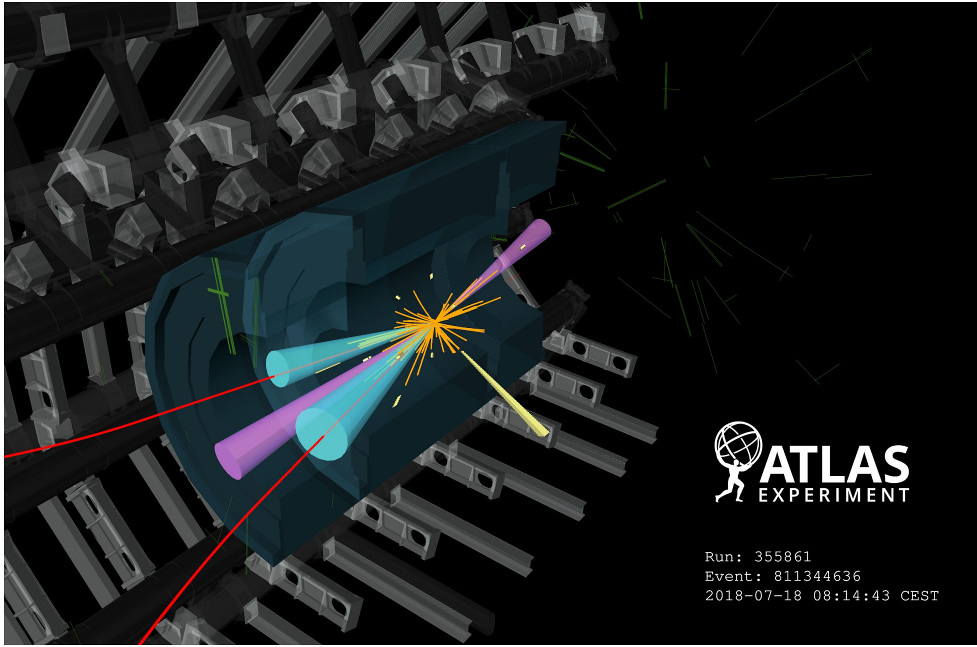
For ttH, performed differential p_T^H measurement up to highest ever p_T^H values for ttH

For ttH, many improvements possible, particularly with improved understanding of background modeling

ggF H→bb with full Run 2 dataset is still in progress

New ATLAS combinations, make new interpretations in MSSM and SMEFT scenarios

Updated already-precise H→inv limits through combination with previous and reinterpreted results



Candidate VBF+γ event

Backup

Citations

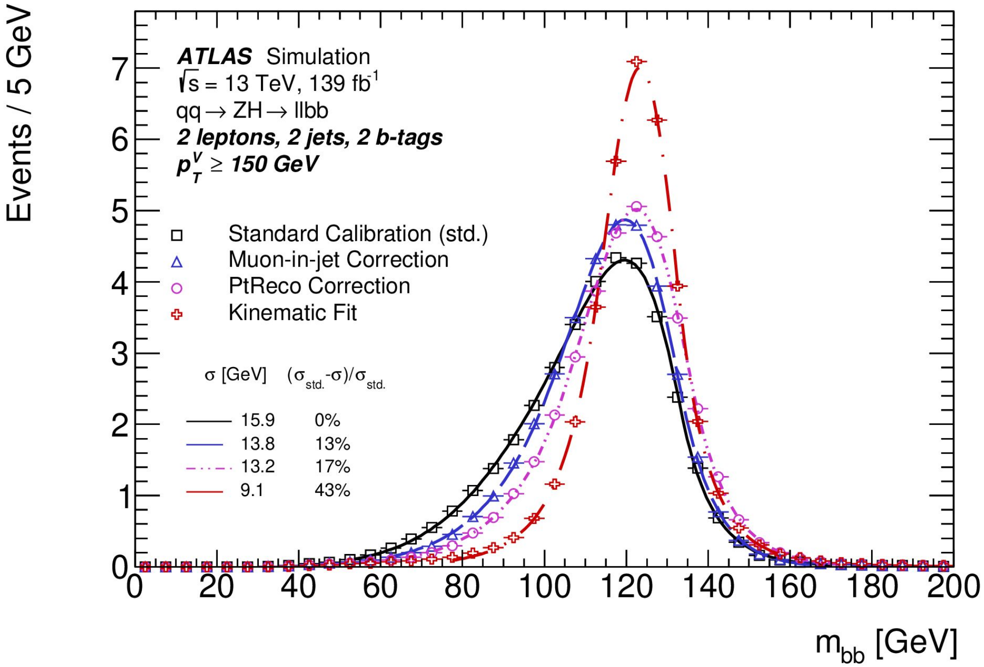
Gabrielli, E., Mele, B., Piccinini, F. *et al.* Asking for an extra photon in Higgs production at the LHC and beyond. *J. High Energ. Phys.* 2016, 3 (2016)

A. D. Bukin, Fitting function for asymmetric peaks, 2007, arXiv: 0711.4449 [physics.data-an]

B-jet Corrections

m_{bb} resolution using different b-jet corrections

VBF and VBF+ɣ use muon-in-jet and PtReco



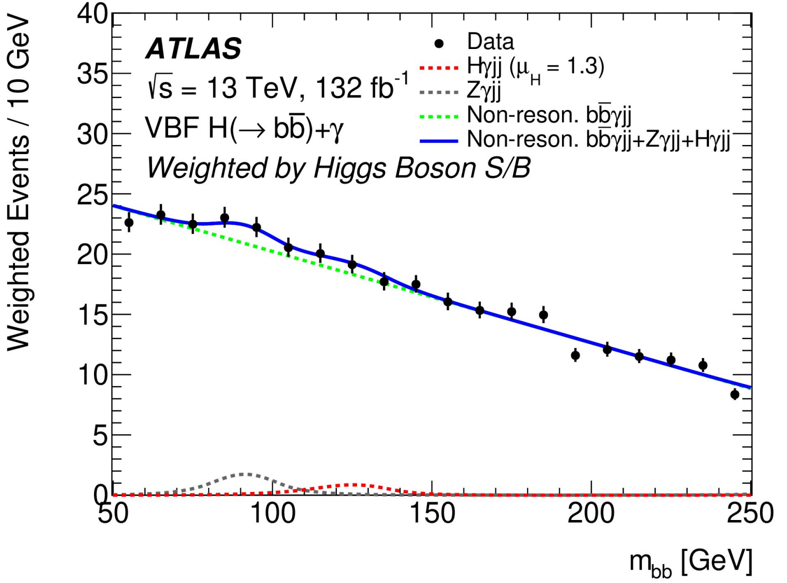
arXiv:2007.02873

VBF+γ: Selection and results

Left: Full event preselection

Right: weighted sum of signal regions, including non-resonant background

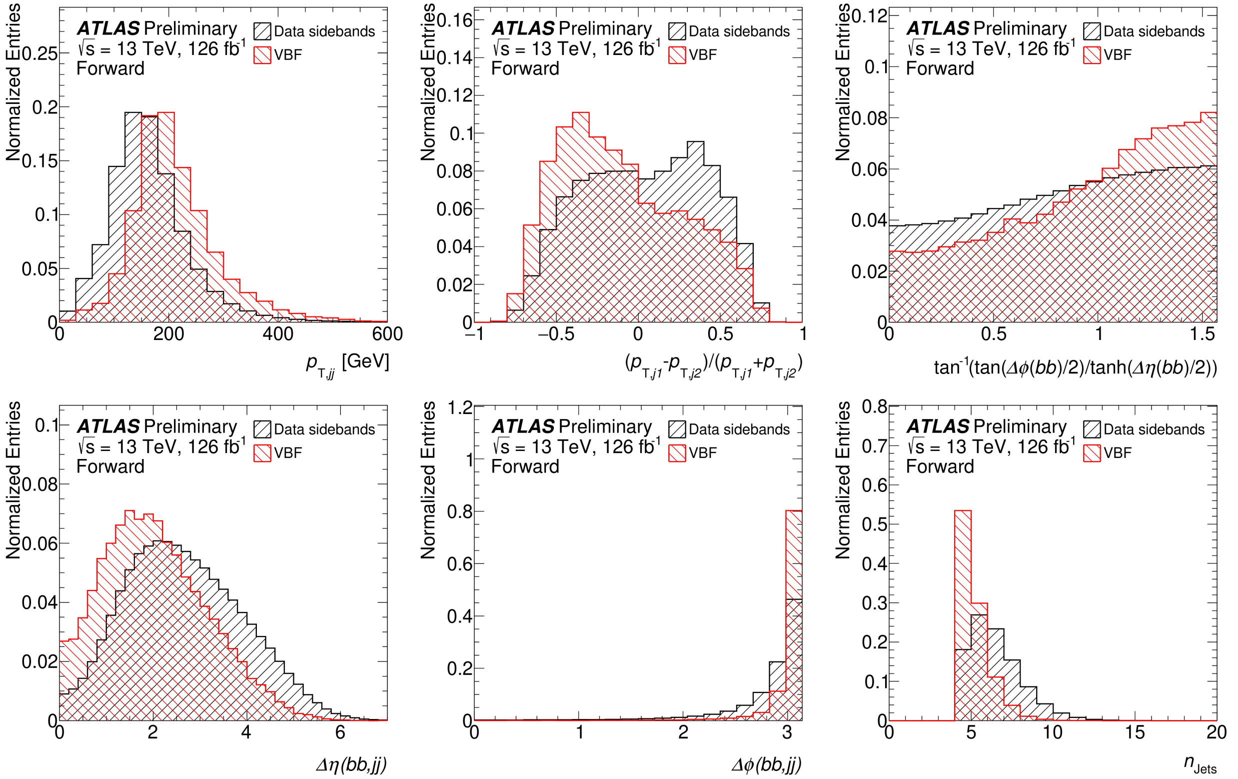
Trigger	L1	≥ 1 photon with $E_T > 22$ GeV
	HLT	≥ 1 photon with $E_T > 25$ GeV
		≥ 4 jets (or ≥ 3 jets and ≥ 1 b-jet) with $E_T > 35$ GeV and $\lvert\eta\rvert < 4.9$
		$m_{jj} > 700$ GeV
Offline		≥ 1 photon with $E_T > 30$ GeV and $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$
		≥ 2 b-jets with $p_T > 40$ GeV and $\lvert\eta\rvert < 2.5$
		≥ 2 jets with $p_T > 40$ GeV and $\lvert\eta\rvert < 4.5$
		$m_{jj} > 800$ GeV
		$p_T(b\bar{b}) > 60$ GeV
		No electrons ($p_T > 25$ GeV, $\lvert\eta\rvert < 2.47$) or muons ($p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$)



All-hadronic VBF H→bb Variable List

11 (12) input variables for Forward (Central) channel. In the Forward channel, N_{trk}^{j1} is not included, as one of the jets is always in the forward region and has no associated tracks

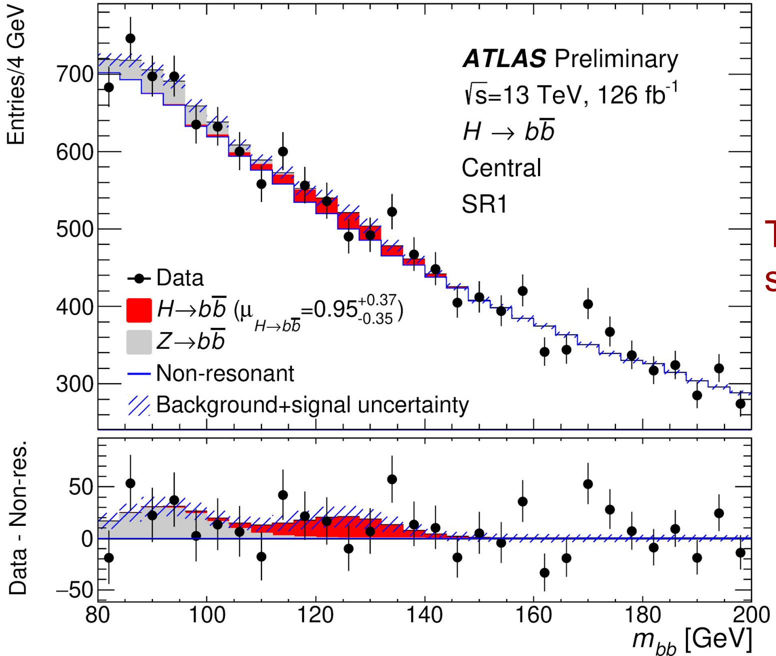
- m_{jj}
- $p_{T,jj}$
- p_T balance
- $\Delta\eta(bb,jj)$
- $\Delta\varphi(bb,jj)$
- N jets
- $(p_T^{j1}-p_T^{j2})/(p_T^{j1}+p_T^{j2})$
- $\tan^{-1}(\tan(½\Delta\varphi^{bb})/\tanh(½\Delta\eta^{bb}))$
- $N_{trk}^{j1\ (2)}$ (q/g tagging)
- $\min(\Delta R(j^{1\ (2)}$, extra jet))



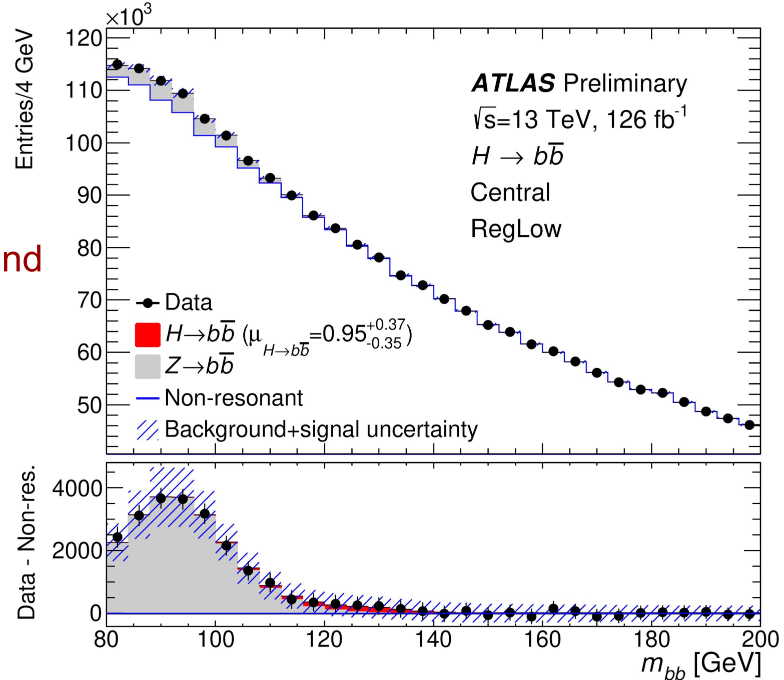
Fits (Central Channel)

- Score and m_{bb} uncorrelated → take background template in high score signal regions from high-statistic low score control region

- Fit 4 high score regions + one low score region in each channel (10 regions total)

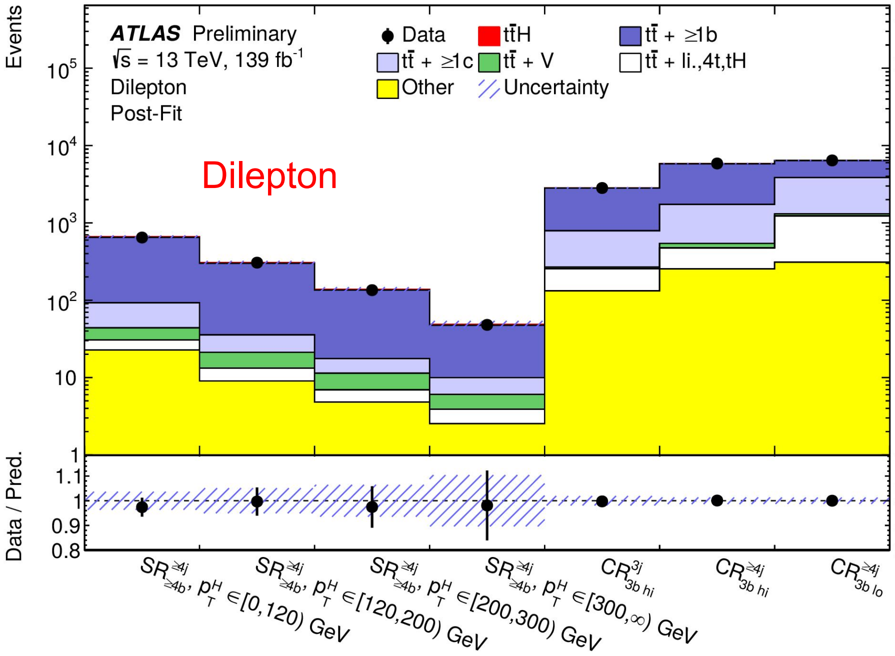


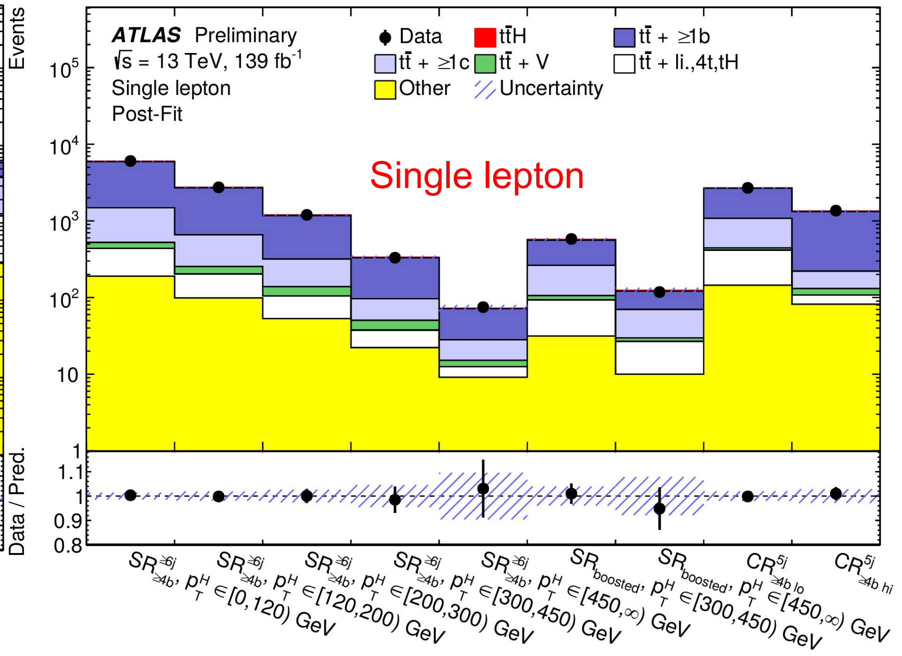
Take background shape from



ttH Post-fit Channels

Event yields in each SR and CR, post-fit





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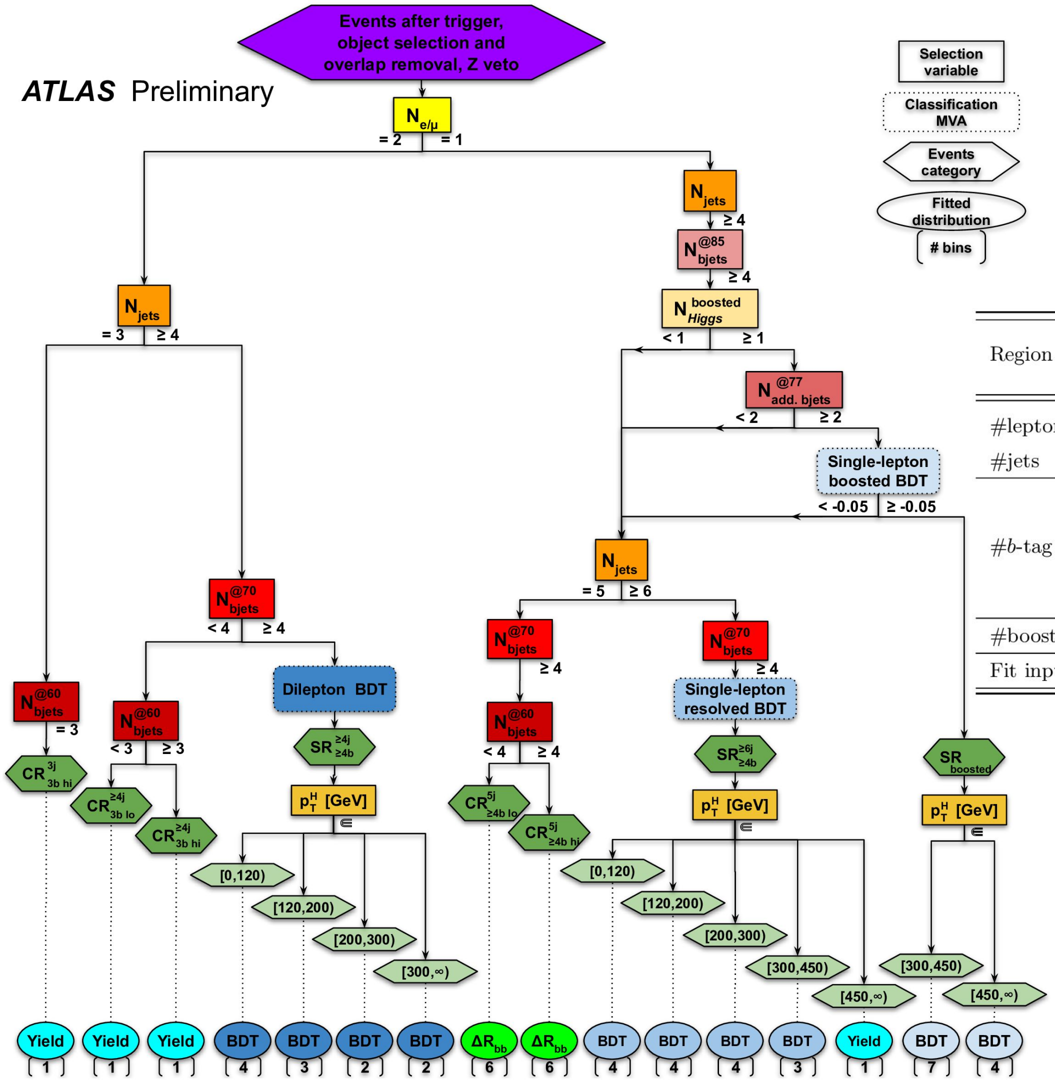
Classification Flowchart



Schematic view of all channels and regions in the analysis

Region	Dilepton $\mathrm{SR}^{\geq 4j}_{\geq 4b}$	Dilepton $\mathrm{CR}^{\geq 4j}_{3b\ \mathrm{hi}}$	Dilepton $\mathrm{CR}^{\geq 4j}_{3b\ \mathrm{lo}}$	Dilepton $\mathrm{CR}^{3j}_{3b\ \mathrm{hi}}$	Single-lepton $\mathrm{SR}^{\geq 6j}_{\geq 4b}$	Single-lepton $\mathrm{CR}^{5j}_{\geq 4b\ \mathrm{hi}}$	Single-lepton $\mathrm{CR}^{5j}_{\geq 4b\ \mathrm{lo}}$	Single-lepton $\mathrm{SR}_{\mathrm{boosted}}$
#leptons	$= 2$				$= 1$			
#jets	≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
#b-tag @85%	–				≥ 4			
#b-tag @77%	–				–			$\geq 2^{\dagger}$
#b-tag @70%	≥ 4	$= 3$			≥ 4			–
#b-tag @60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
#boosted cand.	–				0			≥ 1
Fit input	BDT	Yield			BDT/Yield	$\Delta R^{\mathrm{avg}}_{bb}$		BDT

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ttH Uncertainties

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modelling	$+0.25$	-0.24
$t\bar{t}H$ modelling	$+0.14$	-0.06
tW modelling	$+0.08$	-0.08
b-tagging efficiency and mis-tag rates	$+0.05$	-0.05
Background-model statistical uncertainty	$+0.05$	-0.05
Jet energy scale and resolution	$+0.03$	-0.03
$t\bar{t} + \geq 1c$ modelling	$+0.03$	-0.03
$t\bar{t}$ + light modelling	$+0.02$	-0.02
Luminosity	$+0.01$	-0.00
Other sources	$+0.03$	-0.03
Total systematic uncertainty	$+0.30$	-0.27
$t\bar{t} + \geq 1b$ normalisation	$+0.03$	-0.05
Total statistical uncertainty	$+0.20$	-0.19
Total uncertainty	$+0.36$	-0.33

Summary of uncertainties, broken down by source

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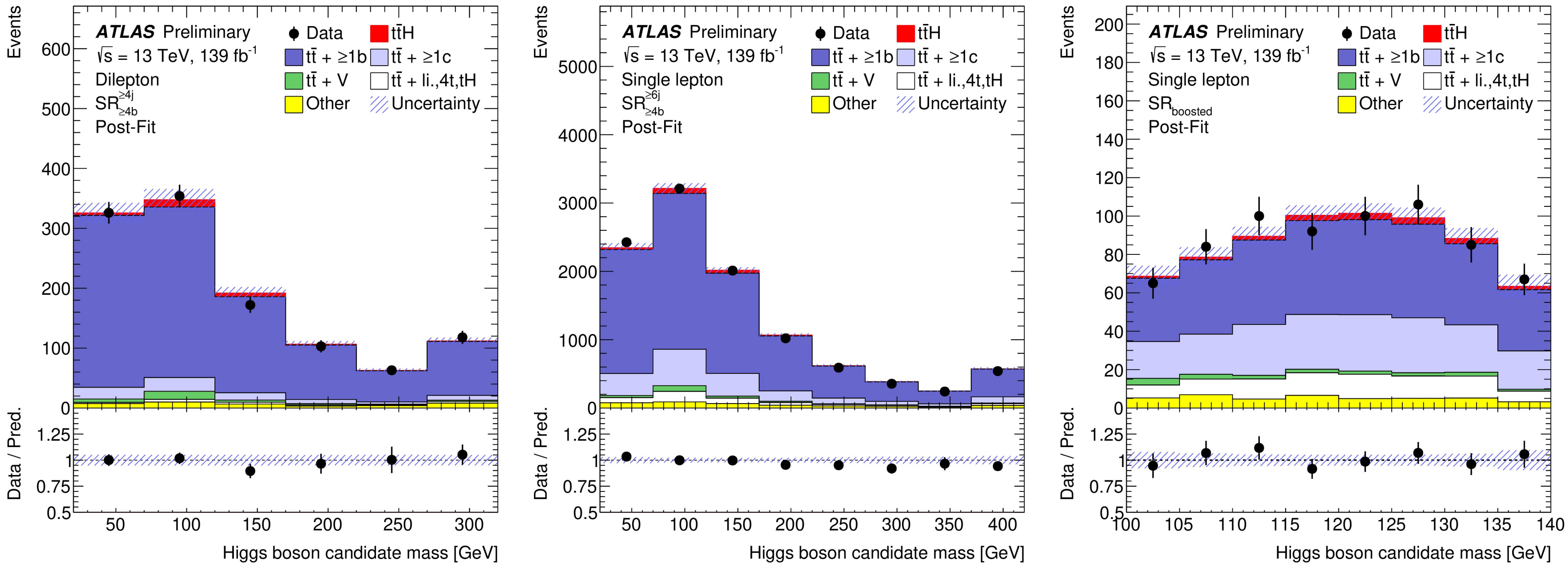
ttH: m_{bb} Distributions

Mass distributions in each analysis channel



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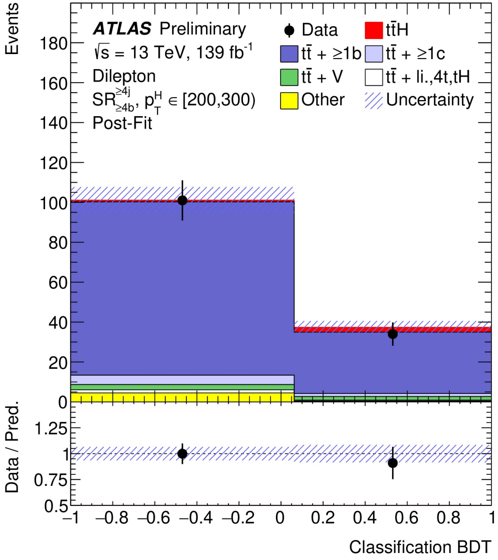
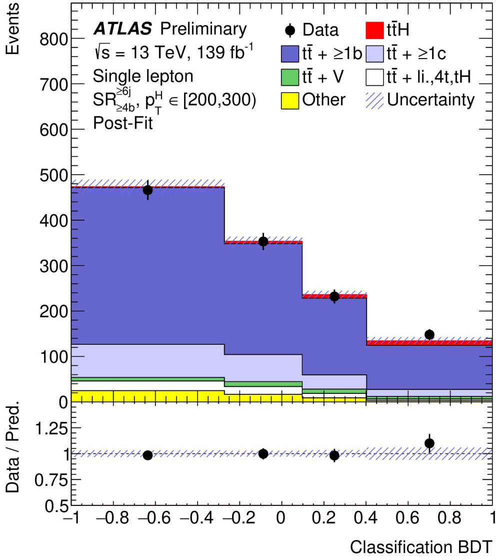
Example: $200<p_T^H<300$ GeV

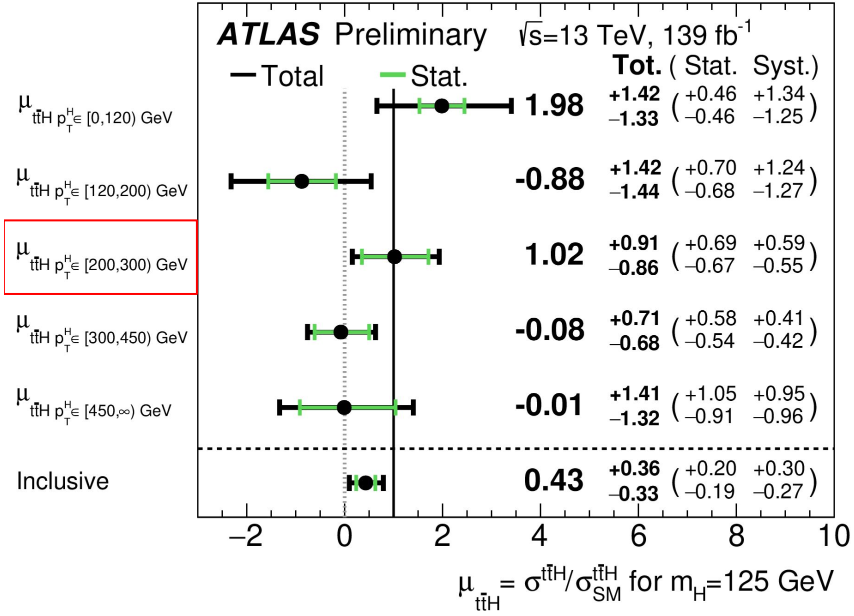
- As example, results from fit for 200-300 GeV bin shown, which generally constrain the signal-strength for $200<p_T^H<300$ GeV
- Table gives measured signal-strength in all p_T^H bins



Dilepton



Single lepton



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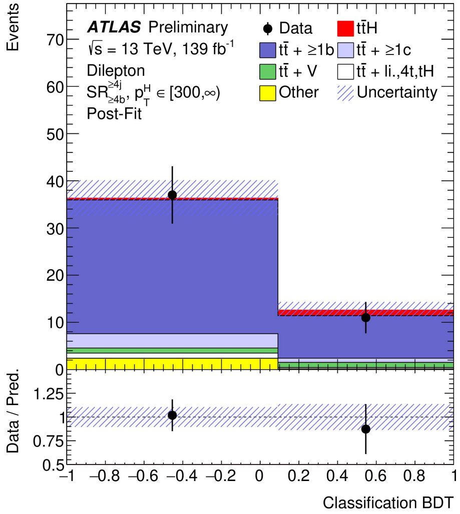
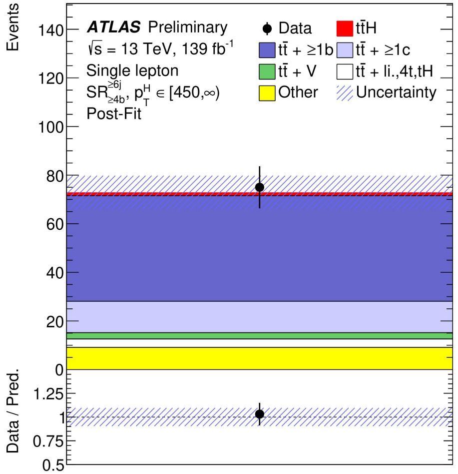
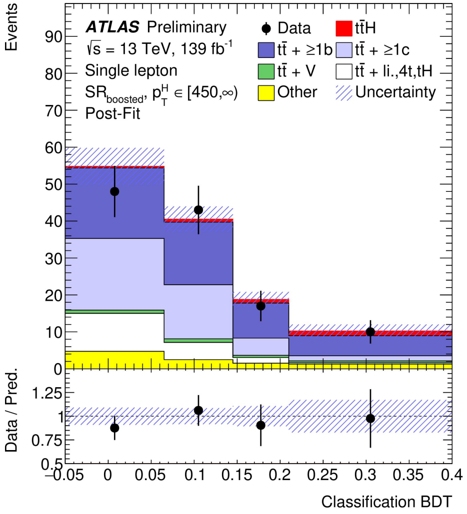
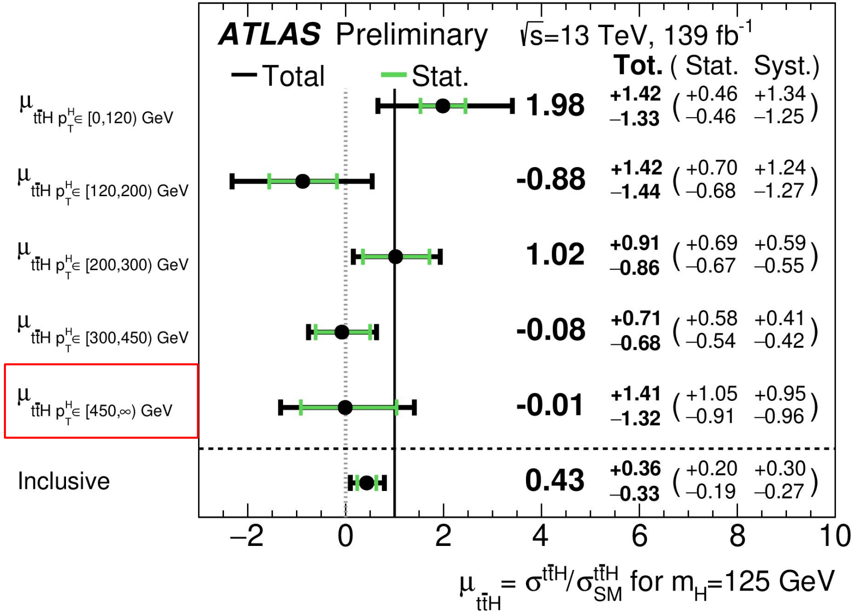
Results: p_T^H>450 GeV

- Results shown for p_T^H>450 GeV bin for 1-lepton channels and p_T^H>300 GeV bin for 2-lepton channel





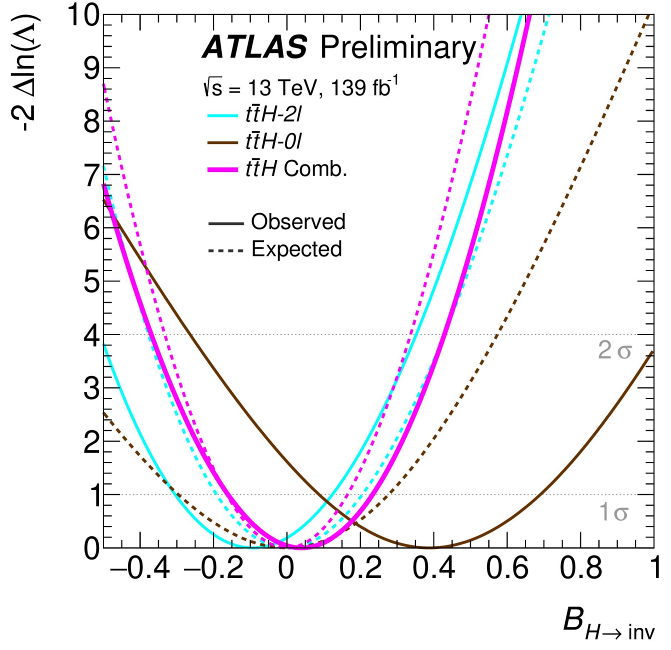


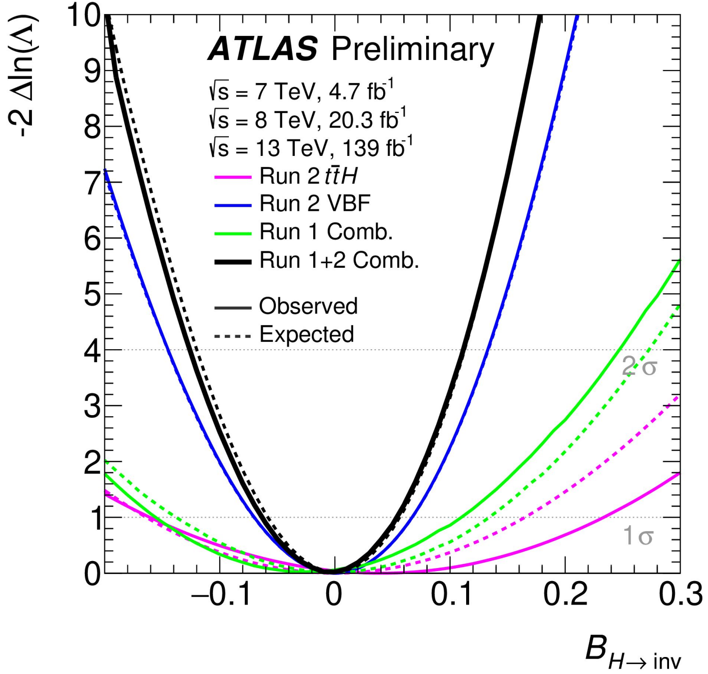


H→invisible: ttH and Expections

Left: Results from individual ttH analyses

Right: Results for each channel, showing both observation and expectation



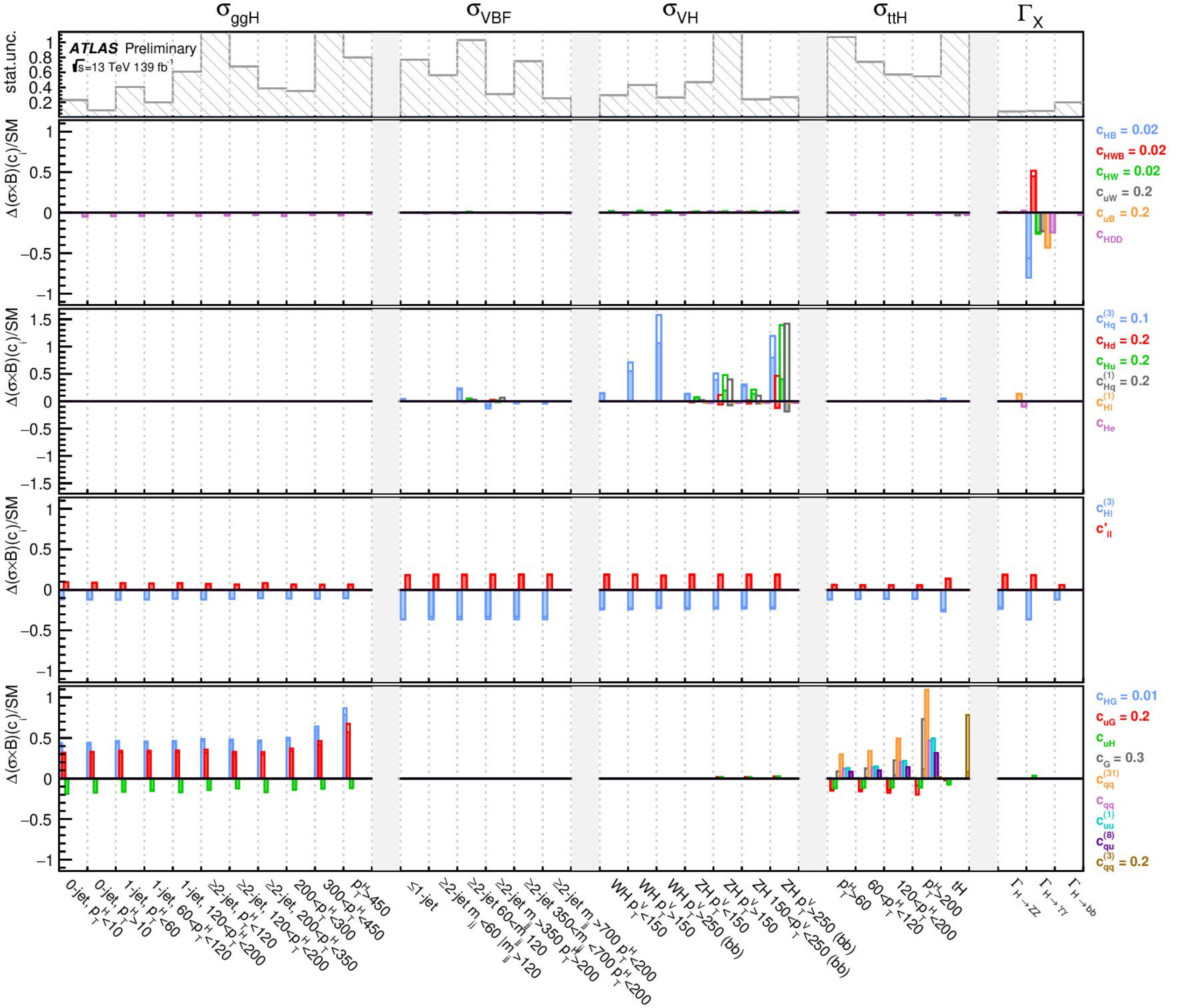


H→invisible: Uncertainties

Source of uncertainty	±Uncertainty on $\mathcal{B}_{H\to\text{inv}}$ Run 2	Run 1+2
Luminosity / pile up	0.002	0.003
Leptons / photons	0.018	0.015
Jets	0.023	0.019
Flavour tagging	0.002	0.002
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.008	0.007
V+jets modelling	0.011	0.017
Other background modelling	0.015	0.015
Data-driven background	0.023	0.019
Signal modelling	0.004	0.003
MC statistics	0.023	0.021
All experimental	0.041	0.036
All theory	0.030	0.030
Total systematic uncertainty	0.051	0.046
Data statistics	0.019	0.018
Floating background norm.	0.031	0.028
Total statistical uncertainty	0.037	0.034
Total uncertainty	0.063	0.057

Source of uncertainty	±Uncertainty on $\mathcal{B}_{H\to\text{inv}}$ $t\bar{t}H$
Luminosity / pile up	0.006
Leptons / photons	0.025
Jets	0.036
Flavour tagging	0.019
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.013
$t\bar{t}$ modelling	0.055
$t\bar{t}+Z$ modelling	0.035
Other background modelling	0.047
Data-driven background	0.003
Signal modelling	0.015
MC statistics	0.009
All experimental	0.053
All theory	0.080
Total systematic uncertainty	0.099
Data statistics	0.116
Floating background norm.	0.064
Total statistical uncertainty	0.132
Total uncertainty	0.165

Linear+Quadratic Model



Impact of each parameter, showing both linear (shaded) and linear+quadratic (open) models

MSSM Interpretation Summary

Overview of benchmark models:

- M_h^{125}:
  - All superparticles heavy that production→MSSM Higgs bosons only mildly affected by them.
  - Heavy Higgs bosons with masses up to 2 TeV decay only to SM particles.
- $M_h^{125}(\tilde{\chi})$:
  - All charginos and neutralinos relatively light, with significant higgsino-gaugino mixing.
  - Weakens exclusion bounds from $H/A \rightarrow \tau\tau$ searches, as well as the decay of the SM-like Higgs boson to photons.
  - Possibility to look for additional Higgs bosons through their decays to charginos and neutralinos opens up.
- $M_h^{125}(\tilde{\tau})$ scenario:
  - Light staus and light gaugino-like charginos and neutralinos.
  - The effect of the light staus on the decays of the heavier Higgs bosons, as well as on the decay of the SM-like Higgs boson to photons, is most relevant at large $\tan\beta$.
  - Compared with the previous scenario, a larger mass for the higgsinos implies that the decays of the heavier Higgs bosons to charginos and neutralinos become relevant at larger values of M_A.
- M_h^{125} (alignment) scenario:
  - In the “alignment without decoupling” scenario, for a given value of $\tan\beta$, one of the two neutral CP-even scalars has SM-like couplings independently of the mass spectrum of the remaining Higgs bosons.
  - In particular, for $\tan\beta$ around 7 the properties of the lighter scalar h are in agreement with those of the observed Higgs boson also for relatively low values of M_A.

MSSM Interpretation Summary

Overview of benchmark models:

- $M_{h,EFT}^{125}$:
    - Characterized by a flexible mass scale M_{SUSY} of the superpartners.
    - The parameter region $\tan\beta < 5$ is ruled out because the mass M_h of the SM-like Higgs boson is predicted to be lower than the measured value.
    - To re-open the parameter region of low $\tan\beta$ values, the sfermion mass scale, M_{SUSY} is adjusted dynamically from 6 TeV to 10^{16} TeV to achieve a 125 GeV Higgs.
    - As in this scenario all superparticles are chosen to be so heavy that production and decays of the MSSM Higgs bosons are only mildly affected by their presence, the SUSY contribution to the Higgs properties is calculated with an effective field theory (EFT).
- $M_{h,EFT}^{125}$ ($\tilde{\chi}$) scenario:
    - Features light neutralinos and charginos whose presence significantly alters the phenomenology of the Higgs boson.
    - The SUSY scale is again adjusted at every parameter point in order to obtain a light Higgs mass of $M_h \approx 125$ GeV.

MSSM Interpretation Summary