# Search of 125 GeV Higgs boson decaying to two pseudo-scalars in four $\tau$ final state with the ATLAS detector

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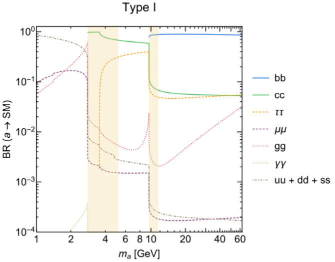
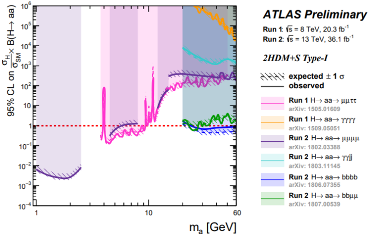
# Motivation

- In searches of the 125 GeV Higgs boson to light pseudo-scalars, the $4\tau$ decay channel is accessible in the range $2m_\tau < m_a < m_H/2$.
- Good sensitivity in this phase space.
  - $a \to \tau\tau$ channel is favored below the $2m_b$ threshold in cases like Type *I* or *II* 2HDM+scalar,
  - Works even better in Type *III* with large $tan\beta$.
  - Other models: theories of supersymmetry, axions, electroweak baryogenesis, dark matter mediators,...

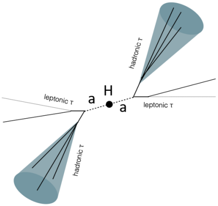



arXiv:1312.4992v6

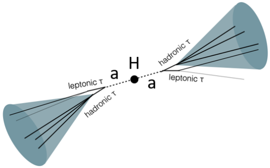


# Analysis overview

- H→aa→4$\tau$ in final states with multiple electrons or muons.
  - Target on inclusive Higgs boson production.
- Focus on same-sign (SS) dilepton signature: H→aa→($e/\mu$ $\tau_{had}$)($e/\mu$ $\tau_{had}$).
  - Clean signature with low background.
  - Resolved objects with standard ID – sensitive to [15,60] GeV.
  - Merged regime needs dedicated ID – sensitive to [3.5,15] GeV.



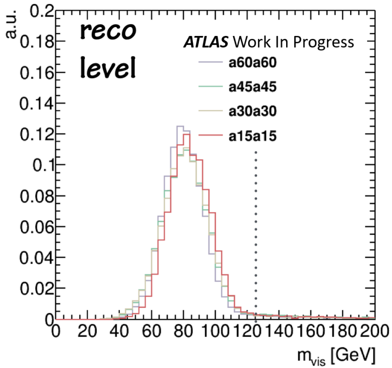

Resolved case



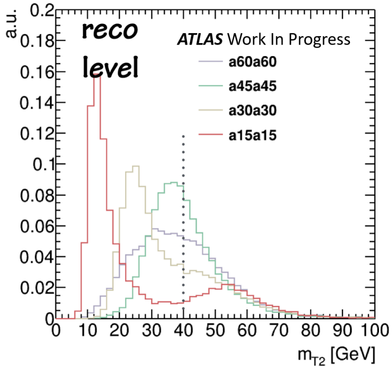

Merged case

# Content

# Signal Selection



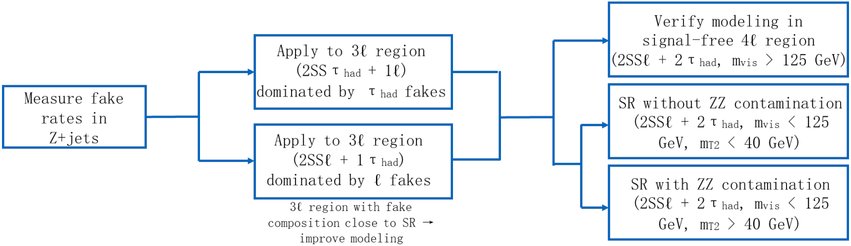

**Visible mass** $m_{Vis}$: Signals consistent with a Higgs boson decay peak $<$ 125 GeV.




**Stransverse mass** $m_{T2}$: Improve S/B for lower masses selecting region with low $m_{T2}$.

# Analysis Strategy

- Focus on SS dilepton signature H→aa→($e/\mu\ \tau_{had}$)($e/\mu\ \tau_{had}$)
- Background largely dominated by tau and lepton fakes.
  - Most of the fakes in our $4\tau$ final state are from Z+jets with subleading contributions from WZ+jets and $t\bar{t}$.
- High-level analysis strategy:




(SS = same-sign, OS = opposite-sign)

# Object Selection

Select events passing single-/di-lepton triggers.

## Baseline Selection

- **Muon**: $p_T > 5$ GeV, Medium ID, d0sig$<7$.
- **Electron**: $p_T > 7$ GeV, Loose ID, d0sig$<5$.
- **Hadronic Tau**: $p_T > 20$ GeV, VeryLoose ID.
- Selection used to select a fake-dominated region to estimate background component using fake-rate method.

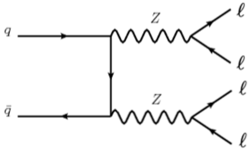
## Signal Selection

- Baseline selection plus:
- **Muon**: FCTight isolation, d0sig$<4$.
- **Electron**: Medium ID, FCTight isolation.
- **Hadronic Tau**: Medium ID.
- Selection used for analysis.

# Prompt-leptons Background

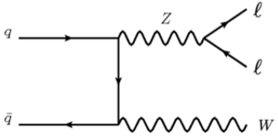
- Estimated from Monte-Carlo.
- Mainly diboson: ZZ in 2l2$\tau$ and ZZ/WZ in 1l2$\tau$, 2l1$\tau$ cases.
- H$\rightarrow$ZZ$\rightarrow$4$\tau$, Z$\gamma$*, VVV, ttV, tt$\gamma$* have negligible contribution in all regions.

ZZ



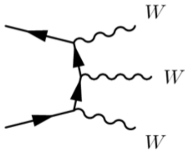

**Mainly in 2l2$\tau$**

WZ




**Mainly in 1l2$\tau$, 2l1$\tau$**

Triboson (VVV)




**Negligible**

- Systematic uncertainties:
  - Object systematics: electrons, muons, taus, b-jets, etc.
  - Theory uncertainties following LHC Higgs XS WG recommendation.

# Fake Background Estimation

- Fake (non-prompt) background:
  - **Fake hadronic tau**: light/heavy flavor quark jets, gluon jets
  - **Fake electron**: photon conversions; light/heavy-flavor hadrons
  - **Fake muon**: heavy-flavor hadrons with semi-leptonic decays, decays in flight.
- Estimate using a fake-rate method based on Z tag-and-probe:
  - Select Z+jets events — pair of electrons or muons within Z mass window.
  - Select a 3rd electron/muon/tau jet to measure the fake rate.
  - Subtract contribution from processes with a prompt 3rd lepton.

## Fake rate

$$f = \frac{\text{additional lepton pass signal selection}}{\text{additional lepton pass baseline selection}}$$

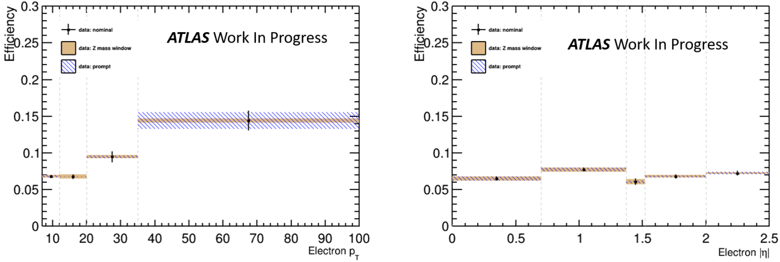
## Converted to fake factor

$$F = \frac{\text{additional lepton pass signal selection}}{\text{additional lepton pass baseline but fail signal selection}} = \frac{f}{1-f}$$

# Hadronic Tau Fake

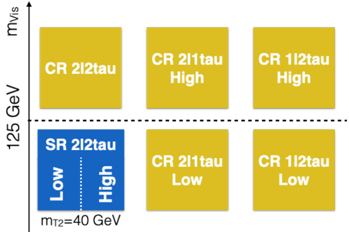
- Fakes from several sources (light/heavy flavor quark jets, gluon jets, electrons mis-identified as 1-prong hadronic taus).
  - Reduce heavy flavor contribution by applying b-veto.
  - Electrons taken from simulation and applied scale factors.
  - Measure fake rates for main contributions $\rightarrow$ light-quark jets and gluon jets.
- Fake rate estimated in different periods and 1-/3-prong tau.
  - **0.25** $\sim$ **0.35** for 1-prong tau.
  - **0.04** $\sim$ **0.07** for 3-prong tau.
- Systematic uncertainties:
  - Difference in quark-gluon composition assessed by track jet width variable.
  - Additional systematic uncertainties from statistics in Z+jets sample and from the subtraction of prompt lepton backgrounds using MC.

# Electron & Muon Fake Rates

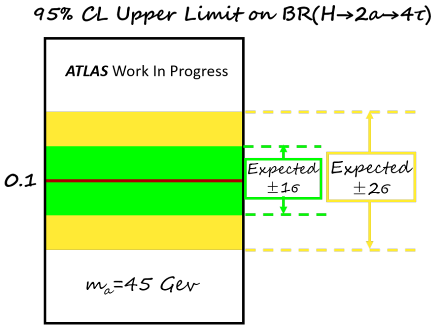



- Use Z($\rightarrow \mu\mu$)+e events for electron and Z($\rightarrow$ee)+$\mu$ for muon fake measurement.
- Parametrize in lepton $p_T$ and $|\eta|$.
- Systematic uncertainties:
  - Composition uncertainty estimated by varying selection criteria.
  - Uncertainty in the subtraction of prompt lepton backgrounds using MC.

# Result on Upper Limit



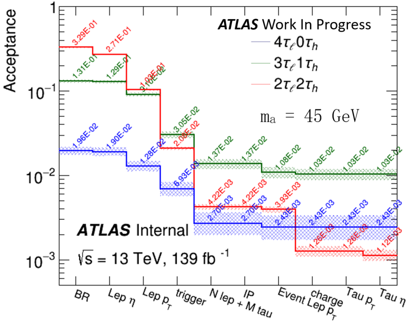

- Signal ragion (SR) in two regions of $m_{T2}$ improves sensitivity at lower $m_a$.
- Other mass points: 15, 22.5, 30, 37.5, 52.5 and 60 GeV.



# Sub-channel Extension

- We have studied the gain of including **3lep1had** and **4lep0had** channels to enhance signal acceptance.
  - **3l1h** can improve the limits by a factor of 10 using exactly the same selection and background estimation method.
  - **4l0h** may not improve the limits significantly, possibly because of smaller BR and smaller S/B.

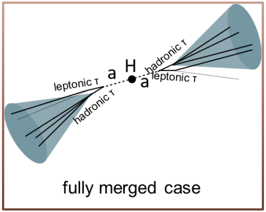
Generator-level acceptance

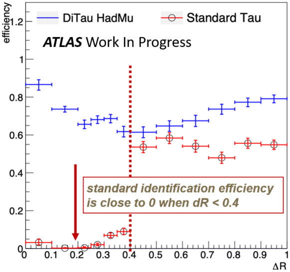


# Content

# Analysis Strategy

- Signal mass range: 4∼15 GeV.
- Selection:
  - The **a** boson decays to a pair of **leptonic** and **hadronic** $\tau$.
  - SS di-lepton to reduce background.
- Only consider **"had-mu"** merged case: "$\mu_\tau$" object with muon track inside of a tau-jet cone, $\Delta R(\mu, \tau_{had}) < 0.4$.
- **Di-$\tau$ identification algorithm**.
  - Previous study of high-$p_T$ di-$\tau$ had-mu tagger shows good identification efficiency on low-mass sample.



# Di-$\tau$ Identification

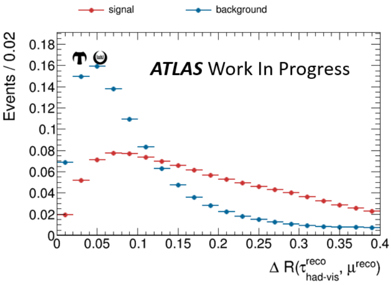
Dedicated BDT training for **low-$p_T$** had-mu di-$\tau$ objects.

## Signal

$H \to 2a \to 4\tau$, $m_a$=**4,6,8,10,15** GeV, filtered by 2Lep-2Had.

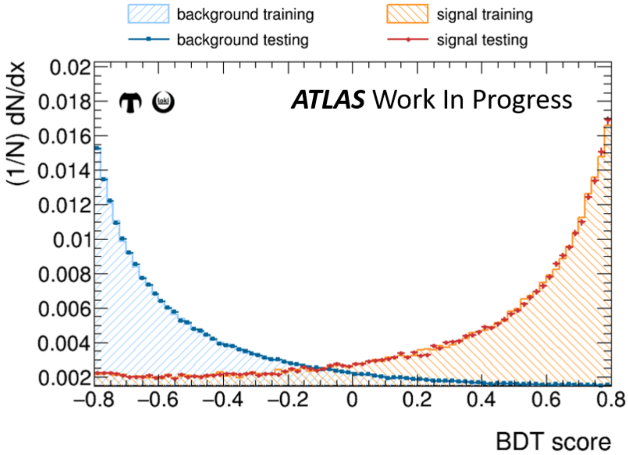
## Background

Di-jet + muon filter.



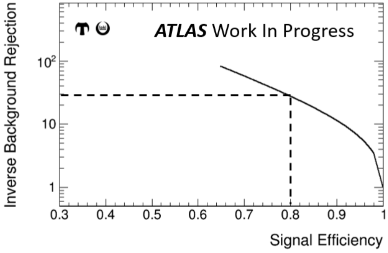

$\Delta R(\tau_{had}, \mu)$ distribution of signal and background as input to BDT.

# BDT Result

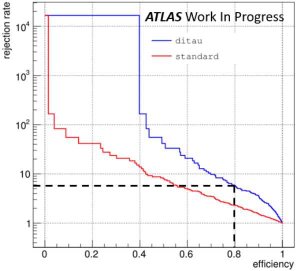



- Good discrimination between signal and background.

# BDT Result




Low-$p_T$ tagger




High-$p_T$ tagger

- The ROC curve shows the **low-$p_T$ tagger** has better performance than the high-$p_T$ tagger on the low mass samples.
  - Increase background rejection by a factor of **5** when signal efficiency @ 80%.

# Summary

- Search for H$\to$aa$\to$4$\tau$ in the SS dilepton 2l2$\tau$ channel is almost completed.
  - Good sensitivity in the mass range $15 < m_a < 60$ GeV.
  - Channels for the H$\to$aa$\to$4$\tau$ analysis targeting signal scenarios where decays to $\tau$s are favored.
  - Will include 3l1$\tau$ and 4l0$\tau$ channels.
    - Promising increase in sensitivity due to increased acceptance.
- Search targeting the merged regime ($m_a < 15$ GeV) is on-going.
  - Dedicated study for low-p$_T$ had-mu di-$\tau$ identification.
  - The BDT result shows good discriminant power and the ROC curve shows it is worthy to train the low-p$_T$ tagger.

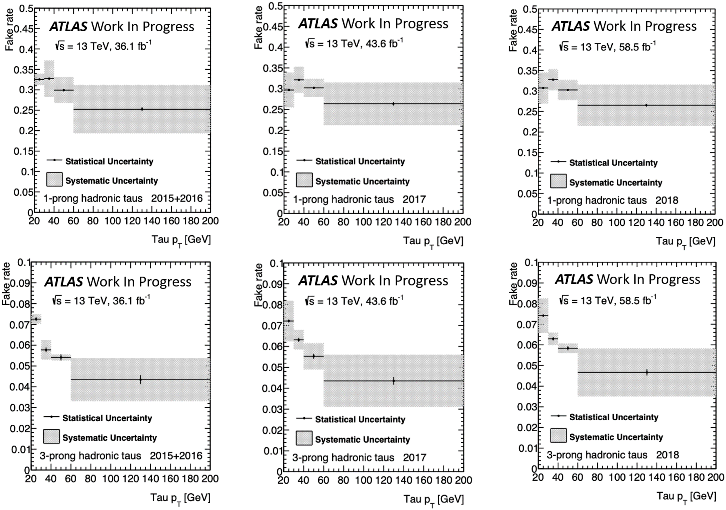
# Thanks for your attention!

# Hadronic Tau Fake Rates

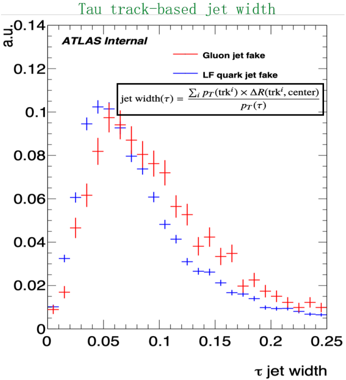
2015-16 | 2017 | 2018

1-prong taus

3-prong taus



# Hadronic Tau Fake Systematics




- Small differences in quark-gluon composition assessed by track jet width variable.
- Reweight data in Z+jets region to match track jet width
- distribution in the 3l CRs.
- Use difference in measured fake-rates before and after reweighting as systematics.

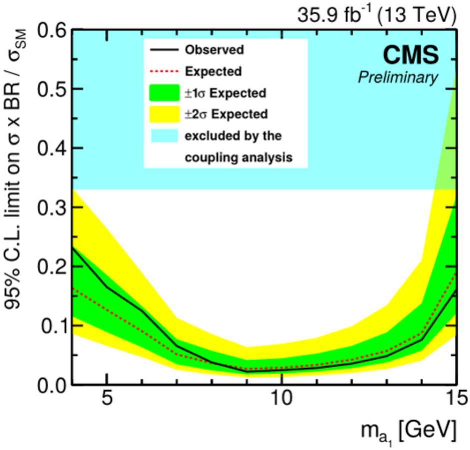
- Additional systematic uncertainties from statistics in Z+jets sample and from the subtraction of prompt lepton backgrounds using MC.

# Object Definition

| **Baseline lepton** | | **Baseline (Hadronic) Tau** |
| --- | --- | --- |
| **Muon** | **Electron** | |
| pT > 5 GeV, \|eta\| < 2.7 | pT > 7 GeV, \|eta\| < 2.47, not in crack region | pT > 20 GeV, \|eta\| < 2.5, not in crack region |
| At least Medium ID | **At LooseAndBLayerLH ID**<br>Loose Charge ID | **At least VeryLoose JETBDT ID**<br>EleOLR |
| z0sinTheta < 0.5 cm, **d0sig < 7** | z0sinTheta < 0.5 cm, d0sig < 5 | 1 or 3 prong |
| pass OLR | pass OLR | pass OLR |

| **Signal lepton** | | **Signal (Hadronic) Tau** |
| --- | --- | --- |
| **Muon** | **Electron** | |
| same as baseline | same as baseline | same as baseline |
| At least Medium ID<br>**FCTight isolation ID** | **At MediumLH ID**<br>Loose Charge ID<br>**FCTight isolation ID** | **At least Medium JETBDT ID** |
| **d0sig < 4** | d0sig < 5 | |

# CMS result at low mass

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