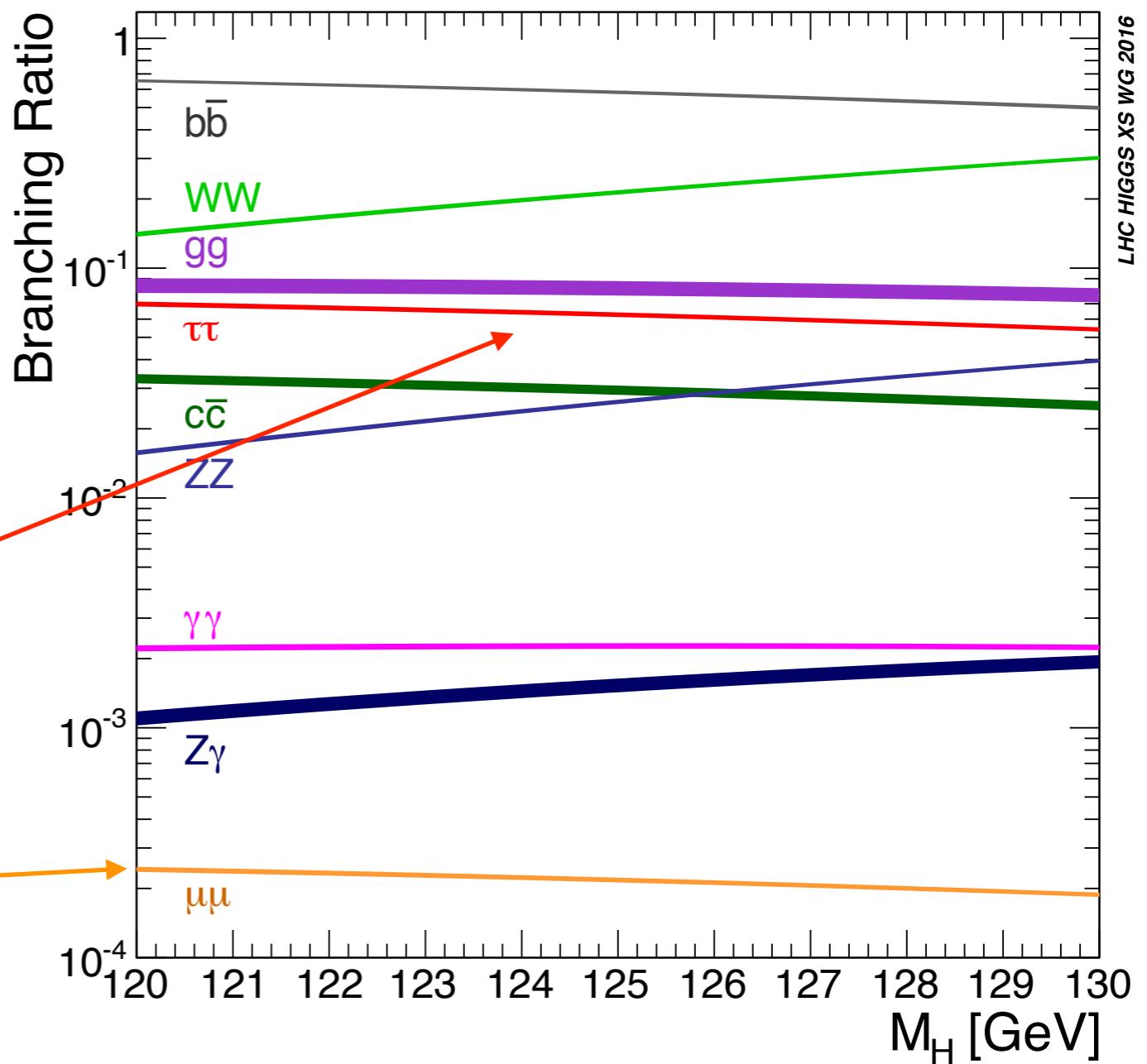


Higgs Boson Decays to Two Leptons with ATLAS

Quentin Buat (CERN) – On behalf of the ATLAS collaboration

Introduction

- Leptonic Yukawa sector
 - H-e coupling is a fundamental parameters
 - Not accessible at any (future) collider...
- But we can explore the heavier generations!
 - $H \rightarrow \tau\tau$
 - $H \rightarrow \mu\mu$

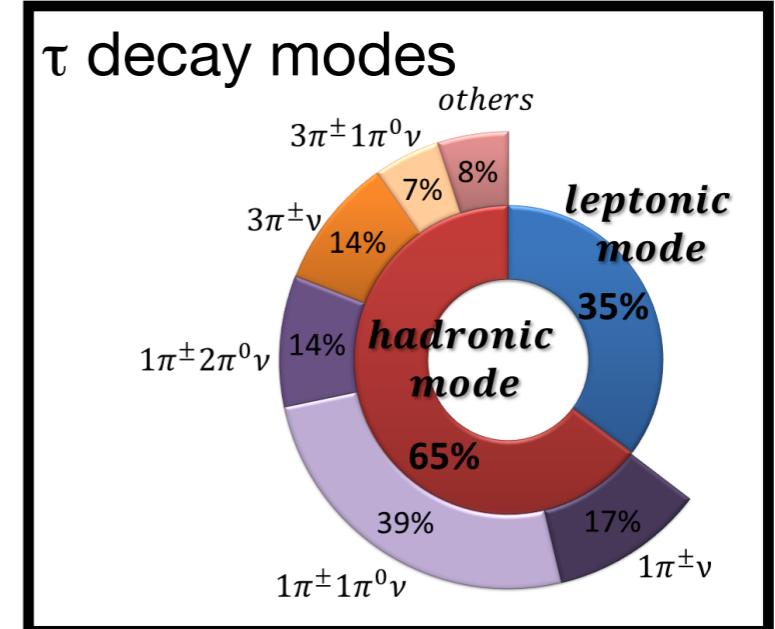


Outline

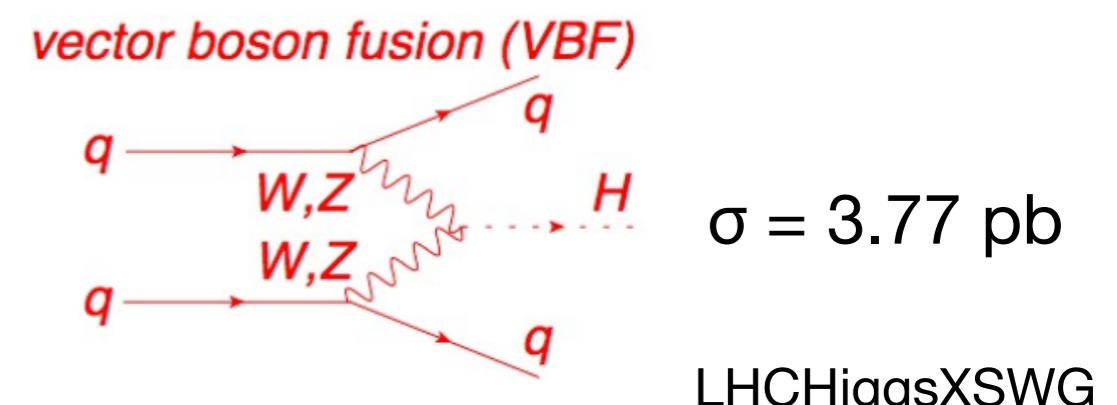
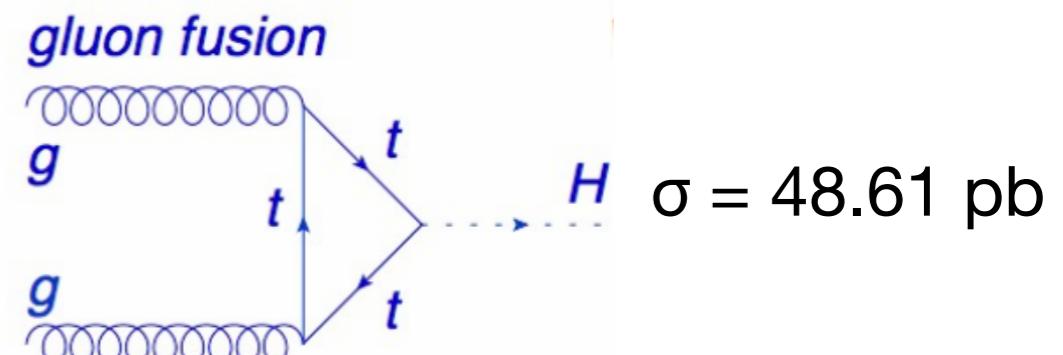
- $H \rightarrow \tau\tau$ measurements
- $H \rightarrow \mu\mu$ search
- Searching beyond the SM Higgs with 2 leptons

$H \rightarrow \tau\tau$ analysis strategy

- $L = 36 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$
- Exploit all the tau decay channels
 - 2 to 4 undetected neutrinos in the event
- Analysis designed to target VBF and boosted ggF
 - Boosted: $p_T(H) > 100 \text{ GeV}$
 - VBF: 2 high- p_T jets with large pseudo-rapidity gap

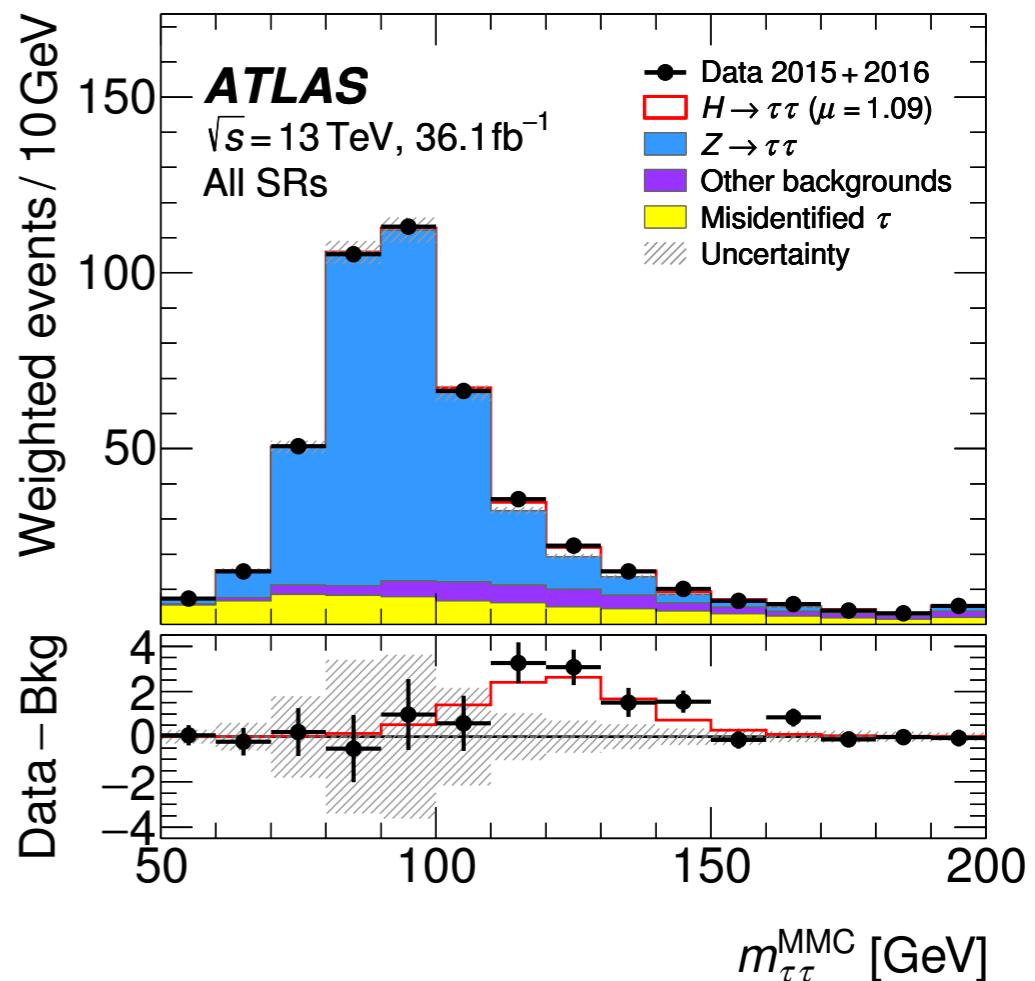
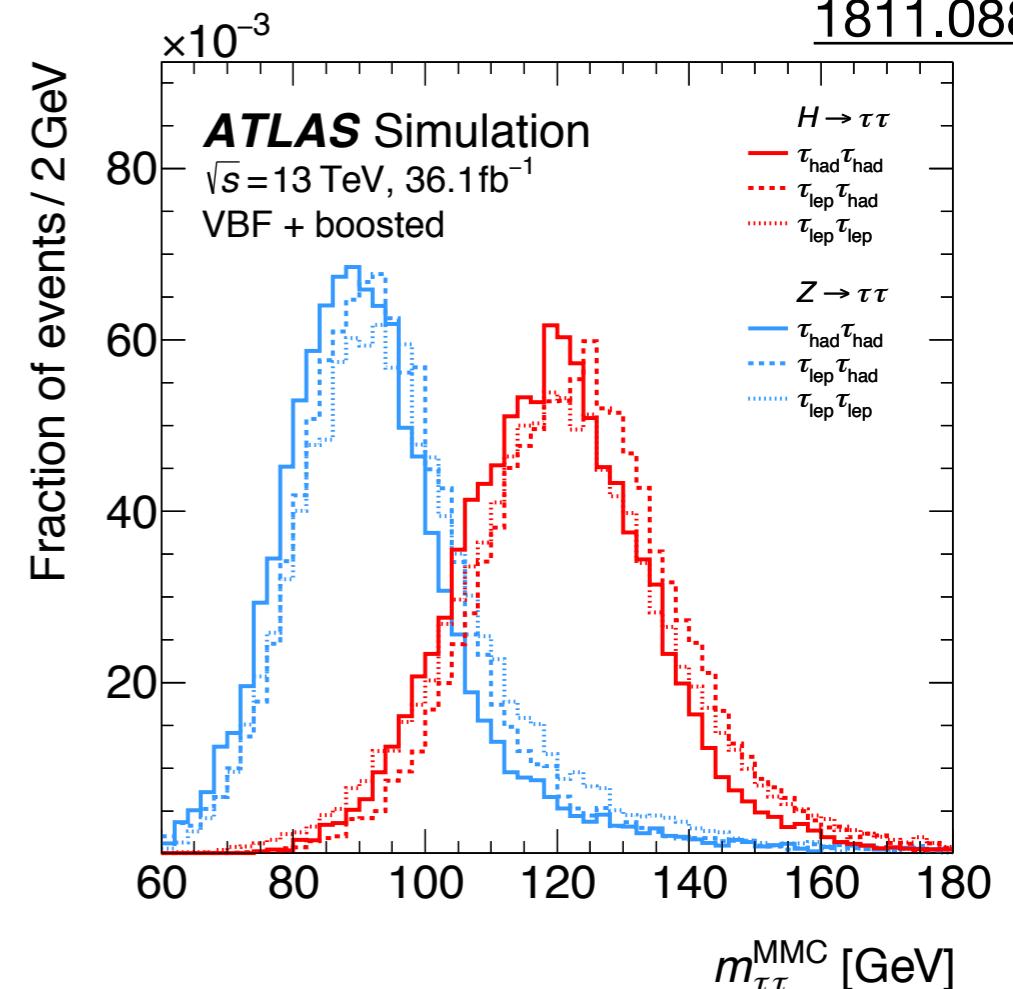


$H \rightarrow \tau\tau$	Visible Final State	BR (%)
Fully-leptonic	$e\bar{e}, \mu\bar{\mu}, e\mu$	13
Semi-leptonic	$e\tau_h, \mu\tau_h$	45
Fully-hadronic	$\tau_h\tau_h$	42



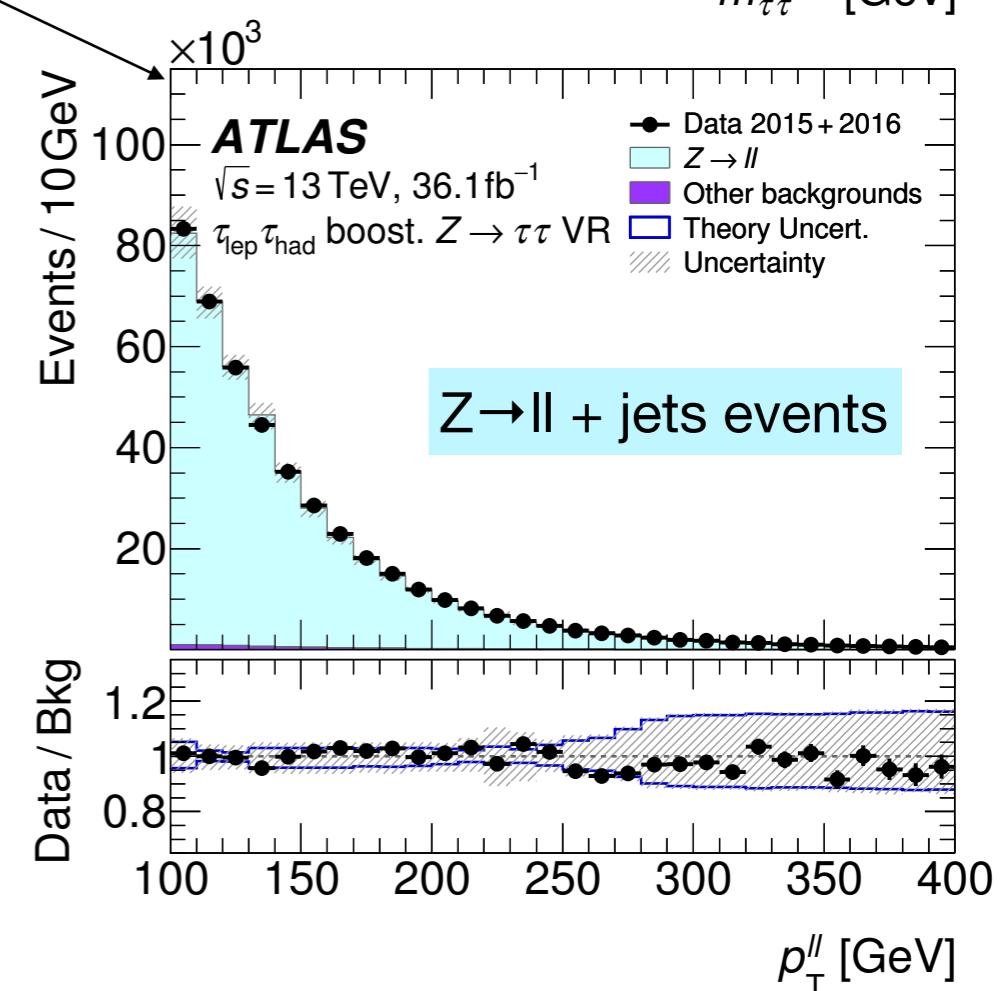
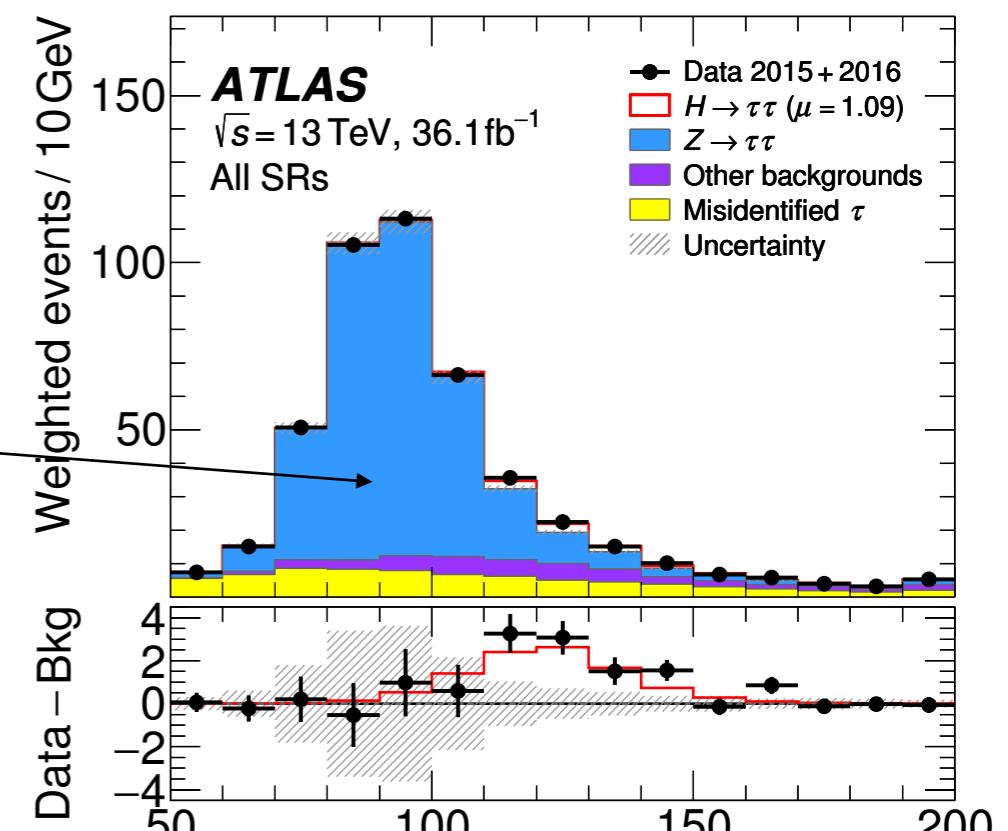
$H \rightarrow \tau\tau$ analysis strategy

- Missing Mass Calculator (MMC)
 - Estimate the direction of the invisible component
 - Use constraints on the tau lepton mass
 - Enhance the separation power over more classic calculations (collinear mass or visible mass)
 - Signal extracted with a binned likelihood fit on MMC in 13 signal regions and 6 control regions



Background estimate

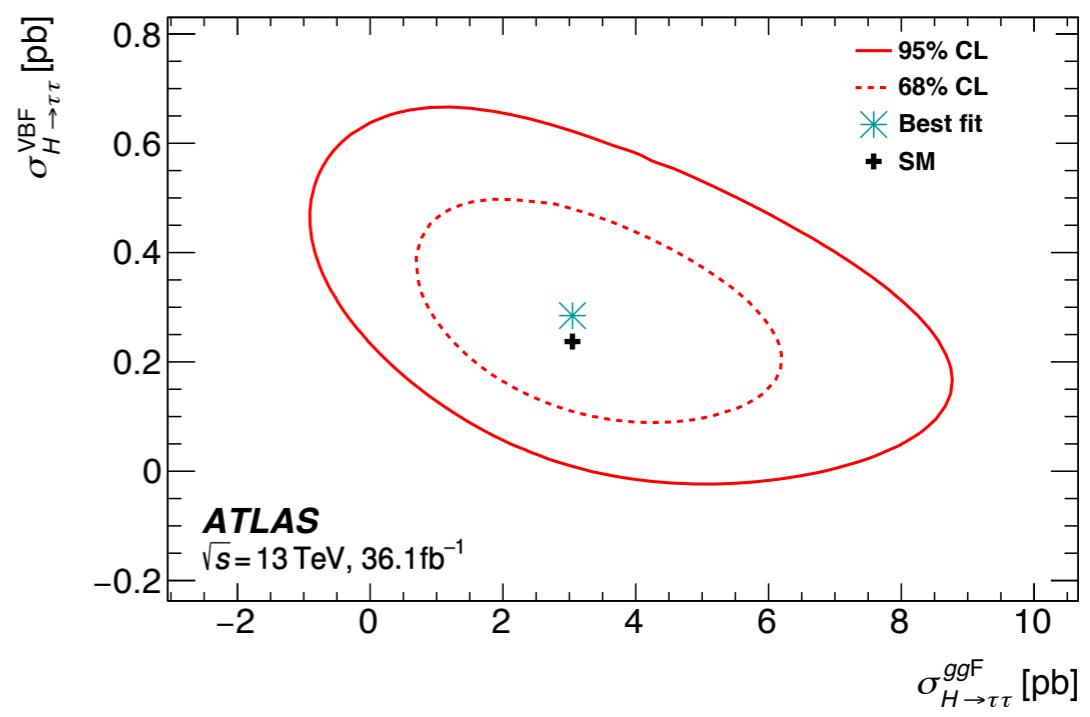
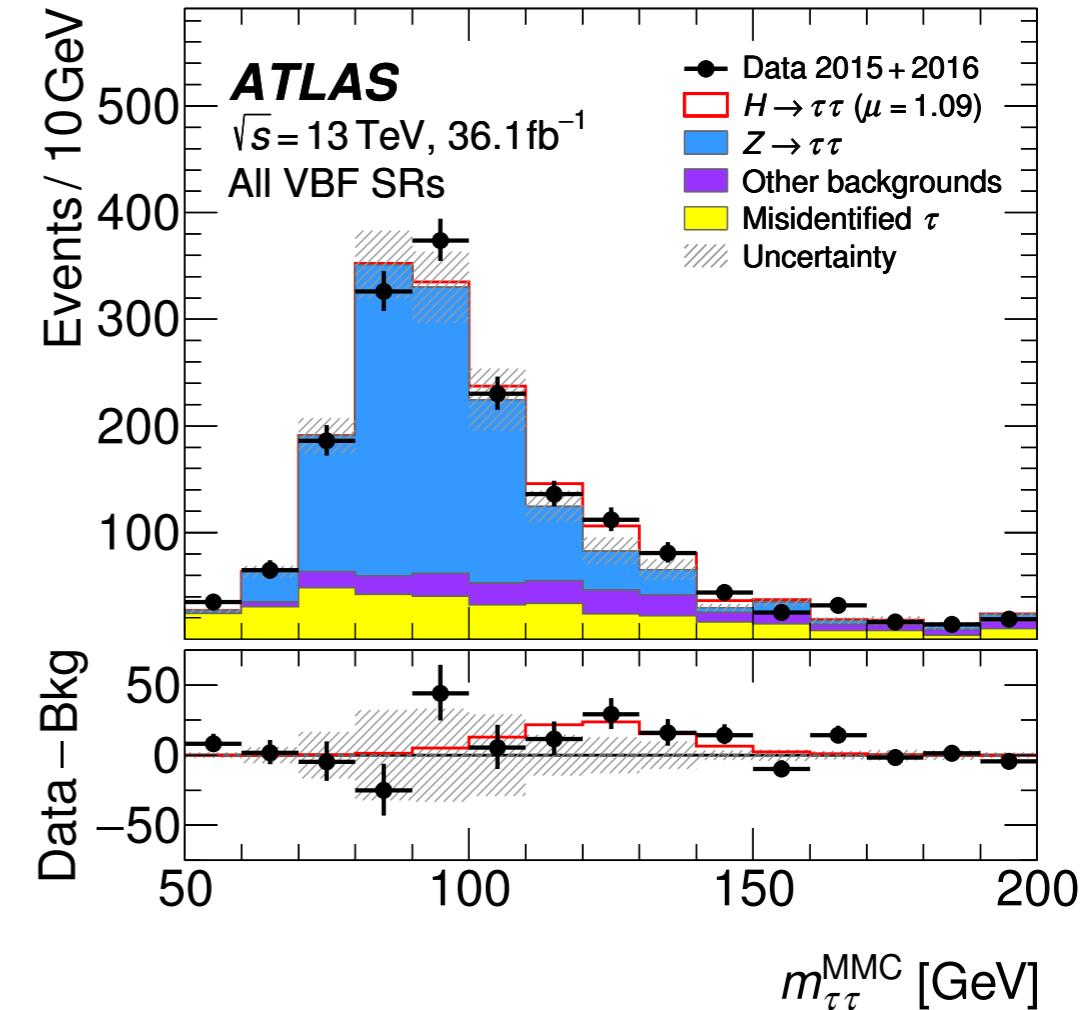
- $Z \rightarrow \tau\tau + \text{jets}$ is the dominant background
 - Modelled with NLO MC simulation (SHERPA)
 - Validated in $Z \rightarrow ll + \text{jets}$ events
 - Good modelling in the phase space of the analysis
- Misidentified tau = QCD Multijet and $W + \text{jets}$
 - Data-driven techniques
 - Other = Top, $Z \rightarrow ll + \text{jets}$, Diboson and $H \rightarrow WW$
 - Estimated using MC simulation
 - Top and $Z \rightarrow ll + \text{jets}$ validated in dedicated control-regions



Results

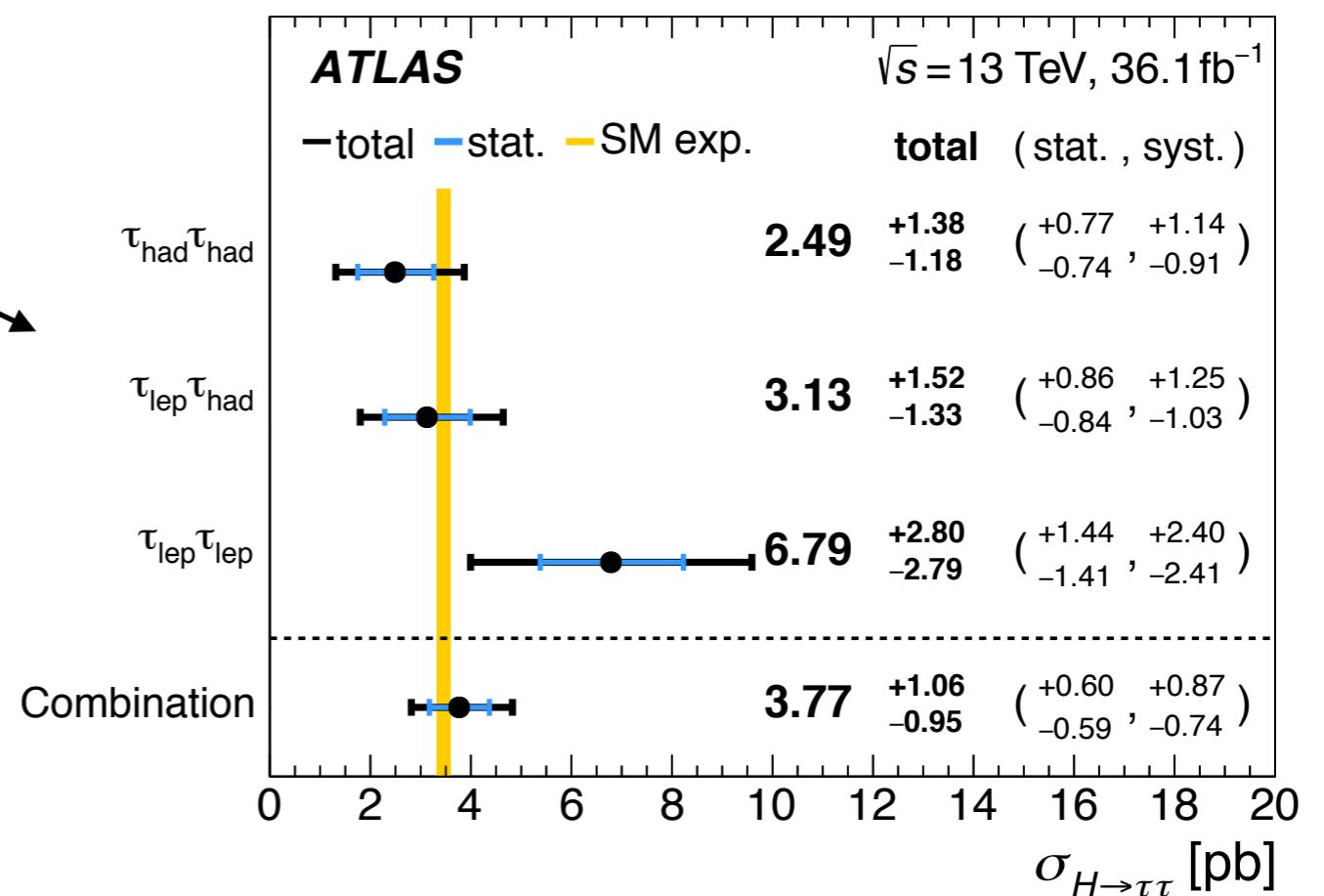
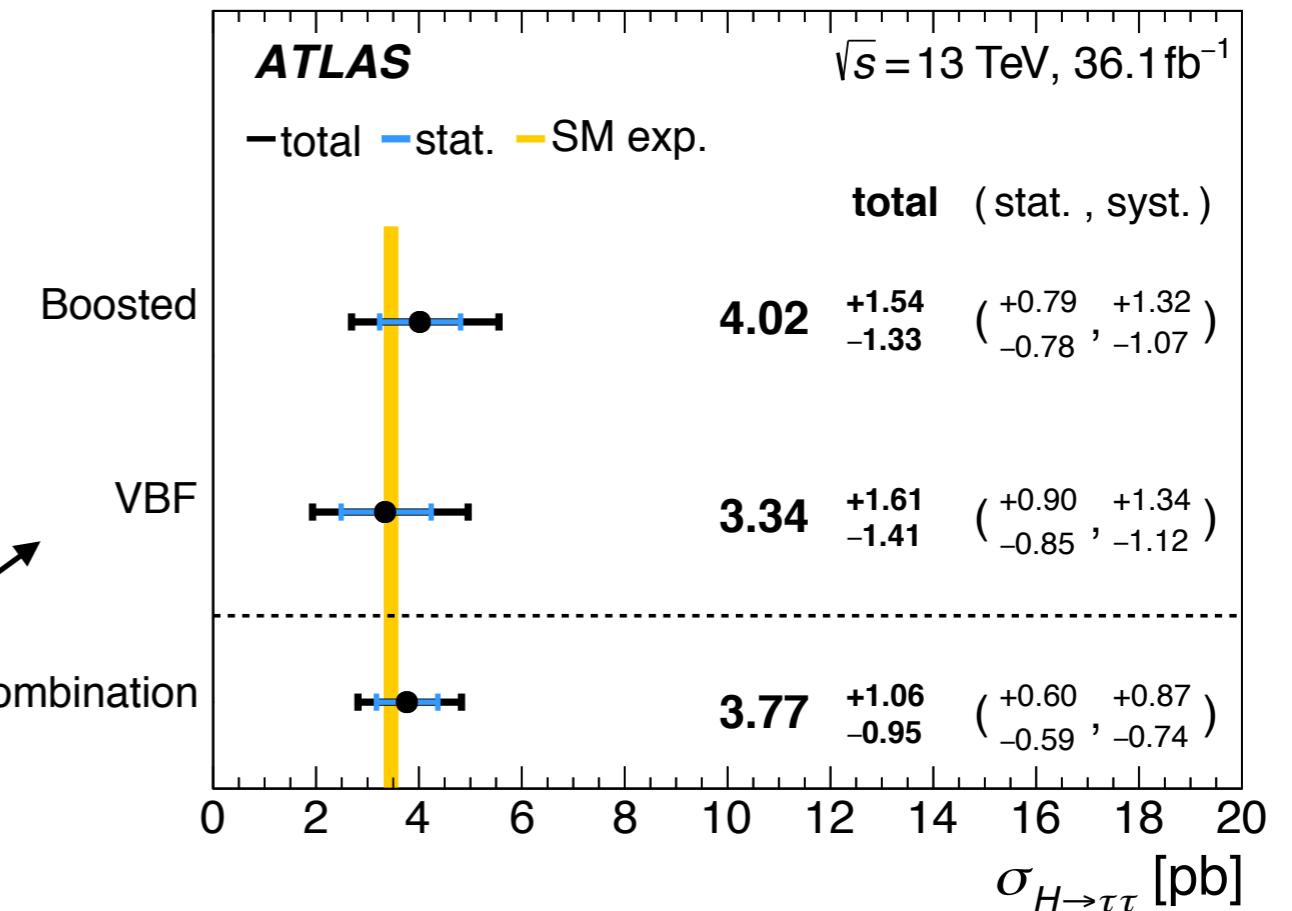
- $4.4 (4.1)\sigma$ observed (expected) significance
- $6.4 (5.4)\sigma$ when combining with Run1 result
- Fit inclusive cross-section and simultaneous fit of $\sigma(\text{VBF})$ and $\sigma(\text{gg} \rightarrow \text{H})$:
 - Very good agreement with SM expectation

	$\sigma/\sigma_{\text{SM}}$	Uncert
Inclusive	1.09	± 0.35
VBF	1.18	± 0.51
ggH	1.02	± 0.62

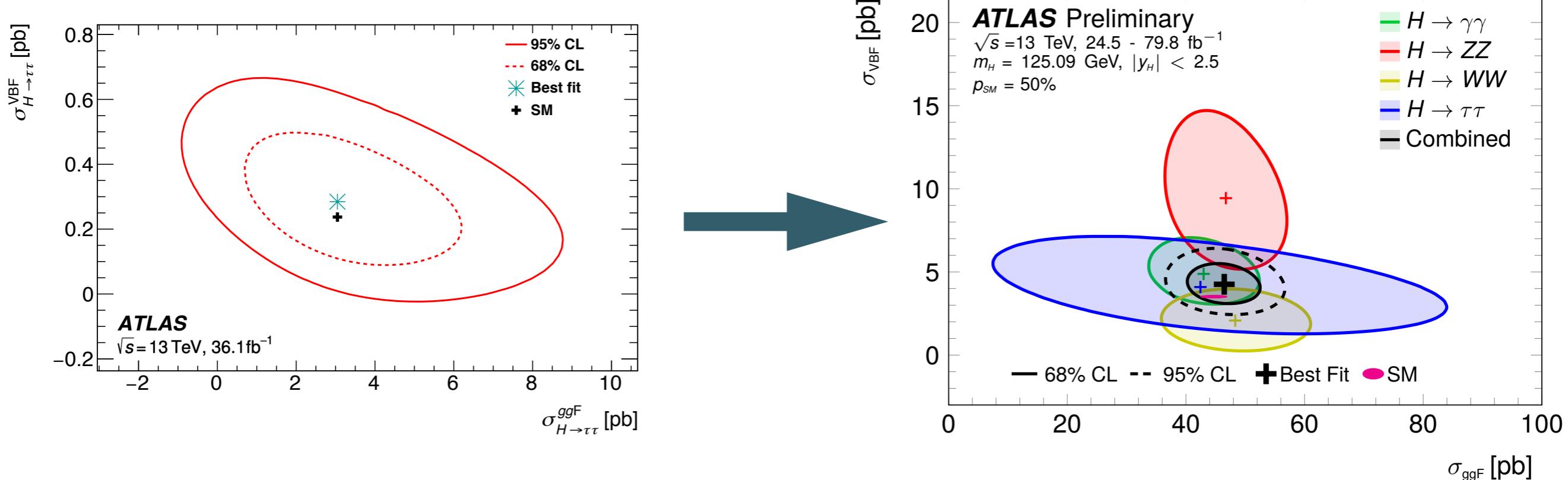


Results

- Perform measurement
 - Per category
 - Per final states
- Very good compatibility between channels / categories and with the SM expectations



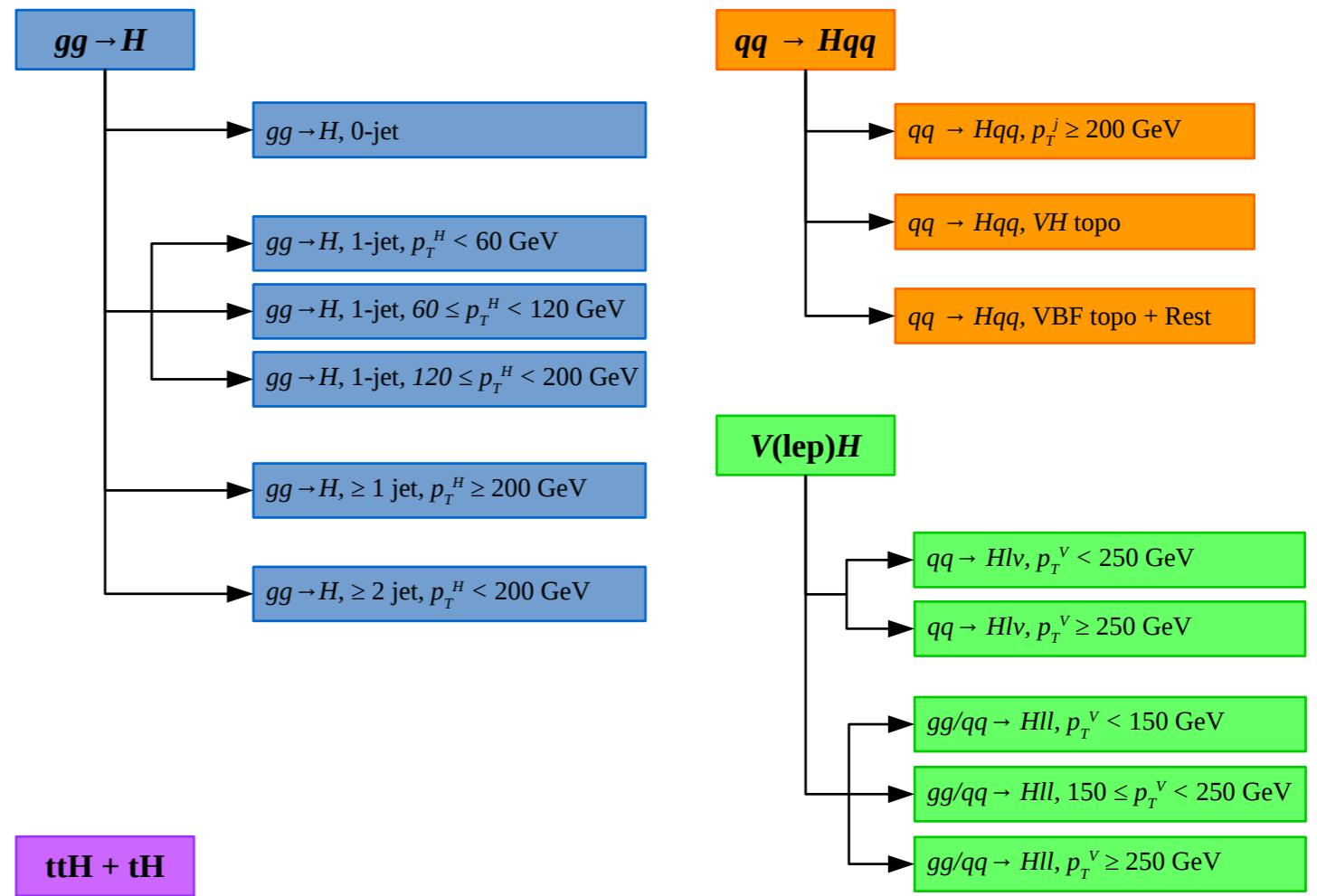
Combining channels



- Significant contribution to the VBF production cross-section
- Weak contribution to the ggH production cross-section in comparison to the bosonic decay channels

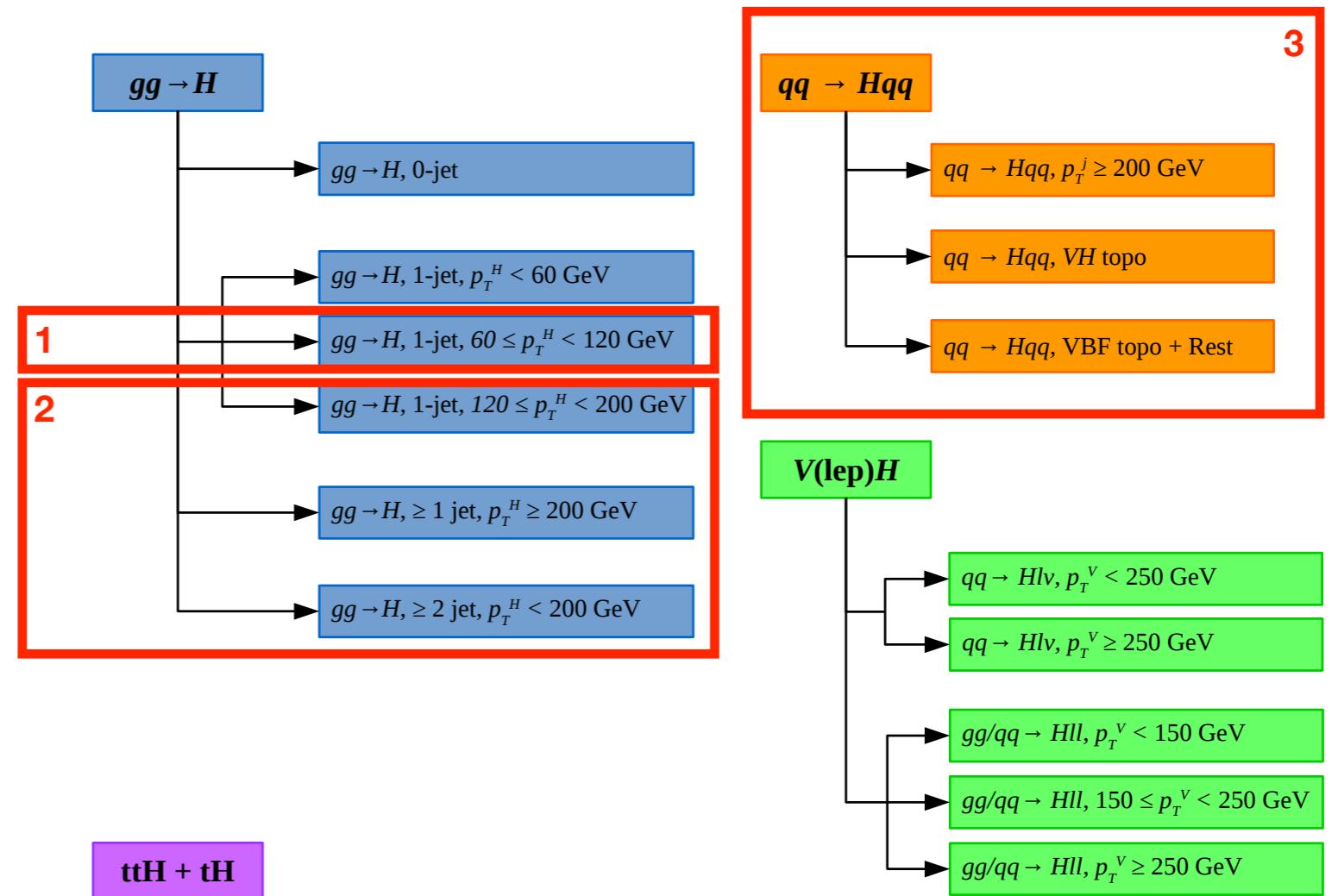
Simplified Template Cross-Section (STXS) results

- Framework to measure cross-sections
 - Per production modes
 - In different phase-spaces ($p_T(H)$, $p_T(V)$, extra jet in VBF)
- Reduces model-dependency
- Enhances sensitivity to BSM effects
- Works best if experimental categorisation matches theory split



Simplified Template Cross-Section (STXS) results

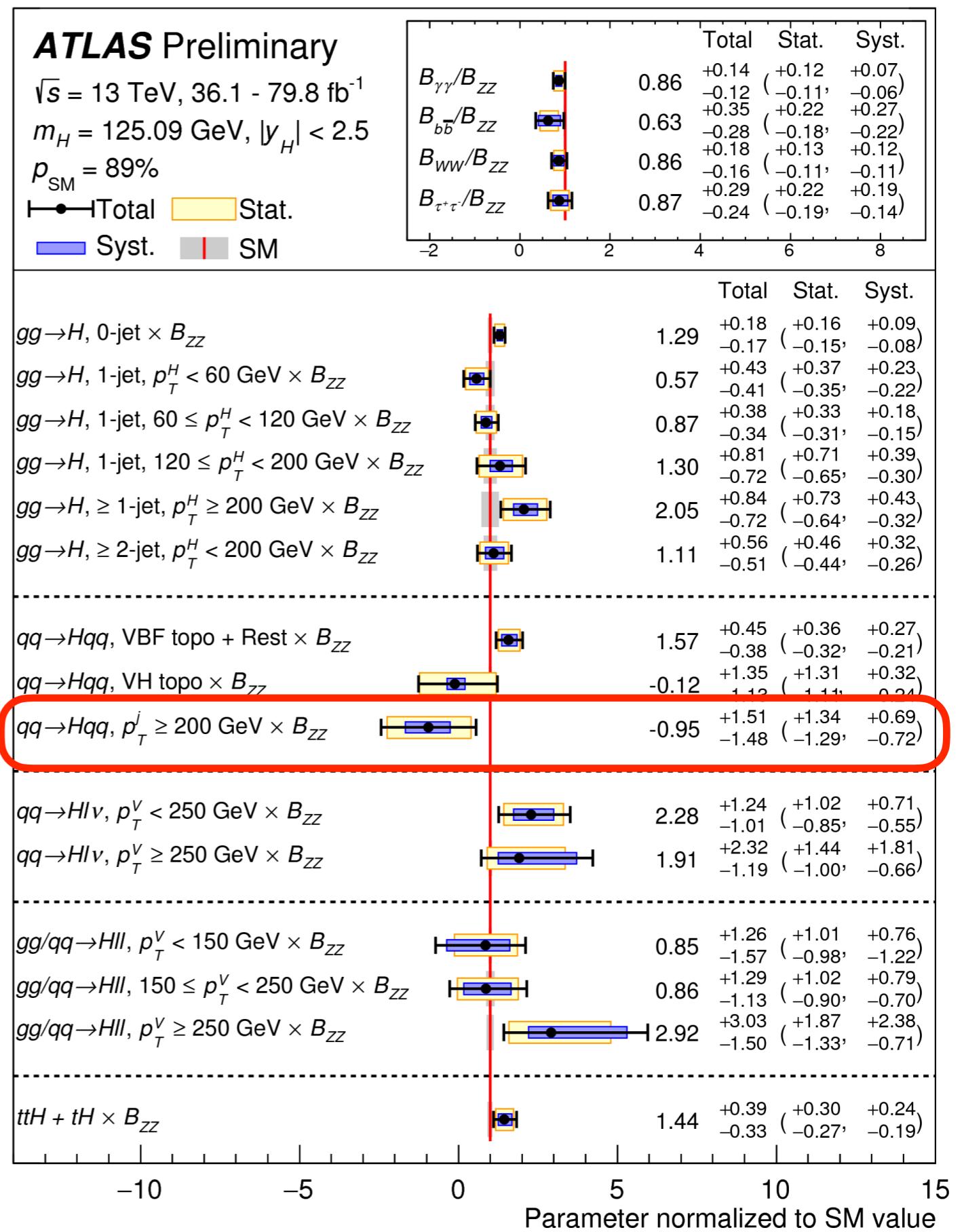
- First attempt in $H \rightarrow \tau\tau$ channel



Process	Particle-level selection	σ [pb]	σ^{SM} [pb]
1 ggF	$N_{\text{jets}} \geq 1, 60 < p_T^H < 120 \text{ GeV}, y_H < 2.5$	$1.79 \pm 0.53 \text{ (stat.)} \pm 0.74 \text{ (syst.)}$	0.40 ± 0.05
2 ggF	$N_{\text{jets}} \geq 1, p_T^H > 120 \text{ GeV}, y_H < 2.5$	$0.12 \pm 0.05 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$	0.14 ± 0.03
3 VBF	$ y_H < 2.5$	$0.25 \pm 0.08 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$	0.22 ± 0.01

STXS combination

- ATLAS full combination of all SM Higgs analyses channels
 - Very good agreement with SM expectations in all bins
 - See Soshi Tsuno's talk later in this session for a full review
- $H \rightarrow \tau\tau$ main contribution:
 - $qq \rightarrow Hqq, p_T(\text{jet}) > 200 \text{ GeV}$



Current limitations on the $H \rightarrow \tau\tau$ couplings measurement

★ Theoretical uncert. in signal

- ggH+2jets in the VBF signal regions

◆ Limited background statistics

- Z+jets events with ≥ 2 high- p_T jets

❖ Jets and Missing- E_T

- VBF phase-space definition
- Mass estimator line-shape

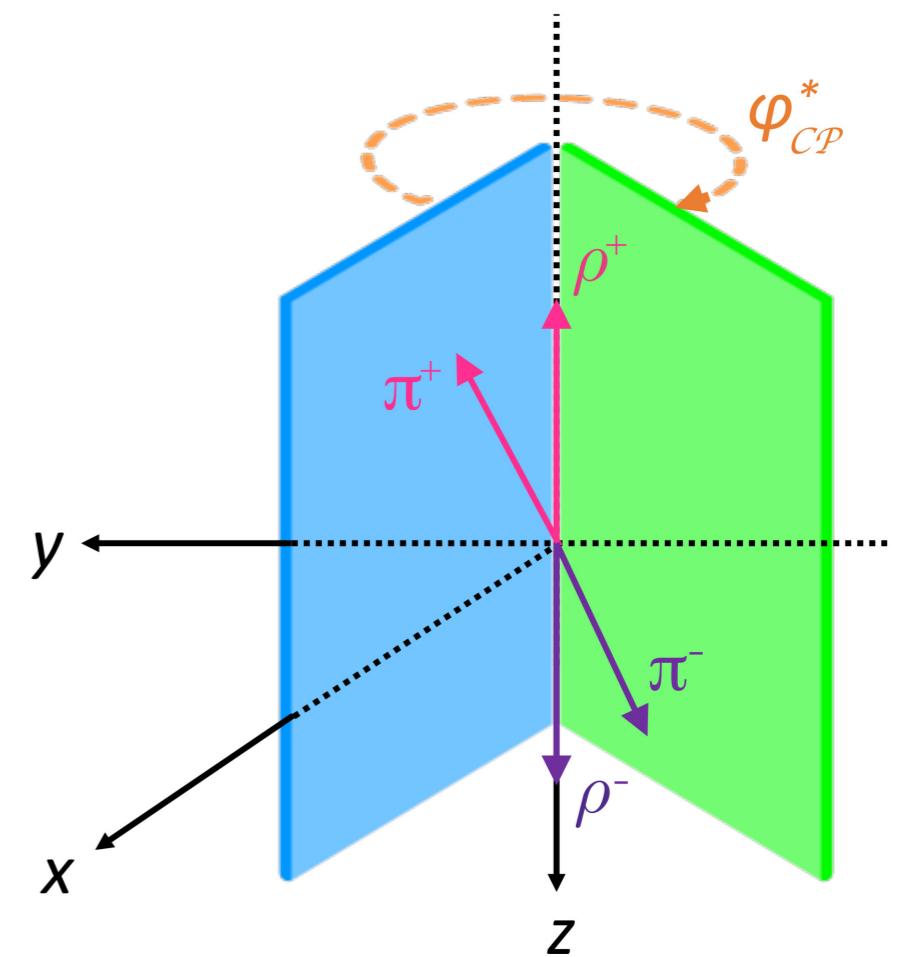
Source of uncertainty	Impact $\Delta\sigma/\sigma_{H \rightarrow \tau\tau}$ [%]	
	Observed	Expected
★ Theoretical uncert. in signal	+13.4 / -8.7	+12.0 / -7.8
◆ Background statistics	+10.8 / -9.9	+10.1 / -9.7
❖ Jets and E_T^{miss}	+11.2 / -9.1	+10.4 / -8.4
Background normalization	+6.3 / -4.4	+6.3 / -4.4
Misidentified τ	+4.5 / -4.2	+3.4 / -3.2
Theoretical uncert. in background	+4.6 / -3.6	+5.0 / -4.0
Hadronic τ decays	+4.4 / -2.9	+5.5 / -4.0
Flavor tagging	+3.4 / -3.4	+3.0 / -2.3
Luminosity	+3.3 / -2.4	+3.1 / -2.2
Electrons and muons	+1.2 / -0.9	+1.1 / -0.8
Total systematic uncert.	+23 / -20	+22 / -19
Data statistics	± 16	± 15
Total	+28 / -25	+27 / -24

→ Exploit the full dataset to mitigate these limitations!

Hff CP properties in the $\tau\tau$ channel

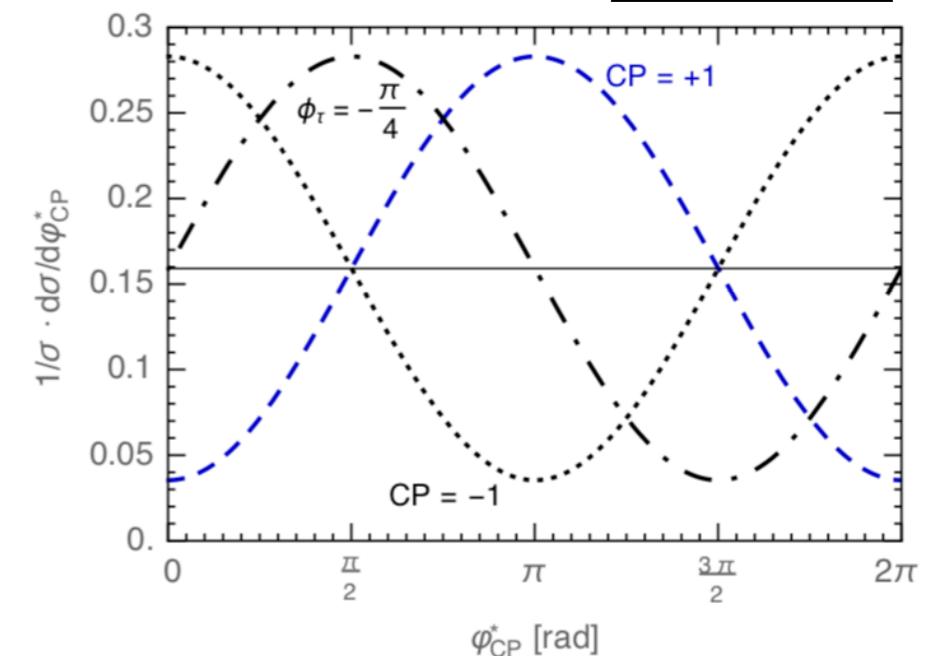
- Prospective study for **HL-LHC**
- Strategy: access the CP mixing angle by measuring the **angle** between the decay planes
- ‘Golden’ channel
 - $H \rightarrow \tau^+ \tau^- \rightarrow \rho^+ \rho^- 2\nu_\tau$
 $\rightarrow \pi^+ \pi^0 \pi^- \pi^0 2\nu_\tau$
 - Reconstruct the decay plane of the visible tau and the charged pion

$$\tau^+ \rightarrow \rho^+ \nu_\tau \rightarrow \pi^+ \pi^0 \nu_\tau$$



$$\tau^- \rightarrow \rho^- \nu_\tau \rightarrow \pi^- \pi^0 \nu_\tau$$

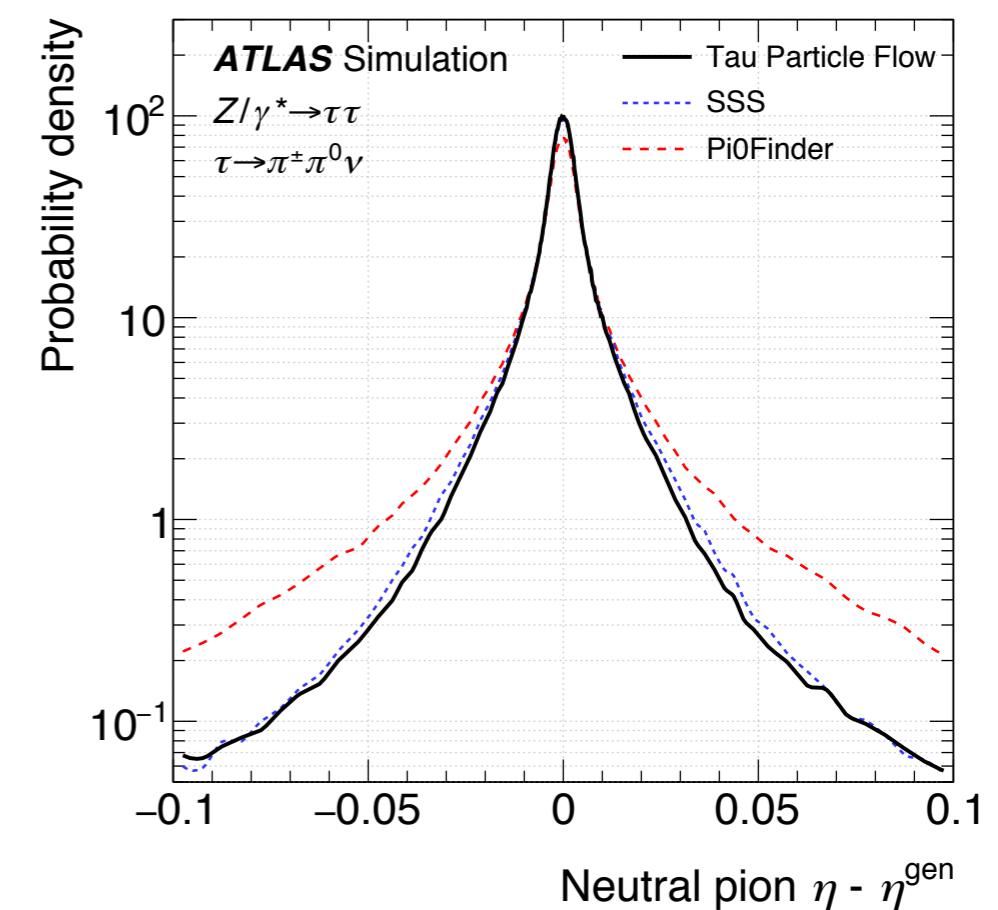
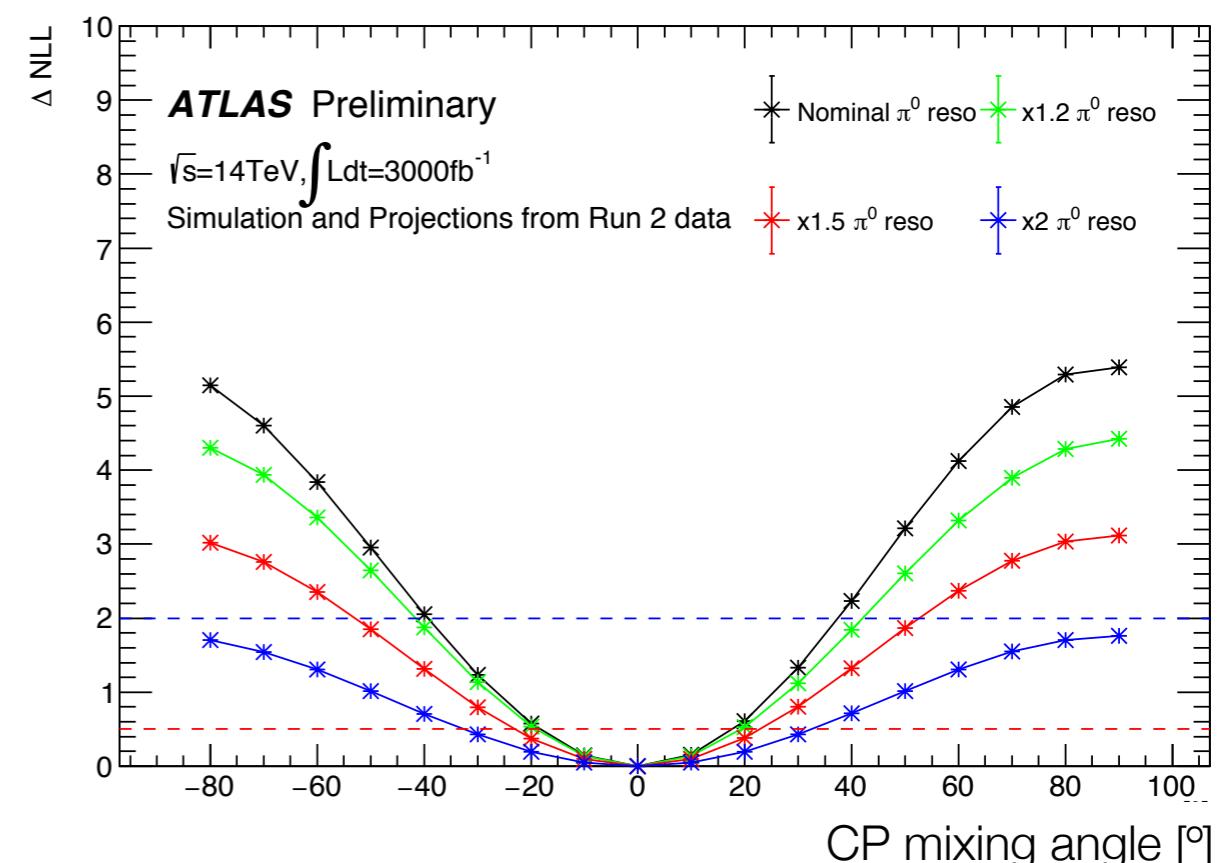
[1510.03850](#)



Hff CP properties in the $\tau\tau$ channel

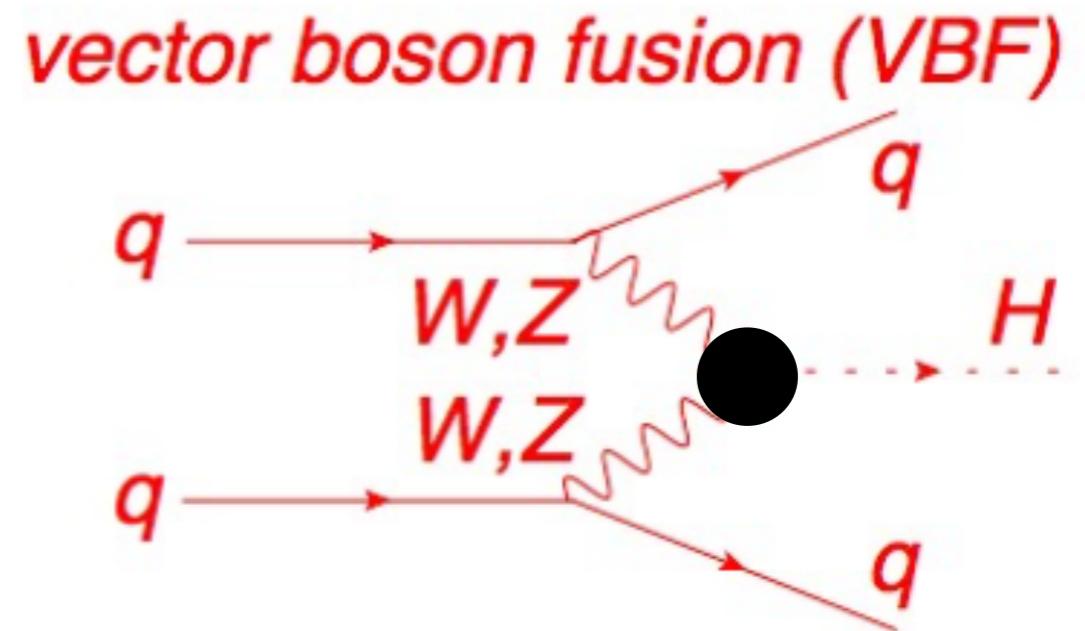
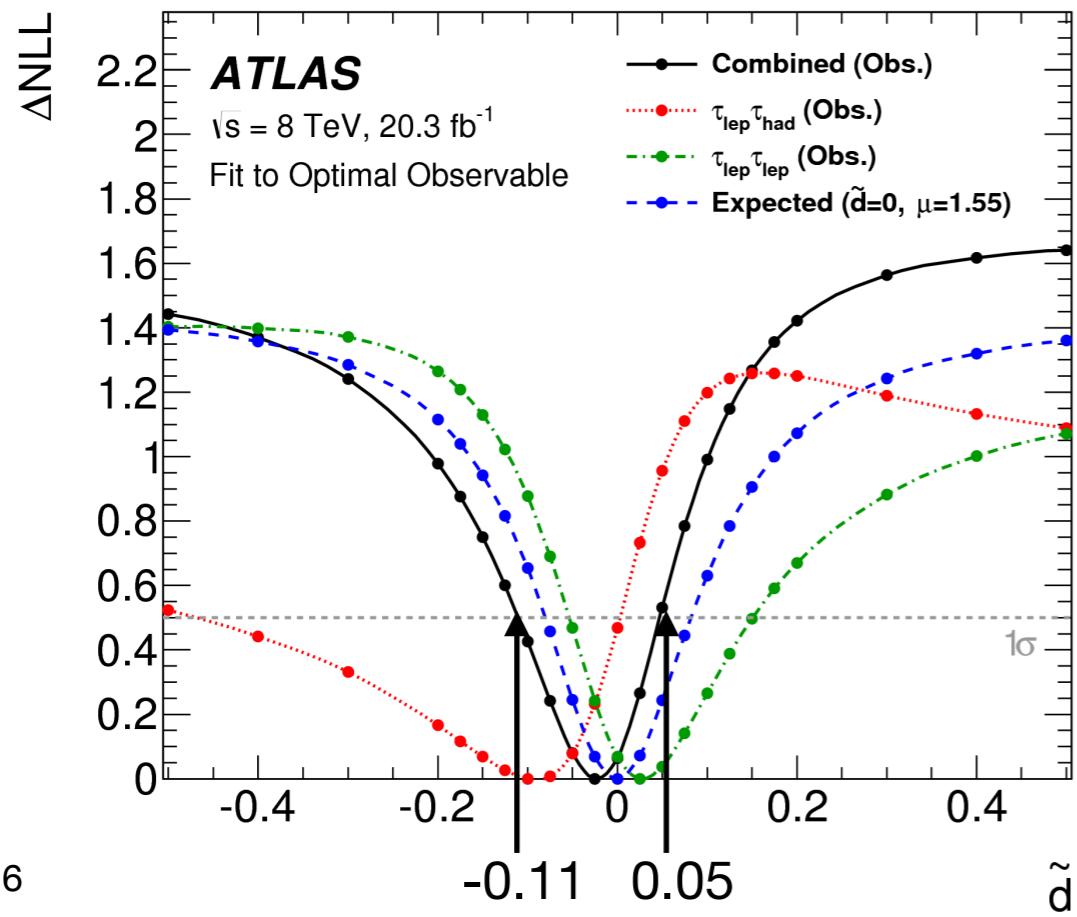
→ Projection: $\pm 20^\circ$ precision on the CP mixing-angle measurement

- Consider only statistical uncertainties
- Precision on π^0 resolution can have a large impact

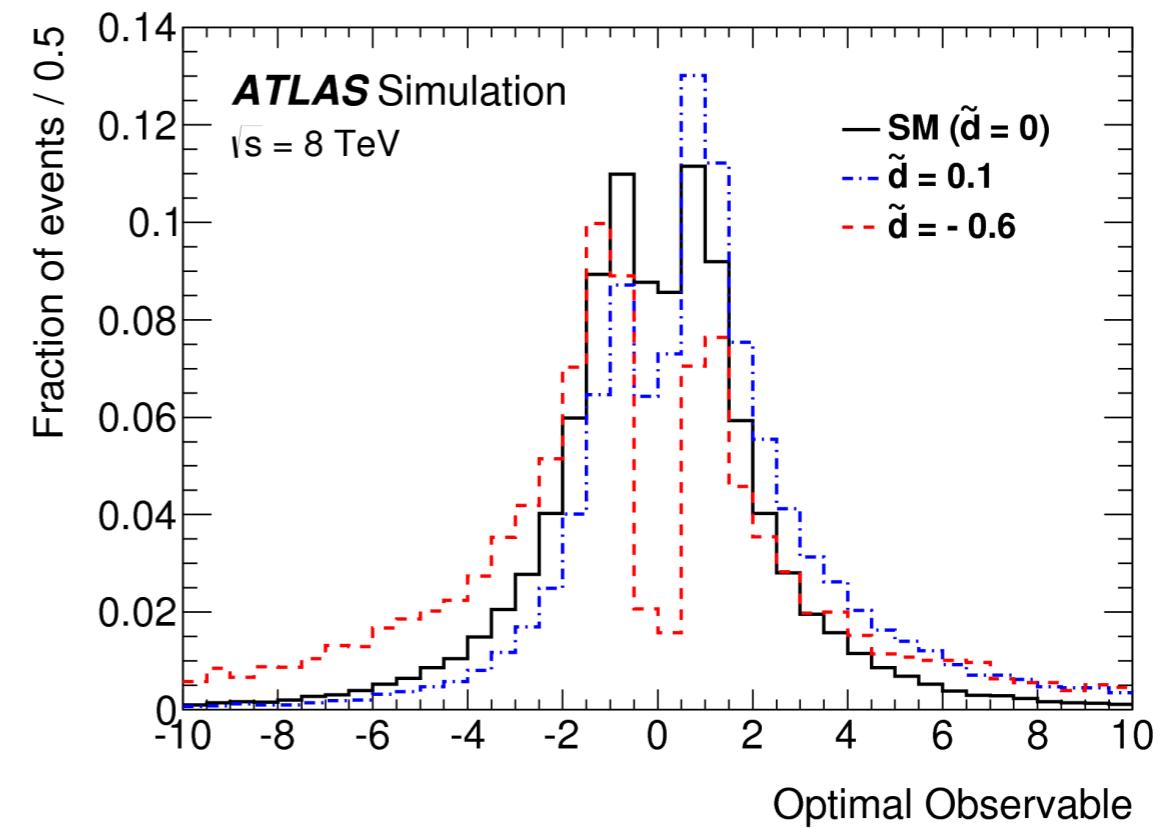


$H \rightarrow \tau\tau$: VBF CP

- Select events with high VBF purity
- Use optimal observable to differentiate CP hypothesis
- Describe all CP-violating effects through a single parameter: \tilde{d}
- $\tilde{d} \sim [-0.11, 0.05]$ at 68% CL



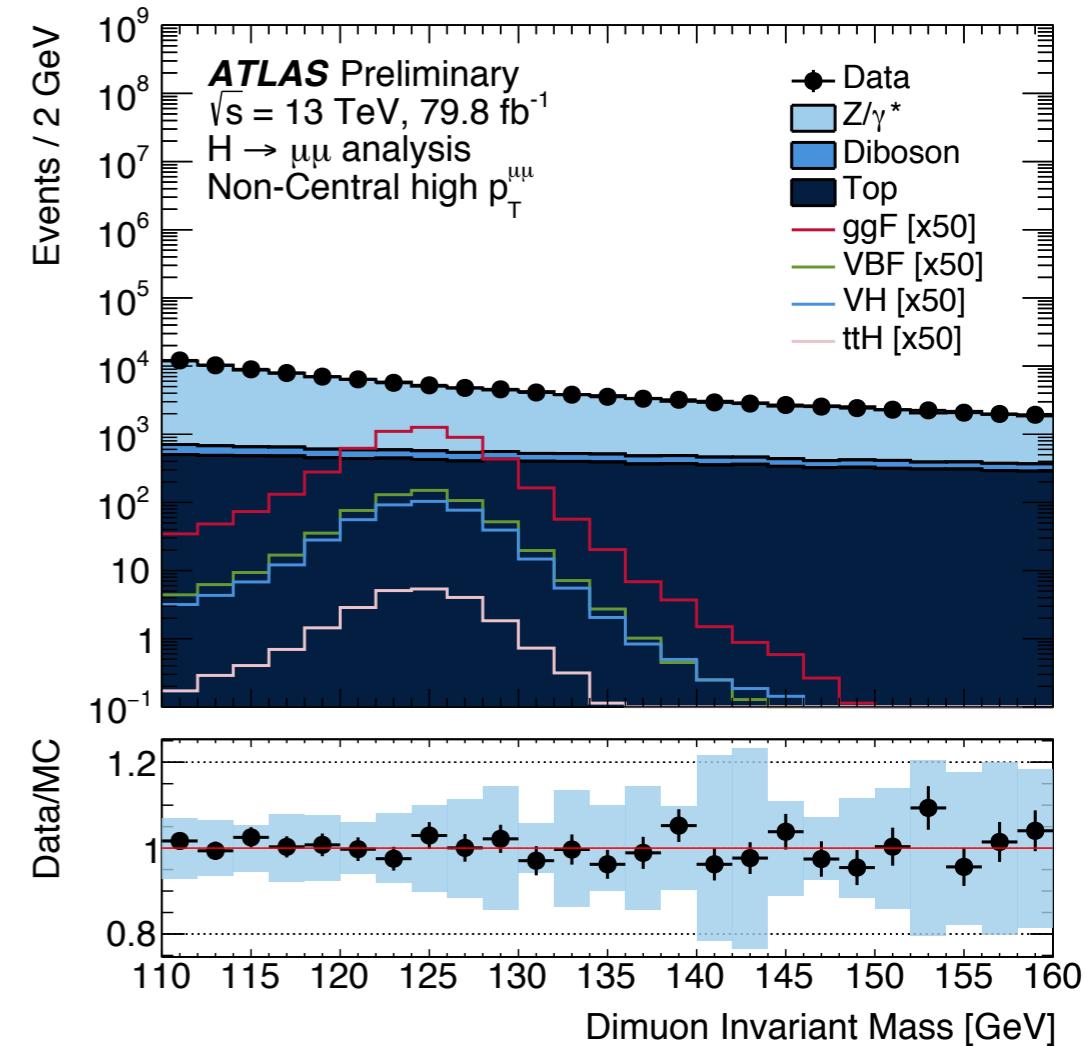
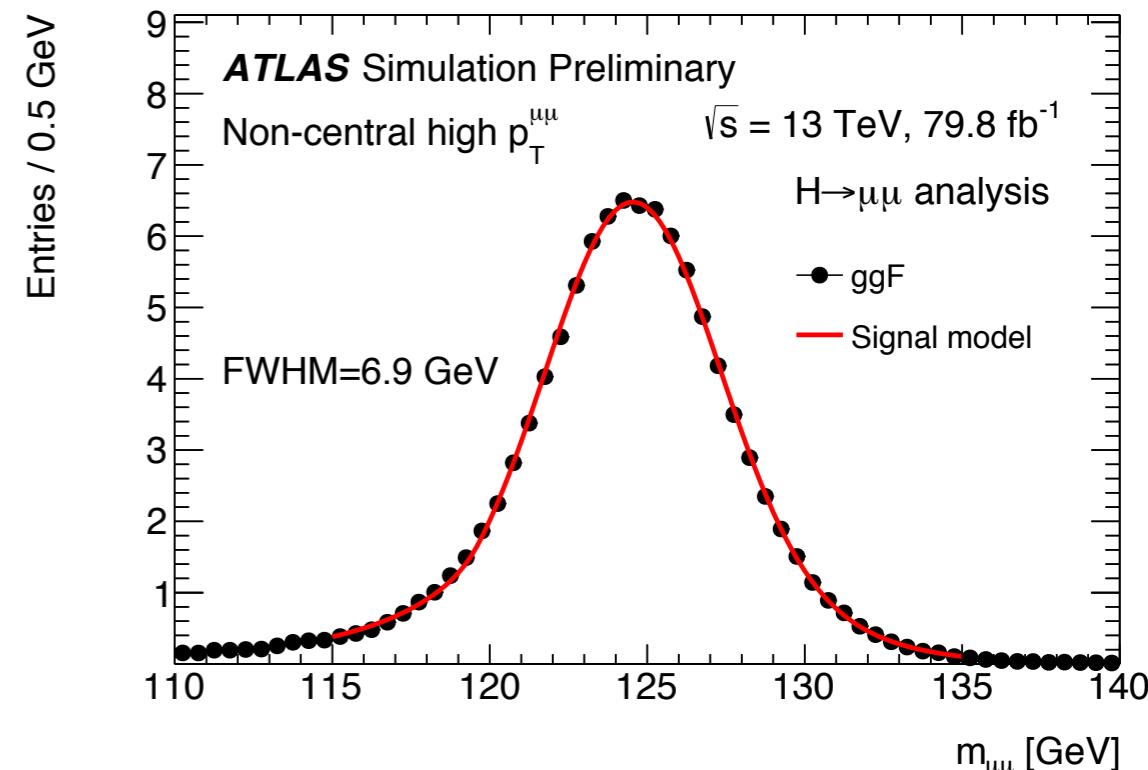
$$\text{Optimal Observable} = \frac{2 \operatorname{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$



-
- $H \rightarrow \tau\tau$ measurements
 - $H \rightarrow \mu\mu$ search
 - Searching beyond the SM Higgs with 2 leptons

$H \rightarrow \mu\mu$: strategy

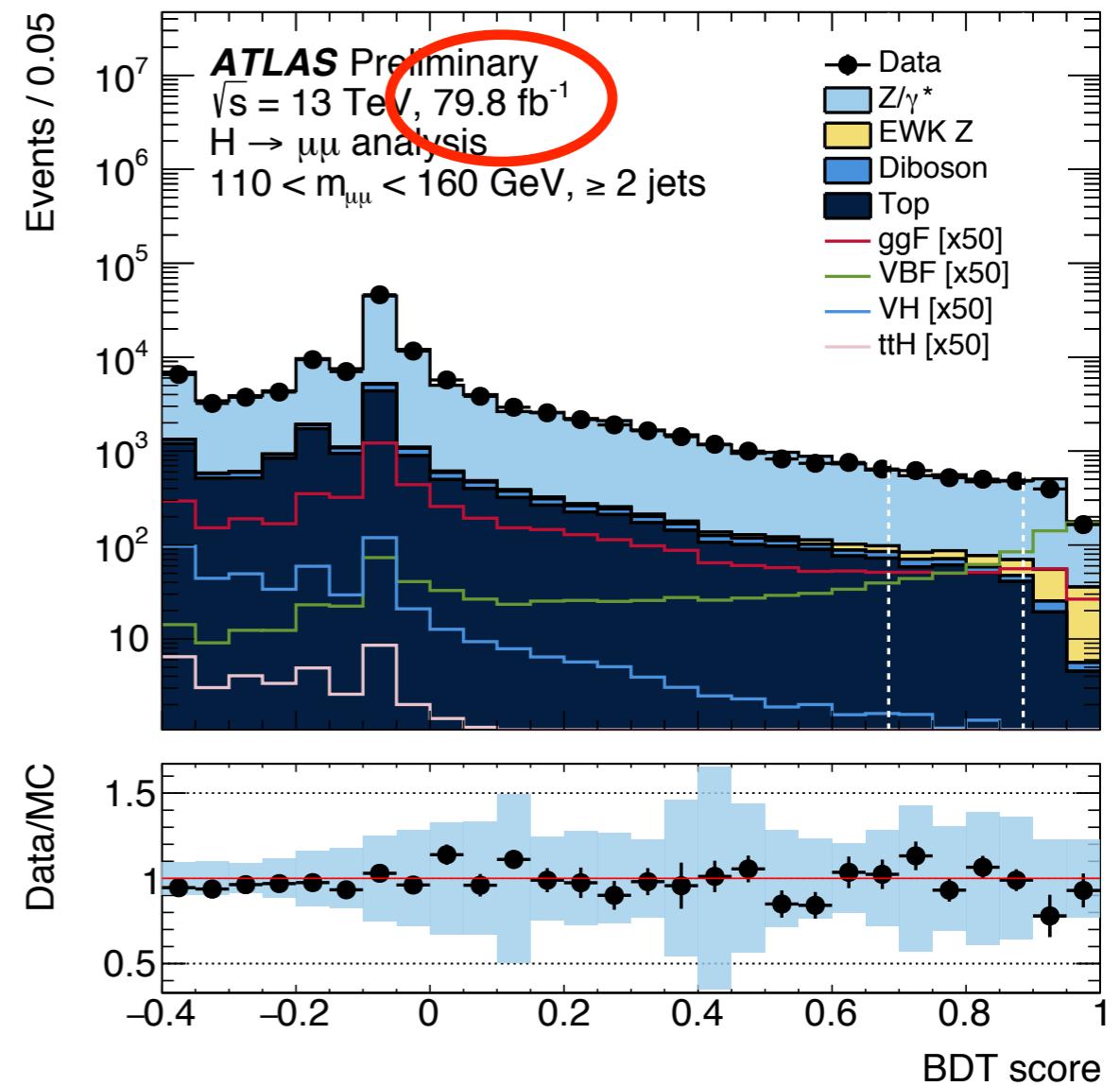
- $\text{BR}(H \rightarrow \mu\mu) = 0.2 \times 10^3$
- Two isolated muons satisfying $110 < m_{\mu\mu} [\text{GeV}] < 160$
- Background parameterised with a functional form
- Signal extraction using a binned likelihood fit
- Excellent mass resolution!
- but... tiny signal buried under overwhelming Drell-Yan production



$H \rightarrow \mu\mu$: results

- Event categorisation
 - Multivariate classifier targeting VBF production mode
 - Achieved a $S/\sqrt{B} = 0.88$
- Observed limit: $2.1 \times \text{SM expectation}$
- Signal strength: 0.1 ± 1.0
- Uncertainties dominated by data statistics
- ATLAS + CMS combination of $H \rightarrow \mu\mu$ may reach the standard model sensitivity by the end of Run2!

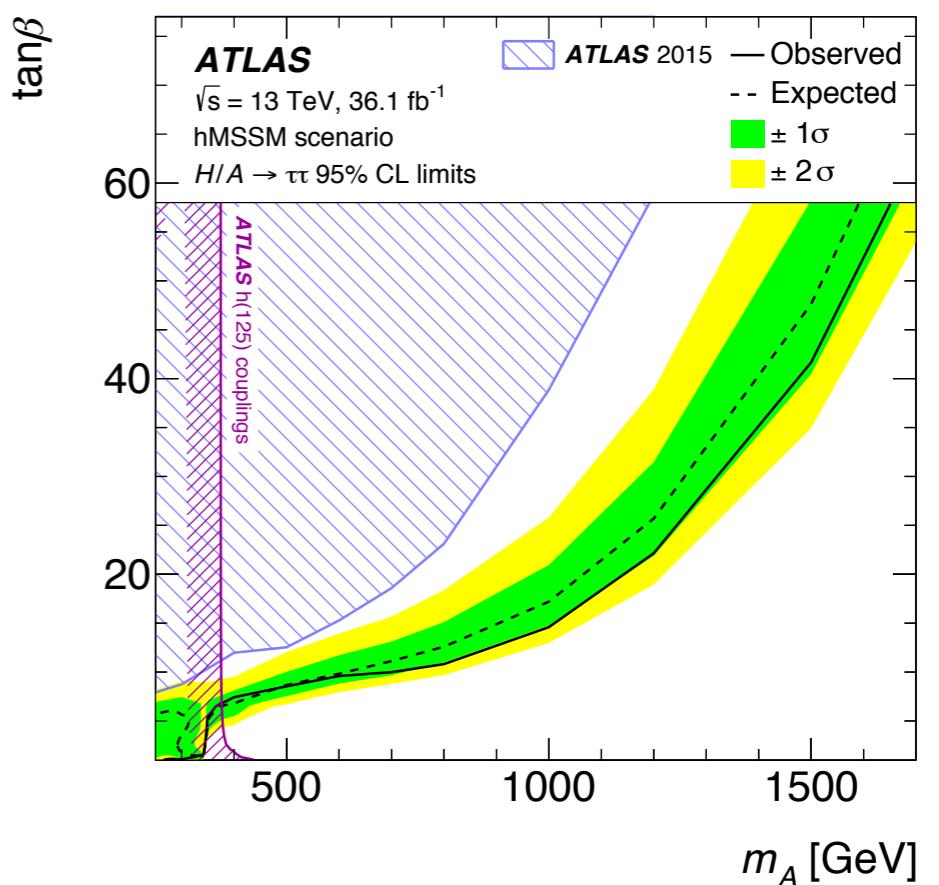
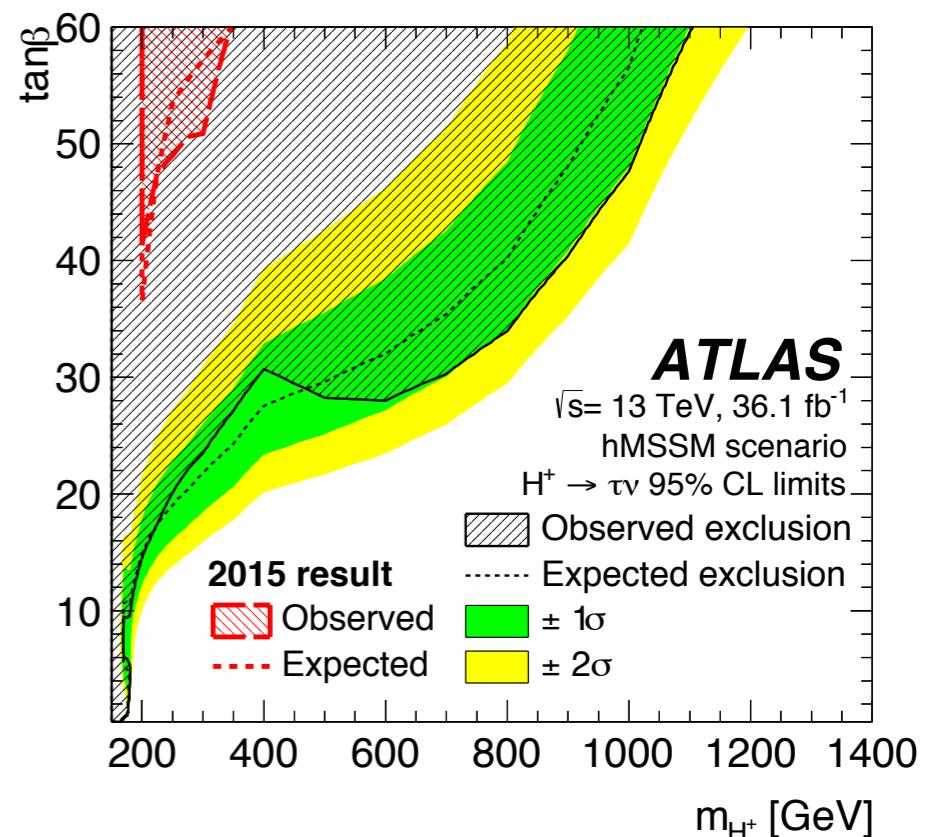
	Expected significance	Observed significance
Central low $p_T^{\mu\mu}$	0.10	-0.49
Non-central low $p_T^{\mu\mu}$	0.03	0.44
Central medium $p_T^{\mu\mu}$	0.31	1.55
Non-central medium $p_T^{\mu\mu}$	0.30	-1.16
Central high $p_T^{\mu\mu}$	0.38	0.48
Non-central high $p_T^{\mu\mu}$	0.43	0.15
VBF Loose	0.24	-0.88
VBF Tight	0.42	-0.26
Combined	0.88	0.04



-
- $H \rightarrow \tau\tau$ measurements
 - $H \rightarrow \mu\mu$ search
 - **Searching beyond the SM Higgs with 2 leptons**

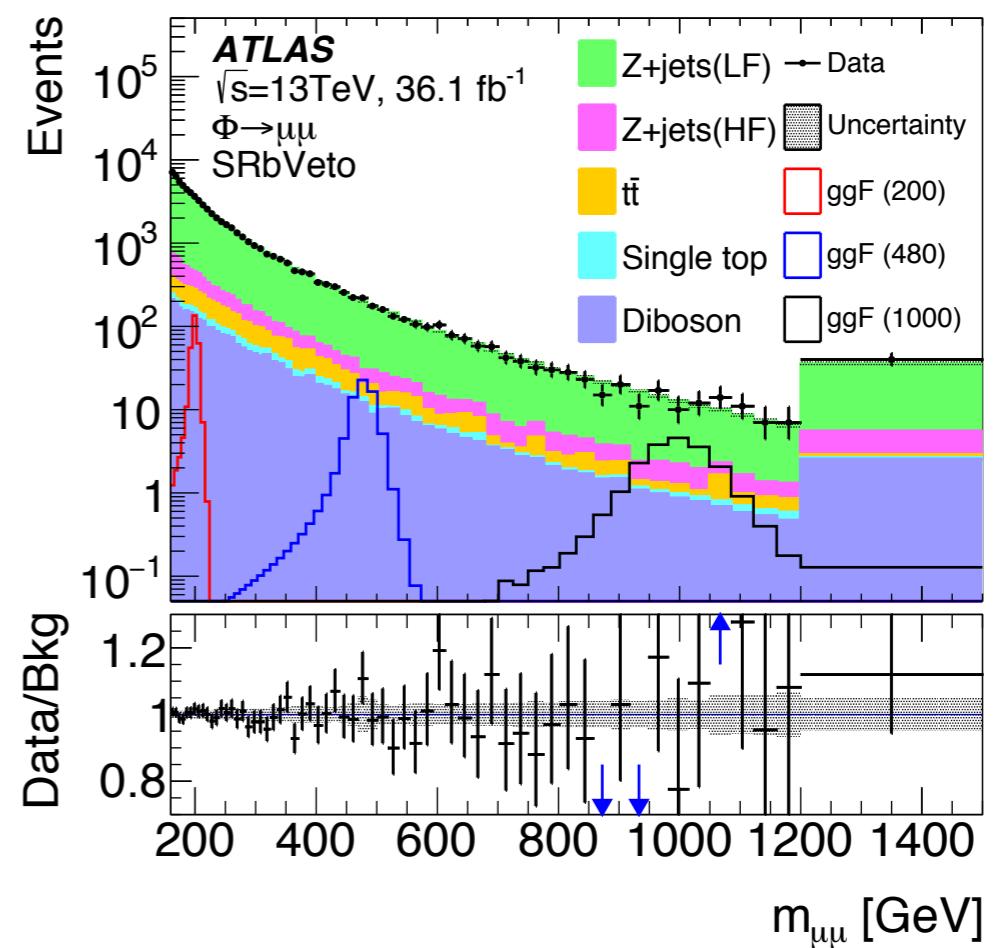
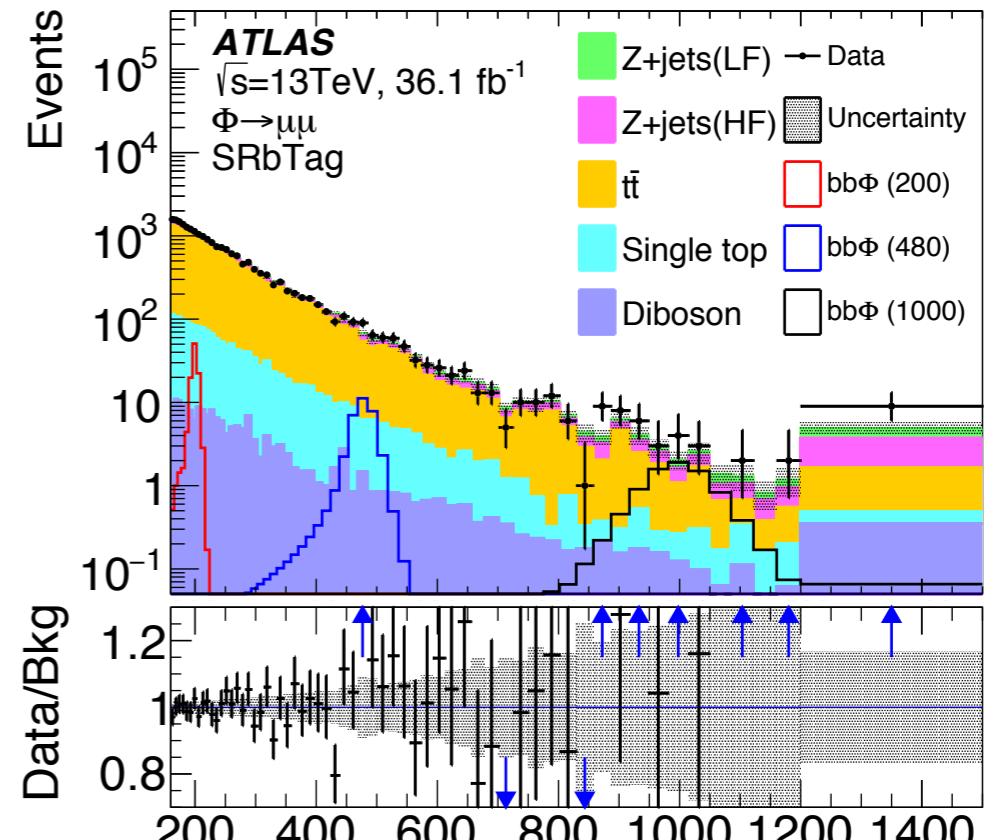
Extended Higgs sector?

- Coupling to the tau lepton plays a key role in many SM extension of the Higgs sector
 - Large BR at high $\tan\beta$ in hMSSM
- ATLAS searches:
 - $H^\pm \rightarrow \tau^\pm V$
 - $A/H \rightarrow \tau\tau$
- No excesses found:
 - Limits set in the hMSSM scenario (among others)



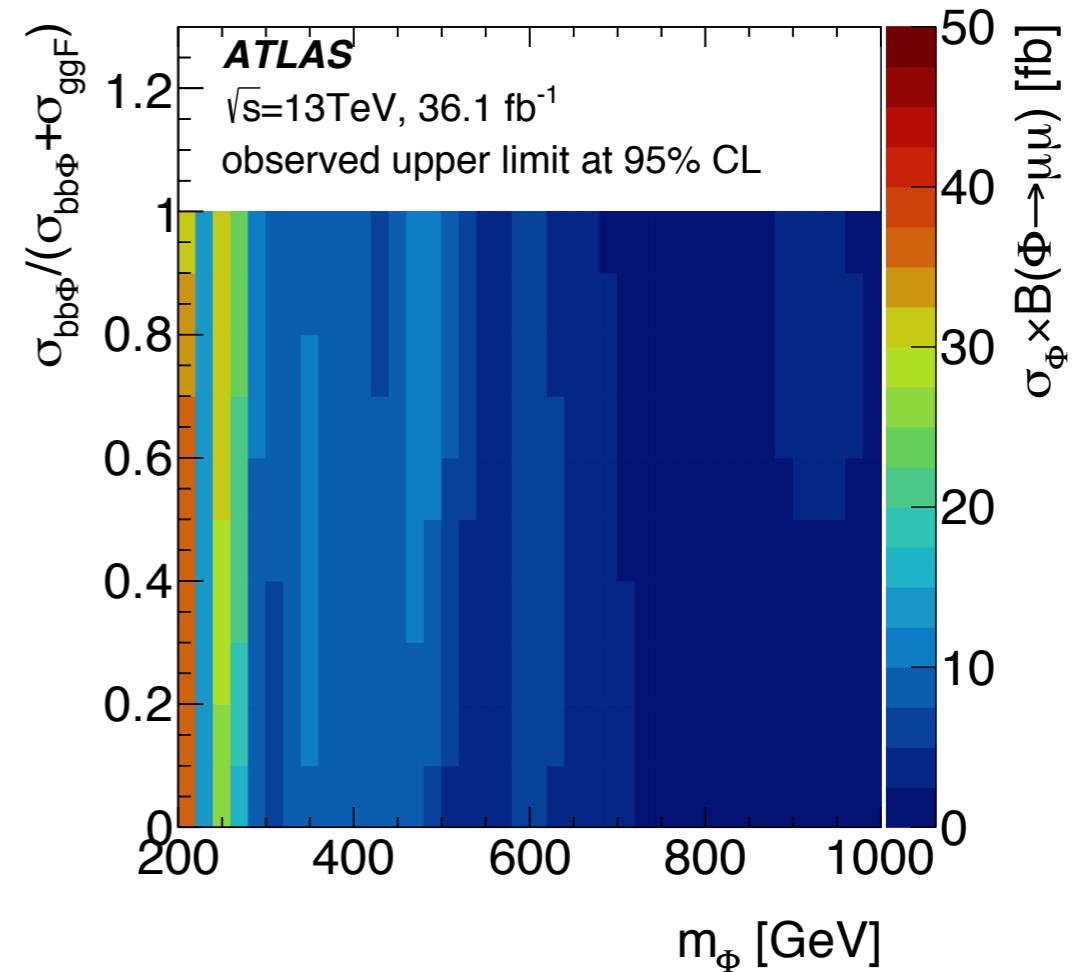
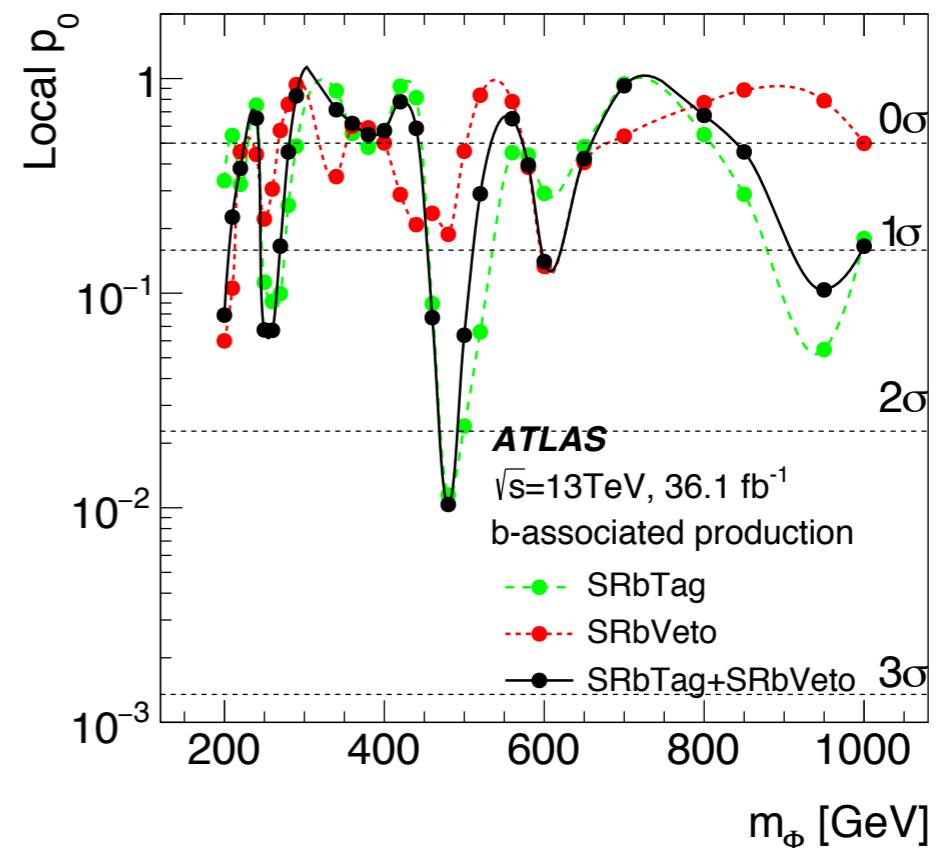
$b\Phi \rightarrow \mu\mu$

- Model-independent search for a high-mass scalar state decaying to two muons
- 2HDM: high mass scalar Φ coupling to muons stronger than to tau leptons
- Look simultaneously into a b-tag and b-veto region
- Simultaneous fit of both regions with 2 different Higgs-like signal hypothesis
 - $gg\Phi \rightarrow \mu\mu$
 - $bb\Phi \rightarrow \mu\mu$



$b\Phi \rightarrow \mu\mu$

- No significant excess observed
- Limits:
 - On each signal hypothesis
 - On the ratio the production mode versus mass
- All the results from [arXiv:1901.08144](#) will be put on HepData for re-interpretation



Conclusions

- **Higgs couplings to the tau lepton has been firmly established**
 - Inclusive cross-section measured with ~30% accuracy
 - Full Run2 dataset analysis will pave the road to the ultimate precision of the HL(LHC) program
- **Sensitivity to SM $H \rightarrow \mu\mu$ is around the corner**
- **Measuring CP properties in the leptonic decays will be very challenging**
- **Extensive search program for extended Higgs sectors with leptons**
 - So far no hint of deviations, analysis of the final Run2 dataset underway

References

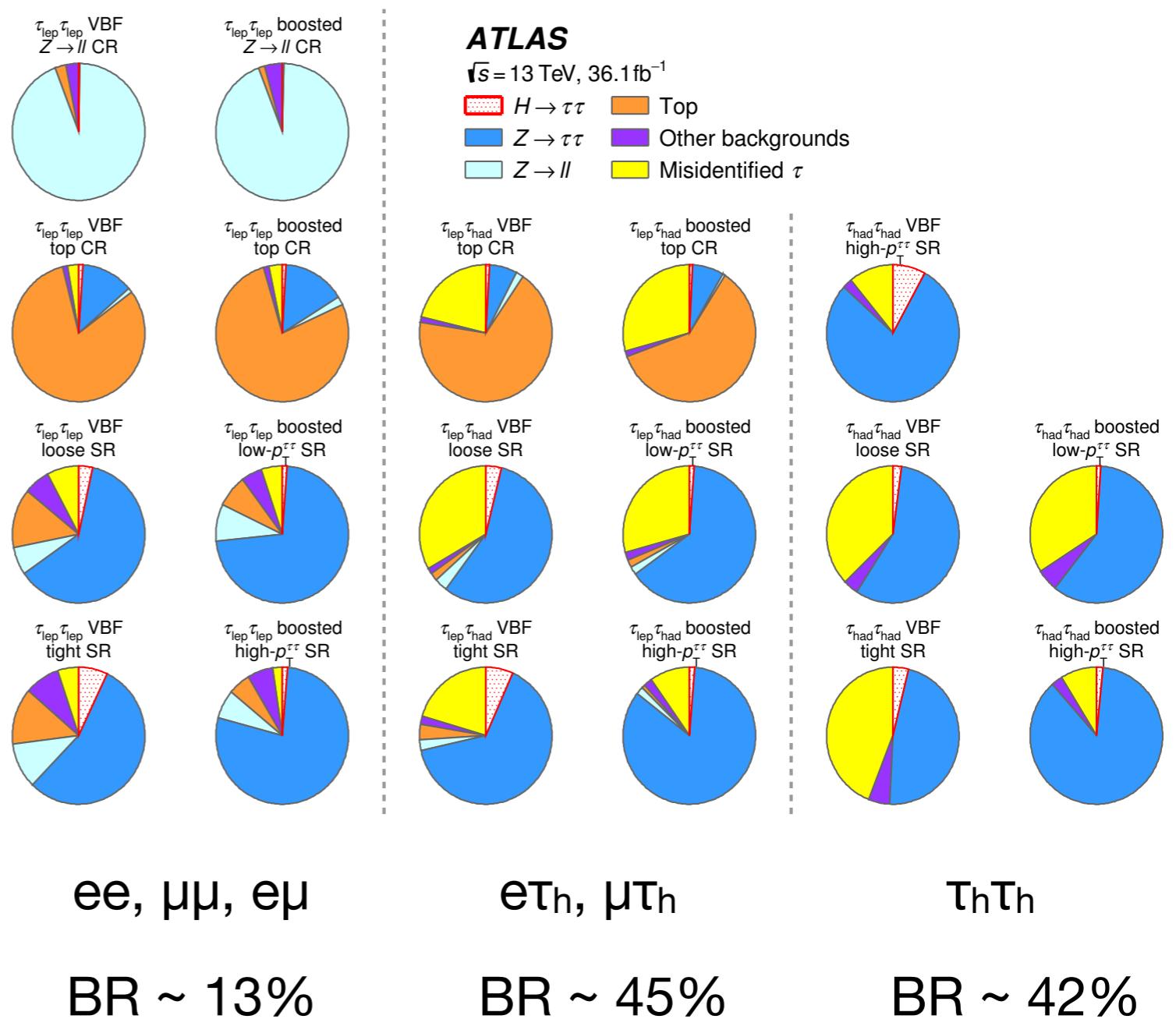
Analysis	Figures and Tables	arXiv/cds	Journal
H \rightarrow $\tau\tau$	HIGG-2017-07	1811.08856	Accepted by PRD
H \rightarrow $\tau\tau$ Decay CP HL-LHC prospects	ATL-PHYS-PUB-2019-008	cds	n/a
VBF H \rightarrow $\tau\tau$ CP	HIGG-2015-06	1602.04516	EPJC76(2016)658
Tau Decay Mode Reconstruction	PERF-2014-06	1512.05955	EPJC76(2016)5
Higgs Couplings Combination	ATLAS-CONF-2019-005	cds	n/a
H \rightarrow $\mu\mu$	ATLAS-CONF-2018-026	cds	n/a
H \rightarrow $\mu\mu$ HL-LHC prospects	ATL-PHYS-PUB-2018-006	cds	n/a
Neutral H \rightarrow $\tau\tau$ high mass search	HIGG-2016-12	1709.07242	JHEP01(2018)055
H $^\pm \rightarrow \tau^\pm \nu$	HIGG-2016-11	1807.07915	JHEP09(2018)139
(b) $\Phi \rightarrow \mu\mu$ high mass search	HIGG-2017-10	1901.08144	Submitted to JHEP

Additional material

Event Categorisation

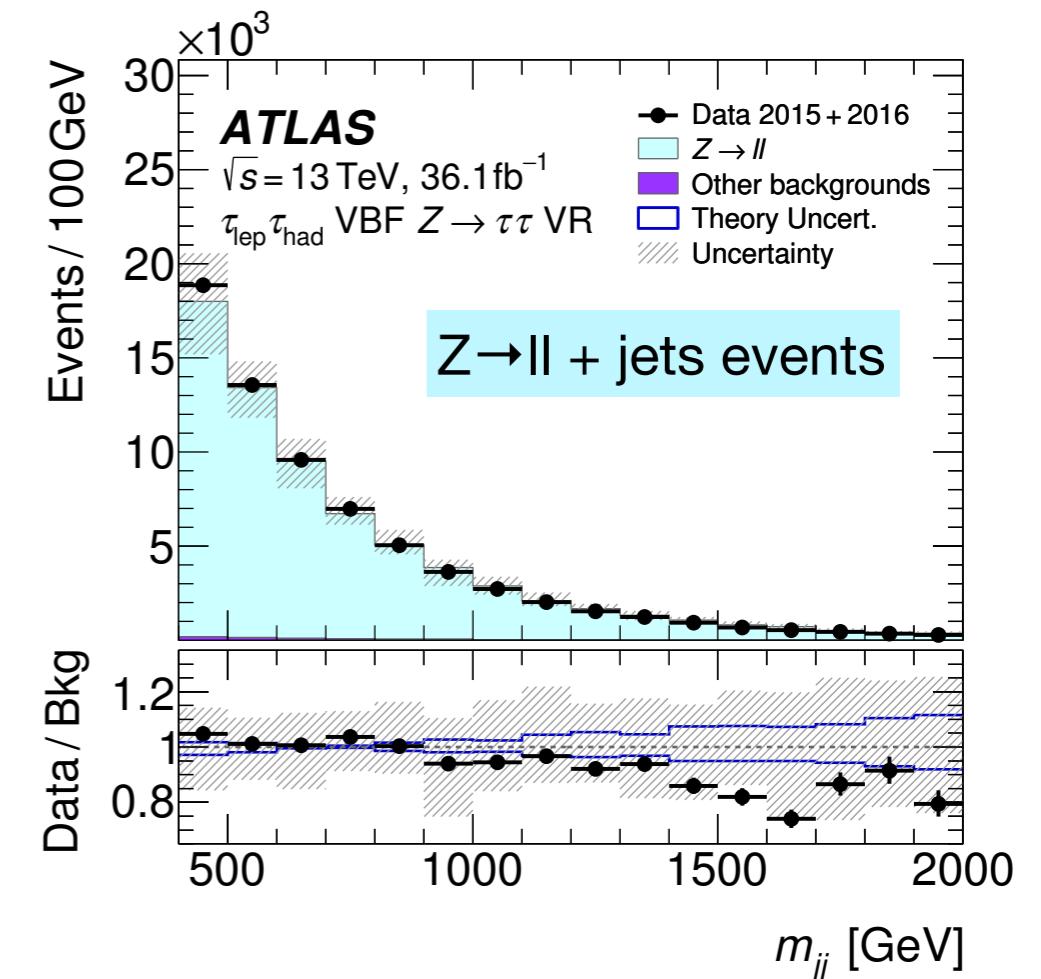
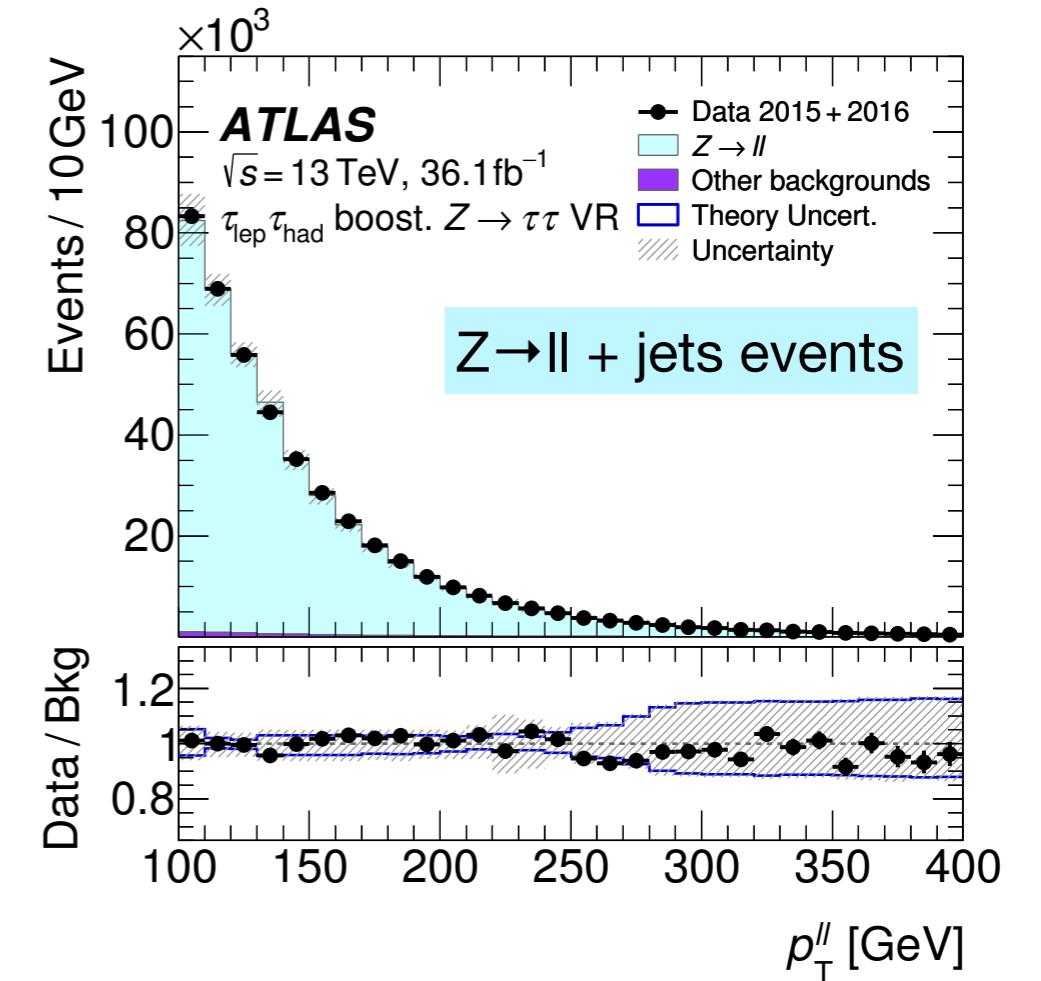
- Categorisation strategy:

- VBF/boost: jet-multiplicity, m_{jj} , $p_T(H)$
- Boost phase space further divided with cuts on $p_T(H)$ and $\Delta R(\tau, \tau)$
- VBF phase space further divided with cuts on m_{jj} , $p_T(H)$ and $\Delta R(\tau, \tau)$
- Dedicated regions to control normalisation of Top and $Z \rightarrow ll + jets$



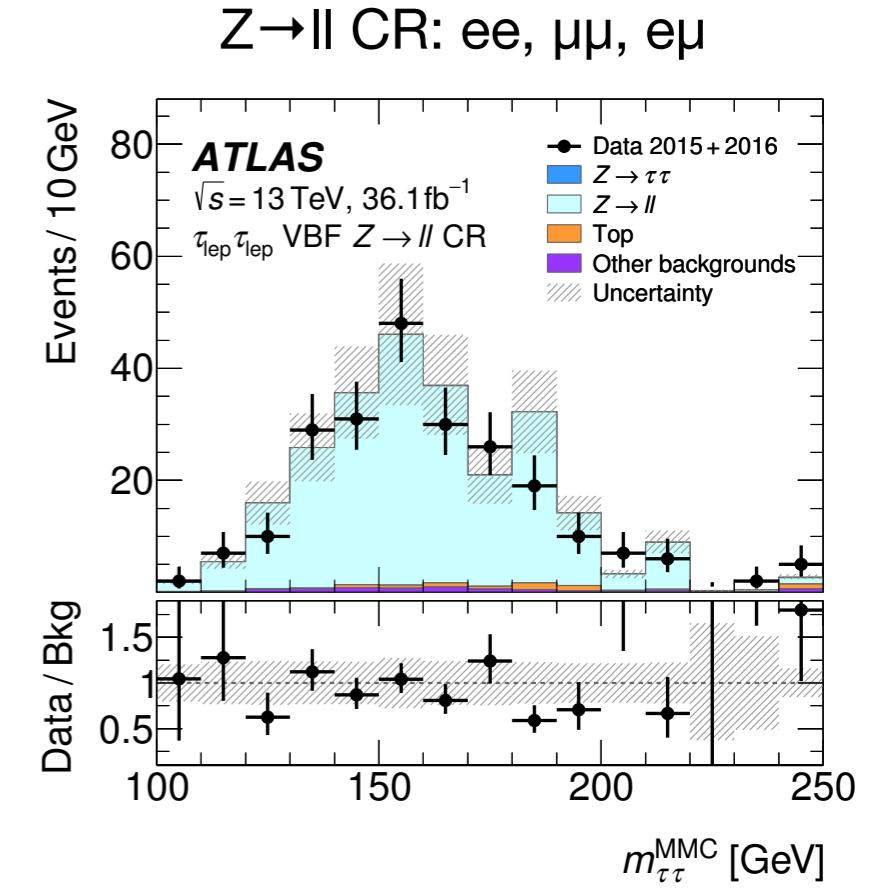
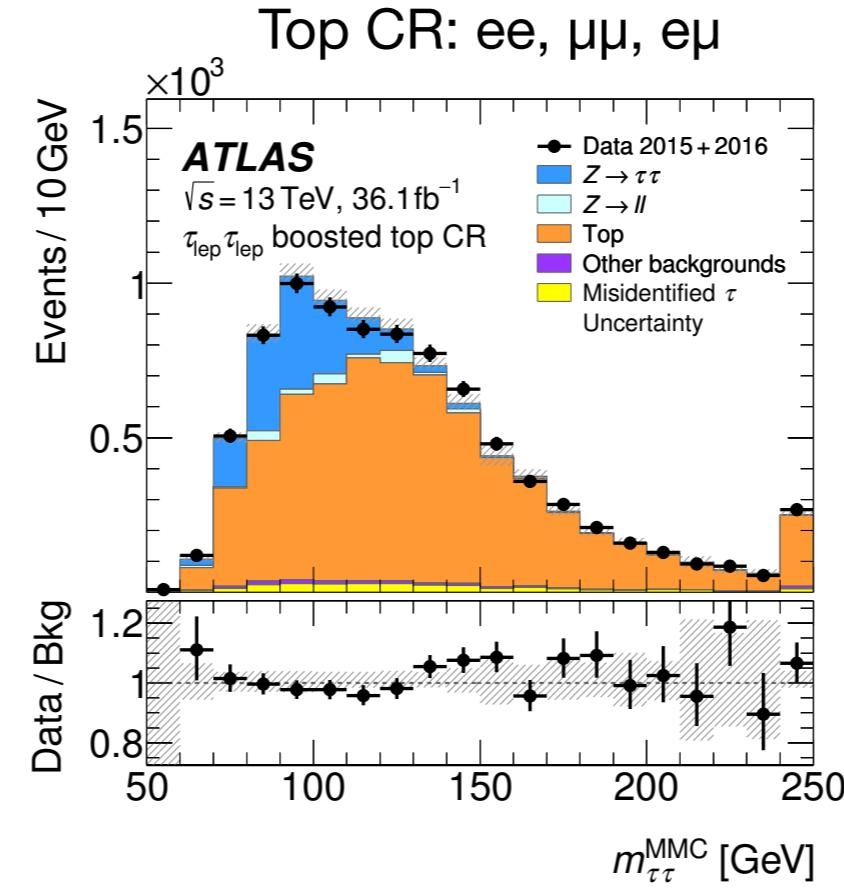
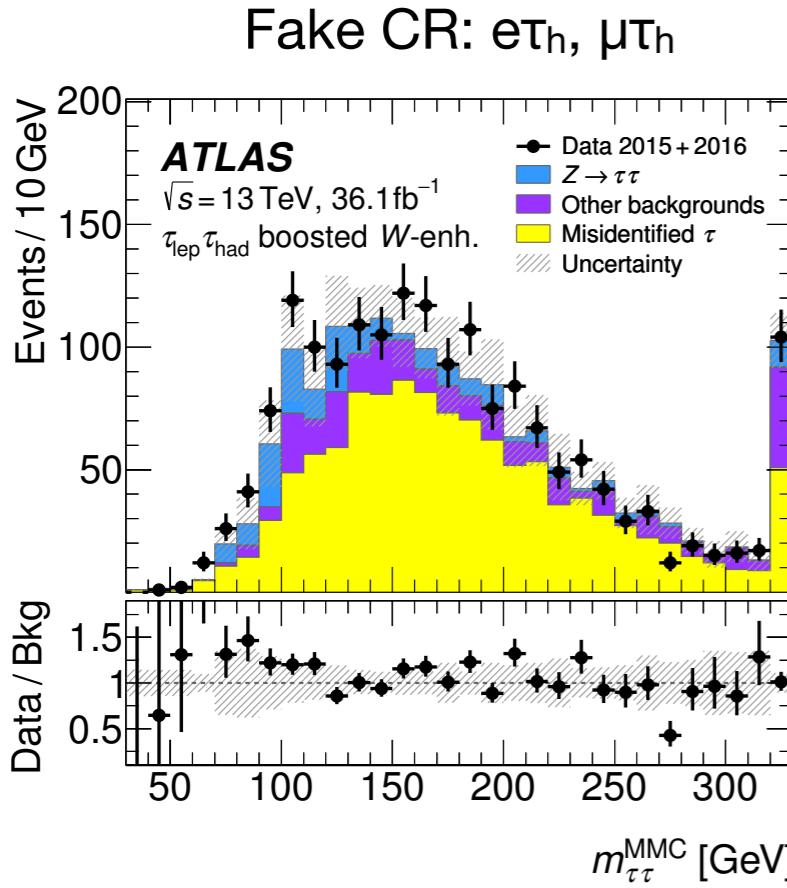
$Z \rightarrow \tau\tau + \text{jets}$ modelling

- SHERPA
 - Up to 2 partons NLO QCD
 - Up to 4 partons LO
- $Z \rightarrow \tau\tau + \text{jets}$ is free floating in Boost and VBF phase space:
 - Simulation to model migration between the signal regions and the shape of the mass estimation
- Validate SHERPA in $Z \rightarrow \text{II} + \text{jets}$ events
 - Good modelling in the phase space of the analysis
 - m_{jj} mismodelling above 1 TeV has a negligible impact on the measurement
- Key variables for the event categorisation: $p_T(Z)$ and m_{jj}

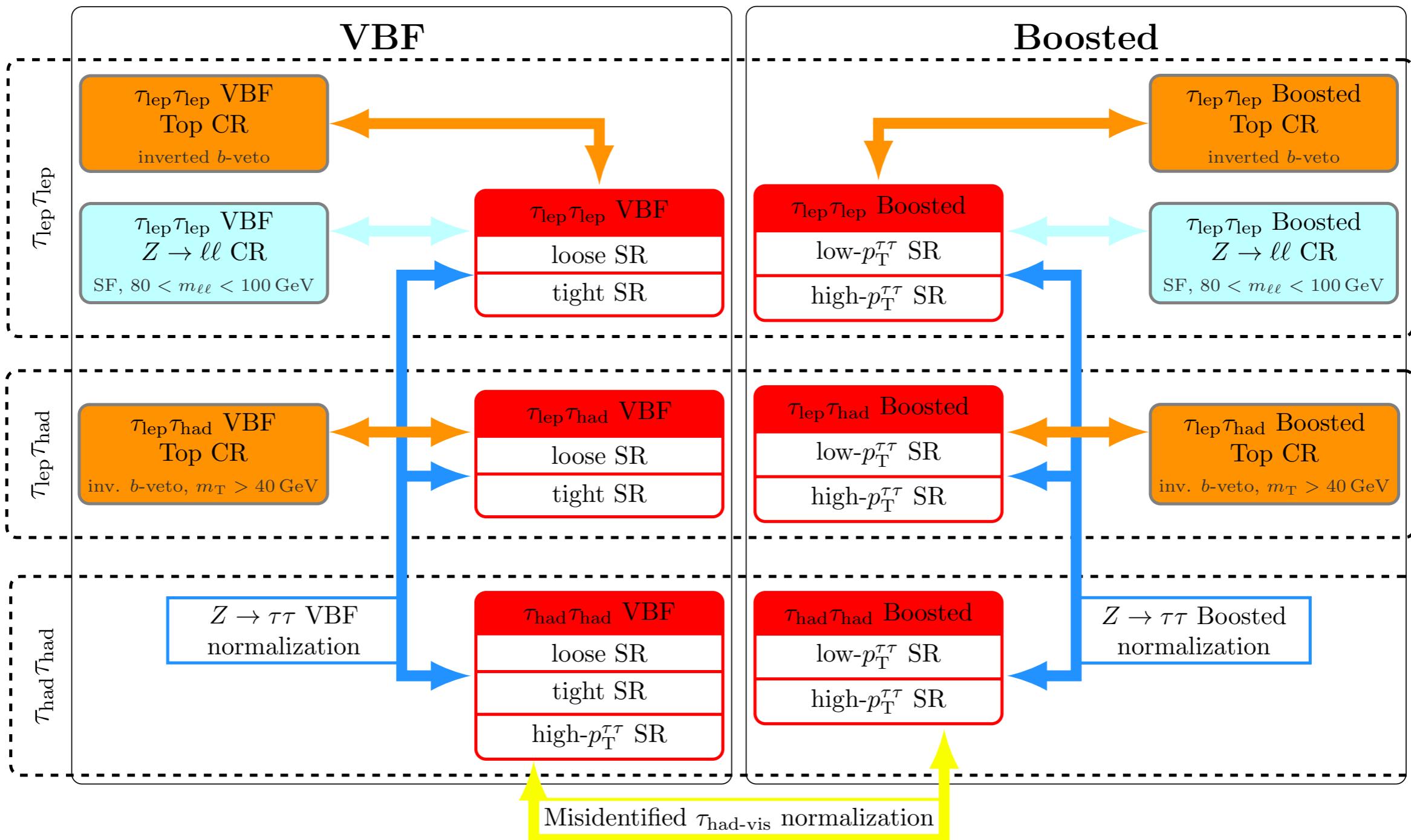


Background validation

- Fakes are estimated using data-driven techniques (revert tau identification or charge product criteria)
- Top and $Z \rightarrow ll + jets$ are estimated using MC simulation
 - Normalisation is constrained by dedicated control regions
 - MC simulation modelling is checked in control regions



$H \rightarrow \tau\tau$ Fit Setup

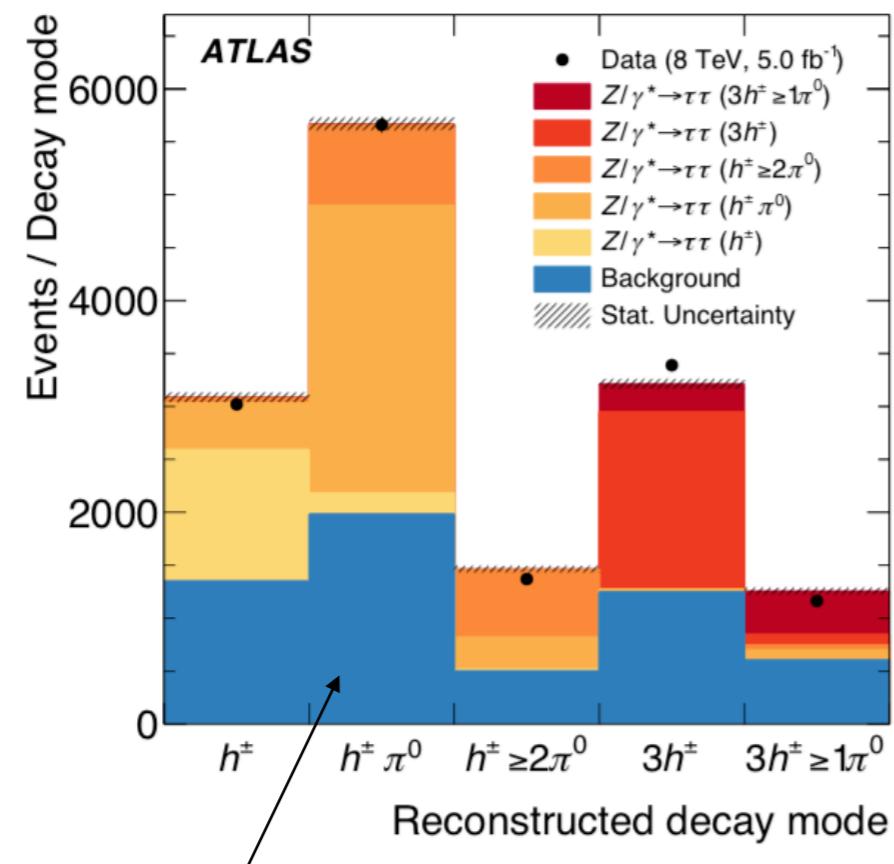


$H \rightarrow \mu\mu$ HLLHC prospects

Category	S	VBF	B	FWHM [GeV]	σ_G [GeV]	$S/\sqrt{S + B}$
VBF-like	386	197	19430	4.37	1.88	2.75
low p_T , central	921	11	350500	3.21	1.37	1.55
med p_T , central	2210	84	300500	3.08	1.32	4.01
hi p_T , central	1810	242	211800	3.50	1.56	3.91
low p_T , non central	2460	28	1740500	4.11	1.79	1.86
med p_T , non central	5860	230	1483600	4.24	1.80	4.80
hi p_T , non central	4380	588	829000	4.70	1.92	4.80
Total	18020	1380	4935500	3.93	1.69	9.53

Hff CP properties in the $\tau\tau$ channel

- Very challenging analysis
 - Selection of pure $\pi^+\pi^0-\pi^+\pi^0$ events
 - Reconstruction of the individual pions 4 momentums



reconstructed $\pi^+\pi^0$ bin

