ATLAS project working diary

Joseph Martin

ATLAS preparation research – what I learnt

- What is ATLAS? : A many layered detector designed to identify some of the tiniest and most energetic particles ever created.
- What are the components? : Calorimeters, muon system, TID, ATLAS magnet system, TAD, computing subsections.
- How does it identify particles? : the detector measures: Trajectory, momentum, and energy of the particles allowing them to be individually identified and measured
- How are particles produced? : beams of protons travelling at 99.9% the speed of light from the LHC collide at the centre of the LHC. This forms Collison debris in the form of new particles flying in all directions.

The standard model

- The standard model describes the elementary subatomic particles of the universe which have been experimentally seen.
- ATLAS searches for new particles and to determine if the standard model is realty fundamental
- The standard model is not considered a stable theory, it is said to be metastable. This means it could – in principle – decay to a lower energy level.

Cross sections and luminosity

- The term cross sections describes the probability that two particles will collide and interact in a certain way.
- The cross section of a process depends on: Type and energy. Having a higher cross section means it will occur more frequently and vice versa.
- Luminosity measures how tightly particles are packed into a given space.
- A higher luminosity means a greater likelihood particles will collide and result in a desired interaction.

Detecting the standard model

Leptons:

- Electrons: Leaves a track in the inner detector since it is charged. Deposits its energy in the electromagnetic calorimeter and creates an EM shower.
- Muons: Leaves a track in the inner detector since it is charged. Barely interacts with the EM calorimeter and passes through. They are then detected in the outer most layer of ATLAS the muon spectrometer.
- Taus: Decay very rapidly but their decay products are detected and then we can work backwards. They can either decay into electrons or muons. Or via hadronic decay with 1 or 3 charged tracks which is then tagged as a tau jet.

Detecting the standard model

Quarks and Gluons:

- Quarks and gluons cannot be observed directly, this is because quarks cannot exist on their own, they are always in pairs or threes. They instead are hadronized into jets (sprays of hadrons). They then deposit their energy in the hadronic detector
- B quarks are the exception because they have a longer lifetime and often produce charged leptons allowing them to be separated from background events
- Gluons are detected through their decay processes.

Detecting the standard model

Neutrinos, photons and the Higgs boson:

- Neutrinos do not interact electromagnetically or via the strong force therefore they are invisible to detectors. They are detected indirectly via missing transverse energy.
- Photons don’t leave a track in the inner detector because they are uncharged. Deposit their energy in the EM calorimeter like electrons. Distinguished from electrons because their lack of track.
- The Higgs boson decays very quickly and is then detected through the decay products.
    - H – yy (two high energy photons)
    - H – ZZ – 4 leptons, called the golden channel
    - H - $b\bar{b}$ - jets with b tagging

The paper

Key objectives of the study:

- Observing invisible decays of the Higgs boson
- Observing the production of dark matter candidates

Method:

- Events are selected with two opposite-charge leptons and significant missing transverse energy indicating the production of particles invisible to ATLAS
- A Boosted decision tree is used to enhance sensitivity to invisible decays of the Higgs boson

The paper

Key results:

- No clear signs of invisible Higgs decay - the number of events matched what was expected from the SM
- So, they refined the search: looking for events where a z boson decays into two visible leptons and events where there is a lot of missing energy as if the Higgs vanished into something invisible (DM)
- They also searched for dark matter particles using simplified models: if dark matter is produced with a z boson extra missing energy would be observed.
- Results found are much stricter than previous ATLAS searches – better by about 45%. This is down to more data and better analysis techniques (BDT)

What does it all mean?

No discovery yet but what have they learnt?:

- The Higgs doesn’t decay invisibly very often
- Dark matter is harder to detect than some models predicted

Comparing dark matter working masses

- The dark matter mass directly affects how likely the particle is to be produced and how it manifests in the detector
- Each mass point corresponds to a different theoretical prediction – some are easier to detect because of the kinematics whilst others produce very subtle signals

Low masses (10-100Gev):

- Generally higher cross section so more events
- MET spectrum is broader and more distinct from standard model backgrounds
- Easier to detect but may overlap with W/Z noise

Comparing dark matter working masses

Intermediate masses (150 – 300GeV):

- Often the sweet spot
- Enough energy to produce a clear MET signal while still having a viable production rate
- Around 200 GeV is particularly effective, produces an MET spectrum that peaks away from SM backgrounds
- Good balance between high acceptance and high signal to background discrimination

Comparing dark matter working masses

High masses (>500GeV to TeV scale):

- Very suppressed production cross section
- Events become rare making it harder to claim significance
- However, if detected they produce huge signals – very high MET

Questions:

- What is a control region?
- Is supersymmetry a feasible theory?
- Why is the lightest supersymmetric particle actually important?

First iteration of the code

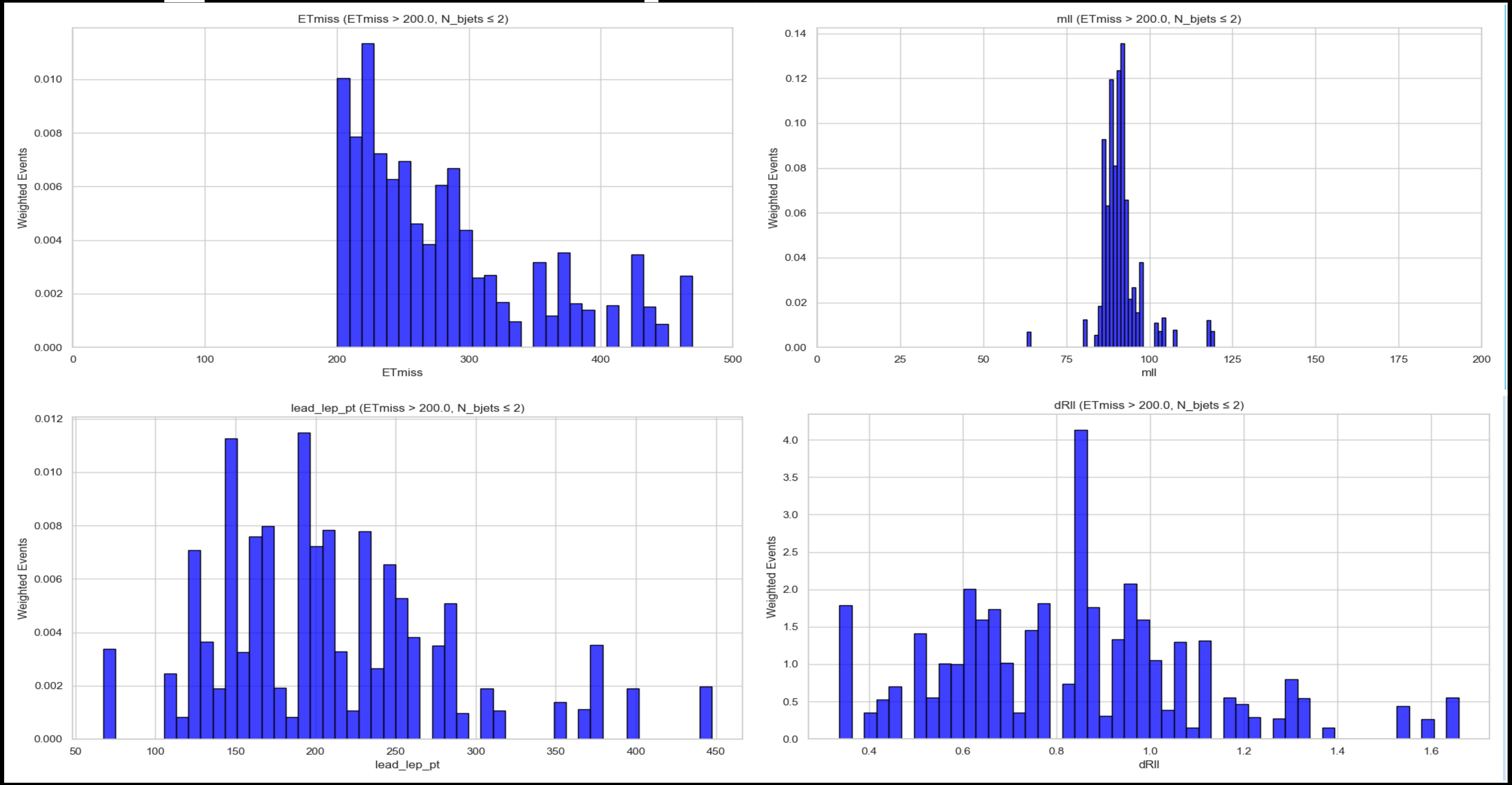
What does it do?:

- Asks you to select a minimum MET and a maximum number of b jets.
- Plots 4 histograms as follows:
  - Missing transverse energy of each event
  - The dilepton invariant mass is the mass of the two leading leptons
  - Leading lepton MET
  - Angular separation between leptons

What that all means

- MET is the imbalance in transverse momentum in the event - a key signature of invisible particles, like dark matter or neutrinos.
- The distribution of dilepton invariant masses will show a peak at the mass of the decaying particle. For example, if a Z boson decays into an electron-positron pair, the invariant mass distribution will show a peak at the Z boson mass.
- High-pt leptons are often associated with high-energy processes like Z, W, or heavy particle decays. In dark matter events, the lepton can come from a boosted Z or W, giving it high pt. Useful for making pt cuts to reduce background.
- Angular separation is how far apart the two leptons are in the detector. Small ΔR (~0.1–1.0) means the leptons are collimated – often from a boosted Z. Large ΔR (~2–3) can indicate back-to-back decay, typical of low-boost events. Helps distinguish between signal-like and background-like lepton pairs.

DM_200 examples



Second iteration of the code

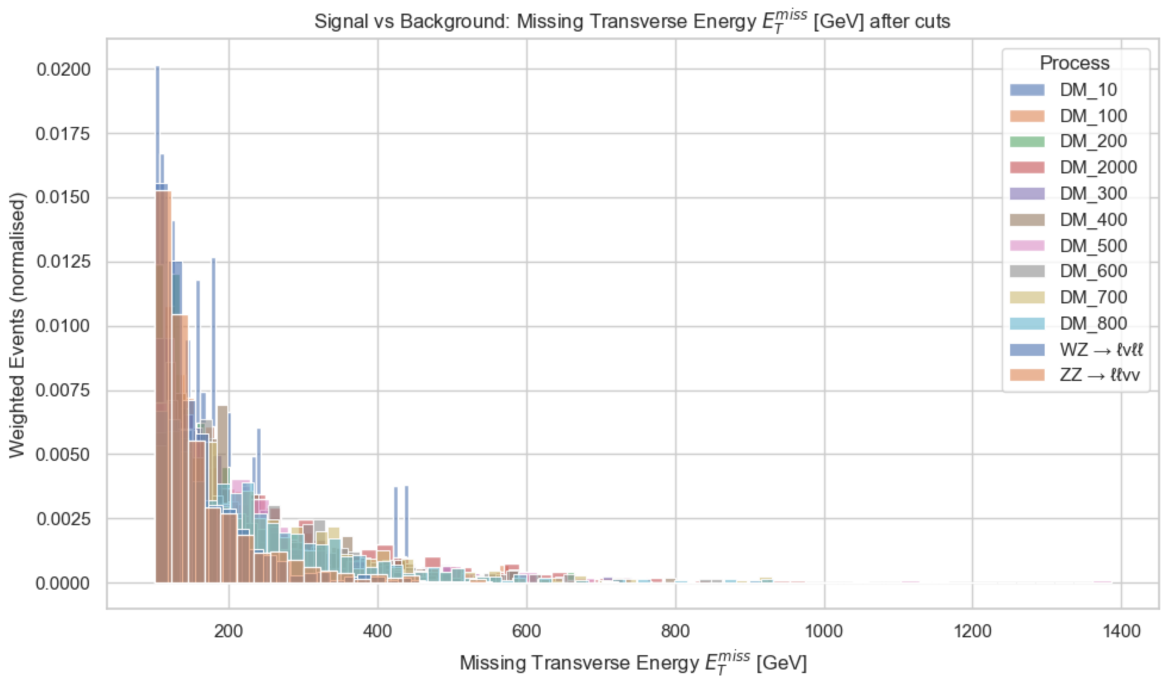
What has been changed:

- Units have been added to X and Y axis
- All data is now plotted on the same graph to directly compare DM working masses
- A page of progress bars shows how many events come from each energy level as well as the overall significance

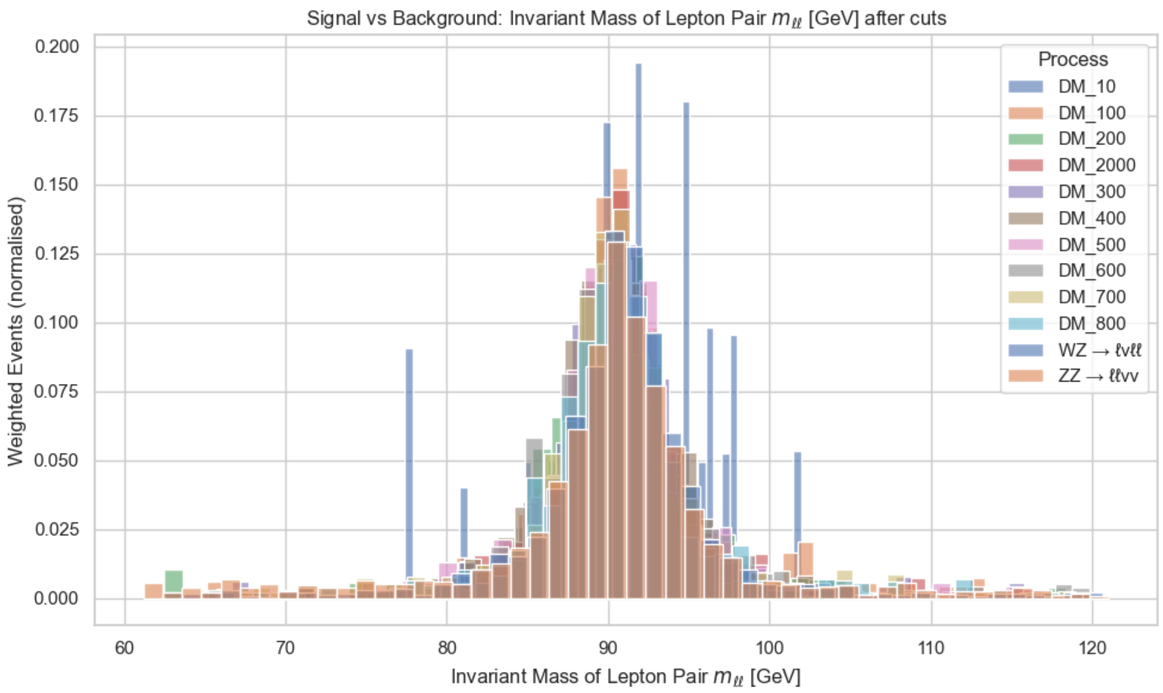
Problems:

- The total weighted events are very low after normalisation. Possibly missing some data?

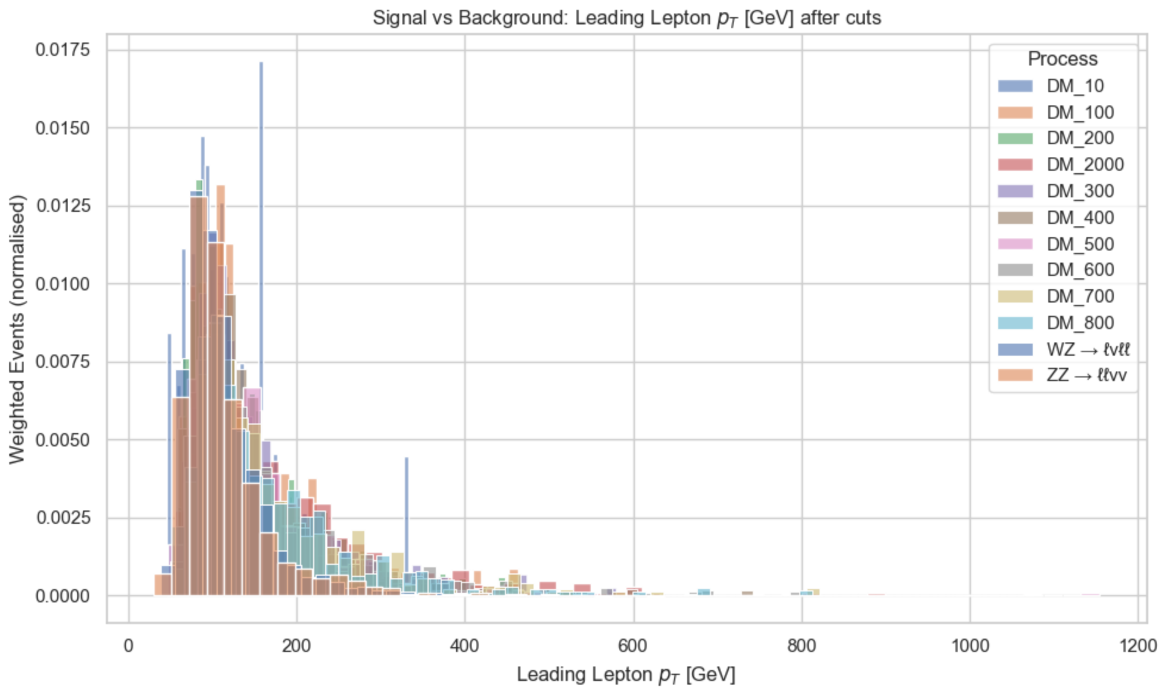
Examples



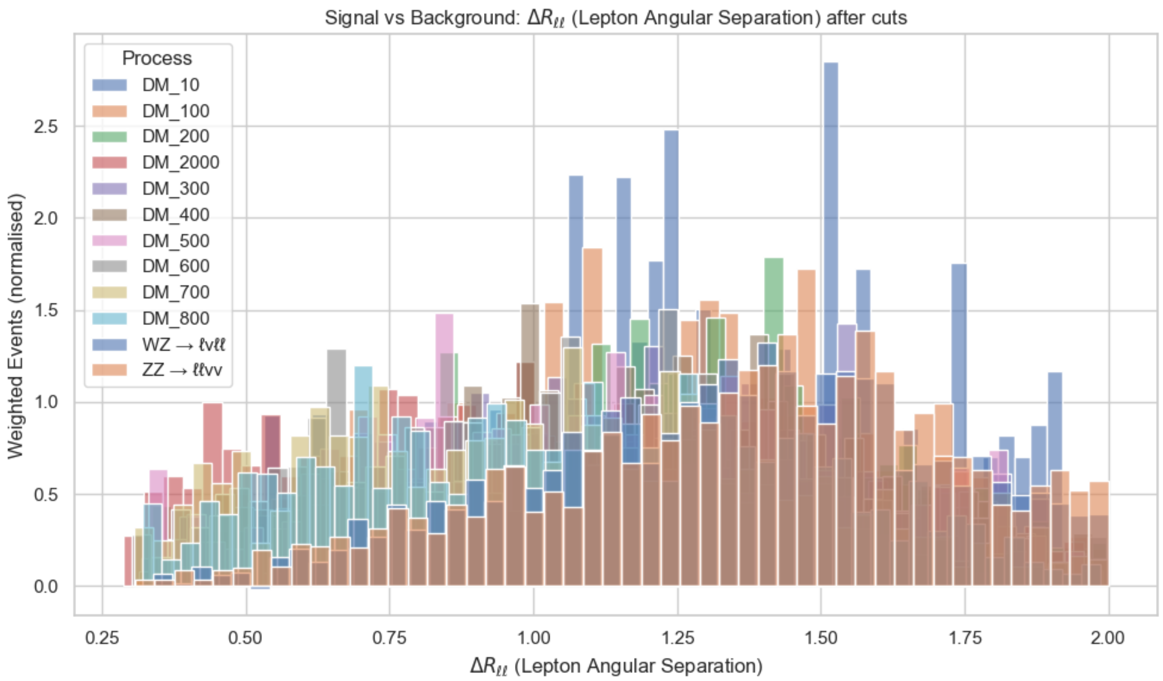
Signal vs Background: Missing Transverse Energy E_T^{miss} [GeV] after cuts
Weighted Events (normalised)
Missing Transverse Energy E_T^{miss} [GeV]
Process
DM_10
DM_100
DM_200
DM_2000
DM_300
DM_400
DM_500
DM_600
DM_700
DM_800
WZ → ℓνℓℓ
ZZ → ℓℓνν



Signal vs Background: Invariant Mass of Lepton Pair $m_{\ell\ell}$ [GeV] after cuts
Weighted Events (normalised)
Invariant Mass of Lepton Pair $m_{\ell\ell}$ [GeV]
Process
DM_10
DM_100
DM_200
DM_2000
DM_300
DM_400
DM_500
DM_600
DM_700
DM_800
WZ → ℓνℓℓ
ZZ → ℓℓνν

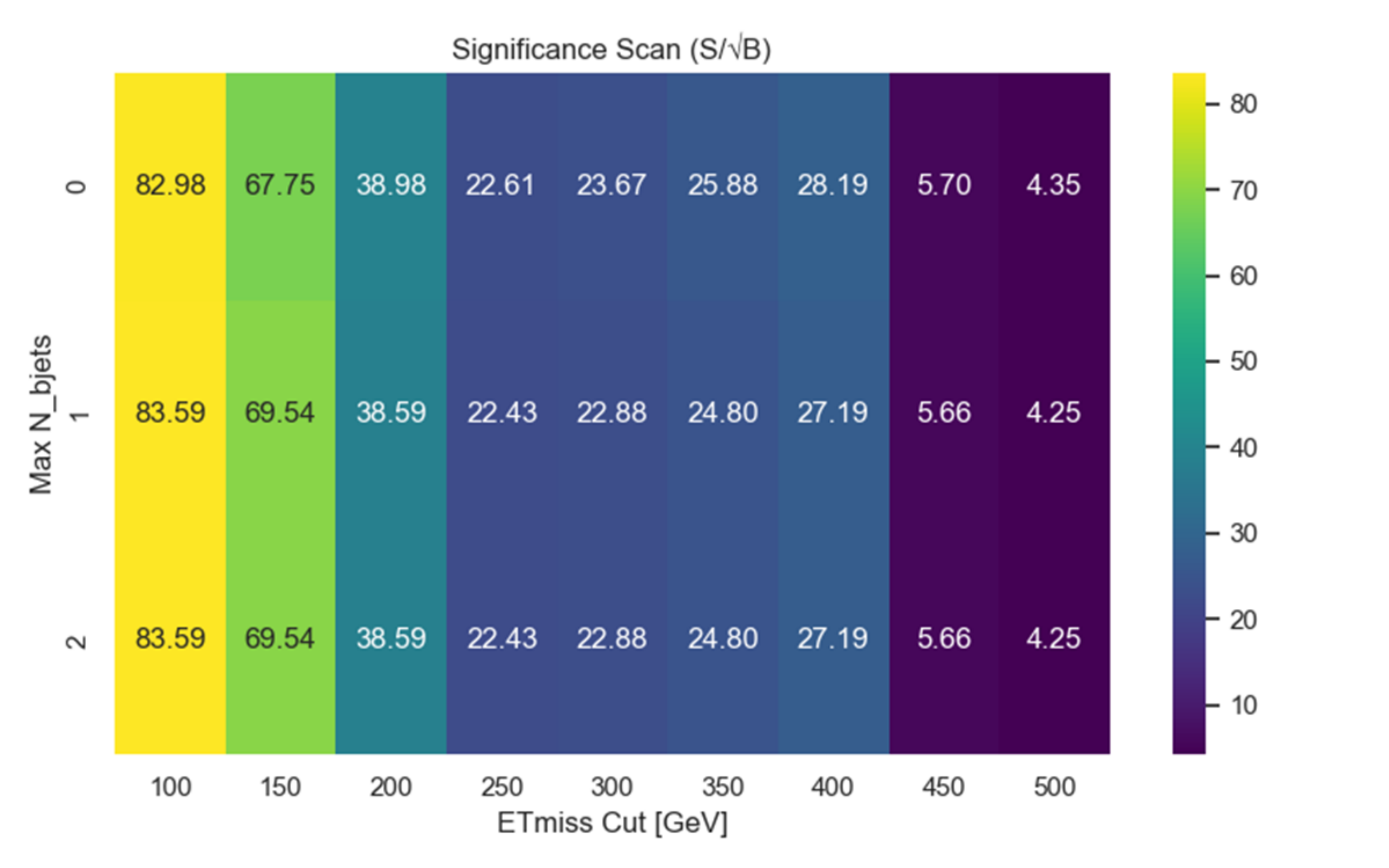


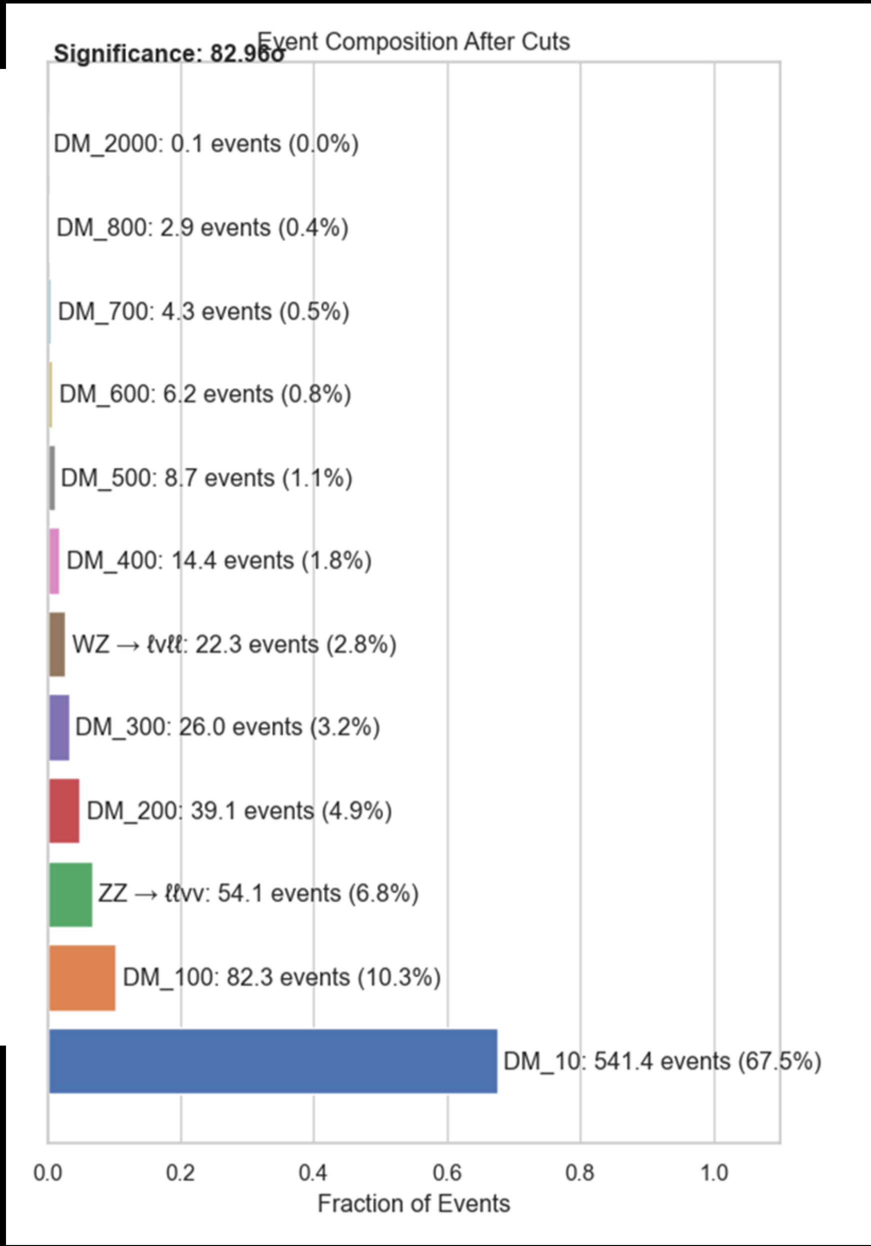
Signal vs Background: Leading Lepton p_T [GeV] after cuts
Weighted Events (normalised)
Leading Lepton p_T [GeV]
Process
DM_10
DM_100
DM_200
DM_2000
DM_300
DM_400
DM_500
DM_600
DM_700
DM_800
WZ → ℓνℓℓ
ZZ → ℓℓνν



Signal vs Background: $\Delta R_{\ell\ell}$ (Lepton Angular Separation) after cuts
Weighted Events (normalised)
$\Delta R_{\ell\ell}$ (Lepton Angular Separation)
Process
DM_10
DM_100
DM_200
DM_2000
DM_300
DM_400
DM_500
DM_600
DM_700
DM_800
WZ → ℓνℓℓ
ZZ → ℓℓνν

Significance



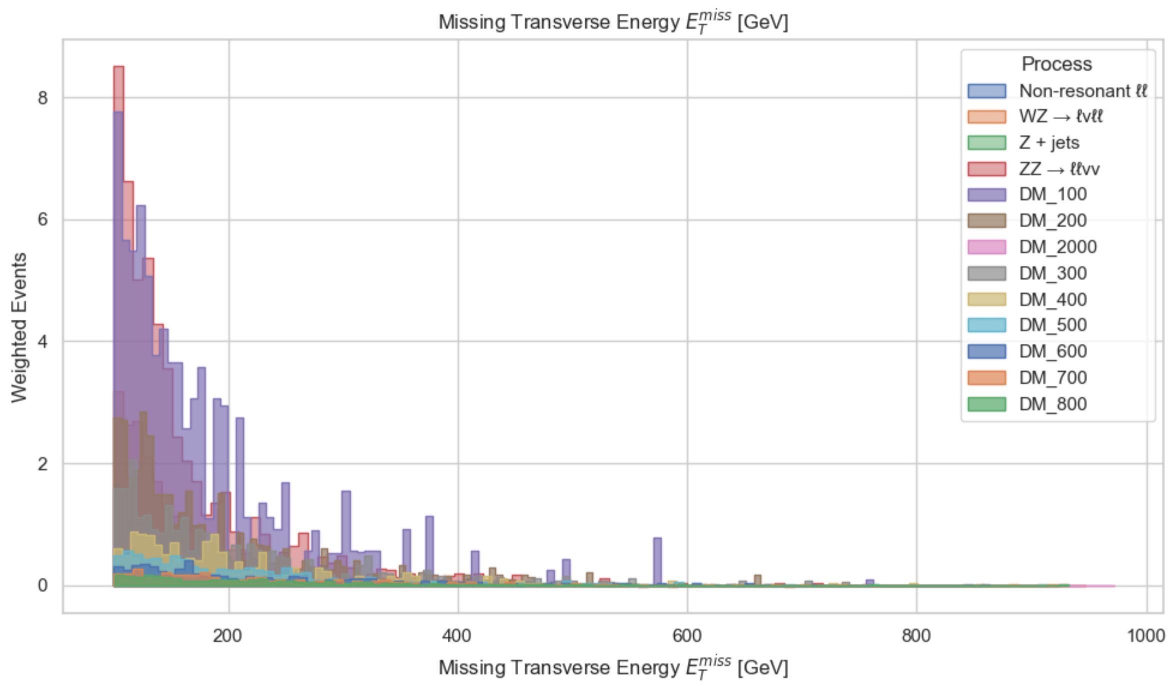


Third iteration of the code

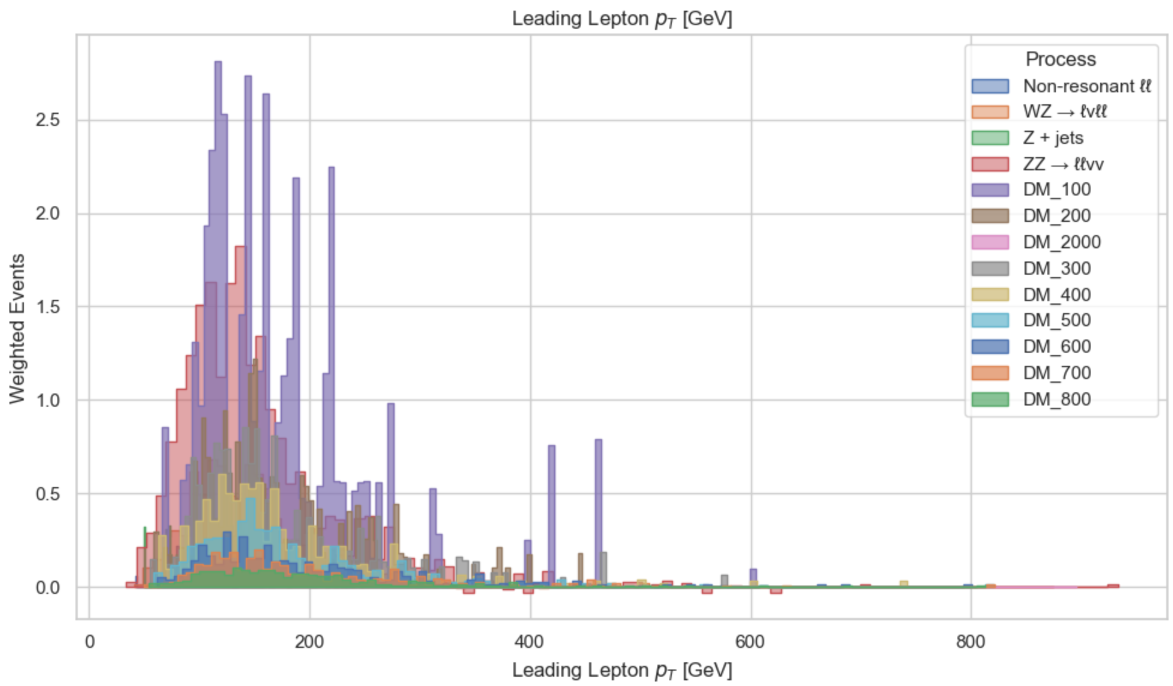
What has been changed?:

- Added non resonant ll background data to the graph
- Improved the significance heat map by correcting the calculation and decreasing the step between data points.
- Created a significance scatter plot which shows how significance changes with cut for every working mass.
- Generate a table with the best cut parameters for each working mass

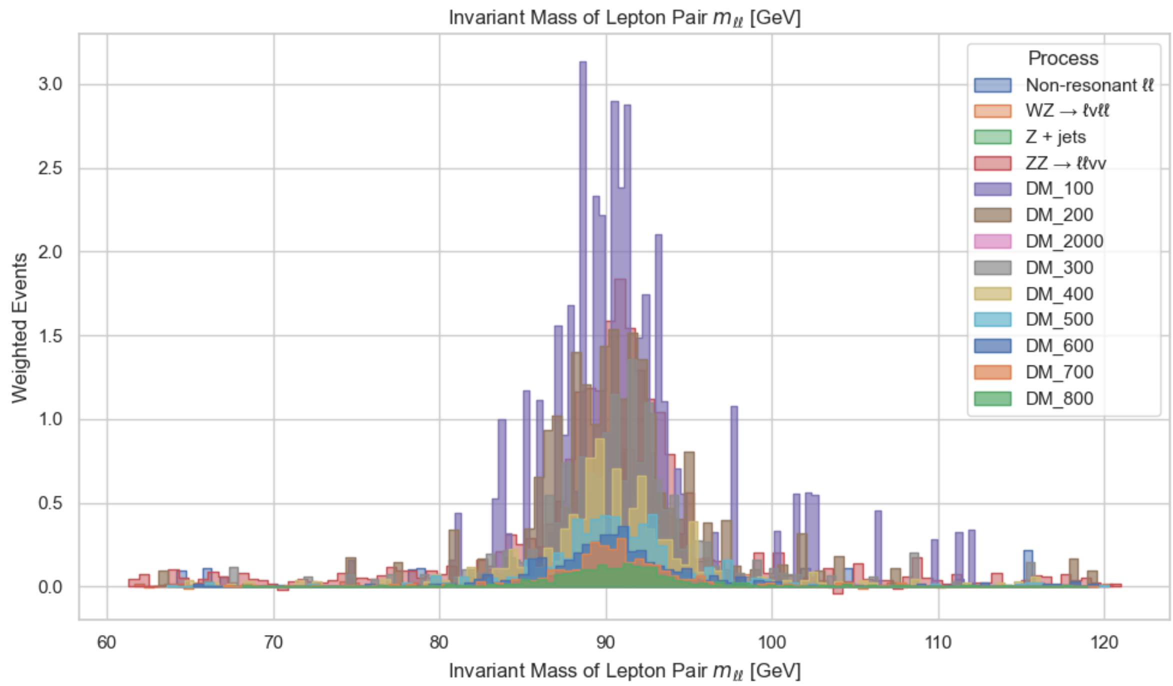
Examples



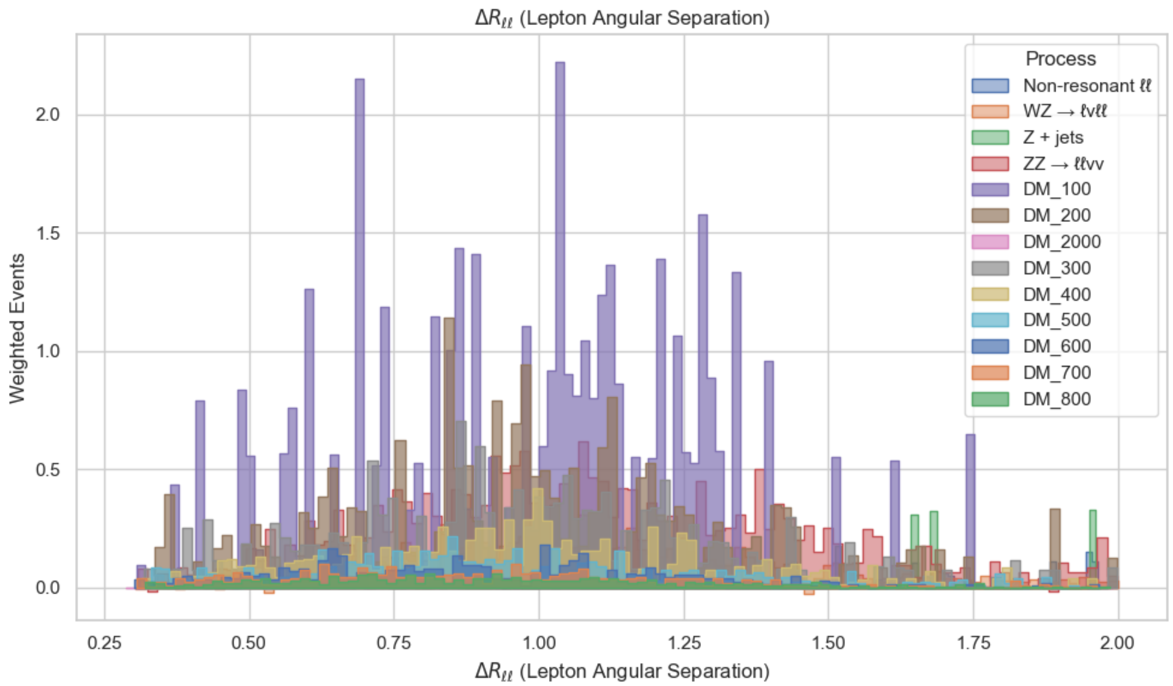
Missing Transverse Energy E_T^{miss} [GeV]
Weighted Events
0
2
4
6
8
200
400
600
800
1000
Missing Transverse Energy E_T^{miss} [GeV]
Process
Non-resonant ℓℓ
WZ → ℓνℓℓ
Z + jets
ZZ → ℓℓνν
DM_100
DM_200
DM_2000
DM_300
DM_400
DM_500
DM_600
DM_700
DM_800



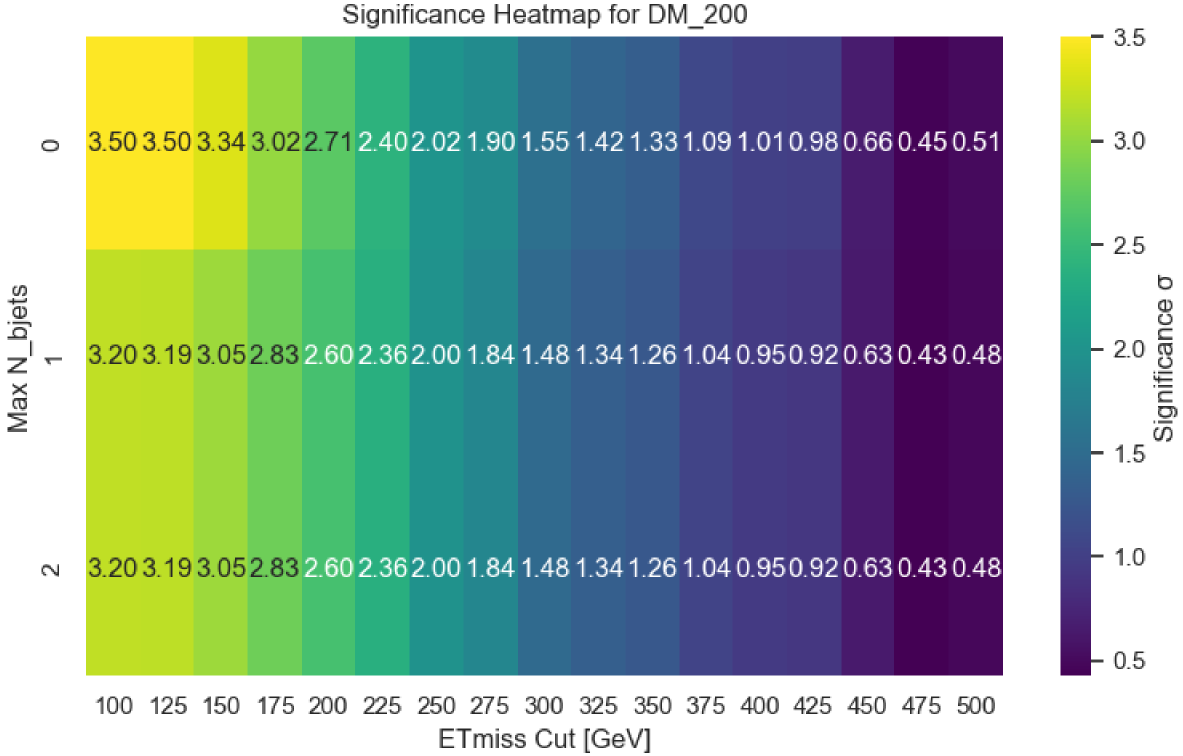
Leading Lepton p_T [GeV]
Weighted Events
0.0
0.5
1.0
1.5
2.0
2.5
0
200
400
600
800
Leading Lepton p_T [GeV]
Process
Non-resonant ℓℓ
WZ → ℓνℓℓ
Z + jets
ZZ → ℓℓνν
DM_100
DM_200
DM_2000
DM_300
DM_400
DM_500
DM_600
DM_700
DM_800

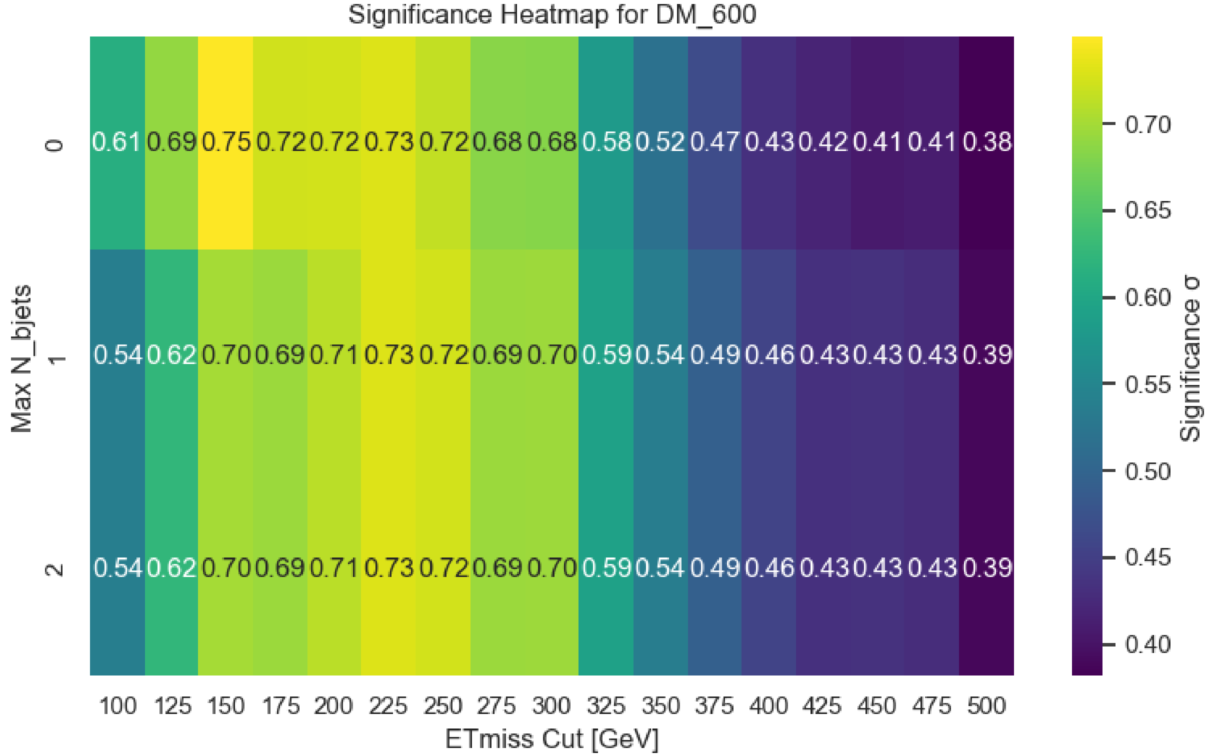


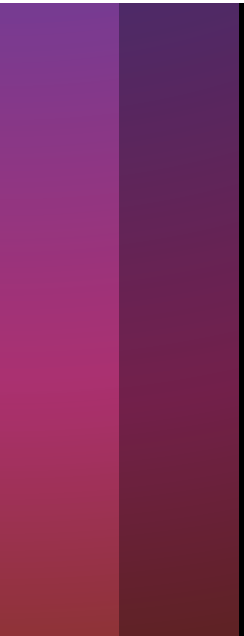
Invariant Mass of Lepton Pair $m_{\ell\ell}$ [GeV]
Weighted Events
0.0
0.5
1.0
1.5
2.0
2.5
3.0
60
70
80
90
100
110
120
Invariant Mass of Lepton Pair $m_{\ell\ell}$ [GeV]
Process
Non-resonant ℓℓ
WZ → ℓνℓℓ
Z + jets
ZZ → ℓℓνν
DM_100
DM_200
DM_2000
DM_300
DM_400
DM_500
DM_600
DM_700
DM_800



$\Delta R_{\ell\ell}$ (Lepton Angular Separation)
Weighted Events
0.0
0.5
1.0
1.5
2.0
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
$\Delta R_{\ell\ell}$ (Lepton Angular Separation)
Process
Non-resonant ℓℓ
WZ → ℓνℓℓ
Z + jets
ZZ → ℓℓνν
DM_100
DM_200
DM_2000
DM_300
DM_400
DM_500
DM_600
DM_700
DM_800







Best cut for DM_100: ETmiss > 100.0 GeV, N_bjets <= 0, Significance = 3.50σ

Best cut for DM_200: ETmiss > 100.0 GeV, N_bjets <= 0, Significance = 3.50σ

Best cut for DM_2000: ETmiss > 225.0 GeV, N_bjets <= 0, Significance = 0.02σ

Best cut for DM_300: ETmiss > 150.0 GeV, N_bjets <= 0, Significance = 2.61σ

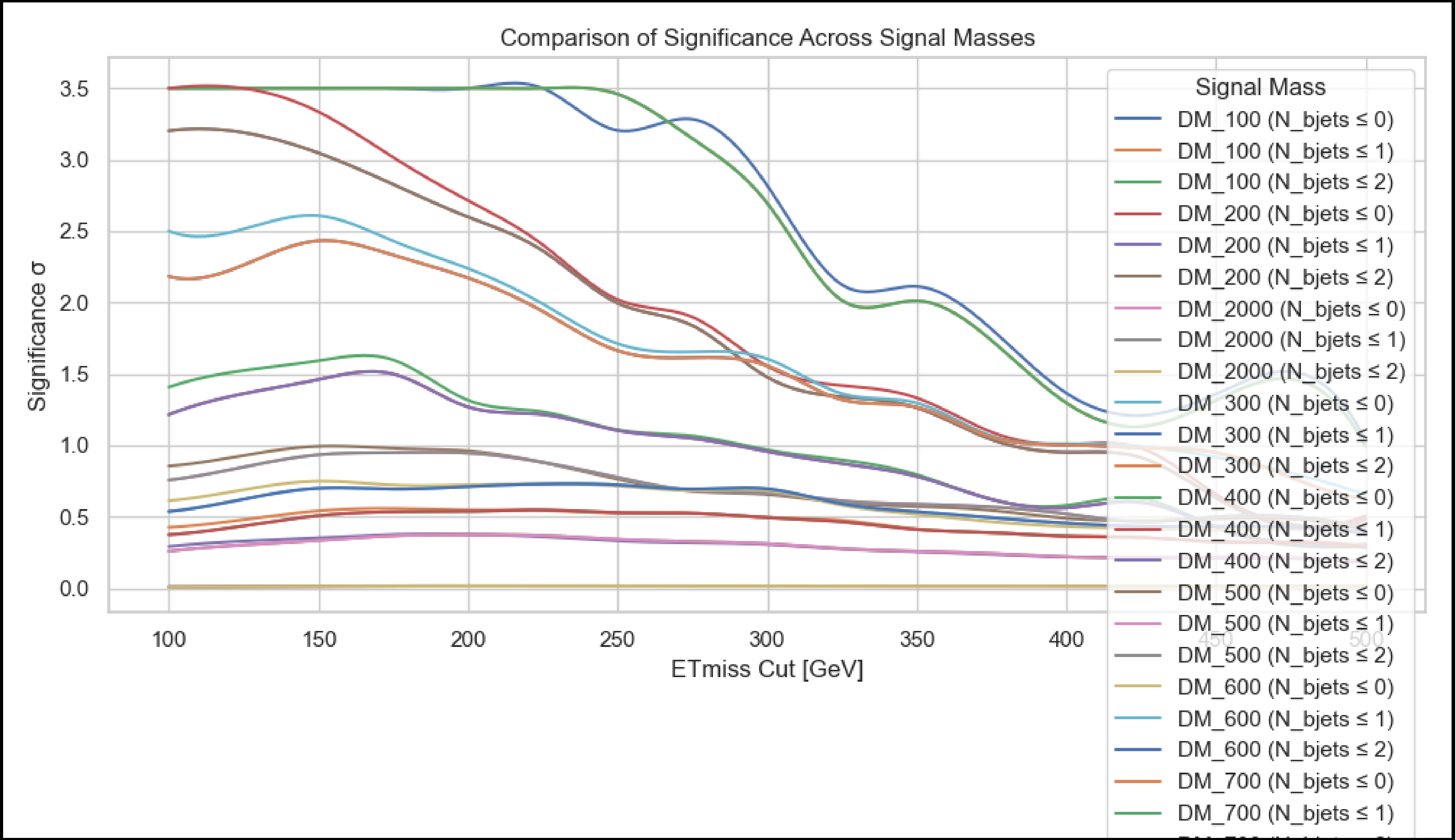
Best cut for DM_400: ETmiss > 175.0 GeV, N_bjets <= 0, Significance = 1.60σ

Best cut for DM_500: ETmiss > 150.0 GeV, N_bjets <= 0, Significance = 0.99σ

Best cut for DM_600: ETmiss > 150.0 GeV, N_bjets <= 0, Significance = 0.75σ

Best cut for DM_700: ETmiss > 175.0 GeV, N_bjets <= 0, Significance = 0.56σ

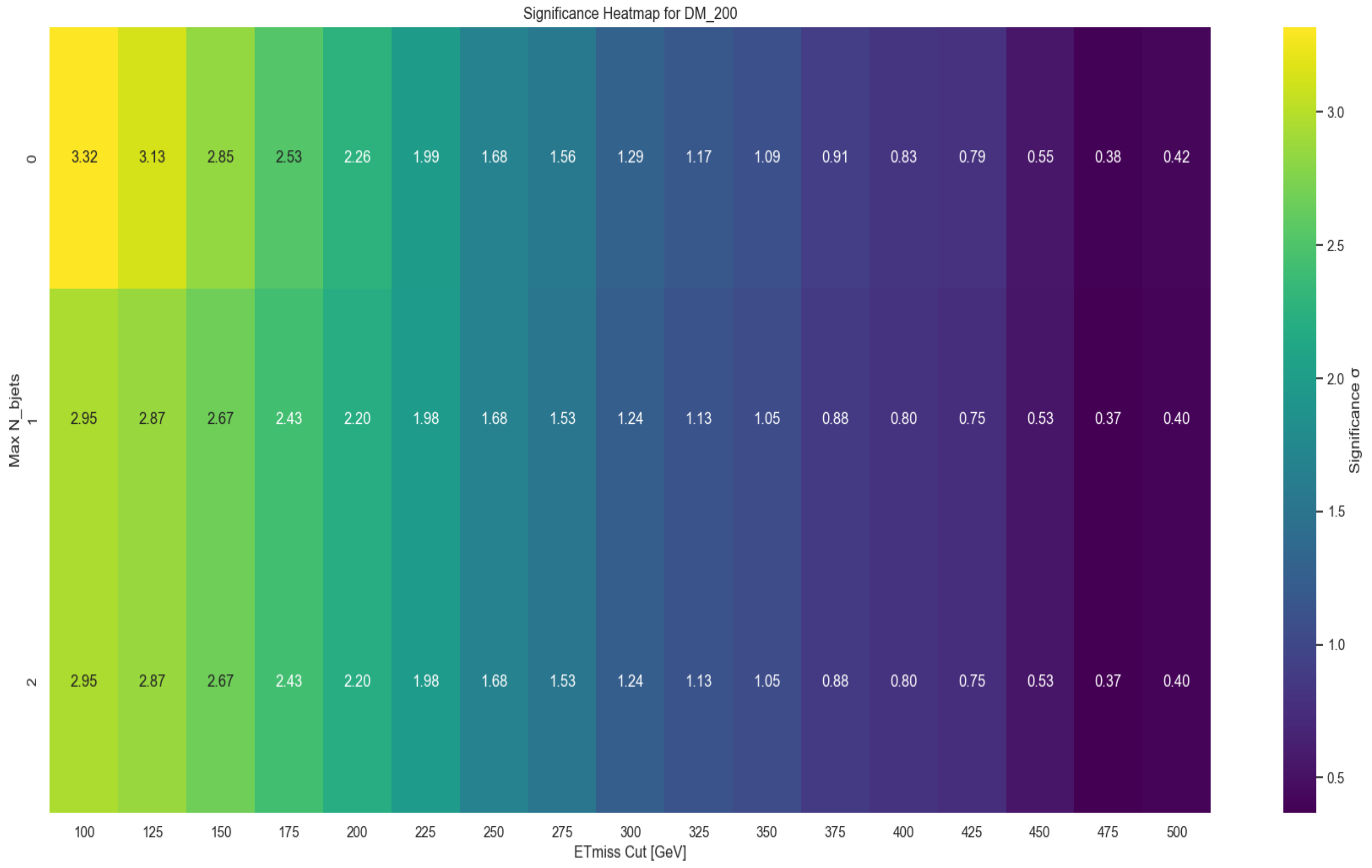
Best cut for DM_800: ETmiss > 200.0 GeV, N_bjets <= 0, Significance = 0.38σ

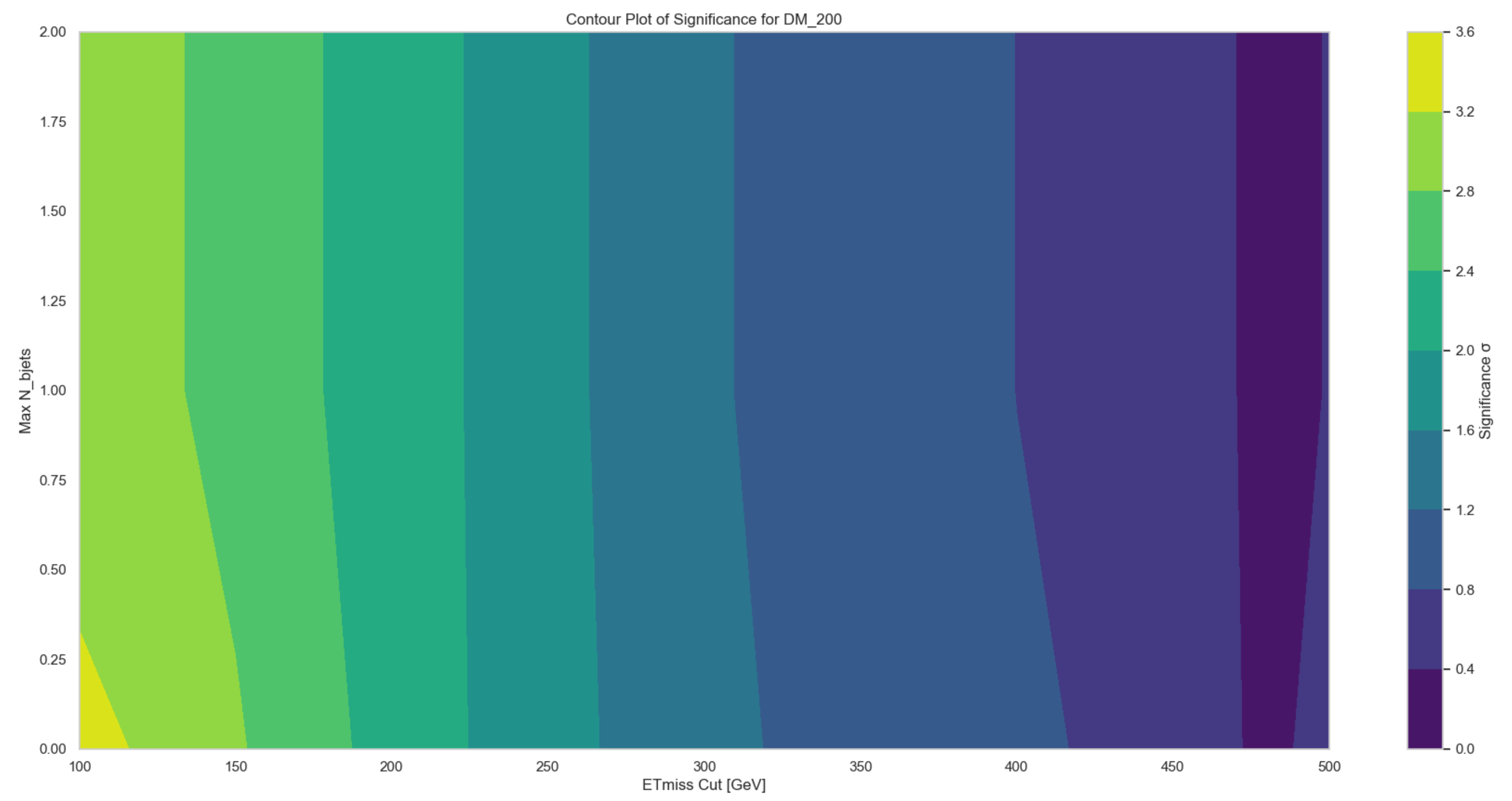

Comparison of Significance Across Signal Masses
Significance σ
ETmiss Cut [GeV]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
100
150
200
250
300
350
400
450
500
Signal Mass
DM_100 (N_bjets ≤ 0)
DM_100 (N_bjets ≤ 1)
DM_100 (N_bjets ≤ 2)
DM_200 (N_bjets ≤ 0)
DM_200 (N_bjets ≤ 1)
DM_200 (N_bjets ≤ 2)
DM_2000 (N_bjets ≤ 0)
DM_2000 (N_bjets ≤ 1)
DM_2000 (N_bjets ≤ 2)
DM_300 (N_bjets ≤ 0)
DM_300 (N_bjets ≤ 1)
DM_300 (N_bjets ≤ 2)
DM_400 (N_bjets ≤ 0)
DM_400 (N_bjets ≤ 1)
DM_400 (N_bjets ≤ 2)
DM_500 (N_bjets ≤ 0)
DM_500 (N_bjets ≤ 1)
DM_500 (N_bjets ≤ 2)
DM_600 (N_bjets ≤ 0)
DM_600 (N_bjets ≤ 1)
DM_600 (N_bjets ≤ 2)
DM_700 (N_bjets ≤ 0)
DM_700 (N_bjets ≤ 1)

Fourth iteration of the code

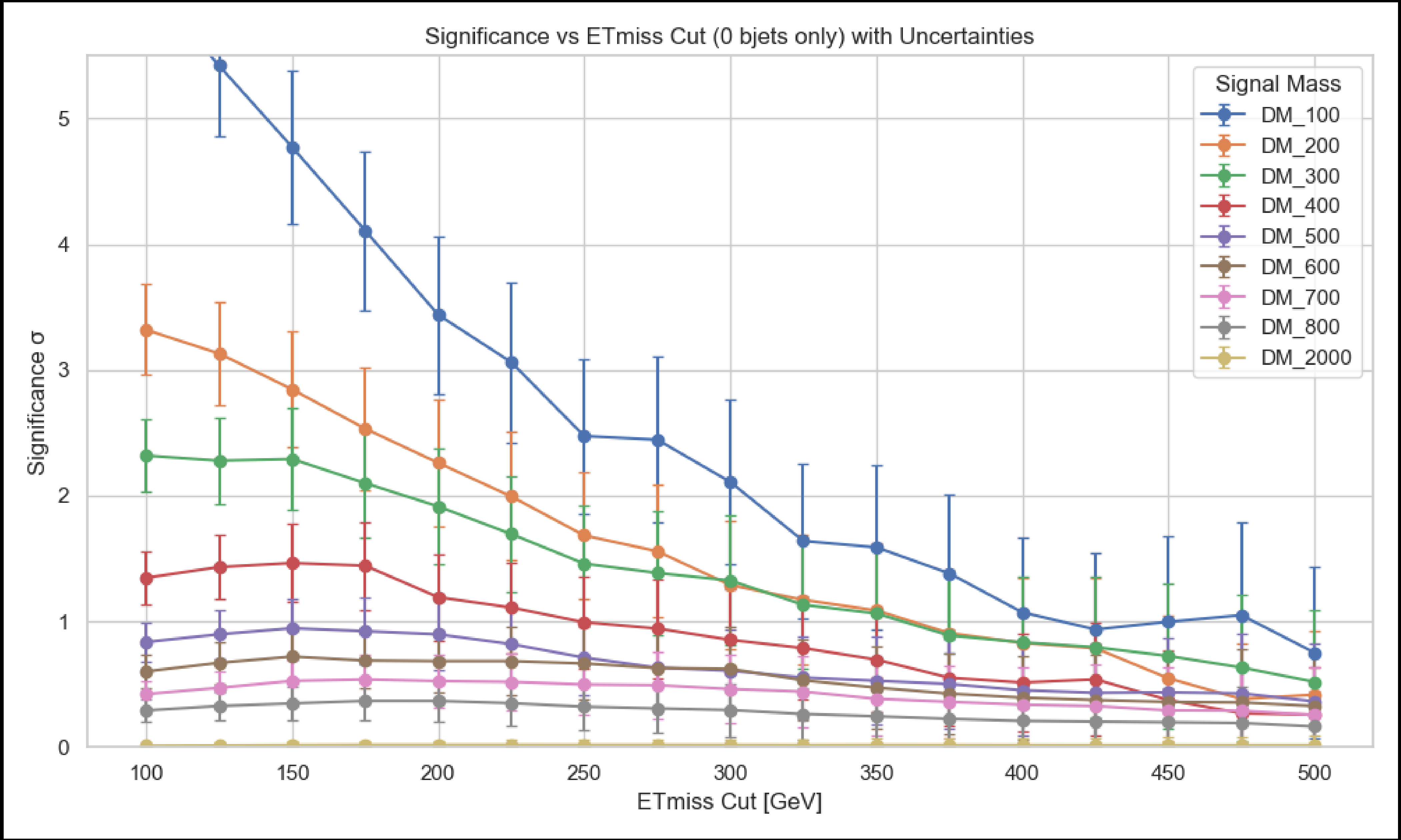
What has been done?:

- Significance heat map has been refined with new significance equation S/sqrt(S+B)
- Also plots significance contour plot for a more visual analysis
- Scatter plot is no longer spline and includes uncertainty
- Plots a contour plot of yield ratio (S/B) for each working mass
- Plots maximum significance with uncertainty on one graph for each working mass.

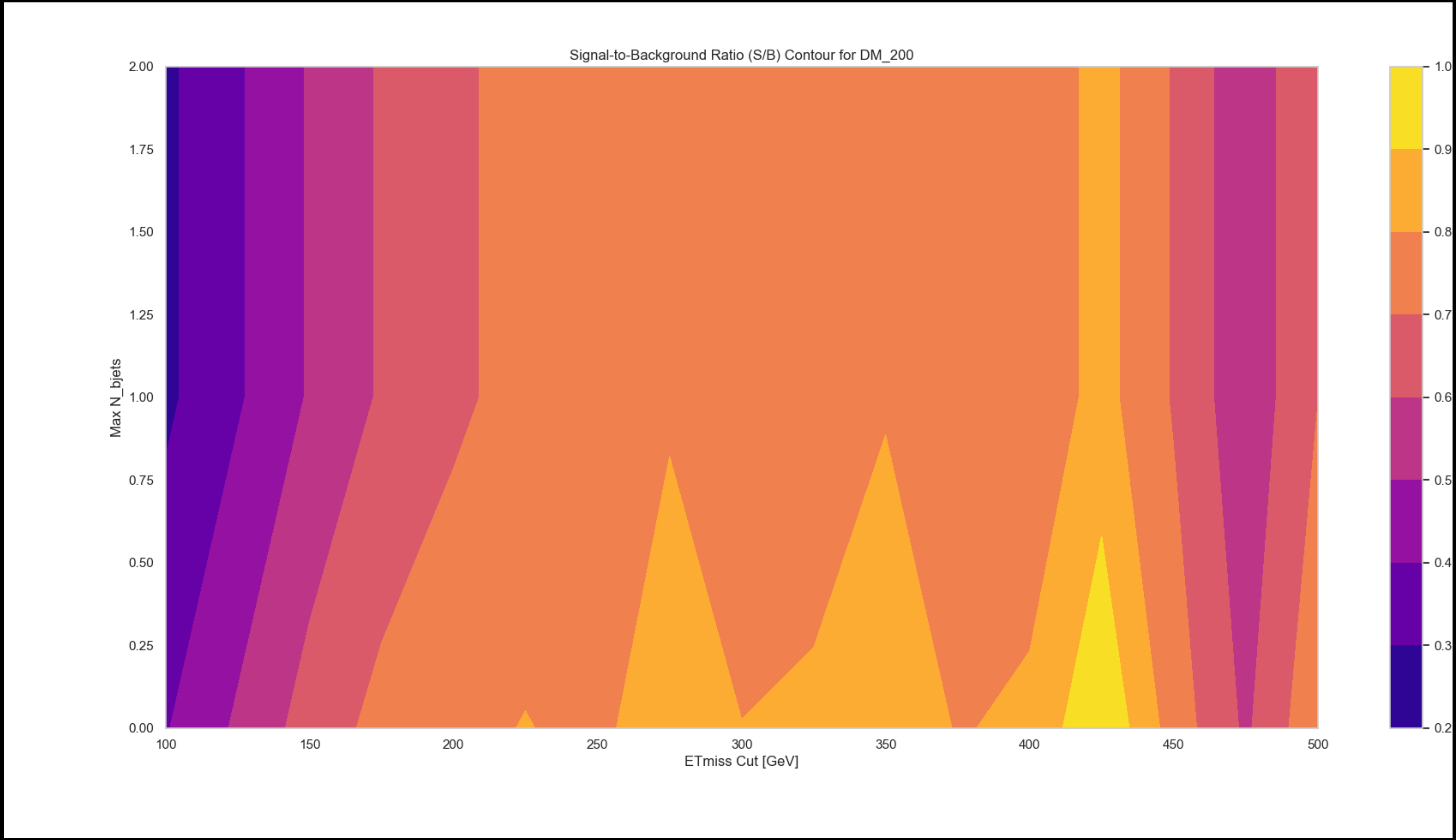

Significance Heatmap for DM_200
Max N_bjets
0
1
2
ETmiss Cut [GeV]
100
125
150
175
200
225
250
275
300
325
350
375
400
425
450
475
500
3.32 3.13 2.85 2.53 2.26 1.99 1.68 1.56 1.29 1.17 1.09 0.91 0.83 0.79 0.55 0.38 0.42
2.95 2.87 2.67 2.43 2.20 1.98 1.68 1.53 1.24 1.13 1.05 0.88 0.80 0.75 0.53 0.37 0.40
2.95 2.87 2.67 2.43 2.20 1.98 1.68 1.53 1.24 1.13 1.05 0.88 0.80 0.75 0.53 0.37 0.40
Significance σ
3.0
2.5
2.0
1.5
1.0
0.5



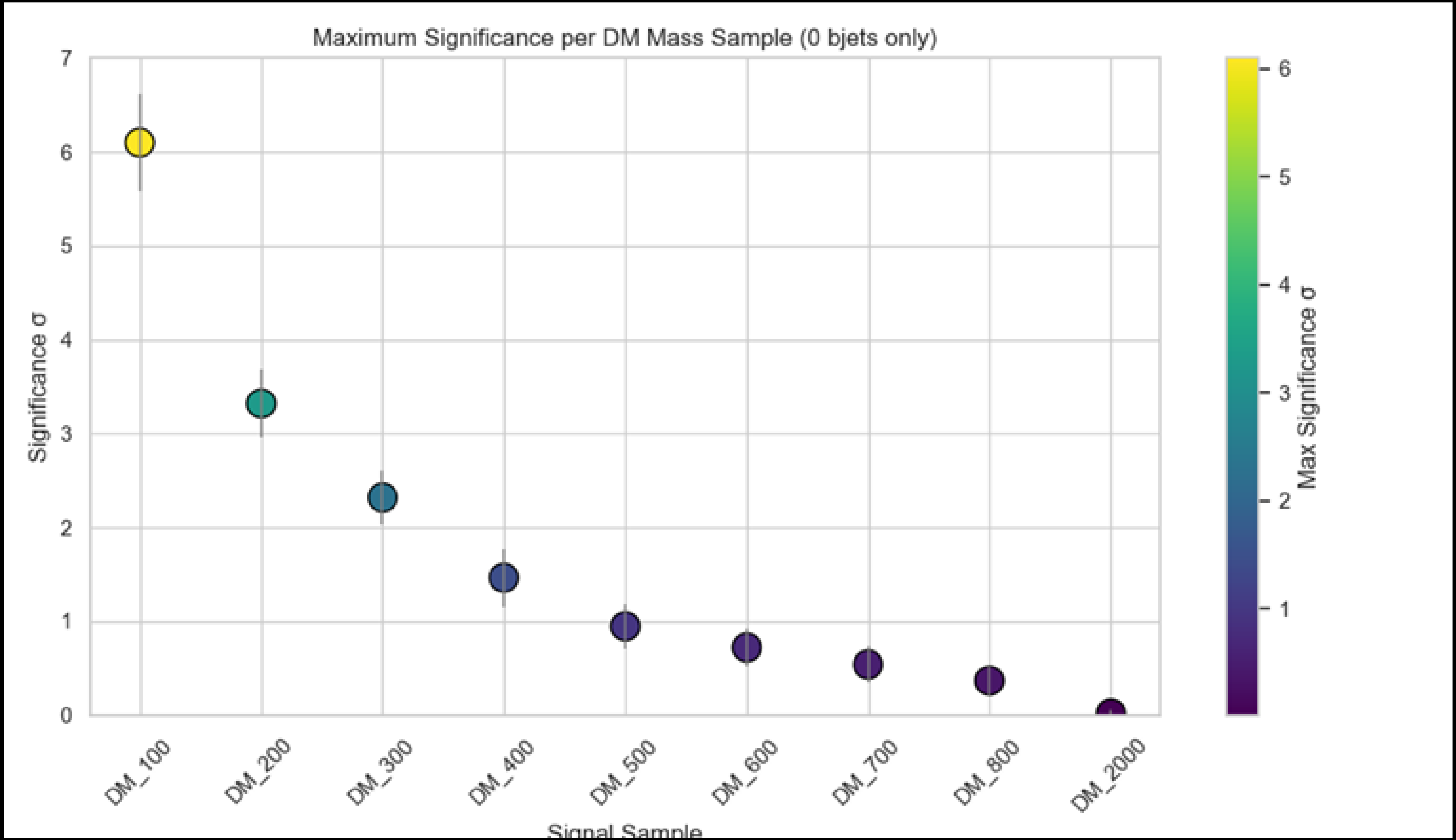
Contour Plot of Significance for DM_200
Max N_bjets
ETmiss Cut [GeV]
Significance σ



Significance vs ETmiss Cut (0 bjets only) with Uncertainties
Signal Mass
DM_100
DM_200
DM_300
DM_400
DM_500
DM_600
DM_700
DM_800
DM_2000
Significance σ
0
1
2
3
4
5
100
150
200
250
300
350
400
450
500
ETmiss Cut [GeV]



Signal-to-Background Ratio (S/B) Contour for DM_200
Max N_bjets
ETmiss Cut [GeV]
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
100
150
200
250
300
350
400
450
500
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2


Maximum Significance per DM Mass Sample (0 bjets only)
Significance σ
0
1
2
3
4
5
6
7
DM_100
DM_200
DM_300
DM_400
DM_500
DM_600
DM_700
DM_800
DM_2000
Signal Sample
Max Significance σ

Final iteration of the code

- What does it do?:
  - Plots the 4 main histograms as mentioned previously
  - Plots a line graph of peak significance for each dark matter working mass
  - Plots a significance heat map for each dark matter working mass
  - Allows maximum and minimum cut to be adjusted via sliders
- What has been changed?:
  - The code has been transitioned to anaconda to make it run smoother and integrate interactive sliders and radio buttons