PHS2350 Logbook

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General Background & Notes

Annihilation of dark matter may produce anti-deuterons

Deuteron

- nucleus of deuterium (1 proton & 1 neutron)
- formed by ionisation of deuterium
- isotope of hydrogen (deuterium)
- anti-deuterons from anti-baryons

Baryon

- 3 quarks
- decay of anti-baryons may produce anti-deuterons

Anti-deuterons as the link between particle physics and astrophysics

From the large scale structure of the Universe, we know that the Universe has a very large component of Dark Matter, but have no ideas about the nature of it. One way to search for Dark Matter is to look for signatures of it annihilating at the centre of our galaxy. Such an annihilation might produce anti-deuterons which could subsequently be detected by space based instruments.

The exact production mechanism of anti-deuterons in the annihilation process lacks experimental measurements and data from the LHCb experiment based at the Large Hadron Collider might be able to provide this. The project will involve developing a new measurement method for the LHCb experiment where we will search for anti-deuterons in the decay of the heavy anti-baryons that are produced. You will during the project learn how data analysis is done in particle physics and develop your programming skills in a large software project. The programming environment will be Python.

- Deuterons consist of one proton and one neutron
- anti-deuterons are suspected to be formed by the annihilation of a proton with a heavier particle such as perhaps a helium nuclei, however the detection of anti-deuterons is hard as the particles are very rare

General notes from paper

$\bar{\Lambda}_b$ bayron → odd number of valence quarks (Heavy, 3 quarks)

Kaons → specific type of meson (1 quark and 1 antiquark) (1 up/down & 1 strange)
Pion → lightest meson

Quantum field theory → construct physical models of subatomic particles

Particles are described as quantum fields pg 1
quarks carry both charge and colour
leptons only charge

QED

- Exchange of photons

QCD

- Theory of the strong force (gluons)

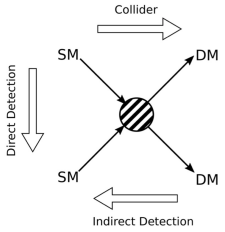
neutrinos predicted to be massless by SM

↳ similar to electron no mass, do not interact with matter

bottom quark most massive particle known
b-hadrons → hadrons containing atleast one bottom quark
Hadron → two or more quarks

Production of DM via annihilation

- DM annihilation must be stable & sufficiently rare



Anti-Deuterons

- anti-proton and anti-neutron bound state
- are light
- only known production collisions between cosmic rays and interstellar gas
- Λ_b baryon can produce anti-deuterons as a decay product (This rate has not been measured)
- Λ_b comprised of anti-up, anti-down and anti-bottom quarks
  ↳ In which case the anti-deuteron is produced by the anti-bottom quark radiating a W-boson and decaying into an anti-up quark (pg 5)
- It is expected that anti-deuterons & deuterons will be produced at the same rate (pg 6)

Statistical Hadronisation

- explains the number of particles produced in heavy ion collisions
- colliding nuclei create fireball which is in thermal equilibrium
- fireball ⇒ Kinetic & chemical thermal equilibrium
  ↓
  Intermediate complex colliding nuclei in thermal equi

Coalescence

- considers the proton & neutron produced
- combine to form deuteron if collective momentum difference is smaller than coalescence momentum
- four momentum not conserved
- inconsistent with SM

Cross-Section

- allows for production channels
- consistent with SM

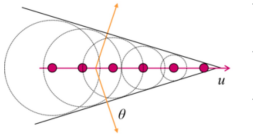
mass ratio of kaons to protons ≈ mass ratio protons to deuterons
∴ deuterons a factor 1000 rarer than protons

Cherenkov Radiation

Arises from the motion of relativistic particles through a dielectric medium, which is a medium characterised by a refractive index.
↳ (n how electromagnetic waves propagate compared to vacuum)

A particle travelling relativist speeds may exceed c media without exceeding c, this leads to the emisson of cherenkov radiation at fixed angle θ_{ch}

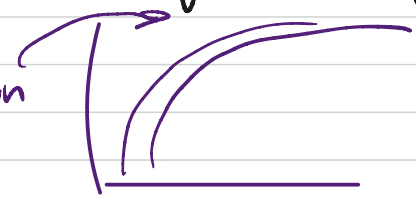
$$\cos(\theta_{ch}) = \frac{1}{n(p)} \rightarrow \frac{v}{c}$$



Different particles will begin to radiate at different momenta
Tracking system → momentum cherenkov radiation → velocity
Count of cherenkov radiation important for number of particles of a different type
Different particles different momenta

* Ultra relativistic momentum
↳ no mass

* Saturation



In order to emit cherenkov radiation of frequency ω, the speed of the particle must be larger than the phase velocity of the electromagnetic fields at that frequency (pg 638) ch13

Ch Rad can be used to measure velocities of fast particles. If particles of a given velocity pass through a medium of known dielectric constant ϵ, then light is emitted at cherenkov angle $\cos\theta_c = \frac{1}{\beta\sqrt{\epsilon(\omega)}}$ $\beta = \frac{v}{c}$ As ϵ varies with frequency ω, different colours of light emit at different angles

a measurment of angle θ_c gives us velocity

$\cos\theta_c = \frac{1}{n\beta}$ Threshold velocity β_t is $\frac{1}{n}$, if the velocity is below this threshold there will be no cherenkov radiation

- Particle cherenkov radiator materials are dispersive
- Different particles produce different radii rings of cherenkov light

Detectors

Cherenkov Detectors

Cherenkov counters contain two main elements
- a radiator which the charged particle passes through
- a photodetector

Cherenkov radiation is a weak source of photons

Imaging counters

- measure the ring-correlated angles of emission of the individual cherenkov photons
- They gather information for both wanted and unwanted particles

ring radii proportional to θ_C

RICH Detectors

- Practical multi track (more recent)
- differentiate between kaons, pions & protons in momentum range 2-100 GeV/c

radiator ↙

RICH1 - layers of C_4F_{10} gas

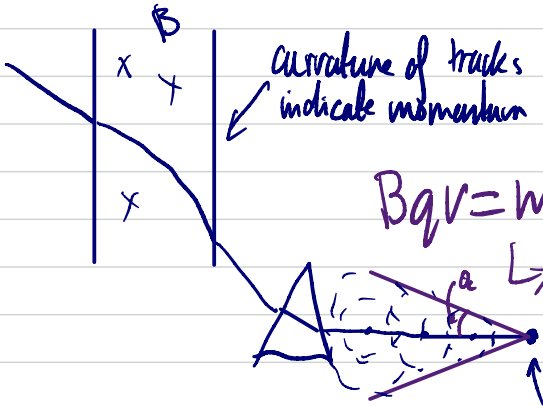
RICH2 - more effective on particles w/ higher relativistic boost, CF_4 gas

Magnet tells us momentum & charge

LHCb Detector

- Uses two seperate counters
- two radiators (aerogel & C_4F_{10}) second volume CF_4
- Photons are mirror focused onto detector arrays of HPDs (hybrid photodiodes) to cover a π/K seperation (particle) momentum range between 1 & 150GeV/c
- specialises in B-physics (at least one bottom quark)

Notes (based on meeting 27/7)

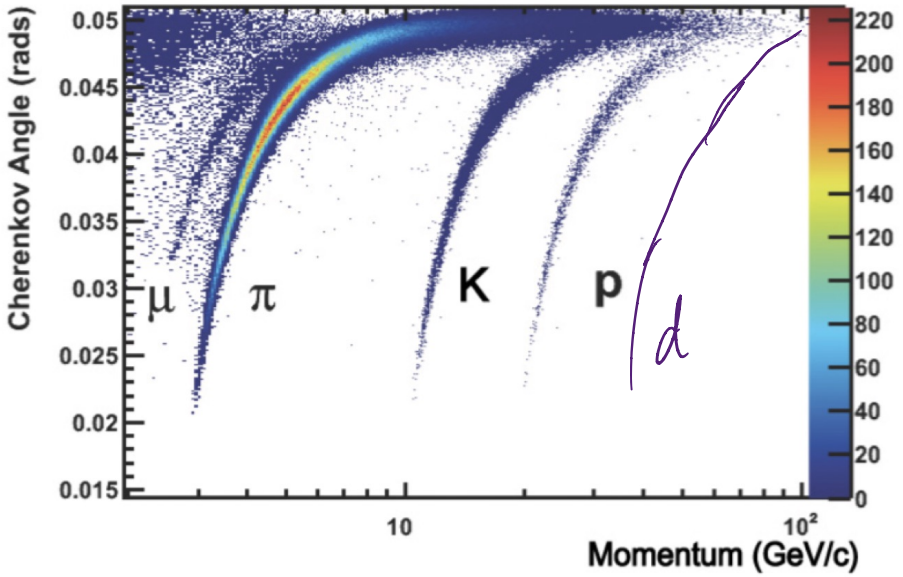


$Bqv = mv^2/r$

↳ $p = Bqr$

↑ from direction

Radii of cherenkov rings
↳ type of particle (mass)
broaded unless range



deuteron heavier than proton (higher momentum)

How is momentum related to n

Figure 8: Measured Cherenkov angle verses momentum for different charged particle species in the RICH 1 detector at the LHCb experiment. Reproduced from Ref. [4].

Figure 1 : Taken from [1]

- Flattening of curve at higher momenta for different particles is called saturation Cherenkov angle approaches $\theta_{sat} = \cos^{-1}\left(\frac{1}{n}\right)$ $\cos\theta_c = \frac{1}{n\beta}$ threshold β_t is $\frac{1}{n}$
- Saturation is the result of ultra-relativistic particles where $\beta \approx 1$, at this limit the mass of the particle becomes negligible
- RICH detector seperates different particles in a region between the threshold & saturation momentum
- tracking systems measure the particles momentum, cherenkov angle measures velocity

Cherenkov threshold for deuterons
momentum range for deuterons

Week 1 (25/7-29/7)

Goals

- Understand motive
- Understand some background
- Start to understand code

Questions

- What is meant by particle/momentum Separation? Range of which particles are found?
- ~~What are HPD's~~
  - ↳ hybrid photodiodes
    Hybrid photo Detector
- How is the data arranged
- How is data gathered
- How is data analysed
- What to do in following week

Tasks

- ~~Read Eliot's thesis~~
- ~~Research Cherenkov radiation~~
- look at code
- Go through readings
- logbook
- Understand graph

Summary

Researched cherenkov radiation & detectors with notes detailed one pages 4&5, looked through example.py & Fitting_code.py with Eliot

Wed 27th July

- Went over background in more detail
  - ↳ Cherenkov radiation
  - ↳ RICH detectors
- Motive → to help with the detection of deuterons through Cherenkov radiation produced by instead of looking for rings where deuterons should be given their mass, to look in a broader range of masses to see if there is a rise in detection around the range deuterons are expected
- First to be done with protons with smaller set of data
- Expect to see a larger bump around 0 for protons with mass range increased

- Arranged meeting to look at some code w/ Eliot

Thur 28th July

- discussed the code for producing graphs using protons first with small data set
- went through reading materials which included:
  - Physics Review
  - David Tong Particle physics lectures
  - Notes on cherenkov radiation
  - Jackson notes
  - Mark Thomson - Modern particle physics
- Below are snapshots of the examples python codes run from terminal, and the graphs produced.

```
(base) Izzys-MacBook:~ izzyweeden$ cd Code\ /
(base) Izzys-MacBook:Code  izzyweeden$ python3 ./example.py
name                 | typename                 | interpretation
---------------------+--------------------------+-------------------------------
track_ghostprob      | double                   | AsDtype('>f8')
P                    | double                   | AsDtype('>f8')
Pt                   | double                   | AsDtype('>f8')
eta                  | double                   | AsDtype('>f8')
charge               | int32_t                  | AsDtype('>i4')
nVtx                 | int32_t                  | AsDtype('>i4')
trackIP              | float[]                  | AsJagged(AsDtype('>f4'))
nPhotons             | int32_t                  | AsDtype('>i4')
CKtheta              | float[]                  | AsJagged(AsDtype('>f4'))
CKphi                | float[]                  | AsJagged(AsDtype('>f4'))
pion                 | float[]                  | AsJagged(AsDtype('>f4'))
kaon                 | float[]                  | AsJagged(AsDtype('>f4'))
proton               | float[]                  | AsJagged(AsDtype('>f4'))
deuteron             | float[]                  | AsJagged(AsDtype('>f4'))
radiator             | float[]                  | AsJagged(AsDtype('>f4'))
```

Figure 2

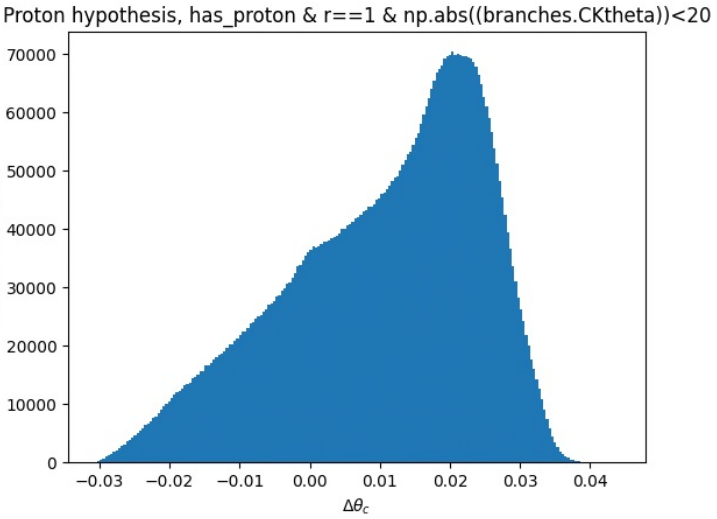


Figure 3. Example for protons with Cherenkov angle on x-axis in mrad and number of photons per 0.4 mrad on y-axis. The smaller bump around 0 mrad represents protons detected.

```
(base) Izzys-MacBook:~ izzyweeden$ cd Code\ /
(base) Izzys-MacBook:Code  izzyweeden$ python3 ./Fitting_Code.py
name                 | typename                 | interpretation
---------------------+--------------------------+-------------------------------
track_ghostprob      | double                   | AsDtype('>f8')
P                    | double                   | AsDtype('>f8')
Pt                   | double                   | AsDtype('>f8')
eta                  | double                   | AsDtype('>f8')
charge               | int32_t                  | AsDtype('>i4')
nVtx                 | int32_t                  | AsDtype('>i4')
trackIP              | float[]                  | AsJagged(AsDtype('>f4'))
nPhotons             | int32_t                  | AsDtype('>i4')
CKtheta              | float[]                  | AsJagged(AsDtype('>f4'))
CKphi                | float[]                  | AsJagged(AsDtype('>f4'))
pion                 | float[]                  | AsJagged(AsDtype('>f4'))
kaon                 | float[]                  | AsJagged(AsDtype('>f4'))
proton               | float[]                  | AsJagged(AsDtype('>f4'))
deuteron             | float[]                  | AsJagged(AsDtype('>f4'))
radiator             | float[]                  | AsJagged(AsDtype('>f4'))

[[proton hypothesis]]
==================
  p-value       = 0.879

[[Fit Statistics]]
    # fitting method   = leastsq
    # function evals   = 25
    # data points      = 50
    # variables        = 4
    chi-square         = 35.1175356
    reduced chi-square = 0.76342469
    Akaike info crit   = -9.66612046
    Bayesian info crit = -2.01802844
[[Variables]]
    slope:   1219.36207 +/- 4.92446534 (0.40%) (init = 1420.8)
    offset:  33951.5703 +/- 43.9191105 (0.13%) (init = 35520)
    mean:    0 (fixed)
    width:   1.79569737 +/- 0.07813884 (4.35%) (init = 1)
    norm:    2290.20894 +/- 75.8825537 (3.31%) (init = 2000)
[[Correlations]] (unreported correlations are < 0.100)
    C(slope, offset) = 0.760
    C(offset, width) = -0.612
    C(slope, width)  = -0.446
    C(offset, norm)  = -0.416
    C(slope, norm)   = -0.324
    C(width, norm)   = -0.155
```

Figure 4.

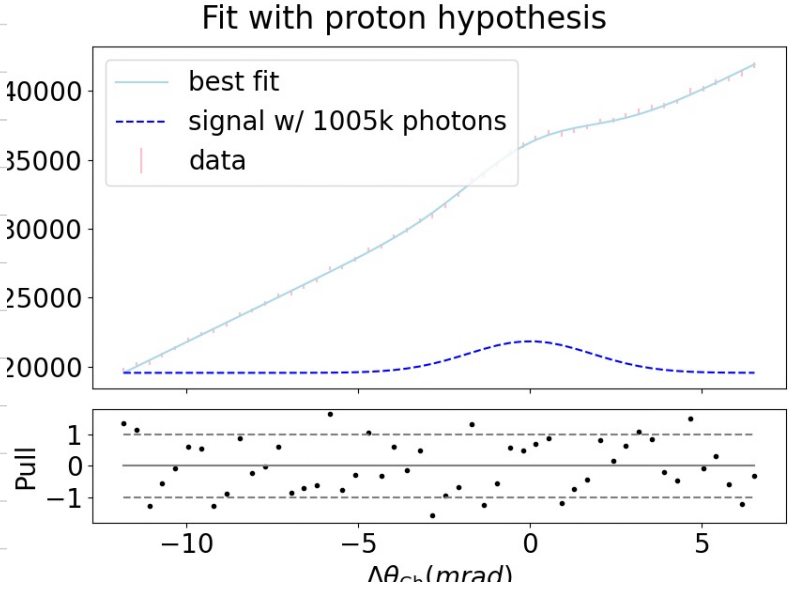


Figure 5. Fit for protons with Cherenkov angle on x-axis and number of photons per 0.4 mrad on y axis. Pull plot is shown below.

Fri 29th July

- looked over code in atom to try and understand better
- Read notes on Cherenkov Radiation (notes above pg 5)

Week 2 (1/8 - 5/8)

Goals

- Understand deuteron formation
- Understand graphs and code
- Research cherenkov radiation further

Questions

- Do deuterons form helium nuclei & are they so rare that this doesn't happen
- What should be done by next week
- fireball? → statistical hadronisation

Tasks

- Read david Tong lectures
- Physics Review
- play with code (change momentum eg)
- Read papers eliot suggested

Summary

Background research

Deuteron formation → coalescence & cross-section

cherenkov radiation → $\cos\theta = \frac{1}{n\beta}$

log likelihood → multiplication of probabilities

Set up example code

Wed 3rd August

Meeting

- disscussed deuteron formation
  - ↳ coalescence method & coloured forces
  - ↳ what binds quarks (quantum chromodynamics)
- Primary vertex → first collision
- log likelyhood
- Went over further what I'll be doing with wider mass range and subtracting background, what would look like for fake particle

Fri 5th

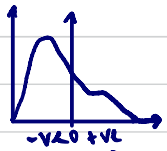
- continued reading David Tong
- looked at notes on deuteron formation
- started to put together references for report
- looked at log likelihood and data notes

Week 3 (8/8 – 12/8)

Goals

- Understand code in more detail
- Have data ready to start processing
- Go over more background
  - ↳ deuteron formation (notes)
  - ↳ Loglikelihoods
- produce first plots
- start progress report

Questions

- Equivalent to 'raciator' and 'CKtheta' with new data?
- Have I plotted the data right way around? → loglikelihood x axis
  y axis?
  ↳ is that correct.
- 

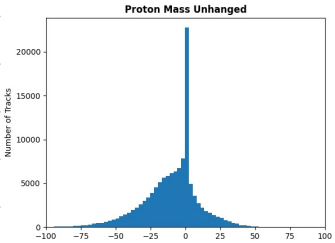
  what does this mean again
- What is the peak at 0? and at -1000?
- Proton/Kaon bump same place?

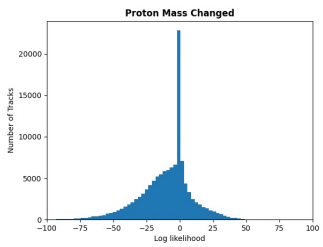
Tasks

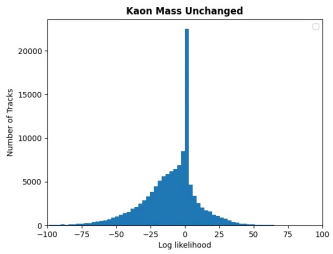
- Change momentum in example codes
- Set up data & script
- play around with overleaf
- produce histograms for proton mass changed and unchanged

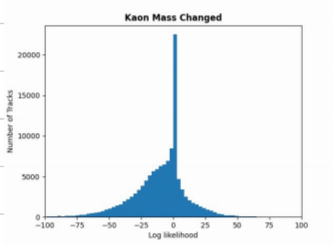
Summary / Results

Produced Histograms of the loglikelihood for protons with mass changed and mass unchanged, and the same for kaons, plots shown below:

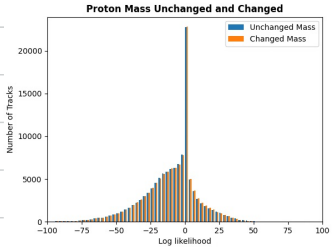




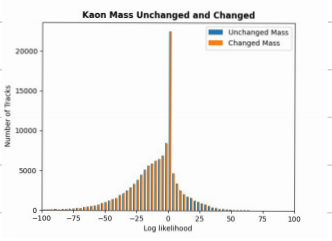




Plotted both changed & unchanged mass on same plot to see if there is a difference



- no obvious difference between changed & unchanged



These results show that there is no noticible difference between changed & unchanged mass so far, and there is no noticible bump where we expect the protons/kaons

- Trying to more easily detect deuterons by looking at masses above and below the deuteron mass so we can interpolate and find the background,
- substract background to see deuterons more clearly
- The mass of the particle is obtained from the momentum of the particle (from the magnetic field) and the velocity of the particle from the cherenkov angle as the particle passes through a medium and emits cherenkov radiation

- We plot the log likelihood for the number of tracks (detections) which shows

Log likelihood à probability A is true where
A is your hypothesis

Mon 8th August

- Read through paper 'An Alternative Formation Model for Antideuterons from dark matter' (L. A. Dal, A. R. Raklev) (Notes pg. 4)
- Played around with code →
  changing -22GeV (moving centre of distribution
  using -20GeV bump gets smaller → still appear close to 0
  using -24GeV bump is larger

20 GeV

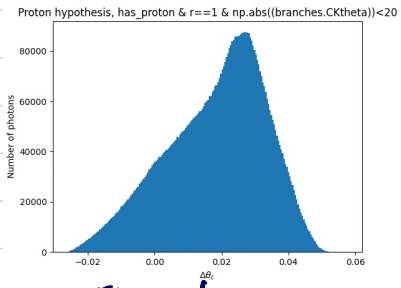
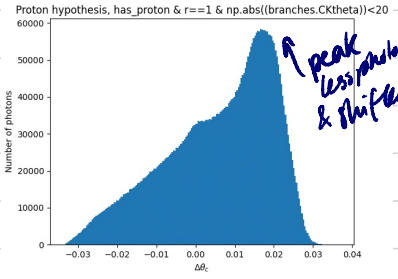


Figure 6.

24 GeV



↑ peak less prominent & shifted right

Figure 7.

Tue 9th August

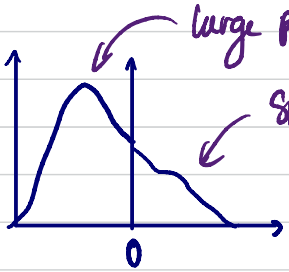
- Organised meeting
- Read David Tong → Feynman diagrams
- Added to references

Wed 10th August

- meeting 2pm, discussed
  - ↳ overview of project
  - ↳ transfered small data & python script over to start going through to produce plots for both protons with mass changed and unchanged.
  - ↳ kaons control varible (compared to proton, should be constant)
  - ↳ went over report writing (looked at overleaf)
  - ↳ subtract changed from unchanged histogram?

What I expect the plots to look like

Something like



- smaller/no peak for changed masses

peak kaons > peak protons
↓more common

Code setting up data (log likelihood for Protons & Kaons and momentum)

```
import uproot
import matplotlib.pyplot as plt
import numpy as np
import awkward as ak

#load the data
particles_unchanged = uproot.open("DVntuple_pions.root:TuplePion/DecayTree;1")
particles_massChange = uproot.open("DVntuple_pions_reprocessed.root:TuplePion/DecayTree;1")

#These lines print the contents of the data file
particles_unchanged.keys()
particles_unchanged.show()

particles_massChange.keys()
particles_massChange.show()

#define branches
branches_unchanged = particles_unchanged.arrays()
branches_massChange = particles_massChange.arrays()

#define some variables; RichDDL means we are only using the RICH information

#protons
Piplus_RichDLLp_unchanged = branches_unchanged.piplus_RichDLLp
Piplus_RichDLLp_massChange = branches_massChange.piplus_RichDLLp

#Kaons
Piplus_RichDLLk_unchanged = branches_unchanged.piplus_RichDLLk
Piplus_RichDLLk_massChange = branches_massChange.piplus_RichDLLk
```

```
#momenta in MeV
Momentum_unchanged = branches_unchanged.piplus_P
Momentum_massChange = branches_massChange.piplus_P

#convert momenta to GeV
Momentum_unchanged = branches_unchanged.piplus_P*10**(-3)
Momentum_massChange = branches_massChange.piplus_P*10**(-3)
```

Fri 12th August

- Looked at pieces of code from example & changed accordingly
- branches → branches_unchanged

```
bins=400
x=Piplus_RichDLLk_unchanged
cx=Piplus_RichDLLk_massChange
plt.hist(x, bins)

plt.xlabel('Log likelihood')
plt.ylabel('Number of Tracks')
plt.title('Kaon Mass unchanged', fontweight ="bold")
plt.show()
```

- to get a histogram for proton mass unchanged
- error → ('no field named 'radiator'), same for 'CKtheta'
  - ↳ commented out 'ia_RICH1 ...' and 'dlk' → ValueError → from ak.flatten(cut)
  - ↳ copied example code for python histogram, resulting in the following code and subsequently the plots shown in figure 8 & 9 for both changed & unchanged Proton mass
- 400 bins were used
- Each Plot was made by altering code in atom, then saving and running it from terminal.

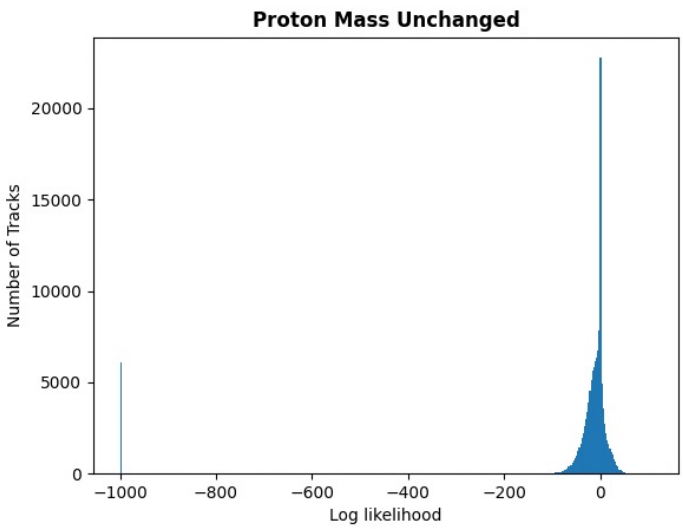


Figure 10.

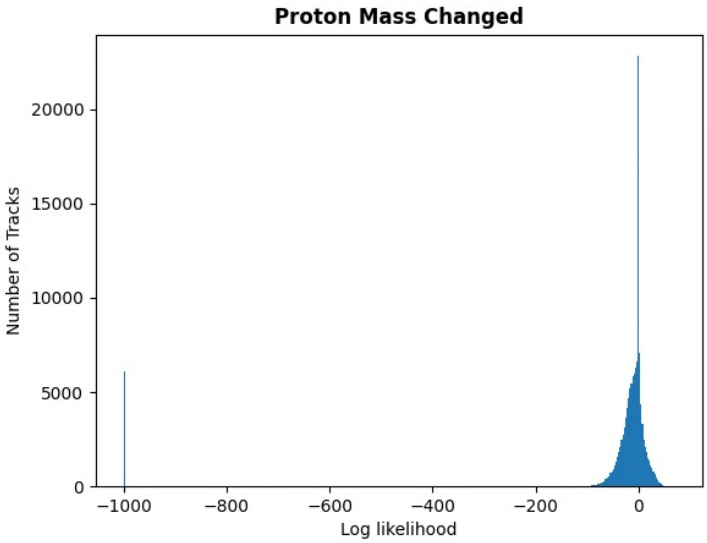


Figure 9.

- The same was done with kaons to produce the following

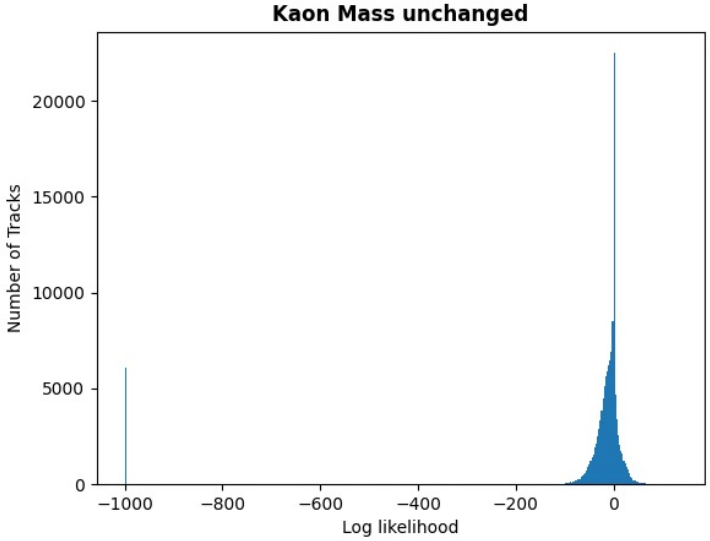


Figure 10.

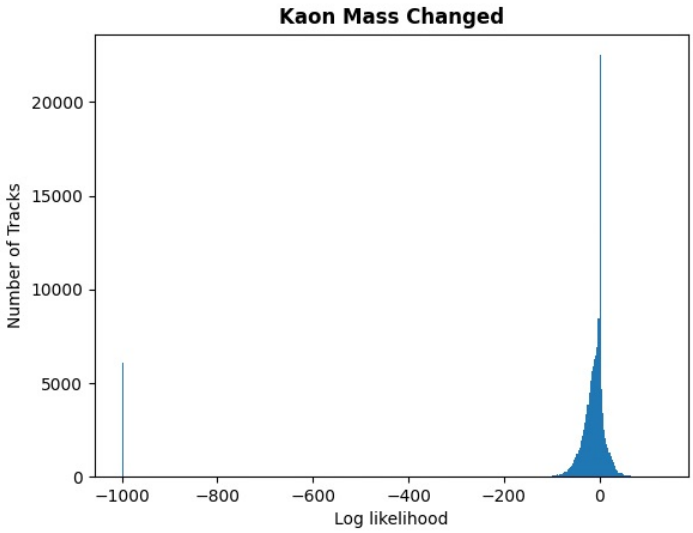


Figure 11.

Sat 13th August

Attempted to plot the histograms to show the main peaks more clearly and tried to change the momentum range with &.

- First tried plt.xlim([-40,40])

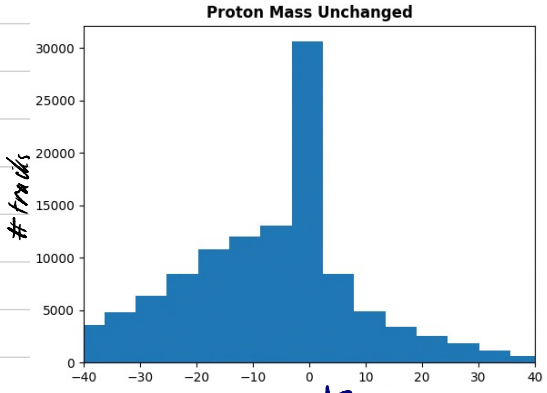


Figure 12.

- bin sizes too big → change to 800 bins

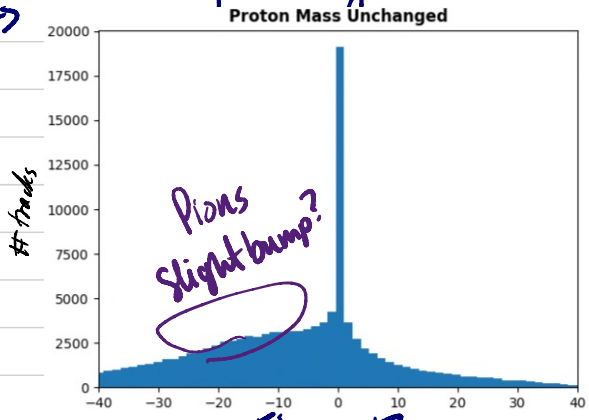


Figure 13.

- Then with plt.xlim([-100,100])

```
52  bins=200
53  x=Piplus_RichDLLp_unchanged
54  plt.hist(x, bins)
55
56  plt.xlabel('Cherenkov Angle (mrad)')
57  plt.ylabel('Number of Photons')
58  plt.title('Proton Mass Unchanged', fontweight ="bold")
59  plt.xlim([-100,100])
60  plt.show()
61
```

Figure 14.

200 bins

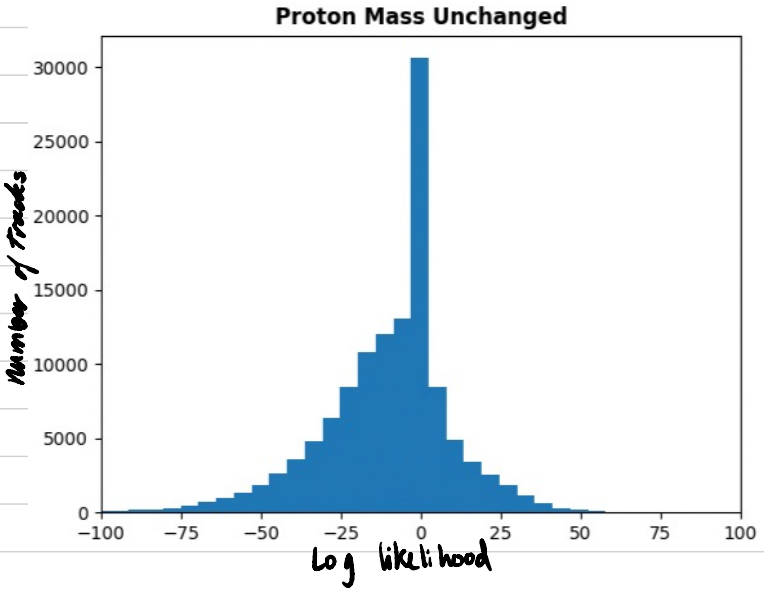


Figure 15.

800 bins

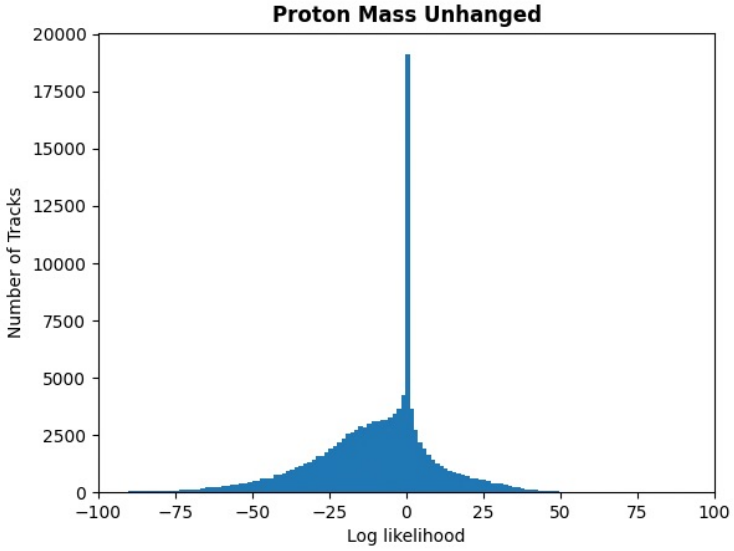
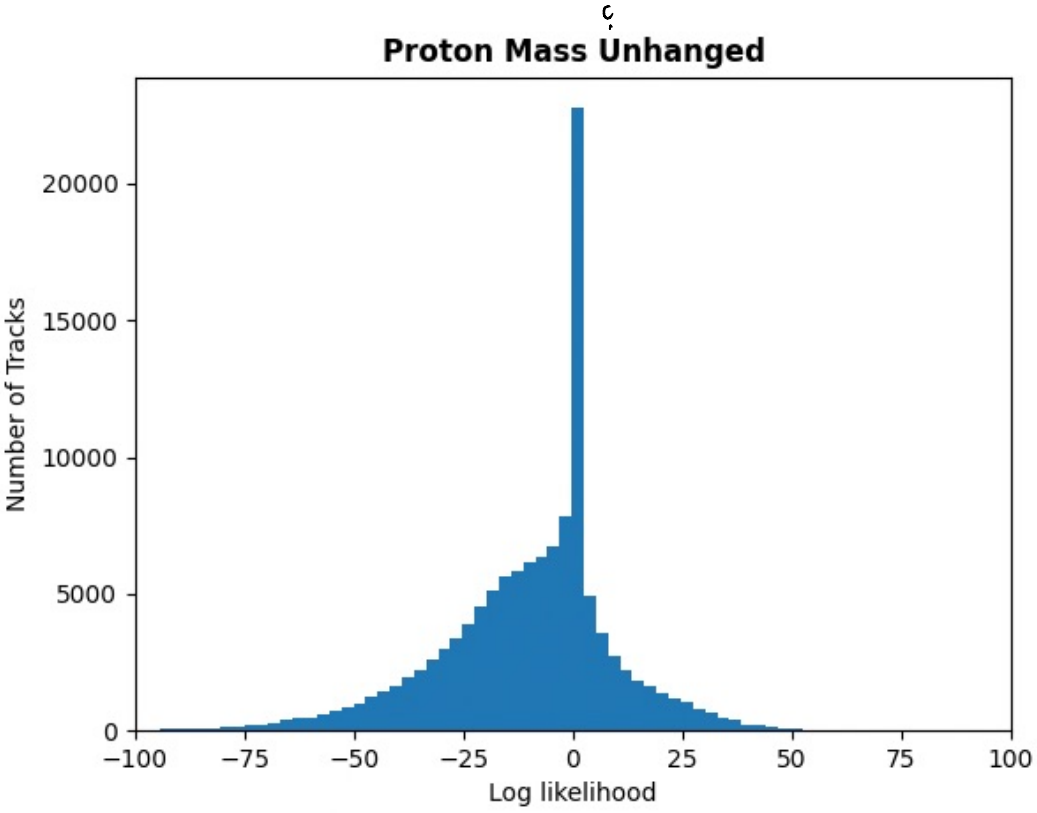
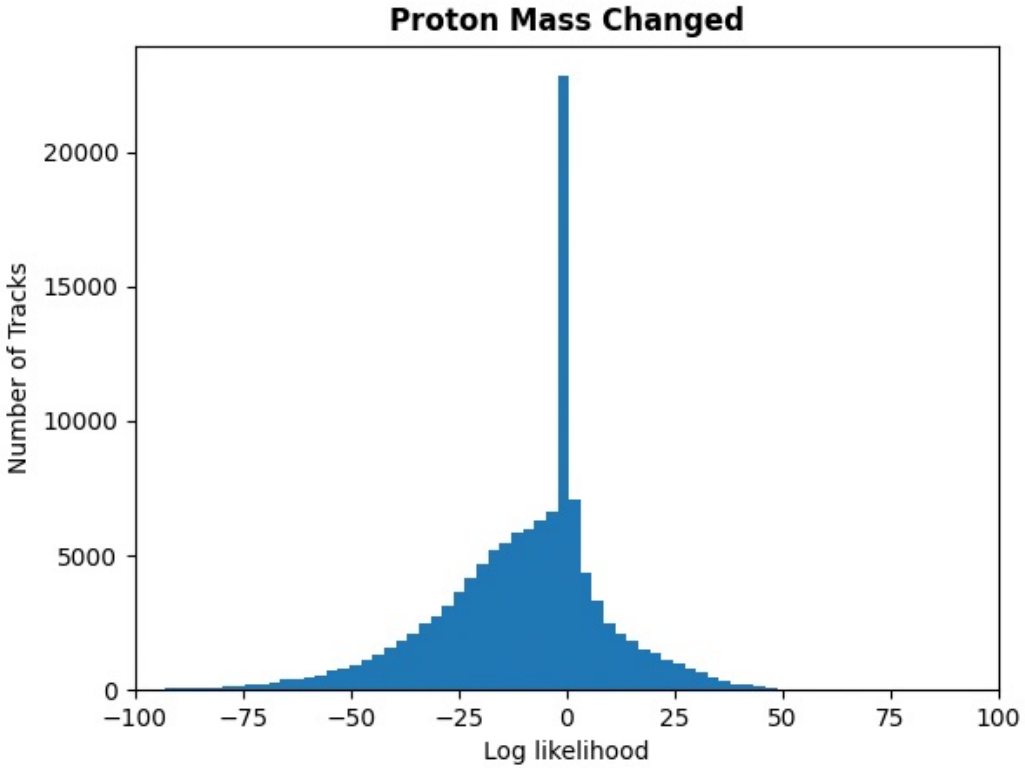
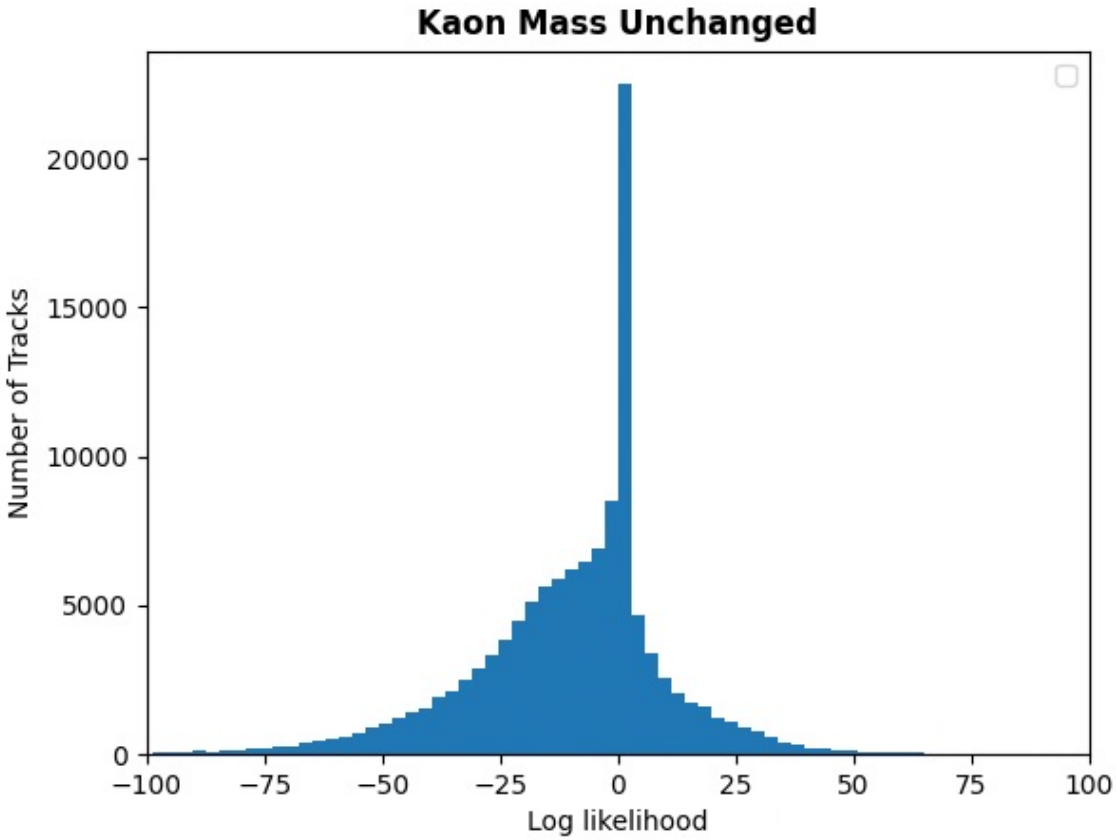


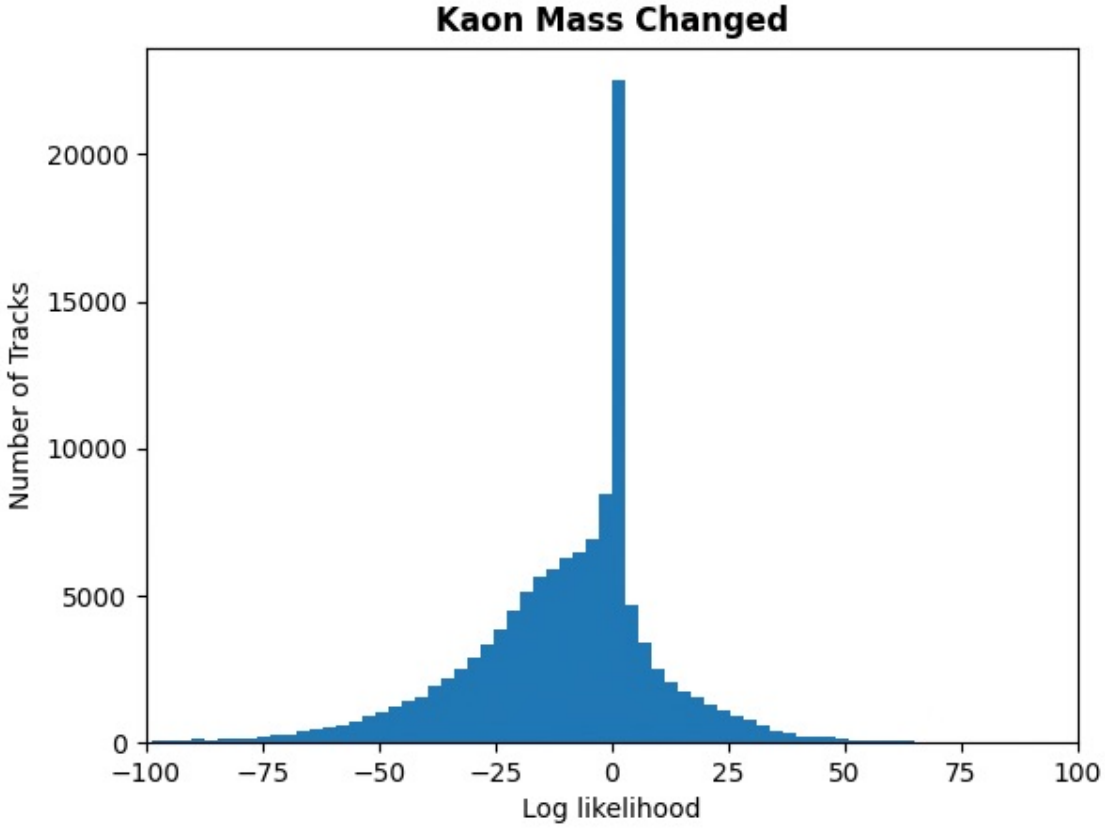
Figure 16.

Bins = 400


Proton Mass Unhanged
Number of Tracks
20000
15000
10000
5000
0
−100
−75
−50
−25
0
25
50
75
100
Log likelihood


Proton Mass Changed
Number of Tracks
20000
15000
10000
5000
0
−100
−75
−50
−25
0
25
50
75
100
Log likelihood


Kaon Mass Unchanged
Number of Tracks
20000
15000
10000
5000
0
−100
−75
−50
−25
0
25
50
75
100
Log likelihood


Kaon Mass Changed
Number of Tracks
20000
15000
10000
5000
0
−100
−75
−50
−25
0
25
50
75
100
Log likelihood

Sun 14th August

The plots on Pg 17, show that there is a peak on the negative side (which is a good sign as we expect this from pions. The peak may not be as large as I expected.

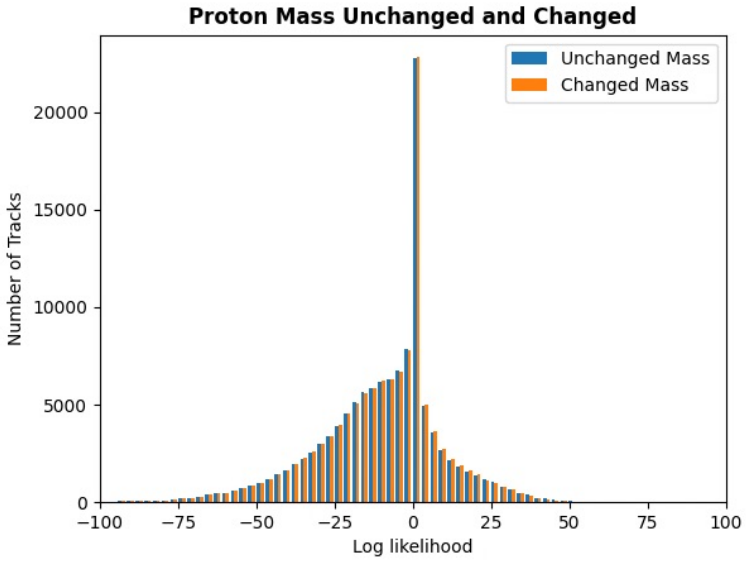
The peak at 0 I'm more unsure about as to whether or not it is expected.
↳ need to ask (looks like plot E hist showed).

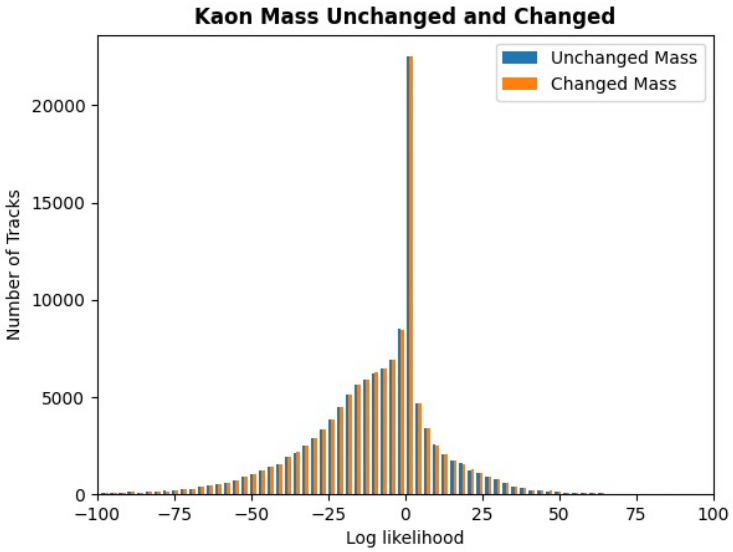
There does not seem to be a noticible peak in the positive region that we expect from protons (and Kaons), with the plots of both changed and unchanged mass looking the same.

- Possibly have plotted wrong / misunderstood data.
- Not sure of peak around -1000

- Need to look at the momentum region & understand how to do that w/ code.
- Plot not clear because not much data?
- more bins?

- Produced histograms with both changed and unchanged masses on same plot for protons and Kaons, by plt.hist, and added labels. (bins = 400)





Week 4 (15/8-19/8)

Goals

- Produce clearer plots to see noticible bump for protons
- Change momentum region
- Possibly use more data
- Finish progress report draft
- Understand LL

Questions

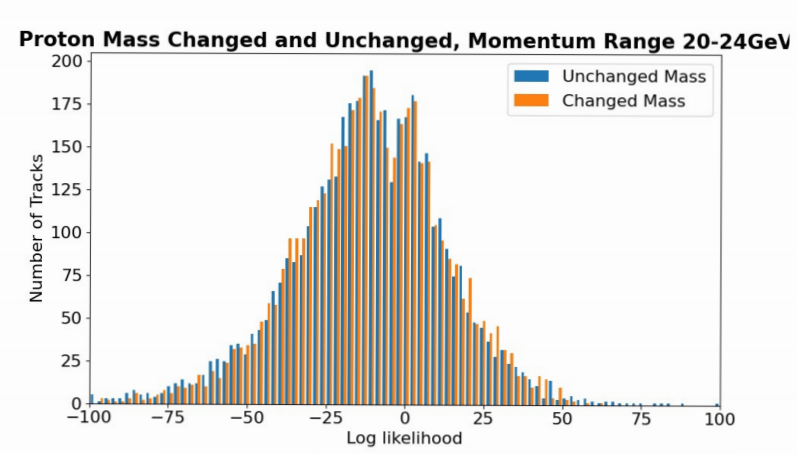
- number of tracks → detections
- peak at 0
- plot histogram → weaker
- subtract bkgd

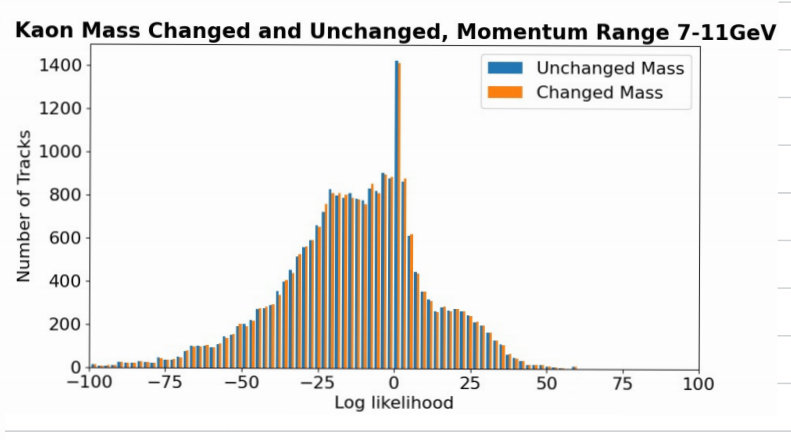
Tasks

- ~~Write progress report~~
- ~~momentum region w/ plots~~
- start plotting with new data set

Summary/Results

Changed the momentum range for first dataset resulting in the following for protons and kaons





No obvious peak for unchanged mass can be seen in either plots for protons or kaons

Thur 18th August

Meeting with Ulrik & Eliot 12 pm
Discussed:
- applying momentum range to plots
- new data set → histograms
- subtract data for histograms
- only select higher values
- - gaps indicates → tracks
- 0 line indicates → probability
- make sure same number of varibles/data for each
- log y-axis

probability $\frac{\text{pion}}{\text{proton}}$ LL

Transferred over new data file with masses changed to ±200MeV and ±400MeV and Python script organising data

Sat 20th August

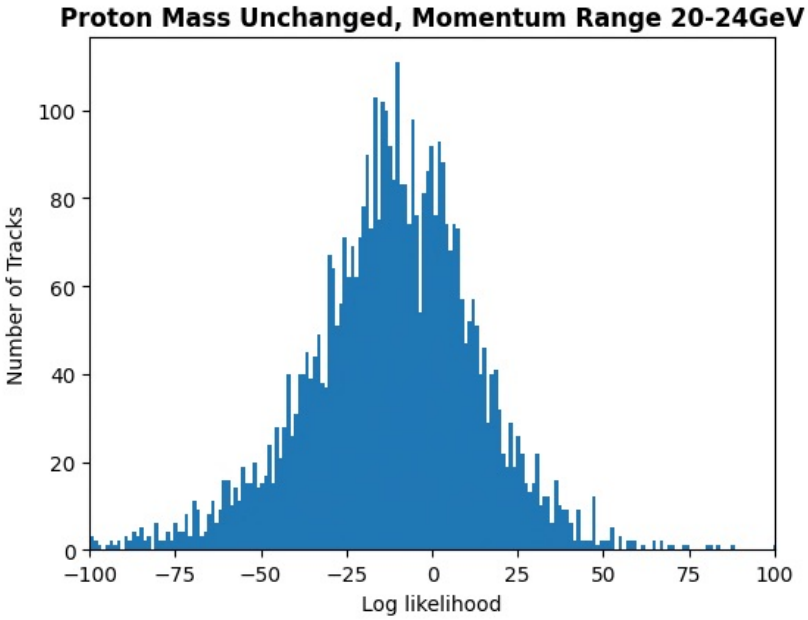
Changed the momentum range for protons

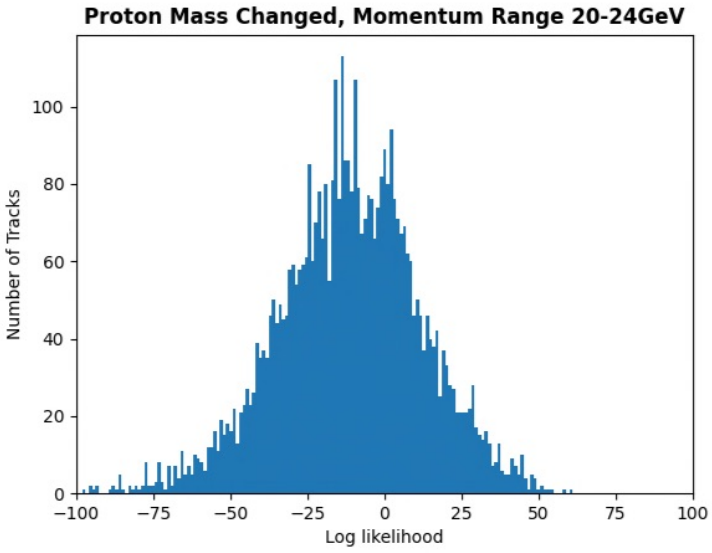
- First to 20-24 GeV based on Eliot's paper, which resulted in (with 1000 bins) xlim[-100,100]

Proton mass unchanged

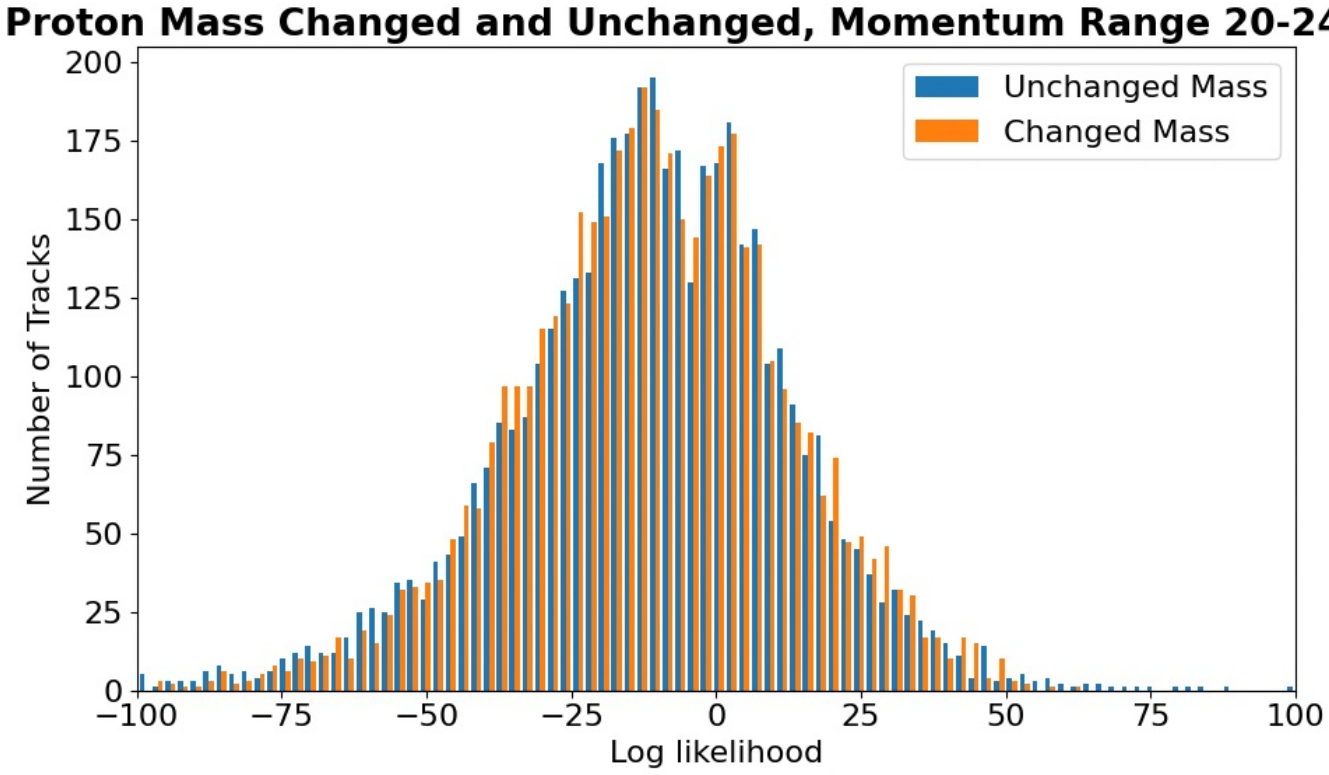
changed

- error occurred with cut
  ↳ use awkward?
- forgot change momentum



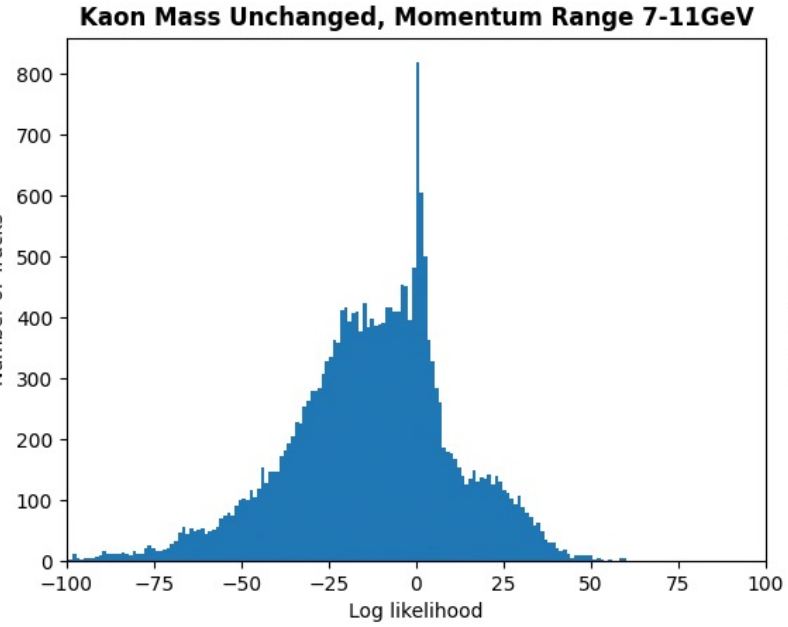


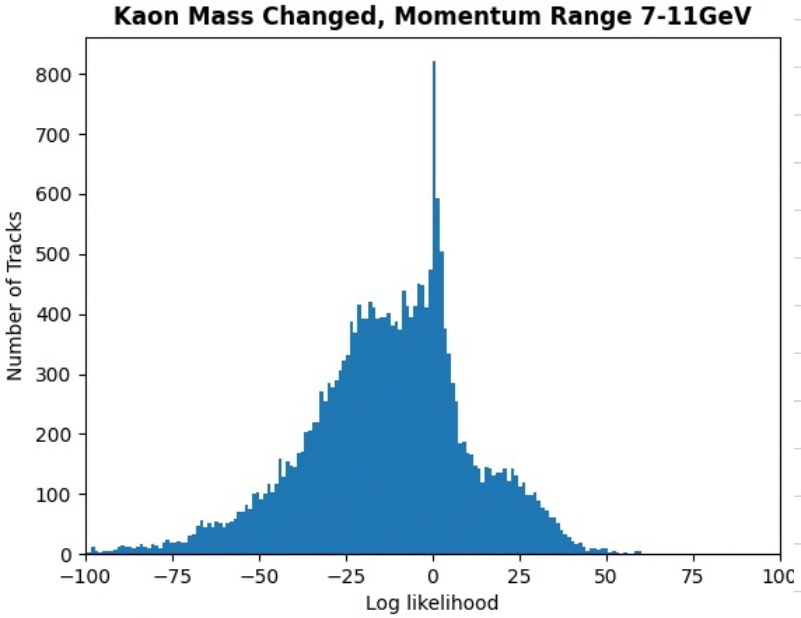
Both with Bin size changed to 500



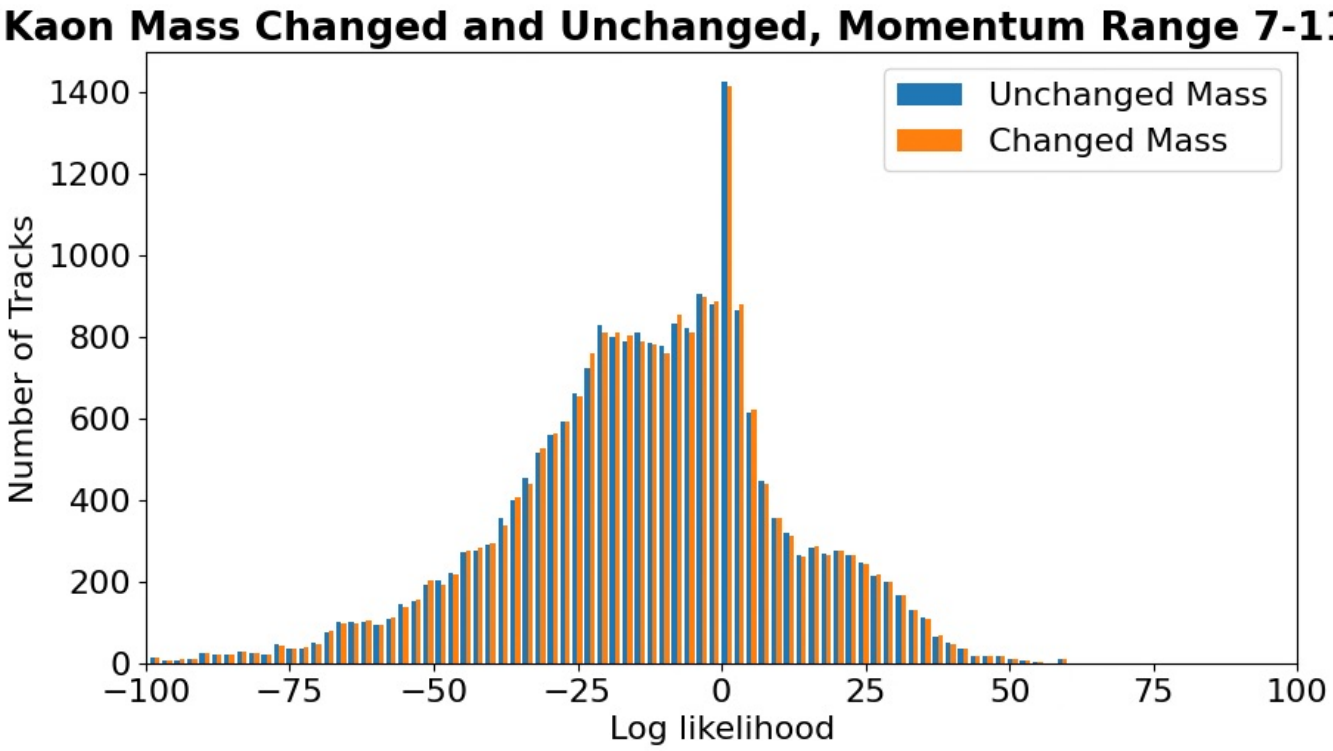
Then did the same with kaons with momentum region 7-11 GeV (1000 bins)

Kaon Unchanged mass changed

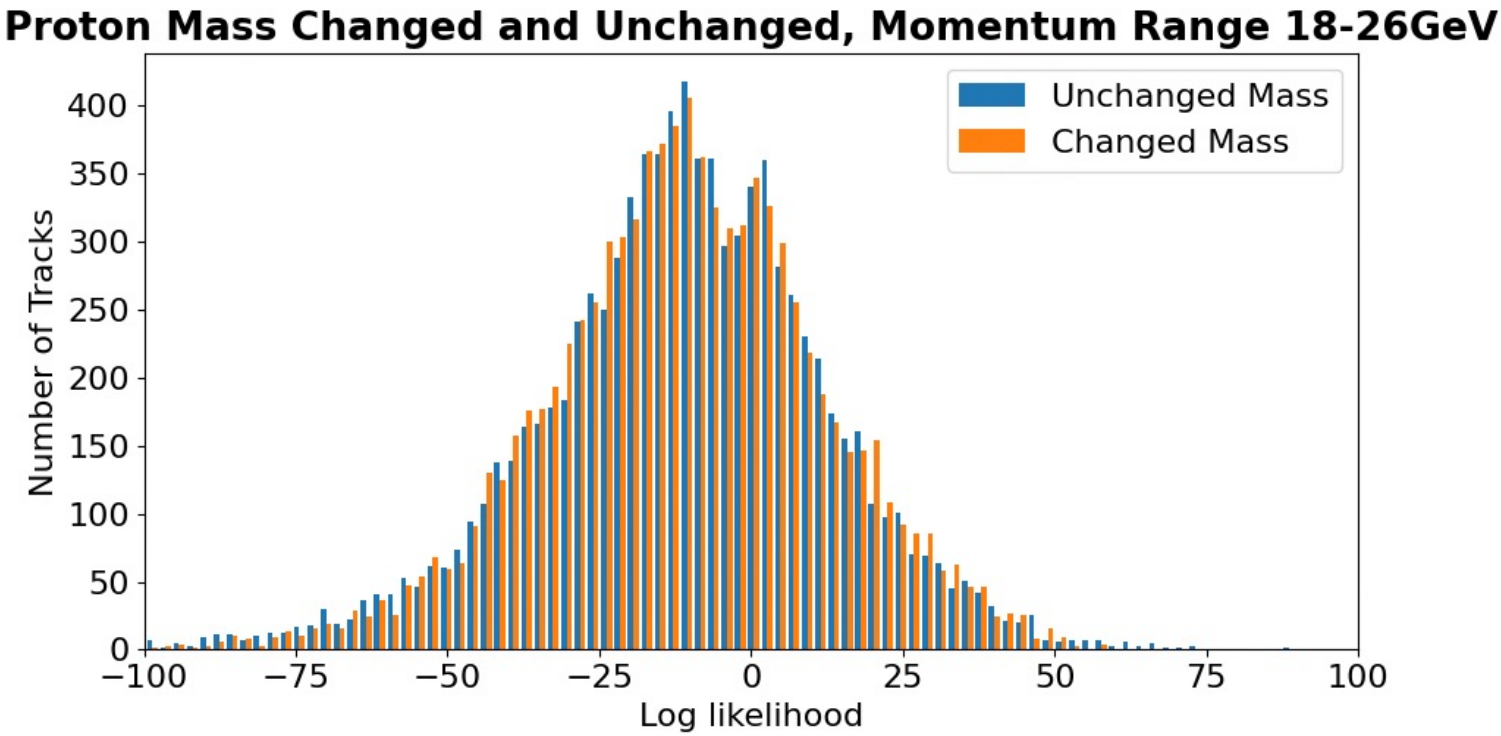




Both with 500 bins



Tried a larger momentum region for protons of 18-26GeV, resulting in



Observations

- The reason we still might not be noticing any difference is because of how the histogram is plotted which makes it unclear.
- Still not enough data
- Incorrect momentum region
- can see a slight difference however

Week 5 (22/8-26/8)

Goals

- Observe a difference in changed & unchanged mass
- Plot with new data at ±200 MeV & +400MeV
- Submit progress report

Questions

- Plotting both changed & unchanged seem to double y-axis
- ~~Include kaons in progress report~~
- plot histograms differently
- How will kaons be implemented?
- Am I doing enough?
- progress report
  - ↳ references
  - ↳ difficulties?
  - ↳ method?
  - ↳ too long?

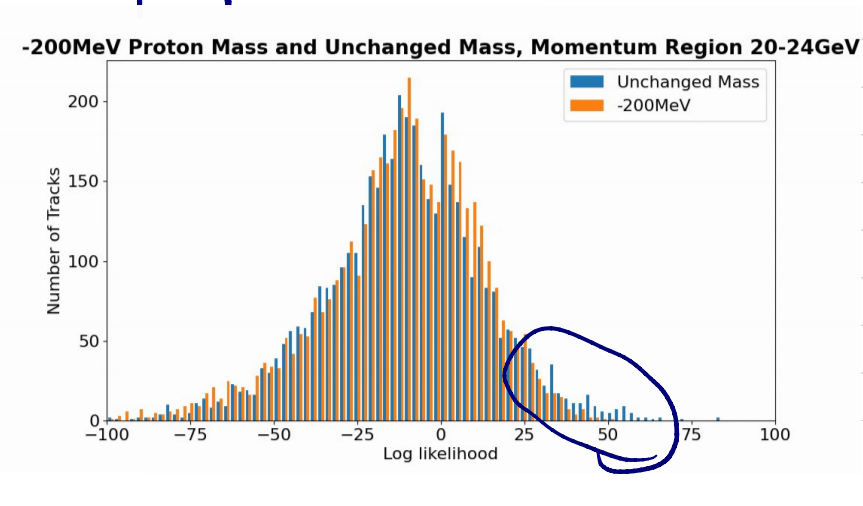
Tasks

- Plot format for histograms
  - ↳ change to be clearer
- subtract changed from unchanged data
- Plot with new data
- submit progress report

Summary

Produced plots for the new data sets with masses changed to +200MeV, -200MeV and +400MeV.

- First plotted seperatly and then comparison for protons
- Did the same thing but with momentum region of 18-24GeV for protons



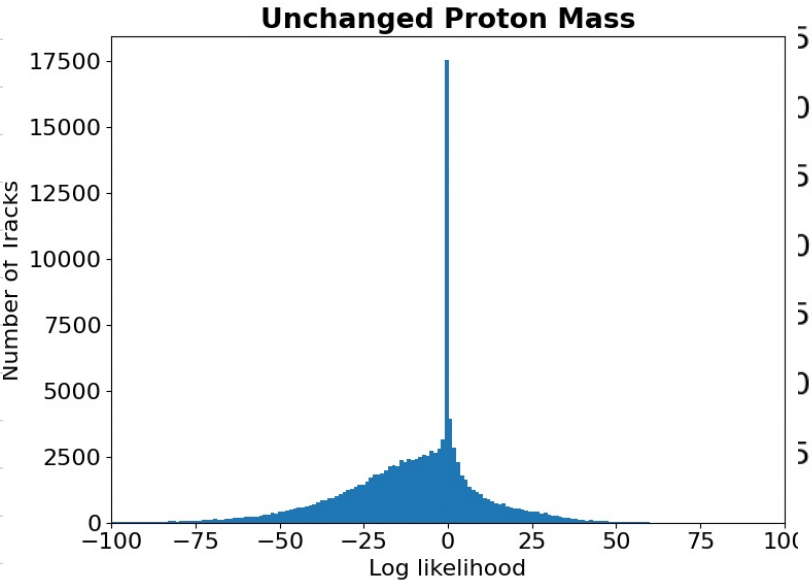
-200MeV gave most promising result for protons

Tue 23rd August

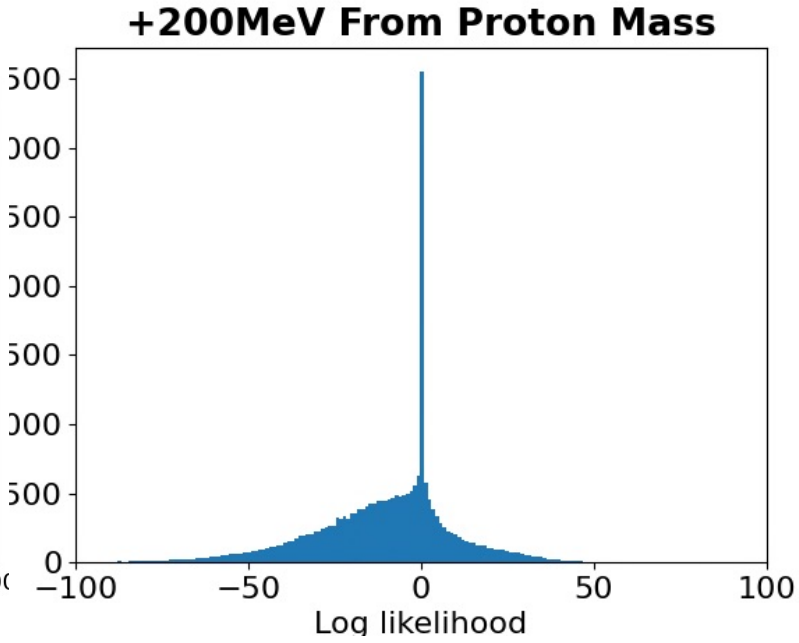
Used same process as previously to produce histograms with new data for changed masses of ±200MeV and +400MeV.
↳ (reprocessed data)

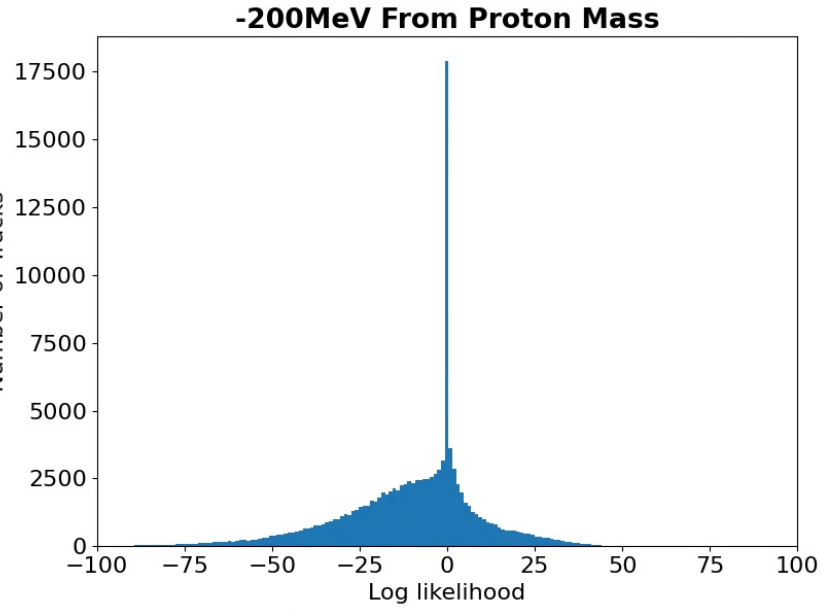
Protons

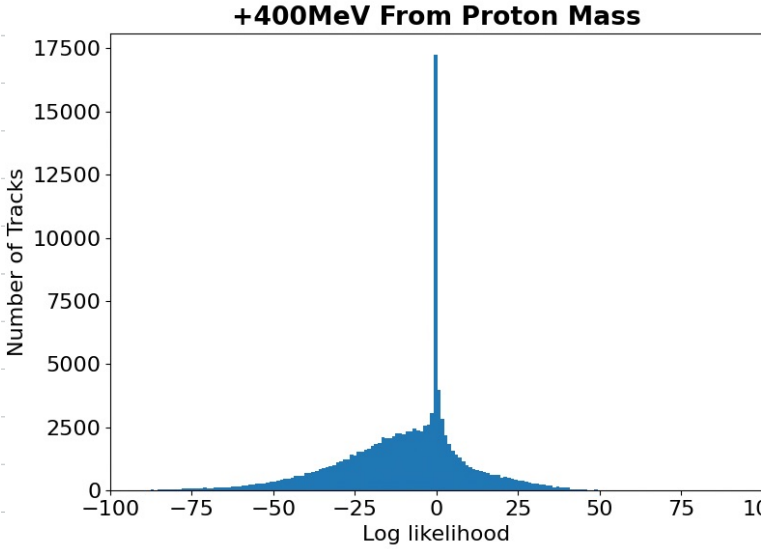
Unchanged



+200MeV



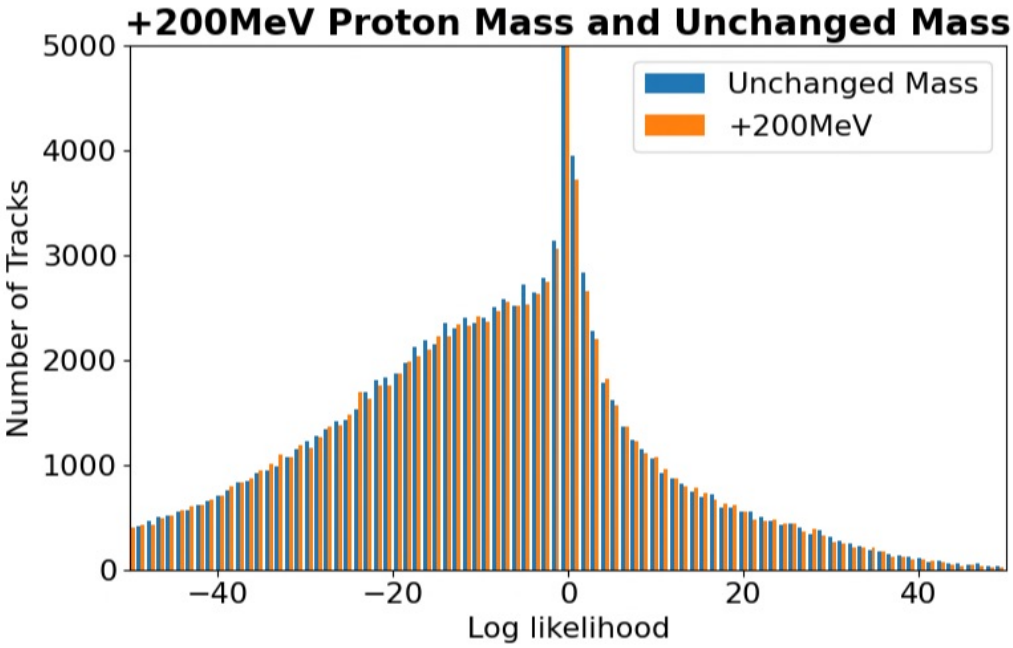




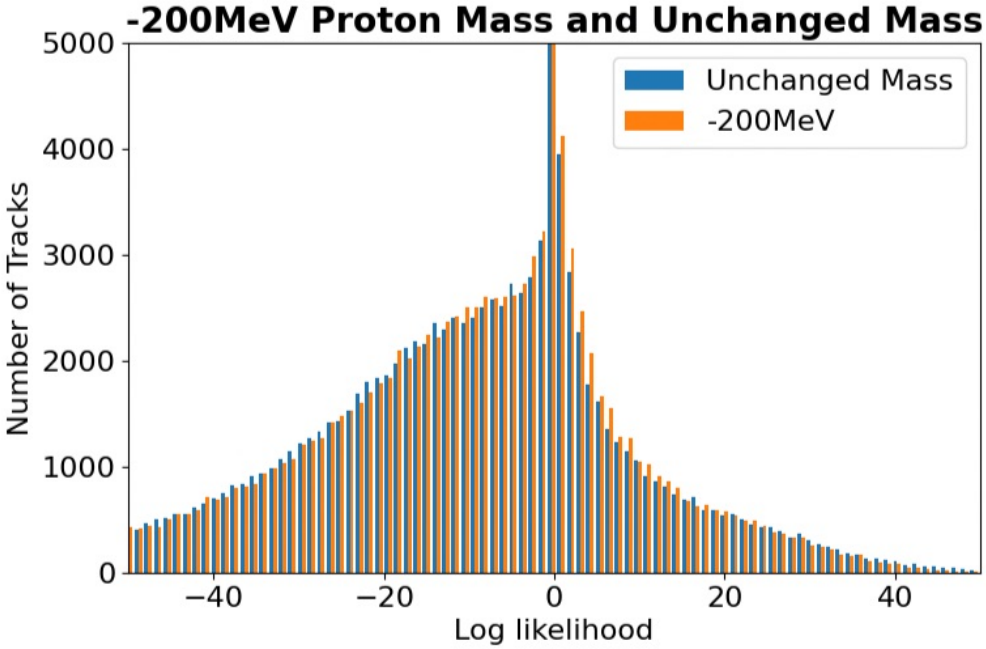
The plots almost look identical with a potential slight difference with −200MeV

Comparison plots protons, changed xlim → [-50, 50] & ylim → (0, 5000) to see better

+200MeV

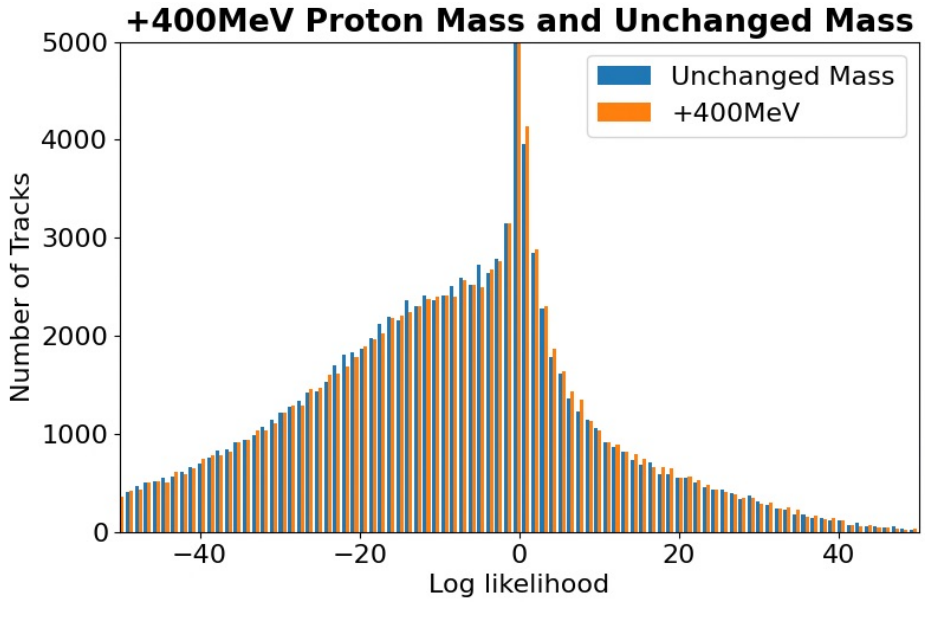


-200MeV



Some slight peaks from changed mass

+400MeV

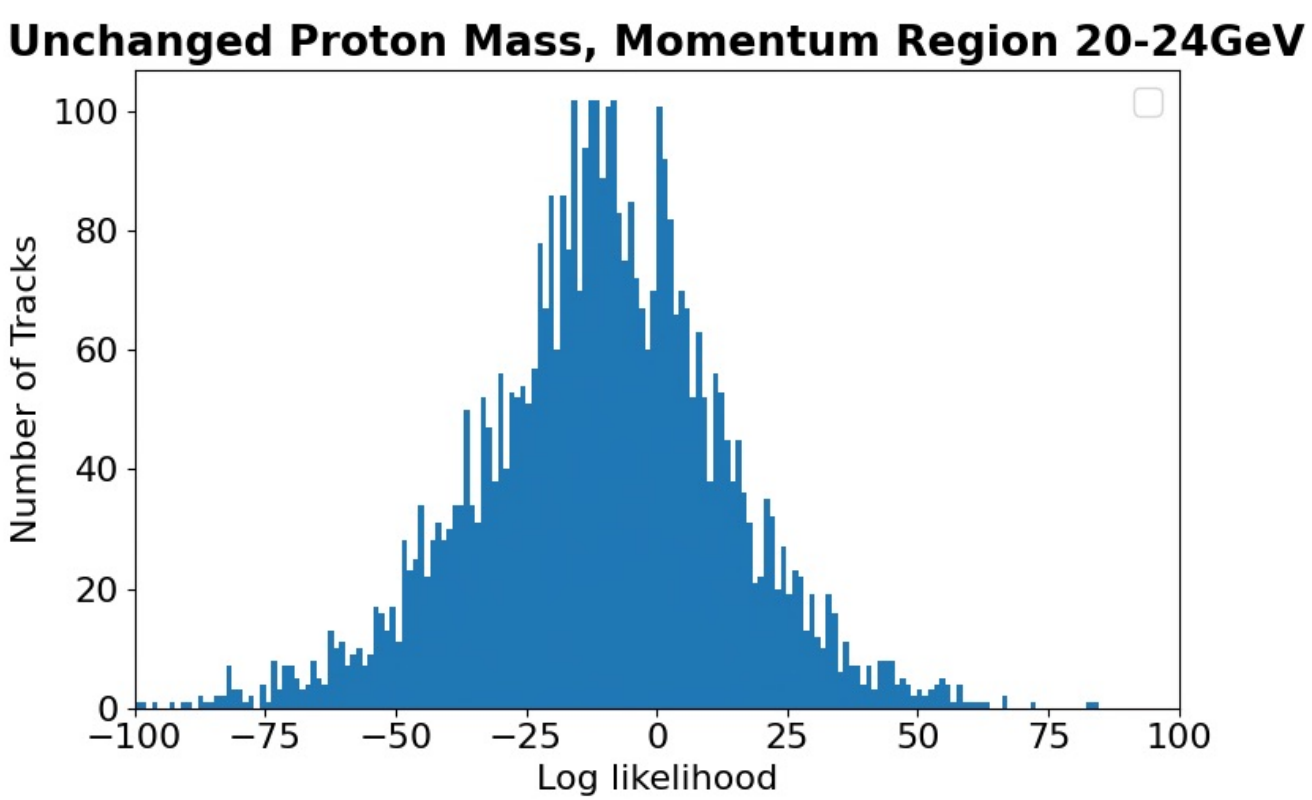


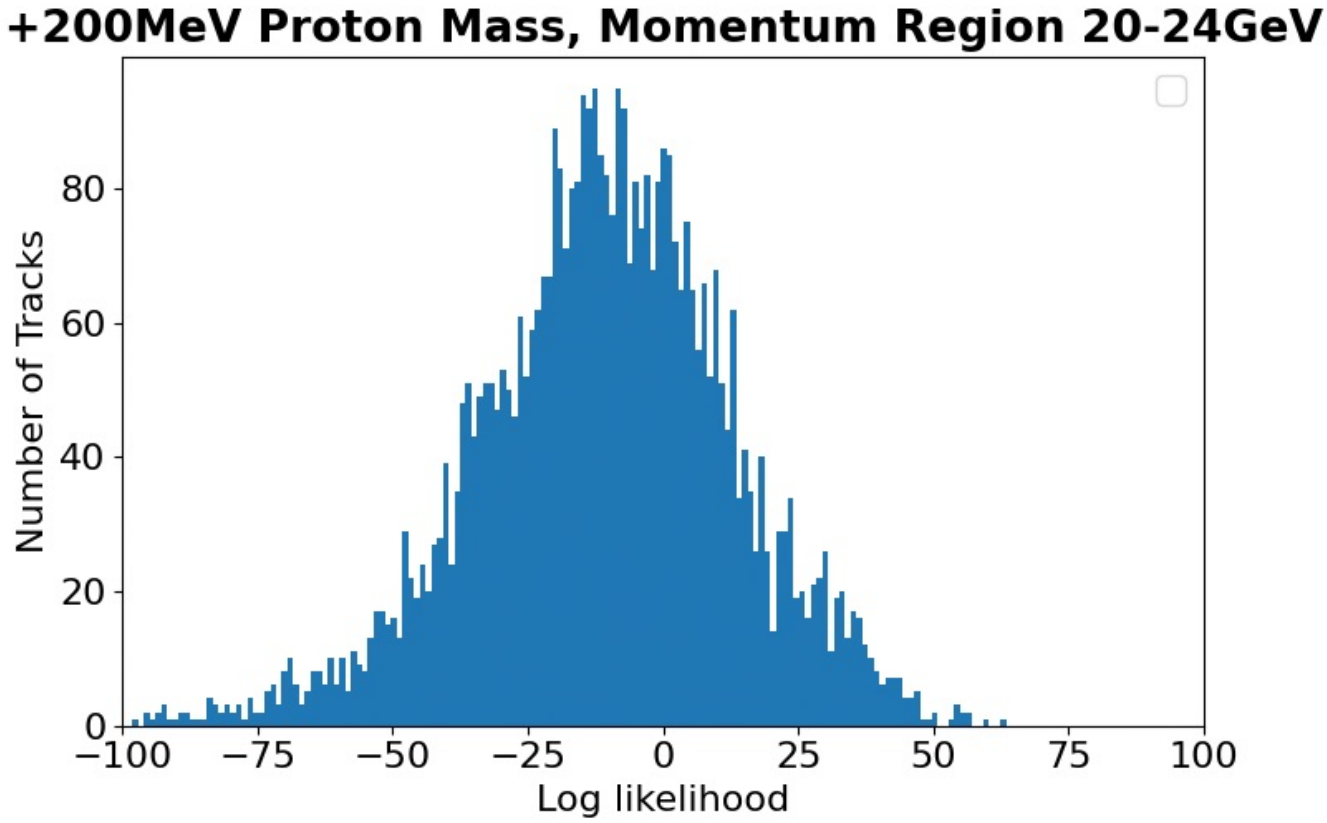
Python code used to plot protons with momentum range

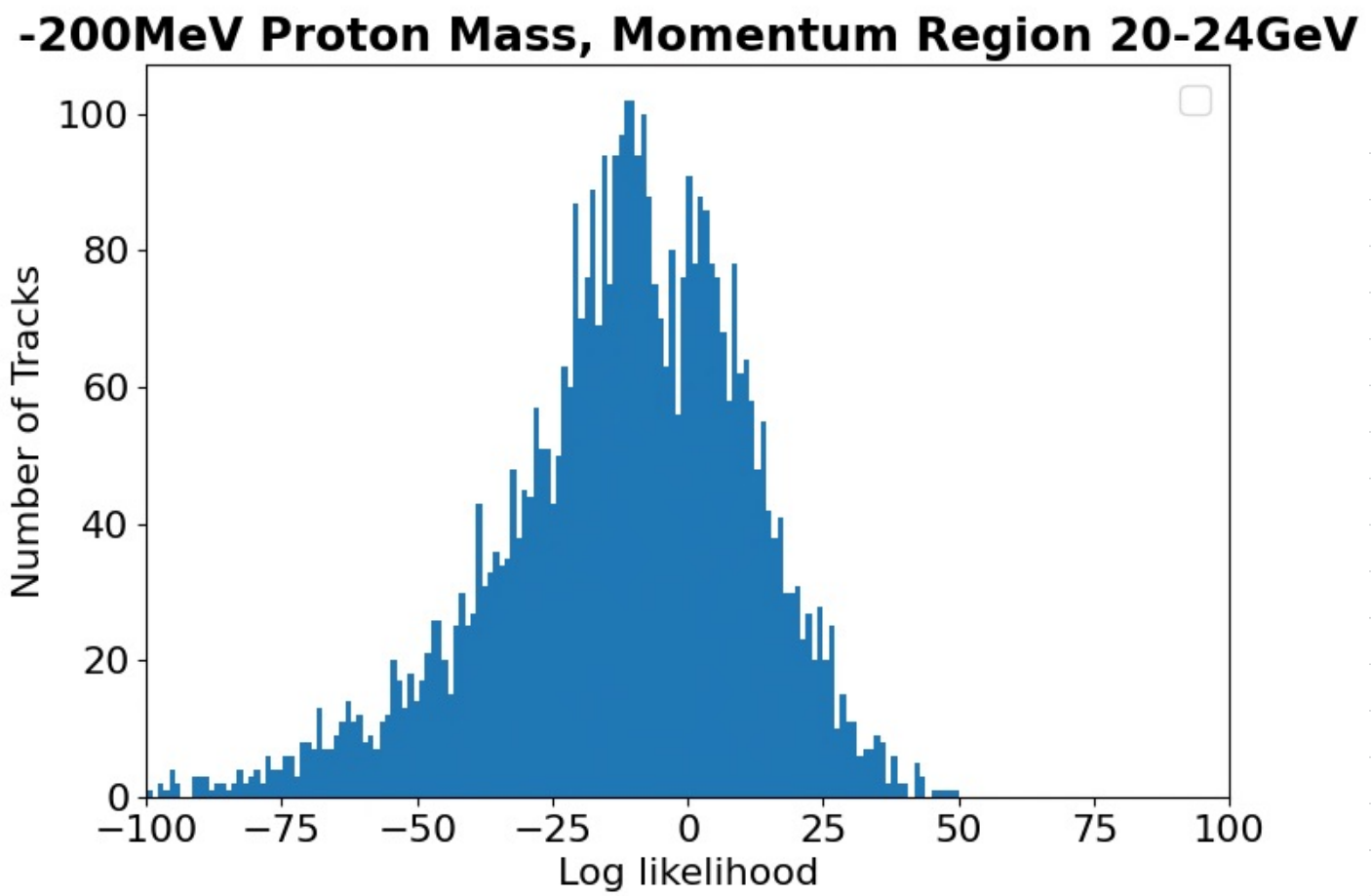
```
import uproot
import matplotlib.pyplot as plt
import numpy as np
import awkward as ak

#load the data
particles_pions_proton_minus_200 = uproot.open("DVntuple_pions_proton_minus_200.root:TuplePion/DecayTree;1")
particles_pions_proton_nominal = uproot.open("DVntuple_pions_proton_nominal.root:TuplePion/DecayTree;1")
particles_pions_proton_plus_200 = uproot.open("DVntuple_pions_proton_plus_200.root:TuplePion/DecayTree;1")
particles_pions_proton_plus_400 = uproot.open("DVntuple_pions_proton_plus_400.root:TuplePion/DecayTree;1")

#define branches
branches_pions_proton_minus_200 = particles_pions_proton_minus_200.arrays()
branches_pions_proton_nominal = particles_pions_proton_nominal.arrays()
branches_pions_proton_plus_200 = particles_pions_proton_plus_200.arrays()
branches_pions_proton_plus_400 = particles_pions_proton_plus_400.arrays()


#define some variables; RichDDL means we are only using the RICH information

#protons
RichDLLp_minus_200 = branches_pions_proton_minus_200.piplus_RichDLLp
RichDLLp_nominal = branches_pions_proton_nominal.piplus_RichDLLp
RichDLLp_plus_200 = branches_pions_proton_plus_200.piplus_RichDLLp
RichDLLp_plus_400 = branches_pions_proton_plus_400.piplus_RichDLLp


#Kaons
RichDLLk_minus_200 = branches_pions_proton_minus_200.piplus_RichDLLk
RichDLLk_nominal = branches_pions_proton_nominal.piplus_RichDLLk
RichDLLk_plus_200 = branches_pions_proton_plus_200.piplus_RichDLLk
RichDLLk_plus_400 = branches_pions_proton_plus_400.piplus_RichDLLk
```

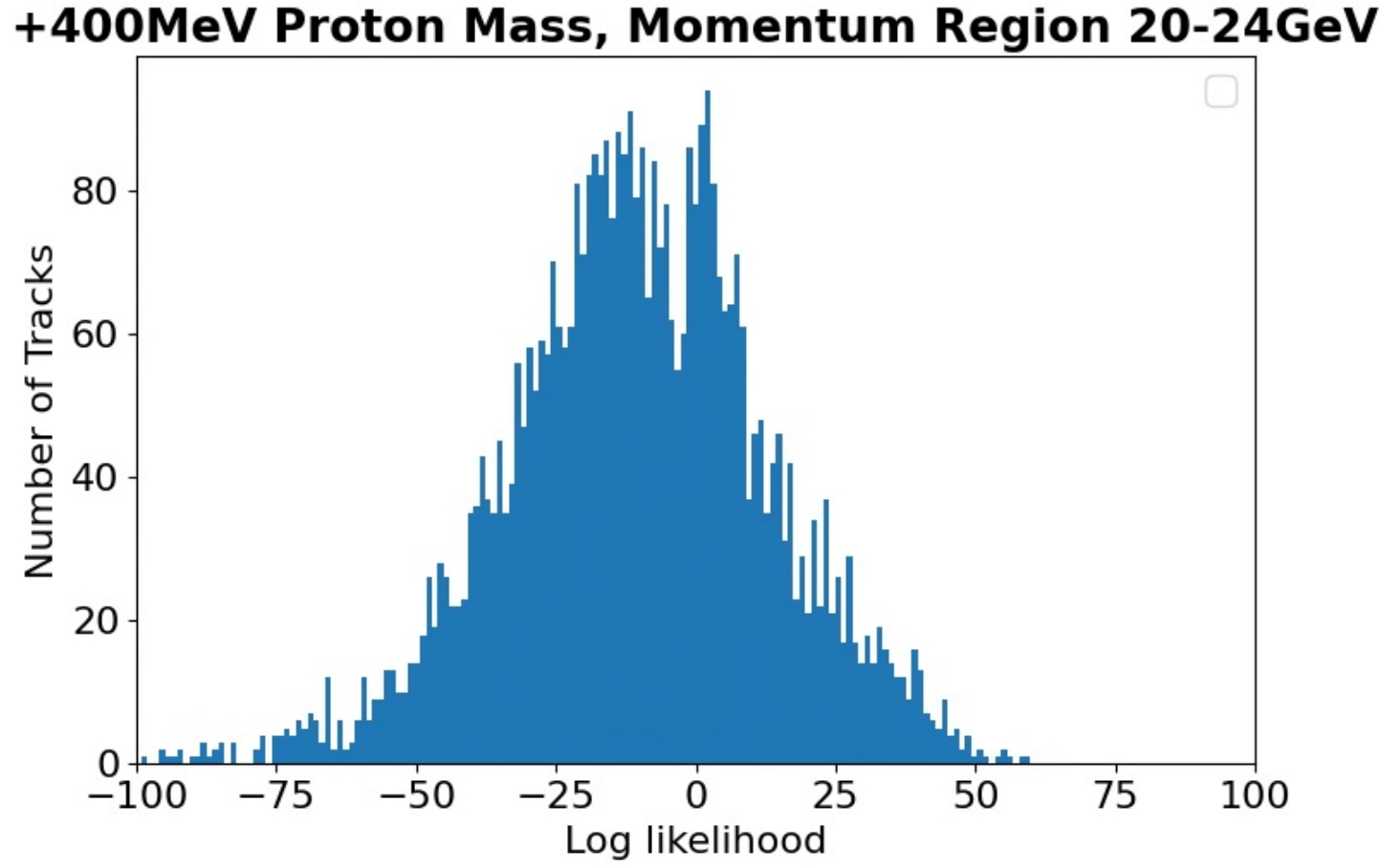
```
lower = Momentum_nominal > 20
upper = Momentum_nominal < 24
cut = lower & upper

lower2 = Momentum_plus_400 > 20
upper2 = Momentum_plus_400 < 24
cut2 = lower2 & upper2


plt.rc('font', size=16)
bins=500
x=RichDLLp_nominal[cut]
cx=RichDLLp_plus_400[cut2]

label=['Unchanged Mass', '+400MeV']
plt.hist((x,cx), bins,label=label)

plt.xlabel('Log likelihood')
plt.ylabel('Number of Tracks')
plt.legend(prop ={'size': 16})
plt.xlim([-100,100])

plt.title('+400MeV Proton Mass and Unchanged Mass, Momentum Region 20-24GeV', fontweight ="bold")
plt.show()
```

Protons with momentum region 20-24 GeV



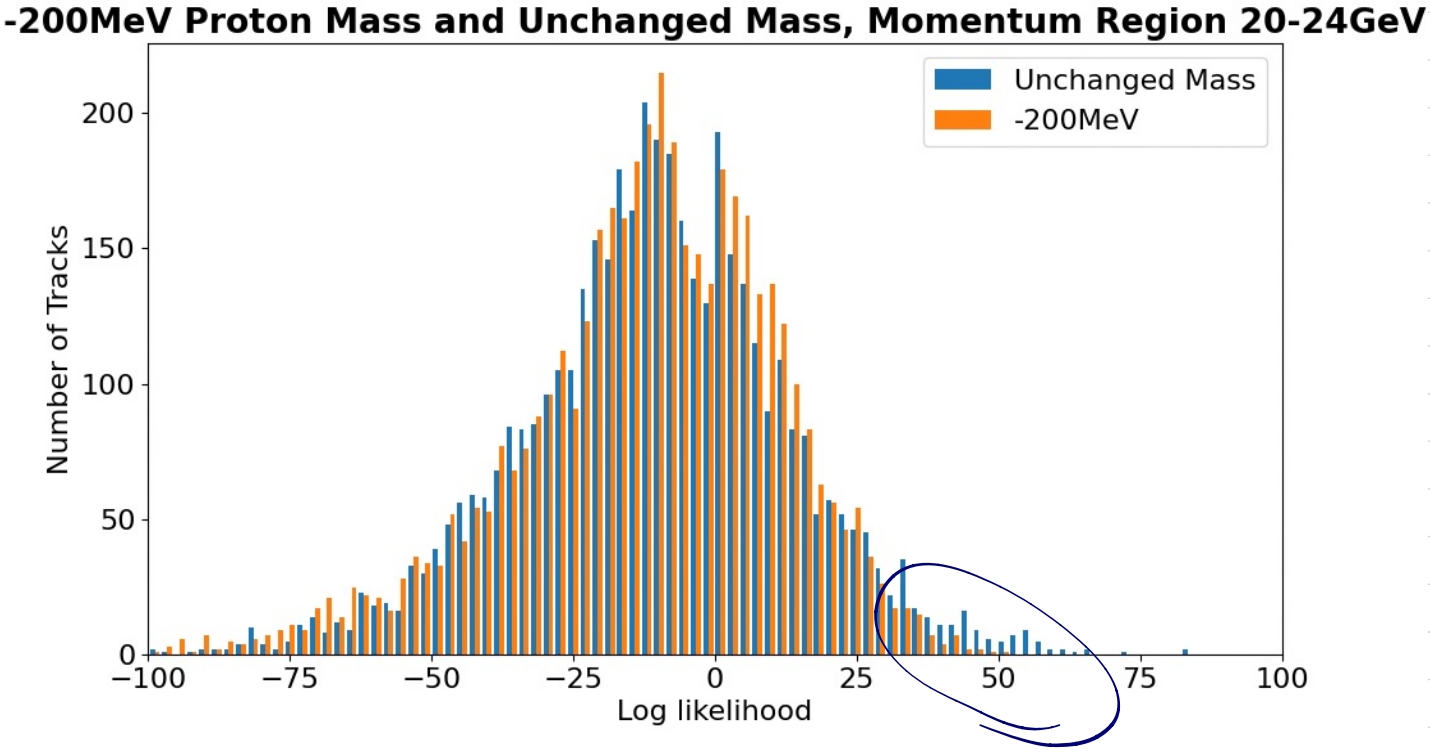




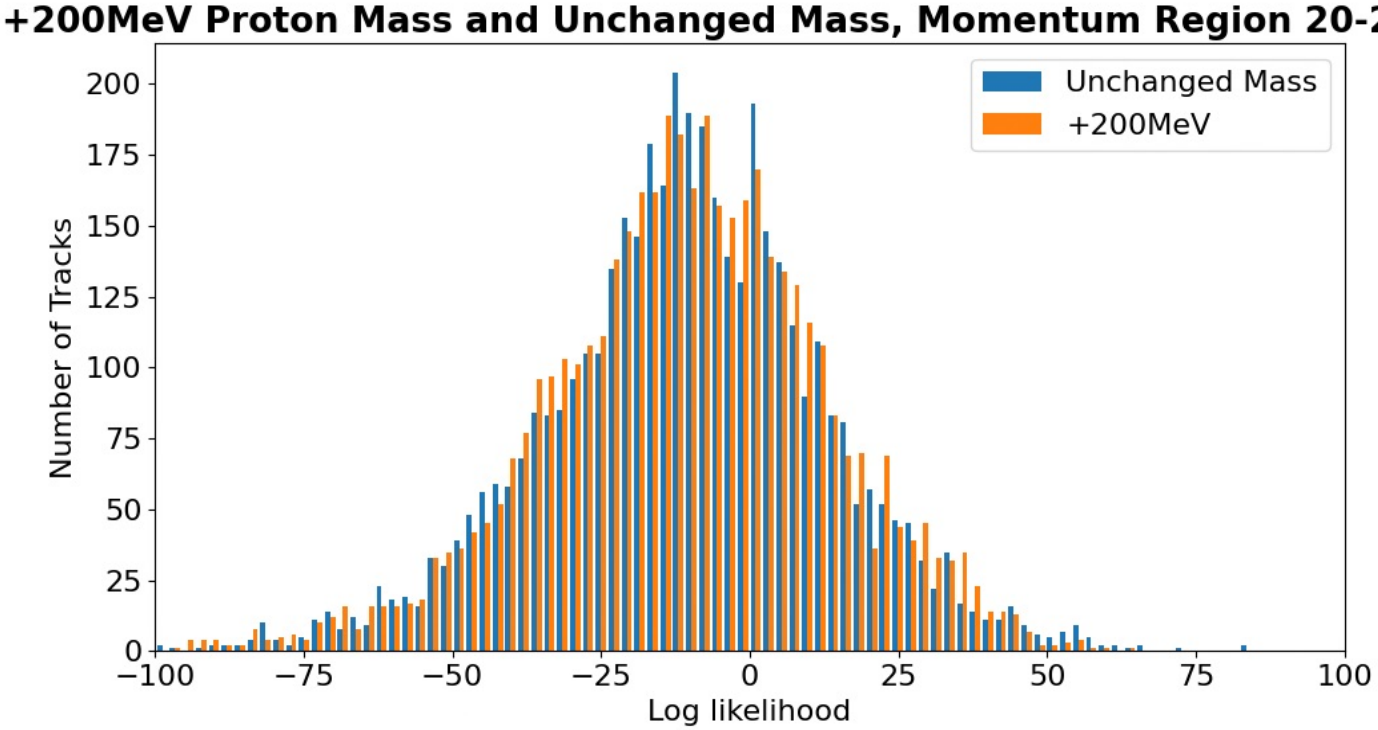


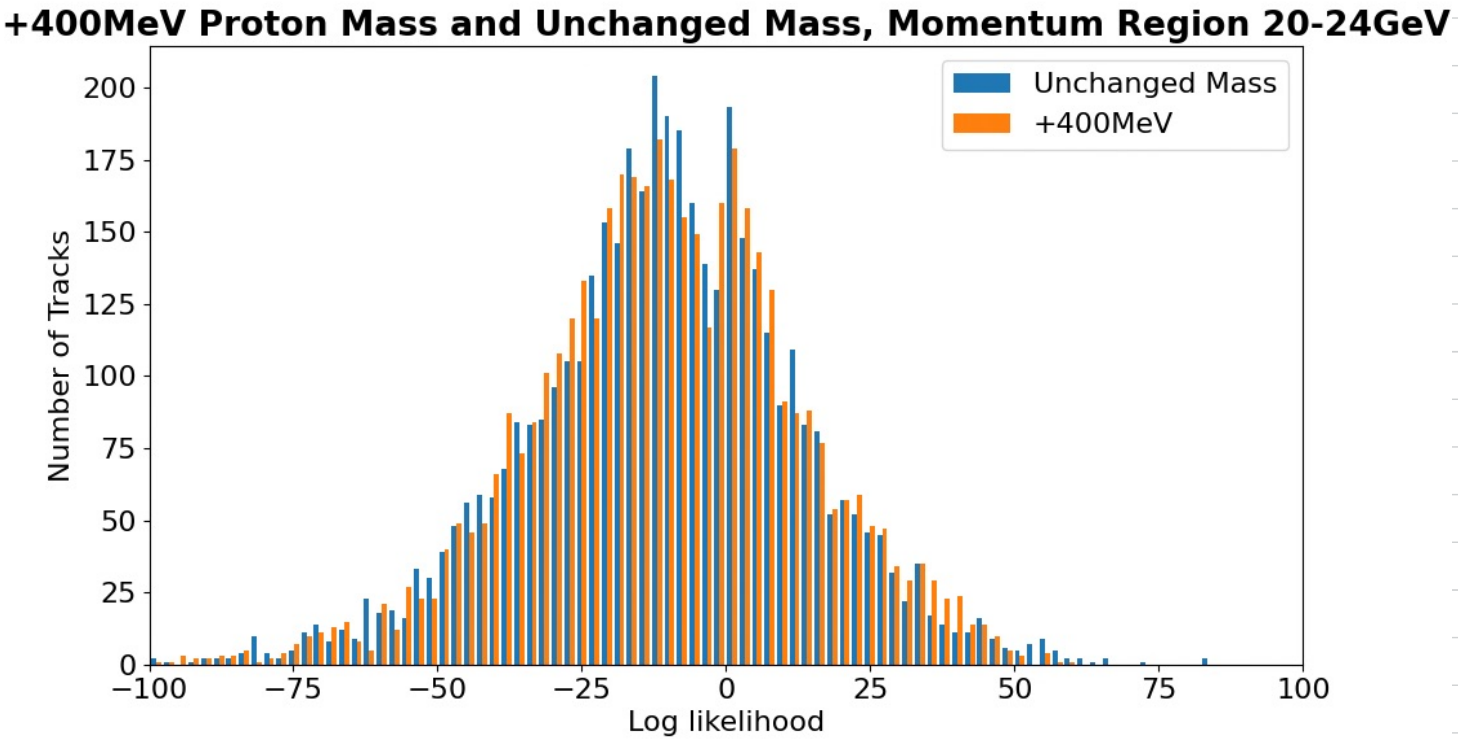
The above 4 plots show more variation that with no momentum region selected

Both for comparison



Shows slight difference with the unchanged mass

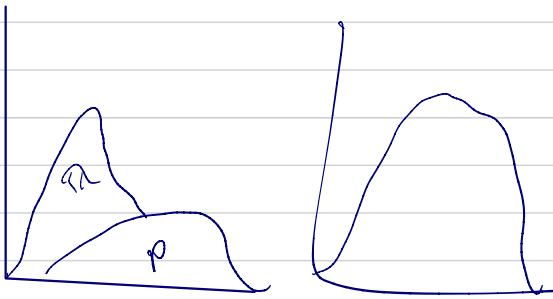


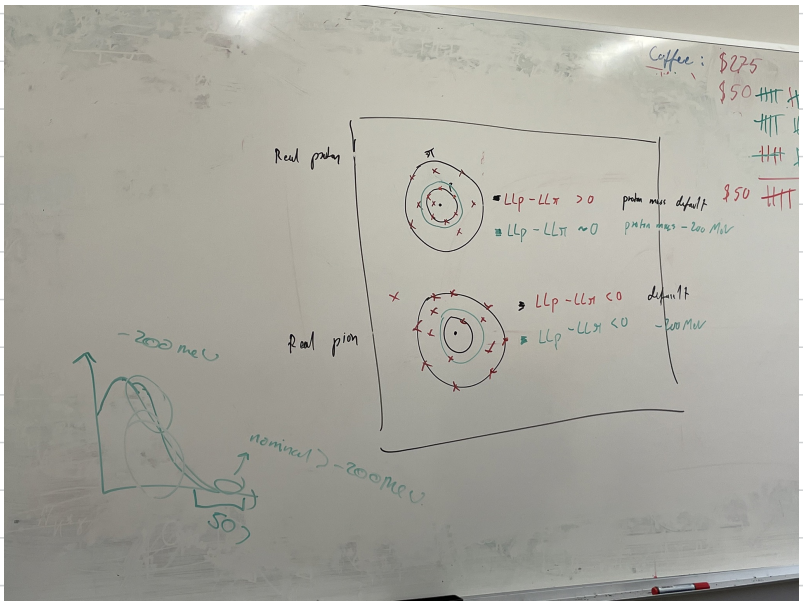

+400MeV Proton Mass and Unchanged Mass, Momentum Region 20-24GeV
Unchanged Mass
+400MeV
Number of Tracks
Log likelihood
200
175
150
125
100
75
50
25
0
−100
−75
−50
−25
0
25
50
75
100

Thur 25th August

Meeting 2:30pm
- discussed plots
  - ↳ slight bump for -200MeV for protons
- Talked about DLL and including LL below threshold/no ring
- progress report
- use momentum range 18-24GeV
- include code snippets

$$\Delta LL = LL_p - LL_\pi$$





Week 6 (29/8-2/9)

Goals

- Produce plots for Kaons w/ reprocessed data
- prepare notes/ understand concepts better for talk
- change plot style
- obtain a more visible difference in plots

Questions

- Kaon plots as control
- double axes
- measure momentum of electron

$$r = \frac{p}{qB}$$

Tasks

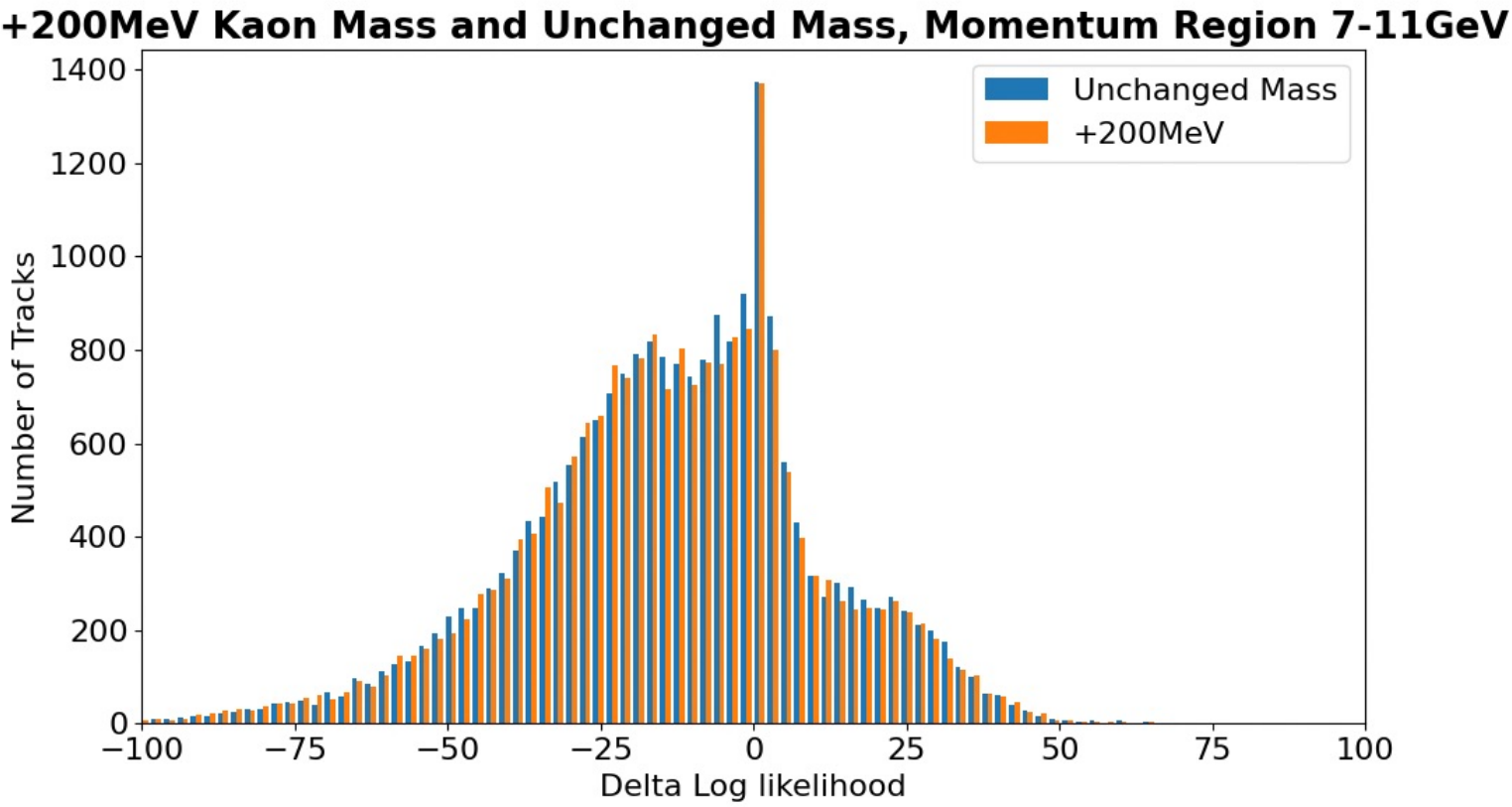
- Work on code to plot subtraction of data
- plot Kaons reprocessed
- log y-axis

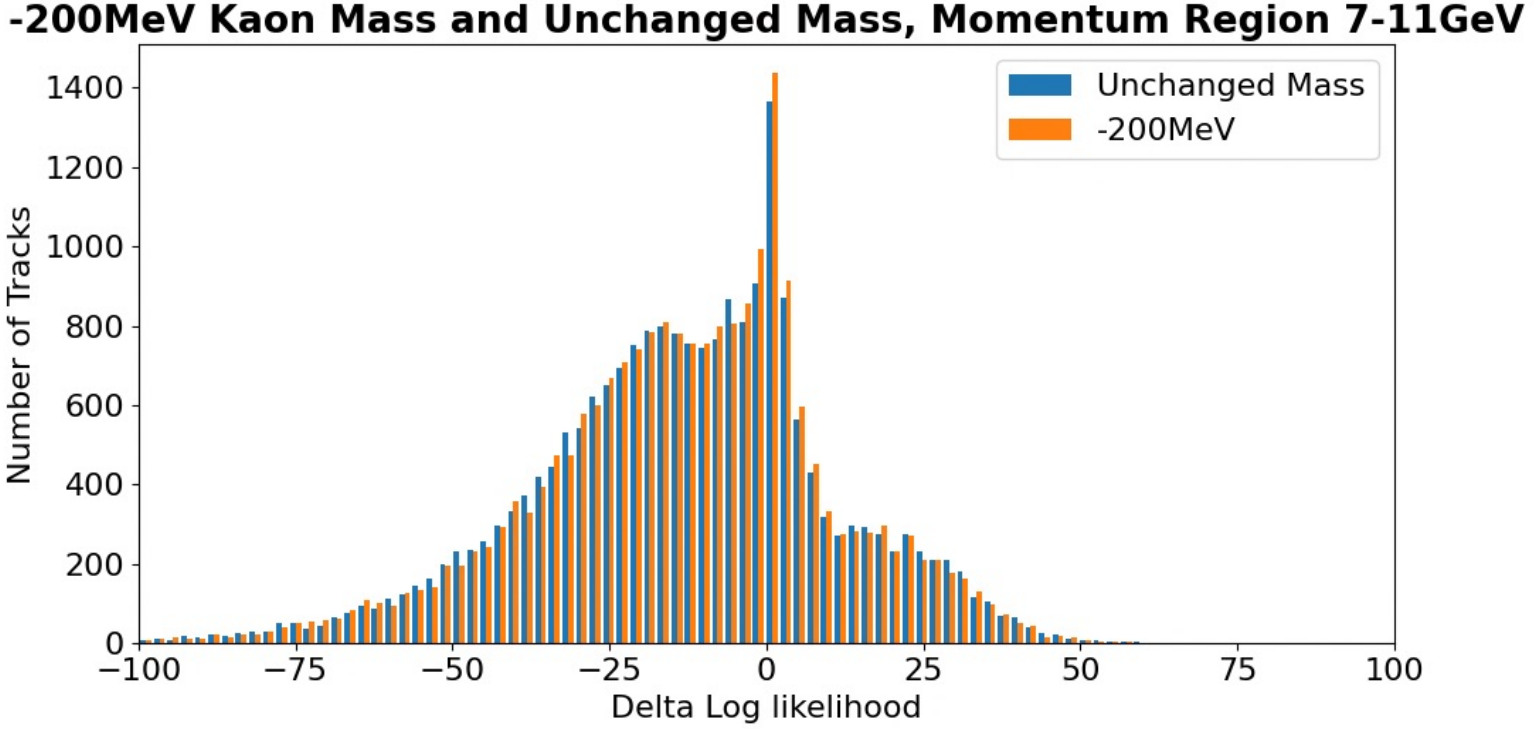
Summary

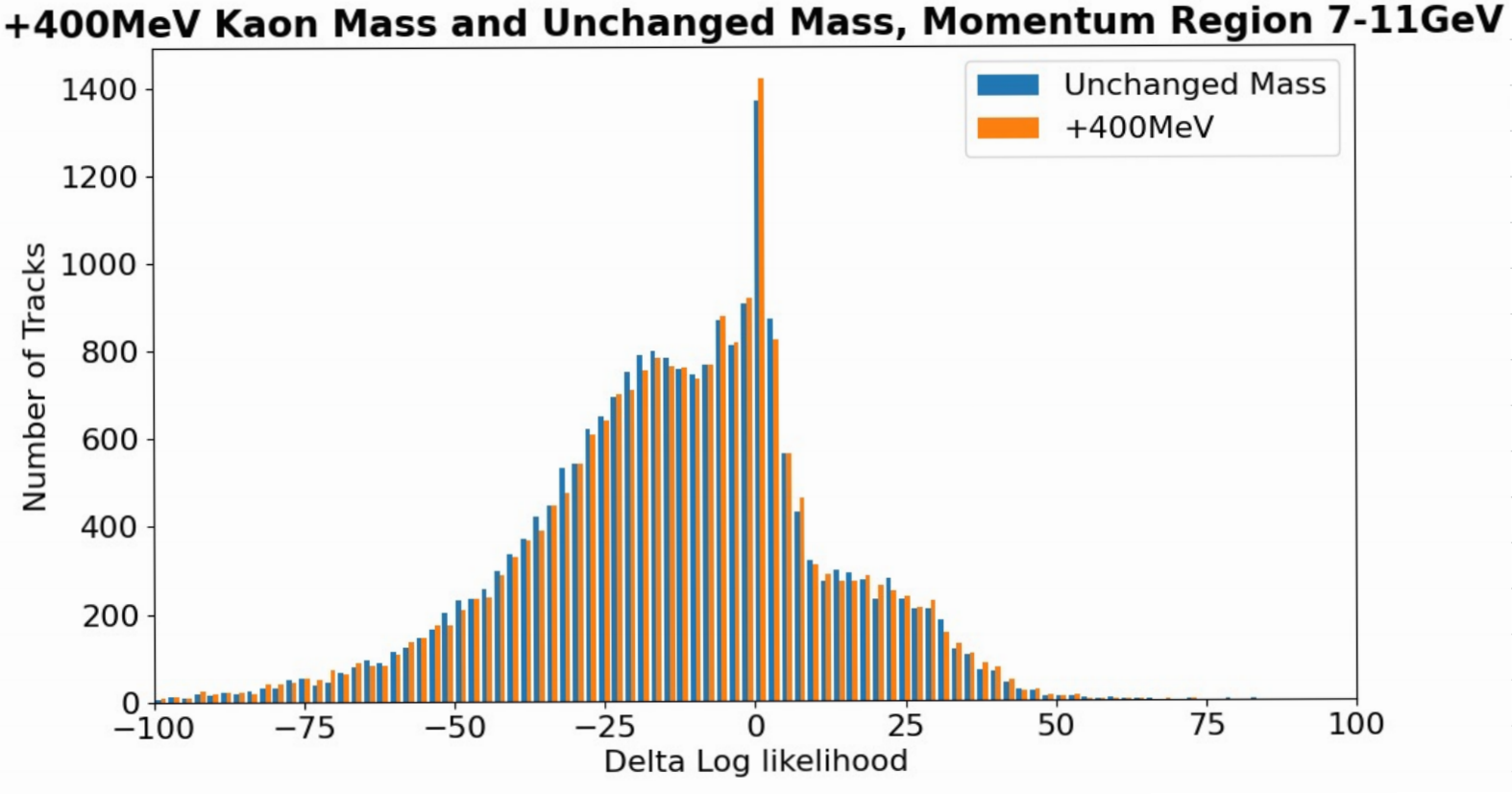
- Produced plots for Kaons with mass changed to -200MeV, +200MeV, and +400MeV, first without momentum region and then with using 7-11GeV
- Attempted to subtract data to plot difference
  ↳ error with array sizes.

Mon 29/8

Began to plot kaons for reprocessed data with same code as for protons but changing the variables and momentum range to 7–11 GeV

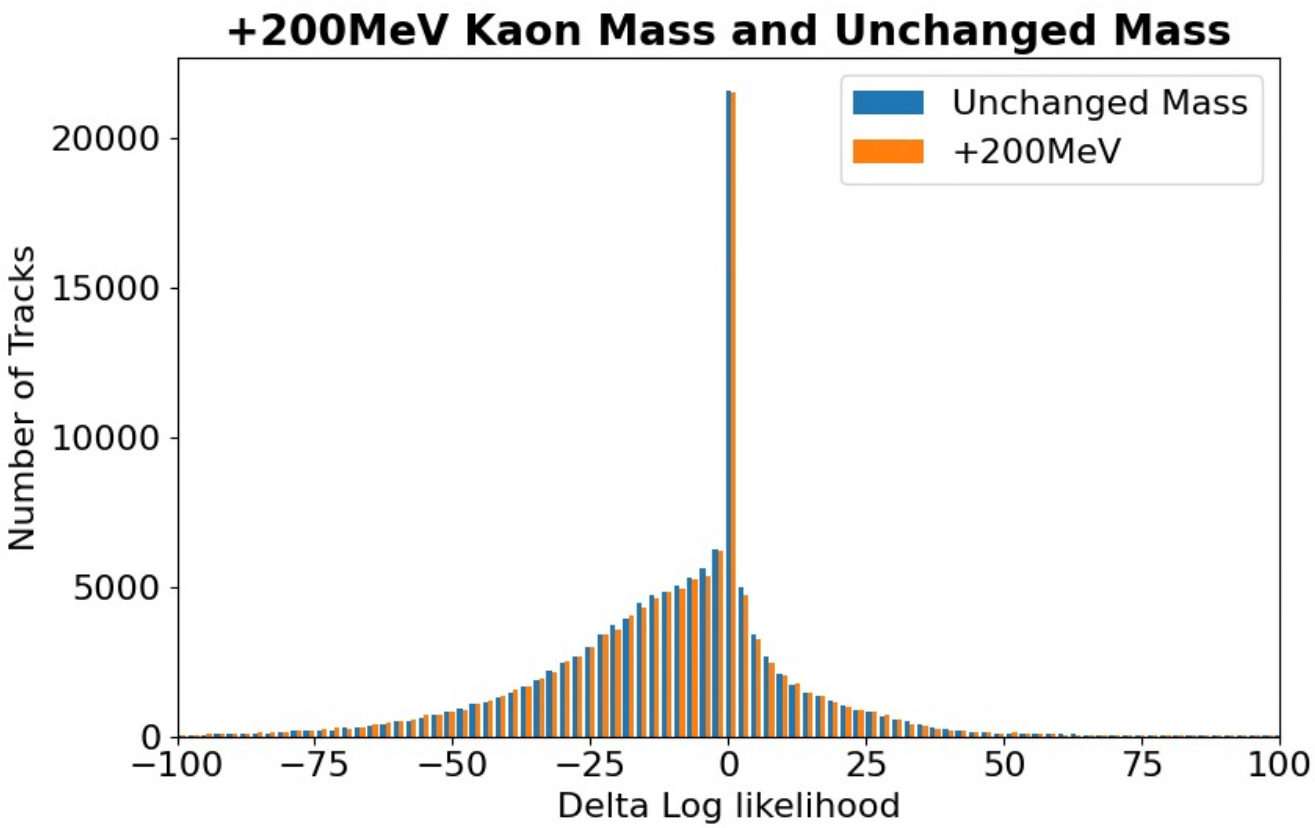


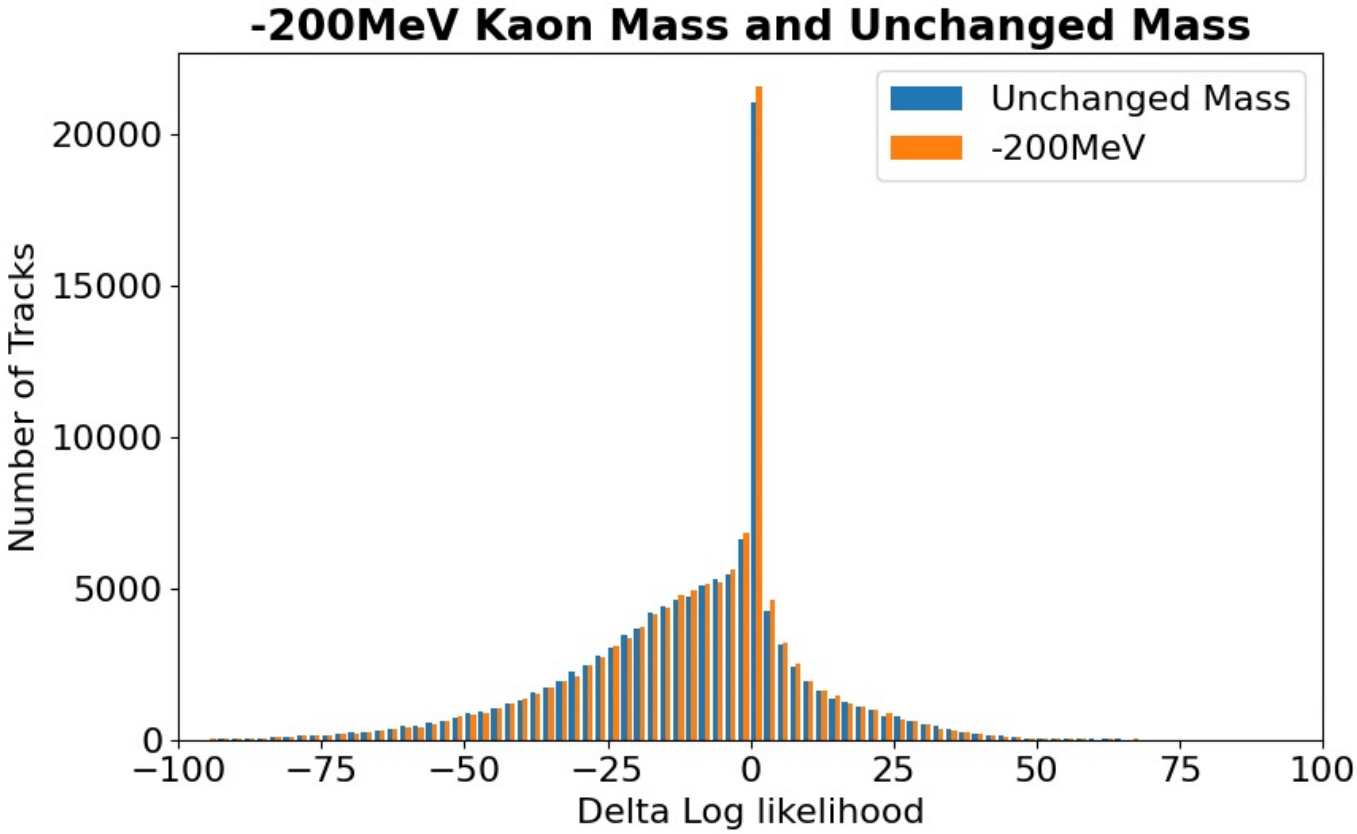


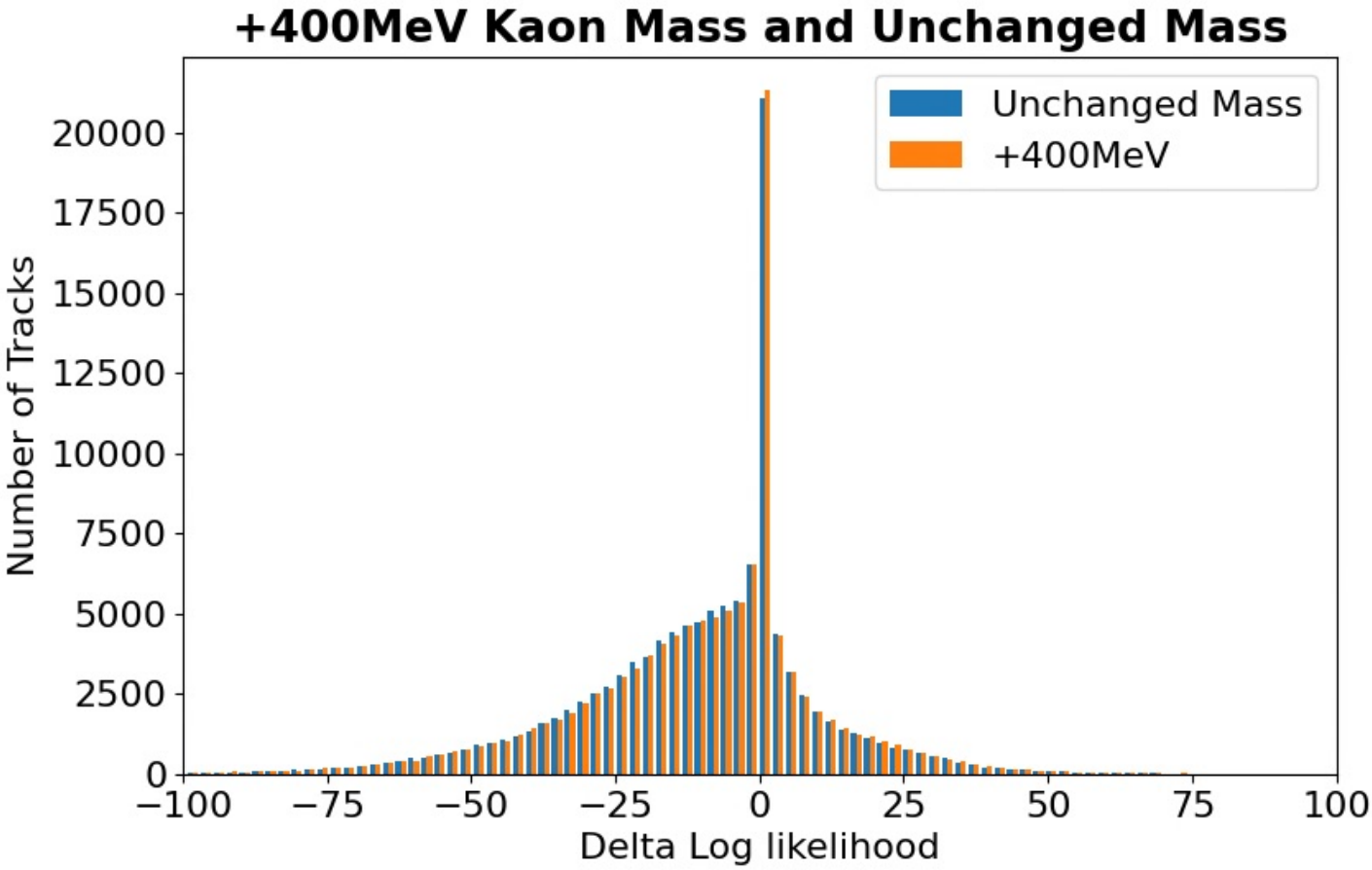


We can see that there are slight variations to the postive side near ~25, but these would be random fluctuations

Kaons plots with momentum region unchanged







These look very similar except for perhaps slight random fluctuations / background

Using same reprocessed data tried different plotting methods
↳ ran into errors subtracting data

Wed 31/8

Meeting 1pm with Eliot

Discussed:

- ↳ Plots for kaons
- ↳ fractional uncertainties with $u(n) = \sqrt{n}$, more data smaller fractional uncertainty
- ↳ pull plots
- ↳ Plotting difference → ran into errors with subtracting arrays of different shapes

Example of code for subtracting data sets (unsuccessful)

```
lower = Momentum_nominal > 18
upper = Momentum_nominal < 24
cut = lower & upper

lower2 = Momentum_plus_200 > 18
upper2 = Momentum_plus_200 < 24
cut2 = lower2 & upper2

print(len)

plt.rc('font', size=16)
bins=500
x=RichDLLp_nominal[cut]
cx=RichDLLp_plus_200[cut2]

entries_protons_nominal, bins_x= np.histogram(x, bins)
entries_protons_plus200, bins_x = np.histogram(cx,bins)

print(len(x)) #7294
print(len(cx)) #7346

print(entries_protons_plus200)
print(entries_protons_nominal)


nominal_minus_plus200 = entries_protons_nominal - entries_protons_plus200, entries_protons_nominal


plt.bar(nominal_minus_plus200,bins_x)
```

Week 7 (5/9 - 9/9)

Goals

- Plot with more data to notice more of a difference of protons
- Figure out data subtraction

Questions

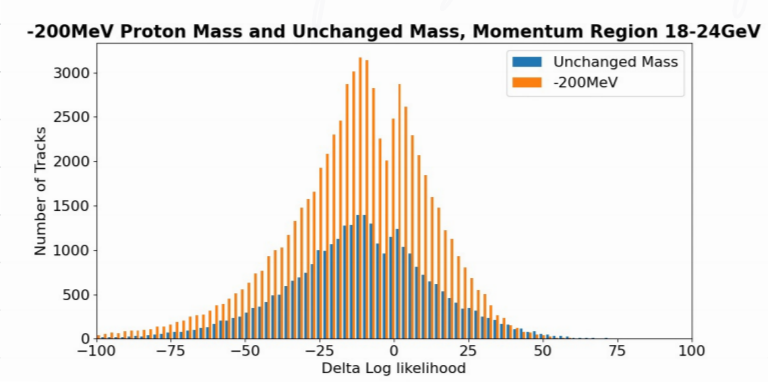
- How should I prepare for talk
- Subtract data for difference.
- units for momentum

Tasks

- Start W9 progress report
- Histograms w/ more data

Summary

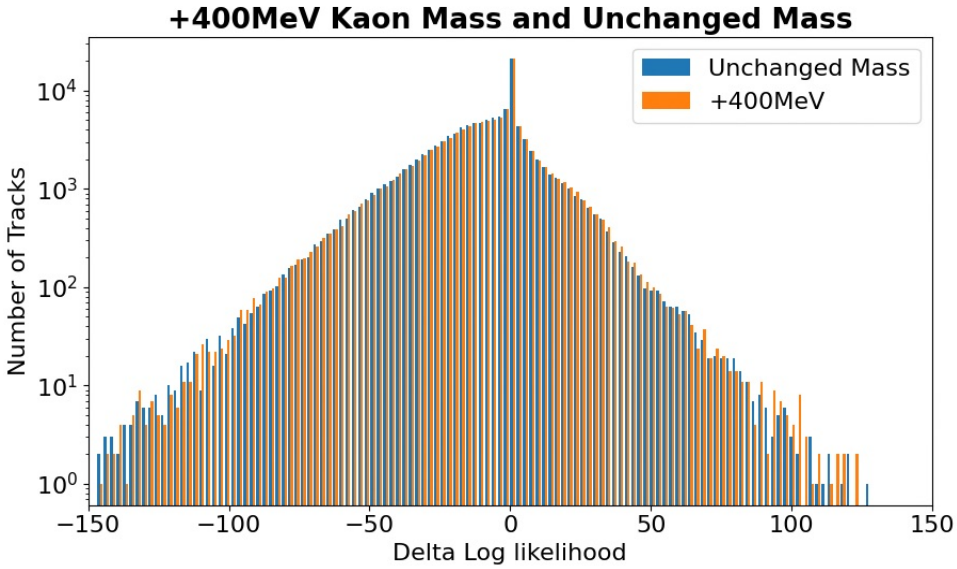
Produced histograms for drive data for protons, plot for -200MeV is shown below with comparison to nominal, as they are of different heights we need to consider normalising.



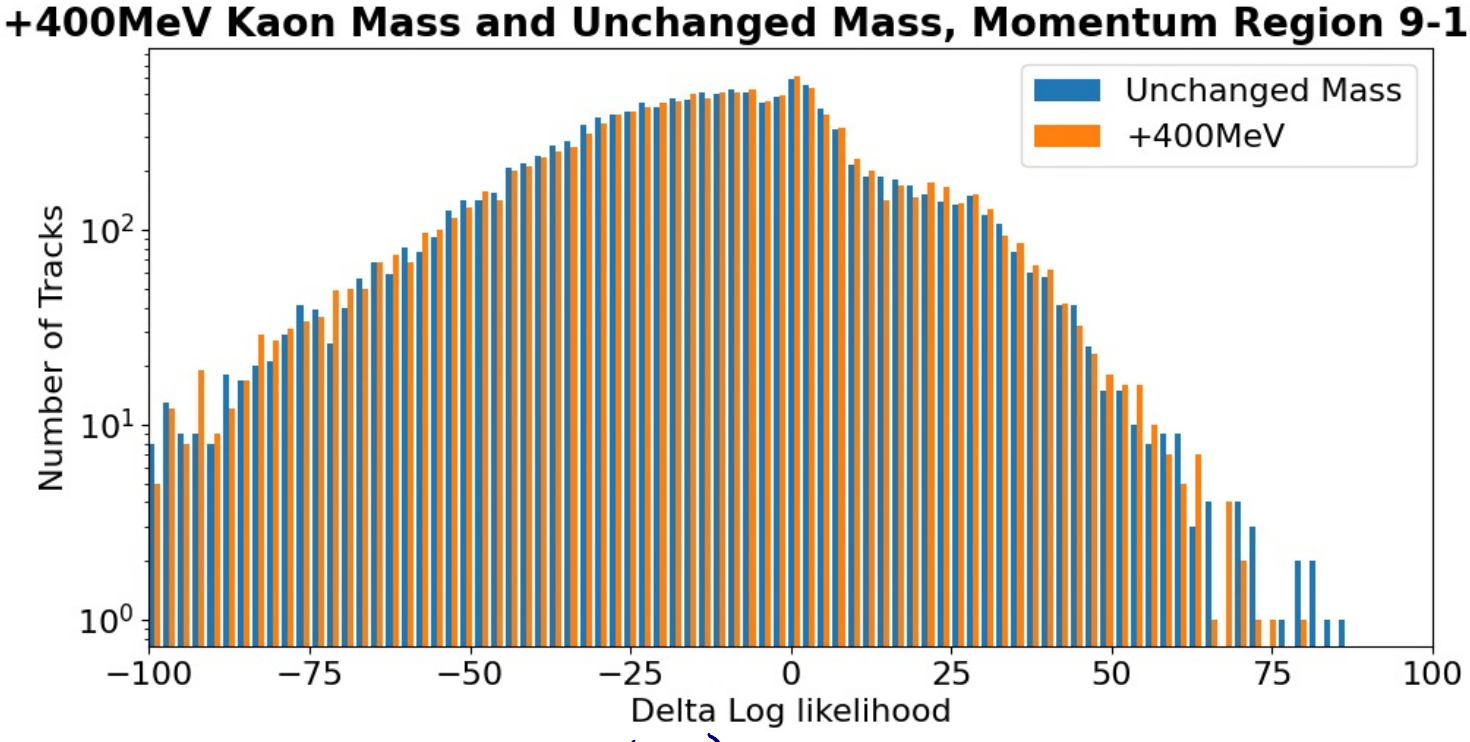
Figured out issue with plotting difference regarding the array sizes & bin sizes

Mon 5/9

Tried plots with log y-axis, example for Kaons +400MeV with momentum region unchanged

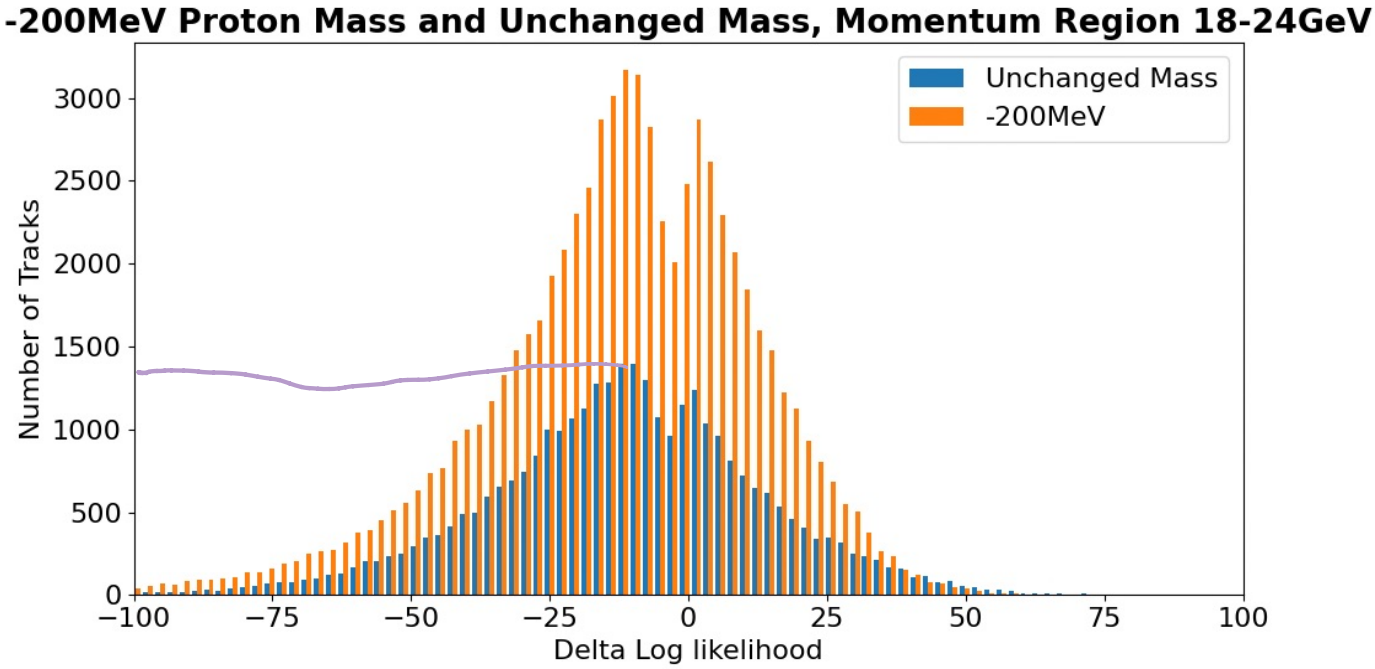


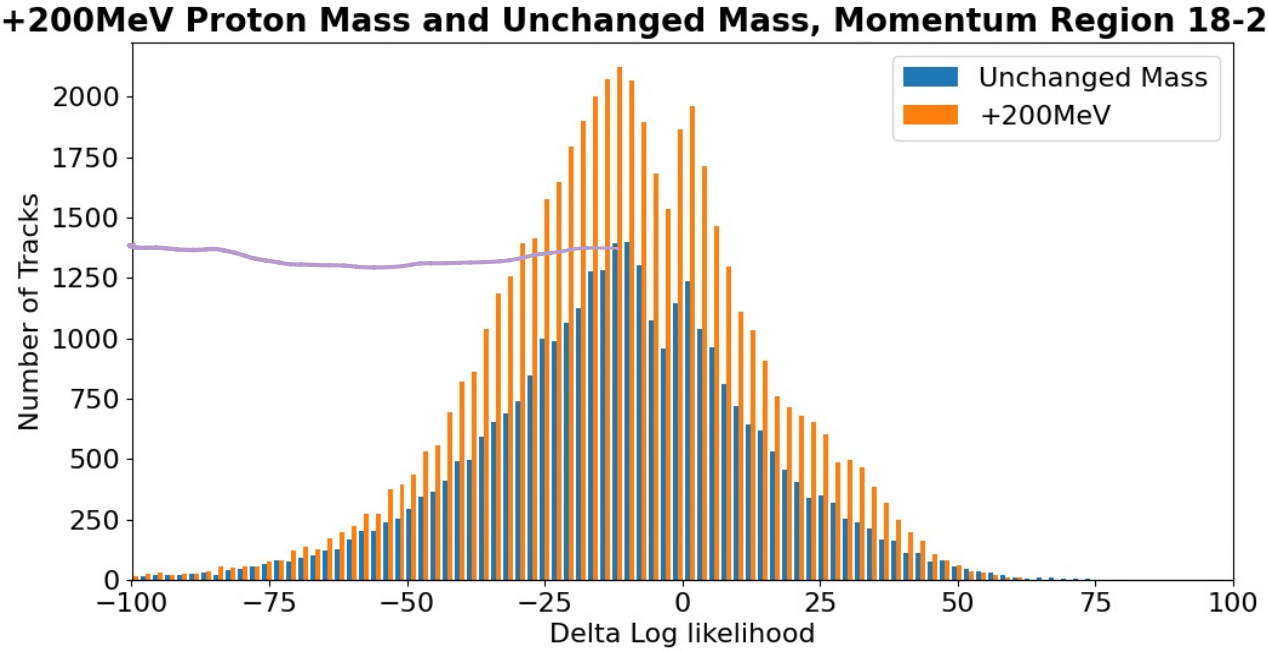
With momentum region changed to 9 - 12 GeV
As discussed in meeting threshold for Kaons above 7GeV about half of protons

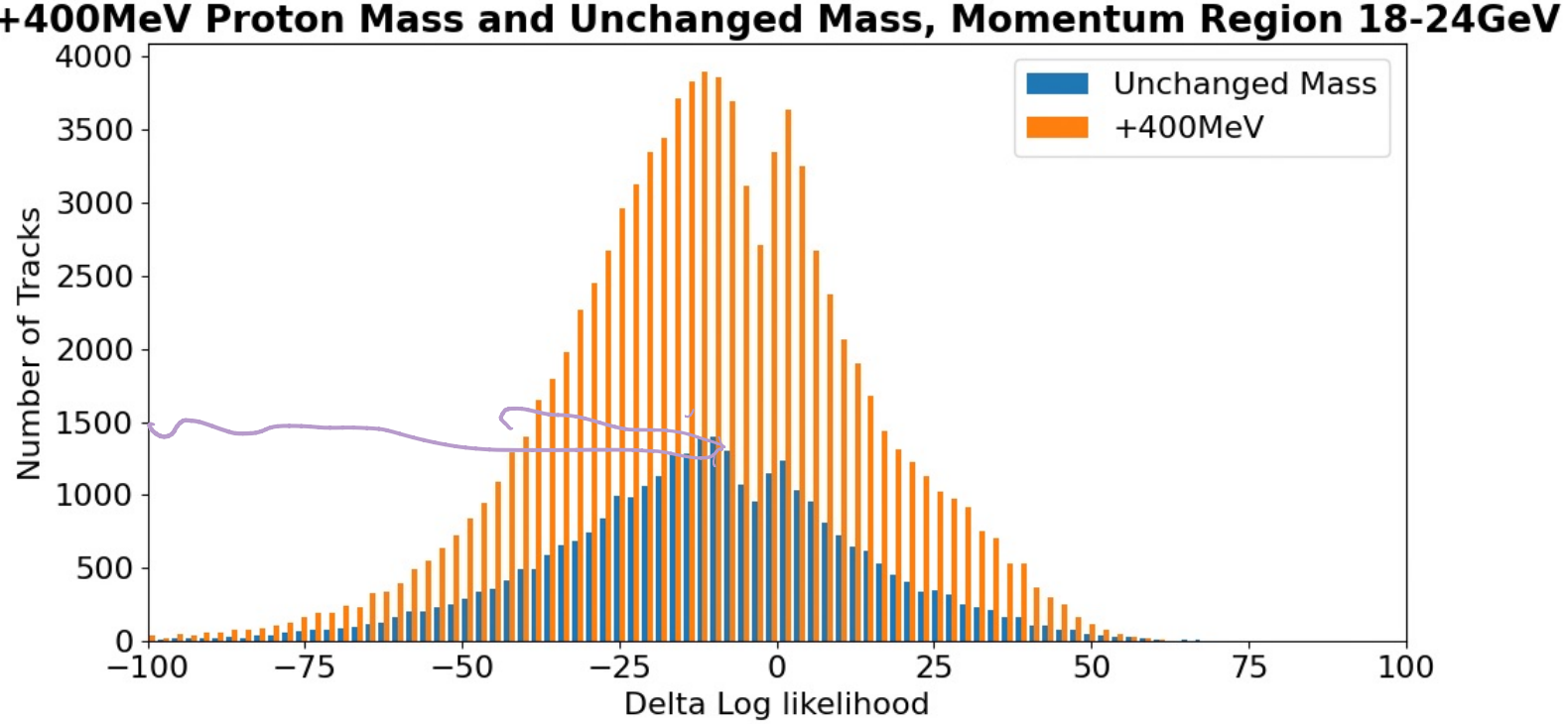


(with 100 bins)

Attempted to subtract data again but with different masses this time -200 MeV, same problem with +200 MeV with arrays being different sizes



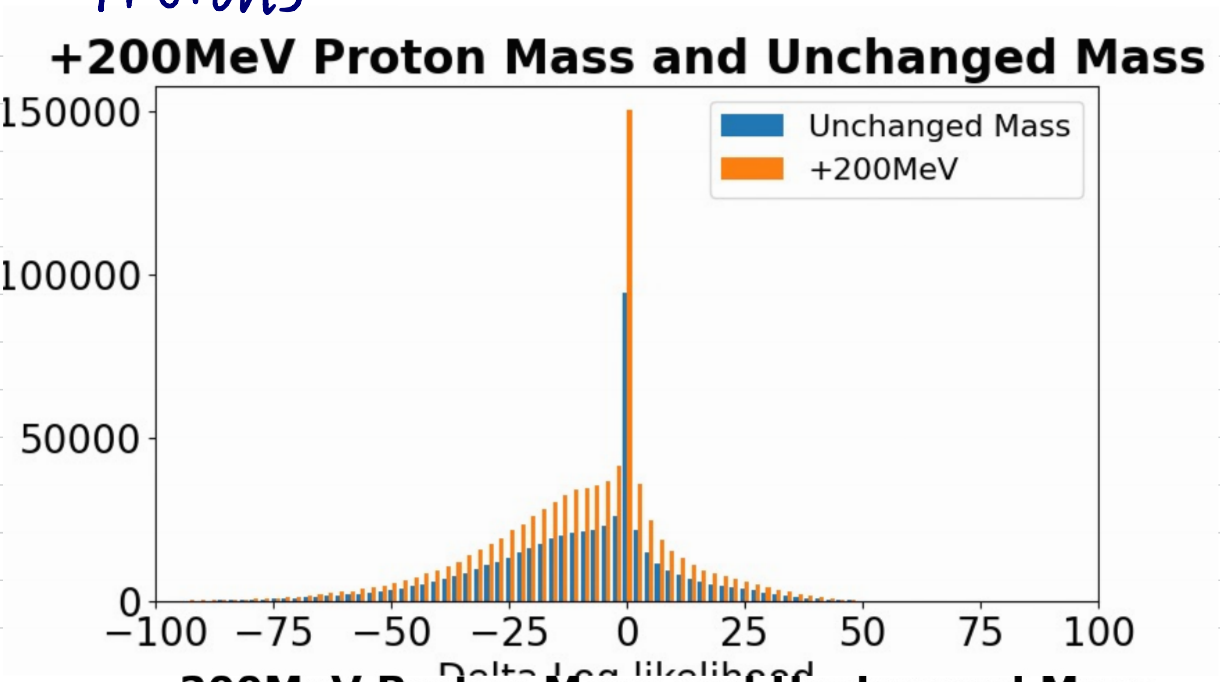


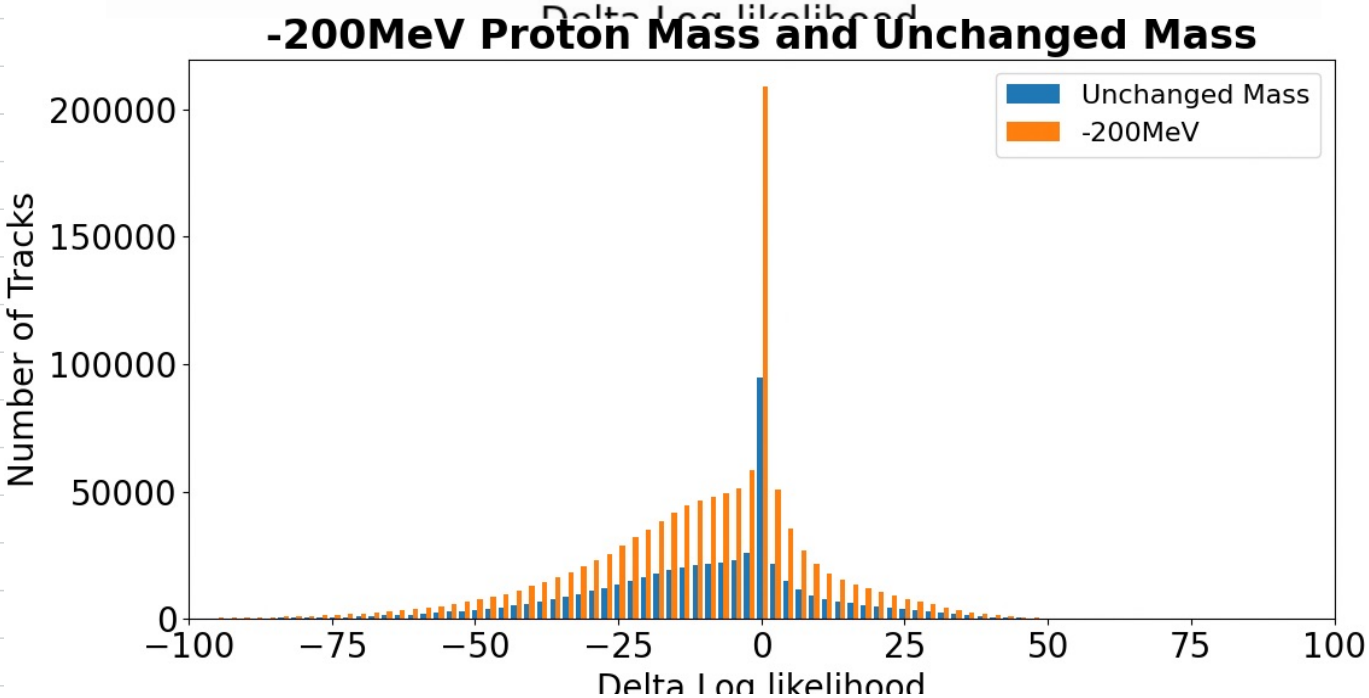


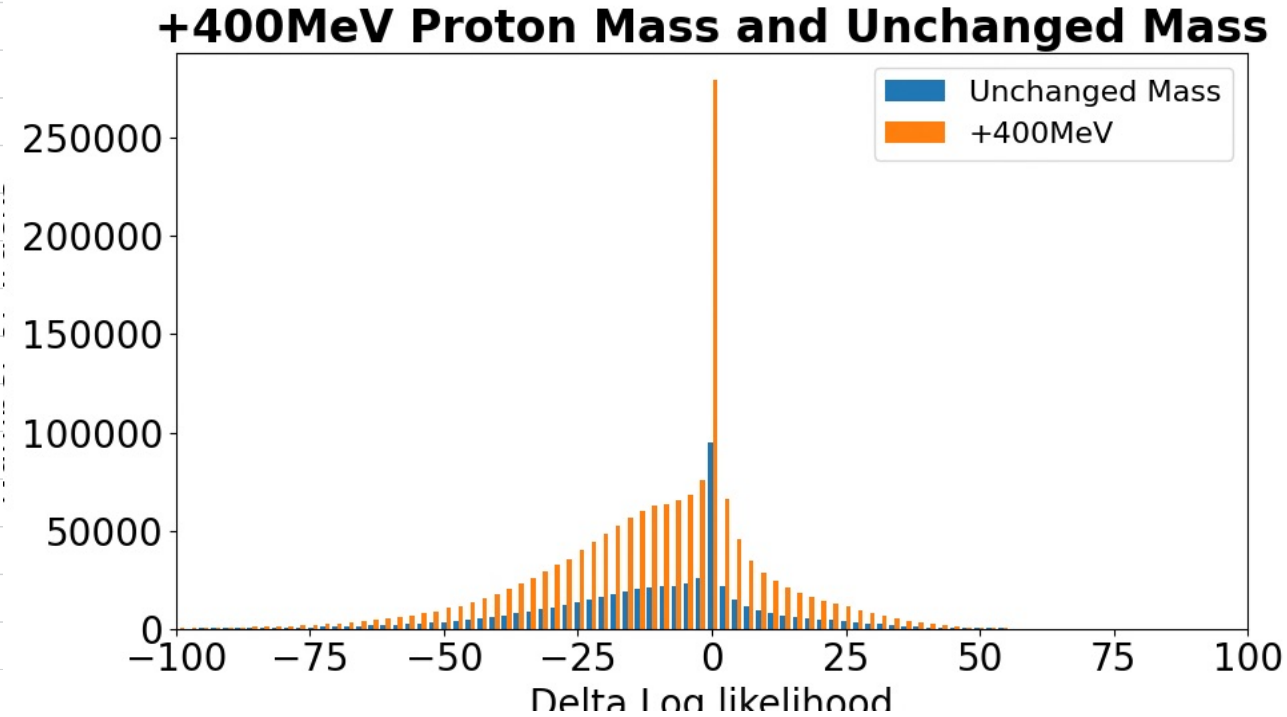
Tue 6/9

Produced plots with more data from google drive using Eliot's Python script to select the DLL of protons and kaons, with the masses changes of +200MeV, -200MeV, +400MeV.
This was a lot quicker than with plots produced previously.
These plots are just for a select momentum region

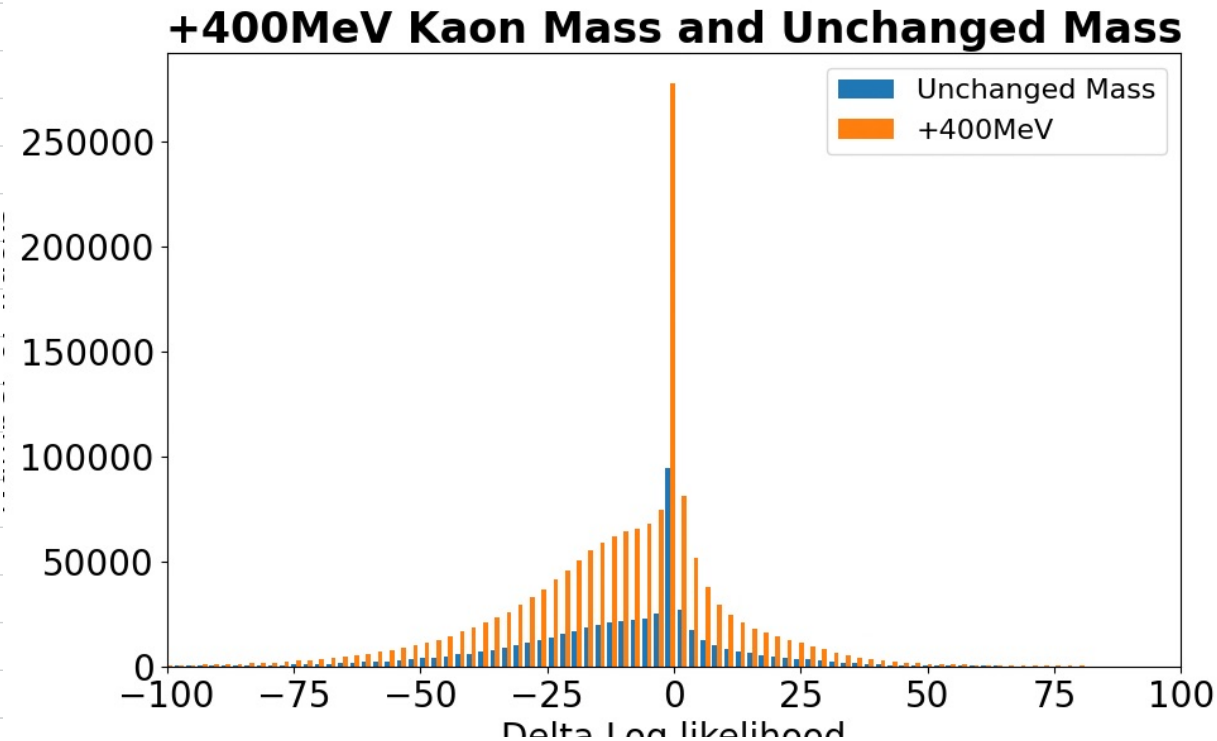
Protons

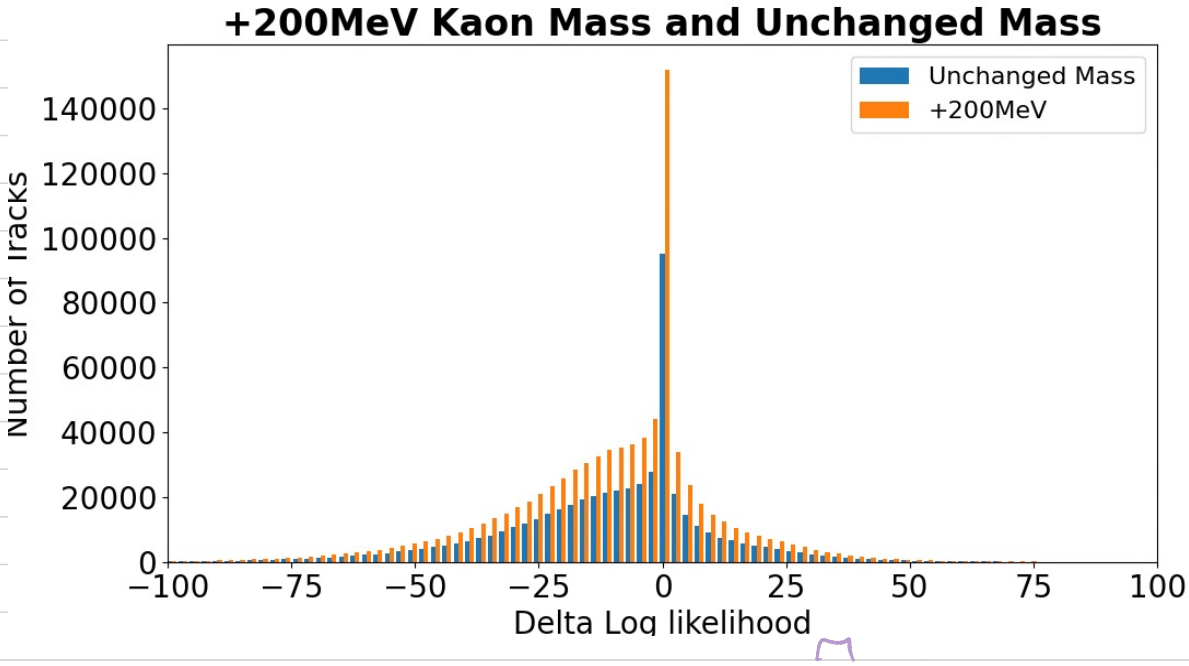

+200MeV Proton Mass and Unchanged Mass
Unchanged Mass
+200MeV
150000
100000
50000
0
−100
−75
−50
−25
0
25
50
75
100

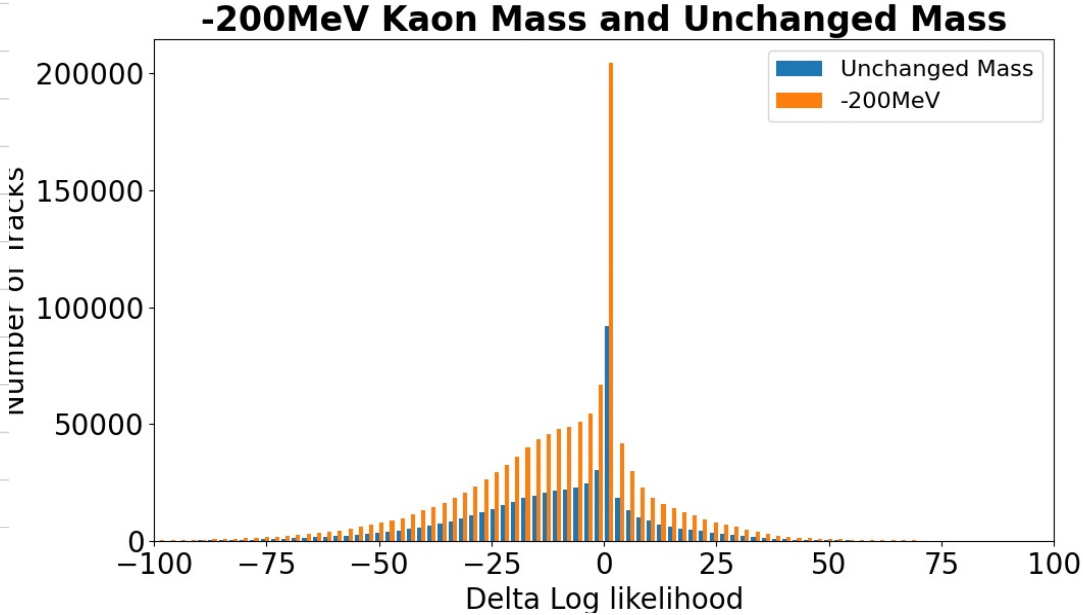

-200MeV Proton Mass and Unchanged Mass
Unchanged Mass
-200MeV
Number of Tracks
200000
150000
100000
50000
0
−100
−75
−50
−25
0
25
50
75
100
Delta Log likelihood


+400MeV Proton Mass and Unchanged Mass
Unchanged Mass
+400MeV
250000
200000
150000
100000
50000
0
−100
−75
−50
−25
0
25
50
75
100
Delta Log likelihood

Kaons







Possibly plotted wrong way around/subtracted?

Thur 8/9

Meeting 12pm with Eliot.

- log y axis
- changing proton mass hypothesis → how on effect for kaon dist to? w/ global likelihood
- Plot normalised density = 'True'
  - ⇒ Area = 1
- error bars
  $u = \sqrt{n}$ poisson statistics

Apply cut to bins to get array lengths same, python code example

- entries_non[cut]

  entries_200[cut]

- bins > 0

  bins' < 50

  cool = bins & bins'

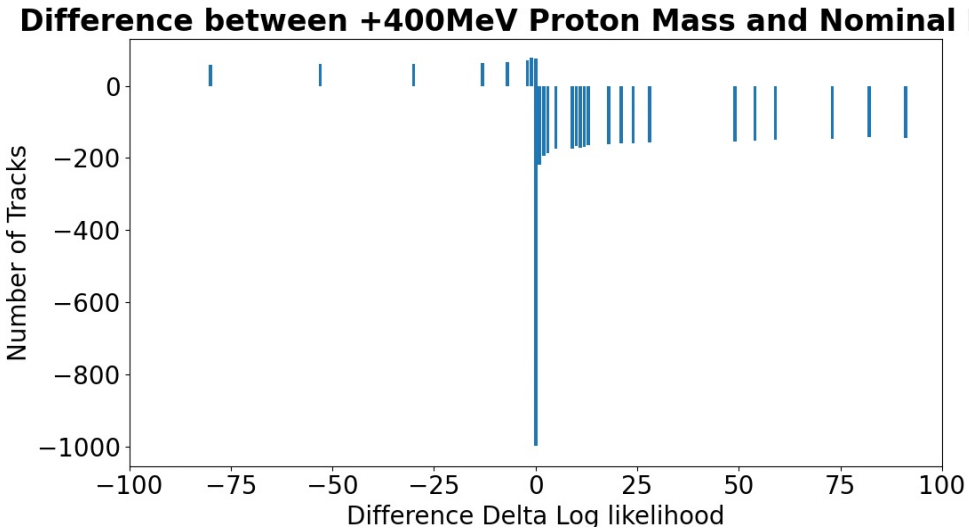
Sat 10/9

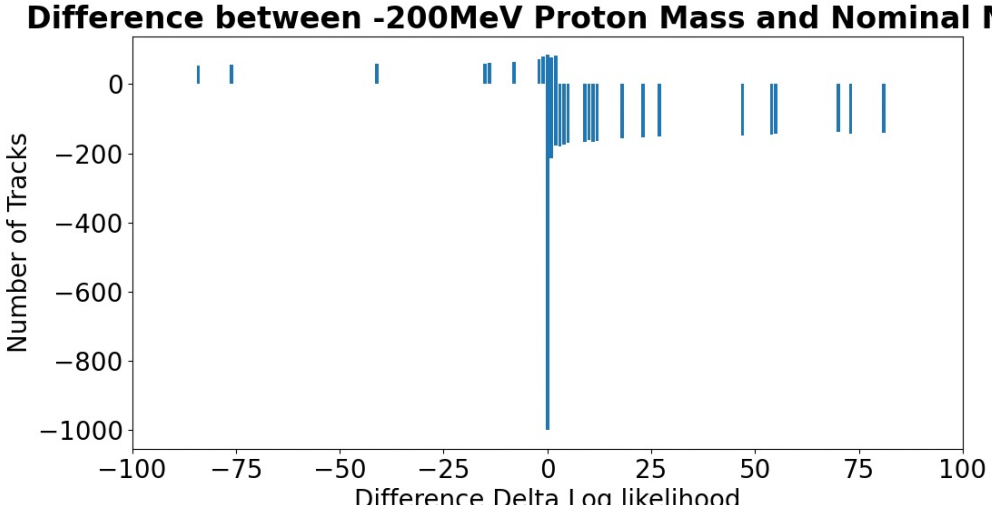
Obtained plots for the difference without momentum region selected.

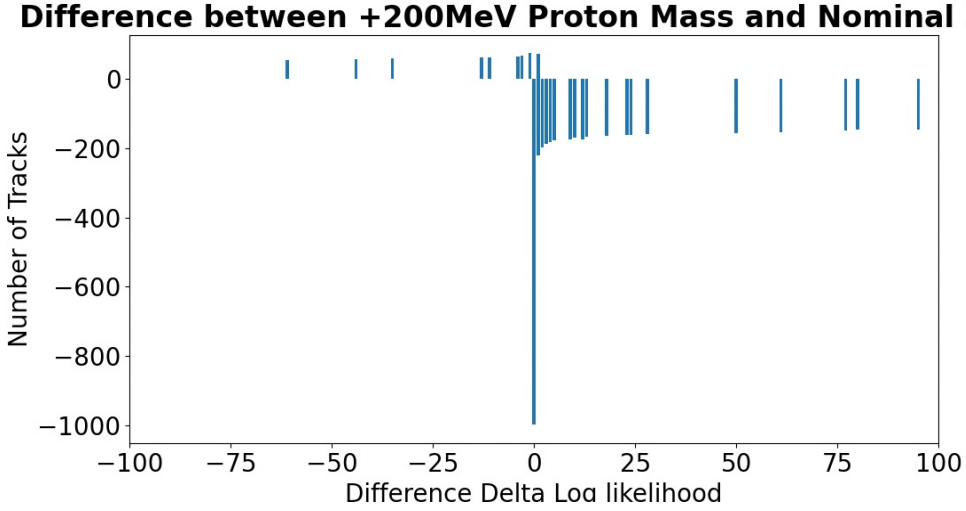
- Had trouble with arrays being different sizes
  - bins_x length was 501, subtracted data length was 500
  - ended up using plt.bar(nominal_ + #, bins_x[0:500])
  - following were obtained

range =(

weights = 1/norm







Need to plot w/ momentum range, maybe log y-axis?

Week 8 12/9-16/9

Goals

- Obtain difference plots
- Normalise plots
- Include Uncertainties
- Start W9 prog report
- Understand plots better / variations in data.

Questions

- error bars/uncertainties? $\sqrt{n}$ i.e. $\sqrt{500}$?
-

Tasks

- produce normalised plots for kaons
- difference plots with momentum region
- change plot style → fill?

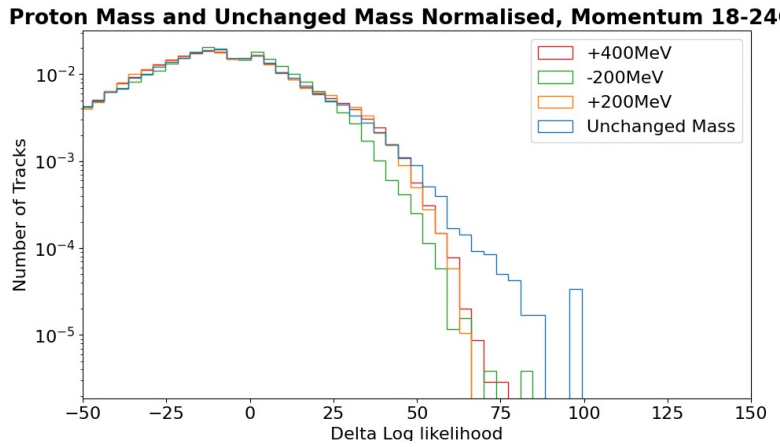
From meeting:

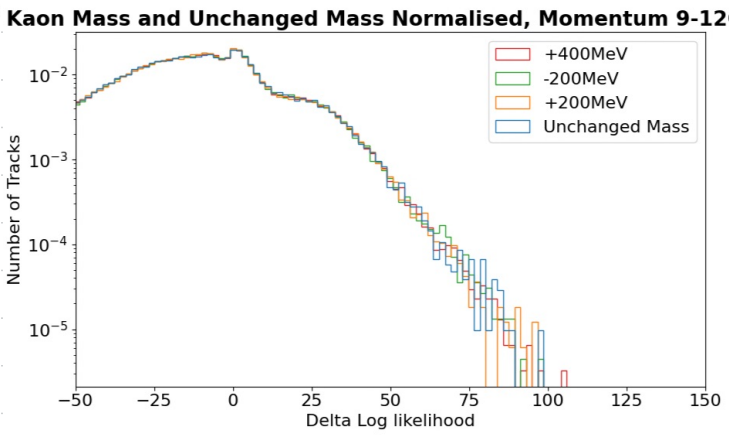
Plot histogram with
- weights = $\frac{1}{norm}$ (norm = len)
- range = (-100, 100)

Plot of Δm over p for momentum
Plot kaons combined fill plot
↳ with momentum region

Summary

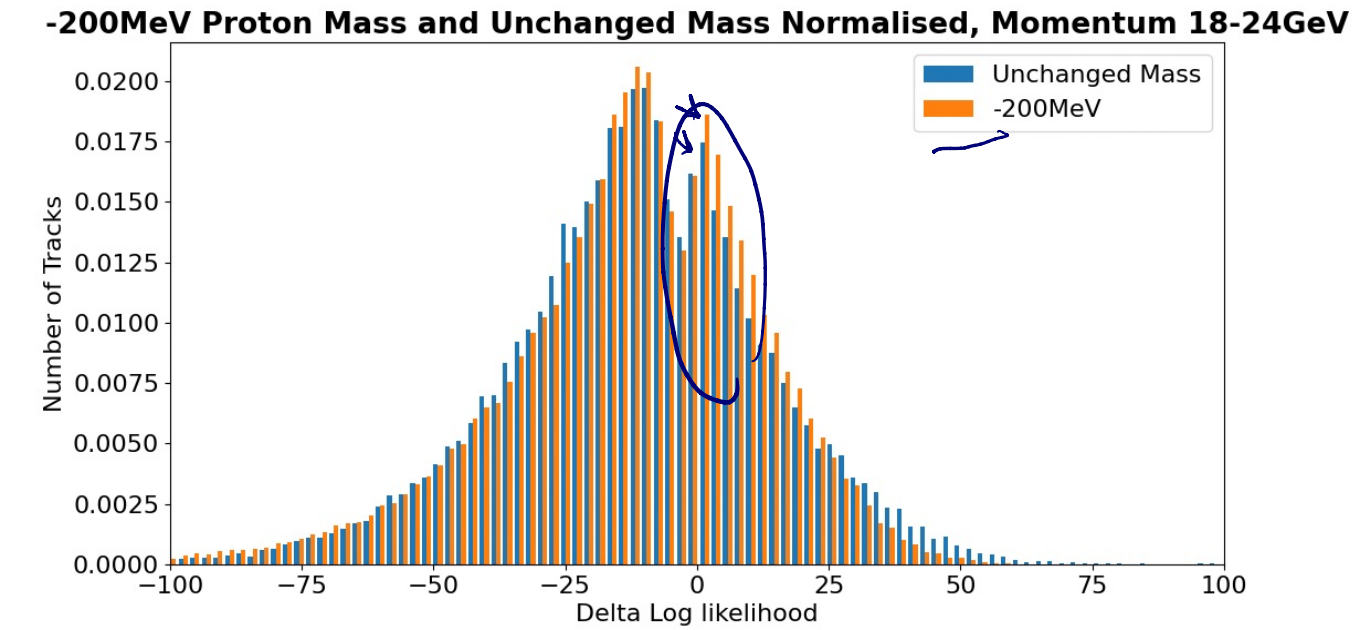
Plots for protons & kaons

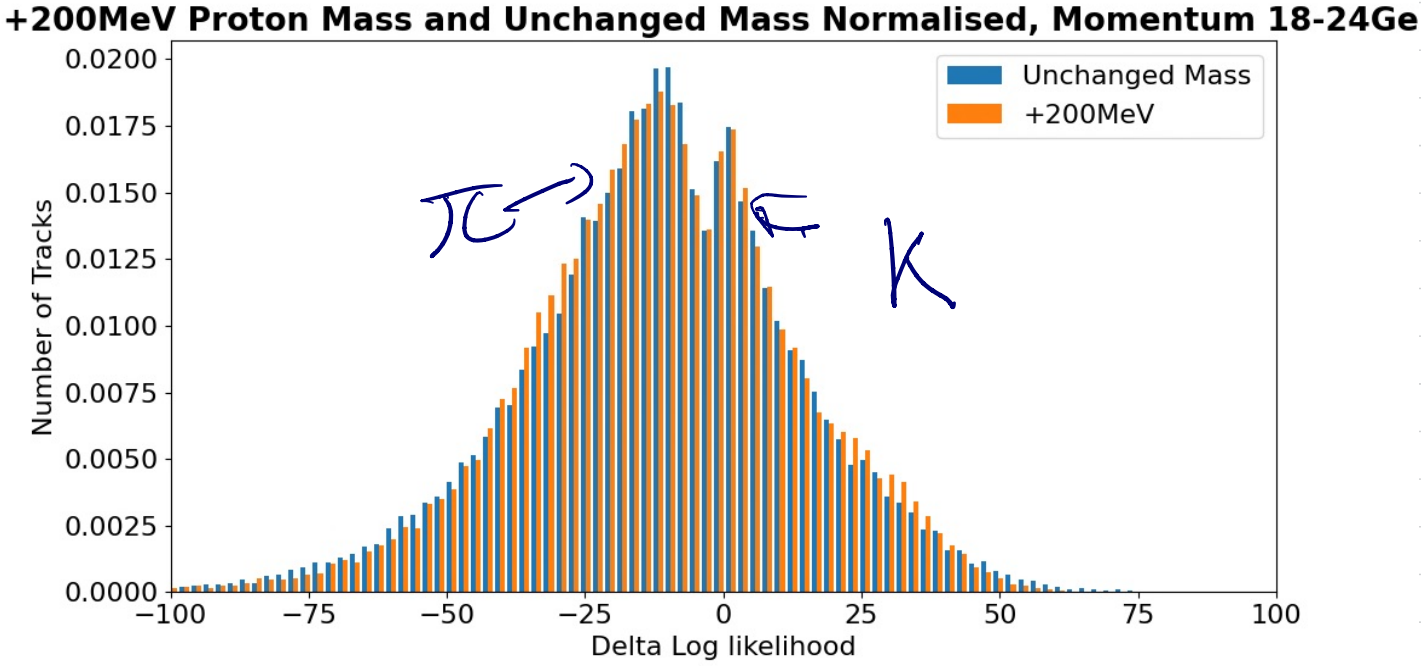




Mon 12/9

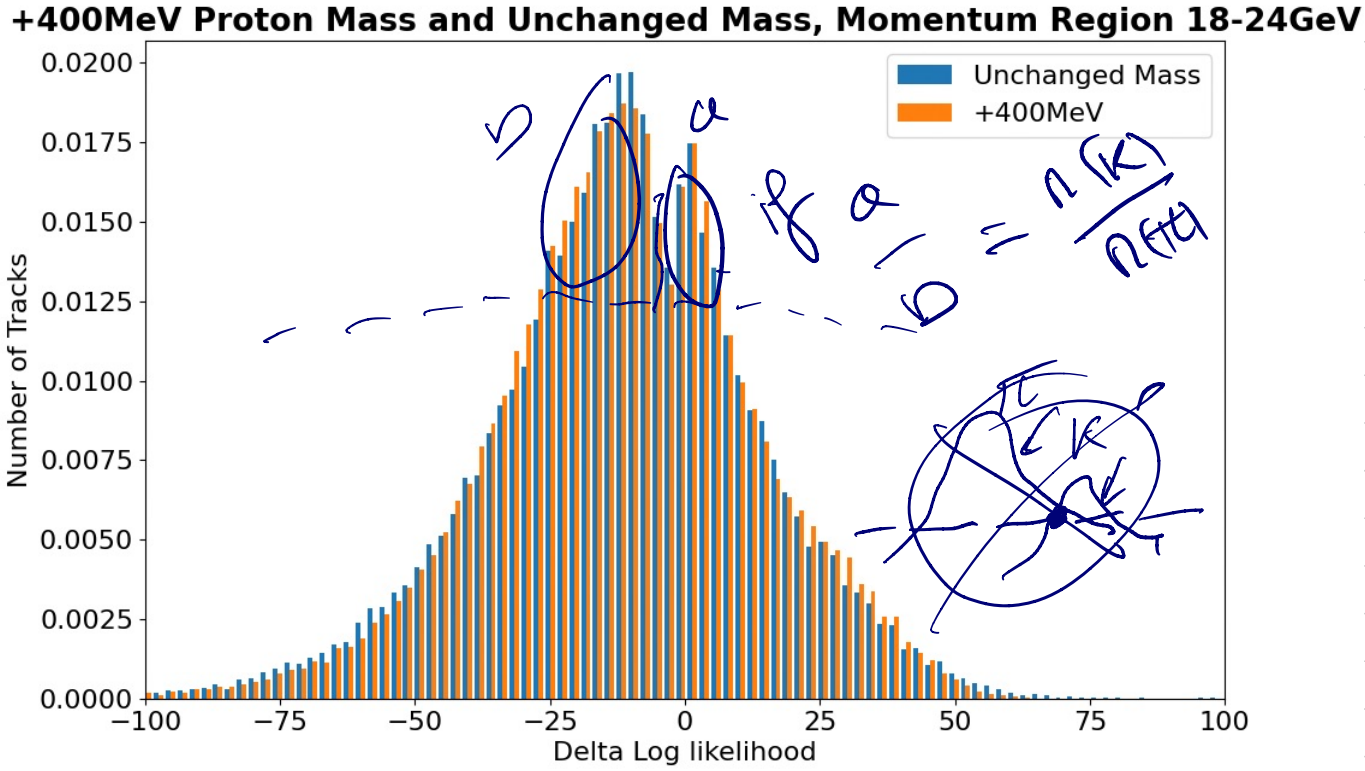
Produced Normalised Plots for reprocessed data from drive with density = 'true', first done without momentum region, as the pynovi script did not have this yet





Plot for -200MeV seems most promising with the difference, though slight peak for changed mass suggests that

Normalised



+200MeV and +400MeV seem to have more prominent peak for changed mass

Tue 13/9

Rough Plan for final report / Talk?

Particle physics / Standard model

Dark matter & deuterons (intention)
- production DM
- what is deuteron
- how can they form? → pp collisions
- Intention to detect deuterons

Detecting deuterons
- momentum & velocity → mass
- Cherenkov Radiation
- RICH detectors LHCb

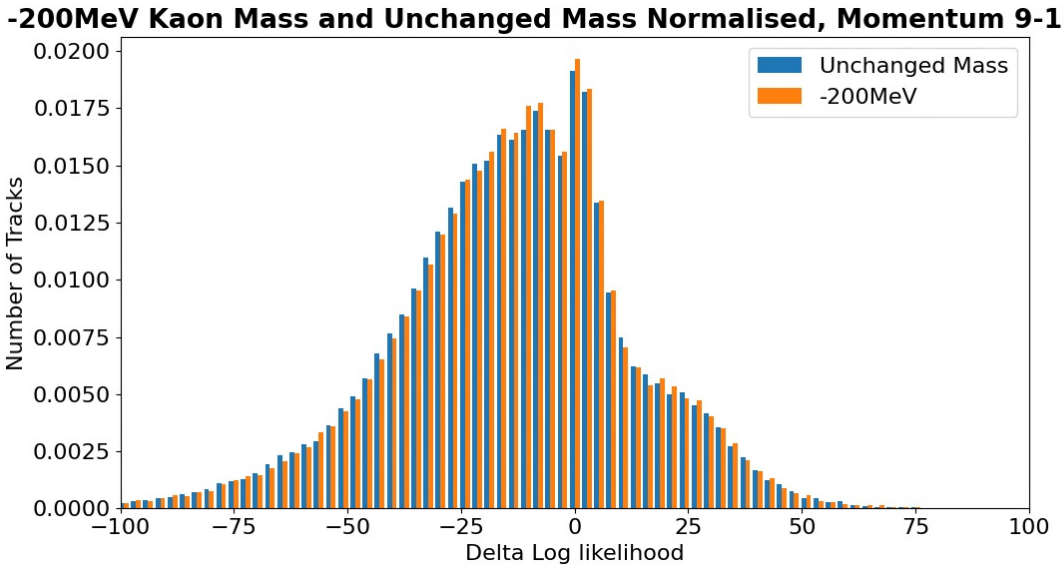
Previous Methods
- Other methods
- Direct
- Statistical

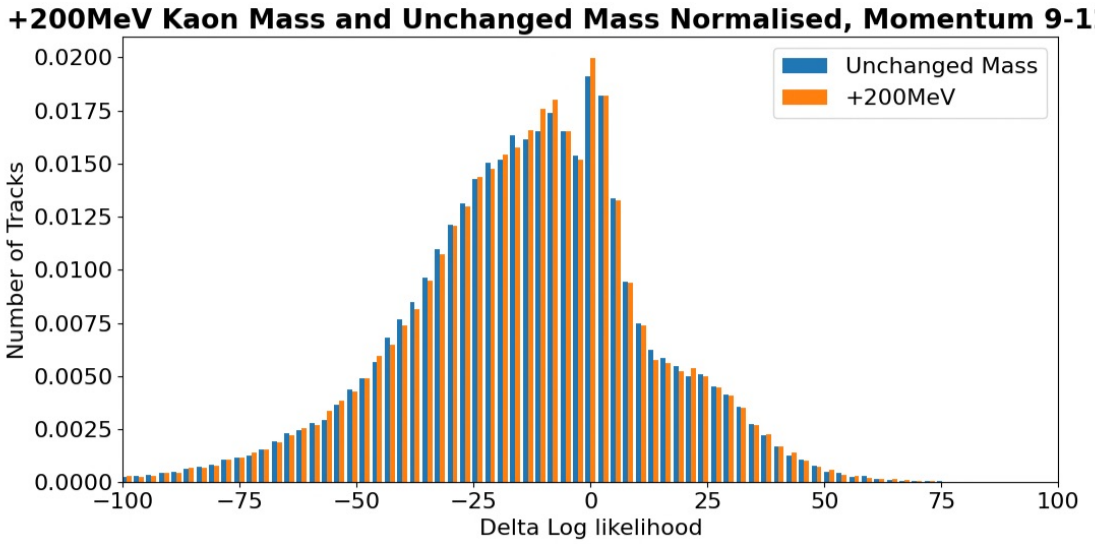
Our Method
- DLL
- After mass to subtract background
- protons, kaons control
- momentum region

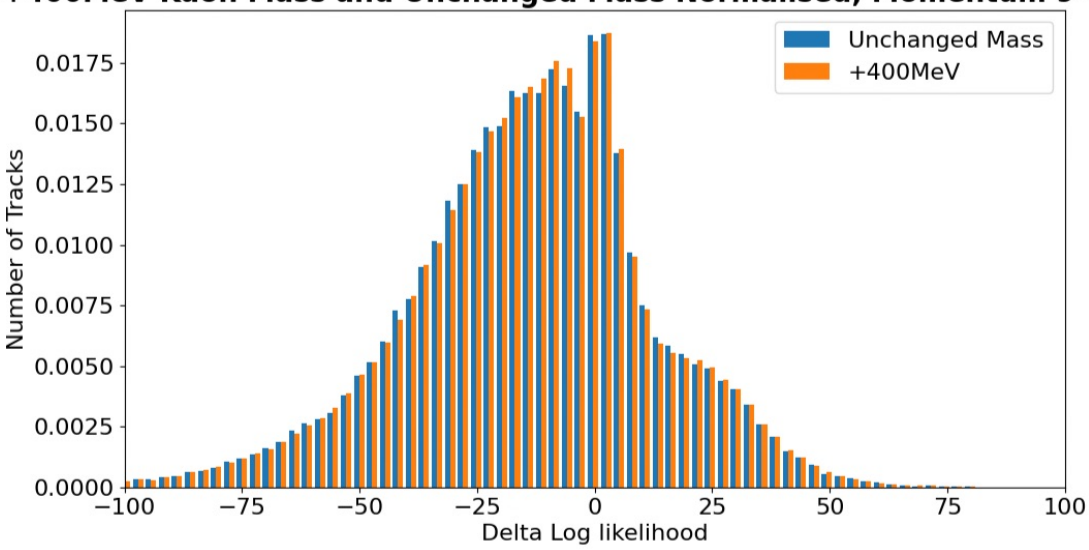
Results
- plots for protons
- difference plots
- deuteron plot?
- Uncertainties

Conclusions
-

Normalised plots for kaons with momentum region 9-12 GeV

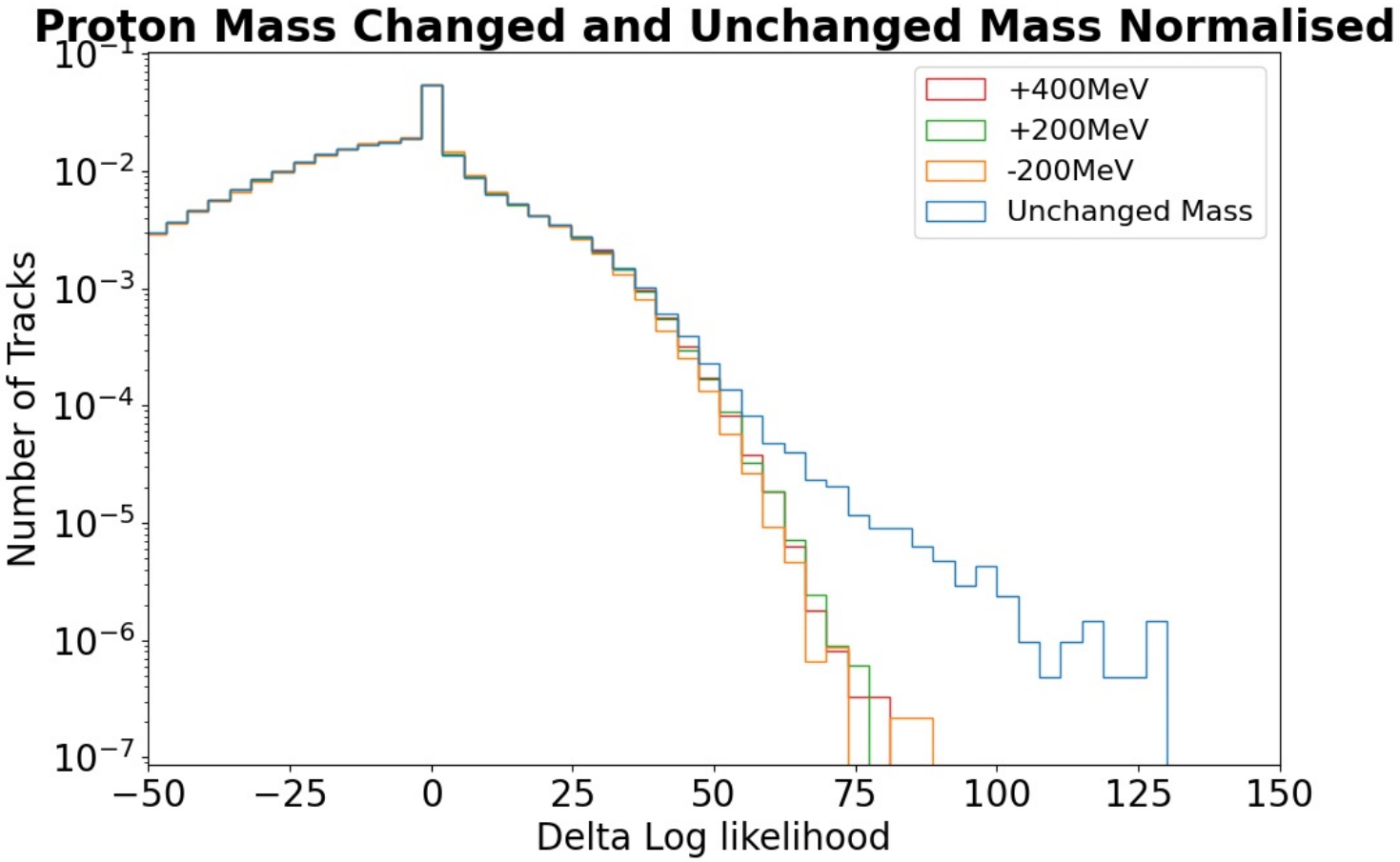


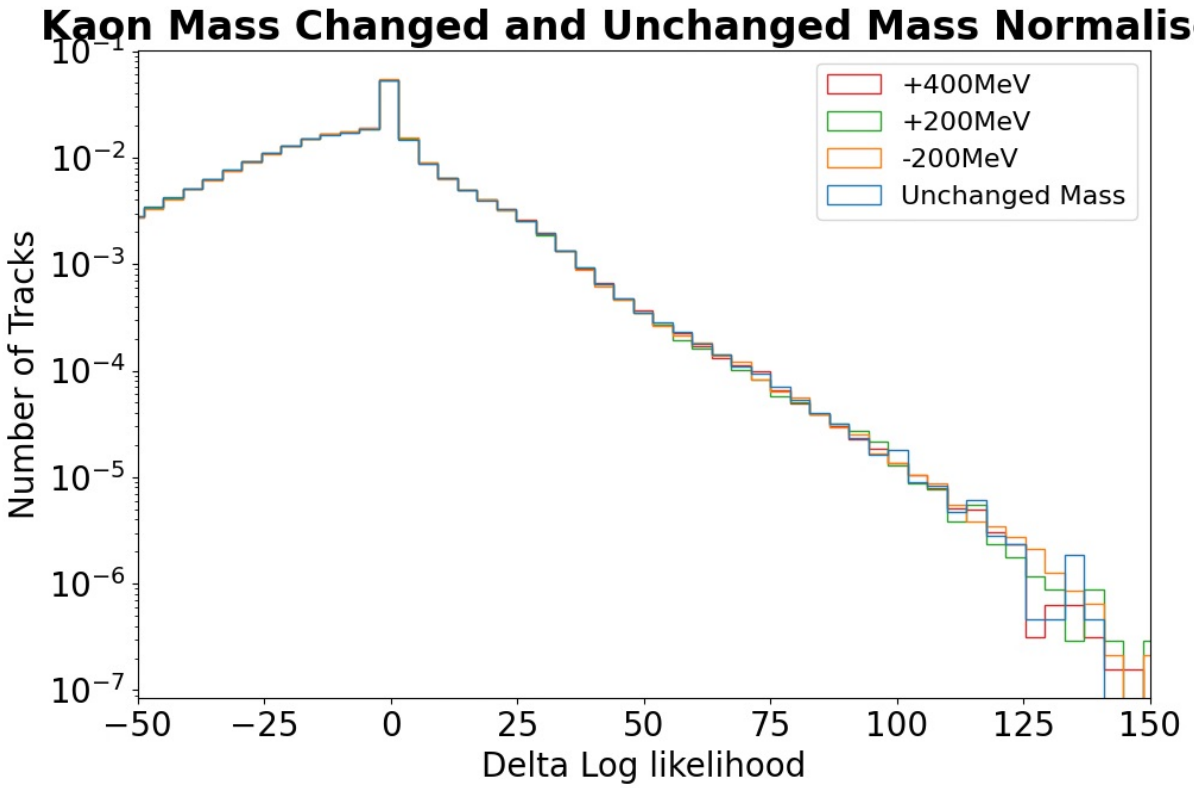




All look very similar

Using histtype='step' with all combined.

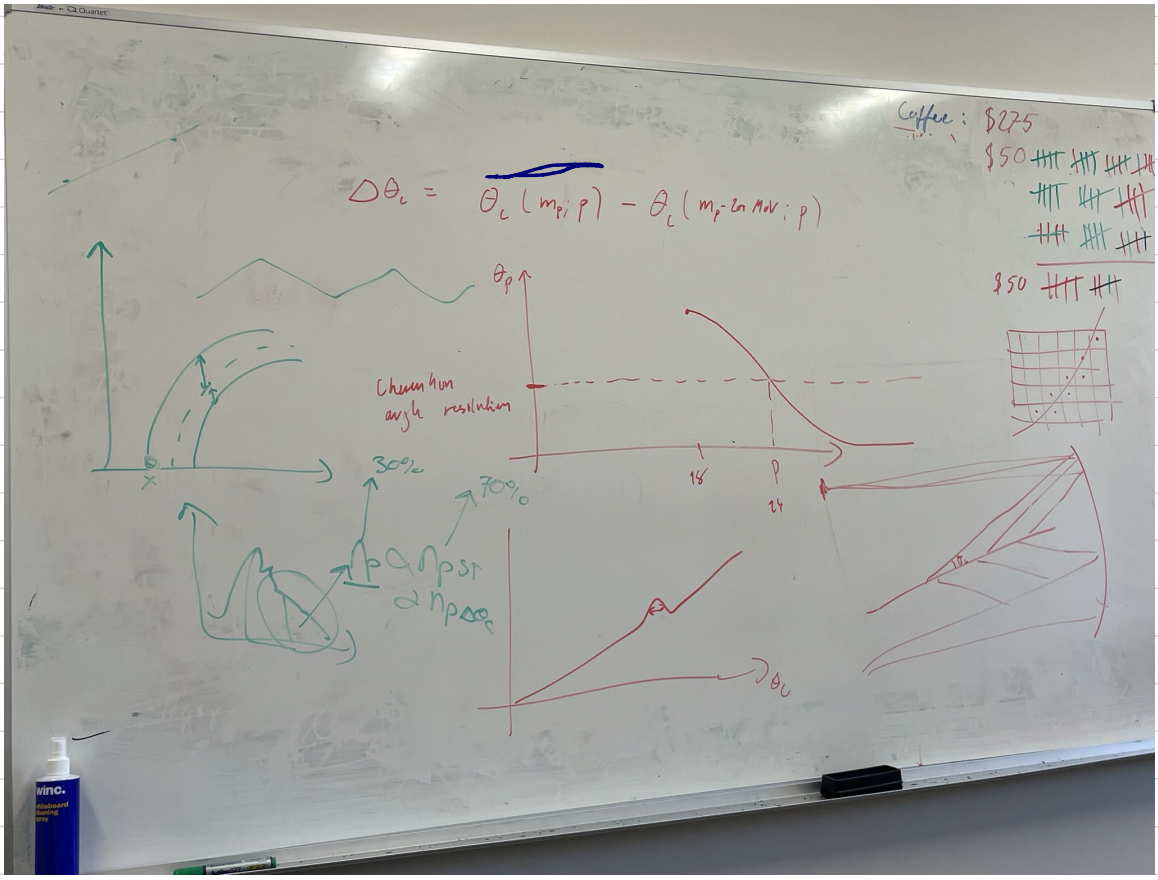




Thur 15/9

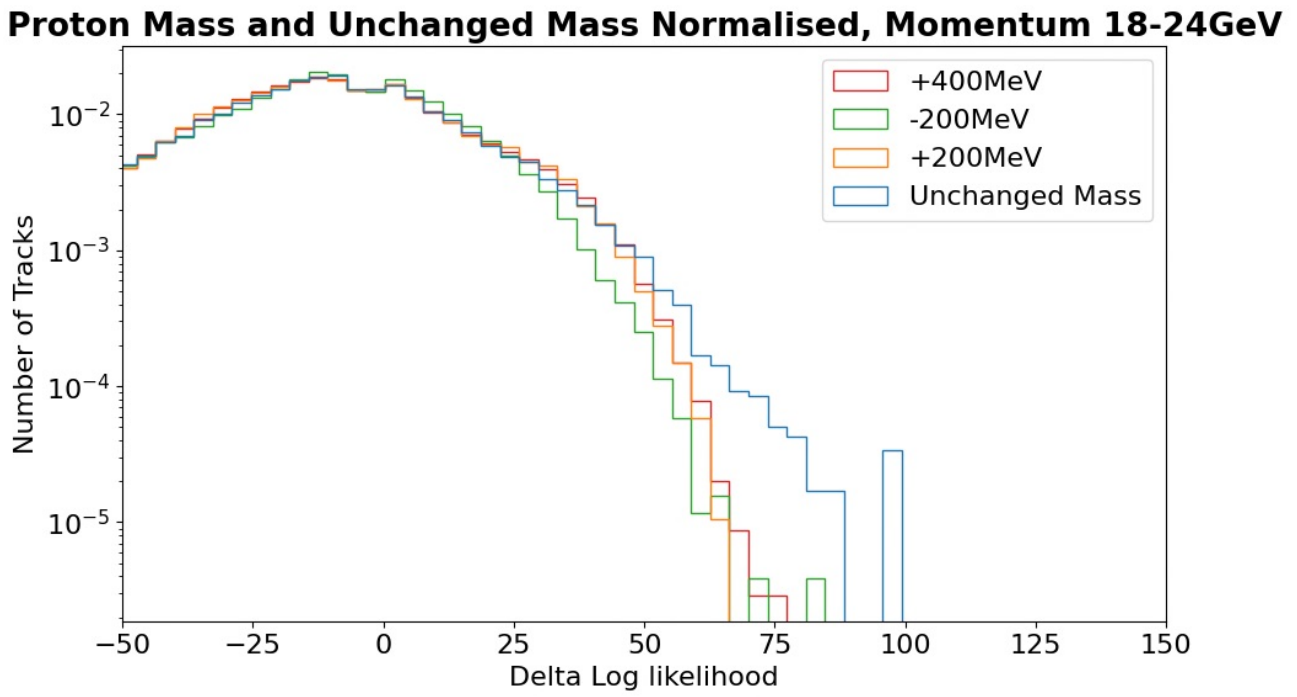
Meeting 12pm Ulrik & Eliot
- plot θ_{ch} over p

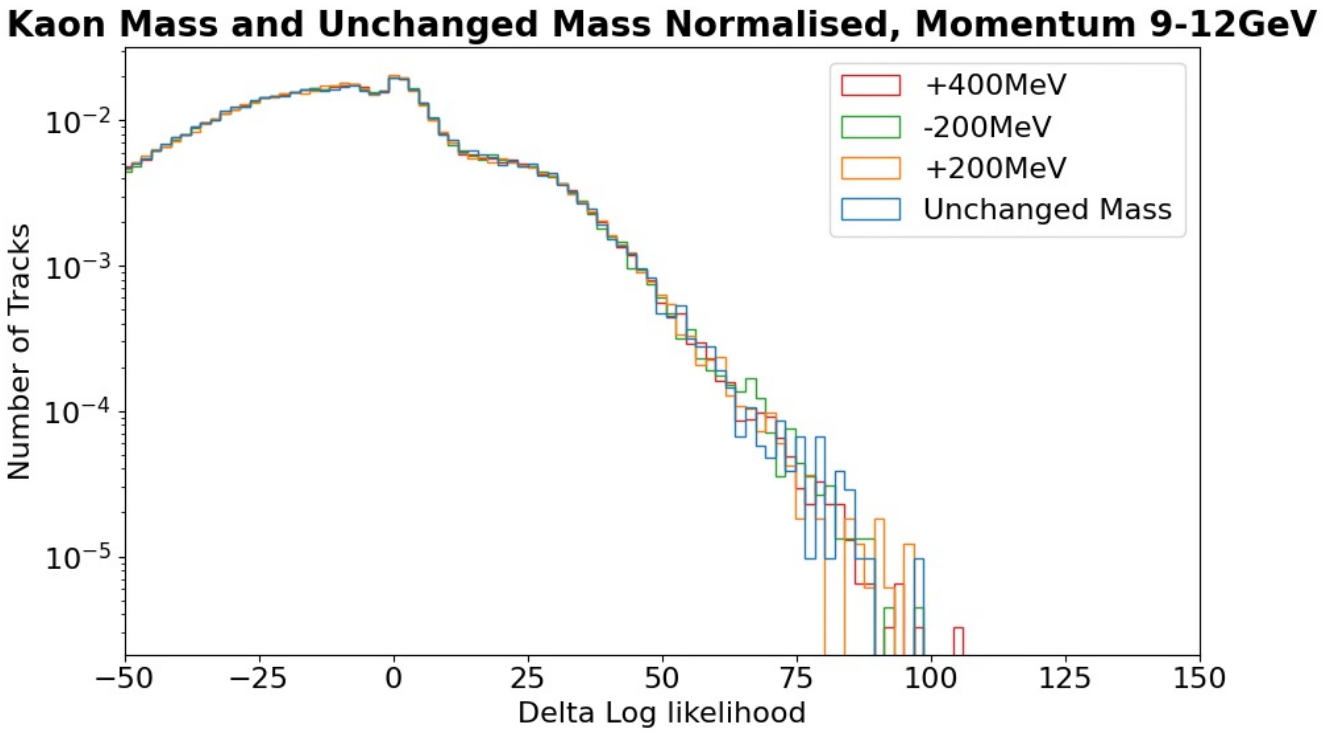
- fixed cherenkov resolution



Fri 16/9

Produced Plots for Normalised w/ log y-axis with momentum region applied



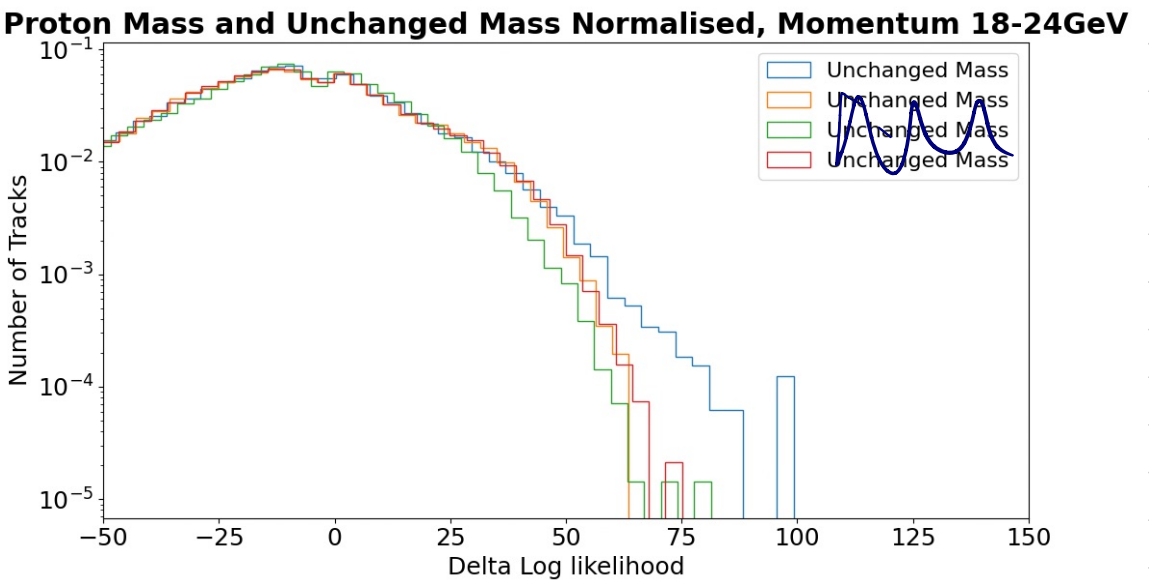


The proton plot shows a peak for the difference through it is smaller compared to without momentum region, probably due to less data? Kaons look roughly same.

Sat 17/9

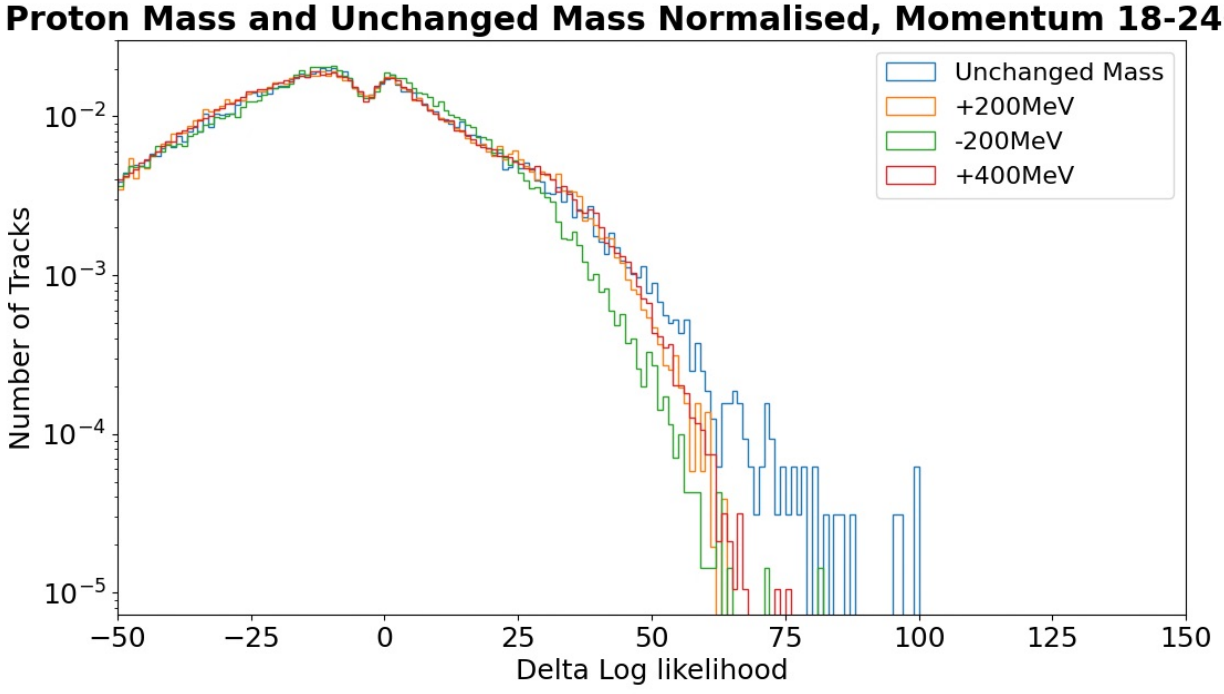
Played around with 'range' & 'weights' to ensure that the data is properly formatted
- weights -> normalises plots
- range -> selects correct data

- Tried to remove density = 'True', replace with weights = 'np.ones_like(x)/len(x)'
  ↳ error 'weights should have same shape as x'



- Similar to plot with densit = True'

Plot with weights and range (-100, 100)



Tue 20/9

Cherenkov angle vs momentum.

Cherenkov resolution angle:

First tried with example small data set with the variables CKTheta and P.
- Had trouble with how variable is stored -> CKTheta also has # tracks?
- Tried to just use plt.plot(...) though perhaps has to be plotted different way?

Moved on to larger reprocessed data set with changed masses,

Week 9

Goals

- Find more accurate momentum region
- Produce accurate difference plots
- Larger data set

Questions

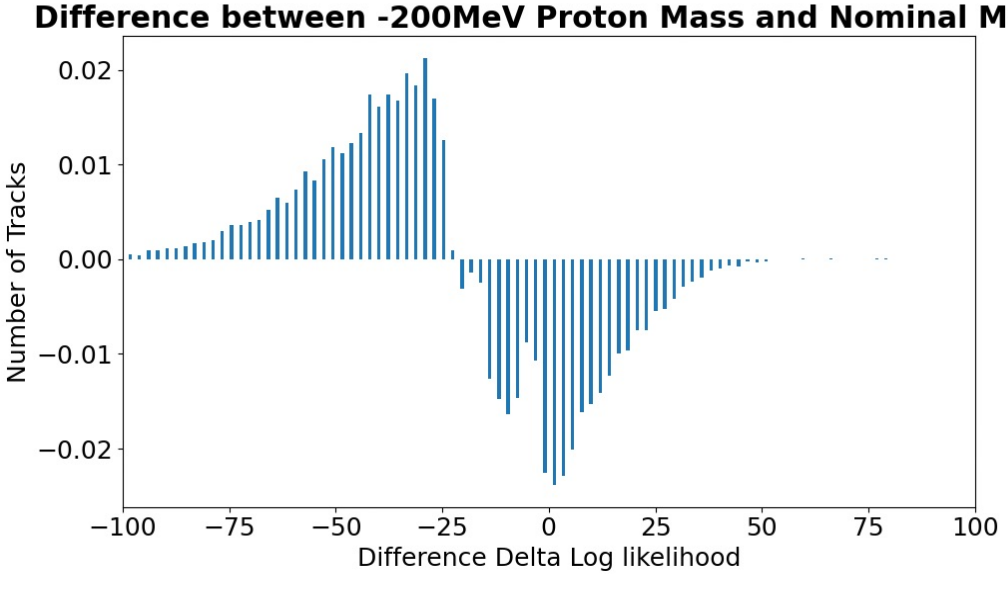
- Check weights/range correct
- o/p plot
- W9 prog report research
- Report plan
- Uncertainties

Tasks

- plot cherenkov angle & momentum
- Work on difference plot with uncertainties
- plot scatter plot first w/ error bars
- compare weights & density

Summary

- Looked at plotting cherenkov angle vs momentum, however data had not been loaded in, so we have considered calculating it.
- Plotted difference more accurately
- Produced scatter plots with error bars



Wed 21/9

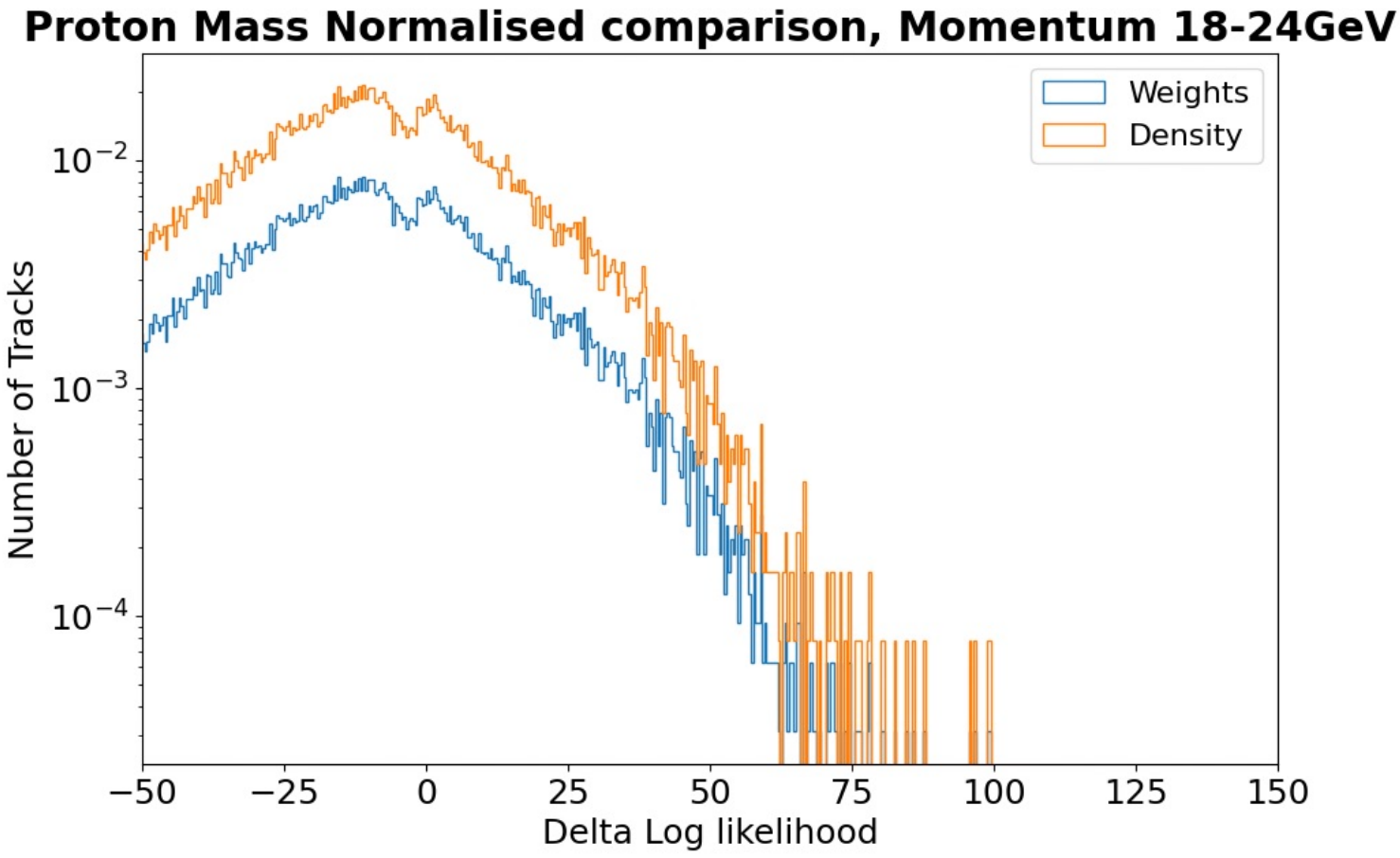
Meeting 2pm with Eliot on zoom,
discussed:
- comparing weights with density on plot to validate
- plot uncertainties on scatter plot first with uncertainty normalised accordingly
- plot error bars on histograms and difference plots

normalised uncertainty ~> $\frac{\sqrt{n}}{\text{len}(n)}$ ← non-normal

↑ array

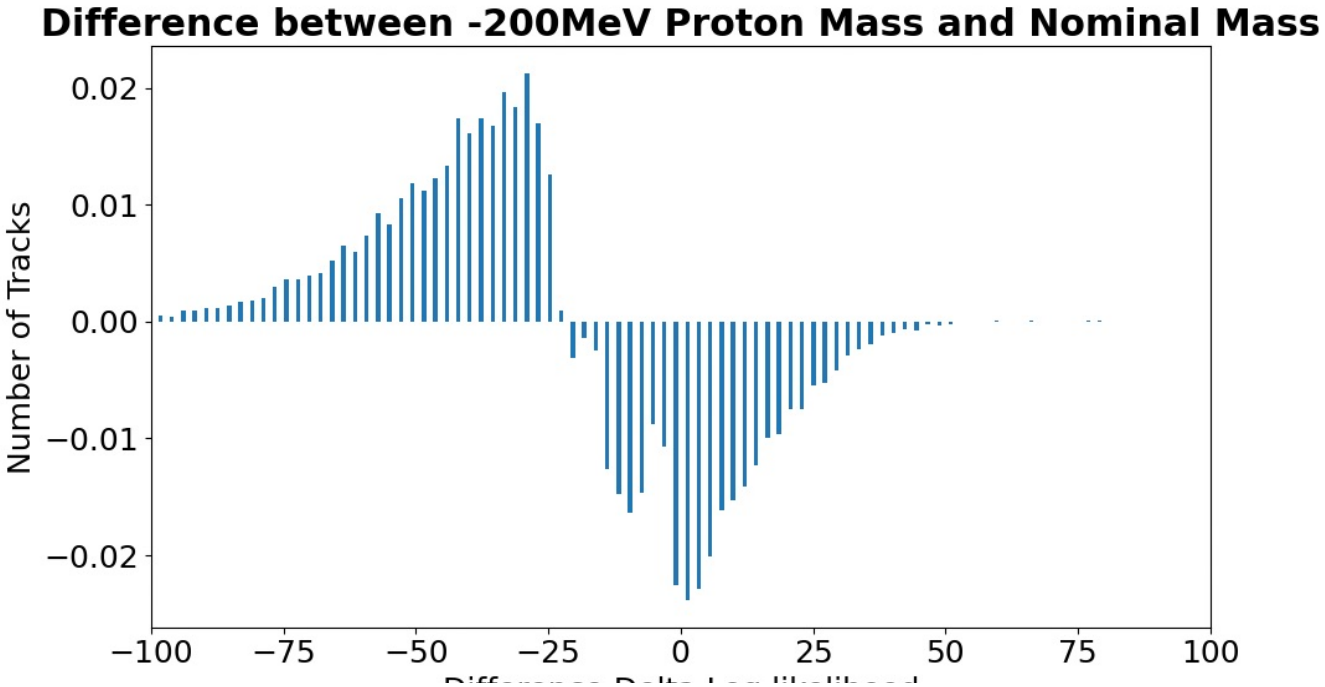
Fri 23/9

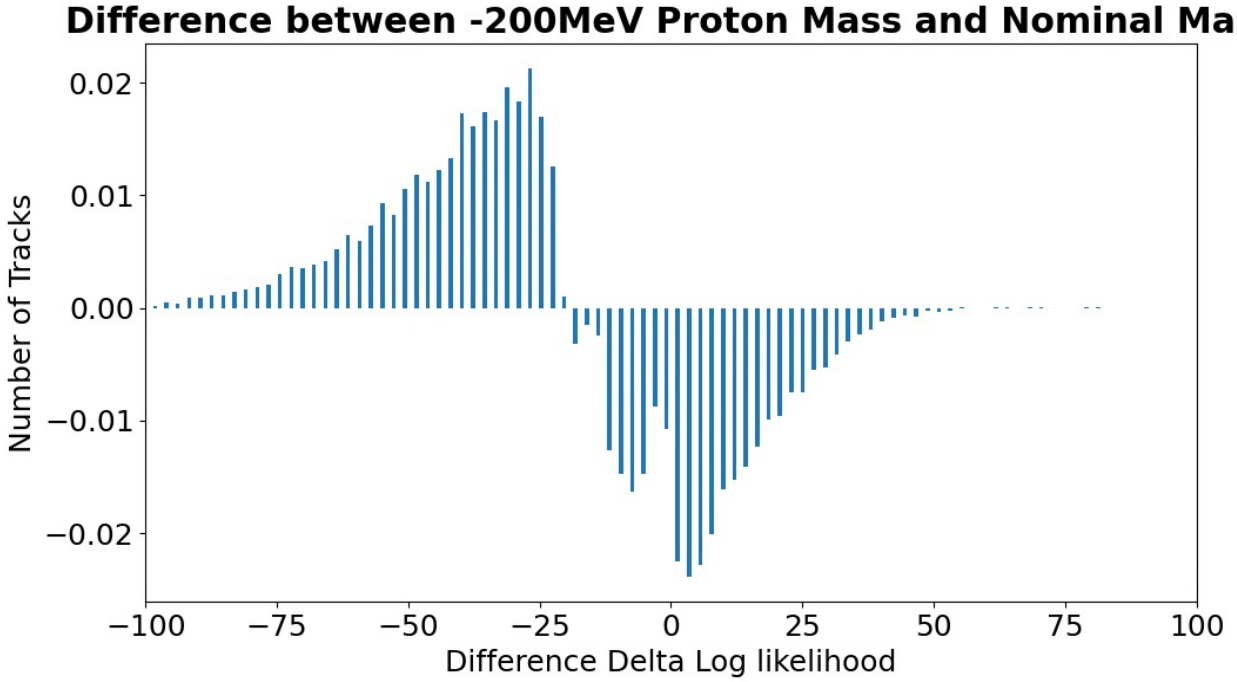
Comparing plots with weights & density



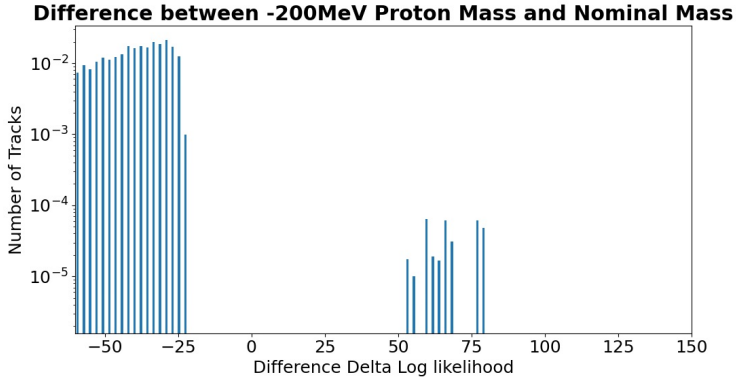
Decided to use weights as more accurate

Difference plot normalised with momentum region 20-24 GeV





Same plot but with log y scale to see the difference

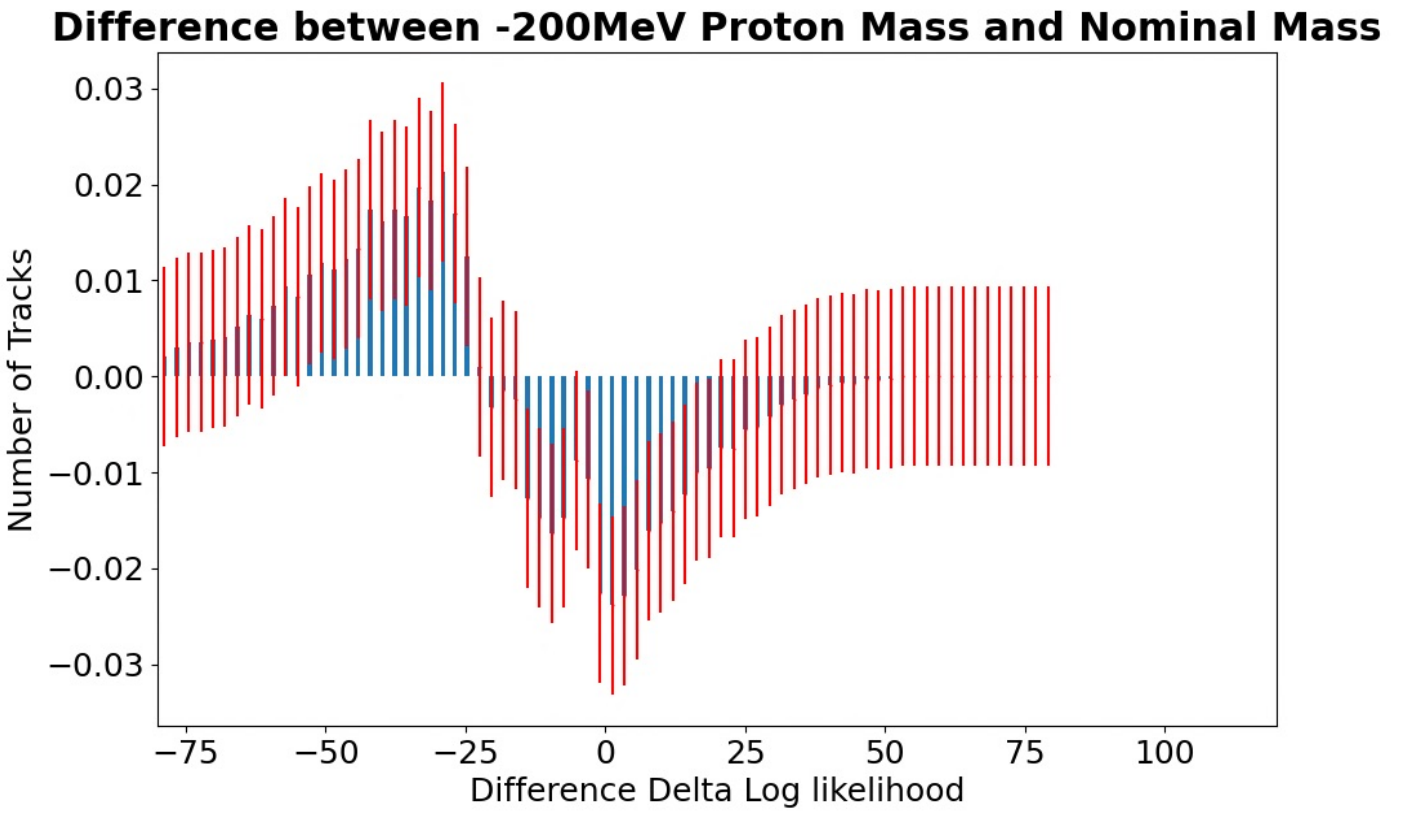


Code used to plot the difference

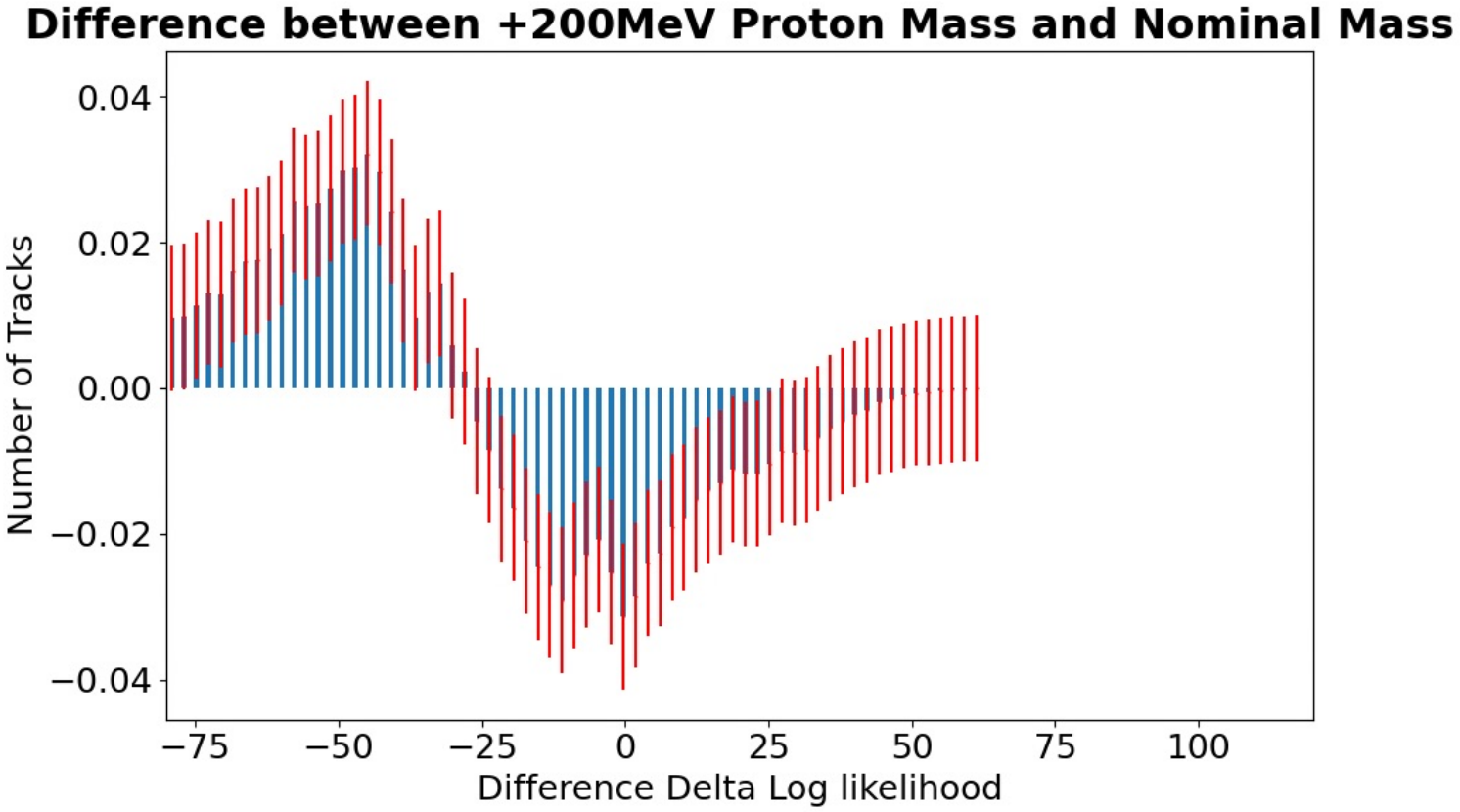
```
plt.rc('font', size=18)
bins=500
x=RichDLLp_nominal[cut]
xm2=RichDLLp_minus_200[cutm2]
xp2=RichDLLp_plus_200[cutp2]
xp4=RichDLLp_plus_400[cutp4]

entries_protons_nominal, bins_x= np.histogram(x, bins,weights=np.ones_like(x)/len(x),range=(-100,100,1))
entries_protons_changed, bins_x = np.histogram(xp4,bins,weights=np.ones_like(xp4)/len(xp4),range=(-100,100,1))

nominal_changed =  entries_protons_nominal-entries_protons_changed


plt.bar(bins_x[0:500],nominal_changed)
#label=['Unchanged Mass', '+200MeV']
plt.errorbar(bins_x[0:500],nominal_changed,yerr=((np.sqrt(len(x))/len(x))+(np.sqrt(len(xp4))/len(xp4))), fmt="o"
plt.xlabel('Difference Delta Log likelihood')
plt.ylabel('Number of Tracks')
plt.xlim([-60,150])
#plt.yscale('log')
plt.title('Difference between +400MeV Proton Mass and Nominal Mass', fontweight ="bold")
plt.show()
```

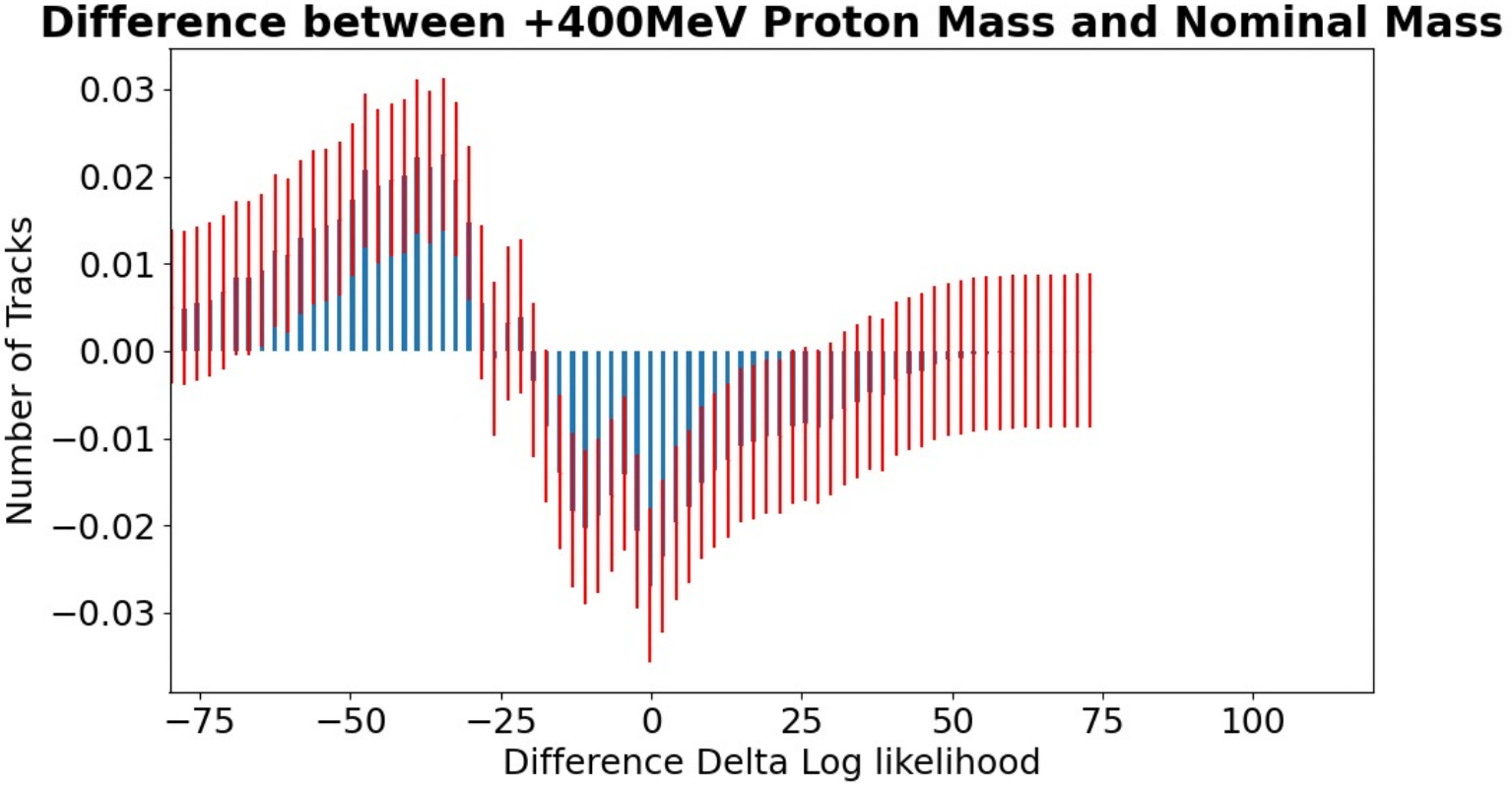
Difference plot with error bars for -200MeV

$$\text{Uncertainty} = \frac{\sqrt{\text{len}(x)}}{\text{len}(x)} + \frac{\sqrt{\text{len}(xp2)}}{\text{len}(xp2)}$$

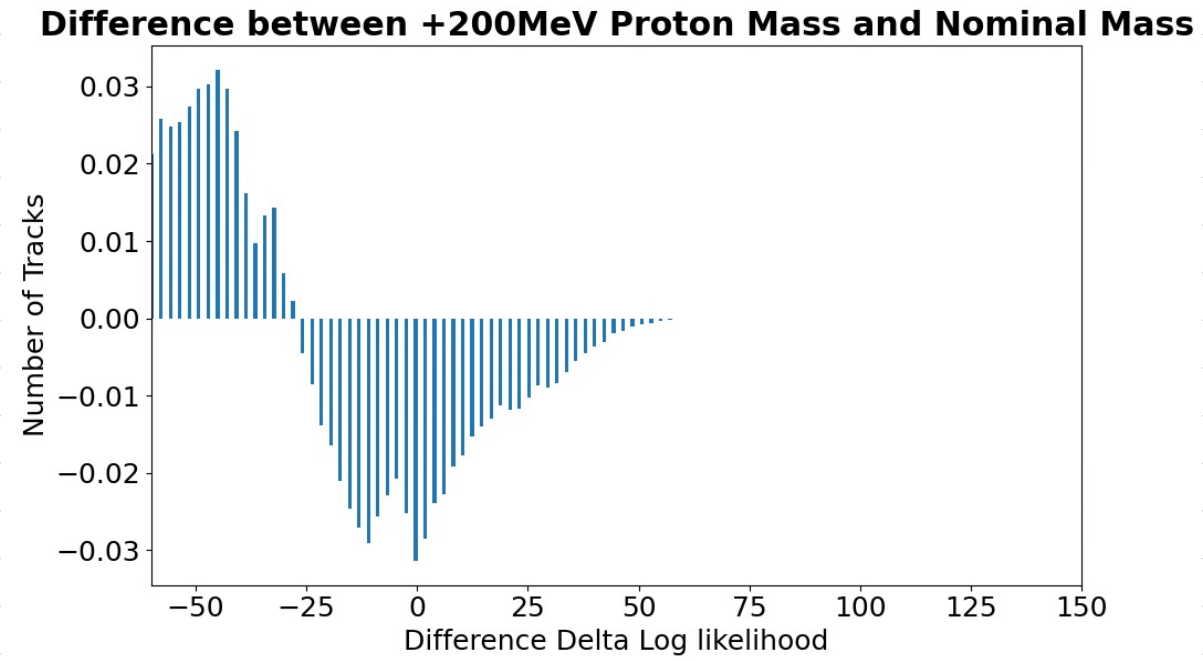


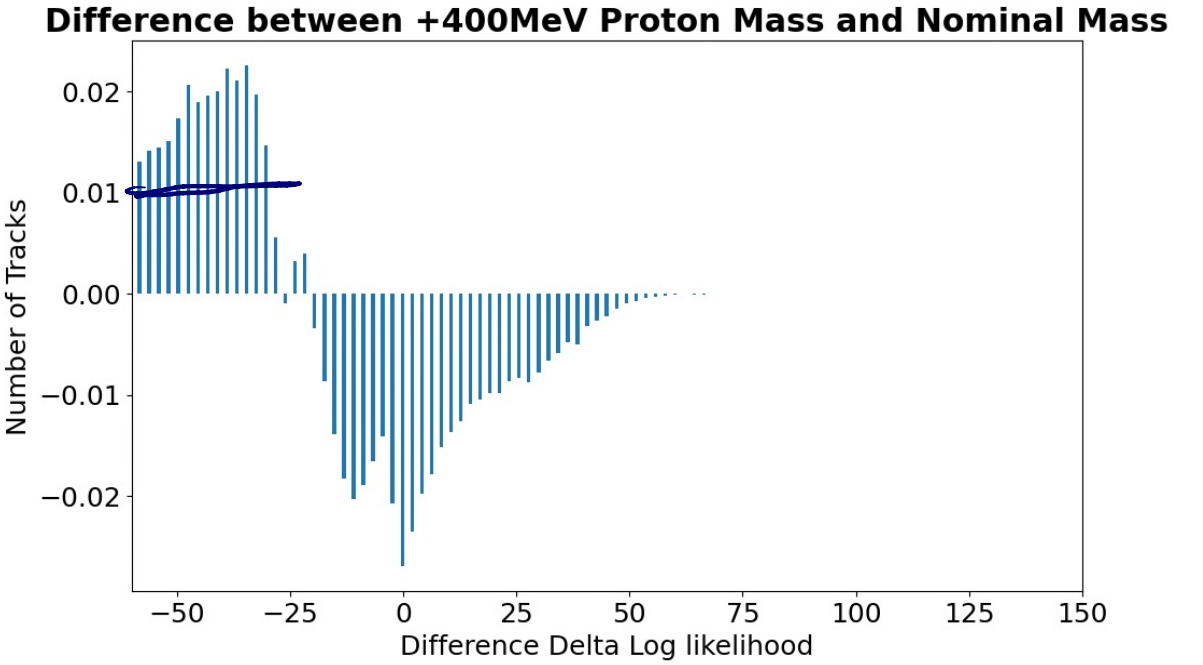
Need to fix error bar format



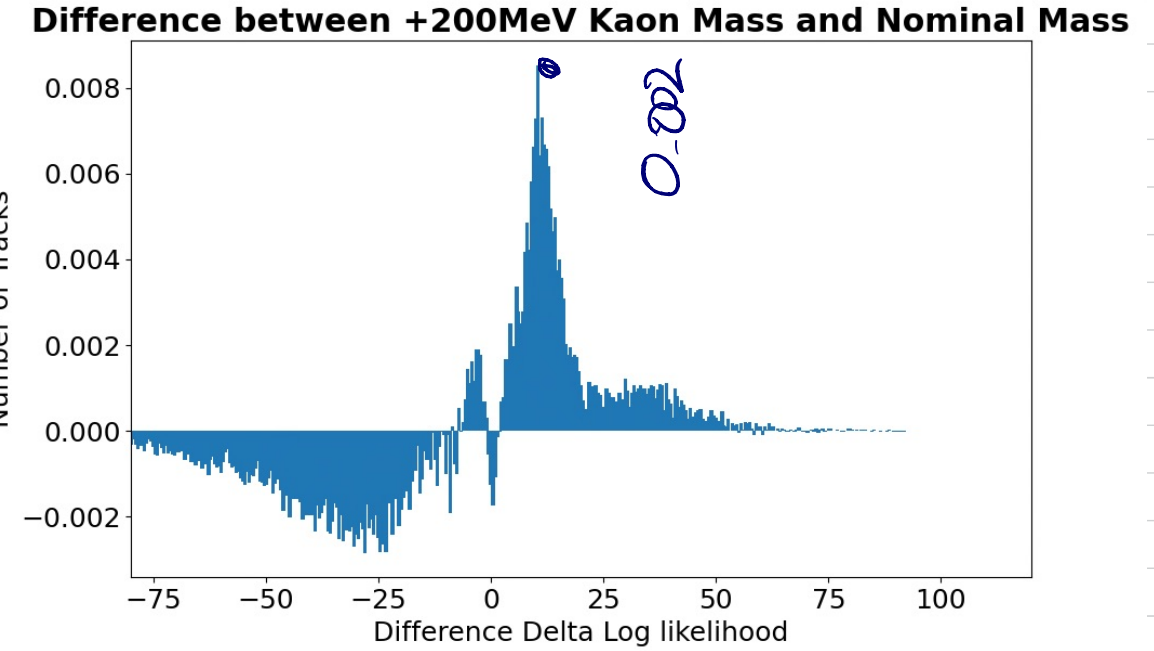


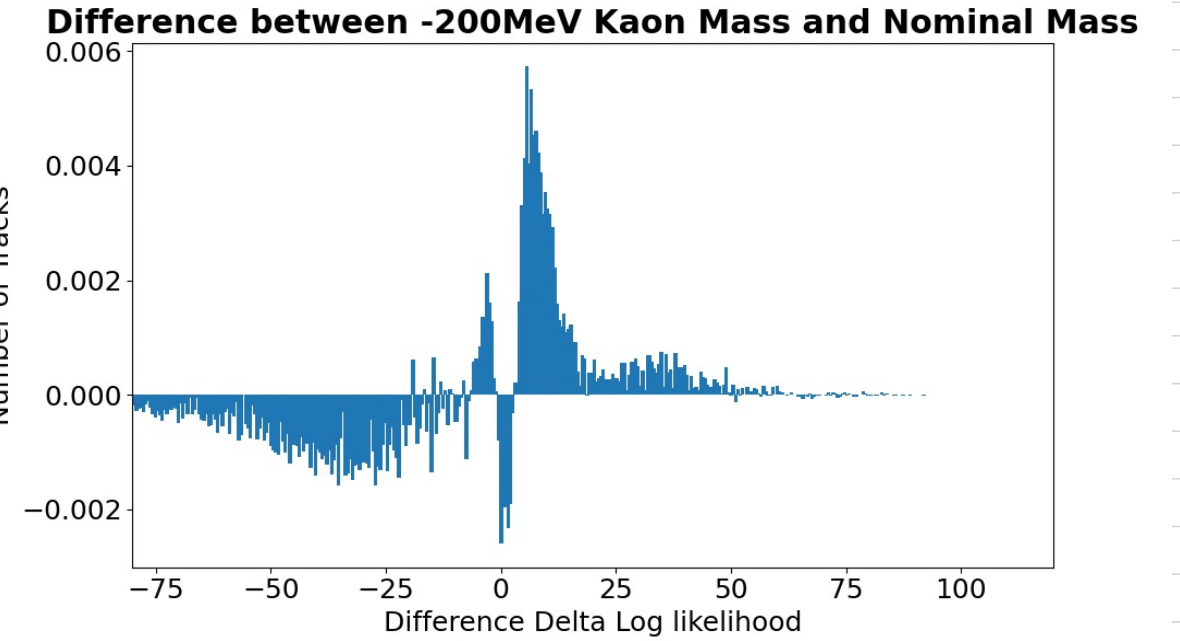
Difference plots for all charged masses with momentum region for protons

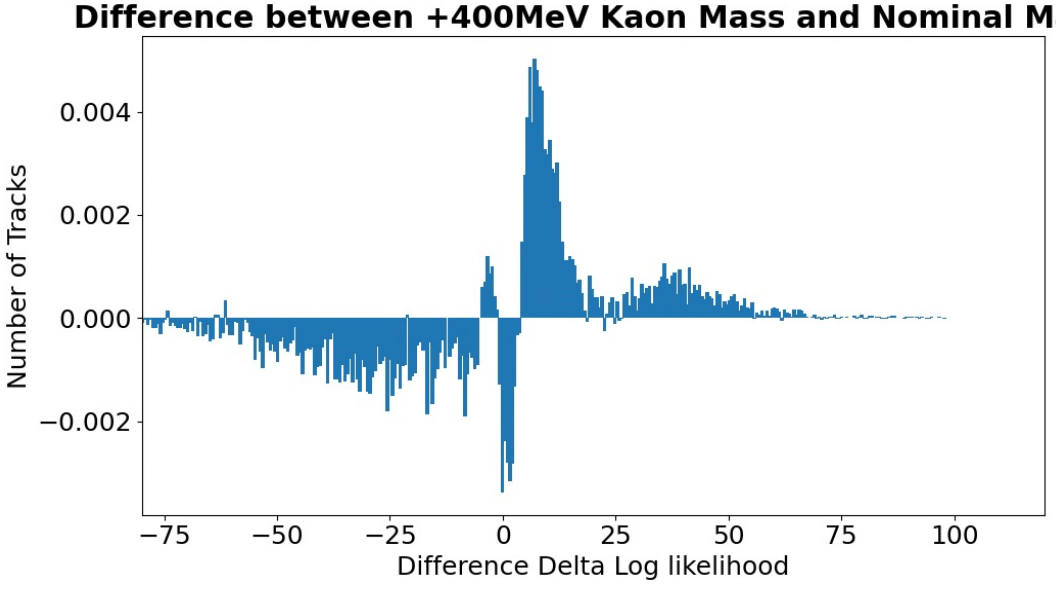




Difference plots for kaons







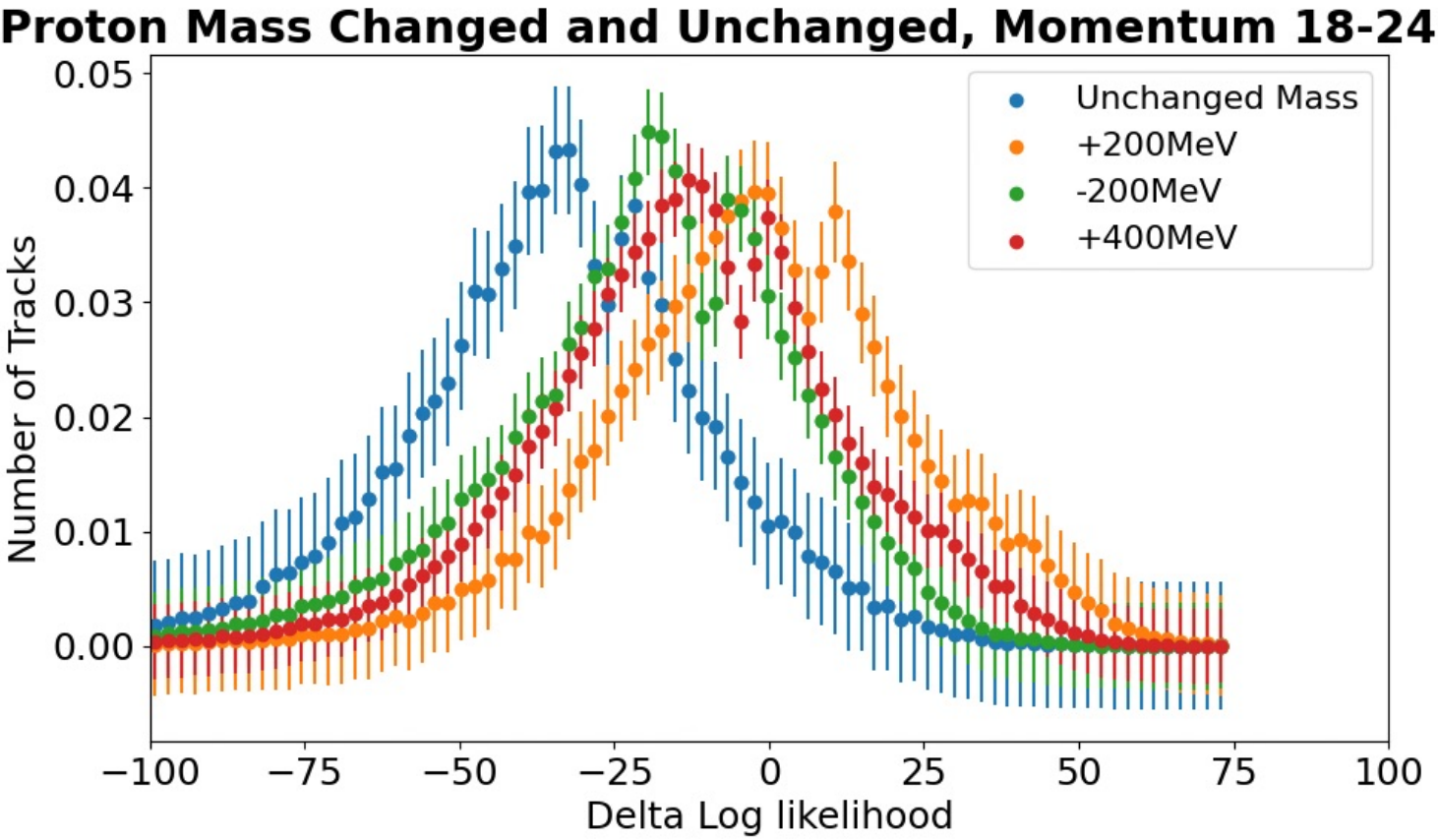
Wed 28/9

- Producing scatter plots with uncertainty

Code used:

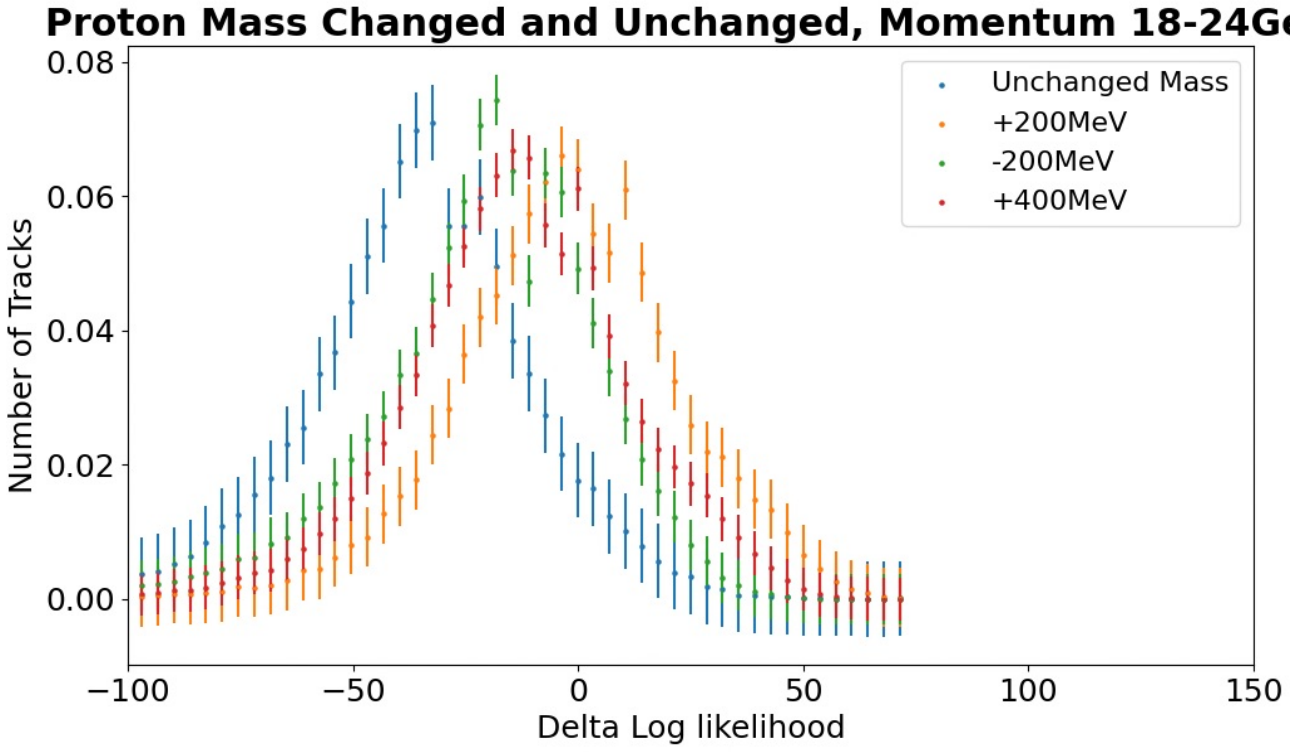
```
plt.rc('font', size=18)
bins=80
x=np.array(RichDLLp_nominal[cut])
xm2=np.array(RichDLLp_minus_200[cutm2])
xp2=np.array(RichDLLp_plus_200[cutp2])
xp4=np.array(RichDLLp_plus_400[cutp4])

entries, bins_x=np.histogram(x,bins,weights=np.ones_like(x)/len(x),range=(-100.0,100.0))
entriesp2, bins_x=np.histogram(xp2,bins,weights=np.ones_like(xp2)/len(xp2),range=(-100.0,100.0))
entriesm2, bins_x =np.histogram(xm2,bins,weights=np.ones_like(xm2)/len(xm2),range=(-100.0,100.0))
entriesp4, bins_x =np.histogram(xp4,bins,weights=np.ones_like(xp4)/len(xp4),range=(-100.0,100.0))

plt.scatter(bins_x[0:80],entries,label='Unchanged Mass',s=5)
plt.scatter(bins_x[0:80],entriesp2,label='+200MeV',s=5)
plt.scatter(bins_x[0:80],entriesm2,label='-200MeV',s=5)
plt.scatter(bins_x[0:80],entriesp4,label='+400MeV',s=5)

plt.errorbar(bins_x[0:80], entries,yerr=np.sqrt(len(x))/len(x), fmt="o",markersize='1')
plt.errorbar(bins_x[0:80],entriesp2, yerr=np.sqrt(len(xp2))/len(xp2), fmt="o",markersize='1')
plt.errorbar(bins_x[0:80],entriesm2, yerr=np.sqrt(len(xm2))/len(xm2), fmt="o",markersize='1')
plt.errorbar(bins_x[0:80],entriesp4,yerr=np.sqrt(len(xp4))/len(xp4), fmt="o",markersize='1')

#plt.hist((xp2), bins,label='+200MeV',histtype='step',weights=np.ones_like(xp2)/len(xp2),range=(-100,100))
#plt.hist((xm2), bins,label='-200MeV',histtype='step',weights=np.ones_like(xm2)/len(xm2),range=(-100,100))
#plt.hist((xp4), bins,label='+400MeV',histtype='step',weights=np.ones_like(xp4)/len(xp4),range=(-100,100))
plt.xlabel('Delta Log likelihood')
plt.ylabel('Number of Tracks')
#plt.yscale('log')
plt.legend(prop ={'size': 16})
plt.xlim([-100,150])
plt.title('Proton Mass Changed and Unchanged, Momentum 18-24GeV', fontweight ="bold")
plt.show()
```

Normalised plot with weights



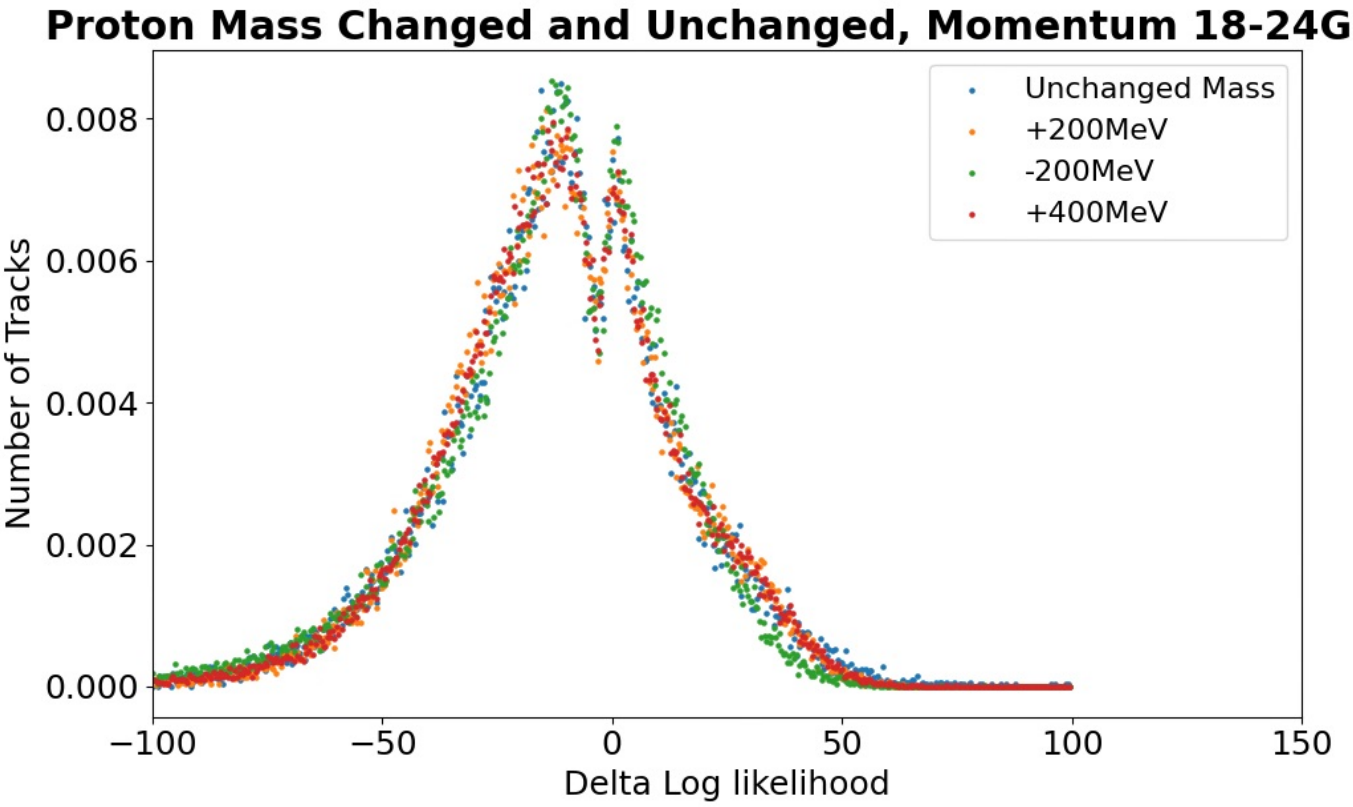
- They do not seem to be lining up right so tried the range function with range = (-100, 100)
- +200MeV shows a peak → mislabeled?

This is the same plot with smaller markers.

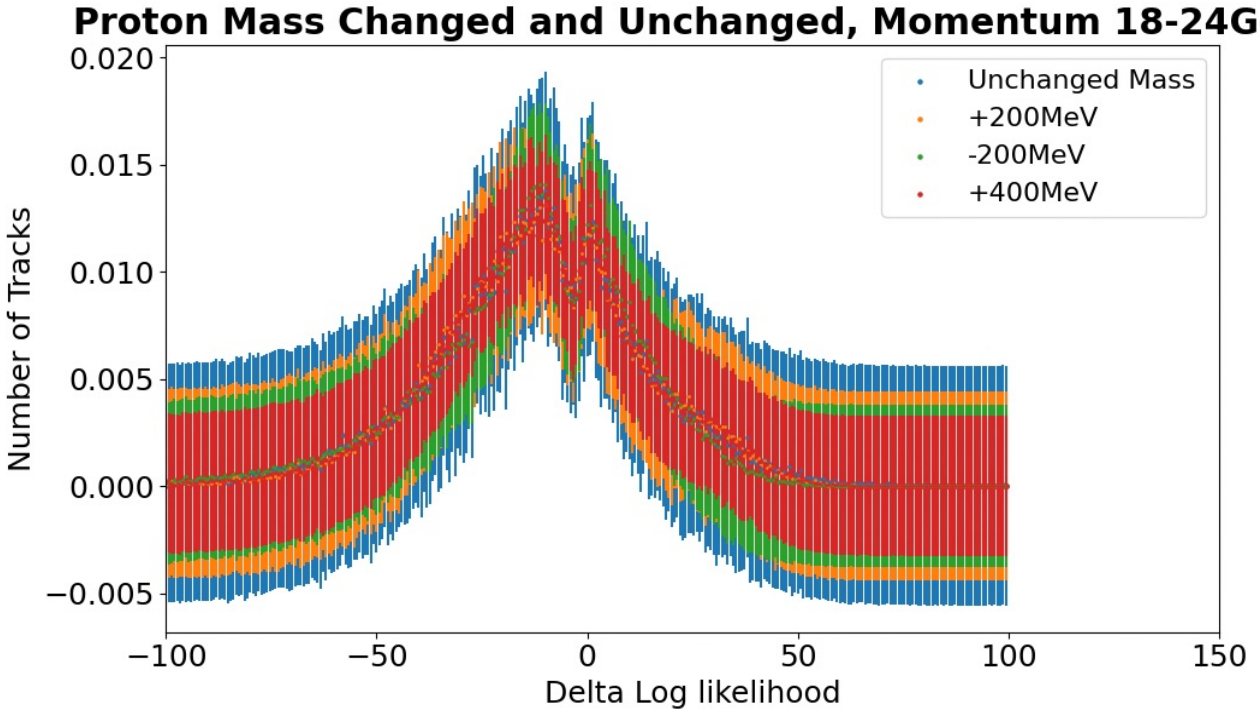


Mon 3/10

To align the data range = (-100, 100) was used, first without error bars.



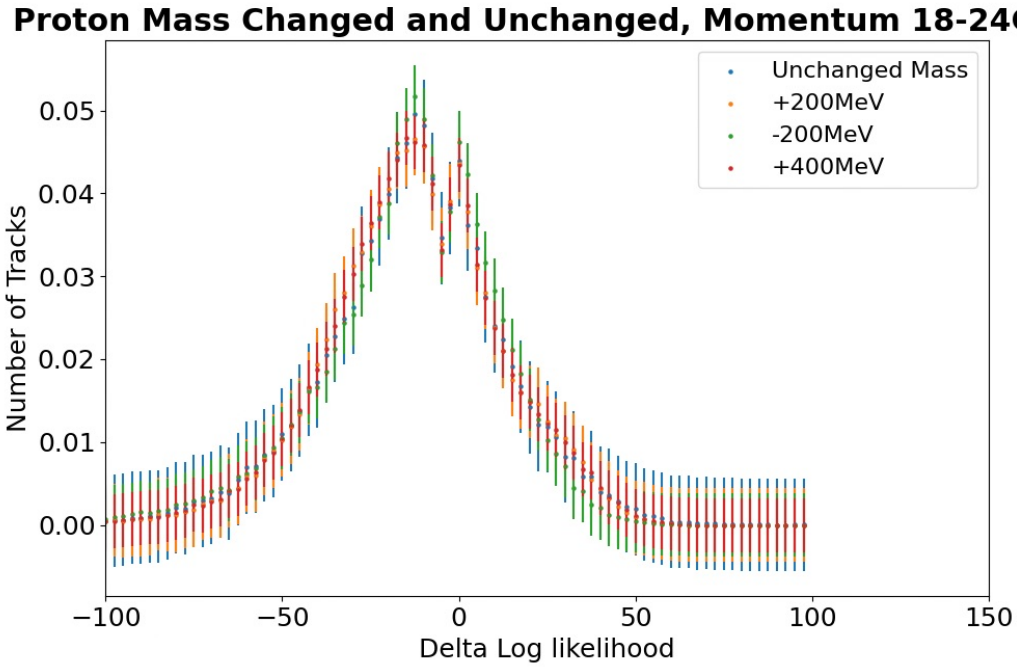
Including error bars seemed to block data



Too many bins?

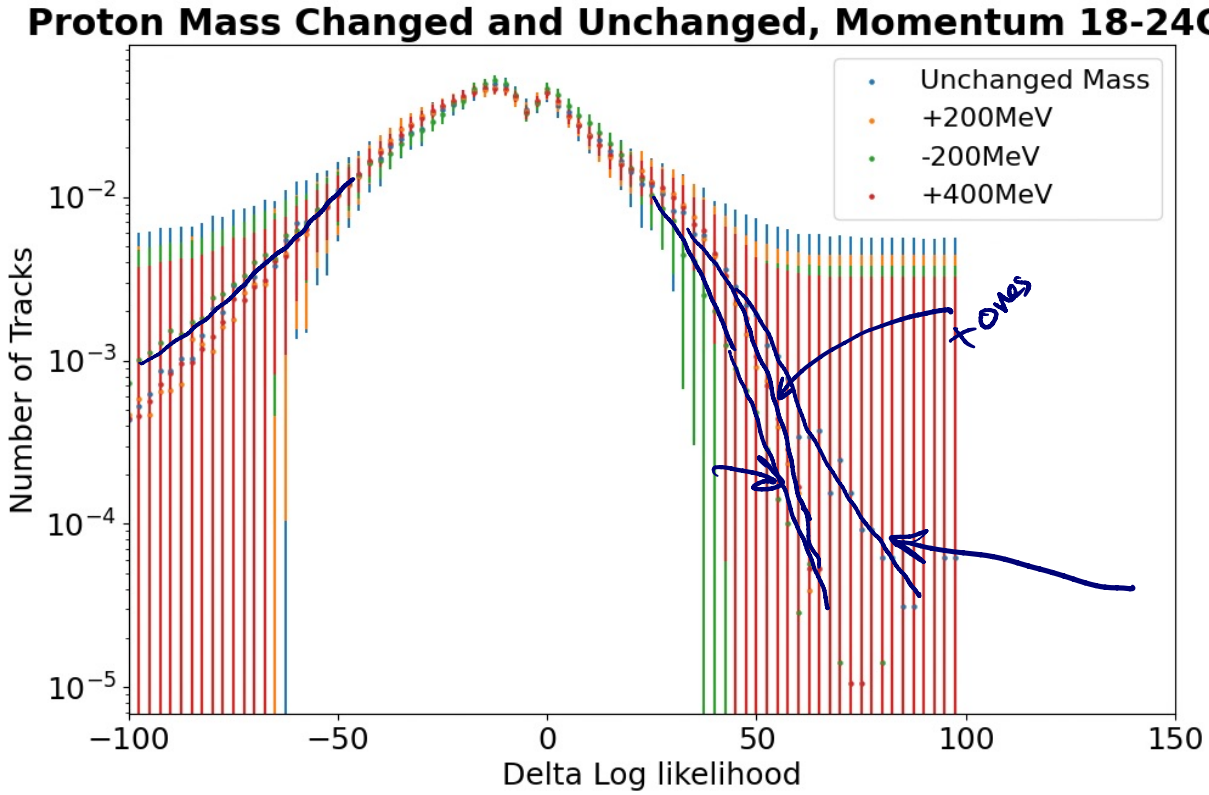
To resolve, tried to apply range to plt.errorbar(), which gave an error

Plotted with a lot less bins → 80 bins



As less bins are used difference becomes less obvious

Scatter plot with log y-axis



Hard to see diffrnce with error bars

Week 10

Goals

- Prepare for talk
- Error bars on plots
- Start report
- Find momentum region from plot or calculate

Questions

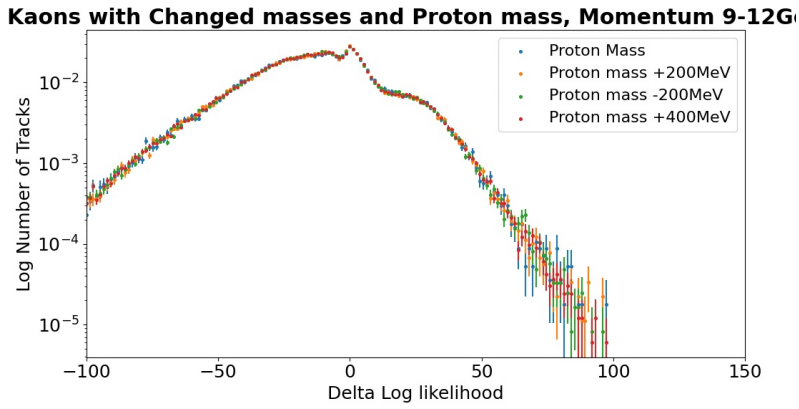
- check that uncertainty is correct
- Chermkov vs momentum
  ↳ use other data?
- Difference plots
- Report plan
- Talk powerpoint & preperation.

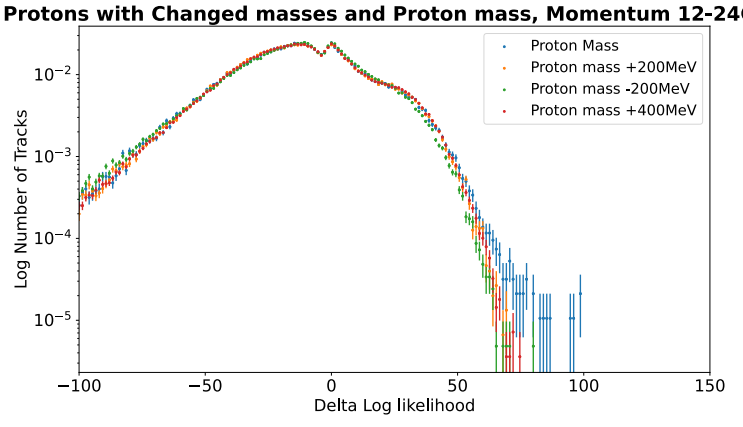
Tasks

- Work on power point for talk
- Start final report
- Calculate momentum region

Summary

Corrected error bars on scatter plots were produced.





Worked on final presentation and practiced

Wed 5/10

Meeting with Eliot 12 pm
Discussed:
- error bars on scatter plots
- Difference plots
- preperation for talk
- 200MeV seems to undershoot
  - ↳ because of kaons?
- Cherenkov angle vs momentum (leave for now)

Other notes:

error bars:

$\sqrt{x}/\ln(x)$ list of n.

$x = [\ldots]$

$\ln(x) = a \; ; \; a \in \mathbb{R}.$

, $\neq n = 100$

$n \neq 10$

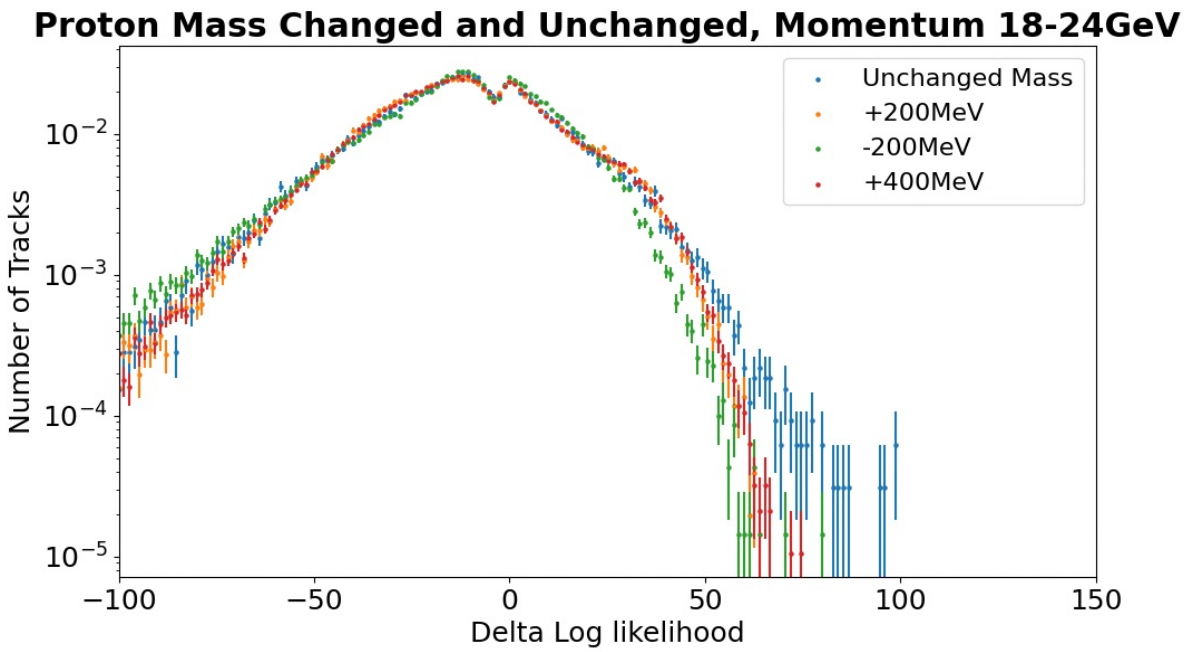
$n = 5$

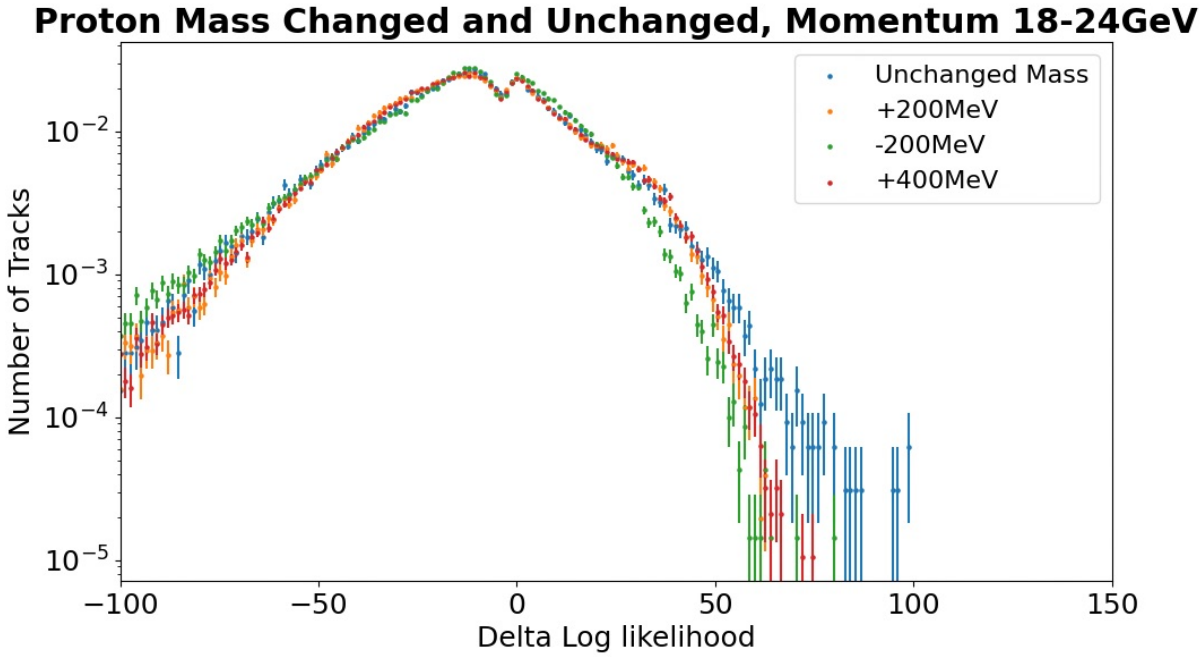
$err = \sqrt{n}$

Thur 6/10

Plotted error bars on scatter plot for protons & kaons, with log y-axis

error bars appear to be formatted correctly





- -200MeV Understood compared to other changed masses, → potentially due to kaons?
  - -200MeV closer to kaon mass than others
- should be looked into further, look at other masses below proton mass to see full effect as we get closer to kaon

Code used to produce plots above

```
plt.rc('font', size=18)
bins=150
x=np.array(RichDLLk_nominal[cut])
xm2=np.array(RichDLLk_minus_200[cutm2])
xp2=np.array(RichDLLk_plus_200[cutp2])
xp4=np.array(RichDLLk_plus_400[cutp4])

entries, bins_x=np.histogram(x,bins,range=(-100.0,100.0))
entriesp2, bins_x=np.histogram(xp2,bins,range=(-100.0,100.0))
entriesm2, bins_x =np.histogram(xm2,bins,range=(-100.0,100.0))
entriesp4, bins_x =np.histogram(xp4,bins,range=(-100.0,100.0))

x_err = np.sqrt(entries)/len(x)
xp2_err = np.sqrt(entriesp2)/len(xp2)
xp4_err = np.sqrt(entriesp4)/len(xp4)
xm2_err = np.sqrt(entriesm2)/len(xm2)

entries, bins_x=np.histogram(x,bins,weights=np.ones_like(x)/len(x),range=(-100.0,100.0))
entriesp2, bins_x=np.histogram(xp2,bins,weights=np.ones_like(xp2)/len(xp2),range=(-100.0,100.0))
entriesm2, bins_x =np.histogram(xm2,bins,weights=np.ones_like(xm2)/len(xm2),range=(-100.0,100.0))
entriesp4, bins_x =np.histogram(xp4,bins,weights=np.ones_like(xp4)/len(xp4),range=(-100.0,100.0))

plt.scatter(bins_x[0:150],entries,label='Unchanged Mass',s=5)
plt.scatter(bins_x[0:150],entriesp2,label='+200MeV',s=5)
plt.scatter(bins_x[0:150],entriesm2,label='-200MeV',s=5)
plt.scatter(bins_x[0:150],entriesp4,label='+400MeV',s=5)

plt.errorbar(bins_x[0:150], entries,yerr=x_err, fmt="o",markersize='1')
plt.errorbar(bins_x[0:150],entriesp2, yerr=xp2_err, fmt="o",markersize='1')
plt.errorbar(bins_x[0:150],entriesm2, yerr=xm2_err, fmt="o",markersize='1')
plt.errorbar(bins_x[0:150],entriesp4,yerr=xp4_err, fmt="o",markersize='1')
```

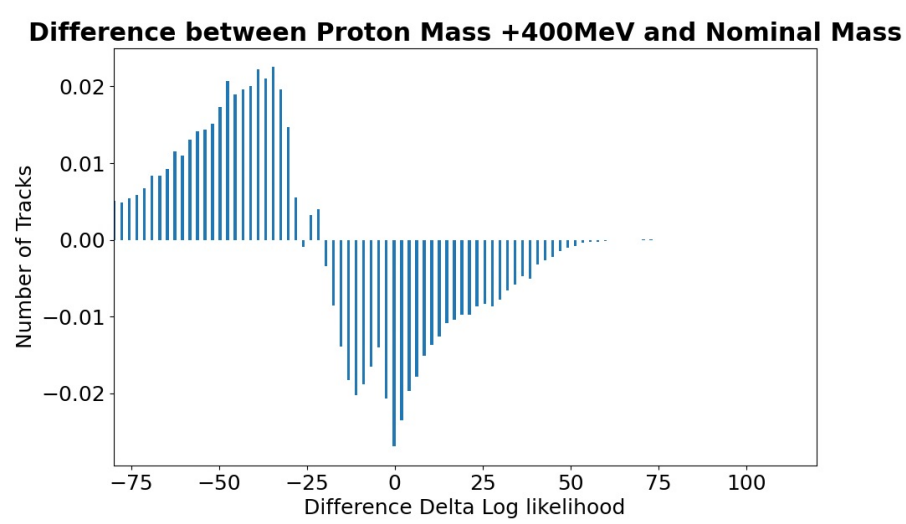
Uncertainty used $err = \frac{\sqrt{entries}}{len(x)}$

Fri 7/10

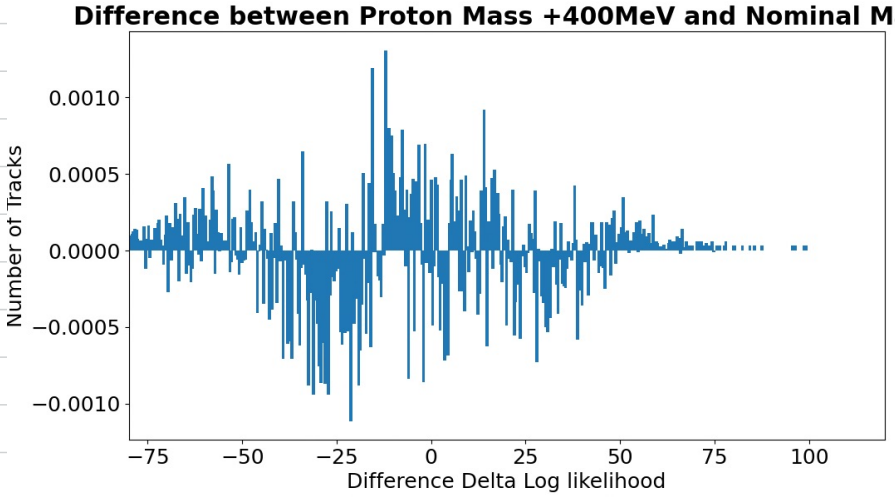
- prepared slides for talk
- started on final report

Mon 10/10

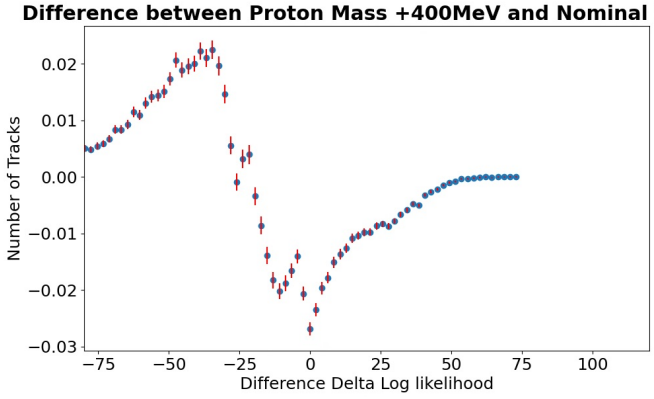
Tried to produce difference plots with corrected error bars like scatter plots



without range (-100,100)



with range (-100, 100)



- uproot

Week 11

Goals

- analyse more data?
- Finalise plots & uncertainties
- Feel confident with presentation
- Start report

Questions

- pull plots?
- More data / deuterons
- cherenkov angle vs momentum
- Difference plots with error bars

Tasks

- Practice presentation
- Start Final report ~ 5 pages
- Potentially look at more data

Summary

- Practiced talk with Eliot
- Produced slides for talk.
- Made progress on final report

Week 12

Goals

- Finalise talk
- practice talk
- understand concepts in more detail
- Write 5 pages of report

Questions

- protons and kaons ↳ data DLL
- Report plan

Tasks

- Finish writing slides for talk
- practice talk
- Write more of report

Summary

- Finalised & practiced talk
- Wrote first section of report → DM & particle physics

Swotvac/Exams

Report

- discussion section seperate?
- LHCb detect
- experiment details/data/method
- other plots