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1 Introduction

- An interesting masters thesis on tau reconstruction using ATLAS detector, with a listing of some interesting variables can be found in [3, Chapter-5].
- The main GitHub link for this work is:

[“https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER”](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”](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”](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”](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 $Z \rightarrow \tau\tau$ 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"](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 `lhpdf` 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"](https://herwig.hepforge.org/tutorials/faq/shower.html)

for details.

By default, Herwig does not force τ 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+;:0nOff Off
set /Herwig/Particles/tau+/tau+>nu_mu,mu+;:0nOff Off
set /Herwig/Particles/tau-/tau-->nu_tau,nu_ebar,e-;:0nOff Off
set /Herwig/Particles/tau-/tau-->nu_tau,nu_mubar,mu-;:0nOff Off
```

A sample run card:

- With MPI:

["https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER/blob/master/HERWIG_PART/LHEWithISR.in"](https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER/blob/master/HERWIG_PART/LHEWithISR.in)

- With out MPI:

["https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER/blob/master/HERWIG_PART/LHNoISRMPI.in"](https://github.com/aravindhv10/MUMBAIPUNETAUTAGGER/blob/master/HERWIG_PART/LHNoISRMPI.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"](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:

$$pp \rightarrow jZ, (Z \rightarrow \tau\bar{\tau}), p_T^Z \geq 200 \text{ GeV}$$

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

$$pp \rightarrow jZ, (Z \rightarrow b\bar{b}), p_T^Z \geq 200 \text{ GeV}$$

$$pp \rightarrow jZ, (Z \rightarrow \tau\bar{\tau}), p_T^Z \geq 0 \text{ GeV}$$

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[2]+filtering) jet to evaluate variables and all of these results are for events with MPI enabled). Note that planar flow [1] [Figure 5, Figure 6] seem to work extremely well.

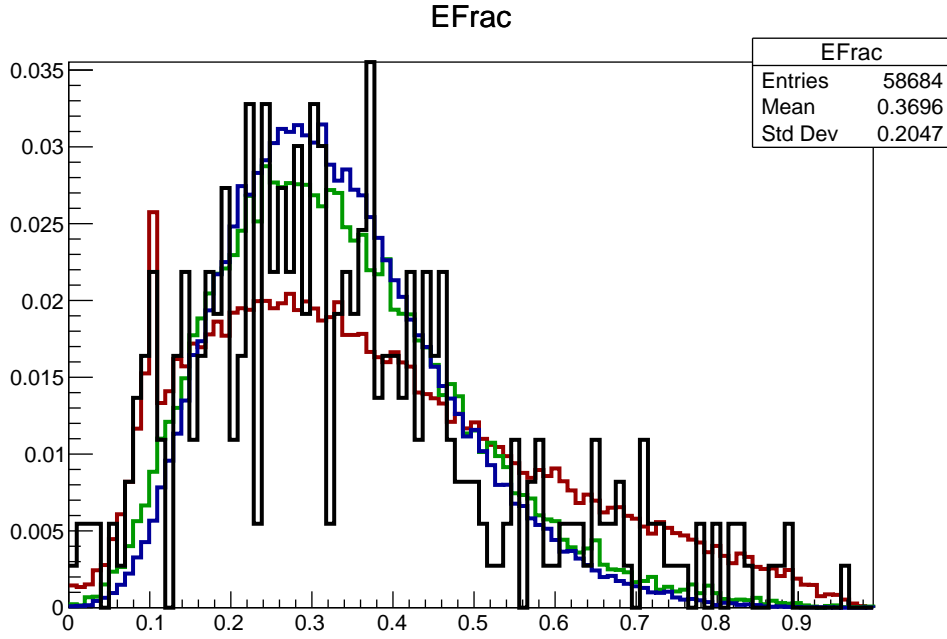


Figure 1: Electromagnetic energy fraction of the jet, normalized to unit area under the curve.

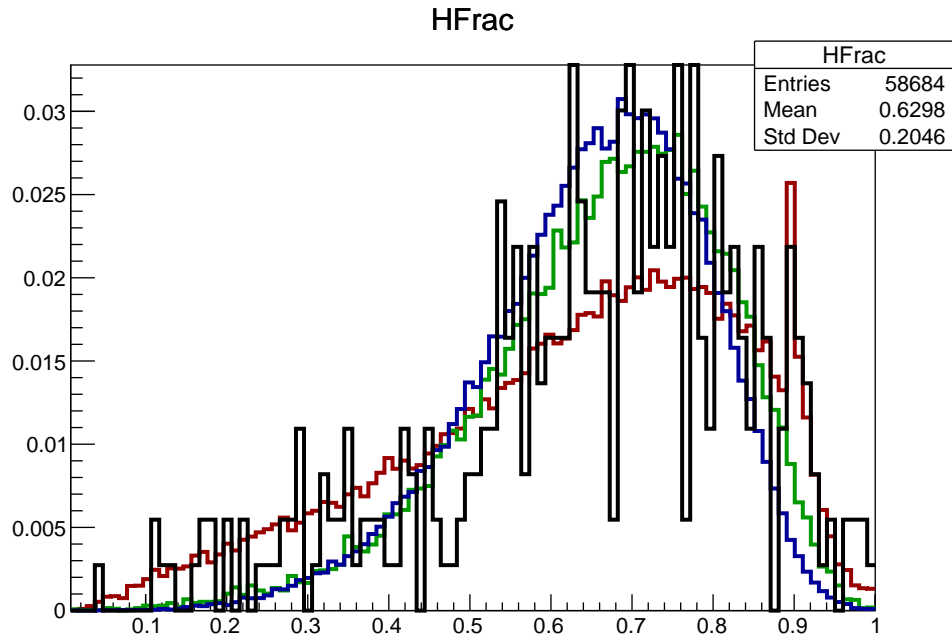


Figure 2: Hadronic energy fraction of the jet, normalized to unit area under the curve.

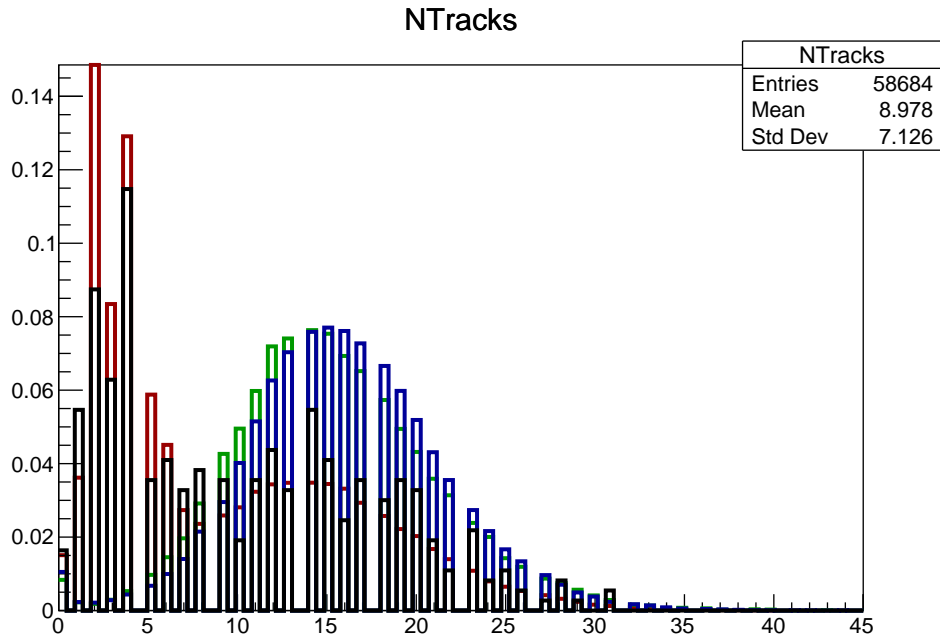


Figure 3: Number of tracks in the jet, normalized to unit area under the curve.

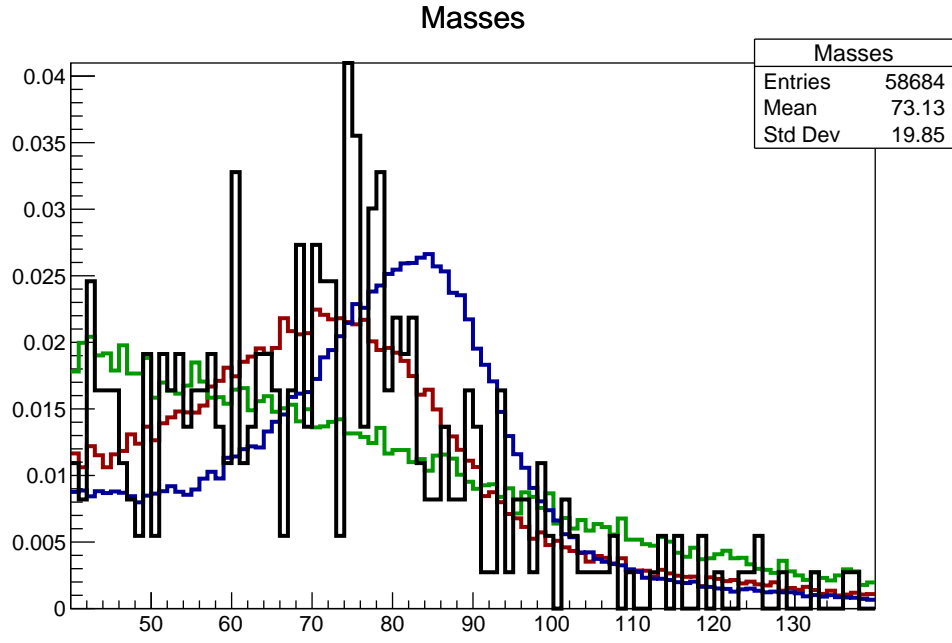


Figure 4: Masses of the jet after BDRS and filtering steps, normalized to unit area under the curve.

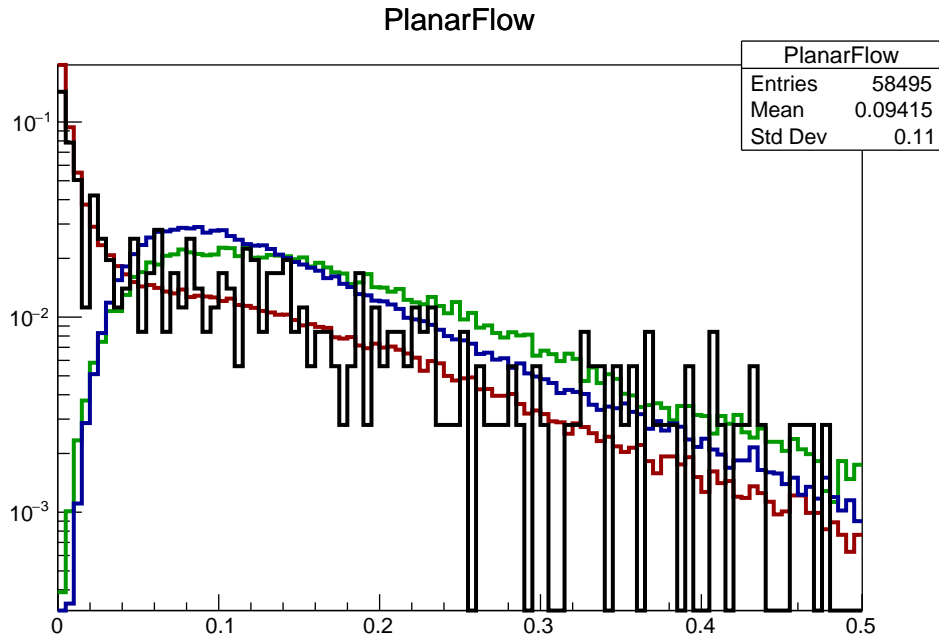


Figure 5: Planar Flow of the jet after BDRS and filtering steps, normalized to unit area under the curve.

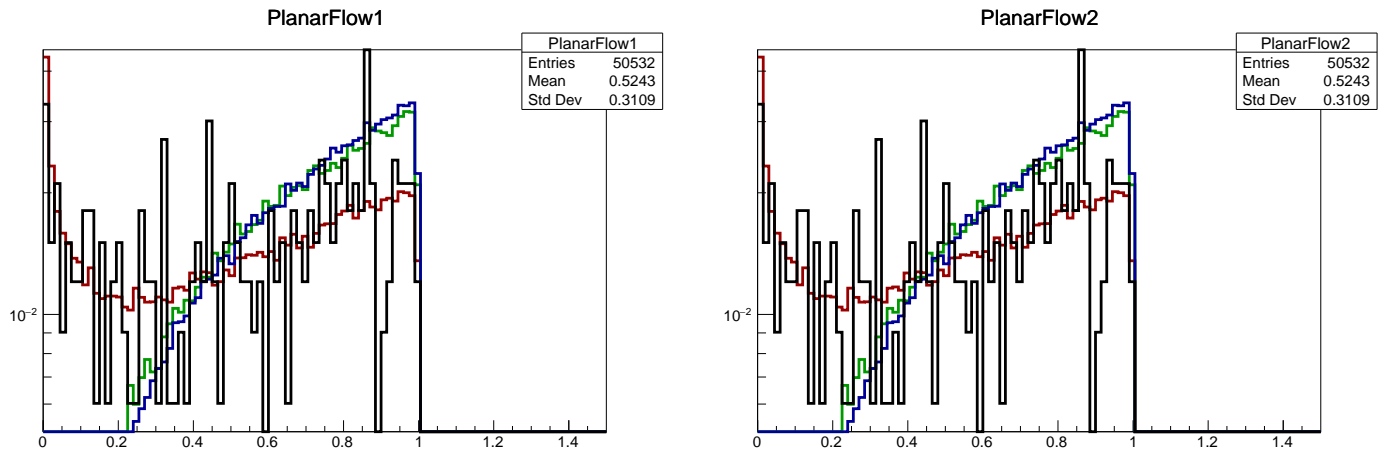


Figure 6: Planar Flow of the two subjects after BDRS and filtering steps, normalized to unit area under the curve.

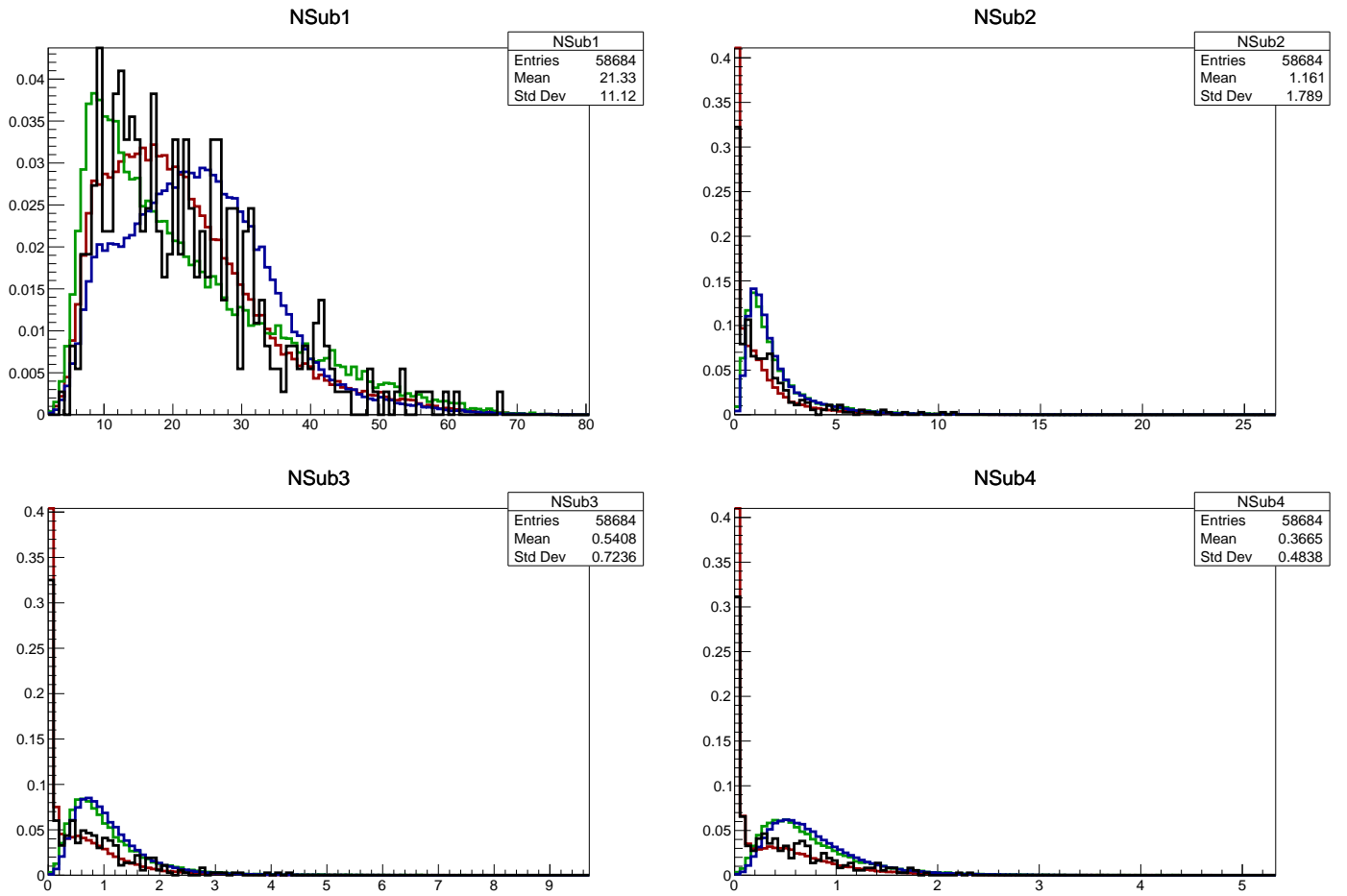


Figure 7: NSubJettiness observable, normalized to unit area under the curve.

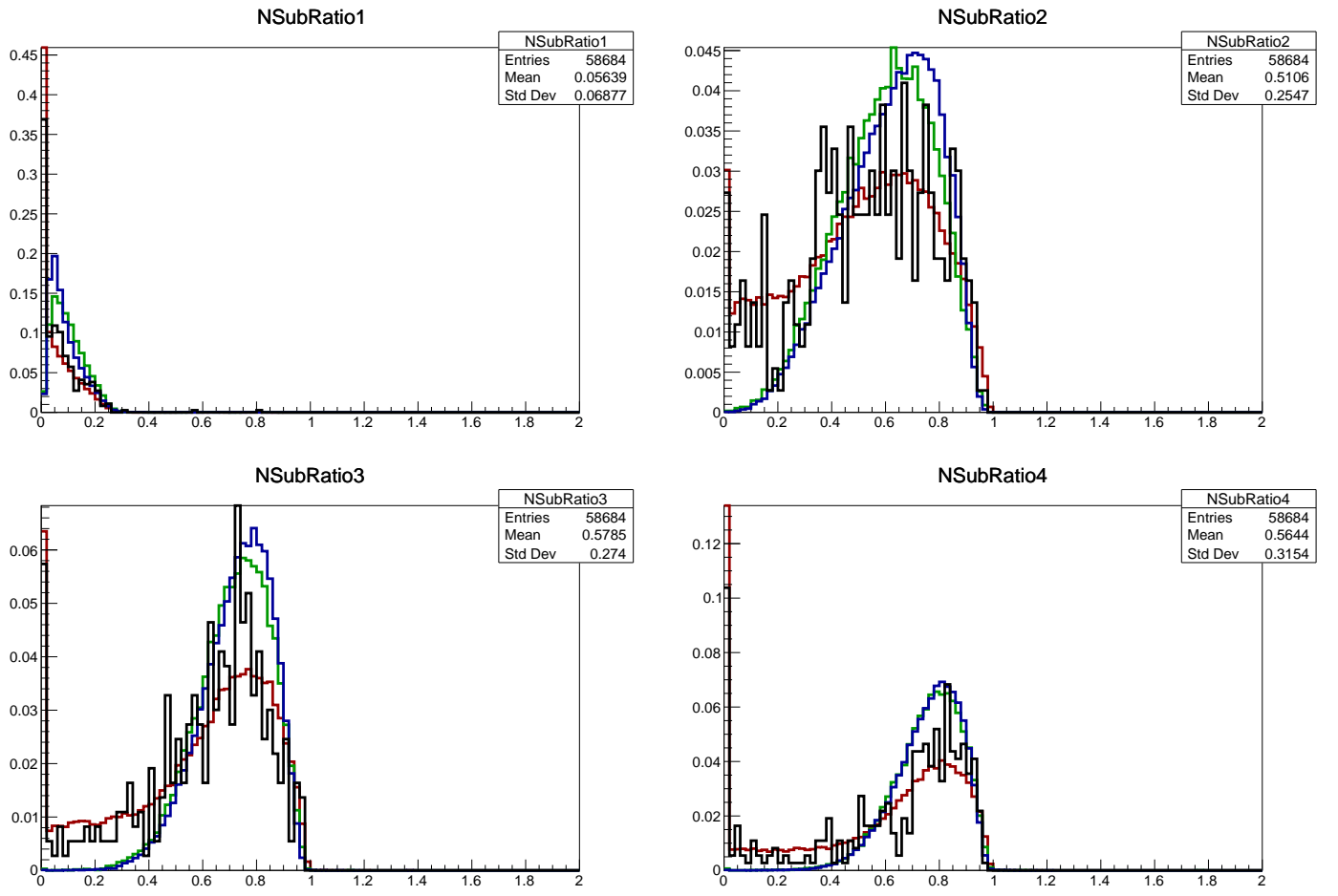


Figure 8: Ratio of `NSubJettiness` observable, normalized to unit area under the curve.

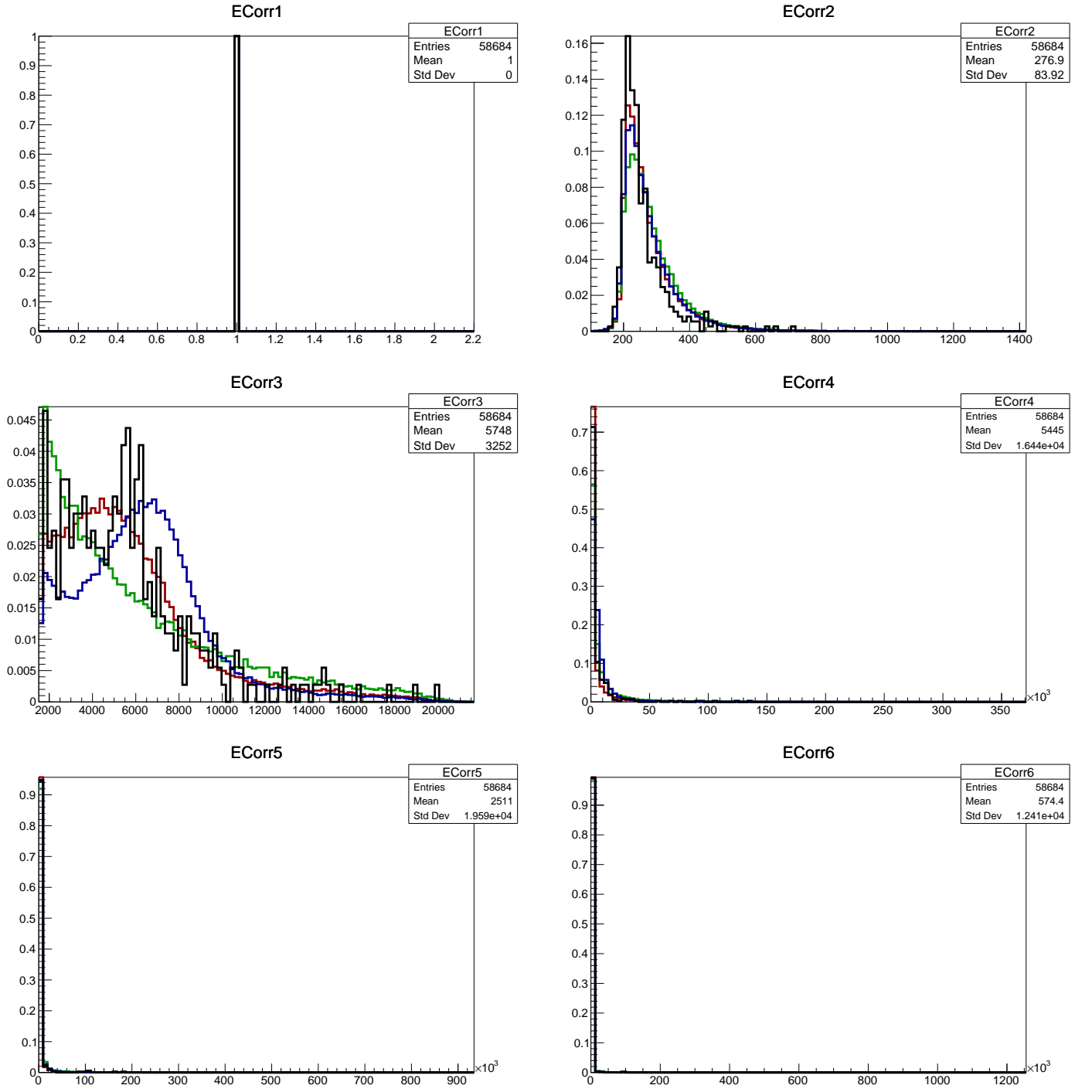


Figure 9: Energy Correlation observable, normalized to unit area under the curve.

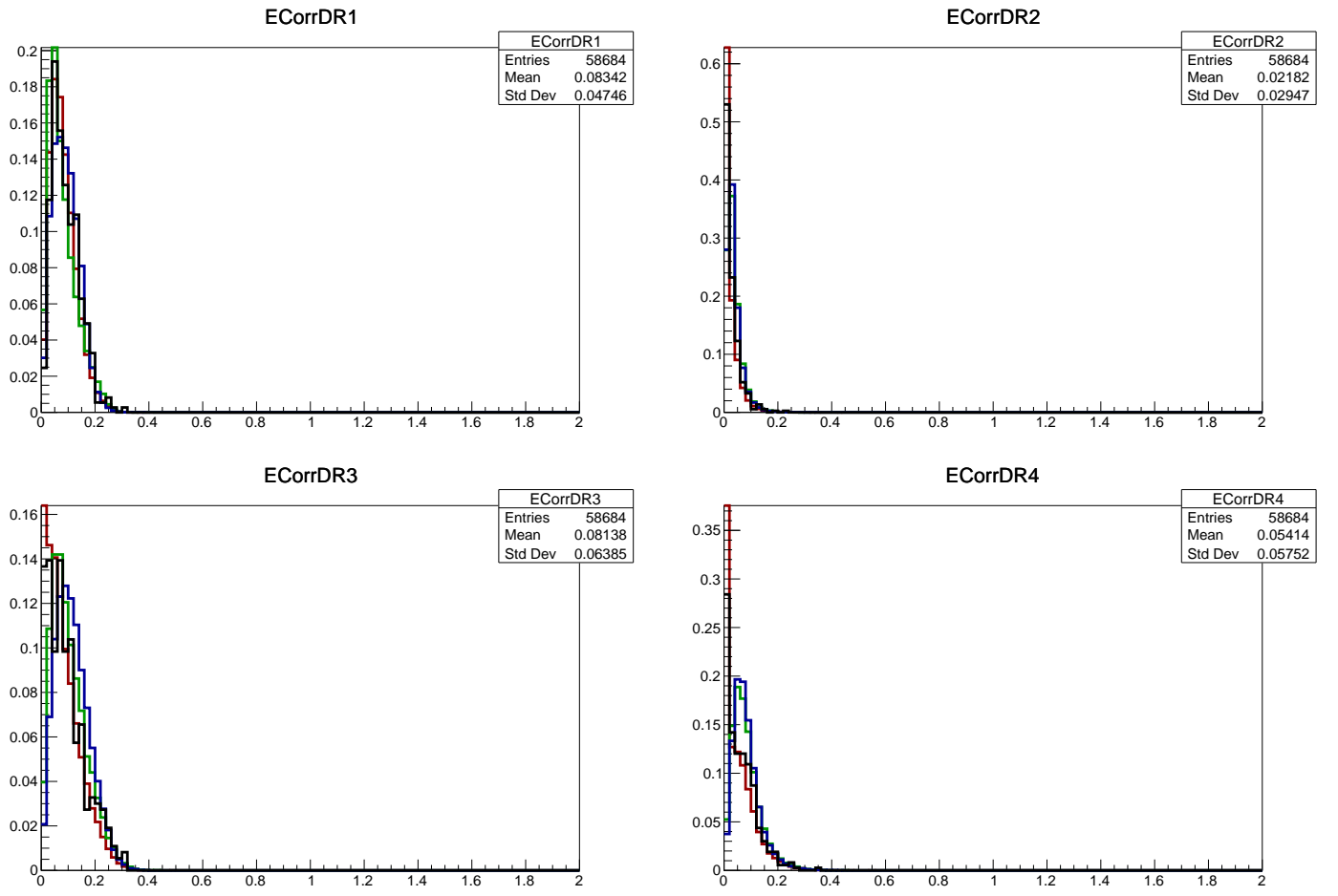


Figure 10: Energy Correlation double ratio observable, normalized to unit area under the curve.

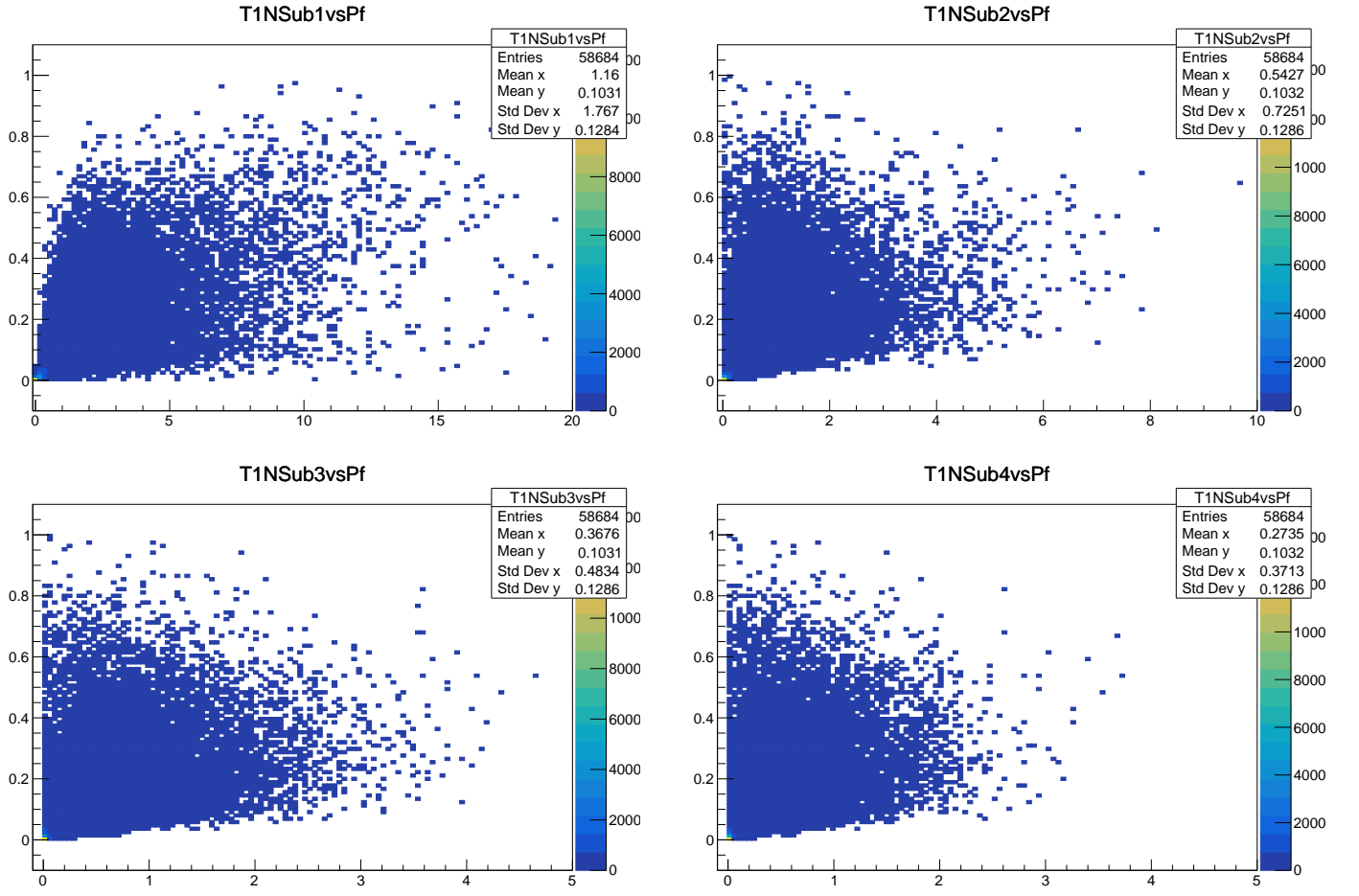


Figure 11: NSubjettiness (x-axis) vs planar flow (y-axis) for boosted $jZ \rightarrow \tau\bar{\tau}$

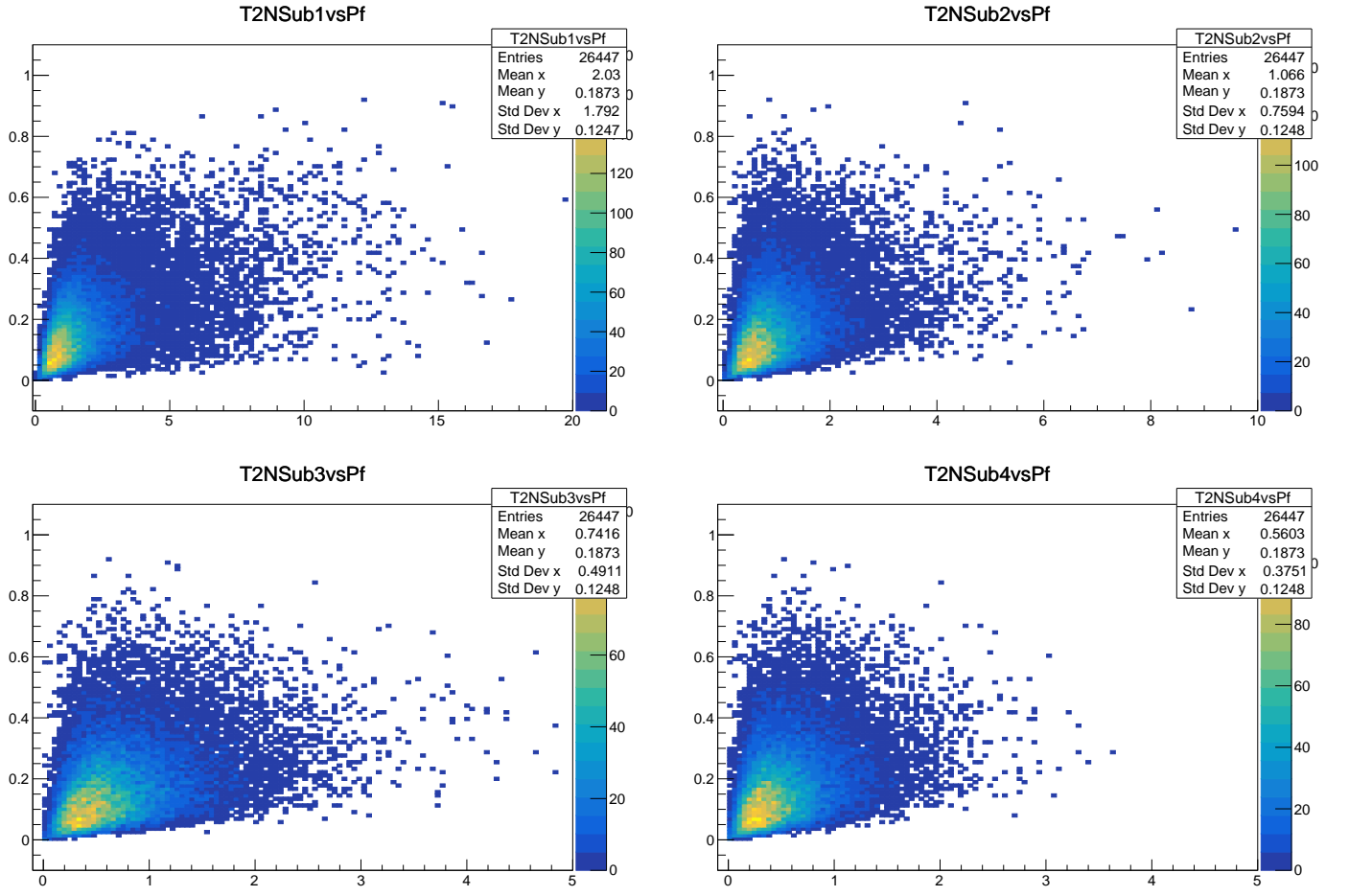


Figure 12: NSubjettiness (x-axis) vs planar flow (y-axis) for boosted $jZ \rightarrow \nu\bar{\nu}$

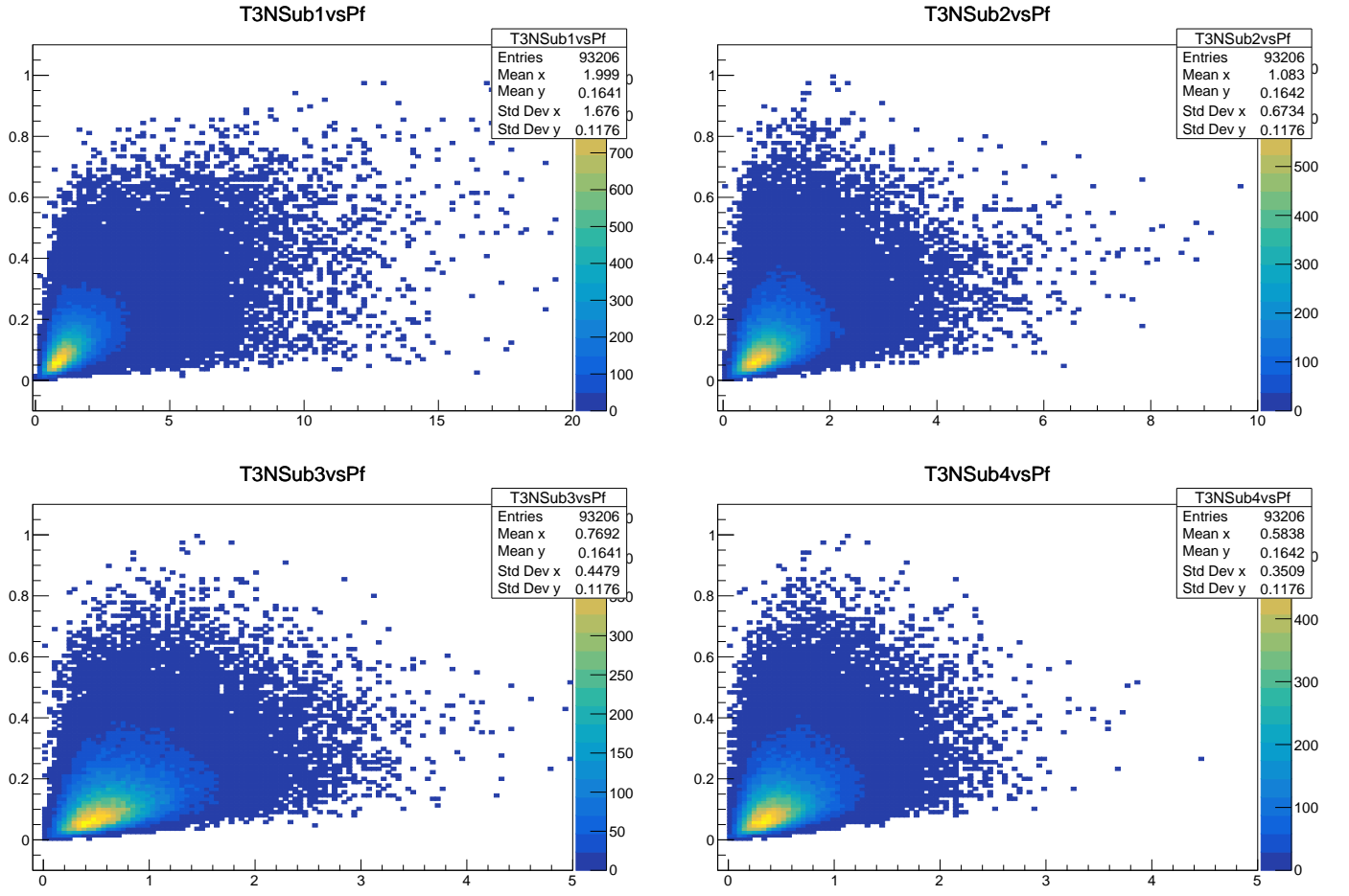


Figure 13: NSubjettiness (x-axis) vs planar flow (y-axis) for boosted $jZ \rightarrow b\bar{b}$

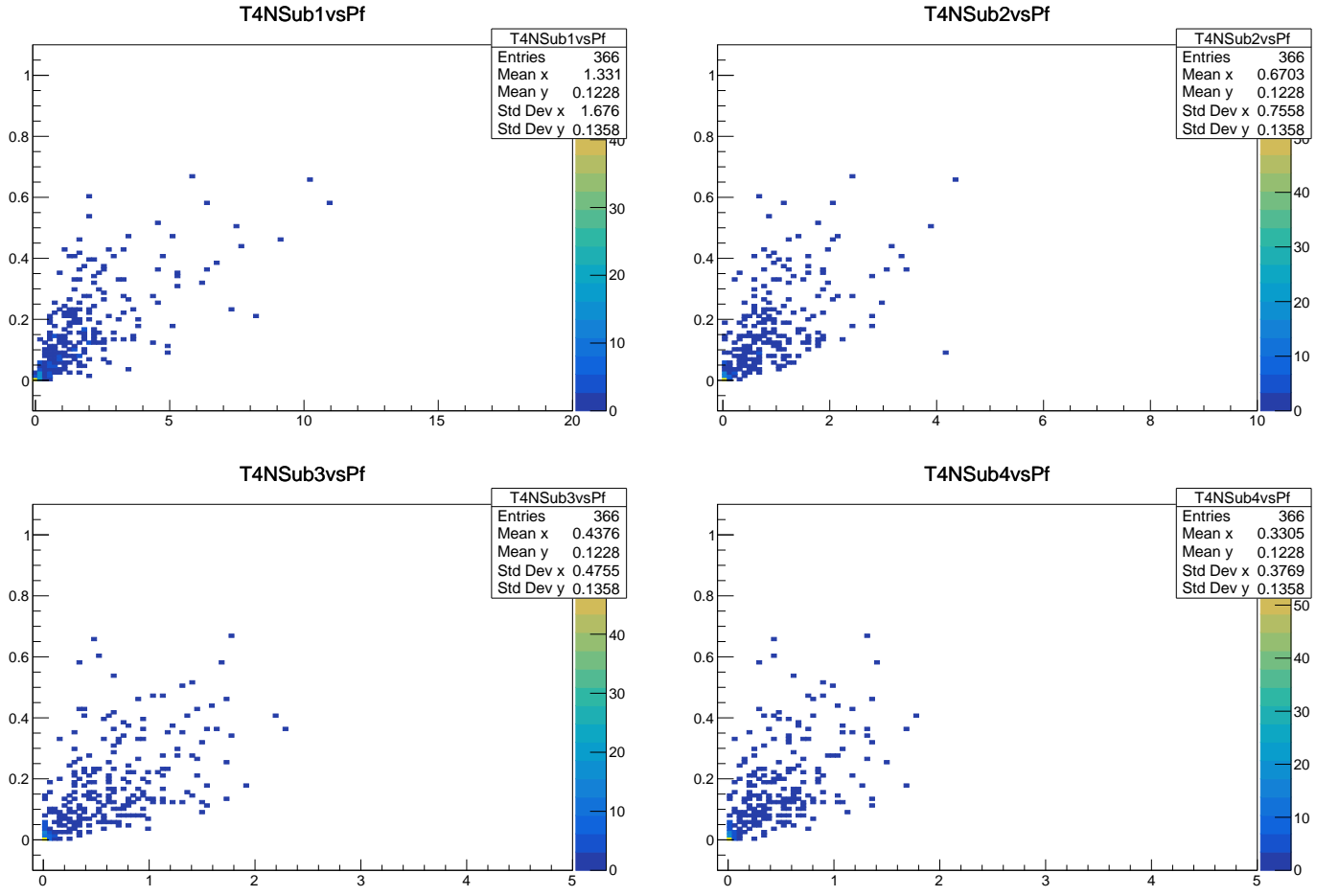


Figure 14: NSubjettiness (x-axis) vs planar flow (y-axis) for unboosted $jZ \rightarrow \tau\bar{\tau}$

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:

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

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

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

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

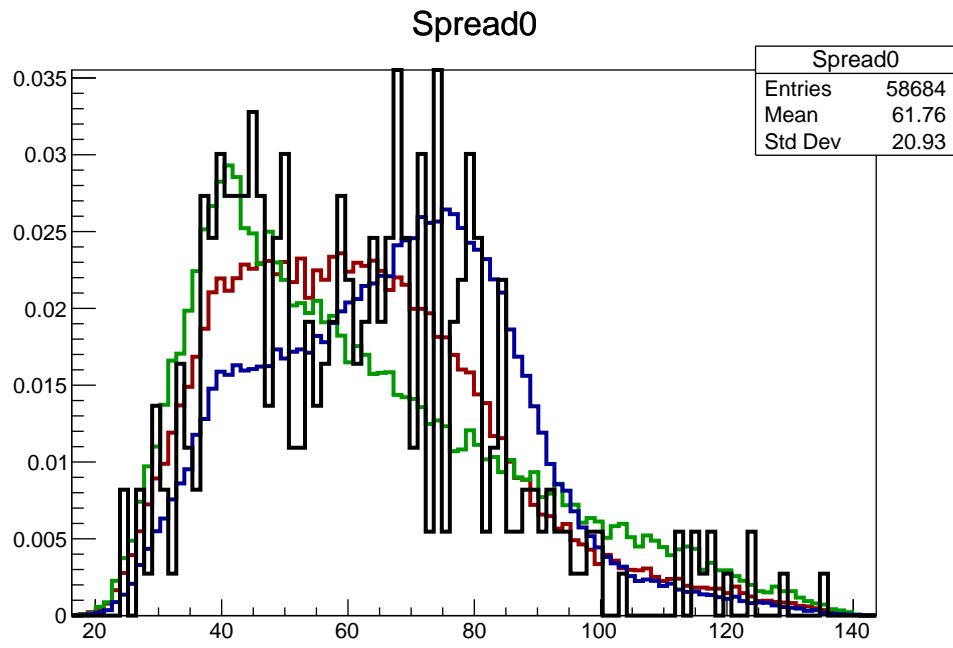


Figure 15: The variable $S(J)$

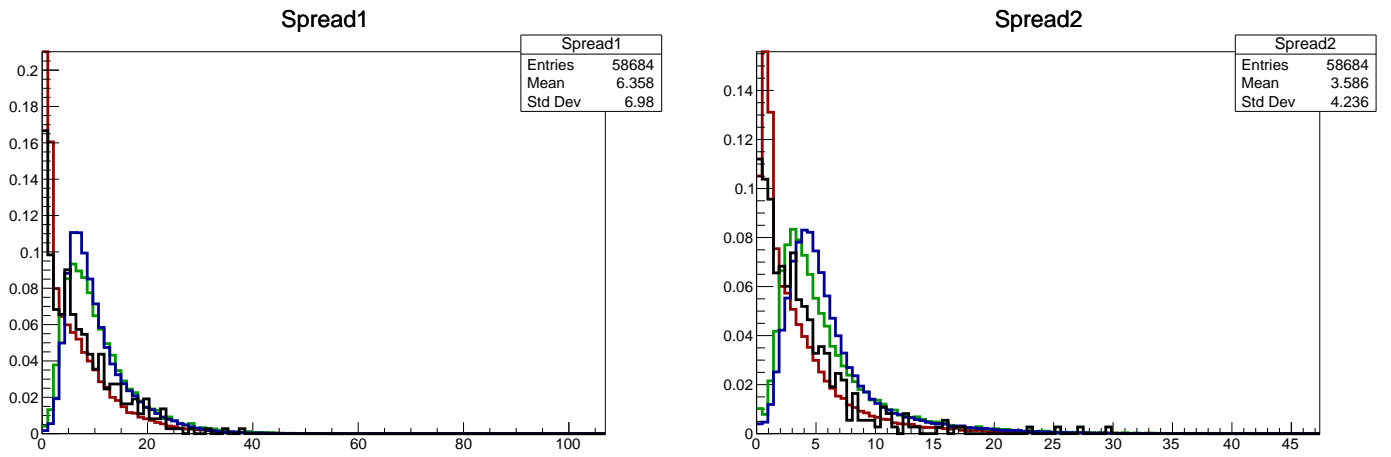


Figure 16: The variable $S(J_1)$ and $S(J_2)$

4.2 Results using Soft Drop (from Suman)

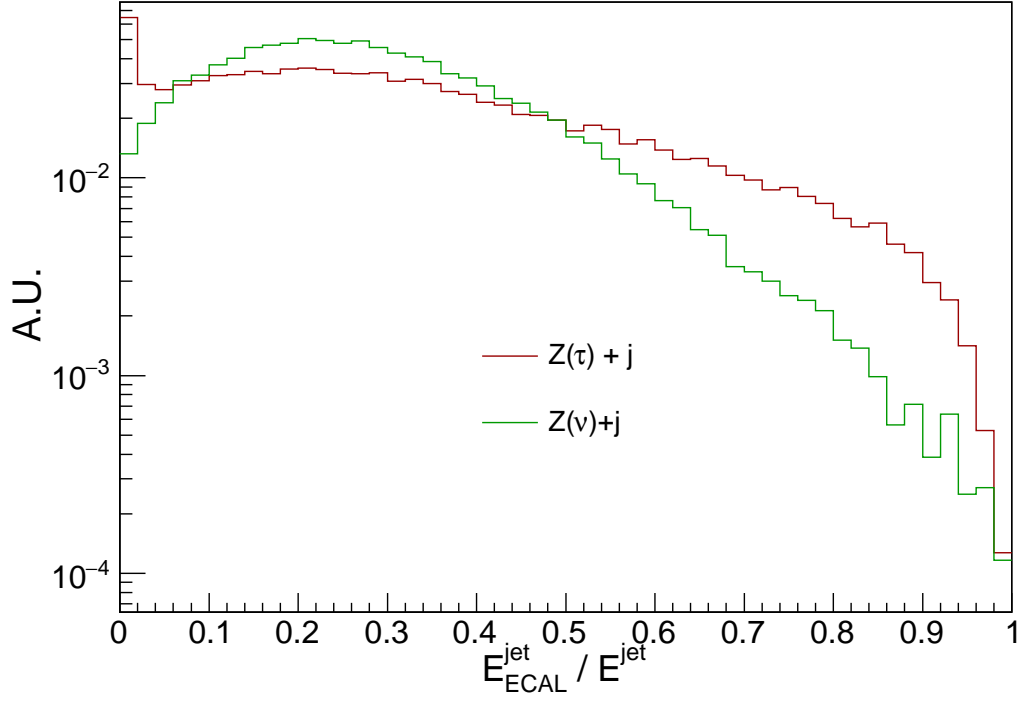


Figure 17: Fraction of jet energy deposited in ECAL (distribution has been normalized to unit area under curve)

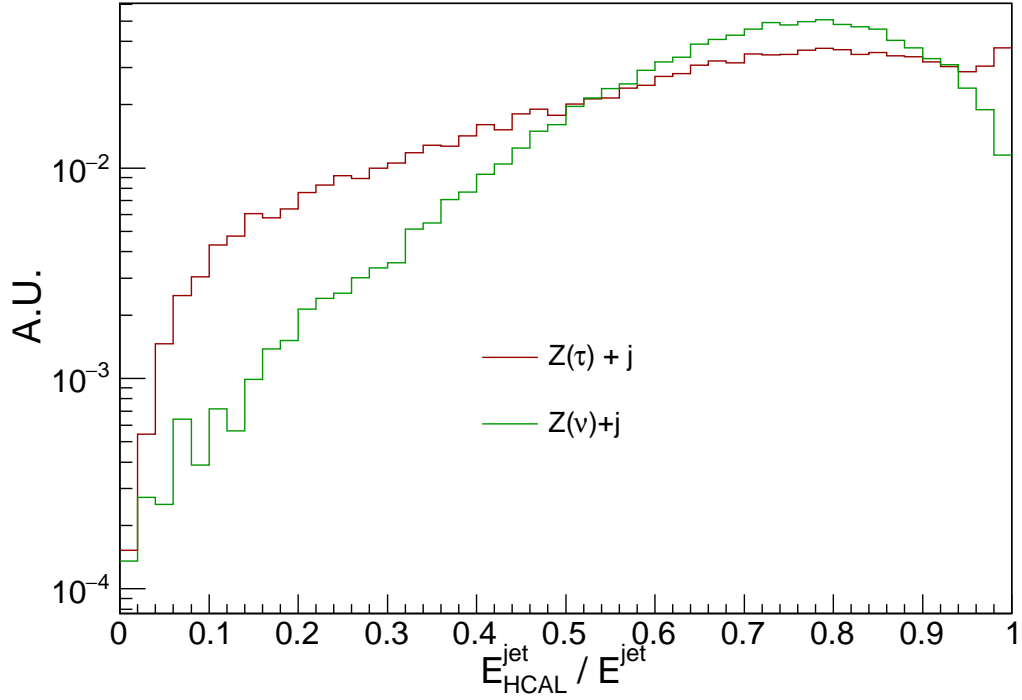


Figure 18: Fraction of jet energy deposited in HCAL (distribution has been normalized to unit area under curve)

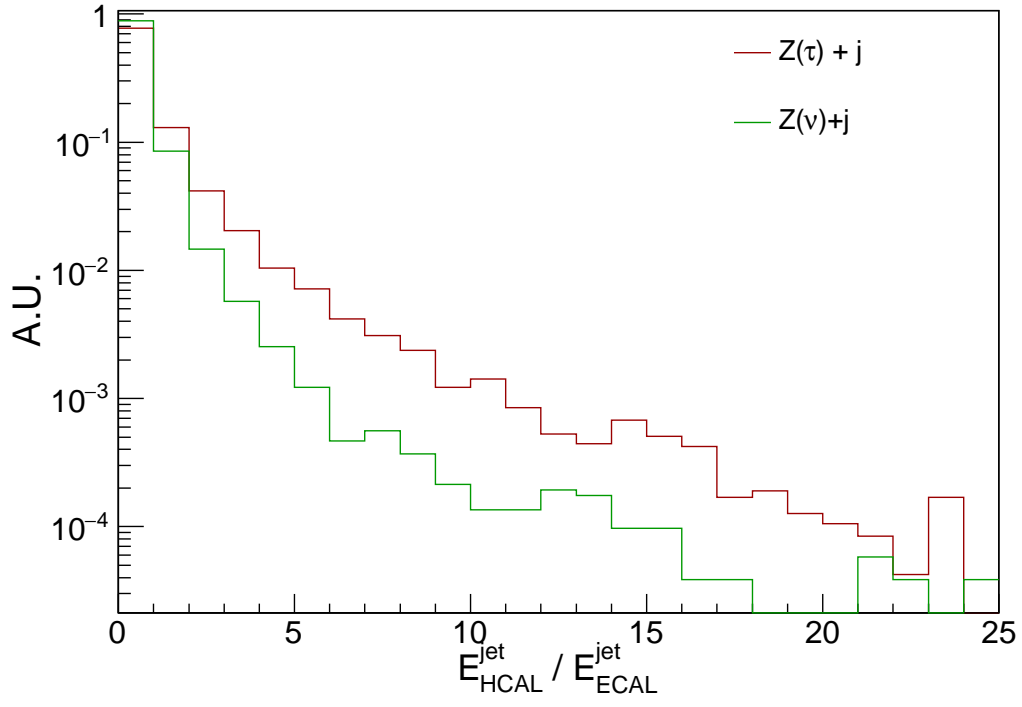


Figure 19: Ratio of jet energy deposited in HCAL with respect to the energy deposit in ECAL (distribution has been normalized to unit area under curve)

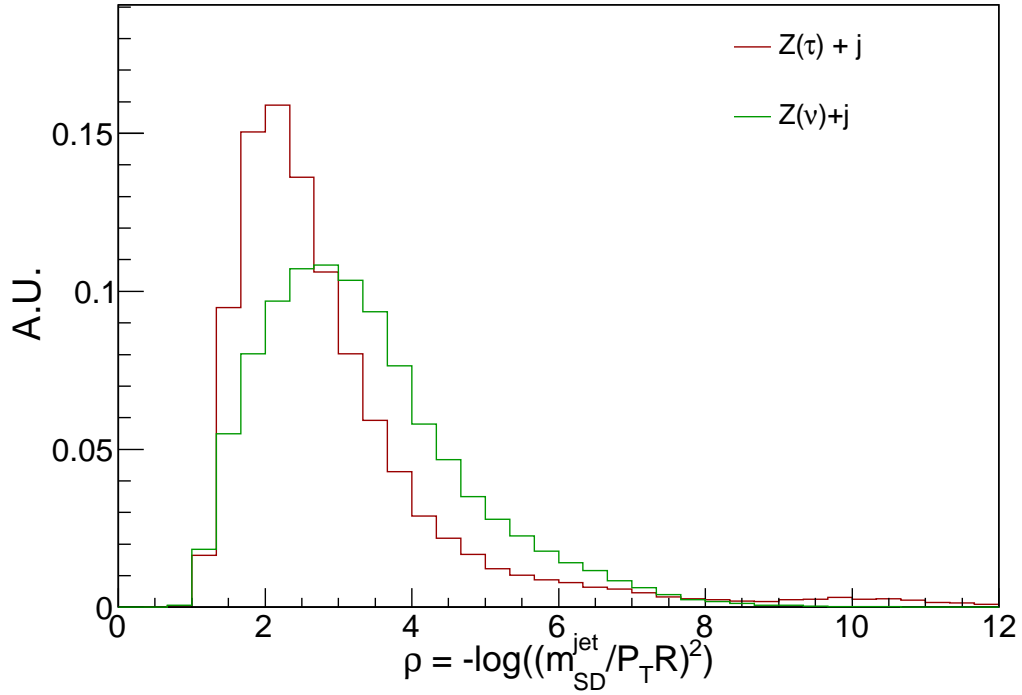


Figure 20: Variable ρ , a logarithmic function of soft drop mass and P_T of the jet (distribution has been normalized to unit area under curve)

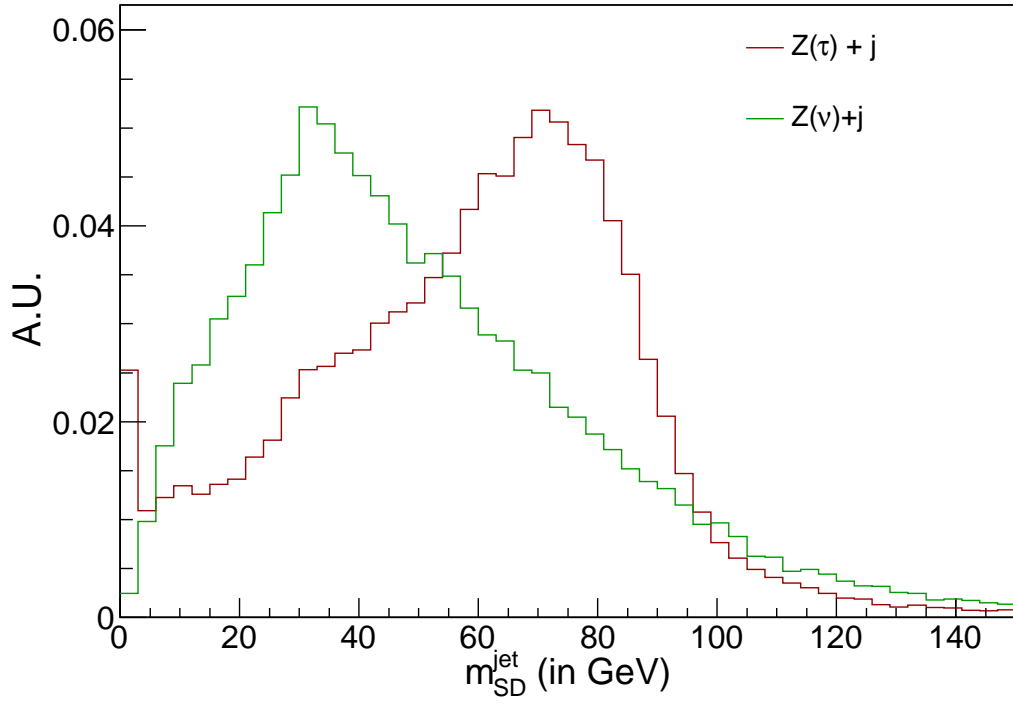


Figure 21: Soft drop mass of jet (in GeV) (distribution has been normalized to unit area under curve)

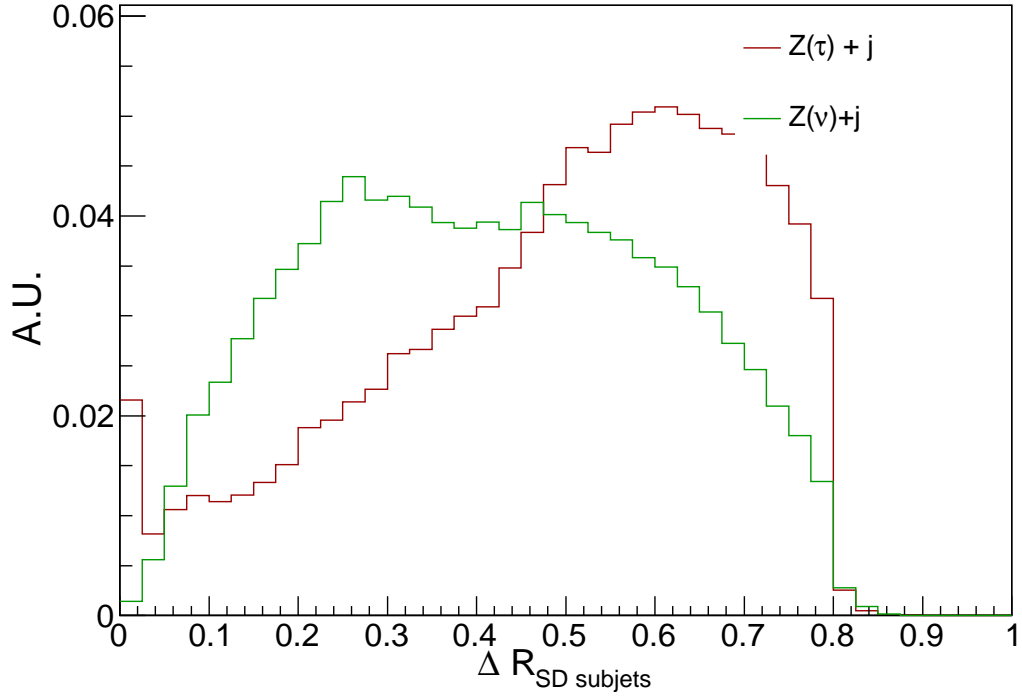


Figure 22: Separation between subjects of the soft dropped jet in rapidity-azimuth plane (distribution has been normalized to unit area under curve)

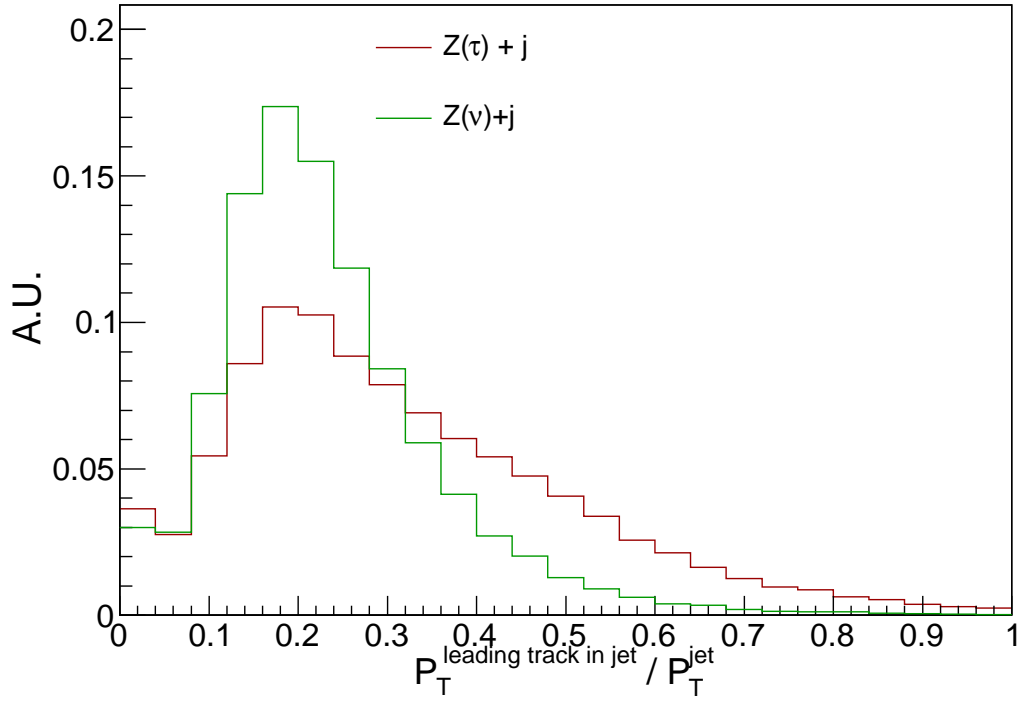


Figure 23: Ratio of P_T of the leading track in the jet with respect to jet P_T (distribution has been normalized to unit area under curve)

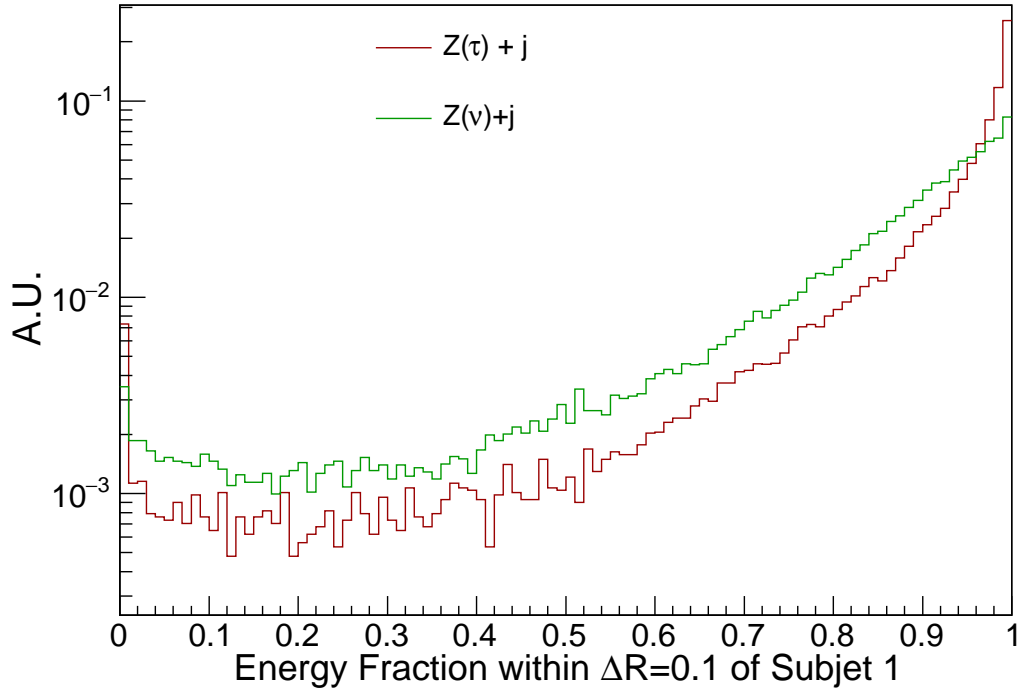


Figure 24: Energy fraction of the leading subjet inside a cone of $\Delta R = 0.1$ around the subjet axis (distribution has been normalized to unit area under curve)

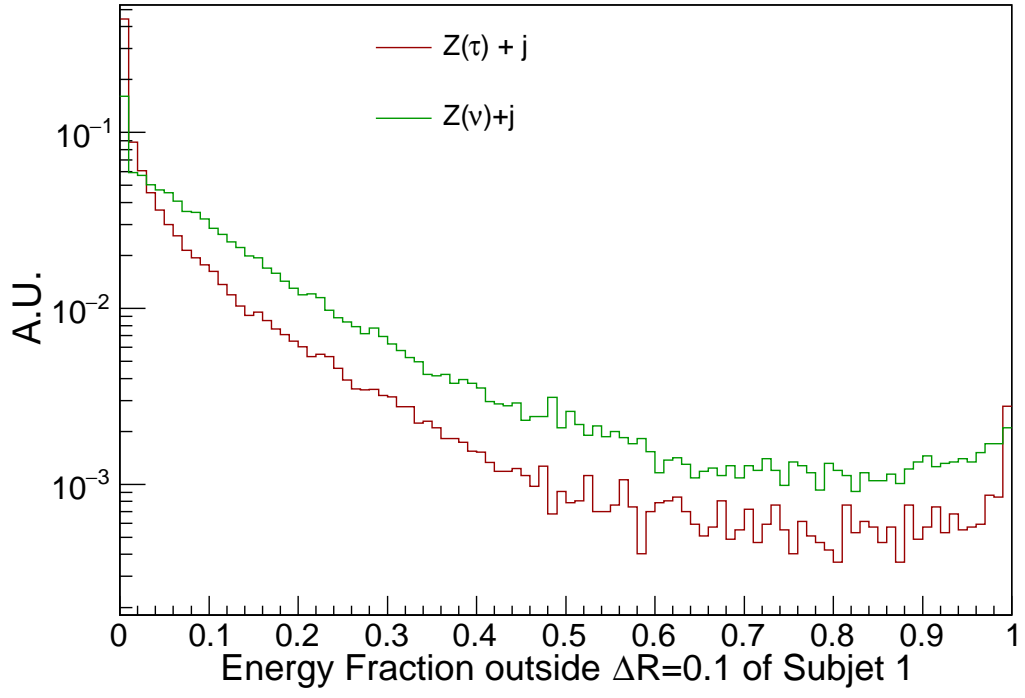


Figure 25: Energy fraction of the leading subjet outside a cone of $\Delta R = 0.1$ around the subjet axis (distribution has been normalized to unit area under curve)

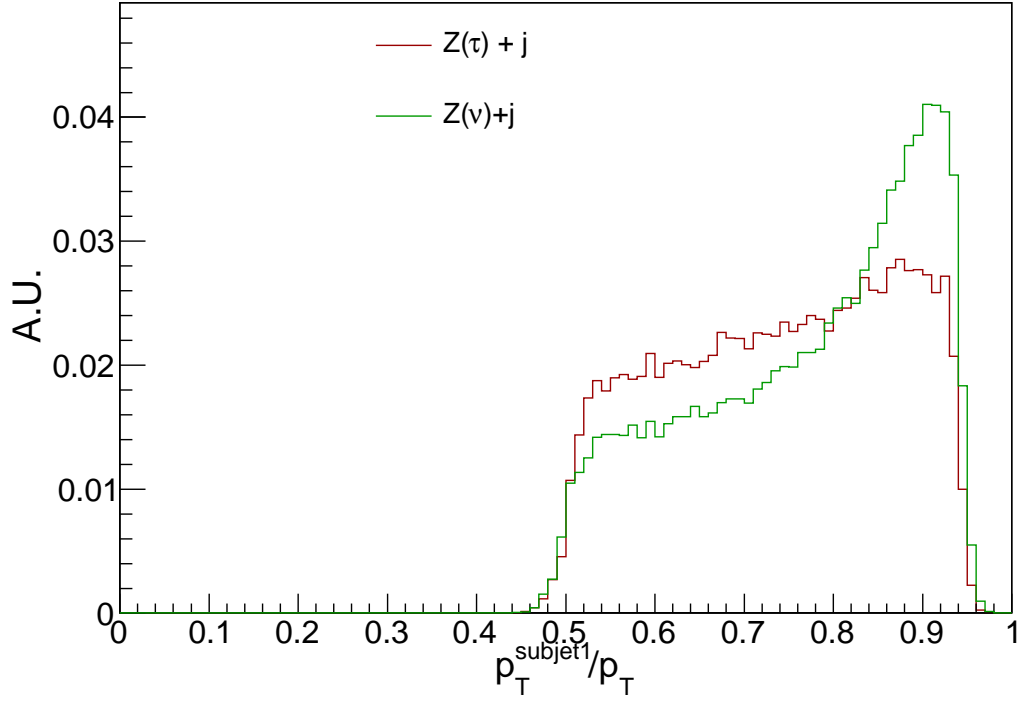


Figure 26: Ratio of leading subjet P_T and jet P_T (distribution has been normalized to unit area under curve)

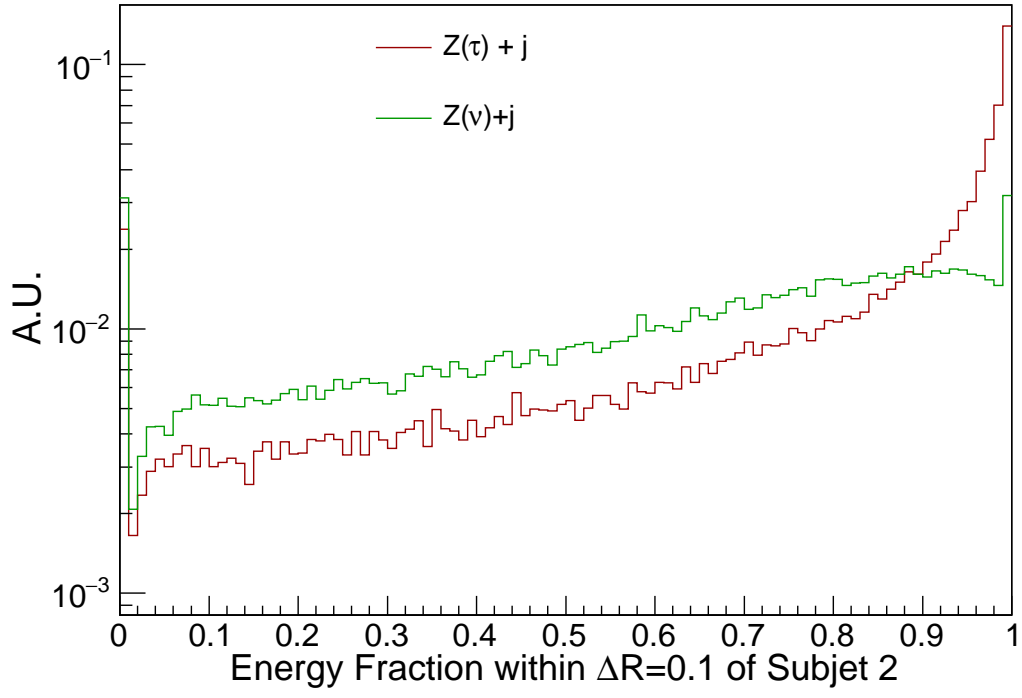


Figure 27: Energy fraction of the subleading subjet inside a cone of $\Delta R = 0.1$ around the subjet axis (distribution has been normalized to unit area under curve)

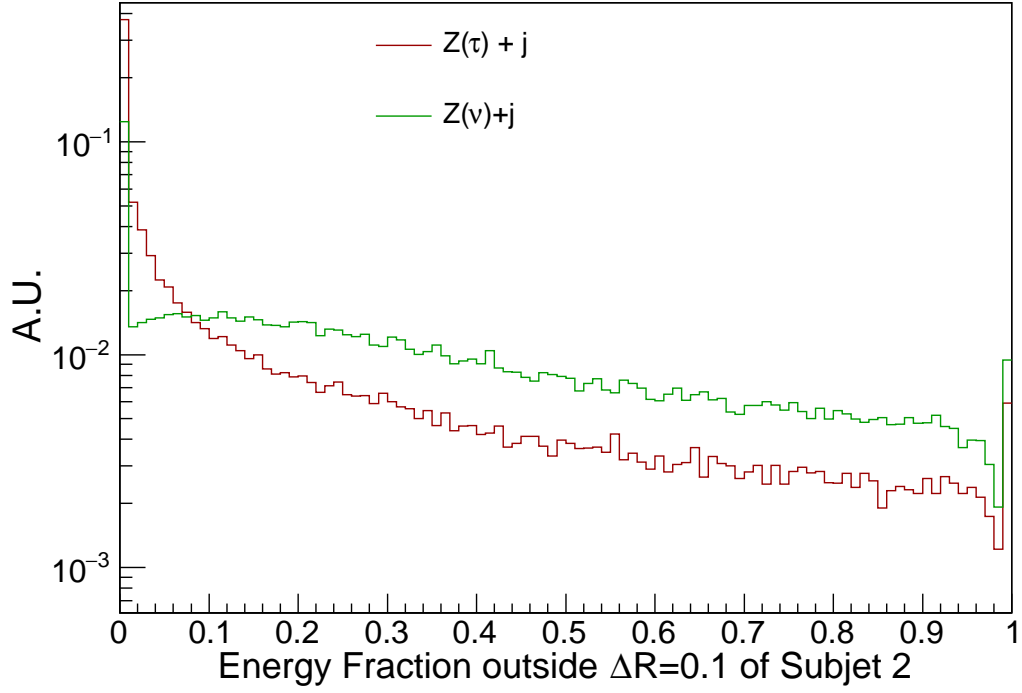


Figure 28: Energy fraction of the subleading subjet outside a cone of $\Delta R = 0.1$ around the subjet axis (distribution has been normalized to unit area under curve)

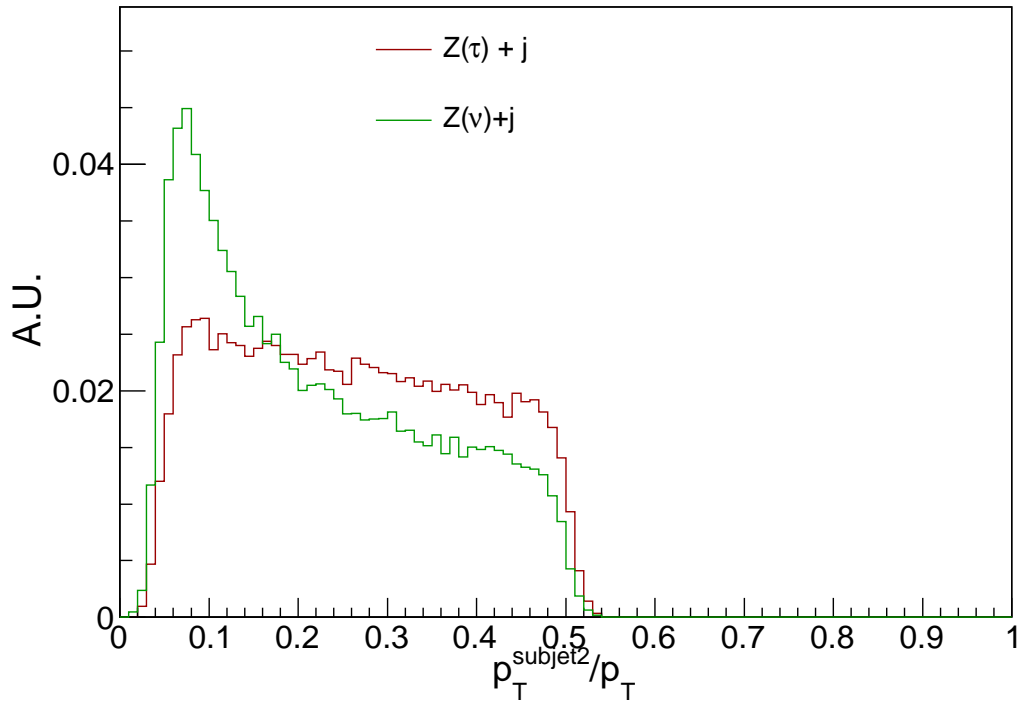


Figure 29: Ratio of subleading subjet P_T and jet P_T (distribution has been normalized to unit area under curve)

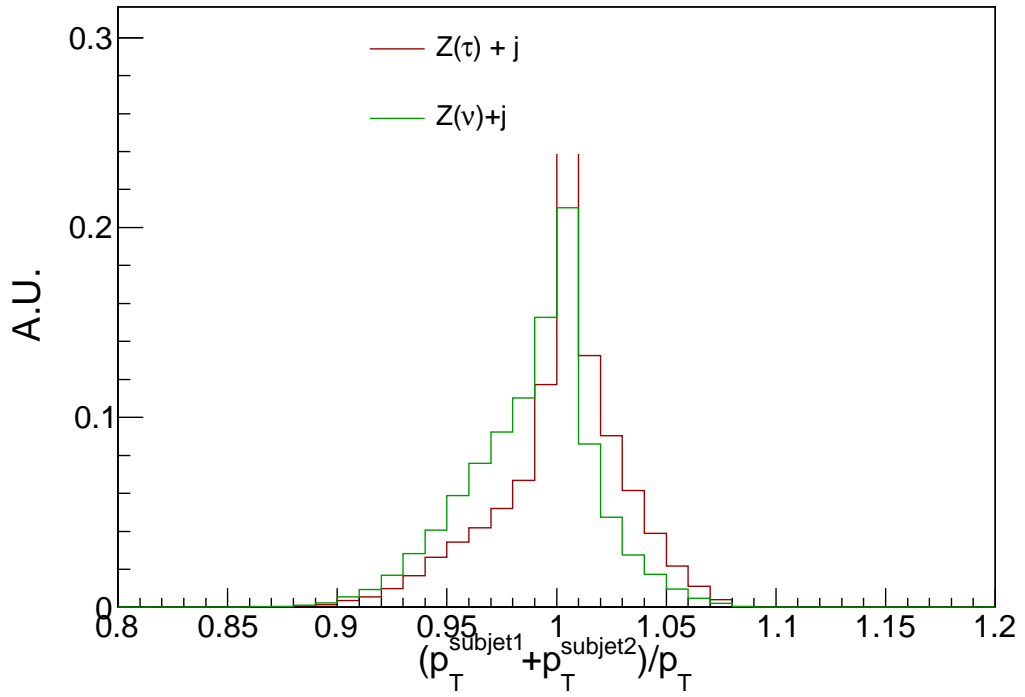


Figure 30: Ratio of sum of P_T of leading and subleading jet with respect to jet P_T (distribution has been normalized to unit area under curve)

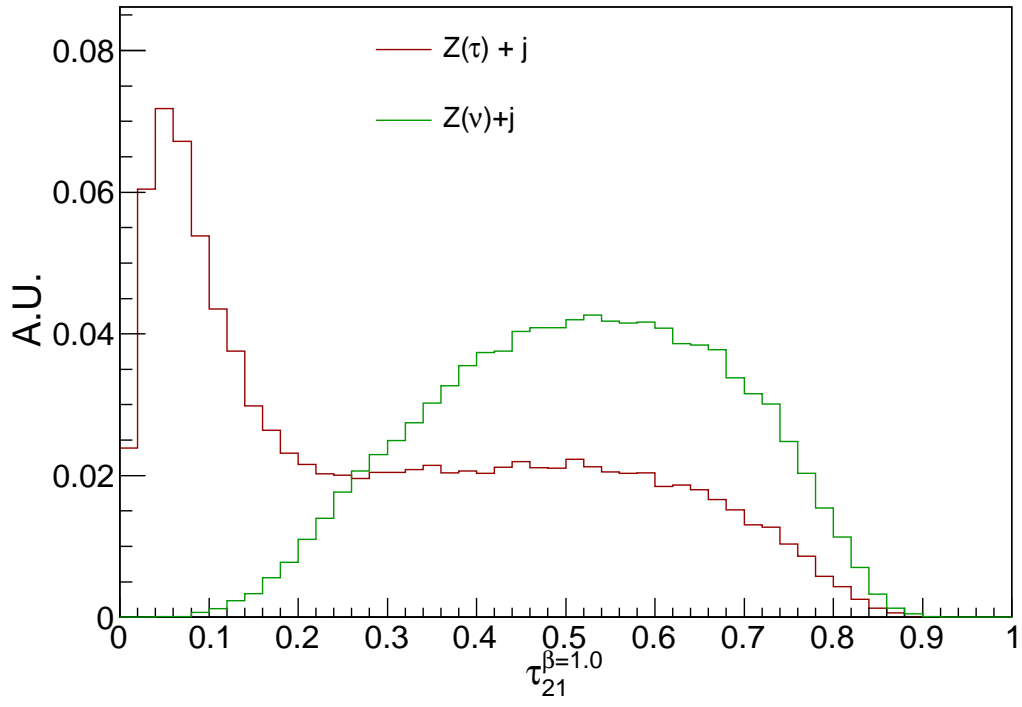


Figure 31: Subjettiness ratio τ_{21} for angular coefficient $\beta = 1.0$ (distribution has been normalized to unit area under curve)

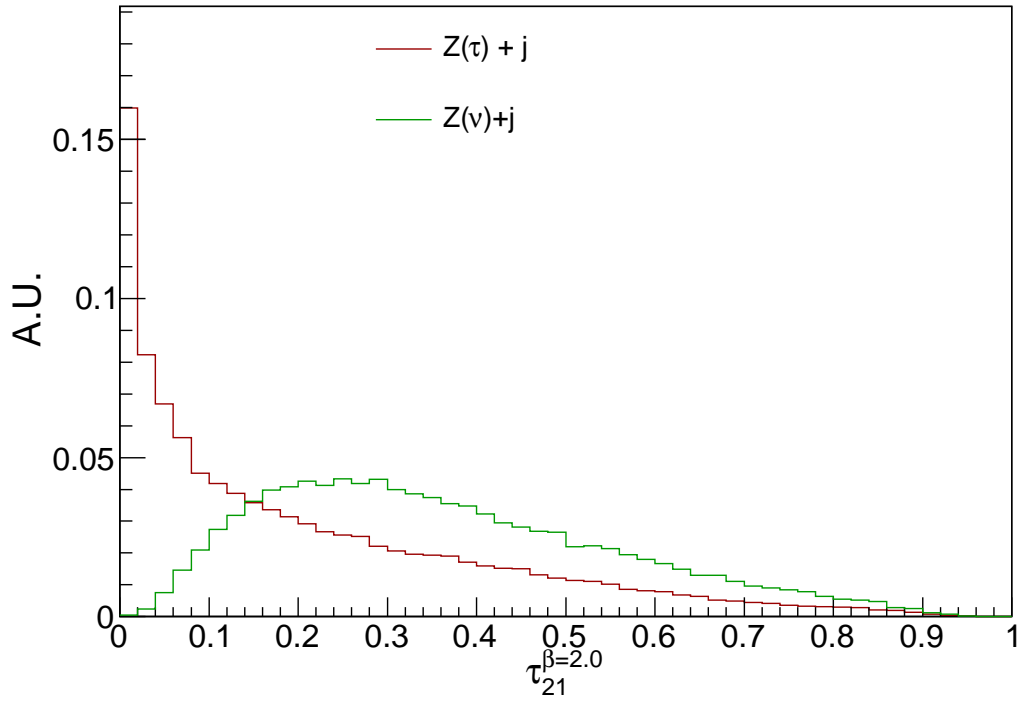


Figure 32: Subjettiness ratio τ_{21} for angular coefficient $\beta = 2.0$. (distribution has been normalized to unit area under curve)

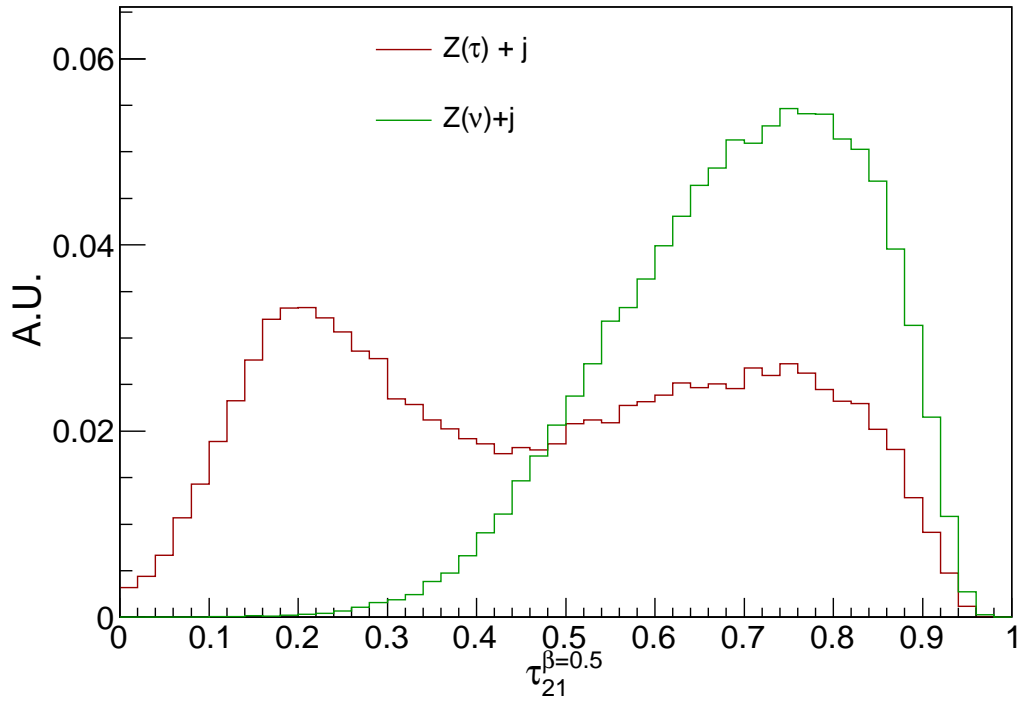


Figure 33: Subjettiness ratio τ_{21} for angular coefficient $\beta = 0.5$ (distribution has been normalized to unit area under curve)

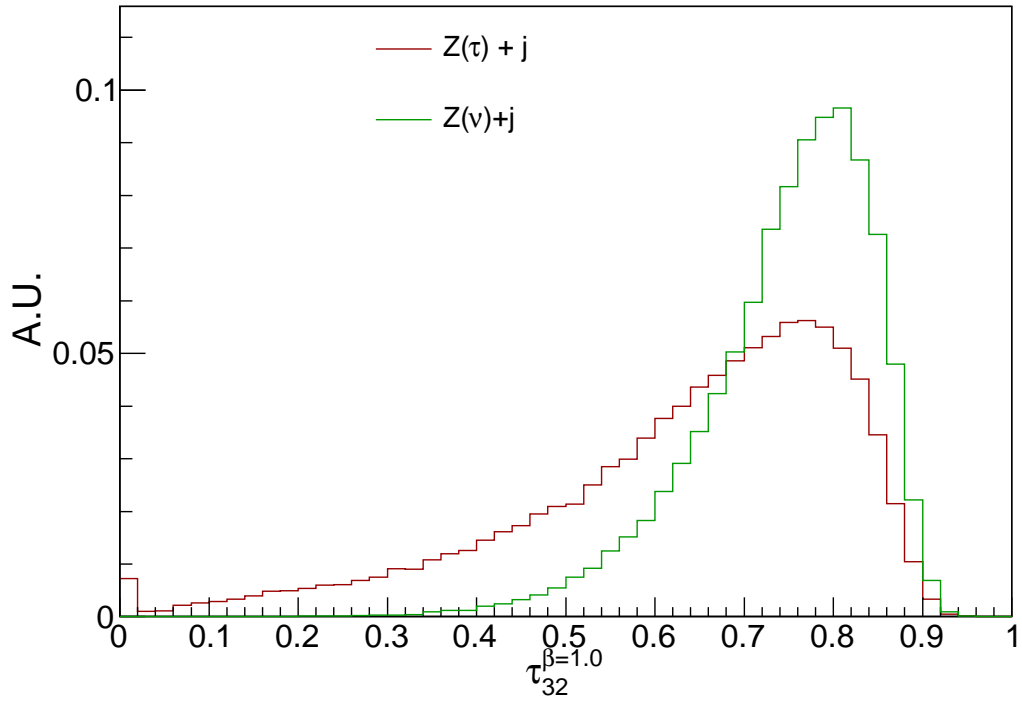


Figure 34: Subjettiness ratio τ_{32} for angular coefficient $\beta = 1$. (distribution has been normalized to unit area under curve)

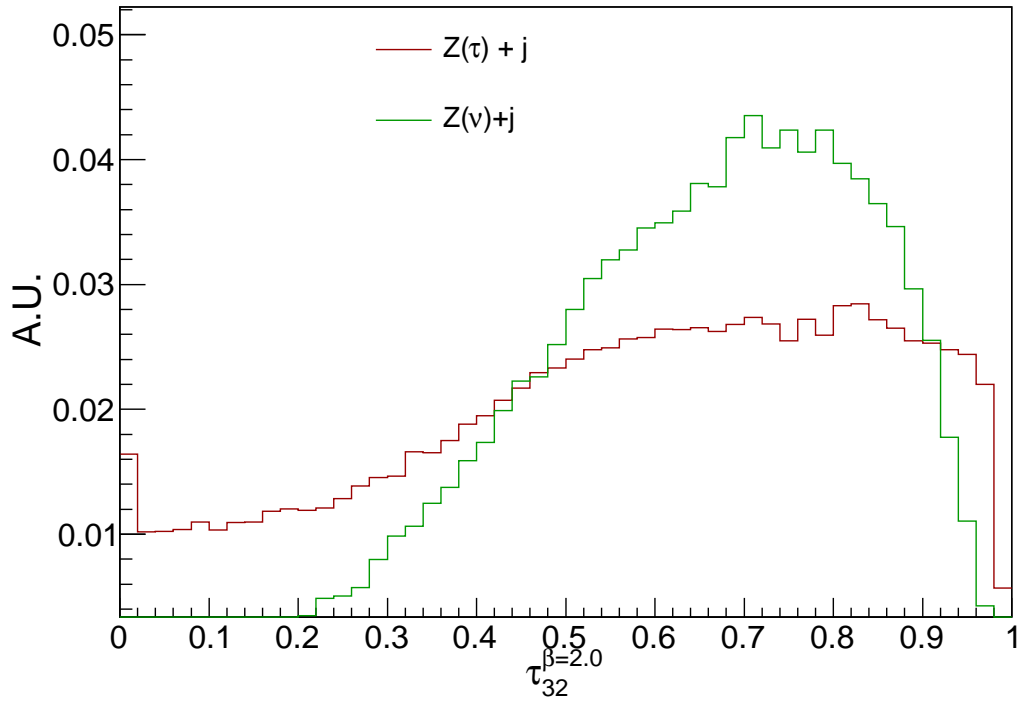


Figure 35: Subjettiness ratio τ_{32} for angular coefficient $\beta = 2$. (distribution has been normalized to unit area under curve)

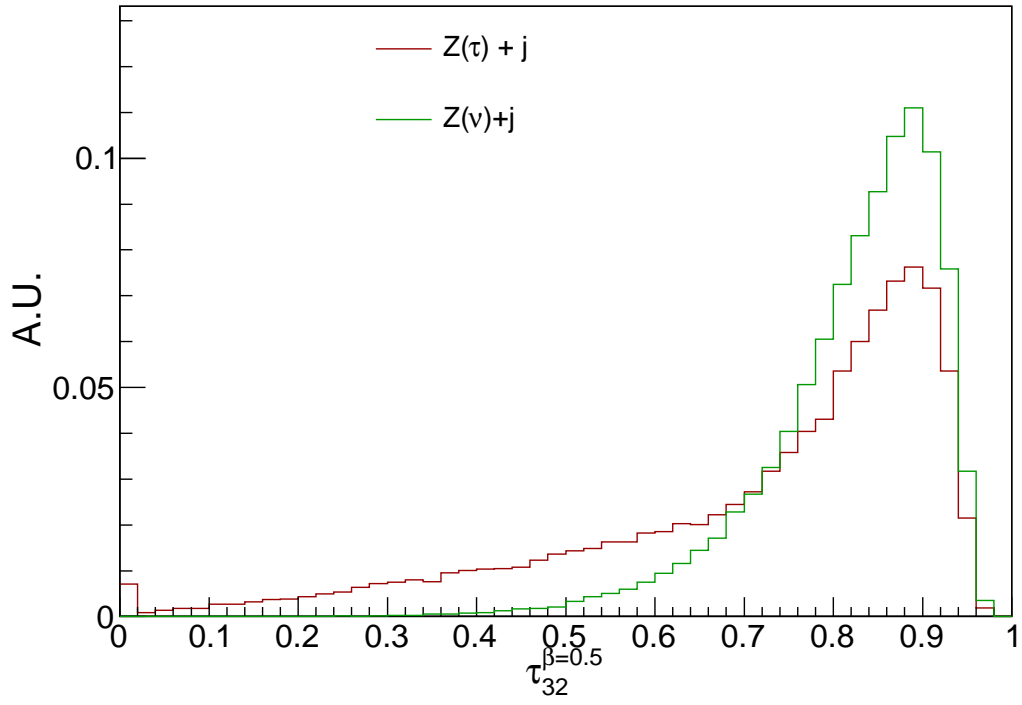


Figure 36: Subjettiness ratio τ_{32} for angular coefficient $\beta = 0.5$ (distribution has been normalized to unit area under curve)

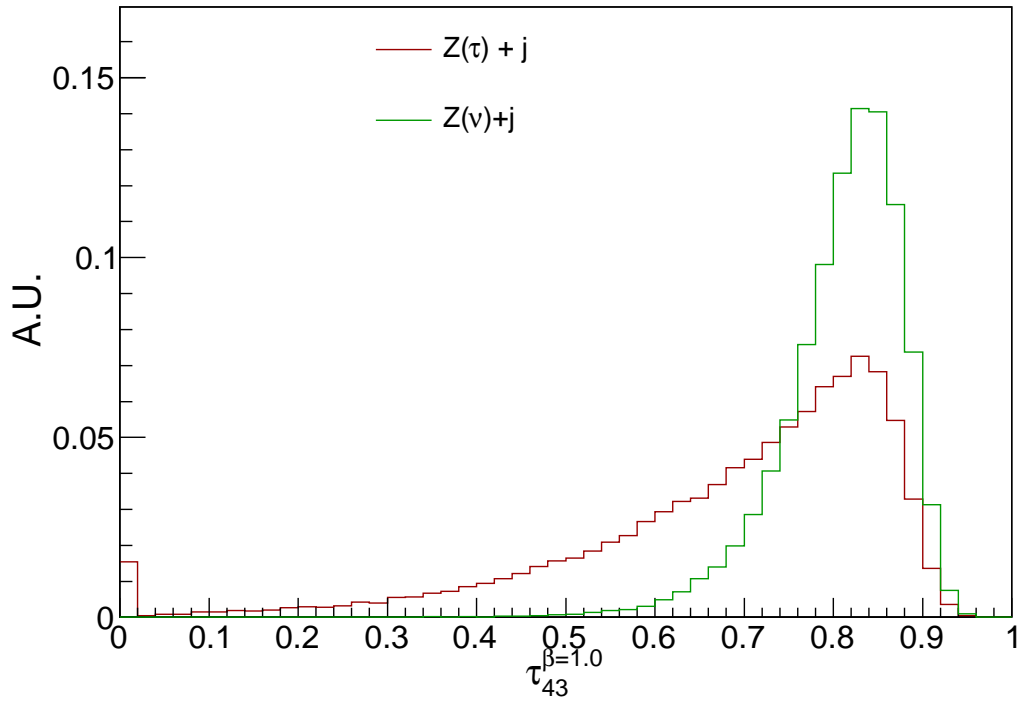


Figure 37: Subjettiness ratio τ_{43} for angular coefficient $\beta = 1$. (distribution has been normalized to unit area under curve)

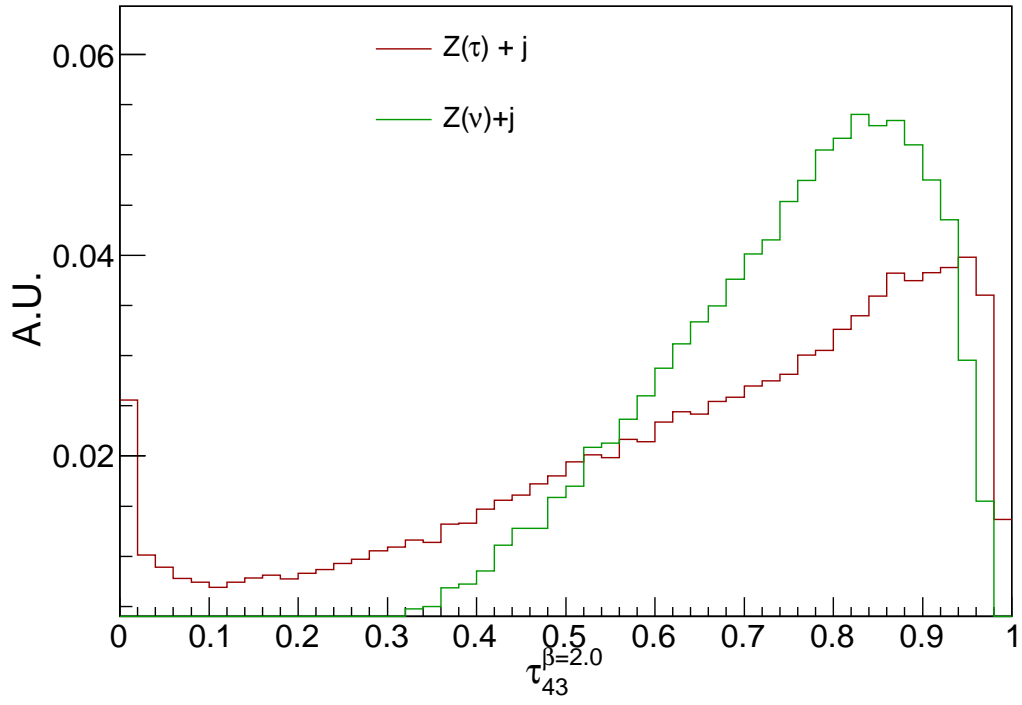


Figure 38: Subjettiness ratio τ_{43} for angular coefficient $\beta = 2$. (distribution has been normalized to unit area under curve)

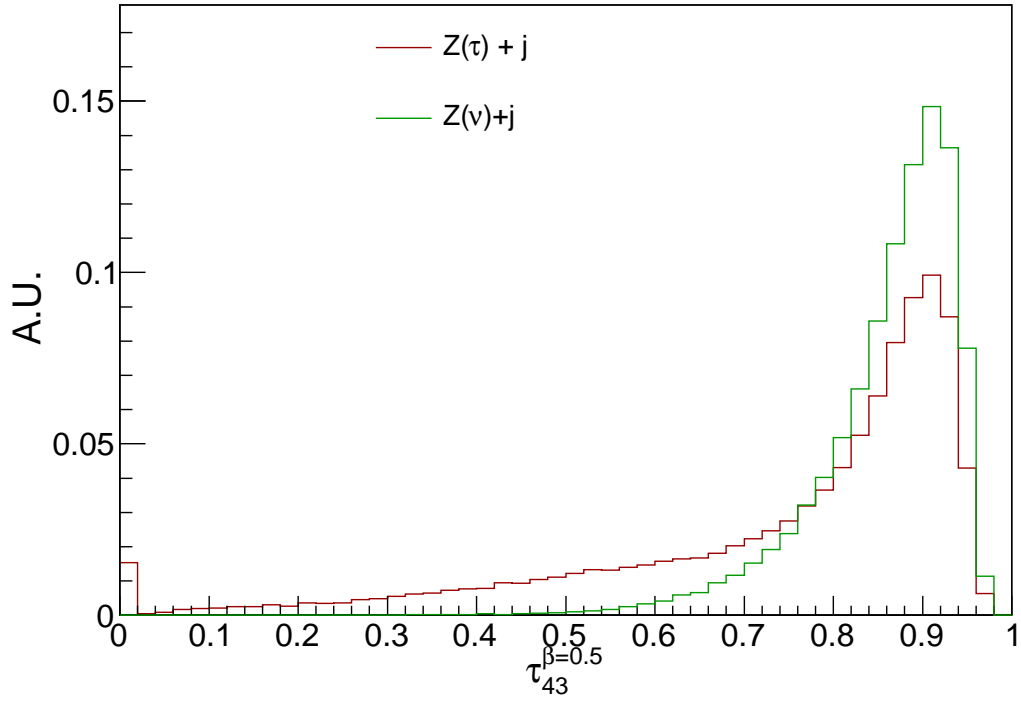


Figure 39: Subjettness ratio τ_{43} for angular coefficient $\beta = 0.5$ (distribution has been normalized to unit area under curve)

References

- [1] ([arXiv:0807.0234 \[hep-ph\]](https://arxiv.org/abs/0807.0234)): **Leandro G. Almeida, Seung J. Lee, Gilad Perez, George Sterman, Ilmo Sung, Joseph Virzi**: Substructure of high- p_T Jets at the LHC. [4](#)
- [2] ([arXiv:0802.2470 \[hep-ph\]](https://arxiv.org/abs/0802.2470)): **Jonathan M. Butterworth, Adam R. Davison, Mathieu Rubin, Gavin P. Salam**: Jet substructure as a new Higgs search channel at the LHC. [4](#)
- [3] (<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](#)