# Contents



# 1 Introduction

- An interesting masters thesis on tau reconstruction using ATLAS detector, with a listing of some interesting variables can be found in [ATLASThesis, Chapter-5].
- The main `GitHub` link for this work is:

"`https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER`".

- The latest version of this document can always be found at:

"`https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER/blob/master/HERWIG_PART/ReadME.pdf`".

- The sources for this document (including the figures in case you want to use them anywhere) can be found at:

"`https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER/tree/master/HERWIG_PART/Documentation`".

## 1.1 Installing Herwig-7

To install Herwig, please make sure you have a **proper** root installation (and source "`thisroot.sh`" if it is installed in non-standard location) as Herwig uses `libpyroot`. Download and install `Herwig` by running the script `https://herwig.hepforge.org/herwig-bootstrap`:

```
wget -c 'https://herwig.hepforge.org/herwig-bootstrap'
chmod +x './herwig-bootstrap'
'./herwig-bootstrap' './HerwigInstall'
```

This will install `Herwig` to the location '`./HerwigInstall`' along with all of it's dependencies (`boost`, `fastjet`, `HepMC`, etc). Full instructions for using this script is found in:
"`https://herwig.hepforge.org/tutorials/installation/bootstrap.html`".

# 2 Generating events:

## 2.1 The Partonic Level Events:

The quickest way I could find to generate events in `Herwig` was by generating parton level events in `MadGraph` and shower using `Herwig` (I also got suggestions to adopt similar method for `Pythia` as this nicely isolates matrix element generation from showering and our main aim is the study effect of different showering and hadronization techniques on our jet substructure algorithms).

```
wget -c 'https://launchpad.net/mg5amcnlo/2.0/2.6.x/+download/MG5_aMC_v2.6.1.tar.gz';
tar -xf "MG5_aMC_v2.6.1.tar.gz";
cd "MG5_aMC_v2_6_1/";
./bin/mg5_aMC
```

This will start madgraph, now you can generate LHE files:

```
generate p p > z j
output zj
exit
```

Once you are done with above steps, `MadGraph` exits, now you will need to edit some configuration files:

```
cd zj/Cards/
<editor> 'run_card.dat'
```

Where, `<editor>` stands for any text editor. You will need to change the following in the file:

```
0.0 = ptheavy !  minimum pt for at least one heavy final state
```

To the value desired, we will pick this to be 200 GeV.

```
200.0 = ptheavy !  minimum pt for at least one heavy final state
```

Next edit `madspin_card_default.dat` and change the line:

```
decay z > all all
```

to:

```
decay z > ta- ta+
```

now madgraph is set up and can be run, in the shell:

```
cd ../;
./bin/generate_events
```

Once you get the `MadGraph` prompt:

```
4
0
0
```

Now note the "4" is important, you will need to run with `MadSpin` (to force $Z \to \tau\bar{\tau}$ decays) once you are done, you will have the LHE files in:

```
./Events/run_01_decayed_1/unweighted_events.lhe.gz
```

you can extract this:

```
gzip -d "./Events/run_01_decayed_1/unweighted_events.lhe.gz"
```

The complete list of LHE files generated using the above methods can be downloaded from:

"https://drive.google.com/file/d/1sVQSYUDPqSB0vgh84Y8II0ucBSMMr9rL/view?usp=sharing"

## 2.2 Showering:

Move the LHE file to another directory where you want to do the showering:

```
mkdir ~/shower;
cp "./Events/run_01_decayed_1/unweighted_events.lhe" ~/shower/1.lhe
```

now you will need to activate `Herwig` (note, `<HerwigInstall>` needs to be replaced by the correct directory):

```
source <HerwigInstall>/bin/activate
```

Once this is done, download the file

"https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER/blob/master/HERWIG_PART/LHEWithISR.in"

to the current directory "~/shower". In LHE.in, edit the line:

```
set LesHouchesReader:FileName unweighted_events.lhe
```

and change "`unweighted_events.lhe`" to the LHE file you want to shower. You can also edit the PDF choices if you want (note that you may need to download the appropriate pdf fits manually using `lhapdf` installed in the `<HerwigInstall>` directory).

note that the lines

```
read snippets/HepMC.in
set /Herwig/Analysis/HepMC:PrintEvent 100
```

is responsible for producing the `HepMC` file, you can then use `Delphes` on these files. We are done. Now run `Herwig`:

```
Herwig read LHE.in
Herwig run LHE.in
```

You can change underlying event, tunes, etc in the LHE.in file, explore

"https://herwig.hepforge.org/tutorials/faq/shower.html"

for details.

By default, `Herwig` does not force $\tau$ to decay hadronically. This can be forced, check the link:

"https://herwig.hepforge.org/tutorials/faq/decay.html"

to know how this can be done. Basically you would need:

```
set /Herwig/Particles/tau+/tau+->nu_taubar,nu_e,e+;:OnOff Off
set /Herwig/Particles/tau+/tau+->nu_taubar,nu_mu,mu+;:OnOff Off
set /Herwig/Particles/tau-/tau-->nu_tau,nu_ebar,e-;:OnOff Off
set /Herwig/Particles/tau-/tau-->nu_tau,nu_mubar,mu-;:OnOff Off
```

A sample run card:

- With MPI:

"https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER/blob/master/HERWIG_PART/LHEWithISR.in"

- With out MPI:

"https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER/blob/master/HERWIG_PART/LHENoISRMPI.in"

is available in the `GitHub` page.

# 3 Reading the root files:

Example for an extremely simple reader is available in:

"https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER/tree/master/COMMON/DelphesReader".

# 4 Results:

## 4.1 Results using BDRS + Filtering.

We use the following color convention for graphs through out the document:

$$pp \to jZ, (Z \to \tau\bar{\tau}),\, p_T^Z \geq 200 \text{ GeV}$$
$$pp \to jZ, (Z \to \nu_\tau\bar{\nu}_\tau),\, p_T^Z \geq 200 \text{ GeV}$$
$$pp \to jZ, (Z \to b\bar{b}),\, p_T^Z \geq 200 \text{ GeV}$$
$$pp \to jZ, (Z \to \tau\bar{\tau}),\, p_T^Z \geq 0 \text{ GeV}$$

We present some simple results obtained using jet substructure variables on jets tagged using BDRS+Filtering methods (Note: we use the final 2 step filtered (BDRS[BDRS]+filtering) jet to evaluate variables and all of these results are for events with MPI enabled). Note that planar flow [PlanarFlow] [Figure 5, Figure 6] seem to work extremely well.

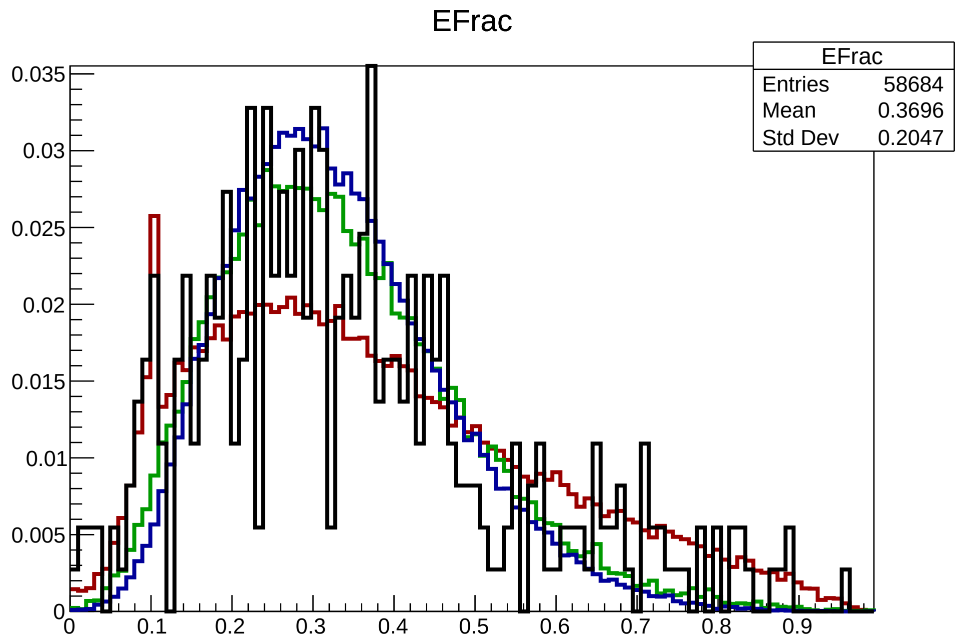


Figure 1: Electromagnetic energy fraction of the jet, normalized to unit area under the curve.

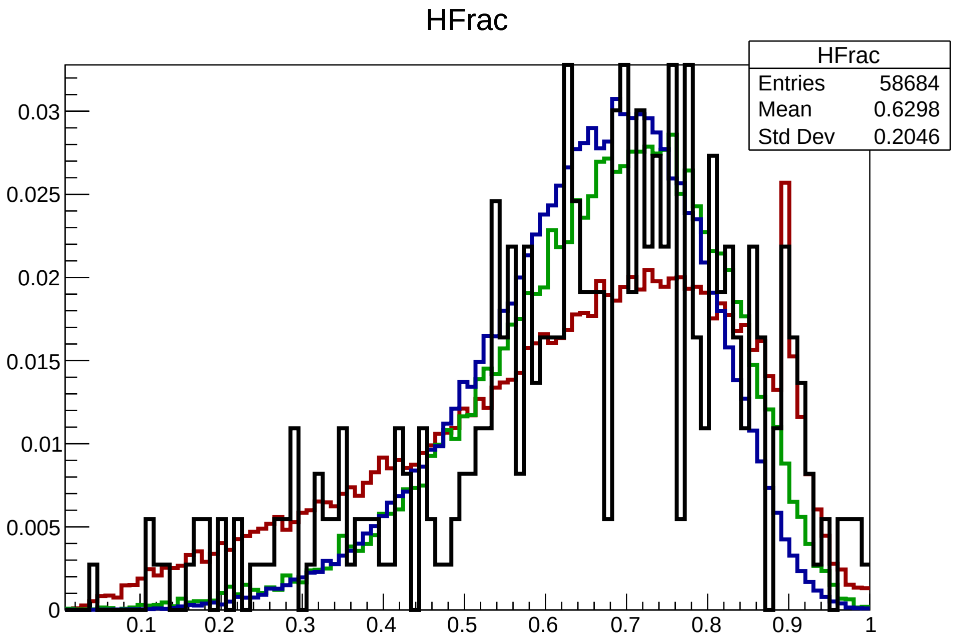


Figure 2: Hadronic energy fraction of the jet, normalized to unit area under the curve.

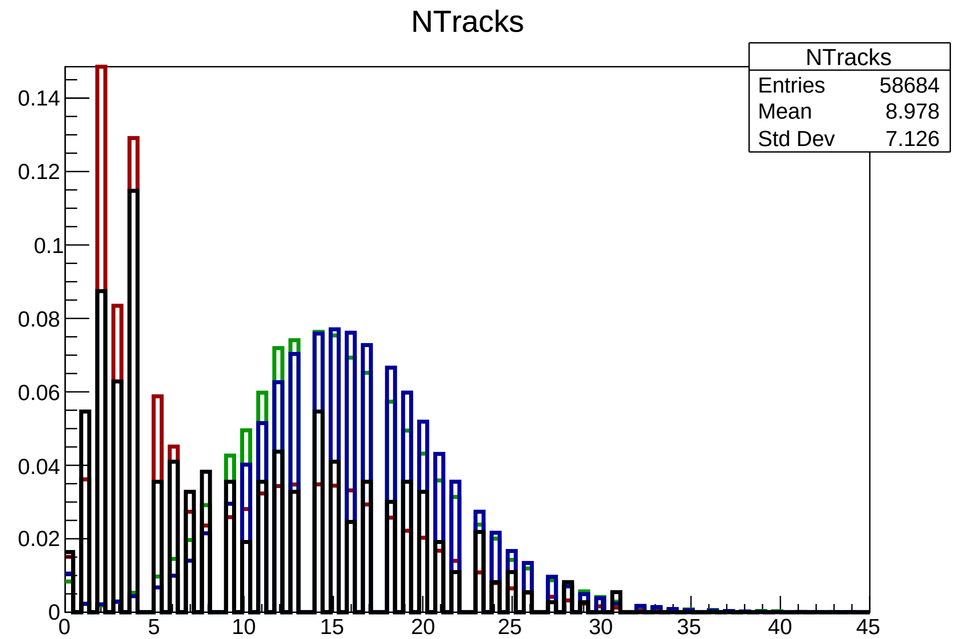


Figure 3: Number of tracks in the jet, normalized to unit area under the curve.

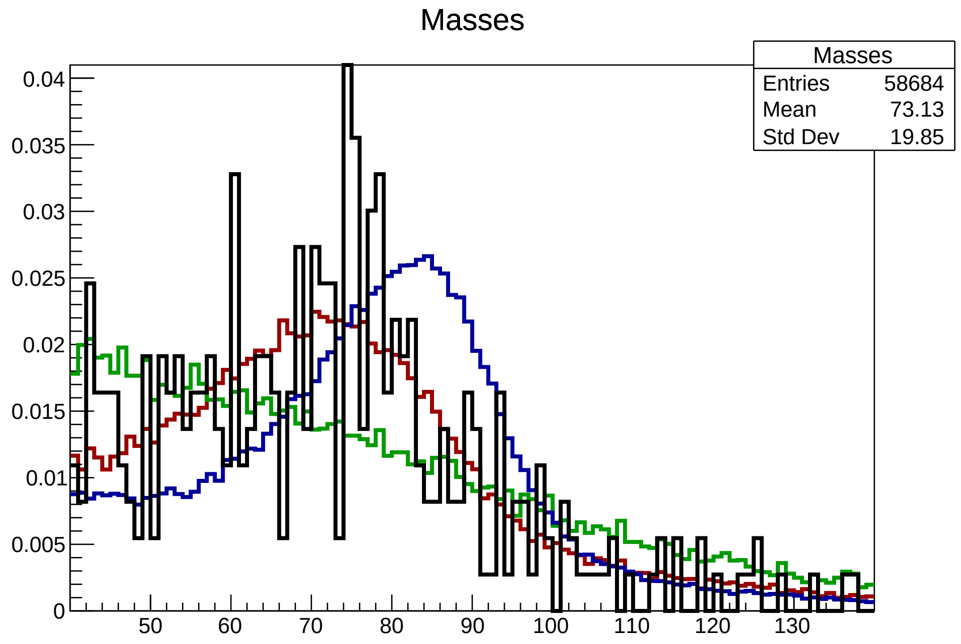


Figure 4: Masses of the jet after BDRS and filtering steps, normalized to unit area under the curve.

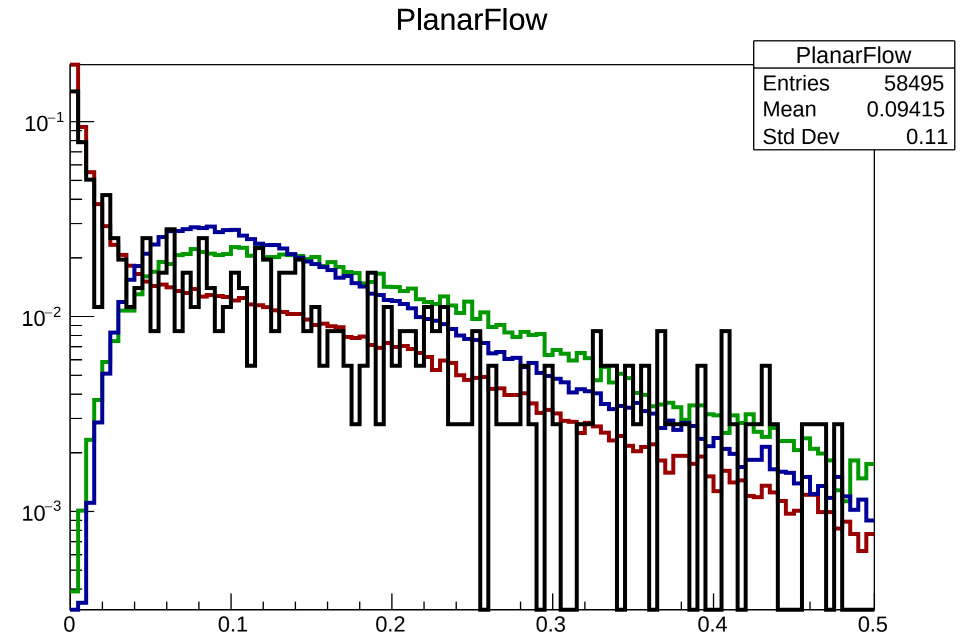


Figure 5: Planar Flow of the jet after BDRS and filtering steps, normalized to unit area under the curve.

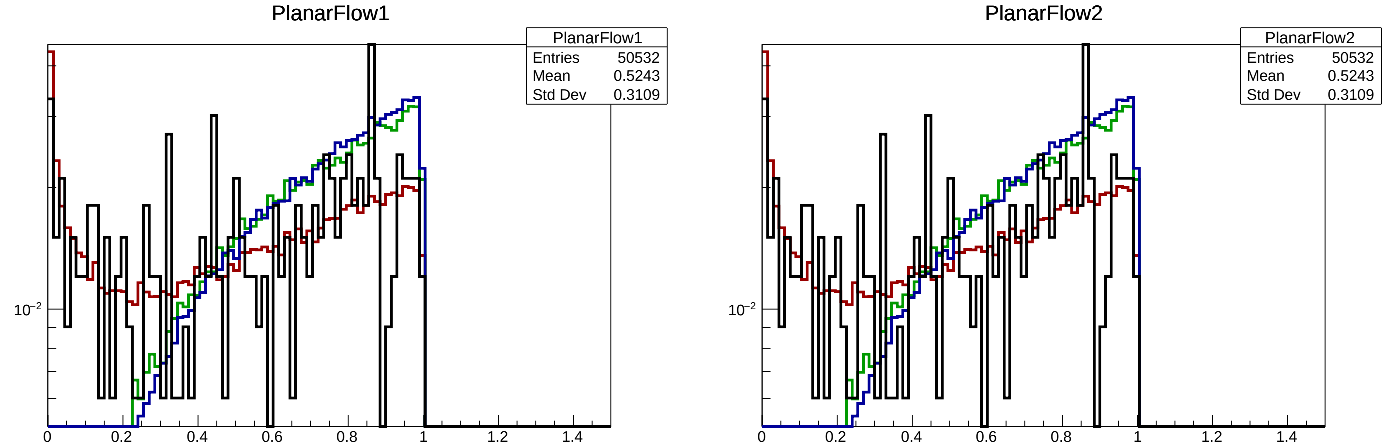


Figure 6: Planar Flow of the two subjets after BDRS and filtering steps, normalized to unit area under the curve.

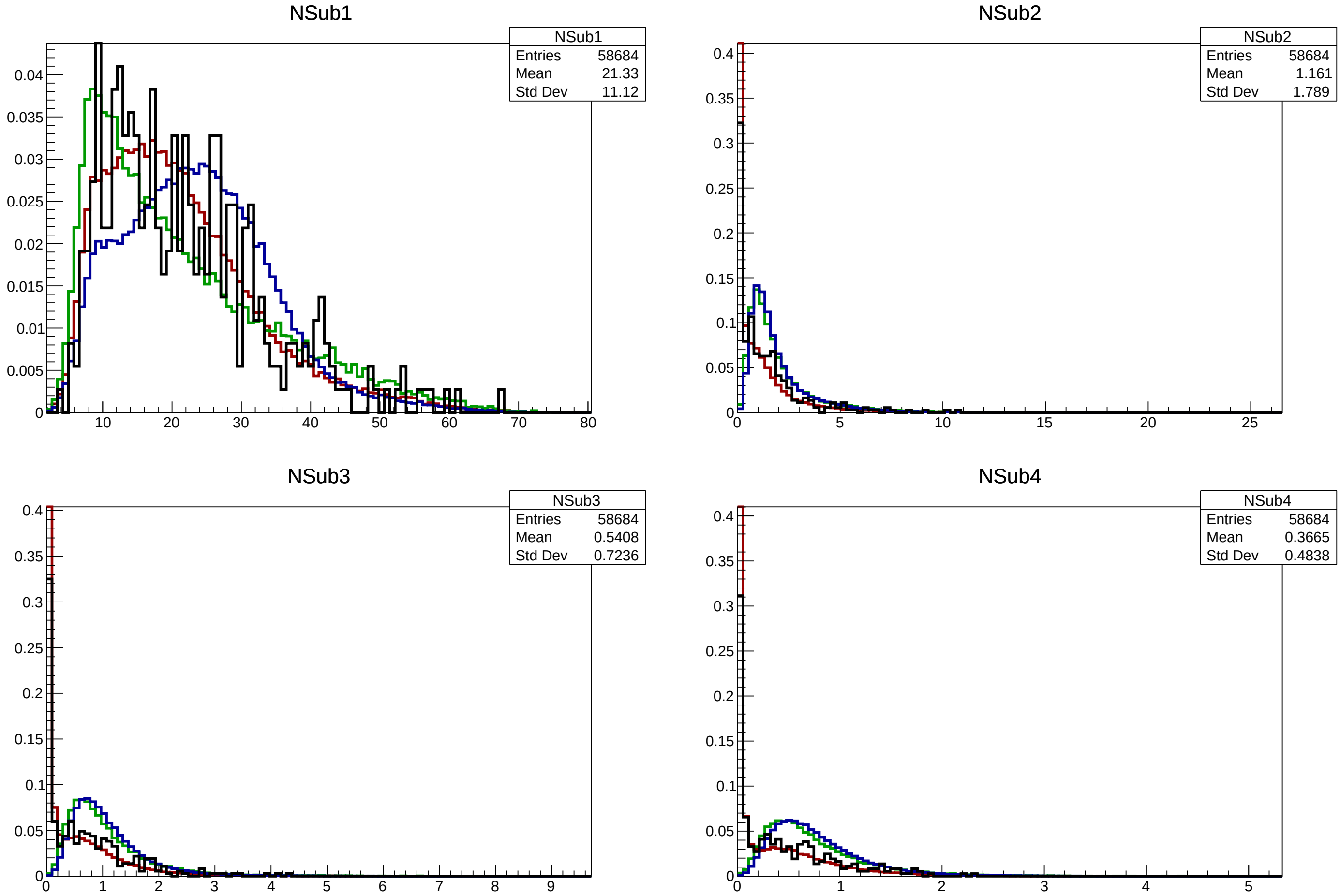


Figure 7: `NSubJettiness` observable, normalized to unit area under the curve.

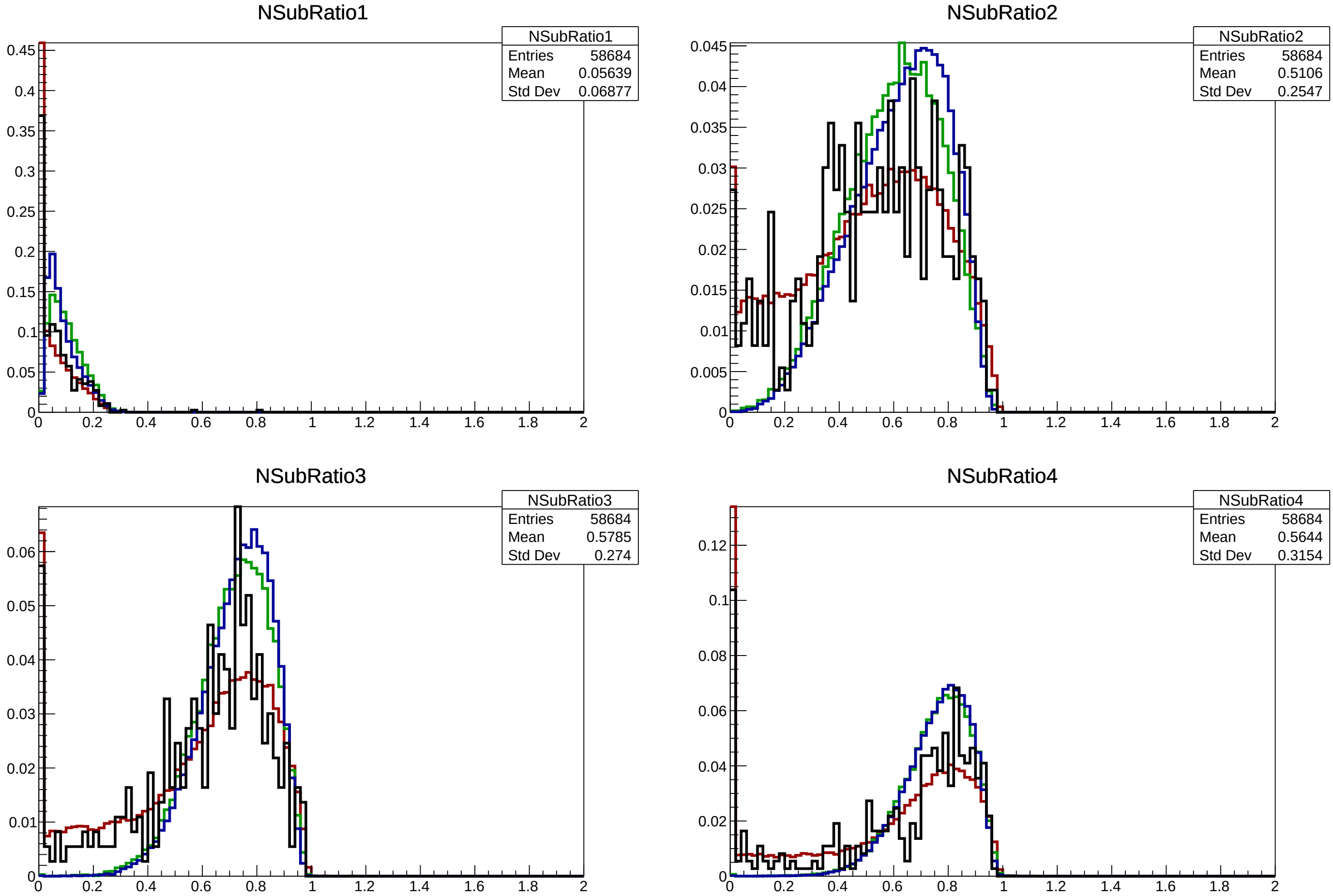


Figure 8: Ratio of `NSubJettiness` observable, normalized to unit area under the curve.

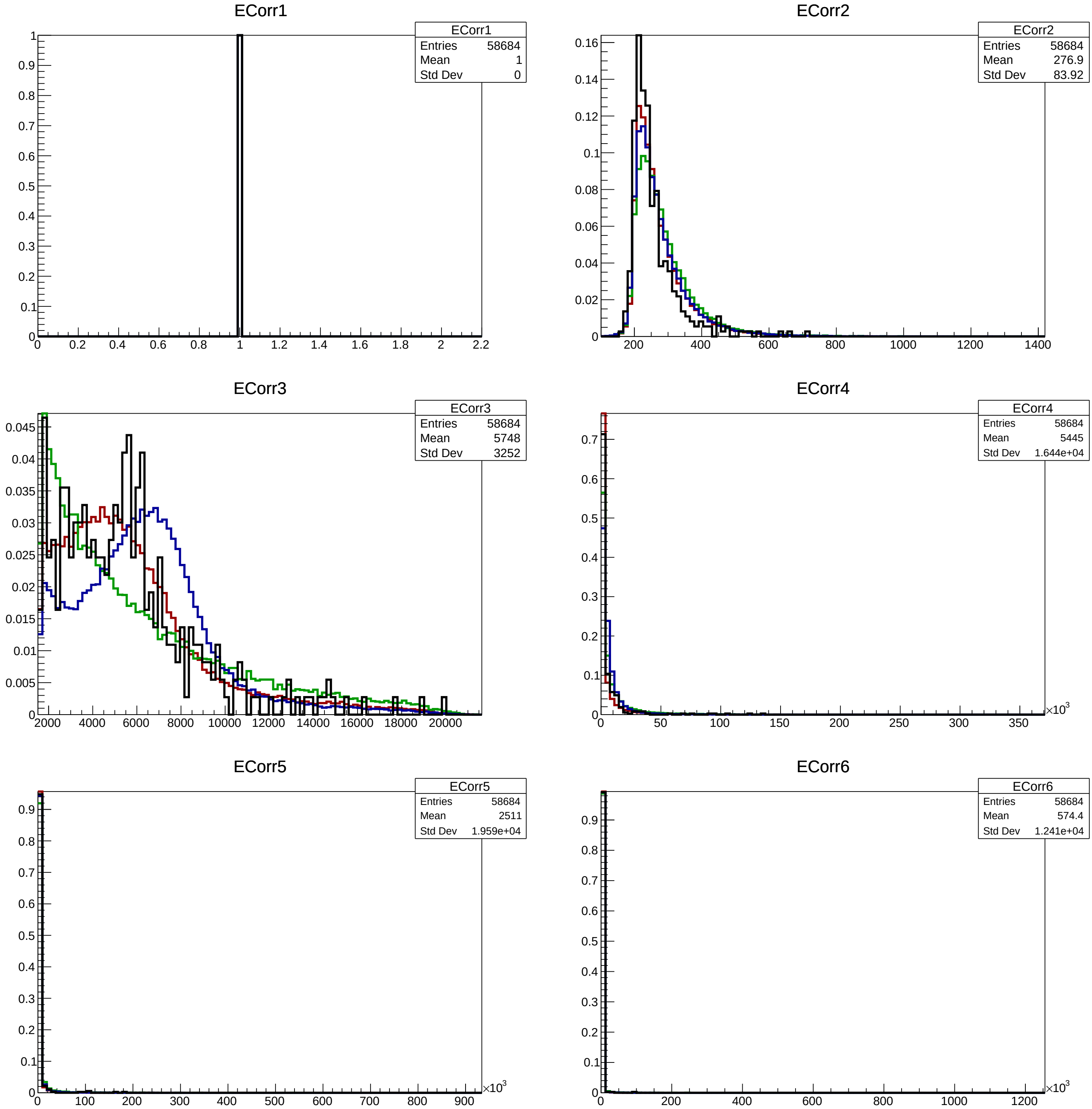


Figure 9: Energy Correlation observable, normalized to unit area under the curve.

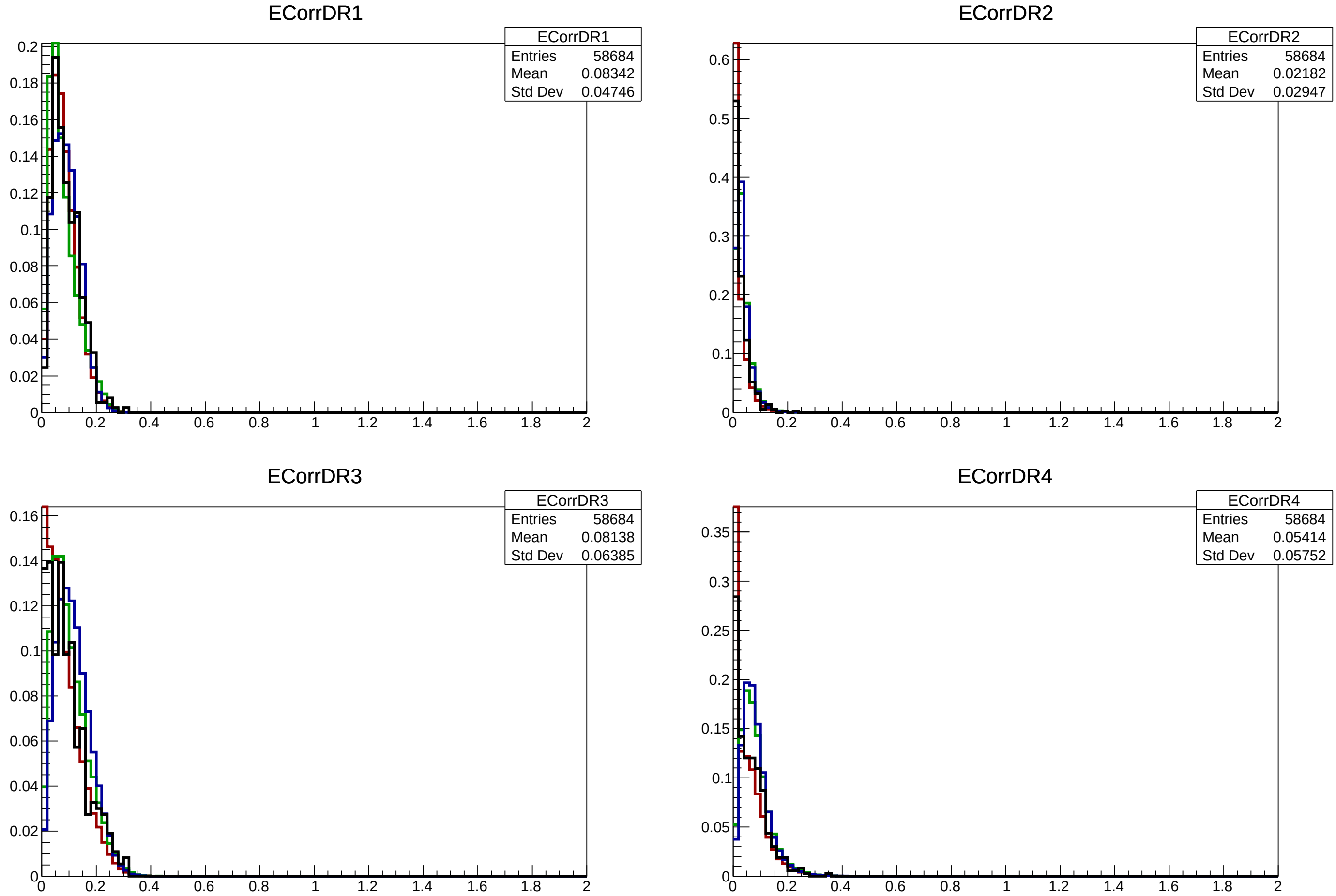


Figure 10: Energy Correlation double ratio observable, normalized to unit area under the curve.

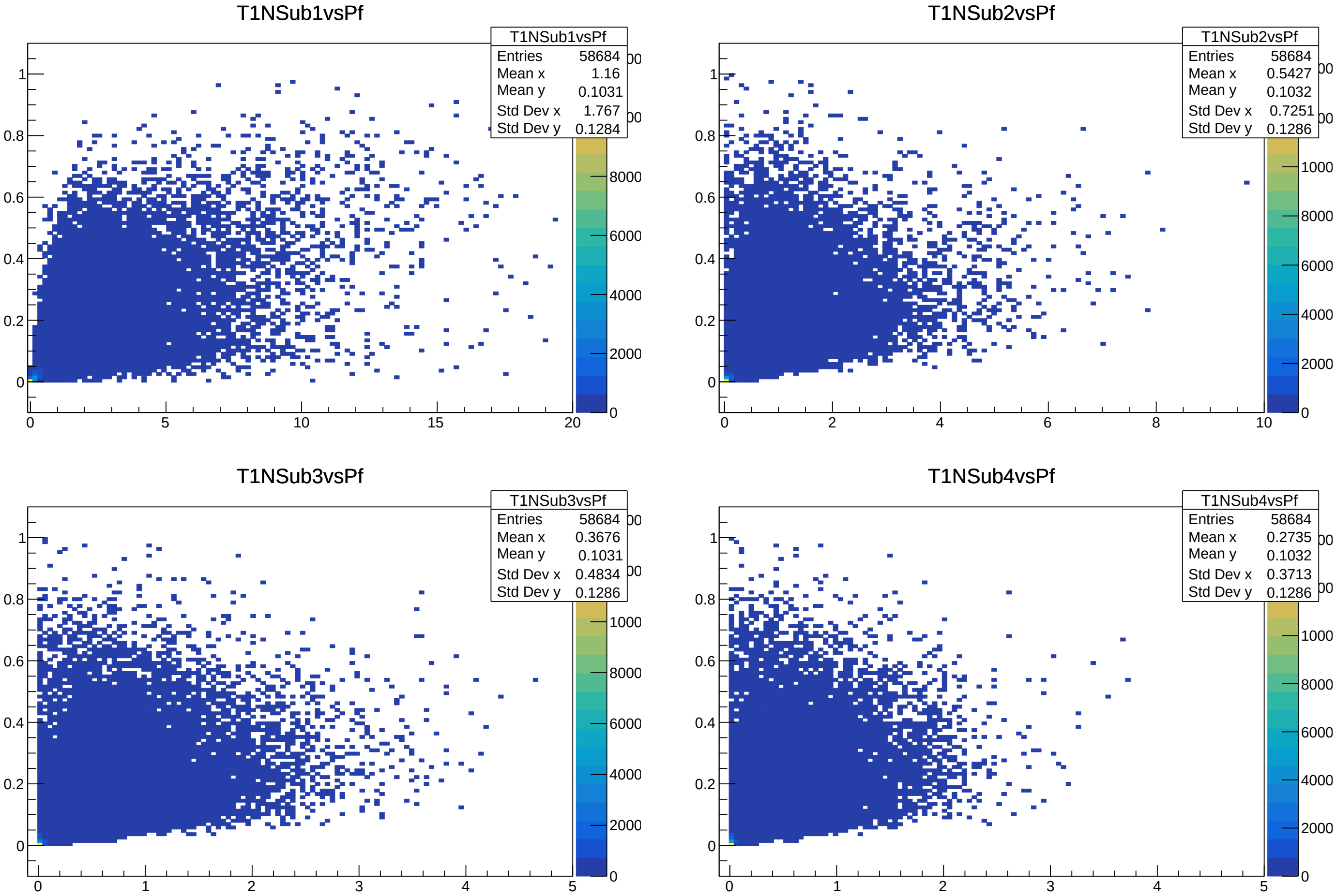


Figure 11: `NSubjettiness` (x-axis) vs planar flow (y-axis) for boosted $jZ \to \tau\bar{\tau}$

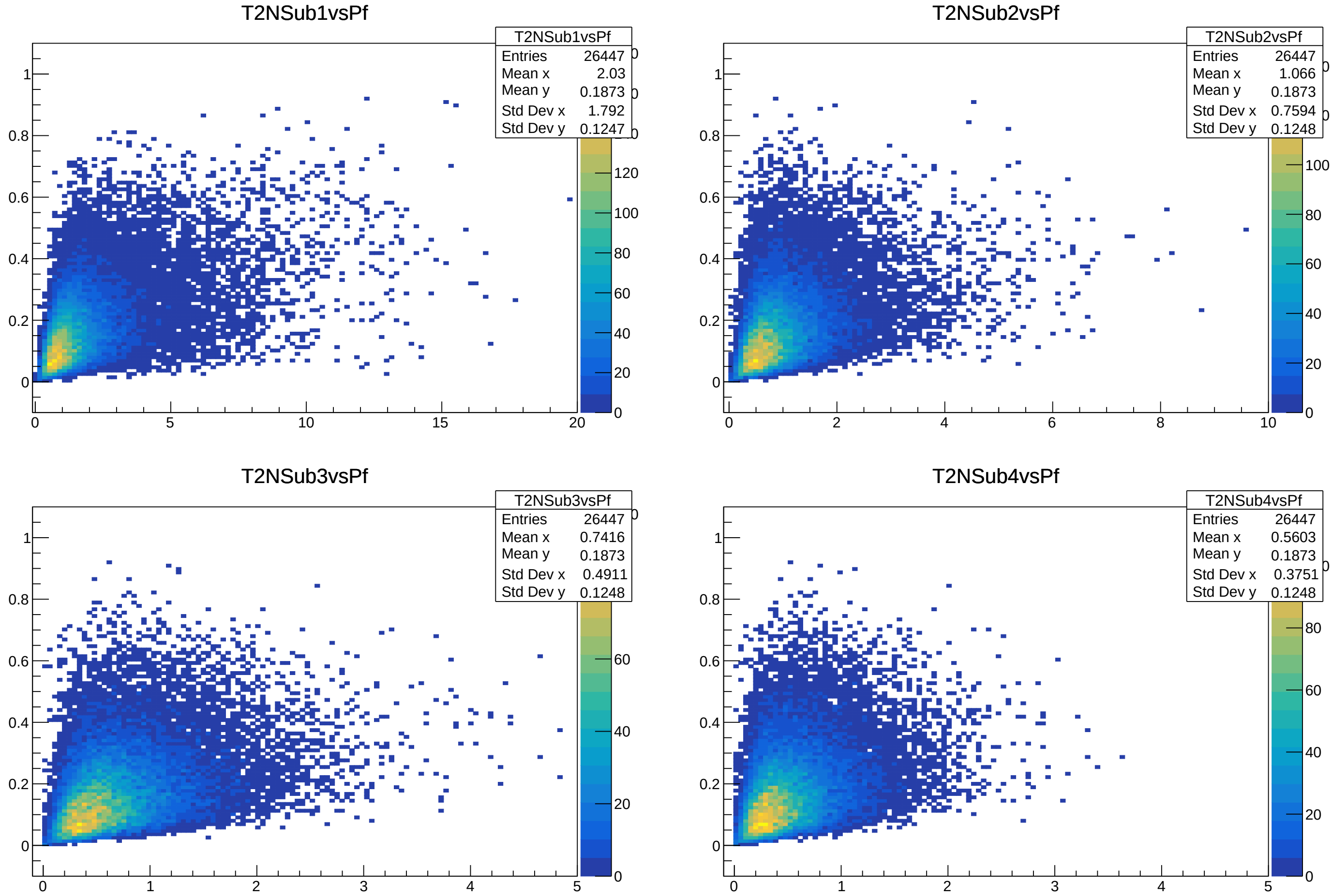


Figure 12: `NSubjettiness` (x-axis) vs planar flow (y-axis) for boosted $jZ \to \nu\bar{\nu}$

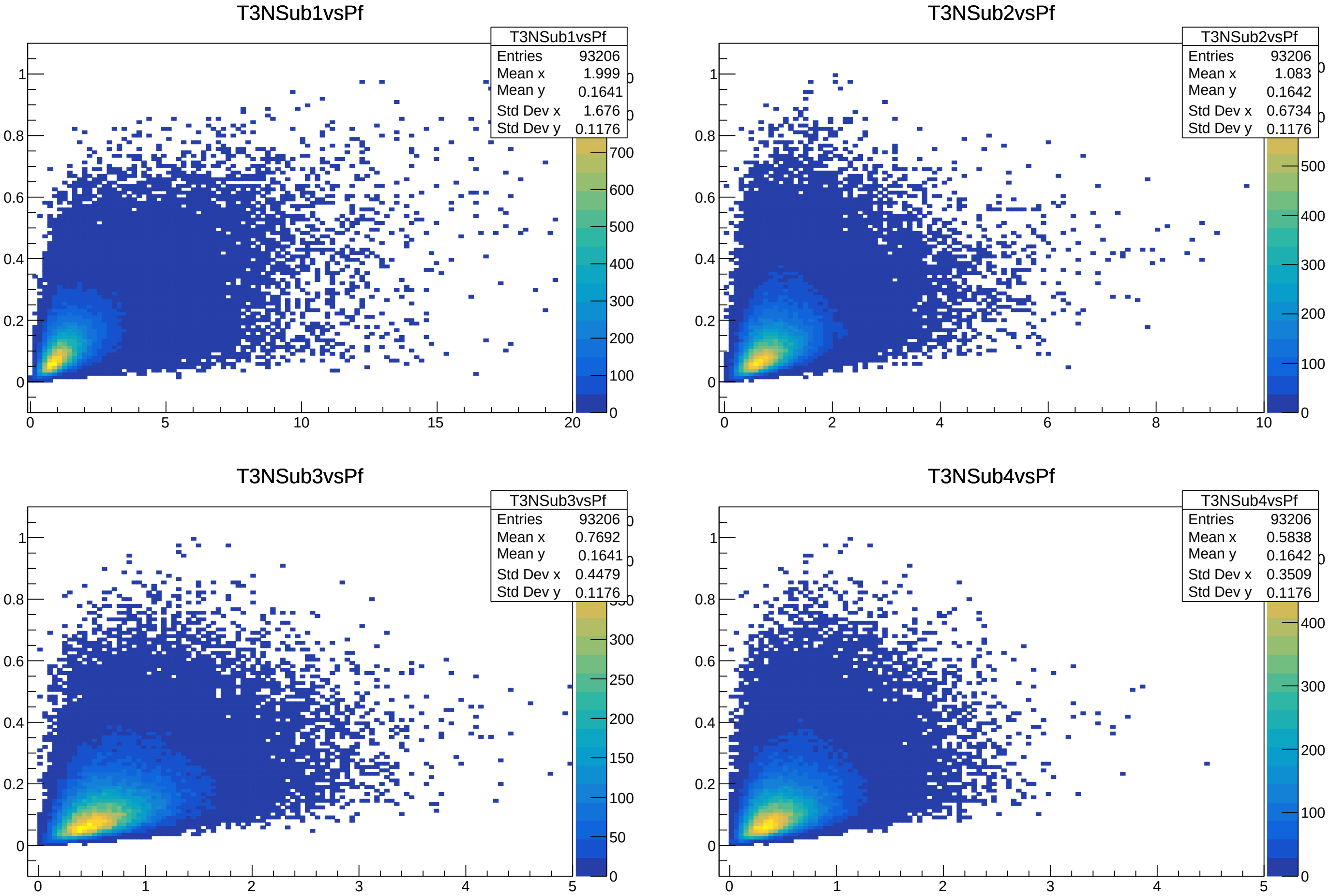


Figure 13: `NSubjettiness` (x-axis) vs planar flow (y-axis) for boosted $jZ \to b\bar{b}$

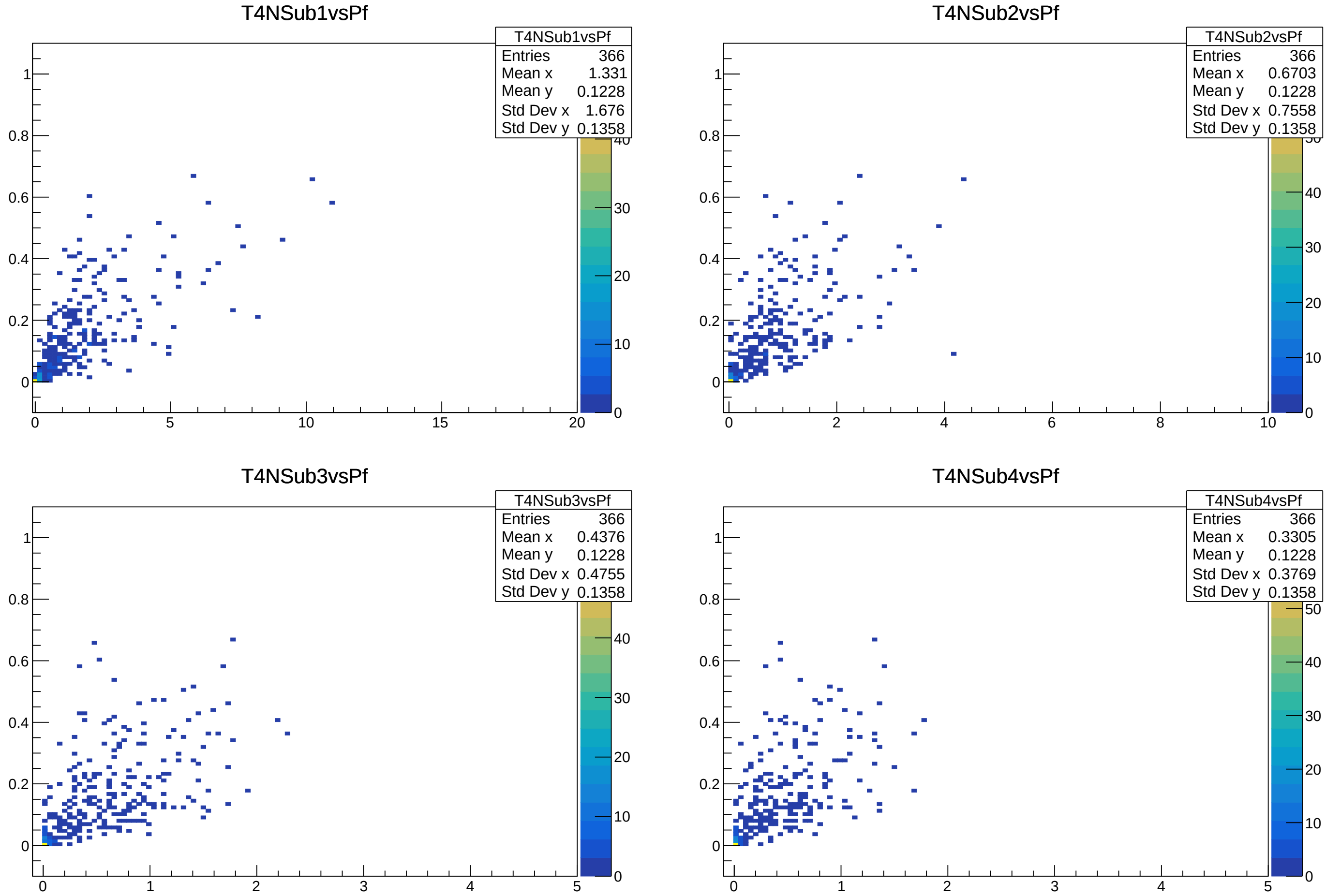


Figure 14: `NSubjettiness` (x-axis) vs planar flow (y-axis) for unboosted $jZ \to \tau\bar{\tau}$

### 4.1.1 Analyzing planar flow:

We suspect Planar Flow might be correlated with `NSubjettiness`, to verify these, we check the following graphs [Figure 11, Figure 12, Figure 13, Figure 14], as can be seen there seems to be some correlation, we quantify this:

$$\begin{aligned}
J &\equiv \text{The } Z-\text{tagged jet obtained after BDRS + Filtering.}\\
J_1 &\equiv \text{The highest } p_T \text{ subjet of } J.\\
J_2 &\equiv \text{The other subjet of } J.\\
P_f &\equiv \text{Planar Flow.}\\
\tau_N &\equiv n^{th}\text{ NSubjettiness.}\\
S(J) &\equiv \sum_{i\in J} p_{T_i}\Delta R(i,J)
\end{aligned}$$

$$\begin{aligned}
\langle P_f(J), \tau_2(J)\rangle &= 3.70\times 10^{-2}\\
\langle P_f(J), \tau_3(J)\rangle &= 4.26\times 10^{-2}\\
\langle P_f(J), \tau_4(J)\rangle &= 4.32\times 10^{-2}\\
\langle P_f(J), \tau_5(J)\rangle &= 4.20\times 10^{-2}\\
\langle P_f(J), S(J)\rangle &= 9.73\times 10^{-3}
\end{aligned}$$

$$\begin{aligned}
\langle P_f(J_1), \tau_2(J_1)\rangle &= 2.37\times 10^{-1}\\
\langle P_f(J_1), \tau_3(J_1)\rangle &= 2.37\times 10^{-1}\\
\langle P_f(J_1), \tau_4(J_1)\rangle &= 2.26\times 10^{-1}\\
\langle P_f(J_1), \tau_5(J_1)\rangle &= 2.15\times 10^{-1}\\
\langle P_f(J_1), S(J_1)\rangle &= 2.88\times 10^{-1}
\end{aligned}$$

$$\begin{aligned}
\langle P_f(J_2), \tau_2(J_2)\rangle &= 2.32\times 10^{-1}\\
\langle P_f(J_2), \tau_3(J_2)\rangle &= 2.19\times 10^{-1}\\
\langle P_f(J_2), \tau_4(J_2)\rangle &= 2.00\times 10^{-1}\\
\langle P_f(J_2), \tau_5(J_2)\rangle &= 1.83\times 10^{-1}\\
\langle P_f(J_2), S(J_2)\rangle &= 2.72\times 10^{-1}
\end{aligned}$$

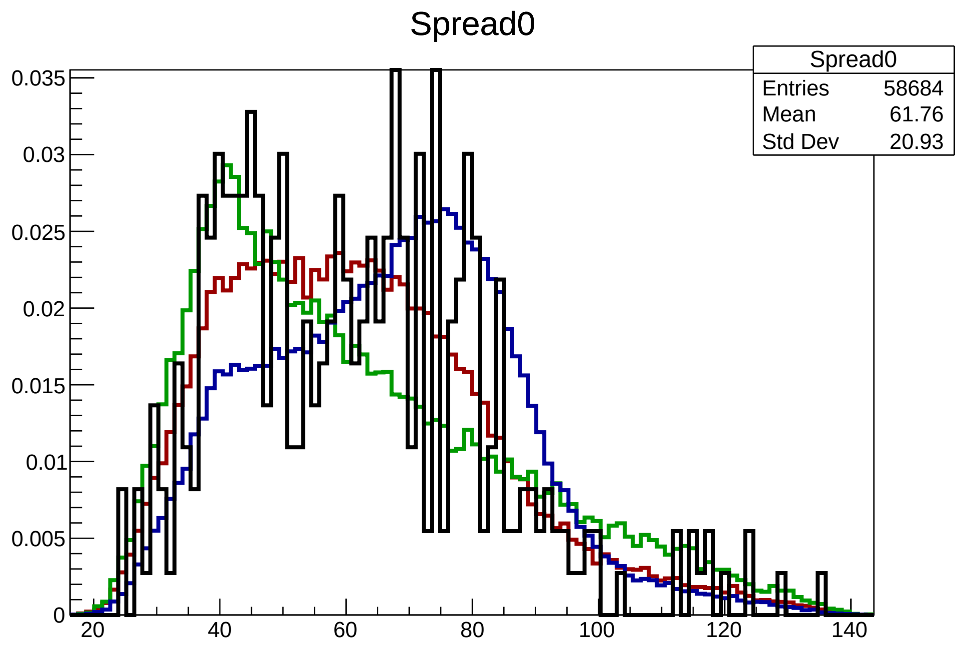


Figure 15: The variable $S(J)$

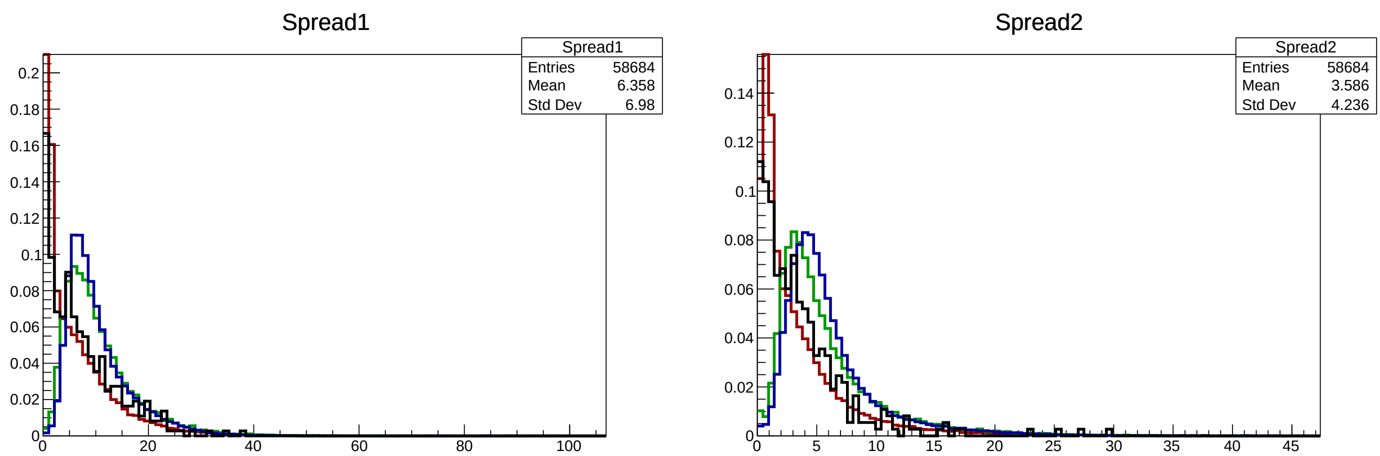


Figure 16: The variable $S(J_1)$ and $S(J_2)$

The definition of planar flow (from [PlanarFlow]) is:

$$
\begin{aligned}
I_w^{kl} &\equiv \frac{1}{m_J}\sum_i w_i \frac{p_{ik}}{w_i}\frac{p_{il}}{w_i} \\
P_f &= \frac{4\det\left(I_w\right)}{\mathrm{tr}\left(I_w\right)^2}
\end{aligned}
$$

we can recast this in the following form:

$$
\begin{aligned}
\vec{A} &\equiv \begin{pmatrix} p_{1,1}/\sqrt{w_1} \\ p_{2,1}/\sqrt{w_2} \\ \vdots \\ p_{N,1}/\sqrt{w_N} \end{pmatrix} \\
\vec{B} &\equiv \begin{pmatrix} p_{1,2}/\sqrt{w_1} \\ p_{2,2}/\sqrt{w_2} \\ \vdots \\ p_{N,2}/\sqrt{w_N} \end{pmatrix}
\end{aligned}
$$

So:

$$
\begin{aligned}
A_i &= p_{i,1}/\sqrt{w_i} \\
B_i &= p_{i,2}/\sqrt{w_i}
\end{aligned}
$$

Now the matrix $I_w$ becomes:

$$
\begin{aligned}
I_w &= \frac{1}{m_J}\begin{pmatrix} \vec{A}\cdot\vec{A} & \vec{A}\cdot\vec{B} \\ \vec{A}\cdot\vec{B} & \vec{B}\cdot\vec{B} \end{pmatrix} \equiv \begin{pmatrix} \left|\left|\vec{A}\right|\right|^2 & \vec{A}\cdot\vec{B} \\ \vec{A}\cdot\vec{B} & \left|\left|\vec{B}\right|\right|^2 \end{pmatrix} \\
P_f &= \frac{4\left[\left|\left|\vec{A}\right|\right|^2\left|\left|\vec{B}\right|\right|^2 - \left(\vec{A}\cdot\vec{B}\right)^2\right]}{\left(\left|\left|\vec{A}\right|\right|^2 + \left|\left|\vec{B}\right|\right|^2\right)^2}
\end{aligned}
$$

Define:

$$
\cos(\theta) \equiv \frac{\left(\vec{A}\cdot\vec{B}\right)}{\left|\left|\vec{A}\right|\right|\left|\left|\vec{B}\right|\right|}
$$

Then:

$$
\begin{aligned}
P_f &= \frac{4\left[\left|\left|\vec{A}\right|\right|^2\left|\left|\vec{B}\right|\right|^2 - \left(\vec{A}\cdot\vec{B}\right)^2\right]}{\left(\left|\left|\vec{A}\right|\right|^4 + \left|\left|\vec{B}\right|\right|^4 + 2\left|\left|\vec{A}\right|\right|^2\left|\left|\vec{B}\right|\right|^2\right)} \\
&= \frac{\left|\left|\vec{A}\right|\right|^2\left|\left|\vec{B}\right|\right|^2\left[4\left(1-\cos^2(\theta)\right)\right]}{\left|\left|\vec{A}\right|\right|^2\left|\left|\vec{B}\right|\right|^2\left(\frac{||\vec{A}||^2}{||\vec{B}||^2} + \frac{||\vec{B}||^2}{||\vec{A}||^2} + 2\right)} \\
P_f &= \frac{4\left[1-\cos^2(\theta)\right]}{\frac{||\vec{A}||^2}{||\vec{B}||^2} + \frac{||\vec{B}||^2}{||\vec{A}||^2} + 2}
\end{aligned}
$$

In this form, analyzing Planar Flow becomes much easier.

$P_f$ is small when denominator is large [either $\left|\left|\vec{A}\right|\right| \to 0$ or $\left|\left|\vec{B}\right|\right| \to 0$ or both] or when numerator is small [$\cos^2(\theta) \to 1$], we will be more interested in the former case (the later is useful in explaining why QCD has smaller $P_f$ compared to say $t\bar{t}$).

If all the constituent particles (in the jet) from a decay lie along a line (in a plane transverse to the momentum vector of the jet), then we can choose the basis (by Gram Schmidt) such that either $\vec{A} = 0$ or $\vec{B} = 0$ and hence the denominator $\to \infty$.

### 4.1.2 Kinematics of jets from $\tau$ decay:

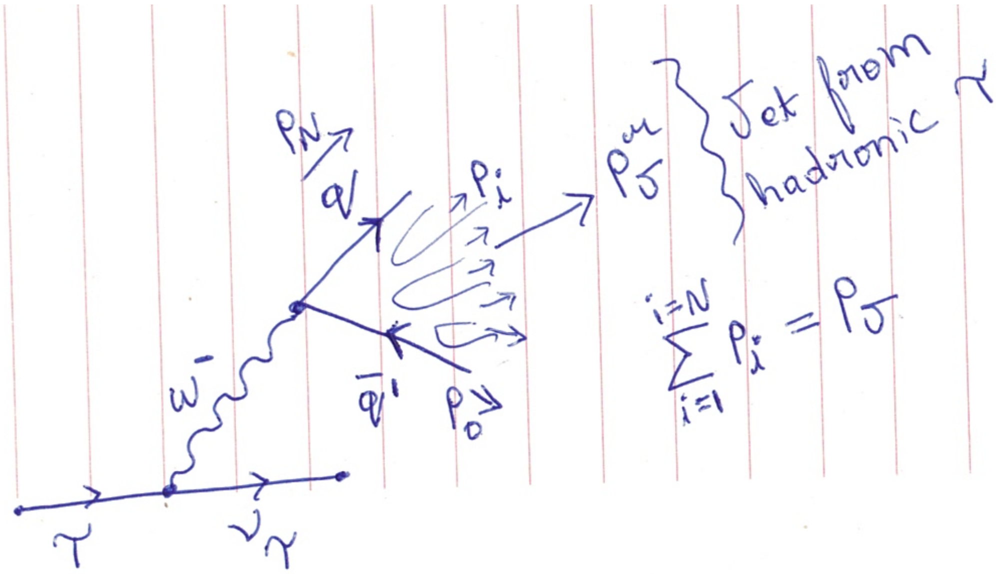


Figure 17: Schematic of a hadronically decaying $\tau$.

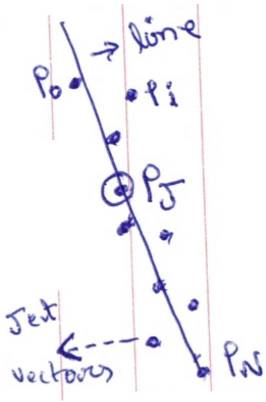


Figure 18: Momentum distribution of the $\tau$ decay products in the transverse (to the jet momentum) plane.

All the (visible) constituents from a (hadronic) $\tau$ decay come from the virtual $W^{\pm}$ and are color connected [Figure 17] $\Rightarrow$ they all lie on a line in the plane transverse to the jet [Figure 18], hence either $\left|\left|\vec{A}\right|\right|$ or $\left|\left|\vec{B}\right|\right| \to 0$ and hence $P_f \to 0$.

### 4.2 Results using Soft Drop (from Suman)

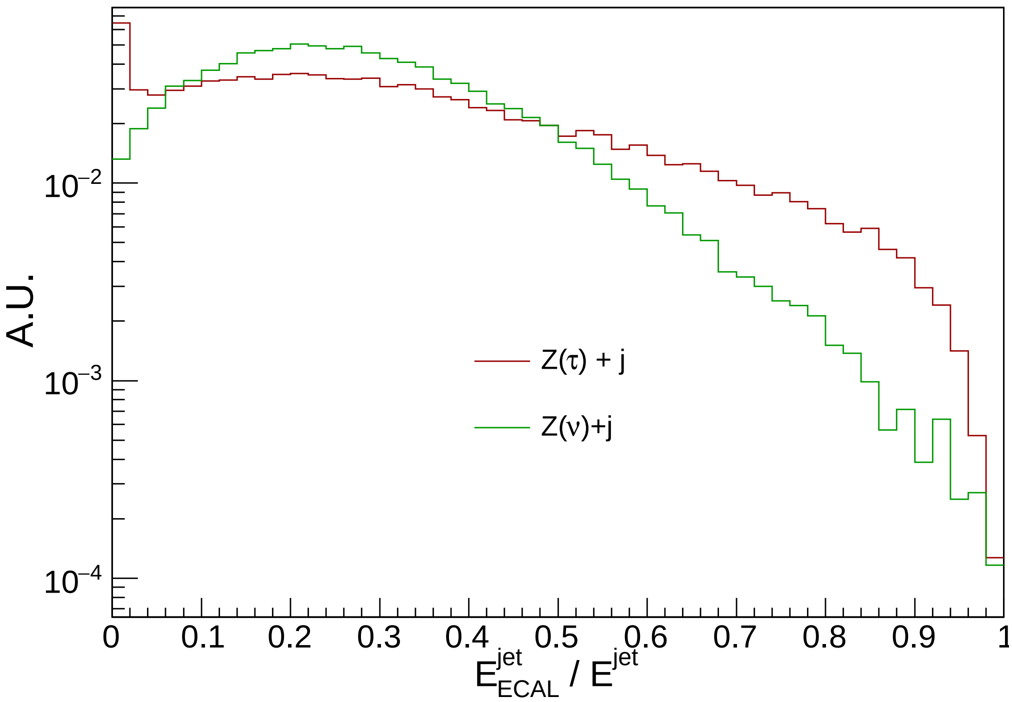


Figure 19: Fraction of jet energy deposited in ECAL (distribution has been normalized to unit area under curve)

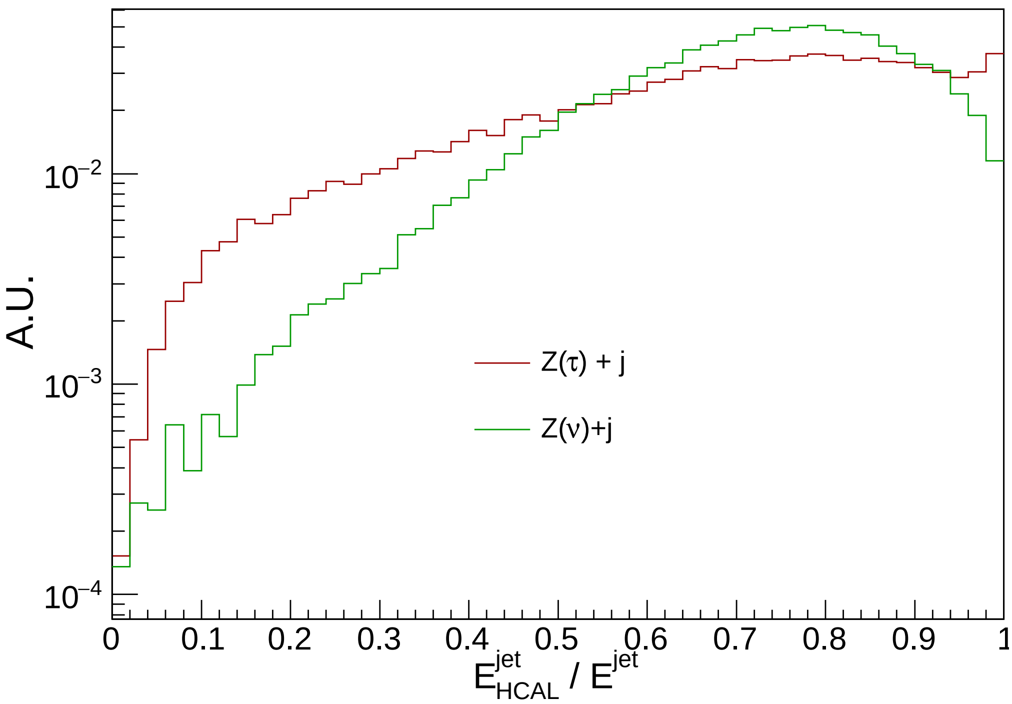


Figure 20: Fraction of jet energy deposited in HCAL (distribution has been normalized to unit area under curve)

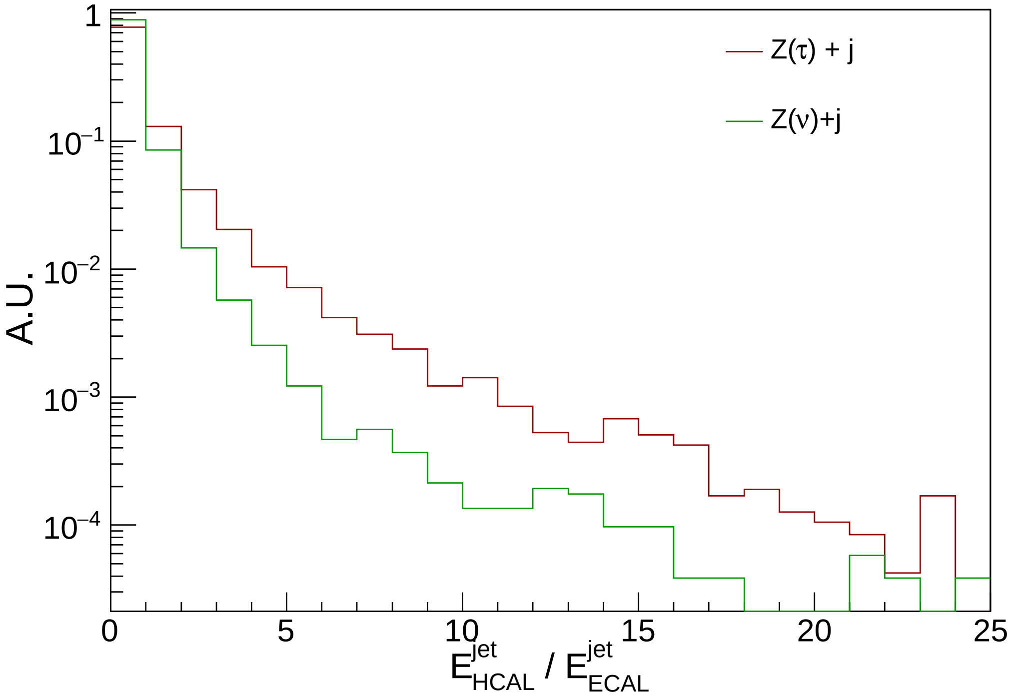


Figure 21: Ratio of jet energy deposited in HCAL with respect to the enrgy deposit in ECAL(distribution has been normalized to unit area under curve)

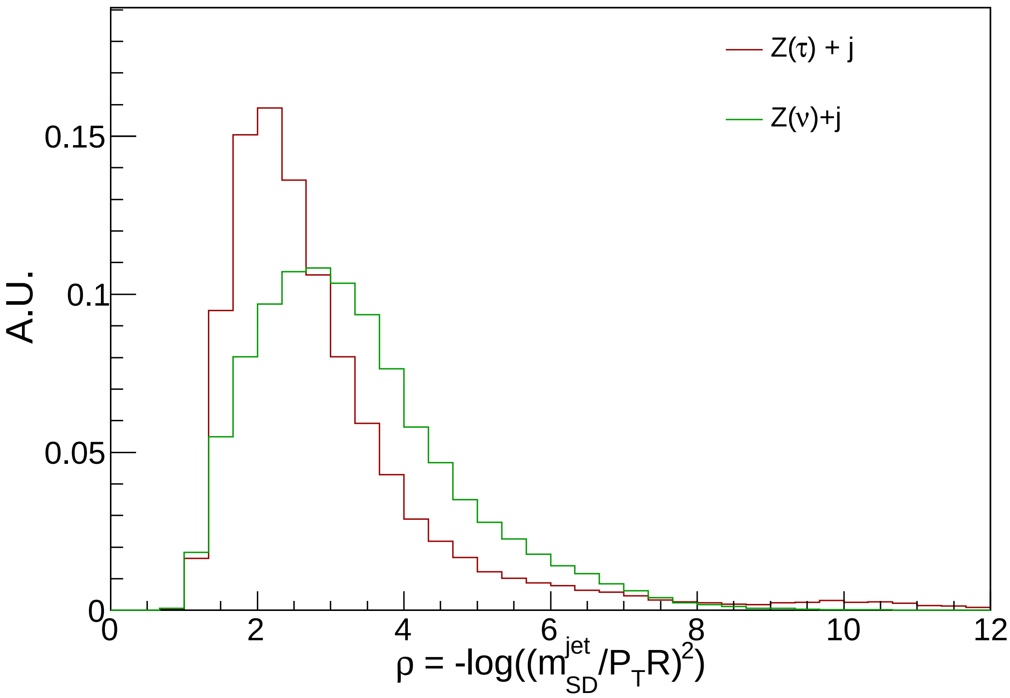


Figure 22: Variable $\rho$, a logarithmic function of soft drop mass and $P_T$ of the jet (distribution has been normalized to unit area under curve)

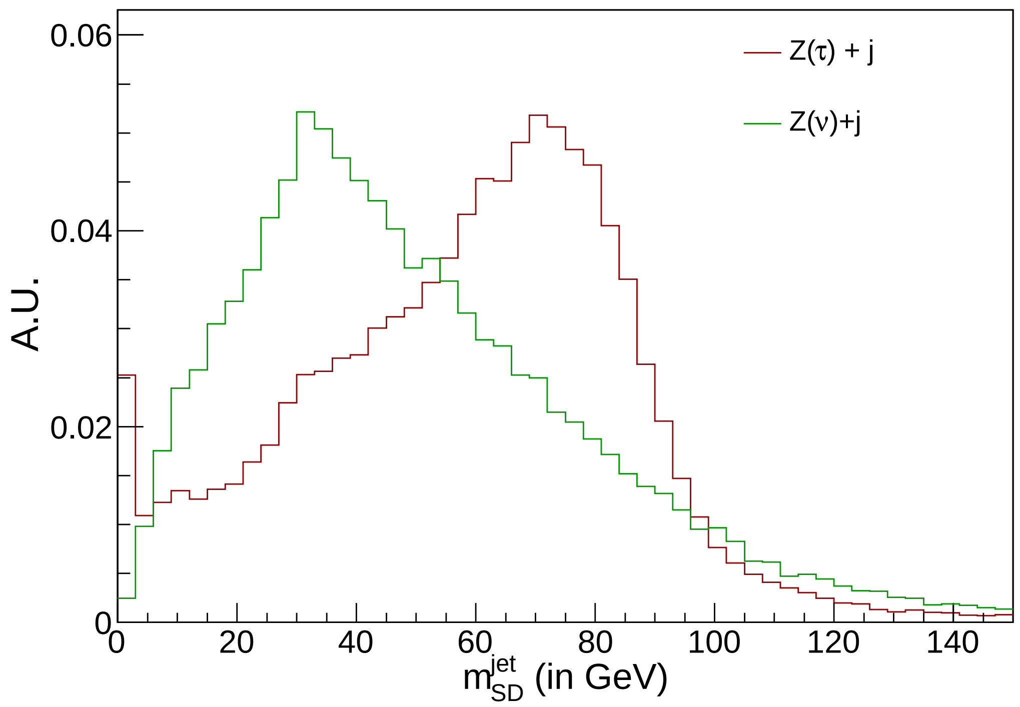


Figure 23: Soft drop mass of jet (in GeV) (distribution has been normalized to unit area under curve)

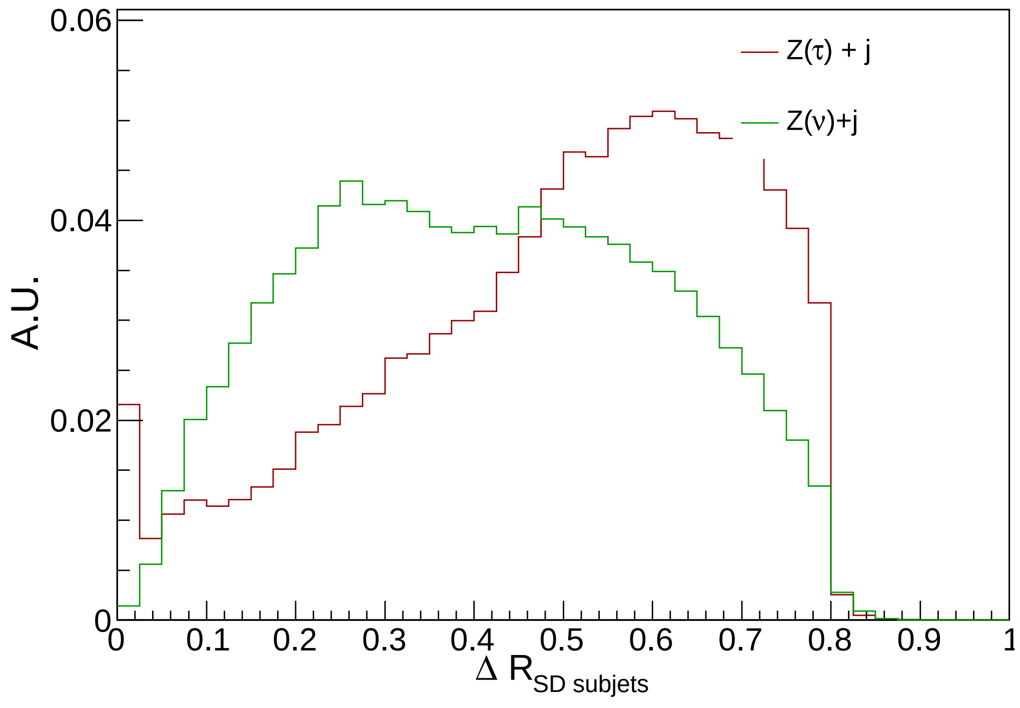


Figure 24: Separation between subjets of the soft dropped jet in rapidity-azimuth plane (distribution has been normalized to unit area under curve)

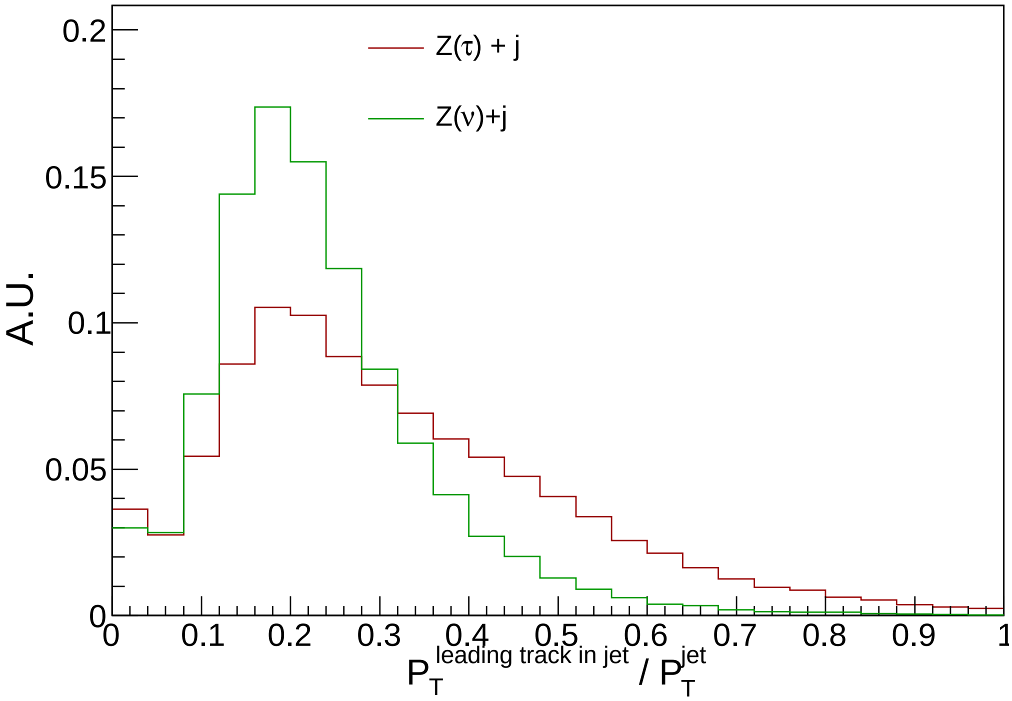


Figure 25: Ratio of $P_T$ of the leading track in the jet with respect to jet $P_T$ (distribution has been normalized to unit area under curve)

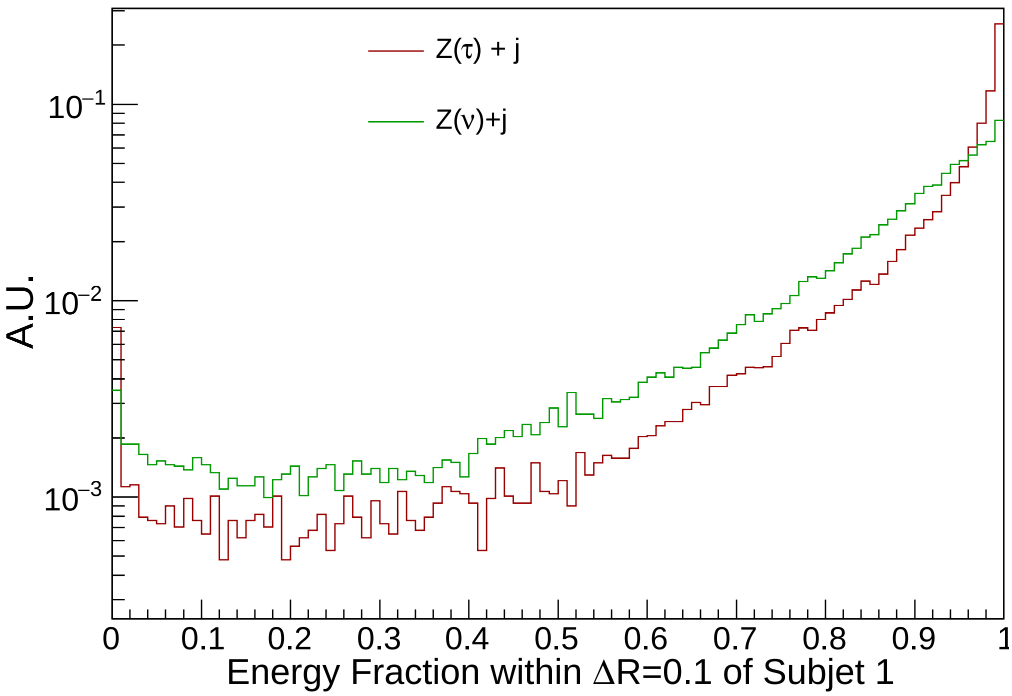


Figure 26: Energy fraction of the leading subjet inside a cone of $\Delta R = 0.1$ around the subjet axis (distribution has been normalized to unit area under curve)

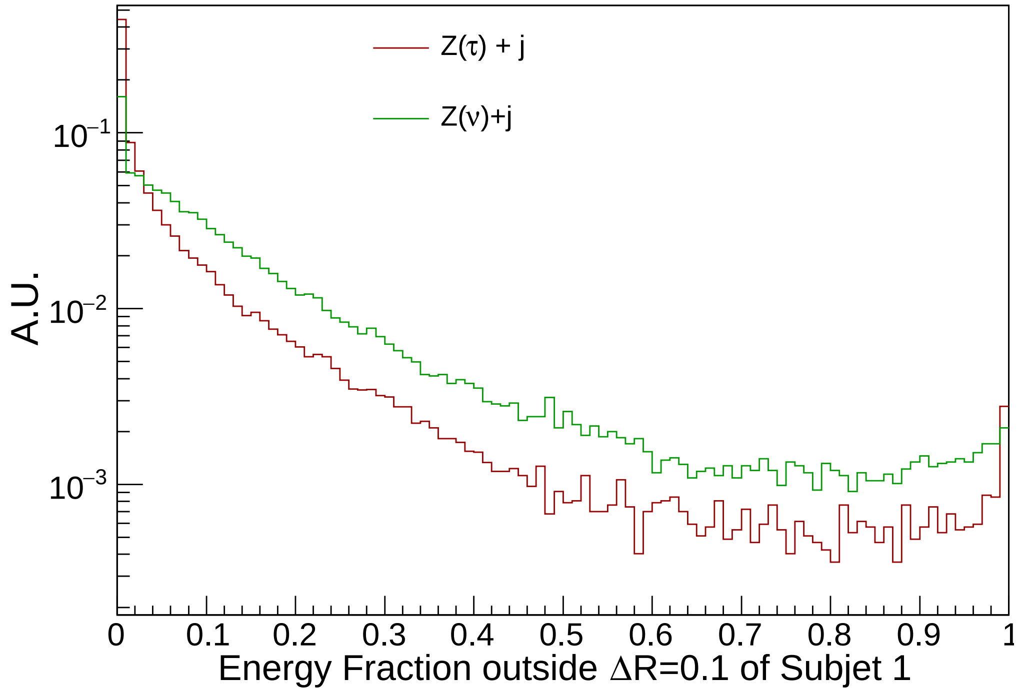


Figure 27: Energy fraction of the leading subjet outside a cone of $\Delta R = 0.1$ around the subjet axis (distribution has been normalized to unit area under curve)

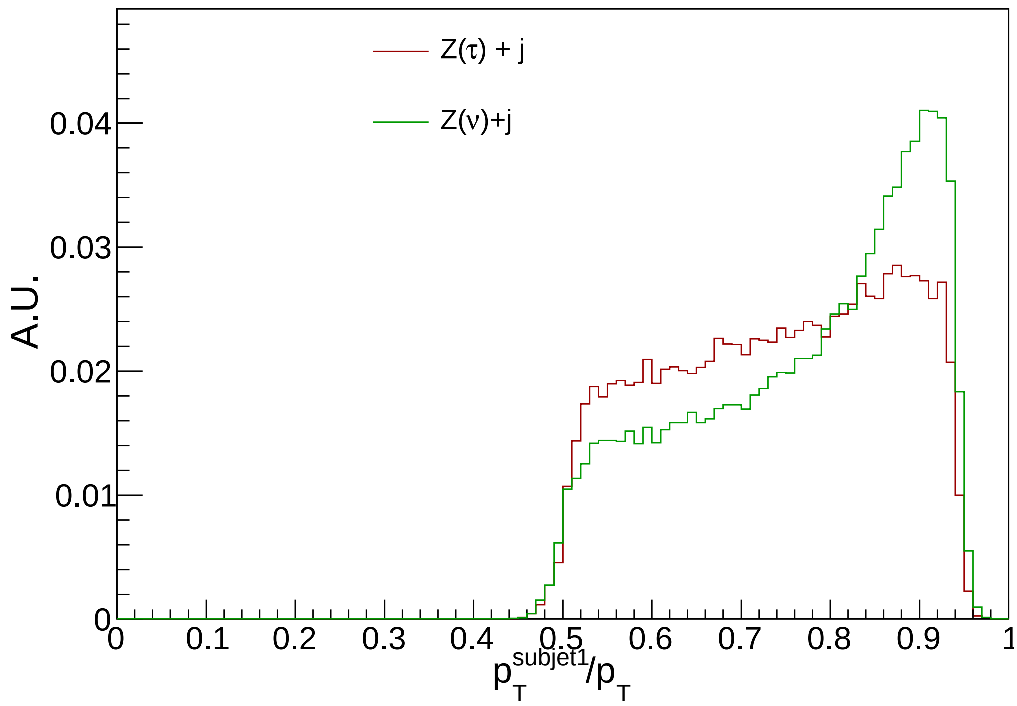


Figure 28: Ratio of leading subjet $P_T$ and jet $P_T$ (distribution has been normalized to unit area under curve)

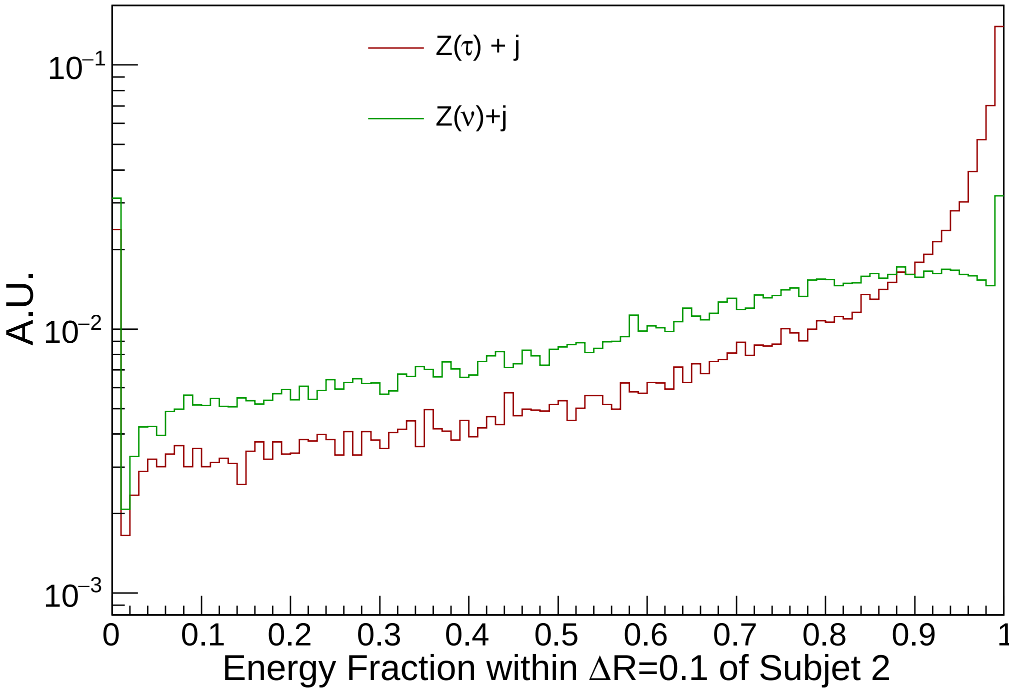


Figure 29: Energy fraction of the subleading subjet inside a cone of $\Delta R = 0.1$ around the subjet axis (distribution has been normalized to unit area under curve)

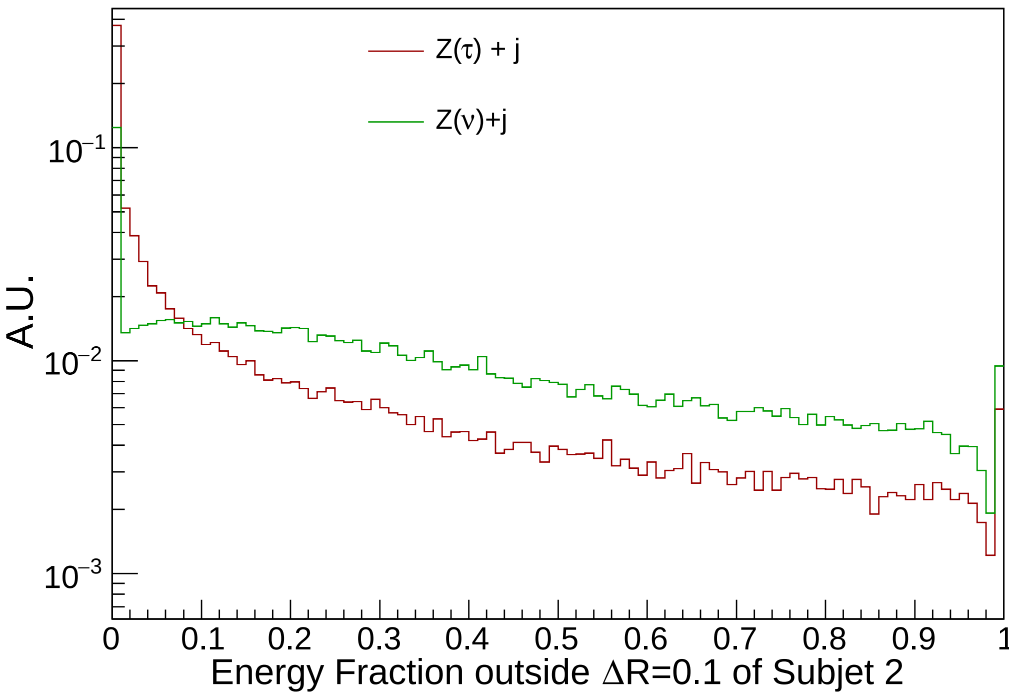


Figure 30: Energy fraction of the subleading subjet outside a cone of $\Delta R = 0.1$ around the subjet axis (distribution has been normalized to unit area under curve)

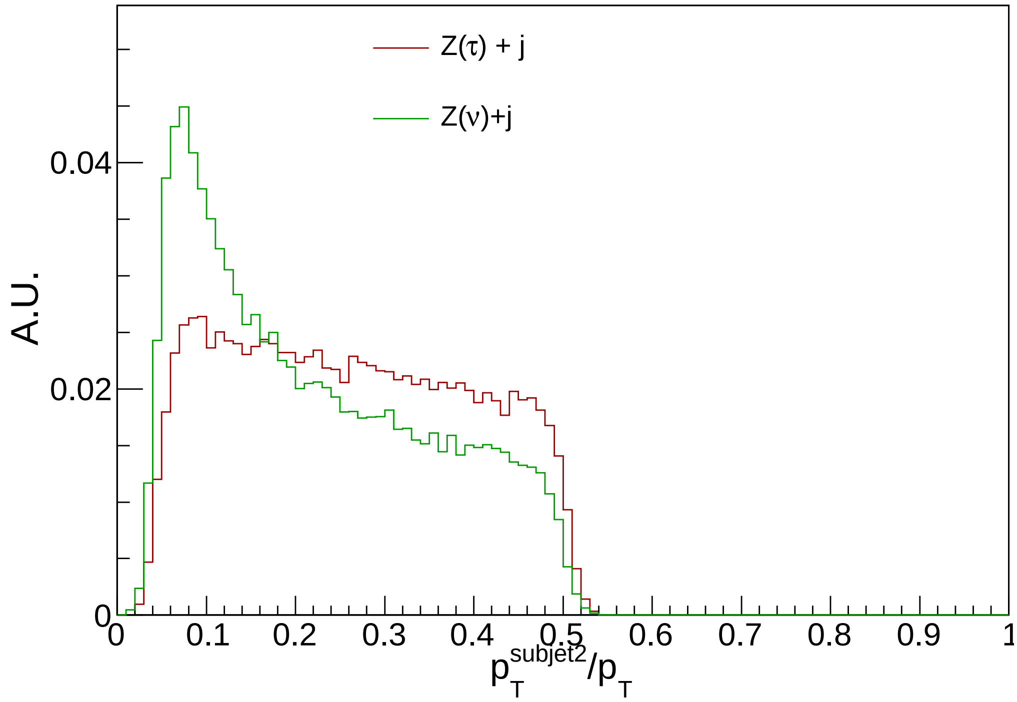


Figure 31: Ratio of subleading subjet $P_T$ and jet $P_T$ (distribution has been normalized to unit area under curve)

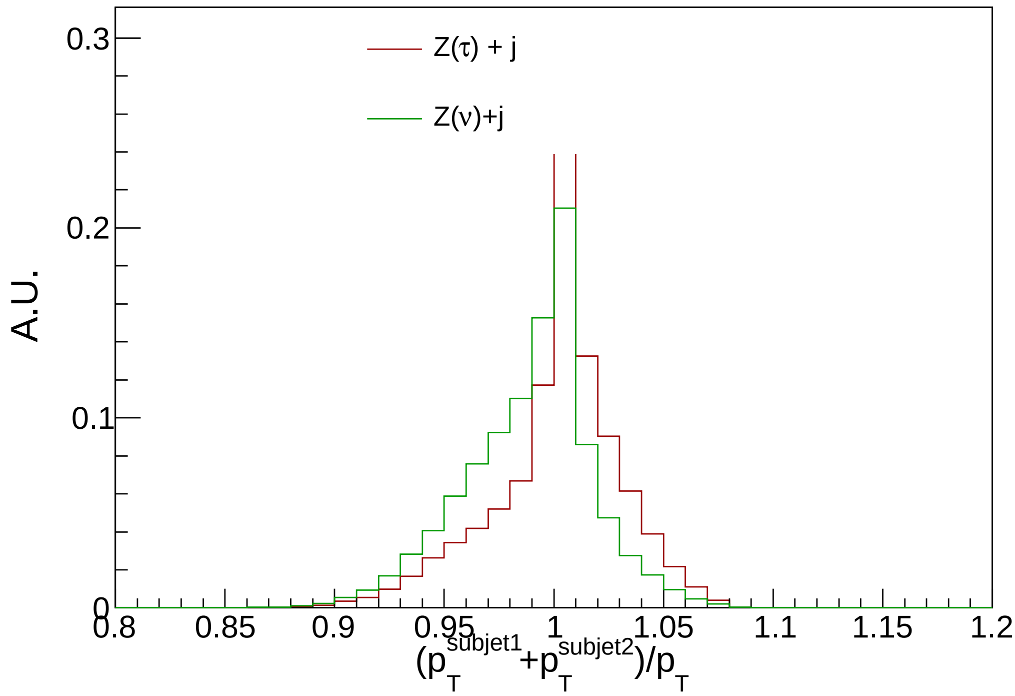


Figure 32: Ratio of sum of $P_T$ of leading and subleading jet with respect to jet $P_T$ (distribution has been normalized to unit area under curve)

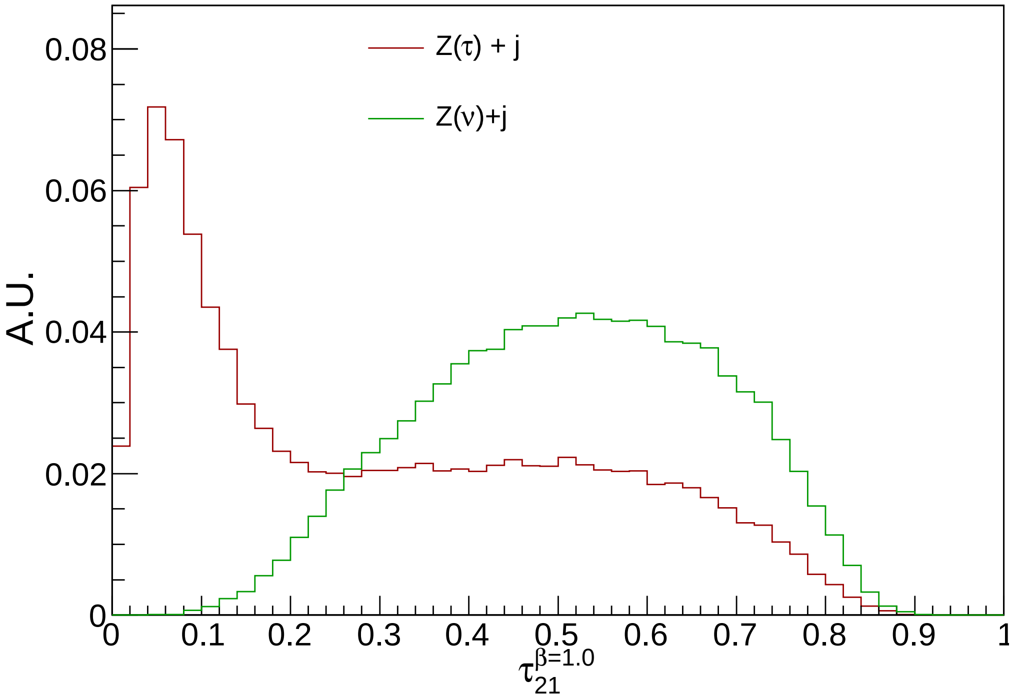


Figure 33: Subjettiness ratio $\tau_{21}$ for angular coefficient $\beta = 1.0$ (distribution has been normalized to unit area under curve)

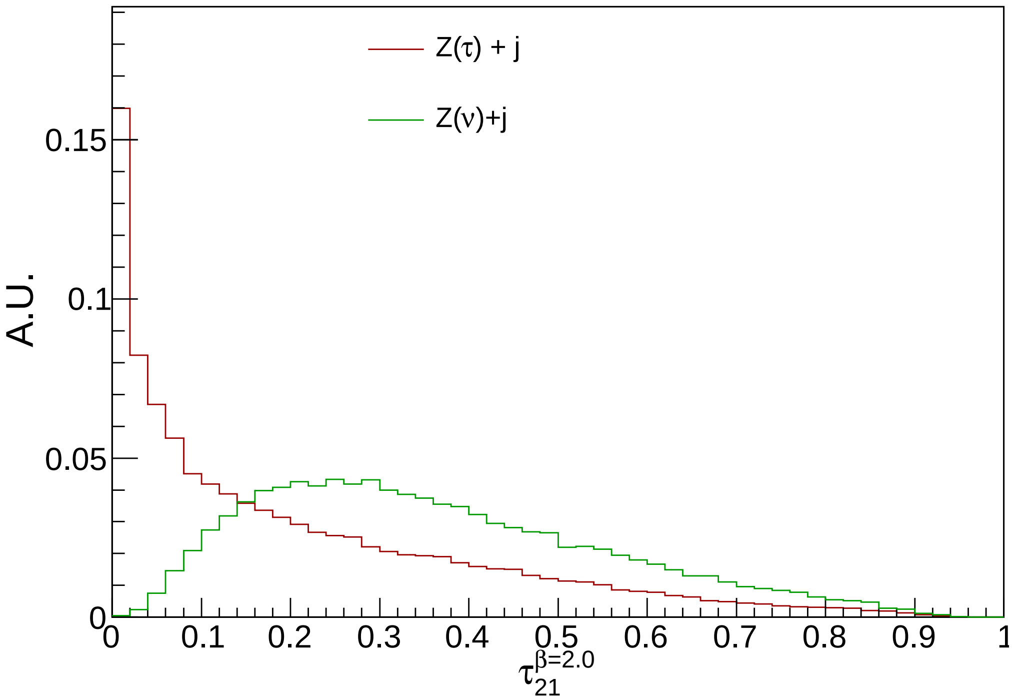


Figure 34: Subjettiness ratio $\tau_{21}$ for angular coefficient $\beta = 2.$ (distribution has been normalized to unit area under curve)

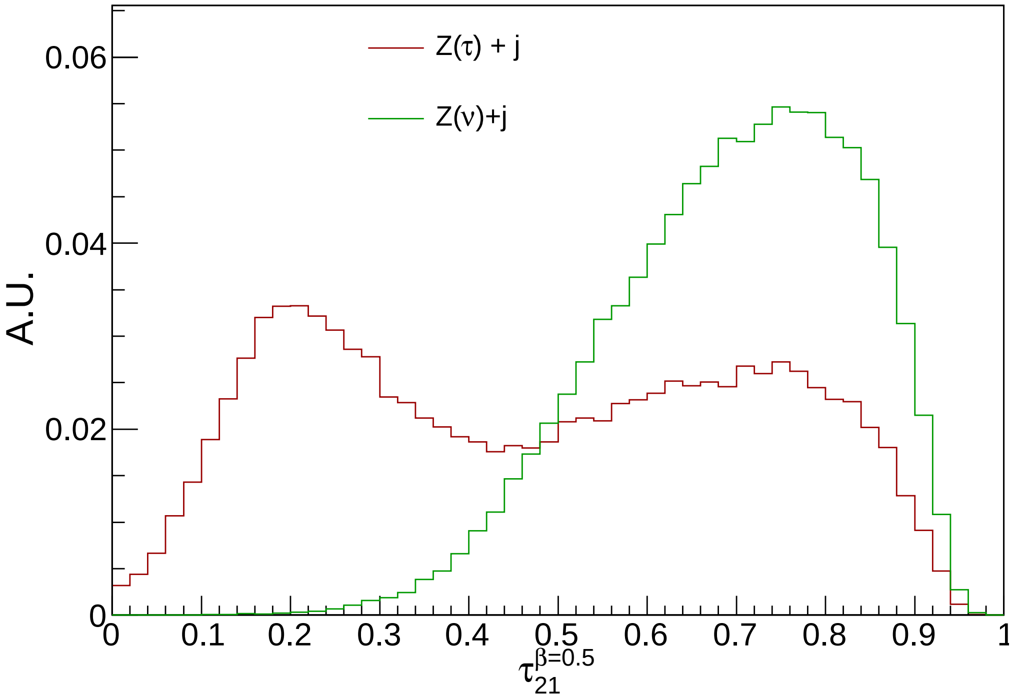


Figure 35: Subjettiness ratio $\tau_{21}$ for angular coefficient $\beta = 0.5$ (distribution has been normalized to unit area under curve)

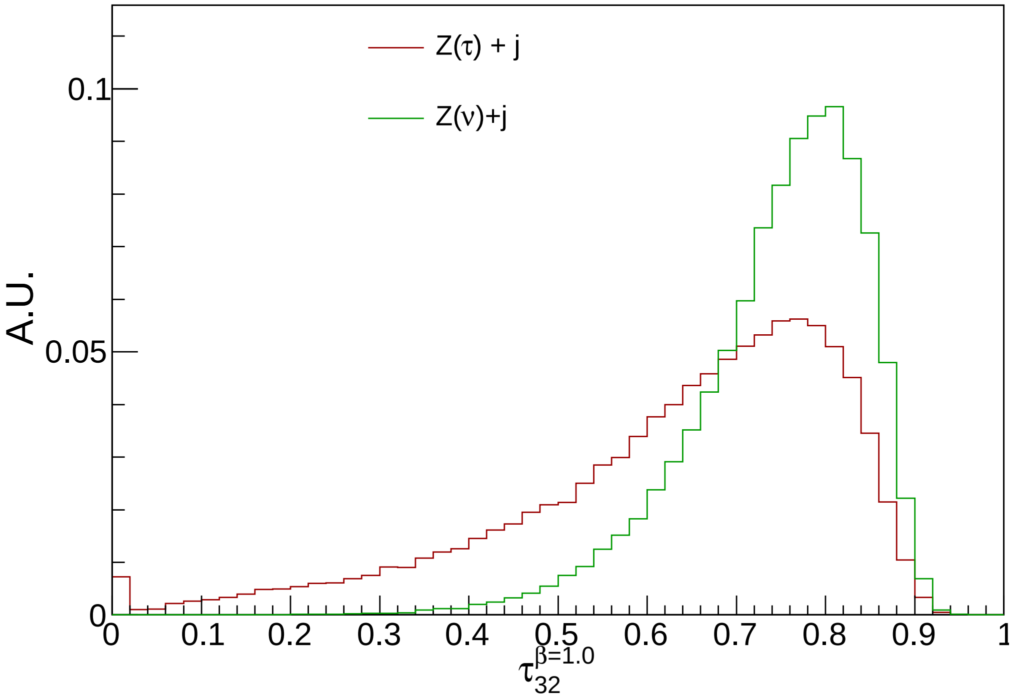


Figure 36: Subjettiness ratio $\tau_{32}$ for angular coefficient $\beta = 1.$ (distribution has been normalized to unit area under curve)

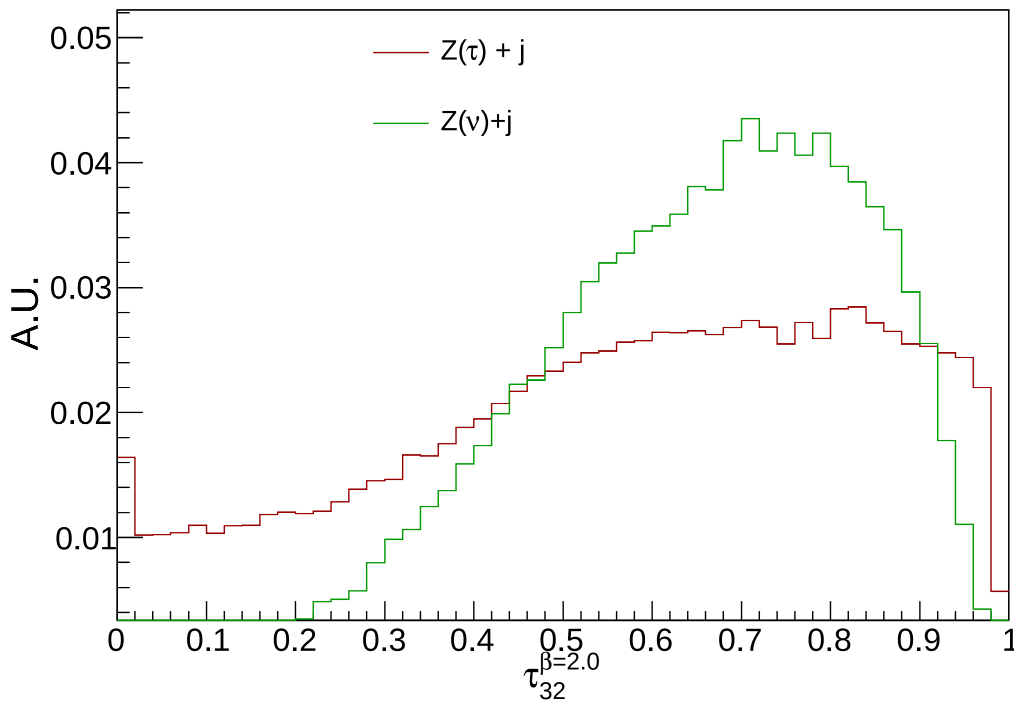


Figure 37: Subjettiness ratio $\tau_{32}$ for angular coefficient $\beta = 2$. (distribution has been normalized to unit area under curve)

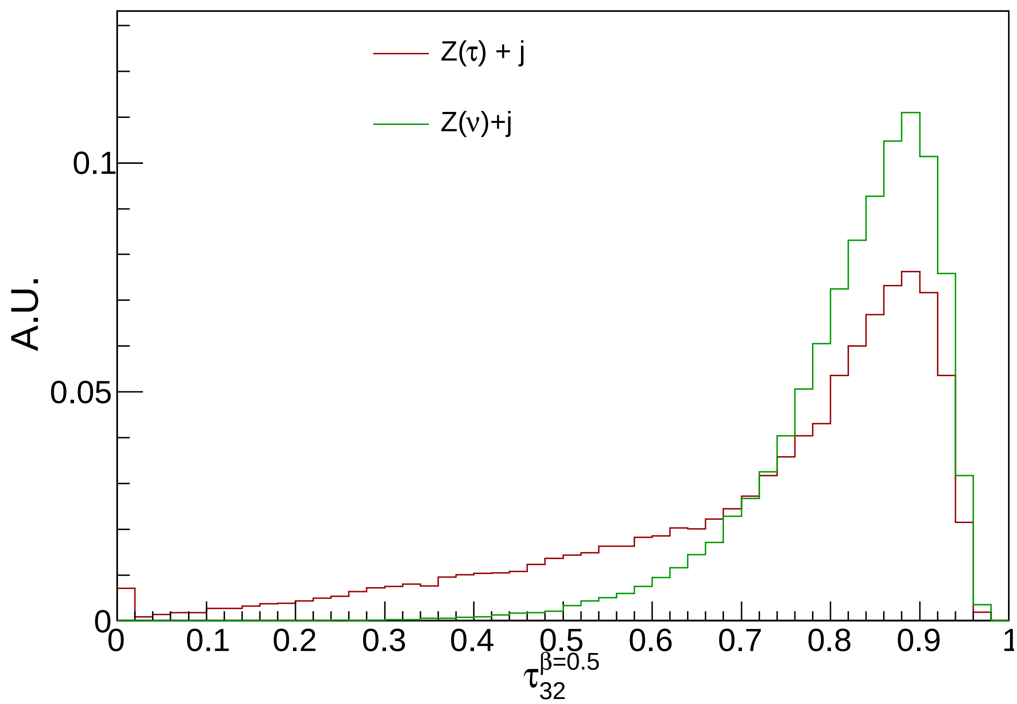


Figure 38: Subjettiness ratio $\tau_{32}$ for angular coefficient $\beta = 0.5$ (distribution has been normalized to unit area under curve)

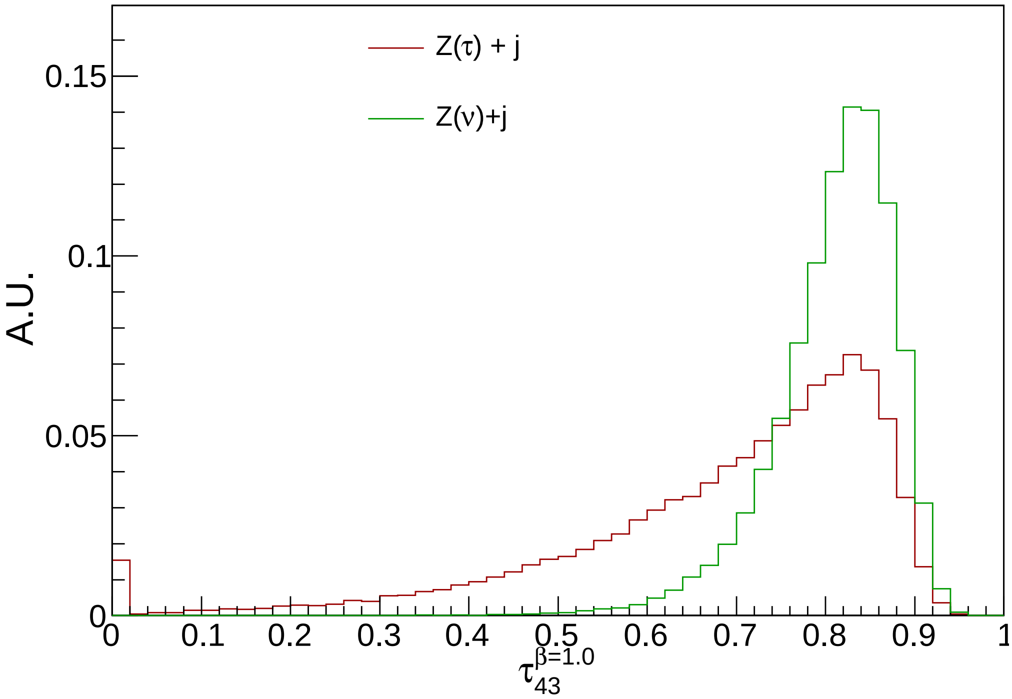


Figure 39: Subjettiness ratio $\tau_{43}$ for angular coefficient $\beta = 1$. (distribution has been normalized to unit area under curve)

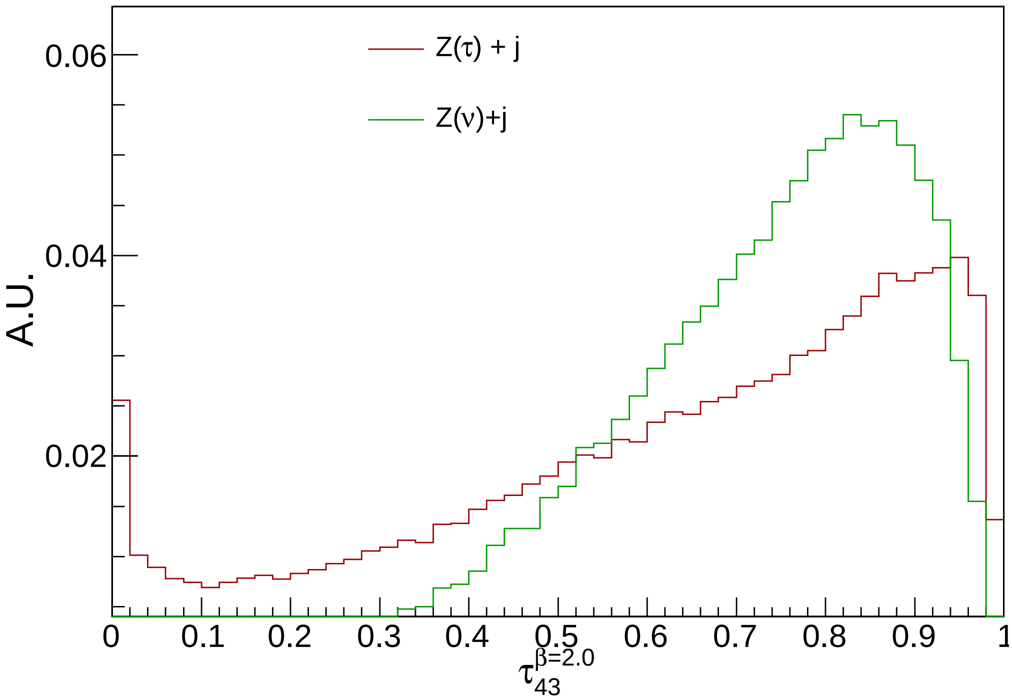


Figure 40: Subjettiness ratio $\tau_{43}$ for angular coefficient $\beta = 2$. (distribution has been normalized to unit area under curve)

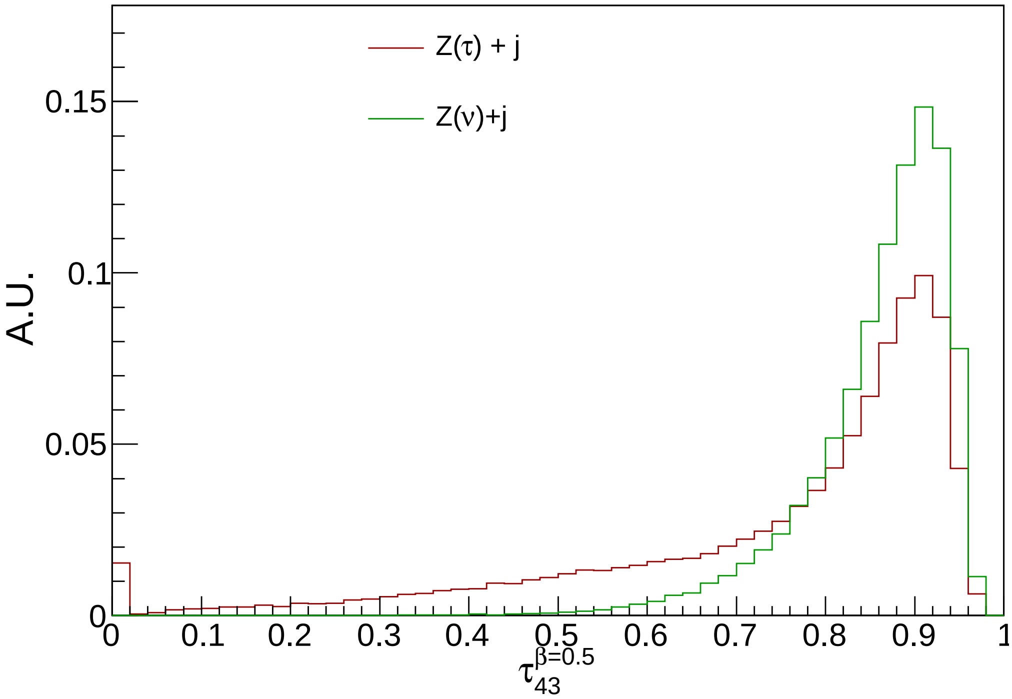


Figure 41: Subjettiness ratio $\tau_{43}$ for angular coefficient $\beta = 0.5$ (distribution has been normalized to unit area under curve)

# References


[PlanarFlow] (arXiv:0807.0234 [hep-ph]): **Leandro G. Almeida, Seung J. Lee, Gilad Perez, George Sterman, Ilmo Sung, Joseph Virzi:** Substructure of high$-p_T$ Jets at the LHC. 4, 16

[BDRS] (arXiv:0802.2470 [hep-ph]): **Jonathan M. Butterworth, Adam R. Davison, Mathieu Rubin, Gavin P. Salam:** Jet substructure as a new Higgs search channel at the LHC. 4

[ATLASThesis] (`https://cds.cern.ch/record/2105592/files/CERN-THESIS-2015-220.pdf`): **David Kirchmeier:** Reconstruction and Identification of Boosted Tau Pair Topologies at ATLAS. 1