Introduction

We will soon be conducting statistical analysis on the Higgs-Boson particle, the particles it decays into, and the jets that it reconstructs into. Prior to this investigation, we will explore the data that we will be using to conduct said investigation.
The purpose of this write-up is to become confortable with the data and concepts that will be used and referenced in the labs to come.

The topics that will be explored in this write up are as follows:

- The Standard Model
- The Higgs-Boson Particle
- The Large Hadron Collider
- The Data and Its Features
- Significant Data Characteristics

An Introduction to the Standard Model

Before proceeding, we must delcare and understand the following facts:

The Fundamental Forces

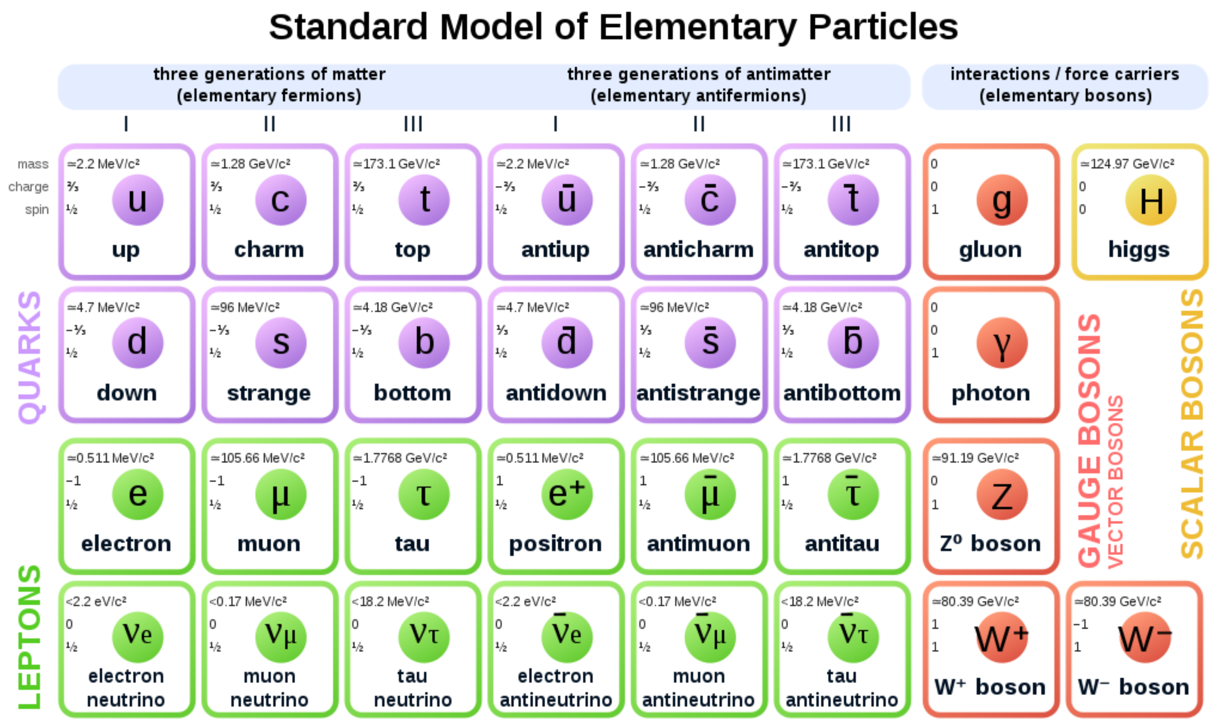
In the universe, there are four known fundamental forces:

- Electromagnetic
  - Explains how both moving and stationary particles interact
- Weak Interaction
  - The mechanism of interaction between subatomic particles that is responsible for the radioactive decay of atoms
- Strong Interactions
  - The attractive force that binds the elementary particles together
- Gravitational Force
  - The force that attracts any two objects wtith mass

Elementary Particles

In particle physics, there are things called "Elementary Particles". These are subatomic particles with no sub structure, therefore not composed of other particles.

The following is a visualization of the known Elementary Particles:



The Standard Model

With the above known, we can now explore the meaning of the "Standard Model": The standard model of particle physics is the theory describing three of the four known fundamental forces (excluding the gravitational force) in the universe, as well as classifying all known elementary particles. In other words, it is a way to explain the properties of forces between the elementary particles.

While the work to develop the standard model was conducted in stages throughout the 20th century, the current formulation was finalized in the mid-1970s upon experimental confirmation of the existence of quarks.

Since then, the confirmation of the top quark, tau neutrino, and the Higgs boson particles have added further credence to the Standard Model. In this write-up, we will be exploring the Higgs boson particle in detail.

The Higgs Boson Particle

As discussed, one of the particles included in the Standard Model is the boson, which the Higgs particle is classified as (hence the name).

Add link referencing quantum excitation

A Brief History

This particle was named after Physicist Peter Higgs. In 1964 he attempted to explain why particles have math with the proposal of the Higgs mechanism. The Higgs mechanism, simply put, is the mechanism by which the Higgs field leads to the breaking of certain symmetry laws of the electroweak interaction. This field, by way of the Higgs mechanism, causes the gauge bosons of the weak force to be massive. The proposal of this Higgs mechanism implied the existence of the Higgs boson.

Its existence was finally confirmed in 2012 by ATLAS and CMS collaborations baed on collisions in the Large Hadron Collider (LHC) at CERN.

Known Characteristics of the Higgs Boson

The Higgs boson was difficult to detect due to the energy required to produce them and their vary rare production (1 in 10 billion at the LHC) even in the event of sufficient energy.

Some of the characteristics that will be of interest to us in the coming experiments are as follows:

- Mass = 125.18 +- .16 GeV/c
- Predicted Mean Lifetime = 1.56x10^-22 s
- Decays Into:
    - Bottom-antibottom pair (observed)
    - Two W bosons (observed)
    - Two gluons (predicted)
    - Two antitau pairs (observed)
    - Two Z bosons (observed)
    - Two photos (observed)
- Spin = 0

The Large Hadron Collider

What Problem the LHC Solves

Shortly after the 19th century declaration of the existence of atoms, physicist have been searching for the fundamental particles of natures.

Through the 1950s and 1960s, a high number of particles were found in collisions of particles from increasingly high-energy beams. These collisions and the need for even higher energy beams gave birth to the idea of what would become the world's largest machine: The Large Hadron Collider

How It Works

The shape of the LHC is extremely important to the success of the machine. The collider is contained in a 3.8 meter wide, concrete, circular tunnel with a circumference of 26.7 km.

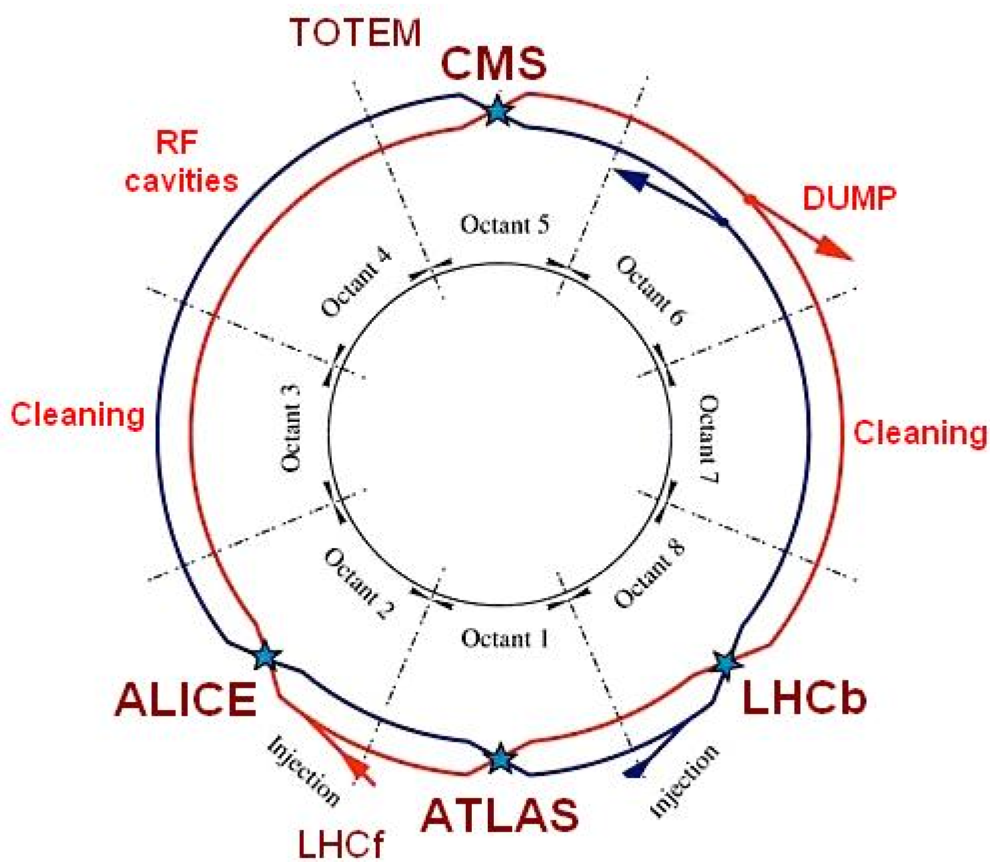
The collider tunnel contains two adjacent parralel beamlines, each containing a beam, which travel in opposite directions around the ring. These are the sources of the particles that are to be collided. These beams intersect at four points around the ring, which is where the actual collision takes place.

The particles would easily stray from a circular path were it not for over 1000 dipole magnets keeping the beams on that path. Even more magnets are needed, nearly 400 quadrupole magnets, to keep the beam focused (with stronger quadrupole magnets near intersections to maximize chances of interaction where the beams cross). In addition to those, there are many more magnets of higher pultipole order used to correct smaller imperfectiosn in the field geometry. All-in-all, there are about 9000 superconducting magnets in use to keep these beams on their circular path to collison.

Detectors

The LHC is only a piece of the machinery that works to detect particles. There are seven different detectors located around the LHC's intersection points. ATLAS and CMS, both paramount in the discovery of the Higgs boson, are both large general-purpose detectors. The others, LHCb, ALICE, TOTEM, MoEDAL, and LHCf are smaller than ATLAS and CMS and have more specific roles, or are used for very specialized research.

Below is a diagram of the layout at CERN:



Explanation of Data

The data we will be working with are simulated data, not actual data from the LHC. It has a specific transverse momentum range of 1000-12000 GeV, and includes two files which have the following data:

- QCD Background
  - Stands for "Quantum Chromodynamics"

    - Generally refers to processes which lead to hadronic jets (narrow cone of hadrons and other particles produced by the formation of hadrons (hadronization) out of quarks and gluons)
- Higgs data (expected)
    - Expected outcome of QCD Background data after optimization and manipulation

Features of Data

There are 14 features included in each data set:

- **Transverse Momentum**
    - Defined by the equation $\sqrt{p_x^2 + p_y^2}$ for some
    - This is the component momentum perpendicular to the beam line

- **Pseudorapidity**
    - Defined by the equation -ln*$\tan(\frac{\theta}{2})\frac{-1}{2}ln\frac{|p|+p_L}{|p|-p_L}$
    - Spacial coordinate describing the angle of a particle relative to the beam axis

- **Azimuthal Angle**
    - Defined by the equation $\cos^{-1}(\frac{x}{r})$ for some plane x, and some vector r
    - On the transverse plane xy, the between x and r

- **Invariant Mass**
    - Defined by the equation $E^2=p^2+m^2$ for some mass m and some momentum p
    - Mass of particle

- **2-Point ECF Ratio**
    - Defined by the equation

$$\sum_{i<j\in J} p_{T,i}\, p_{T,j}\, \Delta R_{ij} * \frac{1}{p_{T,J}^2}$$

- **3-Point ECF Ratio**
    - Defined by the equation

$$\sum_{i<j<k\in J} p_{T,i}\, p_{T,j}\, p_{T,k}\, \Delta R_{ij}\, \Delta R_{ik}\, \Delta R_{jk} * \frac{1}{p_{T,J}^3}$$

- **3-to-2 Point ECF Ratio**
    - Defined by the equation $\frac{e_3}{e_2^3}$

- **Angularity**
    - Defined by the equation

$$\frac{1}{m_J} \sum_{i\in J} E_i \sin^{-2}(\Theta_i) * \cos^3(\Theta_i)$$

- **N-Subjettiness**
    - Defined by the Greek letter τ

- A jet shape designed to identify boosted hadronically-decaying (decaying and producing a hadron) objects

Exploring the Data

Setup:

In [2]:

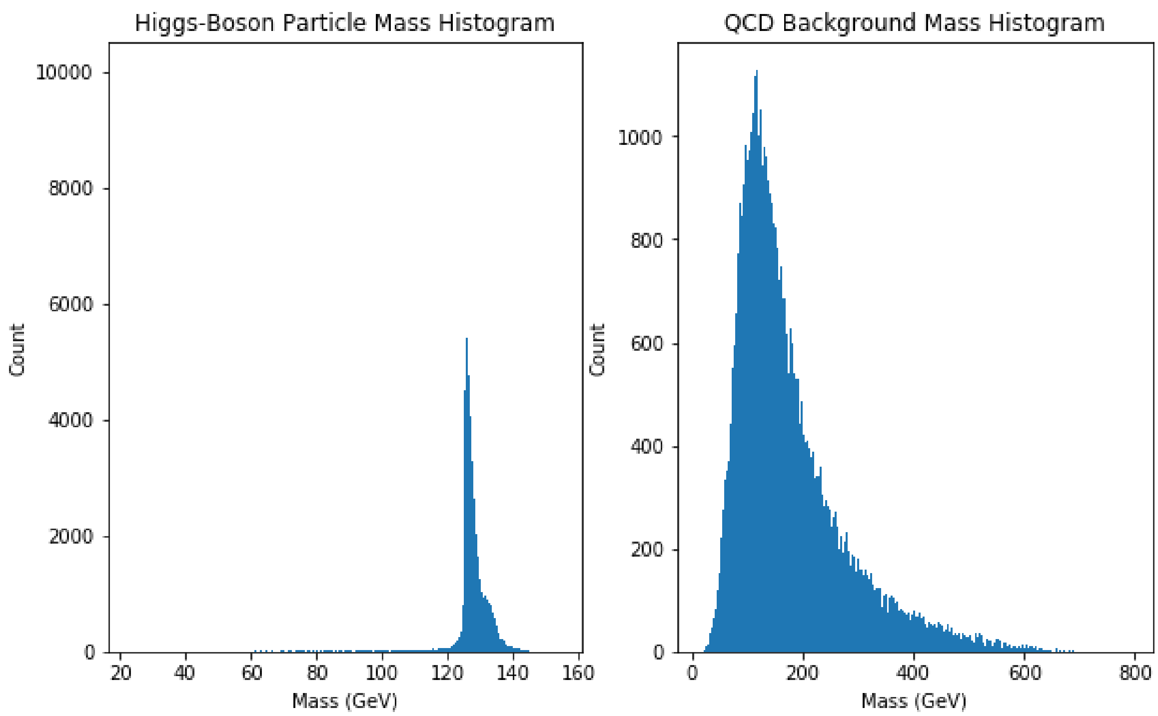
```
import pickle
import numpy as np
import matplotlib.pyplot as plt
from scipy import stats,signal

higg = open ("higgs_100000_pt_1000_1200.pkl",'rb')
higgD = pickle.load(higg)

qcd = open ("qcd_100000_pt_1000_1200.pkl",'rb')
qcdD = pickle.load(qcd)

higgsPt=higgD['pt']
higgsEta=higgD['eta']
higgsPhi=higgD['phi']
higgsMass=higgD['mass']
higgsEe2=higgD['ee2']
higgsEe3=higgD['ee3']
higgsD2=higgD['d2']
higgsAng=higgD['angularity']
higgsT1=higgD['t1']
higgsT2=higgD['t2']
higgsT3=higgD['t3']
higgsT21=higgD['t21']
higgsT32=higgD['t32']
higgsKtD=higgD['KtDeltaR']
qcdPt=qcdD['pt']
qcdEta=qcdD['eta']
qcdPhi=qcdD['phi']
qcdMass=qcdD['mass']
qcdEe2=qcdD['ee2']
qcdEe3=qcdD['ee3']
qcdD2=qcdD['d2']
qcdAng=qcdD['angularity']
qcdT1=qcdD['t1']
qcdT2=qcdD['t2']
qcdT3=qcdD['t3']
qcdT21=qcdD['t21']
qcdT32=qcdD['t32']
qcdKtD=qcdD['KtDeltaR']
```

Mass

Below I have graphed the mass from both the Higgs data and the QCD background data.

In [5]:

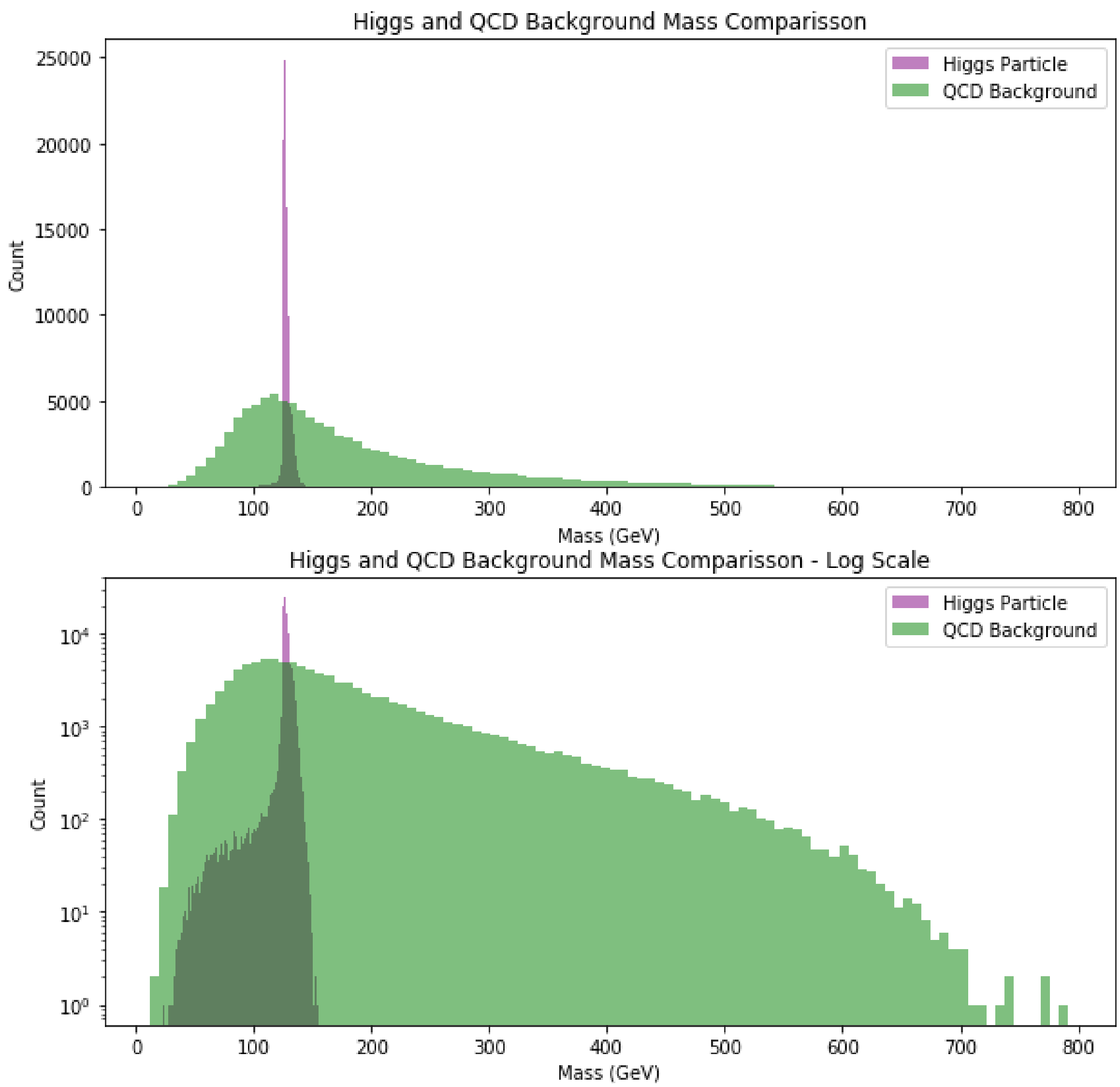
```
fig, ax = plt.subplots(1, 2, figsize=(10,6))
ax[0].hist(higgsMass,500)
ax[1].hist(qcdMass,500)
ax[0].set_title("Higgs-Boson Particle Mass Histogram")
ax[1].set_title("QCD Background Mass Histogram")
ax[0].set_ylabel("Count")
ax[0].set_xlabel("Mass (GeV)")
ax[1].set_ylabel("Count")
ax[1].set_xlabel("Mass (GeV)")
plt.show()
```



While the two are interesting on their own, it is important to truly note the significance of the shapes. It is easiest to observe when the two are graphed on the same axis, as shown below.

In [83]:

```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsMass,bins=100,color='purple',alpha=0.5, label='Higgs Particle
ax[0].hist(qcdMass,bins=100,color='green',alpha=0.5, label='QCD Background')
ax[1].hist(higgsMass,bins=100,color='purple',alpha=0.5, label='Higgs Particle
ax[1].hist(qcdMass,bins=100,color='green',alpha=0.5, label='QCD Background')
ax[1].set_yscale('log')
ax[0].set_title("Higgs and QCD Background Mass Comparisson")
ax[0].legend(loc='upper right')
ax[1].legend(loc='upper right')
ax[1].set_title("Higgs and QCD Background Mass Comparisson - Log Scale")
ax[0].set_ylabel("Count")
ax[0].set_xlabel("Mass (GeV)")
ax[1].set_ylabel("Count")
ax[1].set_xlabel("Mass (GeV)")
plt.show()
```



You can see on both the linear and log-scale graphs that the Higgs data has a clear spike at approximately 125.

Given that this is a visualization of the mass, one can conclude that, given some data where a Higgs boson particle is expected, the mass of that particle would be approximately 125 GeV.

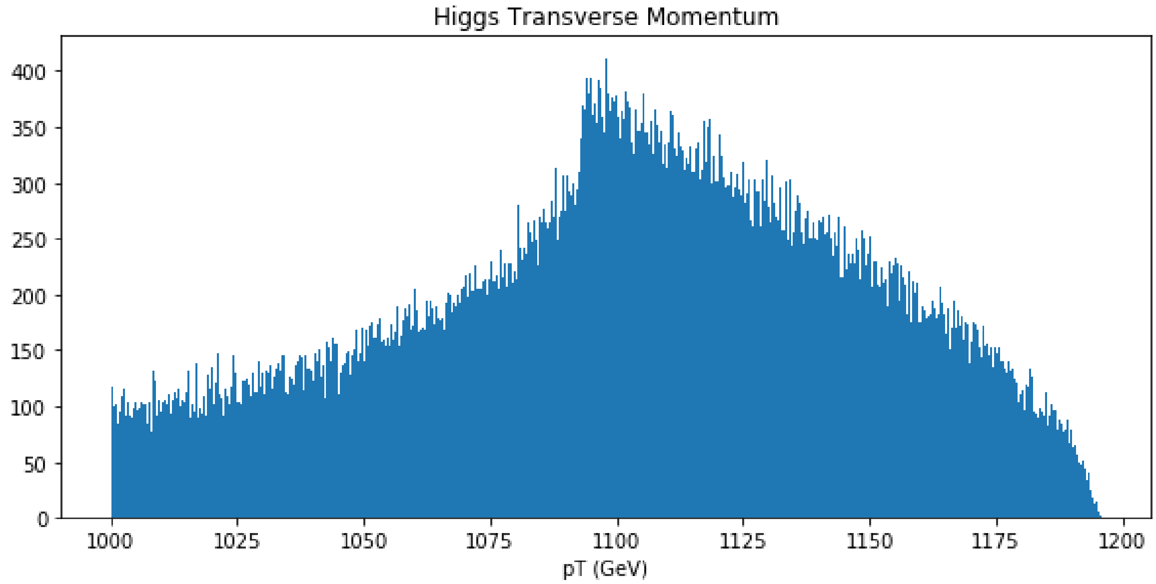
As previously discussed, the Higgs boson does have a mass of 125 GeV, and such a deduction would be accurate.

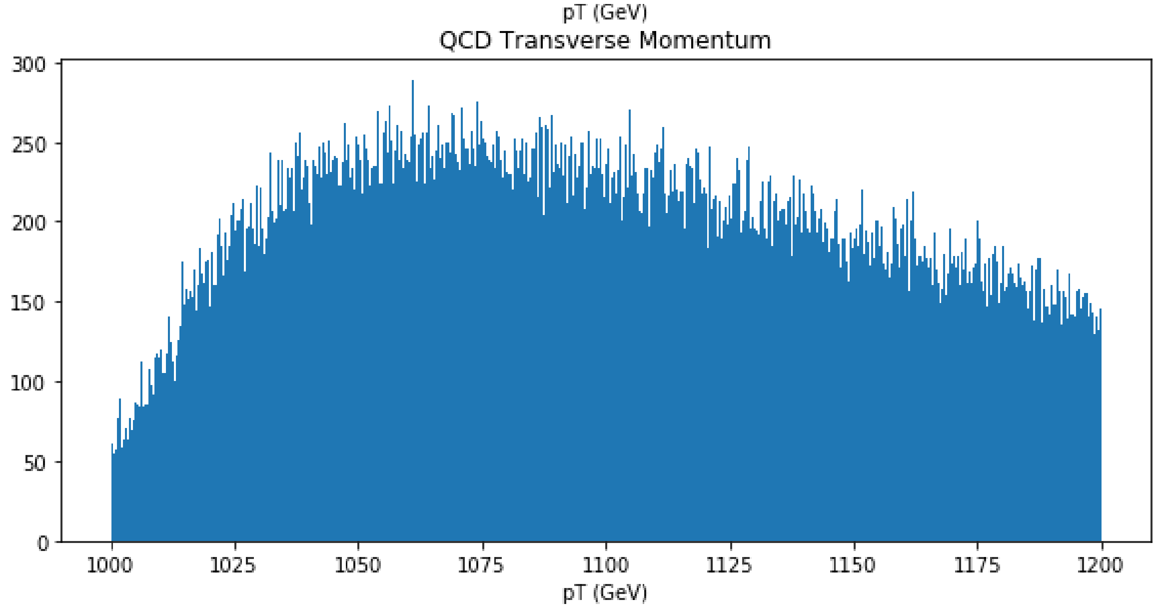
Transverse Momentum

Shown below are the histograms of pT for both the background and higgs data.

In [6]:

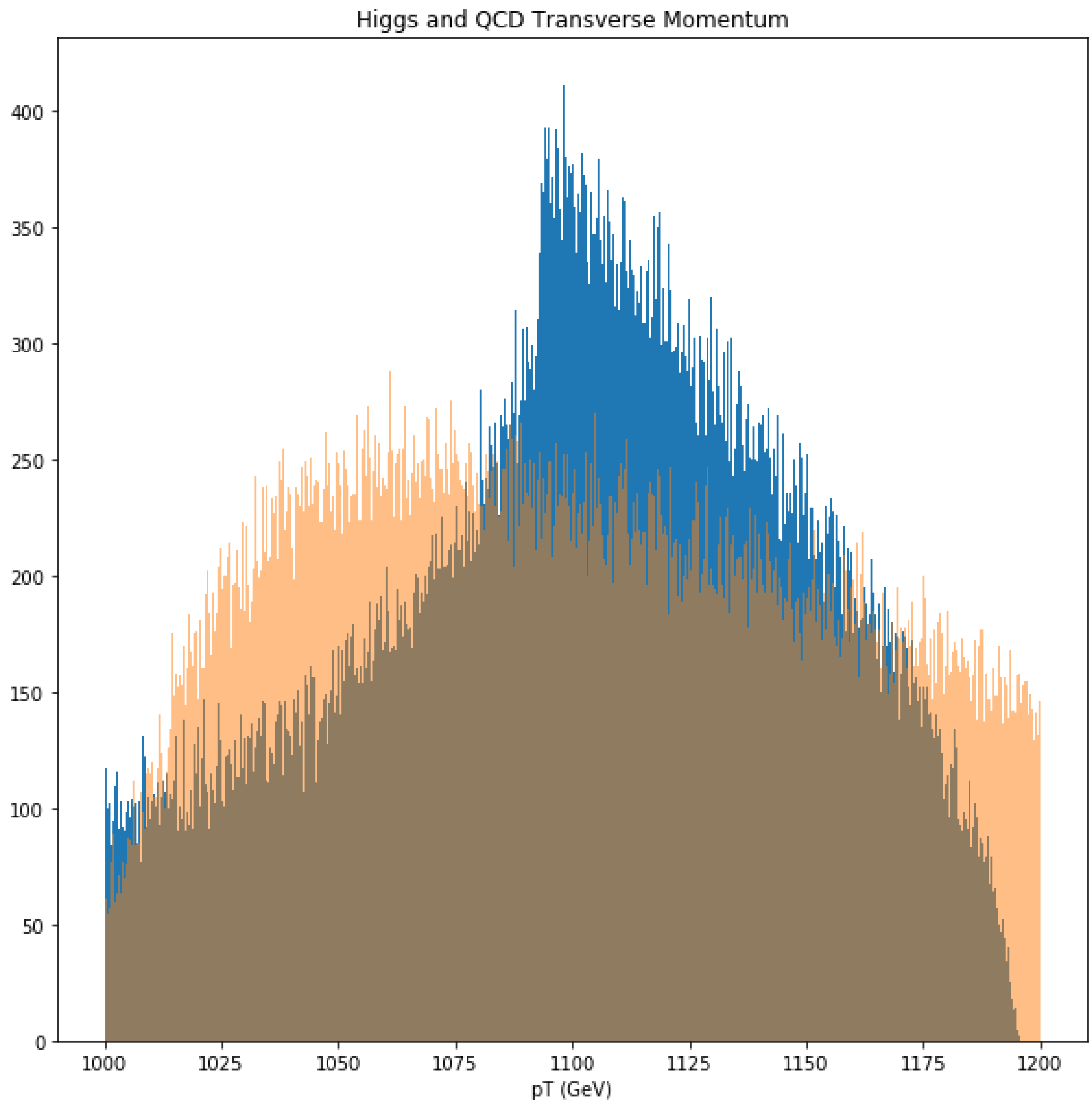
```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsPt,500)
ax[1].hist(qcdPt,500)
ax[0].set_title("Higgs Transverse Momentum")
ax[1].set_title("QCD Transverse Momentum")
ax[0].set_xlabel("pT (GeV)")
ax[1].set_xlabel("pT (GeV)")
plt.show()
```





Again I will graph them on the same visualization in order to truly appreciate some of the features.

In [8]:
```
fig, ax = plt.subplots(1, 1, figsize=(10,10))
ax.hist(higgsPt,500)
ax.hist(qcdPt,500,alpha=0.5)
ax.set_title("Higgs and QCD Transverse Momentum")
ax.set_xlabel("pT (GeV)")

plt.show()
```



The QCD background in light orange, and the Higgs data in blue, we can see an interesting feature approaching the 1200 GeV pT limit (as defined by our data range).

Note that the background is clearly continuing, and cut off, when the data range ends. However, the Higgs data we see that it rapidly tapers off just before 1200 GeV at an estimated range of 1190-1199 GeV. At this time in the lab procedure, the significance (if any) of the transverse momentum dropping off here is unknown.

Another interesting feature that may prove useful in the future experiment is the dramatic increase of the Higgs data at just below 1100 GeV. The QCD background shows no such jump at this point. Again, at this time in the exploration of the data, the significance of this point is unknown (if there is any significance).

Remaining Features

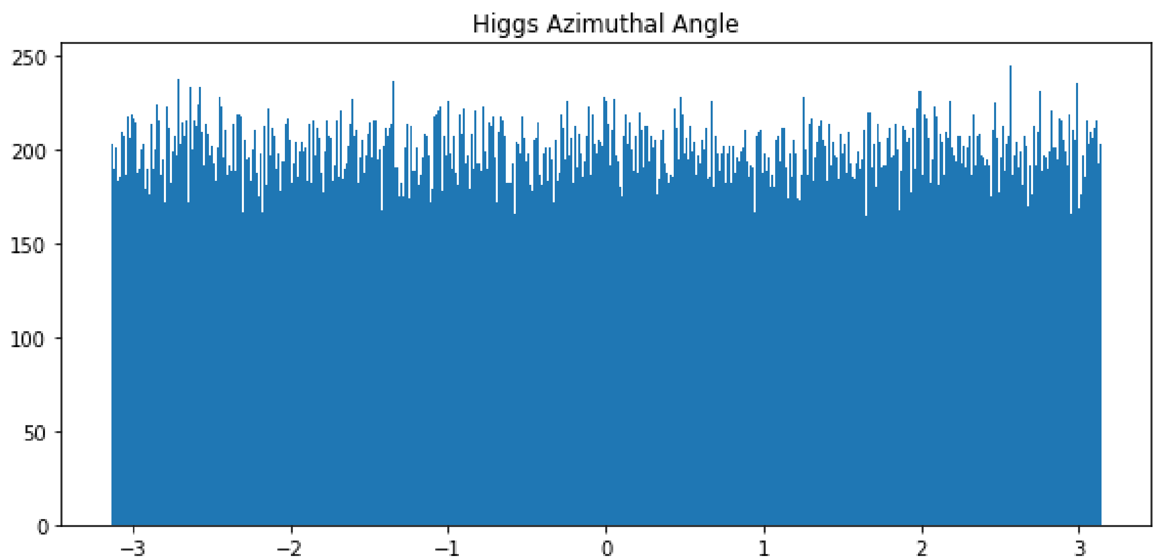
The remaining features, at this point in the lab, show no real significance that has real meaning.

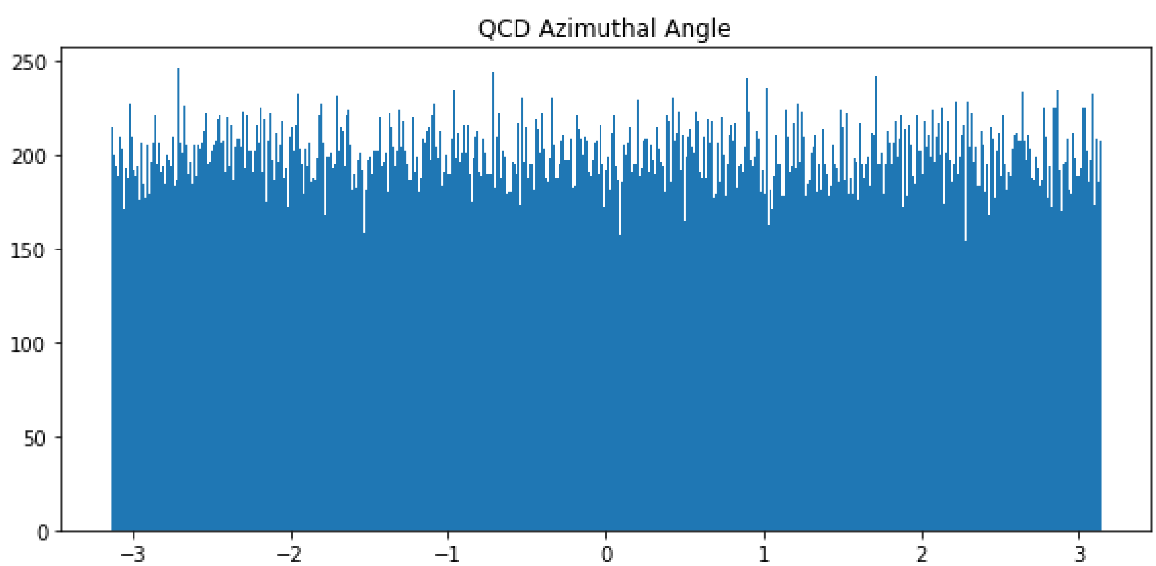
At this time, the remaining features will be graphed for visualization purposes only.

Azimuthal Angle

In [9]:

```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsPhi,500)
ax[1].hist(qcdPhi,500)
ax[0].set_title("Higgs Azimuthal Angle")
ax[1].set_title("QCD Azimuthal Angle")
plt.show()
```

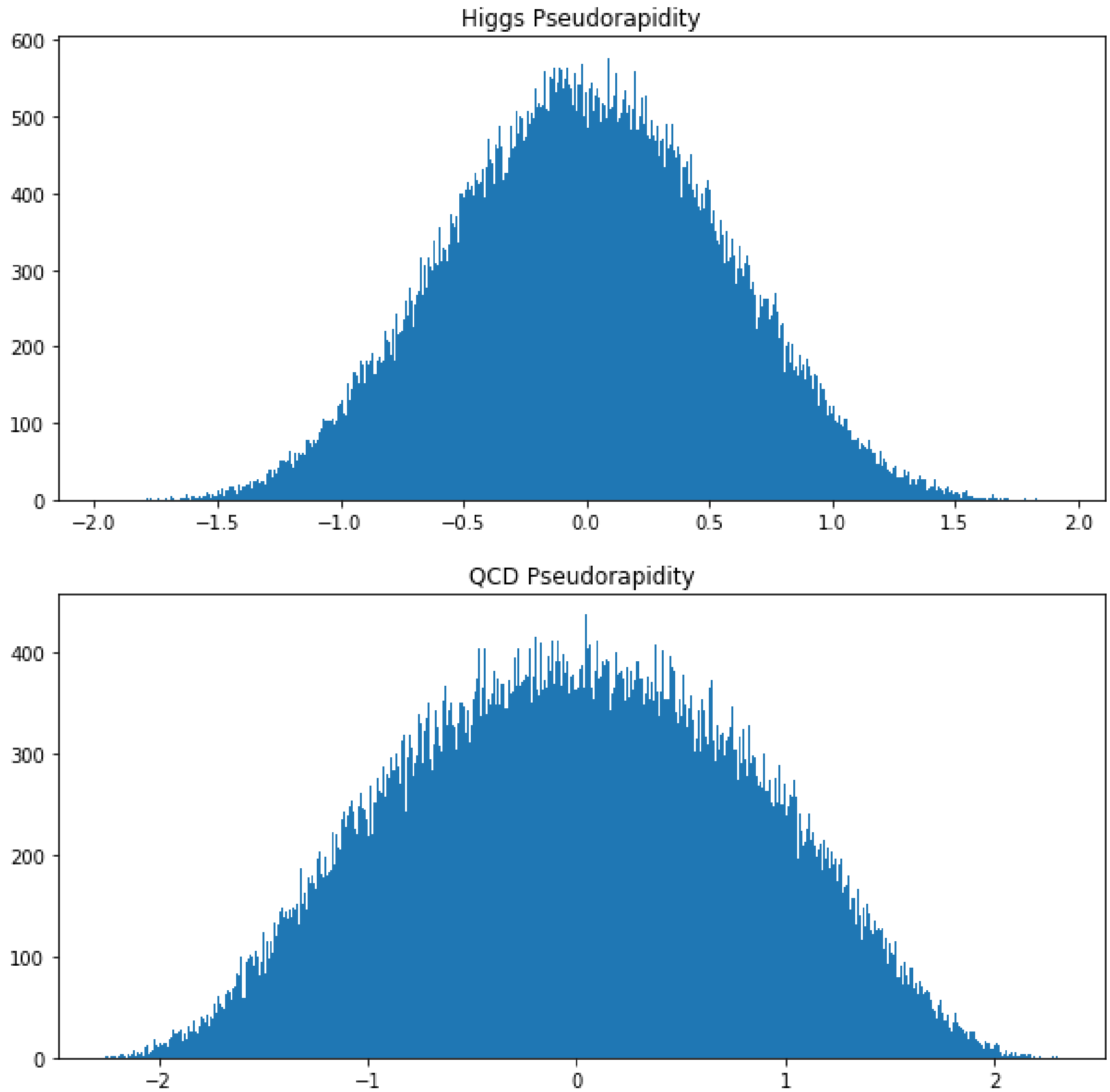




Pseudorapidity

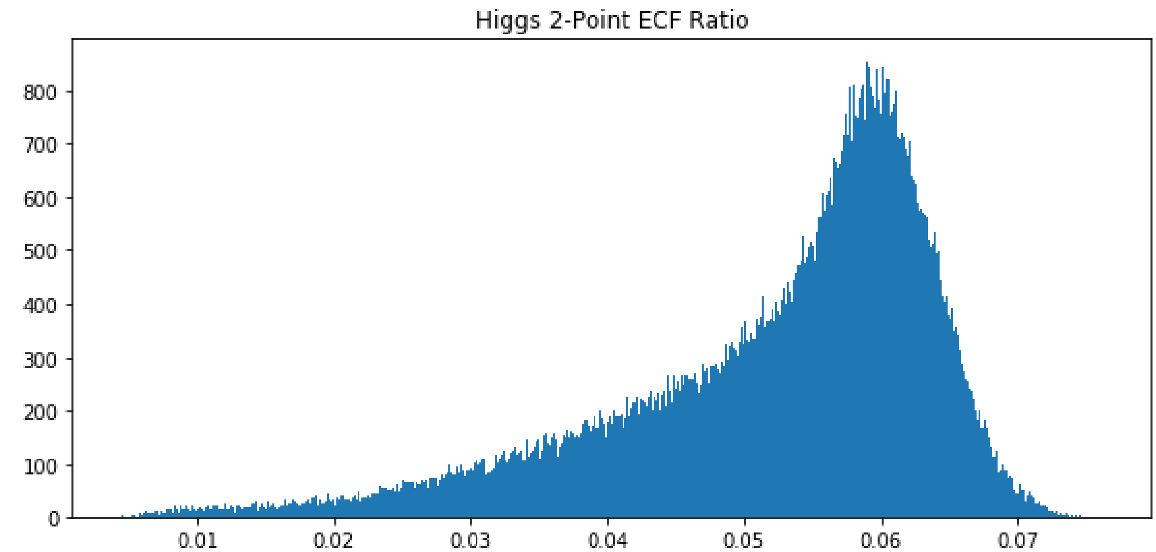
In [10]:

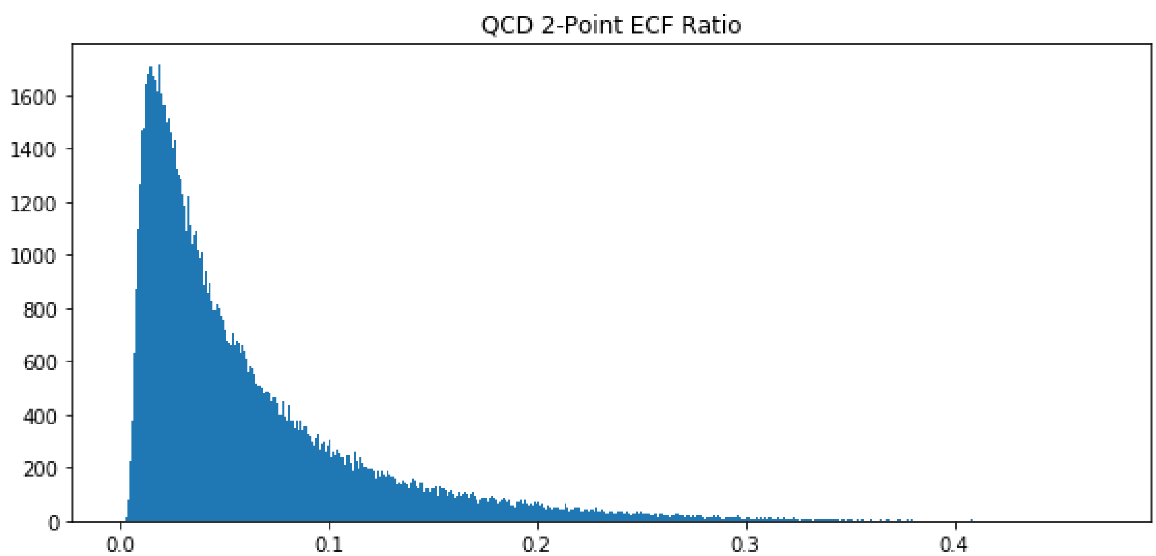
```python
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsEta,500)
ax[1].hist(qcdEta,500)
ax[0].set_title("Higgs Pseudorapidity")
ax[1].set_title("QCD Pseudorapidity")
plt.show()
```



2-Point ECF Ratio

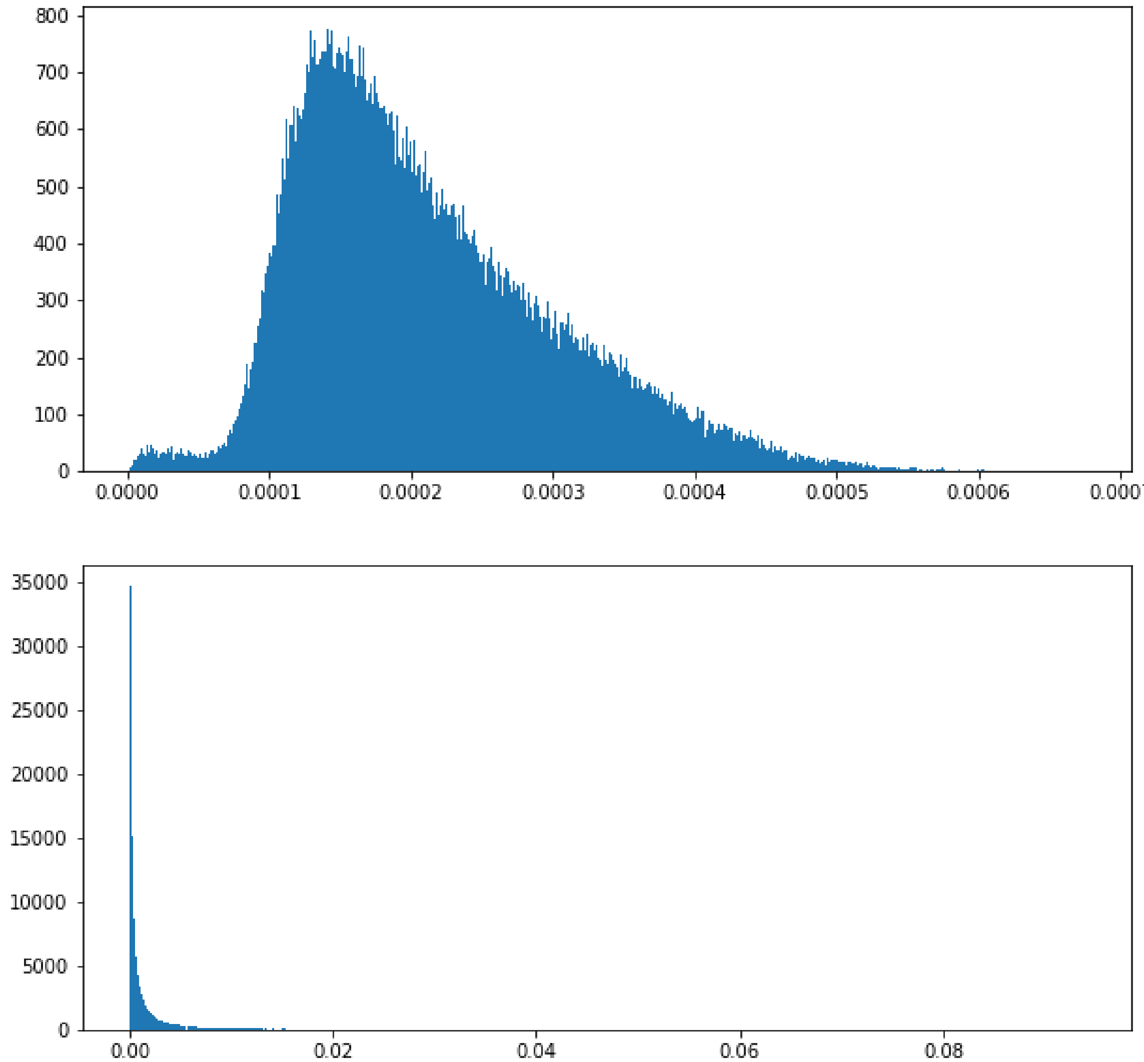
In [11]:
```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsEe2,500)
ax[1].hist(qcdEe2,500)
ax[0].set_title("Higgs 2-Point ECF Ratio")
ax[1].set_title("QCD 2-Point ECF Ratio")
plt.show()
```





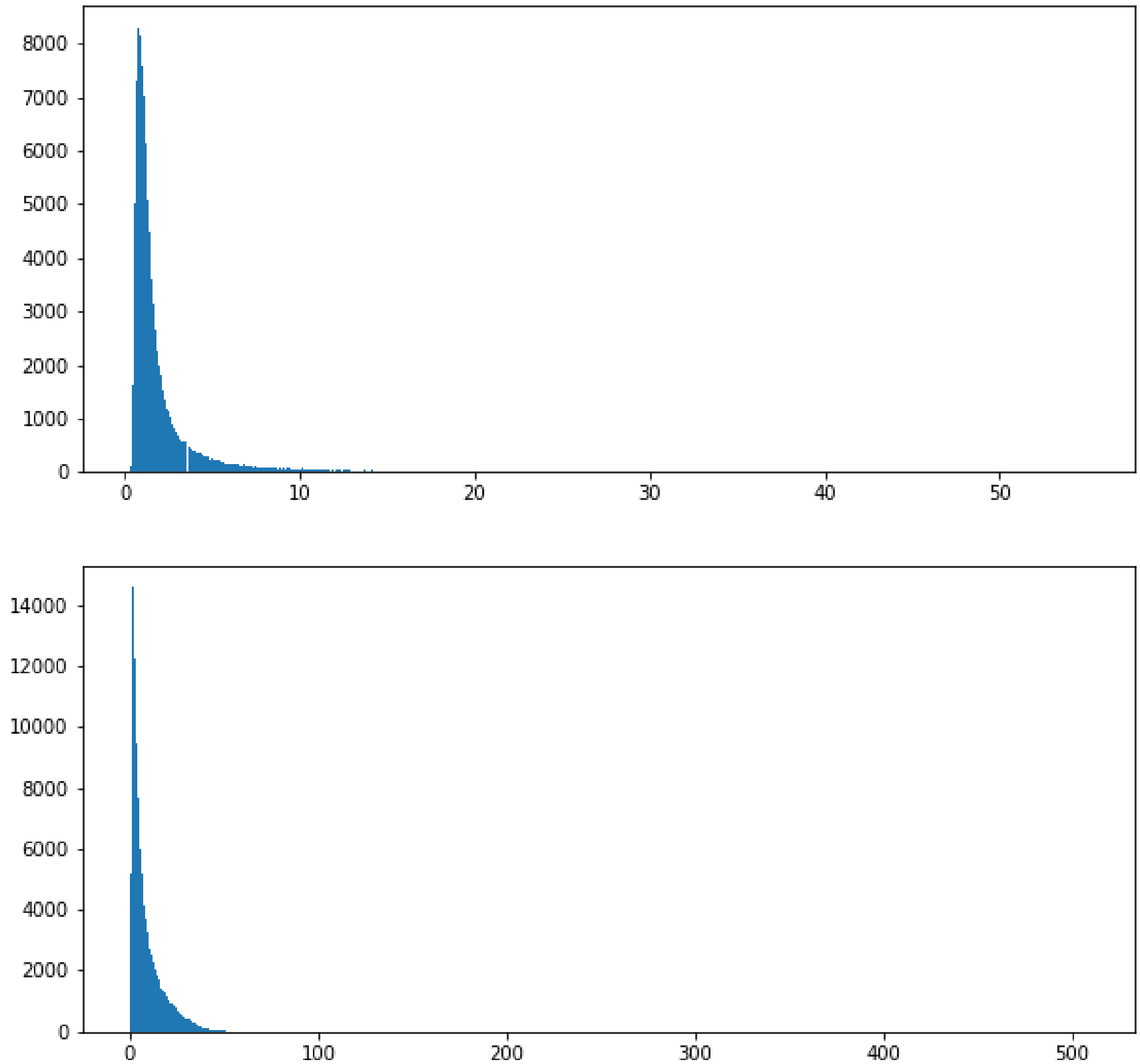
3-Point ECF Ratio

In [101]:
```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsEe3,500)
ax[1].hist(qcdEe3,500)
plt.show()
```



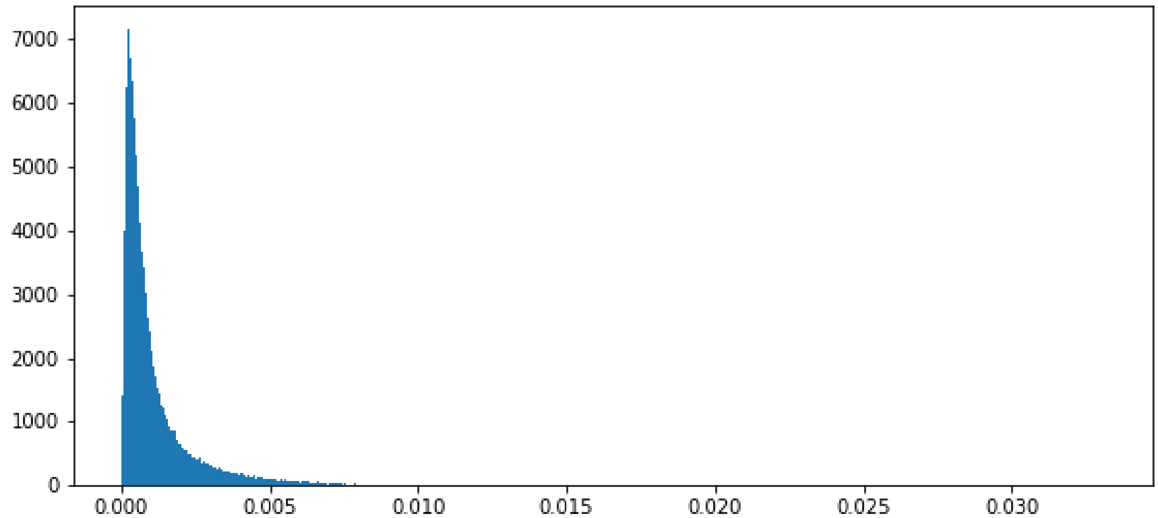
3-to-2 Point ECF Ratio

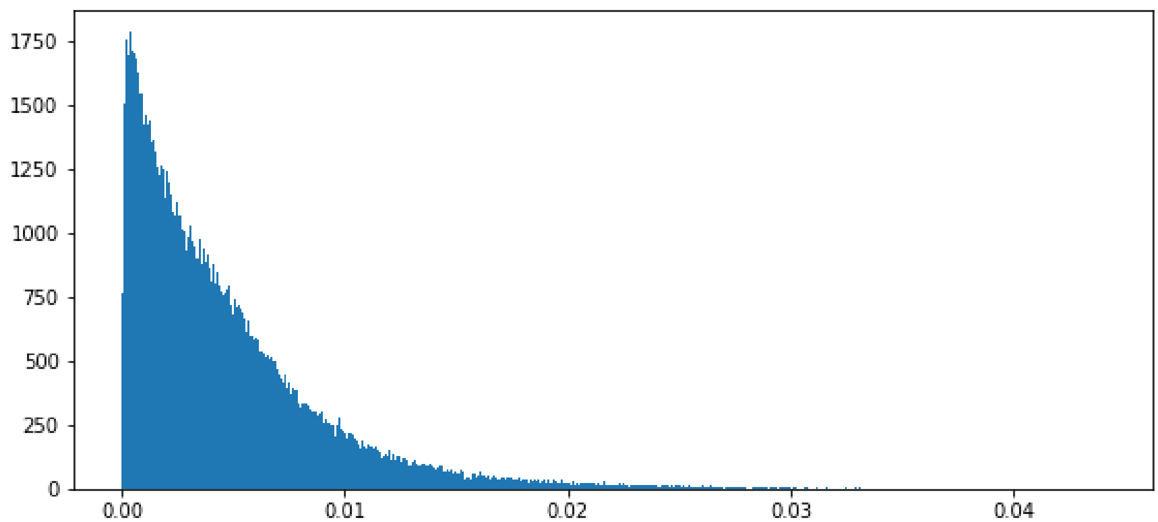
In [90]:
```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsD2,500)
ax[1].hist(qcdD2,500)
plt.show()
```



Angularity

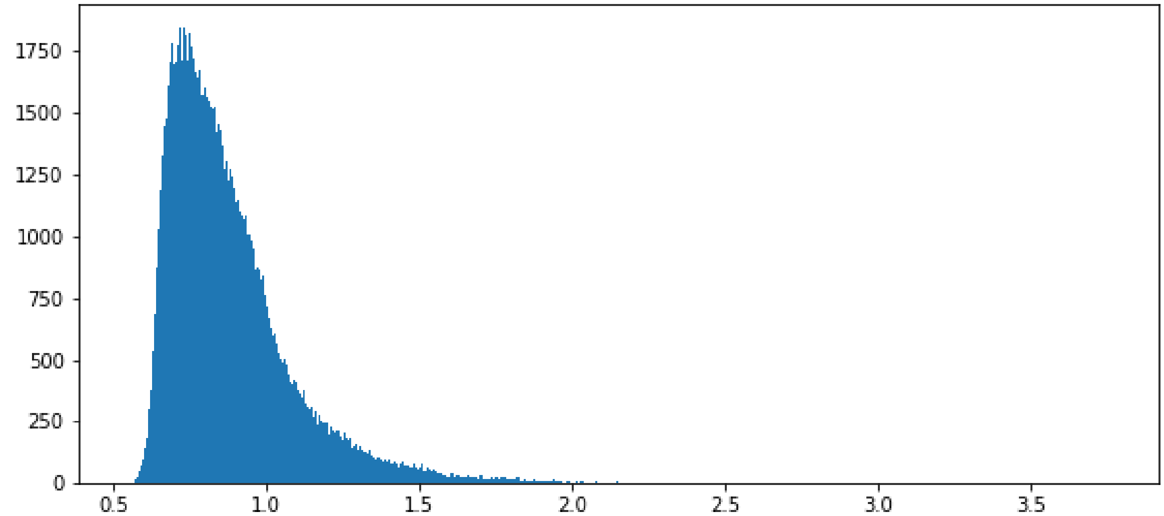
In [91]:
```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsAng,500)
ax[1].hist(qcdAng,500)
plt.show()
```

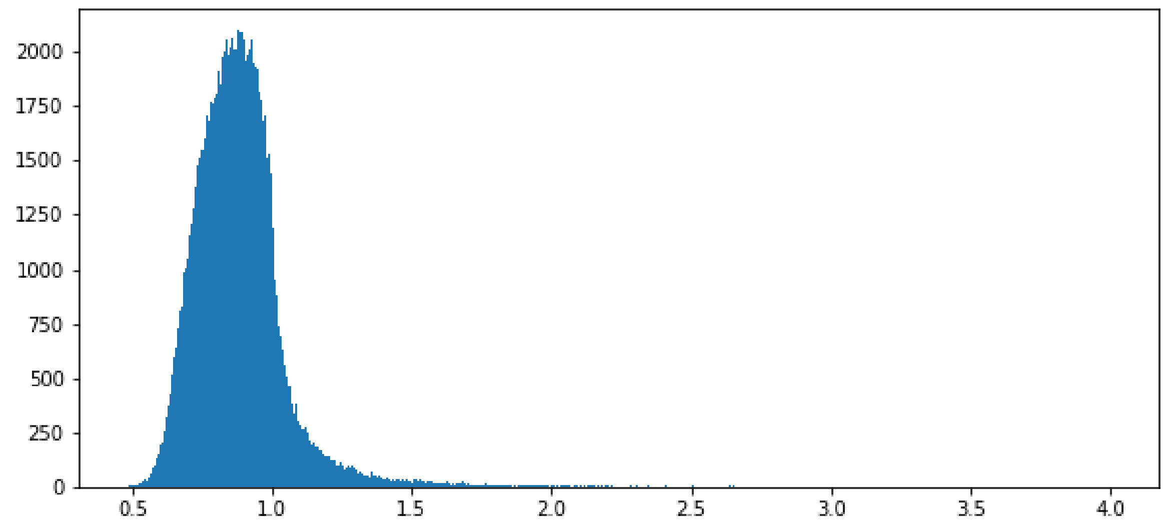




Subjettiness

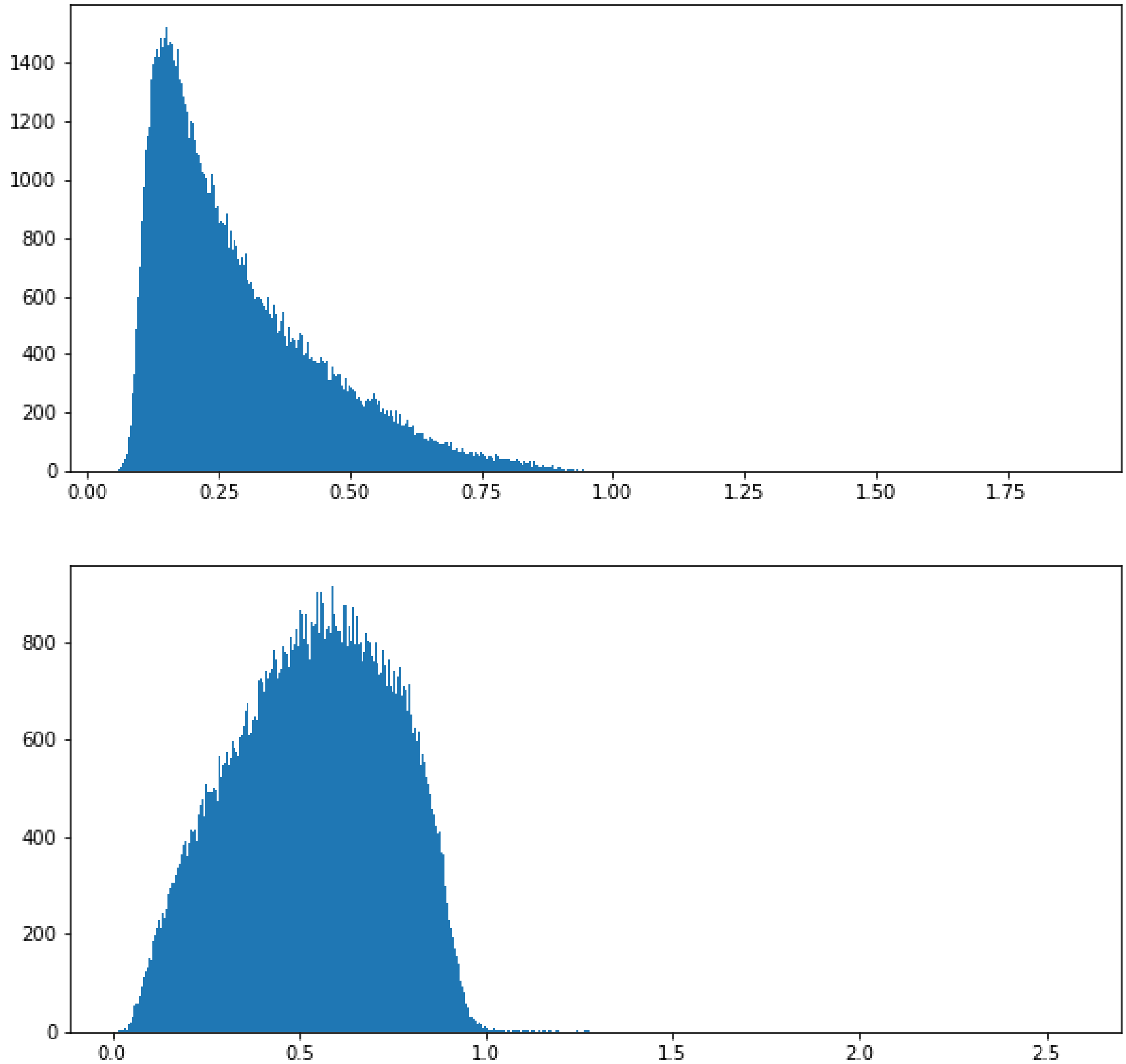
In [92]:
```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsT1,500)
ax[1].hist(qcdT1,500)
plt.show()
```



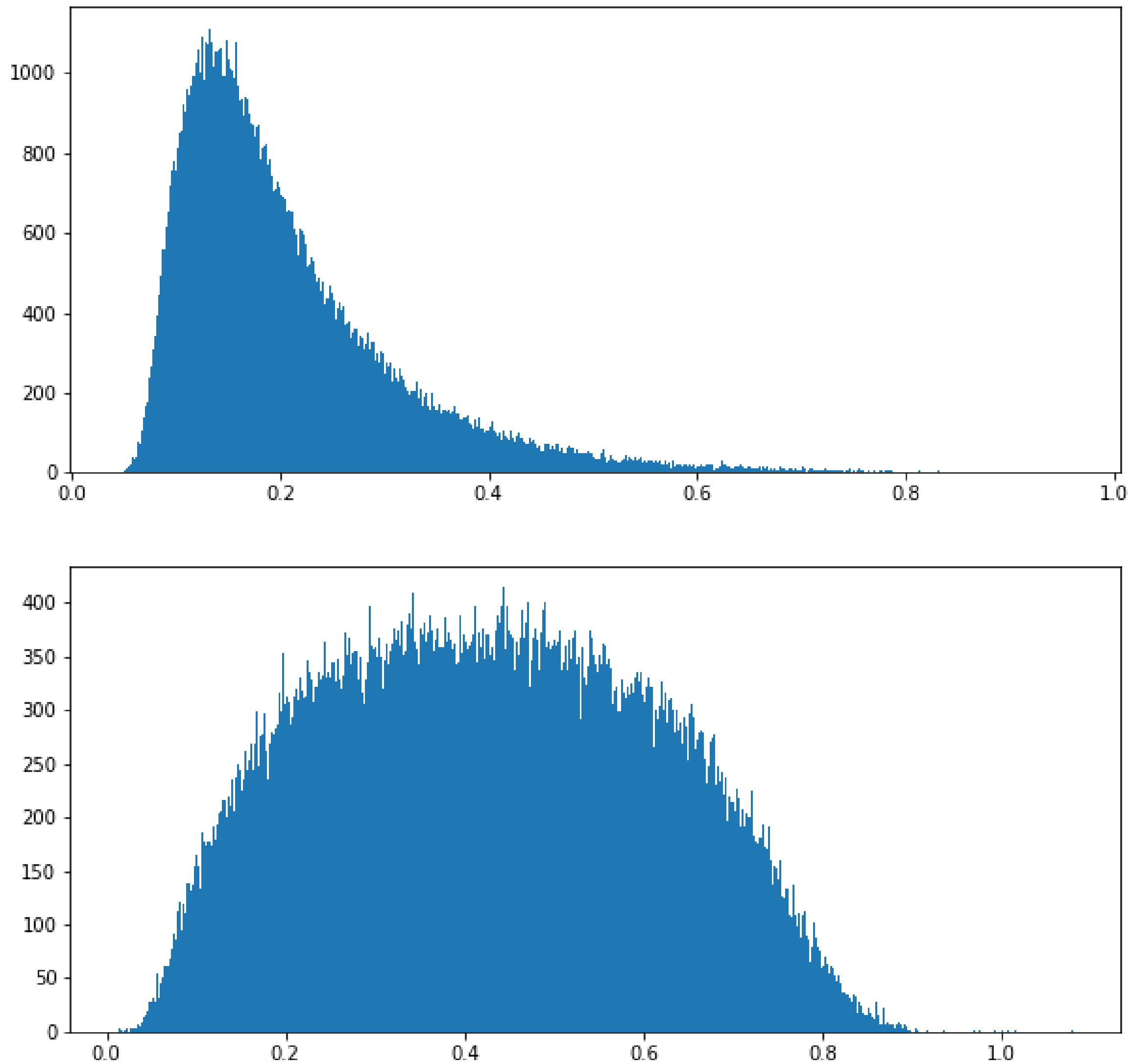


In [93]:

```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsT2,500)
ax[1].hist(qcdT2,500)
plt.show()
```

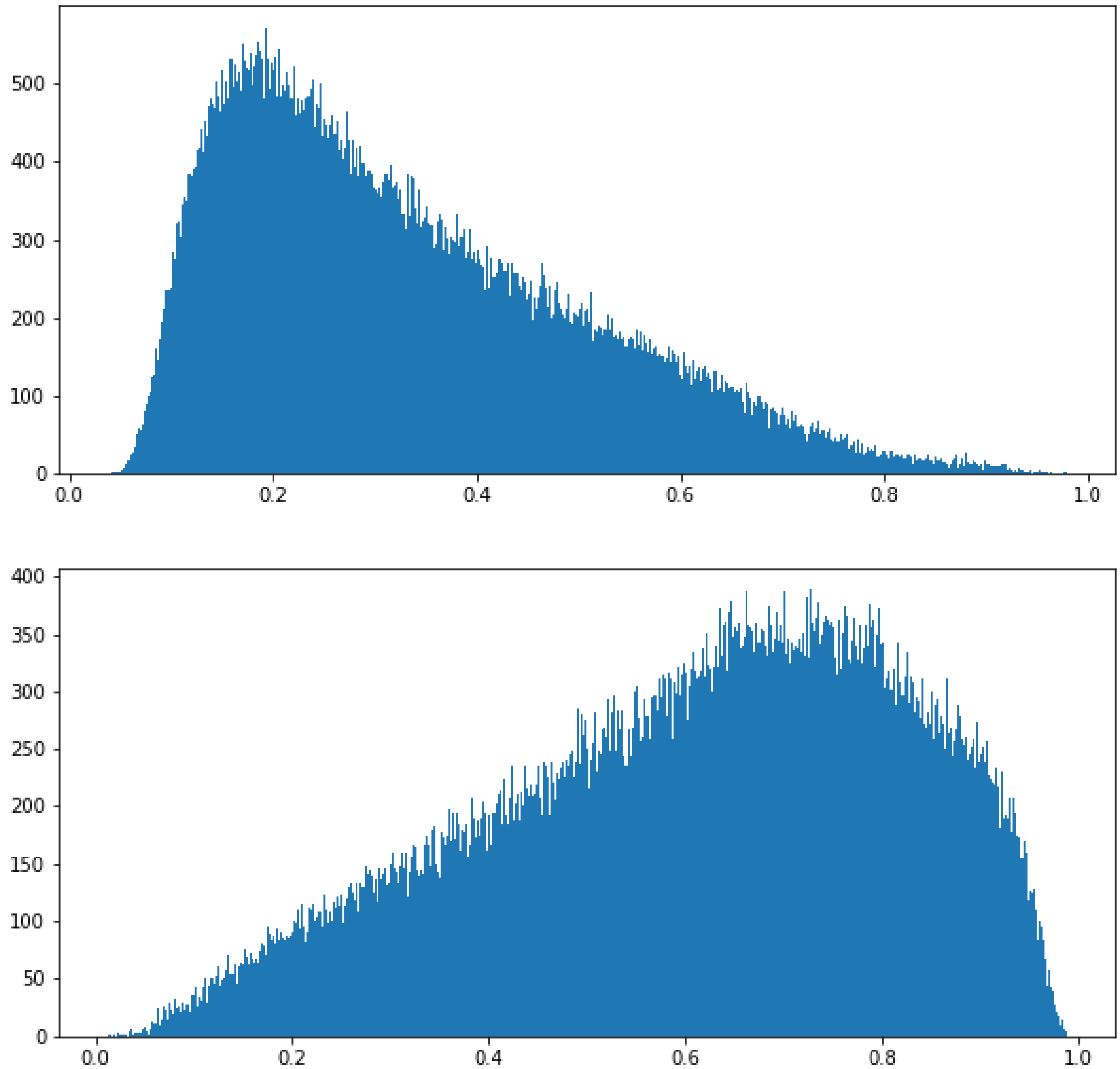


In [94]:
```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsT3,500)
ax[1].hist(qcdT3,500)
plt.show()
```



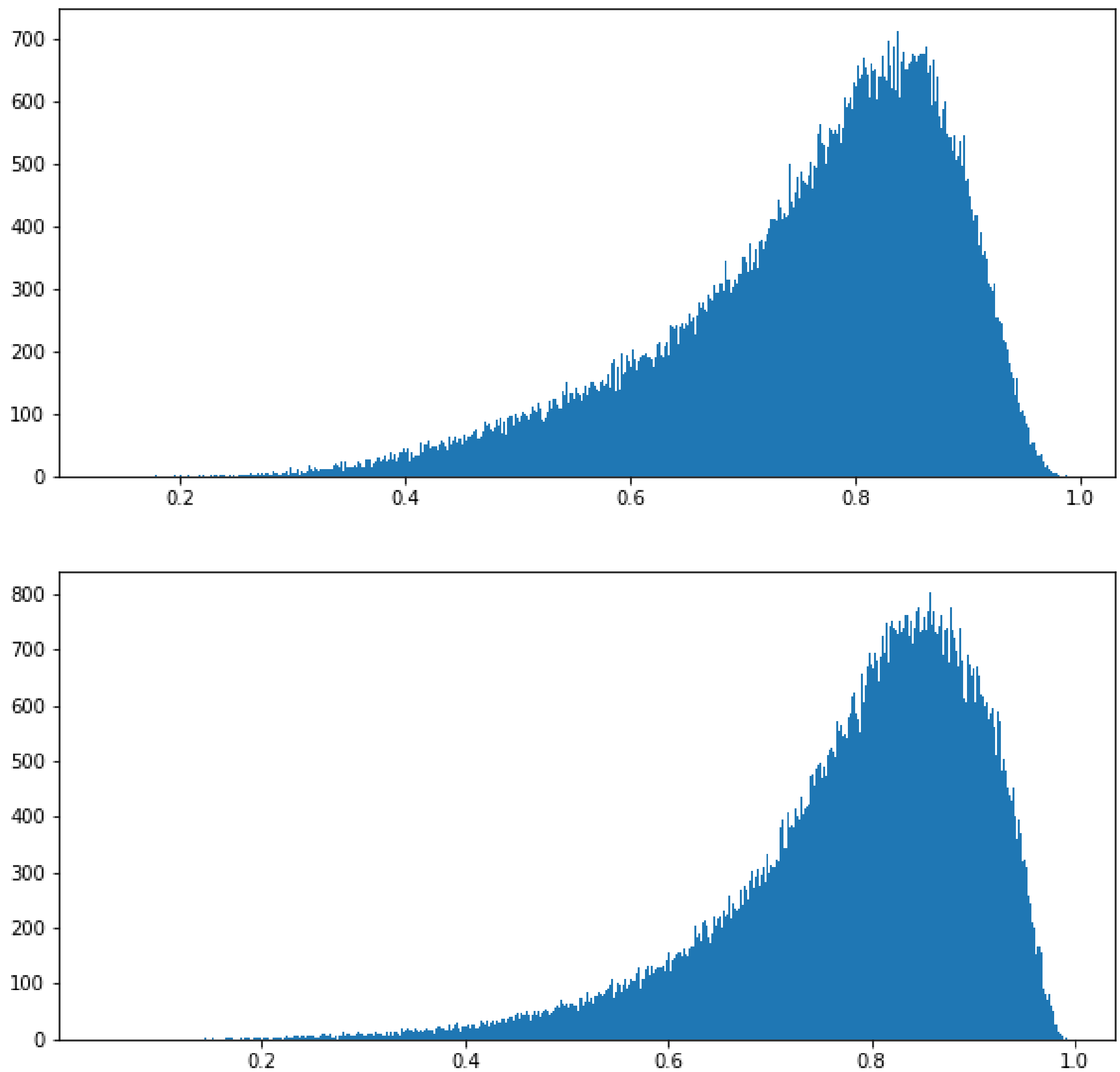
In [95]:

```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsT21,500)
ax[1].hist(qcdT21,500)
plt.show()
```



In [96]:

```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsT32,500)
ax[1].hist(qcdT32,500)
plt.show()
```



In [97]:
```
fig, ax = plt.subplots(2, 1, figsize=(10,10))
ax[0].hist(higgsKtD,500)
ax[1].hist(qcdKtD,500)
plt.show()
```