Differential cross section measurement of the Higgs boson decaying into two taus at the ATLAS experiment

Antonio De Maria

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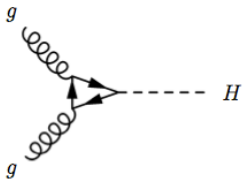
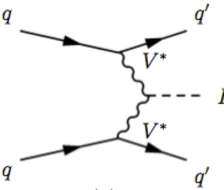
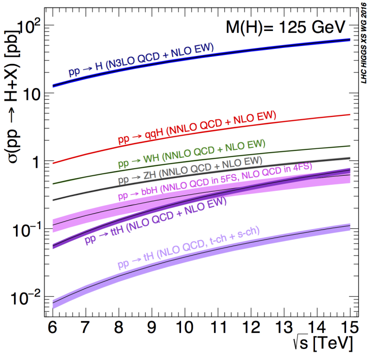
Higgs boson production modes



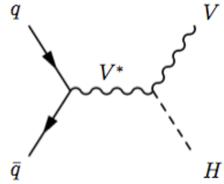
gluon fusion (ggF)
Cross section : 48.6 pb.*



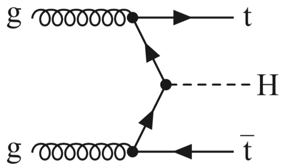
vector boson fusion (VBF).
Cross section : 3.8 pb.*



Higgs boson production cross section



associated production with a gauge boson (VH).
Cross section : 2.3 pb.*



associated production with a $t\bar{t}$ pair (ttH).
Cross section : 0.5 pb.*

* predicted cross section for m_H=125 GeV at $\sqrt{s}$=13 TeV

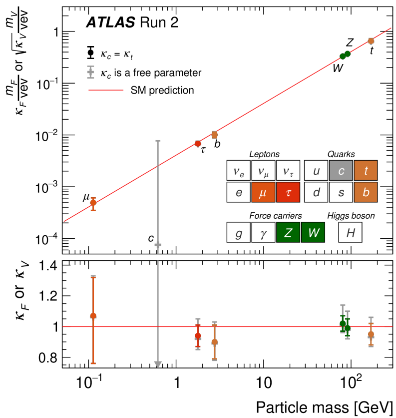
Higgs boson couplings

- 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 bosons $\rightarrow$ main couplings with W and Z
  - m_F for fermions $\rightarrow$ main couplings with third generation of quark and leptons (b and τ)

- Coupling as function of particle mass in good agreement with SM prediction over 3 order of magnitude



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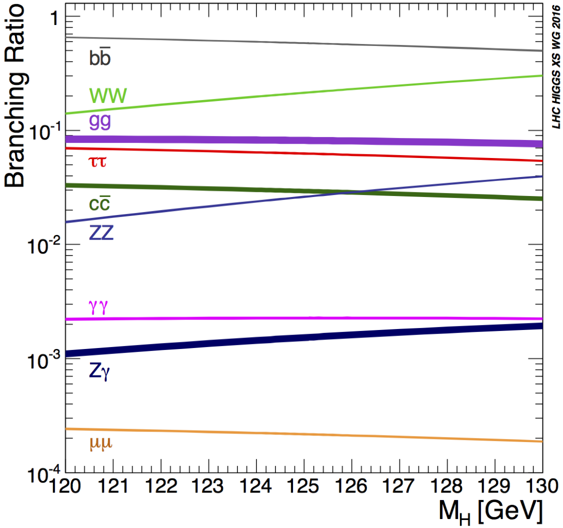
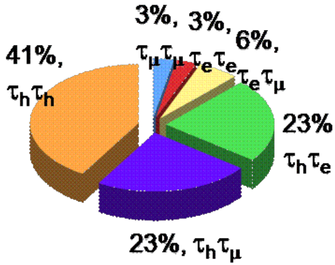
Higgs boson decay branching ratios



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

$H \to \tau\tau$ measurements - arxiv-2407.16320

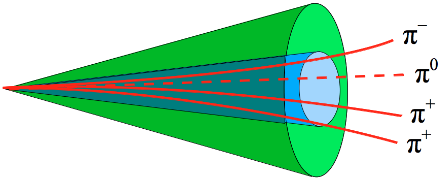
- Considering all main Higgs boson production modes, with dedicated selection to enhance each mode
- Considering all di-τ final states, $\tau_{lep}\tau_{lep}/\tau_{lep}\tau_{had}/\tau_{had}\tau_{had}$
- Measure cross section per production mode, cross section in the *Simplified Template Cross Section* (STXS) framework and differential cross section in VBF phase space
- Results extracted from likelihood fits on the di-τ invariant mass estimated using Missing Mass Calculator (MMC) Link



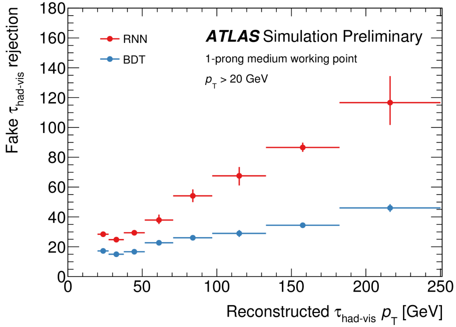
VBF inclusive STXS	$N_{\text{jets}} \geq 2$, sub-leading jet $p_T > 30$ GeV $m_{jj} > 350$ GeV, $\lvert\Delta\eta_{jj}\rvert > 3$ $\eta(j_0) \times \eta(j_1) < 0$ lepton centrality: visible decay products of the τ-leptons between VBF jets
VBF inclusive differential	$N_{\text{jets}} \geq 2$, sub-leading jet $p_T > 30$ GeV $m_{jj} > 600$ GeV, $\lvert\Delta\eta_{jj}\rvert > 3.4$, $p_T(jj) > 30$ GeV $\eta(j_0) \times \eta(j_1) < 0$ lepton centrality: visible decay products of the τ-leptons between VBF jets $p_T(Hjj) < 50$ GeV
VH inclusive	$N_{\text{jets}} \geq 2$, sub-leading jet $p_T > 30$ GeV 60 GeV $< m_{jj} <$ 120 GeV
tt(0ℓ)$H \to \tau_{\text{had}}\tau_{\text{had}}$	$N_{\text{jets}} \geq 6$ and $N_{b\text{-jets}} \geq 1$ or $N_{\text{jets}} \geq 5$ and $N_{b\text{-jets}} \geq 2$
Boost inclusive	Not VBF inclusive Not VH inclusive $p_T^{\text{reco}}(H) > 100$ GeV

Tau Reconstruction/Identification

- Attempt to reconstruct only hadronically decaying taus
- Tau candidates are seeded by anti-k_t LC jets with a distance parameter R $= 0.4$
- Track selected in the *core* $(0 < \Delta R < 0.2)$ and *isolation* $(0.2 < \Delta R < 0.4)$ regions around the tau candidate axis.
- Identification algorithm based on RNN to reject background from q/g jets
  - trained using track and cluster information



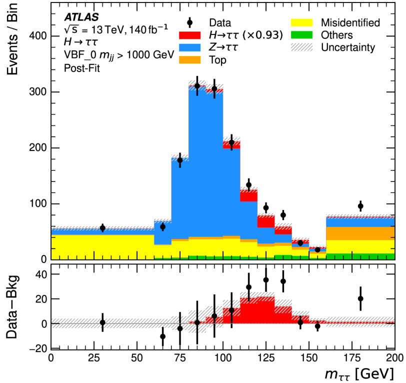
had τ Decay Mode	BR (%)
$h^{\pm}$	11.5
$h^{\pm}\pi^{0}$	30.0
$h^{\pm} \geqslant 2\pi^{0}$	10.6
$3h^{\pm}$	9.5
$3h^{\pm} \geqslant 2\pi^{0}$	5.1

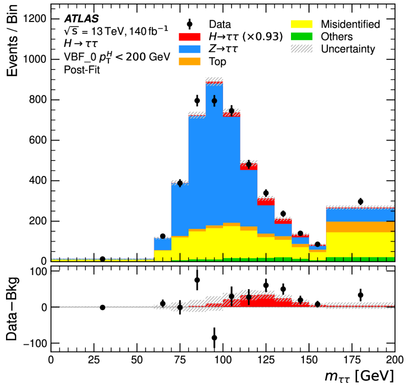


ATL-PHYS-PUB-2019-033

Background estimation

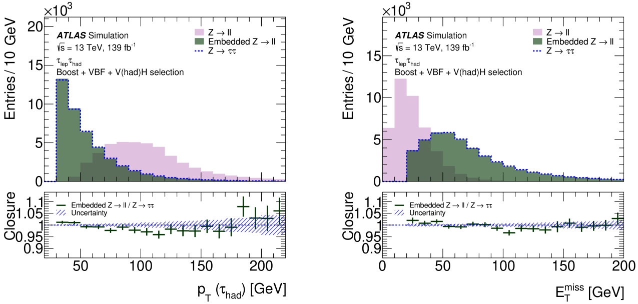
- Mostly based on simulation except for *misidentified* τ, which is data-driven
- Z$\rightarrow\tau\tau$ (70-90%): validated and normalised using *embedded* Z$\rightarrow$ *ll* CRs
- Misidentified τ (5-20 %): estimated using Matrix Method ($\tau_{lep}\tau_{lep}$) and Fake Factor Method ($\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$)
- Top ($<$ 5% but 35-50% in ttH SRs): validated in Top CRs
- Other backgrounds: small, evaluated through simulation



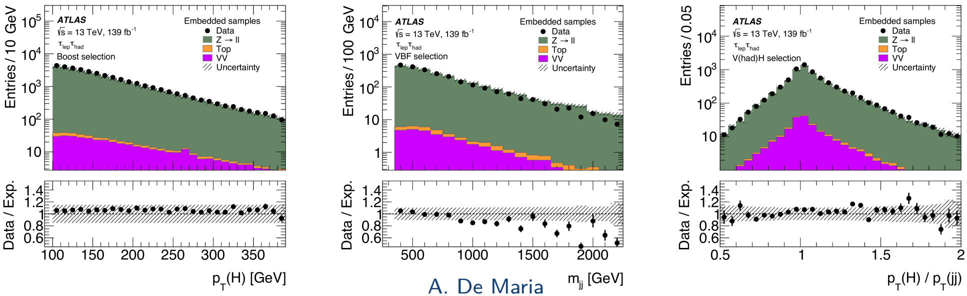


Kinematic Embedding JHEP 08 (2022) 175

- Select Z$\rightarrow$ *ll* + jets events in CRs defined orthogonal to the signal region
- *Unfold* Z$\rightarrow$ *ll* events taking into account lepton reconstruction efficiencies
- *Mimic* Z$\rightarrow \tau\tau$ events through kinematic parameterisation of τ decay products

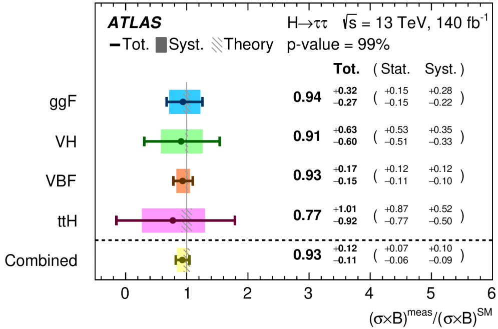


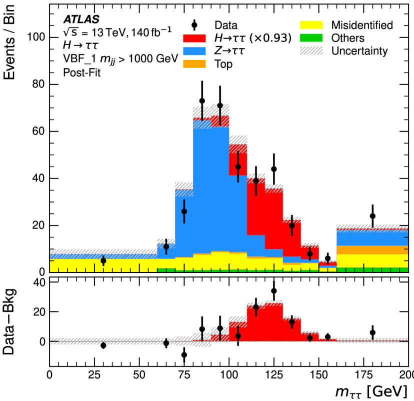
- Procedure validated in different kinematic phase spaces



Cross section per production mode

- Most precise VBF cross section measurement per-single channel in the ATLAS experiment
- ggH cross section uncertainty limited by syst. uncertainties, mostly from theoretical uncertainty
- ttH and V(had)H cross section measurement limited by statistics

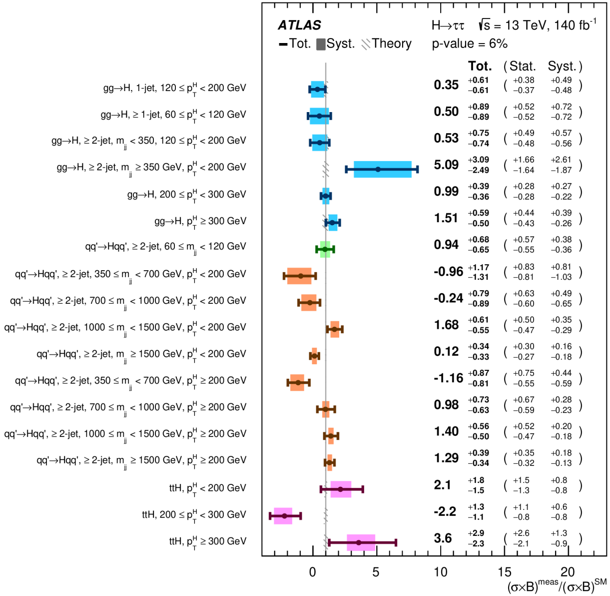


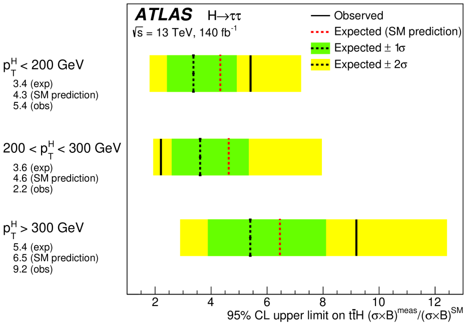


Production mode	ggF	ttH	VBF	VH
Best-fit value	0.94	0.77	0.93	0.91
Total uncertainty	±0.30	±0.97	±0.16	±0.62
Statistical uncertainty	±0.15	±0.82	±0.12	±0.52
Total systematic uncertainty	±0.26	±0.51	±0.11	±0.34
Samples size	±0.09	±0.32	±0.03	±0.25
Theoretical uncertainty in signal	±0.19	±0.14	±0.10	±0.13
Jet and E_T^{miss}	±0.12	±0.14	±0.03	±0.11
Hadronic τ-lepton decays	±0.05	±0.09	±0.01	±0.04
Misidentified τ-lepton background	±0.05	±0.05	±0.02	±0.11
Luminosity	±0.01	±0.01	±0.01	±0.02
Theoretical uncertainty in top-quark processes	±0.01	±0.30	–	±0.02
Theoretical uncertainty in Z + jets processes	±0.03	±0.07	–	±0.02
Flavour tagging	±0.02	±0.05	±0.01	±0.01
Electrons and muons	±0.02	±0.01	±0.01	±0.02

Simplified template cross section results

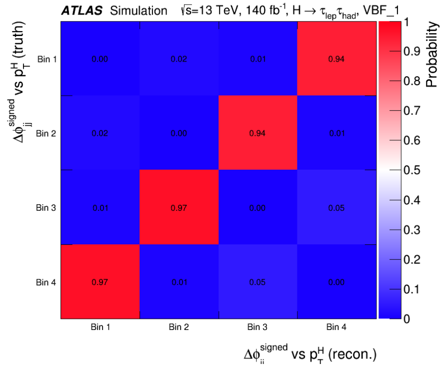
- Measurement performed in 18 different kinematic phase spaces
- No significant deviation from SM
- For VBF, first (most precise) measurement for $p_T(H) > (<)$ 200 GeV and $m_{jj} > 1.5$ TeV
- Found large anti-correlation between VBF and ggH in-VBF phase space cross sections
- ttH measurement used to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

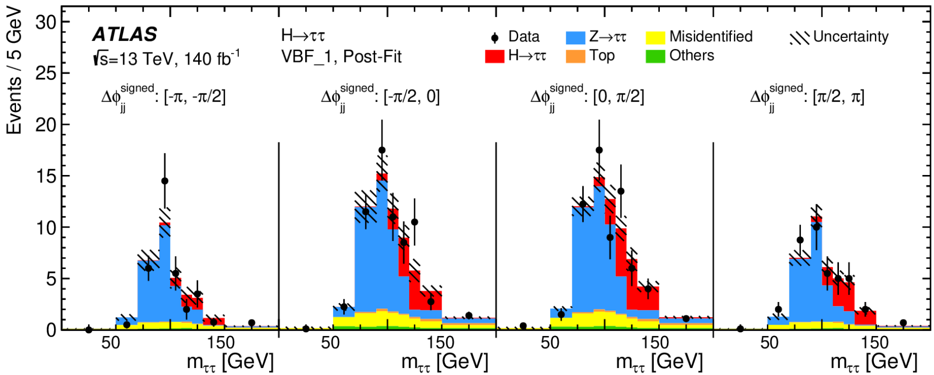




Differential cross section measurement

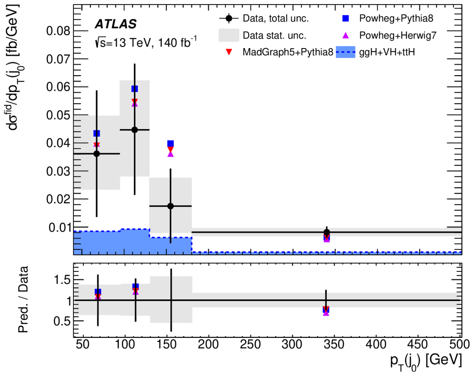
- Measurement performed in dedicated fiducial phase space for VBF production, minimising ggH contamination
- Considering several variables for unfolding, like $p_T(H)$/leading jet p_T and $\Delta\phi_{jj}^{\text{signed}}$ (sensitive to Higgs Charge-Parity (CP) symmetry)

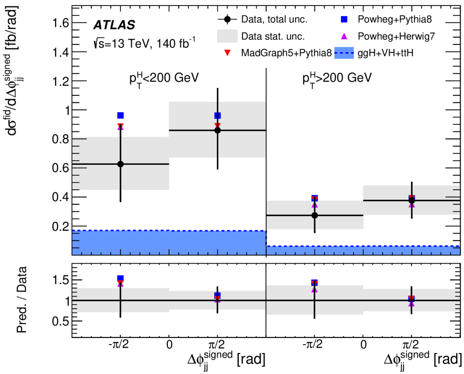


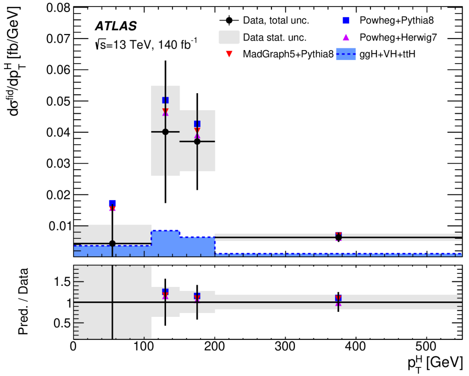


Differential cross section Results

- Per-bin precision typically within 25-50%, limited by statistical uncertainties in most of the bins
- Results compared with predictions from the PoPy8, PoHer7 and MadPy8 generators; found no significant deviations from SM predictions



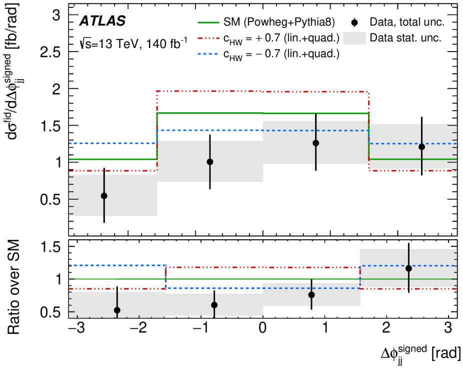


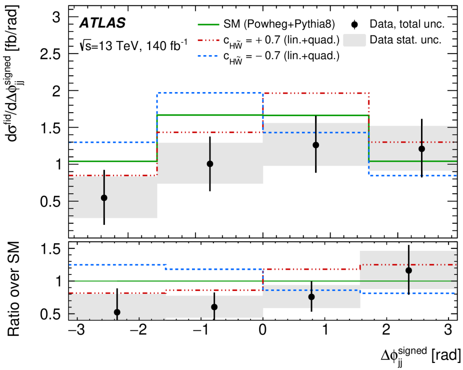


Effective Field Theory interpretation

- Results from differential analysis are interpreted in the SMEFT formalism
- For VBF, 3 CP-even and 3 CP-odd operators are investigated for the H-V interaction
- Measure the Wilson coefficient (*strength*) for each operator, setting BSM physics scale $\Lambda = 1$ TeV

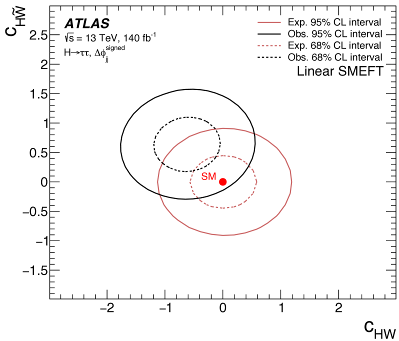
	CP-even		
Operator $O_i^{(d=6)}$	$H^\dagger H W^n_{\mu\nu} W^{n\mu\nu}$	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	$H^\dagger \tau^n H W^n_{\mu\nu} B^{\mu\nu}$
Wilson coefficient	c_{HW}	c_{HB}	c_{HWB}
	CP-odd		
Operator $O_i^{(d=6)}$	$H^\dagger H \tilde{W}^n_{\mu\nu} W^{n\mu\nu}$	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	$H^\dagger \tau^n H \tilde{W}^n_{\mu\nu} B^{\mu\nu}$
Wilson coefficient	$c_{H\tilde{W}}$	$c_{H\tilde{B}}$	$c_{H\tilde{W}B}$

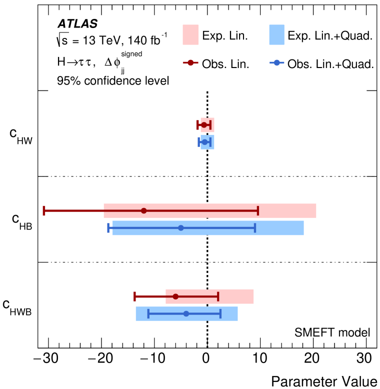


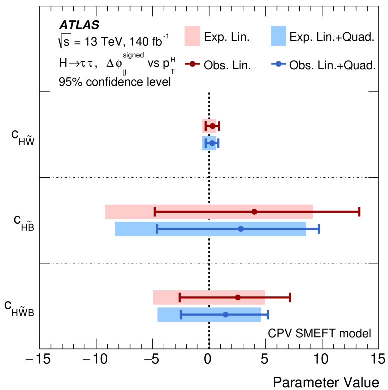


EFT interpretation results

- Measuring one Wilson coefficient while fixing all others to 0 (1-dim), as well as 2-dim measurements
- Most stringent observed results for 1-dim are $c_{HW} \epsilon [-1.85, +0.57]$ and $c_{H\tilde{W}} \epsilon [-0.31, +0.88]$ in the linear scenario
- Tightest constraint to date for $c_{H\tilde{W}}$
- No evidence of BSM physics







Summary

- $H \rightarrow \tau\tau$ is currently the best decay at LHC to study Higgs-Yukawa coupling
- Considering all main Higgs boson production modes and all di-τ final states
- Most precise VBF cross section measurement per-single channel in ATLAS
- cross section measured in 18 different *bins* within the STXS framework
- Performed also differential cross section measurement in VBF with a per-bin precision mostly within 25-50%
- EFT interpretation of the differential results led to tightest constraint to date for $c_{H\tilde{W}}$ for $\Lambda = 1$ TeV

Thanks For Your Attention

Backup

Misidentified τ background

- Aim to estimate jet mis-identified as τ (light leptons) in $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ ($\tau_{lep}\tau_{lep}$) final states
- Validated in dedicated CRs and residual mis-modelling assigned as systematic uncertainty