High Energy Physics - Phenomenology Midyear Exercises

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Midyear Exercise 1

Production Process

The pythia initialization of the simulation:

```
Top:all = on
Main:numberOfEvents = 10000
Beams:idA = 2212
Beams:idB = 2212
Beams:eCM = 13000.
```

The simulation is run using main42 files from Pythia8245

The production channels which produces the ttbar are shown below:

```
Top:gg2ttbar
Top:qqbar2ttbar
Top:qq2tq
Top:ffbar2ttbar
Top:ffbar2tqbar
Top:gmgm2ttbar
Top:ggm2ttbar
```

The source of all the top-antitop production is from the pythia online manual [1]

1. Gluon - gluon to top-antitop
   asdas
2. Quark - antiquark to top-antitop by gluon exchange
   asdasd
3. Quark - quark/antiquark to top-quark/antiquark by t-channel exchange of W boson
   asdasd
4. Lepton-antilepton to top-antitop by s-channel exchange of virtual photon or Z boson
   asdasdasd
5. Lepton-antilepton to to top-antiquark by s-channel exchange of W boson
   asdasda
6. Photon-photon to top-antitop
   asdasd
7. Gluon-photon to top-antitop
   asdasd

Decay Process

In the SM model, the decay $t \to W^+ + b$ has a branching ratio very close to 100%. The same goes for its anti counterpart. Now the the W boson has these decay channels with their branching ratios:

W^+ Decays

Hadronic

- $W^+ \rightarrow \bar{b} + c$ (0%)
- $W^+ \rightarrow \bar{d} + c$ (1.5%)
- $W^+ \rightarrow \bar{s} + c$ (29.2%)
- $W^+ \rightarrow \bar{d} + u$ (29.4%)
- $W^+ \rightarrow \bar{s} + u$ (1.7%)

Leptonic

- $W^+ \rightarrow e^+ + v_e$ (10%)
- $W^+ \rightarrow \mu^+ + v_\mu$ (10%)
- $W^+ \rightarrow \tau^+ + v_\tau$ (9.7%)

W^- Decays

Hadronic

- $W^- \rightarrow b + \bar{c}$ (0%)
- $W^- \rightarrow d + \bar{c}$ (1.4%)
- $W^- \rightarrow s + \bar{c}$ (27.4%)
- $W^- \rightarrow d + \bar{u}$ (27.8%)
- $W^- \rightarrow s + \bar{u}$ (1.5%)

Leptonic

- $W^- \rightarrow e^- + \bar{v_e}$ (9%)
- $W^- \rightarrow \mu^- + \bar{v_\mu}$ (9.2%)
- $W^- \rightarrow \tau^- + \bar{v_\tau}$ (9.1%)

These decay channels and branching ratio's are obtain using pythia8312. See the Wneg_decay.log and Wplus_decay.log in this repository link.

Reconstruction of Top

Using the event generation of PYTHIA, the top is reconstructed using the MC_TTBAR Analysis of Rivet [2].

```
ChargedLeptons lfs(FinalState(Cuts::abseta < 4.2 && Cuts::pT > 30*GeV));
declare(lfs, "LFS");
```

This code block defines the object lfs by getting the final state particles that have $\eta = |4.2|$ and $pT > 30$ GeV. The 4.2 η value is from the limitation of the detector. The purpose of the 30 GeV pT cut is for reduction of soft backgrounds. Soft background interactions are usually in non-perturbative processes regions. This means that the interaction strength (e.g. Strong force) is too strong for perturbation theory to be useful. Overall, this line of code is for counting the lepton particle decays.

```
1 VetoedFinalState fs(FinalState(Cuts::abseta < 4.2));
2 fs.addVetoOnThisFinalState(lfs);
```

This code block defines the object fs which is all the particle decays by using the $\eta = |4.2|$ cut. The line 2 exclude the lepton particles from the previous code block.

```
declare(FastJets(fs, JetAlg::ANTIKT, 0.6), "Jets");
declare(MissingMomentum(fs), "MissingET");
```

This line of code declare the b-jet decay and the missing transverse energy for the neutrino by products.

Proceeding to the analyze function of the MC_TTBAR Analysis.

```
const ChargedLeptons& lfs = apply<ChargedLeptons>(event, "LFS");
MSG_DEBUG("Charged lepton multiplicity = " << lfs.chargedLeptons().size());
for (const Particle& lepton : lfs.chargedLeptons()) {
    MSG_DEBUG("Lepton pT = " << lepton.pT());
}
```

This code block applies the ChargedLepton object to the event, which gets the Lepton Final State of the event

```
size_t nLeps = lfs.chargedLeptons().size();
bool leptonMultiFail = _mode == 3 && nLeps == 0; // non-all-hadronic
leptonMultiFail |= _mode == 2 && nLeps != 2; // dilepton
leptonMultiFail |= _mode == 1 && nLeps != 1; // single lepton
leptonMultiFail |= _mode == 0 && nLeps != 0; // all-hadronic
if (leptonMultiFail) {
    MSG_DEBUG("Event failed lepton multiplicity cut");
vetoEvent;
}
```

nLeps contain the number of lepton decays of the $t\bar{t}$. This code block performs the lepton multiplicity cut. It can only fail if the mode does not match the number of leptons.

```
const Vector3& met = apply<MissingMomentum>(event, "MissingET").vectorMissingPt();
MSG_DEBUG("Vector pT = " << met.mod() << " GeV");
if (_mode > 0 && met.mod() < 30*GeV) {
    MSG_DEBUG("Event failed missing ET cut");
```

```
    vetoEvent;
}
```

This code block applies the missing transverse energy cut. The cut fails if the missing transverse energy is too small. Which is for non-hadronic decay, it must have a value greater than 30GeV.

```
const FastJets& jetpro = apply<FastJets>(event, "Jets");
const Jets jets = discardIfAnyDeltaRLess(jetpro.jetsByPt(Cuts::pT > 30*GeV), lfs.chargedLeptons(), 0
if (     _mode == 0 && jets.size() < 6)  vetoEvent; // all-hadronic
else if (_mode == 1 && jets.size() < 4)  vetoEvent; // single lepton
else if (_mode == 2 && jets.size() < 2)  vetoEvent; // dilepton
else if (_mode == 3 && nLeps == 1 && jets.size() < 4)  vetoEvent; // non-allhadronic
else if (_mode == 3 && nLeps == 2 && jets.size() < 2)  vetoEvent;
MSG_DEBUG("Event failed jet multiplicity cut");
```

This code block performs the jet multiplicity cut. For the decay be possible, at mode = 0 (All Hadronic decay) must have 6 jets; at mode = 1 (One lepton decay) it must have 4 jets; at mode = 2 (dilepton decay) it must have 2 jets. Lastly for mode = 3, if the decay has 1 lepton decay it must have 4 jets and if it has 2 lepton decay it must have 2 jets.

Next differentiating the jets into a b-jet and a light jet (ljet).

```
Jets bjets, ljets;
for (const Jet& jet : jets) {
if (jet.bTagged())  bjets += jet;
else                ljets += jet;
}
MSG_DEBUG("Number of b-jets = " << bjets.size());
MSG_DEBUG("Number of l-jets = " << ljets.size());
if (bjets.size() != 2) {
  MSG_DEBUG("Event failed post-lepton-isolation b-tagging cut");
  vetoEvent;
}
if (_mode == 0 && ljets.size() < 4)  vetoEvent;
else if (_mode == 1 && ljets.size() < 2)  vetoEvent;
else if (_mode == 3 && nLeps == 1 && ljets.size() < 2)  vetoEvent;
```

The function used in differentiating the b jets from ljets is .bTagged(). Per decay of $t\bar{t}$, it must have 2 bjets always. So the cut will fail if the bjet number is not 2. In addition it will fail if mode = 0 (all hadronic) and the ljet is less than 4. The same goes for mode = 1 (single lepton decay) which must have ljet number of atleast 2.

```
FourMomentum ttpair = bjets[0].mom() + bjets[1].mom();
if (_mode == 0) {
ttpair += ljets[0].mom() + ljets[1].mom() + ljets[2].mom() + ljets[3].mom();
}
else if (nLeps < 2) {
    ttpair += ljets[0].mom() + ljets[1].mom();
    const FourMomentum lep = lfs.chargedLeptons()[0].mom();
    double pz = findZcomponent(lep, met);
    FourMomentum neutrino(sqrt(sqr(met.x()) + sqr(met.y()) + sqr(pz)), met.x(), met.y(), pz);
    ttpair += lep + neutrino;
}
if (nLeps < 2)  _h["tt_mass"]->fill(ttpair.mass()/GeV);
```

The ttpair comes from the bjets. If it is all hadronic, you must add the jets from the W boson decay (which is 4 jets). If it is a single lepton decay, you add the lepton decay, which is the lepton and the MET (neutrino), and the 2 jet decay.

Apprently this analysis did not include the mode 3 and mode 2 in calculating the ttbar. The same goes for constructing the W boson mass.

```
if (_mode < 2) {
    FourMomentum W(10*(sqrtS()>0.?sqrtS():14000.), 0, 0, 0);
    for (size_t i = 0; i < ljets.size()-1; ++i) {
```

```
    for (size_t j = i + 1; j < ljets.size(); ++j) {
        const FourMomentum Wcand = ljets[i].momentum() + ljets[j].momentum();
        MSG_TRACE(i << "," << j << ": candidate W mass = " << Wcand.mass()/GeV
        << " GeV, vs. incumbent candidate with " << W.mass()/GeV << " GeV");
        if (fabs(Wcand.mass() - 80.4*GeV) < fabs(W.mass() - 80.4*GeV)) {
            W = Wcand;
        }
    }
}
MSG_DEBUG("Candidate W mass = " << W.mass() << " GeV");
```

It started with a terrible W boson mass guess, and is replaced by better and better guesses. The theoretical value of W boson is 80.4 GeV, which is what the value of this code block approaches.

```
const FourMomentum t1 = W + bjets[0].momentum();
const FourMomentum t2 = W + bjets[1].momentum();
_h["W_mass"]->fill(W.mass());
_h["t_mass"]->fill(t1.mass());
_h["t_mass"]->fill(t2.mass());
```

This part of the code now calculates the t and $\bar{t}$ which has essentially the same mass. Since it cannot be determined whether W is the W^+ or W^- and which bjet is partnered to the W. So 2 top mass is calculated.

```
if (!inRange(W.mass()/GeV, 75.0, 85.0))  vetoEvent;
MSG_DEBUG("W found with mass " << W.mass()/GeV << " GeV");

_h["t_mass_W_cut"]->fill(t1.mass());
_h["t_mass_W_cut"]->fill(t2.mass());
```

If there is no W boson mass found in the range 75.0 GeV to 85.0 GeV then it is not included in the analysis. The ?? b. contains the top reconstruction which has a W close to its theoretical value.

Shown below is the MC_TTBAR Analysis plots.

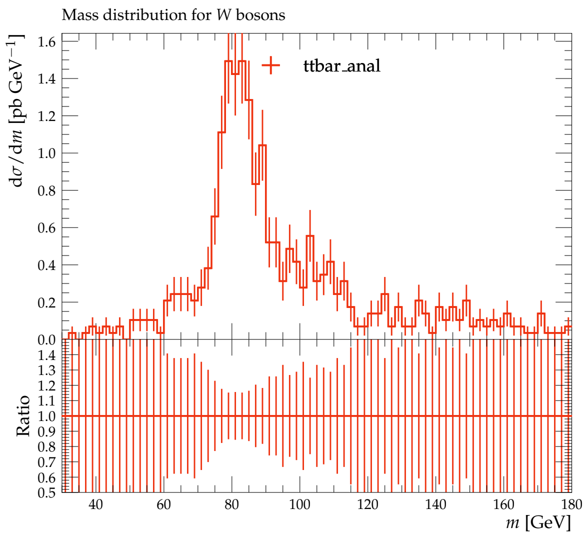
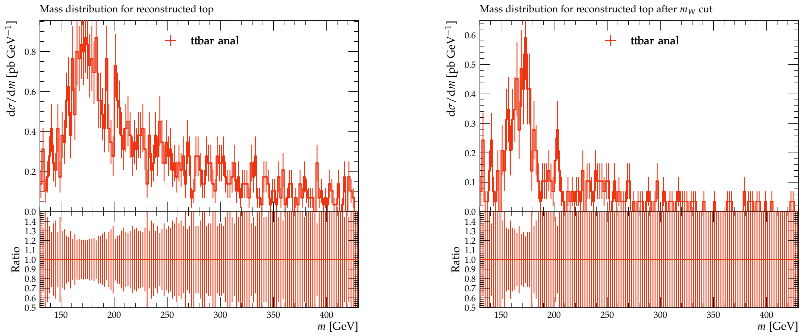


Figure 1: W boson mass distribution

As we can see here in the figure, there is a peak near 80.4 GeV, which suggest strongly that the reconstruction of the W boson tends to go to the theoretical. I do not know yet how to find the exact value in the graph and its uncertainty.



(a) top reconstruction with W boson

(b) top reconstruction without W boson found

Figure 2: top reconstruction

Here we can see that the reconstruction of the top mass is close to 173 GeV. It is close to the current accepted value of 172.76±0.3 GeV.

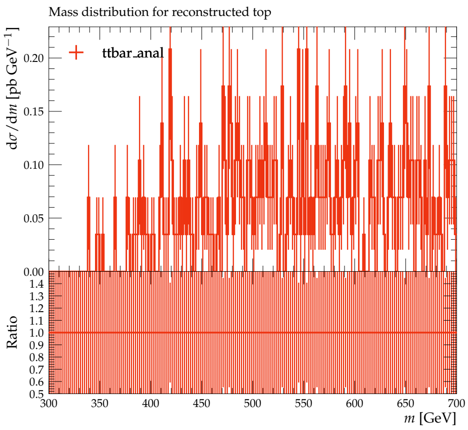


Figure 3: $t\bar{t}$ mass distribution

The $t\bar{t}$ mass is constructed by adding the momentum of the bjets and ljets depending on the mode. It is expected that the momentum is near 0.

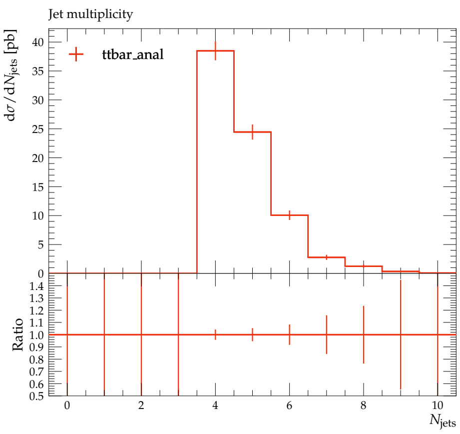
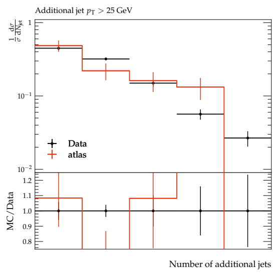


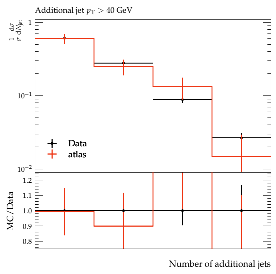
Figure 4: Jet multiplicity

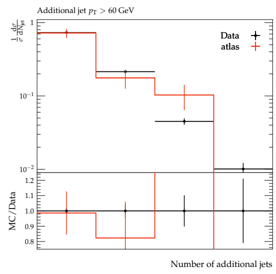
Finally, this figure shows how many jets are per event. We can see in the figure that majority of the time the decay is a single leptonic decay (2 bjet and 2 ljet). Surprisingly, there is no dileptonic decay as seen in the multiplicity.

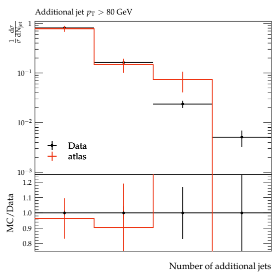
Comparisson to Actual Data

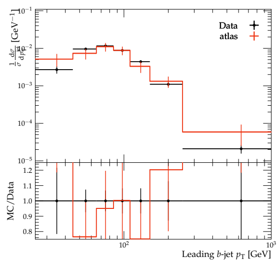
Using the ATLAS Collaboration paper on ttbar from 2016: https://arxiv.org/abs/1610.09978, which is the ATLAS_2017_I1495243 analysis from RIVET [3].
These are the comparison plots from the analysis.

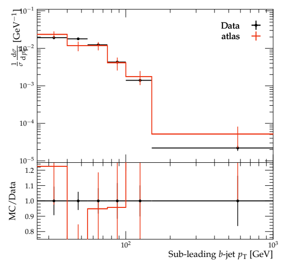


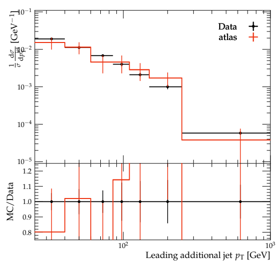


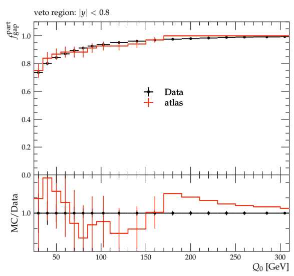


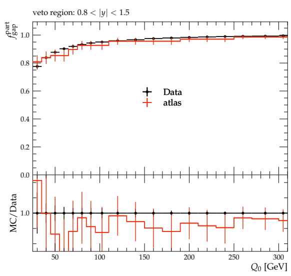


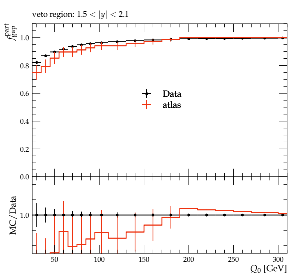


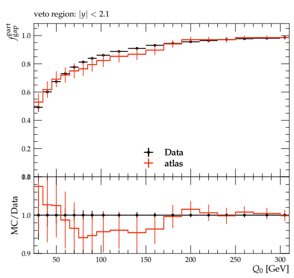


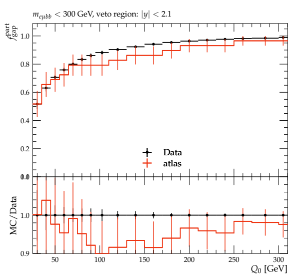


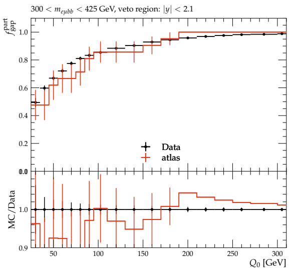


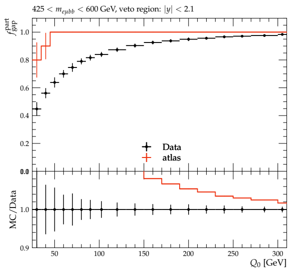


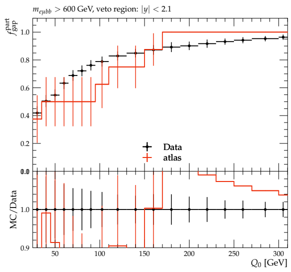


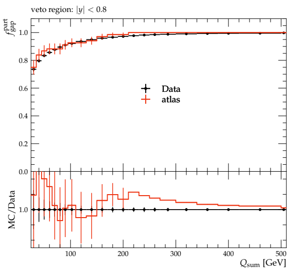


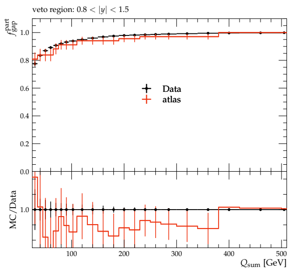


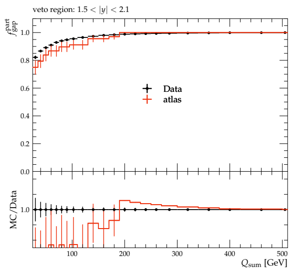


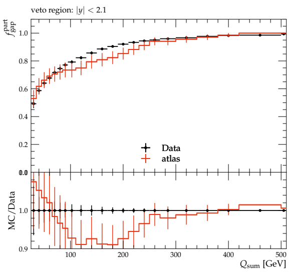


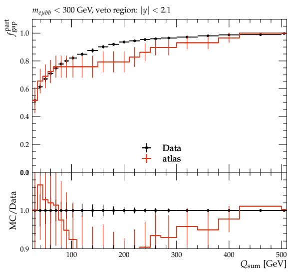


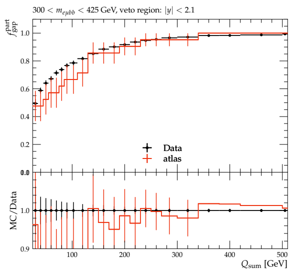


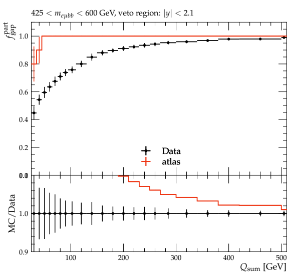


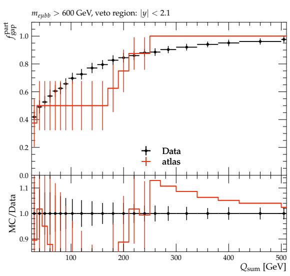












Upon looking at the graphs, it can be seen that the simulated data agree with the atlas data to a certain extent (I do not know how to quantify the similarness yet). The graph that has (I think) the greatest deviations is the 14th and 22th graph which is $425 < m_{e\mu bb} < 600$GeV, veto region: $|y| < 2.1$ and $425 < m_{e\mu bb} < 600$GeV, veto region: $|y| = 2.1$.

CheckMATE

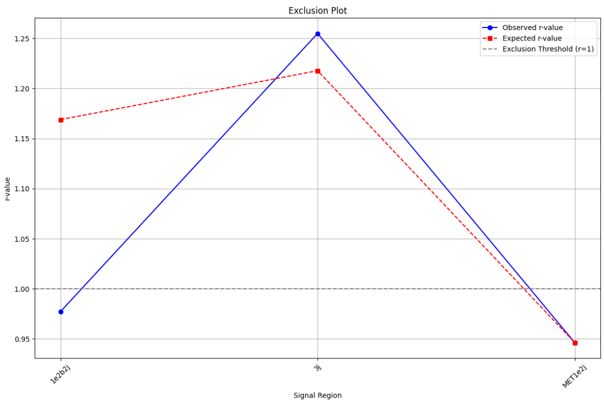


Figure 5: Exclusion plot

There are only 3 analysis that are within the $0.87 < r < 1.3$ region which is the atlas_1807_07447. The sr region at which this is possible are the 1e2b2j, 3j, and MET1e2j.

1. 1e2b2j Signal Region
   The "1e2b2j" signal region refers to events containing one electron, two b-tagged jets, and a total of two jets. This configuration is designed to target specific interactions that might indicate the presence of new physics, particularly those involving heavy particles decaying into multiple jets and leptons.
2. 3j Signal Region
   The "3j" signal region is characterized by events with a total of three jets. The selection criteria for this region help in separating standard model backgrounds from potential signals that may hint at new physics, as higher jet multiplicities can be indicative of complex decay processes involving heavy new particles.
3. MET1e2j Signal Region
   The "MET1e2j" signal region involves events with one electron, two jets, and significant missing transverse energy (MET). This region is particularly important in analyses looking for neutral particles that escape detection, which is often indicative of new physics phenomena such as supersymmetry or other beyond-standard model scenarios.

Those are the closes to the r = 1 values but here is the full allowed r-values for this event.

```
165         atlas_1807_07447
196         atlas_1807_07447
225         atlas_1807_07447
232         atlas_1807_07447
269         atlas_1807_07447
304         atlas_1807_07447
377         atlas_1807_07447
384         atlas_1807_07447
399         atlas_1807_07447
405         atlas_1807_07447
425         atlas_1807_07447
468         atlas_1807_07447
500         atlas_1807_07447
578         atlas_1807_07447
587         atlas_1807_07447
594         atlas_1807_07447
632         atlas_1807_07447
661         atlas_1807_07447
699         atlas_1807_07447
710         atlas_1807_07447
746         atlas_1807_07447
```

```
774        atlas_1807_07447
781        atlas_1807_07447
1155    atlas_conf_2016_013
1217    atlas_conf_2020_048
1230    atlas_conf_2020_048
1261     cms_pas_sus_15_011
1262     cms_pas_sus_15_011
```

Here is the graph to show the r-values

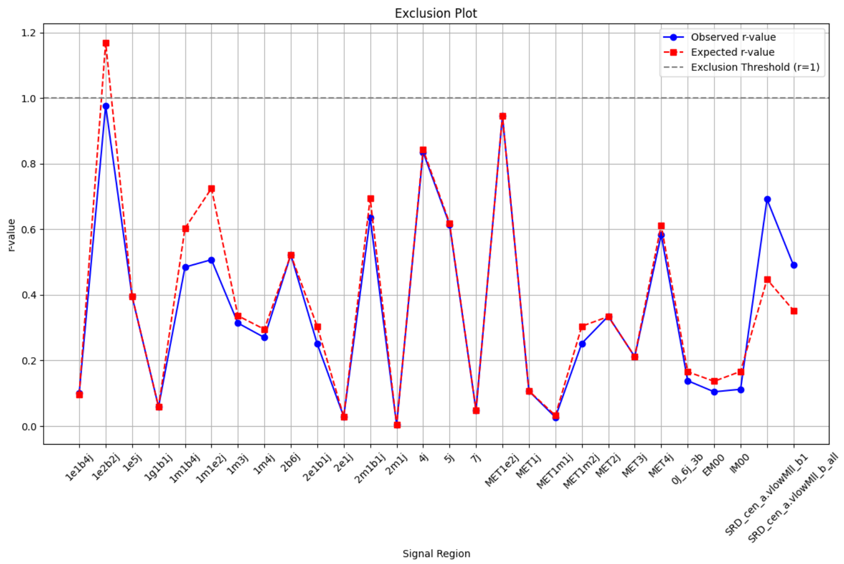


Figure 6: All the allowed signal events

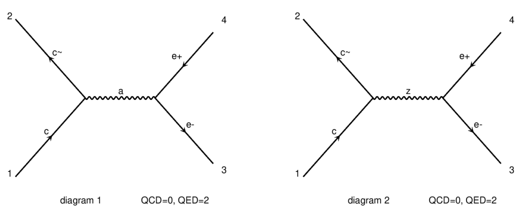
Midyear Exercise 2

MadGraph Event Generation

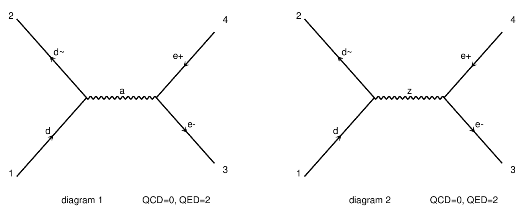
In generating proton-proton to electron-positron events, these are the processes.

1. Process: $u\bar{u} \to e^-e^+$ WEIGHTED<= 4@1
2. Process: $c\bar{c} \to e^-e^+$ WEIGHTED<= 4@1
3. Process: $d\bar{d} \to e^-e^+$ WEIGHTED<= 4@1
4. Process: $s\bar{s} \to e^-e^+$ WEIGHTED<= 4@1

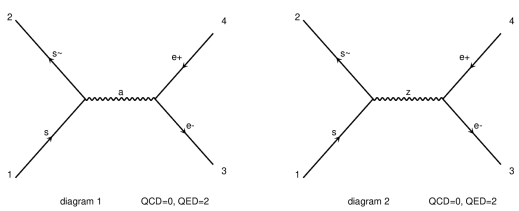
Here are the Feynman diagrams of the processes.



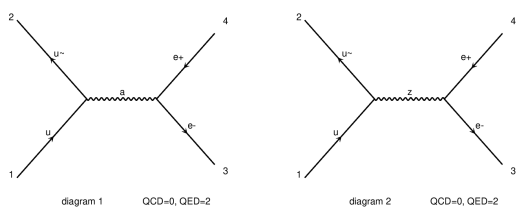
(a) ccbar2e-e+



(b) ddbar2e-e+



(c) ssbar2e-e+

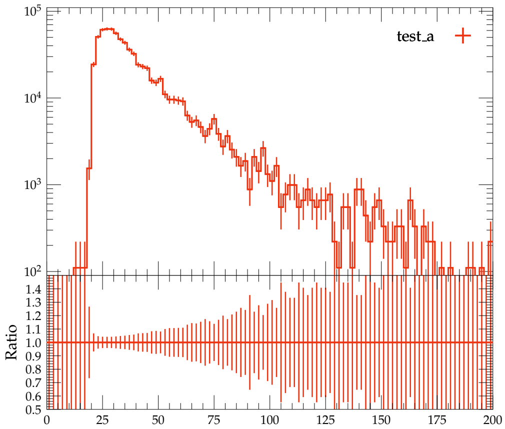


(d) uubar2e-e+

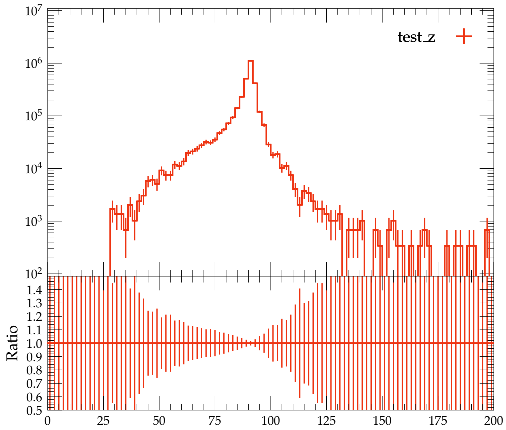
The initial particles are a quark and antiquark ($q\bar{q}$) and the final particles are electron and positron (e^-e^+). The exchange boson must be uncharged and colorless since leptons do not carry color. Therefore the only possible boson carriers are the photon and Z boson.

Rivet Analysis

I found no existing MC plots that have the positron-electron invariant mass distribution. So I just created one from the MC_DILEPTON analysis[4].
Here is the invariant mass distribution for the events mediated by photon or Z boson.



(e) Mediator with photon



(f) Mediator with Z boson

Now this is the invariant mass distribution for the unrestricted case.

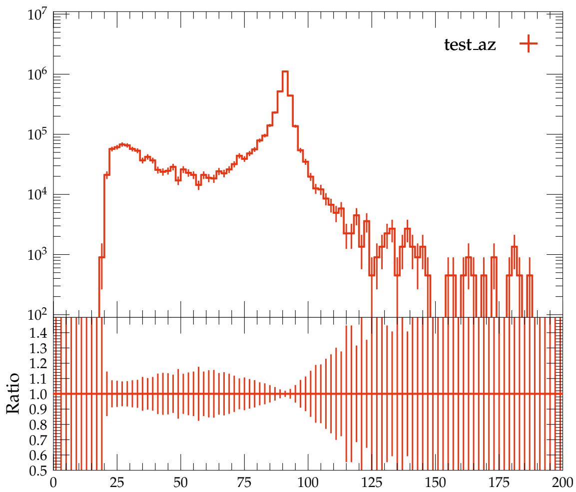


Figure 7: Mediator with photon and Z boson

The combined mass invariant just added the two restricted events. Which we can see here that the bump is from the mass construction of Z boson.

CheckMATE

Here are the analyses that have acceptable signal events

```
433     atlas_1807_07447
465     atlas_1807_07447
```

Now this is the plot for better visual.

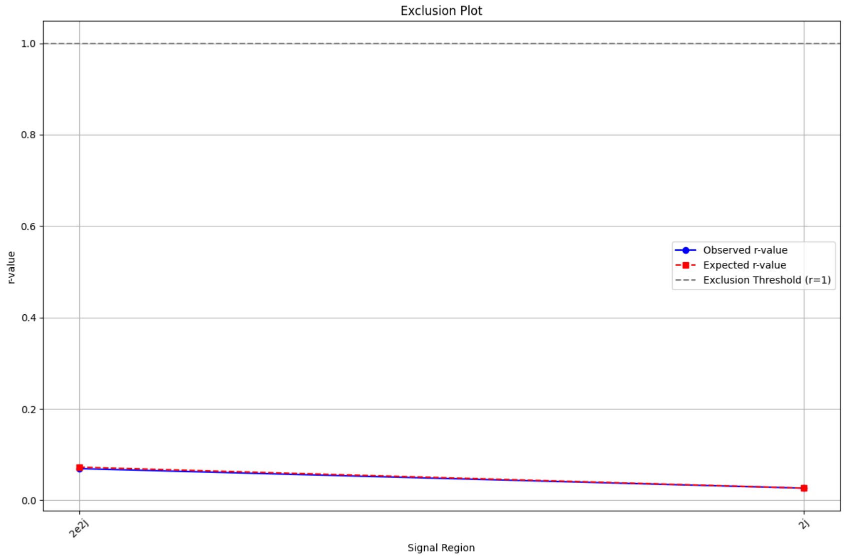


Figure 8: Accepted r-vals in 13TeV analyses

This is expected because the decay is event is 2 leptons which are electrons. That is why there is signal in the 2e2j. Though I am not able to explain why the r value is small. The 2 j signal can come from the parton distribution of the proton.

That is all, for my Midyear Exercises. All the files I used is in this Github repository: https://github.com/sherkaicode/HepPh_Midyear. Feel free to replicate and critique

References

[1] *Online Manual*, PYTHIA (2024), "https://www.pythia.org//latest-manual/Welcome.html".

[2] *MC_TTBAR*, RIVET (2019), "https://rivet.hepforge.org/analyses/MC_TTBAR.html".

[3] *ATLAS_2017_I1495243"*, RIVET (2019), "https://rivet.hepforge.org/analyses/ATLAS_2017_I1495243".

[4] *MC_DILEPTON*, RIVET (2019), "https://rivet.hepforge.org/analyses/MC_DILEPTON.html".