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Study the CP property of the Higgs boson in ATLAS experiment

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南京大学研究生毕业论文中文摘要首页用纸

毕业论文题目：在 ATLAS 实验中研究希格斯玻色子的 CP 性质

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对称性与守恒定律是物理学最基本的内容。电荷共轭与宇称联合对称性（ CP 对称性）与正反物质守恒息息相关。在粒子物理学中，标准模型是描述物质及其相互作用的最成功的且被完全验证的理论。在标准模型中，我们用小林-益川（KM）机制来解释宇宙中观察到的正反物质不对称现象。然而，利用 KM 机制所计算出的正反物质不对称的结果并不足以解释实验观察得到的数量级。因此在粒子物理学中，寻找新的 CP 破坏源尤为重要。

2012 年，在大型强子对撞机上发现希格斯玻色子，尽管这意味着所有标准模型粒子都被发现，但物理学中仍存在着诸如正反物质不对称等诸多未解决的问题。因此，我们希望通过精确测量希格斯玻色子的性质，来进一步验证标准模型的准确性，从而帮助我们发现超出标准模型的新物理的迹象例如新的 CP 破坏源。在标准模型中，希格斯玻色子不仅能与弱相互作用规范玻色子 $W^\pm$ 、 Z 通过电弱耦合相互作用，而且能与费米子通过汤川耦合相互作用。

在这篇论文中，我们将描述关于希格斯玻色子在与陶轻子汤川耦合顶点下的 CP 性质的研究。通过分析在 LHC 上的 ATLAS 实验记录的质心能量为 13 TeV 积分亮度为 139 fb^{-1} 的数据，我们将利用希格斯玻色子到两个陶轻子的衰变道来探究希格斯玻色子在与陶轻子的汤川耦合顶点下的 CP 性质。

在希格斯玻色子到两个陶轻子的衰变道的分析中，我们是用 CP 混合角 ϕ_τ 描述希格斯玻色子在与陶轻子的汤川耦合顶点下的 CP 性质，通过分析两个陶轻子的衰变平面夹角的分布将其测量出来。为了选取敏感的双陶衰变道，我们选取一个陶轻子衰变到轻子末态且另一个陶轻子衰变到强子末态（ $\tau_{\text{lep}}\tau_{\text{had}}$ ）的衰变道，和两个陶轻子都衰变到强子末态（ $\tau_{\text{had}}\tau_{\text{had}}$ ）的衰变道，并考虑所有希格斯玻色子的主要产生模式进行分析。在重建两个陶轻子的衰变平面之后，我们在可观测的陶轻子衰变产物的零动量系统中将观测量 φ_{CP}^* 计算出来。通过数据分析，我们拟合得到 CP 混合角 ϕ_τ 在 68% 的置信区间下的观测值（预期值）为 $9 \pm 16^\circ$ （ $0 \pm 28^\circ$ ）。结果的观测值（预期值）在 3.4σ （ 2.1σ ）下排除了纯 CP -odd 态的希格斯玻色子。测量结果在考虑误差范围内与标准模型预言结果相符合。这是 ATLAS 实验首次对希格斯玻色子与轻子汤川耦合顶点的 CP 性质的测量。

关键词：ATLAS 实验； CP 破坏；希格斯玻色子；陶轻子

南京大学研究生毕业论文英文摘要首页用纸

THESIS: Study the CP property of the Higgs boson in ATLAS experiment

SPECIALIZATION: Particle Physics and Nuclear Physics

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MENTOR: Professor Zhang Lei

Symmetry and conservation are elementary parts in the physics. The charge conjugation parity symmetry (CP -symmetry) is related to the conservation of matter and antimatter. Currently, the most successful and validated theory of depicting matter and its interaction is the Standard Model (SM) in particle physics. In the universe, there exists an imbalance between matter and antimatter and it is explained by CP violation (CPV) by introducing the Kobayashi-Maskawa (KM) mechanism in SM. However, the theoretical calculated results by the KM mechanism are not sufficient to explain the magnitude of the matter-antimatter asymmetry. Thus, a new source of the CPV is crucial in particle physics.

Although the discovery of the Higgs boson at the Large Hadron Collider (LHC) in 2012 meant that SM particles have been discovered completely, there are still some questions remained to be solved such as matter-antimatter asymmetry. Therefore, we want to measure the properties of the Higgs boson precisely, not only for further validation of the SM but also we want to find some hints of beyond Standard Model (BSM) physics like a new source of CPV in the Higgs sector for new physics. In SM, the Higgs boson can interact with weak gauge bosons by electroweak interaction, and with fermions by Yukawa coupling.

In this thesis, a rigorous study of CP property of the Higgs boson is presented in Higgs τ -lepton Yukawa coupling vertices. By analyzing data recorded by the ATLAS experiment at LHC in the center-of-mass of 13 TeV with an integrated luminosity of 139 fb^{-1} , we probed CP property of the Higgs boson in H - τ Yukawa coupling vertex in $H \rightarrow \tau\tau$ decay channel.

In the $H \rightarrow \tau\tau$ decay analysis, the Higgs boson CP property in interaction with τ lepton parameterized by the CP mixing angle ϕ_τ is measured by the distribution of the acoplanarity angle between di- τ decay planes. One leptonically decayed τ and the other hadronically decayed τ (marked as $\tau_{\text{lep}}\tau_{\text{had}}$) channel and both hadronically decayed τ (marked as $\tau_{\text{had}}\tau_{\text{had}}$) channels are considered with all main Higgs production modes in this analysis for sensitivity. After the reconstruction of two τ decay planes, an observable φ_{CP}^* is calculated in di- τ_{vis} zero-momentum-frame (ZMF). With statistic analysis, the mixing angle ϕ_τ is measured to be $9 \pm 16^\circ$ ($0 \pm 28^\circ$) as observed (expected) value at 68% confidence level (CL). And the pure CP -odd Higgs hypothesis is excluded at 3.4σ (2.1σ) level as observed (expected) value. The results are consistent with the Standard Model prediction considering the uncertainties. This is the first measurement of the CP property in the Higgs-lepton Yukawa coupling vertices

in the ATLAS experiment.

KEYWORDS: ATLAS experiment; Standard Model; CP violation; Higgs boson; tau lepton

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Introduction

Discovery of Higgs boson in the ATLAS [1] and CMS [2] experiment in LHC is a huge success of Standard Model. After that we are now more interested in some open questions which can not be resolved by the SM especially related to evolution of the universe. One of the questions related to this is why there are much more matter than antimatter in the universe? This question is expected to be explained by the Baryogenesis [3] process in which three conditions is needed for generating a baryon asymmetry called Sakharov conditions [4]:

- Baryon number violation
- C and CP violation
- Departure from the thermal equilibrium

Thus CP violation is a central topic for explanation of the matter-antimatter asymmetry. In SM, CP violation is introduced by Kobayashi-Maskawa mechanics [5]. Matter in the universe consists of the fundamental fermion particles and fermions are depicted by mass eigenstates and weak interaction eigenstates according to interaction processes. Transformation of these two states in quark sector is accomplished by Cabbibo-Kobayashi-Maskawa (CKM) matrix. If there are three generations in quark sector, the CKM matrix elements will have four degree of freedom and can be complex number thus the complex CP phase angle need to be introduced, then CP symmetry is naturally violated. However, calculation of CP violation results predicted by SM is not consistent with current observation of the universe. The magnitude of theory calculation can not satisfy the experiment measured data. Therefore, new source of CP violation is desired to account for the baryon asymmetry [6].

Higgs sector is one of the possible sources of CP violation. By precise measurement of the Higgs boson and its properties, we can obtain some prospective prompts of the physics beyond the SM. In SM the Higgs boson is predicted as a scalar which is a CP -even particle. Any deviation from the pure CP -even state of the Higgs will indicate new CP violation source in Higgs sector. In experiment measurement, Higgs CP property is measured by different interaction of vertices with SM particles [7–12]. In vertices of Higgs interacted with the fermion, the generalized lagrangian with also CP -odd part is employed to describe the Yukawa coupling. While in vertices of Higgs interacted with the vector boson, we are using the effective field theory in the Standard Model Effective Field Theory (SMEFT) framework

in Warsaw basis to extend CP violated HVV interaction. In the ATLAS experiment, such kind of measurements are implemented by several channels.

During a period from 2015 to 2018, the ATLAS experiment in LHC has finished the second run (Run2) of data collection. The data was recorded in the center-of-mass of 13 TeV with integrated luminosity of 139 fb^{-1} . With this set of data we can implement many researches and measurement to validation the SM and probe hints of BSM. The Higgs boson in the proton-proton collision is mainly produced by four kinds of production mode: gluon fusion (ggH), vector boson fusion (VBF), vector boson associated (VH) and $t\bar{t}$ associated ($t\bar{t}H$). And it mainly decays into b-quark pair ($b\bar{b}$), vector boson pair (WW^* , ZZ^*) and τ -lepton pair ($\tau^+\tau^-$). When measured the CP property of the Higgs boson, both production vertices and decay vertices are carefully considered for interpretation of the results. The Hff vertices CP results will be presented in this thesis.

Structure of the thesis

This thesis is arranged by sequence as follow: Chapter 1 will introduce some fundamental theory of the SM and CP physics. The ATLAS detector and experiment will be introduced in chapter 2. Chapter 3 will focus on the $H \rightarrow \tau\tau$ decay analysis which measured Higgs CP property, the analysis strategies and results will be presented in detail.

Clarification of personal contributions

The ATLAS experiment is run by over 3000 scientists from 182 institutions in 42 countries so it is a huge collaboration in research. Thus clarification of my personal contributions is necessary.

$H \rightarrow \tau\tau$ decay CP analysis

The $H \rightarrow \tau\tau$ decay analysis is using $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channel to measure the Higgs CP property. I am one of the main analyzer and focused on $\tau_{\text{lep}}\tau_{\text{had}}$ channel. I worked on event selection, background estimation and categorization optimization for sensitivity. I also worked on workspace preparation for statistics fit, and statistic interpretation and understanding of systematics. Besides, I helped with understanding of the $Z \rightarrow \tau\tau$ background behaviours. I was the editor of the internal note and presented the whole analysis to the ATLAS collaboration for approval of this analysis.

$H \rightarrow \tau\tau$ differential/STXS analysis

The $H \rightarrow \tau\tau$ legacy analysis for the Run2 data is mainly separated of two parts, differential and STXS analysis. This two parts are sharing the same data set and Monte Carlo (MC) samples. I helped with n-tuple preparations for the group. In this analysis I focused on the differential part and mainly on the EFT interpretation of the results. I prepared MC samples for EFT parameterization and implement the truth analysis as well as codes for these. Furthermore, I also did a statistic interpretation in EFT part.

HL-LHC ATLAS detector upgrade related work

To be added in author list in ATLAS experiment, it requires the one to pass a qualification task. My qualification task is about upgrade project of the High Granularity Time Detector (HGTD) in High Luminosity Large Hadron Collider (HL-LHC). I worked on optimization task of the link scheme between sensor modules to the peripheral board electronics.

Chapter 1

Theory

This chapter will give a brief introduction of the fundamental theory which will be used in the thesis. In this chapter, the CPT symmetry, Standard Model and the CP violation physics will be mainly presented. The main references are [13–18].

1.1 Symmetry and Conservation

Symmetry and conservation is an eternal topic in physics. It is related to the elemental properties of the physics system. In this section, an overview of the relationship between the symmetry and conservation described by Noether's theorem will be talked in Section 1.1.1. Following the Lorentz symmetry group and some representation of it will be discussed in Section 1.1.2. Then we will give the definition of the transformation of the charge conjugation, parity and time reversal and introduce the CPT theorem in Section 1.1.3.

1.1.1 Noether's theorem

Symmetry is about the invariance of the system under the transformation. In quantum physics, the symmetry can be briefly divided into the continuous and the discrete according to the differentiability of the transformation. For each symmetry there exists the corresponded conservation. The conservation of the continues is additional and the discrete quantum number is multiple.

The relationship between the continues symmetry and the conservation law is described by the Noether's theorem [19]

Noether's Theorem. *If a Lagrangian has a continuous symmetry then there exists a current associated with that symmetry that is conserved when the equations of motion are satisfied.*

This can be checked in the system with the Lagrangian $\mathcal{L}[\phi, \partial_\mu \phi]$ respected to the field

ϕ . The variation of the Lagrangian

$$\delta\mathcal{L} = \int d^4x \left\{ \left[\frac{\partial\mathcal{L}}{\partial\phi} - \partial_\mu \frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)} \right] \delta\phi + \partial_\mu \left[\frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)} \delta\phi \right] \right\} = 0 \quad (1.1)$$

with the Euler-Lagrangian equation

$$\frac{\partial\mathcal{L}}{\partial\phi} - \partial_\mu \frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)} = 0 \quad (1.2)$$

there will be the current

$$J^\mu \equiv \frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)} \delta\phi \quad (1.3)$$

and satisfied the conservation law $\partial_\mu J^\mu = 0$. This conserved current is called the Noether current.

1.1.2 Lorentz group and representation

The theory who is compatible with the special relativity will have the Lorentz invariance, which will be symmetric under the transformation of the Lorentz group. To start with, we first look at the Lorentz transformation Λ in the proper orthochronous Lorentz group $SO^+(1, 3)$ which is the subgroup of the Lorentz group $O(1, 3)$. The Lorentz transformation will keep the four dimension spacetime to be flat, which means

$$g^{\rho\sigma} = \Lambda^\rho_\mu g^{\mu\nu} \Lambda^\sigma_\nu$$

$$g^{\mu\nu} = \begin{bmatrix} +1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{bmatrix} \quad (1.4)$$

where the $g^{\mu\nu} = \text{diag}\{+1, -1, -1, -1\}$ is the Minkowski metric.

Consider the Lorentz transformation acts on the quantum fields. For the notation, we are using the $\phi(x)$ as the scalar, the $\psi_a(x)$ with $(a = 1, 2)$ as the Weyl spinor who has two complex components, the $A^\mu(x)$ with $(\mu = 0, 1, 2, 3)$ as the vector, and $F^{\mu\nu}(x)$ as the second order tensor. The Lorentz transformation can be presented as

$$\begin{aligned} U(\Lambda)^{-1} \phi(x) U(\Lambda) &= \phi(\Lambda^{-1}x) \\ U(\Lambda)^{-1} \psi(x)_a U(\Lambda) &= S_a^b \psi_b(\Lambda^{-1}x) \\ U(\Lambda)^{-1} A_\mu(x) U(\Lambda) &= \Lambda_\mu^\nu A_\nu(\Lambda^{-1}x) \\ U(\Lambda)^{-1} F_{\mu\nu}(x) U(\Lambda) &= \Lambda_\mu^\rho \Lambda_\nu^\sigma F_{\rho\sigma}(\Lambda^{-1}x) \end{aligned} \quad (1.5)$$

The element Λ in the Lorentz group can be written as the expression by the generators of $\text{SO}^+(1, 3)$.

$$\Lambda = \exp[i(\theta_i J_i + \beta_i K_i)] = \exp(i\omega_{\mu\nu} V^{\mu\nu}) \quad (1.6)$$

where the θ_i is the angle of the rotation and the β_i is rapidity. They could also be arranged as the rank-2 tensor $\omega_{\mu\nu}$.

There are six generators of $\text{SO}^+(1, 3)$ group as J_i and K_i with $(i = 1, 2, 3)$ in the 4-vector basis. The J_i is for the 3-D rotation and K_i is for the Lorentz boost. And they can be tidied up in to the anti-symmetry 16-dimensional matrices $V^{\mu\nu}$

$$\begin{aligned} J_1 &= i \begin{bmatrix} 0 & & & \\ & 0 & & \\ & & 0 & -1 \\ & & +1 & 0 \end{bmatrix}, J_2 = i \begin{bmatrix} 0 & & & \\ & 0 & -1 & \\ & & 0 & \\ +1 & & & 0 \end{bmatrix}, J_3 = i \begin{bmatrix} 0 & & & \\ & 0 & -1 & \\ +1 & & 0 & \\ & & & 0 \end{bmatrix} \\ K_1 &= i \begin{bmatrix} 0 & -1 & & \\ -1 & 0 & & \\ & & 0 & \\ & & & 0 \end{bmatrix}, K_2 = i \begin{bmatrix} 0 & -1 & & \\ & 0 & & \\ -1 & & 0 & \\ & & & 0 \end{bmatrix}, K_3 = i \begin{bmatrix} 0 & & -1 & \\ & 0 & & \\ & & 0 & \\ -1 & & & 0 \end{bmatrix} \\ V^{\mu\nu} &= \begin{bmatrix} 0 & K_1 & K_2 & K_3 \\ -K_1 & 0 & J_3 & -J_2 \\ -K_2 & -J_3 & 0 & J_1 \\ -K_3 & J_2 & -J_1 & 0 \end{bmatrix} \end{aligned} \quad (1.7)$$

We can find these six generators satisfied the relation

$$\begin{aligned} [J_i, J_j] &= i\varepsilon_{ijk} J_k \\ [J_i, K_j] &= i\varepsilon_{ijk} K_k \\ [K_i, K_j] &= -i\varepsilon_{ijk} J_k \end{aligned} \quad (1.8)$$

these are called the Lorentz algebra, the algebra structure of the $\text{SO}^+(1, 3)$ group.

Take a close look of the Lorentz algebra, we could construct the irreducible representation by defining the linear combinations of the generators

$$\begin{aligned} J_i^+ &\equiv \frac{1}{2}(J_i + iK_i) \\ J_i^- &\equiv \frac{1}{2}(J_i - iK_i) \end{aligned} \quad (1.9)$$

then the algebra will correspondingly become as

$$\begin{aligned} [J_i^+, J_j^+] &= i\varepsilon_{ijk} J_k^+ \\ [J_i^-, J_j^-] &= i\varepsilon_{ijk} J_k^- \\ [J_i^+, J_j^-] &= 0 \end{aligned} \tag{1.10}$$

these are exactly the Lie algebra of the SU(2). Thus the $SO^+(1, 3)$ group has the irreducible representation of the direct sum of two SU(2) group. The decomposition is

$$SO^+(3) = SU(2) \oplus SU(2) \tag{1.11}$$

This decomposition can also be presented when $J_i = J_i^+ + J_i^-$. Since the SU(2) group is homomorphism to the SO(3) group, the SO(3) group is one of the subgroup of the $SO^+(1, 3)$ group and it can be used for the description of spin. The quantum number of the spin can be related by the Clebsch-Gordan coefficients between these two representations. This is showed in the Table 1.1.

Table 1.1: Decomposition of the representation of $SU(2) \oplus SU(2)$ group and the corresponded quantum in SO(3) group

Representation of $SU(2) \oplus SU(2)$	(0,0)	$(\frac{1}{2}, 0)$	$(0, \frac{1}{2})$	$(\frac{1}{2}, \frac{1}{2})$	(1,0)	(1,1)
Representation of SO(3)	0	$\frac{1}{2}$	$\frac{1}{2}$	$1 \oplus 0$	1	$2 \oplus 1 \oplus 0$

Let us focus on the spinor case with the spin $\frac{1}{2}$. For a Weyl spinor with two components $\psi(x)$ there are two adjoint representation of $SU(2) \oplus SU(2)$ group $(\frac{1}{2}, 0)$ and $(0, \frac{1}{2})$ from the table. Define the $(\frac{1}{2}, 0)$ spinor as the left-handed spinor while the $(0, \frac{1}{2})$ as the right-handed spinor. They will have the generators with the Pauli matrices σ_i

- Left-handed spinor $(\frac{1}{2}, 0)$: $J_i^- = \frac{1}{2}\sigma_i$, $J_i^+ = 0$ or equivalently $J_i = \frac{1}{2}\sigma_i$, $K_i = \frac{i}{2}\sigma_i$
- Right-handed spinor $(0, \frac{1}{2})$: $J_i^- = 0$, $J_i^+ = \frac{1}{2}\sigma_i$ or equivalently $J_i = \frac{1}{2}\sigma_i$, $K_i = -\frac{i}{2}\sigma_i$

To determine the form of the Lorentz transformation over the spinor S in Equation (1.5), we extend the spinor to the four components with the direct sum of the left-handed and right-handed Weyl spinor as $\psi = \begin{bmatrix} \psi_L(x) \\ \psi_R(x) \end{bmatrix}$, then the S_a^b will become to the 4×4 matrices with the spinor indices $a, b = (1, 2, 3, 4)$.

The S can be generated by the set of generators of $SU(2) \oplus SU(2)$ group, with defining

the Pauli matrices $\vec{\sigma}$ into

$$\begin{aligned}\sigma^\mu &\equiv (\mathbb{1}, \vec{\sigma}) \\ \bar{\sigma}^\mu &\equiv (\mathbb{1}, -\vec{\sigma}) \\ \gamma^\mu &= \begin{bmatrix} & \sigma^\mu \\ \bar{\sigma}^\mu & \end{bmatrix}\end{aligned}\tag{1.12}$$

and the gamma matrices γ^μ satisfied the relationship

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}\tag{1.13}$$

this is called the Clifford algebra. The gamma matrices γ^μ is always satisfied the Clifford algebra regardless of what representation is used.

Then the Lorentz transformation over the spinor S can be written as

$$S = \exp(i\omega_{\mu\nu}S^{\mu\nu})\tag{1.14}$$

with six generators $S^{\mu\nu}$ for $SU(2) \oplus SU(2)$ group. Notice they are different to the Lorentz transformation of the vector defined by $V^{\mu\nu}$. The $S^{\mu\nu}$ can be written by the gamma matrices

$$S^{\mu\nu} = \frac{i}{4} [\gamma^\mu, \gamma^\nu] = \frac{1}{2} \sigma^{\mu\nu}\tag{1.15}$$

The explicit expression of the γ^μ and $S^{\mu\nu}$ will rely on the representation, here we show the form in the Weyl representation

$$\gamma^0 = \begin{bmatrix} & \mathbb{1} \\ \mathbb{1} & \end{bmatrix}, \gamma^i = \begin{bmatrix} & \sigma^i \\ -\sigma^i & \end{bmatrix}\tag{1.16}$$

$$S^{ij} = \frac{1}{2} \epsilon^{ijk} \begin{bmatrix} \sigma^k & \\ & \sigma^k \end{bmatrix}, S^{0i} = -\frac{i}{2} \begin{bmatrix} \sigma^i & \\ & -\sigma^i \end{bmatrix}\tag{1.17}$$

The other useful definition related to the gamma matrices γ^μ is γ^5 . And its explicit expression in the Weyl representation

$$\begin{aligned}\gamma^5 &\equiv i\gamma^0\gamma^1\gamma^2\gamma^3 \\ \gamma^5 &= \begin{bmatrix} -\mathbb{1} & \\ & \mathbb{1} \end{bmatrix}\end{aligned}\tag{1.18}$$

with the four components spinor $\psi = \begin{bmatrix} \psi_L \\ \psi_R \end{bmatrix}$ we can define the chirality projection operators

$$\begin{aligned} P_L &= \frac{1 - \gamma^5}{2} = \begin{bmatrix} \mathbb{1} & 0 \\ 0 & 0 \end{bmatrix} \\ P_R &= \frac{1 + \gamma^5}{2} = \begin{bmatrix} 0 & 0 \\ 0 & \mathbb{1} \end{bmatrix} \end{aligned} \quad (1.19)$$

then we can get each chirality component by the projection operators. the left-handed spinor $P_L\psi = \begin{bmatrix} \psi_L \\ 0 \end{bmatrix}$ and the right-handed spinor $P_R\psi = \begin{bmatrix} 0 \\ \psi_R \end{bmatrix}$.

There are two types of four components spinor, divided by whether the left-handed and right-handed components are same we have the Dirac spinor and the Majorana spinor. Here we would specify the spinor indices for each component. We would use the dot to distinguish the left-handed spinor indices to right-handed spinor (e.g. if one left-handed spinor is with indices a the corresponded right-handed spinor will be $\dot{a}$) and they are related by the Hermite conjugation $(\psi_a)^\dagger = \psi_{\dot{a}}^\dagger$. For the Weyl spinor, the position of the indices will introduce the different result. We can use the ε symbol to related the upper and lower spinor indices as $\psi^a = \varepsilon^{ab}\psi_b$. And the $\varepsilon^{ab} = \varepsilon^{\dot{a}\dot{b}} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$ and $\varepsilon_{ab} = \varepsilon_{\dot{a}\dot{b}} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$.

The Dirac spinor has two different components and using the χ and ξ for the left-handed and right-handed Weyl spinor

$$\psi \equiv \begin{bmatrix} \chi_a \\ \xi^{\dagger\dot{a}} \end{bmatrix} \quad (1.20)$$

with the Weyl spinor indices $a = (1, 2)$ and the Dirac spinor will have the intrinsic U(1) symmetry for these two component under the transformation $\chi \rightarrow e^{-i\alpha}\chi$ and $\xi \rightarrow e^{i\alpha}\xi$. The adjoint Dirac spinor will be defined as $\bar{\psi} \equiv \psi^\dagger\gamma^0 = \begin{bmatrix} \xi^a & \chi_{\dot{a}}^\dagger \end{bmatrix}$. But we should be careful of the chirality of the adjoint spinor it should be $\bar{\psi} = \begin{bmatrix} \psi_R^\dagger & \psi_L^\dagger \end{bmatrix}$ and compatible to $\bar{P}_L\bar{\psi} = \bar{\psi}P_R = \begin{bmatrix} 0 & \psi_L^\dagger \end{bmatrix}$. With this the Lagrangian of the Dirac spinor and with the spinor indices form will be

$$\begin{aligned} \mathcal{L}_{Dirac} &= \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi \\ &= i(\xi^a\sigma_{ac}^\mu\partial_\mu\xi^{\dagger\dot{c}} + \chi_{\dot{a}}^\dagger\bar{\sigma}^{\mu\dot{a}c}\partial_\mu\chi_c) - m(\xi^a\chi_a + \chi_{\dot{a}}^\dagger\xi^{\dagger\dot{a}}) \end{aligned} \quad (1.21)$$

be careful of the consequence of the product of the spinor since the fermions obey the Fermi-Dirac statistic, there will be a minus sign when exchange two fermions. For convention, define the spinor indices contract as $\chi\psi = \chi^a\psi_a$ and $\chi^\dagger\psi^\dagger = \chi^{\dagger\dot{a}}\psi_{\dot{a}}^\dagger$. The opposite contract will also introduce the minus sign like $\chi^a\psi_a = \varepsilon^{ab}\chi_b\psi_a = -\varepsilon^{ba}\chi_b\psi_a = -\chi_b\psi^b$. Then we will have the relation $\chi\psi = \chi^a\psi_a = -\psi_a\chi^a = \psi^a\chi_a = \psi\chi$. The anticommutative property of

the spinor will make it to satisfy the Grassmann algebra.

The Majorana spinor has the same component

$$\psi \equiv \begin{bmatrix} \psi_a \\ \psi^{\dagger\dot{a}} \end{bmatrix} \quad (1.22)$$

with the Weyl spinor indices $a = (1, 2)$ and the Majorana spinor will have the intrinsic $\text{SO}(2)$ symmetry for these two component under the transformation $\begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix} \rightarrow \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix}$. Similarly, the Lagrangian of the Majorana spinor and with the spinor indices form will be

$$\begin{aligned} \mathcal{L}_{Majorana} &= \frac{1}{2} \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi \\ &= i\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi - \frac{1}{2} m (\psi^a \psi_a + \psi_a^\dagger \psi^{\dagger\dot{a}}) \end{aligned} \quad (1.23)$$

We now have the Lagrangian of the free spinor field for both Dirac and Majorana type. These two kinds of spinor will behave differently under the charge conjugation transformation discussed in the next section.

1.1.3 Charge conjugation, parity, time reversal and CPT theorem

In Section 1.1.2 we focus on the proper orthochronous Lorentz group $\text{SO}^+(1, 3)$. The proper group requires the determination of the group elements to be 1 ($\det \Lambda = +1$), while when $\det \Lambda = -1$ it will be called the improper group. The orthochronous means that the first element of the matrices is greater than or equal to 1 $\Lambda^0_0 \geq +1$.

There exists the Lorentz transformation which can not be generated within the $\text{SO}^+(1, 3)$. Typically, the parity transformation is improper and the time reversal transformation is both nonorthochronous and improper. Their action on the four vector form can be presented as $\mathcal{P}$ and $\mathcal{T}$ and the matrices will be

$$\mathcal{P}^\mu_\nu = \begin{bmatrix} +1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{bmatrix} \quad (1.24)$$

$$\mathcal{T}^\mu_\nu = \begin{bmatrix} -1 & & & \\ & +1 & & \\ & & +1 & \\ & & & +1 \end{bmatrix} \quad (1.25)$$

with the parity and time reversal transformation we can extend to the Lorentz group $O(1, 3)$.

In the previous section we also have the Lagrangian the free spinor fields, applying it to the Euler-Lagrangian we can get the Dirac equation which is the equation of motion of the free spinor

$$i(\gamma^\mu \partial_\mu - m)\psi = 0 \quad (1.26)$$

with four plane wave solutions when the momentum is 0, $u_+(0) = \sqrt{m} \begin{bmatrix} 1 & 0 & 1 & 0 \end{bmatrix}^T$, $u_-(0) = \sqrt{m} \begin{bmatrix} 0 & 1 & 0 & 1 \end{bmatrix}^T$, $v_+(0) = \sqrt{m} \begin{bmatrix} 0 & 1 & 0 & -1 \end{bmatrix}^T$ and $v_-(0) = \sqrt{m} \begin{bmatrix} -1 & 0 & 1 & 0 \end{bmatrix}^T$. The u is solutions for particle while the v is the solutions for antiparticle. These solution can be generalized to any momentum $\mathbf{p}$ with $u_s(\mathbf{p}) = \exp(i\beta \hat{\mathbf{p}} \cdot \mathbf{K})u_s(0)$ and $v_s(\mathbf{p}) = \exp(i\beta \hat{\mathbf{p}} \cdot \mathbf{K})v_s(0)$, where the $s = (+, -)$ is the degree of freedom of the spin, the $\beta = \sinh^{-1}(|\mathbf{p}|/m)$ is the rapidity and K is the generators of the Lorentz group. With this sets of solution we can get the charge conjugation relation between the particle and antiparticle.

The symmetry study of the spinor bilinear structure is very useful for the construction of the possible Lagrangian. The common spinor bilinear $\bar{\psi}\Gamma\psi$ will be the $\bar{\psi}\psi$, $\bar{\psi}\gamma^5\psi$, $\bar{\psi}\gamma^\mu\psi$, $\bar{\psi}\gamma^\mu\gamma^5\psi$, $\bar{\psi}\sigma^{\mu\nu}\psi$. In this section, we are particularly interested in the spinor bilinear and their symmetry under the C , P , T transformation will be discussed in detail.

1.1.3.1 Charge conjugation

The charge conjugation transformation C will change the particle into its antiparticle partner and vice versa. From the respective of the group theory, it will transform one representation to its complex conjugate representation. In this transformation all the charge number will become opposite. Charge conjugation transformation acting on the scalar will be $C^{-1}\phi(x)C = \phi^*(x)$, and for vector boson $C^{-1}A_\mu(x)C = -A_\mu^\dagger(x)$.

Define the charge conjugation over the spinor as

$$\psi^C(x) = C^{-1}\psi(x)C = -i\gamma^2\psi^*(x) \quad (1.27)$$

it can be quickly verified by the plane wave solutions that $C^{-1}u_sC = v_s$ and $C^{-1}v_sC = u_s$.

There will be an equivalent definition which will use the charge conjugation $\mathcal{C} = \begin{bmatrix} -\varepsilon^{ac} & \\ 0 & \varepsilon_{\dot{a}\dot{c}} \end{bmatrix}$.

The charge conjugation will become

$$\psi^C(x) = C^{-1}\psi(x)C = \mathcal{C}\bar{\psi}^T(x) \quad (1.28)$$

this is exactly identical to the previous definition because $\mathcal{C}\gamma^0 = -i\gamma^2$, and this expression will be more precise when using the spinor indices.

Apply the charge conjugation to both Dirac spinor ψ_D and Majorana ψ_M . We can find

that $\psi_D^C = \begin{bmatrix} \xi_a \\ \chi^{\dagger\dot{a}} \end{bmatrix}$ and $\psi_M^C = \begin{bmatrix} \psi_a \\ \psi^{\dagger\dot{a}} \end{bmatrix}$. For the Dirac spinor it indicates that $C^{-1}\xi C = \chi$ and $C^{-1}\chi C = \xi$, and the antiparticle of a Majorana spinor is itself.

Consider the charge conjugation on the spinor bilinear $\bar{\psi}\Gamma\psi$, the sign will be determined by $\gamma^0\gamma^2\Gamma^T\gamma^0\gamma^2$. The summary of the charge conjugation on the spinor bilinear is

$$\begin{aligned} C^{-1}(\bar{\psi}\psi)C &= +\bar{\psi}\psi \\ C^{-1}(\bar{\psi}i\gamma^5\psi)C &= +\bar{\psi}i\gamma^5\psi \\ C^{-1}(\bar{\psi}\gamma^\mu\psi)C &= -\bar{\psi}\gamma^\mu\psi \\ C^{-1}(\bar{\psi}\gamma^\mu\gamma^5\psi)C &= +\bar{\psi}\gamma^\mu\gamma^5\psi \end{aligned} \tag{1.29}$$

1.1.3.2 Parity

The parity transformation P is also called the space reversal or the mirror reflection, it will flip the sign of the spatial coordinate. The parity is the symmetry to exchange the chiral structure. If a scalar system after the parity transformation is $P^{-1}\phi(x)P = \pm\phi(\mathcal{P}x)$, with a plus $+$ it is said that the system has the even parity while the minus $-$ is the odd parity. For the vector boson $P^{-1}A_\mu(x)P = \mathcal{P}_\mu^\nu A_\nu(\mathcal{P}x)$.

The form of the parity transformation over the spinor will be

$$P^{-1}\psi(x)P = \gamma^0\psi(\mathcal{P}x) \tag{1.30}$$

for a Dirac spinor we have $P^{-1}\chi_a(x)P = \xi^{\dagger\dot{a}}(\mathcal{P}x)$ and $P^{-1}\xi^{\dagger\dot{a}}(x)P = \chi_a(\mathcal{P}x)$, the parity will exchange the chiral part.

The sign of acting the parity on the spinor bilinear $\bar{\psi}\Gamma\psi$ will be determined by $\gamma^0\Gamma\gamma^0$, this will be summarized below

$$\begin{aligned} P^{-1}(\bar{\psi}\psi)P &= +\bar{\psi}\psi \\ P^{-1}(\bar{\psi}i\gamma^5\psi)P &= -\bar{\psi}i\gamma^5\psi \\ P^{-1}(\bar{\psi}\gamma^\mu\psi)P &= +\mathcal{P}^\mu_\nu\bar{\psi}\gamma^\nu\psi \\ P^{-1}(\bar{\psi}\gamma^\mu\gamma^5\psi)P &= -\mathcal{P}^\mu_\nu\bar{\psi}\gamma^\nu\gamma^5\psi \end{aligned} \tag{1.31}$$

by these relation the $\bar{\psi}\psi$ will be called scalar, $\bar{\psi}i\gamma^5\psi$ is pseudoscalar, $\bar{\psi}\gamma^\mu\psi$ is polar vector and $\bar{\psi}\gamma^\mu\gamma^5\psi$ is axial vector.

1.1.3.3 Time reversal

The time reversal transformation T will change the direction of the time evolution. In quantum mechanism, the Schrodinger equation is $i\partial_t\psi(x) = \hat{H}\psi(x)$. Act the time reversal on it and it becomes $-i\partial_t\psi^*(\mathcal{T}x) = \hat{H}\psi^*(\mathcal{T}x)$. To make the form of the Schrodinger equation

unchanged, the time reversal transformation should be antiunitary which indicates that $T^{-1}iT = -i$. This will require that the gamma matrices changed as $T : \gamma^{0,1,3,5} \rightarrow \gamma^{0,1,3,5}$ and $T : \gamma^2 \rightarrow -\gamma^2$ under the time reversal. Thus for the spinor

$$T^{-1}\psi(x)T = \gamma^1\gamma^3\psi(\mathcal{T}x) \quad (1.32)$$

For the spinor bilinear $\bar{\psi}\Gamma\psi$ under the time reversal transformation, the sign will rely on the $\gamma^3\gamma^1\Gamma^*\gamma^1\gamma^3$. These relations are

$$\begin{aligned} T^{-1}(\bar{\psi}\psi)T &= +\bar{\psi}\psi \\ T^{-1}(\bar{\psi}i\gamma^5\psi)T &= -\bar{\psi}i\gamma^5\psi \\ T^{-1}(\bar{\psi}\gamma^\mu\psi)T &= -\mathcal{T}^\mu_\nu\bar{\psi}\gamma^\nu\psi \\ T^{-1}(\bar{\psi}\gamma^\mu\gamma^5\psi)T &= -\mathcal{T}^\mu_\nu\bar{\psi}\gamma^\nu\gamma^5\psi \end{aligned} \quad (1.33)$$

1.1.3.4 CPT theorem

Now let us consider the combined transformation CPT . Following the definition before, the CPT transformation on the spinor will be expressed as

$$(CPT)^{-1}\psi(x)CPT = -i\gamma^2\gamma^0\gamma^1\gamma^3\psi^*(-x) = -\gamma^5\psi^*(-x) \quad (1.34)$$

Similarly, the spinor bilinear $\bar{\psi}\Gamma\psi$ under the CPT transformation will related to $\gamma^0\gamma^5\Gamma^\dagger\gamma^5\gamma^0$. They can be also easily gotten by the combination of the C , P , T transformation

$$\begin{aligned} (CPT)^{-1}(\bar{\psi}\psi)(CPT) &= +\bar{\psi}\psi \\ (CPT)^{-1}(\bar{\psi}i\gamma^5\psi)(CPT) &= +\bar{\psi}i\gamma^5\psi \\ (CPT)^{-1}(\bar{\psi}\gamma^\mu\psi)(CPT) &= -\bar{\psi}\gamma^\mu\psi \\ (CPT)^{-1}(\bar{\psi}\gamma^\mu\gamma^5\psi)(CPT) &= -\bar{\psi}\gamma^\mu\gamma^5\psi \end{aligned} \quad (1.35)$$

For the derivation $CPT : \partial_\mu \rightarrow -\partial_\mu$ it will be minus sign under the CPT since the combined P and T transformation. Therefore, for the spinor bilinear we can count the uncontracted Lorentz indices μ , if it is even(odd) then the CPT symmetry will be even(odd).

As the common Lagrangian $\mathcal{L}$ will be constructed with the corresponded scalar, spinor bilinear and vector fields with all Lorentz indices contracted, we have the CPT symmetry under the transformation $CPT : \mathcal{L}(x) \rightarrow \mathcal{L}(-x)$. This is known as the CPT theorem

CPT Theorem. *For the physics system that all laws of physics must be invariant under the combination of CPT transformation.*

1.2 The Standard Model

The Standard Model is the paramount theory to describe the fundamental particles and their interactions in particle physics in current. It is a theory based on the renormalizable quantum field theory (QFT). In this section, the Yang-Mills theory which describes the interaction by introducing the gauge invariance will be presented in Section 1.2.1. And the Higgs mechanism with the spontaneous symmetry breaking that allows the particle to acquire the mass will be introduced in Section 1.2.2. Then the fundamental particles and their interactions as well as the unification of weak and electromagnetic interactions will be discussed in Section 1.2.3.

1.2.1 Gauge invariance and Yang-Mills theory

The information of a physics system is described by the Lagrangian for its properties and kinematics. By the Hamilton's principle (principle of least action) we can get the equation of motion of the system using the Euler-Lagrange equation by its Lagrangian. In QFT, the interaction can be naturally introduced by requiring the local gauge invariance to a free system [20].

To start with the system of N Dirac fermions described by N free spinor fields $\Psi = (\psi_1, \dots, \psi_N)^T$, the Lagrangian of this system is

$$\mathcal{L}_0 = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi \quad (1.36)$$

if applying the Euler-Lagrangian equation we will get the Dirac equation for N equations of motion of free fermions.

The system can be operated under the transformation $\hat{U}$ in the $SU(N)$ symmetry group, which is a unitary transformation $\hat{U}^\dagger \hat{U} = I$. The $SU(N)$ symmetry can be either global or local depends on whether the group parameter is dependent on x . Here we focus on the local gauge transformation

$$\begin{aligned} \Psi(x) &\rightarrow \Psi'(x) = \hat{U}\Psi(x) \\ \hat{U}[\alpha(x)] &= e^{i\alpha^a(x)\hat{T}^a} \end{aligned} \quad (1.37)$$

with $\alpha(x)$ are the group parameters, and $\hat{T} = (\hat{T}^1, \dots, \hat{T}^n)$ are n generators of the $SU(N)$ symmetry group ($n = N^2 - 1$) and satisfied the Lie algebra and also non-Abelian when $N > 1$

$$[\hat{T}^a, \hat{T}^b] = if^{abc}\hat{T}^c \quad (1.38)$$

Supposed the system is local gauge invariant which means that we can find a local gauge transformation to make the Lagrangian invariant under the $SU(N)$ symmetry transforma-

tion, this require the derivative to become to the covariant derivative

$$D_\mu \equiv \partial_\mu - ig\hat{T}^a A_\mu^a(x) \quad (1.39)$$

with g is the coupling constant, and $A_\mu^a(x)$ are the 4-dimension gauge boson vector field.

By specifying the invariance of the derivative term $D_\mu \Psi \rightarrow \hat{U} \cdot D_\mu \Psi$, the local gauge transformation can be presented to ensure the gauge invariance

$$\begin{aligned} A_\mu^a &\rightarrow A'^a_\mu = \hat{U} A_\mu^a \hat{U}^{-1} - \frac{i}{g} (\partial_\mu \hat{U}) \hat{U}^{-1} \\ &= A_\mu^a + \frac{1}{g} \partial_\mu \alpha^a - f^{abc} \alpha^b A_\mu^c \end{aligned} \quad (1.40)$$

Using Equation (1.39) to elevate the derivative in Equation (1.36), now we have the Lagrangian

$$\mathcal{L} = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi - g\bar{\Psi}\gamma^\mu \hat{T}^a \Psi A_\mu^a \quad (1.41)$$

in which $\mathcal{L}_{kin} = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi$ is the kinematic term and the $\mathcal{L}_{int} = -g\bar{\Psi}\gamma^\mu \hat{T}^a \Psi A_\mu^a$ term represents the interaction of fermion and gauge vector boson. Hence, we get the interaction term by requiring the local gauge invariance of the free fermion fields system.

Defining the gauge boson field tensor

$$\begin{aligned} F_{\mu\nu} &= \frac{i}{g} [D_\mu, D_\nu] = \hat{T}^a F_{\mu\nu}^a \\ F_{\mu\nu}^a &= \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf^{abc} A_\mu^b A_\nu^c \end{aligned} \quad (1.42)$$

then we have the kinematic term of the vector boson, as well as the gauge boson self coupling when the gauge field is non-Abelian

$$\mathcal{L}_{YM} = -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu,a} \quad (1.43)$$

this term is also local gauge invariant, now the system of the fermions and vector boson with the interaction can be presented as $\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{int} + \mathcal{L}_{YM}$.

1.2.2 Spontaneous symmetry breaking and Brout-Englert-Higgs mechanism

In the discussion before, we got the interaction term by introducing the local gauge invariance. However, the gauge boson terms are required to be massless. This is because if we add the mass term of gauge boson $\mathcal{L}_m = -m_A^2 A_\mu^a \cdot A^{a,\mu}$ artificially, this term will break the local gauge invariance. To describe the gauge boson with mass, the Brout-Englert-Higgs mechanism [21, 22] is in effect.

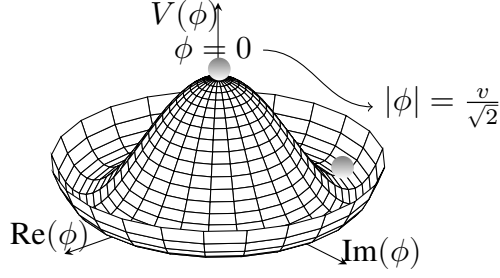


Figure 1.1: Complex scalar field potential when $\mu^2 < 0$.

This mechanism is highly related to the concept of the spontaneous symmetry breaking. If the system has a symmetry at the unstable state, the symmetry will be lost when the system tends to the stable state which is called the spontaneous symmetry breaking. In QFT, considering the complex scalar field ϕ with the potential $V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2$

$$\begin{aligned} \mathcal{L} &= T(\phi) - V(\phi) \\ &= (\partial_\mu \phi)^* (\partial^\mu \phi) - \mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2 \end{aligned} \quad (1.44)$$

To determine the shape of the scalar field potential, we try to find the extremum point by $\frac{\partial V(\phi)}{\partial |\phi|} = 2\mu^2 |\phi| + 4\lambda |\phi|^3 = 0$. The minimal value is divided in two cases. If the $\mu^2 > 0$ the minimum $|\phi|_{min} = 0$ will be the point of origin in coordinates and it is a trivial case and no spontaneous symmetry breaking happens. What is interested to us is the case of $\mu^2 < 0$, the shape of the complex scalar field potential shape is shown in Figure 1.1 and the minimum will be

$$|\phi|_{min} = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}} \quad (1.45)$$

where the v is named as vacuum expectation value (VEV). The process that the system tend to be stable from $\phi = 0$ to $|\phi| = \frac{v}{\sqrt{2}}$ is called spontaneous symmetry breaking.

Before the spontaneous symmetry breaking, the Lagrangian has the local U(1) gauge symmetry under the transformation $\phi(x) \rightarrow \phi'(x) = e^{i\alpha(x)} \phi(x)$. This symmetry will be hidden if the spontaneous symmetry breaking happened under the scalar field substitution

$$\phi(x) = \frac{1}{\sqrt{2}} e^{i\frac{\xi(x)}{v}} [h(x) + v] \quad (1.46)$$

in which the complex scalar field is replaced by two real scalar fields, the $\xi(x)$ is called the Goldstone field and the $h(x)$ is called the Higgs field. With the Taylor expansion of the exponential term we can get the lowest order $\phi(x) = \frac{1}{\sqrt{2}} [h(x) + i\xi(x) + v]$, the $h(x)$ and $\xi(x)$ can represent the real and imagine part of the complex scalar, respectively. For the spontaneous symmetry breaking of the SU(n) symmetry group, there will be $N = n^2 - 1$ massless Goldstone boson for each group generator and this is called Goldstone's theorem.

To introduce the gauge field, elevating the derivative in Equation (1.44) into covariant

derivative and with the gauge transformation in U(1) case

$$\begin{aligned}\partial_\mu &\rightarrow D_\mu = \partial_\mu - ieA_\mu(x) \\ A_\mu(x) &\rightarrow A'_\mu(x) = A_\mu(x) + \frac{1}{e}\partial_\mu\alpha(x)\end{aligned}\tag{1.47}$$

with the coupling constant e and the gauge vector field $A_\mu(x)$.

To eliminate the unobserved Goldstone field, let $\alpha(x) = -\frac{\xi(x)}{v}$. Then the scalar field spontaneous symmetry breaking and U(1) gauge transformation will become to

$$\begin{aligned}\phi(x) &\rightarrow \phi'(x) = \frac{1}{\sqrt{2}}e^{i\frac{\xi(x)}{v}}[h(x) + v] \\ A_\mu(x) &\rightarrow A'_\mu(x) = A_\mu(x) - \frac{1}{ev}\partial_\mu\xi(x)\end{aligned}\tag{1.48}$$

Substituting the Equation (1.48) into Equation (1.44) with the covariant derivative, we can get the Lagrangian

$$\begin{aligned}\mathcal{L} = &\frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda v^4 \\ &- \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}e^2 v^2 A_\mu A^\mu + e^2 v A_\mu A^\mu h + \frac{1}{2}e^2 A_\mu A^\mu h^2\end{aligned}\tag{1.49}$$

From the Lagrangian we found that there is the mass term of the gauge field $\frac{1}{2}e^2 v^2 A_\mu A^\mu$ with the mass $m_A = ev$. With the gauge transformation in Equation (1.48), the gauge boson acquire the mass by absorbing the Goldstone boson in the process of spontaneous symmetry breaking and this is called the Higgs mechanism.

1.2.3 Electroweak unification and Glashow-Weinberg-Salam model

This section will introduce fundamental particles and interactions in Standard Model. There are three kinds of fundamental particles in SM, the fermions to form the substances, the gauge boson to propagate the interactions and the scalar to provide the mass.

With the Yang-Mills theory and Brout-Englert-Higgs mechanism, we can construct the interaction and mass terms of the fundamental particles in SM. The fundamental interactions in SM are described by the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry group, where the $SU(3)_C$ symmetry group will be used for the strong interaction while the $SU(2)_L \otimes U(1)_Y$ is for the electroweak interaction [23–25]. And the spontaneous symmetry breaking will happen in the $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$, resulting the massive weak gauge boson and massless electromagnetic gauge boson.

The whole Standard Model Lagrangian consist of the Quantum Chromodynamics (QCD) part and Electroweak (EW) part and each part will be introduced in detail in the subsections

below

$$\mathcal{L}_{SM} = \mathcal{L}_{QCD} + \mathcal{L}_{EW} \quad (1.50)$$

1.2.3.1 Fundamental particles

The particles are divided into fermion and boson according to its spin and statistical properties.

- Fermion: the particle with the spin of the half integer, and obey Fermi-Dirac statistics
- Boson: the particle with the spin of the integer, and obey Bose-Einstein statistics

In SM, the fundamental fermions are divided into two categories as leptons and quarks according their interactions. The lepton can only engage in the EW interaction while the quark can engage in both QCD and EW. Both lepton and quark are grouped into three families known as the generation.

There are six type of leptons as electron(e), muon(μ), tau(τ), electron neutrino(ν_e), muon neutrino(ν_μ) and tau neutrino(ν_τ). And also six type of quarks called up(u), down(d), charm(c), strange(s), top(t) and bottom(b). The type of the lepton or quark is known as the flavour. Each type of the fermion has its anti-particle partner with the opposite quantum number. The properties of the fundamental fermions are summarized in the Table 1.2.

Table 1.2: Fundamental fermions grouped in three generations with the main properties in Standard Model

Fermion	Generation			Charge	Spin
	1 st	2 nd	3 rd		
Lepton	ν_e	ν_μ	ν_τ	0	1/2
	e	μ	τ	-1	
Quark	u	c	t	2/3	
	d	s	b	-1/3	

There are mainly two type of bosons in SM, the vector boson with the spin 1 who is the propagator of the interactions and the scalar boson with spin 0 to endue the mass to the massive particles.

The vector bosons also known as the gauge bosons are derived from the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry group. In QCD $SU(3)_C$ gauge symmetry group there are eight generators and corresponded to eight massless bi-colour gluons(g) to propagate the strong interaction. The $SU(2)_L \otimes U(1)_Y$ gauge symmetry group will have only $U(1)_{EM}$ symmetry remained after the spontaneous symmetry breaking, resulting three massive gauge boson $W^\pm$, Z to carry the weak interaction and one massless gauge boson photon(γ) corresponded to $U(1)_{EM}$ for the electromagnetic interaction. And the scalar boson named as the Higgs boson(H) is for the mass term by the Higgs mechanism introduced in Section 1.2.2. The properties of the fundamental bosons are summarized in the Table 1.3.

Table 1.3: Fundamental bosons with the main properties in Standard Model

Boson	Charge	Spin	Mass(GeV)
g	0	1	0
$W^\pm$	± 1		80.38
Z	0		91.19
γ	0		0
H	0	0	125.25

1.2.3.2 Quantum Chromodynamics (QCD)

The strong interaction is described by the QCD which is one case of the non-Abelian gauge symmetry group $SU(3)_C$ as Section 1.2.1 introduced. In SM only quarks experience the strong interaction and this is described by the Lagrangian

$$\mathcal{L}_{QCD} = i\bar{Q}\gamma^\mu D_\mu Q - \frac{1}{4}G_{\mu\nu}^a G^{\mu\nu,a} \quad (1.51)$$

with the covariant derivative and the gluon gauge field tensor

$$\begin{aligned} D_\mu &= \partial_\mu - ig_s T^a G_\mu^a \\ G_{\mu\nu}^a &= \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c \end{aligned} \quad (1.52)$$

where the $Q(x)$ represents the quark field, G_μ^a is the massless gluon boson field and g_s is the strong coupling constant. The $T^a = \frac{1}{2}\lambda^a$ are the generators of $SU(3)_C$ symmetry group with λ^a are the Gell-Mann matrices. The $SU(3)_C$ symmetry group has eight generators thus the index $a = 1, \dots, 8$ and there are eight kinds of gluons. The f^{abc} is the Lie group structure constants and the non-Abelian terms indicate the self-coupling of the gluons.

The self-coupling of the gluon will have large impact on the QCD behaviours. When calculating the loop correction of the QCD process, the gluon self-coupling will contribute to the loop. The strong coupling constant relies on the energy Q of the propagation $\alpha_s(Q^2) = \frac{g_s(Q^2)}{4\pi}$. Considering the gluon self-coupling in loop correction, the constant $\alpha_s(Q^2)$ will tend to 0 when Q tends to the very large number, this is called the asymptotic freedom. And the $\alpha_s(Q^2)$ will become to very large when Q is small and resulting the colour confinement, which leads to no free quark would be observed in the experiment.

1.2.3.3 Electroweak and Glashow-Weinberg-Salam model

The electroweak interaction is described by the $SU(2)_L \otimes U(1)_Y$ gauge symmetry group with the spontaneous symmetry breaking $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$.

For the non-Abelian weak interaction gauge group $SU(2)_L$, there would be the $SU(2)$ doublets of the left-handed fermions (left-handed particles and right-handed antiparticles)

and the weak interaction in the charged current is left-handed chiral structure and maximally parity-violated. The right-handed chiral structure fermions will be the SU(2) singlets and will occur in the neutral current of the weak interaction.

The Abelian gauge group $U(1)_Y$ denotes the conservation of the hypercharge. The hypercharge Y is related to the charge number Q and the third component of the quantum number in the SU(2) group named as weak isospin T . This is presented by the Gell-Mann Nishijima equation

$$\frac{Y}{2} = Q - T_3 \quad (1.53)$$

The fundamental particle fields who can participate the electroweak interaction included the left-handed fermion doublets Ψ'_L (lepton L'_L and quark Q'_L), the right-handed fermion singlets ψ'_R (lepton l'_R and quark q'_R) and the scalar doublets Φ . Notice that up to now there is no right-handed neutrino observed. These particle fields are the eigenstates in the flavour basis of the weak interaction so we add the apostrophe to distinguish to the mass eigenstates and their quantum numbers are summarized in Table 1.4.

Table 1.4: Fundamental particles engaged in the electroweak interaction with the quantum number related to $SU(2)_L \otimes U(1)_Y$ gauge symmetry group

Particles field	T	T_3	Q	$\frac{Y}{2}$	Structure
$L'_{iL} = \begin{pmatrix} \nu'_{iL} \\ l'_{iL} \end{pmatrix} : \begin{pmatrix} \nu'_{eL} \\ e'_{iL} \end{pmatrix}, \begin{pmatrix} \nu'_{\mu L} \\ \mu'_{iL} \end{pmatrix}, \begin{pmatrix} \nu'_{\tau L} \\ \tau'_{iL} \end{pmatrix}$	1/2	+1/2 -1/2	0 -1	-1/2	$\hat{P}_L = \frac{1}{2}(1 - \gamma^5)$
$Q'_{iL} = \begin{pmatrix} u'_{iL} \\ d'_{iL} \end{pmatrix} : \begin{pmatrix} u'_L \\ d'_L \end{pmatrix}, \begin{pmatrix} c'_L \\ s'_L \end{pmatrix}, \begin{pmatrix} t'_L \\ b'_L \end{pmatrix}$	1/2	+1/2 -1/2	+2/3 -1/3	+1/6	
$l'_{iR} : e'_R, \mu'_R, \tau'_R$	0	0	-1	-1	$\hat{P}_R = \frac{1}{2}(1 + \gamma^5)$
$u'_{iR} : u'_R, c'_R, t'_R$	0	0	+2/3	+2/3	
$d'_{iR} : d'_R, s'_R, b'_R$	0	0	-1/3	-1/3	
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	1/2	+1/2 -1/2	+1 0	1/2	-

The complete electroweak Lagrangian can be presented as

$$\begin{aligned}
\mathcal{L}_{EW} &= \mathcal{L}_{f-G} + \mathcal{L}_G + \mathcal{L}_H + \mathcal{L}_{Yukawa} \\
\mathcal{L}_{f-G} &= i(\bar{\Psi}'_L \not{D} \Psi'_L + \bar{\psi}'_R \not{D} \psi'_R) \\
\mathcal{L}_G &= -\frac{1}{4}(W_{\mu\nu}^a W^{a,\mu\nu} + B_{\mu\nu} B^{\mu\nu}) \\
\mathcal{L}_H &= (D_\mu \Phi)^*(D^\mu \Phi) - \mu^2 \Phi^* \Phi - \lambda(\Phi^* \Phi)^2 \\
\mathcal{L}_{Yukawa} &= - \sum_{i=1,2,3} \sum_{j=1,2,3} (Y_{ij}^L \bar{L}'_{iL} \Phi l'_{jR} + Y_{ij}^d \bar{Q}'_{iL} \Phi d'_{jR} + Y_{ij}^u \bar{Q}'_{iL} \tilde{\Phi} u'_{jR} + h.c.)
\end{aligned} \quad (1.54)$$

with all scalar and fermion fields notation summarized in the table before, and the Feynman slashed notation to stand for the Einstein sum of the γ^μ matrices with the spacetime indices (e.g. $\not{D} = \gamma^\mu D_\mu$). The Y^i is the 3×3 complex matrix for the Yukawa coupling constants.

The $\mathcal{L}_{f-G}$ is the fermion kinematic and the fermion-gauge boson interaction term, $\mathcal{L}_G$ is the gauge boson kinematic and self-coupling term, $\mathcal{L}_H$ is the Higgs boson field term and provide the mass to the gauge boson, and the $\mathcal{L}_{Yukawa}$ is the term for the Higgs-fermion Yukawa coupling and the fermion mass term. The detail of the Lagrangian will be discussed later.

Before the spontaneous symmetry breaking, the system has the symmetry under the local gauge transformation $\hat{U}(\alpha, \theta) = e^{i\alpha(x) \cdot \frac{\hat{\sigma}}{2}} e^{i\theta(x) \frac{\hat{Y}}{2}}$ corresponded to the symmetry group $SU(2)_L \otimes U(1)_Y$. The $\hat{T} = \frac{\hat{\sigma}}{2}$ and $\frac{\hat{Y}}{2} = \frac{\hat{I}}{2}$ are the generators of the $SU(2)$ and the $U(1)$ symmetry group, respectively. With the $\hat{\sigma}$ and the $\hat{I}$ are the Pauli matrices and the identity matrix.

The covariant derivative corresponded to the $SU(2)_L \otimes U(1)_Y$ symmetry group is

$$D_\mu = \partial_\mu - ig \frac{\sigma^a}{2} W_\mu^a - ig' \frac{Y}{2} B_\mu \quad (1.55)$$

where the $W_\mu^a (a = 1, 2, 3)$ and B_μ are vector gauge fields.

With the covariant derivative Equation (1.55) the Lagrangian $\mathcal{L}_{int}$ will become to

$$\begin{aligned} \mathcal{L}_{f-G} &= \sum_{\substack{i=\nu_l, q_u \\ j=l, q_d}} [\bar{\psi}'_{iL} \quad \bar{\psi}'_{jL}] \begin{bmatrix} i\hat{\phi} - \frac{1}{2}(gW^3 + g'Y_{iL}\hat{B}) & -\frac{1}{2}[g(W^1 - iW^2)] \\ -\frac{1}{2}[g(W^1 + iW^2)] & i\hat{\phi} + \frac{1}{2}(gW^3 - g'Y_{jL}\hat{B}) \end{bmatrix} \begin{bmatrix} \psi'_{iL} \\ \psi'_{jL} \end{bmatrix} \\ &\quad + \bar{\psi}'_{iR}(i\hat{\phi} - \frac{1}{2}g'Y_{iR}\hat{B})\psi'_{iR} + \bar{\psi}'_{jR}(i\hat{\phi} - \frac{1}{2}g'Y_{jR}\hat{B})\psi'_{jR} \\ &= \mathcal{L}_{f,kin} + \mathcal{L}_{f-G,int} \end{aligned} \quad (1.56)$$

except the kinematic $\mathcal{L}_{f,kin} = i(\bar{\Psi}'_L \hat{\phi} \Psi'_L + \bar{\psi}'_R \hat{\phi} \psi'_R)$ term, we will call the diagonal term the neutral current (NC) and the off-diagonal the charged current (CC) interaction term, and notice that the indices i, j should always be in same generation.

Consider the physical states of the interaction term, define the gauge boson

$$\begin{aligned} \begin{bmatrix} W_\mu \\ W_\mu^\dagger \end{bmatrix} &= \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -i \\ 1 & i \end{bmatrix} \begin{bmatrix} W_\mu^1 \\ W_\mu^2 \end{bmatrix} \\ \begin{bmatrix} Z_\mu \\ A_\mu \end{bmatrix} &= \begin{bmatrix} \cos \theta_W & -\sin \theta_W \\ \sin \theta_W & \cos \theta_W \end{bmatrix} \begin{bmatrix} W_\mu^3 \\ B_\mu \end{bmatrix} \end{aligned} \quad (1.57)$$

the gauge fields W_μ , $W_\mu^\dagger$ and Z_μ propagate the weak interaction and corresponded to $W^\pm$ and Z gauge boson, and gauge field A_μ is the propagator of the electromagnetic interaction and its particle is γ . By knowing the neutrinos would not participate the electromagnetic interaction, we can get the relationship between the coupling constant and the weak mixing angle (a.k.a. Weinberg angle) θ_W as $\tan \theta_W = \frac{g'}{g}$ and $g \sin \theta_W = e$ with the e and g are the electromagnetic and weak coupling constant, respectively.

After substituting the transformation Equation (1.57) into the interaction Lagrangian term, it will be

$$\begin{aligned}
\mathcal{L}_{f-G,int} &= \left(-\frac{g}{2\sqrt{2}}j_W^\mu W_\mu + h.c.\right) - \frac{g}{2\cos\theta_W}j_Z^\mu Z_\mu - ej_\gamma^\mu A_\mu \\
j_W^\mu &= \sum_{\substack{i=\nu_l, q_u \\ j=l, q_d}} \bar{\psi}'_i \gamma^\mu (1 - \gamma^5) \psi'_j \\
j_Z^\mu &= \sum_{i=\nu_l, l, q_u, q_d} \bar{\psi}'_i \gamma^\mu (c_V^i - c_A^i \gamma^5) \psi'_i \\
j_\gamma^\mu &= \sum_{i=l, q_u, q_d} Q_i \bar{\psi}'_i \gamma^\mu \psi'_i
\end{aligned} \tag{1.58}$$

where the $c_V^i = T_3^i - 2Q^i \sin^2 \theta_W$ and $c_A^i = T_3^i$ are the constants of the vector and axial-vector current in the neutral weak interaction which indicates it is partial parity-violated. The charged weak current is left-handed chiral structure with the indices i, j should always being in same generation. Obviously, there are charged weak, neutral weak and electromagnetic interactions of the fermion current and the gauge vector boson in the Lagrangian.

The gauge boson term $\mathcal{L}_G$ with the transformation in Equation (1.57) will become to

$$\begin{aligned}
\mathcal{L}_G &= -\frac{1}{4}[2W_{\mu\nu}W^{\dagger\mu\nu} + Z_{\mu\nu}Z^{\mu\nu} + F_{\mu\nu}F^{\mu\nu}] \\
&+ ig\cos\theta_W[W_{\mu\nu}Z^\mu W^{\dagger\nu} - W_{\mu\nu}^\dagger Z^\mu W^\nu + Z_{\mu\nu}W^{\dagger\mu}W^\nu] \\
&+ ie[W_{\mu\nu}A^\mu W^{\dagger\nu} - W_{\mu\nu}^\dagger A^\mu W^\nu + F_{\mu\nu}W^{\dagger\mu}W^\nu] \\
&+ g^2\cos^2\theta_W[(W_\mu Z^\mu)(W_\nu^\dagger Z^\nu) - (W_\mu W^{\dagger\mu})(Z_\nu Z^\nu)] \\
&+ e^2[(W_\mu A^\mu)(W_\nu^\dagger A^\nu) - (W_\mu W^{\dagger\mu})(A_\nu A^\nu)] \\
&+ eg\cos\theta_W[(W_\mu A^\mu)(W_\nu^\dagger A^\nu) + (W_\mu^\dagger Z^\mu)(W_\nu A^\nu) - 2(W_\mu W^{\dagger\mu})(Z_\nu A^\nu)] \\
&+ \frac{1}{2}g^2[(W_\mu W^\mu)(W_\nu^\dagger W^{\dagger\nu}) - (W_\mu W^{\dagger\mu})^2]
\end{aligned} \tag{1.59}$$

with the first line is the gauge fields kinematic and the rest are the gauge field coupling.

For the scalar term, the complex scalar doublets can be wrote as $\Phi = \begin{bmatrix} \phi^+ \\ \phi^0 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{bmatrix}$ equivalent as four real scalars. When the spontaneous symmetry breaking described in the Section 1.2.2 happens, three goldstone bosons will be gauged-away to let the $W^\pm$ and Z boson acquire the mass, then remaining one Higgs boson $H(x)$. This process is corresponded as the $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$ and the remaining $U(1)_{EM}$ symmetry is related to the massless photon field. The spontaneous symmetry breaking will introduce the transformation of the complex scalar field around the vacuum expectation value v

$$\Phi(x) = \frac{1}{\sqrt{2}} e^{i\frac{\hat{\sigma}^a}{2} \cdot \frac{\xi^a(x)}{v}} \begin{bmatrix} 0 \\ v + H(x) \end{bmatrix} \tag{1.60}$$

With this Equation (1.60) and the covariant derivative in Equation (1.55) as well as the gauge boson field transformation in Equation (1.57), the scalar Lagrangian term will become to

$$\begin{aligned}\mathcal{L}_H = & \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - \lambda v^2 H^2 - \lambda v H^3 - \frac{1}{8}\lambda H^8 \\ & + \frac{v^2 g^2}{8} W_\mu W^{\dagger\mu} + \frac{v^2 g^2}{8 \cos^2 \theta_W} Z_\mu Z^\mu \\ & + \frac{v g^2}{2} W_\mu W^{\dagger\mu} H + \frac{v g^2}{8 \cos^2 \theta_W} Z_\mu Z^\mu H + \frac{g^2}{4} W_\mu W^{\dagger\mu} H^2 + \frac{g^2}{8 \cos^2 \theta_W} Z_\mu Z^\mu H^2\end{aligned}\quad (1.61)$$

where the first line is the Higgs field kinematic, mass and self-interaction term with the Higgs boson mass $m_H = \sqrt{2\lambda v^2} = \sqrt{-\mu^2}$. The second line is the mass term of the $W^\pm$ and Z boson in which the $W^\pm$ boson mass $m_W = \frac{1}{2}vg$ and Z boson mass $m_Z = \frac{vg}{2\cos\theta_W}$. The third line is the interaction term of the Higgs boson and $W^\pm$, Z boson.

The Yukawa coupling term is divided into the down-type fermions (leptons and d , s , b quarks) and up-type fermions (neutrinos and u , c , t quarks). The down-type fermions couple with the Φ while the up-type fermions couple with $\tilde{\Phi} = i\sigma^2\Phi^*$ to ensure the gauge invariance before the spontaneous symmetry breaking. After the spontaneous symmetry breaking, the scalar field becomes to $\Phi = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v+H \end{bmatrix}$ and the $\tilde{\Phi} = \frac{1}{\sqrt{2}} \begin{bmatrix} v+H \\ 0 \end{bmatrix}$.

Remember that the weak eigenstates is not identical to the mass eigenstates which is shown in the complex Yukawa coupling matrices Y^i is the 3×3 non-diagonal since there will be the mixing across the three generations in the same type (e.g. $\psi'_l = \begin{bmatrix} e' & \mu' & \tau' \end{bmatrix}^T$, $\psi'_d = \begin{bmatrix} d' & s' & b' \end{bmatrix}^T$, $\psi'_u = \begin{bmatrix} u' & c' & t' \end{bmatrix}^T$). To present the mass term in the mass-basis, using the transformation for $\psi' = U\psi$ to diagonalize the Y^i to make $U_L^i Y^i U_R^{i\dagger}$ diagonal.

For any spinor mass term we have $\mathcal{L}_{mass} = -m\bar{\psi}\psi = -m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$, together with the diagonal transformation into the mass-basis and scalar field after spontaneous symmetry breaking, the Yukawa Lagrangian will become to

$$\mathcal{L}_{Yukawa} = - \sum_{i=l,q_u,q_d} \left(\frac{y_i v}{\sqrt{2}} \bar{\psi}_i \psi_i + \frac{y_i}{\sqrt{2}} \bar{\psi}_i \psi_i H \right) \quad (1.62)$$

where the first term is the fermion mass term with $m_i = \frac{y_i v}{\sqrt{2}}$ and the second term is the fermion-Higgs Yukawa coupling, with the free Yukawa coupling parameters y_i should be measured by the fermion mass in the experiment.

1.3 The CP Physics

With the Standard Model Lagrangian introduced in Section 1.2, we can consider its symmetry property with the knowledge in Section 1.1. The CP transformation will change

a particle into its corresponded antiparticle partner with the opposite chiral structure thus the CP violation is related to the matter-antimatter asymmetry. In SM, there will be the CP violation source in the weak interaction by the Kobayashi-Maskawa mechanism described in Section 1.3.1. The CP violation can be also introduced in the strong interaction as showed in Section 1.3.2. At last, in order to find more CP violation sources for the possible solution to the matter-antimatter asymmetry puzzle, the CP in Higgs sector is discussed in the Section 1.3.3.

1.3.1 Weak CP violation and Kobayashi-Maskawa mechanism

It is obviously that the weak interaction violates the parity symmetry. As for the CP symmetry, the CP violation in the weak interaction will occur when the mixing matrix transformed the spinor flavour eigenstates into the mass eigenstates has the complex matrix elements, which is described as the Kobayashi-Maskawa mechanism [5]. In this section, the weak interaction in the quark and lepton sectors will be discussed separately.

1.3.1.1 CP in the quark sector and Cabibbo-Kobayashi-Maskawa matrix

The weak interaction showed in Equation (1.58) is spanned by the flavour basis and in the Yukawa coupling Equation (1.62) we discussed a way to transform the flavour basis of the spinor into its mass basis.

The unitary transformation $\psi' = U\psi$ on the spinor bilinear will be trivial if the adjoint spinor is same as the spinor thus the neutral current will be the same form. The nontrivial matrix elements will occur when the spinor is mixed over the generation then the charged current will have the extra matrix term compared with the flavour basis. In terms of the mass basis of Equation (1.58) the quark sector is

$$\begin{aligned} \mathcal{L}_{q-G, mass} = & - \sum_{i,j=1,2,3} \frac{g}{2\sqrt{2}} [\bar{u}_i \gamma^\mu (1 - \gamma^5) (V)^{ij} d_j W_\mu^+ + \bar{d}_i \gamma^\mu (1 - \gamma^5) (V^\dagger)^{ij} u_j W_\mu^-] \\ & - \frac{g}{2 \cos \theta_W} j_Z^\mu Z_\mu - e j_\gamma^\mu A_\mu \end{aligned} \quad (1.63)$$

where the V^{ij} is the complex mixing matrix elements and by definition it is

$$V \equiv U_L^{u\dagger} U_L^d = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \quad (1.64)$$

which is known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

Consider the general scenario that there are n generations of fermions, then there will be $n \times n$ complex matrix elements in the mixing matrix which will have $2n^2$ real degree

of freedom. The unitarity will provide n^2 equation to eliminate n^2 real degree of freedom. For $2n$ Dirac type of spinor there is the residual $U(1)^{2n}$ global symmetry with $\psi \rightarrow e^{i\alpha}\psi$ thus there are $2n$ extra phases, but the overall phase is float so this condition will eliminate $2n - 1$ real degree of freedom. In a word, for the n generation Dirac spinor, the degree of freedom for the mixing matrix will be $2n^2 - n^2 - (2n - 1) = (n - 1)^2$.

Therefore, the 3×3 CKM matrix will have 4 real parameters. We can either choose standard parameterization with 3 rotation angles and 1 complex phase $(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ or Wolfenstein parameterization (λ, A, ρ, η) . After parameterization the CKM matrix will be

$$V = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{bmatrix} \begin{bmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{bmatrix} \begin{bmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1.65)$$

$$V = \begin{bmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}(\lambda^4) \quad (1.66)$$

With the unitarity of the CKM matrix, we can get its geometry illustration called the unitarity triangle. Unitarity requirement is $\sum_i V_{ij} V_{ik}^* = \delta_{jk}$, choose one equation $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$, we can get the complex vector sum as

$$\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} + \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} + 1 = 0 \quad (1.67)$$

and this is showed in the complex plane as a unitarity triangle in Figure 1.2

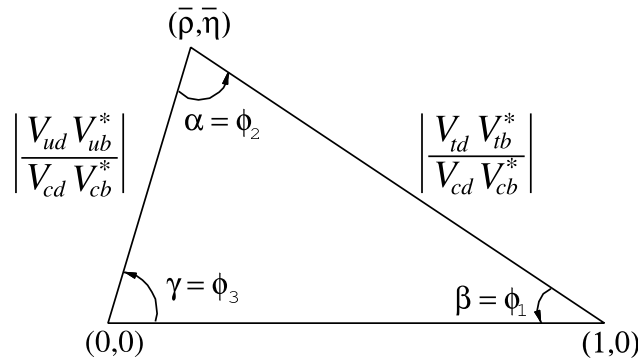


Figure 1.2: The unitarity triangle of the CKM matrix in the complex plane.

Now consider the CP transformation on the Equation (1.63), with the transformation in Equation (1.29) and Equation (1.31), for the vector field $(CP)^{-1} W_\mu^+ (CP) = -\mathcal{P}^\mu{}_\nu W_\mu^-$

and $(CP)^{-1}W_\mu^-(CP) = -\mathcal{P}^\mu_\nu W_\mu^+$, the charged current part will become to

$$\begin{aligned}\mathcal{L}_{CC}^{CP} &= (CP)^{-1}\mathcal{L}_{CC}CP \\ &= - \sum_{i,j=1,2,3} \frac{g}{2\sqrt{2}} \{ \bar{u}_i \gamma^\mu (1 - \gamma^5) [(V^\dagger)^T]^{ij} d_j W_\mu^+ + \bar{d}_i \gamma^\mu (1 - \gamma^5) [V^T]^{ij} u_j W_\mu^- \} \quad (1.68)\end{aligned}$$

compared with Equation (1.63), the Lagrangian will be invariant under the CP transformation if and only if the CKM matrix is real $V^* = V$. Thus we can say that it is the complex phase in CKM matrix that introduces the CP violation, which is called the Kobayashi-Maskawa mechanism.

The CP violation can be quantified by the basis independent variable Jarlskog invariant. This can be defined by whether we can diagonalize the up type and down type quark simultaneously. Without lose the generality, we can calculate it in the Hermitian basis that we can diagonalize the complex mass matrices in the flavour basis into the mass basis by $UM_u U^\dagger = D_u = \text{diag}(\frac{m_u}{m_t}, \frac{m_c}{m_t}, 1)$ and $U' M_d U'^\dagger = D_d = \text{diag}(\frac{m_d}{m_b}, \frac{m_s}{m_b}, 1)$, and the mixing matrix $V = UU'^\dagger$. By studying the commutator $-iC = [M_u, M_d] = -U^\dagger [D_u, V D_d V^\dagger] U$, we can know if these two mass matrices can be diagonalized simultaneously with calculating its determinant

$$\begin{aligned}\det C &= -2F_u F_d J \\ F_u &= \frac{1}{m_t^3} (m_t - m_c)(m_t - m_u)(m_c - m_u) \\ F_d &= \frac{1}{m_b^3} (m_b - m_s)(m_b - m_d)(m_s - m_d) \\ \sum_{m,n} \varepsilon_{ikm} \varepsilon_{jln} J &= \text{Im}(V_{ij} V_{kl} V_{il}^* V_{kj}^*)\end{aligned} \quad (1.69)$$

in the standard parameterization the J will be

$$J = s_{12} s_{23} s_{31} c_{12} c_{23} c_{31}^2 \sin \delta \quad (1.70)$$

with $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$. The Jarlskog invariant J is proportional to the $\sin \delta$ and if the $J \neq 0$ the CP will be violated. There is also the geometry interpretation of the J that it is the area twice of the unitarity triangle Figure 1.2.

The weak CP violation in the quark sector can be measured by the decay of kaon or B meson. With the measurement of the branching ratio of the mass eigenstates kaon K_S and K_L mixed by the CP eigenstates $K_1 = \frac{d\bar{s}+s\bar{d}}{2}$ and $K_2 = \frac{d\bar{s}-s\bar{d}}{2}$ decayed into 2π and 3π respectively, the results will be related to the CP violation.

In Section 1.1.3.4 the CPT theorem told us that the Lagrangian is always with the CPT symmetry. Therefore, if the CP symmetry is broken in one system, then the T symmetry is also broken. It is indicated in Equation (1.63) the charged current process with the complex

CKM elements will not be invariant under the T transformation since it is antiunitary $T^{-1}iT = -i$. The CP violation indicates the T is violated, which results that the process will behave different running forwards and backwards in time.

1.3.1.2 CP in the lepton sector and Pontecorvo-Maki-Nakagawa-Sakata matrix

This section will focus on the weak interaction in the lepton sector. In the introduction of the Standard Model, the neutrinos are described as the massless fermions, then there will not be the mixing in neutrino eigenstates. However, the neutrino oscillation is observed in the experiment which indicated that the neutrinos do have the mass. Thus, the mixing matrix of between the flavour and mass eigenstates can also be defined like before in lepton sector, and this is called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.

Since the neutrinos are neutral fermions, they can be either Dirac spinors or the Majorana spinors. For the Dirac spinors, the degree of freedom of the mixing matrix is $(n - 1)^2$ counted as the CKM matrix. Since the antiparticle of the Majorana spinor is itself, it can not provide the extra phase to eliminate the degree of freedom. Therefore, the degree of freedom of the PMNS matrix for n Majorana neutrinos and n charged Dirac leptons is $2n^2 - n^2 - n = n(n - 1)$.

For the three generation leptons, the Standard parameterization of the PMNS matrix can choose 3 rotation angles with 1 complex Dirac phase and 2 complex Majorana phases $(\phi_{12}, \phi_{13}, \phi_{23}, \alpha, \beta_1, \beta_2)$ if the neutrinos are Majorana spinors

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi_{23} & \sin \phi_{23} \\ 0 & -\sin \phi_{23} & \cos \phi_{23} \end{bmatrix} \begin{bmatrix} \cos \phi_{13} & 0 & \sin \phi_{13} e^{i\alpha} \\ 0 & 1 & 0 \\ -\sin \phi_{13} e^{i\alpha} & 0 & \cos \phi_{13} \end{bmatrix} \begin{bmatrix} \cos \phi_{12} & \sin \phi_{12} & 0 \\ -\sin \phi_{12} & \cos \phi_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{i\frac{\beta_1}{2}} \\ 0 & 0 & e^{i\frac{\beta_2}{2}} \end{bmatrix} \quad (1.71)$$

The CP violation in lepton sector is indicated by the complex phases in PMNS matrix. And this can be measured in the processes of the neutrino oscillation. The processes of $P(\nu_e) \rightarrow P(\nu_\mu)$ under the CP transformation is $P(\bar{\nu}_e) \rightarrow P(\bar{\nu}_\mu)$ and the difference between these two will indicate the CP violated which is also related to the Jarlskog invariant J .

1.3.2 Strong CP problem

The strong interaction Lagrangian in SM is given by Equation (1.51) and this term has the CP -even symmetry under CP transformation. Consider the global chiral symmetry, the Lagrangian with the mass term will be extended as

$$\mathcal{L} = -\frac{1}{4}G_{\mu\nu}^a G^{\mu\nu,a} + \theta \frac{g_s^2}{32} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + \bar{Q}(i\gamma^\mu D_\mu - m e^{-i\phi\gamma^5})Q \quad (1.72)$$

where the $\tilde{G}^{\mu\nu}$ is the Hodge dual tensor relative to the $G_{\mu\nu}$

$$\tilde{G}^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}F_{\rho\sigma} \quad (1.73)$$

Using the C , P transformation introduced in Section 1.1.3.1 and Section 1.1.3.2, and CP properties for the vector boson $(CP)^{-1}A_\mu(CP) = -\mathcal{P}_\mu{}^\nu A_\nu$ and for the field tensor $(CP)^{-1}F_{\mu\nu}(CP) = -\mathcal{P}_\mu{}^\rho\mathcal{P}_\nu{}^\sigma F_{\rho\sigma}$, we can get that the $G_{\mu\nu}^a G^{\mu\nu,a}$ term is C -even, P -even and CP -even, and the $\varepsilon^{\mu\nu\rho\sigma}G_{\mu\nu}^a G_{\rho\sigma}^a$ term is C -even, P -odd and CP -odd. Thus the Lagrangian with the sum of these two terms in Equation (1.72) will violate the CP symmetry.

The global $U(1)_A$ chiral symmetry transformation $\Psi \rightarrow e^{-i\alpha\gamma^5}\Psi$ and $\bar{\Psi} \rightarrow e^{i\alpha\gamma^5}\bar{\Psi}$ will give the extra phase factor in the path integral $\int \mathcal{D}\bar{\Psi}\mathcal{D}\Psi \rightarrow \int \mathcal{D}\bar{\Psi}\mathcal{D}\Psi \exp\left[-i\alpha \int \frac{g_s^2}{16\pi^2}G_{\mu\nu}^a \tilde{G}^{\mu\nu,a}\right]$. These transformation will provide the phase in Equation (1.72) for the $G_{\mu\nu}^a \tilde{G}^{\mu\nu,a}$ term that $\theta \rightarrow \theta - 2\alpha$ and the phase of the mass term $\phi \rightarrow \phi - 2\alpha$ simultaneously. The unchanged equivalent phase will be $\theta - \phi$. We would like to deal with the real mass then we can choose the α to estimate the ϕ which is related to the Yukawa matrix Y^u and Y^d and get the $G_{\mu\nu}^a \tilde{G}^{\mu\nu,a}$ term relies on the strong CP phase $\bar{\theta}$

$$\begin{aligned} \phi &= \arg \det(Y^u Y^d) \\ \bar{\theta} &= \theta - \arg \det(Y^u Y^d) \end{aligned} \quad (1.74)$$

thus the $\bar{\theta} \frac{g_s^2}{32} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a}$ will be the CP violated term in the strong interaction.

This global $U(1)_A$ chiral symmetry will also introduce the anomalous which means it is a symmetry in the classical fields but not in the quantum theory. Since the $G_{\mu\nu}^a \tilde{G}^{\mu\nu,a}$ term can be written as a differential form completely

$$\begin{aligned} \varepsilon^{\mu\nu\rho\sigma}G_{\mu\nu}^a G_{\rho\sigma}^a &= \partial_\mu J_{CS}^\mu \\ J_{CS}^\mu &= \varepsilon^{\mu\nu\rho\sigma}(A_{nu}^a F_{\rho\sigma}^a - \frac{g_s}{3}f^{abc}A_\nu^a A_\rho^b A_\sigma^c) \end{aligned} \quad (1.75)$$

the J_{CS}^μ is named as the Chern-Simons current. Since this term is a total derivative it will not go in the perturbation Feynman diagram as the in and out momentum will be conserved and with the sum of zero. Such $\bar{\theta}$ effect can only be measured in the non-perturbation process like the electric dipole moment (EDM) of the neutron. The EDM results constrain $\bar{\theta} < 10^{-10}$. The smallness of the $\bar{\theta}$ compared with the CP violation in weak part known as the strong CP problem. There are many endeavors and one of the solution is the Axion which is the Goldstone boson introduced by the $U(1)_{PQ}$ Peccei-Quinn symmetry spontaneously broke. Interestingly, the axions are also one of the candidates for the dark matter.

1.3.3 CP in the Higgs sector

In the previous section the Kobayashi-Maskawa mechanism is introduced for the weak CP violation while the CP violation in strong interaction is almost negligible in SM. With the measurement of the CKM matrix we can estimate the matter-antimatter asymmetry in the universe. However, compared with the observed baryon asymmetry of the universe (BUA) $\eta = (n_b - n_{\bar{b}}/n_\gamma 10^{-10})$, the calculation results from SM CP violation by the complex phase in CKM matrix δ is insufficient to interpret such scale. Thus the new source of CP violation is required to explain the matter-antimatter asymmetry in the universe.

The Higgs boson is discovered by the ATLAS and CMS experiments in LHC and its properties are in particular interest. In the Section 1.2.3.3 the Higgs boson is predicted as the CP -even particle. And the Higgs sector is a strong candidate for the new source of CP violation. The generalized Yukawa coupling in the Hff vertices and the extended HVV vertices in the SM supplemented with higher dimensional operators (the SMEFT) framework for the Higgs CP study will be introduced in this section.

1.3.3.1 Generalized Yukawa coupling and the Hff vertices

It is indicated in Equation (1.62) that the Higgs-fermion Yukawa coupling has CP -even symmetry in SM. We can extend the Yukawa coupling with also the CP -odd part

$$\mathcal{L}_{H\psi\psi} = -\frac{m_\psi}{v}\kappa_\psi(\cos\phi_\psi\bar{\psi}\psi + \sin\phi_\psi\bar{\psi}i\gamma^5\psi)H \quad (1.76)$$

where the ϕ_ψ is Higgs CP mixing angle. With the knowledge in Section 1.1.3, it is easy to see that the $\bar{\psi}i\gamma^5\psi H$ is CP -odd, thus the $\mathcal{L}_{H\psi\psi}$ violates the CP symmetry when $\phi_\psi \neq 0$.

1.3.3.2 SMEFT and the HVV vertices

Equation (1.61) showed the CP -even symmetry in HVV vertices in SM. This can be also extended into Standard Model Effective Field Theory Lagrangian spanned by Warsaw basis and can be interpreted with the dimension 6 operators $\mathcal{O}_i^{(6)}$

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} \quad (1.77)$$

in which we have CP -odd part of HVV vertices represented by $\mathcal{O}_{H\widetilde{W}} = H^\dagger H \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$, $\mathcal{O}_{H\widetilde{B}} = H^\dagger H \widetilde{B}_{\mu\nu} B^{\mu\nu}$ and $\mathcal{O}_{H\widetilde{WB}} = H^\dagger \sigma^I H \widetilde{W}_{\mu\nu}^I B^{I\mu\nu}$, where the H and B are the vector boson fields before the spontaneous symmetry as showed in Equation (1.55) and its Hodge dual tensor and by constructed as Equation (1.73).

In the experiment, we can constrain the corresponding Wilson coefficients c_i with the measurement to check the CP properties in the HVV vertices.

Chapter 2

The ATLAS Experiment

This chapter will give a brief introduction of the ATLAS experiment in LHC at CERN. Description of the LHC and ATLAS experiment will be in Section 2.1 and Section 2.2. And we will concisely introduce upgrade to the High-Luminosity Large Hadron Collider (HL-LHC) in Section 2.3.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [26] is the largest particle accelerator with the highest center-of-mass energy that human can reach up to now. It is located at CERN around the Geneva lake in Switzerland.

The machine is a two-ring-superconducting-hadron accelerator and the ring is around 26.7 kilometers long, lies between 45 to 170 meters underground. It is mainly used to collide the proton-proton beam, besides we can run some heavy-ion beams. The accelerator is designed with the maximum center-of-mass energy of $\sqrt{s} = 14$ TeV and peak luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Inside of the LHC, number of protons per bunch is up to 10^{11} and collision frequency is about 40 MHz, with the interval between each bunch about 25 ns.

The acceleration process is illustrated in Figure 2.1. The proton beam will start at the linear accelerator *Linac2* reach up to 50 MeV, then come to the *Proton Synchrotron Booster (Booster)* accelerated to about 1.4 GeV, and next step is *Proton Synchrotron (PS)* with energy about 25 GeV, finally go to the *Super Proton Synchrotron (SPS)* to achieve to 450 GeV which is the injection energy to the LHC.

There are mainly four major experiments on LHC ring, the ATLAS [27] and CMS [28] experiments aimed for the SM, Higgs and supersymmetry physics, the LHCb [29] is designed as the B-factory to study the CP violation, beauty and charm quark physics, and the ALICE [30] experiment mainly for the heavy-ion collisions to explore the QCD and quark-gluon plasma physics.

The LHC is operated by period. In 2011 and 2012 the center-of-mass (CoM) energy of proton-proton collision is 7 TeV and 8 TeV respectively, the totally luminosity used for

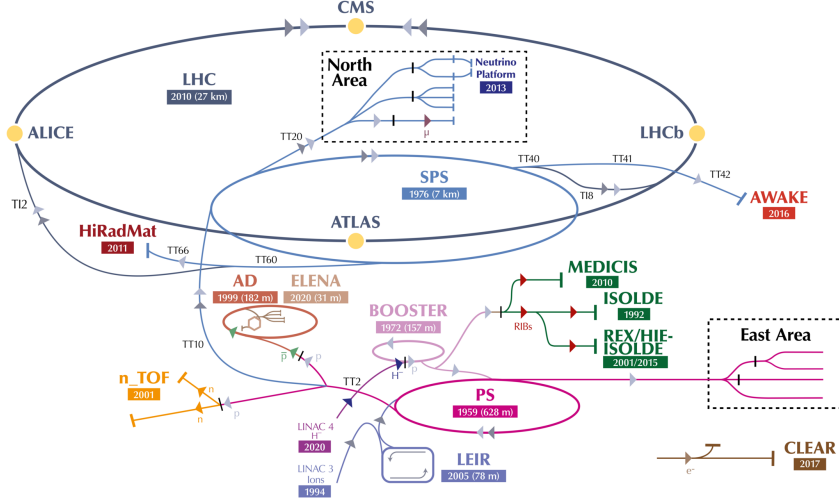


Figure 2.1: The acceleration process and experiment sites of the LHC.

physics analyses in ATLAS experiment is about 24.9 fb^{-1} and this period is named Run-1. After the first Long Shutdown (LS1) for two years, the LHC started the operation for the Run-2 data from 2015 to 2018. In this period the CoM energy reached to 13 TeV and the integrated luminosity used for analyses in ATLAS experiment is about 139 fb^{-1} . The Figure 2.2 showed the integrated luminosity in Run-2 for ATLAS experiment and the average number of interaction per proton in each bunch crossing named pile-up (μ). We then stopped the machine for three year so called the second Long Shutdown (LS2), and relaunched the Run-3 in 2022 in which the CoM will come to 13.6 TeV and collisions are still ongoing when this thesis is writing. Furthermore, after Run-3 is finished the accelerator will be upgraded to HL-LHC for larger peak and integrated luminosity.

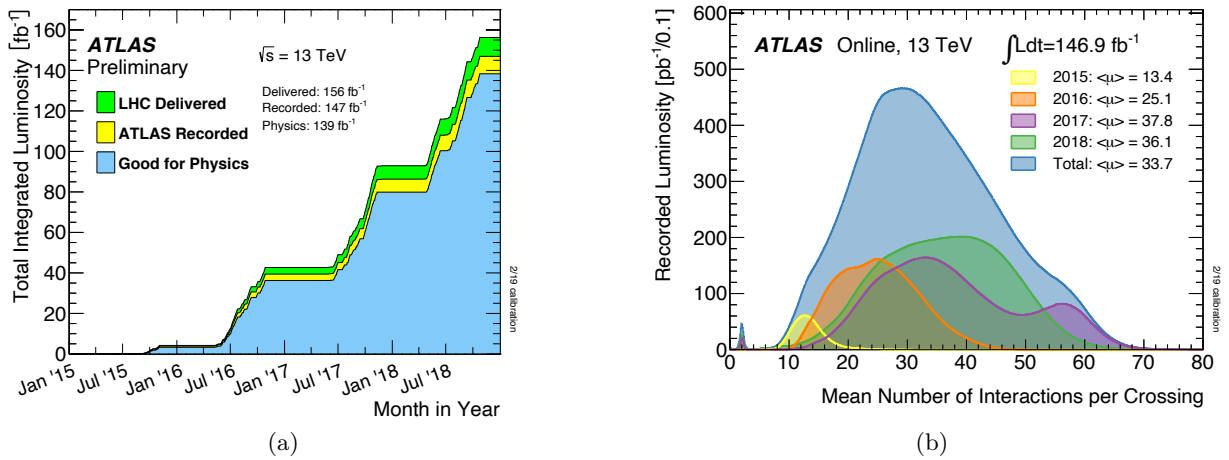


Figure 2.2: (a) Cumulation of luminosity during the Run2 p - p collision data-taking. (b) Mean number of interactions per crossing of the ATLAS recorded dataset.

2.2 The ATLAS detector

The ATLAS(A Toroidal LHC ApparatuS) [27] experiment is built mainly for proton-proton ($p-p$) collisions and for heavy-ion ($A-A$) beam collisions as well. It is a detector which is about 25 m in height and 44 m in length and weights about 7000 tons. This huge experimental apparatus consists of the magnet system, the detector system including inner detector, calorimetry and muon spectrometer, and the trigger and data acquisition system.

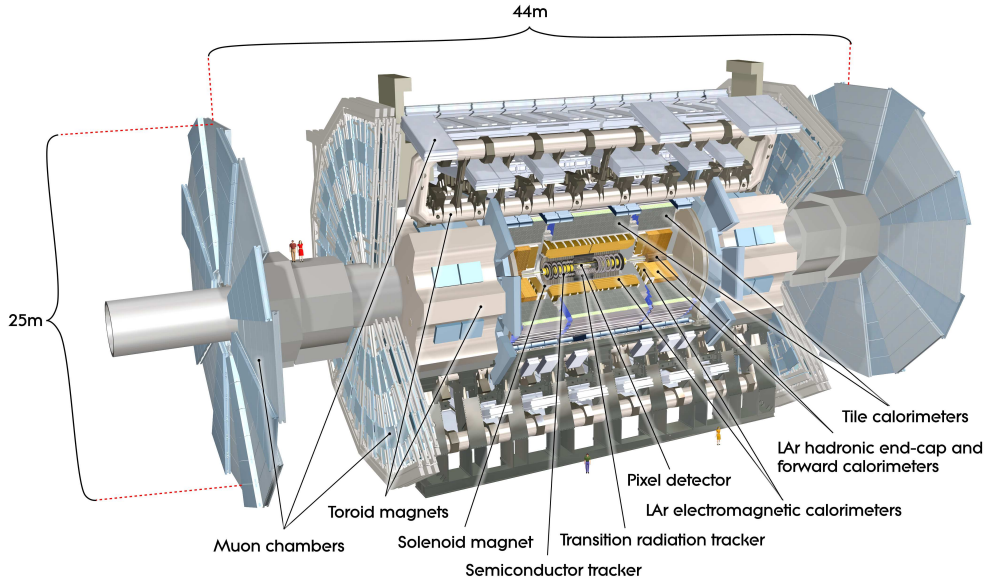


Figure 2.3: Illustration of the ATLAS experiment detector.

The ATLAS experiment is designed for various physics topics from precise measurement of SM to directly search of BSM particles. With extreme high CoM energy for nucleus-nucleus collisions, the ATLAS experiment has unprecedented chance to study QCD, electroweak and flavour physics. Initially, one of the essential aim of ATLAS is to find the Higgs boson, so the $\gamma\gamma$, $ZZ^{(*)}$ channels will provide the cleanest final states for search, and $b\bar{b}$ and $WW^{(*)}$ will be two largest decay branching ratio channel when the Higgs mass is around 125 GeV. And for the search of extra BSM Higgs sector such as minimal supersymmetric extension of the Standard Model, the good study of τ lepton and b -jet related channels is required. Besides, to probe the heavy gauge bosons like Z' and W' whose mass is up to 6 TeV, good resolution of high- p_T lepton and jet is necessary. Good calibration of μ lepton is important to the study of lepton flavour violation. Furthermore, some research of the SUSY particle, cold dark matter and extra dimensions with emission of the gravitons will involve significant missing transverse energy E_T^{miss} in final states.

To realize these benchmark physics targets mentioned above, we need to design the ATLAS detector with large acceptance of pseudo-rapidity and full azimuthal angle coverage. Good charge particles momentum resolution is vital for the inner track detector to achieve good reconstruction of the vertices for offline τ lepton and b -jet tagging. Electromagnetic

and hadronic calorimetry is essential to the electron and γ , jet energy and E_T^{miss} measurement and identification. Muon spectrometer plays an important role for the muon identification and momentum measurement. Besides, highly efficient trigger is principal to background rejection for analyses. The components of the ATLAS detector is illustrated by Figure 2.3 and the coverage and resolution is summarized in Table 2.1. More detailed introduction of each detectors will be found in subsection below.

Table 2.1: Overview of the resolution and coverage of each component of the ATLAS detector

Component	Resolution (p_T and E in GeV)	η coverage	
		Measurement	Trigger
Inner Detector	$\sigma_{p_T}/p_T = 0.05\% \cdot p_T \oplus 1\%$	$ \eta < 2.5$	
Electromagnetic calorimeter	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	$ \eta < 3.2$	$ \eta < 2.5$
Hadronic calorimeter			
Barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	$ \eta < 3.2$	$ \eta < 3.2$
Forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$	$3.1 < \eta < 4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV	$ \eta < 2.7$	$ \eta < 2.4$

Finally, let's introduce the right-hand coordinates which are widely used in ATLAS experiment analyses. The origin point of the coordinates is set at the interaction point, and the x -axis points to the center of the ring, while the y -axis points upwards then the z -axis will be aligned with beam direction. The polar angle θ is from the beam line and azimuthal angle ϕ is with the axis of beam line. The pseudo-rapidity is defined as $\eta = \ln \tan(\theta/2)$ and the angular distant $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

2.2.1 Inner detector

The ATLAS Inner Detector (ID) is designed for the precise measurement of the primary and secondary vertices, as well as particle momentum with high resolution to give accurate track information for analysis. Thus, the impact parameters can also be measured for heavy-flavour and τ -lepton tagging. It can recognize charge track above the p_T threshold around 0.5 GeV. The ID has a coverage of pseudo-rapidity $|\eta| < 2.5$. And it provide the electron identification range about $|\eta| < 2.0$ with energy from 0.5 GeV to 150 GeV. Figure 2.4a is a sketch of the ATLAS Inner Detector.

There are three components in ID, the silicon pixel tracker, silicon microstrip tracker (SemiConductor Tracker, SCT) and the Transition Radiation Tracker (TRT) from inside to outside showed in Figure 2.4b. The size of this cylindrical shape detector is about ± 3512 mm for length and 1150 mm for radius and it is immersed in a magnetic field of 2 T. The pixel detector and SCT is using silicon sensors for detection and the TRT comprises many layers of xenon-based gaseous straw drift tubes.

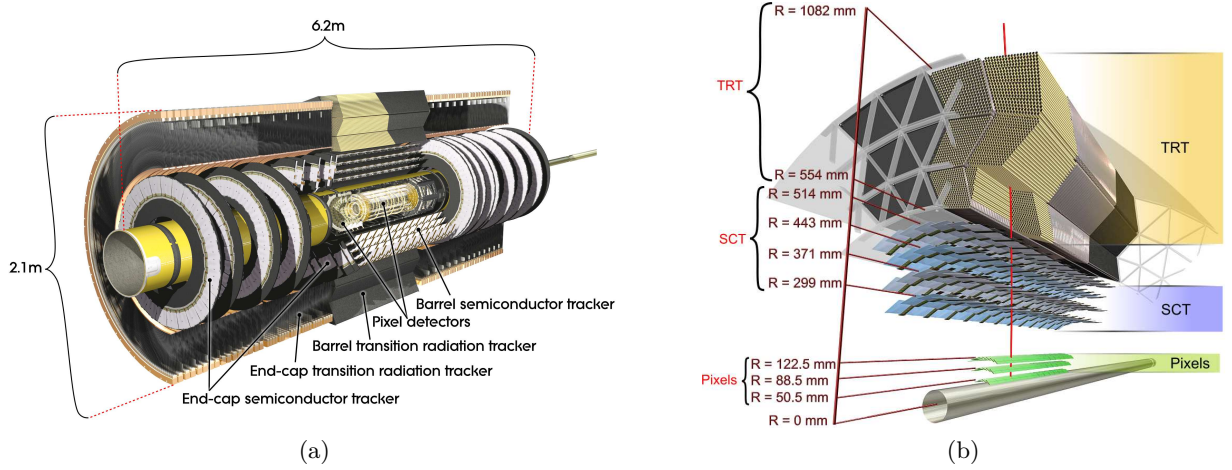


Figure 2.4: (a) Sketch of the ATLAS Inner Detector.

(b) Three independent but complementary sub-detectors of the ATLAS Inner Detector.

The geometric layout of the Inner Detector is illustrated in Figure 2.5. For pixel detector, it has the radial extension about $45.5 \text{ mm} < R < 242 \text{ mm}$ and length of $|z| < 3092 \text{ mm}$ with 3 cylindrical layers in barrel area and 2×3 disks in end-cap area. There are 4 cylindrical layers of SCT in barrel extended $255 \text{ mm} < R < 549 \text{ mm}$ in radius and $|z| < 3092 \text{ mm}$ in length, and 2×9 disks of SCT in end-cap extended $251 \text{ mm} < R < 610 \text{ mm}$ in radius and $810 \text{ mm} < |z| < 2797 \text{ mm}$ in length. And the TRT has 73 straw planes with radii of $554 \text{ mm} < R < 1082 \text{ mm}$ and length of $|z| < 780 \text{ mm}$ in barrel and 160 straw planes with radii of $617 \text{ mm} < R < 1106 \text{ mm}$ and length of $827 \text{ mm} < |z| < 2744 \text{ mm}$ in end-cup.

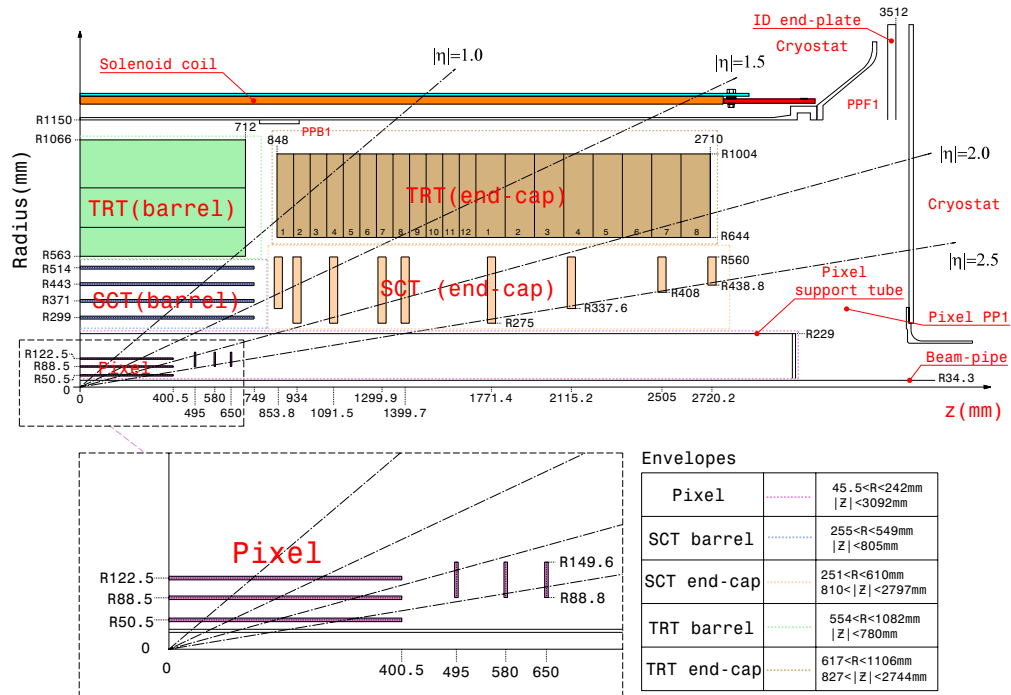


Figure 2.5: Geometric layout of the ATLAS Inner Detector. Location of pixel detector, SCT and TRT is showed.

2.2.2 Calorimetry

To measure the energy of photons, electrons, jets precisely, the ATLAS calorimeters are designed with good pseudo-rapidity coverage and granularity. These calorimeters are in large η -range about $|\eta| < 4.9$ and full ϕ -coverage around the beam line, with the proper thickness they ensure good E_T^{miss} measurement which is important for many physics signatures and in particular the search of the SUSY particles.

Mainly two kinds of calorimeters are placed in the ATLAS experiment, the electromagnetic (EM) calorimeter to measure the energy of photons and electrons, and the hadronic calorimeter for hadrons energy measurement. The high granularity liquid-argon (LAr) EM calorimeter consists of one barrel and two end-cap (EMEC) components, with also a part of forward calorimeter (FCal) for EM measurement. The hadronic calorimeter comprises the tile calorimeter with a barrel and two extended barrel part, the LAr hadronic end-cap (HEC) calorimeter, and also a part of FCal for hadrons measurement. The sketch of the ATLAS calorimeters are showed in Figure 2.6.

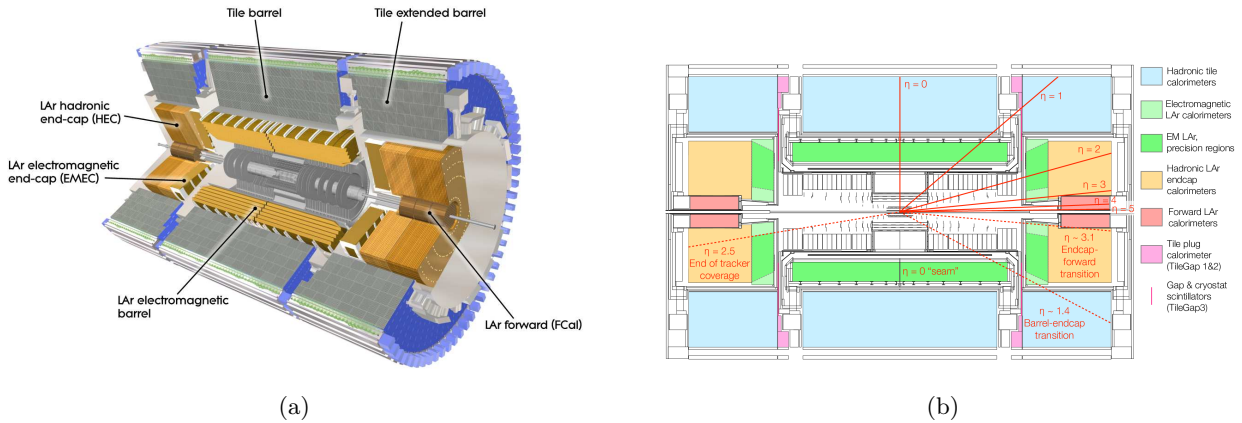


Figure 2.6: (a) Sketch of the ATLAS calorimeters.
(b) Layout of the ATLAS calorimeters of different part of calorimeters [31].

2.2.2.1 Electromagnetic calorimeter

The electromagnetic calorimeter using the lead-liquid argon detectors interacts with the electromagnetic showers which is produced by a series of cascaded particles from the high energy electrons or photons. It is divided into a barrel part with $|\eta| < 1.475$ and two end-cap parts with $1.375 < |\eta| < 3.2$. There is a presampler layer and three electromagnetic calorimeter layers (EM1, EM2, EM3) in both barrel and end-cup regions. An accordion geometry is chosen for the absorbers and the electrodes for both barrel and end-cup EM calorimeter, which will provide an uniform performance of resolution to cover full ϕ range without any cracks.

To provide good containment for electromagnetic showers in order to avoid them punch-through into the muon spectrometer, the length of EM calorimeter is an important param-

ter. The total thickness of EM calorimeter is designed to be larger than 22 radiation lengths ($> 22X_0$) and around 9.7 interaction lengths (λ) in barrel area, while $> 24X_0$ and about 10 λ in end-cap part. The EM barrel calorimeter is a hollow cylinder with half-length about 3.2 m and inner and outer radii about 1.4 m and 2 m. And the EMEC calorimeter has two same co-axial wheels, each is with internal and external radii of 330 mm and 2098 mm and thickness of 630 mm. Geometric illustration of EM calorimeter can be found in Figure 2.7.

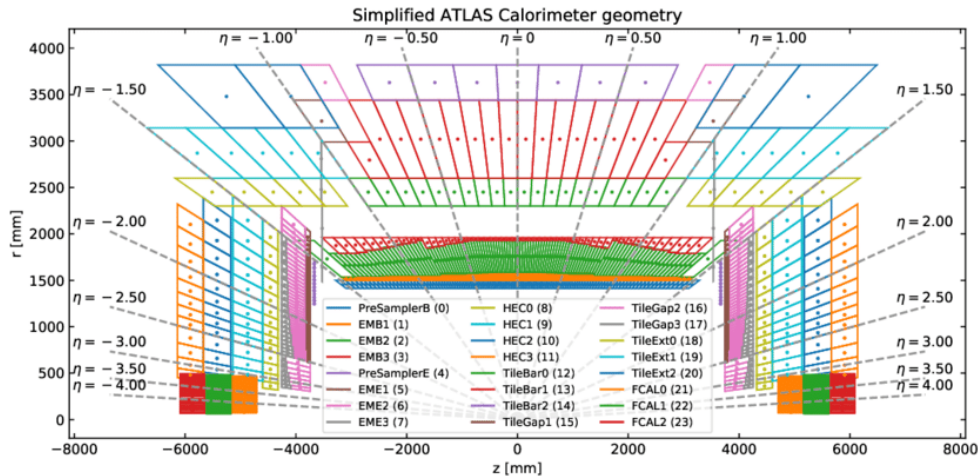


Figure 2.7: Geometric and topological layout of the ATLAS calorimeters [32].

2.2.2.2 Hadronic calorimeter

The tile calorimeter uses steel as the absorber and scintillating tiles as the interaction material. It has a pseudo-rapidity range of $|\eta| < 1.0$ for barrel area and $0.8 < |\eta| < 1.7$ in extended barrel. The size of this hollow cylinder is 2.28 m of inner radius and 4.25 m of outer radius, and 5.8 m in half-length. It is segmented into three layers in depth, with 1.5, 4.1 and 1.8 interaction lengths (λ) and 1.5, 2.6, and 3.3 λ for barrel and extended barrel, respectively. Thus the total length is 7.4 λ .

The HEC holding two wheels is made of LAr detectors and copper plates, covering the η from 1.5 to 3.2. Each wheel has two segments with four layers in depth, and total 32 identical wedge-shaped modules. The radii are about 475 mm and 2030 mm for inner and outer, and the thickness is 1818 mm.

The FCal comprises three sections with total 10 interaction lengths deep to reduce radiation background for muon system. The first part is made of copper for electromagnetic measurement while the other two are made of tungsten for the hadronic energy measurement. It provides $|\eta|$ -coverage of $3.1 < |\eta| < 4.9$. There are also some small LAr gaps to avoid the ion build-up.

The ATLAS muon system contains the toroid magnets to provide magnetic field and the muon spectrometer for the measurement of muon track and momentum. The muon spectrometer has a pseudo-rapidity coverage of $|\eta| < 2.7$ and with trigger region in $|\eta| < 2.4$. It can detect muon transverse momentum with a resolution approximately 10% for 1 TeV track, with a muon momentum threshold of 3 GeV. An overview of the ATLAS muon spectrometer can be seen in Figure 2.8.

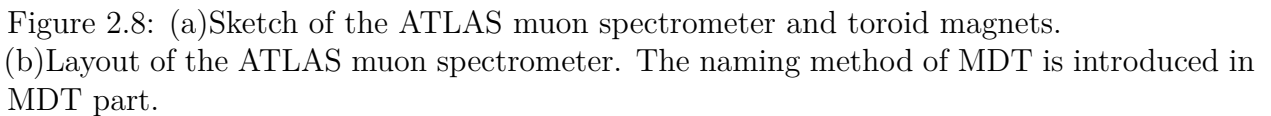


Table 2.2: Function and spacial and time resolution of four ATLAS muon detectors.

The MDT covered a region of $|\eta| < 2.7$ for precise measurement of muon tracks. It is composed of the monitored drift tube chambers as the basic element which have compressed Ar/CO₂ (93/7) gases mixture and a tungsten-rhenium wire with high voltage (3080 V) in center. The MDT in barrel region is arranged as 3 concentric cylindrical octants in radii

of about 5 m, 7.5 m, and 10 m. And in end-cup area the MDT forms 2×4 hexadecagon wheels located at $|z| \approx 7.4$ m, 10.8 m, 14 m, and 21.5 m. Each cylinder/wheel has eight large parts and eight small parts arranged as the octants, then interleave to each other with a small overlap. The location arrangement is showed in Figure 2.9. The naming scheme of the MDT is using three letters, the first one stands for barrel or end-cup (B, E), the second one represents inner, middle or outer layer (I, M, O), and the third one denotes the large or small sector (L, S). There are some exceptions like BEE (Barrel End-cap Extra) and EEL (End-cap Extra Large), and also BOF or BOG as the modified chambers to adjust shape for installation.

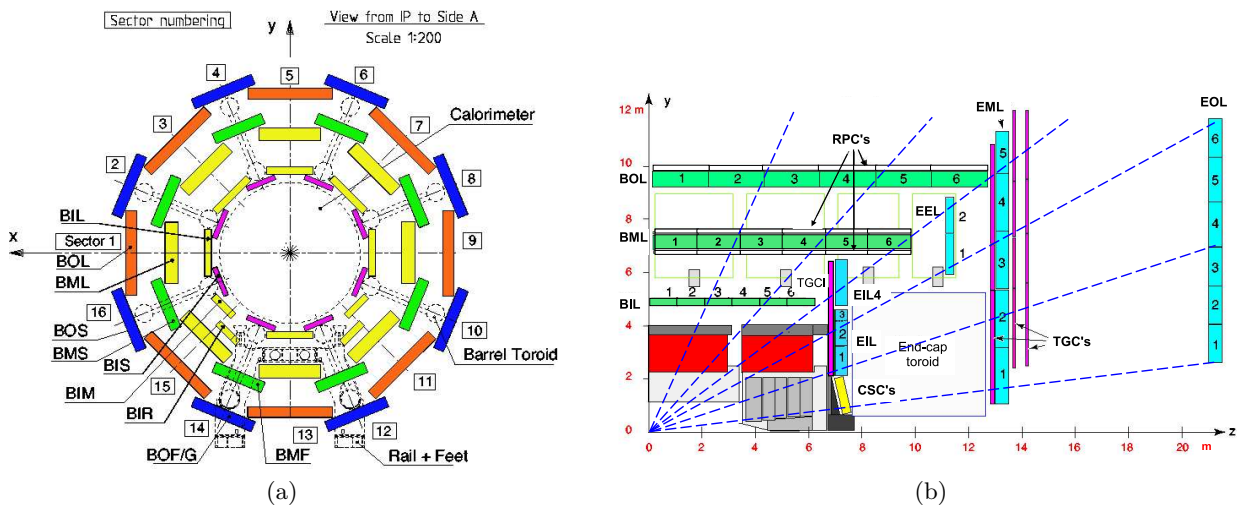


Figure 2.9: (a)Side-view of the ATLAS muon spectrometer of the barrel part.
(b)Front view of the ATLAS muon spectrometer in a half-plane.

For higher resolution with high-rate capability in forward region ($2.0 < |\eta| < 2.7$), the CSC replaces the MDT located at a distance of approximately 7 m in this area. The CSC has 2×1 wheels with eight large and eight small chambers form as two octants to interleave with each other. The CSC has multi-wire proportional chambers with the wires aligned in the radial direction, and cathodes are segmented into strips perpendicular to the wires. In strips it has the Ar/CO₂ gases mixture as (80/20).

The RPC located in $|\eta| < 1.05$ in barrel region incorporates three concentric cylindrical layers. It is a gaseous parallel electrode plate without wires made of phenolic-melaminic plastic laminate with gases mixture C₂H₂F₄/Iso-C₄H₁₀/SF₆. The PRC can provide high- p_T trigger in range of 9-35 GeV and low- p_T trigger in range of 6-9 GeV.

The TGC is placed in $1.05 < |\eta| < 2.4$ in end-cup area. It contains the inner layer segmented as end-cap and forward doublet, and the middle layer complemented by seven layers (M1 triplet, M2 doublet and doublet). The TGC are multi-wire proportional chambers with CO₂/n-C₅H₁₂ (55/45) gases mixture. It has two main functions as complementary measurement of MDT in bending direction and the muon trigger system.

2.2.4 Trigger and data acquisition

The Trigger and Data Acquisition (TDAQ) system in ATLAS is designed to pass the data recording which is more interested for analyses to suppress very large event number. There are three level of triggers in the ATLAS experiment: Level-1 (L1), Level-2 (L2), and event filter. The last two are also called High Level Trigger (HLT), collectively.

The L1 trigger employs information from RPC and TGC for muons, from calorimeters for electrons, photons, jets, τ -leptons, E_T^{miss} and total transverse energy, to pass the high- p_T events for recording. It can deal with maximum input rate about 75 kHz and the L1 latency defined as the time between beam collisions and L1 trigger decision must be within $2.5 \mu\text{s}$. Regions-of-Interest (RoI) are chosen during L1 as the possible triggered objects regions as well.

The HLT further process the event and suppress the rate. The HLT algorithm handles the information from full granularity and precision of calorimeter, muon chamber, as well as the inner detector to further limit the trigger selections. L2 trigger is seeded by RoI and uses the RoI information to limit the amount of events. It reduces event rate to 3.5 kHz with the event processing time of about 40 ms. The event filter uses offline analysis procedures to decrease the event rate to approximately 200 Hz with the event processing time of around 4 s.

2.3 Upgrade for HL-LHC

After the Run-3 data taken, the ATLAS experiment is expected to facilitate Phase-II upgrades towards to the high-luminosity phase of the LHC (HL-LHC) during the Long Shutdown 3 (LS3). The HL-LHC will aim to deliver an integrated luminosity of up to 4000 fb^{-1} and the instantaneous luminosity will reach up to $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Besides, the pile-up during the HL-LHC collision will reach to about $\langle\mu\rangle = 200$.

In order to overcome these challenges, we designed the Phase-II upgrades on the pixel detector [33] and SCT [34] for new Inner Tracker (ITk), the LAr calorimeter [35] and Tile calorimeter [36], the muon spectrometer [37], and TDAQ system [38]. Furthermore, a novel detector named High-Granularity Timing Detector (HGTD) [39] is designed as a new augment in ITk in forward region.

This section will only introduce the HGTD briefly and a qualification task for read-out design will be the main content.

2.3.1 High-Granularity Timing Detector

The HGTD is designed to cope with the large pile-up in high-luminosity run, to measure charged-particle trajectories in time as well as space in the forward region. The good time

resolution of HGTD will suppress the effects of pileup in the forward region, improve the reconstruction of the forward jets and leptons, which benefits the measurement of Higgs VBF production mode and also vector boson scattering (VBS) processes for electroweak study.

The HGTD consists of two vessels located in a distance about ± 3.5 m from the interaction point at z-direction. It covers a pseudo-rapidity range of $2.4 < |\eta| < 4.0$. Each vessel has the thickness about 75 mm and extends radii from 110 mm to 1100 mm, while the active area for detector modules is $120 \text{ mm} < r < 640 \text{ mm}$. One vessel has 2 double-side layers and each side of layer will be divided into 4 quarters in the same structure. The illustration of HGTD and its location can be found in Figure 2.10.

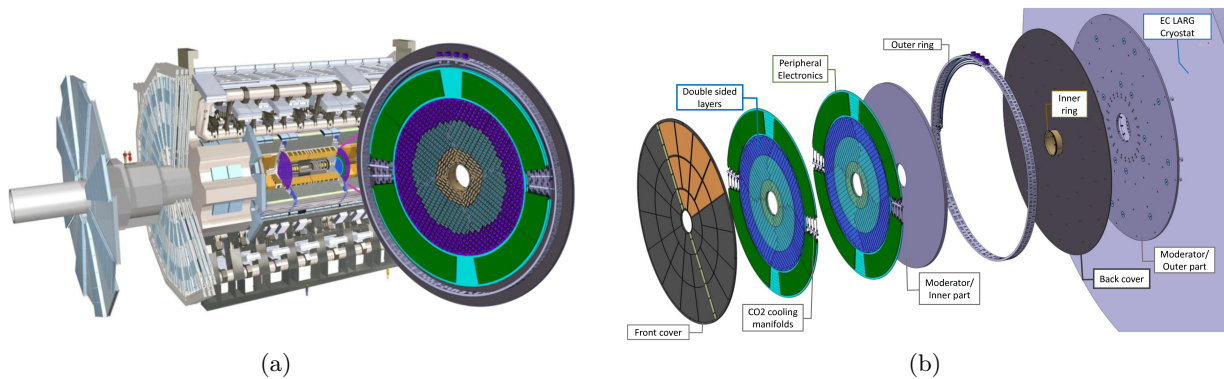


Figure 2.10: (a) Location of the HGTD in the ATLAS detector.
(b) Structure and components of HGTD.

2.3.2 Optimization of connection between detector modules and peripheral electronics in HGTD

In HGTD vessels, the detector modules are located in the active region in $120 \text{ mm} < r < 640 \text{ mm}$, and the outer part is used for peripheral electronic boards (PEB). For this link task, we consider one quarter of a ring with double sides as a minimum unit as it is designed symmetrically in one vessel.

The hit rate varies as a function of radius, it will be larger when radius is closer to the beam line showed in Figure 2.11a. We arrange different module overlap of two sides in one layer to deal with this as illustrated in Figure 2.11b. The module region is roughly divided into $120 \text{ mm} < r < 230 \text{ mm}$ as inner part, $230 \text{ mm} < r < 470 \text{ mm}$ as middle part, and $470 \text{ mm} < r < 640 \text{ mm}$ as outer part. In inner part, the module overlap in one ring is about 70%, for middle part it is about 50 %, and 20 % in outer part.

The active detector element is made of Low-Gain Avalanche Silicon Detectors (LGADs) read-out by dedicated front-end electronics ASICs (ALTIROC). A LGAD sensor and two ASICs will be assembled into one module, and in some modules it will work for data trans-

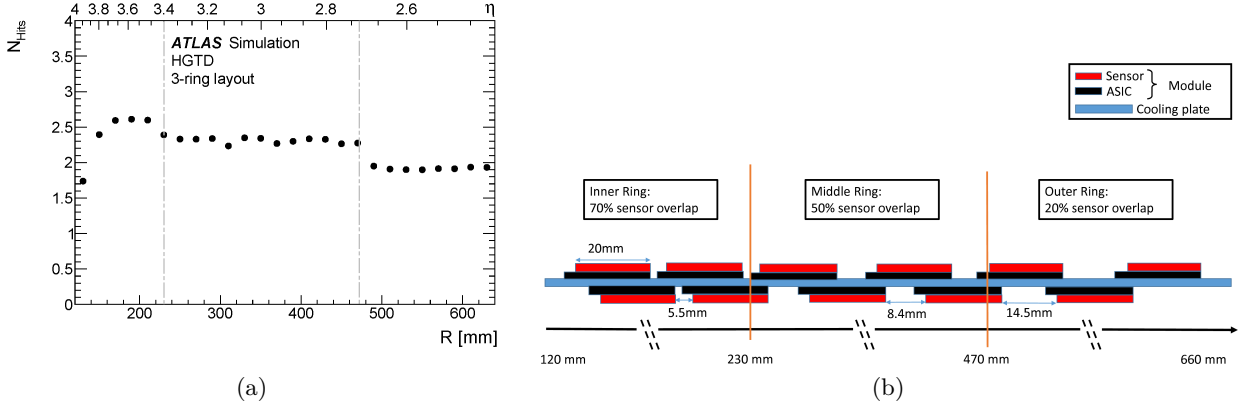


Figure 2.11: (a) Hit multiplicity as function of radius in HGTD. (b) Overlap of modules in double sides of one layer in HGTD.

mission and also for luminosity information transfer. Broader bandwidth will be assigned to inner part modules for data transfer considering the hit rate dependence on radius. We assign bandwidth of 1.28 Gbps at radius below 250 mm, 640 Mbps in radius between 250 mm and 410 mm, and 320 Mbps for radius larger than 410 mm. Furthermore, it is requested by that the bandwidth usage should not exceed 55% in principle and the simulation results is presented in Figure 2.12. Totally 251 modules are grouped in different rows in a quarter on one side of a layer.

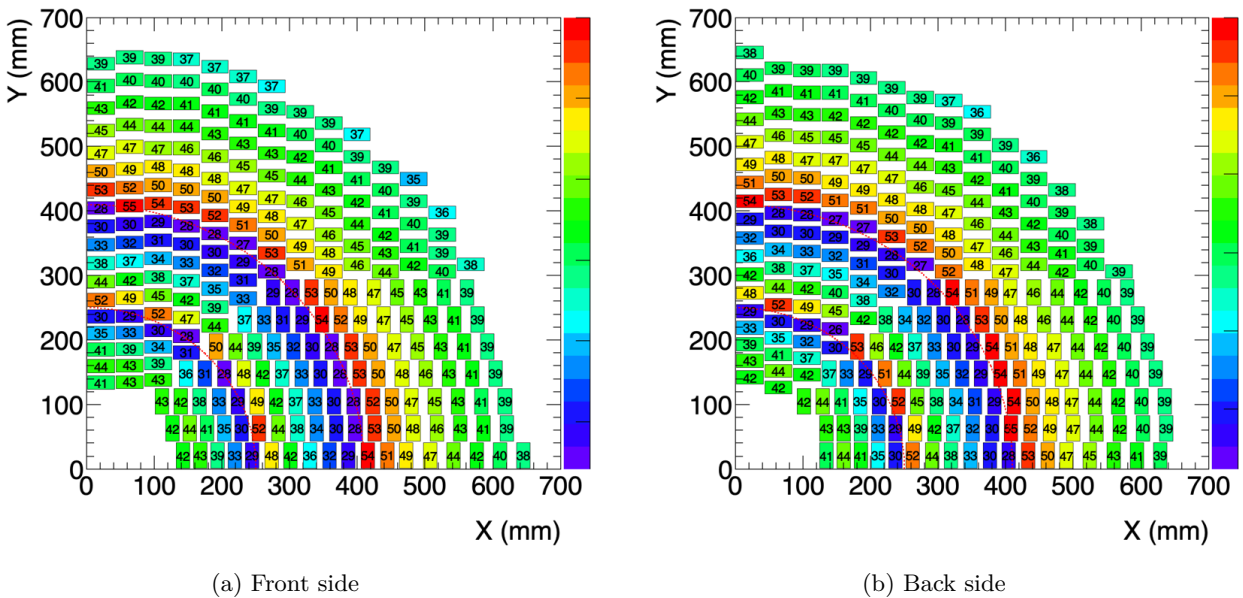


Figure 2.12: Bandwidth average usage as the number on each module for front side and back side of detector layer illustrated in (a) and (b) in HGTD.

In one quarter of a ring, there are 5 PEBs in one side and all detector modules are aligned into 21 rows then grouped for the connection. By a mirror symmetry of front-side and back-side, we design totally 6 types of PEBs as showed in Figure 2.13. An electronic unit named lpGBT will work for the data transmission, mainly two types of lpGBTs are in

PEBs one is for DAQ system and the other is for luminosity. Besides, the DC-DC converters are also located in PEBs for the power supply to detector modules.

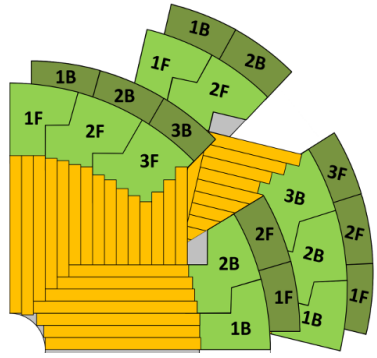


Figure 2.13: Design of 6 types PEBs according to the mirror symmetry of front and back side in one layer.

Connection between the detector modules and peripheral electronics is designed for data link (connecting to lpGBT) and power link (connecting to DC-DC converter), separately. Two elementary laws are taken into consideration:

- Minimum cost: use the units for connection as less as possible to save the spend of detector construction
- Minimum broken: connection scheme should be designed to minimize the impacts of component failure

The connection between lpGBTs and modules is considered for DAQ and luminosity, separately. For one DAQ lpGBT, there are 7 groups for up link and 4 groups for the down link, and one group of the up-link for data transmission is at maximum data rate of 1.28 Gbps. One group can connect to one 1.28 Gbps or two 640 Mbps or four 320 Mbps ASICs by the bandwidth and interface limitation, and one DAQ lpGBT can not exceed the total bandwidth of 8.96 Gbps and up to 28 ASICs (14 modules). The connection scheme is summarized in Table 2.3. For one luminosity lpGBT, it will connected to the ASICs which are at radius larger than 430mm to transmit the luminosity data information. Same as the DAQ uplink system but since there is only one type of bandwidth of 640 Mbps for luminosity data transmission, one luminosity lpGBT can be connected to 14 ASICs (7 modules).

DC-DC converters will convert the voltage from 10V to 1.2V which is used for voltage supply for modules. Two ASICs in the same module share the supplies and the analogue and the digital voltages are supplied separately to the ASICs. In a circumstance that the work current about 3 A, we can connect at most three modules to two DC-DC converter estimated by the efficiency, that one DC-DC converter can supply 3.6 W while each ASIC will consume 0.5 W for analogue and 0.7 W for digital. In view of the drop of voltages and minimum broken, modules grouped in 3×3 or 2×3 will be considered to link to DC-DC converters. In 3×3 group, three modules in diagonal line will connect to two DC-DC converters, while

Table 2.3: Number of DAQ lpGBT and connection scheme in each peripheral board, the number in the bracket is the redundancy.

1F board					1B board				
	1280 Mbps	640 Mbps	320 Mbps	lpGBT		1280 Mbps	640 Mbps	320 Mbps	lpGBT
Mixing 1	4	-	12	3	Mixing 1	4	-	12	3
Mixing 3	-	12	4	3	Mixing 3	-	12	4	3
Pure 1	6	-	-	3	Pure 1	6	-	-	3
Sum	30	34(+2)	46(+2)	9	Sum	30	34(+2)	44(+4)	9

2F board					2B board				
	1280 Mbps	640 Mbps	320 Mbps	lpGBT		1280 Mbps	640 Mbps	320 Mbps	lpGBT
Mixing 1	4	-	12	1	Mixing 1	4	-	12	1
Mixing 2-1	2	4	10	1	Mixing 2-2	2	2	4	1
Mixing 3	-	12	4	3	Mixing 3	-	12	4	3
Pure 3	-	-	16	2	Pure 3	-	-	16	2
Sum	6	40	66	7	Sum	6	38	60	7

3F board					3B board				
	1280 Mbps	640 Mbps	320 Mbps	lpGBT		1280 Mbps	640 Mbps	320 Mbps	lpGBT
Pure 3	-	-	28	3	Pure 3	-	-	28	3
Sum	-	-	78(+6)	3	Sum	-	-	78(+6)	3

in 2×3 group three modules in triangle shape connect to two DC-DC converters.

As a summary, the overall connection scheme and total number for each type of electronic unit is showed in Table 2.4. This result is fully optimized and will be used for the final connection between detector models and peripheral electronics in HGTD.

Table 2.4: Summary of the numbers of each component in each peripheral board.

Peripheral board	Readout rows	Number of modules	1.28 Gb/s ASICs	640 Mb/s ASICs	320 Mb/s ASICs	Luminosity ASICs	DAQ lpGBTs	luminosity lpGBTs	DC-DC converters
Front									
1(1F)	1-3	54	28	34	46	42	9	3	40
2(2F)	4-7	52	4	34	66	56	7	4	44
3(3F)	8-14	39	0	0	78	70	3	5	30
4(2B)	15-18	52	6	38	60	56	7	4	40
5(1B)	19-21	54	30	34	44	42	9	3	40
Back									
1(1B)	1-3	53	28	34	44	42	9	3	40
2(2B)	4-7	48	4	32	60	56	7	4	40
3(3B)	8-14	39	0	0	78	70	3	5	30
4(2F)	15-18	56	6	40	66	56	7	4	44
5(1F)	19-21	55	30	34	46	42	9	3	40

Chapter 3

Measure CP property of Higgs boson Yukawa coupling to τ -leptons

The CP structure in Higgs boson Yukawa coupling to τ -lepton vertex is first measured with the ATLAS experiment Run2 data and published in [40]. This chapter will present the full workflow of this analysis and show the final results of Higgs CP property interacted with τ -leptons.

3.1 Analysis strategy

As introduced in Section 1.3.3, the Higgs CP structure is expected as pure CP -even (as known as the Higgs boson is scalar). Since the Higgs CP structure should be measured by different interaction vertices, several Higgs CP analyses [41–46] are implemented in different Higgs production or decay channels with ATLAS experiment data, and pure CP -odd 125 GeV Higgs boson is excluded at 3.9σ level. However, the CP -mixing state of Higgs boson is not completely excluded so we need to measure Higgs CP property precisely. The CP odd part enters into Higgs bosonic coupling in electroweak interaction is by dimension 6 operator thus is suppressed by $1/\Lambda^2$ in which Λ is the new physics energy scale [47]. While the CP odd Higgs can be mixing in the Higgs Yukawa coupling to fermions in tree level. This analysis will focus on Higgs interacted with τ -leptons vertices to measure its CP property.

The general effective τ -lepton Yukawa coupling [48–50] in Higgs sector can be described by

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma^5\tau)H \quad (3.1)$$

where $v = 246$ GeV is the VEV of the Higgs field, and κ_τ is Higgs- τ Yukawa coupling strength. This Lagrangian is parameterized two part with CP -mixing angle ϕ_τ , in which $\cos\phi_\tau$ term is CP -even part while $\sin\phi_\tau$ term is CP -odd part.

To find an observable to measure this CP effect [51–53], $H \rightarrow \tau\tau$ decay channel with further di- τ decay products are considered. The CP property can effect the chiral structure and then it will cause polarization and spin correlation in decay products system. Therefore, the cross-section of $H \rightarrow \tau\tau$ decay can be calculated in angular distribution [48–50] in di- τ zero momentum system (ZMF)

$$\begin{aligned} d\Gamma_{H \rightarrow \tau^+ \tau^-} &\propto 1 - s_z^- s_z^+ + \cos(2\phi_\tau)(\mathbf{s}_\perp^- \cdot \mathbf{s}_\perp^+) + \sin(2\phi_\tau)[(\mathbf{s}_\perp^- \times \mathbf{s}_\perp^+) \cdot \hat{\mathbf{k}}^-] \\ &\propto 1 - \cos\theta^- \cos\theta^+ + \cos(2\phi_\tau) \cos(\phi^- - \phi^+) \sin\theta^- \sin\theta^+ \\ &\quad + \sin(2\phi_\tau) \sin(\phi^- - \phi^+) \sin\theta^- \sin\theta^+ \end{aligned} \quad (3.2)$$

where $\hat{\mathbf{k}}^-$ is the normalized 3-momentum of τ^- in di- τ ZMF, and $\hat{\mathbf{s}}^\mp$ is unit spin vectors of the $\tau^\mp$, with $s_z^\mp(s_\perp^\mp)$ is the longitudinal (perpendicular) part of $\hat{\mathbf{s}}^\mp$ with respect to $\hat{\mathbf{k}}^-$. We can also convert this formula into angular expression, with $\theta^\mp$ and $\phi^\mp$ are defined as polar and azimuthal angle of $\tau^\mp$ spin vectors in the coordination whose original point is Higgs decay to di- τ vertex and z-axis point at the direction of the normalized τ^- 3-momentum in di- τ ZMF. The observable for measuring the CP structure in H- τ Yukawa coupling can be easily [48, 49, 54] get after considering di- τ decay

$$d\Gamma_{H \rightarrow \tau^+ \tau^-} \propto 1 - b(E_-)b(E_+) \frac{\pi^2}{16} \cos(\varphi_{CP}^* - 2\phi_\tau) \quad (3.3)$$

where $E^\pm$ is the energy of charged decay particles from $\tau^\mp$ in respective τ rest frame and $b(E_\mp)$ are spectral function [55] to describe the spin analyzing power of corresponded decay mode. The φ_{CP}^* is defined as signed acoplanarity angle between two τ decay planes who is related to $\phi^- - \phi^+$ showed in Figure 3.1a, and asterisk indicates this variable is in di- τ ZMF.

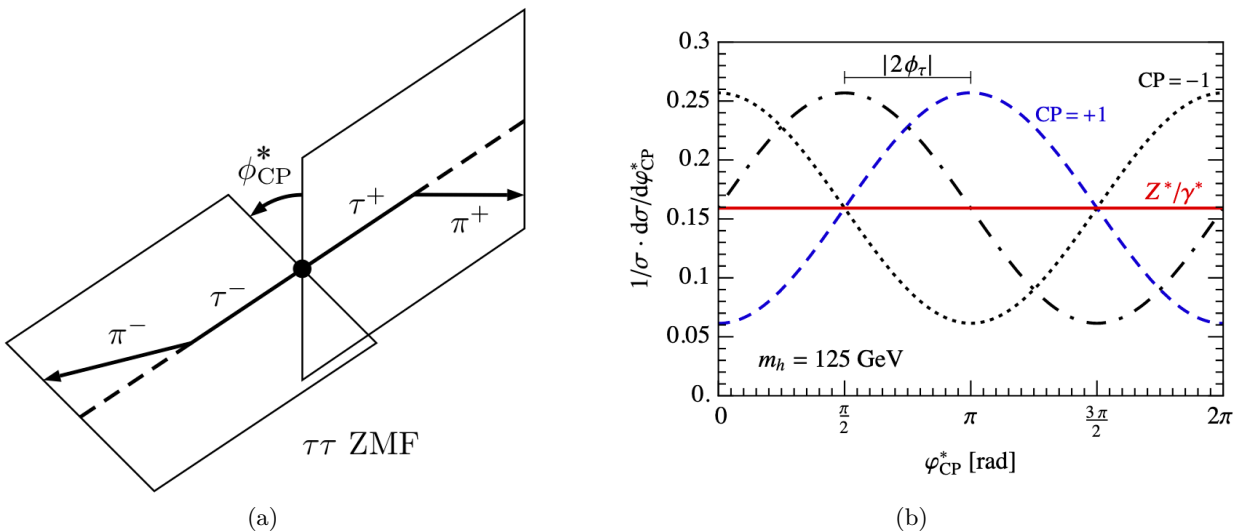


Figure 3.1: (a) Illustration of definition of the φ_{CP}^* in di- τ ZMF. (b) φ_{CP}^* in di- τ distribution function in different ϕ_τ scenarios.

Therefore, the φ_{CP}^* is a good observation for the measurement of the Higgs CP property, because its distribution can be modulated by ϕ_τ as a phase shift as illustrated in Figure 3.1b. The pure CP -even Higgs boson which is corresponded to the SM predictions will be like the $-\cos$ function in φ_{CP}^* distribution, while pure CP -odd case will be as the $\cos$ function. Different Higgs CP hypotheses parameterized by ϕ_τ will provide different phase shift to this harmonic function. Thus, we can determine the Higgs CP property interacted with τ -leptons by the φ_{CP}^* as the observation.

The φ_{CP}^* distribution can be comprehended intuitively by the di- τ spin correlation affected by the Higgs CP structure [56]. The $\tau^-\tau^+$ system will constrain the total angular momentum from Higgs system. And the spin correlation of di- τ system $S = \mathbf{s}_{\tau^-} \cdot \mathbf{s}_{\tau^+}$ discriminates the scalar and pseudo-scalar Higgs boson powerfully, as $\langle S \rangle_{\tau\tau} = 1/4$ and $-3/4$ for a $J^{PC} = 0^{++}$ and $J^{PC} = 0^{-+}$ Higgs boson, respectively. The scalar Higgs will lead to spin-triplet state then two τ spin prefer to be parallel, while pseudo-scalar Higgs leads to spin-singlet state with two τ spin tend to be anti-parallel sketched by Figure 3.2. This effect further pass to τ decay and we know there are only left-handed neutrinos and right-handed anti-neutrinos, who carry the spin information in τ decay system. Thus, this process cause that the angle between rest visible parts of di- τ decay products concentrate around π in scalar Higgs boson and 0 in pseudo-scalar Higgs boson case.

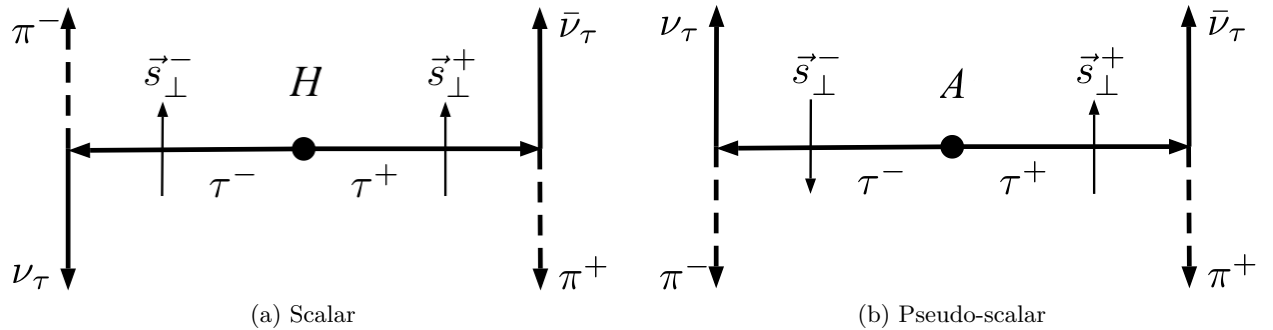


Figure 3.2: Illustration of spin correlation of the di- τ system decayed from scalar and pseudo-scalar Higgs boson in (a) and (b), respectively. All (solid or dash) lines named by particles present as the 3-momentum of that particle, and the arrows labeled by $\vec{s}_\perp$ are the transverse spin of that τ -lepton.

To calculate the signed acoplanarity angle between two τ decay planes φ_{CP}^* , the reconstruction of di- τ decay planes is vital. In phenomenology study, one τ decay plane is reconstructed by different method for different τ decay mode and then combine two τ planes to calculate φ_{CP}^* . Main τ decay modes considered in this analysis are summarized in Table 3.1. For τ decay products with only one charged track in visible component, the τ decay plane is reconstructed by charged track and its impact parameter named as IP method. For τ decays into one charged particle and several neutral visible particles, its decay plane is reconstructed by the spatial momentum of these two components known as ρ method. Besides, a

Table 3.1: Single τ decay mode and branching ratio used in this analysis cited from [57], with notation $\ell^\pm$ stands for light lepton $e^\pm$ and $\mu^\pm$, and $h^\pm$ as hadrons included $\pi^\pm$ and $K^\pm$.

Notation	Decay mode	Branching fraction
ℓ	$\ell^\pm \bar{\nu} \nu$	35.2%
1p0n	$h^\pm \nu$ ($\pi^\pm \nu$)	11.5% (10.8%)
1p1n	$h^\pm \pi^0 \nu$ ($\pi^\pm \pi^0 \nu$)	25.9% (25.5%)
1pXn	$h^\pm \geq 2\pi^0 \nu$ ($\pi^\pm 2\pi^0 \nu$)	10.8% (9.3%)
3p0n	$3h^\pm \nu$ ($3\pi^\pm \nu$)	9.8% (9.0%)

method called a_1 method is designed for three charged particles decayed τ . These methods will be introduced in detail in the subsections below. Practically, we can not reconstruct the di- τ ZMF in ATLAS experiment because in p - p collision only E_T^{miss} can be extracted. Instead, the di- τ_{vis} ZMF is used for φ_{CP}^* calculation as a well validated approximation.

3.1.1 Impact parameter (IP) method

The IP method [58] is applied to τ decay into only one charged particle as the visible component, specifically the leptonic τ decay $\tau^\pm \rightarrow \ell^\pm \nu \nu$ and single charged hadronic decay $\tau^\pm \rightarrow \pi^\pm \nu$. As for di- τ mode combination, the ℓ -1p0n and 1p0n-1p0n decay mode combinations are considered to use the IP method. In this method, the spatial momentum $\mathbf{q}^\pm$ of charged particle ($\ell^\pm$, $\pi^\pm$) decayed from $\tau^\pm$ is extracted and its 3-dimension impact parameter vector $\mathbf{n}^\pm$ is reconstructed with respect to the primary vertex (PV) of this event. The four momentum of charged track $q_\mu^\pm$ and impact parameter $n_\mu^\pm = (0, \mathbf{n}^\pm)$ are boosted into di- τ_{vis} ZMF, in which $\hat{\mathbf{q}}^{*-}$ and $\hat{\mathbf{q}}^{*+}$ are aligned and opposite (the asterisk denotes as in di- τ_{vis} ZMF and hat mark means the normalized vector). Then the boosted and normalized impact parameter vector $\hat{\mathbf{n}}^{*\pm}$ can be decomposed into parallel part and transverse part $\hat{\mathbf{n}}_\perp^{*\pm}$ to the direction of the associated normalized spatial momentum $\hat{\mathbf{q}}^{*\pm}$. Therefore, the φ_{CP}^* can be calculated and its sign can be referred by the CP -odd triple correlation $\mathcal{O}_{CP}^*$

$$\begin{aligned} \varphi^* &= \arccos(\hat{\mathbf{n}}_\perp^{*+} \cdot \hat{\mathbf{n}}_\perp^{*-}) \quad \text{and} \quad \mathcal{O}_{CP}^* = \hat{\mathbf{q}}^{*-} \cdot (\hat{\mathbf{n}}_\perp^{*+} \times \hat{\mathbf{n}}_\perp^{*-}) \\ \varphi_{CP}^* &= \begin{cases} \varphi^* & \text{if } \mathcal{O}_{CP}^* \geq 0 \\ 360^\circ - \varphi^* & \text{if } \mathcal{O}_{CP}^* < 0 \end{cases} \end{aligned} \quad (3.4)$$

the calculation of this method is illustrated by Figure 3.3 and φ_{CP}^* can be ranged from 0° to 360° with the direction defined by $\mathcal{O}_{CP}^*$. In case of leptonic decayed τ , there is an extra phase shift of 180° introduced by different sign of spectral function and we applied an addition sign to eliminate this to synchronize the phase with the other decays.

The normalized distribution of φ_{CP}^* simulated in ℓ -1p0n and 1p0n-1p0n are show in Figure 3.4, with the red circle curve represents as pure CP -even hypothesis in shape of

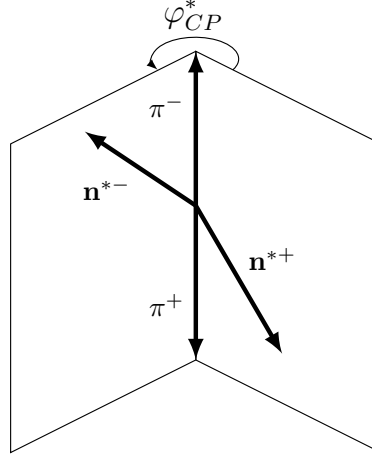
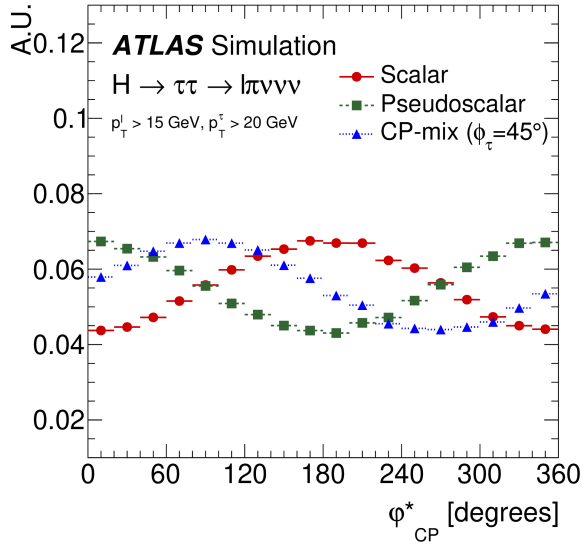
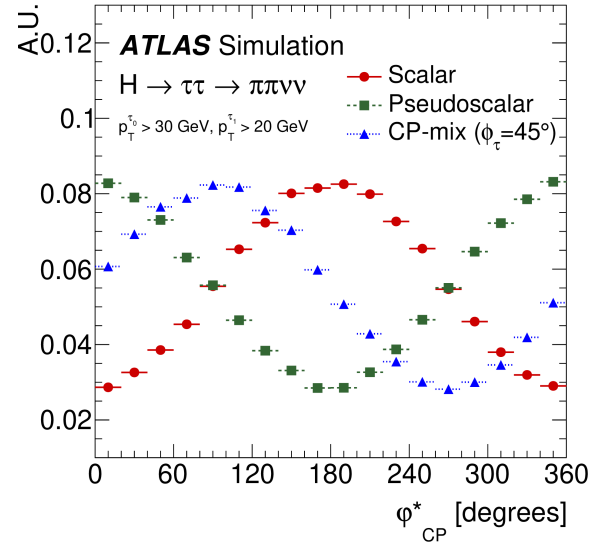


Figure 3.3: Illustration of the IP method for di- τ decay mode reconstruction in di- τ_{vis} ZMF. The method is used for ℓ -1p0n and 1p0n-1p0n decay mode combinations.

minus cosine function, the green square curve depicts pure CP -odd hypothesis as cosine function shape, and the blue triangle curve shows CP -mixing of $\phi_\tau = 45^\circ$ hypothesis. The simulation events are at generator level and with p_T selection for both τ -leptons.



(a) Normalized φ_{CP}^* distribution in ℓ -1p0n channel



(b) Normalized φ_{CP}^* distribution in 1p0n-1p0n channel

Figure 3.4: Normalized φ_{CP}^* distributions which is calculated by the IP method in ℓ -1p0n and 1p0n-1p0n channel showed in figure (a) and (b), respectively.

3.1.2 ρ -decay plane (ρ) method

The ρ method [59–61] reconstructs τ decay planes in τ decay mode of $\tau^\pm \rightarrow \rho^\pm \nu$, $\rho^\pm \rightarrow \pi^\pm \pi^0$. The τ decays to a_1 resonant further decays into one charged pions and multiple neutral pions will also use the ρ method. The di- τ decay mode combinations considered this method are 1p1n-1p1n and 1p1n-1pXn. In this method, the charged track spatial momentum $\mathbf{q}^\pm$ and

neutral pion (clusters) momentum $\mathbf{q}^0$ are used to form the decay planes. They are boosted into the di- τ_{vis} ($\rho^\pm$ pair) ZMF and normalized neutral spacial momentum is composed into parallel part and transverse part $\hat{\mathbf{q}}_\perp^{*0}$ with respect to boosted charged track momentum $\hat{\mathbf{q}}^{*\pm}$. Then the φ_{CP}^* can be calculated and the ρ method can be showed in Figure 3.5.

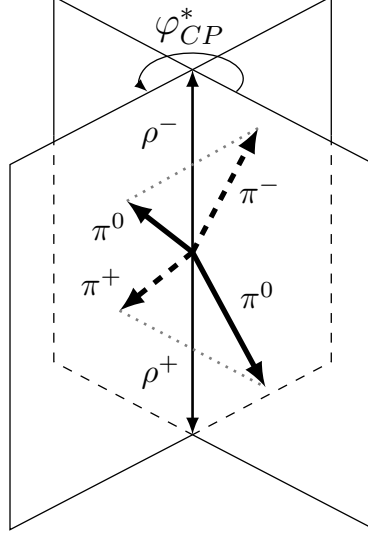


Figure 3.5: Illustration of the ρ method for di- τ decay mode reconstruction in di- τ_{vis} ZMF. This method is used for 1p1n-1p1n and 1p1n-1pXn decay mode combinations.

In calculation of the φ_{CP}^* by ρ method, an addition sign should be considered depended on the sign of τ -lepton spin analyzing functions as discussed in Equation (3.3). This can be determined by $y_\pm^\rho = (E_{\pi^\pm} - E_{\pi^0}) / (E_{\pi^\pm} + E_{\pi^0})$, in which $E_{\pi^\pm}$ and E_{π^0} are $\pi^\pm$ and π^0 energy in laboratory frame. With this and same CP -odd triple correlation $\mathcal{O}_{CP}^*$ definition, the φ_{CP}^* can be defined as

$$\begin{aligned} \varphi^* &= \arccos(\hat{\mathbf{q}}_\perp^{*0+} \cdot \hat{\mathbf{q}}_\perp^{*0-}) \quad \text{and} \quad \mathcal{O}_{CP}^* = \hat{\mathbf{q}}^{*-} \cdot (\hat{\mathbf{q}}_\perp^{*0+} \times \hat{\mathbf{q}}_\perp^{*0-}) \\ \varphi^{*'} &= \begin{cases} \varphi^* & \text{if } \mathcal{O}_{CP}^* \geq 0 \\ 360^\circ - \varphi^* & \text{if } \mathcal{O}_{CP}^* < 0 \end{cases} \\ \varphi_{\text{CP}}^* &= \begin{cases} \varphi^{*'} & \text{if } y_+^\rho y_-^\rho \geq 0 \\ \varphi^{*'} + 180^\circ & \text{if } y_+^\rho y_-^\rho < 0 \end{cases} \end{aligned} \quad (3.5)$$

in case of 1pXn ($X \geq 2$) decay, the sum of four momentums of all neutral pions decayed from τ is taken as the the neutral component in the ρ method.

Figure 3.6 shows the normalized φ_{CP}^* distributions simulated in 1p1n-1p1n channel at generator level with different CP hypothesis. The red circle curve indicates the SM scalar Higgs boson (pure CP -even), green square curve denotes the pseudo-scalar Higgs boson (pure CP -odd), and the blue triangle illustrates the CP -mixing with $\phi_\tau = 45^\circ$ hypothesis. All these distributions are in the shape of expecting as predicted in Equation (3.3).

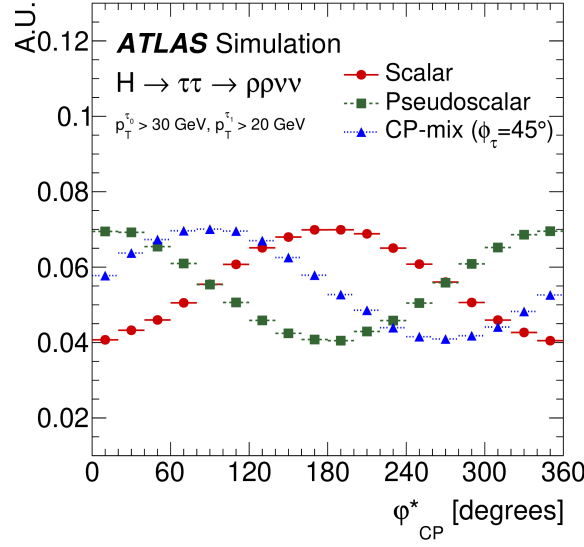


Figure 3.6: Normalized φ_{CP}^* distributions calculated by the ρ method in 1p1n-1p1n channel.

3.1.3 Combined IP and ρ (IP- ρ) method

There are some di- τ decay mode combinations such as ℓ -1p1n, ℓ -1pXn, 1p0n-1p1n, and 1p0n-1pXn needed to combine both IP and ρ methods for reconstruction of di- τ decay planes. The decay plane with only one charged particle will use the IP method to reconstruct while the one with also neutral pions will use ρ method. This is showed in Figure 3.7 and the φ_{CP}^* calculation is very analogous to Equation (3.5), only with y^ρ criterion modified as

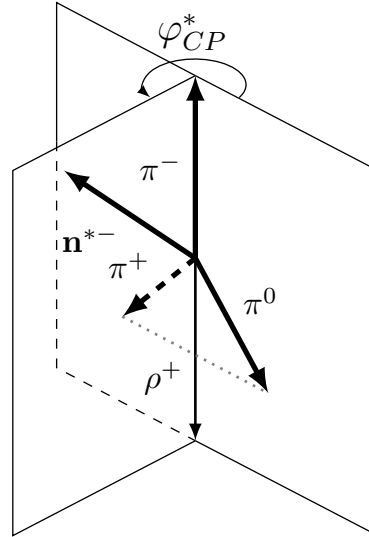
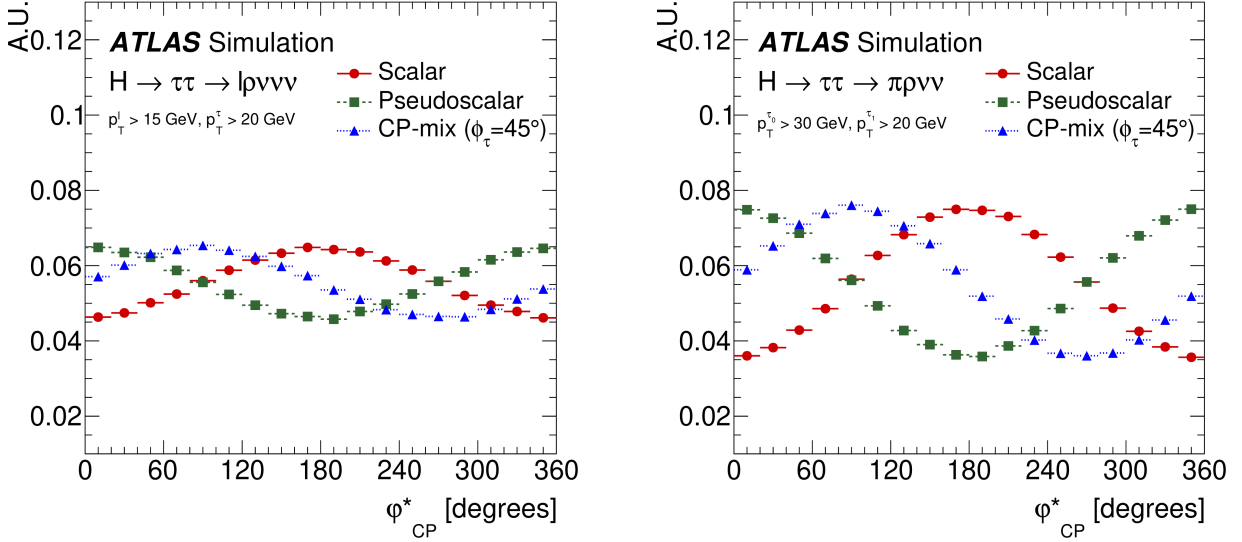


Figure 3.7: Illustration of the IP- ρ method for di- τ decay mode reconstruction in di- τ_{vis} ZMF used for ℓ -1p1n, ℓ -1pXn, 1p0n-1p1n, and 1p0n-1pXn decay mode combinations.

$$\varphi_{CP}^* = \begin{cases} \varphi^{*'} & \text{if } y^\rho \geq 0 \\ \varphi^{*'} + 180^\circ & \text{if } y^\rho < 0 \end{cases} \quad (3.6)$$

with a phase shift of 180° depending on the sign of y^ρ .

The normalized distributions of φ_{CP}^* of the simulated events in ℓ -1p1n and 1p0n-1p1n channel on generator level illustrated in Figure 3.8. The red circle (green square, blue triangle) curve is used to describe the pure CP -even (pure CP -odd, CP -mixing with $\phi_\tau = 45^\circ$) hypothesis.



(a) Normalized φ_{CP}^* distribution in ℓ -1p1n channel

(b) Normalized φ_{CP}^* distribution in 1p0n-1p1n channel

Figure 3.8: Normalized φ_{CP}^* distributions which is calculated by the IP- ρ method in ℓ -1p1n and 1p0n-1p1n channel showed in figure (a) and (b), respectively.

3.1.4 a_1 -decay plane (a_1) method

The a_1 method [62] is an extension of ρ method to be used for reconstruction of $\tau^\pm \rightarrow a_1^{\pm,L,T} \nu, a_1^{\pm,L,T} \rightarrow \pi^\pm \pi^+ \pi^-$ decay plane (as known as 3p0n), in which the a_1 resonant is in longitudinal(L) or transverse(T) helicity states coupled through the axial vector. This τ decay plane is formed by the charged pion ($\pi_1^\pm$) with the highest transverse momentum and the vector sum of the rest two pions spatial momentum. The $y_\pm^\rho$ in a_1 method will be modified as

$$y_\pm^{a_1} = \frac{E_{2\pi} - E_{\pi_1^\pm}}{E_{2\pi} + E_{\pi_1^\pm}} - \frac{m_{3\pi}^2 - m_{\pi_1^\pm}^2 + m_{2\pi}^2}{2m_{3\pi}^2} \quad (3.7)$$

with $m_{3\pi}$ denotes as the invariant mass of three charged pions system, and $m_{2\pi}$ ($E_{2\pi}$) is the invariant mass (energy) of two pions system whose transverse momentum is not highest.

The combined IP- a_1 method is used for ℓ -3p0n decay mode, and ρ - a_1 for 1p1n-3p0n decay mode. Similar as Equation (3.5) and Equation (3.6), the φ_{CP}^* calculation using a_1 method will use the Equation (3.7) to substitute the corresponded y definition.

All di- τ decay mode combinations used in this analysis as well as the methods applied

for its decay plane reconstruction and its branching ratio are summarized in Table 3.2. The fraction is calculated by the statistics from Table 3.1 using the inclusive hadronic τ decay.

Table 3.2: Di- τ decay mode combinations and its branching ratio, as well as the method used for its decay plane reconstruction.

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

3.2 Data and simulated samples

The analysis is using the data sets with good operating conditions [63] from ATLAS experiment run during year of 2015 to 2018. The data were collected from p - p collision with CoM energy of 13 TeV and the integrated luminosity of 139 fb^{-1} . This data were recorded with single-lepton trigger for $\tau_{\text{lep}}\tau_{\text{had}}$ decay and di-hadronic τ trigger for $\tau_{\text{had}}\tau_{\text{had}}$ decay [64–67]. The HLT thresholds are set differently by run period. In 2015 data with luminosity of 3.22 fb^{-1} , the single-lepton trigger used the p_{T} thresholds of 24 GeV and 20 GeV for electron and muon candidates, and the di-hadronic τ trigger used the p_{T} thresholds of 35 GeV for the leading τ and 25 GeV for the sub-leading τ candidate. In years of 2016-2018 with luminosity of 32.99 fb^{-1} , 44.31 fb^{-1} and 58.45 fb^{-1} respectively, the single-lepton trigger elevated the p_{T} thresholds of electron and muon particles both to 26 GeV, and the di-hadronic τ trigger accepted the events with same p_{T} thresholds as before that 35 GeV for the leading τ and 25 GeV for the sub-leading τ , as well as an addition L1 calorimeter trigger jet with $p_{\text{T}} > 25 \text{ GeV}$ and $|\eta| < 3.2$.

The signal and background samples are modelled by the Monte (MC) simulation. For signal samples, four main Higgs production processes are considered: gluon-gluon fusion (ggF), vector-boson fusion (VBF), associated production with a vector boson (VH), and associated production with top-quark pair ($t\bar{t}H$). These signal processes are produced by POWHEG NNLOPS generator [68–72] at next-to-next-leading-order (NNLO) accuracy for ggF Higgs production mode, and at NLO accuracy in QCD for VBF and VH production mode. The POWHEG BOX v2 [70–74] is used at NLO with the NNPDF3.0NLO [75] PDF

set for $t\bar{t}H$. All signal processes are then decayed and showered by PYTHIA 8 [76] and the τ -leptons are decayed without any spin correlations. The spin correlations are later implemented by **TauSpinner** [77–79] package with event-by-event weights for different Higgs CP -mixing hypotheses. There are four kinds of main background are using the Monte Carlo simulation samples for modelling: V + jets, dibosons, $t\bar{t}$ and single-top. The V + jets and dibosons samples are produced by SHERPA 2.2.1 [80] including τ -lepton decays process, while the $t\bar{t}$ and single-top are modelled by POWHEG+PYTHIA 8 with PYTHIA to perform τ -leptons decay. All MC samples with their generator setting are summarized in Table 3.3.

Table 3.3: Overview of the MC generators used for the main signal and background samples.

Process	Generator		PDF set		Tune	Order
	ME	PS	ME	PS		
$H \rightarrow \tau\tau$ signal						
ggF	POWHEG	PYTHIA 8	PDF4LHC15	CTEQ6L1	AZNLO	NNLO+NNLL
VBF	POWHEG	PYTHIA 8	PDF4LHC15	CTEQ6L1	AZNLO	NNLO
VH	POWHEG	PYTHIA 8	PDF4LHC15	CTEQ6L1	AZNLO	NNLO
$t\bar{t}H$	POWHEG	PYTHIA 8	NNPDF2.3		A14	NLO
Background						
V + jets	SHERPA 2.2.1		NNPDF30		SHERPA	NNLO
Di-Boson	SHERPA 2.2.1		NNPDF30		SHERPA	NNLO
$t\bar{t}$	POWHEG	PYTHIA 8	NNPDF2.3		A14	NLO
Single top	POWHEG	PYTHIA 8	NNPDF2.3		A14	NLO

All samples are then passed to a full simulation of the ATLAS detector response [81] using GEANT4 [82]. The pile-up effects in beam collision are estimated by overlaying each hard-scatter event with minimum-bias events, simulated with soft QCD process by PYTHIA 8. These simulated events are then weighted to matches the one observed in ATLAS data.

3.3 Object reconstruction

The analysis needs the object reconstruction of electrons, muons, hadronic τ -leptons, jets, and missing transverse momentum. As the introduction of IP method, the primary vertex and track information are very important. Besides, the analysis sensitivity heavily depends on the classification of the τ decay modes thus the reconstruction of the hadronic τ -lepton decay modes is fundamental. The main features of the object reconstruction are listed below:

- **Primary vertex and tracks:** Vertices are reconstructed from the charged tracks measured in the ID with $p_T > 500$ MeV. The vertex which has the highest $\sum p_T^2$ will be selected as the primary vertex. Each event should have at least one vertex and at least two associated tracks. Then the impact parameter is defined as the closest distance

from the primary vertex to the track, with the transverse part of the impact parameter denoted as d_0 and the longitudinal part as z_0 . We further defined the significance of the track impact parameter as $d_0^{\text{sig}} = |d_0/\sigma(d_0)|$ [83, 84] for categorization, where $\sigma(d_0)$ is the resolution of the transverse impact parameter.

- **Electrons:** Electrons are reconstructed from the energy deposits in the electromagnetic calorimeter which are matched to a charged track in the ID [85]. The electrons are selected to have $p_T > 15$ GeV and $|\eta| < 2.47$ with the crack region $1.37 < |\eta| < 1.52$ vetoed. The electrons are required to pass the MEDIUM identification and FCLOOSE isolation criteria.
- **Muons:** Muons are reconstructed by the information from the Muon Spectrometer matched with tracks inside the ID. The muons need to have $p_T > 10$ GeV and $|\eta| < 2.47$ with the crack region rejected. The muons are further required to satisfy the LOOSE identification and FCTIGHTTRACKONLY isolation criteria.
- **Taus:** Hadronic decay τ -leptons comprise a set of visible decay products, usually one or three charged pions/kaons and up to two neutral pions, which are used for the reconstruction of the $\tau_{\text{had-vis}}$. The τ reconstruction is seeded by jets reconstructed using calibrated topological clusters as inputs with the anti- k_t algorithm and a distance parameter of $R = 0.4$. A Recurrent Neural Network (RNN) [86] identification algorithm is designed to classify the $\tau_{\text{had-vis}}$ candidates to jets initiated by quarks or gluons, employing information from reconstructed charged tracks and clusters of energy in the calorimeter associated with $\tau_{\text{had-vis}}$ candidates. A boosted decision tree (BDT) algorithm is designed to reject the electrons which is misidentified as the $\tau_{\text{had-vis}}$ using information from the calorimeter and the tracking detector, especially the transition radiation information from the TRT system. The $\tau_{\text{had-vis}}$ candidates are required to fulfill the RNN classifier MEDIUM working point [86] identification criteria, and to have one or three associated tracks, with $p_T > 20$ GeV and $|\eta| < 2.47$ excluded the crack region.
- **Jets:** Jets are reconstructed from the particle-flow objects using the anti- k_t algorithm [87] with distance parameter of $R = 0.4$. The jets should have $p_T > 20$ GeV and $|\eta| < 4.5$, and pass the LOOSEBAD cleaning working point criteria. The (forward) jet-vertex-tagger (JVT) algorithm is employed to suppress jets originating from pileup with the MEDIUM JVT working point is used as recommended for particle flow jets. As the jets initiated by b -quarks, the DL1r b -tagging algorithm is used for jet flavour tagging with the 85% efficiency working point.
- **Missing transverse momentum:** The missing transverse momentum $\vec{p}_T^{\text{miss}}$ (with its magnitude denoted as missing transverse energy E_T^{miss}) [88] is calculated as the negative vector sum of all transverse momenta of electrons, muons, $\tau_{\text{had-vis}}$, jets, as well as the *soft-term* which is defined as the tracks matched to the primary vertex but

not associated to any reconstructed objects.

An overlap removal (OLR) procedure is applied to make sure that two different objects do not share their constituents. This ambiguity could happen because all objects used in this analysis are not built from a set of mutually exclusive tracks or calorimeter clusters. To avoid this, the OLR is implemented using the ASSOCIATIONUTILS package with STANDARD working point. The OLR steps are summarized in Table 3.4 step by step.

Table 3.4: Overlap removal of the standard working selection, these selection criteria are applied sequentially as ordered in this table.

Object to remove	Object to keep	Criteria
electron	electron	Share the same track, keep the electron with the highest transverse momentum
$\tau_{\text{had-vis}}$	electron	$\Delta R < 0.2$, keep the electron
$\tau_{\text{had-vis}}$	muon	$\Delta R < 0.2$, keep the muon
electron	muon	Share the same track, keep the muon if it is associated with a signature in the muon spectrometer
jet	electron	Remove the jet within $\Delta R = 0.2$ of an electron
jet	muon	Remove the jet within $\Delta R = 0.2$ of a muon if it has fewer than three associated tracks
electron	jet	Remove the electron within $\Delta R = 0.4$ of a jet
muon	jet	Remove the muon within $\Delta R = 0.4$ of a jet
jet	$\tau_{\text{had-vis}}$	Remove the jet within $\Delta R = 0.2$ of a $\tau_{\text{had-vis}}$

Reconstruction of the invariant mass of the di- τ system in this analysis is using the Missing Mass Calculator (MMC) technique [89]. The MMC uses the τ_{vis} kinematics and $E_{\text{T}}^{\text{miss}}$ as the inputs, combined with the possibility distribution function information of the ΔR between visible and invisible part of the τ decay, to develop a likelihood-based algorithm to estimate the kinematic information of neutrino(s) decayed from each τ -lepton which is unknown in ATLAS experiment. By scanning the invisible kinematic phase space points, the MMC will choose the most likely decayed neutrinos case to calculate the final di- τ system invariant mass $m_{\tau\tau}^{\text{MMC}}$.

Besides, the reconstruction of τ decay mode is crucial in this analysis because the calculation methods of the φ_{CP}^* heavily relies on the classification of the di- τ decay mode. This is accomplished by Tau Particle Flow [90] reconstruction algorithm which determines the four momentum information of charged and neutral pions decayed from τ -leptons by the combination of the tracking detector and the calorimeter measurements. The decay mode classification is achieved by counting the number of charged and neutral pions, and further employs three BDTs trained by τ -lepton decay products kinematics to separate 1p0n vs 1p1n, 1p1n vs 1pXn and 3p0n vs 3pXn decay modes, respectively. The efficiency and purity of this decay mode classification are showed in Figure 3.9.

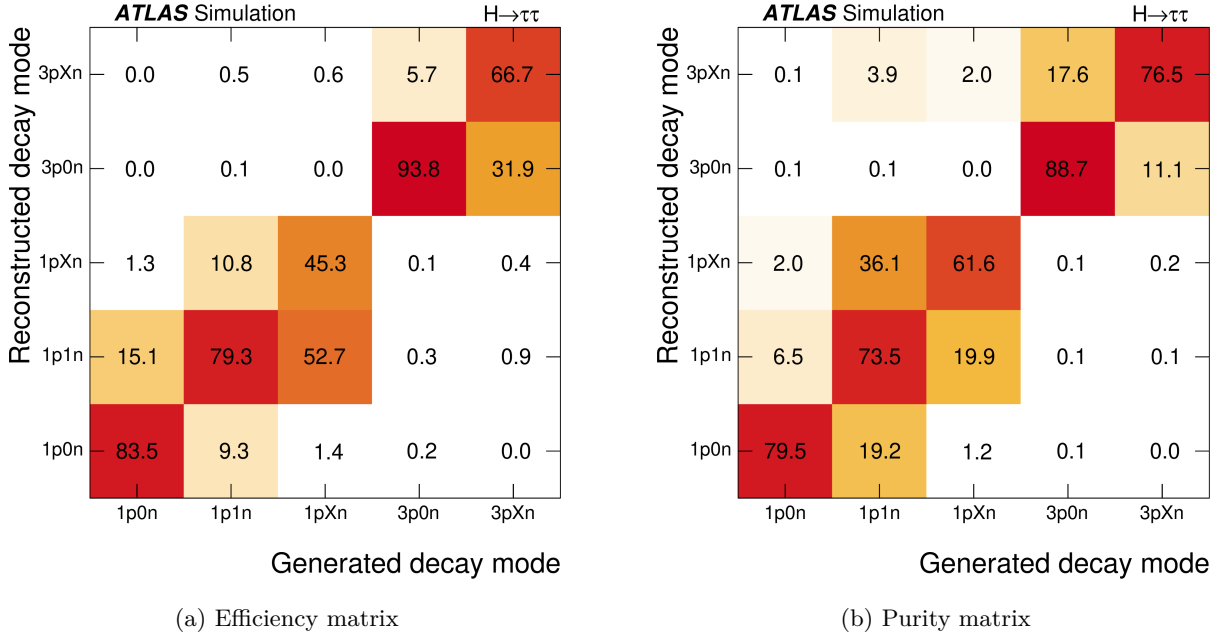


Figure 3.9: Efficiency and purity matrices of the τ -lepton decay mode classification of $H \rightarrow \tau\tau$ signal sample used in the analysis.

After applying this decay mode classification into this analysis, the reconstructed di- τ decay mode distributions are well described and in good agreement with data. These are shown in Figure 3.10 for the decay mode used in both $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$. The events include all signal regions defined in the later section.

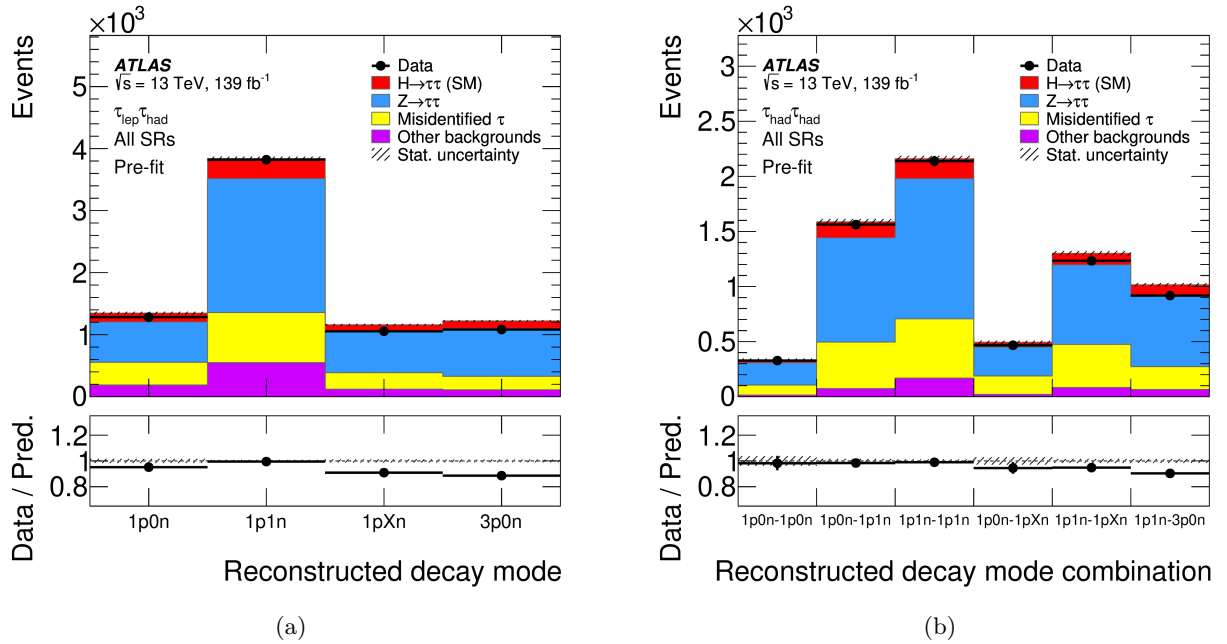


Figure 3.10: Number of events distributed by τ_{had} decay mode. These are showed for single τ_{had} decay mode in $\tau_{\text{lep}}\tau_{\text{had}}$ channel and di- τ_{had} decay mode combination in $\tau_{\text{had}}\tau_{\text{had}}$ channel in figure (a) and (b), respectively.

3.4 Event selection and categorization

The analysis selected events with the final states which contain the $\tau_{\text{lep}}\tau_{\text{had}}$ or $\tau_{\text{had}}\tau_{\text{had}}$ decay products with opposite electric charge for two τ -leptons. In $\tau_{\text{lep}}\tau_{\text{had}}$ channel, the electron or muon is selected to have $p_T > 21.0\text{-}27.3$ GeV while $\tau_{\text{had-vis}}$ with $p_T > 30$ GeV due to the offline trigger requirements, same in [91]. For the same reason in $\tau_{\text{had}}\tau_{\text{had}}$ channel, two $\tau_{\text{had-vis}}$ are required to have p_T greater than 40 and 30 GeV, respectively. The angular distances between two τ candidates need to be $\Delta R_{\tau\tau} < 2.5$ and $|\Delta\eta_{\tau\tau}| < 1.5$ ($0.6 < \Delta R_{\tau\tau} < 2.5$ and $|\Delta\eta_{\tau\tau}| < 1.5$) to satisfy the topological requirement of Higgs peak and reject non-resonant events in $\tau_{\text{lep}}\tau_{\text{had}}$ ($\tau_{\text{had}}\tau_{\text{had}}$) channel. All events are required to have at least one jet with $p_T > 40$ GeV, and this jet is further required to have $p_T > 70$ GeV and $|\Delta\eta| < 3.2$ in $\tau_{\text{had}}\tau_{\text{had}}$ channel according to the trigger conditions. The E_T^{miss} is required to be larger than 20 GeV in all events. The collinear approximation x_1, x_2 which is used to describe the momentum fraction carried by the visible decay products of each τ -lepton used in the calculation of di- τ collinear mass $m_{\tau\tau}^{\text{coll}}$ are required to be $0.1 < x_1 < 1.4$, $0.1 < x_2 < 1.2$ ($0.1 < x_1 < 1.4$, $0.1 < x_2 < 1.4$) in the $\tau_{\text{lep}}\tau_{\text{had}}$ ($\tau_{\text{had}}\tau_{\text{had}}$) channel. Besides, in $\tau_{\text{lep}}\tau_{\text{had}}$ channel the transverse mass m_T of lepton+ E_T^{miss} system is required to be smaller than 70 GeV to efficiently suppress the W+jet processes. All these selection requirements are summarized in Table 3.5.

Table 3.5: Summary of preselection requirements in both $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channel.

Preselection	
$\tau_{\text{had}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
One lepton (e or μ) as τ_{lep} candidate	Two τ_{had} candidates
One τ_{had} candidate	No electron or muon
Opposite electric charge of τ_{lep} and τ_{had}	Opposite electric charge of two τ_{had}
$p_T(\tau_{\text{lep}}) > 21$ to 27.3 GeV, $p_T(\tau_{\text{had}}) > 30$ GeV	$p_T(\tau_1) > 40$ GeV, $p_T(\tau_2) > 30$ GeV
$\Delta R_{\tau\tau} < 2.5$, $ \Delta\eta_{\tau\tau} < 1.5$	$0.6 < \Delta R_{\tau\tau} < 2.5$, $ \Delta\eta_{\tau\tau} < 1.5$
Leading jet $p_T(j_1) > 40$ GeV	Leading jet $p_T(j_1) > 70$ GeV, $ \eta < 3.2$
$E_T^{\text{miss}} > 20$ GeV	$E_T^{\text{miss}} > 20$ GeV
$0.1 < x_1 < 1.4$, $0.1 < x_2 < 1.2$	$0.1 < x_1 < 1.4$, $0.1 < x_2 < 1.4$
$m_T < 70$ GeV	

After the preselection, the events are categorized by Higgs production modes in the vector-boson fusion like (VBF) category and the gluon-gluon fusion like (Boost) category. The VBF category chooses events to have at least two jets with p_T thresholds of 70 and 30 GeV, respectively. Besides, VBF requires two jets to have the geometric features that the pseudo-rapidity between the leading jets is $|\Delta\eta_{jj}| > 3.0$, and the production of two jet pseudo-rapidities needs to be negative, with the invariant mass of these di-jet system to be $m_{jj} > 400$ GeV. Further, two τ candidates should lie between those two leading jets marked as ‘central leptons’. Moreover, in order to enhance the purity of VBF Higgs process, a VBF

BDT tagger is trained to further divide VBF region into VBF_1 and VBF_0 (in which VBF_1 category has an enhanced fraction of VBF Higgs boson production events) with the cut point of 0. The Boost category contains events which failed the VBF selection, and select the events in which Higgs boson recoils against jets by requiring the transverse momentum of Higgs boson $p_T^{\tau\tau} > 100$ GeV. The p_T of Higgs $p_T^{\tau\tau}$ is calculated as the vector sum of the visible di- τ decay products transverse momenta and the missing transverse momentum. This Boost category is further separated as Boost_1 region requiring $\Delta R_{\tau\tau} < 1.5$ and $p_T^{\tau\tau} > 140$ GeV, and Boost_0 region which failed the previous selections. These production mode categorizations are listed in Table 3.6.

In each category, the Higgs-enriched signal region (SR) is defined in a $m_{\tau\tau}^{\text{MMC}}$ window of $110 < m_{\tau\tau}^{\text{MMC}} < 150$ GeV, while the $Z \rightarrow \tau\tau$ control region (ZCR) is located in $60 < m_{\tau\tau}^{\text{MMC}} < 110$ GeV. Events in ZCR are assigned to either ZCR_0 or ZCR_1 based on a random number uniformly distributed between 0 and 1 to be statistically independent. The ZCR_0 is split into VBF_1, VBF_0, Boost_1, and Boost_0 with the same criteria listed above, to extract the $Z \rightarrow \tau\tau$ normalizations from data for the respective SR. A subset with only $\tau^\pm \rightarrow \rho^\pm \nu \rightarrow \pi^\pm \pi^0 \nu$ process events (ℓ -1p1n for $\tau_{\text{lep}}\tau_{\text{had}}$ and 1p1n-1p1n for $\tau_{\text{had}}\tau_{\text{had}}$) are selected as ZCR_1 as two additional ZCRs to constrain the π^0 related uncertainties.

Table 3.6: Summary of the production mode categorization criteria for the VBF and Boost categories in this analysis. The criteria are same to the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ decay channels.

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

The SRs in each Higgs production category are further divided into subcategories depending on the di- τ decay modes and corresponded optimization variables to improve the sensitivity. For the IP method, the φ_{CP}^* will be more sensitive to discriminate different ϕ_τ values if the impact parameter vector has a magnitude larger than its resolution. Thus we can use the d_0^{sig} defined in Section 3.3 for categorization. For the ρ method, the φ_{CP}^* will

be more effective to measure the ϕ_τ depending on the large production of $|y_+^\rho y_-^\rho|$ discussed in Section 3.1.2. As for the IP- ρ method, both large d_0^{sig} and $|y^\rho|$ are preferred for more sensitivity. In a_1 method the $|y^{a_1}|$ will be taken into account. Among all di- τ mode combinations, some of them are dominant channel with higher sensitivity. These are 1p0n-1p1n, 1p1n-1p1n, and 1p0n-1p0n in $\tau_{\text{had}}\tau_{\text{had}}$ channel, and ℓ -1p1n and ℓ -1p0n in $\tau_{\text{lep}}\tau_{\text{had}}$ channel. Therefore, we further divide the SRs into ‘High’, ‘Medium’ and ‘Low’ subregions. The ‘High’ region selects the dominant decay channel with the corresponded optimization variables cut, and the ‘Medium’ region contains the rest weaker decay channel which included 1pXn and 3p0n decay mode with the corresponded optimization variables selection, for all the rest events failed all criteria will be categorized into ‘Low’ region. The explicit decay mode categorization criteria are summarized in Table 3.7.

Table 3.7: Summary of the decay mode categorization criteria for the High, Medium and Low categories in this analysis to further divide each signal regions.

Decay mode categorization				
		High	Medium	Low
hh	1p0n-1p0n	both τ $d_0^{\text{sig}}(\tau_{1p0n}) > 1.5$	-	Failed
	1p0n-1p1n	$d_0^{\text{sig}}(\tau_{1p0n}) > 1.5, y^\rho(\tau_{1p1n}) > 0.1$	-	
	1p1n-1p1n	$ y^\rho(\tau_{1p1n})y^\rho(\tau_{1p1n}) > 0.2$	-	
	1p0n-1pXn	-	$d_0^{\text{sig}} > 1.5, y^\rho(\tau_{1pXn}) > 0.1$	
	1p1n-1pXn	-	$ y^\rho(\tau_{1p1n})y^\rho(\tau_{1pXn}) > 0.2$	
	1p1n-3p0n	-	$ y^\rho(\tau_{1pXn}) > 0.1, y^{a_1}(\tau_{3p0n}) > 0.6$	
lh		lepton $d_0^{\text{sig}}(e) > 2.5$ or $d_0^{\text{sig}}(\mu) > 2.0$		Failed
	l-1p0n	$d_0^{\text{sig}}(\tau_{1p0n}) > 1.5$	-	
	l-1p1n	$ y^\rho(\tau_{1p1n}) > 0.1$	-	
	l-1pXn	-	$ y^\rho(\tau_{1pXn}) > 0.1$	
	l-3p0n	-	$ y^{a_1}(\tau_{3p0n}) > 0.6$	

In this configuration, there are twelve signal regions in $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channel, separately, for a total of twenty-four signal regions. Four Z control regions in $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channel, with two additional ZCRs as consequently ten ZCRs in total. Each signal or control region is orthogonal to the others.

The modelling check of the variable distributions used for the selection are showed in Figure 3.11, Figure 3.12 and Figure 3.13 for preselection, VBF and Boost categories, respectively. These are checked by $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channel separately and they are in good modelling, and the cut on each variable is showed in each plots.

3.4.1 Sensitivity optimization selection in $\tau_{\text{lep}}\tau_{\text{had}}$ channel

The selection for the sensitivity categorization is optimized for each decay channel. In this section, the optimization on leptonically decayed τ in $\tau_{\text{lep}}\tau_{\text{had}}$ channel is especially discussed.

As introduced in Section 3.3, the optimization variable for IP method is d_0^{sig} . To choose

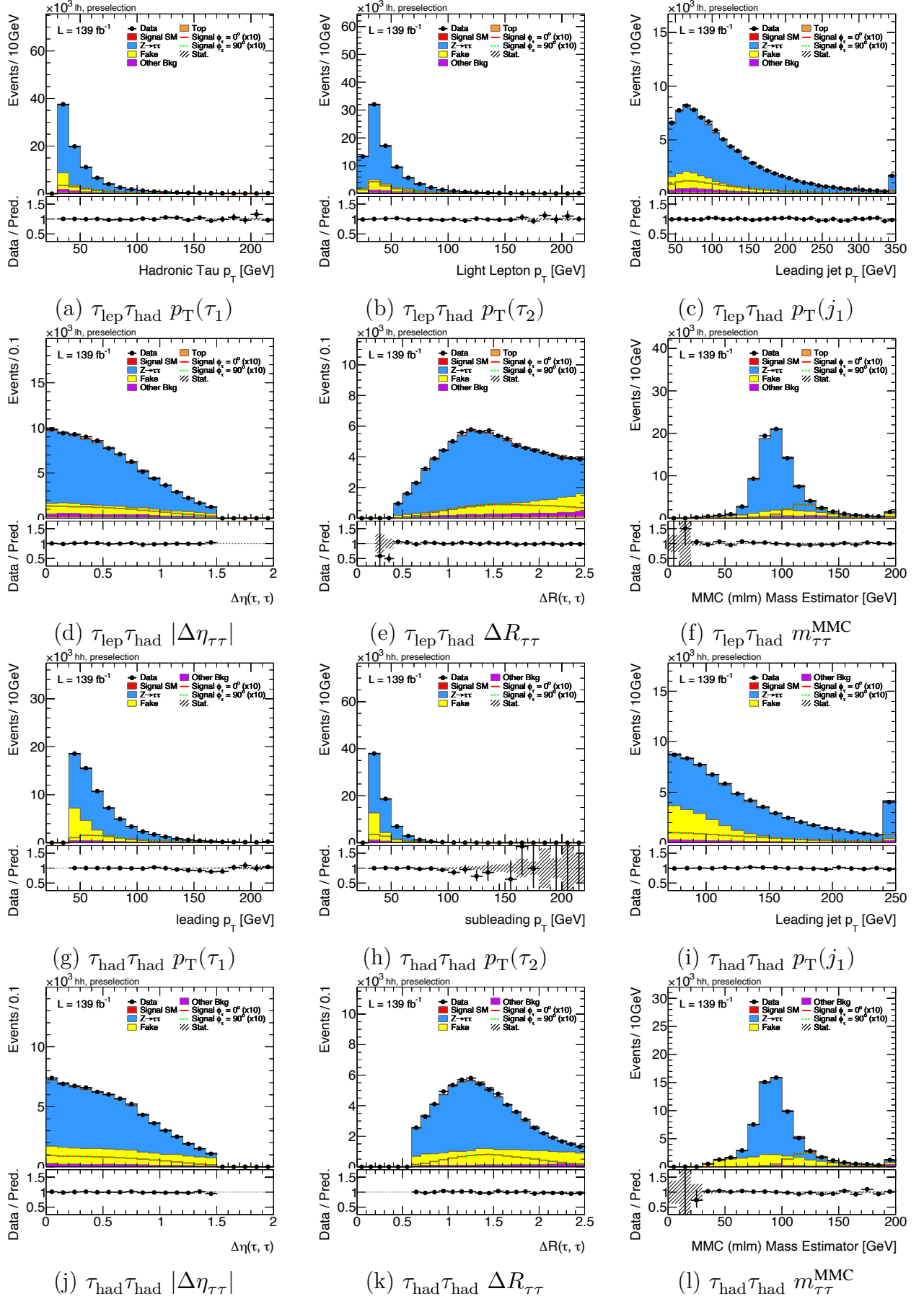


Figure 3.11: Modeling check of the variables which are used for the selection at preselection level in $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channel.

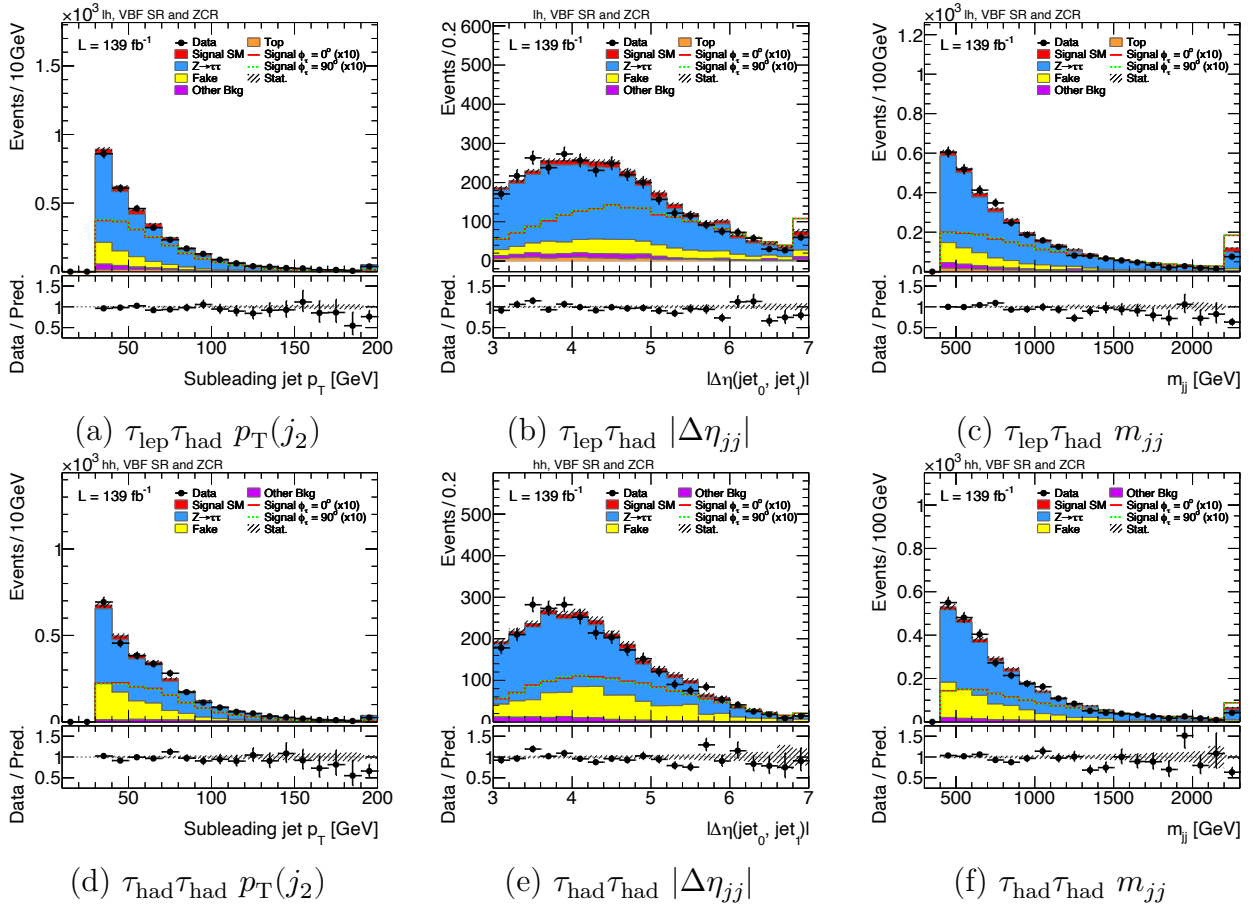


Figure 3.12: Modeling check of the variables which are used for the selection at VBF level in $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channel.

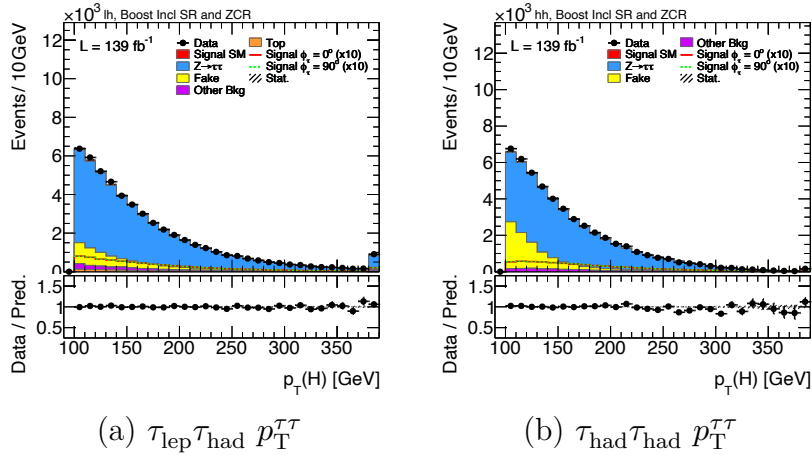


Figure 3.13: Modeling check of the variables which are used for the selection at Boost level in $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channel.

the value cut on τ_{lep} (e or μ), a set of likelihood scan with different cut value on τ_{lep} is implemented.

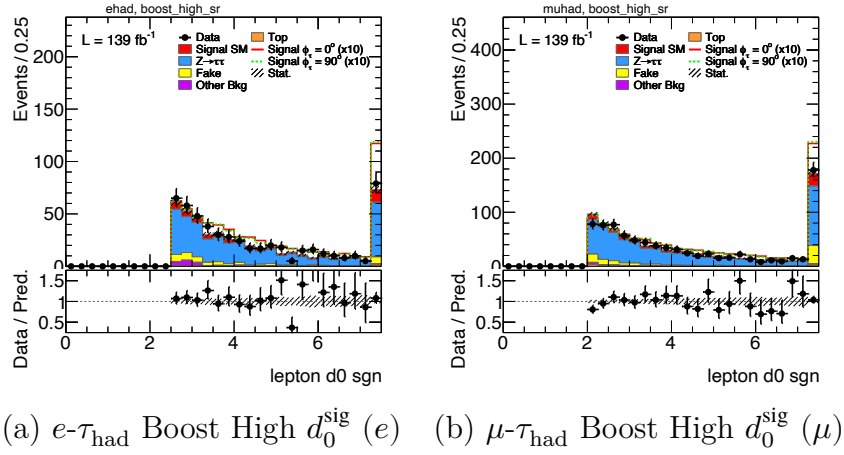


Figure 3.14: $d_0^{\text{sig}}(\ell)$ distributions in boost high region with $e\text{-}\tau_{\text{had}}$ and $\mu\text{-}\tau_{\text{had}}$ channel separated.

To determine the best optimized selection on τ_{lep} d_0^{sig} , we do the likelihood scan with τ_{lep} separated to e and μ with the inclusive τ_{had} decay mode. We do the same setting of the fit with different d_0^{sig} value cuts on the e and μ , and then check the inclusive $\tau_{\text{lep}}\tau_{\text{had}}$ decay mode sensitivity. The selection on τ_{lep} d_0^{sig} for the division of high/medium/low optimized categorization is showed in Figure 3.14 and it can be seen that we applied the different cuts on $d_0^{\text{sig}}(e)$ and $d_0^{\text{sig}}(\mu)$, separately.

The plots of likelihood scan are showed in Figure 3.15. It looks that the best sensitivity cut for $d_0^{\text{sig}}(e)$ is 2.5 and for $d_0^{\text{sig}}(\mu)$ is 2. The ‘mix’ label in inclusive $\tau_{\text{lep}}\tau_{\text{had}}$ decay mode check denotes d_0^{sig} cut on 2.5 for e and 2 for μ , while other number means cut on that same number for e and μ d_0^{sig} . The likelihood scan shows that the ‘mix’ scheme is most sensitive for the τ_{lep} d_0^{sig} cut, and we choose this cut as in Table 3.7.

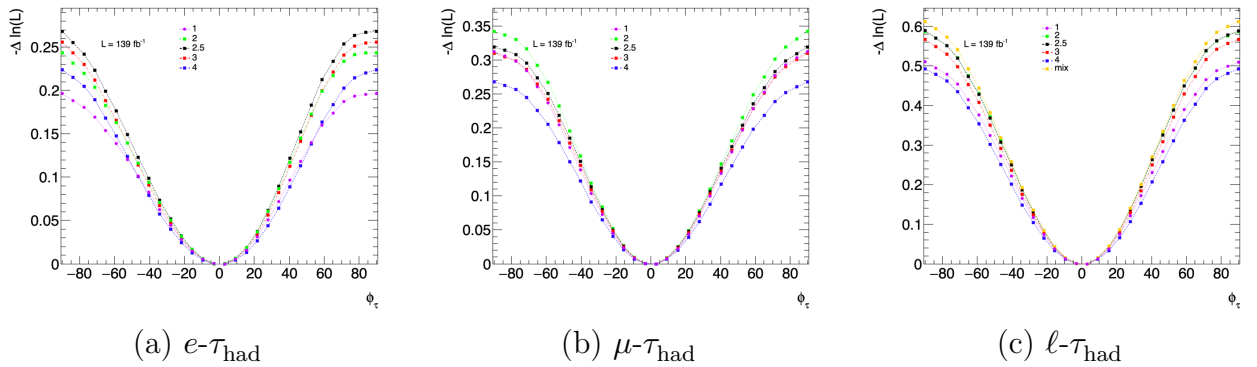


Figure 3.15: Likelihood scan of different cut value on τ_{lep} d_0^{sig} with inclusive τ_{had} decay mode.

3.5 Background estimation

The background processes of this analysis are roughly attributed into two types, one is two true τ -leptons from other processes and the other is jets are misidentified as one or two $\tau_{\text{had-vis}}$. For the first type, there will be the $Z(\rightarrow \tau\tau) + \text{jets}$ process which is the dominant background of this analysis, as well as a few contributions from diboson, $H \rightarrow WW^*$ and $t\bar{t}$ processes. In the misidentification case, the main contributions are from $W + \text{jets}$ and QCD multijet processes.

Due to such features we combine Monte Carlo simulation and data-driven techniques to estimate the background. For the processes of $Z(\rightarrow \tau\tau) + \text{jets}$, $Z(\rightarrow \ell\ell) + \text{jets}$, diboson and $t\bar{t}$ are modelled by Monte Carlo samples introduced in Section 3.2. The misidentified $\tau_{\text{had-vis}}$ (a.k.a *fake* τ) by $W + \text{jets}$ and QCD multijet processes are estimated through data-driven method. The detailed estimation methods for the main background processes are presented in the sections below.

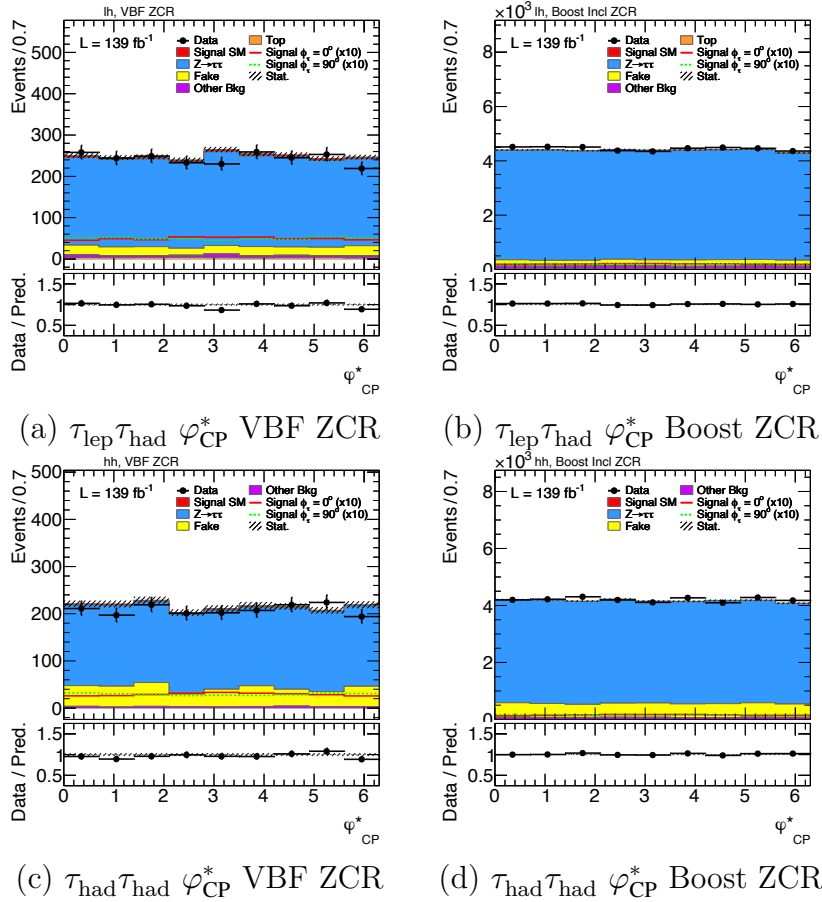


Figure 3.16: φ_{CP}^* distributions in VBF and Boost categories in Z control region for $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channel.

3.5.1 $Z \rightarrow \tau\tau + \text{jets}$ background

The $Z(\rightarrow \tau\tau) + \text{jets}$ background is modelled by MC samples generated by SHERPA. Besides, $Z \rightarrow \tau\tau$ control regions defined by the $m_{\tau\tau}^{\text{MMC}}$ window around the Z peak in $60 < m_{\tau\tau}^{\text{MMC}} < 110$ GeV as introduced in Section 3.4 are used to extract the $Z \rightarrow \tau\tau$ process normalization from data. The φ_{CP}^* distributions in VBF and Boost categories in Z control region for $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channel are checked in Figure 3.16, $Z \rightarrow \tau\tau$ process is estimated very well.

3.5.2 Misidentified- τ background

3.5.2.1 Fake background in $\tau_{\text{lep}}\tau_{\text{had}}$ channel

In $\tau_{\text{lep}}\tau_{\text{had}}$ channel one of the main background is jets misidentified as the $\tau_{\text{had-vis}}$. It consists mostly $W + \text{jets}$ and QCD multijet events, and a small component from the single top process. This source of background is estimated by data-driven method which calculates the ratio of the number of data events which will not be modelled by MC between passed and failed the identification criterion in background control regions, and this ratio will be called as *fake factor* $\mathcal{F}$, then applying this *fake factor* to the failed identification events in signal region to evaluate the fake number in signal region with passing the identification criterion.

In this analysis, the *fake* τ events in this analysis can be estimated as

$$N_{\text{fakes}}^{SR} = (N_{\text{Data}}^{\text{anti-}\tau, SR} - N_{\text{MC, no jet} \rightarrow \tau}^{\text{anti-}\tau, SR}) \times \mathcal{F} \quad (3.8)$$

with the upper index *anti- τ* indicates these events passes all analysis requirements except failing the MEDIUM identification criterion, with a low threshold on $\tau_{\text{had-vis}}$ identification score 0.01 is applied to reject these very low score events dominated by gluon-induced and pileup jets. The data events subtract the MC estimated part in this anti- τ sector is believed to be enriched by the misidentified τ_{had} events. Then a combined *fake factor* $\mathcal{F}$ is applied to correct for the different selection efficiency between passed and failed identification, transferring the event number from anti- τ to pass- τ sector in signal region.

Table 3.8: $W + \text{jets}$, QCD and Top control regions definition.

Control region	Definition with respect SRs
$W + \text{jets CR}$	Invert m_{T} cut ($m_{\text{T}} > 70$ GeV)
QCD CR	Invert lepton isolation requirement
Top CR	Reverse B veto cut and $m_{\text{T}} > 40$ GeV

The *fake factor* depends on quark/gluon components therefore is different from back-

ground source. Considering the main fake sources are W + jets and QCD multijet and ignoring tiny contribution from single top process, the combined *fake factor* $\mathcal{F}$ is constructed as the sum of each individual *fake factor* for each relevant process, and weighted by the expected fractional contribution for the considered process in anti- τ sector

$$\mathcal{F} = F_W R_W + F_{QCD} R_{QCD} \quad (3.9)$$

the individual *fake factor* $F_i (i = W, QCD)$ is obtained in corresponded background control region as the ratio of data events subtract the MC estimated part of the pass- τ events over those in the anti- τ sector formulated as

$$F_i = \frac{N_{Data}^{pass-\tau, CR_i} - N_{MC, no\ jet \rightarrow \tau}^{pass-\tau, CR_i}}{N_{Data}^{anti-\tau, CR_i} - N_{MC, no\ jet \rightarrow \tau}^{anti-\tau, CR_i}} \quad (3.10)$$

in which the W + jets and QCD control region are defined by inverting one selection criterion with respect to signal region to ensure the orthogonality between signal region and each control region. These definitions are listed in Table 3.8.

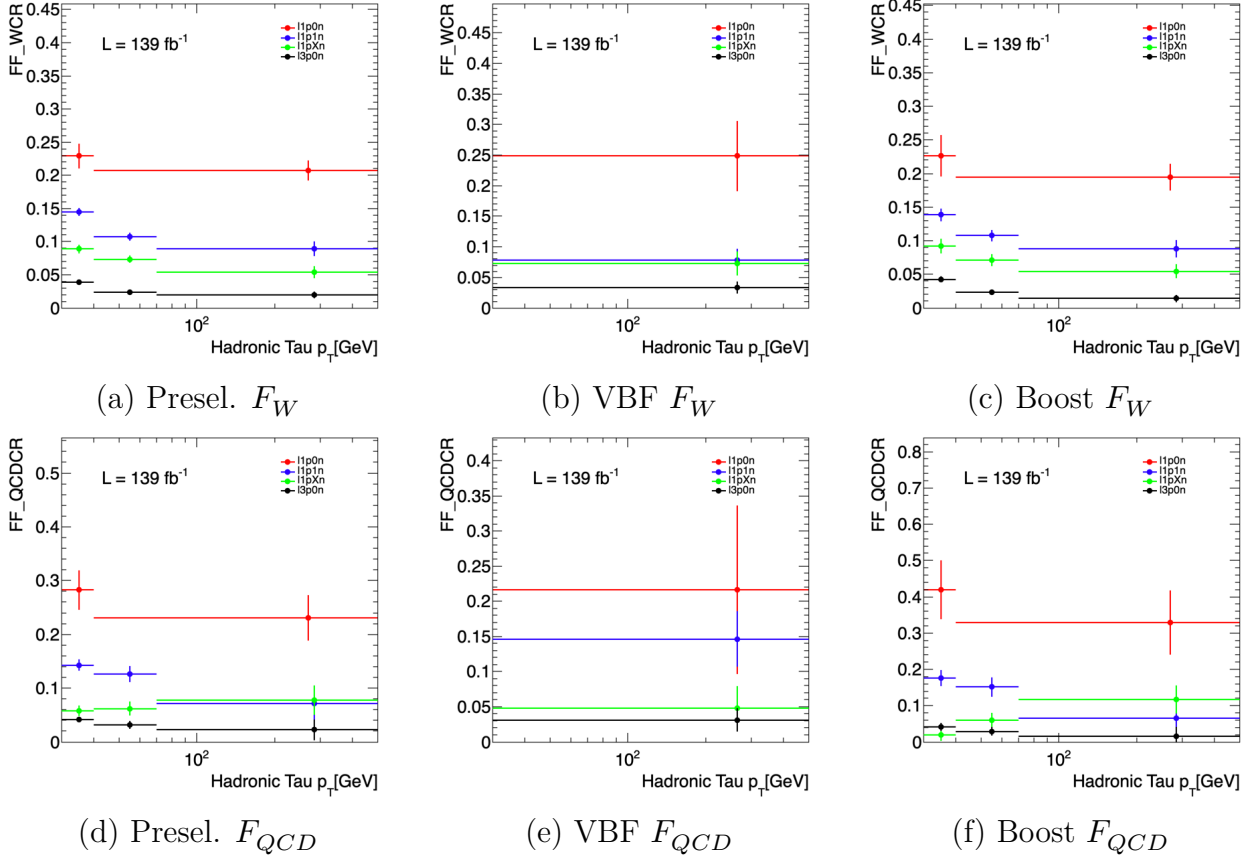


Figure 3.17: *Fake factor* calculated as a function of $p_T \tau_{had}$ from W and QCD control regions $F_i (i = W, QCD)$ used in $\tau_{lep} \tau_{had}$ channel with decay mode separated in preselection, VBF and Boost categories.

The *fake factor* are calculated as the function of $\tau_{\text{had-vis}} p_T$ in preselection, Boost and VBF categorization with different decay mode separated showed in Figure 3.17. This $\tau_{\text{had-vis}} p_T$ depended *fake factor* will not only pass the scale to evaluate the *fake* number, but also propagate the shape information of the *fake*.

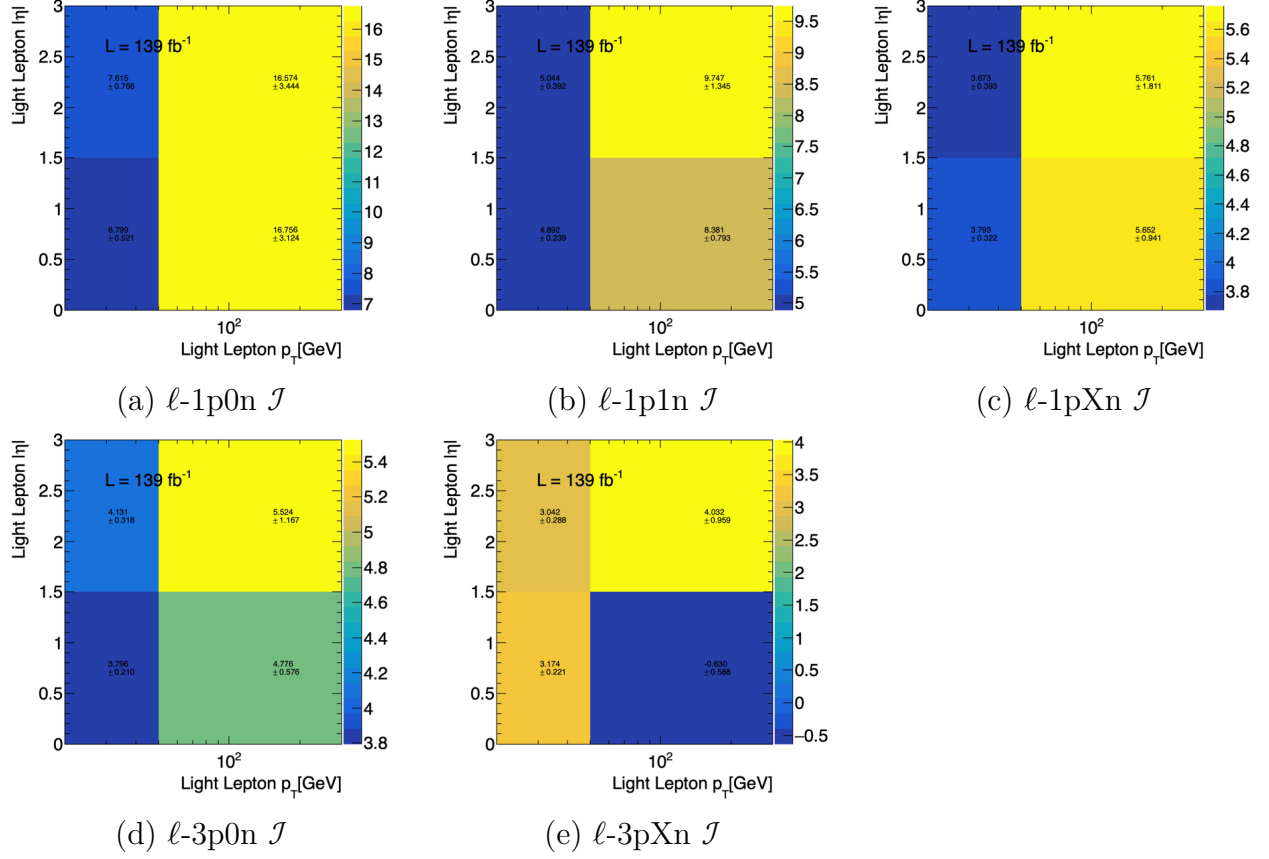


Figure 3.18: $\mathcal{J}$ calculated as a function of $p_T \tau_{\text{had}}$ and $\Delta\phi(\tau, E_T^{\text{miss}})$ used in $\tau_{\text{lep}} \tau_{\text{had}}$ channel with decay mode separated in preselection categories.

These individual *fake factors* are added with weight $R_i (i = W, QCD)$ to combined *fake factor* $\mathcal{F}$, in which this weight is considered as the fractional contribution from each background source. If it is supposed that the *fake* is from $W + \text{jets}$ and QCD multijet two parts thus the $R_W = 1 - R_{QCD}$, and fraction of QCD multijet events in SR anti- τ sector is particularly calculated. The equation will be

$$R_{QCD} = \frac{N_{Data, QCD}^{anti-\tau, SR}}{N_{Data}^{anti-\tau, SR} - N_{MC \text{ no } jet \rightarrow \tau}^{anti-\tau, SR}} \quad (3.11)$$

the number of QCD events in the SR anti- τ sector $N_{Data, QCD}^{anti-\tau, SR}$ occurred in numerator need to be estimated. This is realized by applying a transfer factor called *isolation factor* $\mathcal{J}$ onto

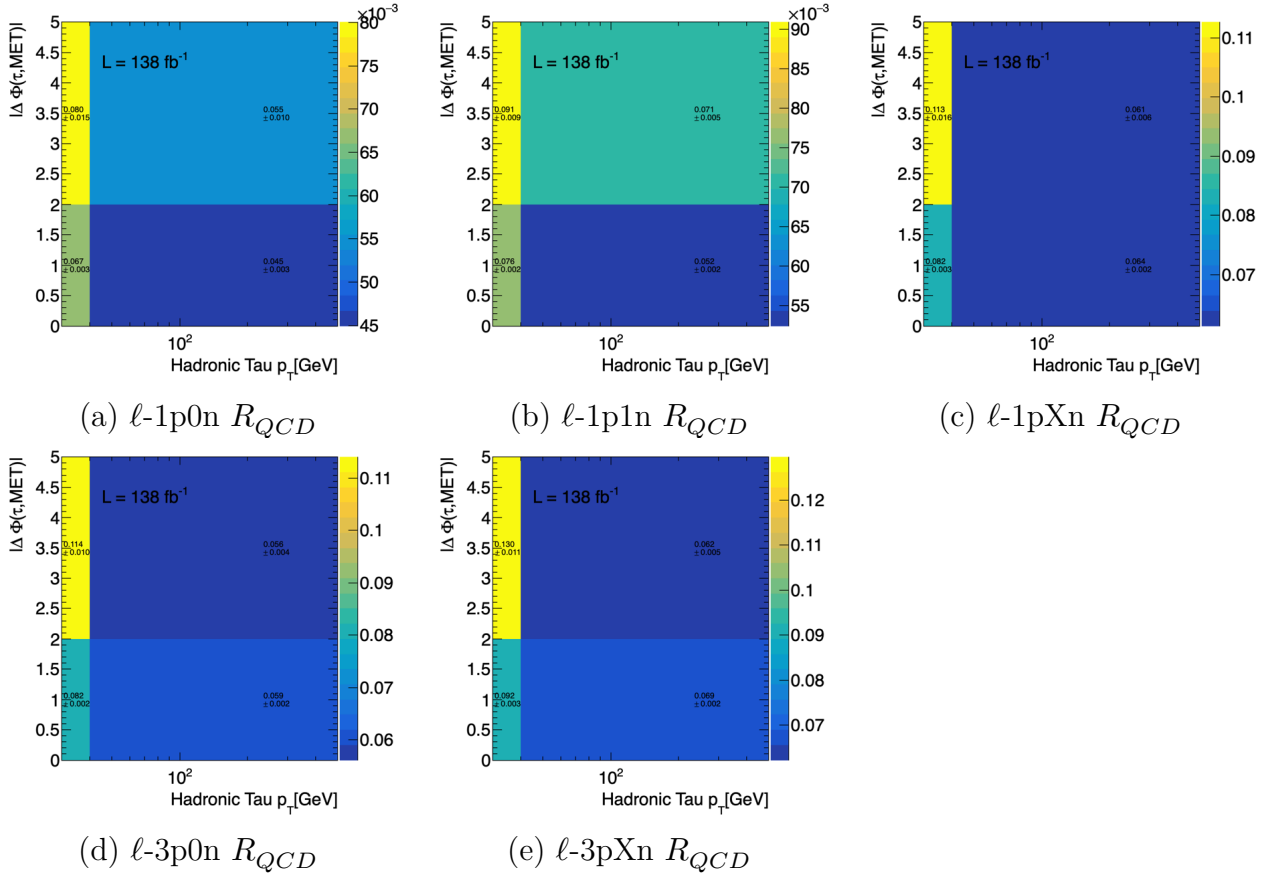


Figure 3.19: R_{QCD} calculated as a function of lepton p_T and lepton $|\eta|$ used in $\tau_{lep}\tau_{had}$ channel with decay mode separated in preselection categories.

the data events subtracted the MC with a true lepton part in QCDCR anti- τ sector

$$N_{Data, QCD}^{anti-\tau, SR} = (N_{Data}^{anti-\tau, QCDCR} - N_{MC \text{ true lepton}}^{anti-\tau, QCDCR}) \times \mathcal{J} \quad (3.12)$$

in which the *isolation factor* $\mathcal{J}$ is calculated by taking the ratio of the events passing the lepton isolation requirement over those that fail it in a dedicated control region, which is defined with exactly the same cuts used in Preselection level with reversing the electric charge sign of the $\tau_{had-vis}$ and lepton to be the same (SS region)

$$\mathcal{J} = \frac{N_{data}^{iso, SS} - N_{MC \text{ true lepton}}^{iso, SS}}{N_{data}^{non-iso, SS} - N_{MC \text{ true lepton}}^{non-iso, SS}} \quad (3.13)$$

then the fraction of QCD multijet *fake* to total *fake* R_{QCD} can be evaluated.

The *isolation factor* is calculated as a 2-dimensional distribution as a function of lepton p_T and lepton $|\eta|$ separated by decay mode at preselection level illustrated in Figure 3.18. And R_{QCD} is also computed as a 2-dimensional function depending on $\tau_{had-vis}$ p_T and the azimuthal angle between the $\tau_{had-vis}$ candidate and the missing transverse momentum, $\Delta\phi(\tau, E_T^{miss})$. It is calculated by different decay mode in preselection, Boost and VBF

categorization. The preselection R_{QCD} is showed in Figure 3.19.

The combined *fake factor* $\mathcal{F}$ calculated for $\tau_{\text{lep}}\tau_{\text{had}}$ *fake* background estimation can be illustrated by Figure 3.20. The yellow and green blocks are $W + \text{jets}$ and QCD control regions defined for the calculation of each individual *fake factor* $F_i (i = W, QCD)$, and the red blocks are the same sign region used for the *isolation factor* $\mathcal{J}$ extraction. Then the R_{QCD} is evaluated by the fraction of the events that applying the *isolation factor* $\mathcal{J}$ to QCDCR anti- τ sector to those in SR, and then we can get the *fake factor* $\mathcal{F}$. Finally applying $\mathcal{F}$ to SR anti- τ sector to estimate the *fake* background in SR pass- τ sector in the blue blocks.

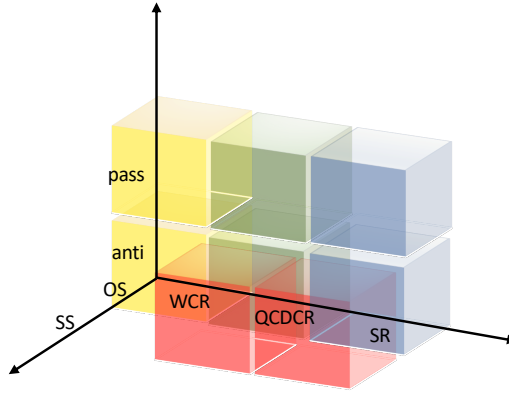


Figure 3.20: Illustration of the control region definition used for $\tau_{\text{lep}}\tau_{\text{had}}$ *fake factor* $\mathcal{F}$ calculation.

3.5.2.2 Fake background in $\tau_{\text{had}}\tau_{\text{had}}$ channel

The *fake* background in $\tau_{\text{had}}\tau_{\text{had}}$ channel includes events in which one or both $\tau_{\text{had-vis}}$ are misidentified. These events are mainly originated from QCD multijet process. To estimate this kind of *fake* background, the data-driven method designed for $\tau_{\text{had}}\tau_{\text{had}}$ channel is employed.

In the selected signal region with passed the τ identification criterion (marked as τ^P), it can be a true $\tau_{\text{had-vis}}$ (τ^T) or a *fake* $\tau_{\text{had-vis}}$ (τ^F) candidate. For $\tau_{\text{had}}\tau_{\text{had}}$ channel, consider single τ as well as both τ -leptons *fake*

$$\tau_1^P \tau_2^P = \tau_1^T \tau_2^T + \tau_1^T \tau_2^F + \tau_1^F \tau_2^T + \tau_1^F \tau_2^F \quad (3.14)$$

with leading and sub-leading $\tau_{\text{had-vis}}$ marked as τ_1 and τ_2 , separately. First in order to estimate the single $\tau_{\text{had-vis}}$ *fake*, the *fake factor* of calculated in corresponded control region is applied to anti-ID sector (τ^A) in SR like

$$\begin{aligned} F^1 \tau_1^A \tau_2^P &= \tau_1^F \tau_2^T + \tau_1^F \tau_2^F \\ F^2 \tau_1^P \tau_2^A &= \tau_1^T \tau_2^F + \tau_1^F \tau_2^F \end{aligned} \quad (3.15)$$

the pass-ID τ can be either true or fake τ . Thus, when doing such calculation for single $\tau_{\text{had-vis}}$ *fake*, it actually also counts the double τ -leptons *fake* twice. Similarly, the both τ -leptons *fake* is evaluated by applying both *fake factors* for each τ to their SR anti-ID sector

$$F^1 F^2 \tau_1^A \tau_2^A = \tau_1^F \tau_2^F \quad (3.16)$$

therefore with Equation (3.15) and Equation (3.16), the Equation (3.14) will be written as

$$\tau_1^P \tau_2^P = \tau_1^T \tau_2^T + F^1 \tau_1^A \tau_2^P + F^2 \tau_1^P \tau_2^A - F^1 F^2 \tau_1^A \tau_2^A \quad (3.17)$$

The explicit calculation of each *fake factor* used for $\tau_{\text{had}}\tau_{\text{had}}$ channel would be computed in $\tau_{\text{lep}}\tau_{\text{had}}$ W + jets control region, implemented in several ID selection sectors to avoid the repeated computation when applying to $\tau_{\text{had}}\tau_{\text{had}}$ anti-ID sector. This is introduced because a minimum ID requirement of at least one $\tau_{\text{had-vis}}$ to pass the LOOSE RNN ID is applied. The ID criterion in W + jets CR for computation of the *fake factor* can be passing MEDIUM (medium, m), failing MEDIUM (not-medium, nm), and passing LOOSE but failing MEDIUM (loose-not-medium, lnm). Then two *fake factors* are calculated with different ID requirement in denominator

$$\begin{aligned} F_{nm} &= \frac{N_{\text{Data}}^{\text{medium}, WCR} - N_{MC}^{\text{medium}, WCR}}{N_{\text{Data}}^{\text{not-medium}, WCR} - N_{MC}^{\text{not-medium}, WCR}} \\ F_{lnm} &= \frac{N_{\text{Data}}^{\text{medium}, WCR} - N_{MC}^{\text{medium}, WCR}}{N_{\text{Data}}^{\text{loose-not-medium}, WCR} - N_{MC}^{\text{loose-not-medium}, WCR}} \end{aligned} \quad (3.18)$$

since the *fake factor* is calculated as the function of $\tau_{\text{had-vis}}$ p_T , it will be different when applying it to leading τ and sub-leading τ . *Fake factors* calculated with different ID requirement $F_i (i = nm, lnm)$ used in $\tau_{\text{had}}\tau_{\text{had}}$ channel are showed in Figure 3.21.

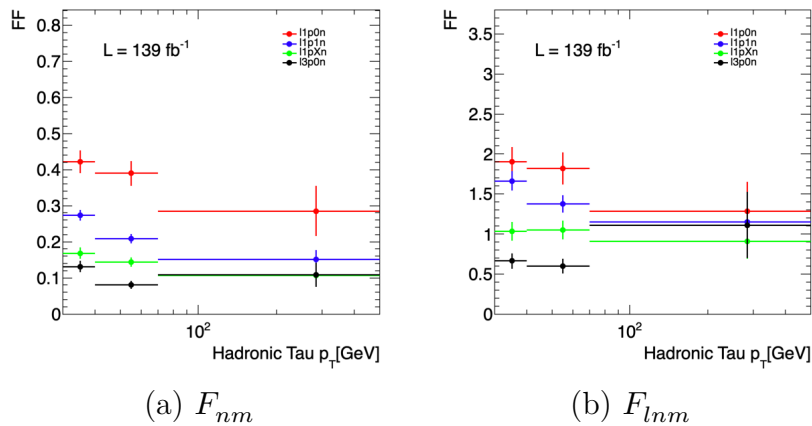


Figure 3.21: *Fake factor* calculated with different ID requirement in $\tau_{\text{lep}}\tau_{\text{had}}$ W control regions $\tau_{\text{had}}\tau_{\text{had}}$ channel.

Table 3.9: Event category region where the *fake factor* is applied in $\tau_{\text{had}}\tau_{\text{had}}$ channel with different $\tau_{\text{had-vis}}$ ID requirement.

region	leading ID	sub-leading ID
anti- $\tau_{\text{had-vis}}$	not-medium	not-medium
lead-anti- $\tau_{\text{had-vis}}$	not-medium	medium
sublead-anti- $\tau_{\text{had-vis}}$	medium	not-medium
lead-anti- $\tau_{\text{had-vis}}$ -loose	loose-not-medium	not-medium
sublead-anti- $\tau_{\text{had-vis}}$ -loose	not-medium	loose-not-medium

The *fake factor* applied regions with both $\tau_{\text{had-vis}}$ ID requirement are summarized in Table 3.9. *fake factor* applied to single *fake* $\tau_{\text{had-vis}}$ in Equation (3.17) will be $F_{nm}(\tau_1)$ and $F_{nm}(\tau_2)$ and they will apply to lead-anti- $\tau_{\text{had-vis}}$ (nm-m) and sublead-anti- $\tau_{\text{had-vis}}$ (m-nm), respectively. The form in double *fake* $\tau_{\text{had-vis}}$ will be a little complicated since we need to avoid both two τ -leptons failing LOOSE (not-loose, nl) case which is already vetoed. The applied sectors for double *fake* estimation are anti- $\tau_{\text{had-vis}}$ in which two τ both failed the MEDIUM ID. To avoid the nl-nl sector, this anti- $\tau_{\text{had-vis}}$ is further divided as lead-anti- $\tau_{\text{had-vis}}$ -loose with (lnm-nm) $F_{lnm}(\tau_1)F_{nm}(\tau_2)$ and sublead-anti- $\tau_{\text{had-vis}}$ -loose (nm-lnm) with $F_{nm}(\tau_1)F_{lnm}(\tau_2)$ applied. These two sectors have an overlap when both τ passed the LOOSE but failed the MEDIUM ID requirement (lnm-lnm) and it will cause an overestimation of the double *fake* by factor two. Thus this overestimation is eliminated by scaling the *fake factor* by $\frac{1}{2}$ and the Equation (3.17) will become to

$$\begin{aligned} \tau_1^m \tau_2^m = & + \tau_1^T \tau_2^T + F_{nm}(\tau_1) \tau_1^{nm} \tau_2^m + F_{nm}(\tau_2) \tau_1^m \tau_2^{nm} \\ & - \frac{1}{2} [F_{lnm}(\tau_1) F_{nm}(\tau_2) \tau_1^{lnm} \tau_2^{nm} + F_{nm}(\tau_1) F_{lnm}(\tau_2) \tau_1^{nm} \tau_2^{lnm}] \end{aligned} \quad (3.19)$$

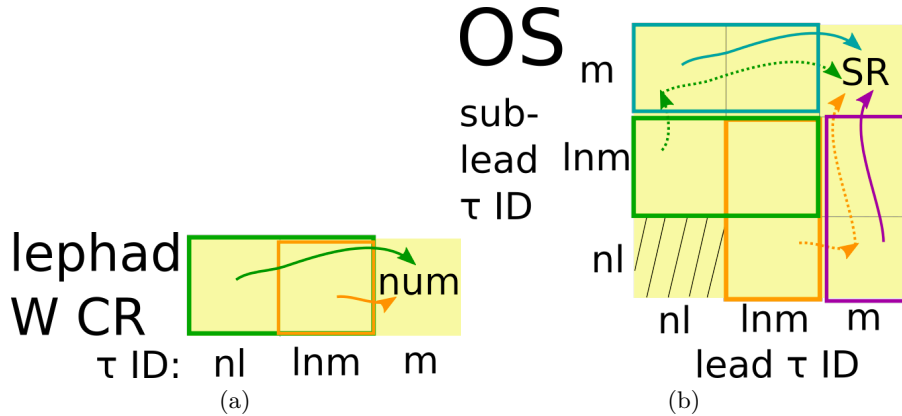


Figure 3.22: (a) Calculation of the *fake factor* in $\tau_{\text{lep}}\tau_{\text{had}}$ WCR with two kinds of $\tau_{\text{had-vis}}$ ID requirement which will be applied for $\tau_{\text{had}}\tau_{\text{had}}$ *fake* estimation. (b) Illustration of the applied region for $\tau_{\text{had}}\tau_{\text{had}}$ *fake* estimation.

This *fake* estimation in $\tau_{\text{had}}\tau_{\text{had}}$ channel is illustrated by Figure 3.22. We first get the *fake factor* functioned as the $\tau_{\text{had-vis}} p_T$ in $\tau_{\text{lep}}\tau_{\text{had}}$ channel WCR with the event selection is modified to close to the $\tau_{\text{had}}\tau_{\text{had}}$ channel selection (except the leading $\tau_{\text{had-vis}} p_T$ kept cut on 40 GeV for statistical reason) for the compatibility with two different $\tau_{\text{had-vis}}$ ID requirement showed in Figure 3.22a. Then the applied regions are depicted in Figure 3.22b, with m-nm (purple rectangle) and nm-m (blue rectangle) for the single *fake* estimation, which also considered twice the double *fake* part. Then the double *fake* are estimated by lnm-nm (orange rectangle) and nm-lnm (green rectangle) sectors in where they have an overlap in lnm-lnm part then this overestimation is eliminated by a factor $\frac{1}{2}$.

The *fake factor* method can be validated in the regions orthogonal to its define region. In $\tau_{\text{had}}\tau_{\text{had}}$ channel, we choose the same-sign region which required the charge sign of two (*fake*) τ candidates to be same, and the high- $\Delta\eta$ region where the di- τ $1.5 < \Delta\eta < 2.0$. Then we use same data-driven method to estimate the *fake* component in these two regions, and the *fake factors* calculated in same-sign region also reversed the charge sign. The validation plots are showed in Figure 3.23. The mismodeling in these two regions are assigned as the ‘closure’ uncertainties in *fake* part as discussed in Section 3.6.2.

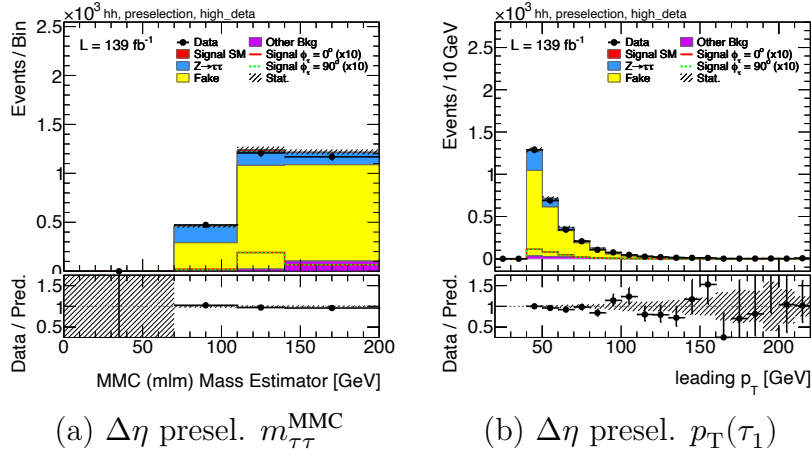


Figure 3.23: Validation of the *fake factor* method in $\tau_{\text{had}}\tau_{\text{had}}$ channel in $\Delta\eta$ regions.

3.6 Systematic uncertainties

Systematic uncertainties in this analysis are generally considered from the experiment uncertainties, theoretical uncertainties, and τ -lepton decay reconstruction related uncertainties. These uncertainties affect not only the shape of the φ_{CP}^* distribution but also its scale.

3.6.1 Theoretical uncertainties

The theoretical uncertainties are considered for signal $H \rightarrow \tau\tau$ process and background $Z \rightarrow \tau\tau$ process. They affect almost normalization rather than the shape of the φ_{CP}^* .

Theory uncertainties on signal predictions

Theoretical uncertainties on the Standard Model $H \rightarrow \tau\tau$ signal predictions used in this analysis comes from three main sources:

- QCD scale uncertainties by reason of missing higher orders in perturbation theory, which impacts also the uncertainty on jet bin migration
- Non-perturbative parts of the calculation (underlying event and hadronization)
- Parton density functions (PDFs) and α_S value uncertainty on experimental input parameters

These uncertainties are derived by comparison of the nominal and alternative signal samples using different underlying event and parton showering models, which is generated by HERWIG 7 instead of PYTHIA 8 to evaluate the different parton shower and hadronization effects.

Theoretical uncertainties on the total production cross-section are evaluated for ggH, VBF, and VH processes by varying the QCD factorization and renormalization scales and the PDF model. They are not expected to have large impacts on fit results because it mainly introduces the normalization effect to signal processes and only the shape information of the φ_{CP}^* distribution is used to extract the best-fit value of the parameter of interest ϕ_τ .

Theory uncertainties on background predictions

The following sources of uncertainty are considered for $Z(\rightarrow \tau\tau) + \text{jets}$:

- PDF: evaluated by considering the standard deviation PDF sets variation event weights compared to NNPDF3.0NNLO PDF set used in Sherpa
- Renormalization and factorization scales (μ_R/μ_F): evaluated by event weights provided by Sherpa
- Jet-to-parton matching uncertainty ($CKKW$): evaluated using truth-level parameterization as a function of jet multiplicity and p_T (Z)
- Resummation scale uncertainty (qsf): evaluated using truth-level parameterization as a function of jet multiplicity and p_T (Z)
- α_S : evaluated using event weights provided by Sherpa

For all the uncertainties, only the shape and migration component of the uncertainty are considered since the absolute normalization is determined by Z control region at fit level.

3.6.2 Experimental uncertainties

The experimental uncertainties considered in this analysis are mainly from the resolution, reconstruction, identification, energy scale and trigger effect of the object measurement. These are estimated by the ATLAS Combined Performance groups. It also includes the uncertainties from misidentifies τ background estimation and luminosity measurement.

- **Electron uncertainties** [92]
 - The resolution of the ID and electromagnetic calorimeter will relate to the electron resolution uncertainty, and the energy scale of electron will arise from the calibration. Besides, the efficiency systematics of the reconstruction, identification, isolation and trigger are also considered in electron side.
- **Muon uncertainties** [93]
 - The muon resolution uncertainty comes from the resolution of the ID and muon spectrum. The muon calibration will also provide the muon energy scale uncertainty. For the efficiency uncertainty of the muon, the reconstruction, identification, isolation and trigger efficiency uncertainties are all counted.
- **Tau uncertainties** [94]
 - The τ_{had} energy scale uncertainty are derived in different ways, by the χ^2 based fit to the data of the visible mass of the μ - τ pair, the E/p measurement, and the comparison of the truth and reconstruction τ_{had} energy distributions between $Z \rightarrow \tau\tau$ POWHEG +PYTHIA 8 sample and alternative sample. In addition, the reconstruction, identification, as well as the trigger by period efficiency uncertainties of τ_{had} are taken into consideration.
- **Jet uncertainties** [95]
 - Jet uncertainties are mainly jet energy scale and resolution, and the jet vertex tagger. The jet flavour and b -tagging uncertainties are also taken into account.
- **$E_{\text{T}}^{\text{miss}}$ uncertainties** [88]
 - $E_{\text{T}}^{\text{miss}}$ uncertainties arise from the soft track energy scale calculated from the total transverse momentum of the hard objects.
- **Luminosity uncertainties**
 - For the integrated luminosity during 2015-2018, the uncertainty is estimated for about 1.7% [96].

Besides, the uncertainties from the misidentified τ estimation are also considered. The fake uncertainties are mainly quantified into four types:

- Uncertainty on the individual *fake factor*, like for F_{QCD} and F_W . These uncertainties arise from the limited statistics in the corresponding control regions where they are calculated.
- Uncertainty on the R_{QCD} estimation and this includes the following sources:
 - Statistical uncertainty of the regions where R_{QCD} is calculated.
 - Statistical uncertainty on the *isolation factor* arising from the limited statistics in the control regions where they are calculated.
 - Uncertainty based on the difference between isolation factors calculated using same sign and opposite sign event selection.
- Uncertainty on the MC subtraction for F_{QCD} , F_W and R_{QCD} calculation.
- The closure uncertainties are calculated by taking the discrepancy between data and prediction in same sign region which is used to account for the difference between the regions where *fake factors* are calculated and applied. In closure test the same fake estimation method is applied in same sign region.

In $\tau_{\text{lep}}\tau_{\text{had}}$ channel, the fake uncertainties are estimated from these four sources. While in $\tau_{\text{had}}\tau_{\text{had}}$ channel, there is no R_{QCD} used then the uncertainties are estimated from the rest three sources.

3.6.3 τ -decay related uncertainties

The τ decay reconstruction related uncertainties include the the τ_{had} decay mode classification, as well as the measurement uncertainties of the impact parameter of the track, charged pion track momentum, and neutral pion momentum. These uncertainties primarily affect the measurement results because they will cause the affect on shape of the φ_{CP}^* distribution.

The uncertainties arise from classification of the τ_{had} decay mode are derived from classification efficiency and correction factor measurement using the probe-and-tag analysis with the μ - τ_{had} final states. These uncertainties consider both the τ_{had} decay mode classification efficiency and event migration between decay modes. The size of these uncertainties are estimated about 6-20% by different decay mode.

The track uncertainties would result in a track smearing of all the objects reconstructed in the final state, including both track of τ_{had} and track of electron/muon. These uncertainties affect the impact parameters and track measurements include those in alignment effects and in impact parameter resolution.

The uncertainties for the π^0 angular resolution and energy resolution are evaluated by the in-situ measurement in dedicated Z control region in the analysis. The variation of π^0 angular resolution and energy resolution are found to have the affect on the shape of

the invariant mass of $\pi^\pm\pi^0$ system $m(\pi^\pm, \pi^0)$. Therefore, the Z control regions defined in Section 3.4 enriched by ℓ -1p1n for $\tau_{\text{lep}}\tau_{\text{had}}$ and 1p1n-1p1n for $\tau_{\text{had}}\tau_{\text{had}}$ are used to evaluate these π^0 related uncertainties from data in the combined fit.

3.7 Statistical analysis

The section will firstly introduce the basic ideas of the statistical data analysis method which is generally used in experimental particle physics. Then the application of the statistical analysis will be used for the interpretation of this analysis.

3.7.1 Statistical analysis

The general purpose for a statistical analysis is to make a discovery, or set a constraint interval or an upper limit for a measured parameter. In this section the basic concepts of statistical hypothesis testing for discovery and maximum likelihood (ML) estimator method for parameter constrain will be briefly introduced [97, 98].

3.7.1.1 Concepts of statistical test

Statistical test is aimed to make a statement about how well the observed data agree with some given hypotheses. We usually measure some random variables (e.g. invariant mass) $\mathbf{x} = (x_1, \dots, x_n)$ of the data. These random variables will have different possibility density function (p.d.f.) $f(\mathbf{x})$ under different hypothesis and thus we can compare their distributions between data and various hypotheses for the statistical test. The nominal hypothesis H_0 is called null hypothesis with the p.d.f. $f(\mathbf{x}|H_0)$, and the alternative hypotheses $H_1(\dots)$ with the p.d.f. $f(\mathbf{x}|H_1)$. For example in BSM search or discovery, the null hypothesis is often taken as the background only while the alternative hypotheses could be background plus various signal in different model. After getting the test statistic $\mathbf{t}(\mathbf{x})$, for each hypothesis we would like to conclude as reject or accept it under the test of the data. Therefore except the right decision, there are two types of error one may make. Type I error is rejecting the null hypothesis when it is true, while type II error is not rejecting the null hypothesis when it is false.

To quantize these errors, some certain regions of the different hypothesis distribution are defined as the critical region, with that cut value t_{cut} named decision boundary as illustrated in Figure 3.24. For type I error, this region is defined under the null hypothesis H_0 and is quantize by the significance level α , which is the possibility to reject the null hypothesis given it is true

$$\alpha = \int_{t_{\text{cut}}}^{\infty} f(t|H_0)dt \quad (3.20)$$

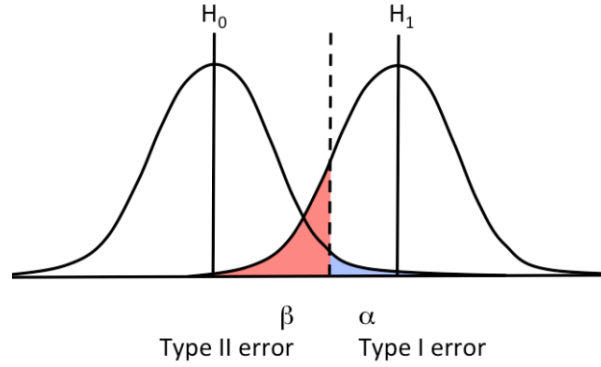


Figure 3.24: Illustration of the definition of significance level α and power of a test β , which used for quantizing two types of error.

the result in these region would be very infrequent if the null hypothesis is true. Sometimes we talk about the confidence level (CL) as the definition $\gamma = (1 - \alpha)$, which gives the interval to show the degree of confidence.

The p -value is the probability of obtaining test results at least as extreme as the result actually observed under the null hypothesis is assumed to be correct. In case of single tail distribution in the illustration it will calculated as $\int_{t_{obs}}^{\infty} f(t|H_0)dt$ where t_{obs} is observed result. The p -value is always compared with the significance level, if when $p \leq \alpha$ we have the $(1 - \alpha)$ confidence that it is right to reject the null hypothesis.

Similarly, for type II error we can define β as the possibility not reject the null hypothesis given it is false

$$\beta = \int_{-\infty}^{t_{cut}} f(t|H_1)dt \quad (3.21)$$

denoted the power of a test as $(1 - \beta)$ to show the chance that successfully reject the false null hypothesis. It is also called the sensitivity in the context of the binary classification.

3.7.1.2 Maximum likelihood method

If we test a random variable x with a p.d.f. $f(x; \theta)$ depend on the parameter θ , one of the target will be to decide the parameter by data. This is realized by the method called the maximum likelihood technique. The random variable will be measured repeatedly as $x_1, \dots, x_n$ or it can represent the multidimensional variable. The likelihood is defined as the function of the parameter θ

$$L(\theta) = \prod_{i=1}^n f(x_i; \theta) \quad (3.22)$$

is a joint p.d.f. for the observed variable.

Since the likelihood function varied with the parameter θ , it will be the largest (most likely) when θ is closed to the true value. Thus the θ is decided as the value corresponded to highest likelihood with all local maximum values. To determine the best fit value and

error of the parameter, consider the Taylor expansion of the log-likelihood function around the ML estimator $\hat{\theta}$ (to distinguish with the true parameter value θ)

$$\log L(\theta) = \log L(\hat{\theta}) + \left[\frac{\partial \log L}{\partial \theta} \right]_{\theta=\hat{\theta}} (\theta - \hat{\theta}) + \frac{1}{2!} \left[\frac{\partial^2 \log L}{\partial \theta^2} \right]_{\theta=\hat{\theta}} (\theta - \hat{\theta})^2 + \dots \quad (3.23)$$

by definition the first derivative is zero $\frac{\partial \log L}{\partial \theta} = 0$ because the $\log L$ should be maximum that $\log L(\hat{\theta}) = \log L_{max}$, and $\frac{\partial^2 \log L}{\partial \theta^2} = \hat{\sigma}_{\hat{\theta}}^2$. The Equation (3.23) will become

$$\log L(\theta) = \log L_{max} - \frac{(\theta - \hat{\theta})^2}{2\hat{\sigma}_{\hat{\theta}}^2} \quad (3.24)$$

then we can get the error of the parameter measurement

$$-\log L(\hat{\theta} \pm N\hat{\sigma}_{\hat{\theta}}) = -\log L_{max} + \frac{N^2}{2} \quad (3.25)$$

This is the reason why we can get the error of parameter measurement from the negative log-likelihood (NLL) plot. First we can determine the best fit value of parameter θ by finding the maximum point of the log-likelihood (minimum point of the NLL), then to determine the error interval by the cross point of $\Delta\text{NLL} = \frac{N^2}{2}$ at a certain confidence level.

Consider the joint p.d.f. is the multiple of some independent Gaussian distribution with the random variable $y_i = y_i(x_i)$ and its true value $\mu = \mu(x_i; \theta_i)$ depend on parameters θ_i

$$f(y_i, \sigma_i; \mu) = \prod_{i=1}^n \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(-\frac{(y_i - \mu)^2}{2\sigma_i^2}\right) \quad (3.26)$$

the corresponded log-likelihood function dropped the additive constant term will be

$$\log L(\theta_i) = -\frac{1}{2} \sum_{i=1}^n \frac{(y_i - \mu(x_i; \theta_i))^2}{\sigma_i^2} = -\frac{1}{2} \chi^2(\theta_i) \quad (3.27)$$

shows that the log-likelihood it self obey the χ^2 distribution. It can reflect the goodness-of-fit with this maximum likelihood method by calculating the p -value in the χ^2 distribution.

Practically there are many parameters affect the measurement but not always interested. We therefore consider one (or more) parameter-of-interest(s) (PoI) μ distinguished to other nuisance parameters (NP) θ which is not interested. In this case we consider the profile likelihood ratio

$$\lambda(\mu) = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})} \quad (3.28)$$

as the function of PoI μ . The denominator is maximized likelihood with both $\hat{\mu}$ and $\hat{\theta}$ as the ML estimator, and $\hat{\theta}$ is the value of θ maximizes the likelihood for specified μ .

3.7.2 Fit model

The analysis aims to measure the Higgs CP -mixing angle ϕ_τ interacted as the PoI, with the float normalization factors for $H \rightarrow \tau\tau$ signal and $Z \rightarrow \tau\tau$ background process, and the assign the systematics as the nuisance parameters. The likelihood function is constructed as the production of the Poisson distribution for the yield in each bin, and using the binned maximum likelihood method to test the parameters. The nuisance parameter from the contribution of the systematics are assigned as the Gaussian distributions for constraint.

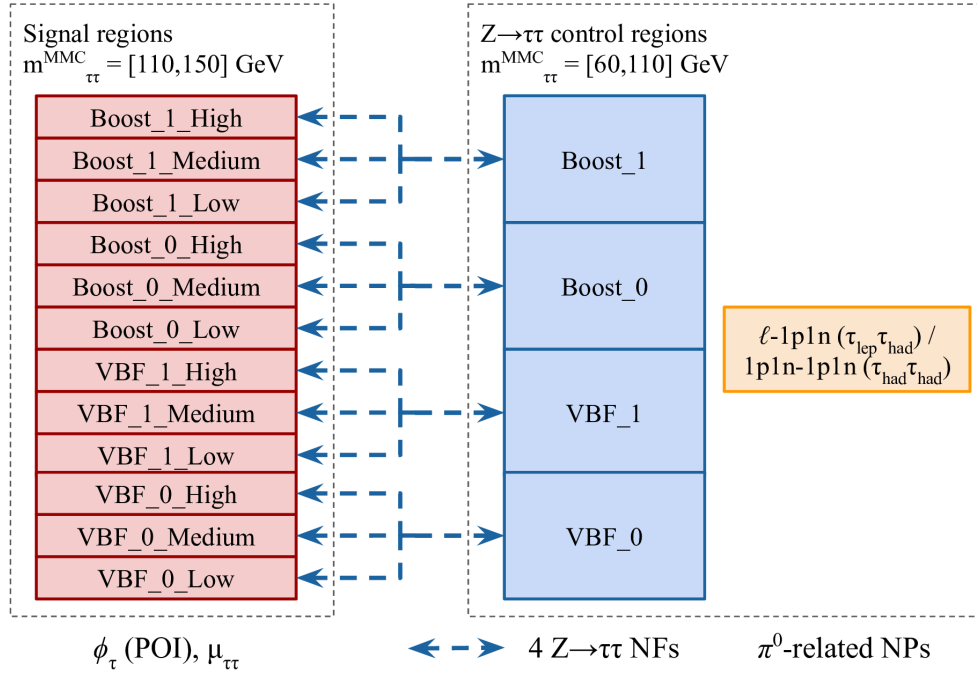


Figure 3.25: Summary of the fit model with total 24 signal regions and 10 $Z \rightarrow \tau\tau$ control regions. This scheme is illustrated similarly for $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ decay channel.

In Section 3.4, totally 24 signal regions and 10 Z control regions are defined to form the likelihood. The scheme of this fit model can be illustrated as Figure 3.25.

The 24 signal regions comprise the cross of two decay categories $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$, four Higgs production categories VBF_0, VBF_1, Boost_0, and Boost_1, and three optimization categories High, Medium, and Low. In each signal region, the φ_{CP}^* distributions are optimized with the binning schemes for the good sensitivity and are used for the statistical test. The condensed post-fit φ_{CP}^* distributions in signal regions are showed in Figure 3.26.

In the Z control regions, 8 of 10 are one bin distribution for the determination of four normalization factors of the $Z \rightarrow \tau\tau$ process as four production categories VBF_0, VBF_1, Boost_0, and Boost_1, cross in two decay categories $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$. The rest two Z control region enriched of the $\tau^\pm \rightarrow \rho^\pm \nu \rightarrow \pi^\pm \pi^0 \nu$ events (one is ℓ -1p1n for $\tau_{\text{lep}}\tau_{\text{had}}$, the other is 1p1n-1p1n for $\tau_{\text{had}}\tau_{\text{had}}$) is using the invariant mass of $\pi^\pm \pi^0$ system $m(\pi^\pm, \pi^0)$ to constrain the π^0 related systematics mentioned in Section 3.6.3. These ZCR post-fit

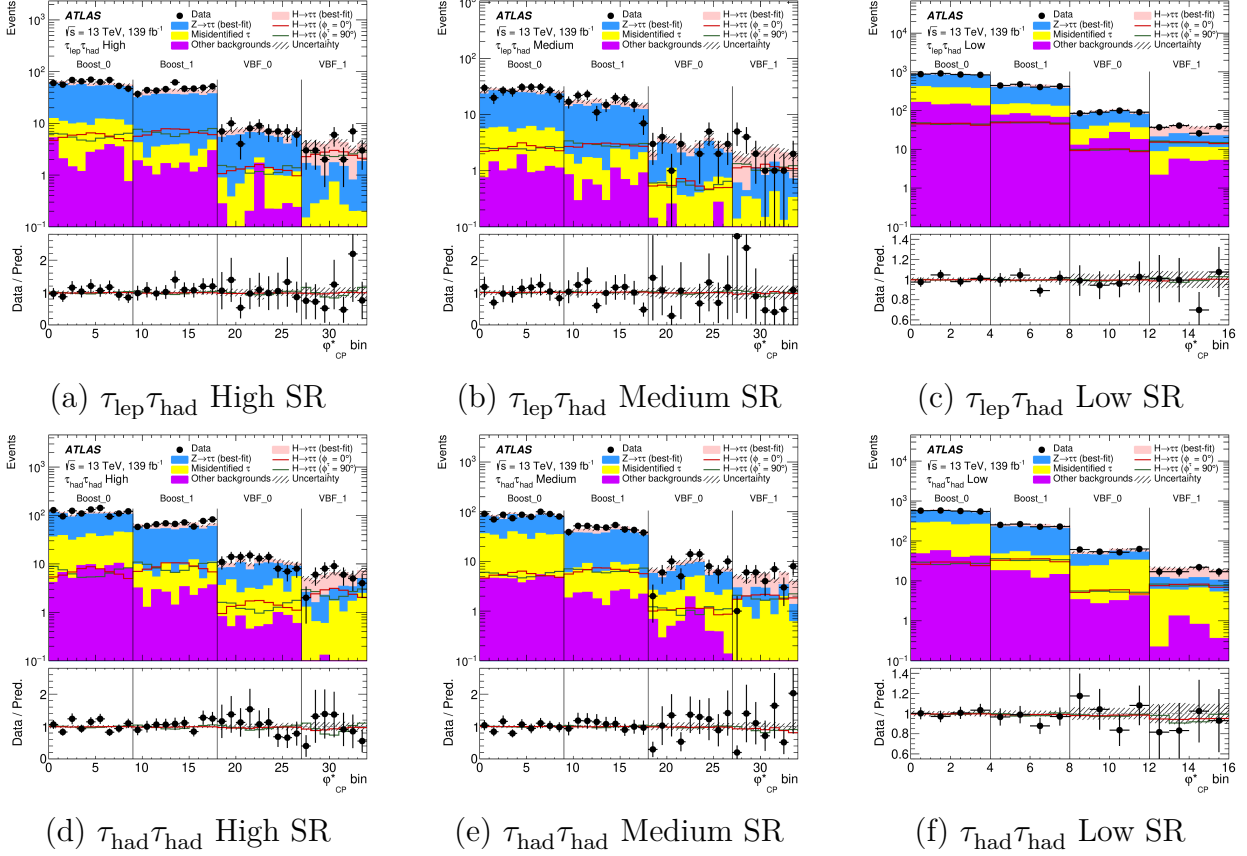


Figure 3.26: Post-fit φ_{CP}^* distributions in signal regions, with $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ condensed four production categories categorized in high, medium and low region.

distributions are showed in Figure 3.27.

The PoI ϕ_τ and Higgs signal strength $\mu_{\tau\tau}$ (defined as the ratio of the measured $H \rightarrow \tau\tau$ yield to the SM prediction) are left float to be measured. The test statistic is based on a profile likelihood ratio for the statistical interpretation. These parameters are fitted by the combined fit of all these regions defined above by maximizing likelihood function.

3.8 Results

After the maximum likelihood method statistic test, the best fit value and error pf the PoI ϕ_τ , Higgs signal strength $\mu_{\tau\tau}$ and all normalization factors of $Z \rightarrow \tau\tau$ process are summarized in Table 3.10. The normalizations of the signal and background processes are compatible with the SM prediction considering the uncertainties.

The negative log-likelihood scan plot for PoI ϕ_τ measurement in expected and observed scenarios is showed in Figure 3.28. It showed that the observe (expected) value of ϕ_τ is $9^\circ \pm 16^\circ$ ($0^\circ \pm 28^\circ$) at 68% confidence level, and $\pm 34^\circ$ ($_{-70^\circ}^{+75^\circ}$) at 2σ level. Besides, the data disfavours the pure CP -odd hypothesis at 3.4σ level, while the expected exclusion level is 2.1σ .

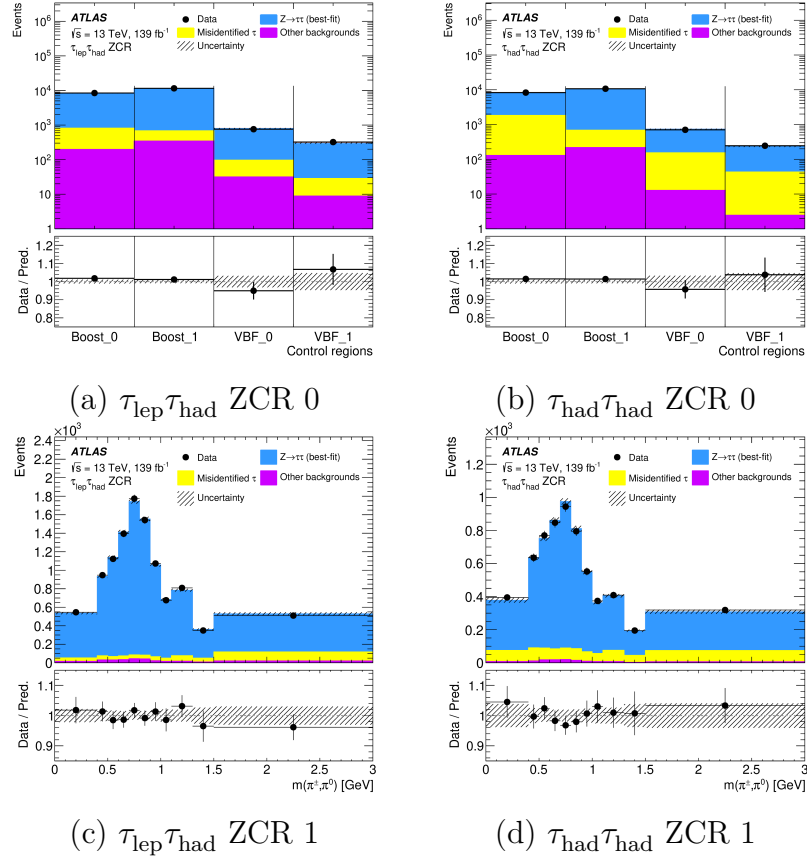


Figure 3.27: Post-fit distributions in ZCR, with the one bin distributions in (a) and (b) for the constraint of $Z \rightarrow \tau\tau$ normalization factors, and $m(\pi^\pm, \pi^0)$ distributions in (c) and (d) for π^0 related systematics constraint.

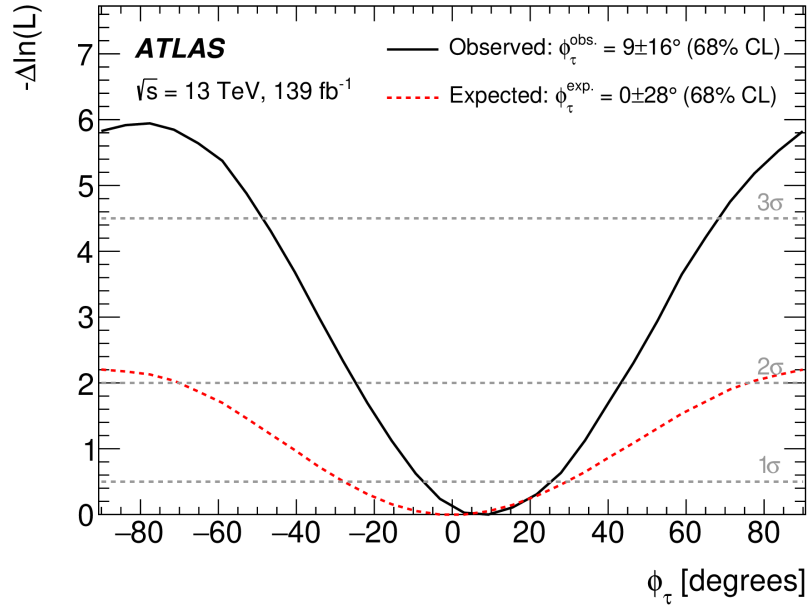


Figure 3.28: One dimensional likelihood scan of the Higgs CP -mixing angle ϕ_τ .

Table 3.10: Summary of the parameter-of-interest ϕ_τ and free floating normalization factors expected and observed value with the uncertainties in this measurement.

Fitted parameters	Observed	Expected
ϕ_τ	$9^\circ \pm 16^\circ$	$0^\circ \pm 28^\circ$
$\mu_{\tau\tau}$	$1.02^{+0.20}_{-0.20}$	$1.00^{+0.21}_{-0.21}$
$\text{NF}_{Z \rightarrow \tau\tau}^{\text{Boost}_1}$	1.01 ± 0.05	1.00 ± 0.04
$\text{NF}_{Z \rightarrow \tau\tau}^{\text{Boost}_0}$	1.02 ± 0.05	1.00 ± 0.05
$\text{NF}_{Z \rightarrow \tau\tau}^{\text{VBF}_1}$	1.04 ± 0.08	1.00 ± 0.08
$\text{NF}_{Z \rightarrow \tau\tau}^{\text{VBF}_0}$	0.95 ± 0.07	1.00 ± 0.08

The error sources of this analysis is summarized in Table 3.11. The analysis uncertainty is dominated by the data statistical error. For the systematics uncertainties, the main uncertainties is from jet related systematics, and then the MC statistical error. This is understood that the jet energy scale and resolution affects on the acceptance of the signal and background through the E_T^{miss} , and passing this effect to $m_{\tau\tau}^{\text{MMC}}$. It also has the direct effect on the selection of the VBF and Boost categories which is depended on the jet kinematics. The π^0 related systematics are found to have small impact on the measurement of ϕ_τ .

The large error difference of observed and expected results can be attributed to a statistical fluctuation in data. The uncertainties on ϕ_τ are relied on the shape of the φ_{CP}^* distribution, and the sensitivity heavily depends on the modulation amplitude of the φ_{CP}^* distributions. To test this, a set of pseudo-experiment data with the Higgs signal strength $\mu_{\tau\tau} = 1$ are performed to fit by the same fit model. This shows that the probability of getting the results at least as extreme as the observed one is 4%, which is quite possible.

A two dimensional likelihood scan of ϕ_τ and $\mu_{\tau\tau}$ is implemented and the result is showed in Figure 3.29. It is found that the SM prediction of $\phi_\tau = 0$ and $\mu_{\tau\tau} = 1$ is within 1σ contour of the observed result, and there is no strong correlation between these two parameters.

To give an intuitive illustration of the results of this analysis, the φ_{CP}^* distribution of the data with the background subtracted of all signal regions combined, together with the best fit $H \rightarrow \tau\tau$ signal process compared with compared with the pure CP -even and pure CP -odd hypotheses are plotted in Figure 3.30. The signal regions are weighted by $\ln(1 + S/B)$, in which the S and B are event yields of signal and background, respectively. The data distribution is more prefer the CP -even hypothesis which is corresponded with the statistical test results.

Table 3.11: Impact from different sources of uncertainty on the ϕ_τ measurement.

Set of nuisance parameters	Impact on ϕ_τ [degrees]
Jet energy scale	3.4
Jet energy resolution	2.5
Pile-up jet tagging	0.5
Jet flavour tagging	0.2
E_T^{miss}	0.4
Electron	0.3
Muon	0.9
τ_{had} reconstruction	1.0
Misidentified τ	0.6
τ_{had} decay mode classification	0.3
π^0 angular resolution and energy scale	0.2
Track ($\pi^\pm$, impact parameter)	0.7
Luminosity	0.1
Theory uncertainty in $H \rightarrow \tau\tau$ processes	1.5
Theory uncertainty in $Z \rightarrow \tau\tau$ processes	1.1
Simulated background sample statistics	1.4
Signal normalisation	1.4
Background normalisation	0.6
Total systematic uncertainty	5.2
Data sample statistics	15.6
Total	16.4

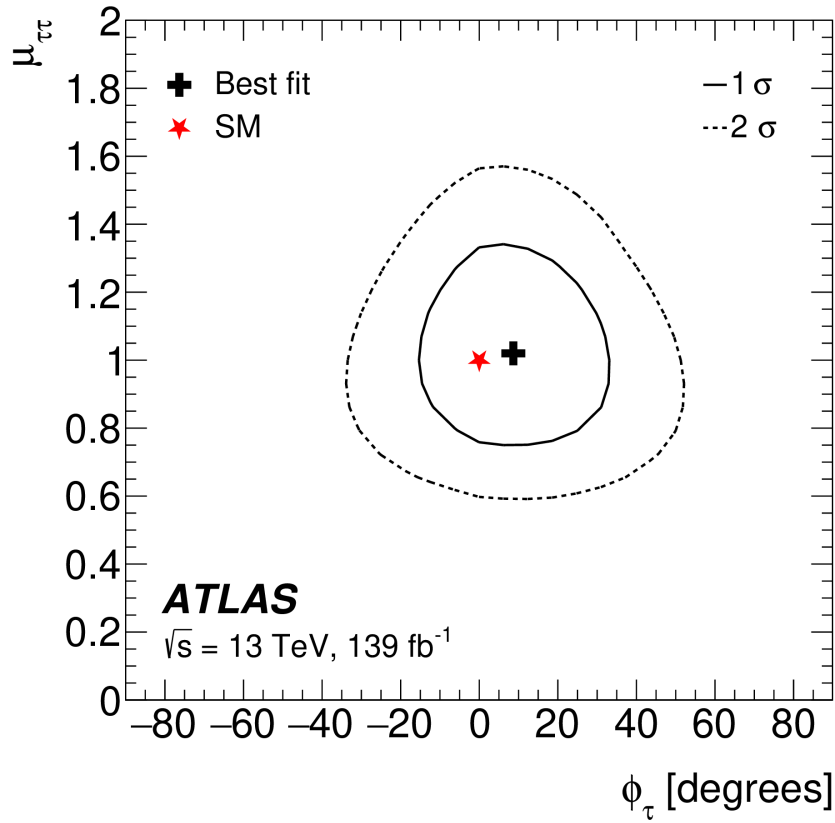


Figure 3.29: Two dimensional likelihood scan of the Higgs CP -mixing angle ϕ_{τ} and Higgs signal strength $\mu_{\tau\tau}$.

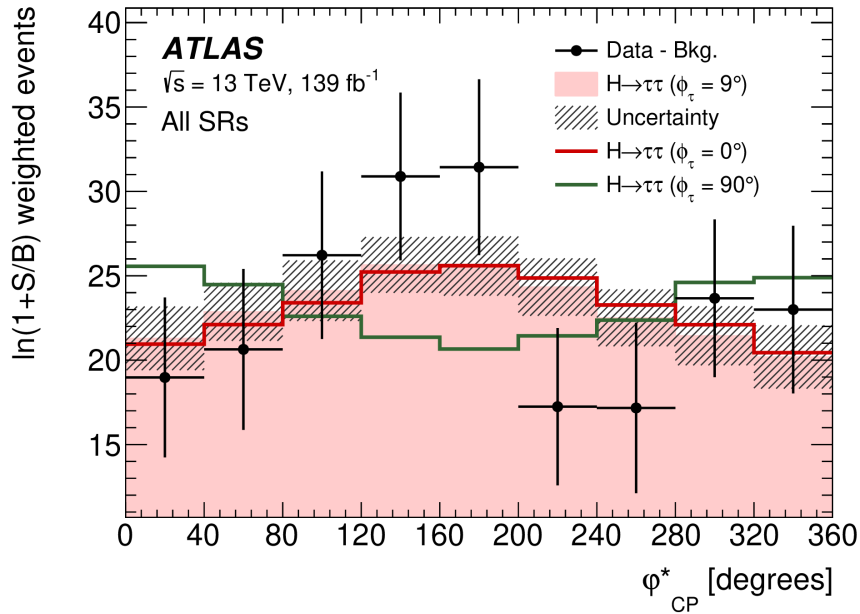


Figure 3.30: Combined post-fit distribution of ϕ_{CP}^* in all signal regions weighted by $\ln(1 + S/B)$ with the background subtracted.

Chapter 4

Conclusion and Outlook

This thesis presents the results of the first measurement of the CP structure in Higgs- τ Yukawa coupling in the ATLAS experiment. The analysis is based on the dataset in center-of-mass of 13 TeV with integrated luminosity of 139 fb^{-1} recorded by ATLAS detectors.

The Higgs-fermion Yukawa coupling is vital to understand the origin of the fermion mass, and its CP structure is important to solve the matter-antimatter asymmetry puzzle. The $H \rightarrow \tau\tau$ decay is the only channel to measure the H- τ Yukawa coupling and it has the advantage that the τ is the heaviest lepton so it is the strongest Yukawa coupling in the lepton sector. To measure its CP property, we choose the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ di- τ final states in analysis considering the sensitivity. We use the φ_{CP}^* which is the acoplanarity angle between the di- τ decay planes as the observable to measure its phase as the harmonic function distribution to determine the CP -mixing angle ϕ_τ . By reconstructing the φ_{CP}^* using different method in different τ decay mode, we implement the statistic interpretation after the categorization and background estimation. The results show that the observe (expected) value of ϕ_τ is $9^\circ \pm 16^\circ$ ($0^\circ \pm 28^\circ$) at 68% confidence level. It agrees with the SM prediction considering the uncertainty.

The results of this analysis is limited by data statistical uncertainty. It is expected to be improved with more data as the LHC run to a higher integrated luminosity, and the improvement from the HL-LHC upgrade are foreseen. The expected constraint on ϕ_τ will be $\pm 20^\circ$ when the luminosity reaches to 300 fb^{-1} which is planed for Run3, and $\pm 5^\circ$ when the integrated luminosity comes to 3000 fb^{-1} as foreseen in the Run4+Run5 dataset. Besides, the refinement of the τ_{had} decay mode classification by neural network MVA method can introduce the improvement because the φ_{CP}^* reconstruction is heavily relied on the τ decay mode. This method is validated and implemented for the τ_{had} decay mode classification in the later ATLAS analysis base release. Furthermore, the possible new analysis method combined with MVA could also enhance the sensitivity.

The measurement of the CP structure of the Higgs coupling to the other SM particles will also deepen the understanding of the baryon asymmetry in the universe. The combine study in the Higgs sector will depict a whole picture in Higgs and CP physics.

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Appendix A

Data manipulation check in $H \rightarrow \tau\tau$ decay CP analysis

A.1 Data manipulation check for the sensitivity difference between expected and observed results

In order to understand the sensitivity difference seen in the Figure 3.28, two sets of check are made in the $H \rightarrow \tau\tau$ decay CP analysis. One is to generate the toy Asimov data for fit check, the other is to manipulate the real data point to see the sensitivity behaviours.

The toy Asimov data sets are generated by throwing the data points in a random Poisson distribution from the initial Asimov dataset distributions. The results of this check showed that the best fit ϕ_τ value consistent with the Gaussian distribution, and the probability for measured error below our observed is 4% out of all toys. This shows that it is possible to get such different sensitivity between the expected and observed results.

In this section we will focus on the method to manipulate the data point by purpose to see the change of sensitivity. One understanding of the sensitivity difference is due to the amplitude. In ϕ_τ measurement, we only measured the phase of φ_{CP}^* distribution but not the amplitude of this harmonic function distribution, and the amplitude will affect the resolution of this distribution. Thought of this, we design the data manipulation to decrease the amplitude by 20% and 50% to see the sensitivity change.

To manipulate the data for decreasing its amplitude, we did this based on the ‘0 amplitude’ φ_{CP}^* distributions which is set as the MC background plus $(CP\text{-even} + CP\text{-odd})/2$ signal. Counting the difference between the reference line and real data, we decrease such difference by 20% or 50% to set as the manipulated data then use them for fit. This is illustrated in Figure A.1, Figure A.2, Figure A.3, and Figure A.4 to decrease the signal amplitude by 20% and 50% for $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ channel, respectively. The red lines are ‘0 amplitude’ line, and the black points are manipulated data, while the grey points are real data.

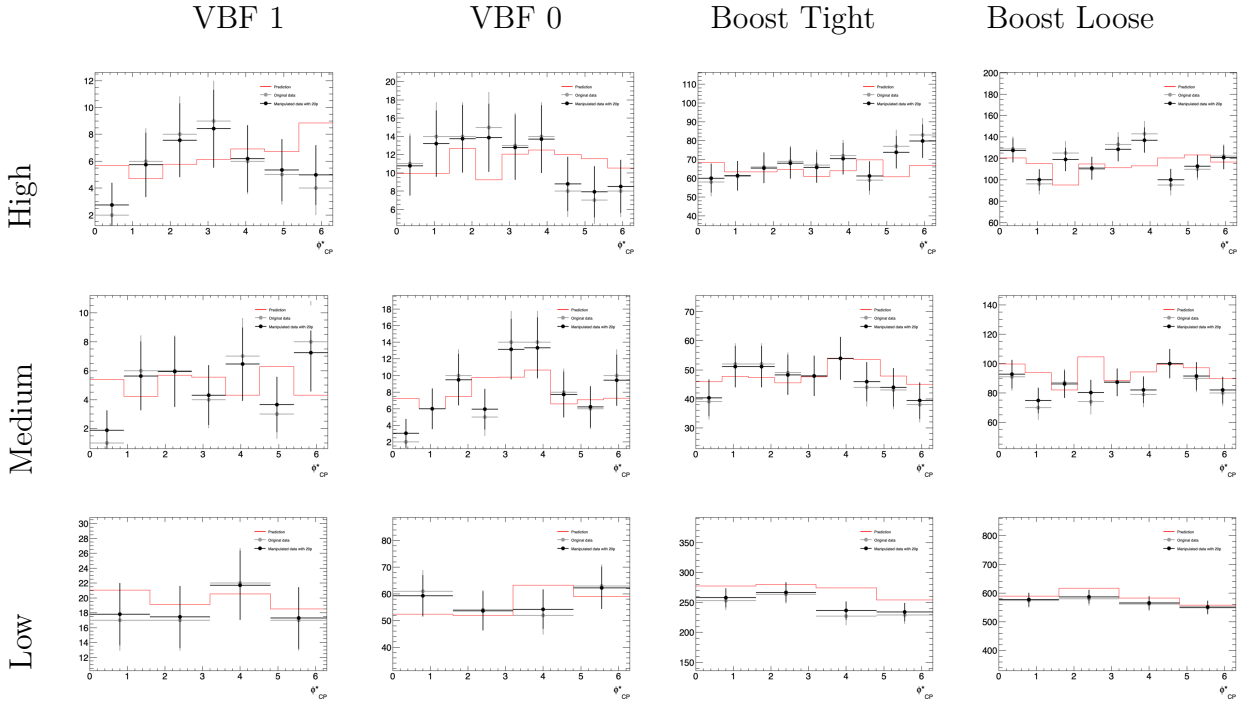


Figure A.1: Illustration of the data manipulation to decrease the amplitude by 20% in $\tau_{\text{had}}\tau_{\text{had}}$ channel.

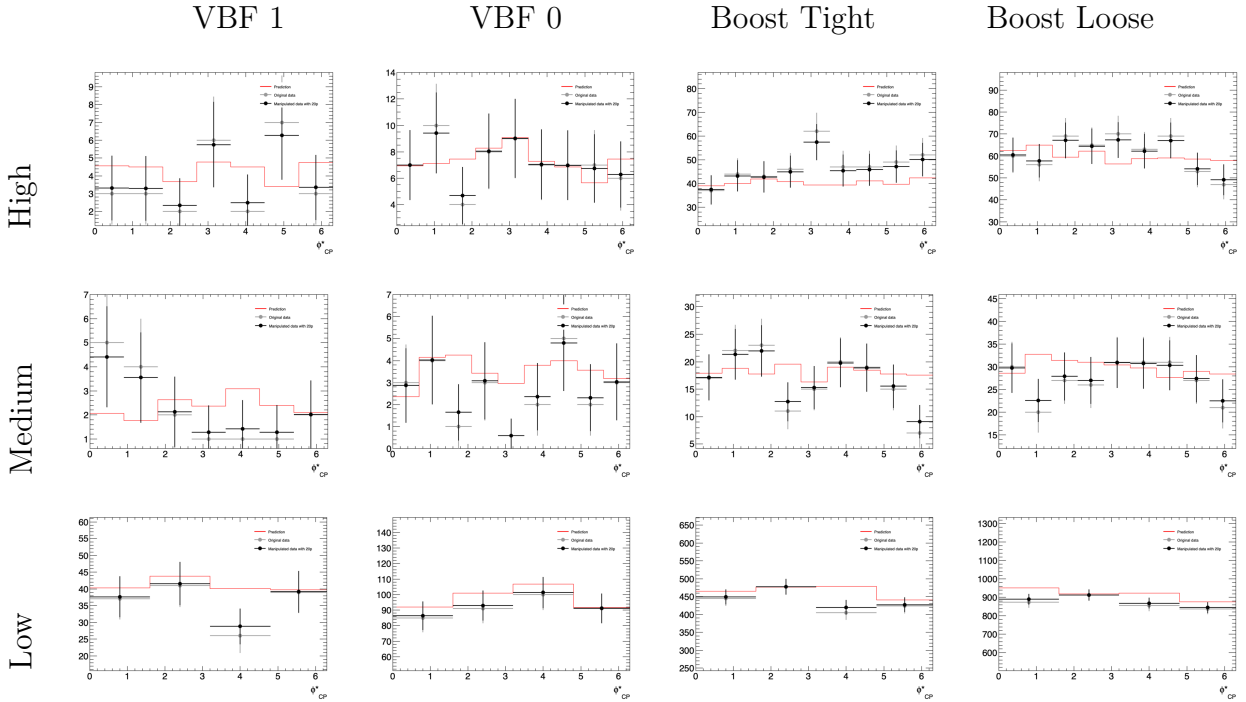


Figure A.2: Illustration of the data manipulation to decrease the amplitude by 20% in $\tau_{\text{lep}}\tau_{\text{had}}$ channel.

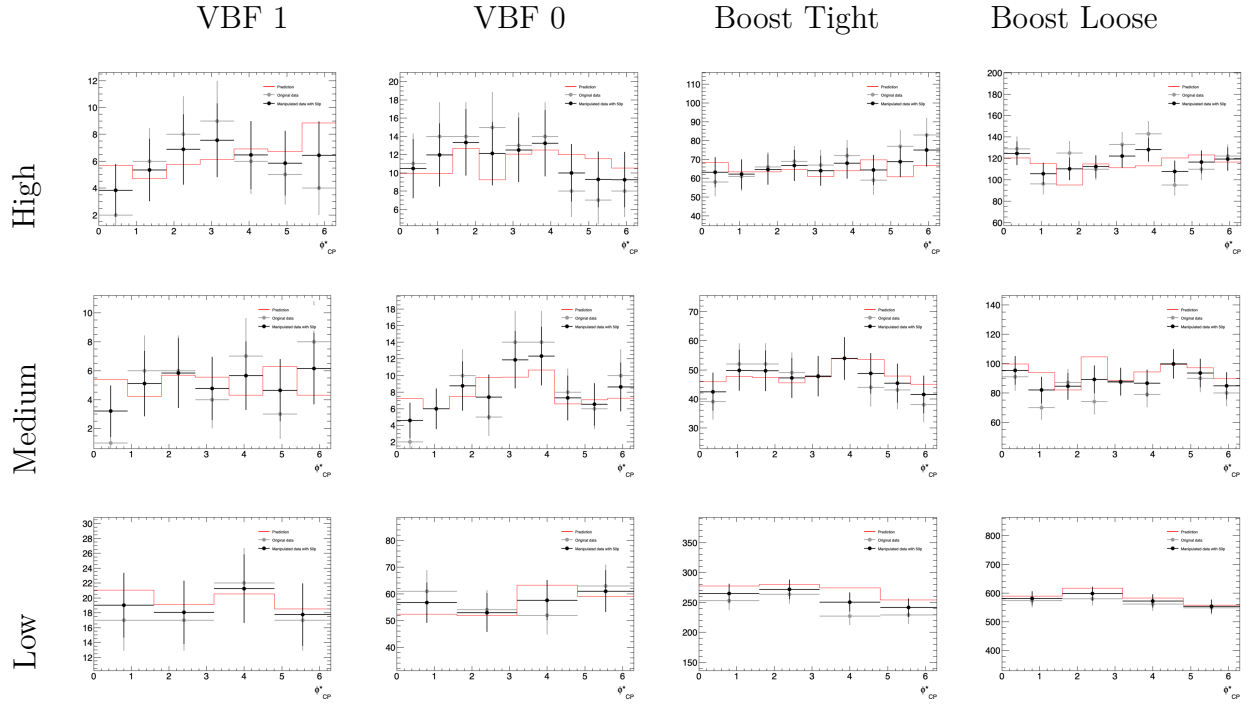


Figure A.3: Illustration of the data manipulation to decrease the amplitude by 50% in $\tau_{\text{had}}\tau_{\text{had}}$ channel.

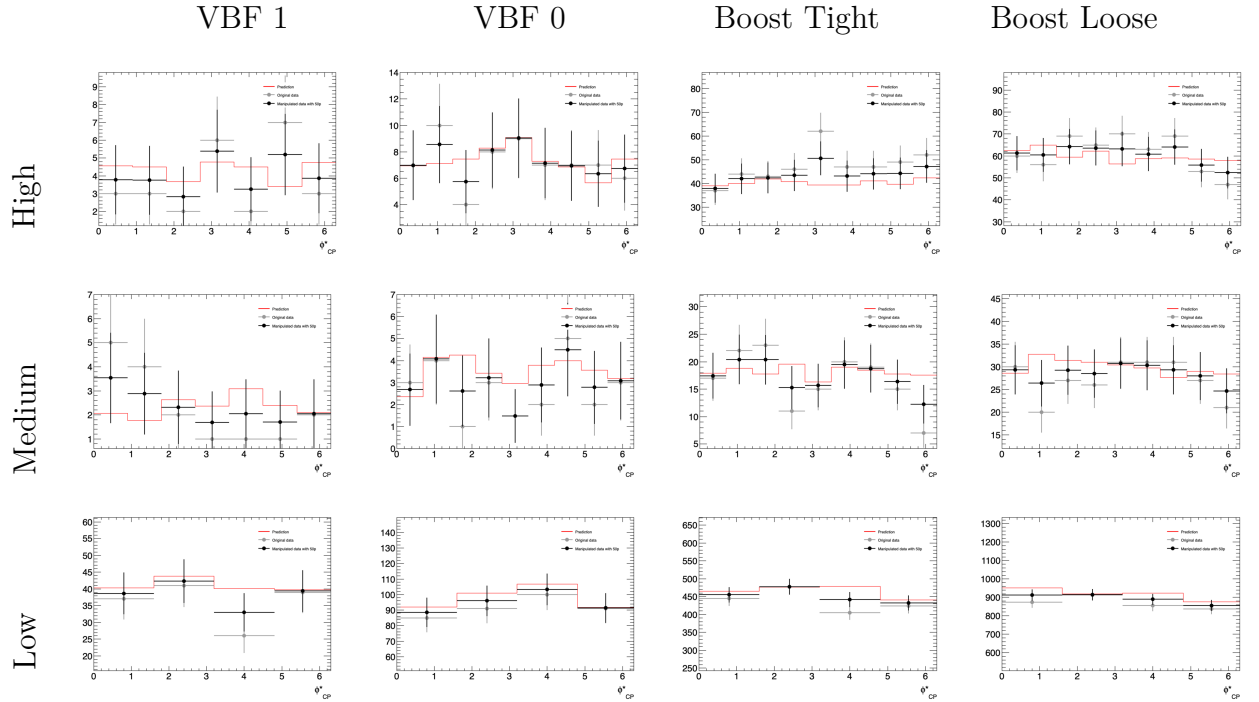


Figure A.4: Illustration of the data manipulation to decrease the amplitude by 50% in $\tau_{\text{lep}}\tau_{\text{had}}$ channel.

After manipulating the data, we used these for the fit to do the likelihood scan. The results are showed in Figure A.5. It is clear that when the amplitude decreased to get closed to the predicted line, the sensitivity will also decrease and closed to the Asimov scenario. This is understood as that the sensitivity difference is likely due to the fluctuation of the data distribution and depends on the amplitude of this harmonic function.

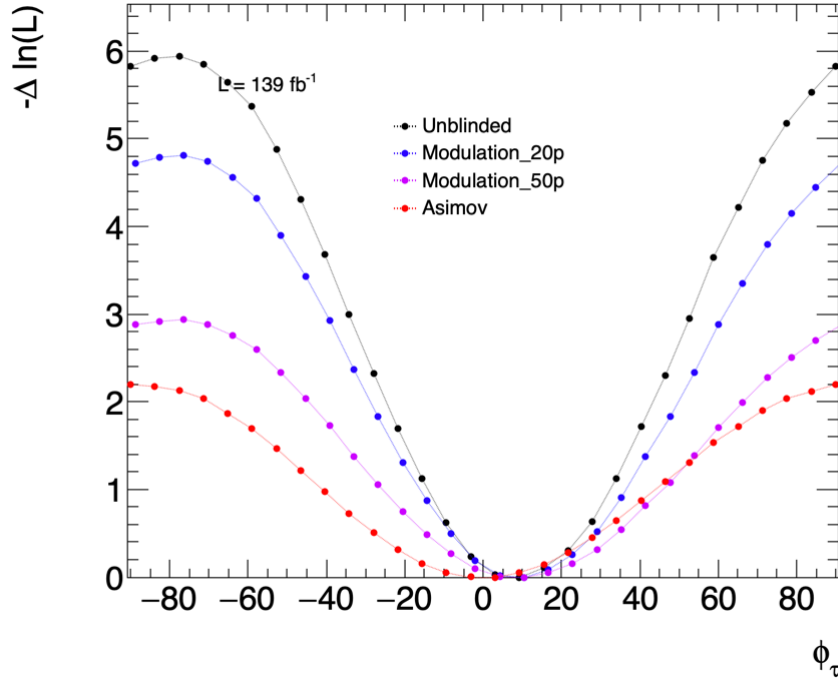


Figure A.5: Likelihood scan for the manipulated data fit.

Appendix B

VBF $H \rightarrow \tau\tau$ differential measurement EFT interpretation

The $H \rightarrow \tau\tau$ Run2 legacy analysis has the STXS and VBF differential cross-section measurement. In this section, the EFT interpretation based on the VBF differential fiducial cross-section measurement will be presented.

B.1 EFT introduction

The Effective Field Theory (EFT) is widely used to interpret the measured results and constrain the BSM effects in analysis. In this analysis, we use the EFT framework known as the Standard Model Effective Field Theory (SMEFT) [99, 100] in the so-called Warsaw basis [101, 102] for the interpretation of the VBF $H \rightarrow \tau\tau$ differential measurement results.

The SMEFT Lagrangian in a certain energy scale Λ is

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} Q_i^{(6)} \quad (\text{B.1})$$

where $Q_i^{(6)}$ are the dimension-6 operators, and $c_i^{(6)}$ are their corresponded Wilson coefficients.

In SMEFT, the complete, minimal non-redundant basis named Warsaw basis is employed for the interpretation. The Warsaw basis is renormalizable, and has global symmetry assumptions on Baryon or Lepton number conservation, $U(3)^5$ flavour symmetry or a flavour subgroup. These sets of dimension-6 operators in Warsaw basis are summarized in Figure B.1, grouped into different types.

In VBF $H \rightarrow \tau\tau$ differential analysis, we are interested in the operators related to the VBF production vertex, especially those are sensitive to our differential observable. The differential measurement is unfolded into the signed azimuthal angle between two VBF jets $\Delta\phi_{jj}^{\text{signed}}$. Therefore, we choose to measure the bosonic operators related to HVV vertex, three CP -even operators and their three CP -odd counterpart operators, listed in Table B.1.

1 : X^3		2 : H^6		3 : $H^4 D^2$		5 : $\psi^2 H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \tilde{H})$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
$Q_{\tilde{W}}$	$\epsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						
4 : $X^2 H^2$		6 : $\psi^2 XH + \text{h.c.}$		7 : $\psi^2 H^2 D$			
Q_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$		
$Q_{H\tilde{G}}$	$H^\dagger H \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$		
Q_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{H} G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$		
$Q_{H\tilde{W}}$	$H^\dagger H \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{H} W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$		
Q_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{H} B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$		
$Q_{H\tilde{B}}$	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$		
Q_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$		
$Q_{H\tilde{W}B}$	$H^\dagger \tau^I H \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$	$Q_{Hud} + \text{h.c.}$	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$		
8 : $(\bar{L}L)(\bar{L}L)$		8 : $(\bar{R}R)(\bar{R}R)$		8 : $(\bar{L}L)(\bar{R}R)$			
$Q_{\ell\ell}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$		
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$		
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$		
$Q_{\ell q}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$		
$Q_{\ell q}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$		
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$		
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$		
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$		
8 : $(\bar{L}R)(\bar{R}L) + \text{h.c.}$		8 : $(\bar{L}R)(\bar{L}R) + \text{h.c.}$		8 : $(\bar{L}R)(\bar{L}R) + \text{h.c.}$			
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_t)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$		
		$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$	$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Figure B.1: Dimension-6 operators in SMEFT Warsaw basis, with grouped into bosonic operators, single fermionic current operators, and four-fermion operators.

Table B.1: Definitions on 6 dimension SMEFT operators and corresponded labels of the Wilson coefficients measured in VBF $H \rightarrow \tau\tau$ differential analysis.

Wilson coefficients	6 dimension operators
c_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$
$c_{H\widetilde{W}}$	$H^\dagger H \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
$c_{H\widetilde{B}}$	$H^\dagger H \widetilde{B}_{\mu\nu} B^{\mu\nu}$
$c_{H\widetilde{WB}}$	$H^\dagger \tau^I H \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

The matrix element amplitude calculated from the SMEFT Lagrangian Equation (B.1) will be

$$|\mathcal{M}_{\text{SMEFT}}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2 \sum_i \frac{c_i}{\Lambda^2} \text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_i) + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} \text{Re}(\mathcal{M}_i^* \mathcal{M}_j) \quad (\text{B.2})$$

where c_i is the Wilson coefficient and $\mathcal{M}_i$ will be the matrix element contributed from corresponded EFT operators.

If we focus on only one operator each time, the cross term of two different operators will vanish and the cross-section considered the EFT contribution will depend on the linear and quadratic terms of c_i compared to the SM cross-section

$$\sigma(c_i) = \sigma_{\text{SM}} \cdot [1 + (\alpha_i c_i + \beta_i c_i^2)] = \sigma_{\text{SM}} + \sigma_{\text{int.}} + \sigma_{\text{quad.}} \quad (\text{B.3})$$

with the linear term interpreted as the interference term between the SM and BSM matrix element, and the quadratic term called the pure BSM contribution term. In VBF $H \rightarrow \tau\tau$ differential analysis, we will use the MC for the generation of the EFT samples varied value of the coefficients to determine cross-section dependence on the Wilson coefficients of linear term α_i and quadratic term β_i .

We will set limits on these 6 individual operators under the assumption that the others are all zero. We will consider to constrain the operators in both linear and quadratic terms contributed to cross-section, and with only linear interference term situation.

B.2 SMEFT samples for VBF $H \rightarrow \tau\tau$ differential analysis

For VBF $H \rightarrow \tau\tau$ differential analysis EFT interpretation, we generate the EFT samples by MADGRAPH5_aMC@NLO at the parton level for matrix element calculation at LO with NNPDF3.0nlo PDF set, using the SMEFTsim model in $U(3)^5$ flavour symmetric limit with

W mass scheme. We use the PYTHIA8 with NNPDF2.31o PDF set for the parton showering and event decay. In this event generation, VBF $H \rightarrow \tau\tau$ process is produced with the EFT anomaly coupling considered only in VBF production HVV vertices, changing the coefficients value listed in Table B.1 considered both interference (linear) term and pure BSM (quadratic) term.

The nominal signal samples for VBF $H \rightarrow \tau\tau$ differential analysis are used the same one introduced in Section 3.2. Thus, the comparison between the POWHEG samples and the MADGRAPH samples with the SM limitation is a good validation. These results are showed in Figure B.3 and we can see a good agreement between these two samples.

We would check how the EFT coefficients effect the shape of our observable $\Delta\phi_{jj}^{\text{signed}}$. In each EFT samples, we change the Wilson coefficients values, we use c_{HW} and $c_{H\widetilde{W}}$ value of $c_i = -1.0, -0.5, -0.1, 0.1, 0.5, 1.0$ while the other Wilson coefficients value of $c_i = -5.0, -3.0, -1.0, 1.0, 3.0, 5.0$ considering the sensitivity. The $\Delta\phi_{jj}^{\text{signed}}$ distributions varied each Wilson coefficients are showed in Figure B.2, and we see the even function structure for CP -even EFT operators and odd function structure for CP -odd EFT operators.

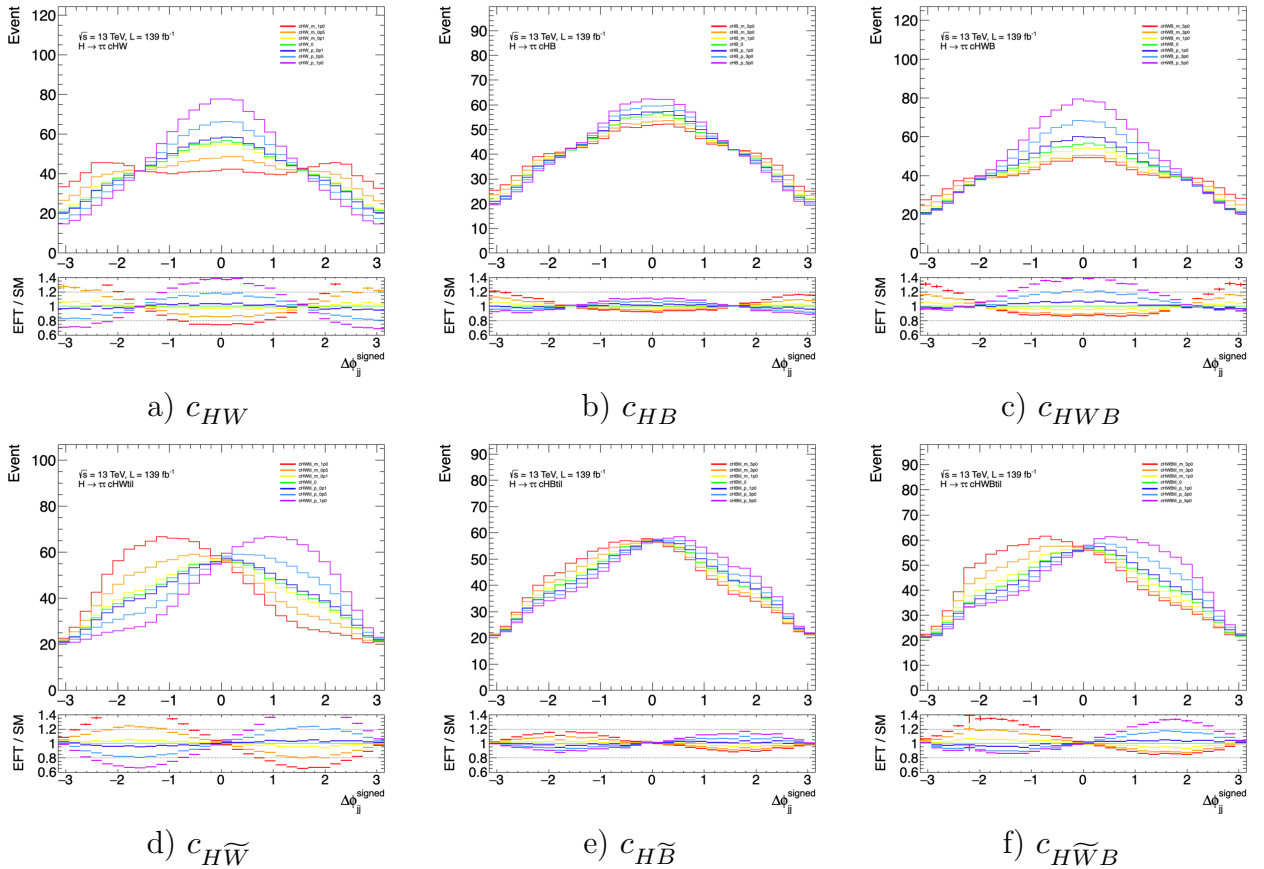


Figure B.2: $\Delta\phi_{jj}^{\text{signed}}$ distributions with each Wilson coefficient varied its value.

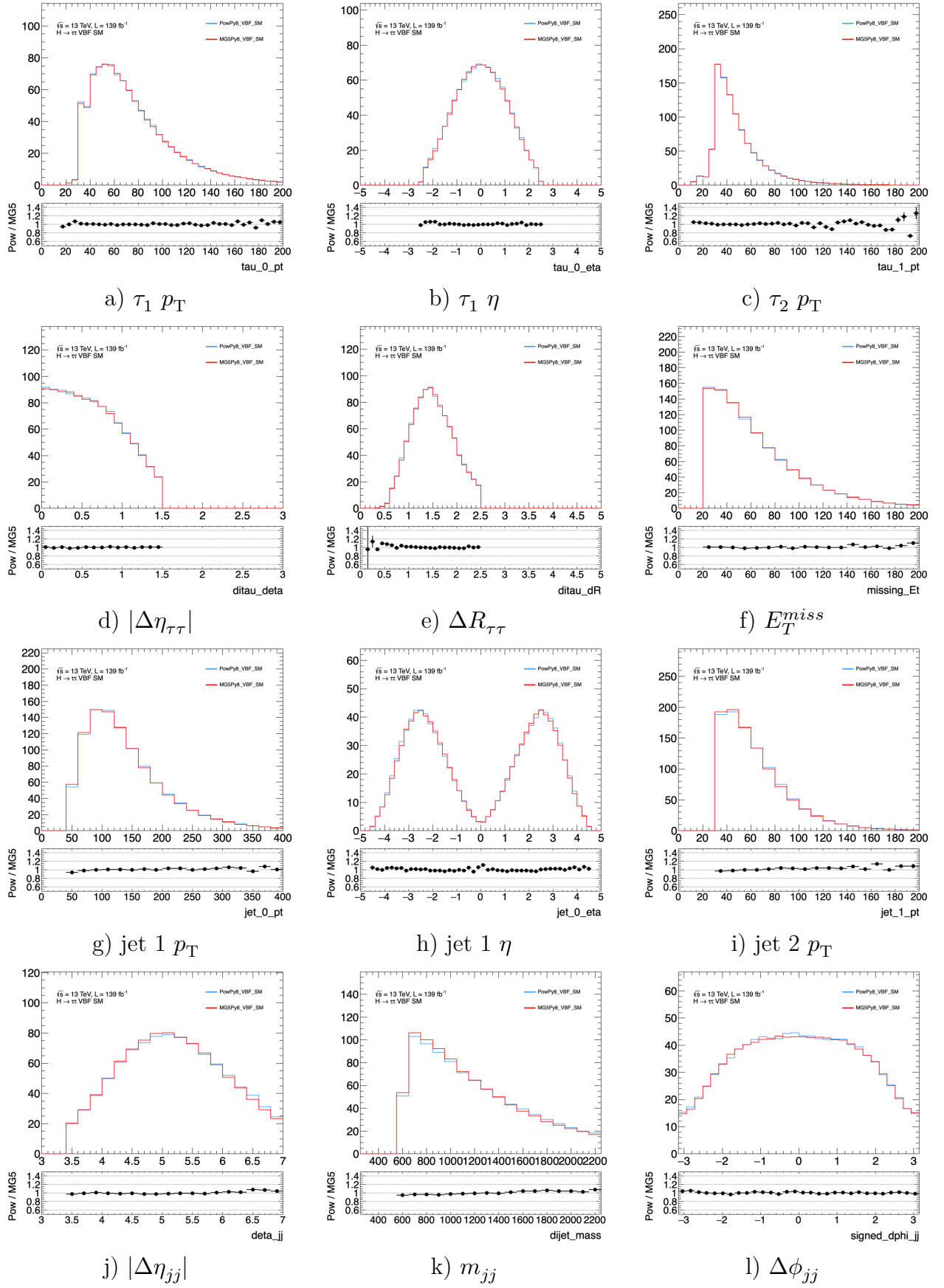


Figure B.3: Comparison between the MADGRAPH5_aMC@NLO SM limitation and the POWHEG VBF $H \rightarrow \tau\tau$ sample.

In VBF $H \rightarrow \tau\tau$ differential analysis, we have four unfold schemes and the unfolded variables are the azimuthal angle between two VBF jets $\Delta\phi_{jj}^{\text{signed}}$, the transverse momentum of the Higgs (di- τ visible system) $p_T(H)$, and the transverse momentum of the leading jet p_T^{jet} . The binning of four unfolded schemes are summarized in Table B.2.

Table B.2: Binning for the unfolded variables in VBF $H \rightarrow \tau\tau$ differential analysis.

bin	p_T^{jet}	$p_T(H)$	$\Delta\phi_{jj}^{\text{signed}}$	$\Delta\phi_{jj}^{\text{signed}}$ vs $p_T H$
bin1	[40, 95]	[0, 110]	$[-\pi, -\pi/2]$	$p_T(H) < 200$ & $\Delta\phi_{jj}^{\text{signed}} < 0$
bin2	[95, 130]	[110, 150]	$[-\pi/2, 0]$	$p_T(H) < 200$ & $\Delta\phi_{jj}^{\text{signed}} > 0$
bin3	[130, 180]	[150, 200]	$[0, \pi/2]$	$p_T(H) > 200$ & $\Delta\phi_{jj}^{\text{signed}} < 0$
bin4	[180, 500]	[200, 550]	$[\pi/2, \pi]$	$p_T(H) > 200$ & $\Delta\phi_{jj}^{\text{signed}} > 0$

After the sensitivity check, we choose to use the $\Delta\phi_{jj}^{\text{signed}}$ unfolded scheme for CP -even coefficients c_{HW} , c_{HB} , c_{HWB} , and the $\Delta\phi_{jj}^{\text{signed}}$ vs $p_T(H)$ unfolded scheme for CP -odd for coefficients $c_{H\widetilde{W}}$, $c_{H\widetilde{B}}$, $c_{H\widetilde{W}B}$. We rebinned the $\Delta\phi_{jj}^{\text{signed}}$ distributions to their corresponded unfolded schemes and determine the cross-section dependence on the Wilson coefficients in each bin. As known from Equation (B.3), we will use the quadratic function to fit for the determination of the α_i and β_i . The parabola fit function lines exemplified with c_{HW} using the $\Delta\phi_{jj}^{\text{signed}}$ binning and $c_{H\widetilde{W}}$ using the $\Delta\phi_{jj}^{\text{signed}}$ vs $p_T(H)$ binning are illustrated in Figure B.4. This will decide both interference linear term and pure BSM quadratic term, for the case with only linear term considered, we directly use the linear factors determined in this fit. The summary of all six operators parameterization with corresponded unfolded scheme is listed in Table B.3. We will use this parameterization to replace the cross-section as the Wilson coefficients in the VBF $H \rightarrow \tau\tau$ differential statistical interpretation for the EFT coefficient constraint.

Table B.3: EFT parameterization for c_{HW} , c_{HB} , c_{HWB} unfolded in $\Delta\phi_{jj}^{\text{signed}}$, and $c_{H\widetilde{W}}$, $c_{H\widetilde{B}}$, $c_{H\widetilde{W}B}$ unfolded in $\Delta\phi_{jj}^{\text{signed}}$ vs $p_T(H)$.

Wilson coefficient	bin1 $[-\pi, -\pi/2]$	bin2 $[-\pi/2, 0]$	bin3 $[0, \pi/2]$	bin4 $[\pi/2, \pi]$
c_{HW}	$1.0 - 0.2559c_i + 0.0605c_i^2$	$1.0 + 0.2277c_i + 0.0391c_i^2$	$1.0 + 0.2262c_i + 0.0370c_i^2$	$1.0 - 0.2523c_i + 0.0547c_i^2$
c_{HB}	$1.0 - 0.0156c_i + 0.0008c_i^2$	$1.0 + 0.0135c_i + 0.0005c_i^2$	$1.0 + 0.0133c_i + 0.0004c_i^2$	$1.0 - 0.0156c_i + 0.0007c_i^2$
c_{HWB}	$1.0 - 0.0099c_i + 0.0026c_i^2$	$1.0 + 0.0442c_i + 0.0041c_i^2$	$1.0 + 0.0422c_i + 0.0038c_i^2$	$1.0 - 0.0108c_i + 0.0028c_i^2$
Wilson coefficient	bin1 $[-\pi, 0]$ $p_T(H) < 200$	bin2 $[0, \pi]$ $p_T(H) < 200$	bin3 $[-\pi, 0]$ $p_T(H) > 200$	bin4 $[0, \pi]$ $p_T(H) > 200$
$c_{H\widetilde{W}}$	$1.0 - 0.2367c_i + 0.0374c_i^2$	$1.0 + 0.2378c_i + 0.0376c_i^2$	$1.0 - 0.6224c_i + 0.2454c_i^2$	$1.0 + 0.6184c_i + 0.2384c_i^2$
$c_{H\widetilde{B}}$	$1.0 - 0.0141c_i + 0.0005c_i^2$	$1.0 + 0.0141c_i + 0.0004c_i^2$	$1.0 - 0.0423c_i + 0.0034c_i^2$	$1.0 + 0.0411c_i + 0.0033c_i^2$
$c_{H\widetilde{W}B}$	$1.0 - 0.0264c_i + 0.0018c_i^2$	$1.0 + 0.0262c_i + 0.0016c_i^2$	$1.0 - 0.0770c_i + 0.0113c_i^2$	$1.0 + 0.0779c_i + 0.0114c_i^2$

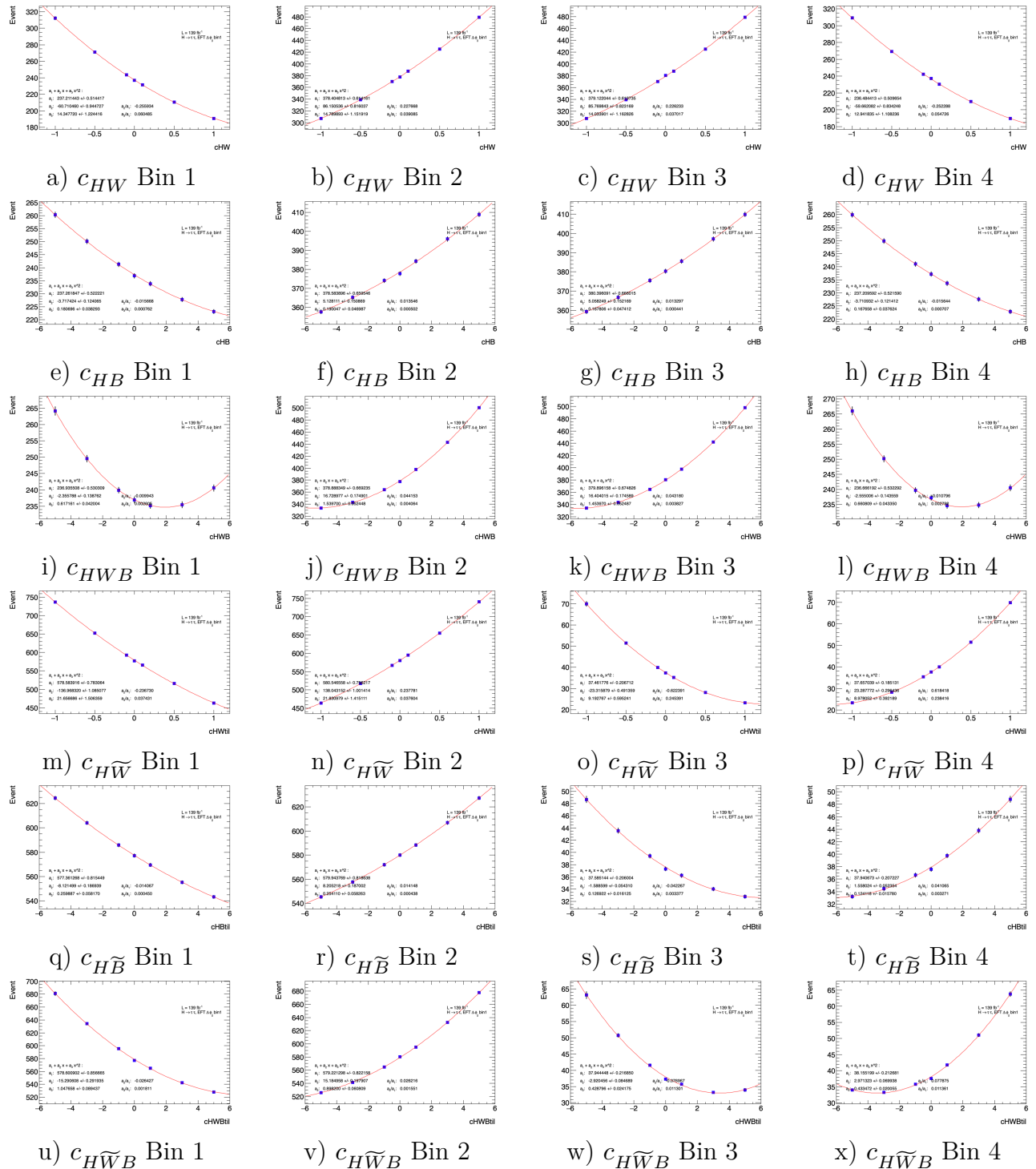


Figure B.4: Quadratic fit for cross-section dependence on the Wilson coefficients with corresponded unfolded scheme in each bin.

B.3 EFT interpretation results of VBF $H \rightarrow \tau\tau$ differential analysis

After getting the EFT parameterization in Appendix B.2, we will implement the statistical interpretation on the EFT limitations. Current stage only the Asimov fit is allowed

and its results will be presented in this section.

The EFT fit is totally following the setup from the VBF $H \rightarrow \tau\tau$ differential analysis, using the combined fit from $\ell^+\ell^-$, $\tau_{\text{lep}}\tau_{\text{had}}$, and $\tau_{\text{had}}\tau_{\text{had}}$ channels focused on the VBF phase space. The fit variable is $m_{\tau\tau}^{\text{MMC}}$ unfolded in $\Delta\phi_{jj}^{\text{signed}}$, and for different EFT coefficients we use the corresponded unfolded scheme introduced in Appendix B.2. We implement the 1D likelihood scan for six EFT coefficients considered both linear and linear+quadratic parameterization and the Asimov results are shoed in Figure B.5.

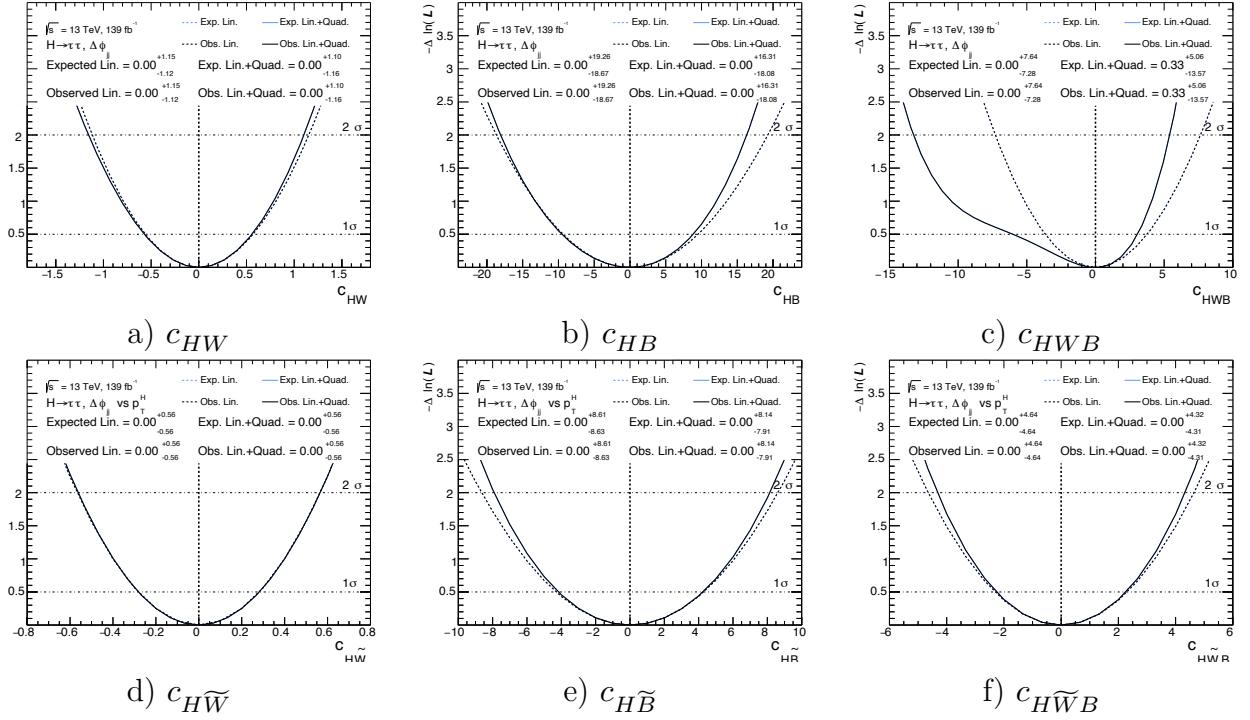
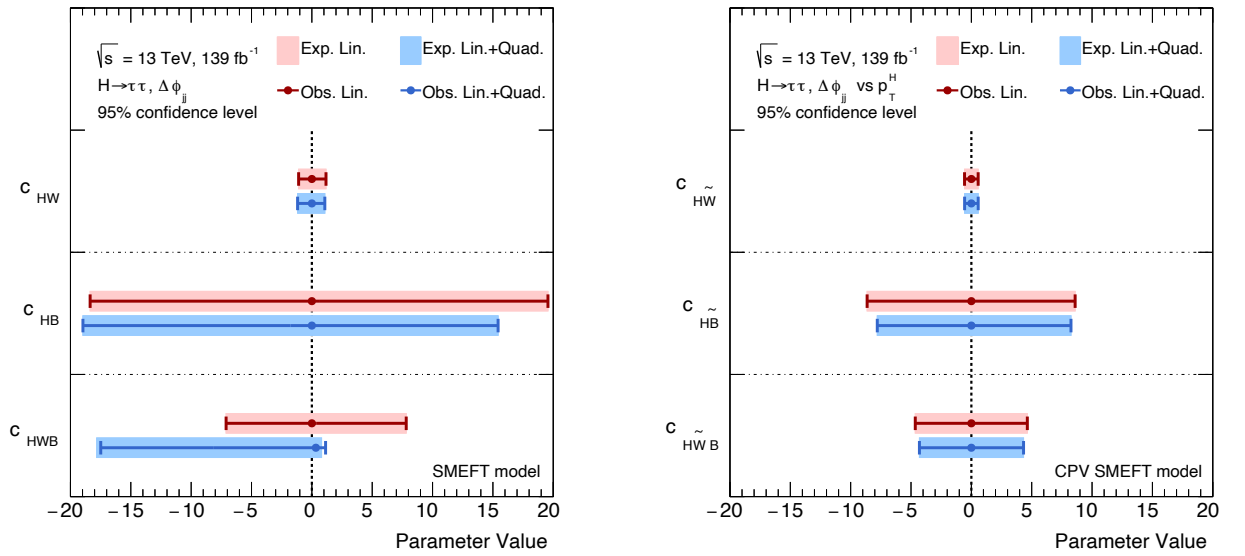


Figure B.5: Likelihood scan of six Wilson coefficients in different unfold schemes with both linear and linear+quadratic parameterization.

The EFT coefficient constraint results with both linear and linear+quadratic parameterization are summarized in Figure B.6. We have the good sensitivity on c_{HW} and $c_{H\widetilde{W}}$ results, and the limitation on 95% CL are $[-1.12, 1.15]$, $[-1.16, 1.10]$ for c_{HW} linear and linear+quadratic, 0 ± 0.56 , 0 ± 0.56 for $c_{H\widetilde{W}}$ linear and linear+quadratic, respectively.



a) Constraints on CP -even SMEFT operators b) Constraints on CP -odd SMEFT operators

Figure B.6: Summary plots of constraints on six Wilson coefficients.

Publications and Conference Talks

Publications with significant contributions:

- ATLAS Collaboration, *Measurement of the CP properties of Higgs boson interactions with τ -leptons with the ATLAS detector*, Eur. Phys. J. C 83 (2023) 563.

Conference talks:

- **ATLAS internal workshop:** *Overview of $H \rightarrow \tau\tau$ decay CP analysis*, TauCP+HLepton workshop, Dec 2021.
- **ATLAS internal conference:** *Analysis Approval: HLep $H \rightarrow \tau\tau$ decay CP measurement approval*, Higgs Group Plenary and Approval Meeting, Mar 2022.
- **ATLAS internal workshop:** *Tools status and readiness for Run3*, TauCP+HLepton Workshop, Feb 2023.
- **ATLAS internal workshop:** *MC and data for Run 3 analyses*, TauCP+HLepton Workshop, Mar 2024.
- **ATLAS internal workshop:** *EFT and combination plan*, TauCP+HLepton Workshop, Mar 2024.
- **Domestic conference:** *Measurements of Higgs boson decaying into τ -leptons using Run2 dataset at the ATLAS experiment*, The 7th China LHC Physics Conference, Nanjing, Nov 2021.
- **Domestic conference:** *Measuring CP properties of Higgs boson interactions with τ -leptons with the ATLAS detector*, The 11th Chinese High Energy Physics Association of Chinese Physics Society Conference, Dalian, Aug 2021.
- **Domestic conference (poster):** *Measuring CP properties of Higgs boson interactions with τ -leptons with the ATLAS detector*, The 8th China LHC Physics Conference, Nanjing, Nov 2022.

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