$H \to \tau\tau$ and $H \to cc$ at ATLAS

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H → τ τ and H → c c at ATLAS

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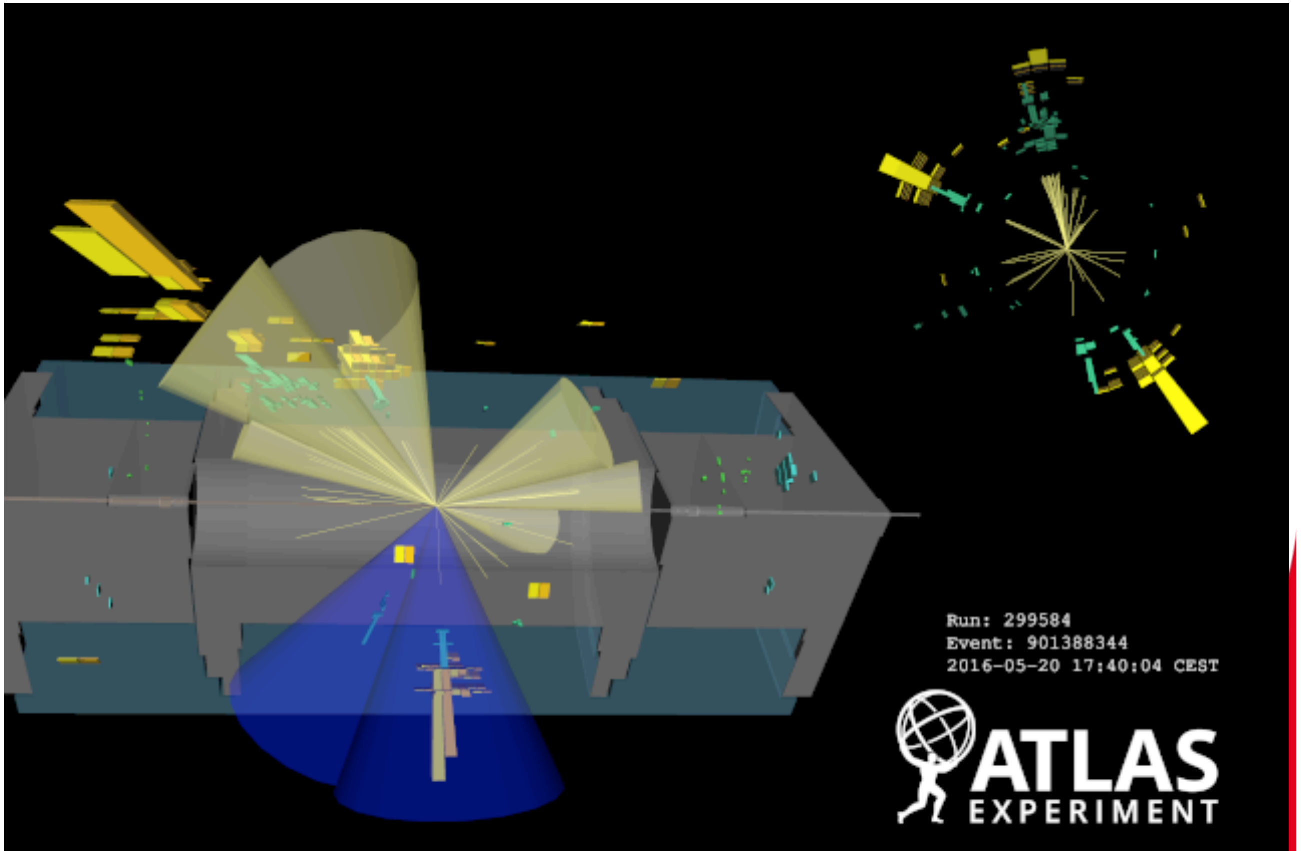
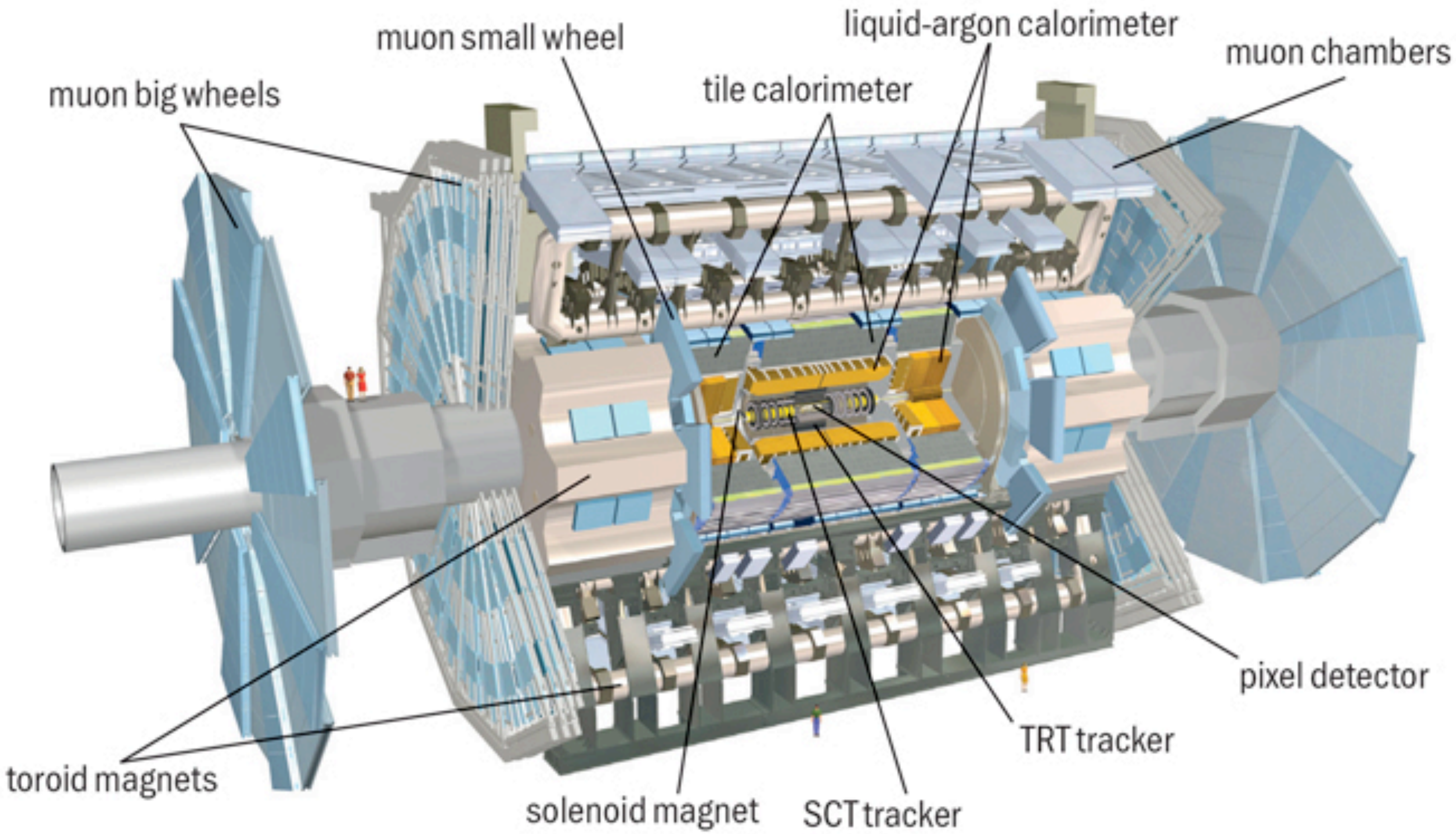


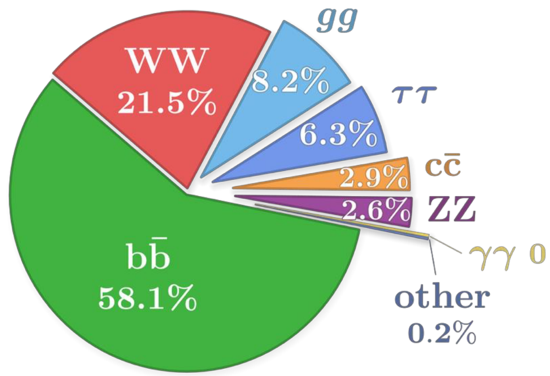
ATLAS Detector



H → τ τ decays

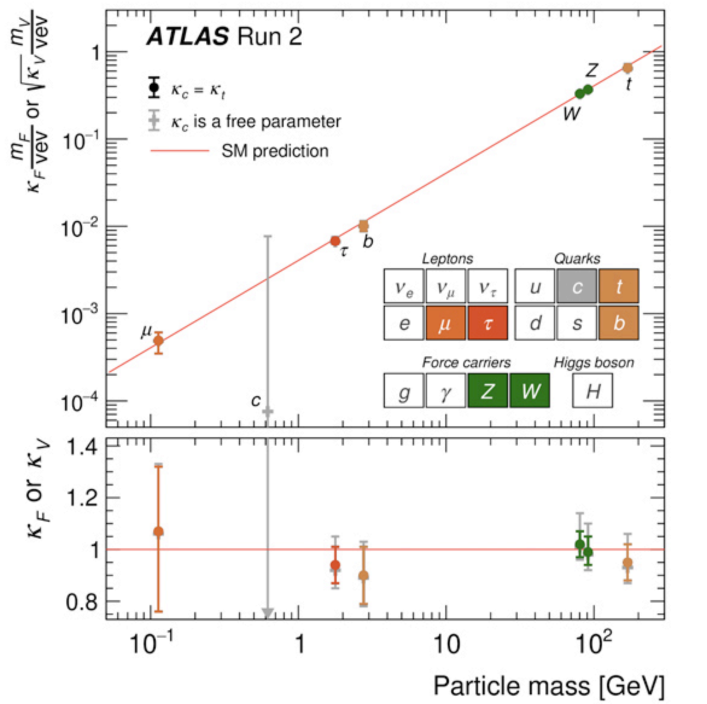
The Higgs boson Yukawa coupling to fermions is proportional to the Fermion mass

- After b-quarks the τ-lepton has the highest branching fraction of 6.3%
- The final state of e, μ, 1- and 3-prongs (π±) can be distinguished from background jets



Test the SM Higgs couplings

- 3rd generation Higgs couplings (τ)
- Differential cross section tests SM even more
  - VBF, ttH, kinematics
- CP properties of the H → τ τ vertex



Use the τ τ final state as tool for other investigations

- VBF H → τ τ probes CP properties of W/Z H vertex
- Search for further scalars in the low / medium / high mass region

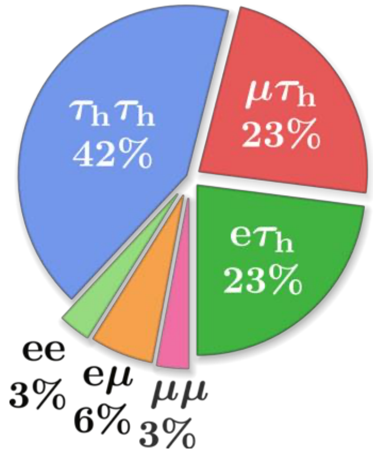
H → τ τ decays

Largest leptonic branching fraction of 6.3%

500k H → τ τ produced

Three different final states:

- Lep - lep: τe + τμ
- Lep - had: τlep + τhad
- Had - had: τhad + τhad



(Re-)Analysis of the full Run 2 dataset of 140/fb

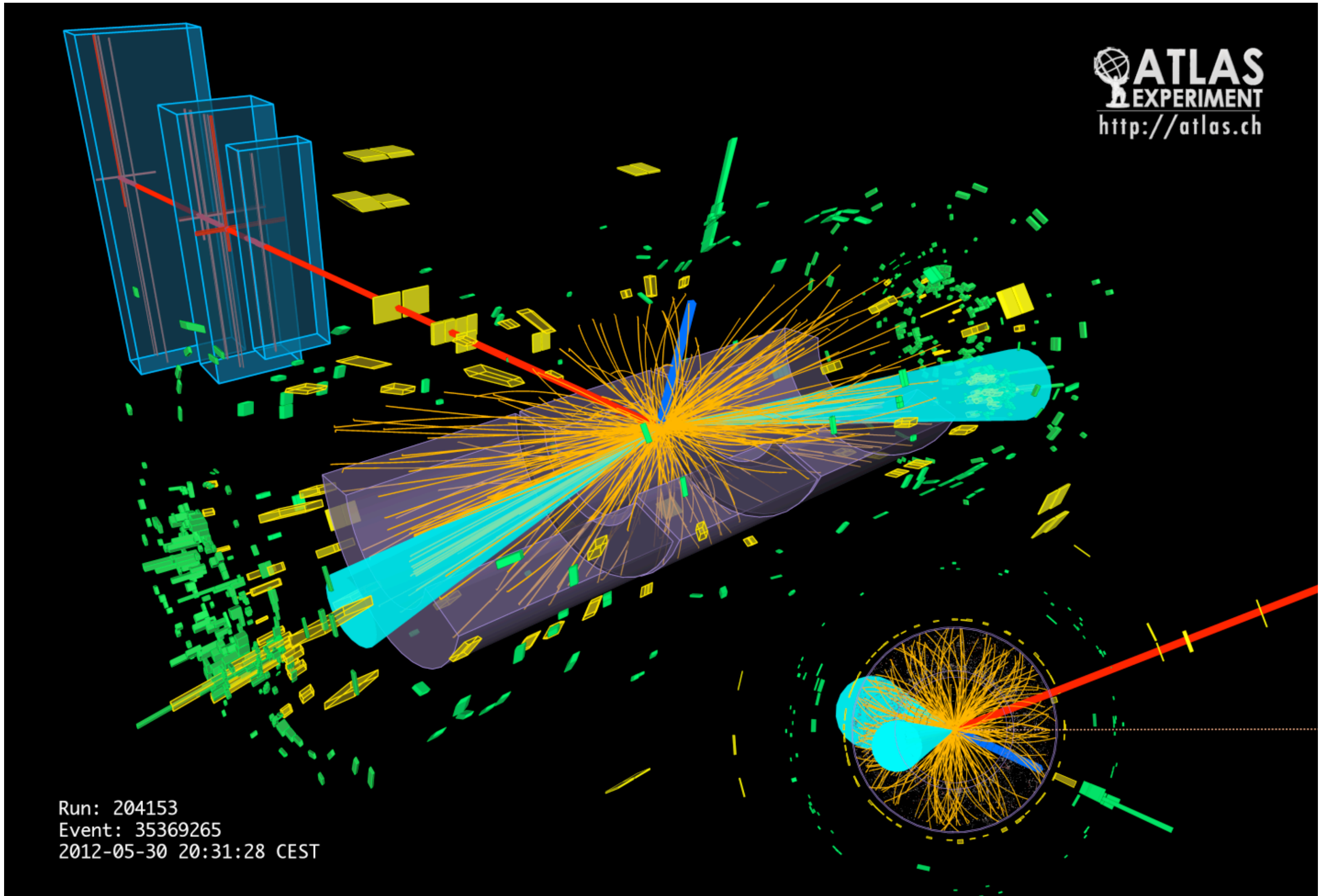
- STXS H → τ τ cross section
- Differential fiducial cross section

  https://arxiv.org/abs/2407.16320

- CP properties

  https://arxiv.org/abs/2212.05833

Early H → τ_μ τ_e + 2 jets candidate



H. Fox

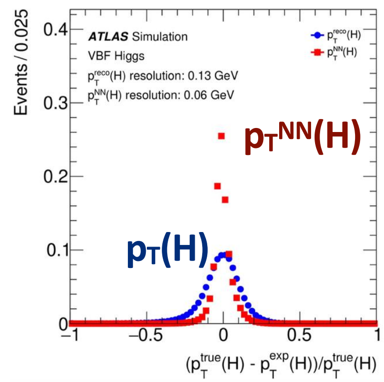
H → τ τ differential cross section

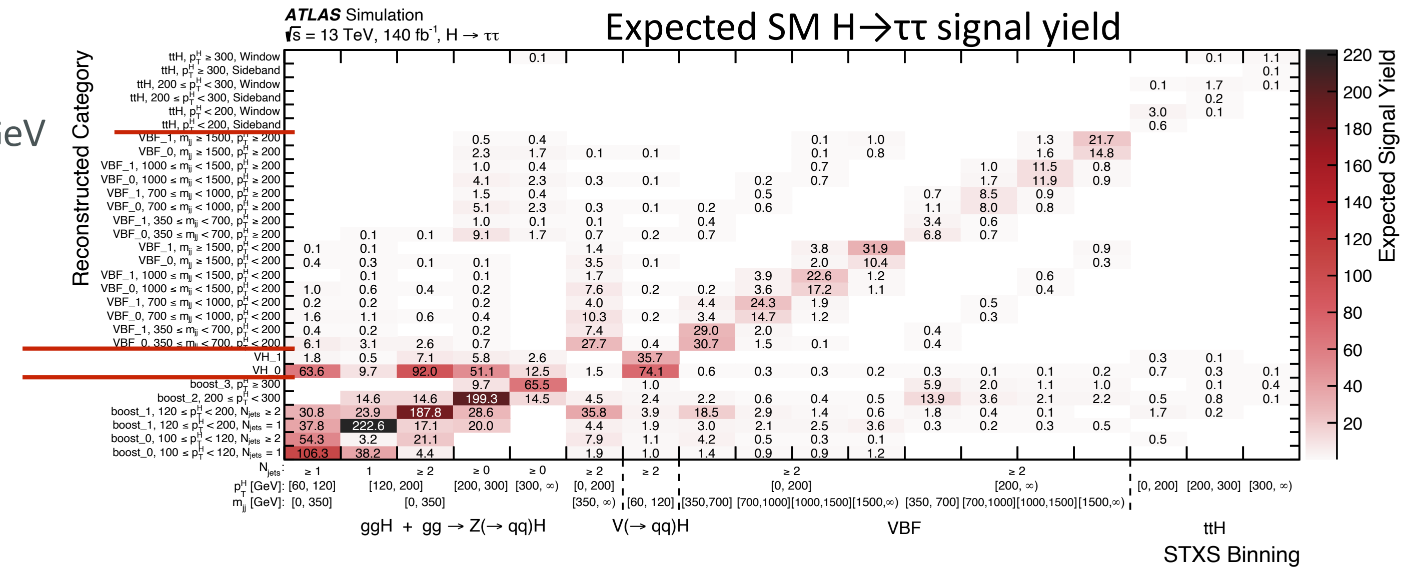
Baseline selection: lepton p_T with high trigger efficiency; medium particle ID, isolation, kinematics (m_{coll}, m_T), no b-jet, E_T^{miss}>20GeV, min jet p_T, ΔR, Δη, τ centrality

Analysis strategy: four main categories

- **VBF H → τ τ**
  - At least **2 forward jets** in opposite hemispheres with pT > 30GeV with large separation
  - m_{jj} > 350 GeV; central leptons
  - split into 8 bins: 4 m_{jj} bins and $p_T^{NN}(H)$ <> 200 GeV for STXS
  - A new NN improves the $p_T(H)$ resolution by 50%
  - A new BDT defines enriched VBF regions for all channels
- **tt(0 lep)H → $\tau_{had}\tau_{had}$**
  - At least 6 / 5 jets; at least 1 / 2 b-jets
  - 3 bins in $p_T^{NN}(H)$ for STXS
  - Multi-class BDT ttH/Zττ/tt
- **V(had)H → τ τ**
  - At least 2 jets with p_T > 30 GeV
  - 60 GeV < m_{jj} < 120 GeV
  - BDT for VH enrichment
- **Boosted H → τ τ**
  - No other category
  - $p_T(H)$ > 100 GeV
  - Binned in $p_T(H)$ and n-jets

$p_T(H)$ reconstruction



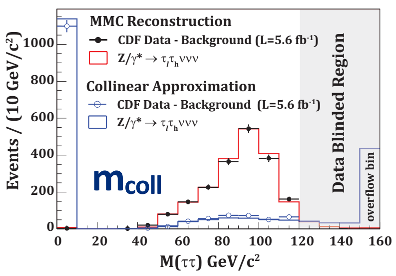


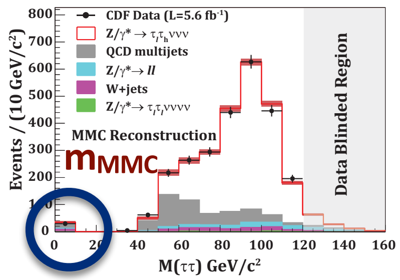
H → τ τ differential cross section

MMC mass reconstruction: Likelihood based approach using visible τ decay products, E_T^{miss} and jets to improve mass resolution. If no solution is found, m_{coll} is used.

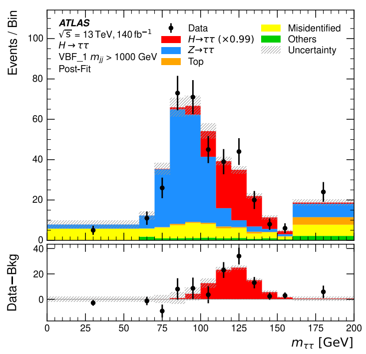
The **output** includes the most likely direction of the true taus and the neutrinos.

https://arxiv.org/abs/1012.4686

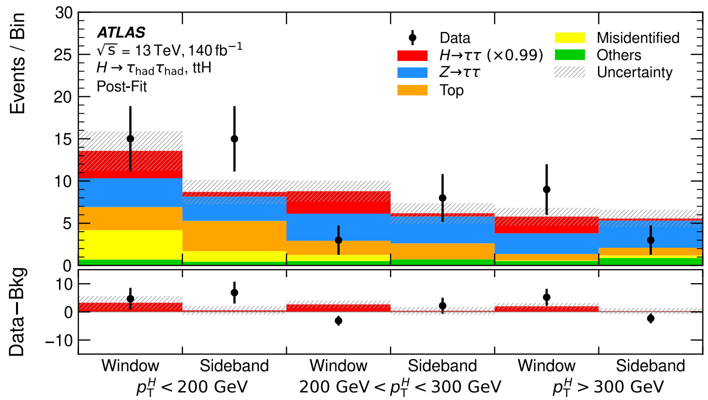




Signal and background in the VBF_1, m_{jj}>1000 GeV category



Signal and background in the ttH signal and sideband regions



The analysis is **limited by statistics.**

Main systematics:

- Theoretical uncertainties
- Jet and E_T^{miss} uncertainty
- τ misidentification for VH

$H \rightarrow \tau\tau$ STXS cross section results

No significant deviation from the SM

Production mode	$\sigma_H \times B(H \rightarrow \tau\tau)$ [pb] SM prediction	Measurement
ggF	2.77 ± 0.09	2.5 ± 0.8
VH	0.117 ± 0.003	0.11 ± 0.08
VBF	0.220 ± 0.005	0.23 ± 0.04
$t\bar{t}H$	0.031 ± 0.003	0.02 ± 0.03

STXS **VBF**

4 bins in m_{jj}

2 bins in $p_T(H)$

$(\sigma \times B) / (\sigma \times B)_{SM} = 1.04^{+0.19}_{-0.17}$

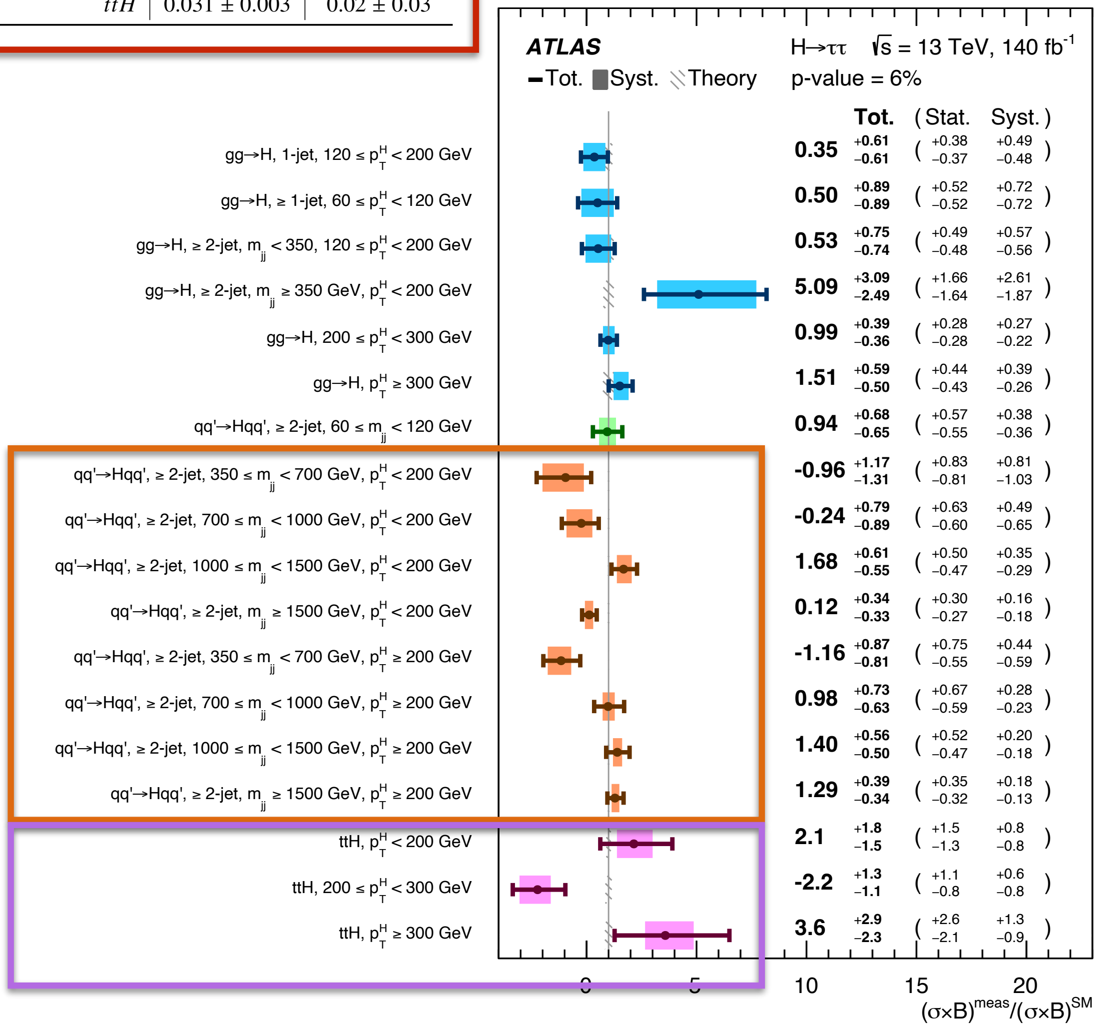
At the time the first measurement at high pT and the most precise at low pT

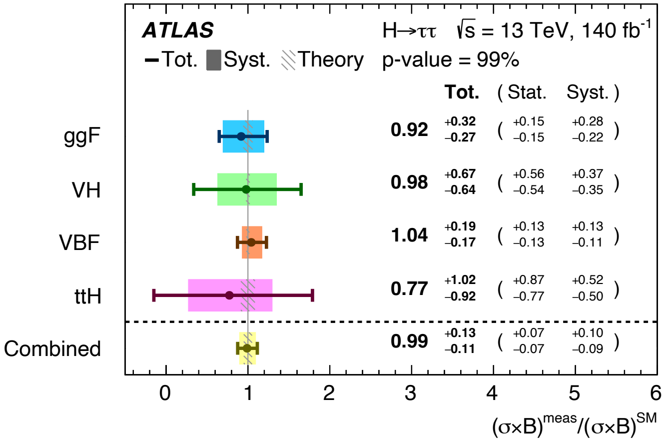
STXS **ttH**

3 bins in $p_T(H)$

$(\sigma \times B) / (\sigma \times B)_{SM} = 0.77^{+1.02}_{-0.92}$

Statistically limited





H → ττ unfolded fiducial differential XS

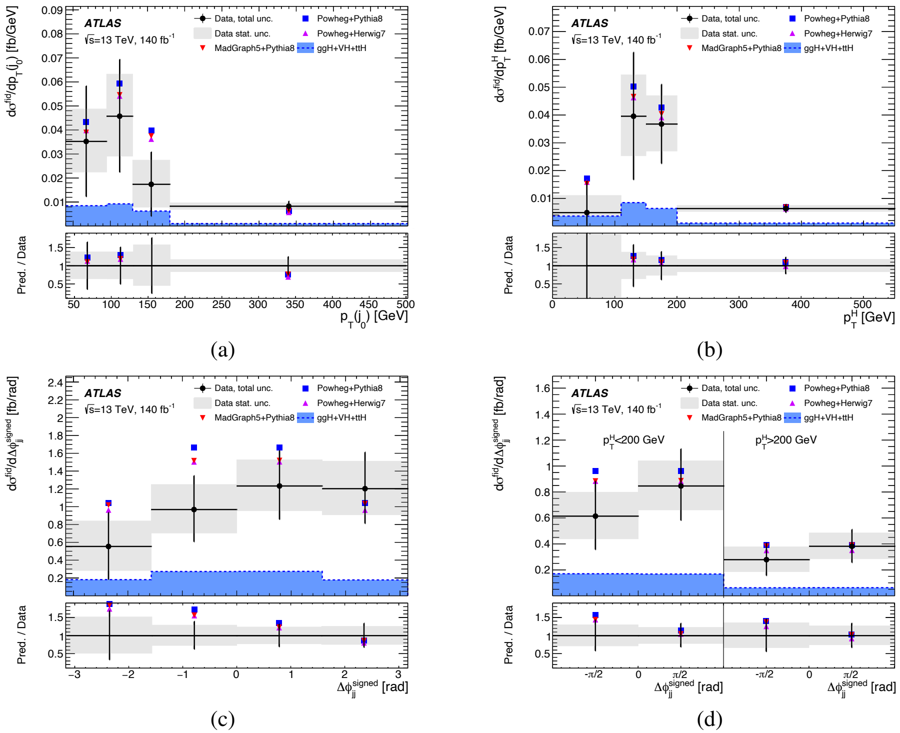
Unfolded for efficiencies and acceptance using MC techniques.

A **different binning** is used to optimise for

- Kinematics of VBF Higgs boson production => **improve sensitivity to BSM**
- Signed angle between jets => **sensitivity to Higgs C, P and CP**
- $p_T^{NN}(H)$ for **Higgs decay kinematics**.

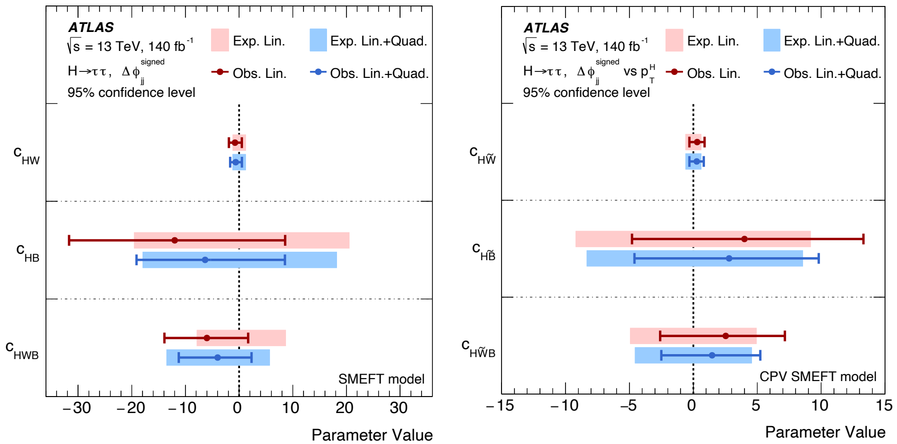
Table 9: Binning of the differential variables.

	$p_T(j_0)$ [GeV]	p_T^H [GeV]	$\Delta\phi_{jj}^{signed}$	$\Delta\phi_{jj}^{signed}$ vs p_T^H [GeV]
Bin 1	[40, 95]	[0, 110]	$[-\pi, -\pi/2]$	$\Delta\phi_{jj}^{signed} < 0$ & $p_T^H < 200$
Bin 2	[95, 130]	[110, 150]	$[-\pi/2, 0]$	$\Delta\phi_{jj}^{signed} > 0$ & $p_T^H < 200$
Bin 3	[130, 180]	[150, 200]	$[0, \pi/2]$	$\Delta\phi_{jj}^{signed} < 0$ & $p_T^H > 200$
Bin 4	[180, 500]	[200, 550]	$[\pi/2, \pi]$	$\Delta\phi_{jj}^{signed} > 0$ & $p_T^H > 200$



Measured fiducial differential cross section and particle level SM prediction

SMEFT interpretation of the cross section results with the Wilson coefficients corresponding to D=6 operators (**CP-even** and **CP-odd**)



$H \rightarrow \tau\tau$ CP properties

The SM predicts the Higgs boson to be CP-even.

A CP-odd admixture is possible and not yet excluded.

The di-tau final state is a unique test lab for this measurement

- Coupling of the Higgs boson to **fermions** (all other measurements are using bosons)
- A CP-odd contribution from BSM physics can be present at **tree level**
- **Weak decay** of the τ-lepton preserves the CP information

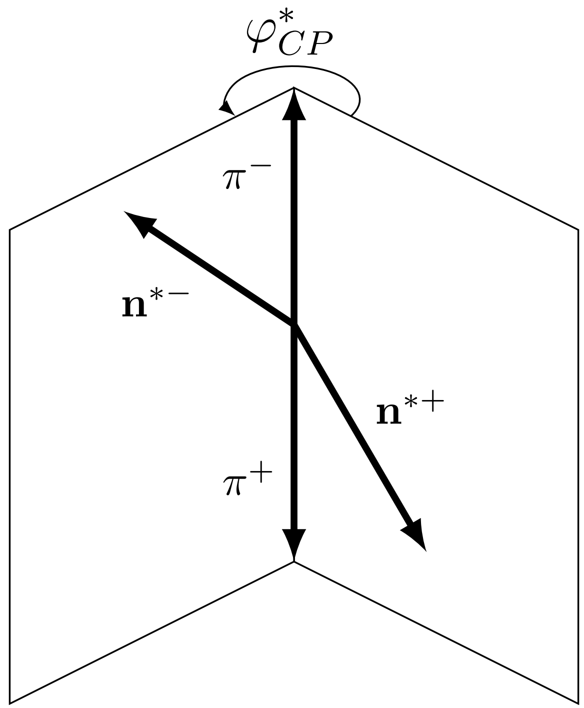
CP-odd admixture is parametrised by the angle ϕ_τ:

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

- $\phi_\tau = 0^o$ → **CP-even**
- $\phi_\tau = \pm 90^o$ → **CP-odd**

ϕ^*_{CP} is the acoplanarity angle between the taus is sensitive to ϕ_τ

n* is the impact parameter (IP) vector or the π^0 vector



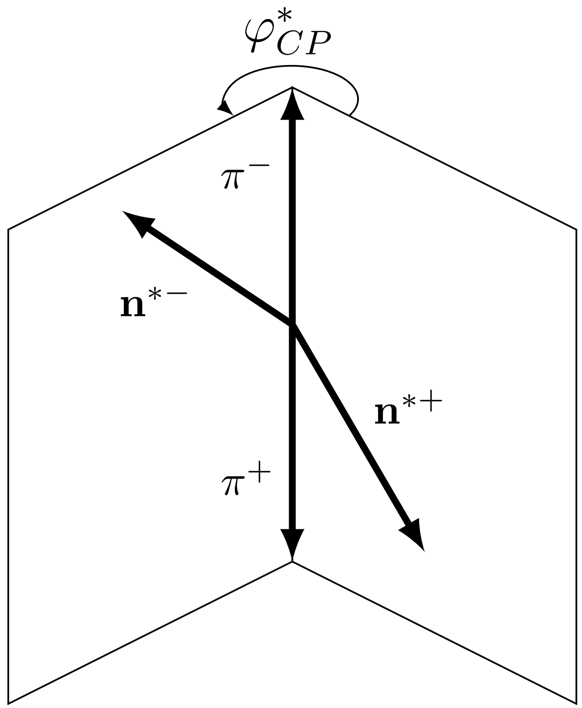
H → τ τ CP properties

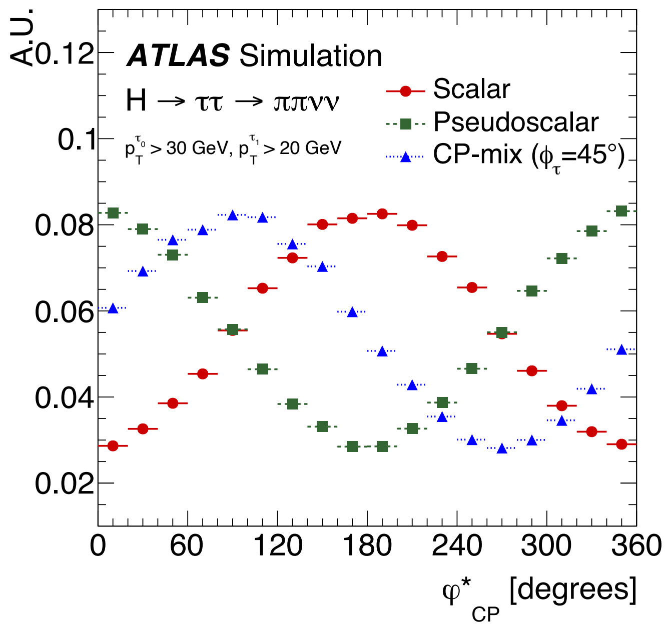
Four methods depending on the τ final state:

- **Impact parameter (IP) method**
  - $\tau^\pm \to \pi^\pm \nu$, $\tau^\pm \to l^\pm \nu \nu$
  - Using the $\pi^\pm$ momentum and the impact parameter vector to define the decay plane
- **ρ - method**
  - $\tau^\pm \to \rho^\pm \nu$, $\rho^\pm \to \pi^\pm \pi^0$
  - Di-ρ rest frame
  - $\pi^\pm$ momentum and π^0 define decay plane
  - $y^\pm$ determines the ϕ_{CP} sign and is correlated with ϕ_τ

$$y^{\rho}_{\pm} = \frac{E_{\pi\pm} - E_{\pi 0}}{E_{\pi\pm} + E_{\pi 0}}$$

- **a1 method**
  - $\tau^\pm \to a_1^\pm \nu$, $a_1^\pm \to \pi^\pm \pi^\pm \pi^0$
  - The highest $\pi^\pm$ momentum and the sum of the other pions determine the decay plane
- The methods can be **mixed** for each tau





$H \rightarrow \tau\tau$ CP properties

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Typically high $p_T(H)$ regions yield cleaner signals.

Four signal regions and **four control regions** are defined: **VBF** (high and low **VBF BDT**), ggF (boosted and very boosted)

VBF		Boost	
$p_T^{j_2} > 30$ GeV $m_{jj} > 400$ GeV $\lvert\Delta\eta_{jj}\rvert > 3.0$ $\eta_{j_1} \cdot \eta_{j_2} < 0$ Central τ-leptons		Not VBF $p_T^{\tau\tau} > 100$ GeV	
Signal region ($110 < m_{\tau\tau}^{MMC} < 150$ GeV)			
VBF_1	VBF_0	Boost_1	Boost_0
BDT(VBF) > 0	BDT(VBF) < 0	$\Delta R_{\tau\tau} < 1.5$ and $p_T^{\tau\tau} > 140$ GeV	$\Delta R_{\tau\tau} > 1.5$ or $p_T^{\tau\tau} < 140$ GeV
$Z \rightarrow \tau\tau$ control region ($60 < m_{\tau\tau}^{MMC} < 110$ GeV)			
VBF_1 Z CR	VBF_0 Z CR	Boost_1 Z CR	Boost_0 Z CR

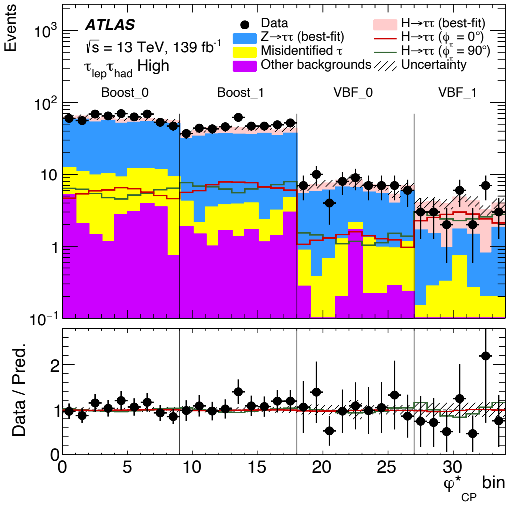
3-prong decays and decays with multiple π^0 are less sensitive to ϕ^*_{CP}.

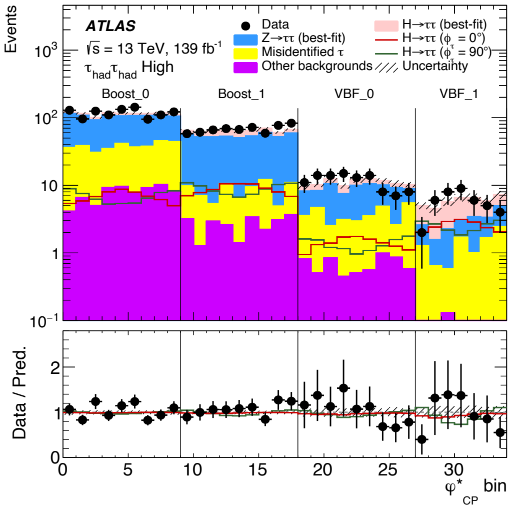
=> Decay mode, impact parameter significance and $|y_+ y_-|$ are used to categorise the signal in **Low, Medium** and **High** signal content

With lep-had / had-had this gives 24 channels

$H \rightarrow \tau\tau$ CP properties

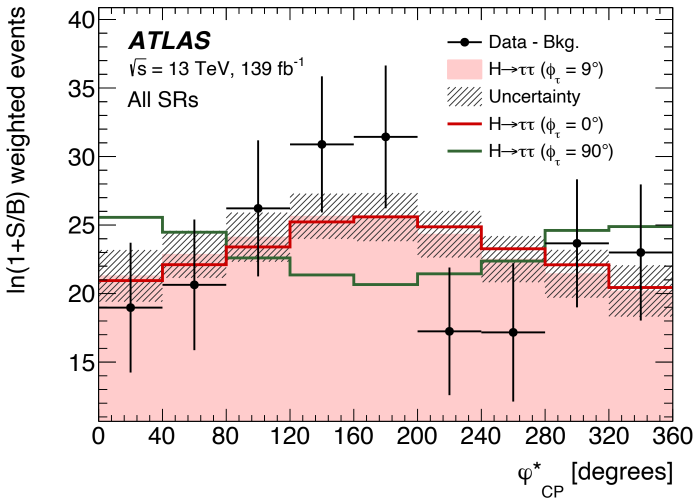
Results for the 4 signal regions in the "High" category for lep-had and had - had decays



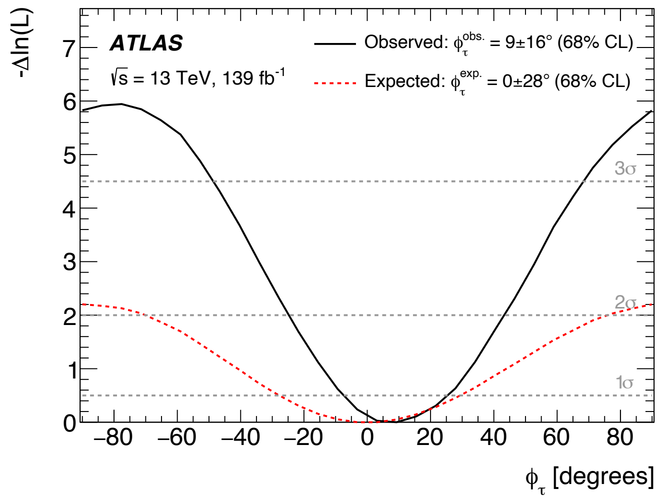


(b) $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ High SR

ln(1+S/B) weighted events for all signal regions and channels after background subtraction.



Likelihood scan for ϕ_τ



The analysis **statistically limited**.

Main systematic uncertainties are **jet energy scale** (3.4⁰) and **jet energy resolution** (2.5⁰)

$$\phi_\tau^{\mathrm{obs}} = 9^o \pm 16^o$$
$$\phi_\tau^{\mathrm{exp}} = 0^o \pm 28^o$$

VH → cc

H → cc is challenging and has not been observed yet.

https://arxiv.org/abs/2201.11428 ATLAS direct VH → cc 139 ifb

2015-2018 26 (31) ✖ SM superseded by

https://arxiv.org/abs/2410.19611 ATLAS VH → cc / bb + X 140ifb

2015-2018 11.5 (10.6) ✖ SM (est. VH → bb)

https://arxiv.org/abs/2511.21911v1 ATLAS VBF H → cc, H → bb,

37.5 + 51.5 ifb Run 2/3, 41 (28) ✖ SM

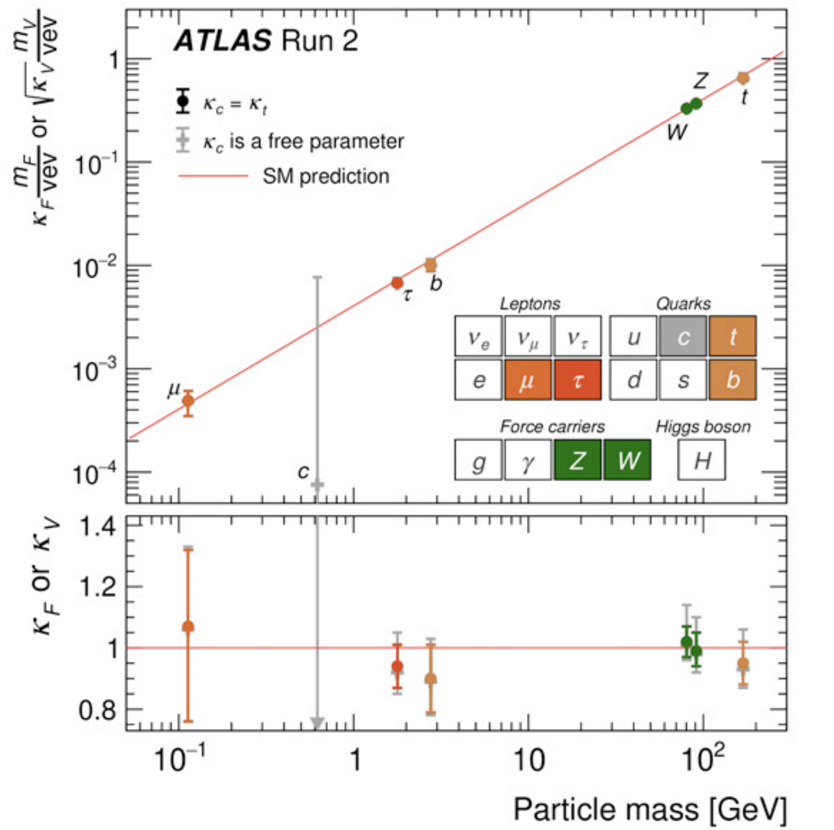
The branching fraction H → cc is 3%

2nd generation particle

Important for understanding the **Yukawa coupling**.

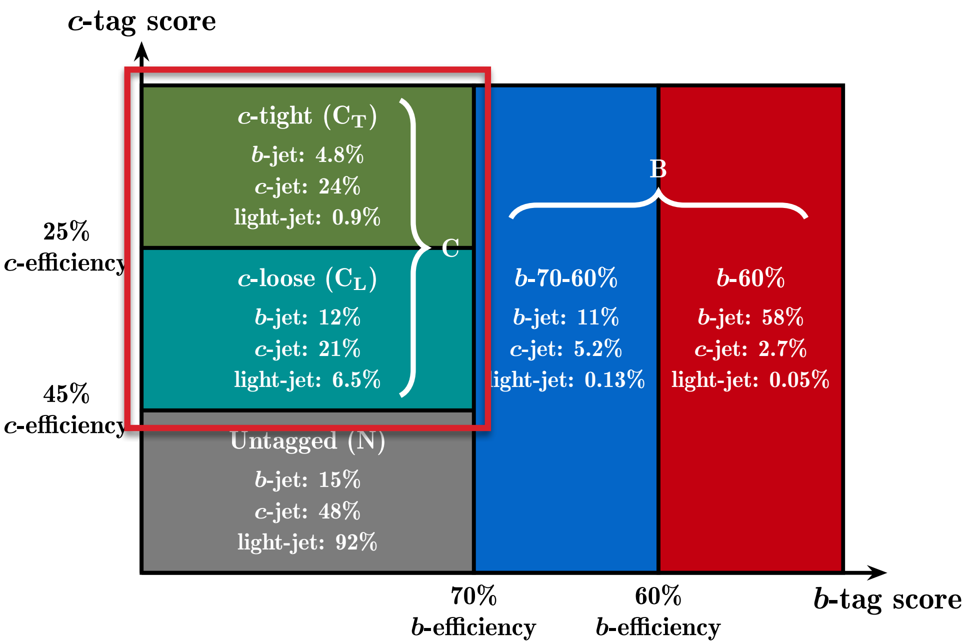
Associated production (VH) for best identification:

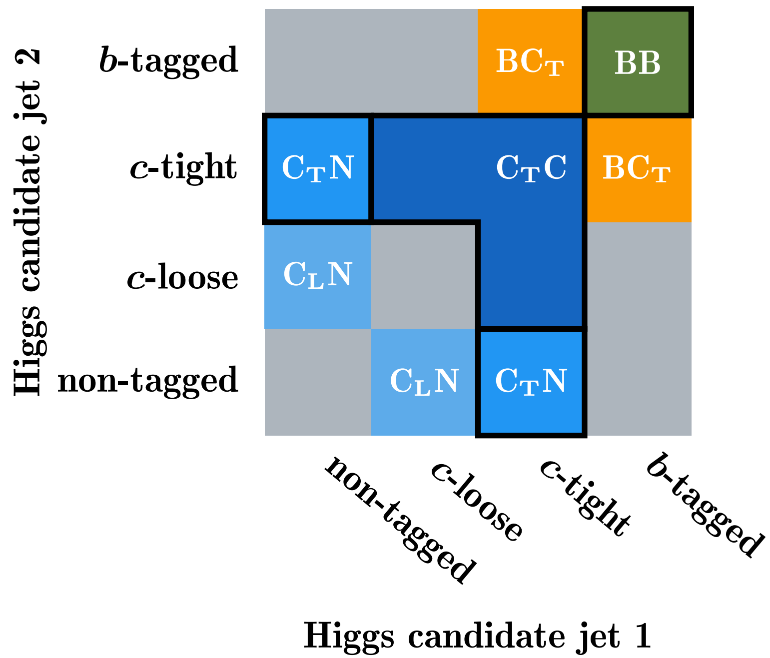
- W boson with **e, μ or τ in the final state**
- Z boson with **ee, μμ or νν** in the final state
- Categorised as 0-, 1-, or 2-leptons



VH → cc

The VH → bb / cc analyses are performed together, allowing for a quasi-continuous jet tagging:





The flavour tagging algorithm is a deep learning NN that combines multiple algorithms

Signal region: at least 1 loose (C_L) and 1 tight (C_T) c-tagged jet

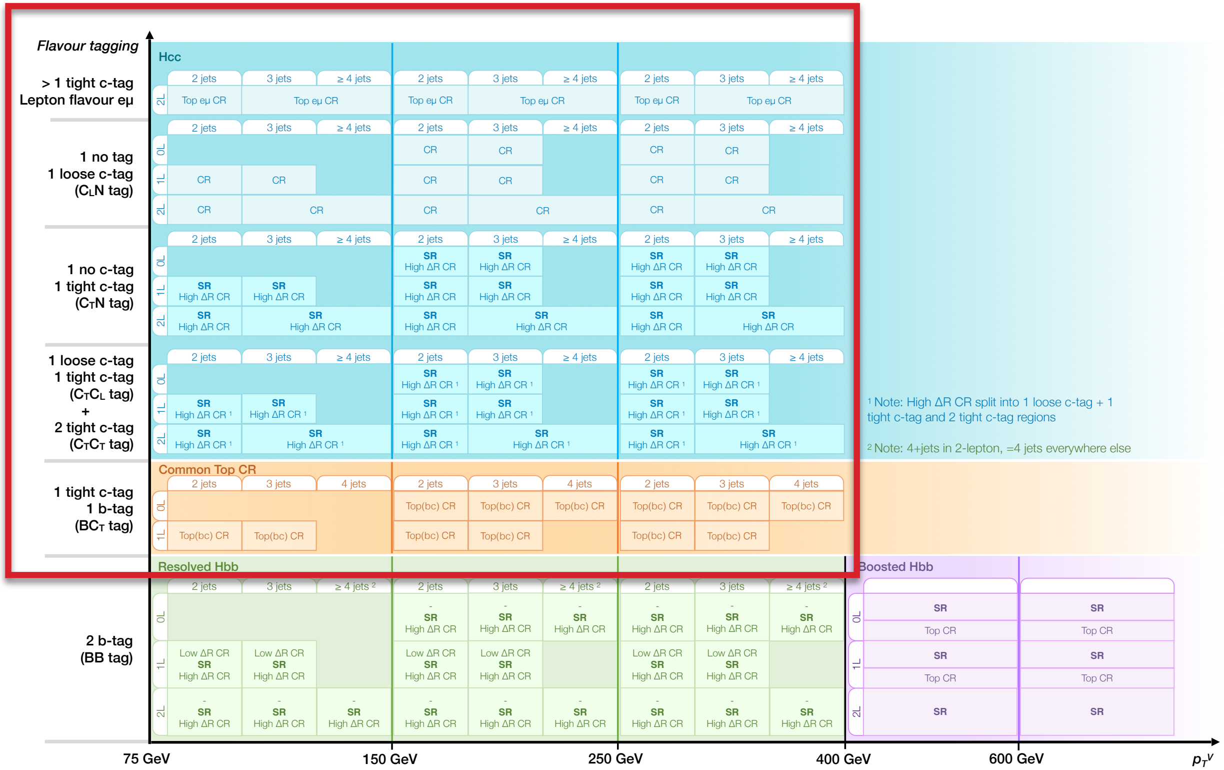
Control region: 1 loose and 1 non-tagged jet.

VH → cc

Categories for type of **c-tag** (5), **number of leptons** (3), **p_T(V)** (3) and number of **additional jets** (3)

SR / CR defined by ΔR of the jets

Just to give an impression how many categories are being used:

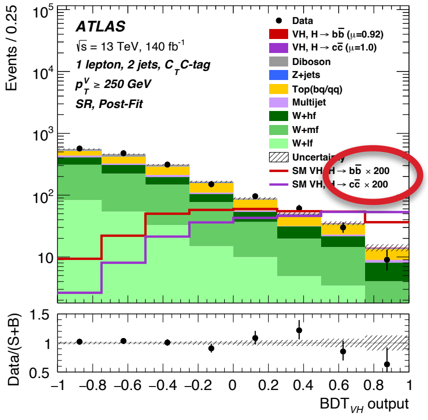


Each signal region has typically **2 BDTs** for S/B separation:

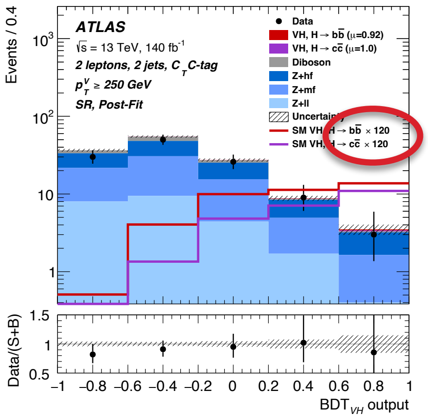
- **BDT_{VH}** : separation of Higgs signal from background
- **BDT_{VZ}** : identification of di-boson background (used for validation of the analysis)

VH → cc

BDT$_{VH}$ output for 2 SR:

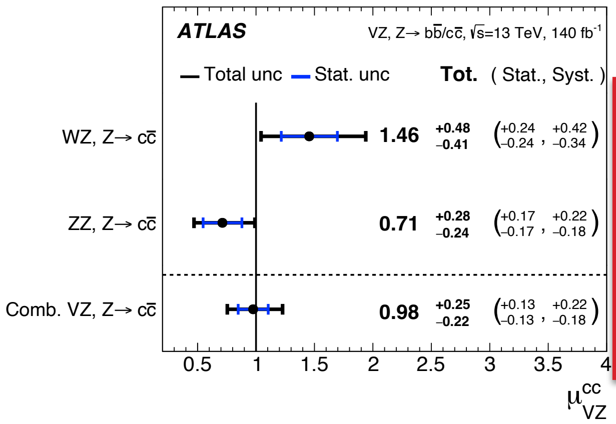


(e)



(h)

Diboson signal strength confirmation:



3.9 σ

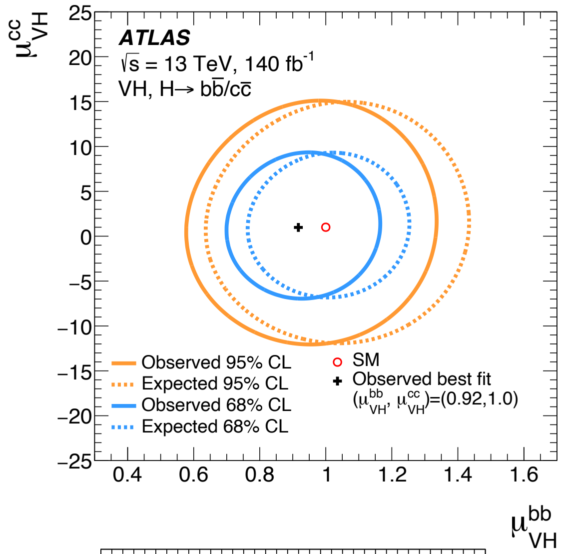
3.1 σ

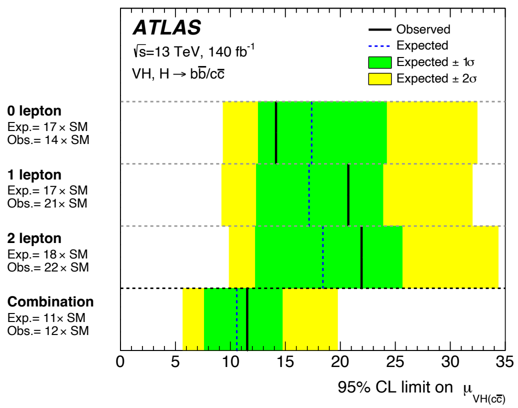
5.2 σ

$$\mu_{VH}^{bb} = 0.92^{+0.16}_{-0.15} = 0.92 \pm 0.10\ (\text{Stat.})^{+0.13}_{-0.11}\ (\text{Syst.})$$

$$\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\ (\text{Stat.})^{+3.7}_{-3.5}\ (\text{Syst.}).$$

CL of cc vs bb signal strength
Correlation 5%
Good agreement to SM





CL (95%) < 11.5 (10.6)
x 3 improvement
(flavour tagging + BDT)

Conclusion

The di-tau final state developed into a precision tool

- Various tests of the SM are possible
  - Higgs Yukawa couplings
  - VBF production kinematics
  - Higgs couplings at the production vertex
  - CP properties

Charm final state is still a factor of ~10 away from a measurement (as opposed to limit)

Stay tuned for HL LHC!