

Preforming a Rivet Analysis For Charged Jet Cross Sections and Fragmentation Functions in PP Collisions at $\sqrt{s} = 7$ TeV

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I. INTRODUCTION

A. Purpose of Proton-Proton Collisions

Protons along with neutrons are contained in the nucleus of every atom and are themselves made up of smaller particles called quarks bound together by gluons. There is a phenomenon called confinement in which a quark has never been observed in isolation and quarks have only been observed bound together to create particles like protons and neutrons. By colliding nuclei at sufficiently high energies, we are able to create extreme enough conditions in which the nuclei can melt into each other which frees the quarks from their gluon bindings called the quark-gluon plasma (QGP).

Proton-proton collisions provide an important reference for studies of the QGP. The data collected from pp collision events can be used to compare to Monte Carlo event generators through the use of a program called Rivet.

B. Rivet

Rivet [1] is an acronym that stands for Robust Independent Validation of Experiment and Theory and is used as a method of validation for Monte Carlo event generators. This is significant because validation of a Monte Carlo event generator allows for researchers to see how well Monte Carlo models agree with data. Rivet also allows for the comparison of different models. See fig. 1.

Rivet works by taking in output from Monte Carlo event generators in the form of a HepMC file and then implements an experimental analysis of those data. Analyses are based on a published paper. The author of the analysis would write code that would preform selections and other analytical tools that were used in the paper on the Monte Carlo simulated events. What makes Rivet so great is that the code needed to preform the analysis is based in C++ and relatively easy to write.

II. THE ANALYSIS

A. The Paper

The paper I implemented presented measurements of charged jet spectra and fragmentation functions at 7 TeV

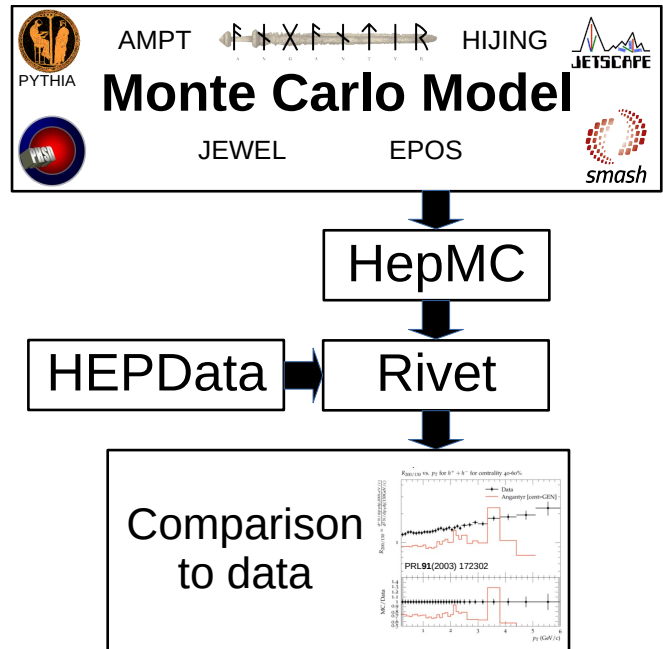


FIG. 1. Flow chart showing the role of Rivet in comparisons between models and data.

using the ALICE experiment in the LHC [2]. In the paper there are four major plots we are trying to reproduce with Rivet. The plots can be separated into two major categories, the jet spectra and the fragmentation functions. One plot corresponds to the spectra while three of them correspond to different transverse momentum (p_T) ranges of fragmentation functions.

1. Jet Spectra

The jet spectra are measured for $5 < p_T < 100$ GeV/c with a resolution parameter $R = 0.4$ with the anti- k_T jet finder were reconstructed from charged tracks within $|\eta| < 0.9$, omitting a minimum p_T . The spectra were normalized as a cross section and are calculated as

$$\frac{d^2\sigma}{d\eta dp_T}(p_T^{chjet}) = \frac{1}{\mathcal{L}^{int}} \frac{\Delta N_{jets}}{\Delta p_T \Delta \eta}(p_T^{chjet}) \quad (1)$$

The measurements from the paper are shown in fig. 2.

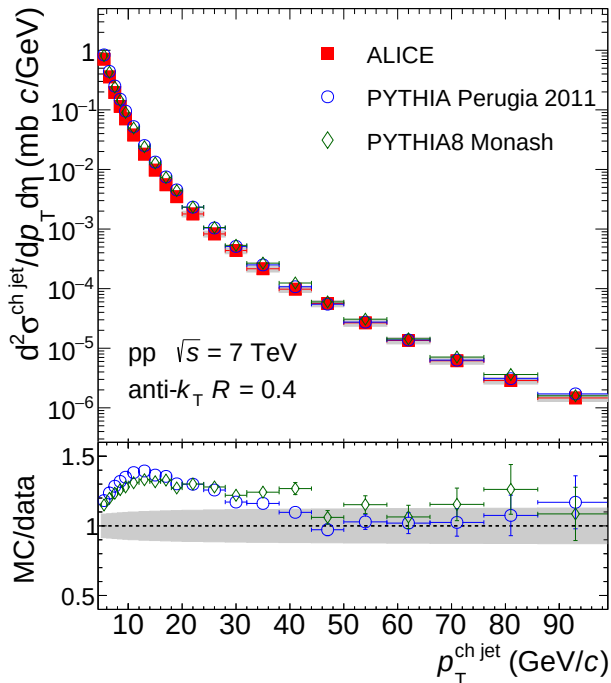


FIG. 2. Jet spectra from [2]

2. Fragmentation Function

The fragmentation functions were sorted into three bins going from 5–10 GeV/c to 10–15 GeV/c and finally to 15–20 GeV/c. For the fragmentation functions charged jets with a resolution parameter $R = 0.4$ were reconstructed from charged tracks with $p_T > 0.15$ GeV/c and within $|\eta| < 0.9$ measured as a function of $z^{ch} = p_{T,particle}/p_{ch,jet}$ represented by

$$\frac{1}{N_{jets}} \frac{dN}{dz^{ch}} \quad (2)$$

Results from the paper are shown in fig. 3.

B. Building the Analysis

The Rivet analysis is split up into three major functions `init()`, `analyze(const Event& event)`, `finalize()`. The `init()` function is run once at the beginning of the analysis, `analyze(const Event& event)` is run once per event, and `finaliza()` is run once at the end of the analysis. To keep through organized we will discuss what is done in each section separately.

1. Initialize

We begin in the `init` function with the creation of two objects of the `ALICE::PrimaryParticles` class since the paper was done using the ALICE experiment. The definition used by ALICE for primary particles is easily implementable through Rivet's available classes. Two objects were created due to how the fragmentation functions have a p_T cut off at 0.15 GeV/c so one object represents the particles that would go into the fragmentation functions while the other represents all the particles down to 0 p_T and would go into the jet spectra. The `ALICE::PrimaryParticles` object created for the jet spectra also houses more selections for specific particles as to further emulate what was done in the paper. The particle selections are for $\pi^\pm$, $K^\pm$, p ($\bar{p}$), $e^\pm$, and $\mu^\pm$. After the `ALICE::PrimaryParticles` is the declaration of our jet finding algorithm, the anti- k_T algorithm implemented in FastJet [3, 4], with a resolution parameter of $R = 0.4$. At the end of the `init` function we book our histograms which are filled in the `analyze` section and are necessary if we are to have plots as an output.

2. Analyze

The `analyze` function begins by applying the objects created in the `init` function onto each event. For example, each event generated by our Monte Carlo event generator of choice would run through the `analyze` function and have the selections defined in the declaration of the object applied to the event which would then be cached. This process is what happens for both the fragmentation function and the jet spectra objects. After the objects are applied we extract the individual particles using a Rivet class called `Particles`. With the individual particles extracted the jet spectra set is then run through FastJet which will give us all the jets present in the data set. Along with the finding of jets for the spectra an underlying event subtraction was implemented to the spectra as well. We then loop through all jets in the event and fill one of the histograms mentioned earlier with the jets p_T and the underlying event subtracted from that. After the spectra loop we have to run the fragmentation function data through FastJet in order to loop through all of the jets in that set. Inside of the jet loop we have another loop that goes through every particle in the jet and fills the p_T of the particle over the p_T of the jet into the corresponding histogram based off of the p_T of the jet. For example, if a jet of 8 GeV/c is run through the loop it would fall into the bin of 5–10 GeV/c and the 5–10 GeV/c histogram would be filled with the p_T of the individual particles over the p_T of the jet. This process goes for all the jets in the set and is split into three sorting bins 5–10 GeV/c, 10–15 GeV/c, and 15–20 GeV/c.

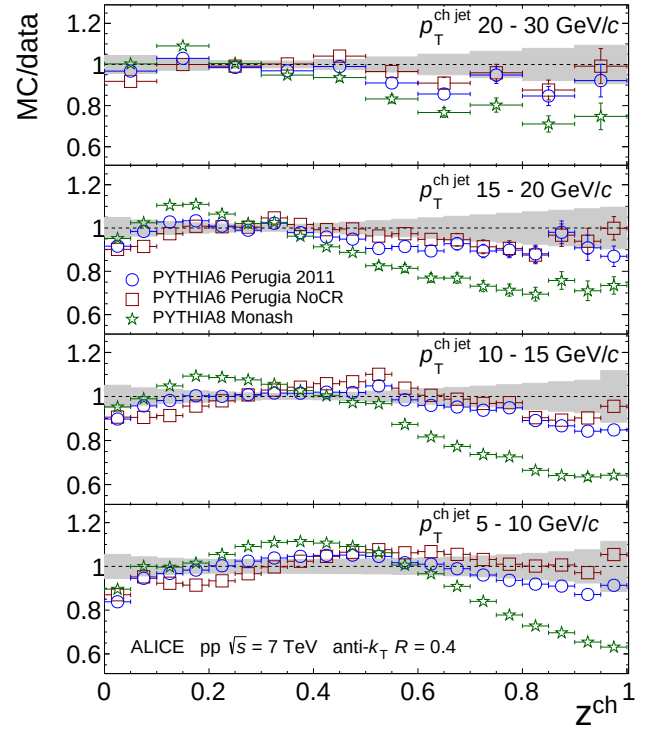
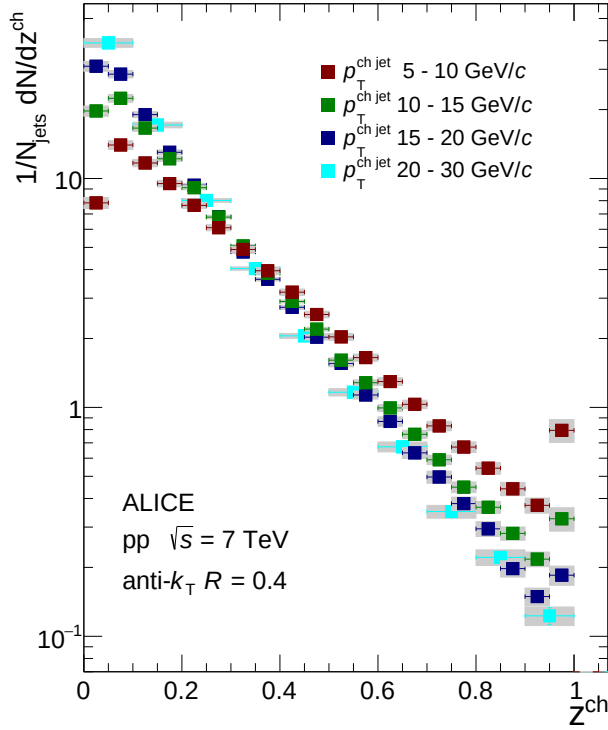


FIG. 3. Jet spectra from [2]

3. Finalize

The finalize function is relatively short and houses one of the most important parts of the analysis, the normalisation. The histograms are normalized based off of eq. 1 for the jet spectra and eq. 2 for the fragmentation functions.

C. Results

Comparisons to PYTHIA [5] Monash [7] are shown in fig. 4. Note that this is the same as one of the calculations done in the paper, allowing direct comparisons. Unfortunately we were not able to reproduce the calculations exactly as the primary author who did these calculations is unfortunately deceased. We were able to identify that the particles included only $\pi^\pm$, $K^\pm$, p ($\bar{p}$), $e^\pm$, and $\mu^\pm$, excluding the $\Sigma^\pm$, through comparisons to these models. Comparisons between our calculations and those in the paper are shown in fig. 5.

Two meetings were had with the jet working group in ALICE in order to show our results and have the analysis approved. Since we couldn't identify what the issues were, due to the reasons stated above, the approval is pending. We decided we would follow this by having other students implement analyses where there are still people around to answer questions - specifically next semester undergraduates at UTK will implement these

analyses [8–10]. This is progressing towards being the first approved Rivet jet analysis in ALICE.

D. Comparisons with JETSCAPE

As the analysis reached completion we found it intriguing to use the Monte Carlo generator JETSCAPE to see how well it compared so the one we had been using PYTHIA, specifically PYTHIA 8.186. This [11] is a paper discussing JETSCAPE in pp including comparisons with the same data. The plots of this comparison can be seen in fig. 6. It is important to note that the JETSCAPE line was created with a total of 10,000 events which is several orders of magnitude lower than the PYTHIA line. To generate these JETSCAPE data we generated 10 bins of 1,000 events ranging the p_T of the hard interaction from 5 GeV/c to 100 GeV/c. We are not certain of the reason as to why the 15–20 GeV/c fragmentation function JETSCAPE line is as low as it is but that leads to further research into the topic as these are some of the first plots showing a comparison between JETSCAPE using any Rivet analysis. This is also the first analysis showing that JETSCAPE's HepMC output is usable for Rivet. I plan to follow this work up by using JETSCAPE and existing Rivet analyses in the Rivet repository to see how well JETSCAPE compares to PYTHIA.

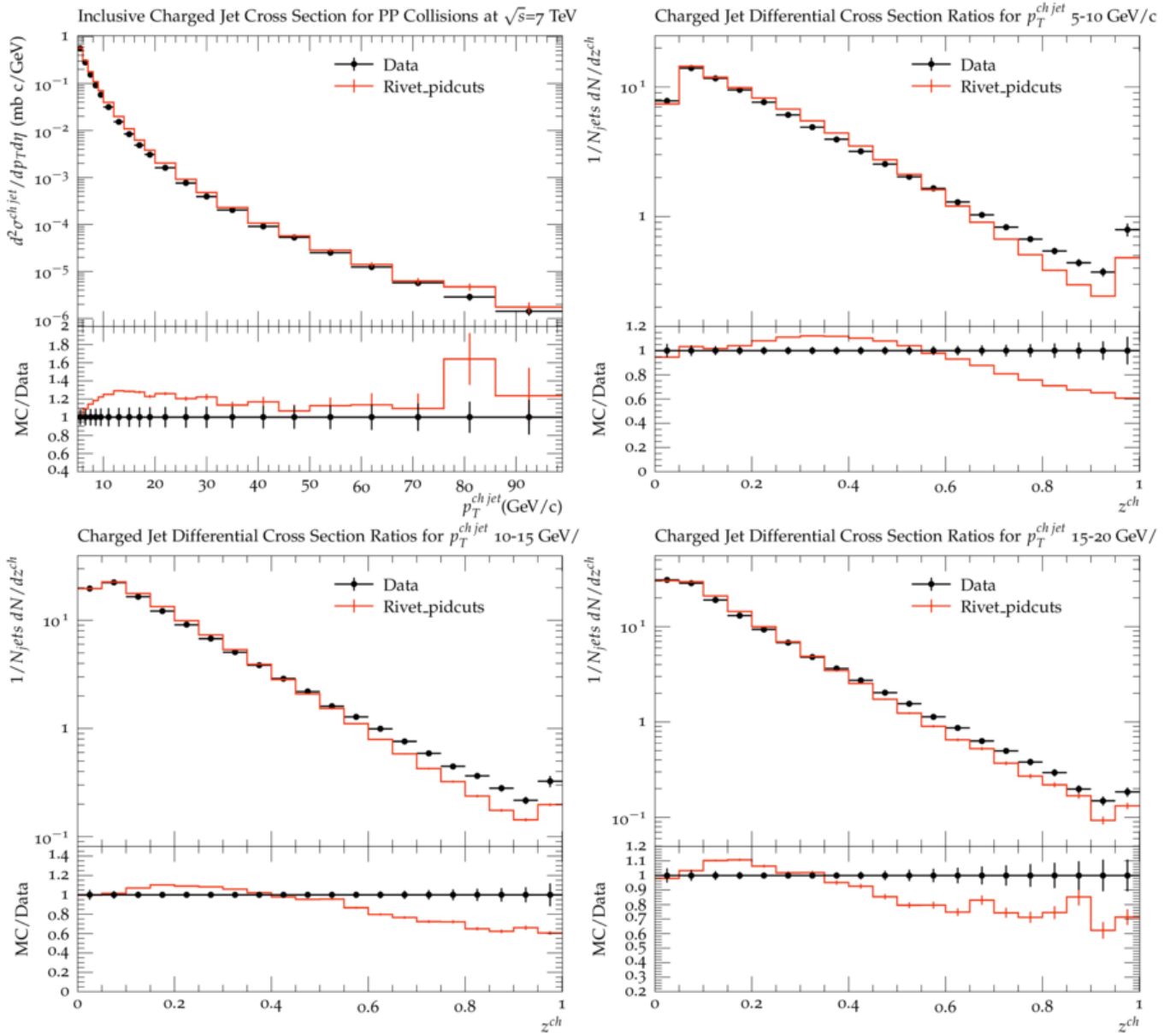


FIG. 4. Results from [2] compared to PYTHIA [5] Angantyr [6].

III. WHAT I LEARNED

- git versioning software
- C++
- Rivet
- Basics of heavy ion physics and jet physics
- How to work collaboratively in a group, particularly in large collaborations
- Practice giving presentations - gave two working group presentations

• Latex

Coming into this program I had next to no expectations for what I was going to do and I came in with only one goal and that was to get experience in some way or another. Whether I achieved that goal feels more complicated than it should be and relates to how the program was set up due to the pandemic that is happening, but I will answer objectively paying no mind to the remote nature of the program.

The objective answer is yes, I did achieve my goal of attaining experience. I was exposed to what it is like to work in a team and to do tasks that might not have a written out solution, as is the nature of research. I

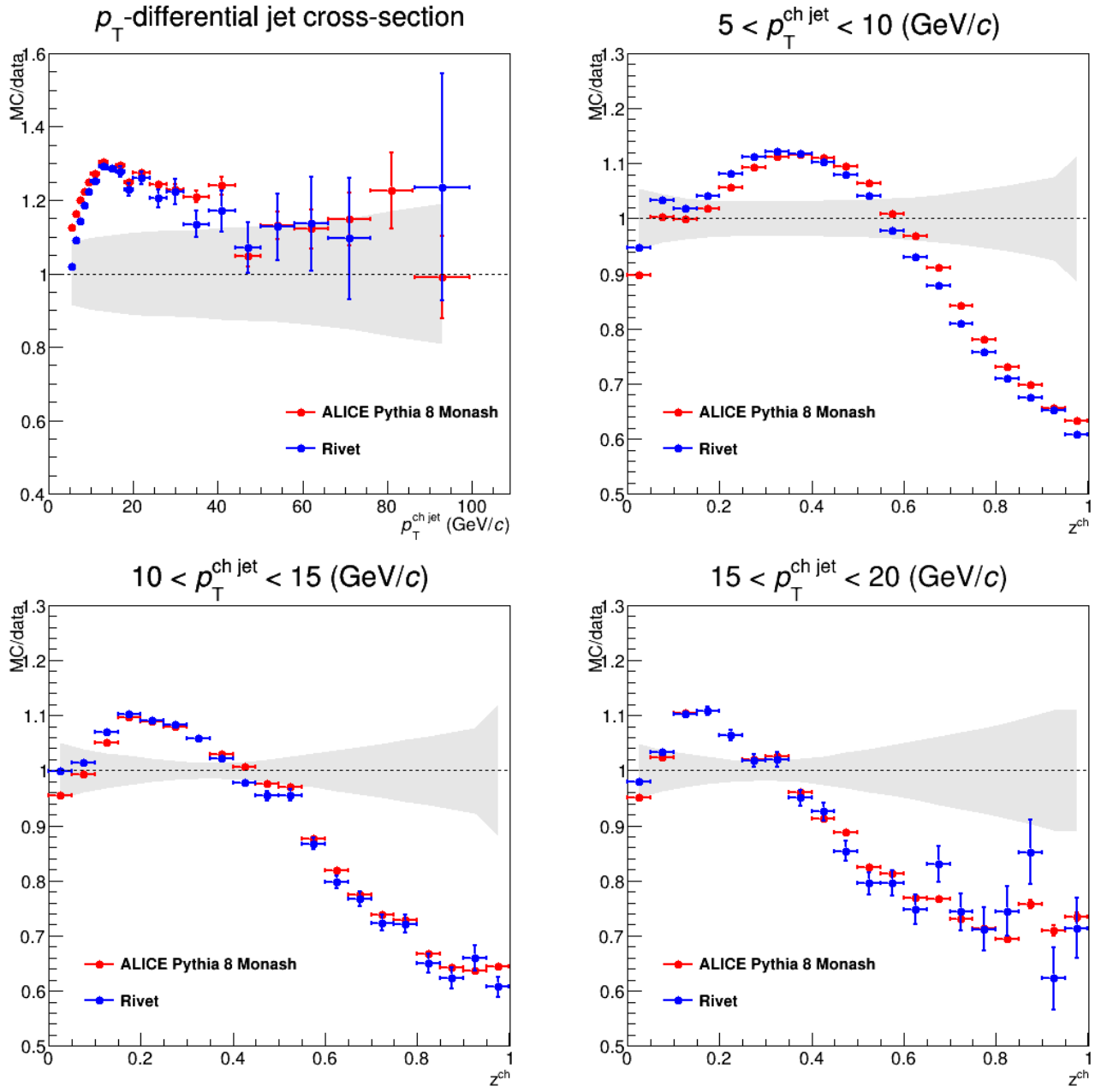


FIG. 5. MC/data from [2] compared to Rivet from Fig.4

learned about presenting to working groups as well as how they operate. I was exposed to knowledge about particle physics that I hadn't know about before, specifically about the QGP and about the existence of jets. I learned how to navigate the Linux command line as well as the basics of C++. Monte Carlo generators were not something that I knew much about prior to this experience and I learned not just how they work but methods of validation and how many different variations there are. Watching the CERN lectures provided me with a wealth of information that was equally challenging to un-

derstand and interesting to hear about and helped me further learn the tools physicists employ in research. All of these are amazing and more than I could ask for but it all came with a caveat of the remoteness of the program which I feel is a necessary evil in order to stay safe in our current world.

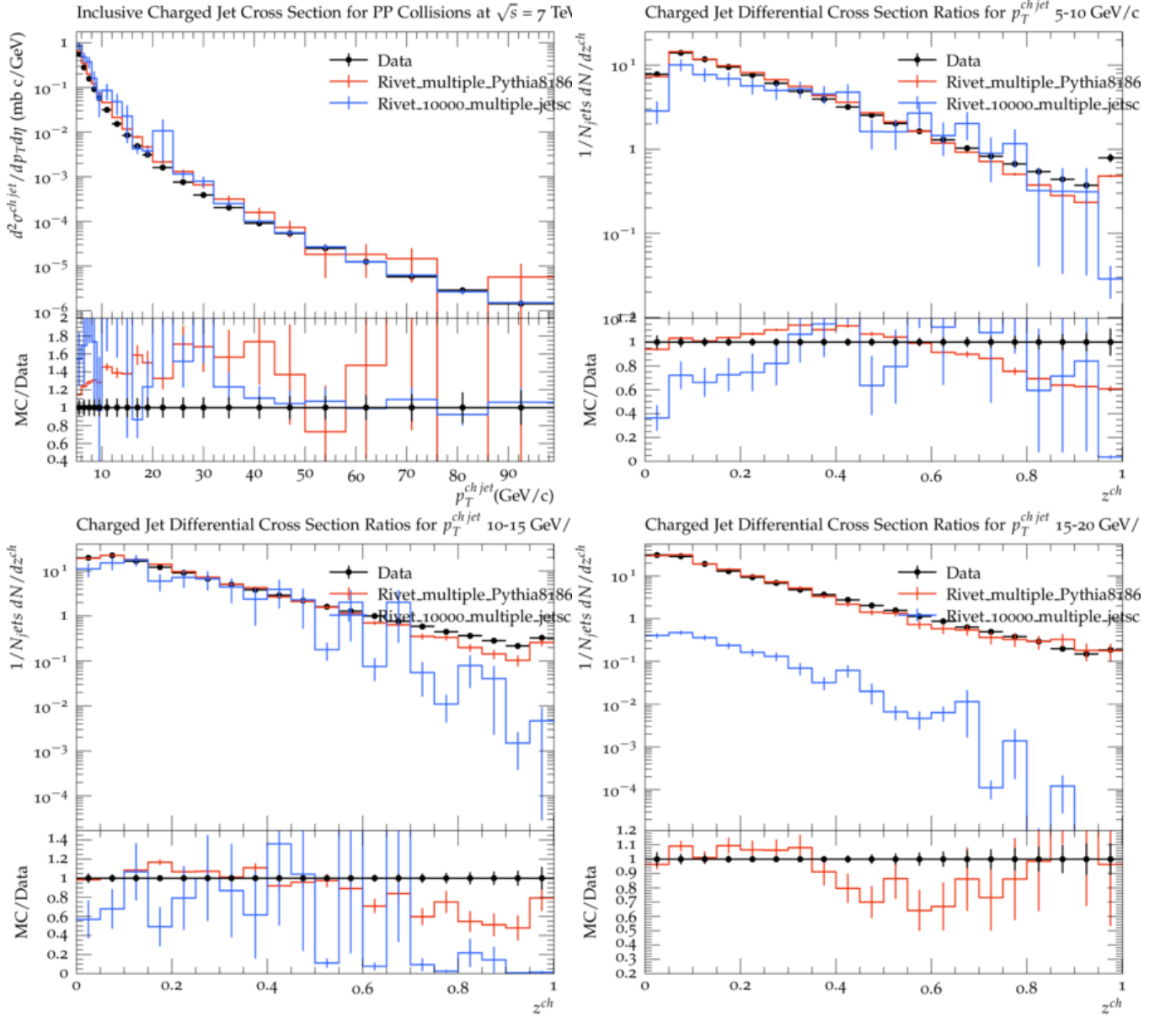


FIG. 6. Results from [2] compared to PYTHIA [5] Angantyr [6] and JETSCAPE.

IV. CONCLUSION

During my time in the program, I participated in building a Rivet analysis for an ALICE paper and using that analysis to make some of the first comparisons of JETSCAPE to another Rivet analysis. Two meetings were held for the ALICE jet working group in order to get the analysis approved. Although approval is pending, I believe we have made a dent into getting that working group up to speed with Rivet, which was another goal of pushing for approval of this analysis.

V. ACKNOWLEDGEMENTS

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