

# Measuring Higgs and DiHiggs interactions with tau leptons

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IFIC Seminar



# The standard model of particle physics



## Standard Model of Elementary Particles

three generations of matter (fermions)

	I	II	III	
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0
charge	2/3	2/3	2/3	0
spin	1/2	1/2	1/2	1
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0
	-1/3	-1/3	-1/3	0
	1/2	1/2	1/2	1
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$
	-1	-1	-1	0
	1/2	1/2	1/2	1
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson
	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$
	0	0	0	±1
	1/2	1/2	1/2	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson

QUARKS

LEPTONS

SCALAR BOSONS

GAUGE BOSONS

- Gauge symmetry group of the Standard Model is:

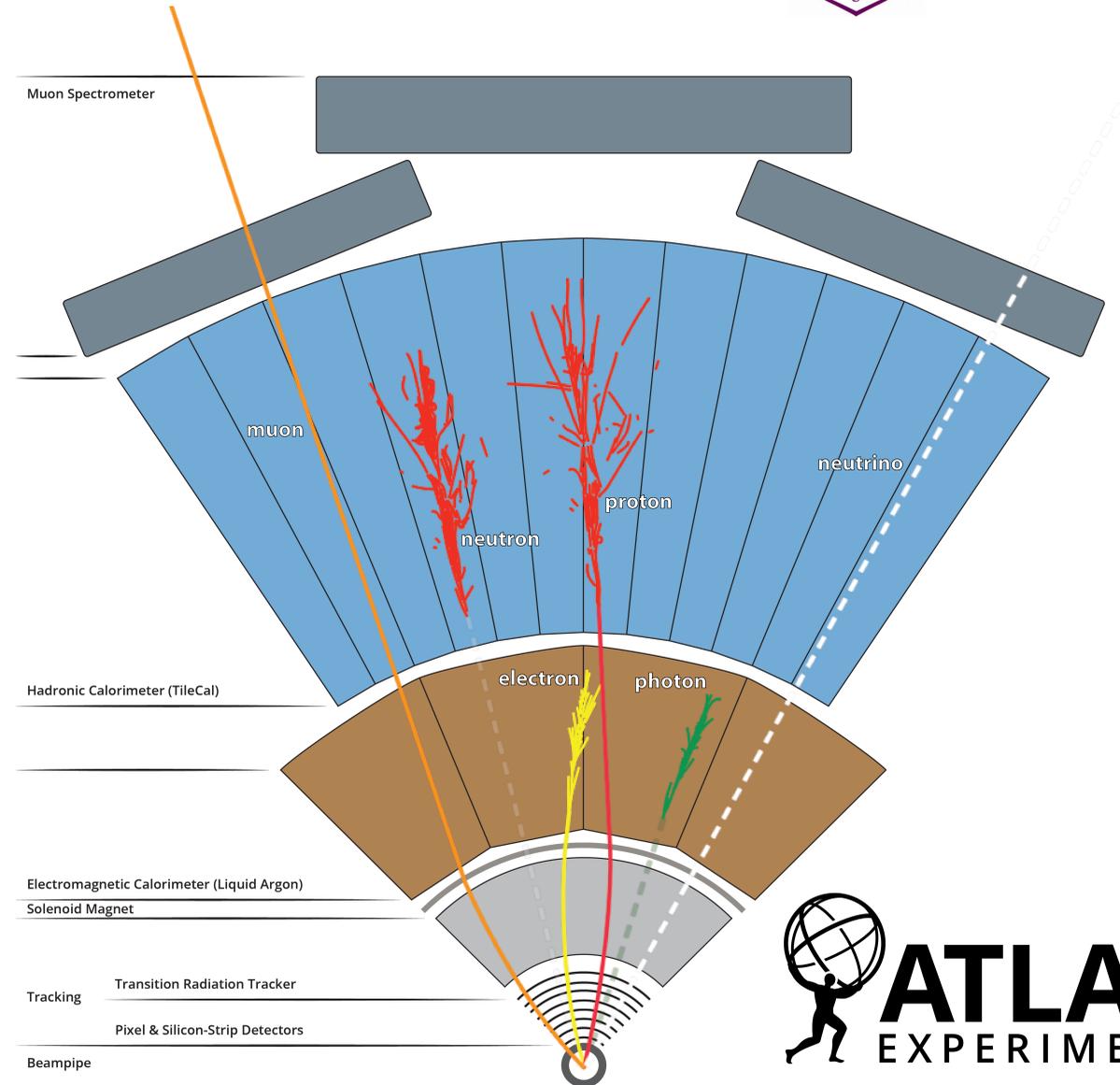
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

- Fermions (Quarks + Leptons):
  - Spin 1/2 particles
  - Matter building blocks
  - Split in 3 families with increasing mass
- Bosons:
  - Integer spin
  - Force carriers:
    - Electromagnetism: photons
    - Weak interactions: W/Z bosons
    - Strong interactions: gluons

# ATLAS experiment particle reconstruction



- Tracker to measure the momentum of charged particles
- Electromagnetic and hadronic calorimeters to measure energy of particles
- Muon spectrometer to detects muons passing through the rest of the detector
- Missing transfer energy for weakly interacting particles (for example neutrinos)



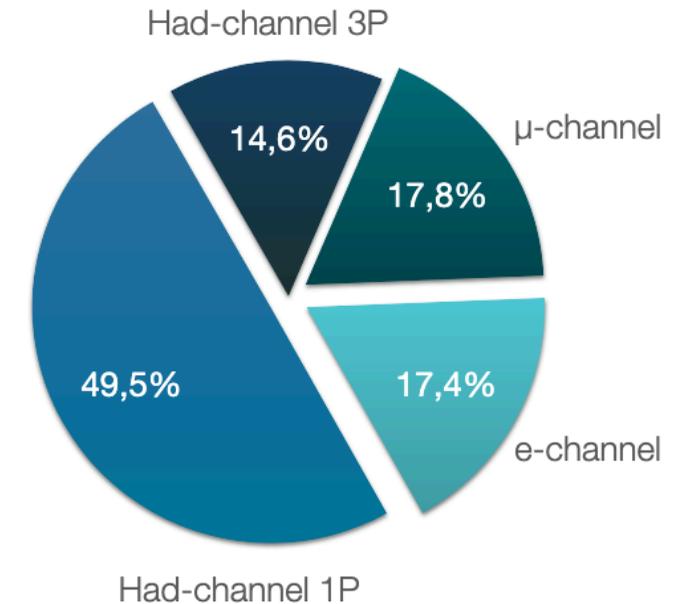
# Tau Lepton in a nutshell



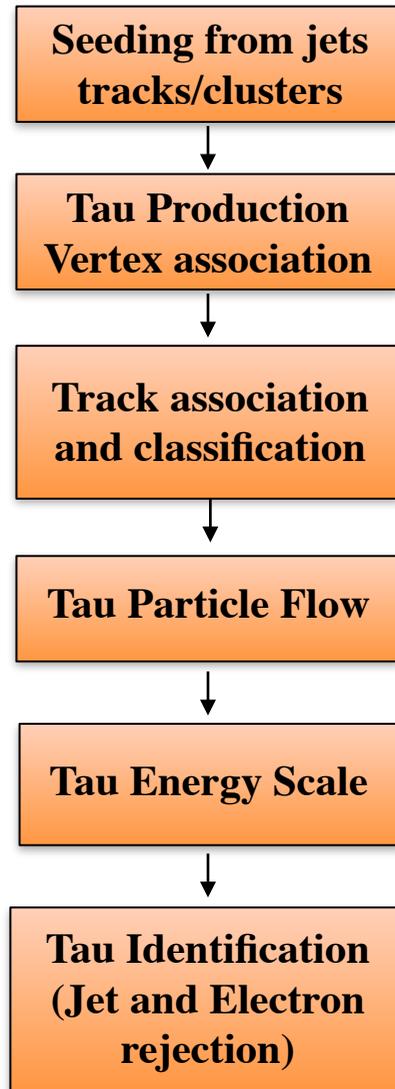
- Heaviest lepton in the Standard Model with a mass of 1.77 GeV
- Small displaced vertex with respect to interaction point and observed in the detector only through the decay products
- Only lepton which can decay in lighter leptons or hadrons:
  - Leptonic signature consist of electron/muon +  $E_T^{miss}$  from neutrinos; no dedicated reconstruction for this type of decay in the ATLAS experiment
  - Hadronic signature consists of 1 or 3 charged mesons +  $E_T^{miss}$ :
    - Decay can also include one or more neutral mesons ( $\pi^0$ )
    - Appears in the detector as more collimated than QCD jets

LEPTONS

$\approx 0.511 \text{ MeV}/c^2$ -1 1/2 <b>e</b> electron	$\approx 105.66 \text{ MeV}/c^2$ -1 1/2 <b><math>\mu</math></b> muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 1/2 <b><math>\tau</math></b> tau
$< 2.2 \text{ eV}/c^2$ 0 1/2 <b><math>\nu_e</math></b> electron neutrino	$< 1.7 \text{ MeV}/c^2$ 0 1/2 <b><math>\nu_\mu</math></b> muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 1/2 <b><math>\nu_\tau</math></b> tau neutrino

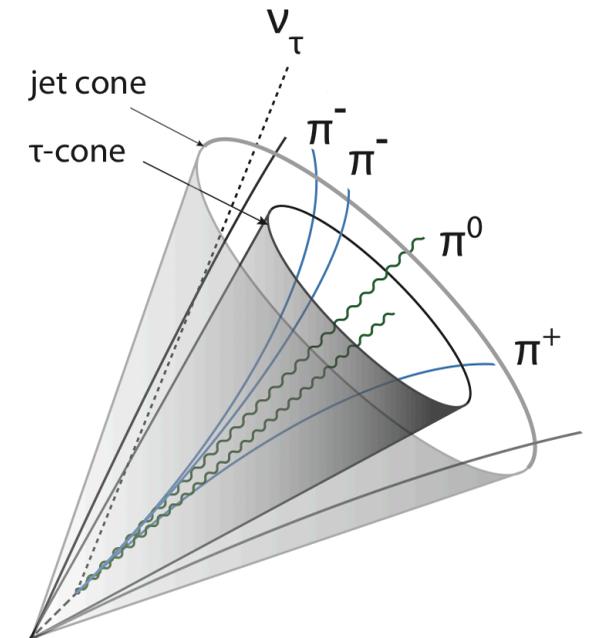


# Main stages of the Tau Reconstruction in ATLAS

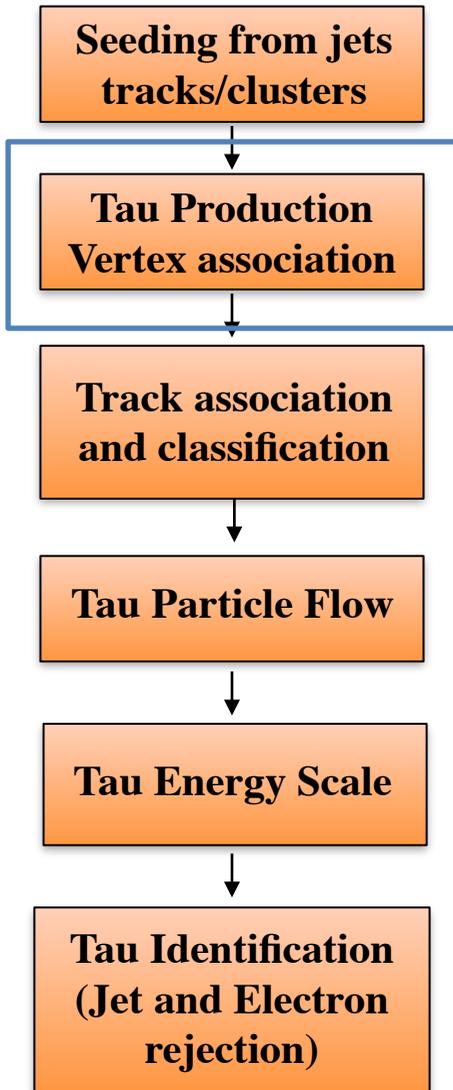


- Start from an (as much as possible) unbiased collection of tracks and clusters, i.e. a *LCTopo* jet
- Attempt to reconstruct and identify the tau decay products within a jet
  - Use the main features of the tau decays
    - Slightly displaced vertex with respect to the interaction point
    - Low track multiplicity (prongness) and collimated decay products

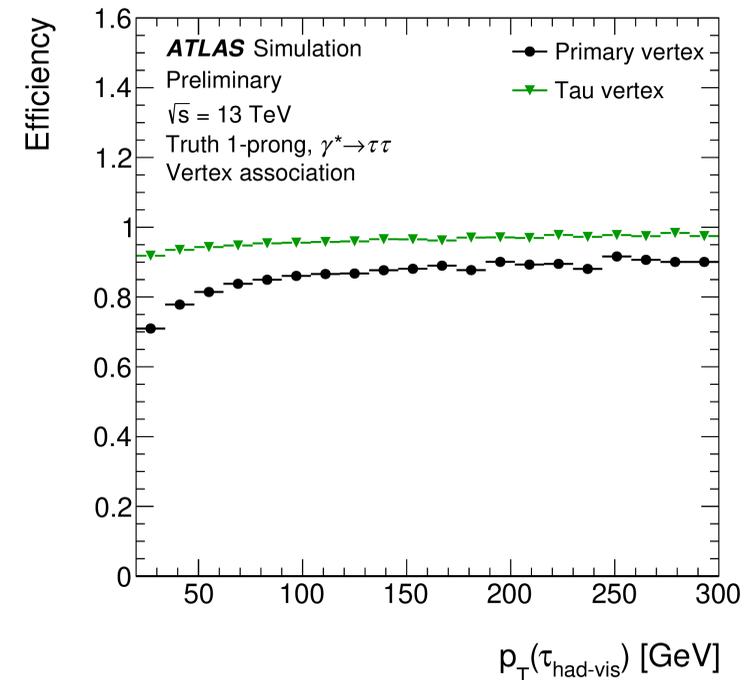
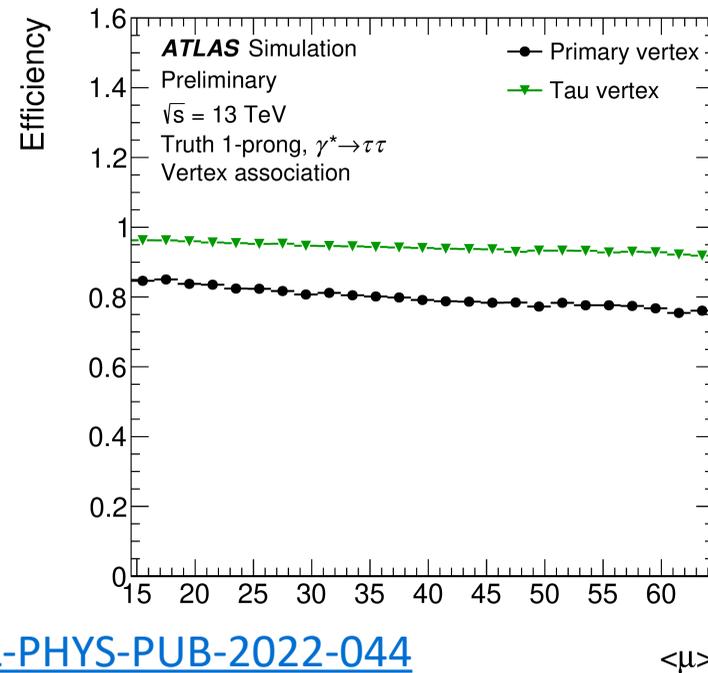
hadronic $\tau$ Decay Mode	BR (%)
$h^\pm \nu$	11.5
$h^\pm \pi^0 \nu$	25.9
$h^\pm \geq 2\pi^0 \nu$	10.8
$3h^\pm \nu$	9.8
$3h^\pm \geq 2\pi^0 \nu$	5.1



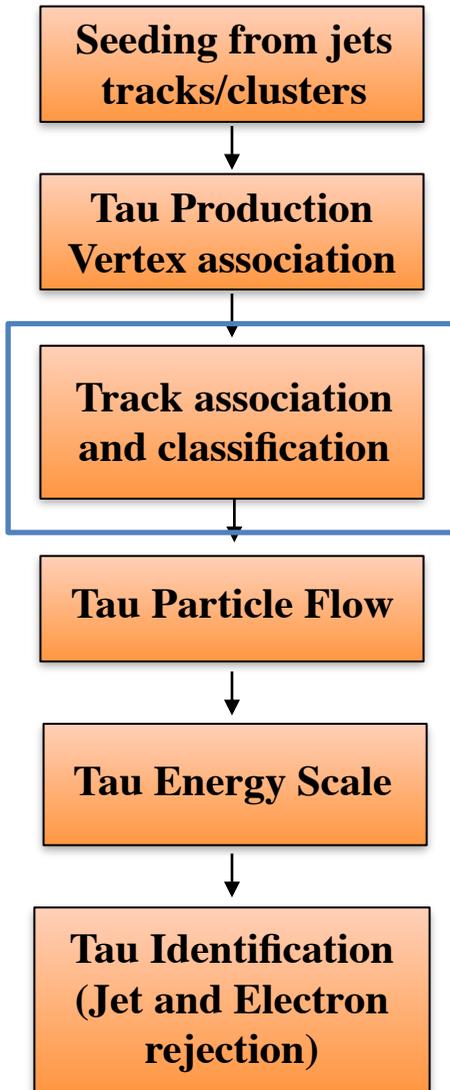
# Main stages of the Tau Reconstruction in ATLAS



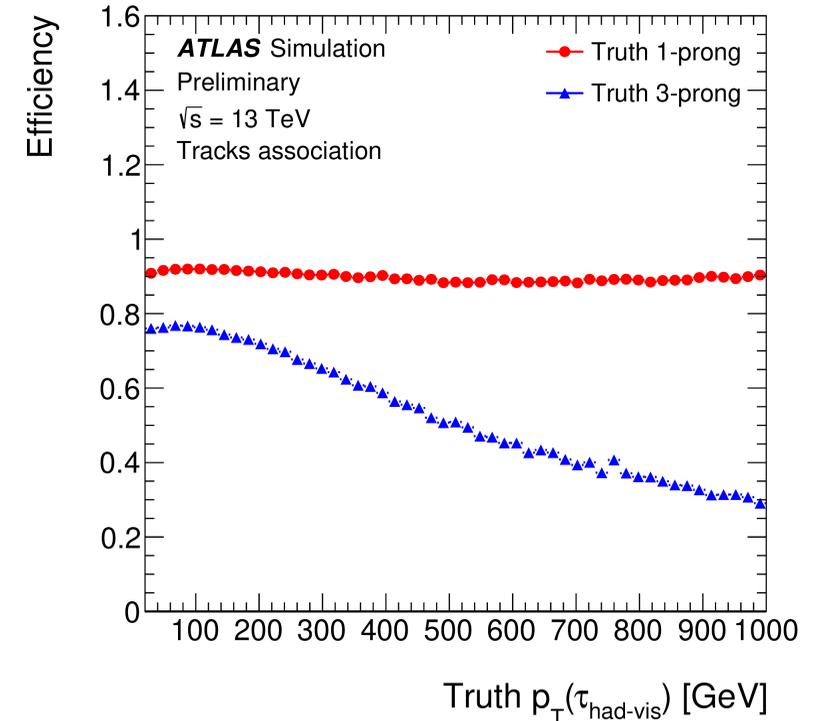
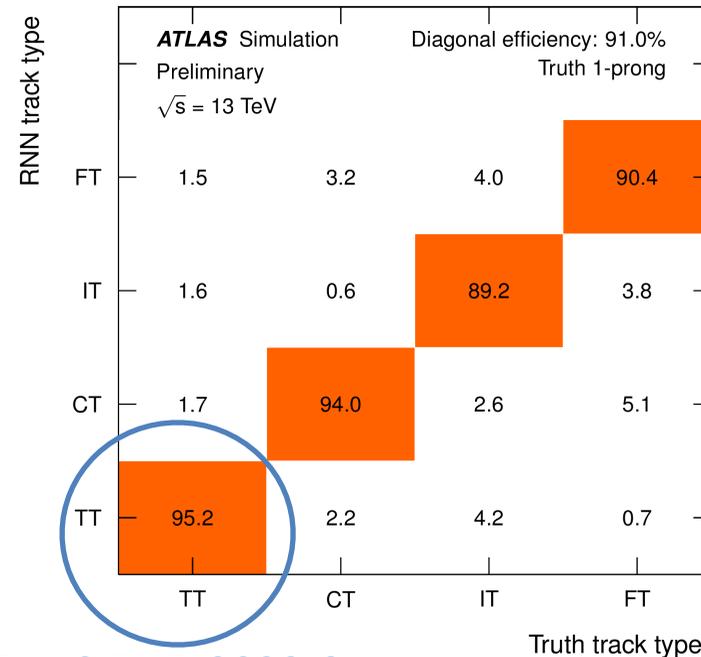
- Select vertex with the highest  $f_{p_T} = \frac{\Sigma p_T(\text{tracks associated to vertex})}{\Sigma p_T(\text{all tracks})}$  considering the tracks within  $\Delta R(\text{track, jet axis}) < 0.2$
- If two vertices has the same  $p_T$  fraction, choose the vertex with the lowest  $\Sigma |\Delta z(\text{track-vertex})|$
- Improves correct vertex assignment with respect to use event primary vertex especially at low  $p_T$



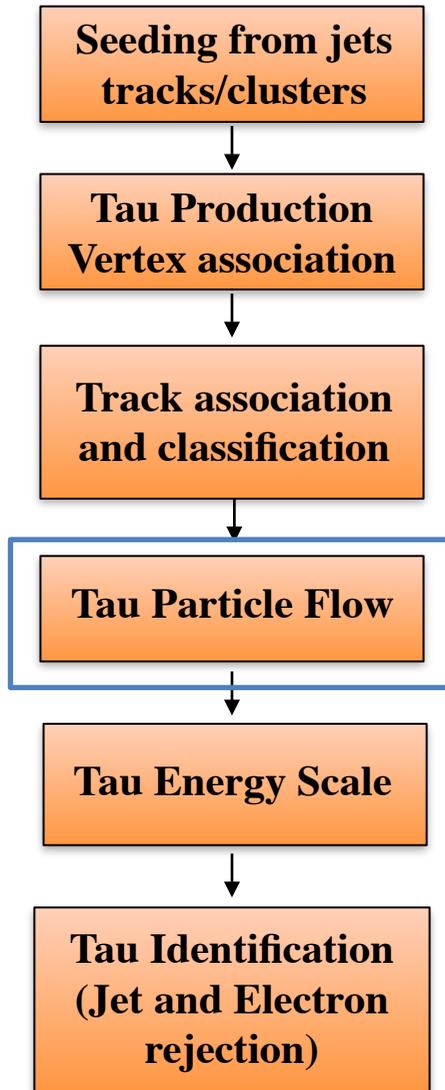
# Main stages of the Tau Reconstruction in ATLAS



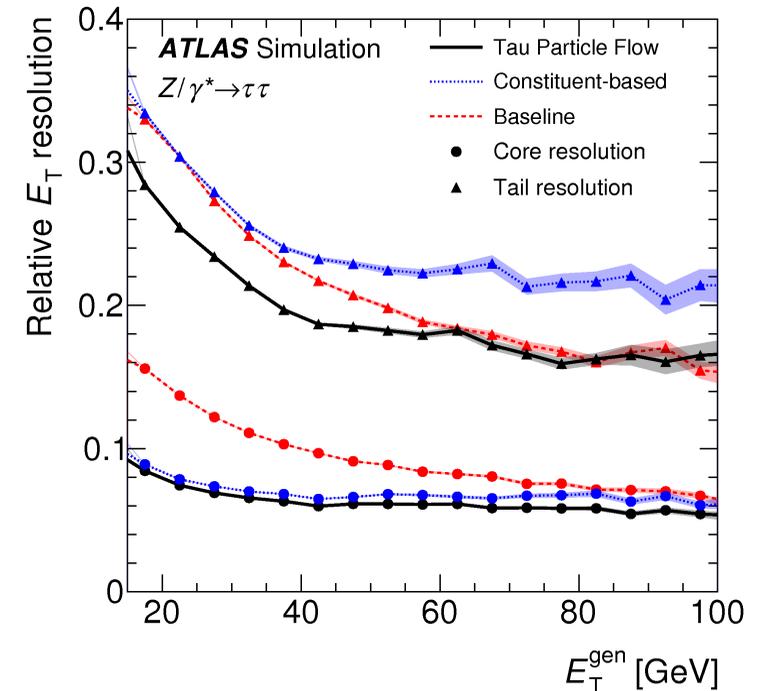
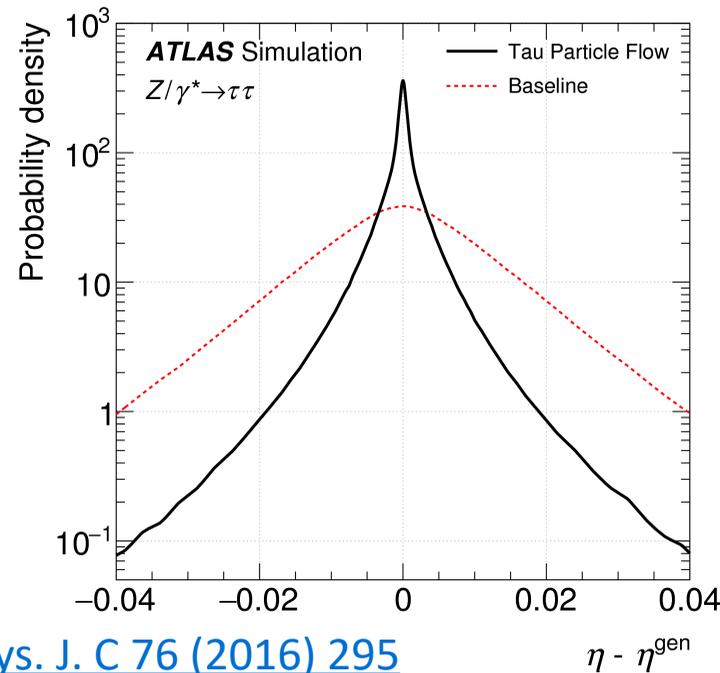
- Use multivariate analysis (MVA) to identify the tracks from tau decay and reject tracks from conversion, quark/gluons arising from remnants of the hard-scattering interactions, pileup
- High efficiency for 1 prong across large tau  $p_T$  spectrum, while lower efficiency for 3 prong at high  $p_T$  because of tracks overlap/merging



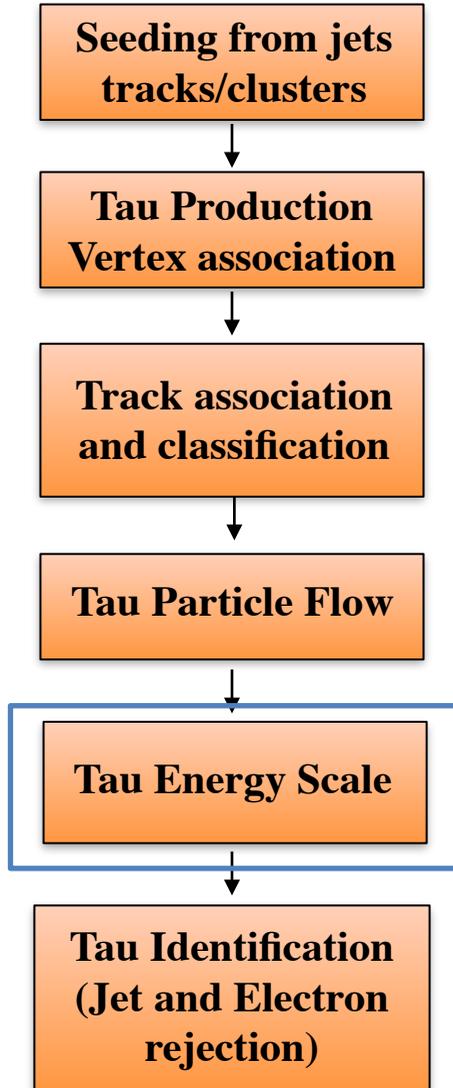
# Main stages of the Tau Reconstruction in ATLAS



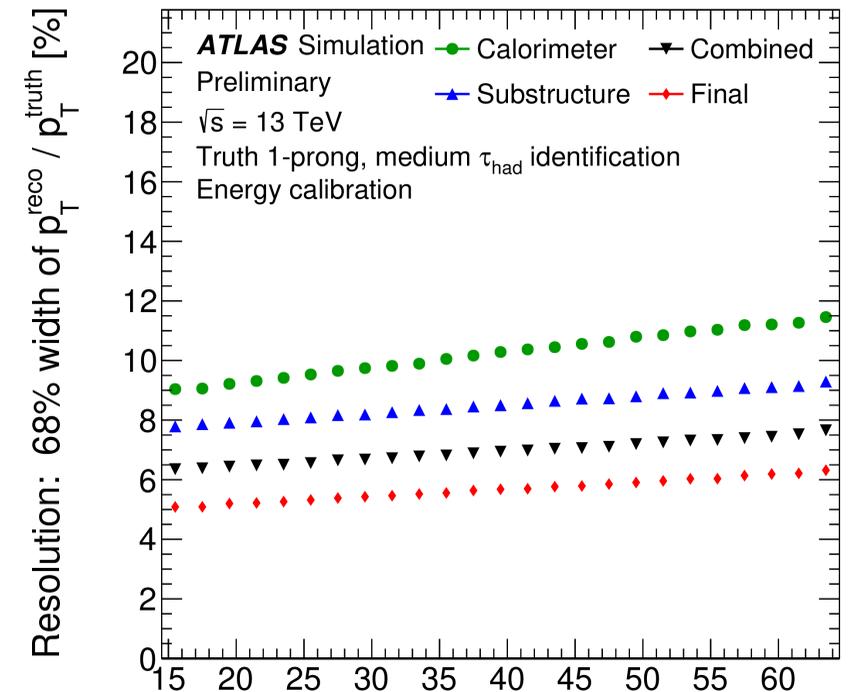
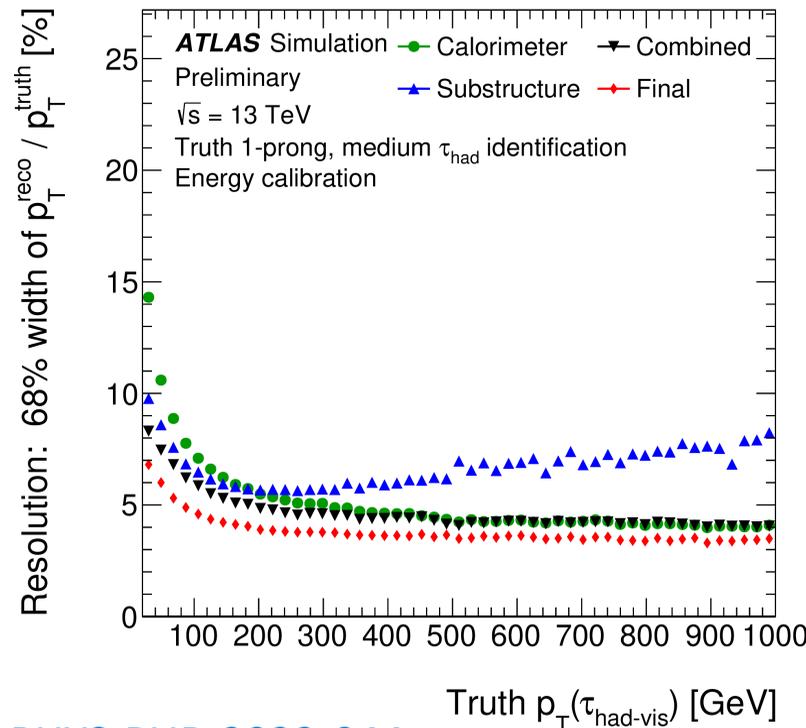
- Match clusters and tracks to differentiate the neutral (mostly  $\pi^0$ ) and charged part of the tau decay
- Attempt to reconstruct  $\pi^0$  through a dedicated MVA
  - Possibility to determine the tau decay mode
- Resulting in a better energy/position measurement of the tau, especially at low  $p_T$



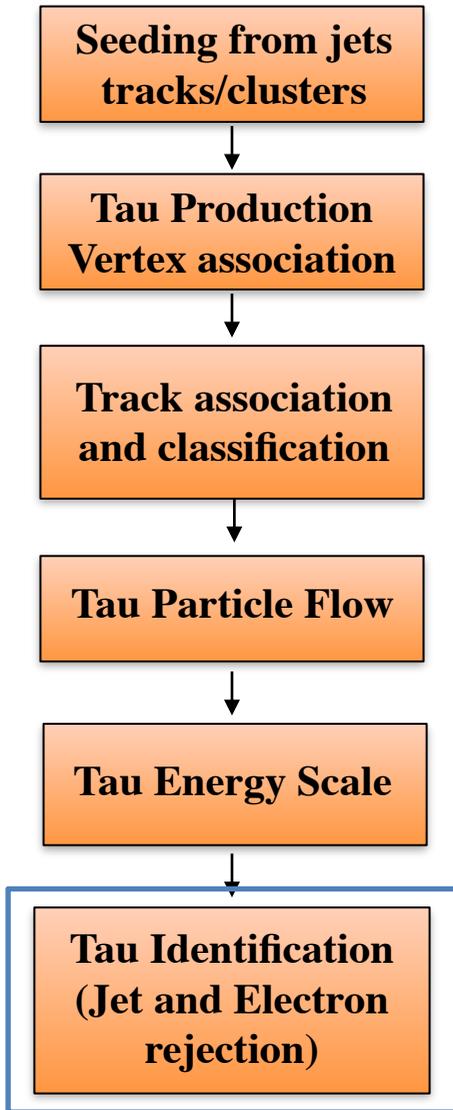
# Main stages of the Tau Reconstruction in ATLAS



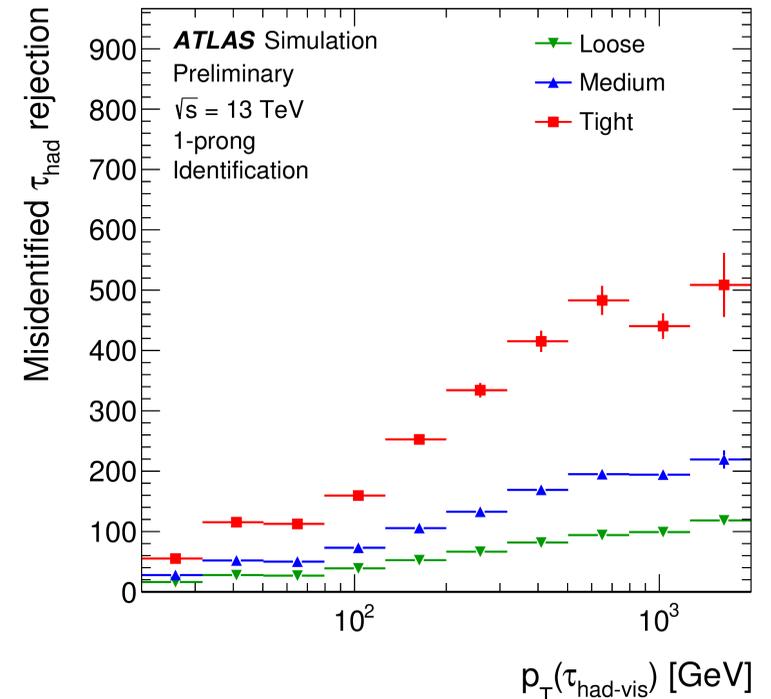
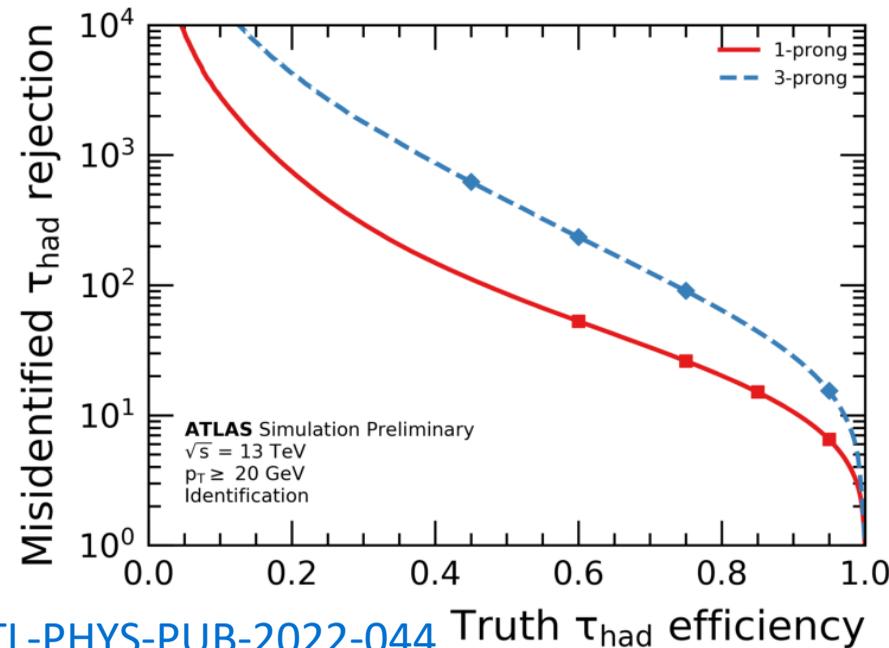
- Combine better tracker (calorimeter) resolution at low (high)  $p_T$
- *Final*  $p_T$  estimation done through MVA regression
- Resolution  $\sim 5\%$  across large tau  $p_T$  spectrum



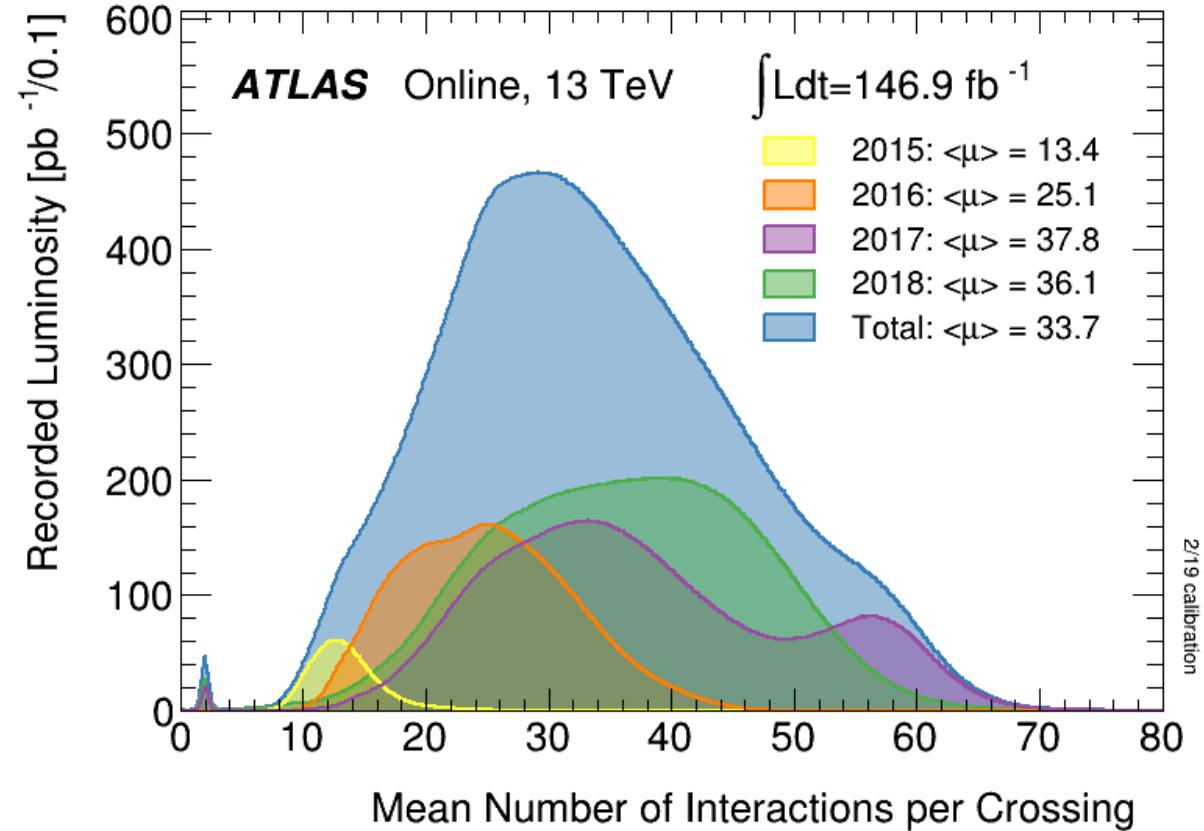
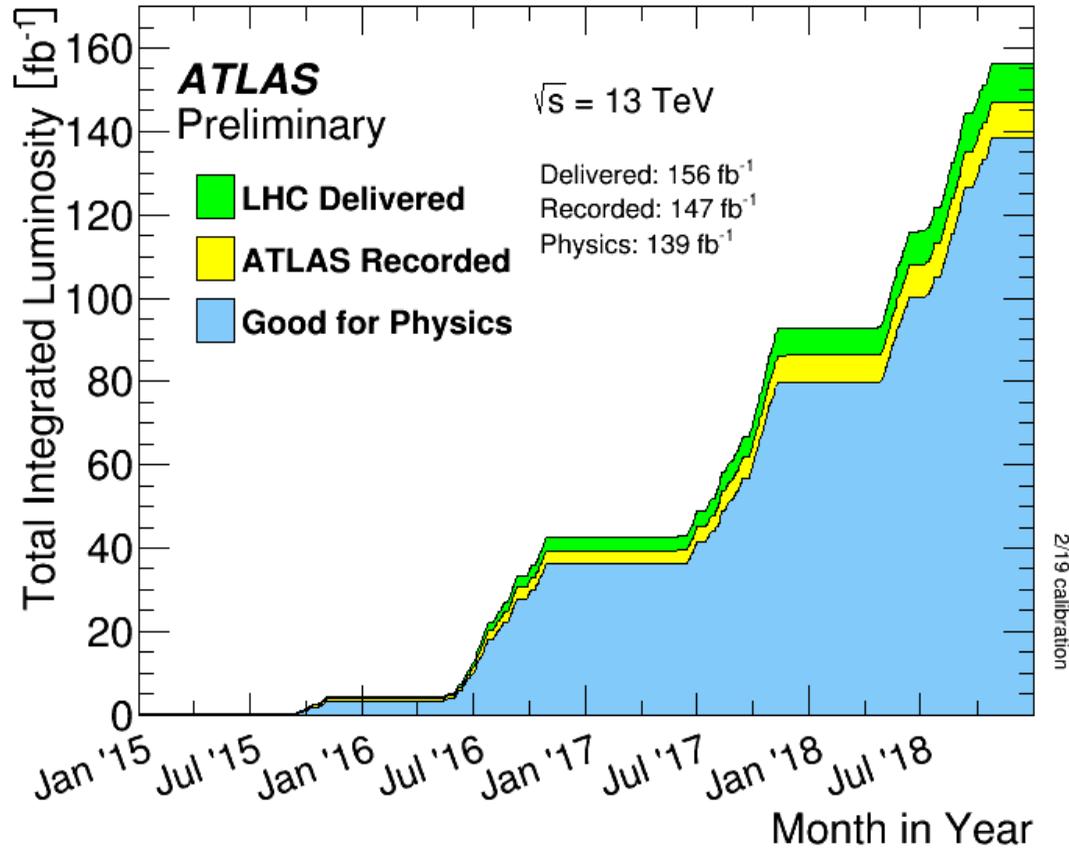
# Main stages of the Tau Reconstruction in ATLAS



- Combine information from tracks, clusters and event level variables in a MVA to distinguish tau from quark/gluon jets
  - Large rejection from the low tau activity in the *isolation region* ( $0.2 < \Delta R < 0.4$ )
  - Through the years several MVA architectures have been used to continuously improving the jet rejection for the same level of true tau identification efficiency



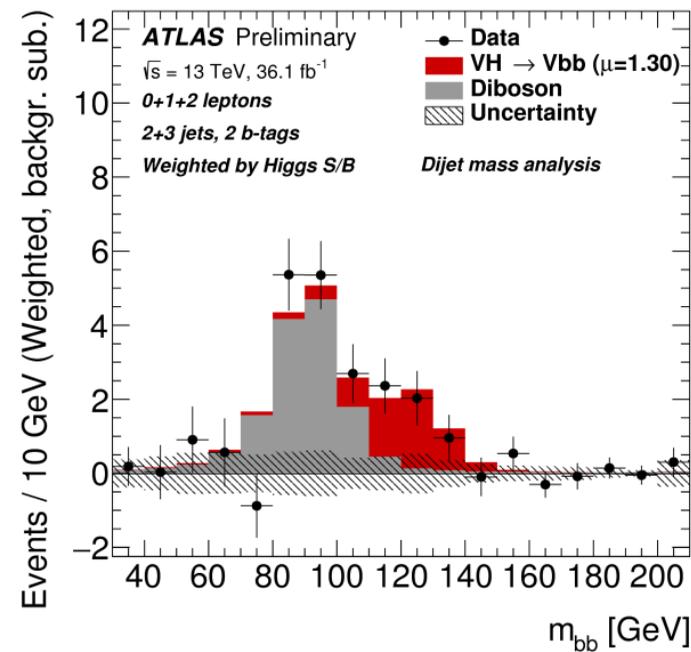
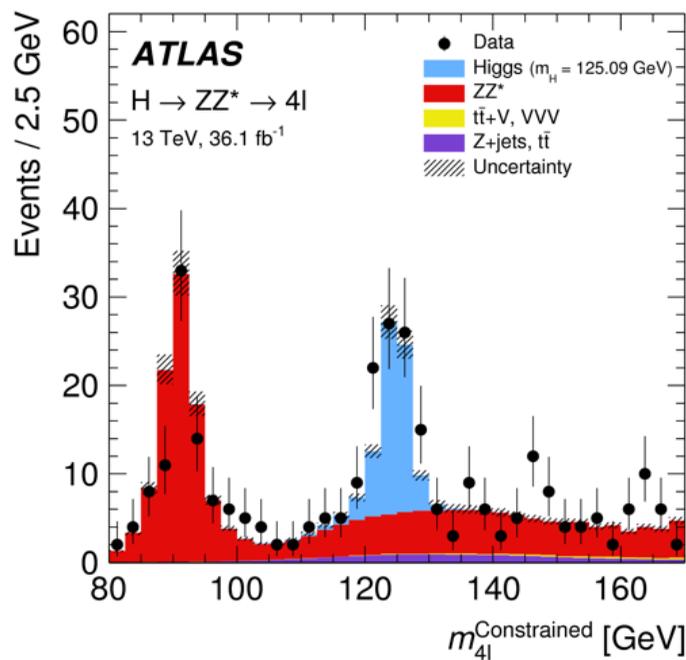
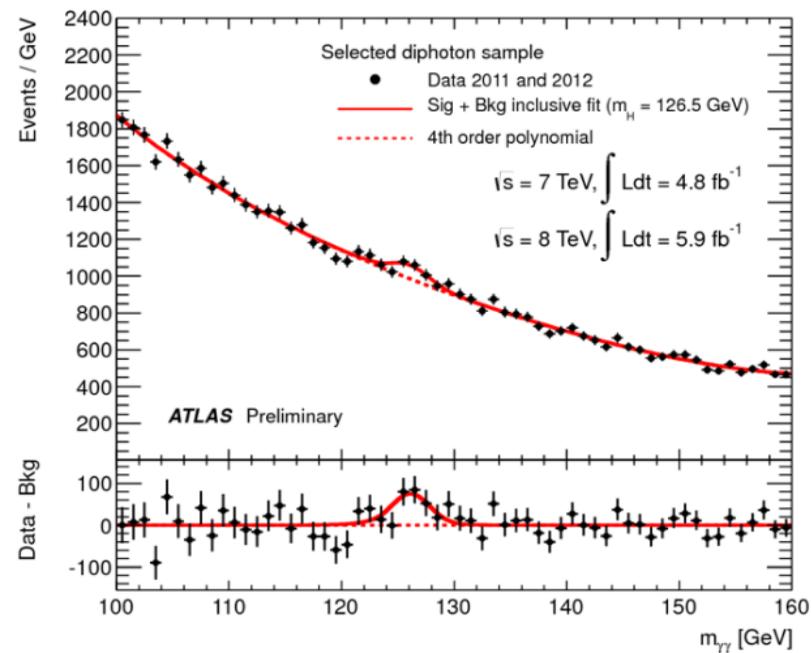
# The LHC Run 2 dataset



- Run2 dataset consists of  $\sim 140 \text{ fb}^{-1}$  recorded by the ATLAS experiment in the period 2015-2018
- Reached an instantaneous luminosity value at  $2.1 \times 10^{34} \text{ cm}^{-1} \text{ s}^{-1}$  with a mean number of interactions per crossing (pileup) of  $\sim 34$

*... now that we know how to reconstruct the particles in the detector and the dataset we are going to use ... let's see what we to measure ...*

# THE HIGGS BOSON

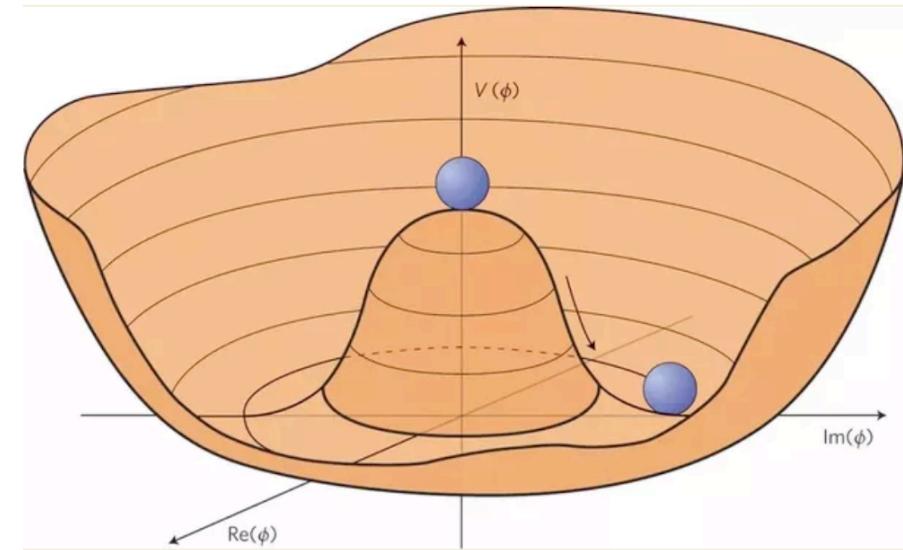


# The electroweak symmetry breaking

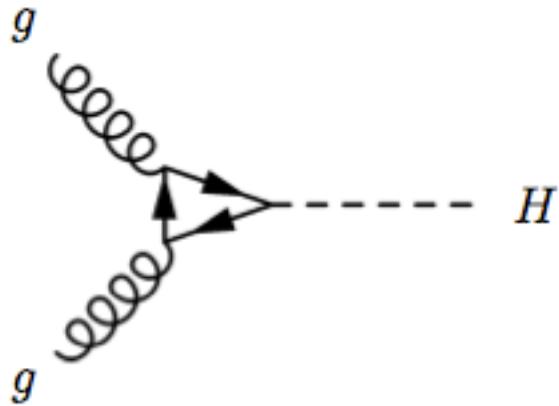
- In the  $SU(2)_L \otimes U(1)_Y$  symmetry, the gauge bosons and fermions are massless. Electroweak symmetry breaking is needed to give mass to the particles
- Introduce a 2 component complex scalar field, the Higgs field:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

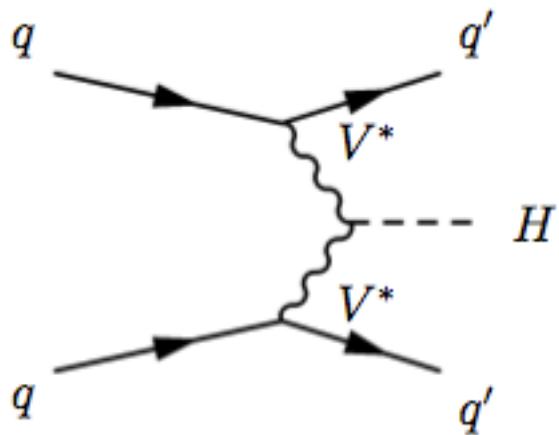
- $W^\pm$ ,  $Z$  and fermions acquire mass through the interaction with the Higgs field
- The Higgs boson is produced by quantum excitation of the Higgs field



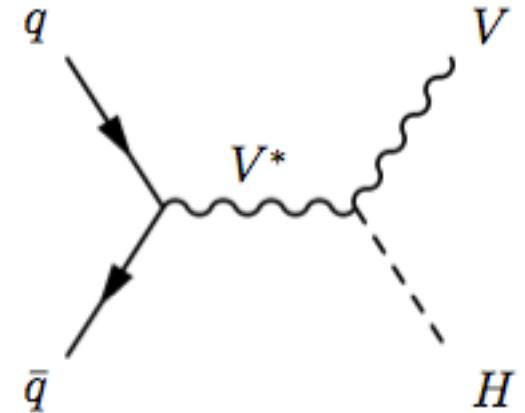
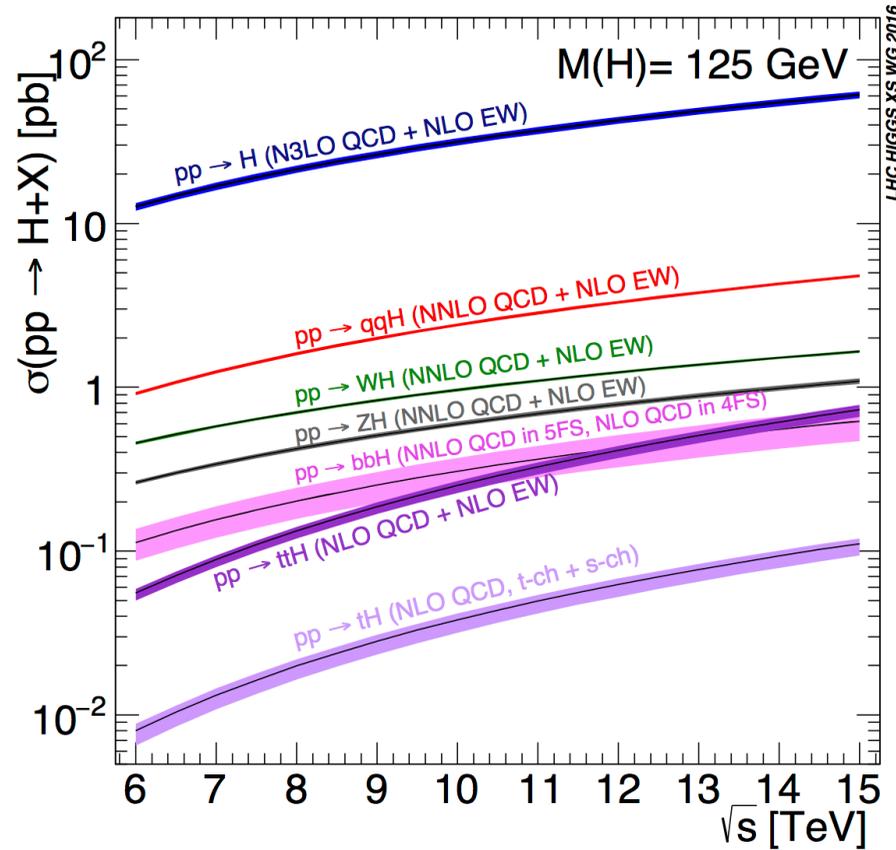
# Higgs production modes



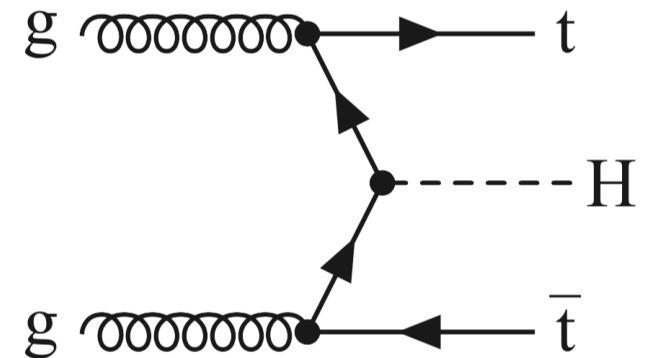
Gluon fusion (ggF)



Vector boson fusion (VBF)



Associated production with a gauge boson (VH)



Associated production with a  $t\bar{t}$  pair (ttH)

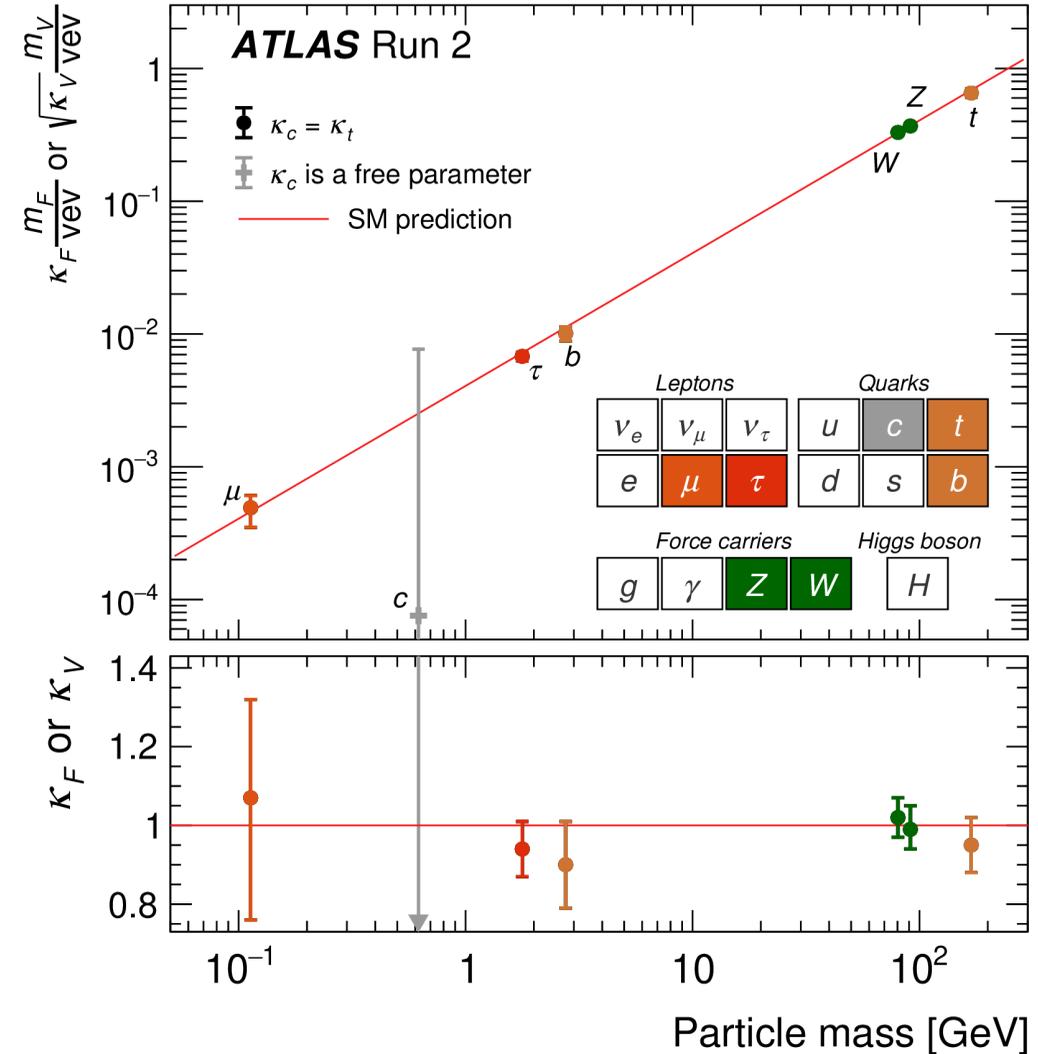
# Higgs boson couplings



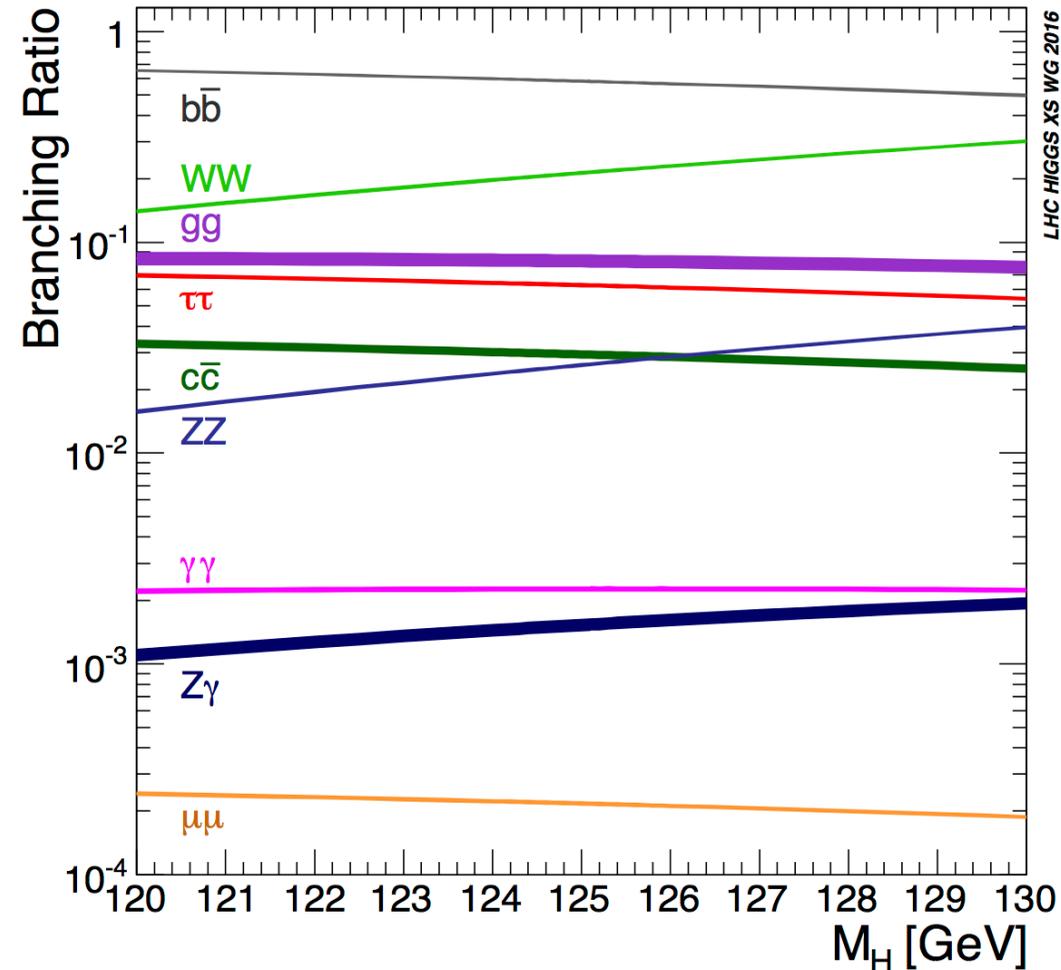
- The SM Higgs boson couplings can be summarised in the Lagrangian

$$\mathcal{L} = -\frac{m_f}{v} f\bar{f}H + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4 + \delta_V V_\mu V^\mu \left( \frac{2m_V^2}{v} H + \frac{m_V^2}{v^2} H^2 \right)$$

- Coupling with SM particles proportional to:
  - $m_V^2$  for boson  $\rightarrow$  main couplings with W and Z
  - $m_f$  for fermions  $\rightarrow$  main couplings with third generation quarks/leptons (b and  $\tau$ )
- Coupling as function of the particle mass in good agreement with SM prediction over 3 order of magnitude



# Higgs boson decays



- Larger branching ratio (BR) for  $H \rightarrow b\bar{b}$ ,  $H \rightarrow WW^*$  and  $H \rightarrow \tau\tau$ , however poor mass resolution and larger background contamination
- $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^*(\rightarrow 4l)$  have lower BR but high mass resolution; therefore they can be used for precision measurements (“golden channels”)
- $H \rightarrow Z\gamma$  and  $H \rightarrow \mu\mu$  now becoming accessible thanks to the large dataset and the good detector performance

# What can we measure with $H \rightarrow \tau\tau$ process ?



Higgs cross section  
and Yukawa Coupling

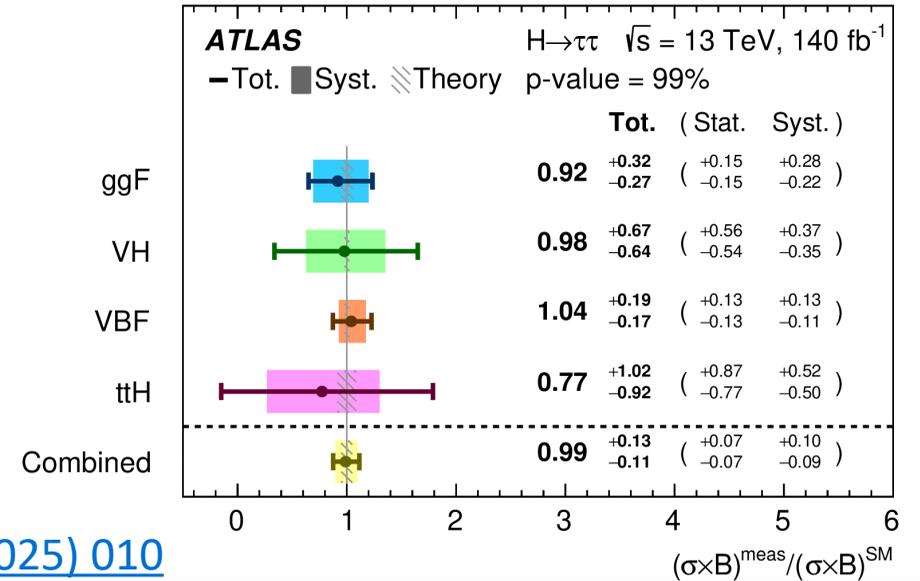
Charge-Parity  
(both in Higgs production  
and decay)

Lepton-Flavour  
Violating decay

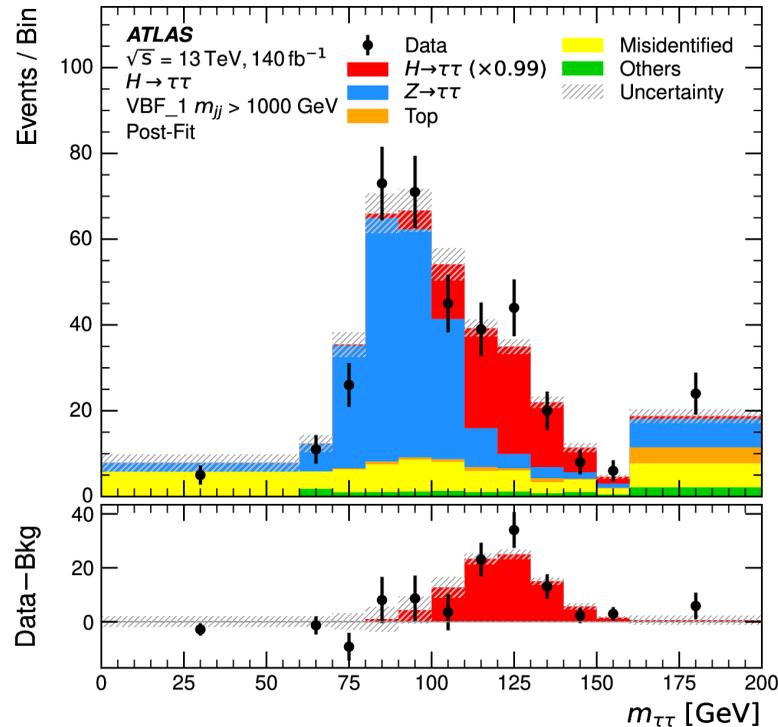
# $H \rightarrow \tau\tau$ inclusive/production mode cross-section



- Most precise VBF cross section measurement per single channel in the ATLAS experiment
- ggH cross section uncertainty limited by systematic uncertainties, mostly from [theoretical uncertainties](#)
- ttH and V(had)H cross section measurement limited by statistical uncertainty



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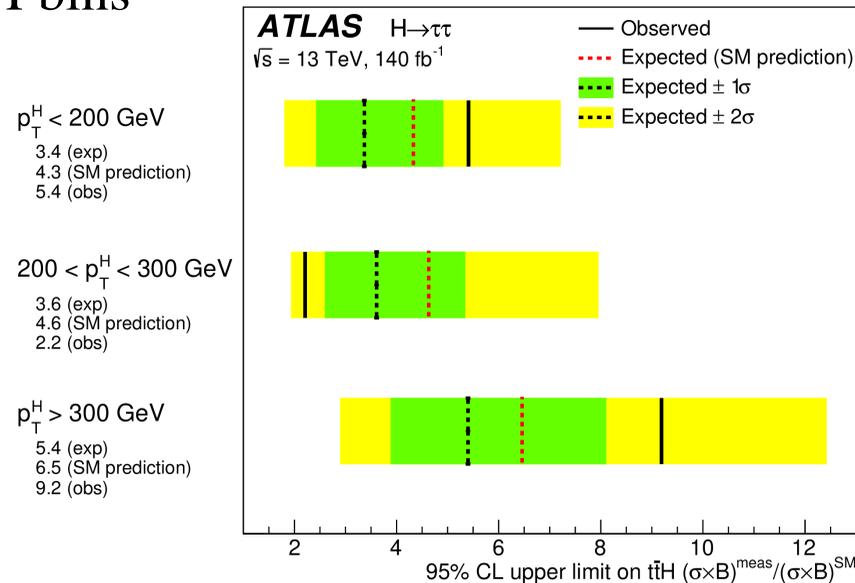


Production mode	ggF	ttH	VBF	VH
Best-fit value	0.92	0.77	1.04	0.98
Total uncertainty	$\pm 0.30$	$\pm 0.97$	$\pm 0.18$	$\pm 0.66$
Statistical uncertainty	$\pm 0.15$	$\pm 0.82$	$\pm 0.13$	$\pm 0.55$
Total systematic uncertainty	$\pm 0.25$	$\pm 0.51$	$\pm 0.12$	$\pm 0.36$
Samples size	$\pm 0.09$	$\pm 0.31$	$\pm 0.04$	$\pm 0.26$
Theoretical uncertainty in signal	$\pm 0.18$	$\pm 0.12$	$\pm 0.11$	$\pm 0.14$
Jet and $E_T^{\text{miss}}$	$\pm 0.12$	$\pm 0.15$	$\pm 0.03$	$\pm 0.12$
Hadronic $\tau$ -lepton decays	$\pm 0.04$	$\pm 0.09$	$\pm 0.01$	$\pm 0.04$
Misidentified $\tau$ -lepton background	$\pm 0.04$	$\pm 0.05$	$\pm 0.02$	$\pm 0.11$
Luminosity	$\pm 0.01$	$\pm 0.01$	$\pm 0.01$	$\pm 0.01$
Theoretical uncertainty in top-quark processes	$\pm 0.01$	$\pm 0.31$	–	$\pm 0.02$
Theoretical uncertainty in Z + jets processes	$\pm 0.02$	$\pm 0.08$	–	$\pm 0.02$
Flavour tagging	$\pm 0.02$	$\pm 0.05$	$\pm 0.01$	$\pm 0.01$
Electrons and muons	$\pm 0.02$	$\pm 0.02$	$\pm 0.01$	$\pm 0.02$

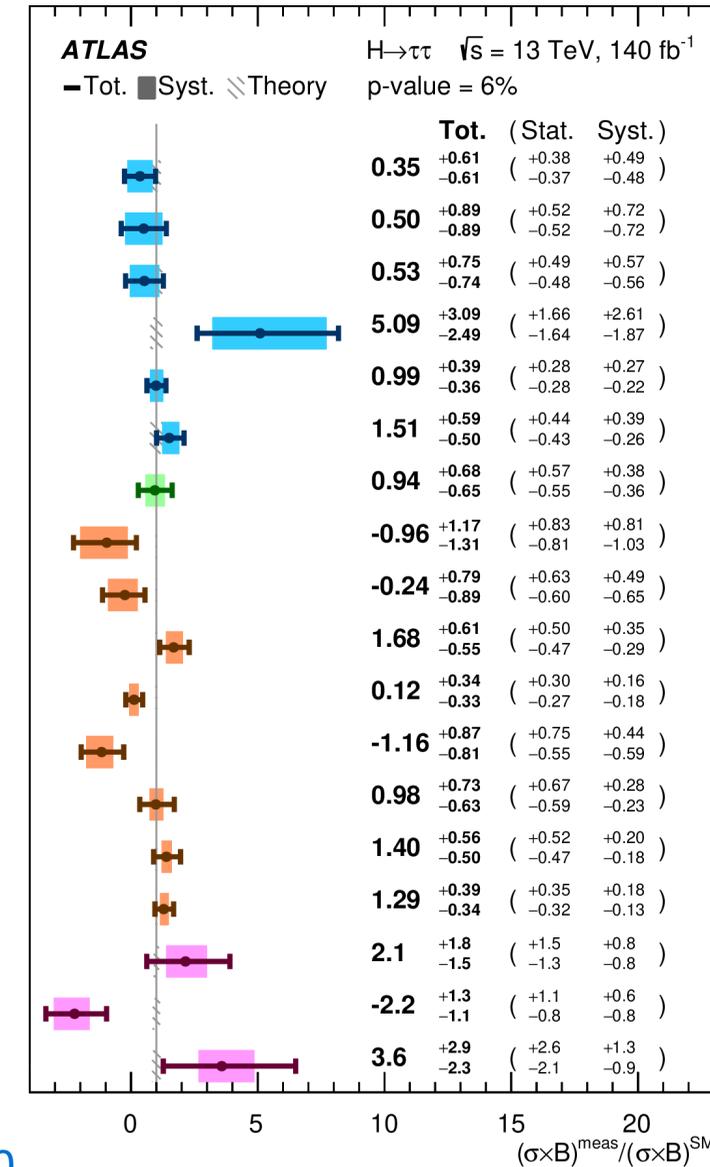
# $H \rightarrow \tau\tau$ simplified template cross section results



- Measurement performed in 18 different kinematic phase spaces; no significant deviation from SM
- For VBF, first (most precise) measurement for  $p_T(H) > (<) 200$  GeV and  $m_{jj} > 1.5$  TeV
- Found large anti-correlation between VBF and ggH in-VBF phase space cross sections
- $t\bar{t}H$  measurement used to derive upper limits on STXS  $t\bar{t}H$  bins



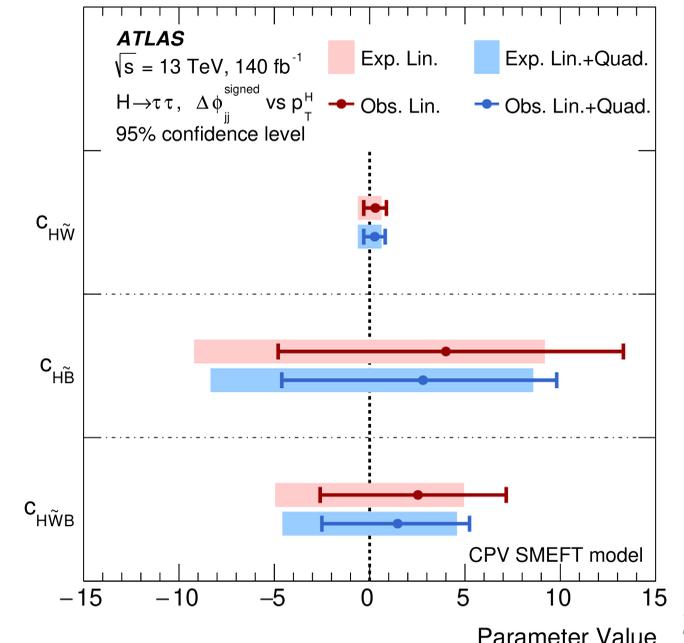
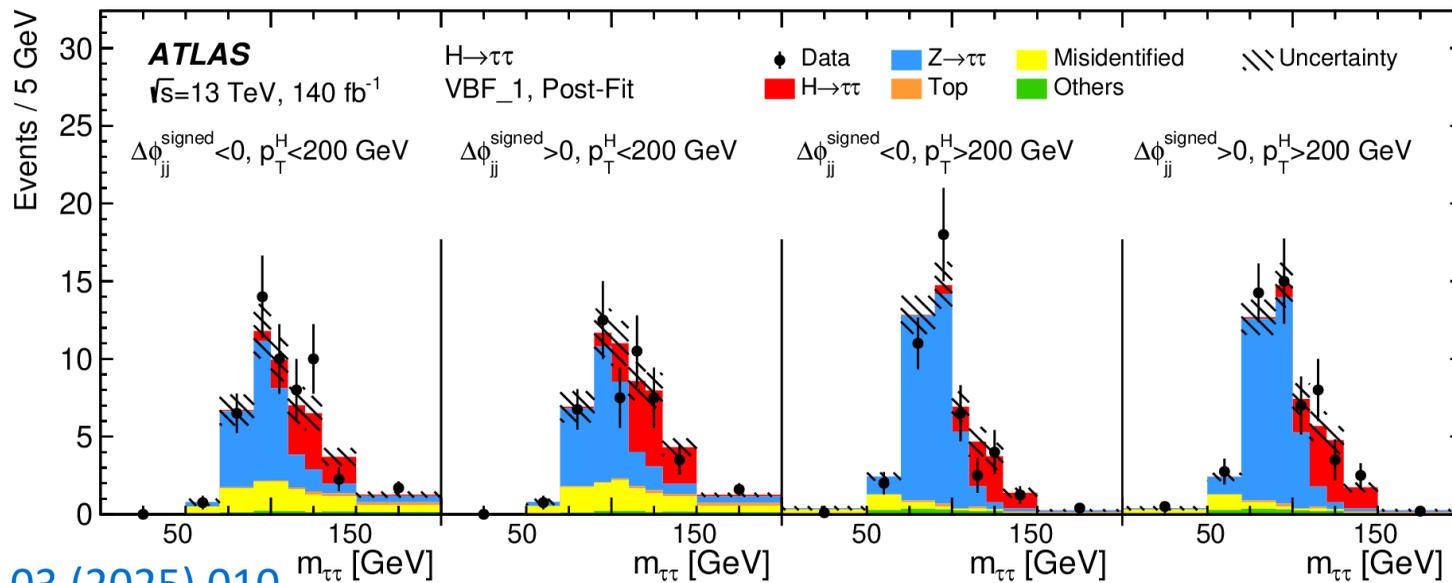
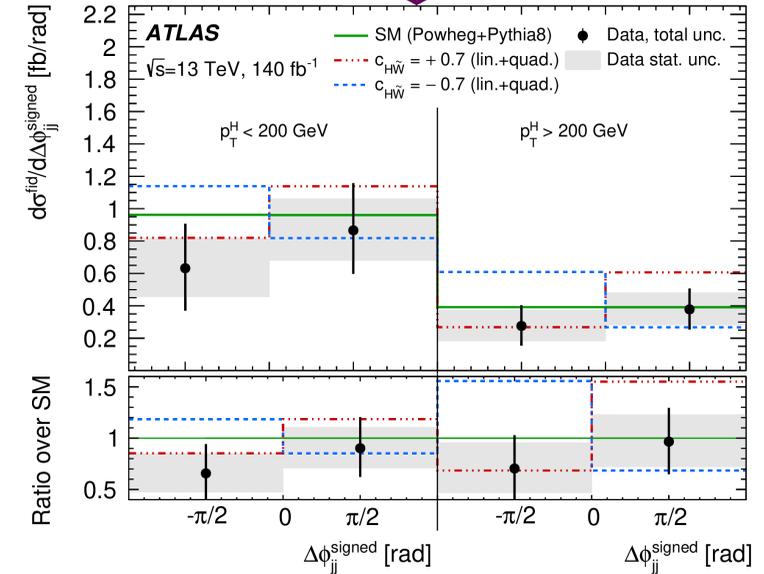
$gg \rightarrow H$ , 1-jet, $120 \leq p_T^H < 200$ GeV	0.35	+0.61	-0.61	(+0.38, -0.37)	(+0.49, -0.48)
$gg \rightarrow H$ , $\geq 1$ -jet, $60 \leq p_T^H < 120$ GeV	0.50	+0.89	-0.89	(+0.52, -0.52)	(+0.72, -0.72)
$gg \rightarrow H$ , $\geq 2$ -jet, $m_{jj} < 350$ , $120 \leq p_T^H < 200$ GeV	0.53	+0.75	-0.74	(+0.49, -0.48)	(+0.57, -0.56)
$gg \rightarrow H$ , $\geq 2$ -jet, $m_{jj} \geq 350$ GeV, $p_T^H < 200$ GeV	5.09	+3.09	-2.49	(+1.66, -1.64)	(+2.61, -1.87)
$gg \rightarrow H$ , $200 \leq p_T^H < 300$ GeV	0.99	+0.39	-0.36	(+0.28, -0.28)	(+0.27, -0.22)
$gg \rightarrow H$ , $p_T^H \geq 300$ GeV	1.51	+0.59	-0.50	(+0.44, -0.43)	(+0.39, -0.26)
$qq' \rightarrow Hqq'$ , $\geq 2$ -jet, $60 \leq m_{jj} < 120$ GeV	0.94	+0.68	-0.65	(+0.57, -0.55)	(+0.38, -0.36)
$qq' \rightarrow Hqq'$ , $\geq 2$ -jet, $350 \leq m_{jj} < 700$ GeV, $p_T^H < 200$ GeV	-0.96	+1.17	-1.31	(+0.83, -0.81)	(+0.81, -1.03)
$qq' \rightarrow Hqq'$ , $\geq 2$ -jet, $700 \leq m_{jj} < 1000$ GeV, $p_T^H < 200$ GeV	-0.24	+0.79	-0.89	(+0.63, -0.60)	(+0.49, -0.65)
$qq' \rightarrow Hqq'$ , $\geq 2$ -jet, $1000 \leq m_{jj} < 1500$ GeV, $p_T^H < 200$ GeV	1.68	+0.61	-0.55	(+0.50, -0.47)	(+0.35, -0.29)
$qq' \rightarrow Hqq'$ , $\geq 2$ -jet, $m_{jj} \geq 1500$ GeV, $p_T^H < 200$ GeV	0.12	+0.34	-0.33	(+0.30, -0.27)	(+0.16, -0.18)
$qq' \rightarrow Hqq'$ , $\geq 2$ -jet, $350 \leq m_{jj} < 700$ GeV, $p_T^H \geq 200$ GeV	-1.16	+0.87	-0.81	(+0.75, -0.55)	(+0.44, -0.59)
$qq' \rightarrow Hqq'$ , $\geq 2$ -jet, $700 \leq m_{jj} < 1000$ GeV, $p_T^H \geq 200$ GeV	0.98	+0.73	-0.63	(+0.67, -0.59)	(+0.28, -0.23)
$qq' \rightarrow Hqq'$ , $\geq 2$ -jet, $1000 \leq m_{jj} < 1500$ GeV, $p_T^H \geq 200$ GeV	1.40	+0.56	-0.50	(+0.52, -0.47)	(+0.20, -0.18)
$qq' \rightarrow Hqq'$ , $\geq 2$ -jet, $m_{jj} \geq 1500$ GeV, $p_T^H \geq 200$ GeV	1.29	+0.39	-0.34	(+0.35, -0.32)	(+0.18, -0.13)
$t\bar{t}H$ , $p_T^H < 200$ GeV	2.1	+1.8	-1.5	(+1.5, -1.3)	(+0.8, -0.8)
$t\bar{t}H$ , $200 \leq p_T^H < 300$ GeV	-2.2	+1.3	-1.1	(+1.1, -0.8)	(+0.6, -0.8)
$t\bar{t}H$ , $p_T^H \geq 300$ GeV	3.6	+2.9	-2.3	(+2.6, -2.1)	(+1.3, -0.9)



# $H \rightarrow \tau\tau$ differential cross section results



- Measurement performed in a dedicated phase space for VBF production and minimising ggH contamination
  - Unfolding several variables, like  $p_T(H)$  and  $\Delta\phi_{jj}^{\text{signed}}$
- Performed EFT interpretation in SMEFT framework to constrain CP-odd Wilson coefficients
- 95% C.L. on CP-odd coefficient  $C_{H\tilde{W}}$ :  $[-0.31, +0.88]$  at  $\Lambda = 1$  TeV

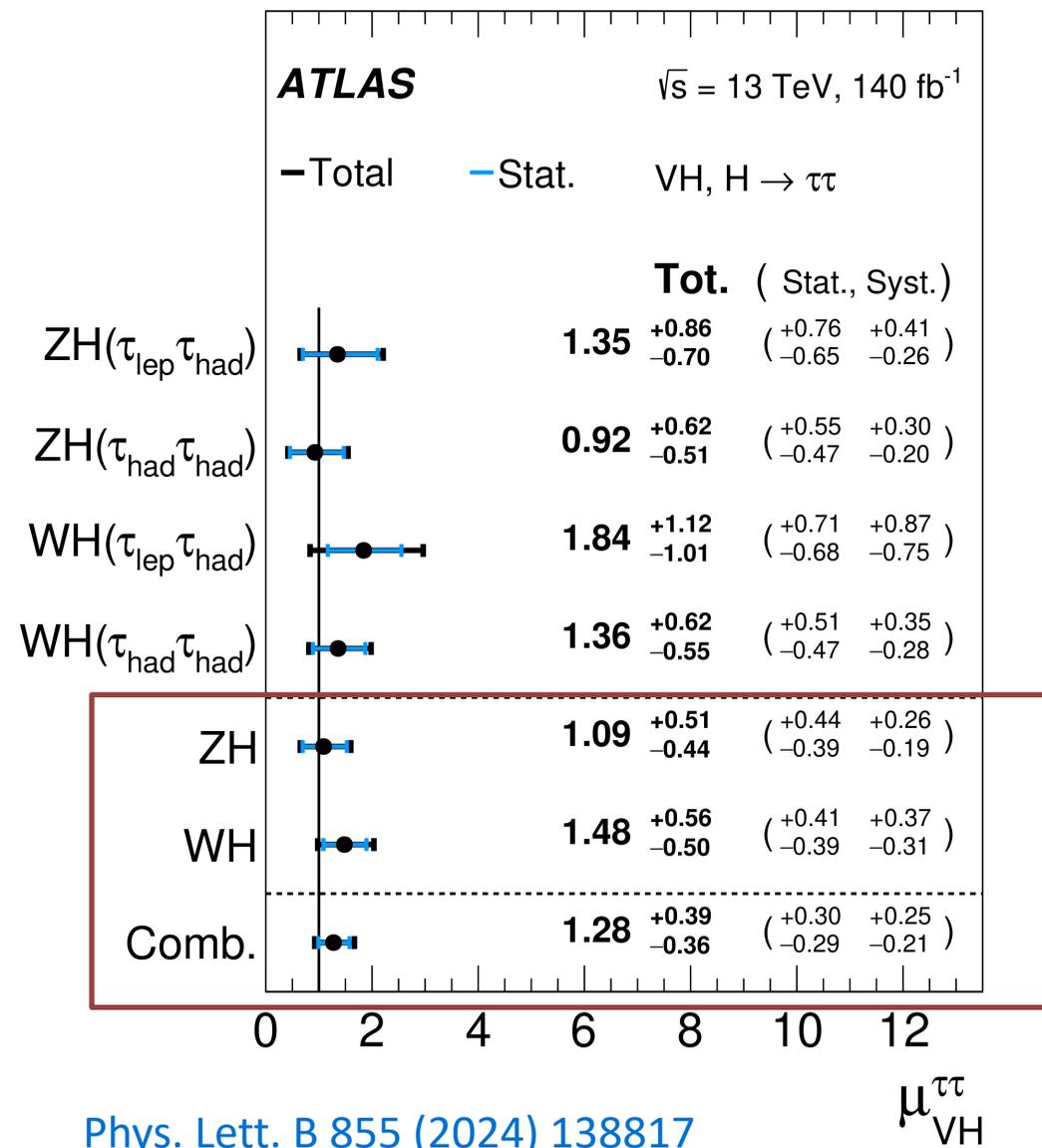


# $V(\text{lep})H \rightarrow \tau\tau$ cross section measurement



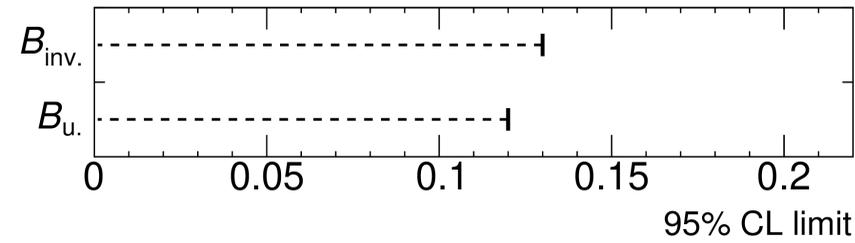
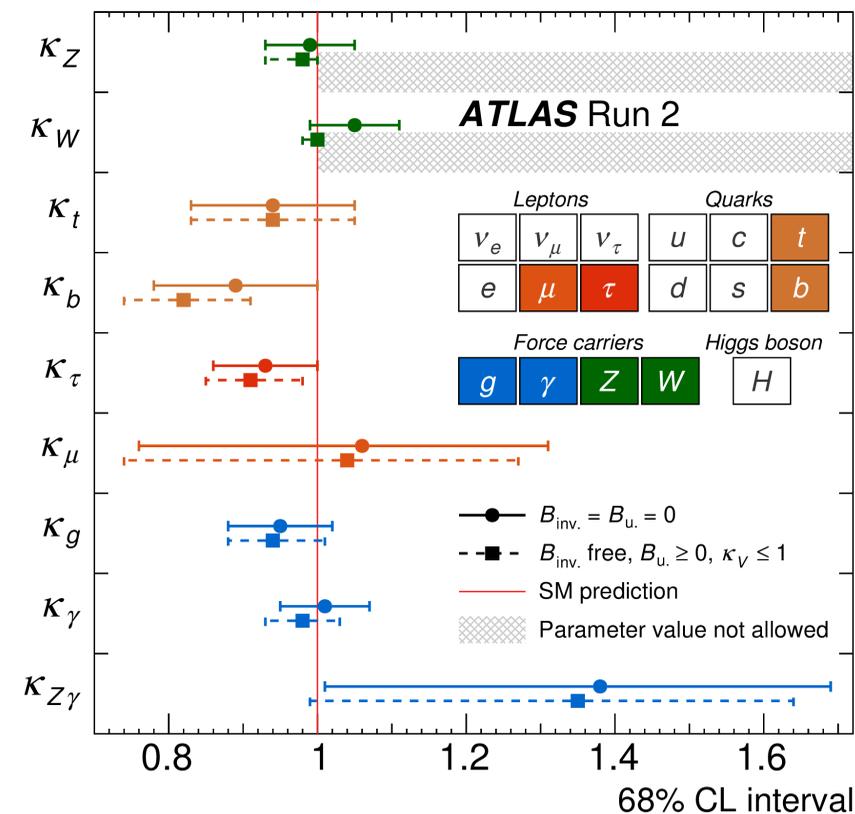
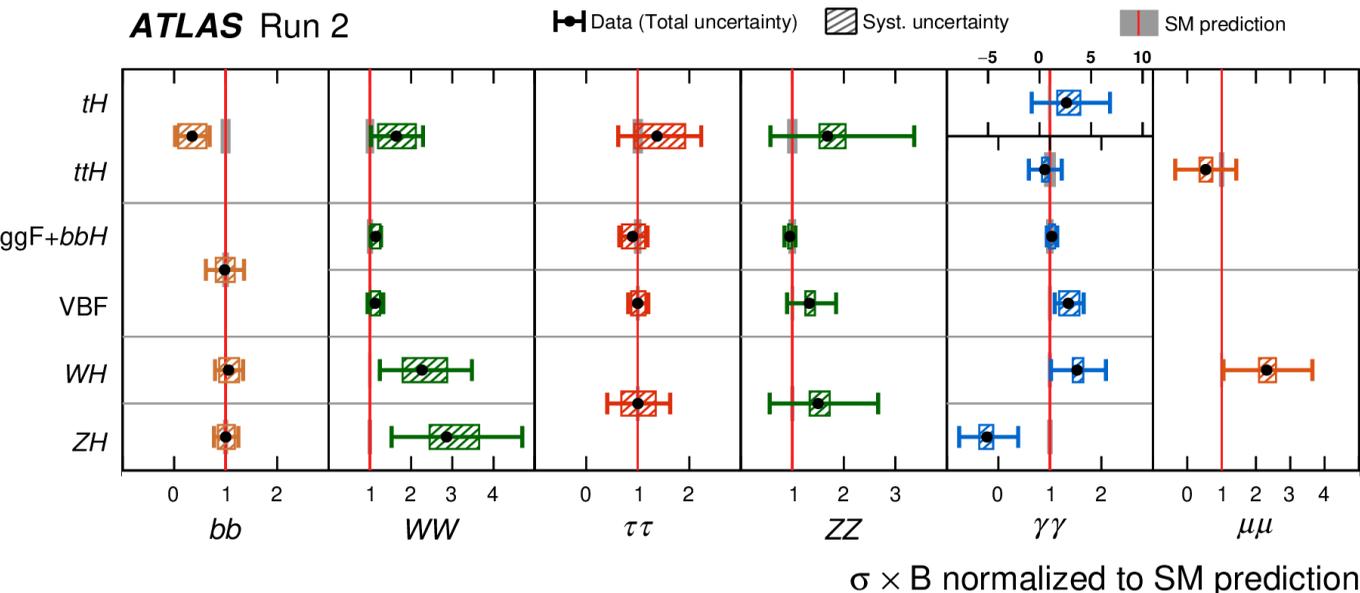
- Dedicated measurement in the  $V(\rightarrow \text{lep})H \rightarrow \tau\tau$  final state considering both W/Z bosons; complementary to the  $V(\text{had})H$  measurement performed in [JHEP 03 \(2025\) 010](#)
- Combined measurement achieved 4.2 (3.6) observed (expected) significance
- Analysis still dominated by statistical uncertainty, while systematic uncertainty dominated MC sample statistic and hadronic tau uncertainties

	$\mu_{\text{VH}}^{\tau\tau}$ obs	Significance	
		exp	obs
<i>WH</i>	$1.48^{+0.56}_{-0.50}$	2.2	3.3
<i>ZH</i>	$1.09^{+0.51}_{-0.44}$	2.9	2.8
Combined	$1.28^{+0.39}_{-0.36}$	3.6	4.2



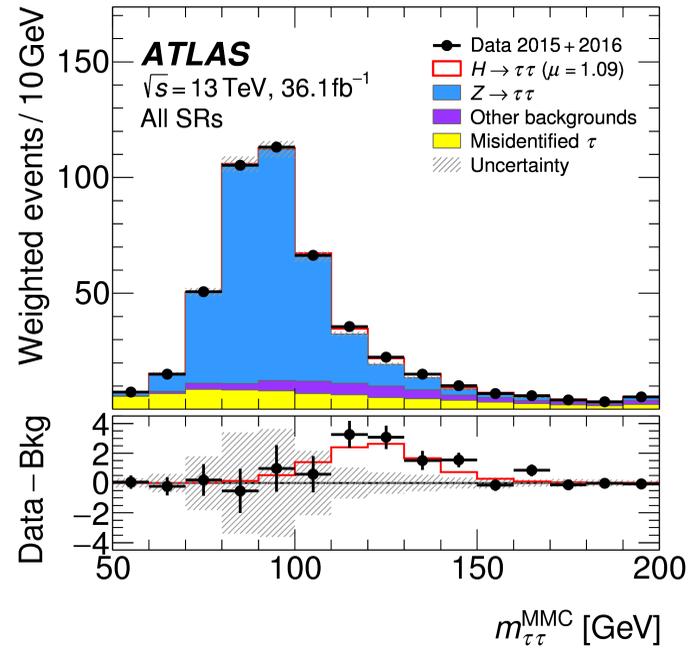
# $H \rightarrow \tau\tau$ impact in Higgs combined measurements

- $BR(H \rightarrow \tau\tau)$  measured with a precision of  $\sim 10\%$
- Provided best input in the k-framework for the measurement on the  $k_\tau$  modifier
- For STXS measurement,  $H \rightarrow \tau\tau$  competitive mostly for VBF (together with  $H \rightarrow \gamma\gamma$  and  $H \rightarrow bb$ ) and ggF at high  $p_T(H)$  measurements



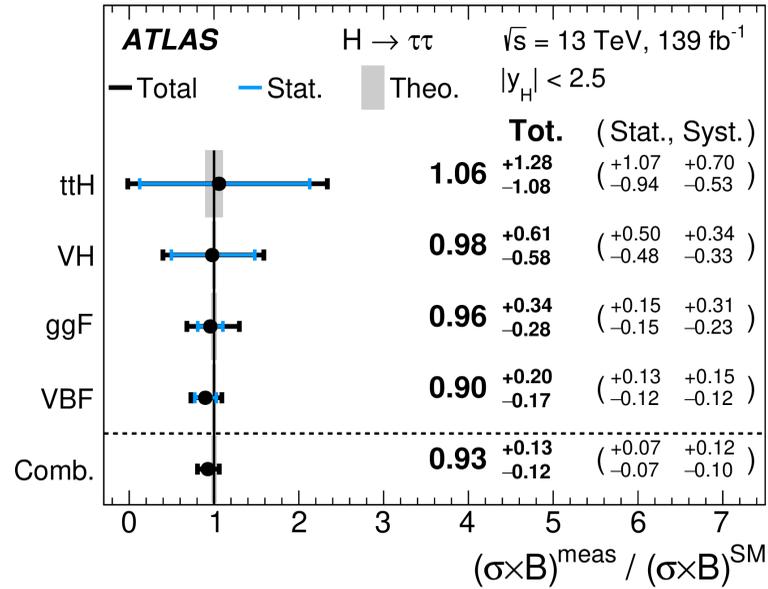
[Nature 607 52 \(2022\)](#)

# Evolution of $H \rightarrow \tau\tau$ cross section measurement



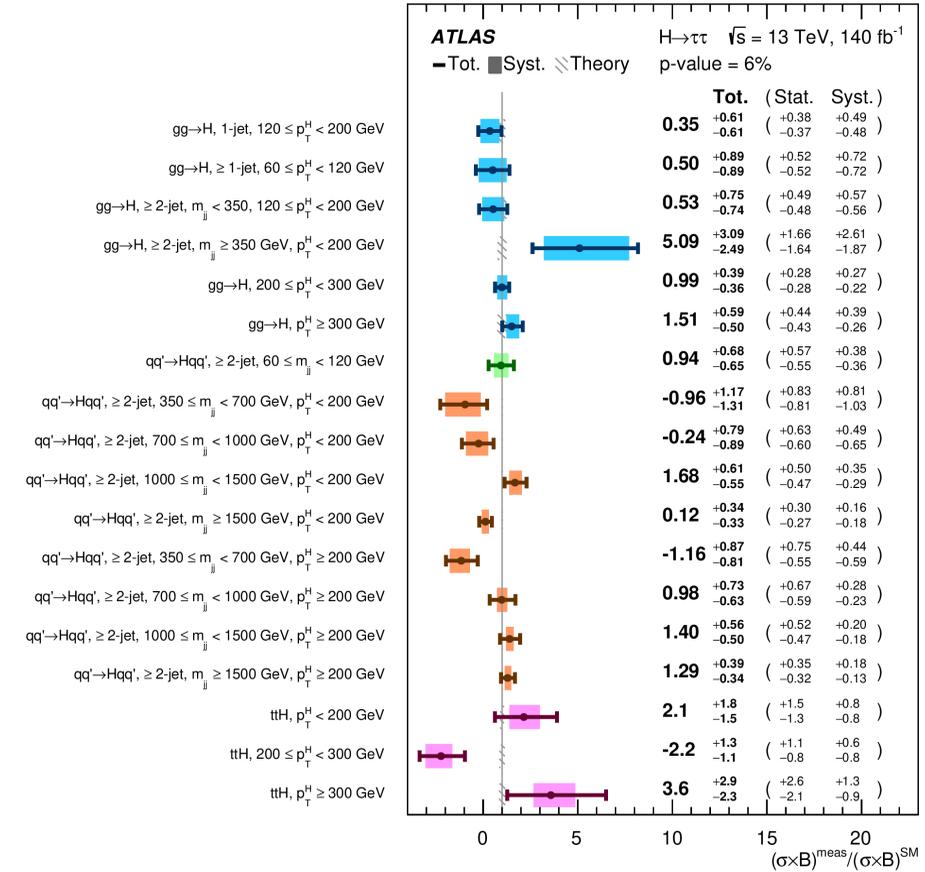
Inclusive

[Phys. Rev. D 99 \(2019\) 072001](#)



Production mode

[JHEP 08 \(2022\) 175](#)



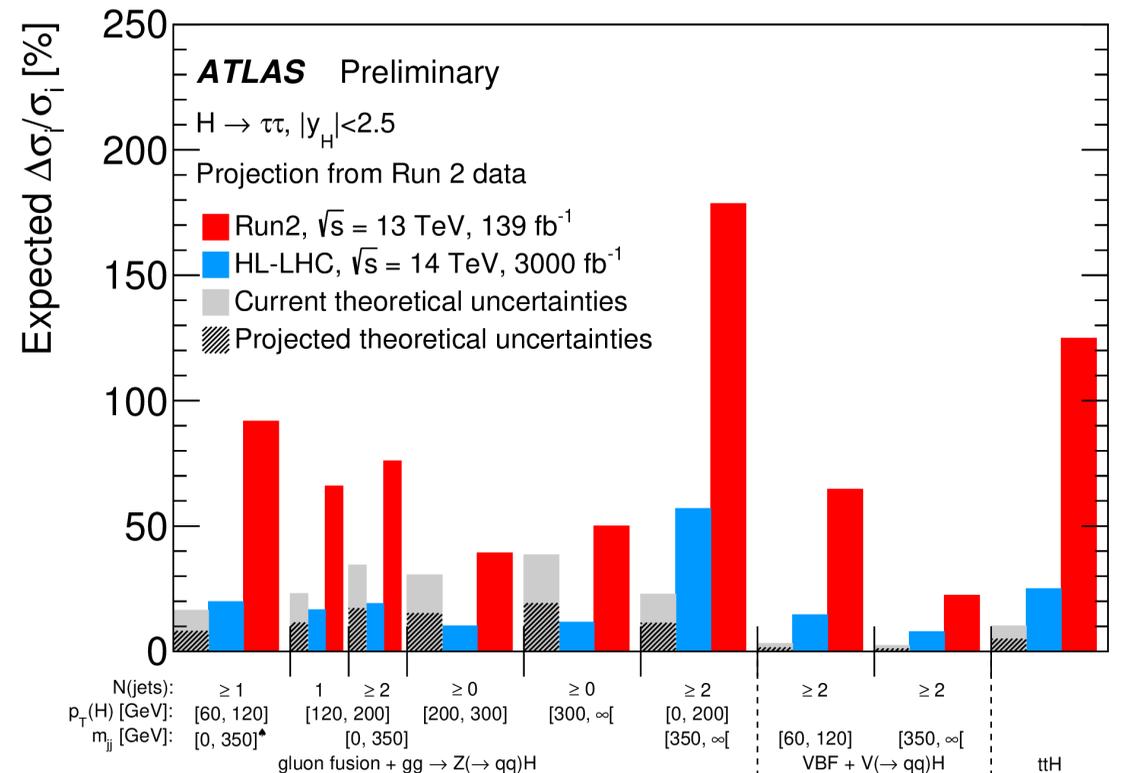
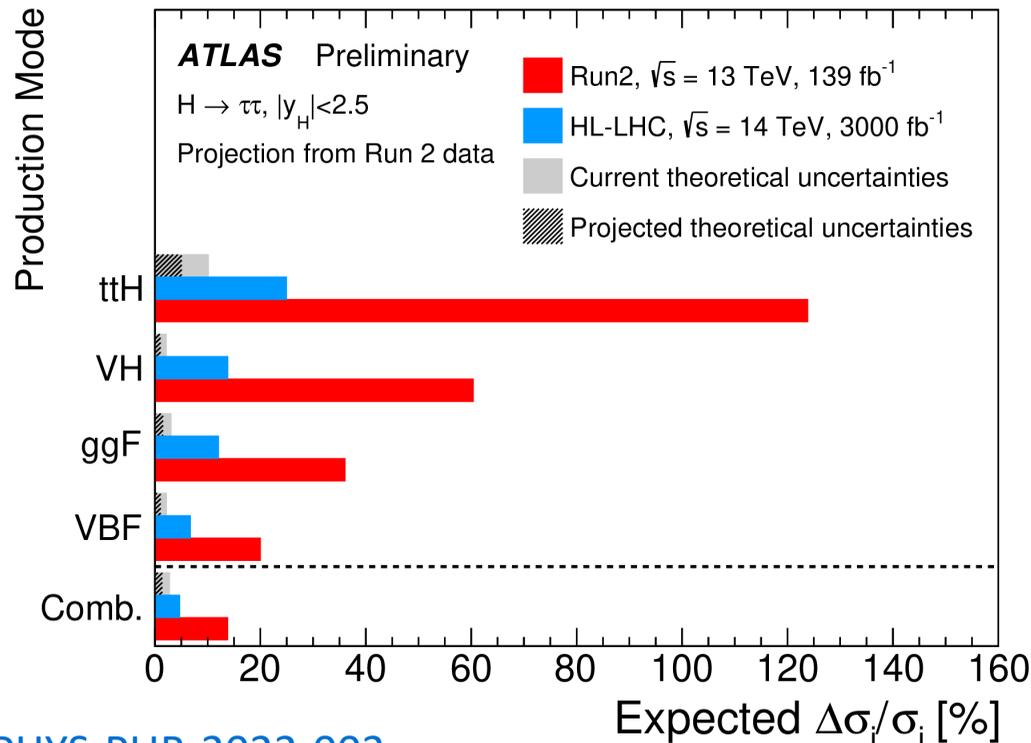
Simplified template cross section

[JHEP 03 \(2025\) 010](#)

# $H \rightarrow \tau\tau$ cross-section extrapolation for HL-LHC

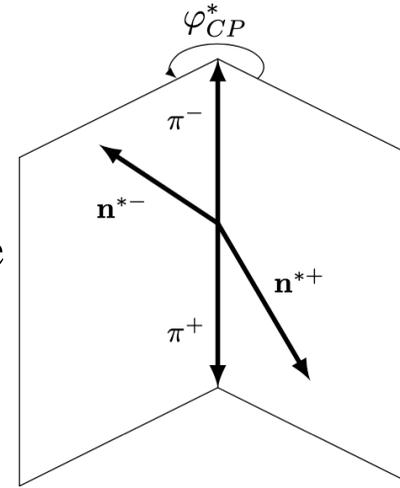


- Extrapolate Run2 measurements to  $3 ab^{-1}$ 
  - Possible to achieve 5% error on inclusive cross-section measurement, while expected uncertainty for ggF (VBF) can be reduced to 11% (7%)
  - For STXS measurements, uncertainty ranges in 7-50% depending on the probed phase space

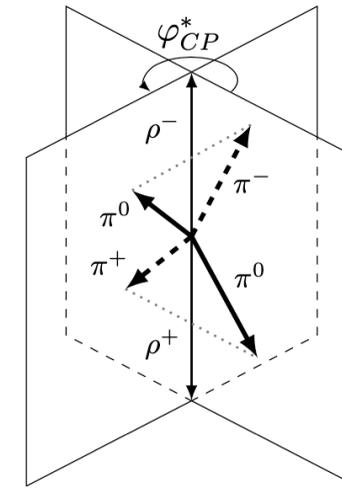


# Study of the Higgs CP in $H \rightarrow \tau\tau$ vertex

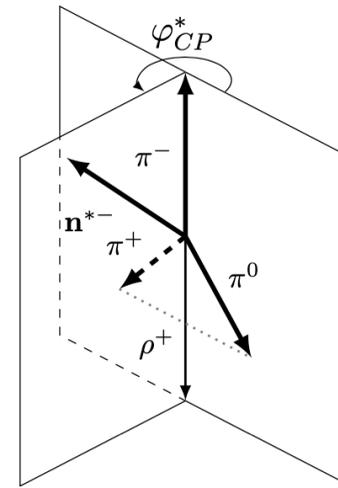
- Information about CP violation encoded in the correlation between the transversal spin components of the taus
- Access spin correlation by reconstructing the angle between the tau decay planes -  $\phi_{CP}^*$



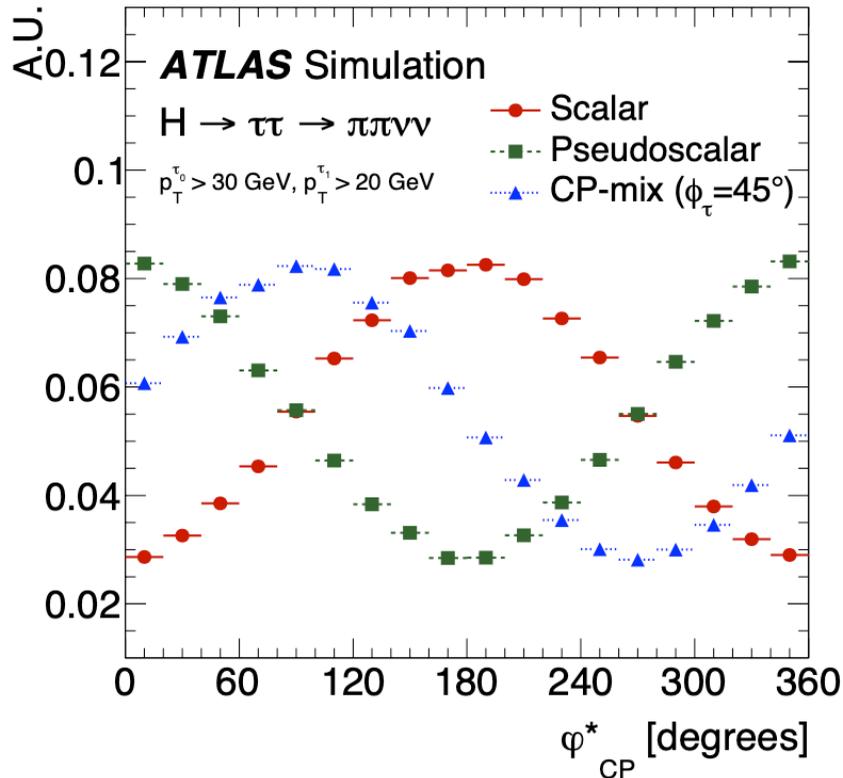
(a)  $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^- + 2\nu$



(b)  $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^0\nu\pi^-\pi^0\nu$



(c)  $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^0\nu\pi^-\nu$

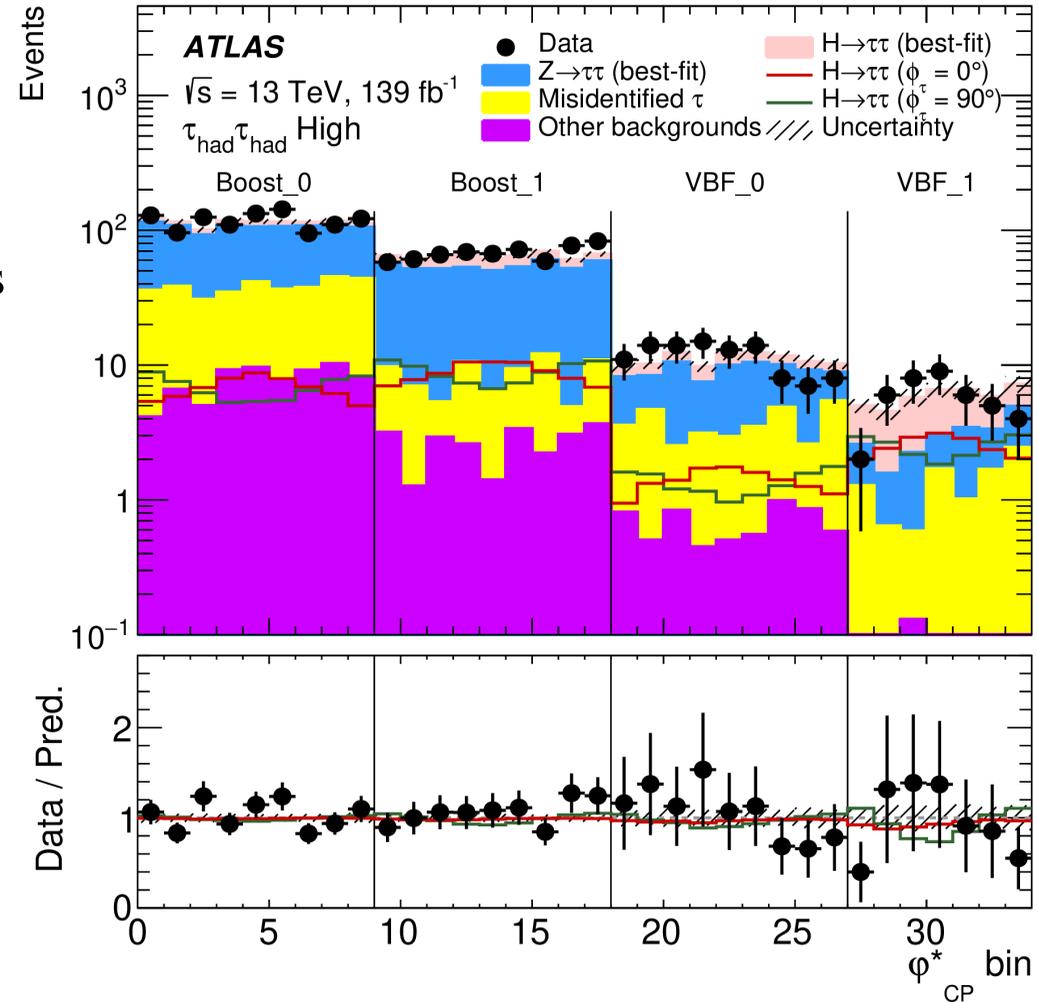
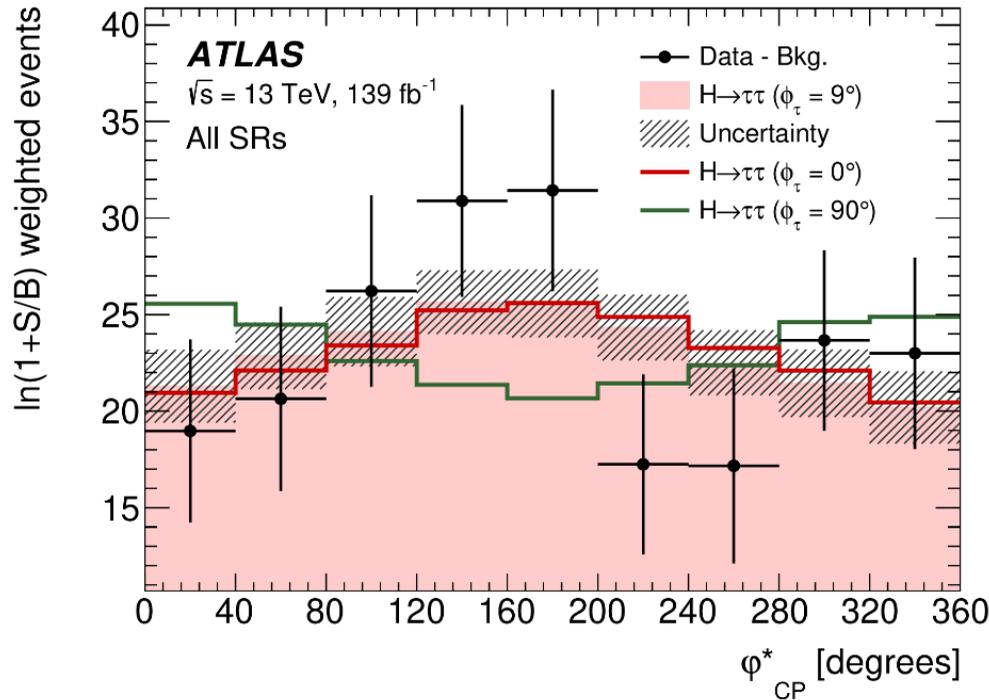


Decay channel	Decay mode combination	Method	Fraction in all $\tau$ -lepton-pair decays
$\tau_{lep}\tau_{had}$	$\ell-1p0n$	IP	8.1%
	$\ell-1p1n$	IP- $\rho$	18.3%
	$\ell-1pXn$	IP- $\rho$	7.6%
	$\ell-3p0n$	IP- $a_1$	6.9%
$\tau_{had}\tau_{had}$	$1p0n-1p0n$	IP	1.3%
	$1p0n-1p1n$	IP- $\rho$	6.0%
	$1p1n-1p1n$	$\rho$	6.7%
	$1p0n-1pXn$	IP- $\rho$	2.5%
	$1p1n-1pXn$	$\rho$	5.6%
	$1p1n-3p0n$	$\rho-a_1$	5.1%

# Study of the Higgs CP in $H \rightarrow \tau\tau$ vertex



- Different sensitivity depending on combination of di- $\tau$  decay modes, resulted in 24 SRs (+ CRs for Z-NF and  $\pi^0$  unc.)
- Understanding of tau performance is crucial
  - Decay-mode-dependent Tau Identification corrections
  - $\pi^0$  uncertainties; evaluated insitu using  $m_{\pi\pi}$  and cross checked with alternative geometry/physics lists samples
- Achieved  $3.4\sigma$  rejection for pure CP-odd hypothesis



[Eur. Phys. J. C 83 \(2023\) 563](#)

# Study of the Higgs CP in VBF and $H \rightarrow \tau\tau$ final state



- Search for possible CP violating effects in HVV vertex for VBF production mode

- EFT Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{f_{\tilde{B}B}}{\Lambda^2} H^\dagger \hat{B}_{\mu\nu} \tilde{B}_{\mu\nu} H + \frac{f_{\tilde{W}W}}{\Lambda^2} H^\dagger \hat{W}_{\mu\nu} \tilde{W}_{\mu\nu} H$$

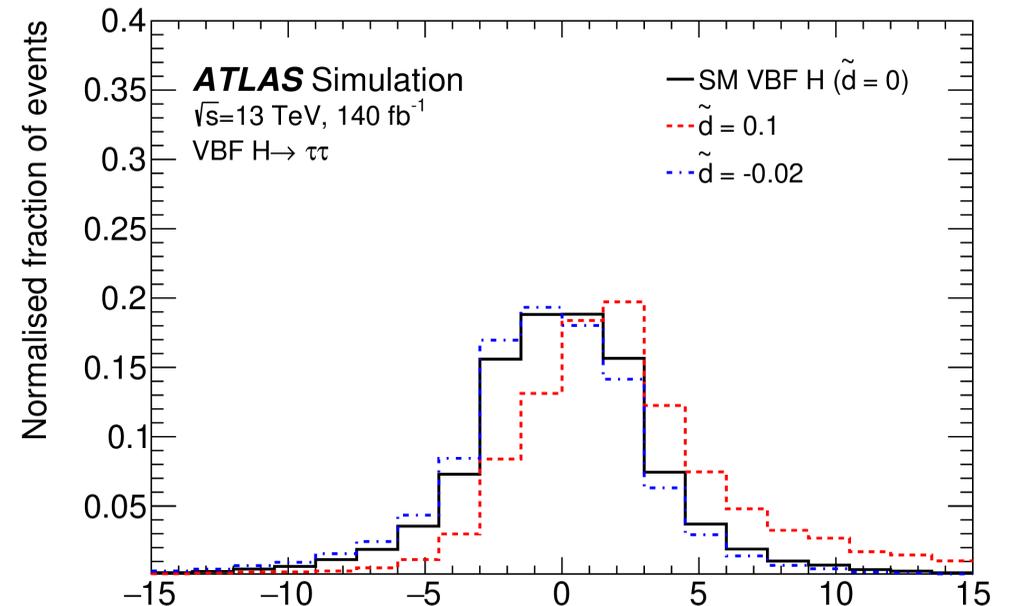
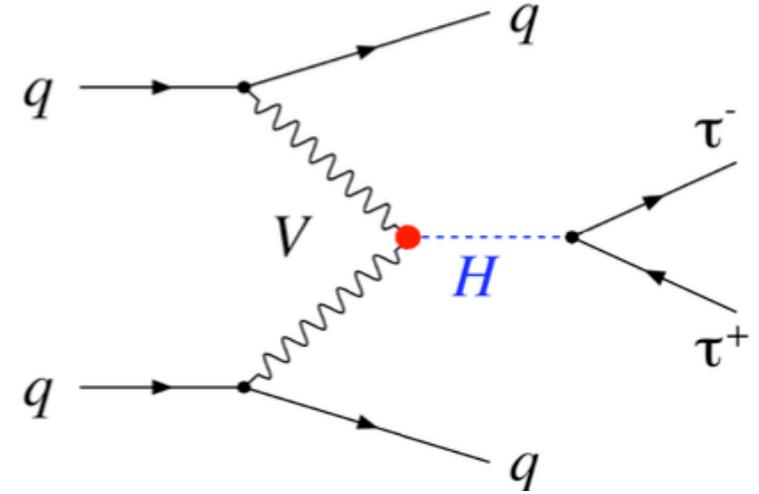
- Simplify using only one CP-violating parameter:

$$\tilde{d} = -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W} = -\frac{m_W^2}{\Lambda^2} \tan^2(\theta_W) f_{\tilde{B}B}$$

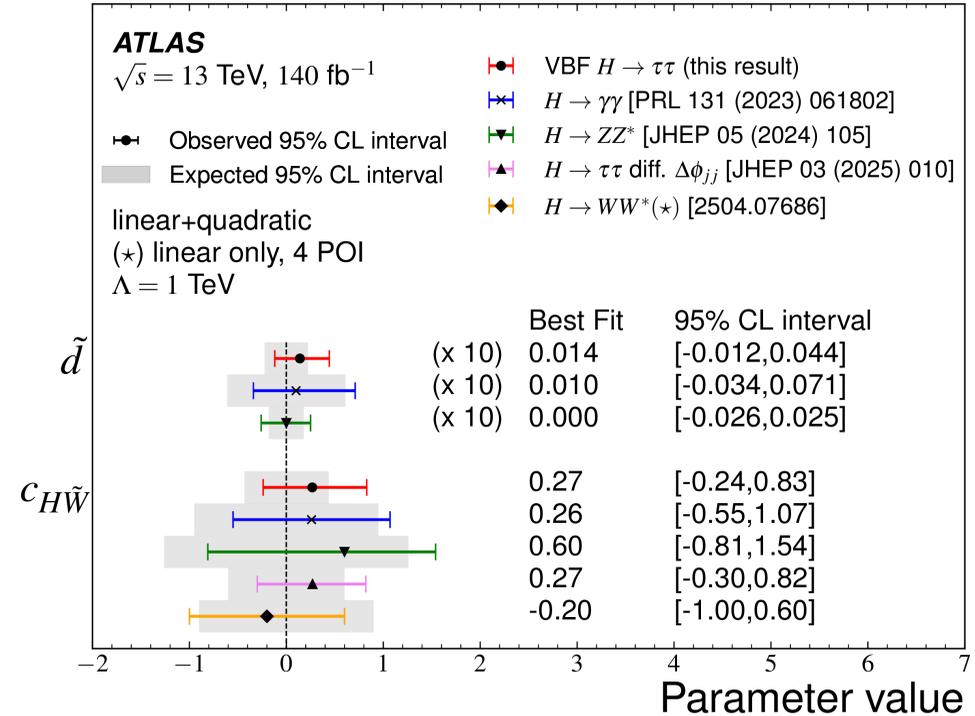
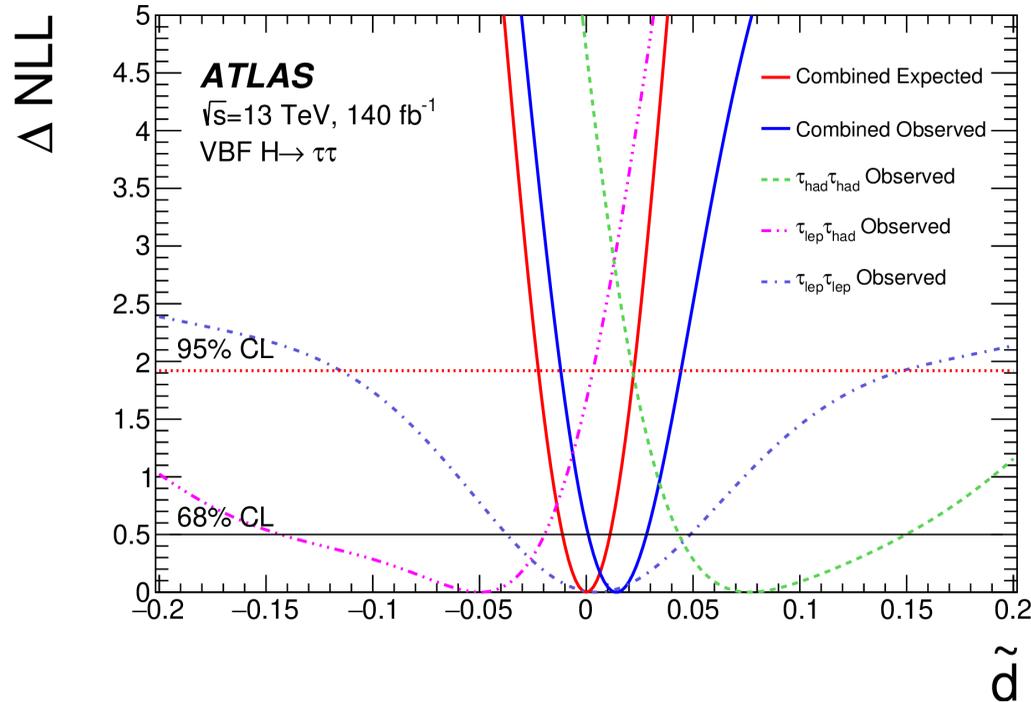
- Use Optimal Observable to measure  $\tilde{d}$ :

$$OO = \frac{\text{Re}(M_{SM}^* M_{CP-Odd})}{|M_{SM}^2|}$$

- Full phase space information in 1-dim. observable for small  $\tilde{d}$ .  $\langle OO \rangle \neq 0 \rightarrow$  CP violation neglecting re-scattering effects by new light particles in loops



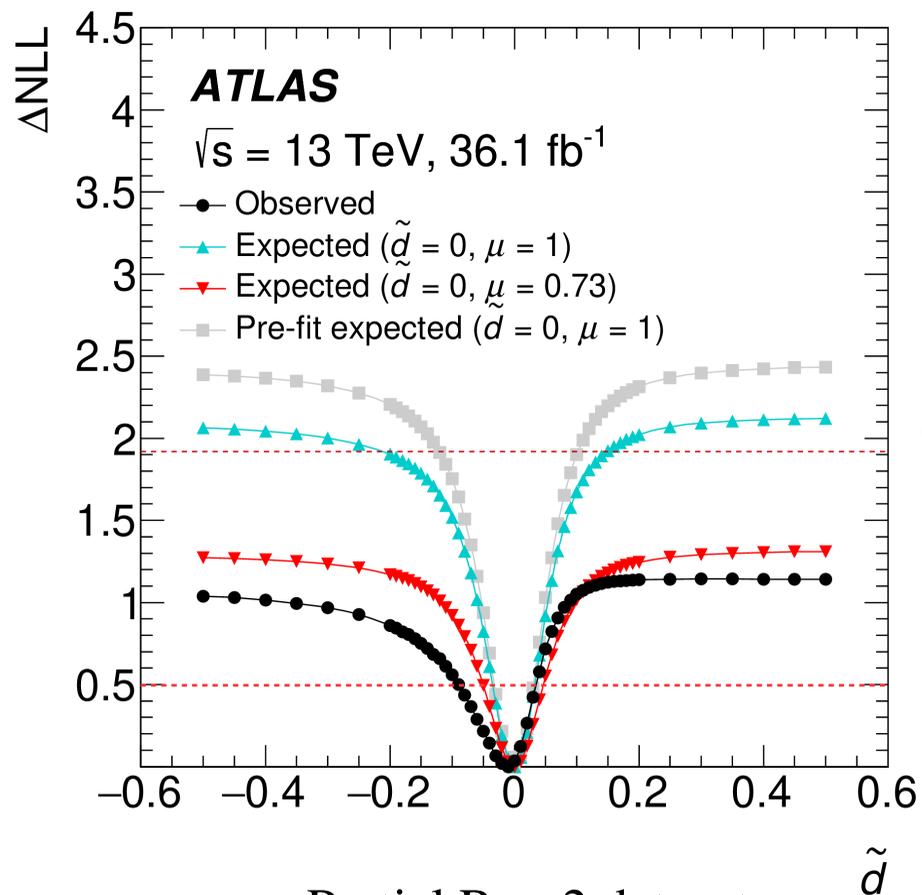
# Results for $\tilde{d}$ interpretation (HISZ basis)



Parameter	Observed best value	68% CL (Exp.)	95% CL (Exp.)	68% CL (Obs.)	95% CL (Obs.)
$\tilde{d}$ (lin.+quad.)	0.014	[-0.011, 0.011]	[-0.022, 0.022]	[0.001, 0.028]	[-0.012, 0.044]
$\tilde{d}$ (lin. only)	0.011	[-0.011, 0.011]	[-0.021, 0.022]	[0.000, 0.023]	[-0.012, 0.034]

- One of the most competitive results for  $C_{H\tilde{W}}$  95% confidence interval when compared to other Higgs decay channel analyses

# Evolution of VBF CP $H \rightarrow \tau\tau$ measurement

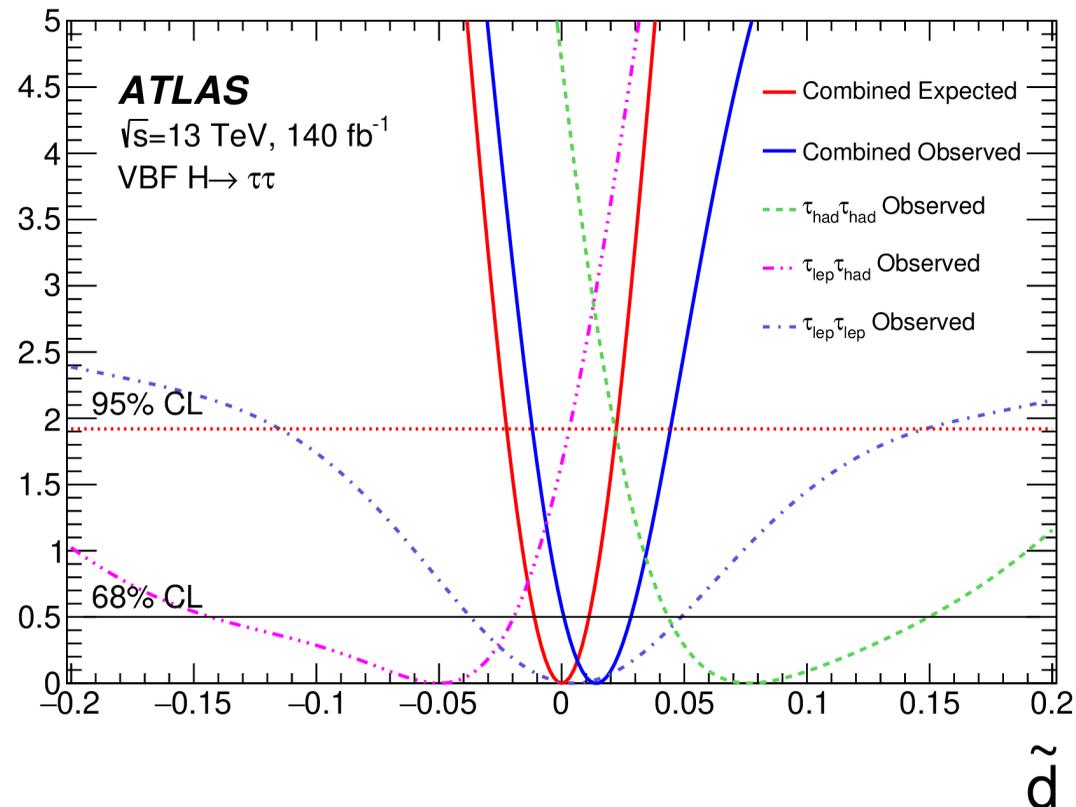


Partial Run 2 dataset

[Phys. Lett. B 805 \(2020\) 135426](#)



ΔNLL



Full Run 2 dataset

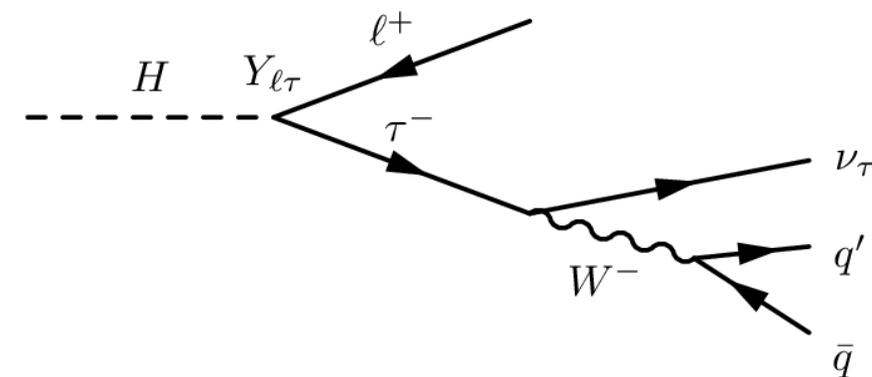
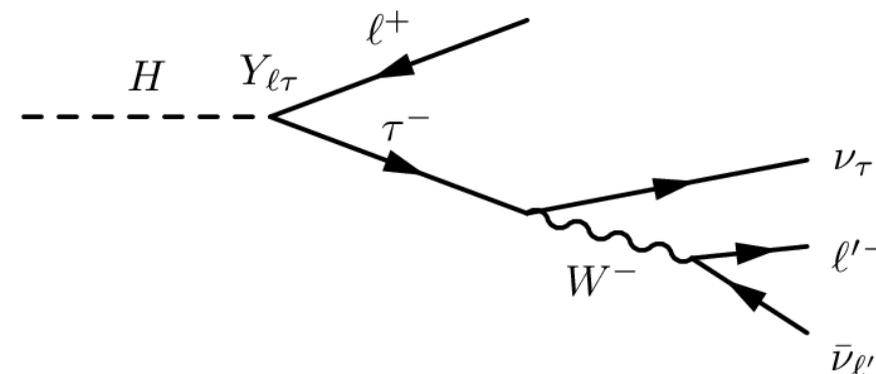
[JHEP 10 \(2025\) 92](#)

- Great improvement with respect to previous analysis using partial Run2 dataset, now being able to set constraints also at 95% C.L.

# Search for Lepton Flavour violation (LFV) in $H \rightarrow l\tau$



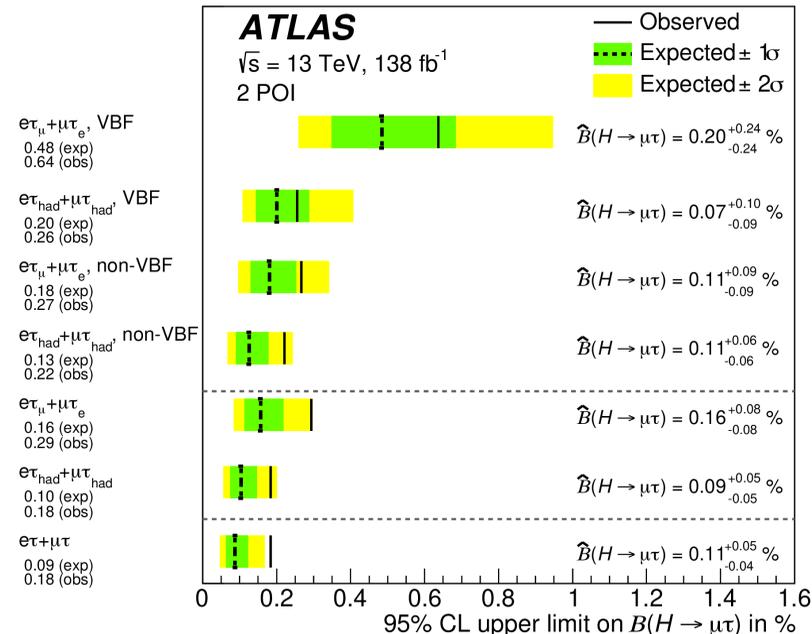
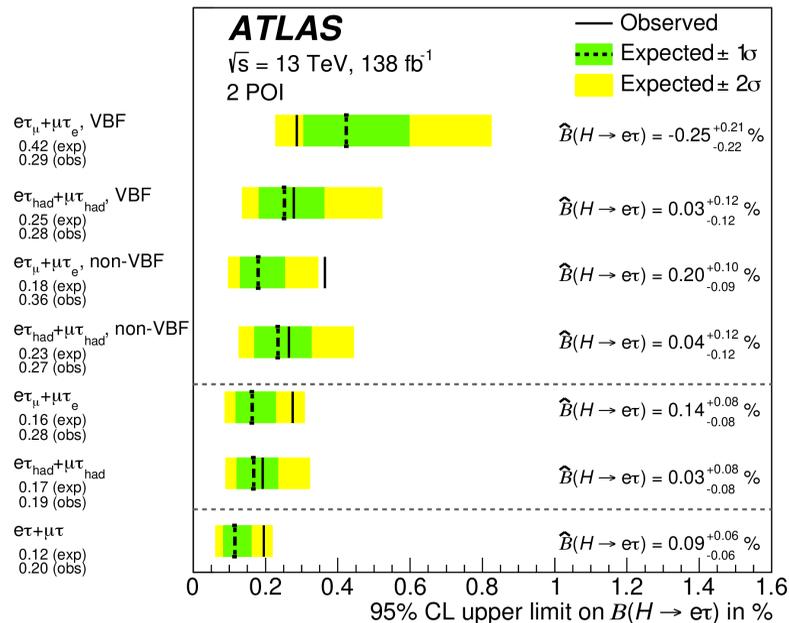
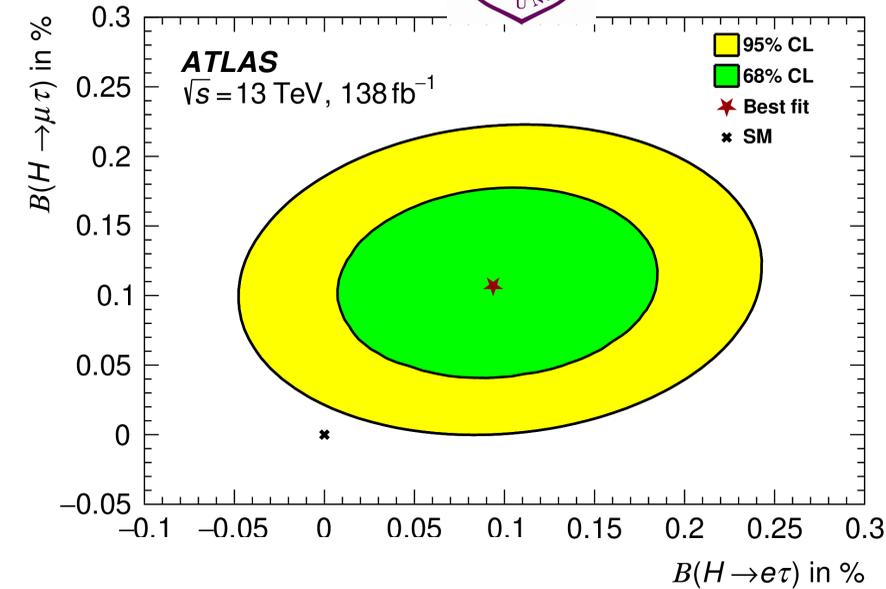
- Analysis searching for two independent signals,  $H \rightarrow e\tau$  and  $H \rightarrow \mu\tau$ , considering both hadronic and leptonic  $\tau$  decays
- Full leptonic final state,  $e\tau_\mu$  and  $\mu\tau_e$ , is using two different estimation methods for the major backgrounds:
  - MC-template method: background estimated using Monte Carlo templates + normalisation through control regions
  - Symmetry method: background estimation via data-driven symmetry method
- Final state with one leptonic and one hadronic decaying  $\tau$ ,  $e\tau_{had}$  and  $\mu\tau_{had}$  is considering only MC-template method



# Lepton Flavour violation in $H \rightarrow l\tau$ results

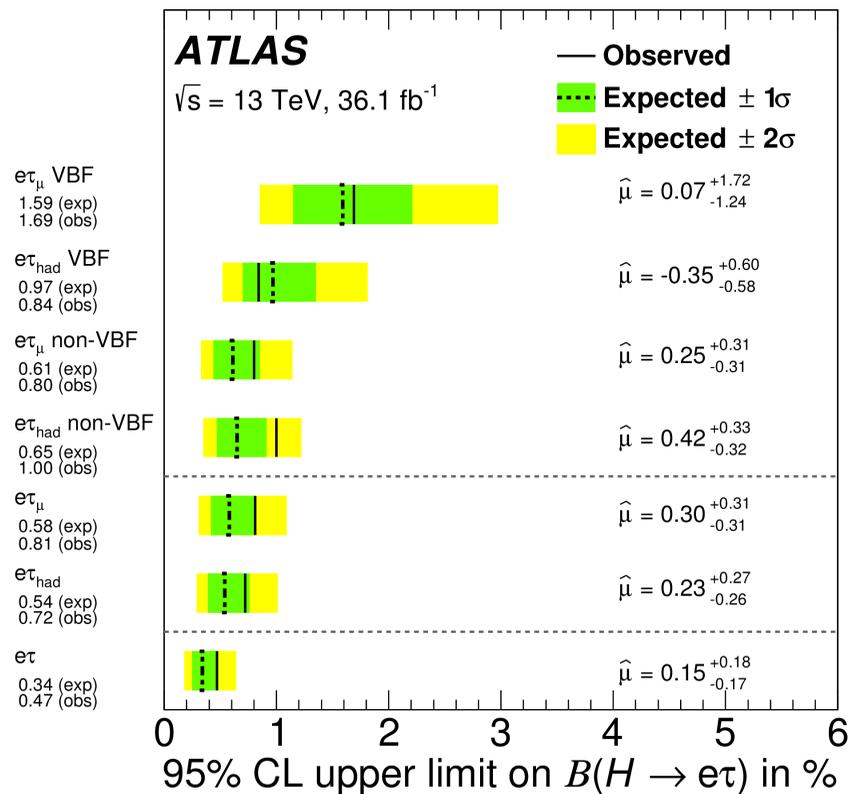


- Results extracted from a simultaneous fit of  $Br(H \rightarrow \mu\tau)$  and  $Br(H \rightarrow e\tau)$ ; for this use MC-template method to remove the assumption of one BR=0
- 2.5 (1.6)  $\sigma$  excess observed for  $Br(H \rightarrow \mu\tau)$  ( $Br(H \rightarrow e\tau)$ )
- Compatibility with SM within 2.2  $\sigma$
- Observed (expected) upper limits at 95% C.L. on Br are 0.20% (0.12%) for  $H \rightarrow e\tau$  and 0.18% (0.09%) for  $H \rightarrow \mu\tau$



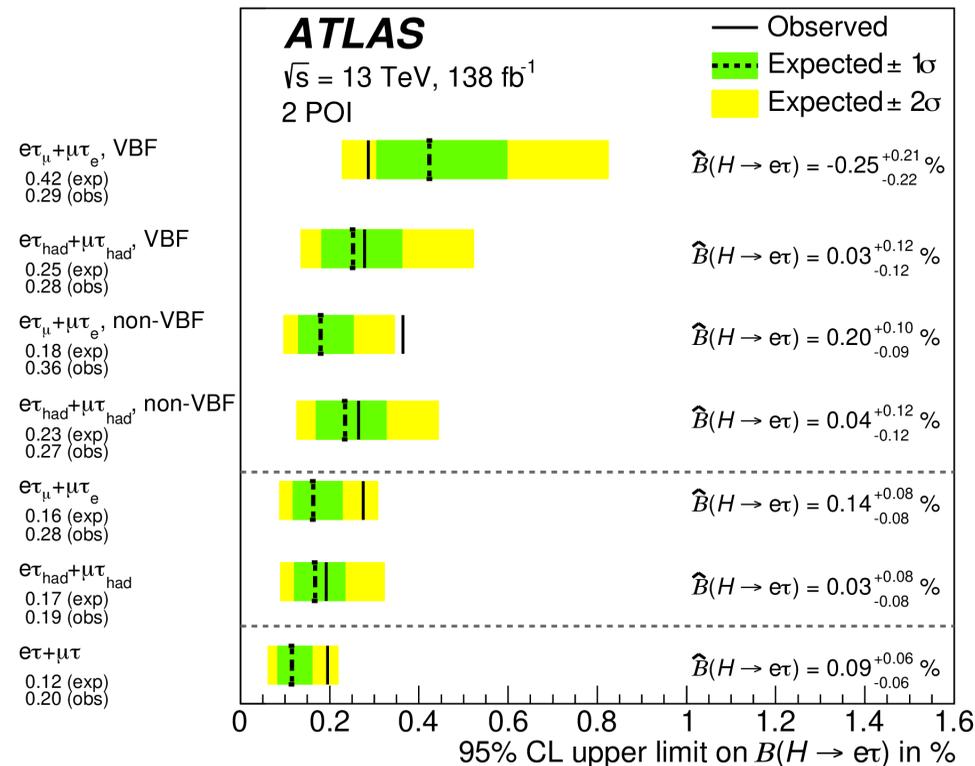
JHEP 07 (2023) 166

# Evolution of LFV $H \rightarrow l\tau$ measurement



Partial Run 2 dataset

[Phys. Lett. B 800 \(2020\) 135069](#)



Full Run 2 dataset

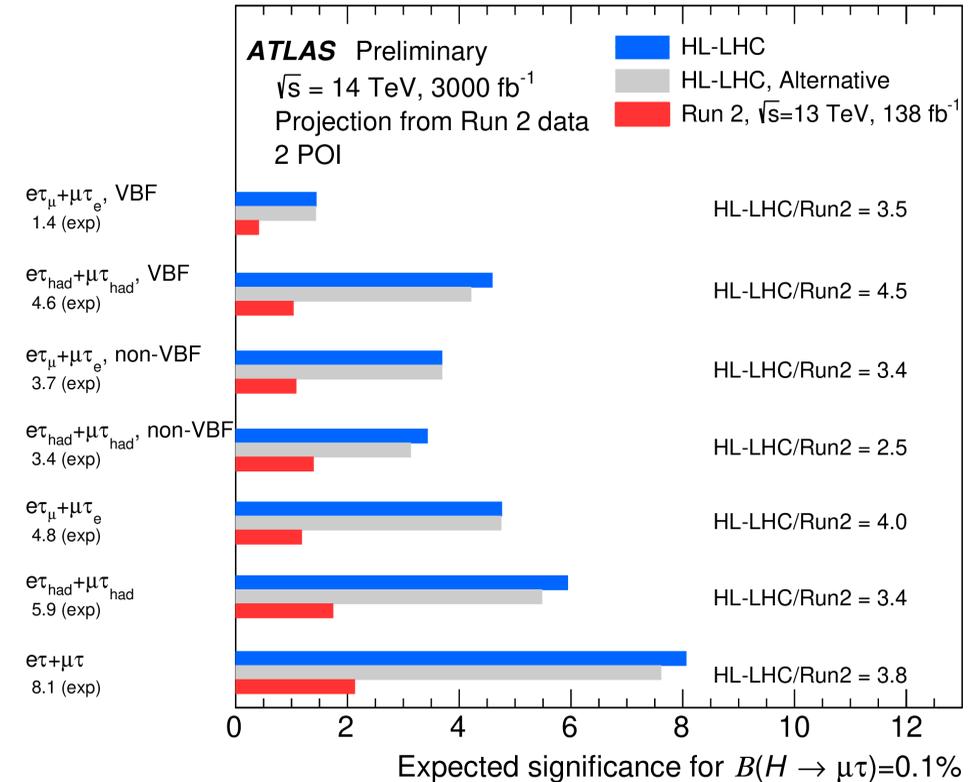
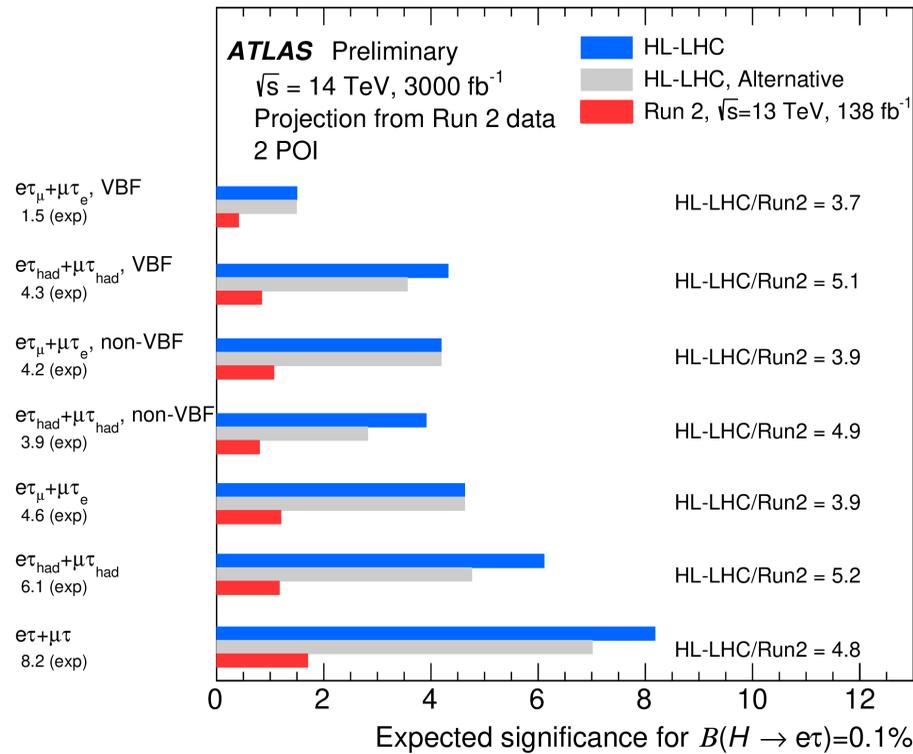
[JHEP 07 \(2023\) 166](#)

- Improvement by factor 2.5 (1.6) depending on the final state. Apart from increased luminosity, used more sophisticated analysis methods (MVA, lepton assignment in Higgs rest frame, tau identification)

# LFV results extrapolation for HL-LHC



- Extrapolate Run2 measurements to  $3 \text{ ab}^{-1}$
- In the presence of signal with a  $\text{BR}(H \rightarrow \tau) = 0.1\%$ , an expected significance of 8.2 (8.1)  $\sigma$  can be achieved for  $H \rightarrow e\tau$  and  $H \rightarrow \mu\tau$ . This is improving the current results by factor 2-5 depending on the probed final state





... there is always place for one more Higgs ...

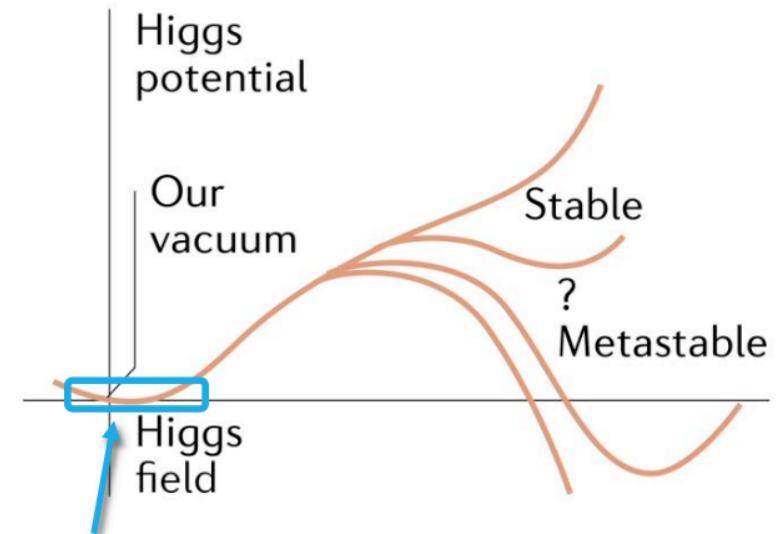
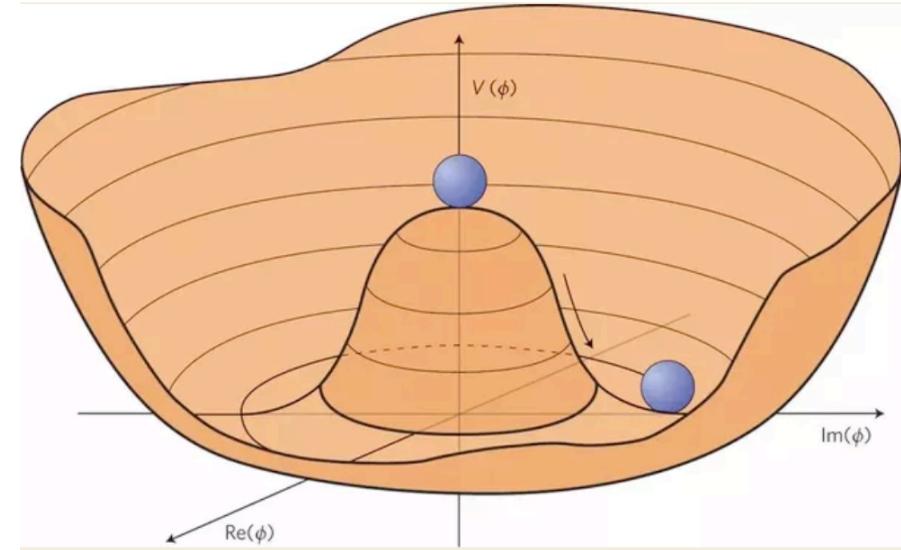
# The Higgs potential

- Precise measurements indicates that the universe might be in a meta-stable phase
- Higgs Boson (H) potential shape is important to determine the properties of the scalar sector and the universe evolution
- With the discovery and accurate measurement of the single Higgs boson production, only a portion of the potential has been measured:

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4 + O(H^5)$$

$$\lambda_3 = \lambda_4 = \lambda_{SM} = \frac{m_H^2}{2v^2} \quad \lambda_i = 0 \text{ for } i \geq 5$$

- HH production probes the Higgs boson self-interaction and, ultimately, the shape of the Higgs potential

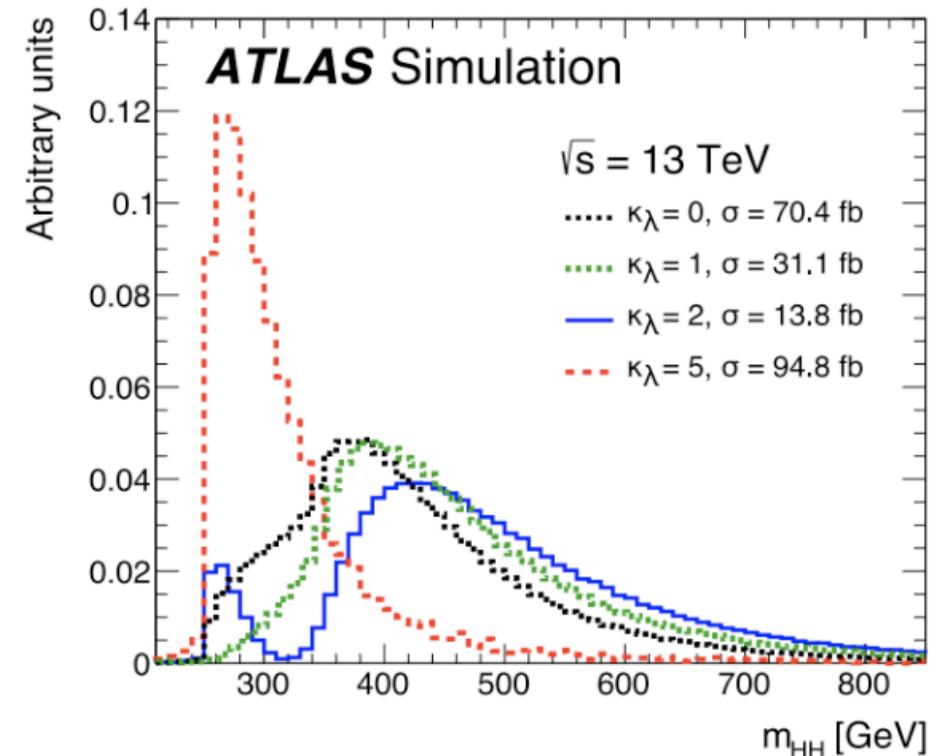
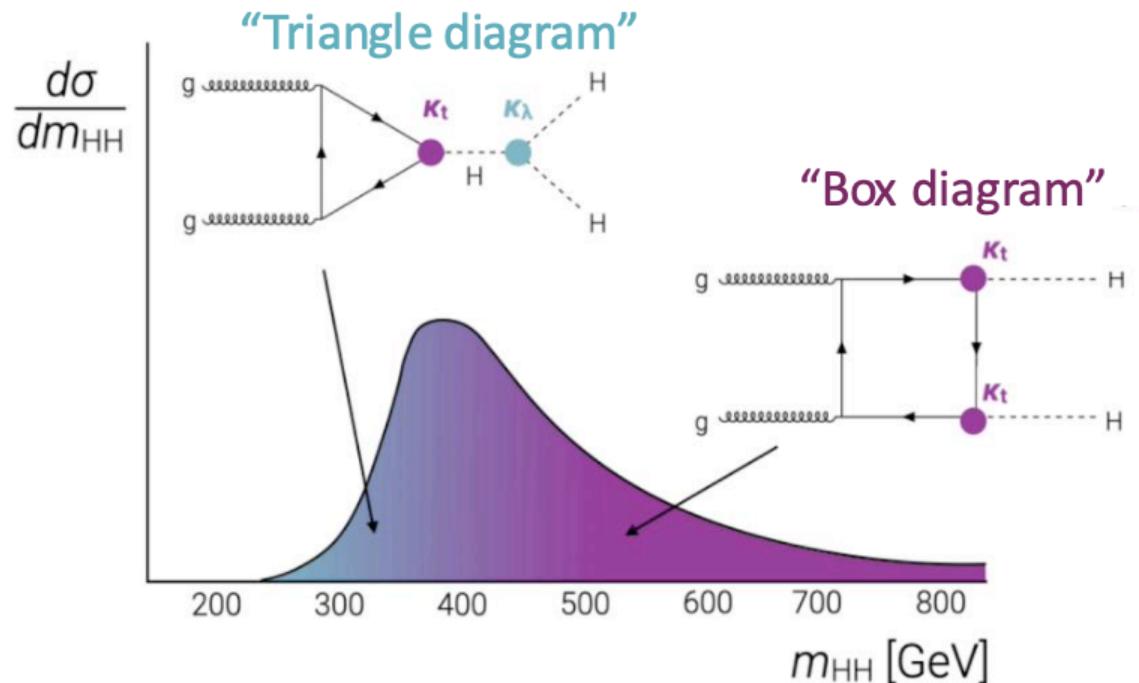


Current knowledge

# Main HH production mode - ggH



- Main HH production is through gluon-gluon fusion (ggH)
  - Low cross-section,  $\sigma_{ggF}^{SM} \simeq 31 \text{ fb}$  (@13 TeV)
  - Non-linear dependency of the cross section on Higgs self-coupling,  $k_\lambda$ , because of the destructive interference between the “triangle” and the “box” production diagram
  - Higher values of  $k_\lambda$  experimentally difficult to probe at LHC because of low momentum objects in the final state

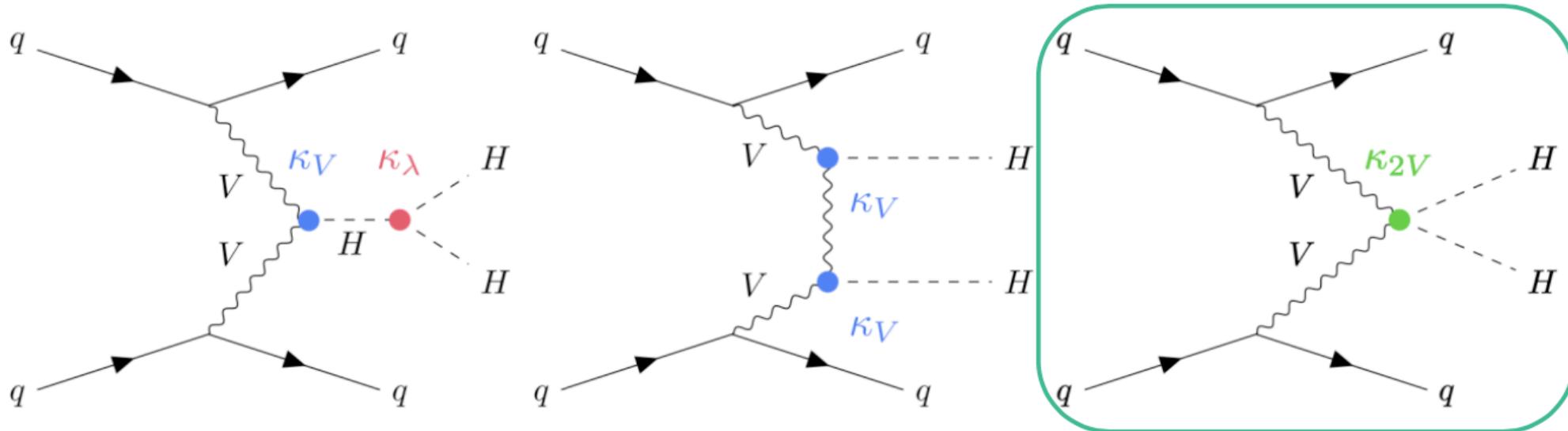


# Main HH production modes - VBF



- Second dominant HH production mode is the vector-boson fusion (VBF)
  - $\simeq 20$  times lower cross section than  $ggH$ ,  $\sigma_{VBF}^{SM} \simeq 1.7$  fb (@13 TeV)
  - Provides a unique way to probe the  $VVHH$  vertex and the coefficient  $k_{2V}$
  - Constraints on  $k_{2V}$  are easier to probe given that possible beyond Standard-Model scenarios predict harder kinematics and higher cross-sections

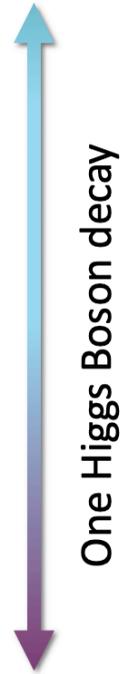
Main contributing diagram



# HH decay channels

Large decay fraction

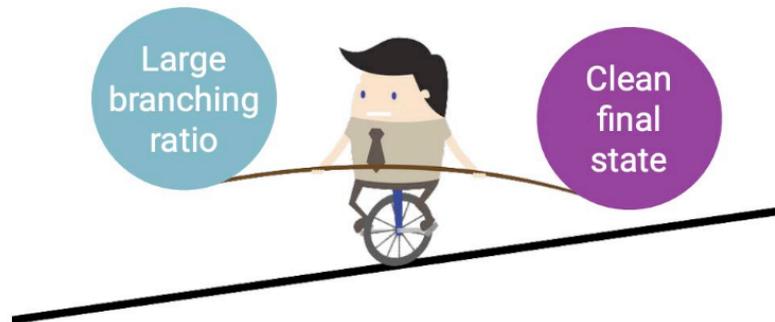
The other Higgs Boson decay



One Higgs Boson decay

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

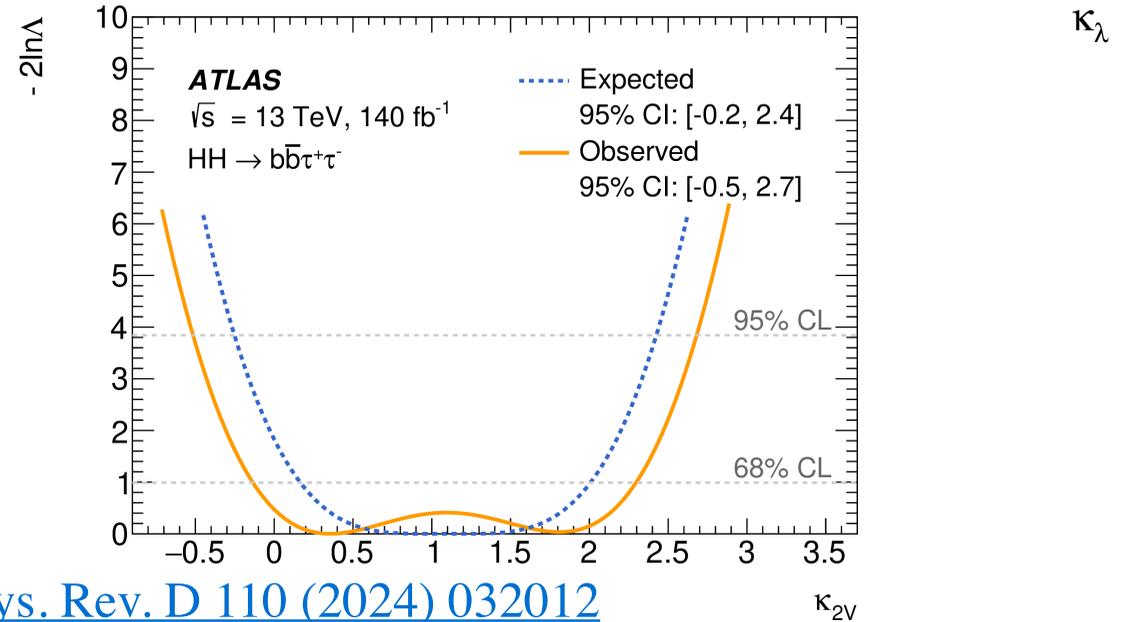
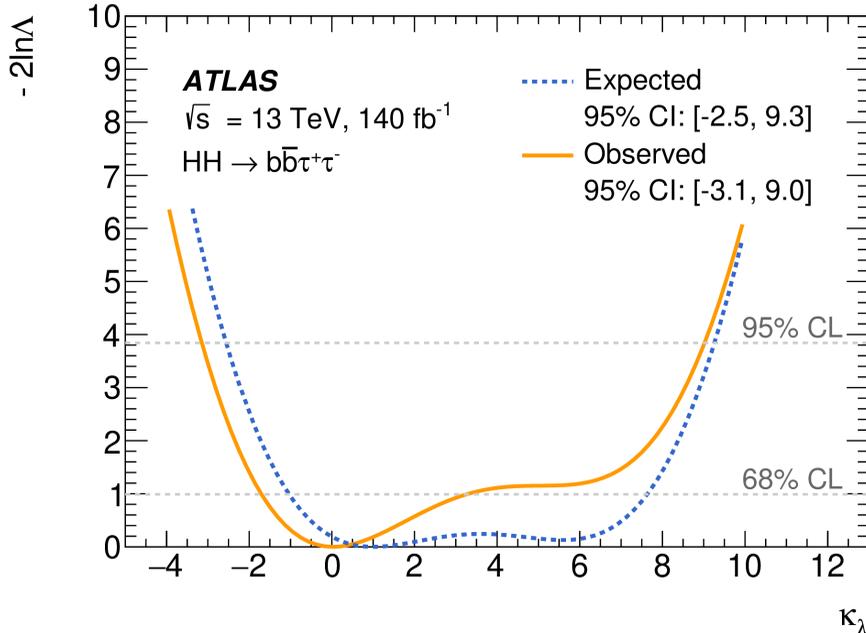
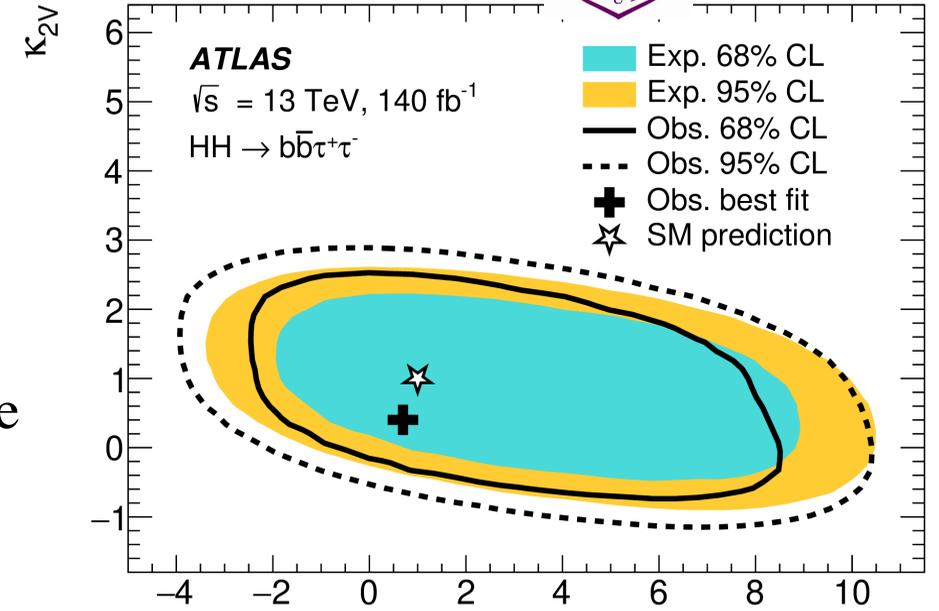
Clean final state



- Lots of possible final states to probe for different HH decays
- Not a single “golden” channel, but 3 “silver” channels guiding the HH searches:  
 $HH \rightarrow bbbb$ ,  $HH \rightarrow bb\gamma\gamma$  and  $HH \rightarrow bb\tau\tau$
- Really challenging searches due to large branching ratio (BR) but low signal over background (S/B),  $HH \rightarrow bbbb$ , or low BR but better S/B,  $HH \rightarrow bb\gamma\gamma$
- $HH \rightarrow bb\tau\tau$  can be consider as channel with medium BR and medium S/B

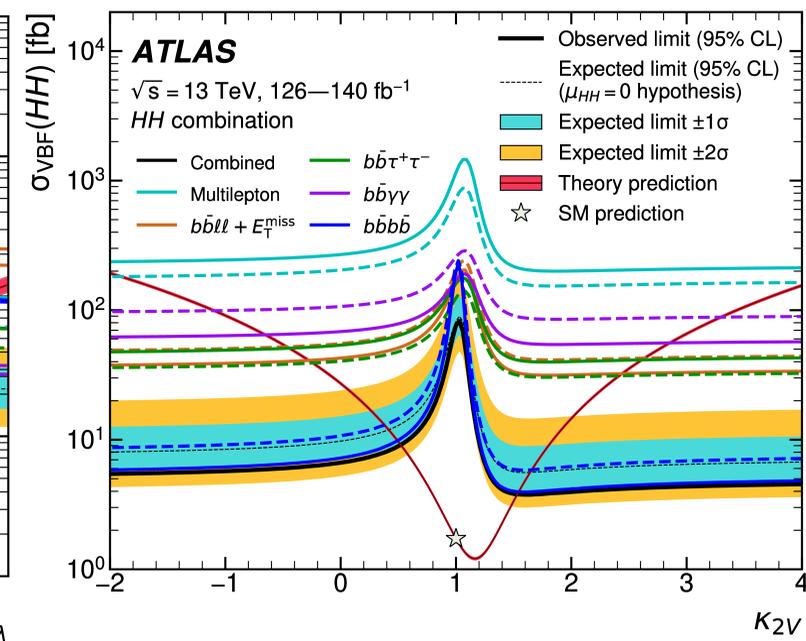
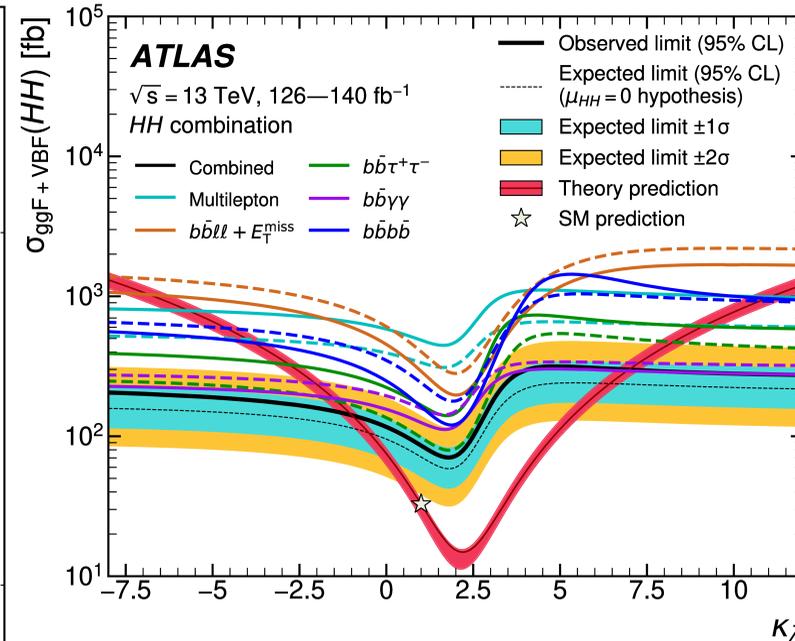
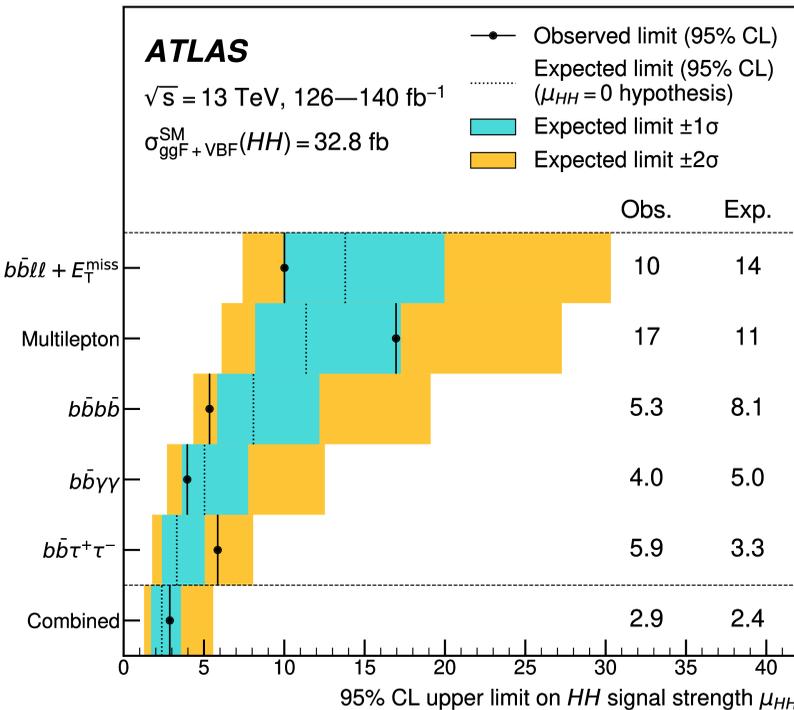
# $HH \rightarrow bb\tau\tau$ Results

- Combined fit allows to set observed (expected) 95% confidence intervals for:
  - $k_\lambda \in [-3.1, 9.0]$  ( $[-2.5, 9.3]$ ) assuming  $k_{2V} = 1$
  - $k_{2V} \in [-0.2, 2.4]$  ( $[-0.5, 2.7]$ ) assuming  $k_\lambda = 1$
- Expected results improved by 11%-19% depending on the parameter of interest compared to previous results from [JHEP 07 \(2023\) 040](#)

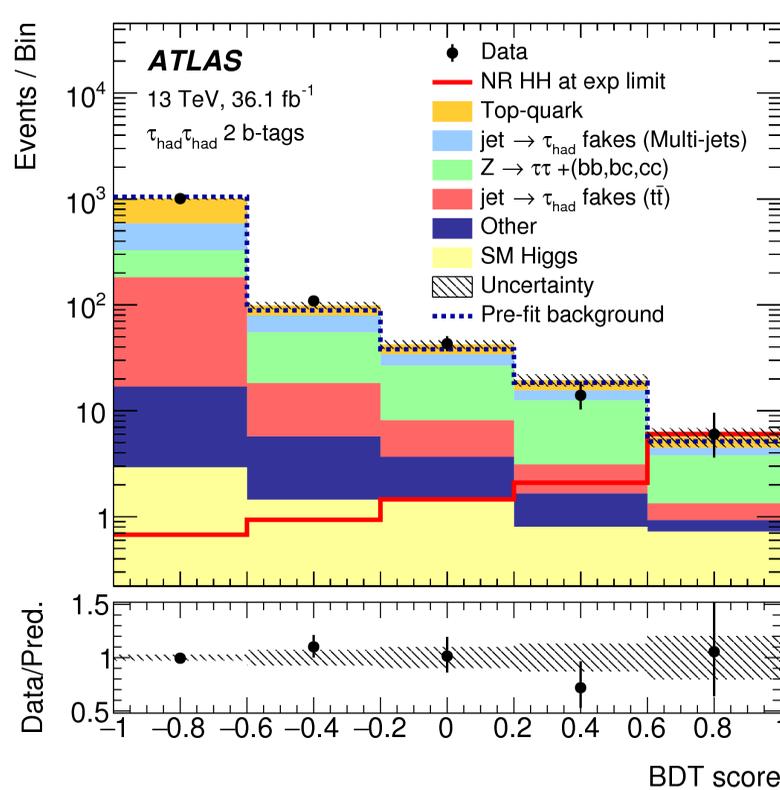


# $HH \rightarrow bb\tau\tau$ in $HH$ combined results

- The observed (expected) upper limit on the inclusive production cross section relative to the standard model expectation is found to be 2.9 (2.4)
- $HH$  production excluded at 95% confidence level (C.L.) for values of  $k_\lambda < -1.2$  or  $k_\lambda > 7.2$
- Similarly,  $HH$  production excluded at 95% C.L. for  $k_{2V} < 0.4$  or  $k_{2V} > 1.6$

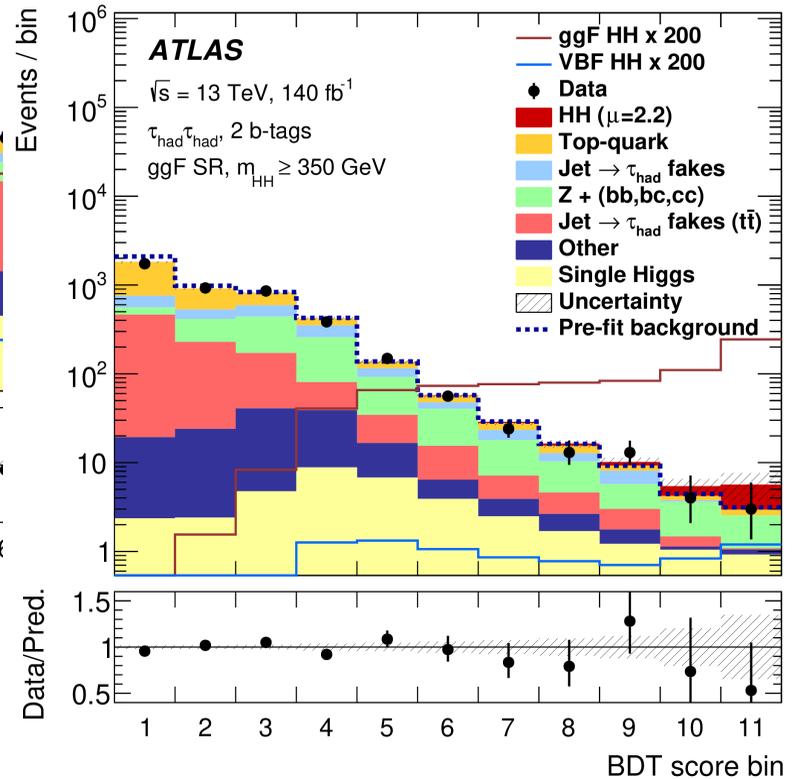
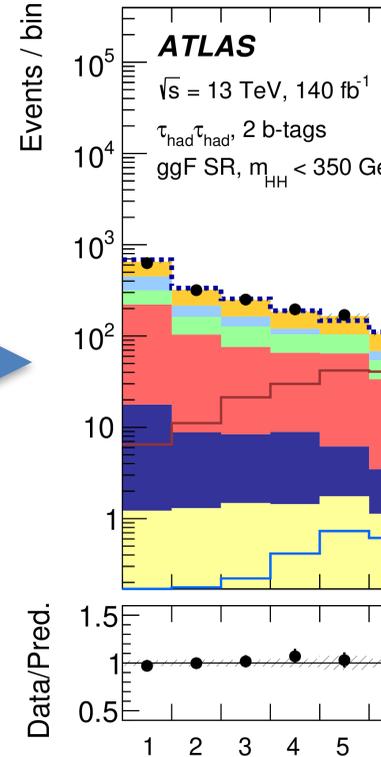


# Evolution of $HH \rightarrow bb\tau\tau$ search



Partial Run 2 dataset

[Phys. Rev. Lett. 121 \(2018\) 191801](https://arxiv.org/abs/1801.09240)



Full Run 2 dataset

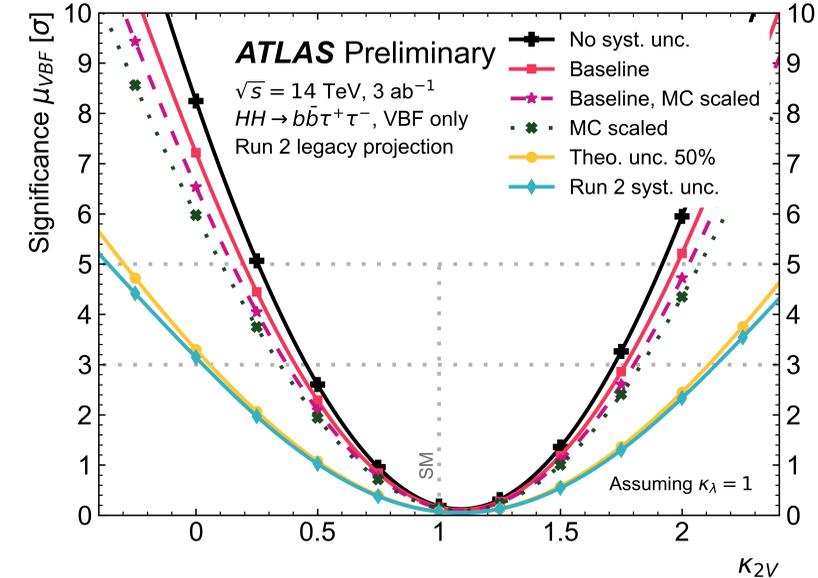
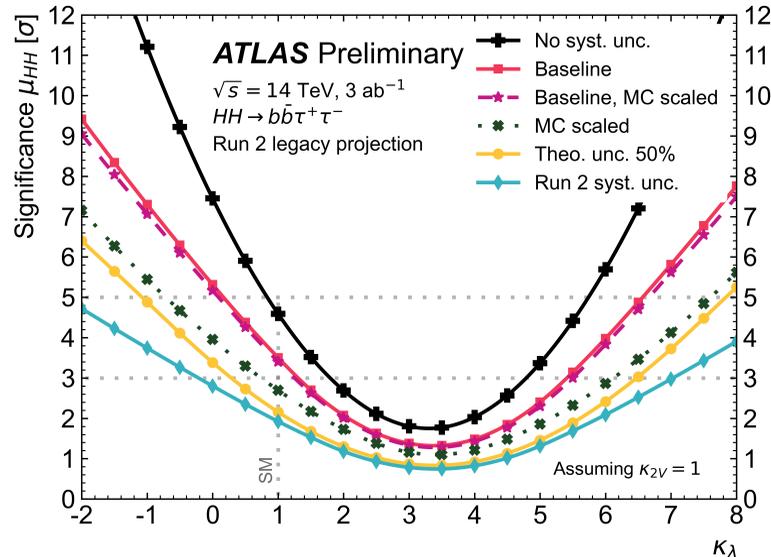
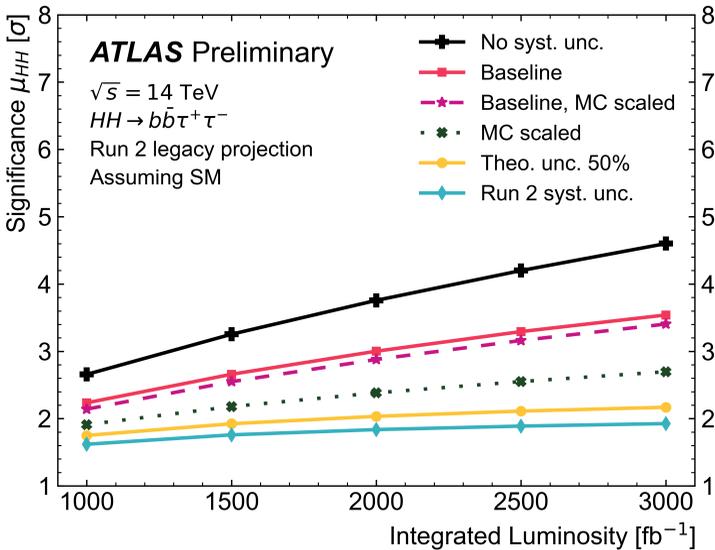
[Phys. Rev. D 110 \(2024\) 032012](https://arxiv.org/abs/2308.12345)

- Moving from 12.7 to 5.9 for 95% upper limit on the cross-section normalised to its Standard Model prediction

# ATLAS $HH \rightarrow bb\tau\tau$ results projection for HL-LHC



- Assuming SM like HH production, a signal significance of 3.5 (4.6)  $\sigma$  is expected in the *baseline* (statistical only) extrapolation scenario for a luminosity of  $3 \text{ ab}^{-1}$
- This translates into a 95% confidence level constraints for  $k_\lambda$  in two regions,  $[-0.1, 2.7]$  and  $[4.5, 6.4]$  in the baseline scenario
- Further improvements in b-tagging algorithm are expected to add  $0.3 \sigma$  to the extrapolated results

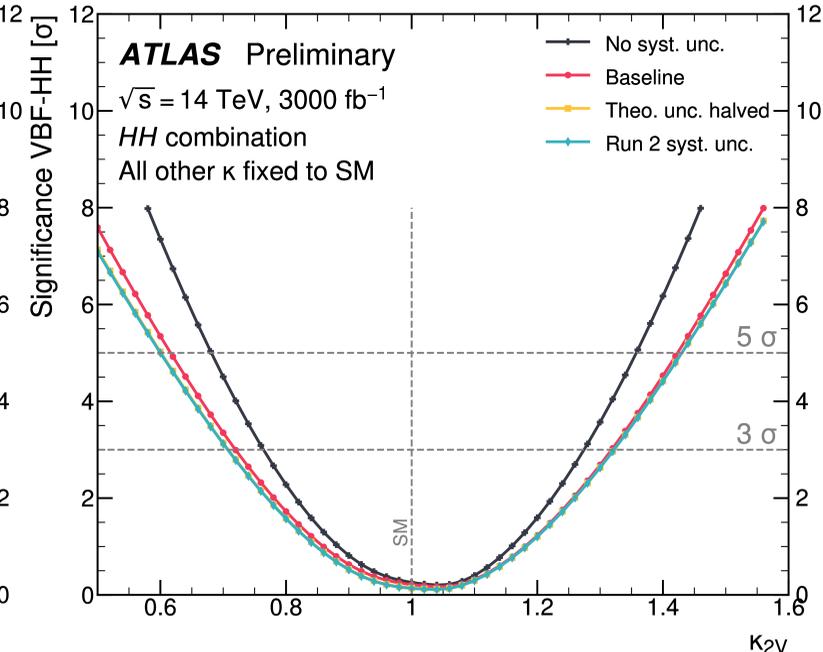
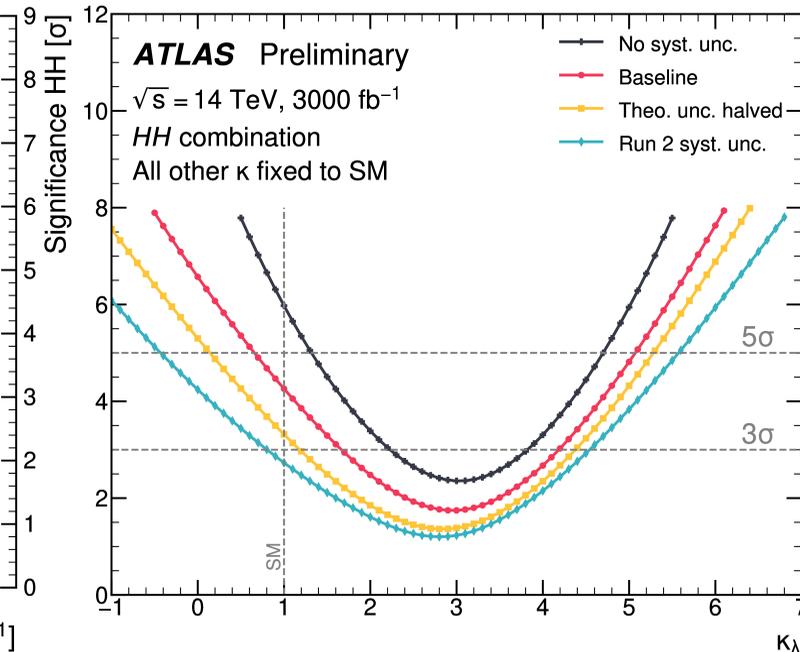
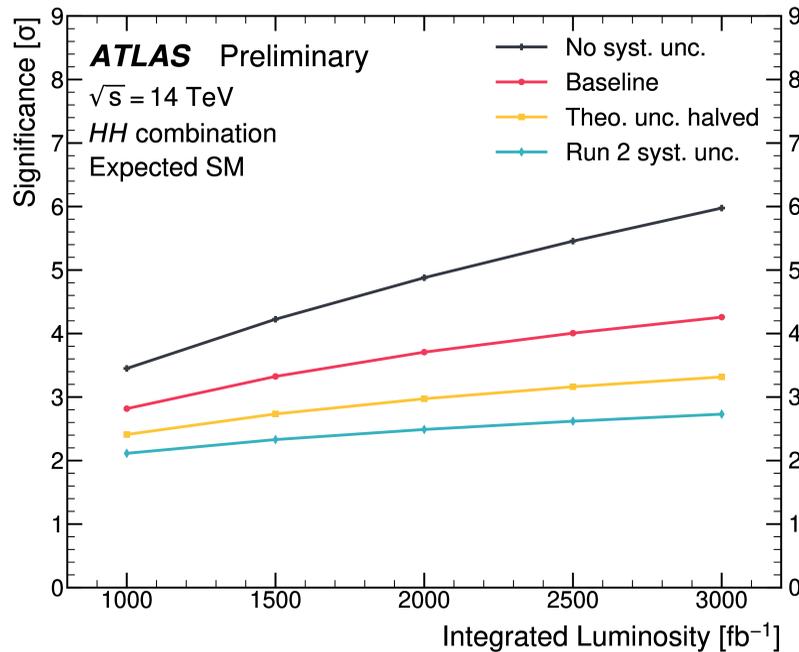


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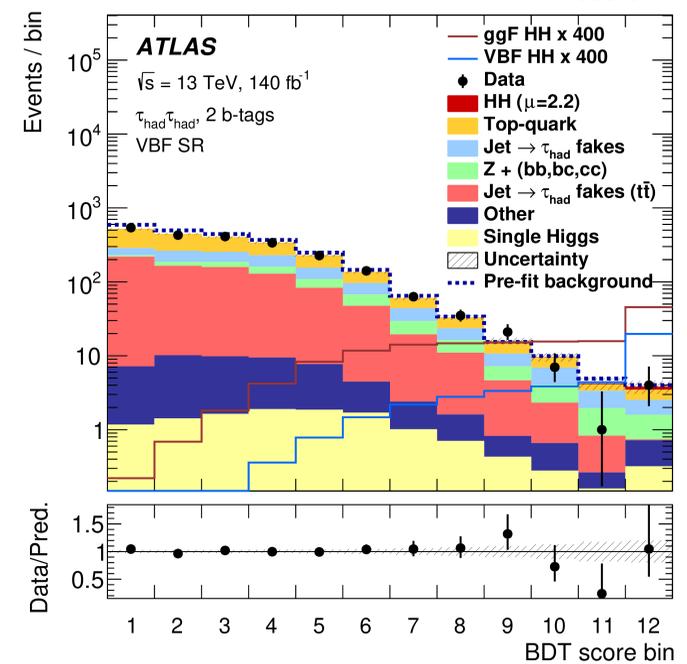
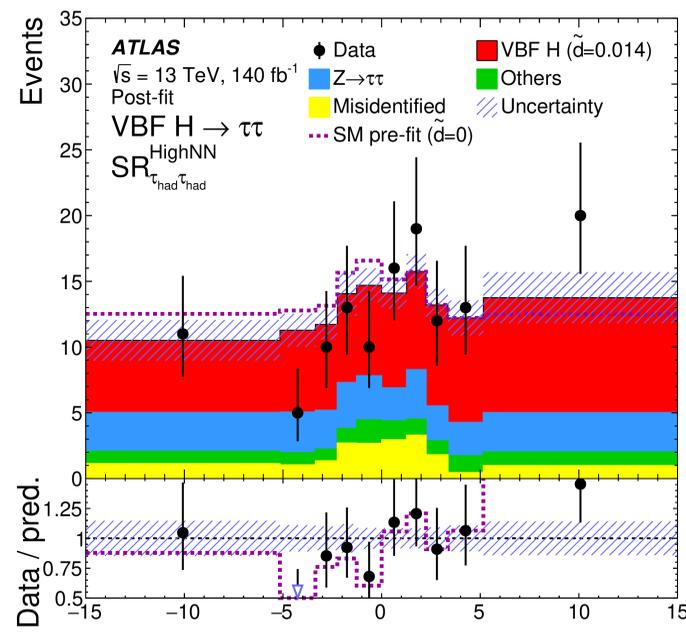
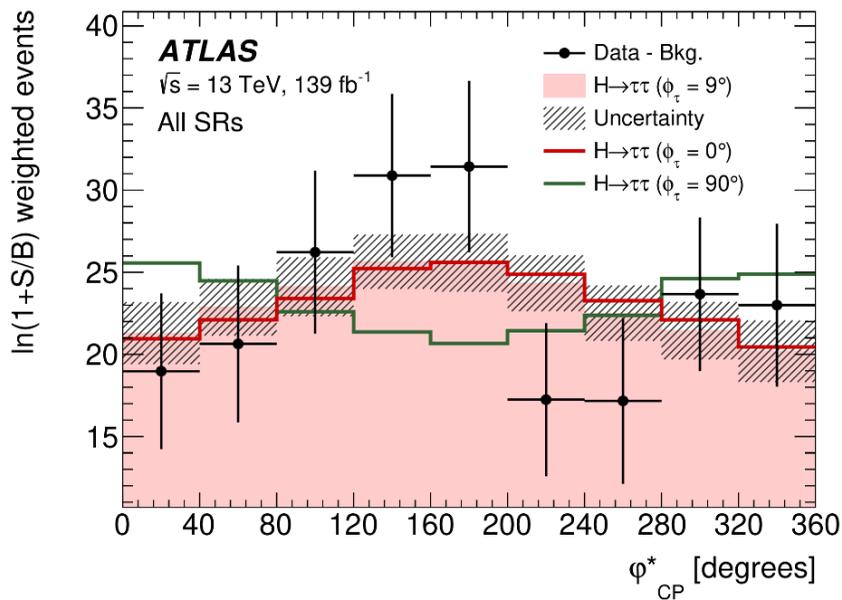
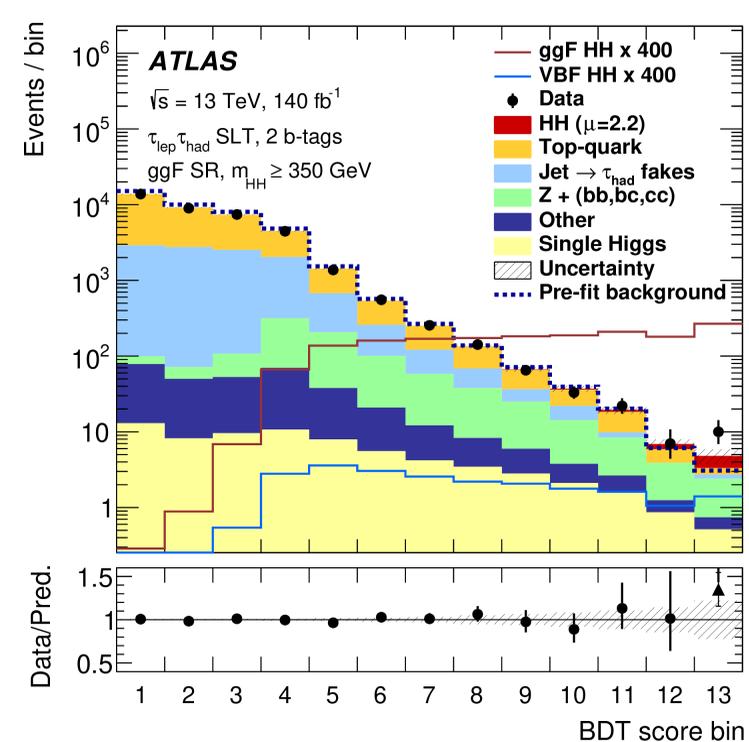
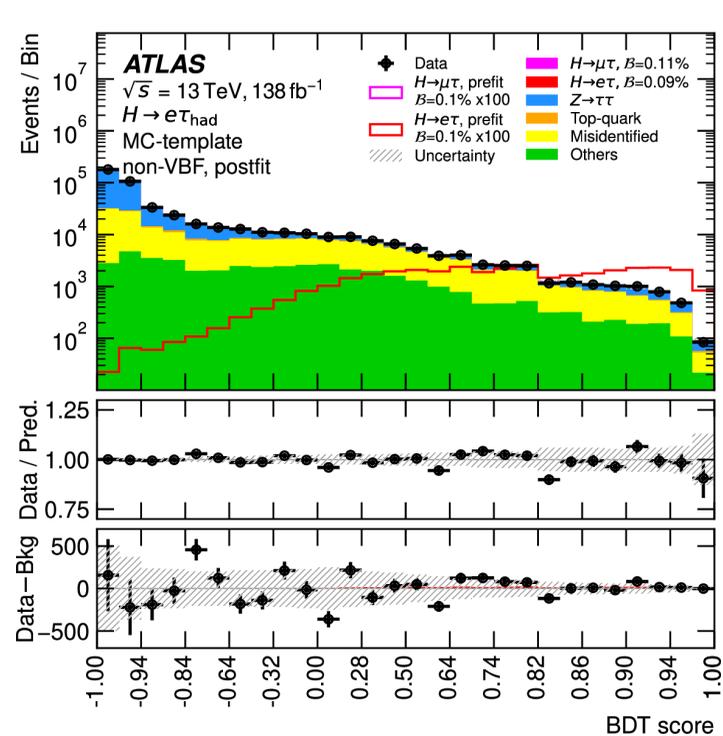
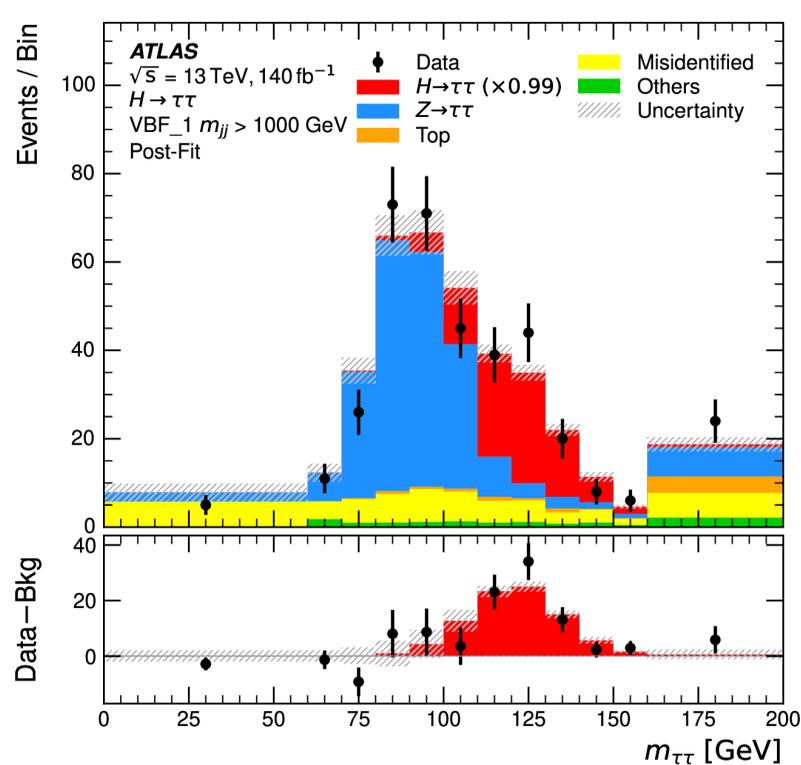
# ATLAS HH results projection for HL-LHC



- Prospects are obtained from a statistical combination of extrapolated results from 6 analyses
- In the baseline scenario for a  $3000 \text{ fb}^{-1}$  at  $\sqrt{s} = 14 \text{ TeV}$ , the discovery significance of SM HH production is found to be  $4.26 \sigma$
- $k_\lambda$  is expected to be measured as  $1.0^{+0.48}_{-0.42}$ , while  $k_{2V}$  is expected to be  $1.0^{+0.18}_{-0.15}$



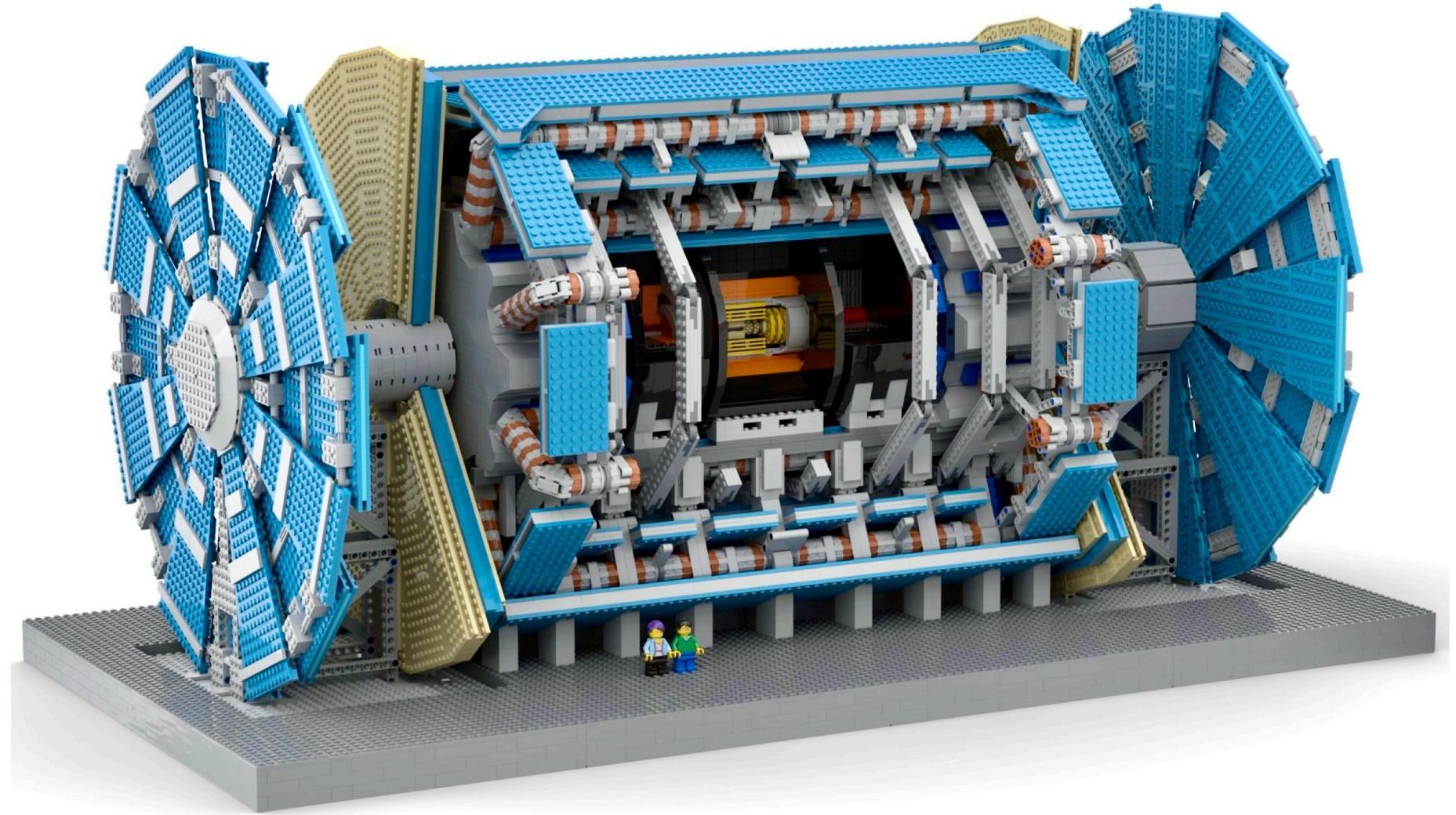
[ATL-PHYS-PUB-2025-006](#)



# Summary

- Tau lepton is a powerful tool to probe physics in the ATLAS experiment
  - Dedicated reconstruction and identification algorithms
  - Continuous algorithm improvements will directly translate in physics analysis gain
- $H \rightarrow \tau\tau$  is a well established channel which allows several studies, from the Yukawa coupling measurement to the Higgs charge parity measurements or the search for Lepton Flavour Violation
- For the Di-Higgs search,  $HH \rightarrow bb\tau\tau$  is one of the most promising channels to measure the Higgs self-coupling





*Thanks a lot for your attention*