Higgs measurements in 3rd generation decay channels (excl. ttH) with ATLAS and CMS

LHCP2020
May 25-30, 2020

On behalf of the ATLAS & CMS Collaborations
Stephen Jiggins

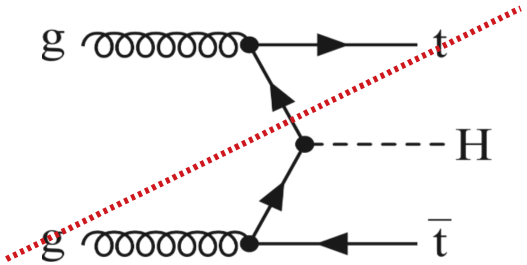
28/05/20

Introduction

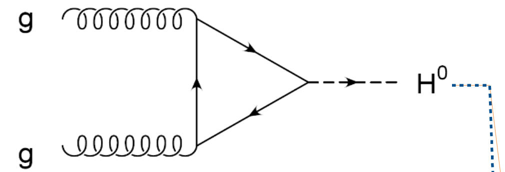
→ Summary of the latest **ATLAS** & **CMS** 3rd generation decay channel Higgs measurements

→ Talk will **only** address **3rd generation** Higgs decays: **H→ [bb,ττ]**

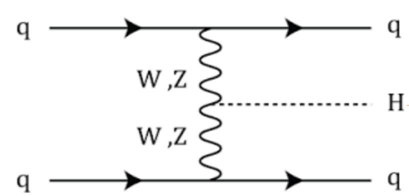
→ Associated top + higgs (ttH) production excluded:



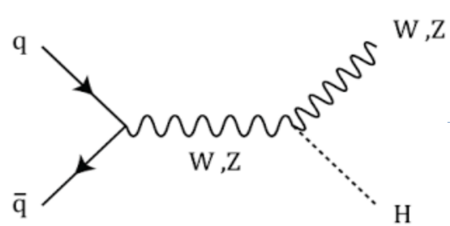
ttH: σ(pp→H+X) ~ 5%



ggF: σ(pp→H+X) ~ 87%

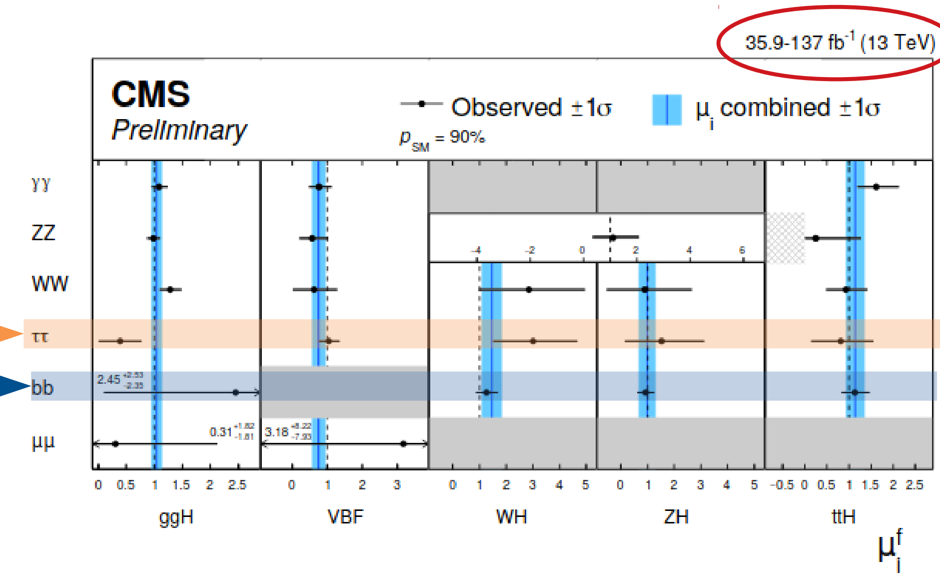


VBF: σ(pp→H+X) ~ 7%



VH: σ(pp→H+X) ~ 5%

Source: HIG-19-005



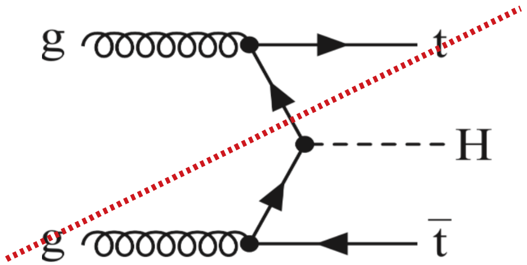
Introduction

→ Summary of the latest **ATLAS** & **CMS** 3rd generation decay channel Higgs measurements

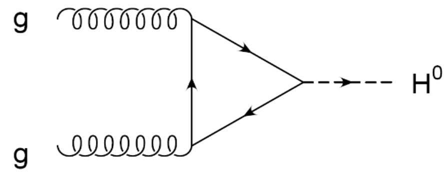
→ Talk will **only** address **3rd generation** Higgs decays: **H→ [bb,ττ]**

Source: PhysRevD 101.012002

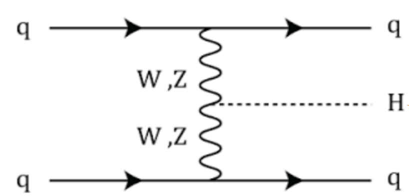
→ Associated top + higgs (ttH) production excluded:



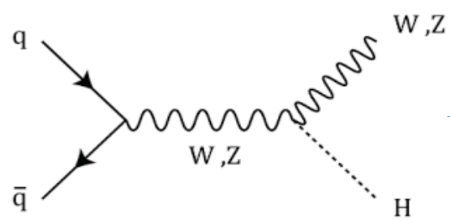
ttH: σ(pp⟶H+X) ~ 5%



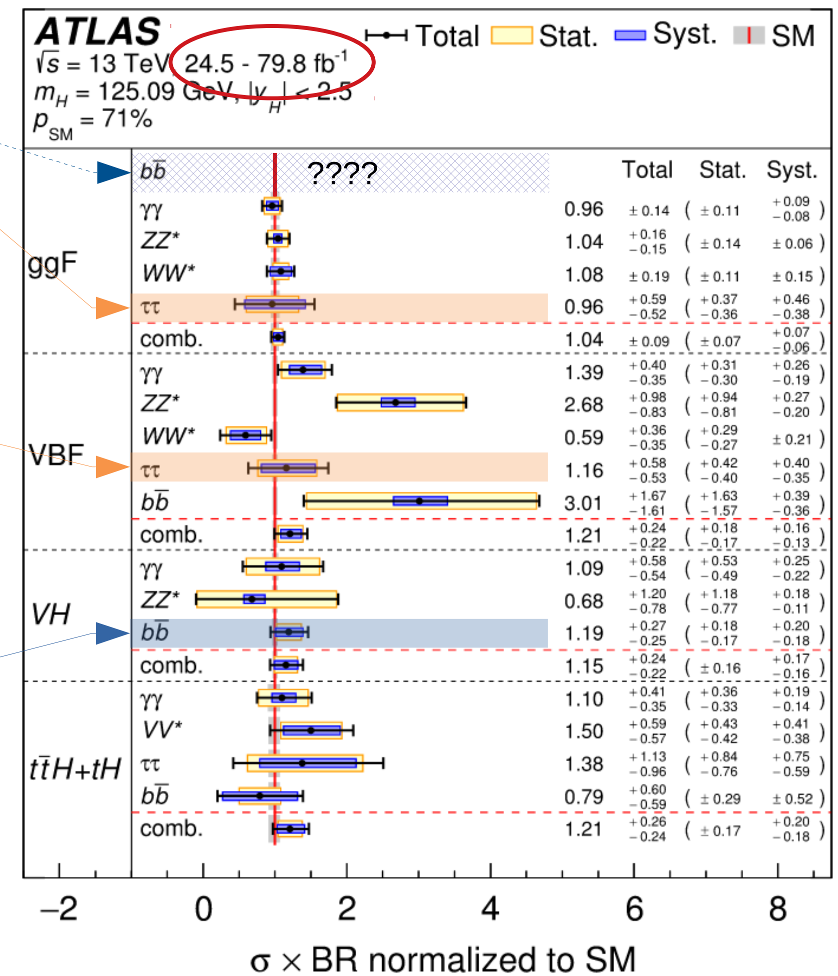
ggF: σ(pp⟶H+X) ~ 87%



VBF: σ(pp⟶H+X) ~ 7%



VH: σ(pp⟶H+X) ~ 5%



→ **Direct H→ bb** measurement of **ggF** production?

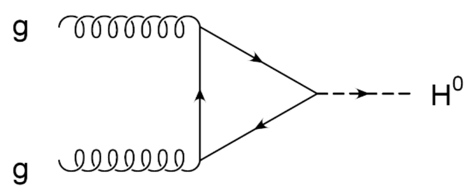
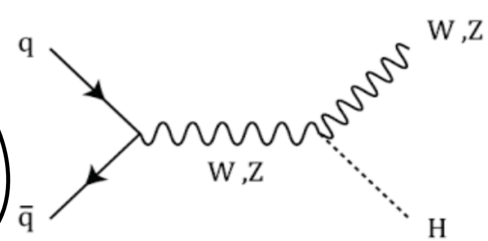
- → QCD background dominant ~ 10^7 > signal
- → Limited by ggF ZH theoretical accuracy
  - →See X, Chen talk
- → ....

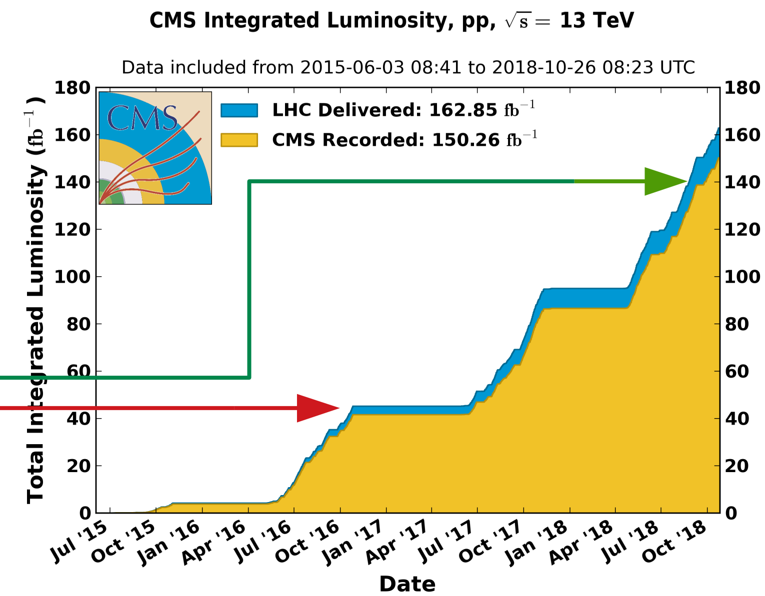
→ Hopefully a new σ^{ggF}_{bb} entry soon...

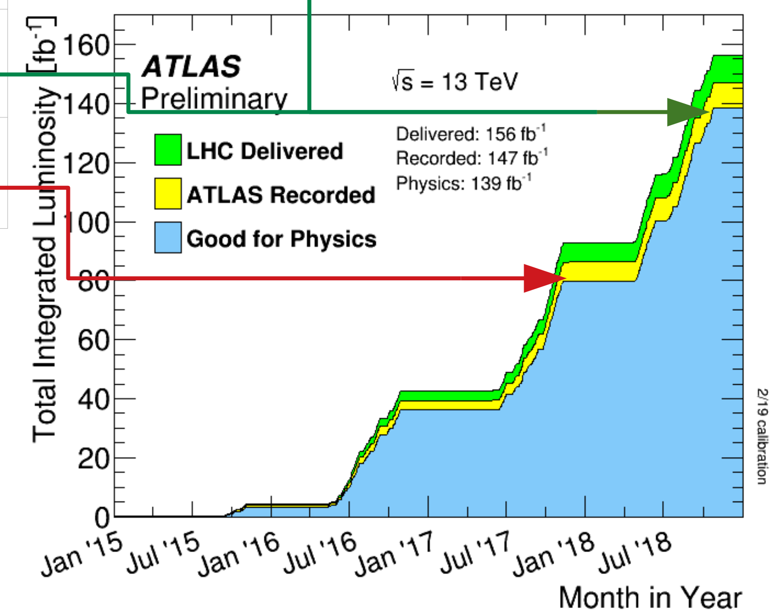
$H \rightarrow bb$

H⟶ bb Searches in ATLAS & CMS

⟶ Will cover new analyses only!

Paper	Luminosity	Signal Process	Date
CMS Publications			
HIG-19-003 *New*	$137fb^{-1}$		April 2020
PhysRevLett. 120, 071802	$35.9fb^{-1}$		Feb. 2018
ATLAS Publications			
ATLAS-CONF-2020-007 *New*	$139fb^{-1}$		April 2020
ATLAS-CONF-2020-006 *New*	$139fb^{-1}$		April 2020
JHEP 05 (2019) 141	$79.8fb^{-1}$		May 2019

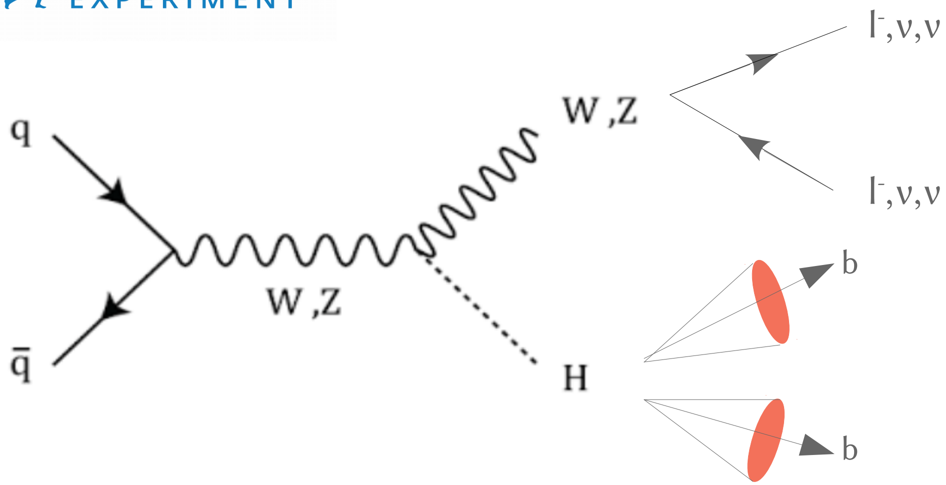




H→ bb: VH→ bb Analyses

ATLAS-CONF-2020-006

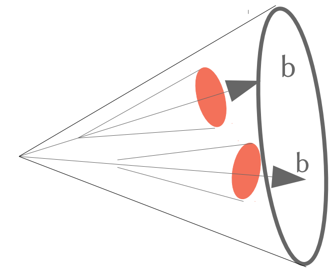
ATLAS-CONF-2020-007



W/Z-Boson Candidate Reconstruction:

- **0-lepton:** Large missing transverse energy (MET)
- **1-lepton:** 1 charged leptons: **l = [e,μ]**+ MET from neutrino **(υ)**
- **2-lepton:** 2 charged leptons: **ll=[ee,μμ]** + $m_{ll} \sim m_Z$

Increase p_T^H



Higgs Candidate Reco.:

Resolved Analysis: p_T^H > ~60 GeV

- 2 anti-k_t R=0.4 jets - **AK4**
- Exactly 2 b-tagged AK4 jets

Boosted Analysis: p_T^H > ~250 GeV

- 1 anti-k_t R = 1.0 jet - **AK10**
- ≥2 matched anti-k_t track jets
- 2 leading track jets b-tagged

More info in poster by K.Al Khoury → ATLAS-CONF-2020-006

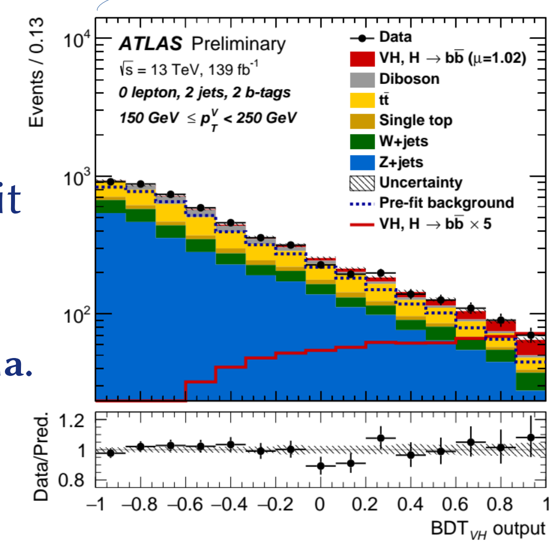
ATLAS-CONF-2020-007

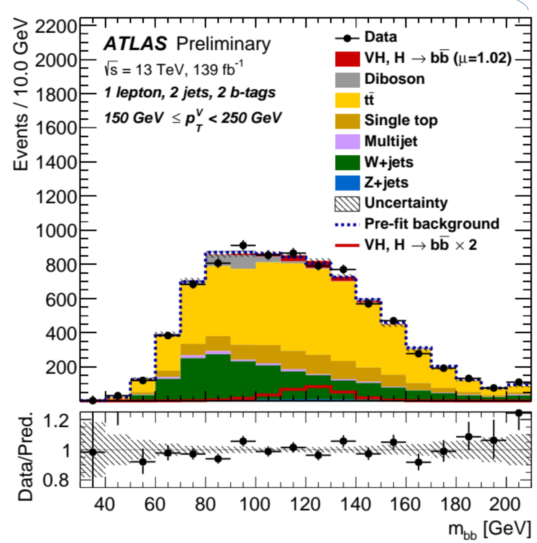
Binned profile likelihood fit

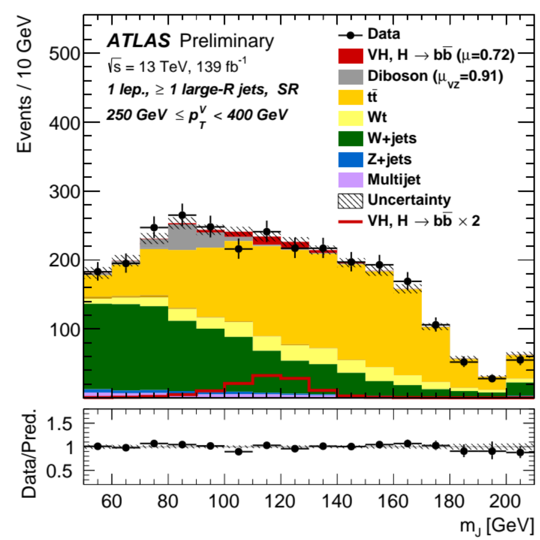
$\mathcal{L}(\mathbf{x}|\ \mu_{VH},\ \theta)$ where **x** is:

→ BDT - **MV analysis**

→ m_{bb}/m_J – **(Di-)Jet Mass ana.**

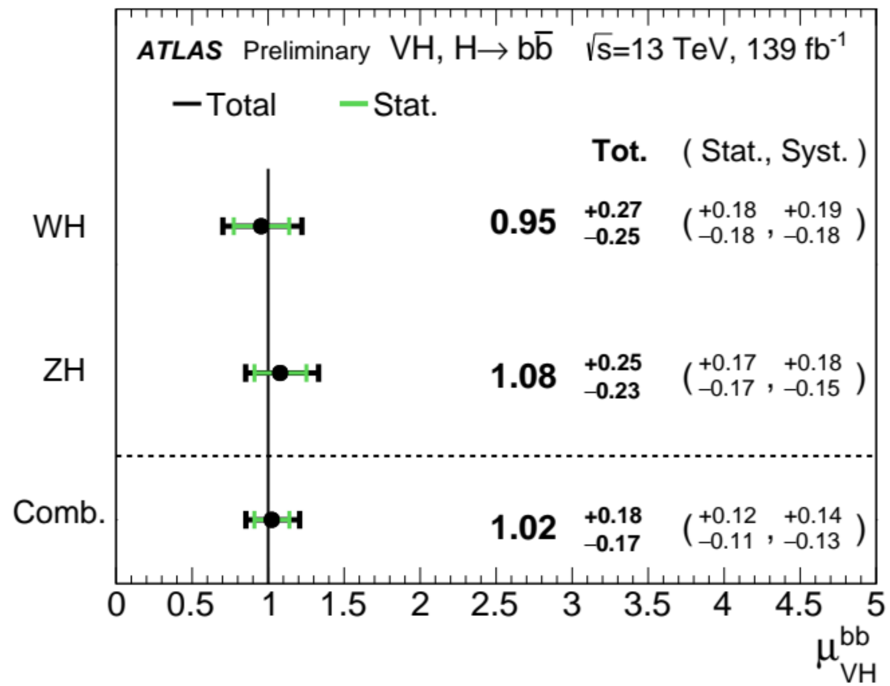






VH⟶ bb Results: Resolved

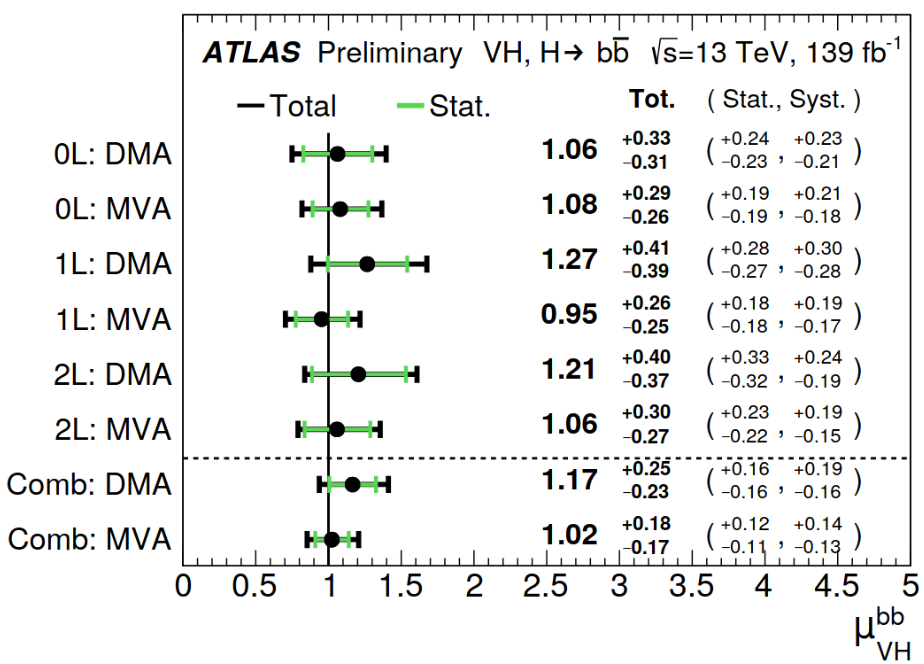
ATLAS-CONF-2020-006



Multivariate Analysis (MVA)

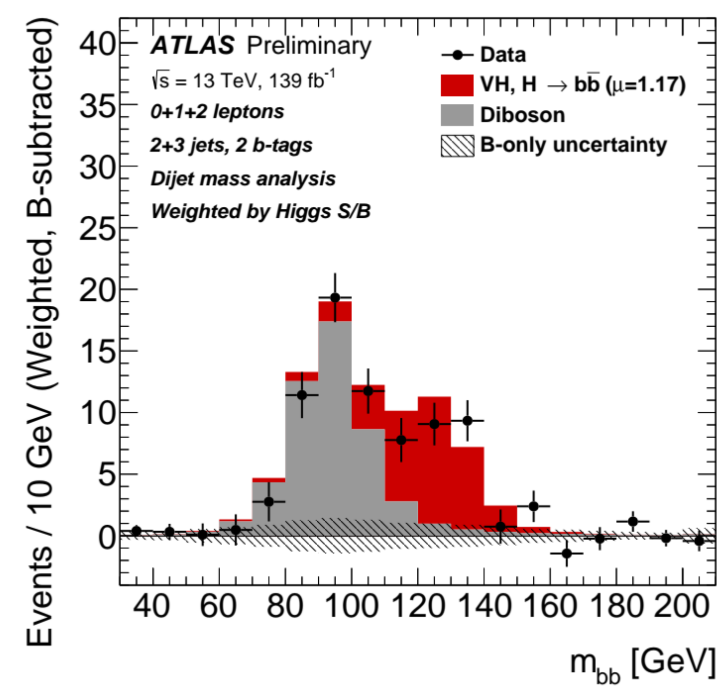
Obs.	(exp.)	
Z_0 = 4.0	(4.1) σ	⟵ Evidence for WH production
Z_0 = 5.3	(5.1) σ	⟵ Observation of ZH prodution
Z_0 = 6.7	(6.7) σ	⟵ Combined WH + ZH observation

Di-jet Mass Analysis (DMA)



S/B Weighted combination of m_{bb} distributions from 0+1+2L channels

Obs.	(exp.)
Z_0 = 5.4	(4.9) σ

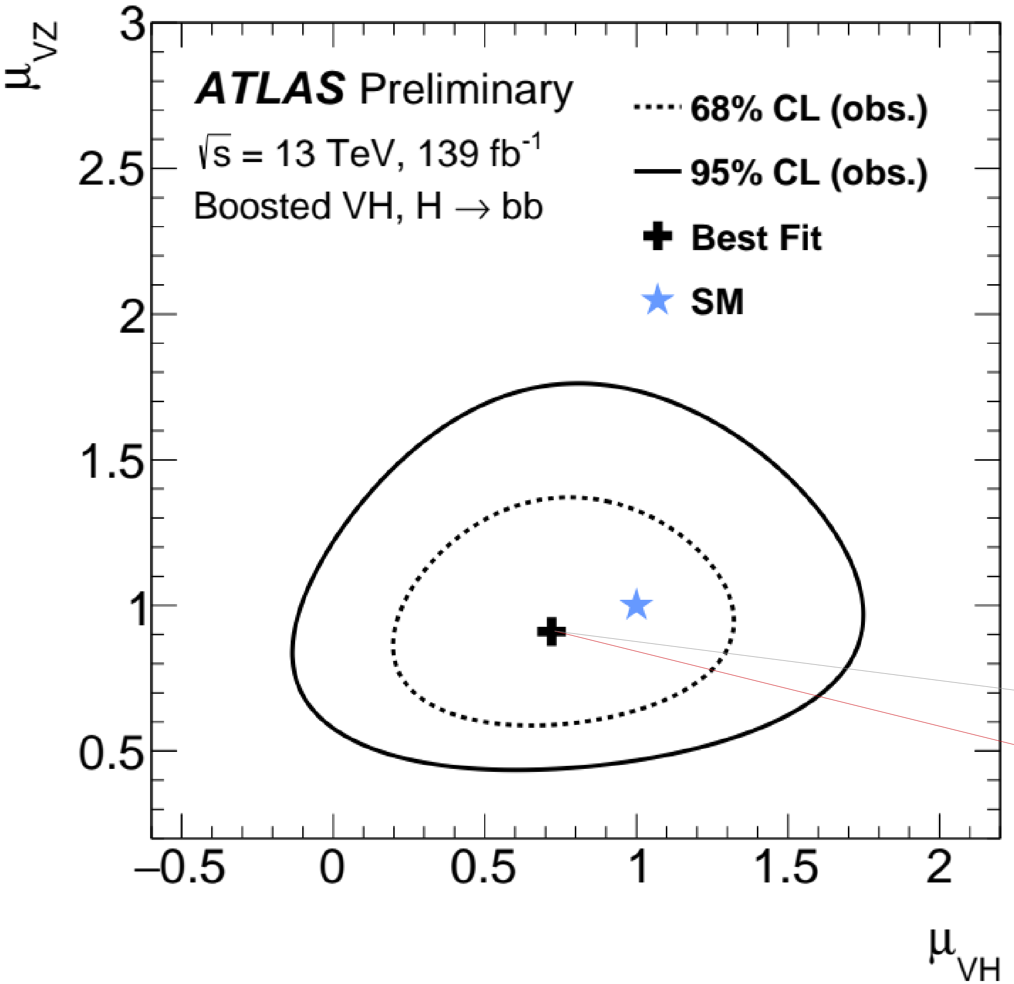


⟶ Good agreement between MVA & DMA

Stephen Jiggins

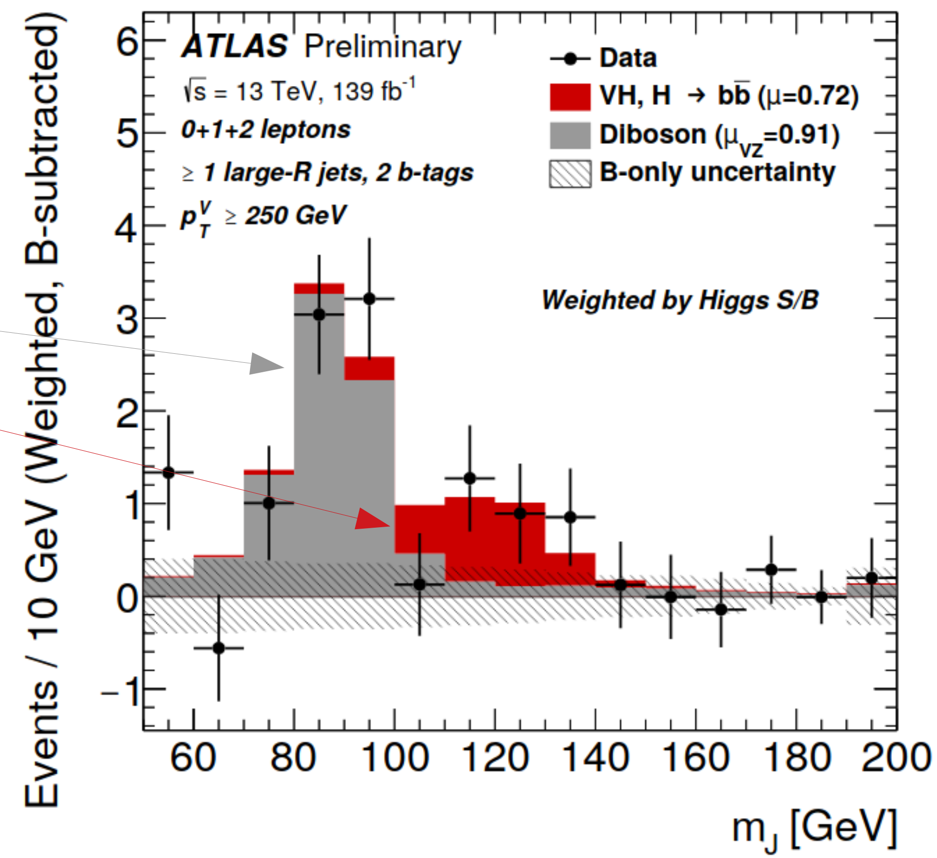
VH→ bb Results: Boosted

→ Simultaneous fit of VZ & VH signal strengths ($[\mu_{VZ},\mu_{VH}]$):



$$\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.25}_{-0.17}(\text{syst.}),$$

	Obs.	(exp.) significance
Z_0 =	5.4	(5.7) σ

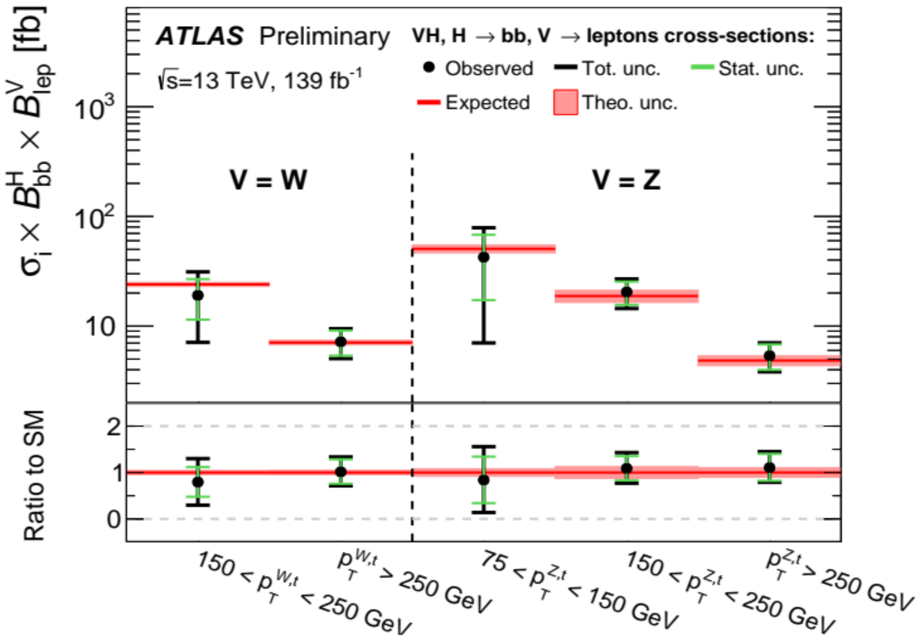


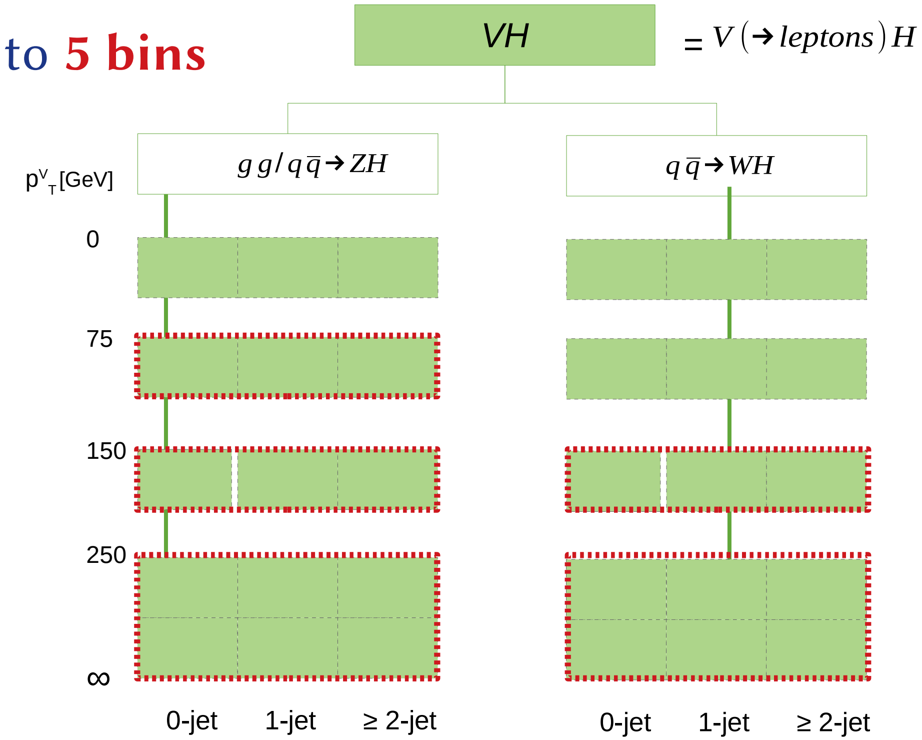
$$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.}).$$

	Obs.	(exp.) significance
Z_0 =	2.1	(2.7) σ

VH⟶ bb STXS

⟶ **VHbb resolved:** Stage 1.2 STXS scheme merged down to **5 bins**





⟶ **VHbb Resolved:** Increased precision of 5 POI $\sigma^{W/ZH}$ results:

80fb^{-1}: 50%-125% uncertainty on $\sigma^{W/ZH}$

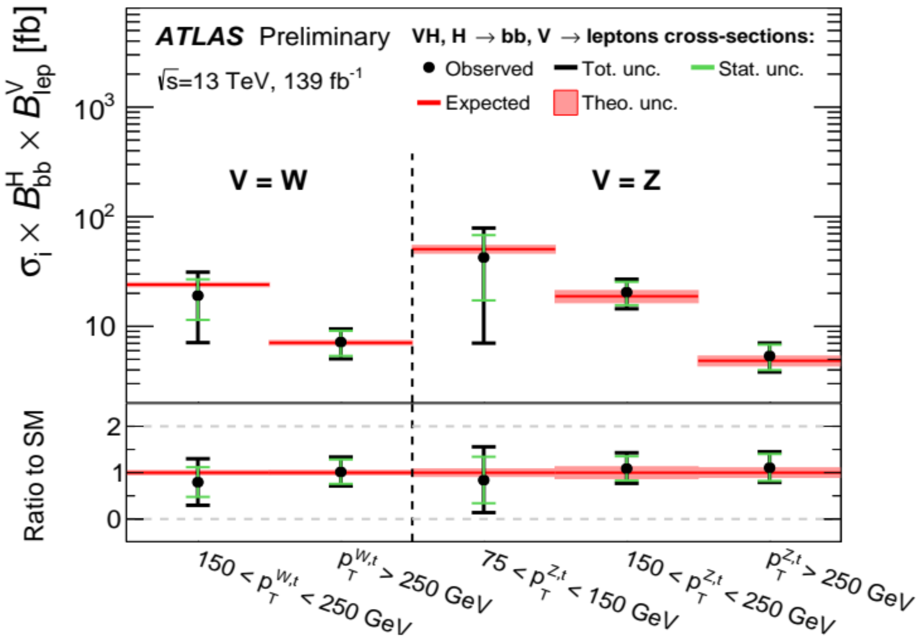
139fb^{-1}: 30%-85% uncertainty on $\sigma^{W/ZH}$

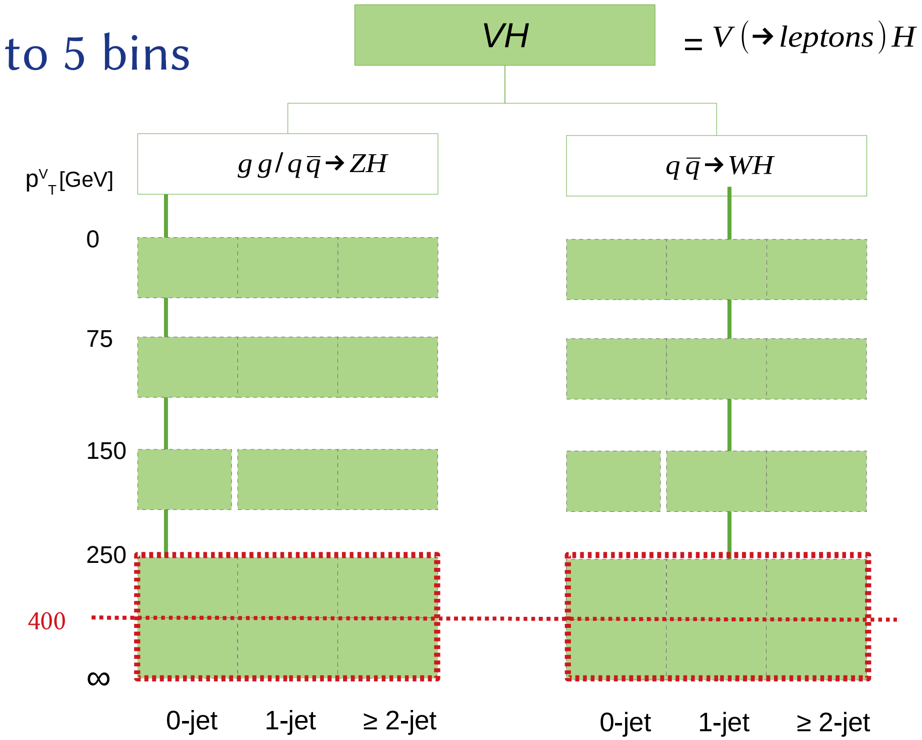
VH→ bb STXS

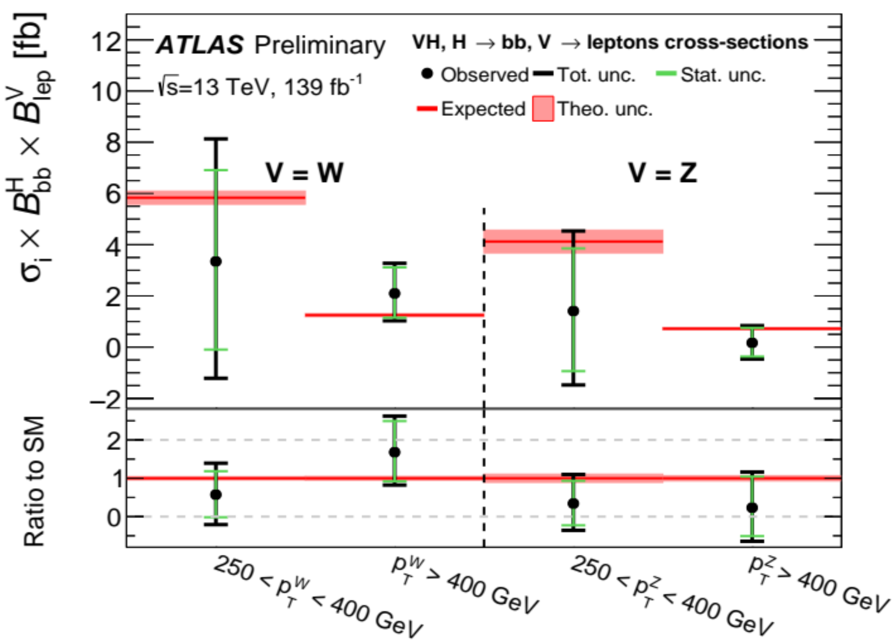
ATLAS-CONF-2020-006

ATLAS-CONF-2020-007

→ **VHbb resolved:** Stage 1.2 STXS scheme merged down to 5 bins







→ **VHbb Resolved:** Increased precision of 5 POI $\sigma^{W/ZH}$ results:

80fb^{-1}: 50%-125% uncertainty on $\sigma^{W/ZH}$

139fb^{-1}: 30%-85% uncertainty on $\sigma^{W/ZH}$

→ **VHbb boosted:** Stage 1.2 STXS scheme merged down to **4 bins**

- Measurement of p^V_T(truth) > 400 GeV

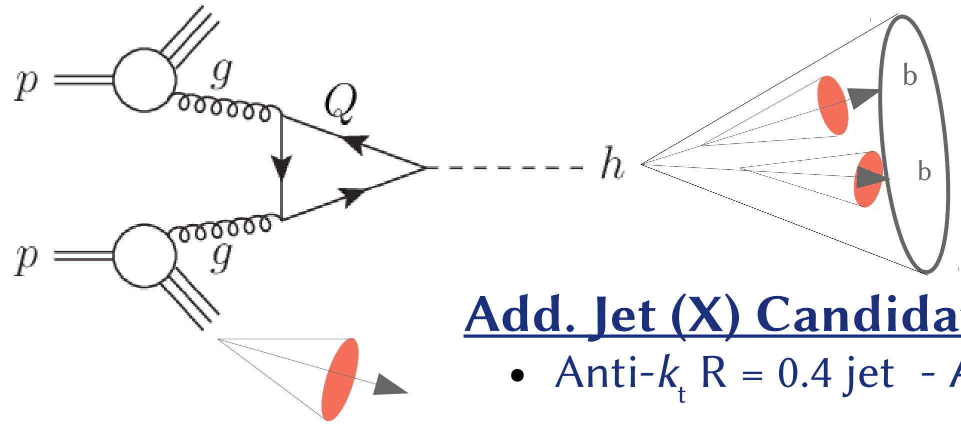
→ VHbb resolved + boosted **not orthogonal!**

→ See talk by Nikita Belyaev for more STXS/EFT results

→ Or backup for questions!

H→ bb: Inclusive ggF high p_T^H

→ **Signal:** pp → H(→bb) + X, via ggF



Higgs Candidate Reco.: $p_T^H \sim p_T^{AK8} > 450$GeV

- Anti-k_t R = 0.8 jet - **AK8 jet**
- Soft-drop algorithm → m_{SD}

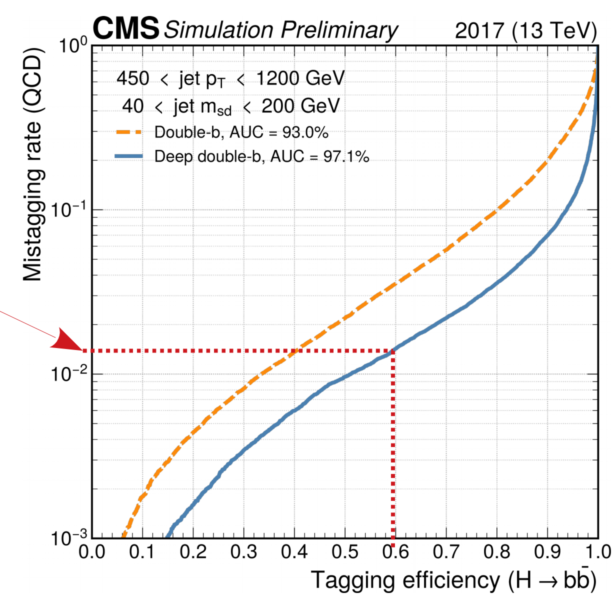
Analysis fit discriminant!

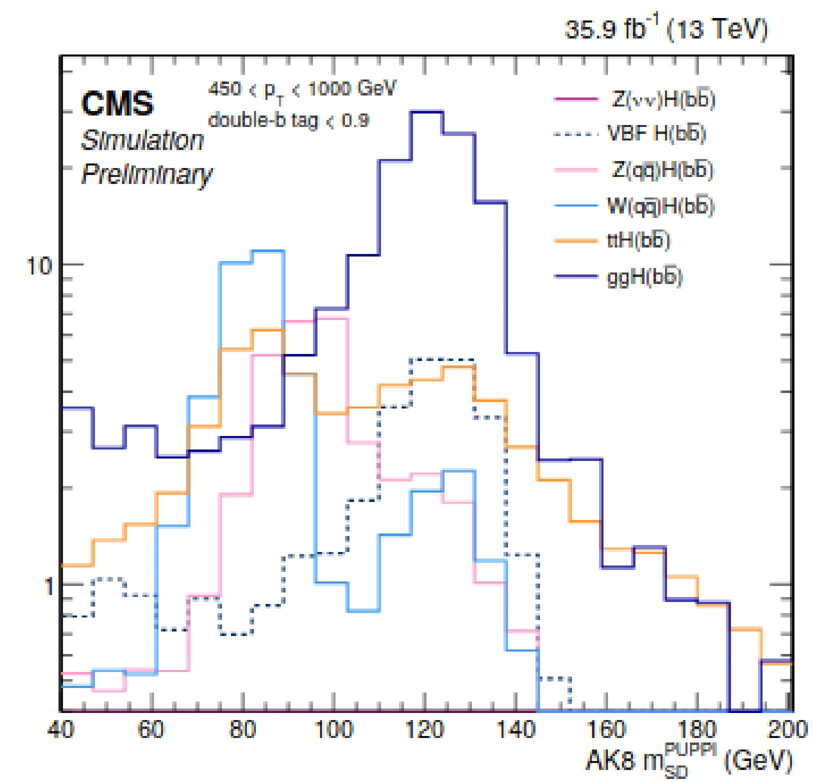
Add. Jet (X) Candidate Reco.:

- Anti-k_t R = 0.4 jet - **AK4 jet**

Double b-jet Identification:

- Double-b tagging algorithm using a new 'deep neural network'
- AK8 jet must contain two b-tags
  - **60% eff.** for **signal**
  - **1%** misidentification rate for **QCD**
- **'Passing'** / **'Failing'** double b-tag
  =
  'Signal' / **'Control'** region
  → Used to constrain QCD background



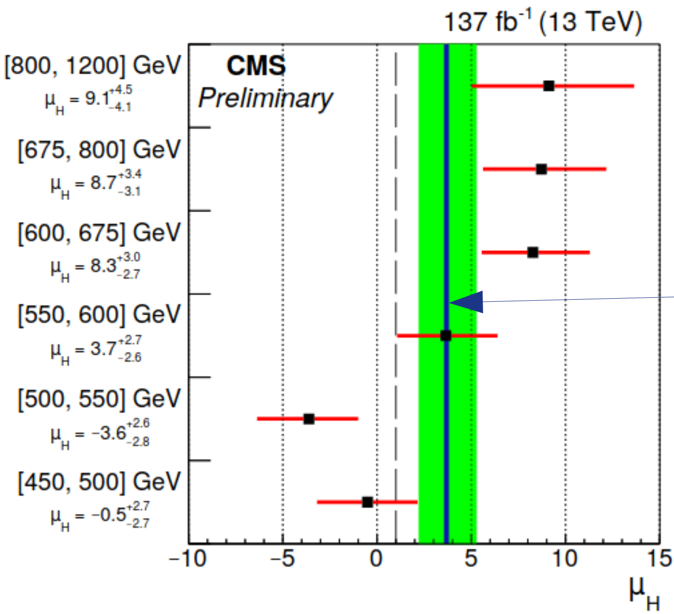


Inclusive ggF high p_T^H: Analysis Strategy

HIG-19-003

→ Maximum likelihood fits of μ^{ggF}_{H}:

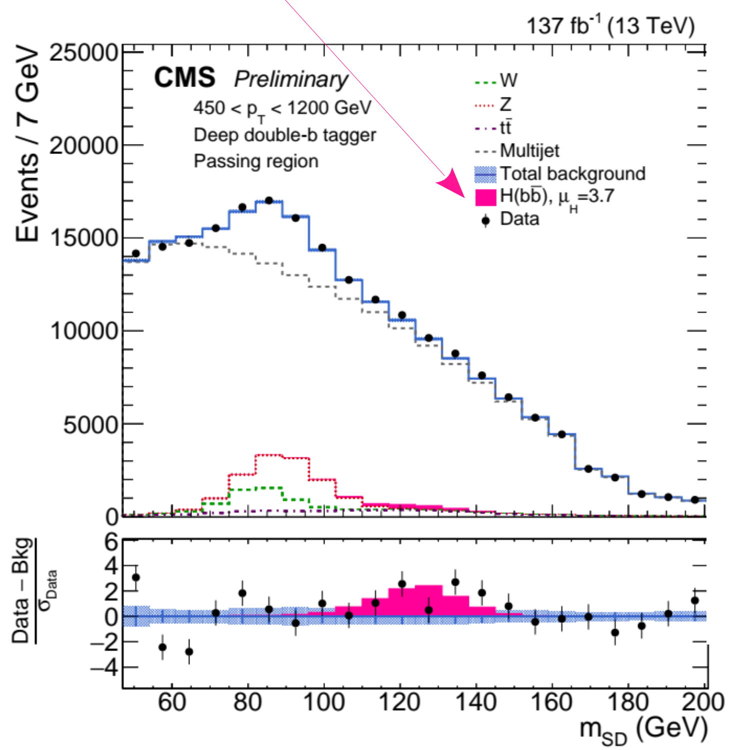
- **p_T AK8 binning:** $[\mu^{450}_{H}, \mu^{550}_{H}, \mu^{600}_{H}, \mu^{675}_{H}, \mu^{800}_{H}]$
- **Combined:** $[\mu^{comb.}_{H}]$



$\mu^{comb.}_{VH} = 3.68^{+1.58}_{-1.46}$

$Z^{obs\,(exp)}_{\mu=0} = 2.54(0.71)\,\sigma$

→ Excess exceeding $\mu_{VH} = 1$ by **1.85σ**

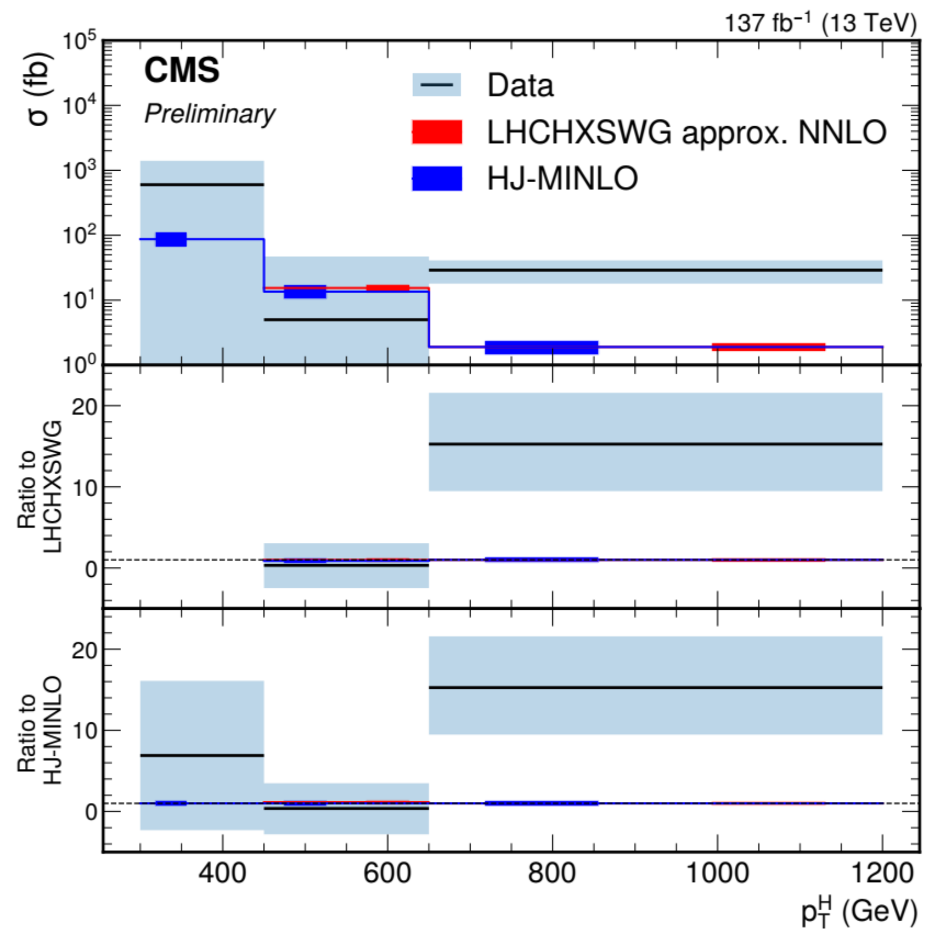


→ Likelihood based unfolding to particle level comparing:

- LHC XS WG $\sigma_{H\to bb}$: LHCHXSWG-2019-002
- HF-MINLO $\sigma_{H\to bb}$: MC generator configurations

→ $\sigma^{300\text{-}1200.}_{H\to bb}$ upward deviation of **1.91σ**

→ $\sigma^{650\text{-}1200.}_{H\to bb}$ upward deviation of **2.65σ**

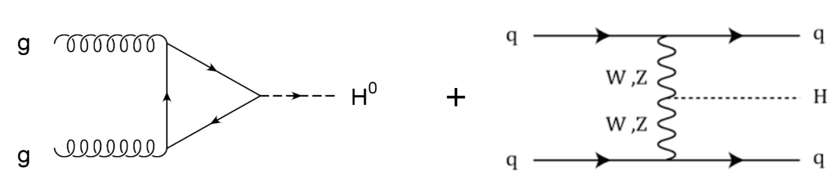
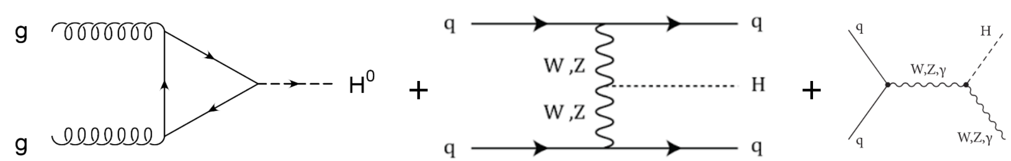


$H \rightarrow \tau\tau$

$H \rightarrow \tau\tau$

→ Only one new paper for $H \rightarrow \tau\tau$

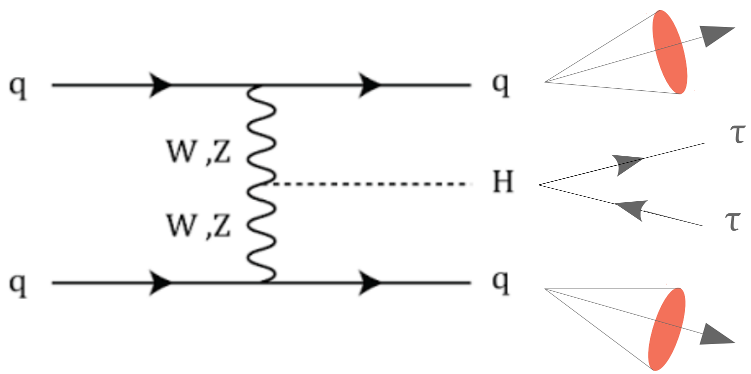
→ ATLAS now published a CP invariance test of BSM using $H \rightarrow \tau\tau$ - counterpart to CMS 2019 publication

ATLAS Publications			
Paper	**Luminosity**	**Signal**	**Date**
Phys. Lett. B 805 (2020) 135426	New 36.1fb^{-1}		Feb. 2020
PhysRevD. 99 072001	36.1fb^{-1}		April 2019
CMS Publications			
PRD 100 (2019) 112002	**Run 2:** 35.9-80.2fb^{-1} **Run 1:** 5.1+19.7fb^{-1}		Dec. 2019
HIG-18-032	77.4fb^{-1}		March 2019

Counterparts

Test of CP Invariance in VBF H⟶ ττ

Phys. Lett. B 805 (2020) 135426



Higgs Candidate Reco.:

- $\tau_{lep}\tau_{lep}$ **SF:** Same flavour leptons
- $\tau_{lep}\tau_{lep}$ **DF:** Different flavour leptons
- $\tau_{lep}\tau_{had}$**:** Semi-leptonic τ decays
- $\tau_{had}\tau_{had}$**:** Hadronic τ decays

'Missing Mass Calculator' ⟶ $m^{MMC}_{\tau\tau}$ (arXiv:1012.4686)

Jet Reco.:

- Anti-k_t R = 0.4 jet - **AK4 jet**

Physics Interpretation:

⟶ Effective lagrangian ($\mathcal{L}_{eff}$) composed of:

- Standard Model: $\mathcal{L}_{SM}$
- CP-odd mass dim. Six: $\mathcal{L}^{6}_{CP}$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{f_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{f_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \mathrm{O}\left(\frac{1}{\Lambda^3}\right)$$

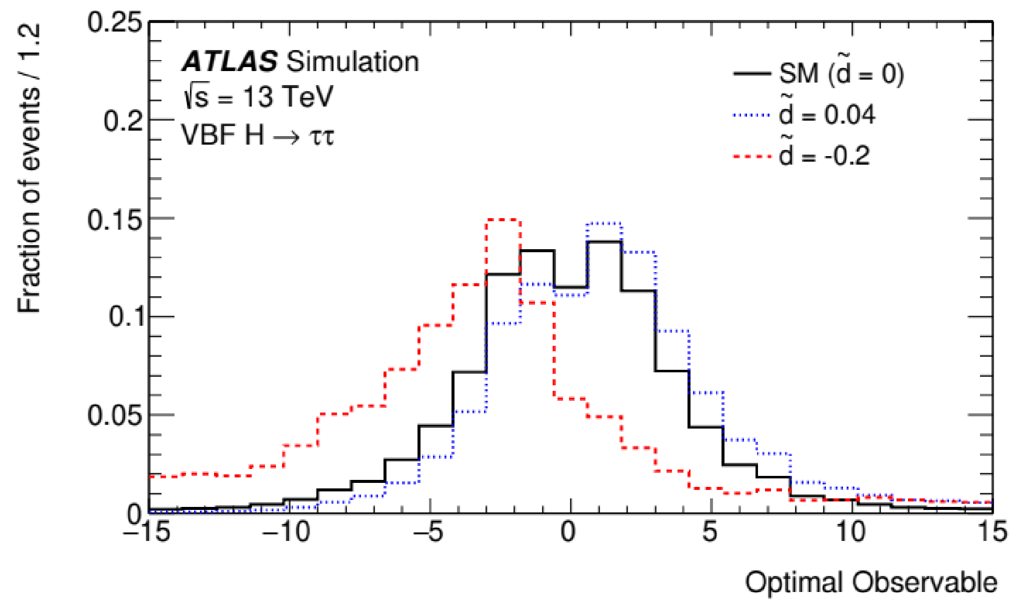
⟶ $\tilde{d}$ parameterises strength of CP-violation:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\tilde{d}\cdot\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}}) + \tilde{d}^2\cdot|\mathcal{M}_{\mathrm{CP\text{-}odd}}|^2$$

Fit Discriminant:

⟶ Utilise matrix element calculated from HAWK [Link]

⟶ **Optimal Observable:** $$O_{\mathrm{opt}} = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}.$$



Test of CP Invariance in VBF H⟶ ττ: Results

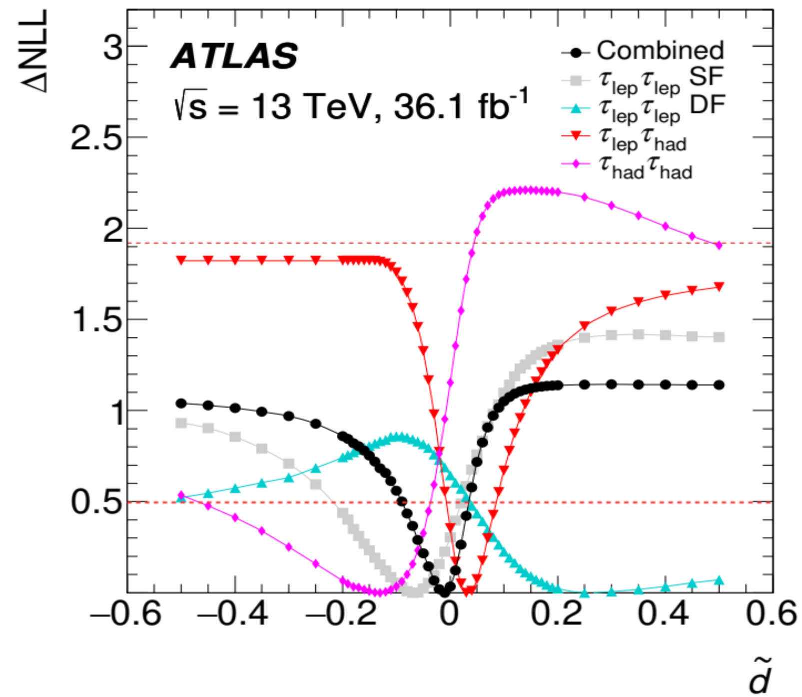
Phys. Lett. B 805 (2020) 135426

⟶ Binned maximum likelihood $\mathcal{L}(\mathbf{x},\mu|\theta)$ as a function of each $\tilde{d}$ hypothesis

⟶ Unconstrained signal normalisation 'μ' - **shape only analysis**

⟶ Summary of mean <Optimal Obs.> for each channel and combined result:

Channel	⟨Optimal Observable⟩
$\tau_{lep}\tau_{lep}$ SF	-0.54 ± 0.72
$\tau_{lep}\tau_{lep}$ DF	0.71 ± 0.81
$\tau_{lep}\tau_{had}$	0.74 ± 0.78
$\tau_{had}\tau_{had}$	-1.13 ± 0.65
Combined	-0.19 ± 0.37



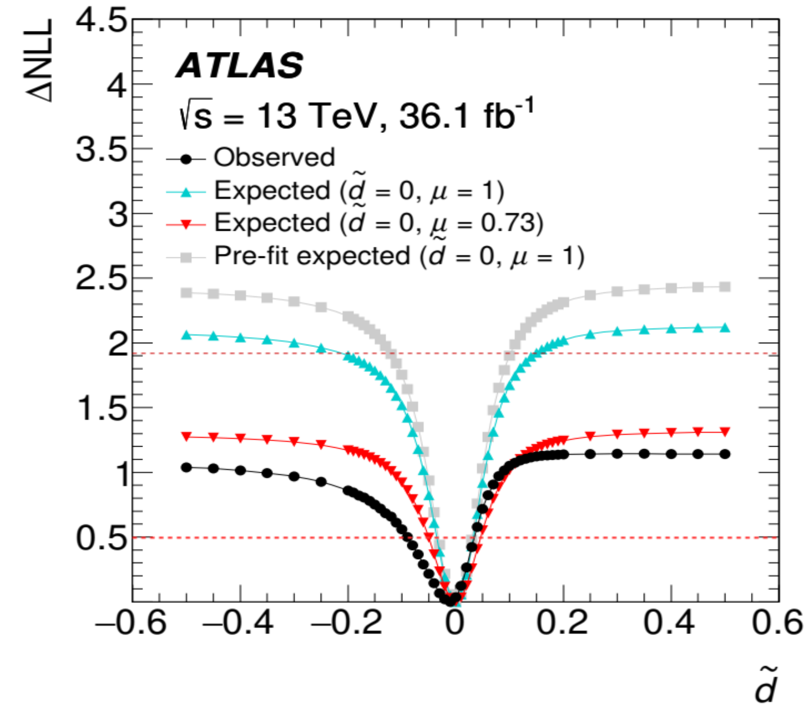
⟶ *Expected results*: Asimov dataset from Np set to observed CR fit only values
Pre-fit Expected: Asimov dataset from Np set to SM expectation asimov fit.

⟶ Conditional [μ=1, $\tilde{d}$ = 0] and [μ=0.73, $\tilde{d}$ = 0] asimov fits demonstrate loss of observed sensitivity due to lower than expected event yields

⟶ 68%(95%) CL interval on $\tilde{d}$ set for observed and expected:

Obs. 68% CL: $\tilde{d} \in [-0.090, 0.035]$
Exp. 68% CL: $\tilde{d} \in [-0.035, 0.033]$
Obs. 95% CL: $\tilde{d} \in [N/A]$
Exp. 95% CL: $\tilde{d} \in [-0.21, 0.15]$

Asymmetry in CL due to asymmetric Opt. Obs.
⟶ See previous slide



Constraints on anomalous HVV couplings: H→ ττ

PRD 100 (2019) 112002

→ Anomalous HVV couplings in VBF/ggF/VH production using:

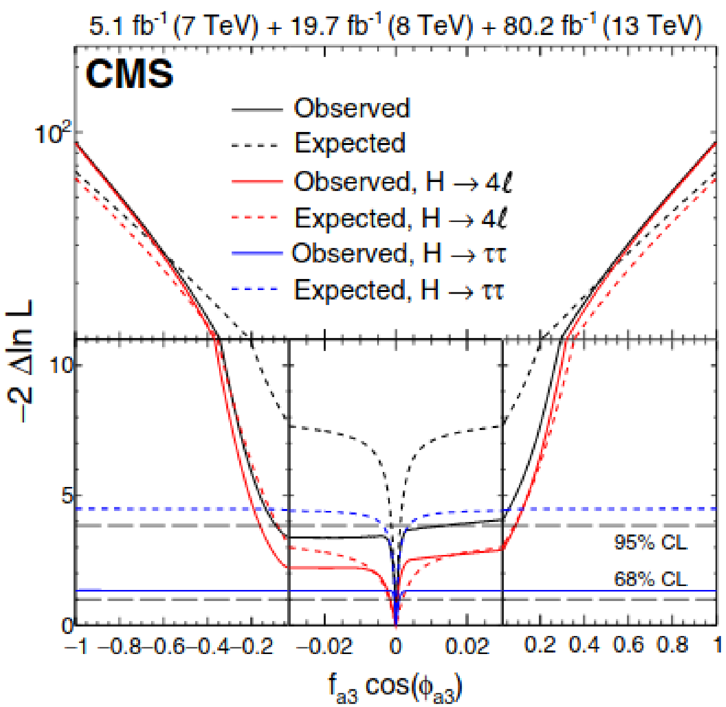
- H→ ττ **35.9fb^{-1}** analysis (see PLB 779 (2018) 283)
- H→4l Run 1+2 analyses (see PhysRevD. 99 112003)

→Amplitude for spin-0 Higgs with two spin-1 gauge bosons VV:

$$A(HVV) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

- Λ_1: BSM scale
- a^{VV}_3 CP-odd interaction
- a^{VV}_2 CP-even interaction

→ HVV anomalous couplings measured using effective cross-section ratios f_{ai}, and relative phase Φ:



$$\phi_{a_i} = arg\left[\frac{a_i}{a_1}\right]$$

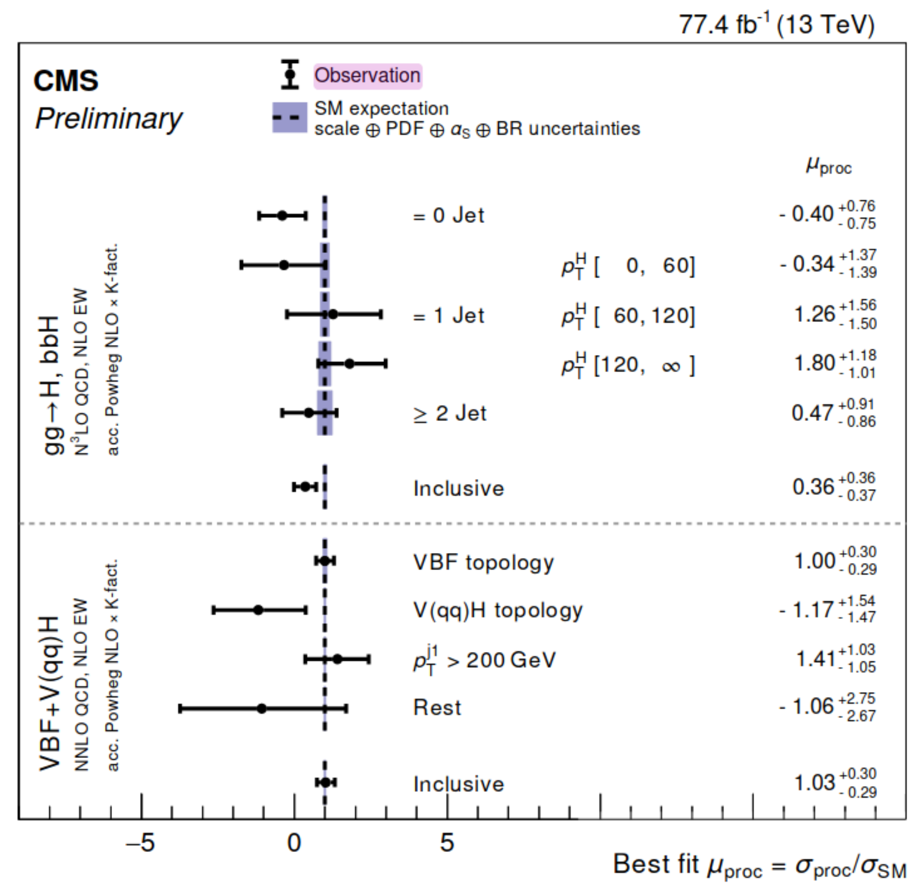
$$f_{a_i} = \frac{a_i^2 \sigma_i}{\sum a_i^2 \sigma_i}$$

HIG-18-032

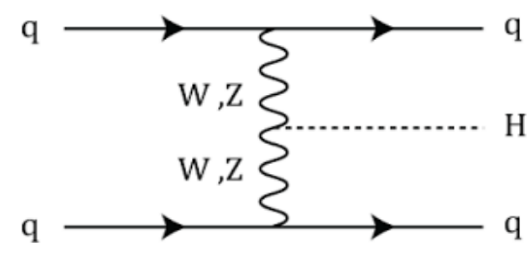
→ Measurement of H→ ττ sensitive to VBF+ggF+VH production modes updated with **77.4fb^{-1}**

→ **Update 1:** Multiclass NN used to separate 9-classes
- [ggF,VBF] signal + 7 bkg

→ **Update 2:** Included a STXS result for ggF and VBF production modes:



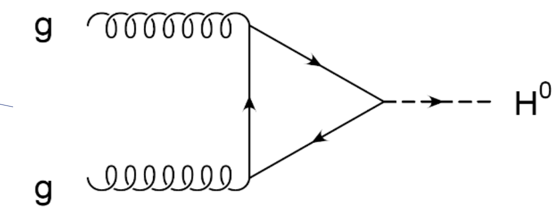
Conclusions



VBF: σ(pp⟶H+X) ~ 7%

Paper	Analysis	Date
Phys. Lett. B 805 (2020) 135426 ATLAS EXPERIMENT	H ⟶ ττ Tests of CP Invariance 36.1 fb^{-1} New	Feb. 2020
HIG-19-003 CMS	Highly boosted H⟶bb at √s= 13 TeV with CMS detector - 137 fb^{-1} New	April 2020
ATLAS-CONF-2020-007 ATLAS EXPERIMENT	Boosted VH ⟶ bb √s=13 TeV with the ATLAS detector – 139.1 fb^{-1} New	April 2020
ATLAS-CONF-2020-006 ATLAS EXPERIMENT	VH ⟶ bb at √s=13 TeV 13TeV with the ATLAS detector – 139.1 fb^{-1} New	April 2020

⟶ Constraints on CP invariance via EFT lagrangian extensions

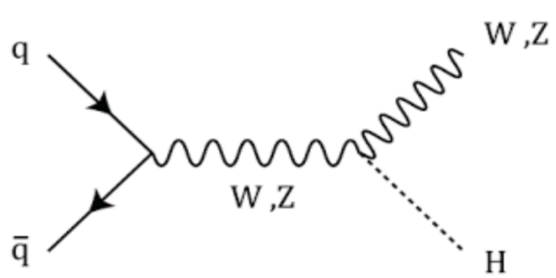


ggF: σ(pp⟶H+X) ~ 87%

⟶Intriguing excess beyond SM ggF H⟶bb production

⟶ High p^H_T excess most dominant

⟶ Keep a close eye in the future!



VH: σ(pp⟶H+X) ~ 5%

⟶ Observation of VH⟶ bb

⟶ Observation of ZH ⟶ bb

Not via combination!

⟶ Strong evidence of WH⟶bb

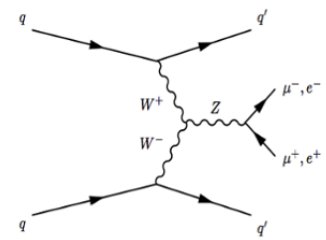
⟶ Proof of concept for boosted VH⟶bb topology

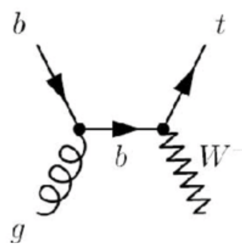
Backup

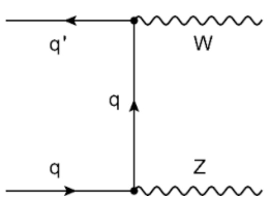
H⟶ bb: VH⟶ bb Analysis Strategies

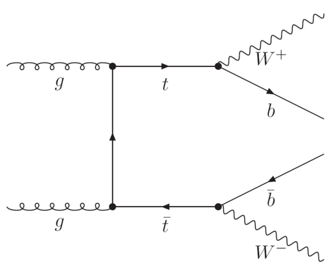
Background Estimation

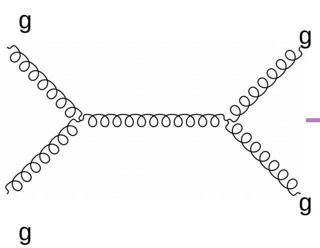
⟶ Common backgrounds in both resolved & boosted:











- W+Jets
- Wt
- VV

Resolved+Boosted: Purely Monte Carlo (MC) estimated

- Z+Jets
- tt

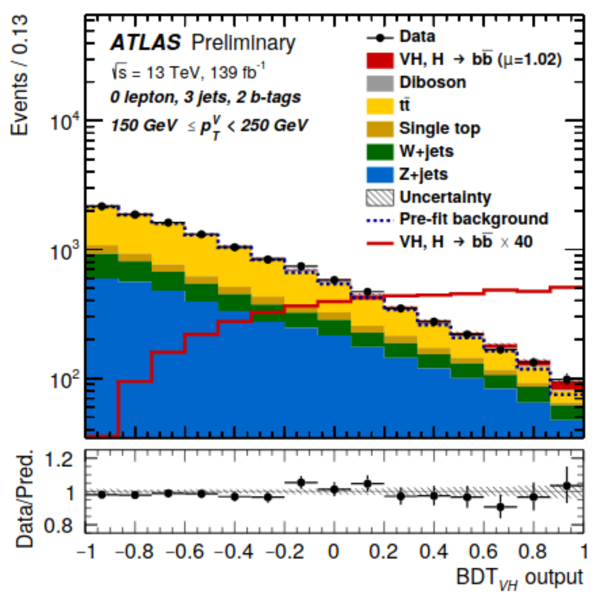
Resolved: Mix of MC/Data-driven estimates/errors
Boosted: Purely MC estimated

- QCD ⟶ **Resolved+Boosted:** Data-driven estimates/errors

Fit Strategy

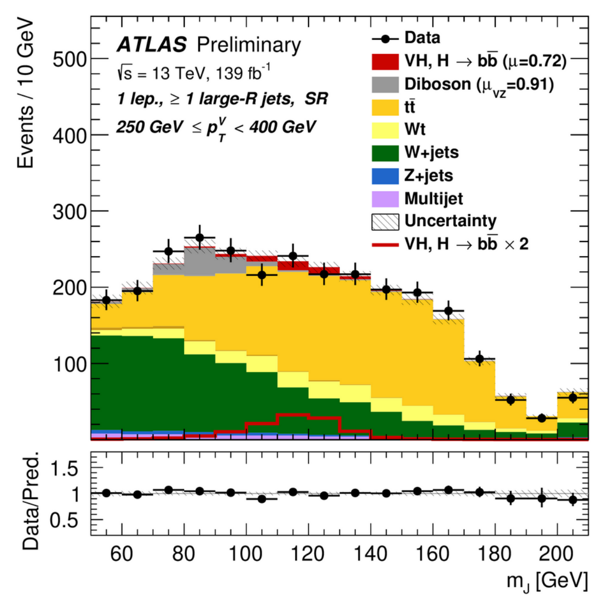
⟶ Binned profile likelihood fit $\mathcal{L}(\mathbf{x}|\ \mu_{VH}, \theta)$ where **x** is:

x = BDT: Resolved only



⟶ **Multi-Variate Analysis (MVA)**

x = $m_{bb/J}$: Resolved + Boosted



⟶ **(Di-)Jet Mass Analysis (DMA)**

⟶ **Resolved:** 42 fit regions

⟶ **Boosted:** 14 fit regions

⟶ 3 signal results quoted:
⟶ $[\mu_{VH}, \mu_{WH}, \mu_{ZH}]$

H→ bb: VH→ bb Analysis Strategies

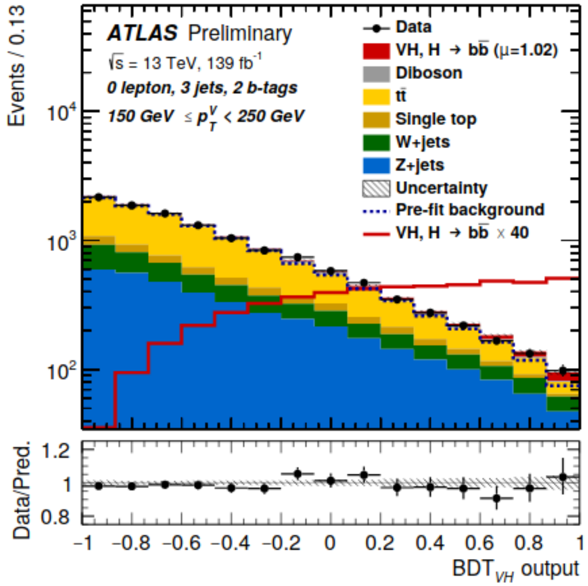
ATLAS-CONF-2020-006
ATLAS-CONF-2020-007

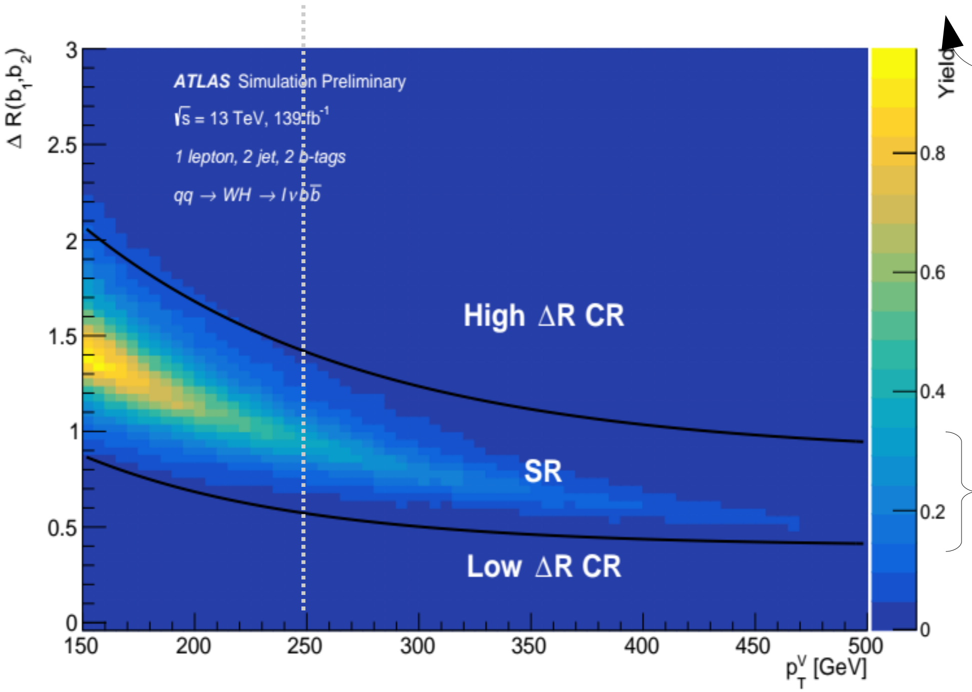
Multi-Variate Analysis (MVA): Resolved only

→ Binned profile likelihood fit $\mathcal{L}(\mathbf{x},\mu_{VH}|\theta)$ using a BDT_{VH} fit discriminant in signal regions (SR)

→ Analysis fit regions defined by **[p^V_T, ΔR(b,b)]** plane:

- [0, 1, 2]-lepton channels
- [2, 3(+)] jets
- [75,150,250+] p^V_T bins
- [CR_{Low}, SR, CR_{high}]

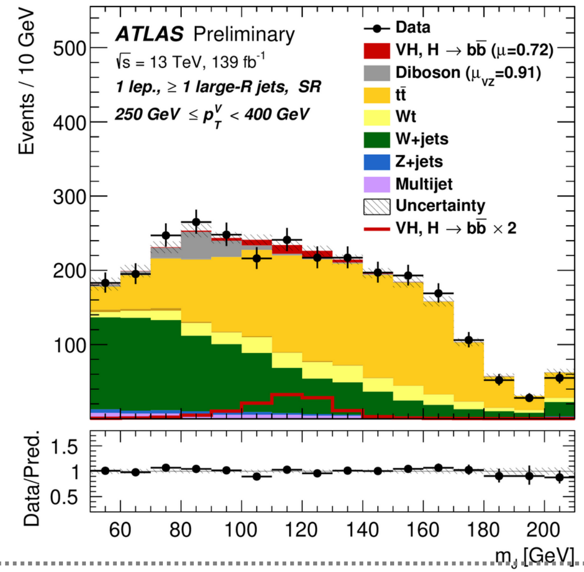




80-90% of signal events

(Di-)Jet Mass Analysis (DMA): Resolved + Boosted

→ Binned profile likelihood fit $\mathcal{L}(\mathbf{x},\mu_{VH}|\theta)$ of m_{bb}/m_J (Res./Boosted):



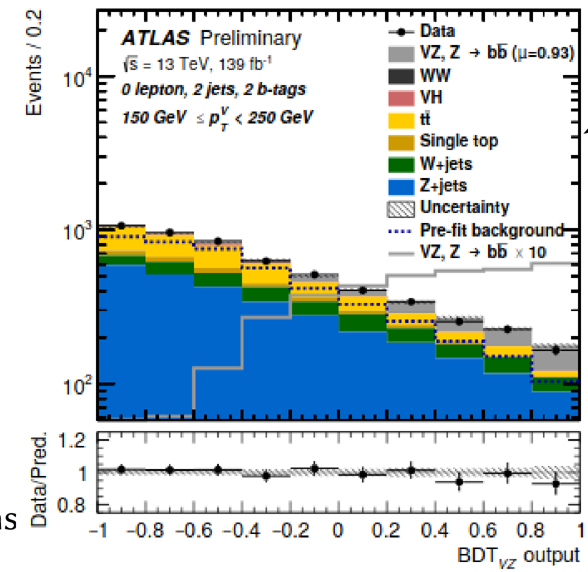
Boosted: m_J

→ Analysis fit regions by:
- [0, 1, 2]-lepton channels
- [0, 1+] b-tag add. track jets
- [250,400+] p^V_T bins
- [0, 1+] add. AK4 jets

14 fit regions

VZ(→bb) Analysis (VZ): Resolved + Boosted

→ VZ(bb) $\mathcal{L}(\mathbf{x},\mu|\theta)$ fit using $\boldsymbol{\mu_{VZ}}$ instead fitting $\mathbf{BDT_{VZ}}$ or $\mathbf{m_J}$

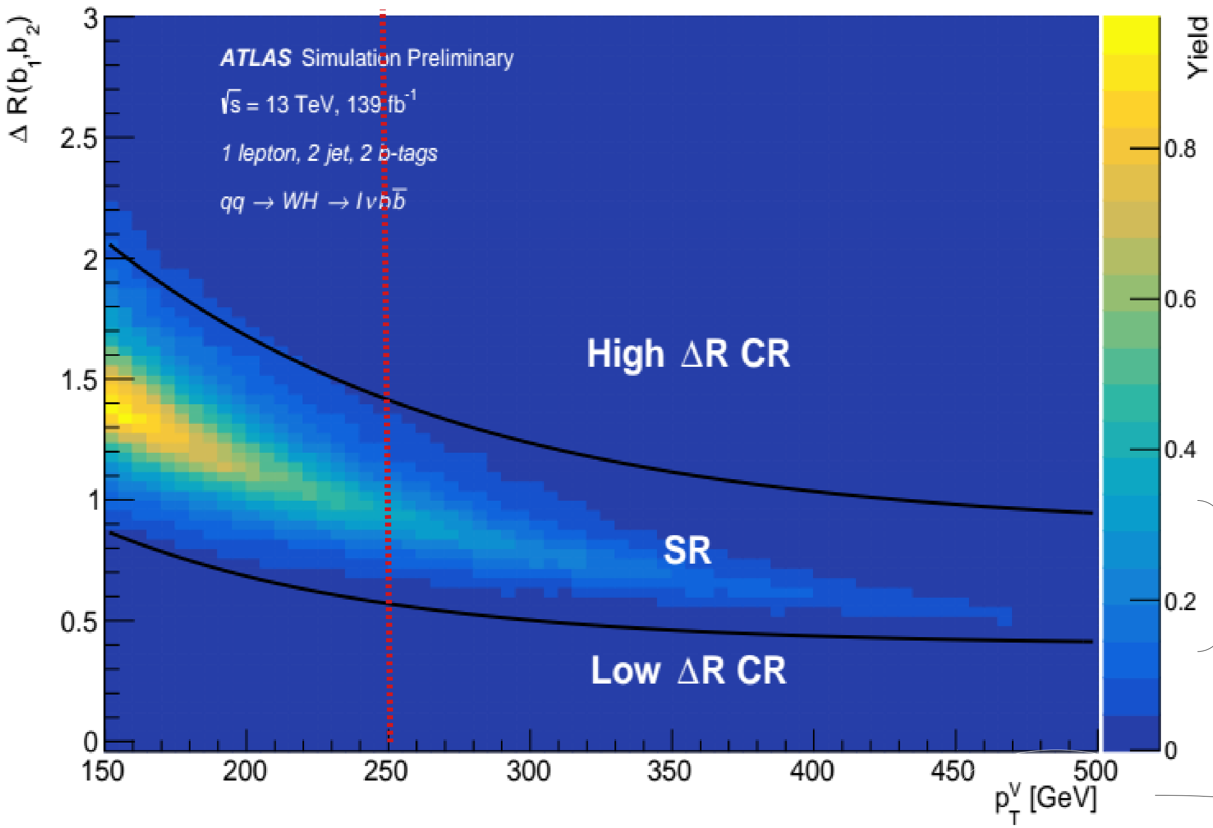


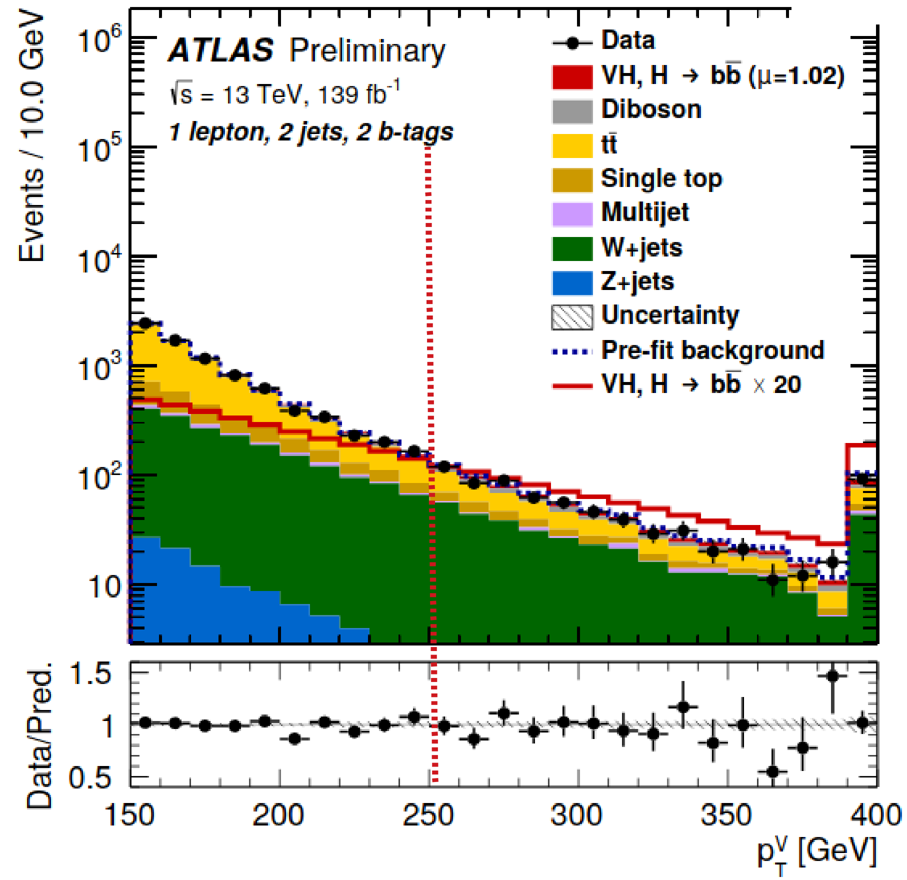
VH→ bb Resolved Event Categorisation

Analysis Event Categorisation:

- ΔR(b,b) and p^V_T define analysis fit regions

80-90% of signal events





Analysis fit regions:

[0, 1, 2]-lepton channels
[2, 3(+)] jets
[75,150,250+] p^V_T bins
[CR_{Low}, SR, CR_{high}]

= 42 fit regions

→ Slice p^V_T axis it 2(3) p^V_T bins: [(75,)150,250+]

→ For 0/1-(2-) lepton channels

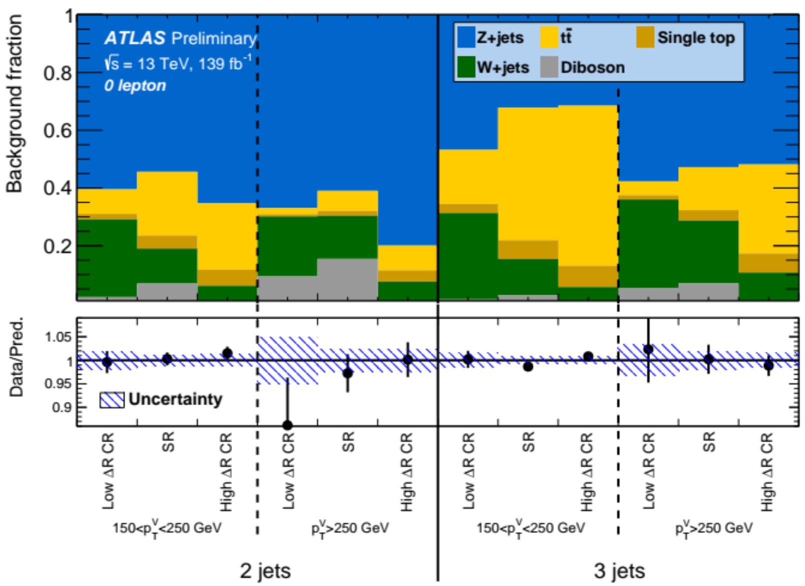
VH⟶ bb Resolved Event Categorisation – Fit Regions

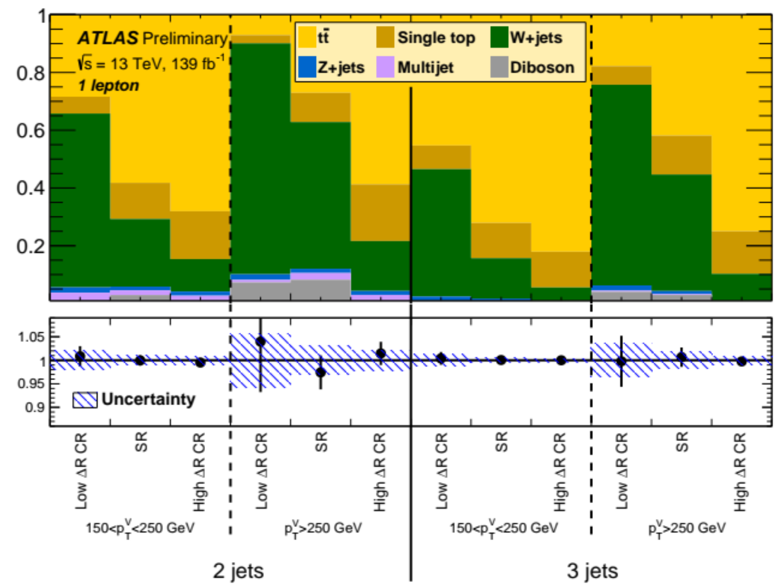
⟶ BDT_{score} used as fit discriminant in SR's

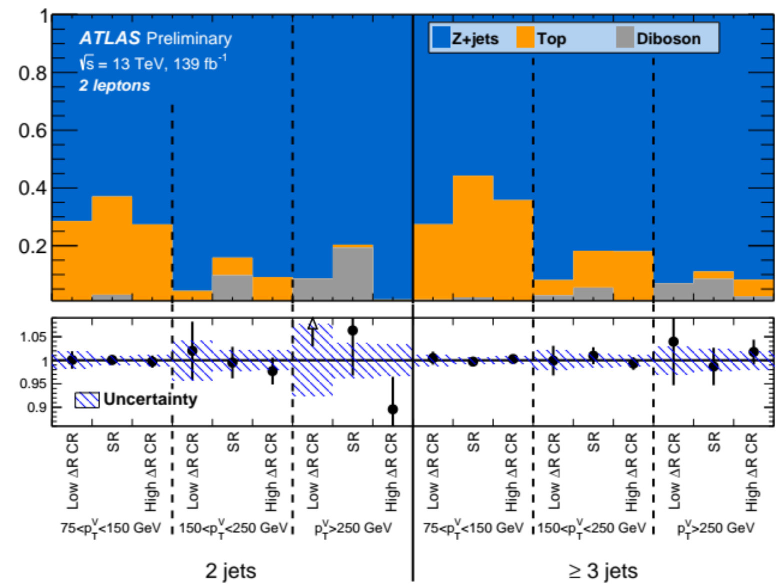
⟶ $CR_{Low/High}$ used only to constrain normalisation – single bin

⟶ Across p^V_T regions CR single bins provide differential shape information

Channel	Region	Categories: 75 GeV< p_T^V < 150 GeV 2-jets	75 GeV< p_T^V < 150 GeV 3-jets	150 GeV< p_T^V < 250 GeV 2-jets	150 GeV< p_T^V < 250 GeV 3-jets	p_T^V > 250 GeV 2-jets	p_T^V > 250 GeV 3-jets
0-lepton	Low-ΔR-CR	–	–	Yields	Yield	Yield	Yield
	Signal region	–	–	BDT	BDT	BDT	BDT
	High-ΔR-CR	–	–	Yield	Yield	Yield	Yield
1-lepton	Low-ΔR-CR	–	–	Yield	Yield	Yield	Yield
	Signal region	–	–	BDT	BDT	BDT	BDT
	High-ΔR-CR	–	–	Yield	Yield	Yield	Yield
2-lepton	Low-ΔR-CR	Yield	Yield	Yield	Yield	Yield	Yield
	Signal region	BDT	BDT	BDT	BDT	BDT	BDT
	High-ΔR-CR	Yield	Yield	Yield	Yield	Yield	Yield



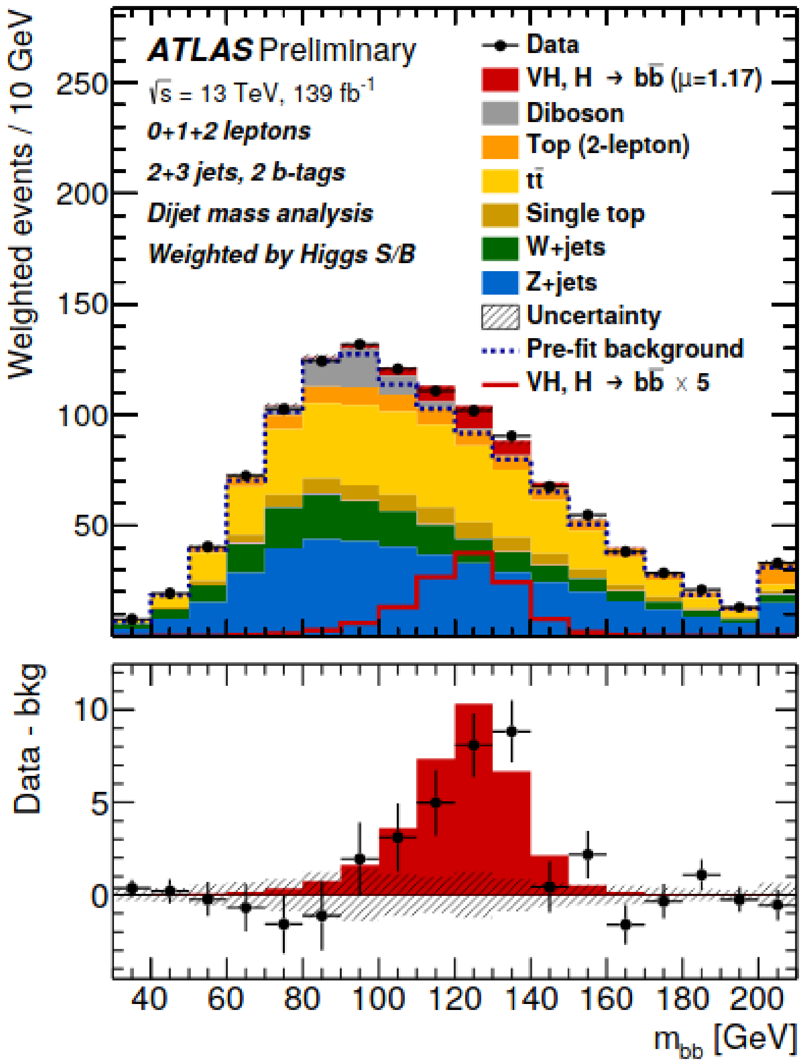


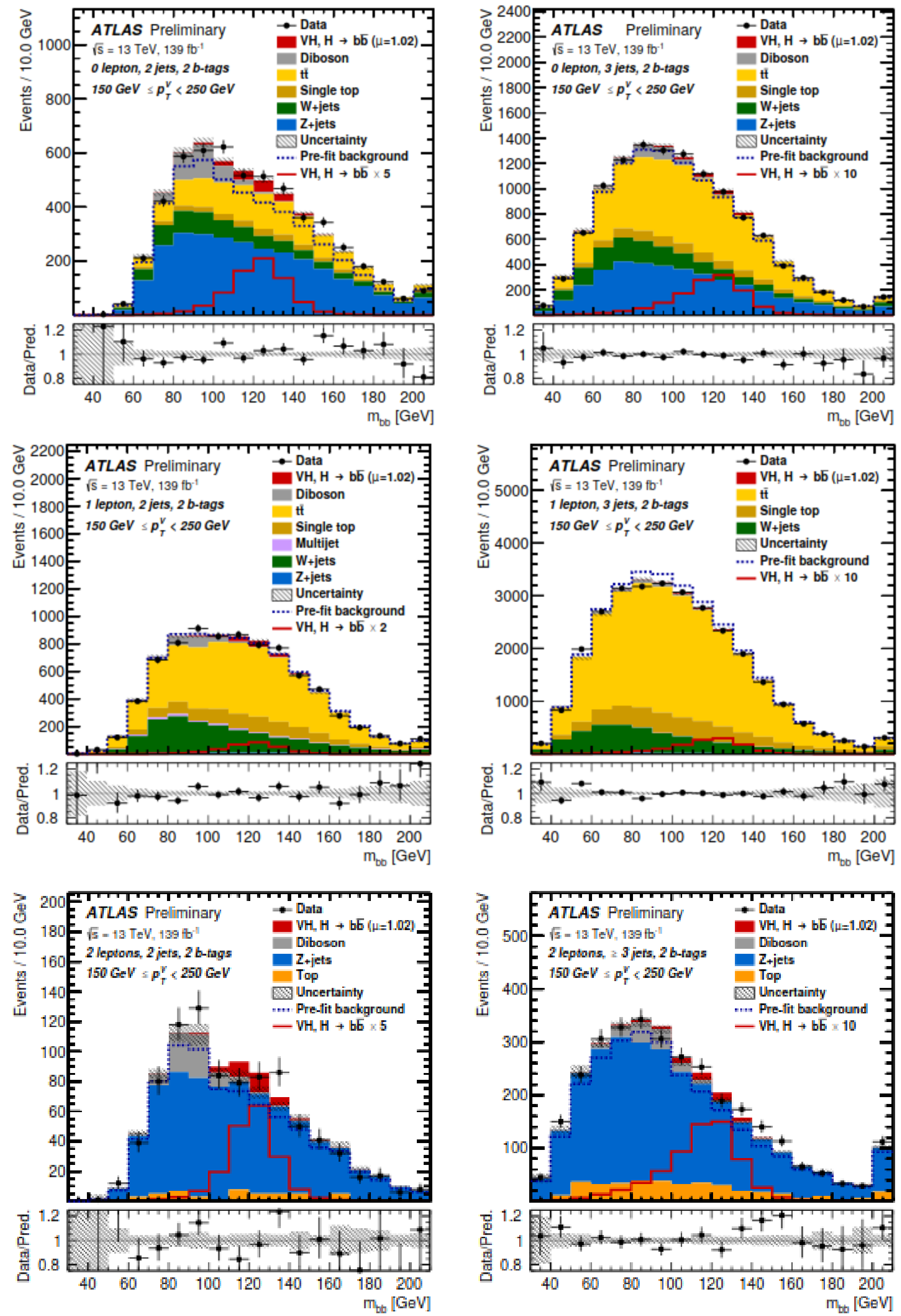


VH→ bb Resolved Di-jet Mass Analysis

→ Identical fit regions as MVA following new 2D **[p^V_T, ΔR(b,b)]** plane definitions:

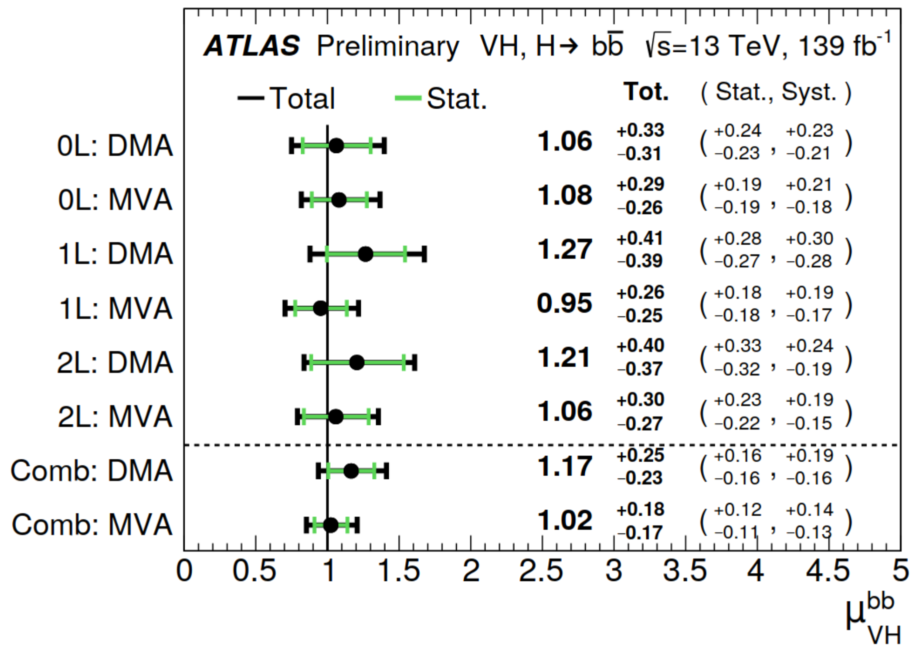
→ Binned profile likelihood fit $\mathcal{L}(\mathbf{x},\mu|\theta)$ with **total** of **42 fit regions**





VH→ bb Results: Resolved

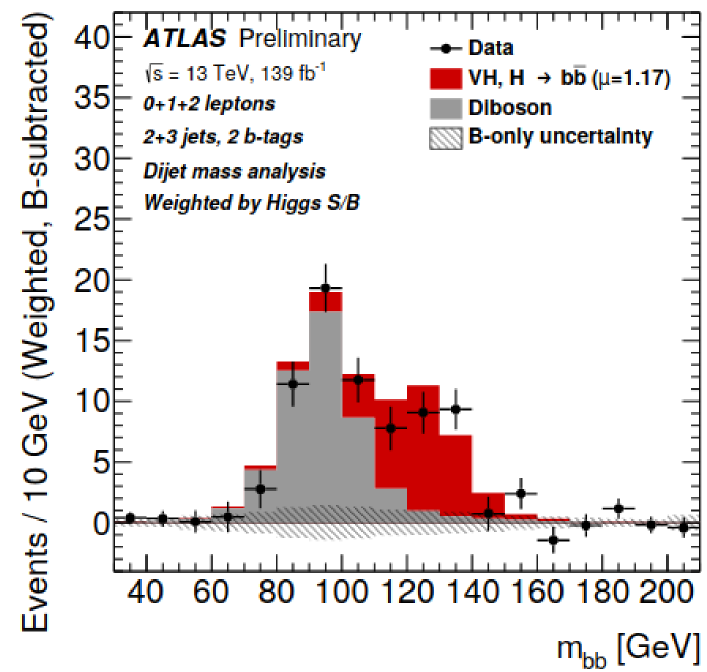
Di-jet Mass Analysis (DMA)



S/B Weighted combination of m_{bb} distributions from 0+1+2L channels

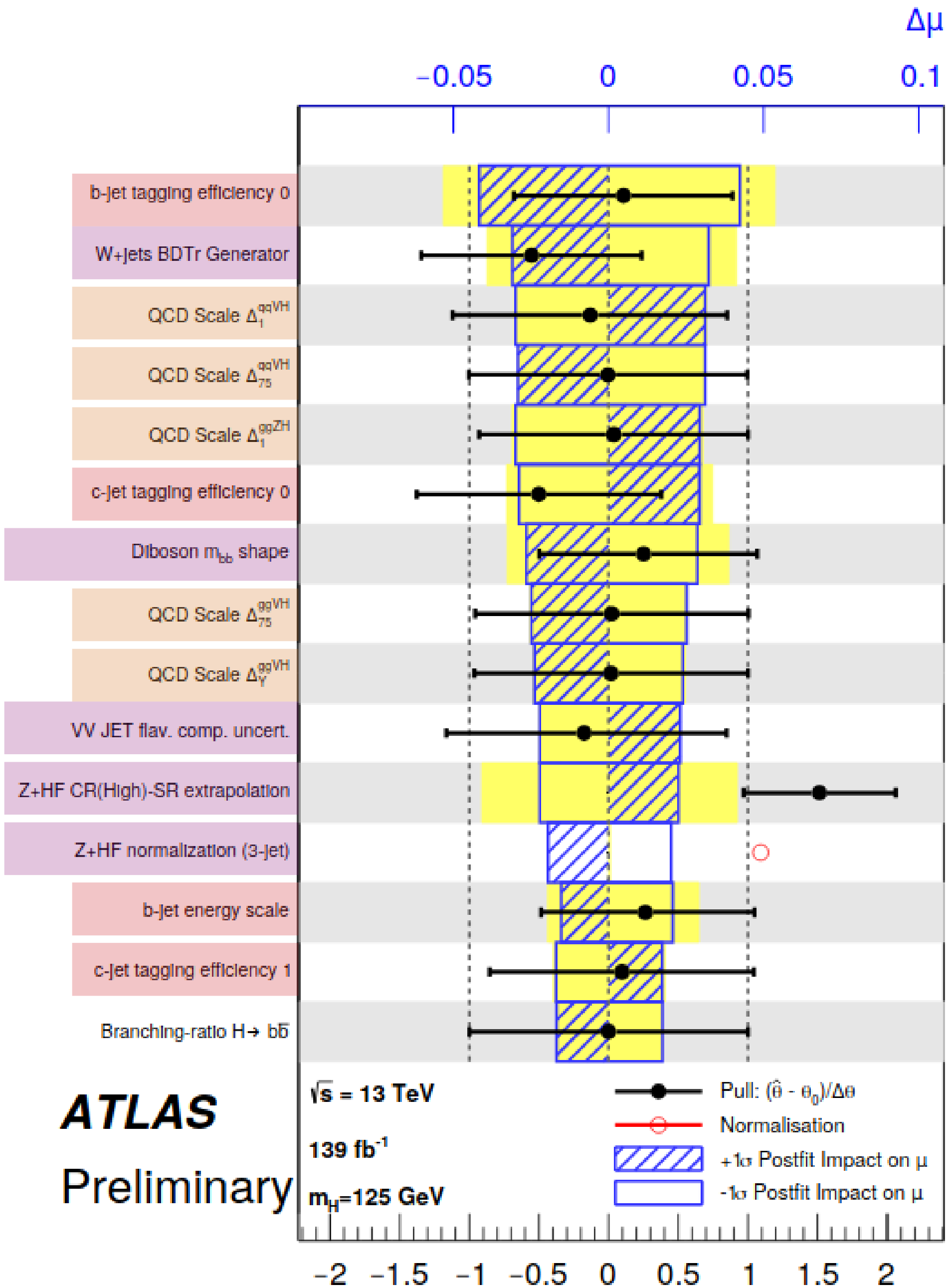
Z_0 = **Obs.** 5.4 **(exp.)** (4.9) σ

→ Good agreement between MVA & DMA



VH→ bb Resolved: Systematics

→ Statistical and systematics approximately the same!
→ Modelling/signal MC uncertainties and b-tagging dominant!



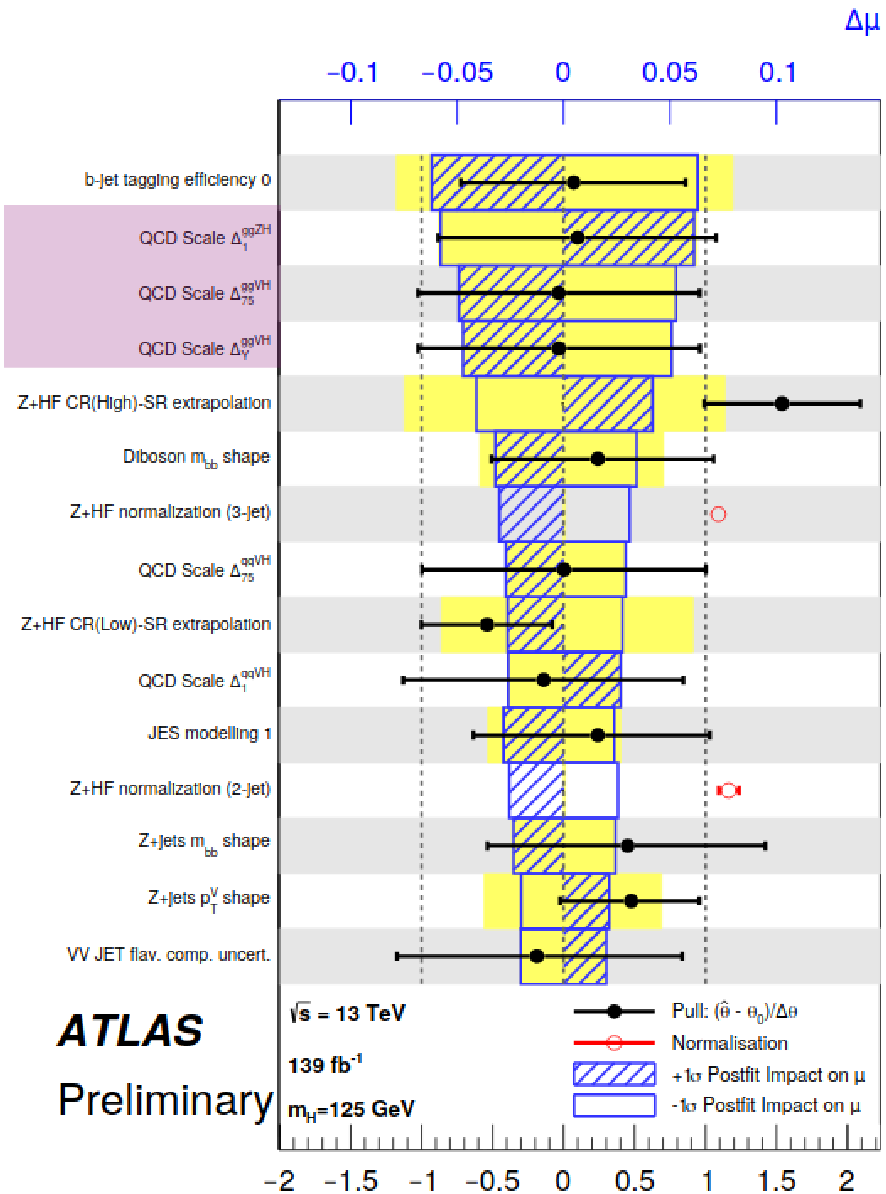
Source of uncertainty		σ_μ VH	σ_μ WH	σ_μ ZH
Total		0.177	0.260	0.240
Statistical		0.115	0.182	0.171
Systematic		0.134	0.186	0.168
Statistical uncertainties				
Data statistical		0.108	0.171	0.157
$t\bar{t}$ $e\mu$ control region		0.014	0.003	0.026
Floating normalisations		0.034	0.061	0.045
Experimental uncertainties				
Jets		0.043	0.050	0.057
E_T^{miss}		0.015	0.045	0.013
Leptons		0.004	0.015	0.005
b-tagging	*b*-jets	0.045	0.025	0.064
	c-jets	0.035	0.068	0.010
	light-flavour jets	0.009	0.004	0.014
Pile-up		0.003	0.002	0.007
Luminosity		0.016	0.016	0.016
Theoretical and modelling uncertainties				
Signal		0.052	0.048	0.072
Z + jets		0.032	0.013	0.059
W + jets		0.040	0.079	0.009
$t\bar{t}$		0.021	0.046	0.029
Single top quark		0.019	0.048	0.015
Diboson		0.033	0.033	0.039
Multi-jet		0.005	0.017	0.005
MC statistical		0.031	0.055	0.038

Stat. ~ Syst uncert.

VH→ bb: Systematics (ZH)

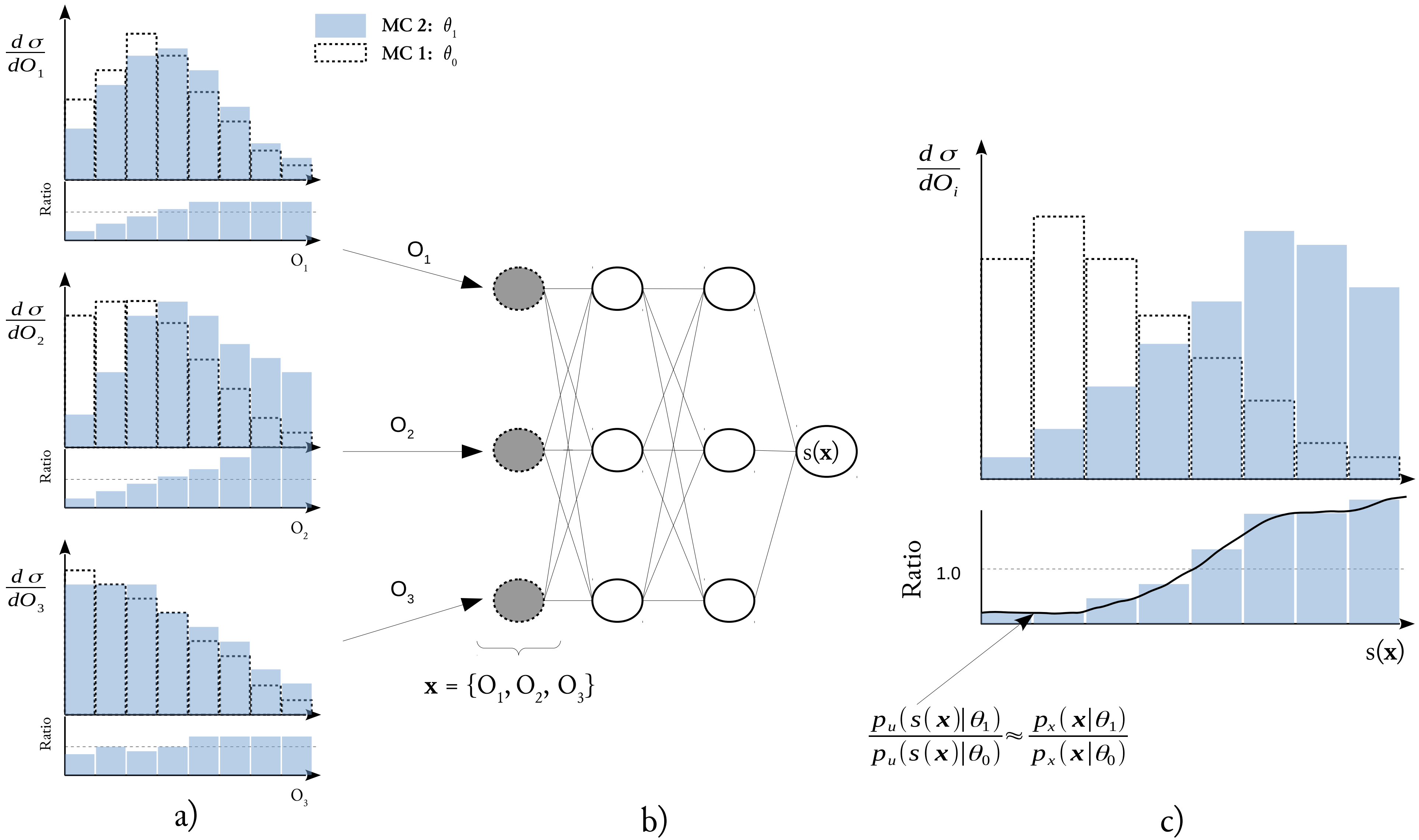
→ **Special statement:** For ZH NLO corrections for gg → ZH production that are missing dominant the measurement precision

→ Limits the H→bb sensitivity to ggF!



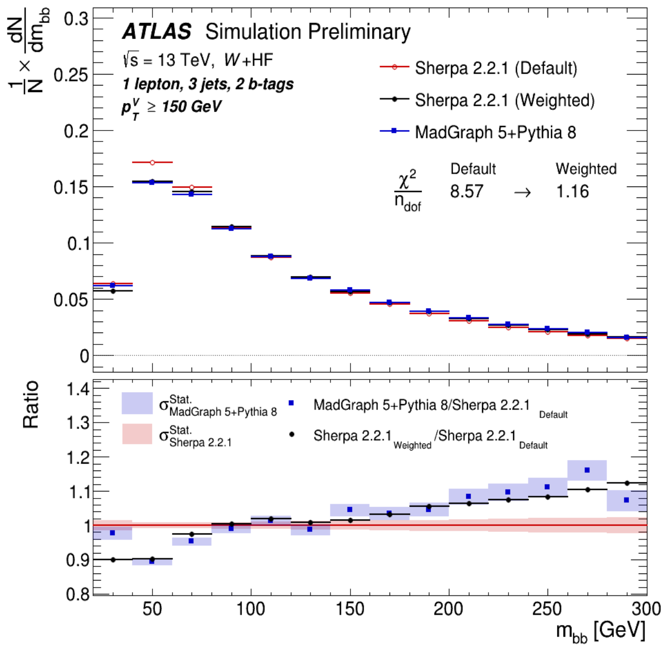
Source of uncertainty	σ_μ VH	σ_μ WH	σ_μ ZH
Total	0.177	0.260	0.240
Statistical	0.115	0.182	0.171
Systematic	0.134	0.186	0.168
Statistical uncertainties			
Data statistical	0.108	0.171	0.157
$t\bar{t}$ $e\mu$ control region	0.014	0.003	0.026
Floating normalisations	0.034	0.061	0.045
Experimental uncertainties			
Jets	0.043	0.050	0.057
E_T^{miss}	0.015	0.045	0.013
Leptons	0.004	0.015	0.005
b-tagging: b-jets	0.045	0.025	0.064
b-tagging: c-jets	0.035	0.068	0.010
b-tagging: light-flavour jets	0.009	0.004	0.014
Pile-up	0.003	0.002	0.007
Luminosity	0.016	0.016	0.016
Theoretical and modelling uncertainties			
Signal	0.052	0.048	0.072
Z + jets	0.032	0.013	0.059
W + jets	0.040	0.079	0.009
$t\bar{t}$	0.021	0.046	0.029
Single top quark	0.019	0.048	0.015
Diboson	0.033	0.033	0.039
Multi-jet	0.005	0.017	0.005
MC statistical	0.031	0.055	0.038

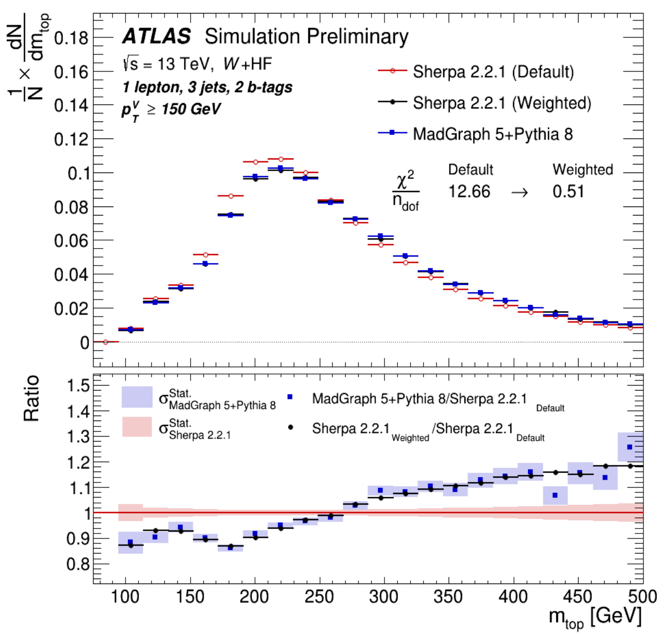
VHbb Resolved: Mutlivariate Parameterisation of MC Systematics

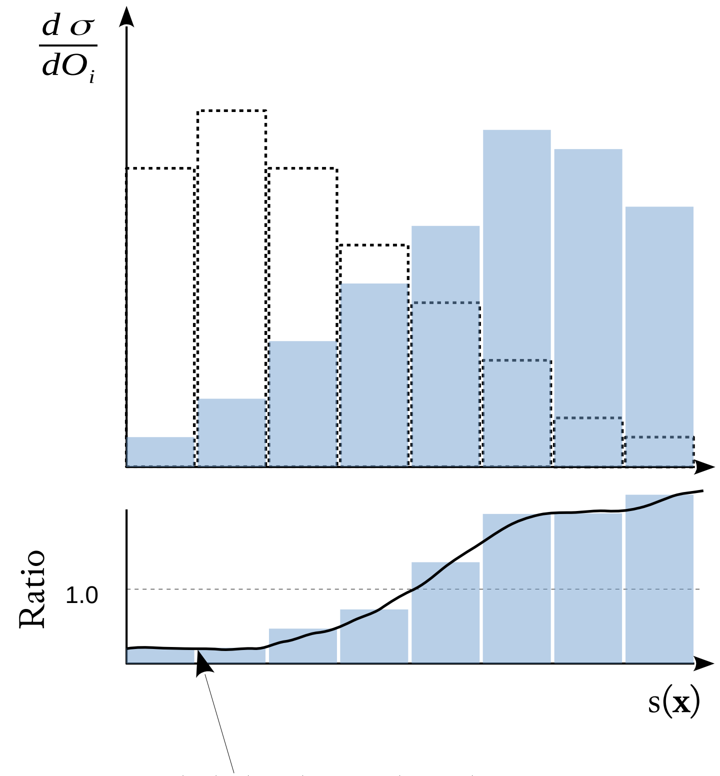


VHbb Resolved: Mutlivariate Parameterisation of MC Systematics

Input Space:



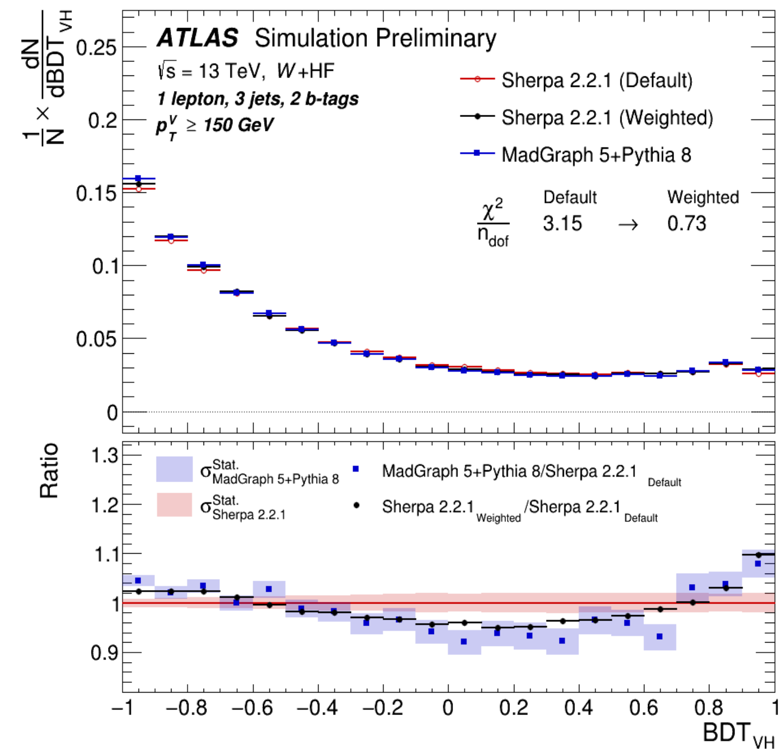




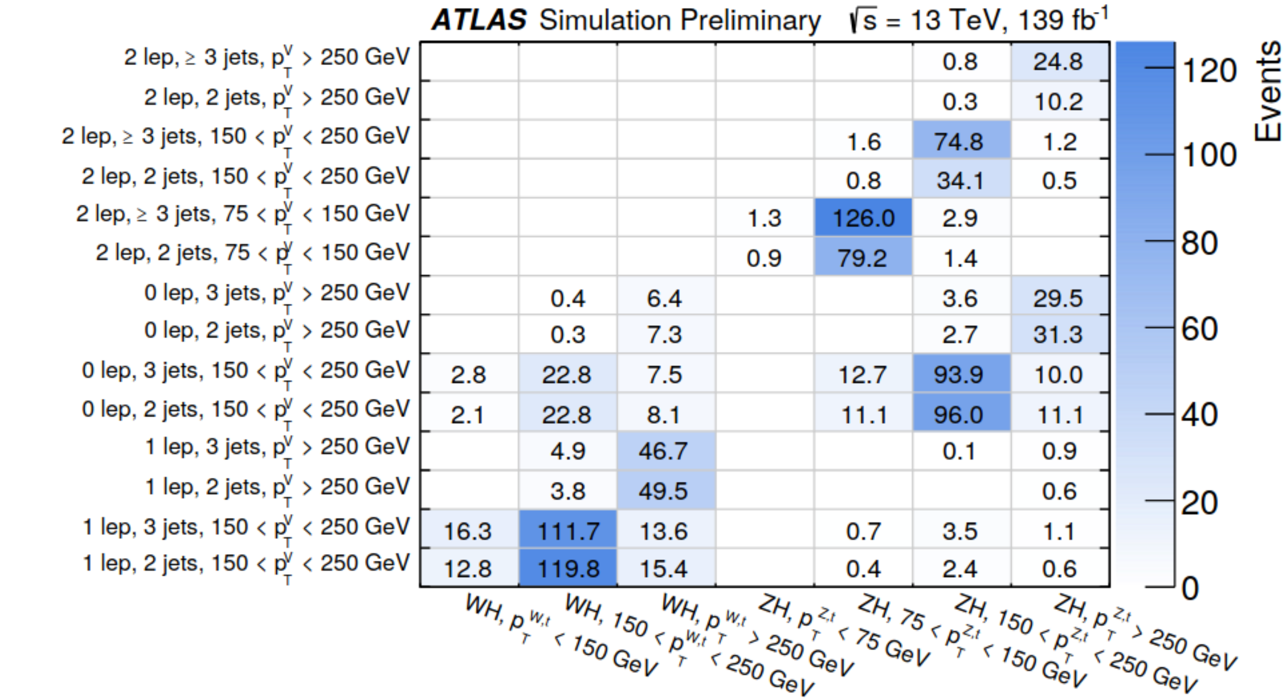
$$\frac{p_u(s(\mathbf{x})|\theta_1)}{p_u(s(\mathbf{x})|\theta_0)} \approx \frac{p_x(\mathbf{x}|\theta_1)}{p_x(\mathbf{x}|\theta_0)}$$

Re-weight using MVA calibrated density ratio estimator and pass to analysis BDT

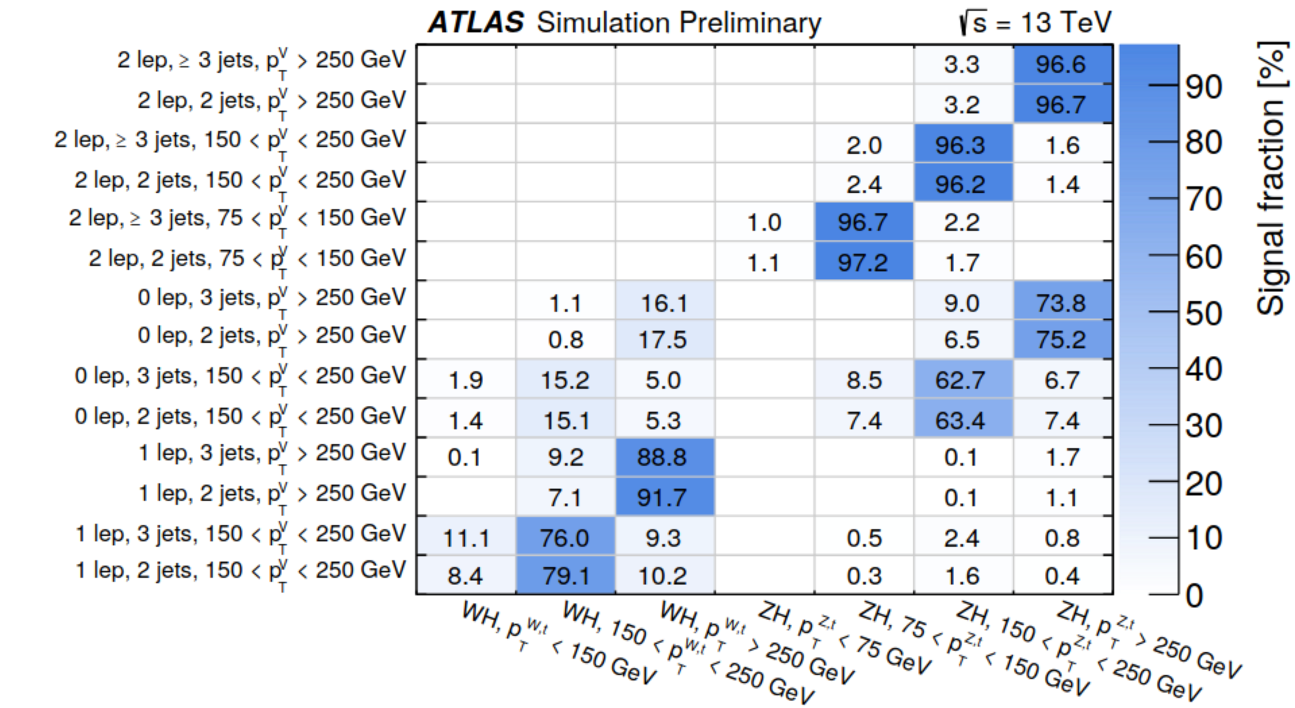
Fit Discriminant Space:



VHbb Resolved: STXS Bin Signal Division



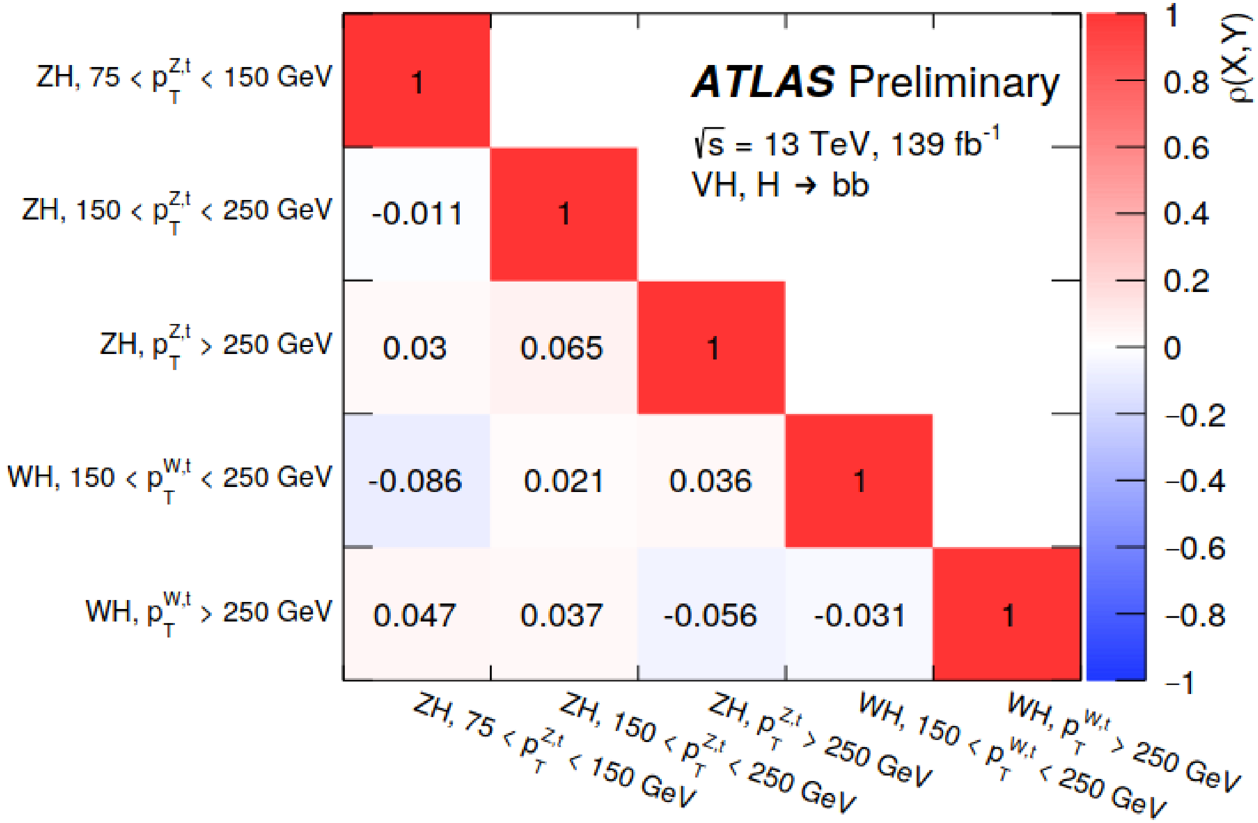
→ Expected signal yields per:
- Reconstruction category (y-axis)
- Truth category (x-axis)



→ Fraction of expected signal yields per:
- Reconstruction category (y-axis)
- Truth category (x-axis)

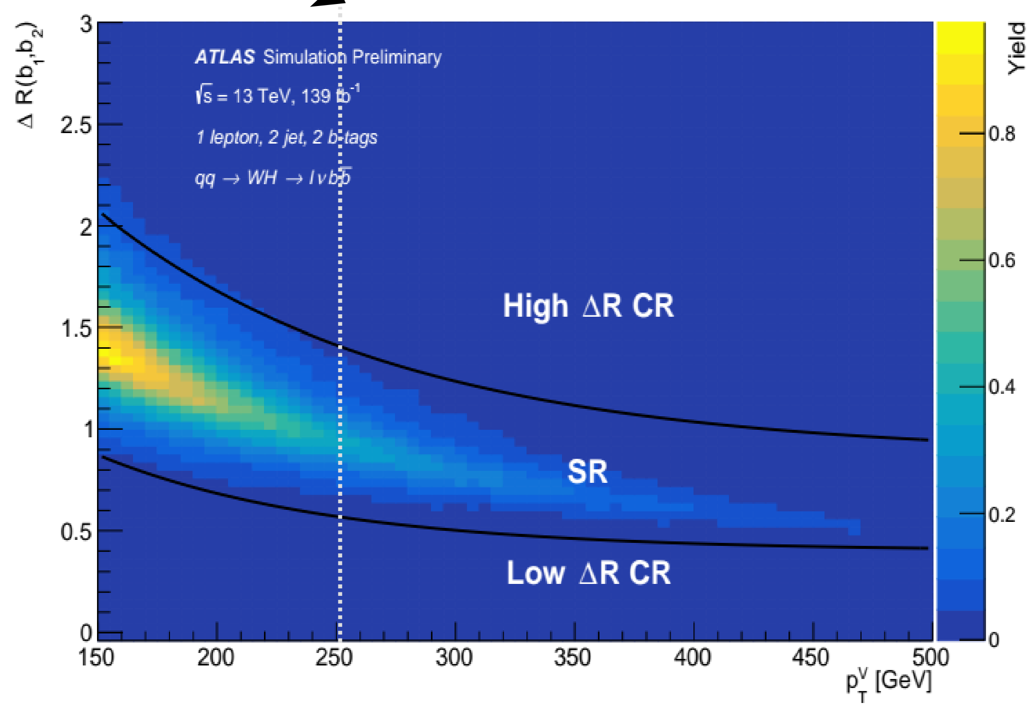
Normalised according to the total fiducial phase space yield.

VHbb Resolved: STXS Bin Correlations



→ Observed correlations between reduced stage 1.2 STXS scheme for 5-POI scheme
- Statistical & Systematics included

→ Expansion of STXS scheme to include an exclusive 150 GeV < p^T_V(truth) < 250 GeV bin reduces cross-correlation



VHbb Resolved: EFT

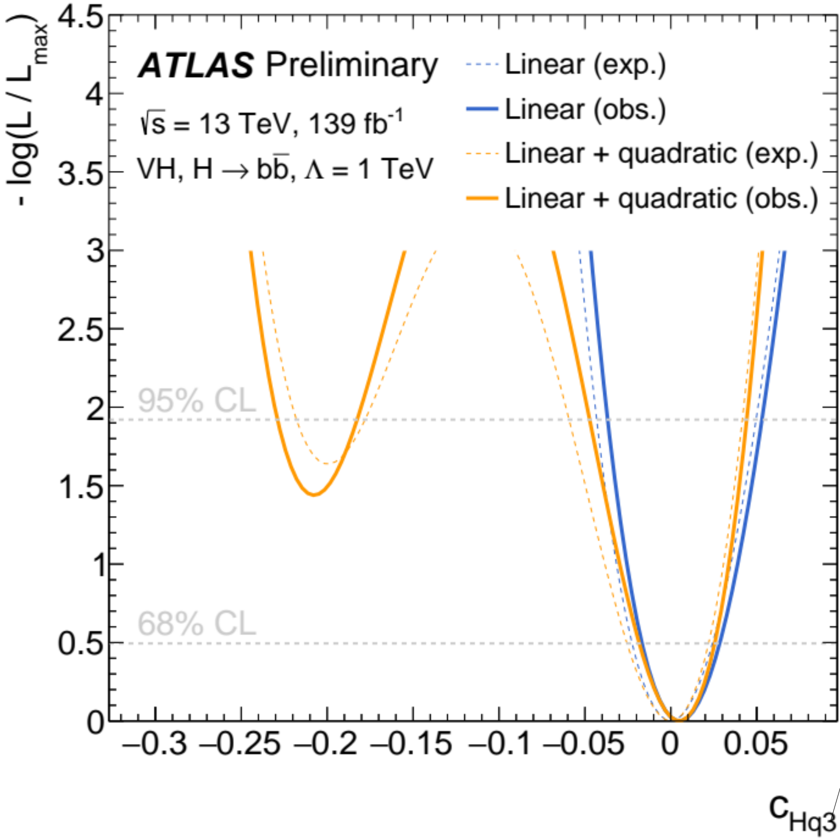
→ Effective lagrangian approach using the Warsaw basis:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)},$$

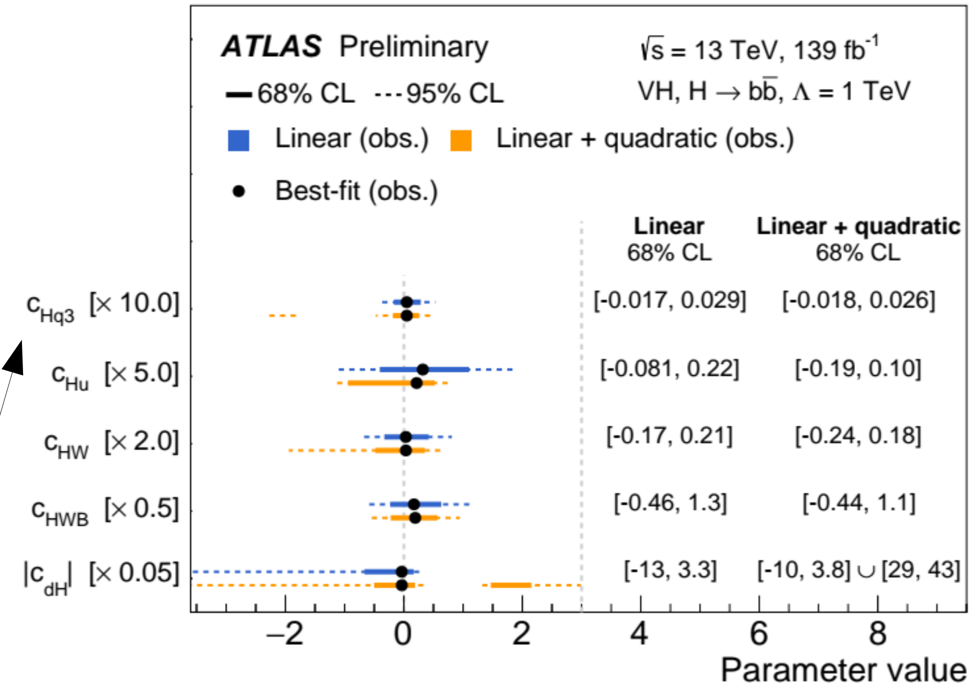
→ Only dimension D=6 operators are considered:

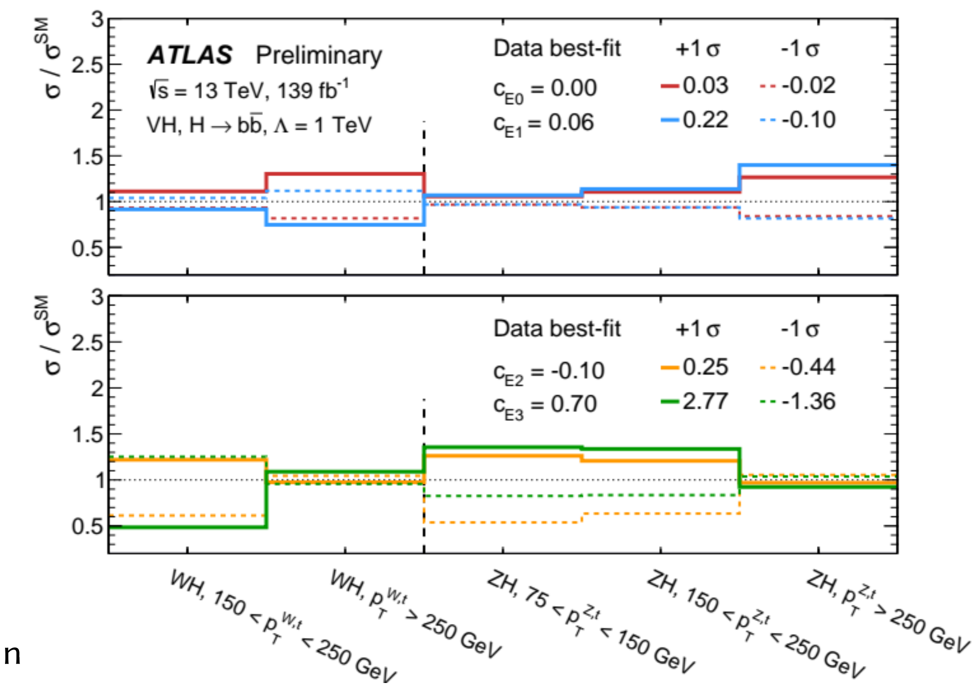
- → D=5 violate lepton/baryon number
- → D=7+ suppressed by further powers of $1/\Lambda$ beyond Λ^4

→ Linear (interference) and quadratic $(D{=}6)^2$ parameterised in each STXS bin:

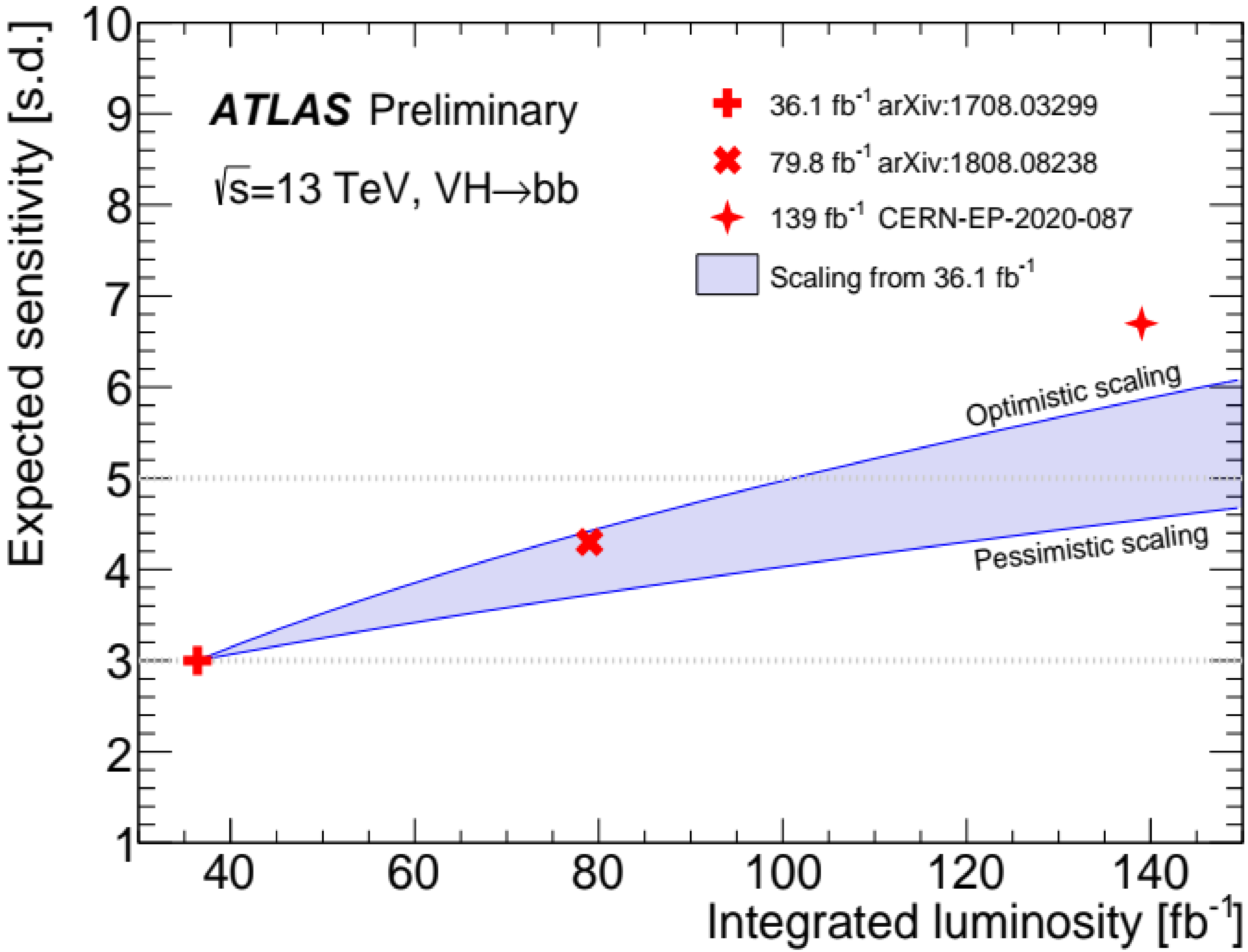


Apply constrained on Wilson co-efficients



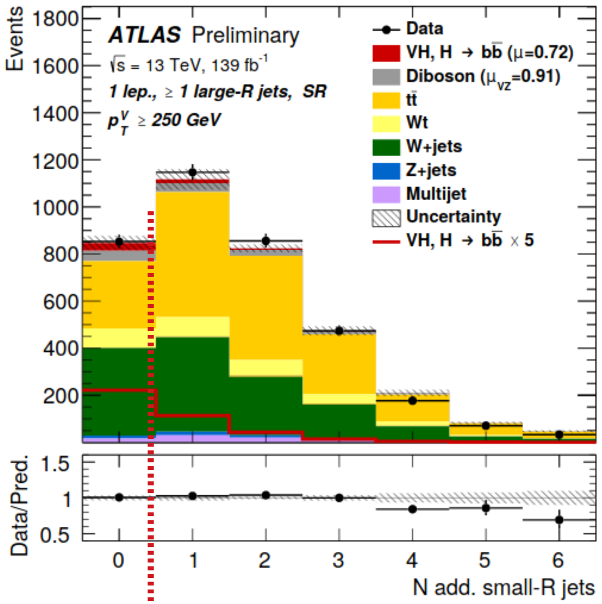


VHbb Resolved: Analysis Sensitivty over the years!



VH→ bb Boosted Event Categorisation – Fit Regions

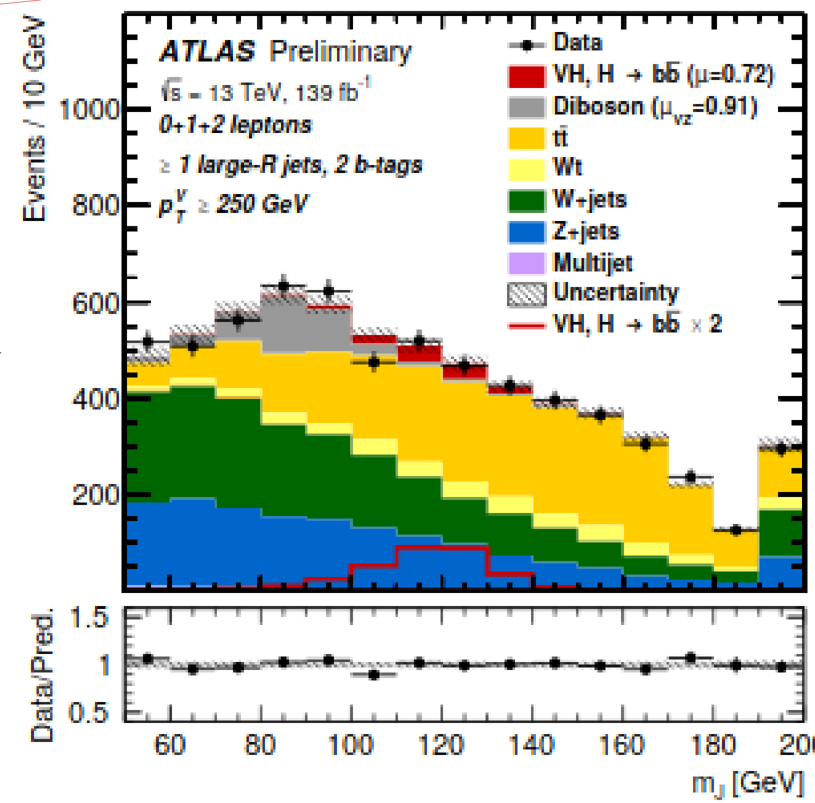
→ Low(High) purity SR's defined by additional AK4 jets:



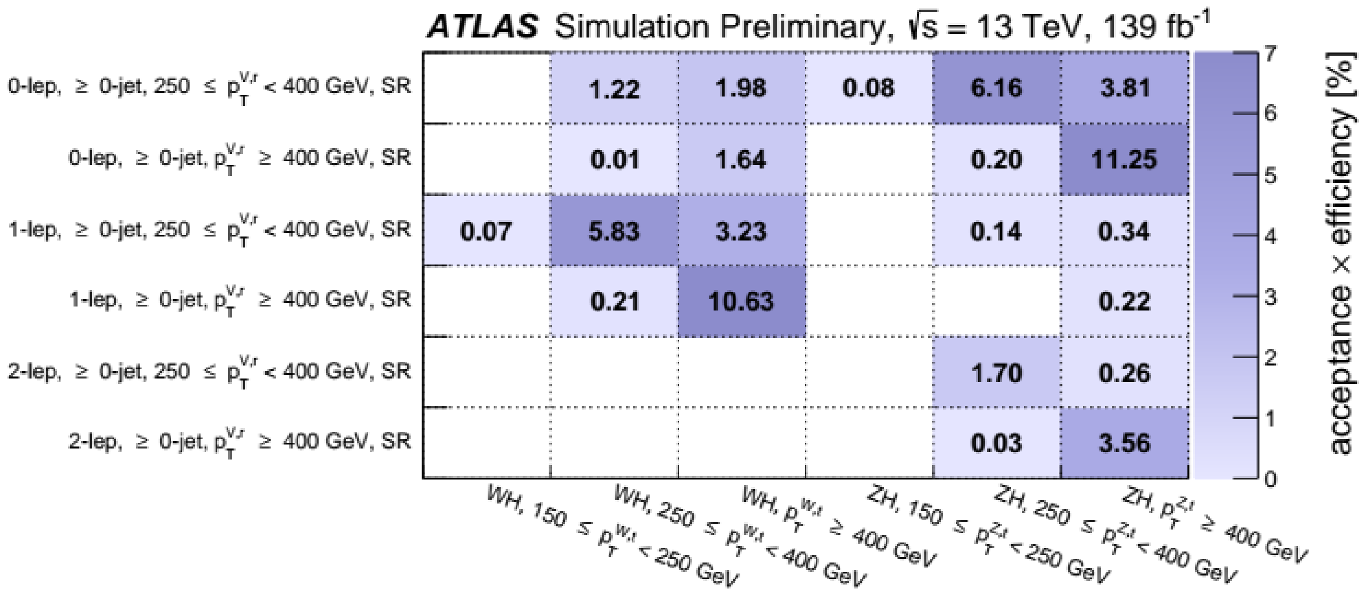
Channel	Categories					
	$250 < p_T^V < 400$ GeV			$p_T^V \geq 400$ GeV		
	0 add. b-track-jets		≥ 1 add. b-track-jets	0 add. b-track-jets		≥ 1 add. b-track-jets
	0 add. small-R jets	≥ 1 add. small-R jets		0 add. small-R jets	≥ 1 add. small-R jets	
0-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
1-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
2-lepton	SR			SR		

→ tt CR's defined by additional AK2 VR track jets

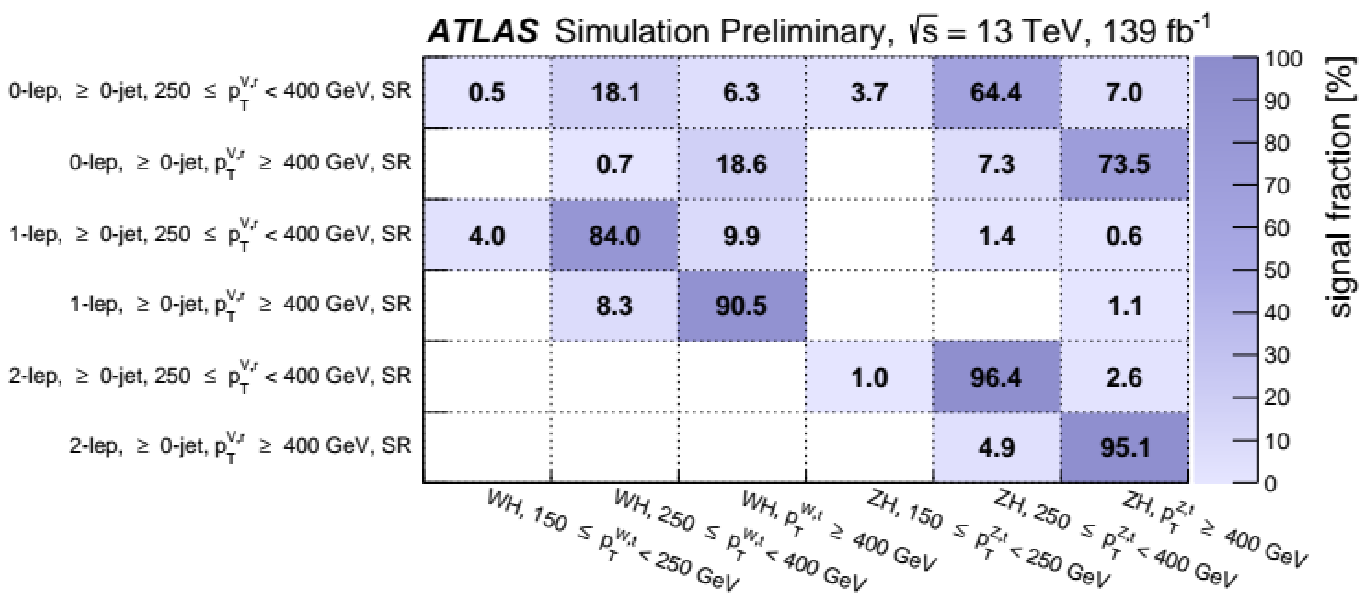
→ **m**$_J$ used as fit discriminant in CR/SR's - showing sum of lepton channel SRs:



VHbb Boosted: STXS Bin Signal Division



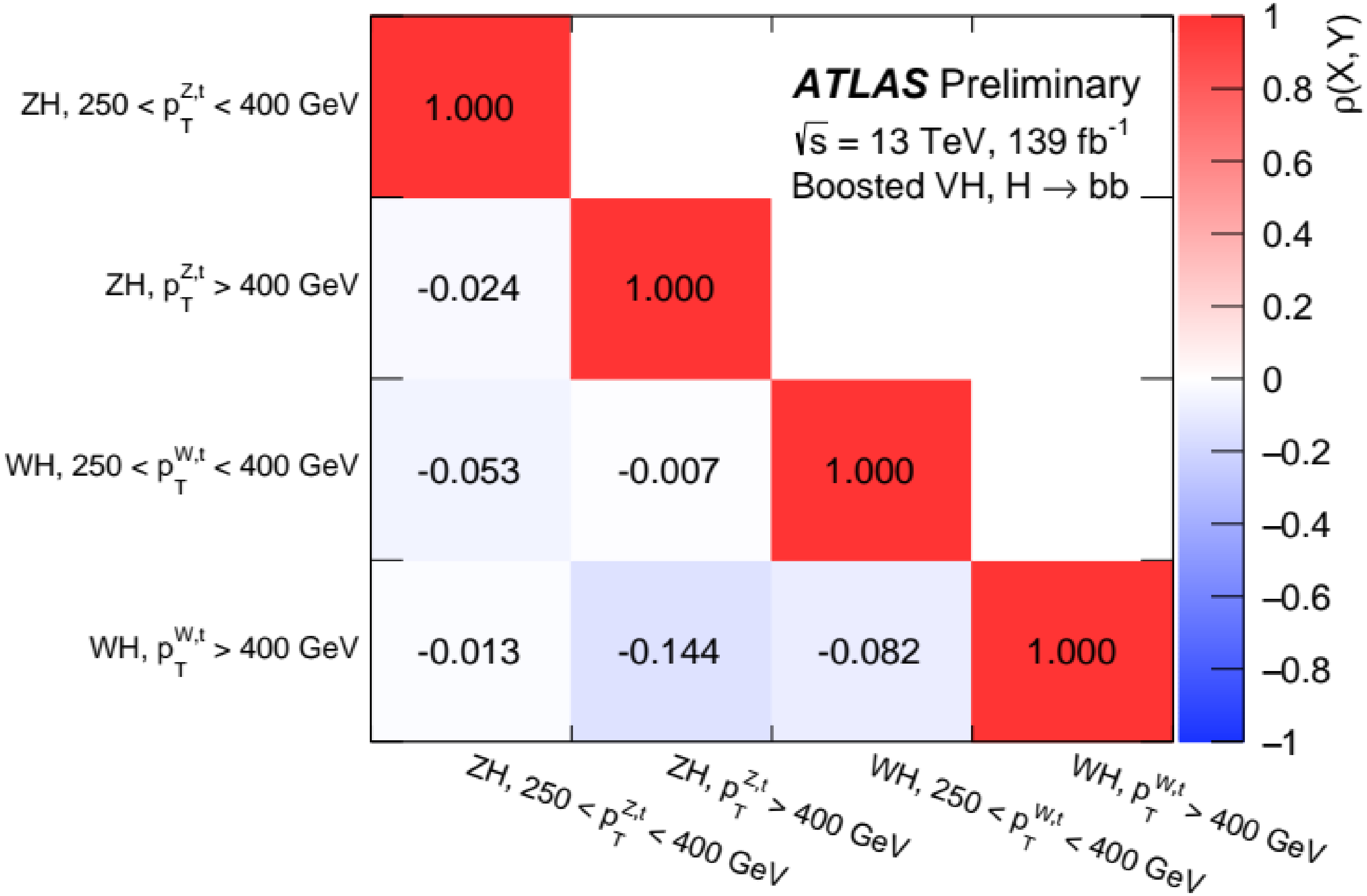
→ Signal acceptance x eff. per:
- Reconstruction category (y-axis)
- Truth category (x-axis)



→ Signal purity:
- Reconstruction category (y-axis)
- Truth category (x-axis)

Normalised according to the total fiducial phase space yield.

VHbb Boosted: STXS Bin Correlations



→ Observed correlations between reduced stage 1.2 STXS scheme for 4-POI scheme

- Statistical & Systematics included

VHbb Boosted: EFT

⟶ Effective lagrangian approach use the Warsaw basis:

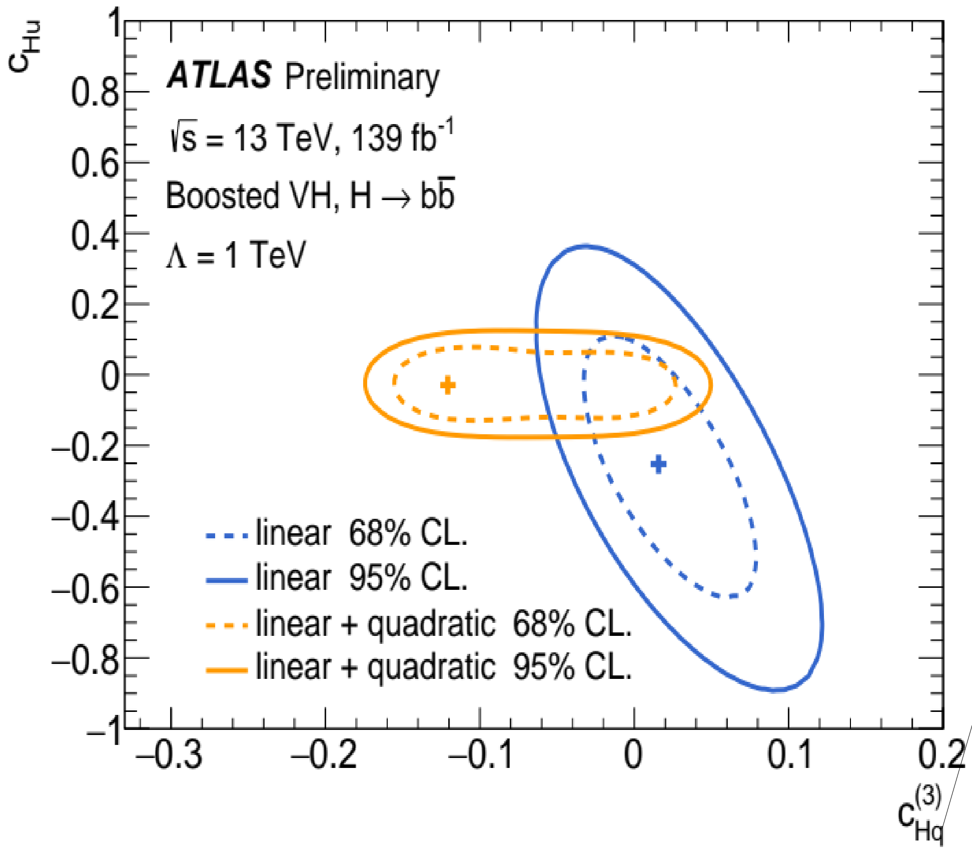
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}} O_i^{(D)},$$

⟶ Only dimension D=6 operators are considered:

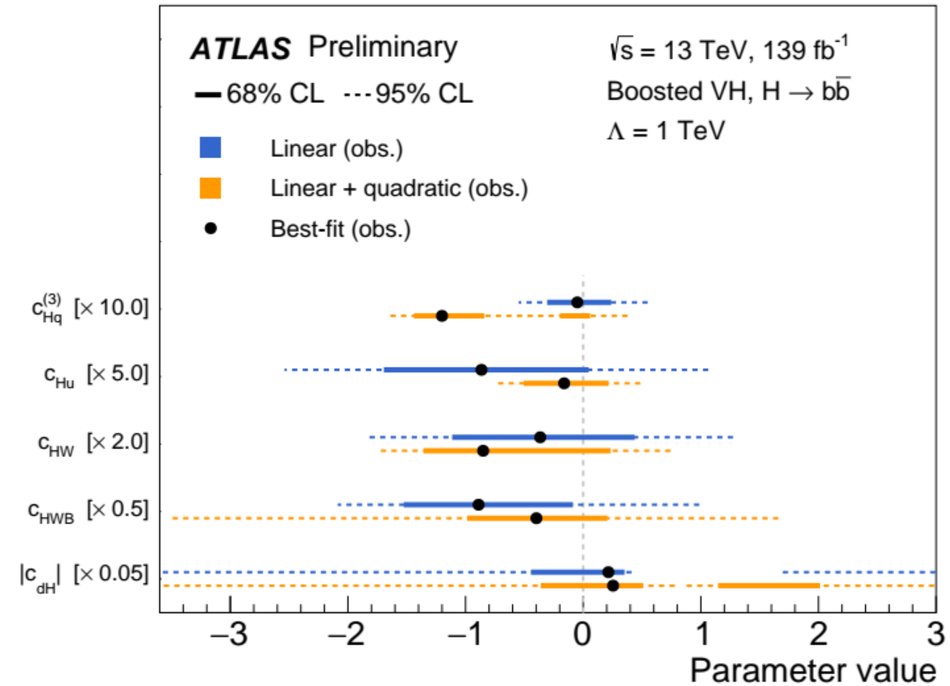
⟶ D=5 violate lepton/baryon number

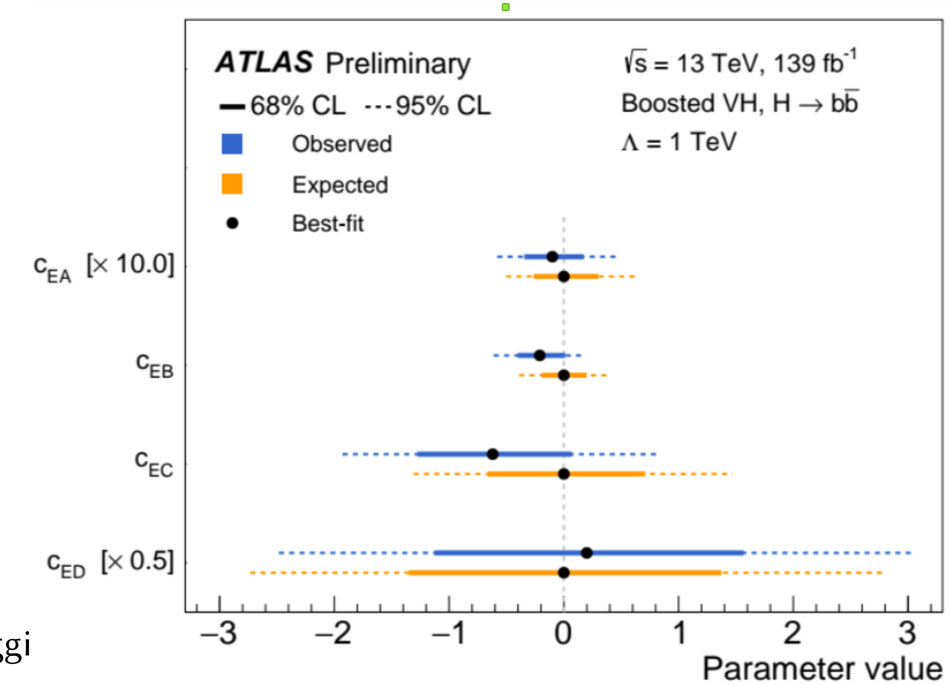
⟶ D=7+ suppressed by further powers of $1/\Lambda$ beyond Λ^4

⟶ Linear (interference) and quadratic $(D=6)^2$ parameterised in each STXS bin:



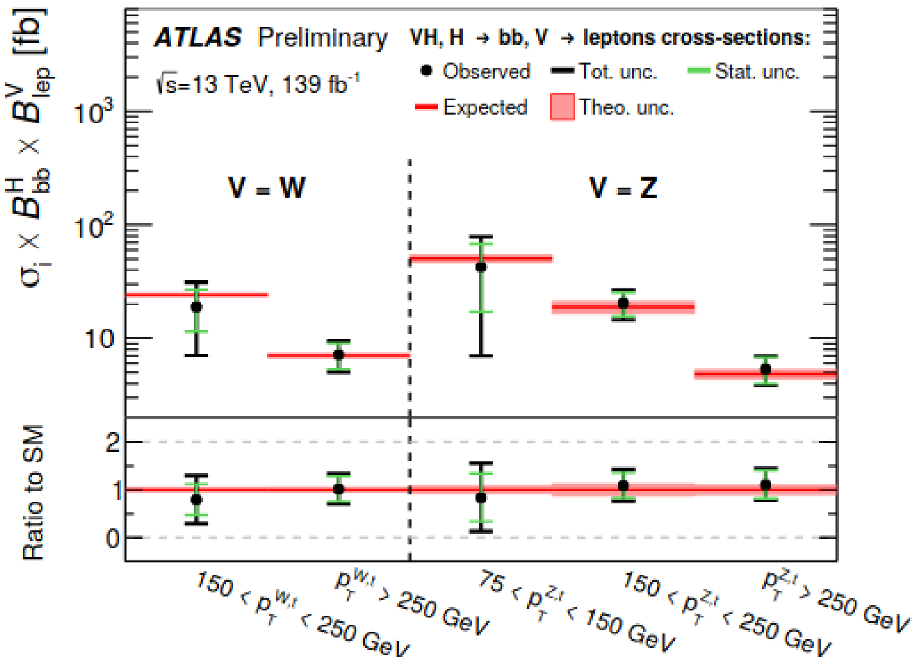
Apply constrained on Wilson co-efficients



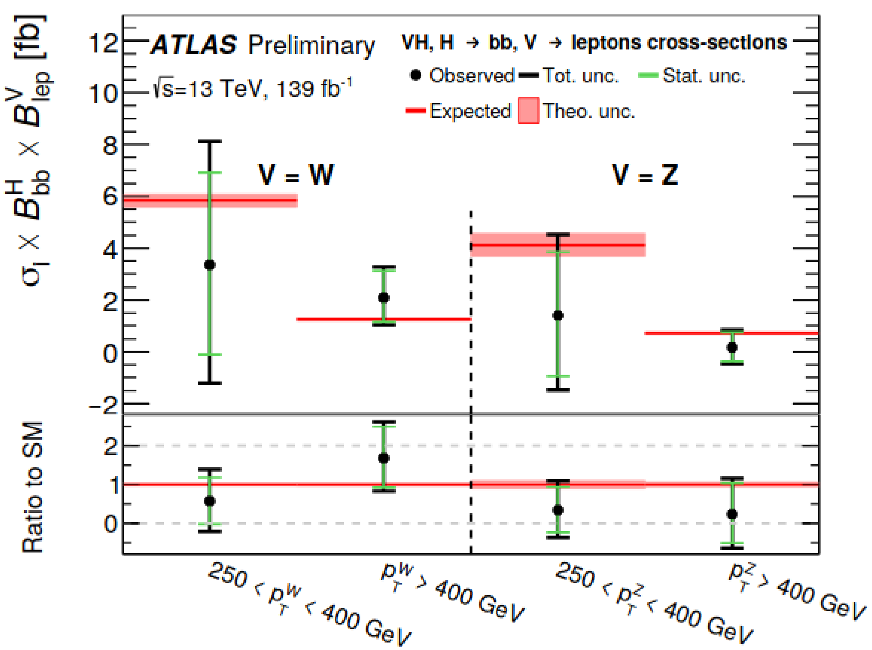


VH→ bb STXS

→ **VHbb resolved:** Stage 1.2 STXS scheme merged down to 5/4 bins



Measurement region ($\|y_H\| < 2.5$, $H \to b\bar{b}$)	SM prediction [fb]	Result [fb]	Stat. unc. [fb]	Syst. unc. [fb] Th. sig.	Th. bkg.	Exp.
5-POI scheme						
$W \to \ell\nu$; $150 < p_T^V < 250$ GeV	24.0 ± 1.1	20 ± 25	± 17	± 2	± 13	± 9
$W \to \ell\nu$; $p_T^V > 250$ GeV	7.1 ± 0.3	8.8 ± 5.2	± 4.4	± 0.5	± 2.5	± 0.9
$Z \to \ell\ell, \nu\nu$; $75 < p_T^V < 150$ GeV	50.6 ± 4.1	81 ± 45	± 35	± 10	± 21	± 19
$Z \to \ell\ell, \nu\nu$; $150 < p_T^V < 250$ GeV	18.8 ± 2.4	14 ± 13	± 11	± 1	± 6	± 3
$Z \to \ell\ell, \nu\nu$; $p_T^V > 250$ GeV	4.9 ± 0.5	8.5 ± 4.0	± 3.7	± 0.8	± 1.2	± 0.6
3-POI scheme						
$W \to \ell\nu$; $p_T^V > 150$ GeV	31.1 ± 1.4	35 ± 14	± 9	± 2	± 9	± 4
$Z \to \ell\ell, \nu\nu$; $75 < p_T^V < 150$ GeV	50.6 ± 4.1	81 ± 45	± 35	± 10	± 21	± 19
$Z \to \ell\ell, \nu\nu$; $p_T^V > 150$ GeV	23.7 ± 3.0	28.4 ± 8.1	± 6.4	± 2.4	± 3.6	± 2.3



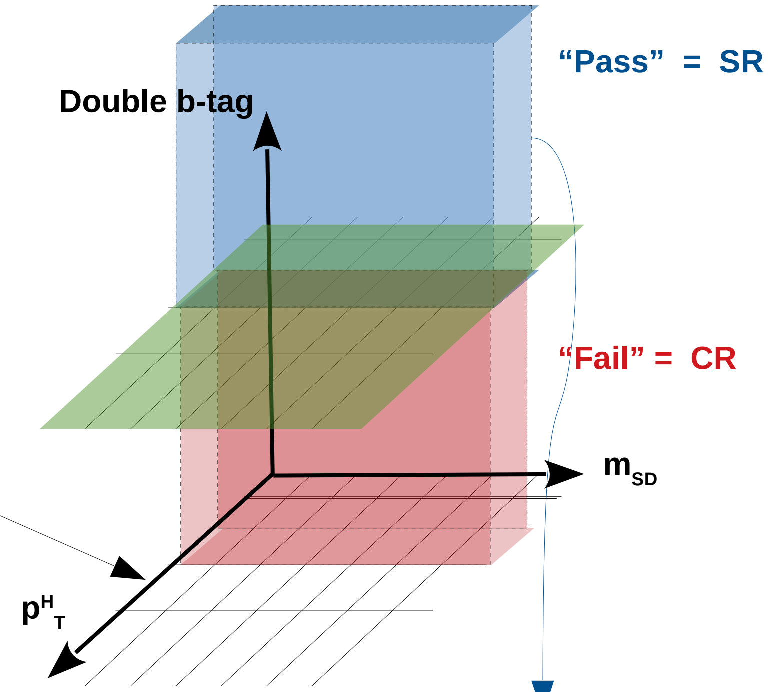
Measurement region ($\|y_H\| < 2.5$, $H \to b\bar{b}$)	SM prediction [fb]	Result [fb]	Stat. unc. [fb]	Syst. unc. [fb]
$W \to \ell\nu$; $p_T^W \in [250, 400[$ GeV	5.83 ± 0.26	3.3 $^{+4.8}_{-4.6}$	$^{+3.6}_{-3.4}$	$^{+3.2}_{-3.0}$
$W \to \ell\nu$; $p_T^W \in [400, \infty[$ GeV	1.25 ± 0.06	2.1 $^{+1.2}_{-1.1}$	$^{+1.0}_{-0.9}$	$^{+0.6}_{-0.5}$
$Z \to \ell\ell, \nu\nu$; $p_T^Z \in [250, 400[$ GeV	4.12 ± 0.45	1.4 $^{+3.1}_{-2.9}$	$^{+2.4}_{-2.3}$	$^{+1.9}_{-1.7}$
$Z \to \ell\ell, \nu\nu$; $p_T^Z \in [400, \infty[$ GeV	0.72 ± 0.05	0.2 $^{+0.7}_{-0.6}$	$^{+0.6}_{-0.5}$	$^{+0.3}_{-0.3}$

Ultra high p^H_T environment!

Inclusive ggF high p_T^H: Analysis Strategy

→ Parameterically fit QCD yield within ($m_{SD,i}$, $p_{T,j}$) bins:

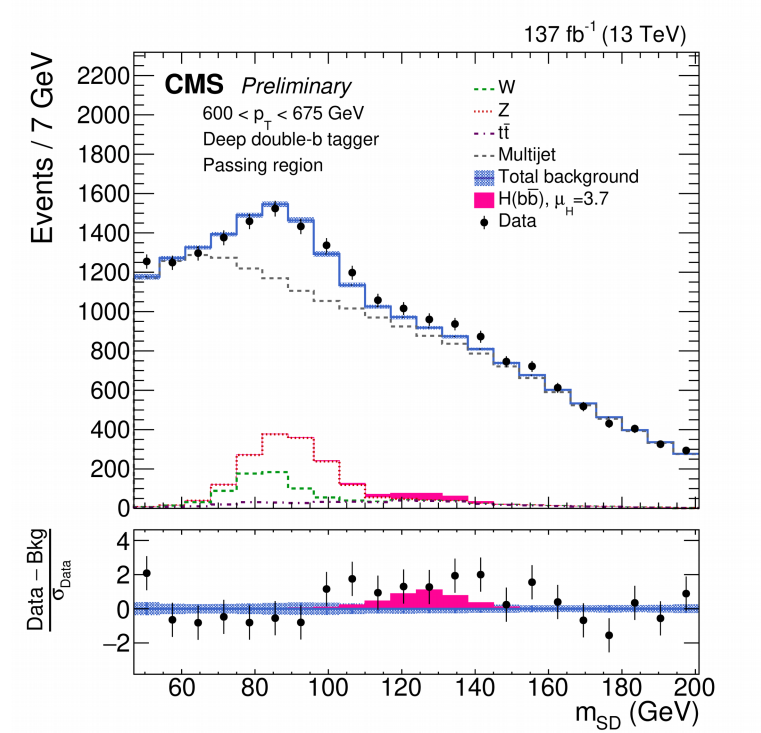
$$N^{\mathrm{QCD}}_{\mathrm{pass}}(m_{\mathrm{SD}i}, p_{\mathrm{T}j}) = \epsilon^{\mathrm{QCD}} \cdot \left(\sum_{k,\ell} a_{k\ell} \rho^{k}_{ij} p_{\mathrm{T}}{}^{\ell}_{j} \right) \cdot N^{\mathrm{QCD}}_{\mathrm{fail}}(m_{\mathrm{SD}i}, p_{\mathrm{T}j}) ,$$



Project cube onto x-axis

→ **W**/**Z+jets** & **tt** estimated from Monte Carlo (MC)

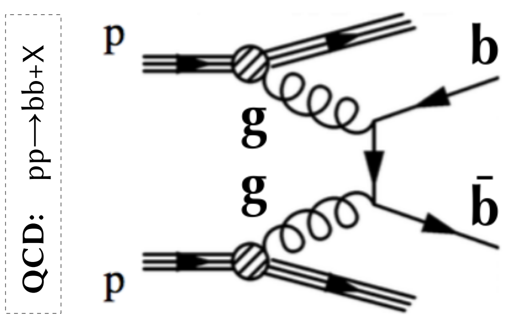
→ **W+Jets**/**Z+Jets**/**tt** control regions used to constrain normalisations/uncertainties

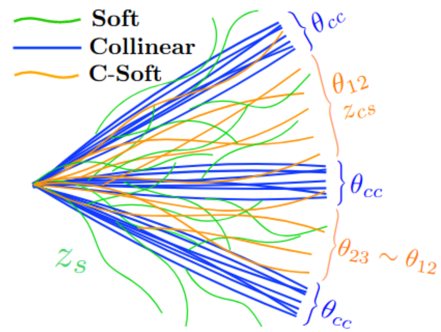


Inclusive ggF high p_T^H: Analysis Strategy

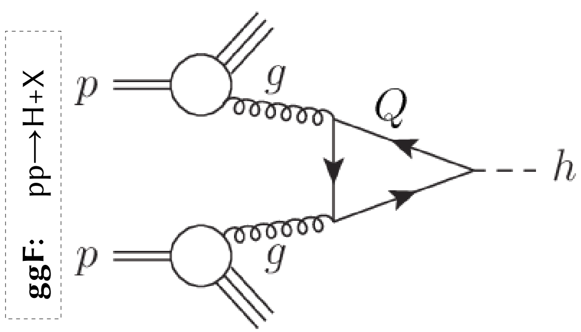
→ QCD ~ 10^7 times greater than signal:

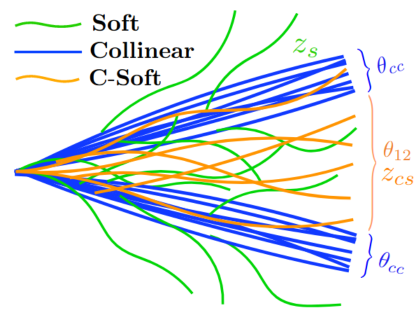
3-prong





2-prong





Source: arXiv:1609.07483

→ Topological handle on QCD vs signal using:

- Ratio of 3-point/2-point energy correlation co-efficients:

$$N_2^1 = \frac{{}_2e_3}{({}_1e_2)^2}.$$

- Use *transformed* $N^{1,DDT}_2 = N^1_2 - X_{(26\%)}$ to discriminate QCD/signal (see here):

$N^{1,DDT}_2$ < 0 for 26% QCD accep. across $[\rho, p_T]$ -plane

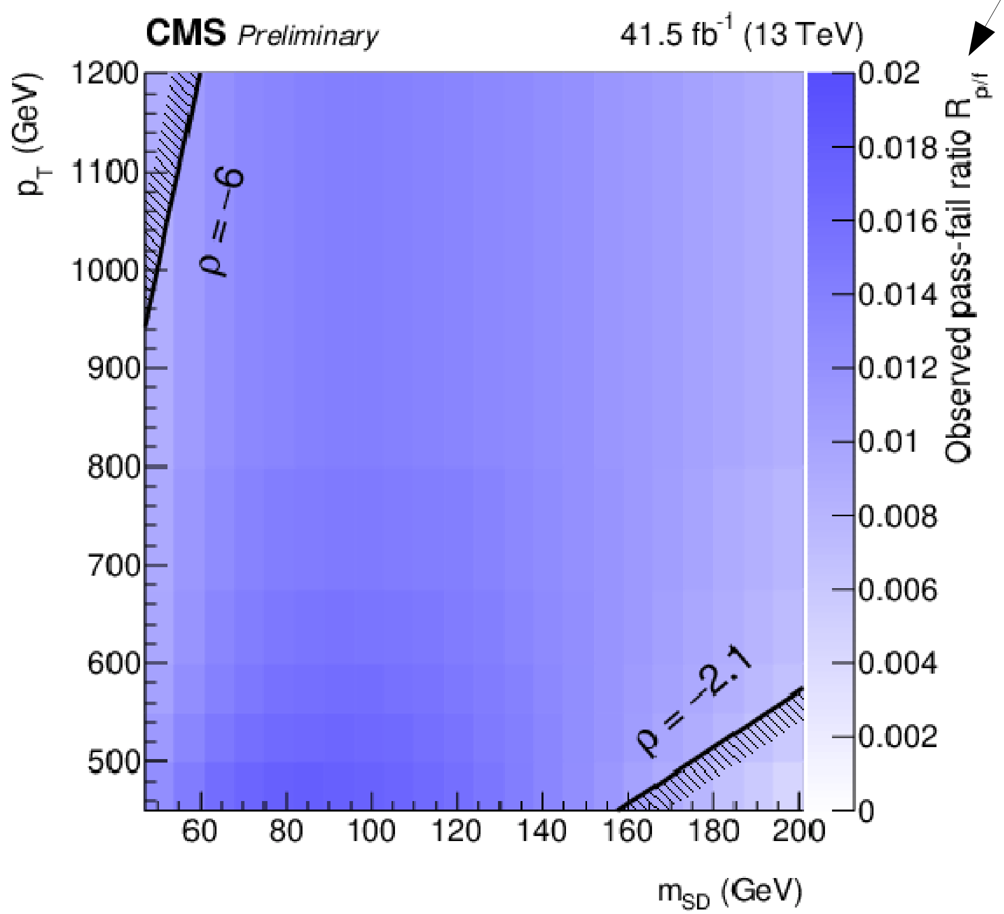
→ QCD Bkg Estimation:

- Parametrically fit QCD yield within $(m_{SD,i}, p_{T,j})$ bins:

$$N^{\mathrm{QCD}}_{\mathrm{pass}}(m_{\mathrm{SD}i}, p_{\mathrm{T}j}) = \epsilon^{\mathrm{QCD}} \cdot \left(\sum_{k,\ell} a_{k\ell} \rho^k_{ij} p_{\mathrm{T}j}^{\ell} \right) \cdot N^{\mathrm{QCD}}_{\mathrm{fail}}(m_{\mathrm{SD}i}, p_{\mathrm{T}j}),$$

- Account for:
  - 'double b-tag' mass dependence
  - 'Residual' data/MC tagger performance

} $R_{p/f}(\rho, p_T)$



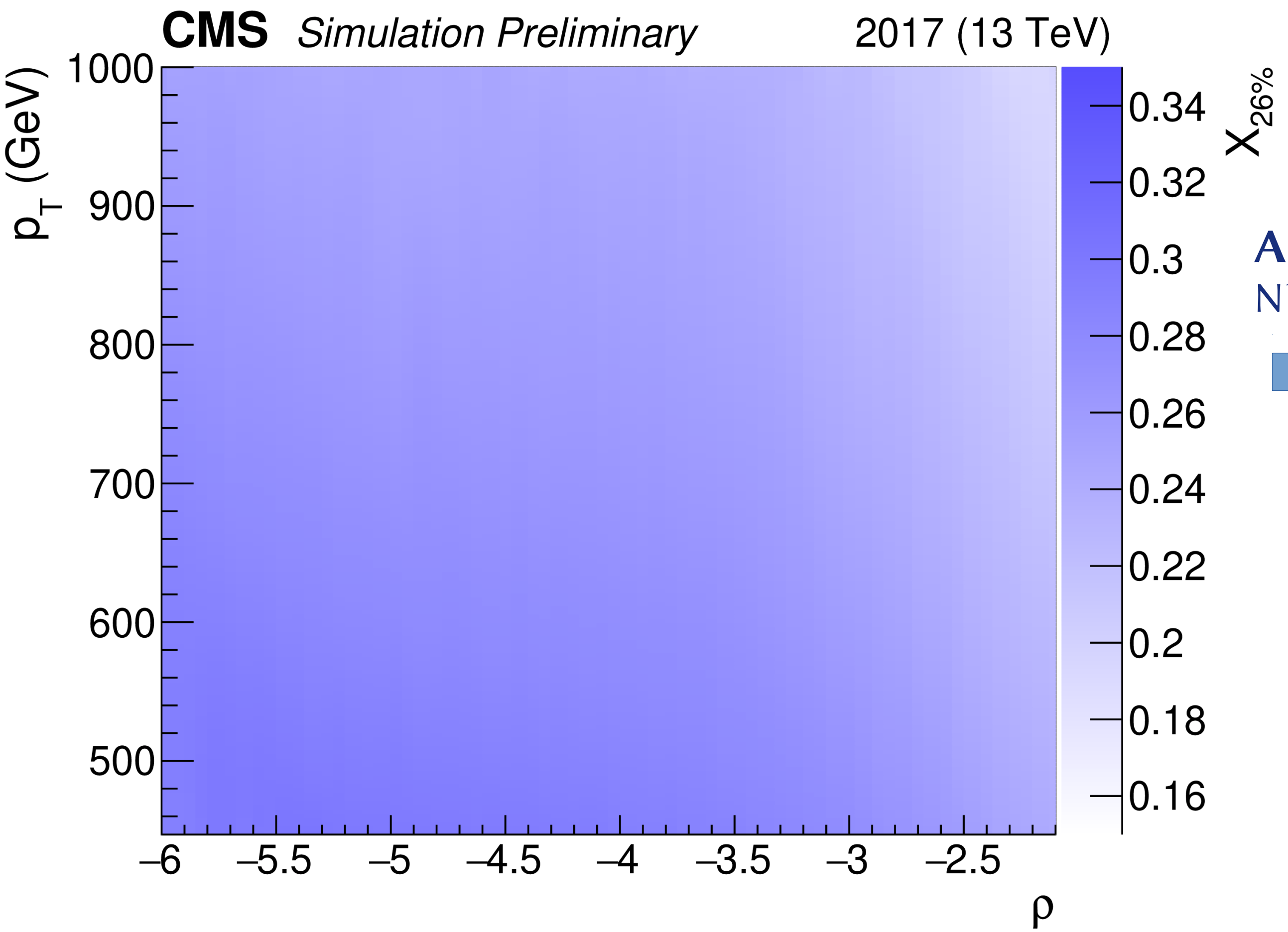
$H \longrightarrow bb$: Inclusive ggF high p^H_T - $N^{DDT,1}_2$

→ Ratio of 3-point/2-point energy correlation co-efficient: $N_2^1 = \frac{{}_2e_3}{({}_1e_2)^2}$.

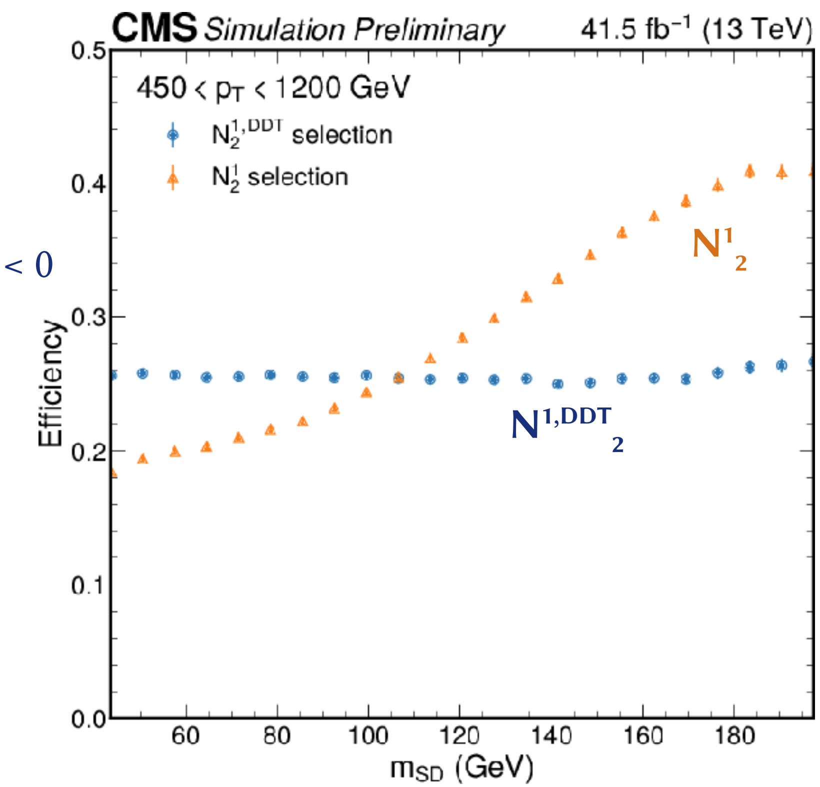
→ N^1_2 is transformed linearly to remove $\mathbf{m_{SD}}$ sculpting via subtracting the N^1_2 value at which **26% of the simulated QCD** events are found:

$$N^{1,DDT}_2 = N^1_2 - X_{(26\%)}$$

→ $X_{(26\%)}$ determined as function of (ρ, p_T):



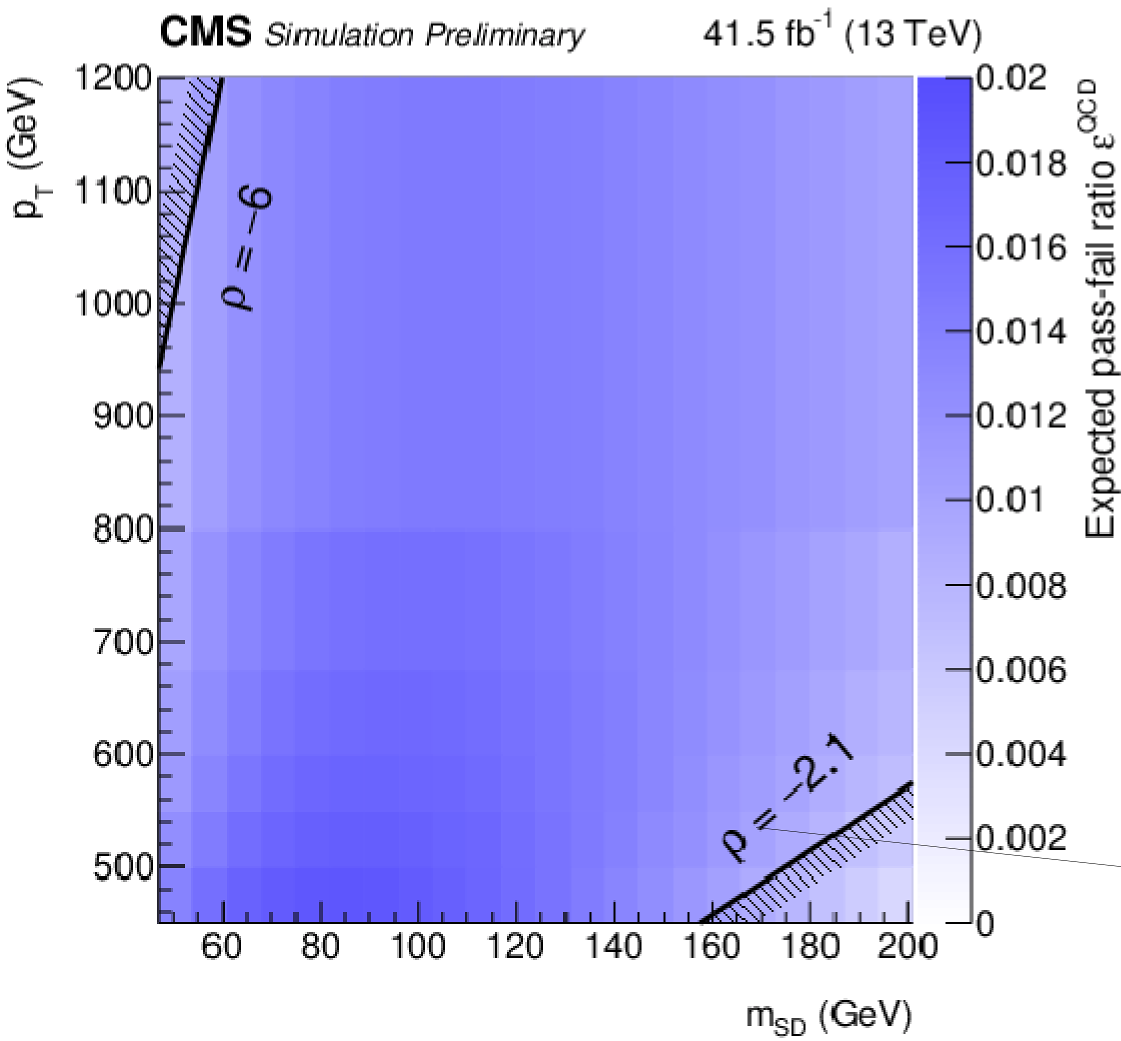
Apply:
$N^{1,DDT}_2 = N^1_2 - X_{(26\%)} < 0$



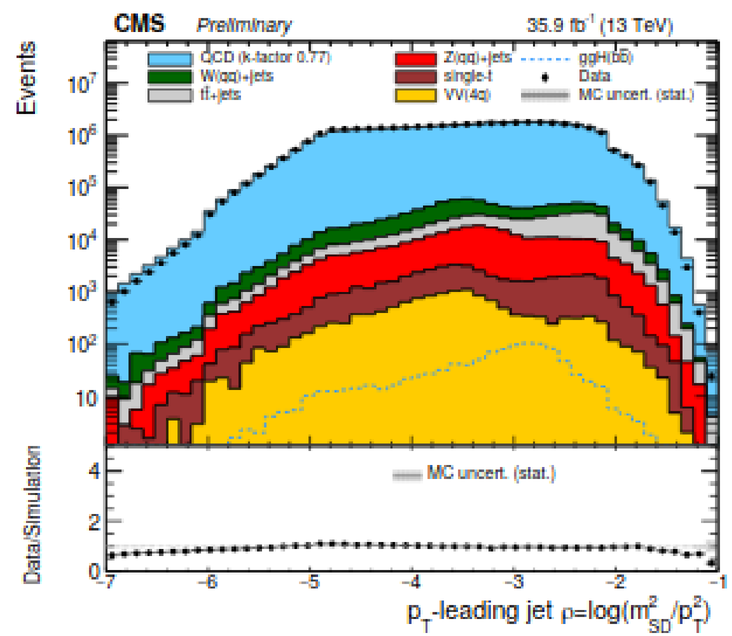
H⟶ bb: Inclusive ggF high p_T^H - ε^{QCD} from QCD MC

⟶ Double b-tagger is designed to be jet mass independent – loss function contains penalty term for differences in jet mass distribution between pass/fail regions.

⟶ Some residual difference exists therefore 2D Bernstein polynominal fitted, $\varepsilon^{QCD}(\rho, p_T)$, that characterises QCD simulated pass-fail ratio of events.



⟶ Dimensionless quantity that is approx. invariant as a function of jet p_T:



⟶ ρ ~ -2 corresponds to AK8 instability from finite cone effects
⟶ ρ ~ -6 correspnds to the non-perturbative regime of the soft-drop alg.

$$\rho = 2\ln\left(m_{SD}/p_T\right)$$

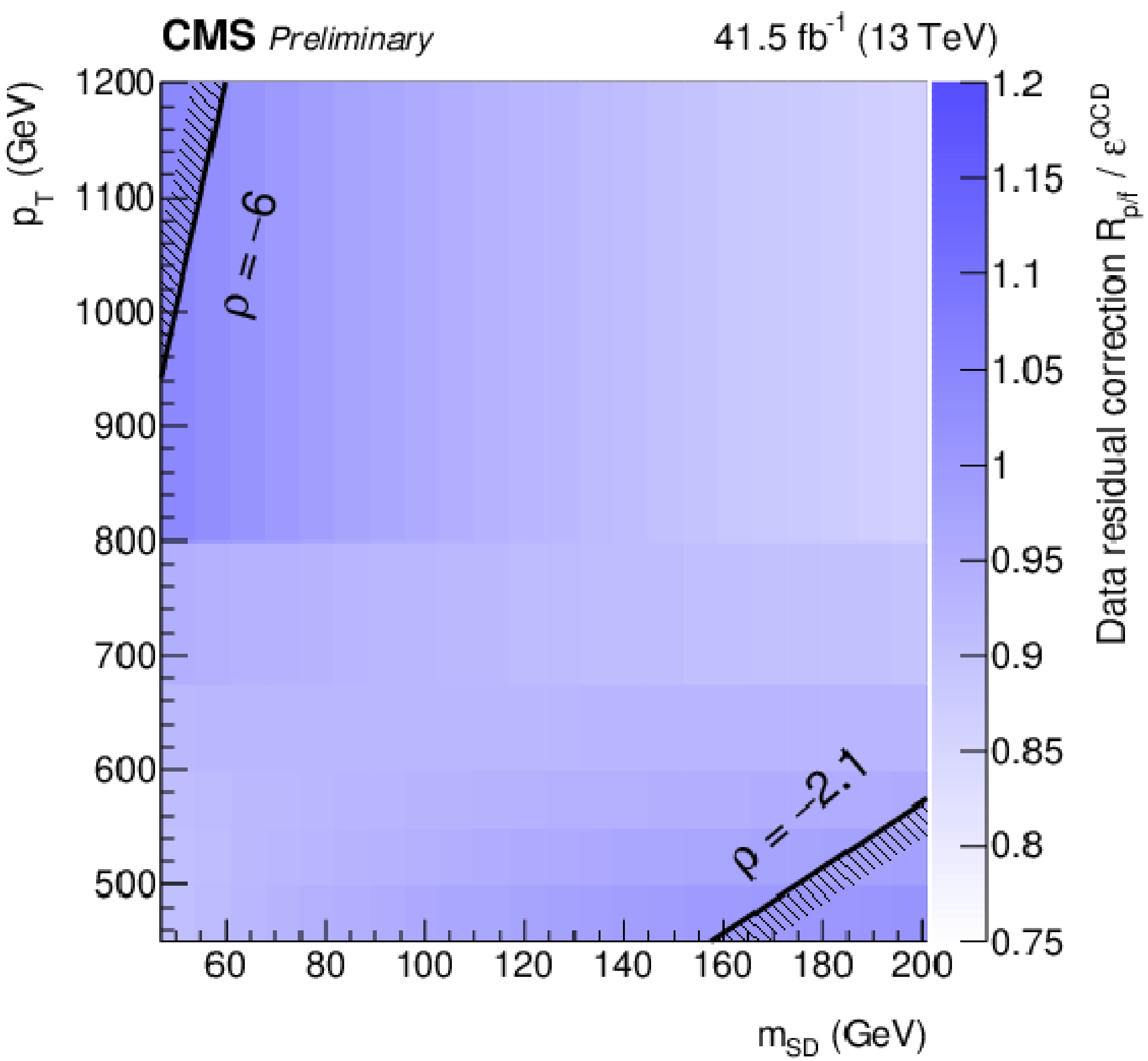
Source: arXiv:1307.0007

$H \to bb$: Inclusive ggF high p^H_T

→ Double b-tagger performance differs in MC and data.

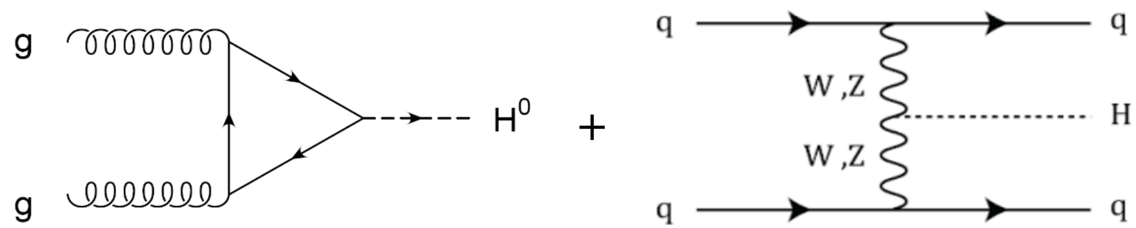
→ Fit simulation to data to extract residual differences – Bernstein polynomial as a function of (ρ,p_T):

$$\left(\sum_{k,\ell} a_{k\ell} \rho_{ij}^{k} {p_T}_j^{\ell} \right)$$



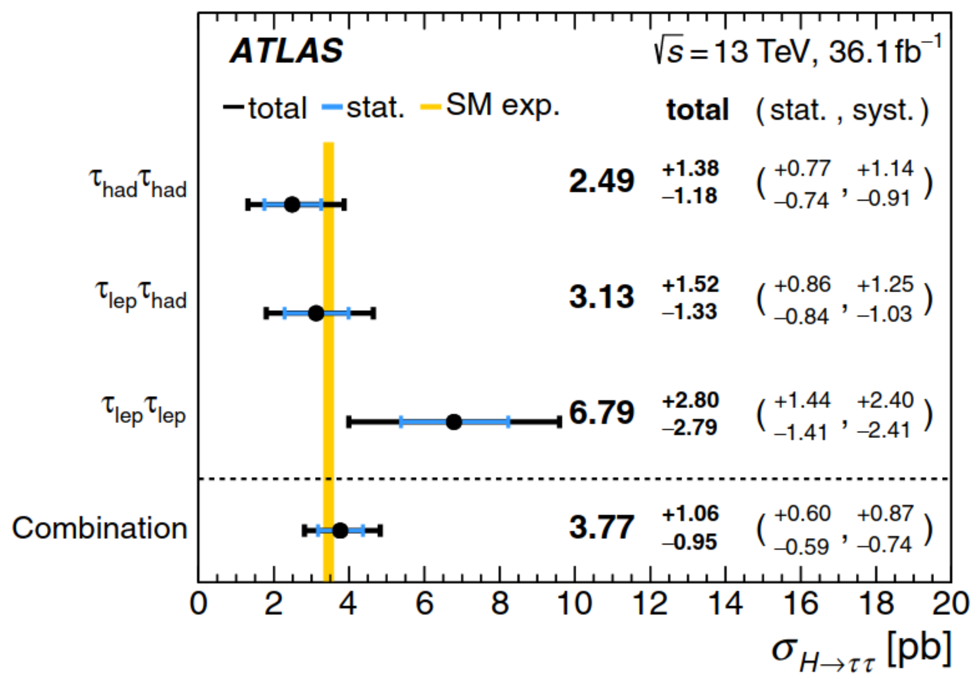
$H \longrightarrow \tau\tau$

Test of CP Invariance in VBF $H \to \tau\tau$

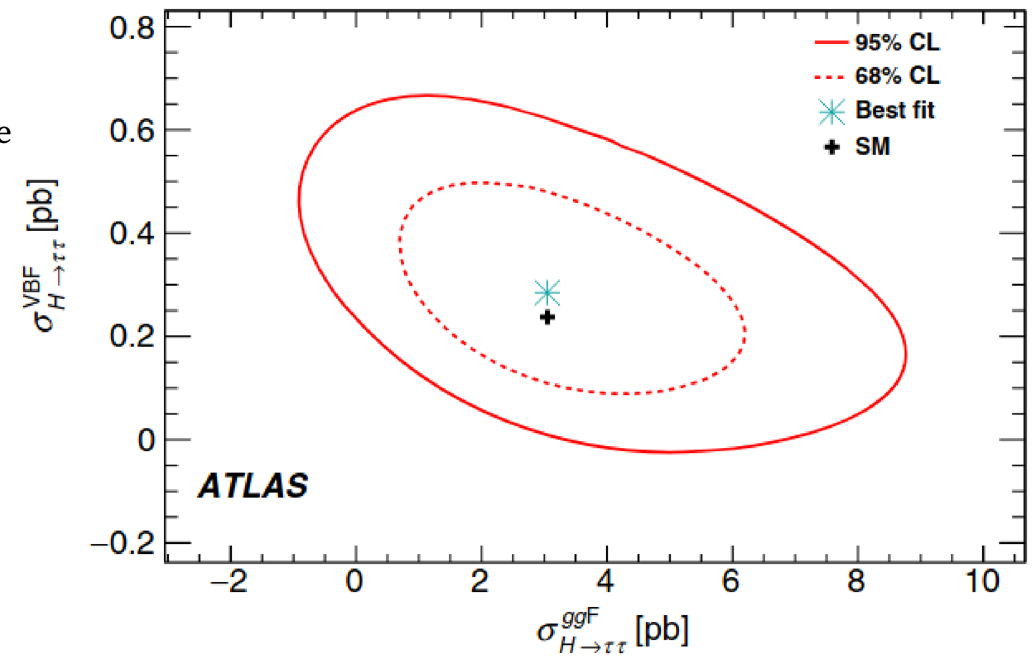
ATLAS Publications			
Paper	**Luminosity**	**Date**	**Signal**
Phys. Lett. B 805 (2020) 135426	36.1fb^{-1}	Feb. 2020	

$\longrightarrow$ Uses same dataset as $H \to \tau\tau$ observation paper:

Source: Phys Rev. D. 99.072001 (2019)



Analysis sensitive to both ggF and VBF production modes



Test of CP Invariance in VBF H⟶ ττ

Phys. Lett. B 805 (2020) 135426

Physics Interpretation:

⟶ Effective lagrangian ($\mathcal{L}_{eff}$) composed of:

- Standard Model: $\mathcal{L}_{SM}$
- CP-odd mass dim. Six: $\mathcal{L}^{6}_{CP}$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{f_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{f_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \mathrm{O}\left(\frac{1}{\Lambda^3}\right)$$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + g_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \widetilde{W}^{+}_{\mu\nu} W^{-,\mu\nu}$$

⟶ CP-violation of VBF production parameterised by:

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d},$$

⟶ Under arbitrary choice that $\tilde{d} = \widetilde{d_B}$, one can parameterise the strength of CP-violation via:

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + \tilde{d}\cdot 2\,\mathrm{Re}(\mathcal{M}^*_{SM}\mathcal{M}_{CP\text{-}odd}) + \tilde{d}^2\cdot|\mathcal{M}_{CP\text{-}odd}|^2$$

⟶ The choice $\tilde{d} = \widetilde{d_B}$, whilst arbitrary is motivated as it yields $\kappa_W = \kappa_Z$ as and VBF HWW vs HZZ not separable:

$$\tilde{d} = -\hat{\kappa}_W = -(\tilde{\kappa}_W/\kappa_{SM})\tan\alpha$$

⟶ This is the same assumption used in the H⟶WW and H⟶ZZ combination.

⟶ VBF sensitive to CP violation due to momentum dependence of CP-violating terms:

$$T^{\mu\nu}(p_1, p_2) = \sum_{V=W,Z} \frac{2m_V^2}{v} g^{\mu\nu} + \sum_{V=W,Z,\gamma} \tilde{d}\frac{2g}{m_W}\epsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma}$$

H⟶VV tensor structure

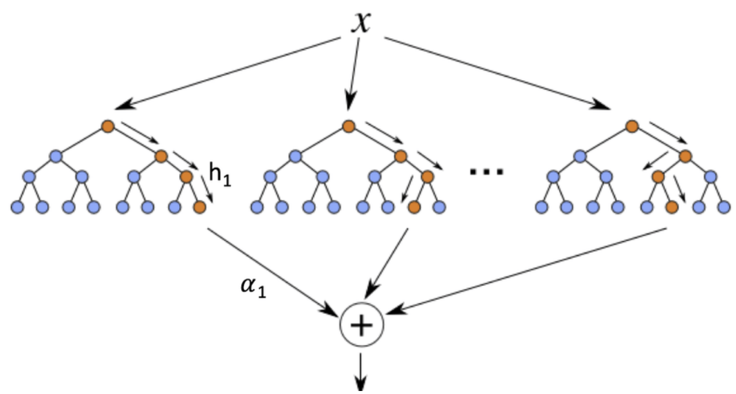
⟶ H⟶VV limited by $m_H = (p_1 + p_2)^2$, but VBFproduction is not.

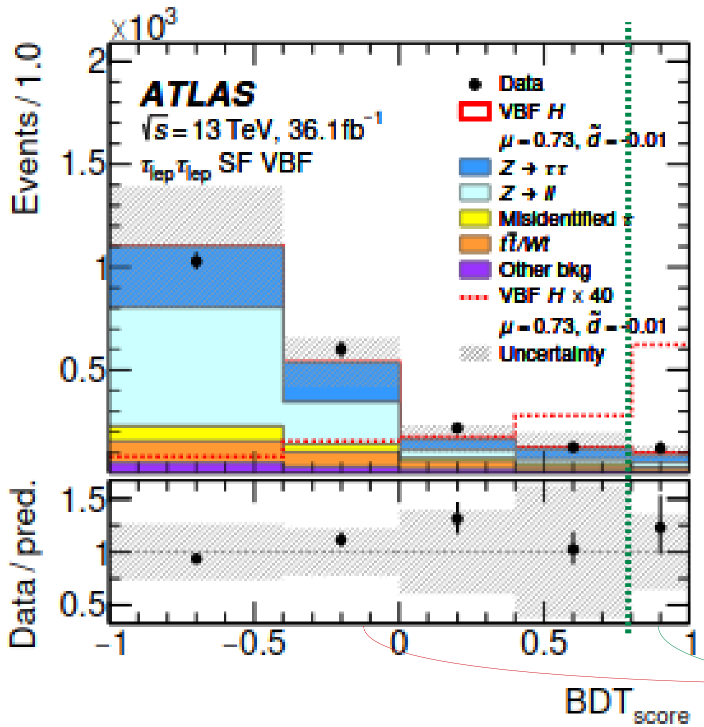
VBF H$\longrightarrow \tau\tau$: Analysis Strategy

Phys. Lett. B 805 (2020) 135426

$\longrightarrow$ Boosted Decision Tree (BDT) to define enriched VBF signal against SM bkg's:

- **H Properties:** $[m^{MMC}_{\tau\tau}, \ldots]$
- **$\tau\tau$ System:** $[\Delta R(\tau\tau), \ldots]$
- **VBF Topo.:** $[m_{jj}, \ldots]$





$\longrightarrow$ **Cut on BDT:**

BDT_{High} = Signal pure

BDT_{Low} = Bkg enriched

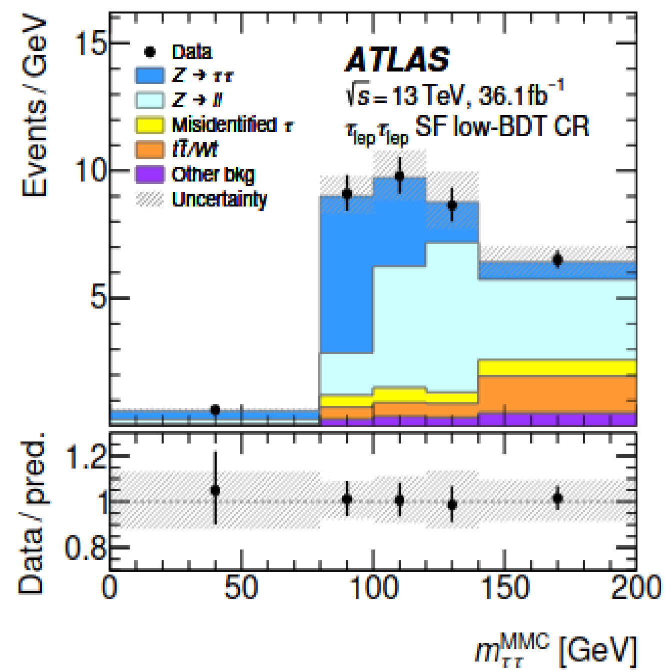
Fit Model:

$\longrightarrow$ Total of **11 fit regions:**

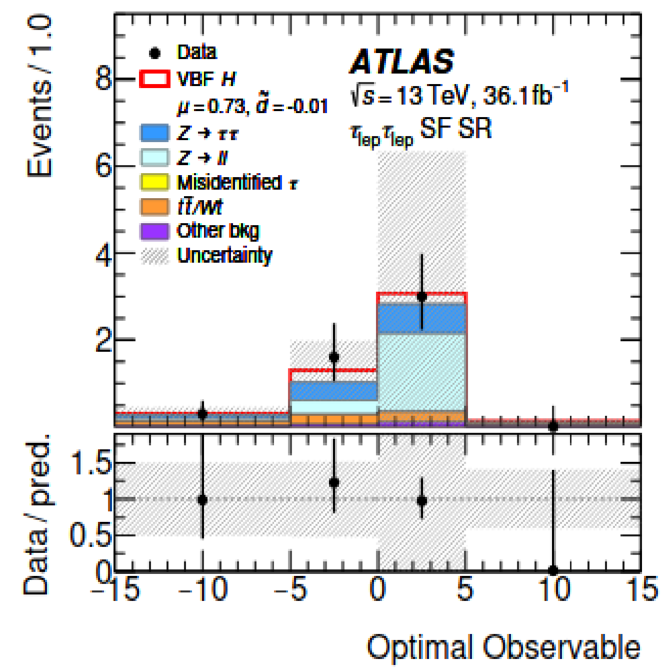
	$\tau_{lep}\tau_{lep}$ SF	$\tau_{lep}\tau_{lep}$ DF	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
BDT^{High}_{Score}	Opt. Obs.	Opt. Obs.	Opt. Obs.	Opt. Obs.
BDT^{low}_{Score}	$m^{MMC}_{\tau\tau}$	$m^{MMC}_{\tau\tau}$	$m^{MMC}_{\tau\tau}$	$m^{MMC}_{\tau\tau}$
Z$\longrightarrow$ ll CR	Yield			
Top CR	Yield	Yield		

$\longrightarrow$ Example of Data/MC for $\tau_{lep}\tau_{lep}$ SF

BDT^{Low}_{score}

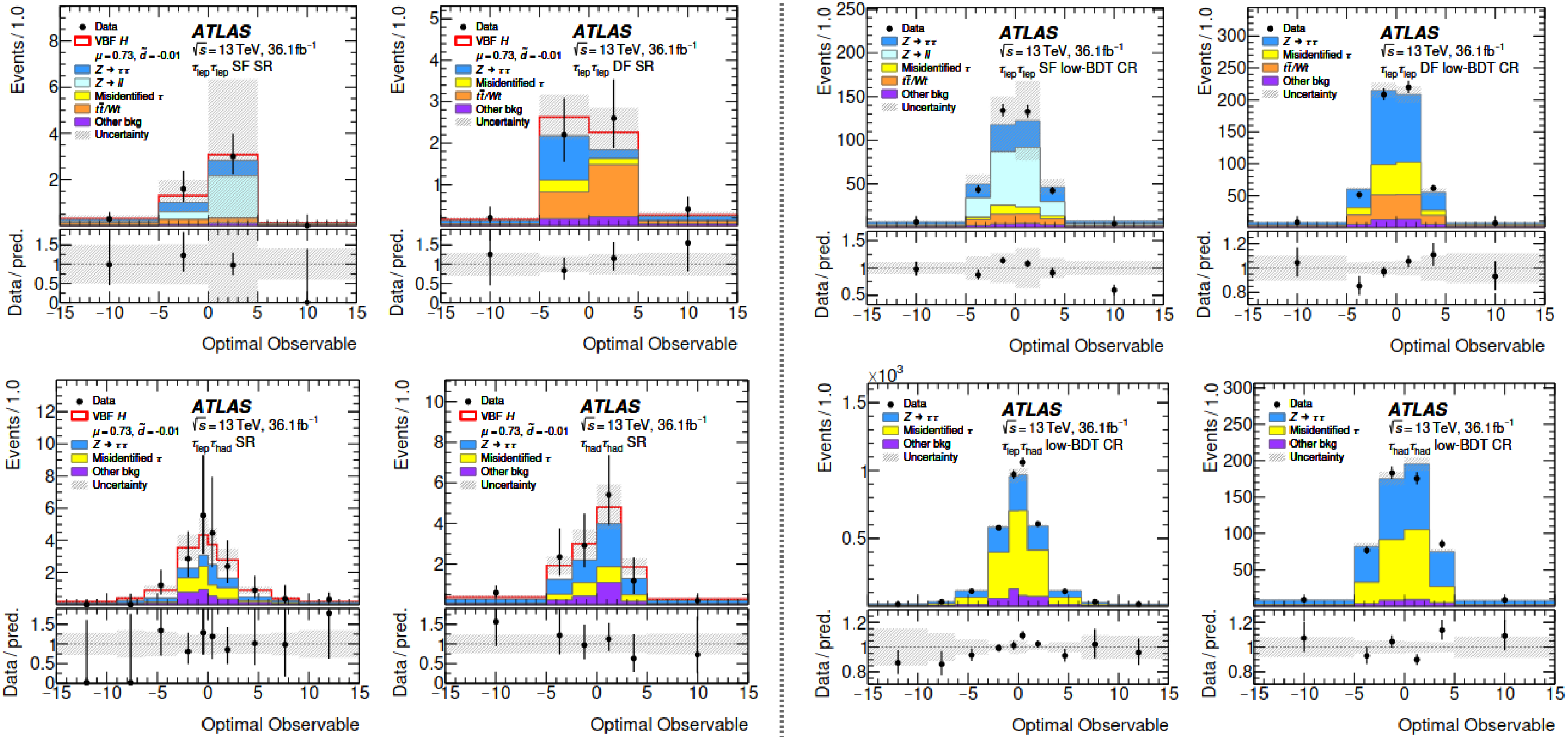


BDT^{High}_{score}



Test of CP Invariance in VBF H⟶ ττ: Fit discriminants

Phys. Lett. B 805 (2020) 135426

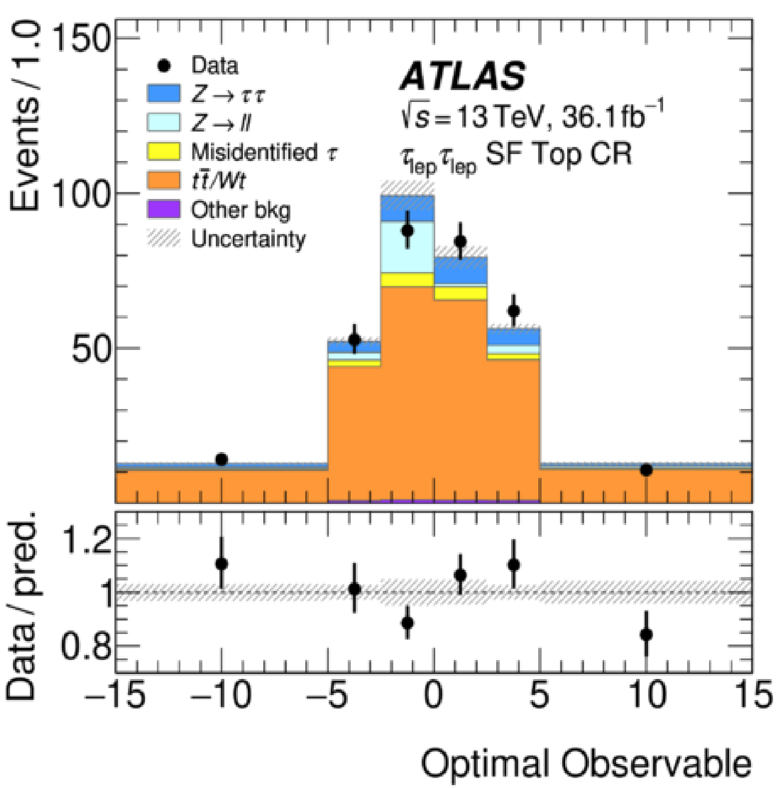


BDT$_{High}$

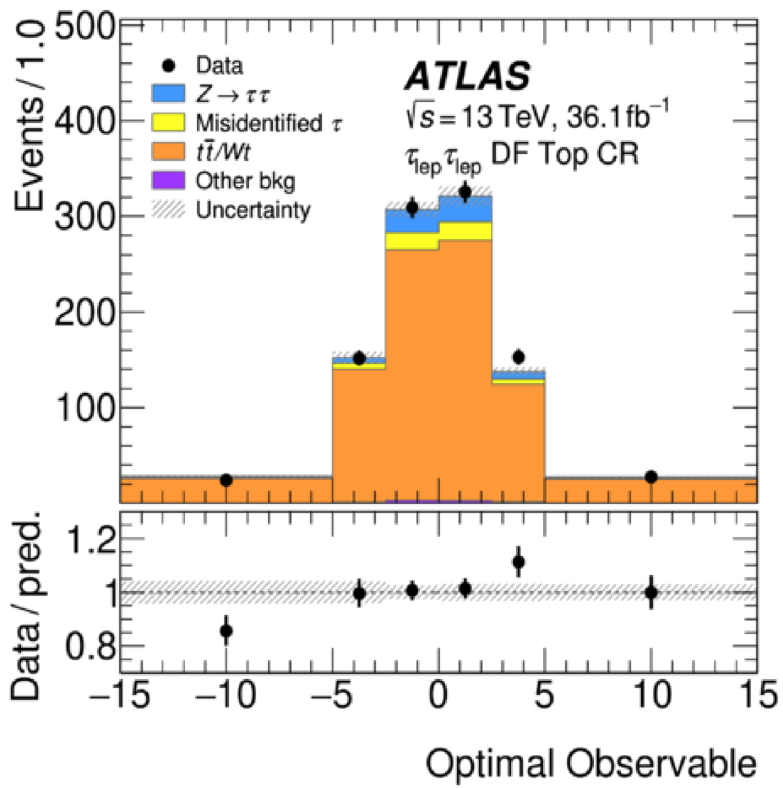
BDT$_{Low}$

Test of CP Invariance in VBF H⟶ ττ: Fit discriminants

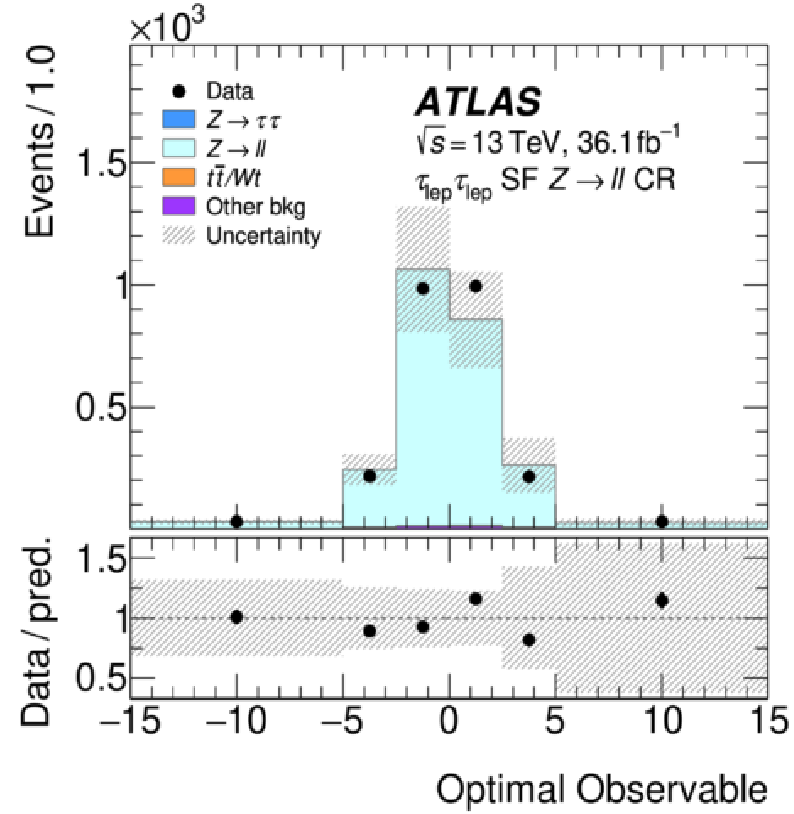
Phys. Lett. B 805 (2020) 135426



Top CR (SF)



Top CR (DF)



Z->ll CR

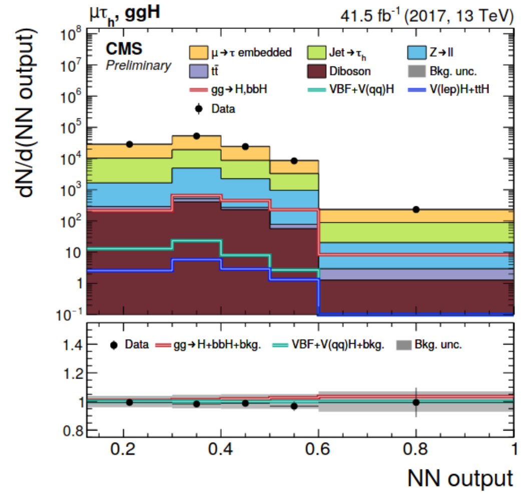
$H \rightarrow \tau\tau$ using 77.4fb^{-1}

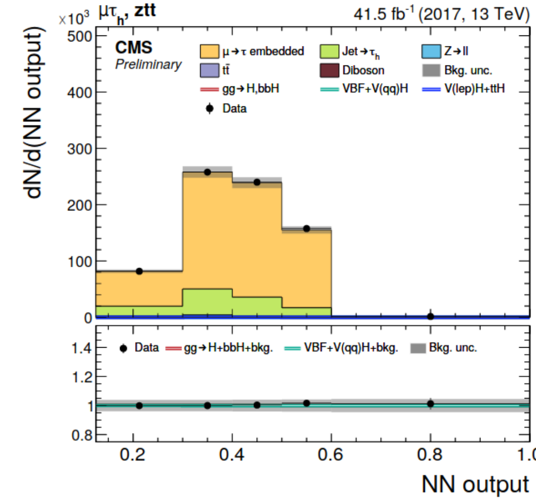
→ **77.4fb^{-1}** measurement of $H \rightarrow \tau\tau$ sensitive to VBF+ggF+VH production modes

→ Utilises [$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$] leptonic channels:

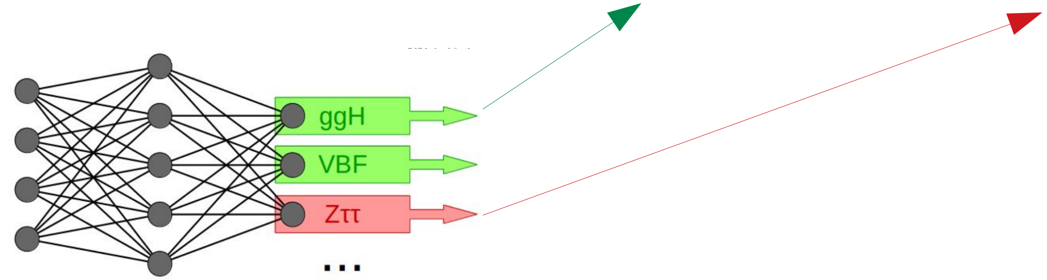
- **$e\mu$:** $Z\rightarrow\tau\tau$ + tt dominant bkg
- **$e(\mu)\tau_h$:** $Z\rightarrow\tau\tau$ + W+Jets bkg
- **$\tau_h\tau_h$:** QCD bkg

90% bkg estimated from data-driven methods





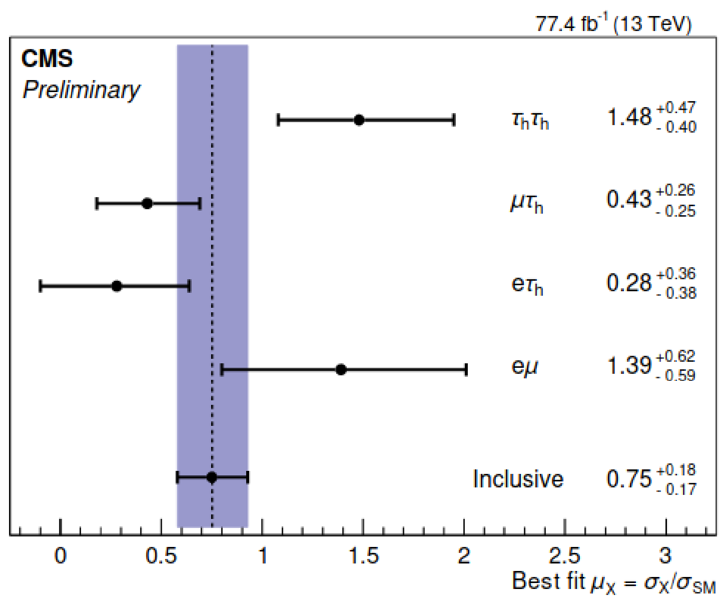
→ Softmax conditional probabilities of events from multiclass NN used to separate 9-classes ([ggF,VBF] signal + 7 bkg):

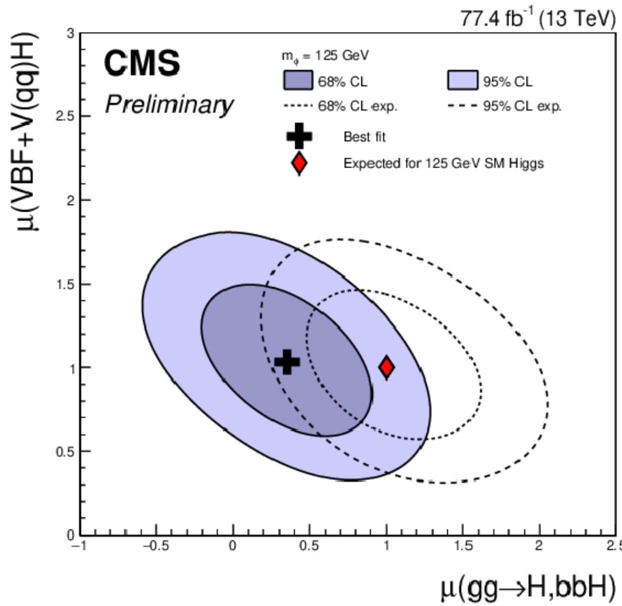


→ Simultaneous binned liklihood fit:

- 21 bkg categories
- 4 lepton channels
- 3 signal models

→ Showing inclusive $\sigma_{H\rightarrow\tau\tau}$ fit results





Constraints HVV EFT couplings: H⟶ ττ

PRD 100 (2019) 112002

CMS + ATLAS EXPERIMENT

⟶ **CMS:** parameterisation of anomalous HVV couplings via:

$$A(HVV) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

- Λ_1: BSM scale
- a^{VV}_3 CP-odd interaction
- a^{VV}_2 CP-even interaction

⟶ HVV anomalous couplings measured using effective cross-section ratios f_{ai}, and relative phase Φ:

$$\phi_{a_i} = arg\left[\frac{a_i}{a_1}\right] \qquad f_{a_i} = \frac{a_i^2 \sigma_i}{\sum a_i^2 \sigma_i}$$

⟶ **ATLAS:** parameterisation of CP odd terms according to:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu},$$

Where:

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d},$$

⟶ Assume that $\tilde{d} = \widetilde{d_B}$ as indistinguishable with dataset

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\,\text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$$

⟶ Transform between the two parameterisations:

$$\tilde{d} = \cos(\phi_3)\sqrt{\frac{f_3 \sigma_1}{(1-f_3)\sigma_3}} \quad \text{and} \quad f_3 = \frac{r_3^2}{1+r_3^2} \quad \text{Where:} \quad r_3^2 = \widetilde{d}^2 . \frac{\sigma_3}{\sigma_1}, \quad sgn(\tilde{d}) = \cos(\phi_3)$$

⟶ Comparison of transformed limits performed internally, regretably can not be shown here today