High Energy **P**article **ID**entification **(PID)**

——————— An update on what I've been working on so far ———————

Quach Christine

Outline.

1. **Setting the Context:** SK/HK experiments and Existing PID Algorithms
2. **My Work:** Adapting Algorithms for High Energy Neutrinos
3. **What's next?**

1 Setting the Context

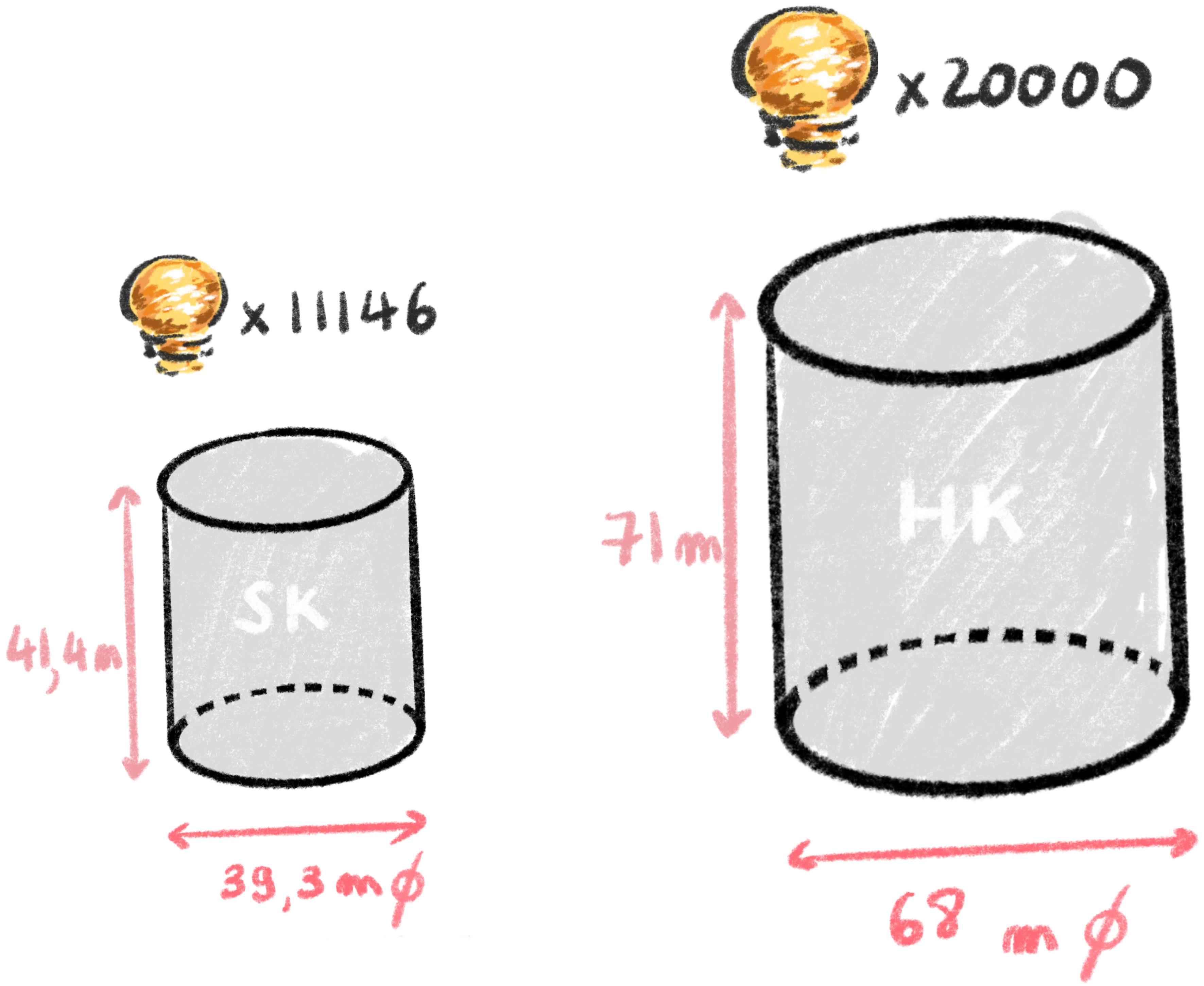
A. Super-Kamiokande: Operational Principles and Observed Neutrinos

B. Current State of PID Algorithms

Experiments

Super-Kamiokande

- 41.4 m in height and 39.3 m in diameter, which holds approximately 50 ktons of ultrapure water.
- 11,146 PMTs



Hyper-Kamiokande

- An order of magnitude bigger than SK,
- 71 m in height and a diameter of 68 m
- 20 000 ultra-high sensitivity PMTs

Observed neutrinos

Relic Supernova neutrinos

- Neutrinos were produced in a supernova that occurred in the distant past and is still traveling through the universe today.
- # of events in SK: 10/year.
- Energy: 2 MeV (LOW)
- Provide a unique opportunity to study the properties of supernovae and the physics of the early universe

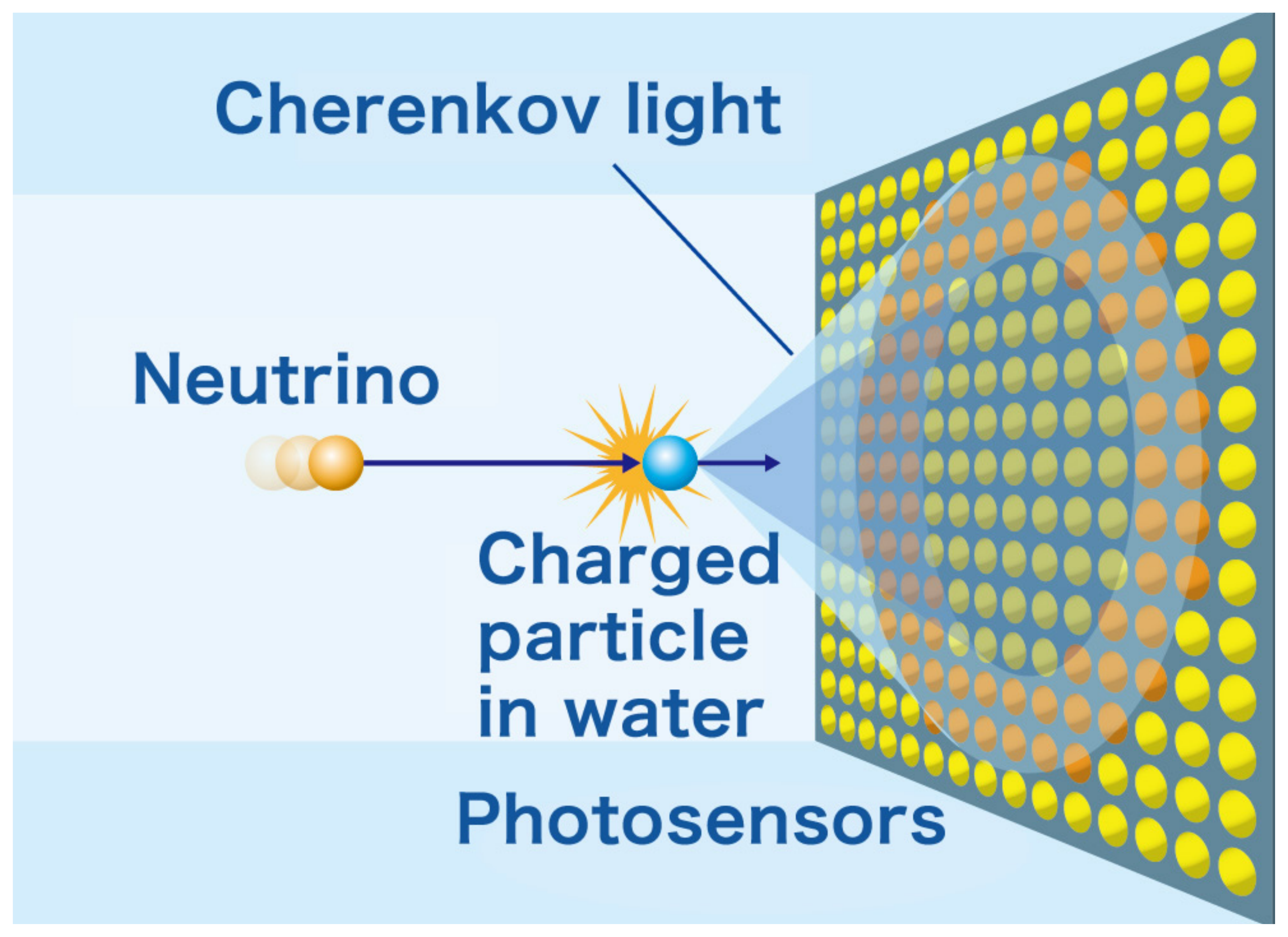
Solar neutrinos

- Neutrinos produced in the Sun by nuclear fusion reactions. Vast majority of neutrinos passing through the Earth
- Most of solar neutrinos have energy below 10 MeV
- Representation of the flux as a function of the energy of solar neutrinos according to the Standard Model of the Sun

Transient Supernova neutrinos

- Neutrinos coming from a supernova explosion
- Energy ranging from 10 to 30 MeV. (HIGH)
- Interesting particles to observe to understand the physics behind the explosion as neutrinos hold 99 % of the information about the explosion.

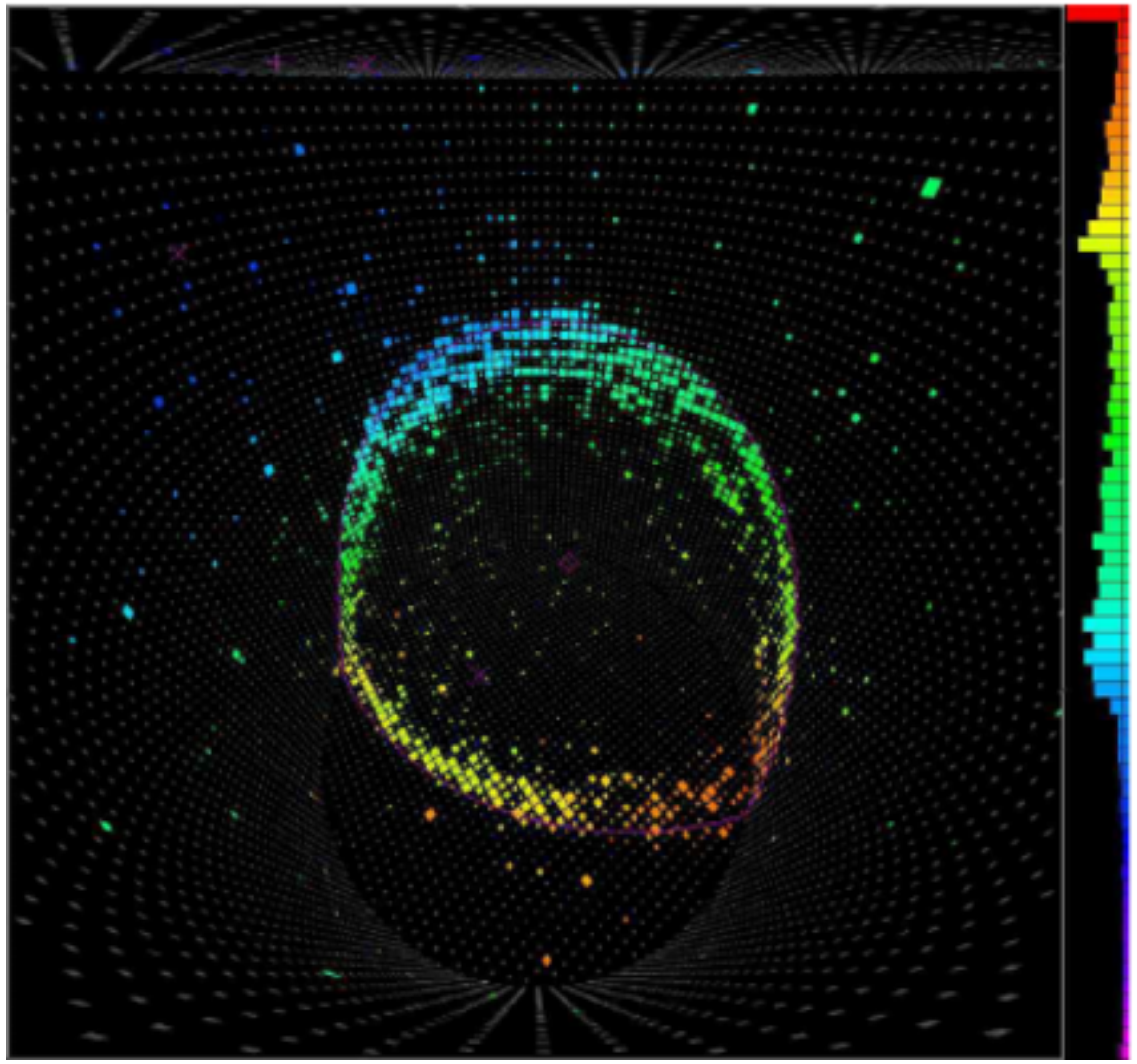
Neutrino detection method



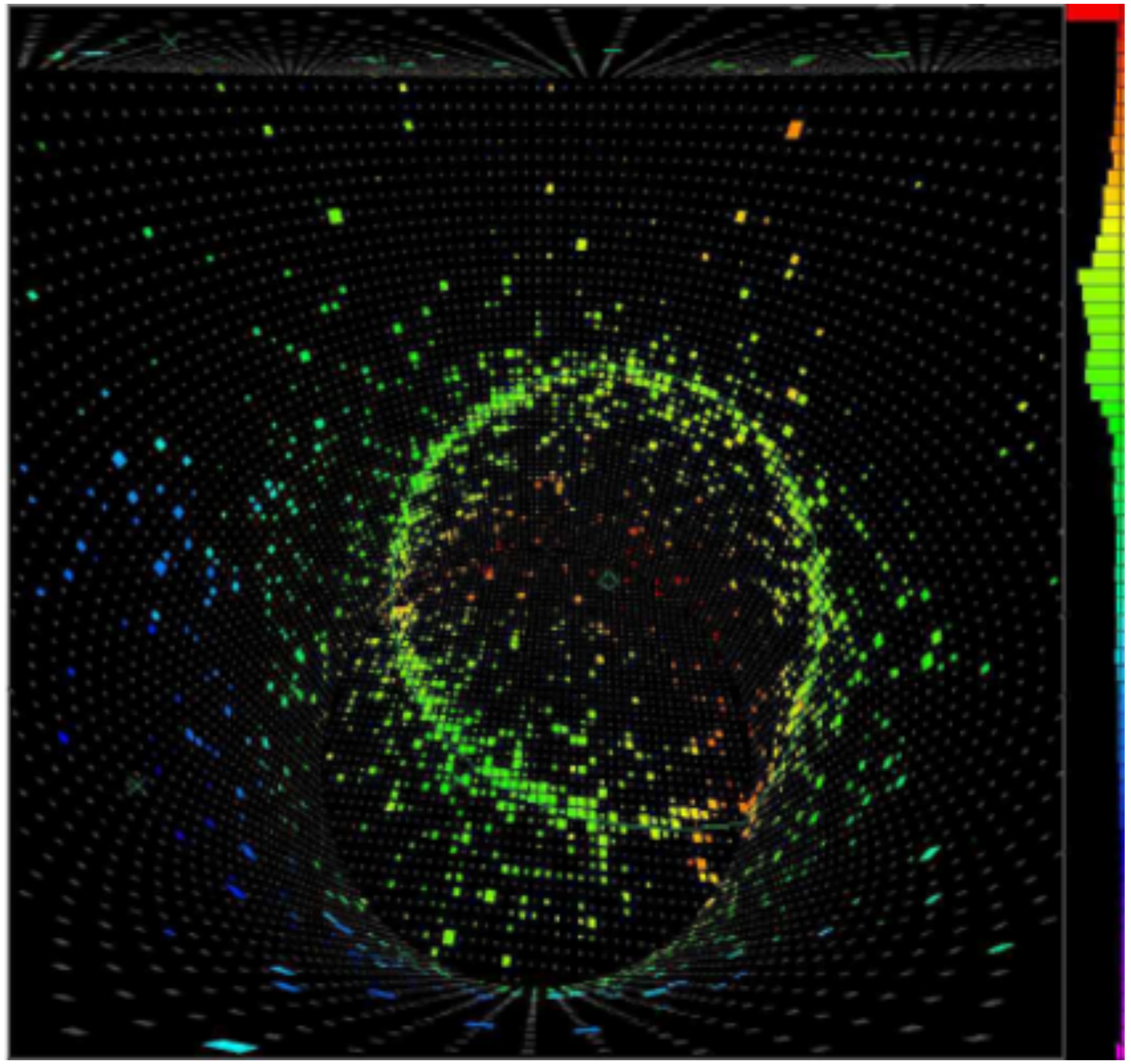
Cherenkov light

- The neutrino that interacts with electrons or nuclei in water produces a charged particle moving faster than the speed of light in water, which is slower than the speed of light in a vacuum.
- A cone of light is formed as a result, which is known as Cherenkov radiation.
- The equivalent in the optical field is the sonic boom. PMTs record the Cherenkov light projected as a ring on the wall of the detector.

Neutrino detection method



Muon (Sharp)



Electron (Blurry)

Low energy

Merci Antoiiiiiiiine

Why a Graph Neural Network (GNN)?

- A Boosted Decision Tree (BDT) has been developed. Can we do better?
  - Use of Deep Learning
- Why not a Convolutional Neural Network (used for image analysis)?
  - One would need to stack images to have the time information of an event (instead of one small graph for a GNN)
  - Small number of hits for the neutron capture on H (a GNN will not be confused with useless information and therefore processed faster)

    ⇒ Smaller dataset and faster processes
  - No direct relation between hits (one can add more complex information on graphs) ⇒ More flexible inputs

Low energy

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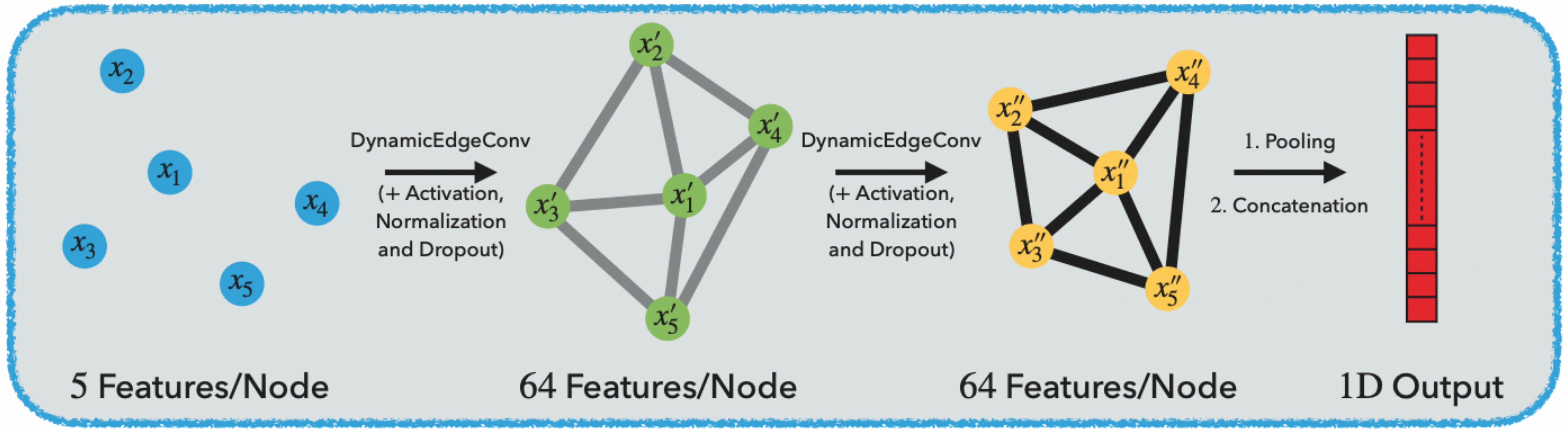
Architecture example

- 2 layers of DynamicEdgeConv [*1801.07829, Wang et al., 2019*]:
- Connects closest (euclidian distance) nodes in feature space by edges
- Edge features: Information about x_i (node feature i) and $x_j - x_i$ (relative difference to nearest neighbours)



Convolutional Part

Low energy

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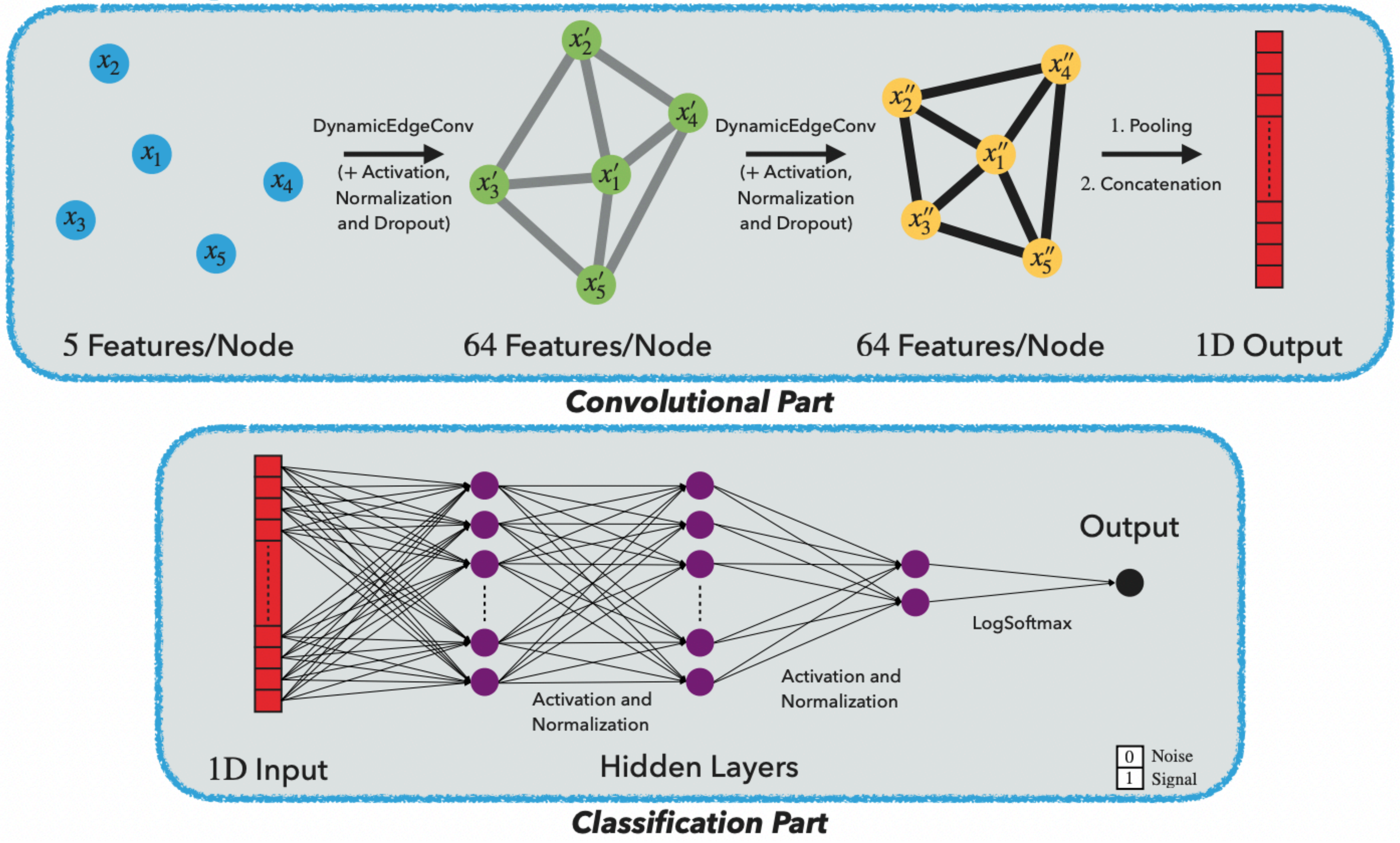
Architecture 6

Architecture example



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My work

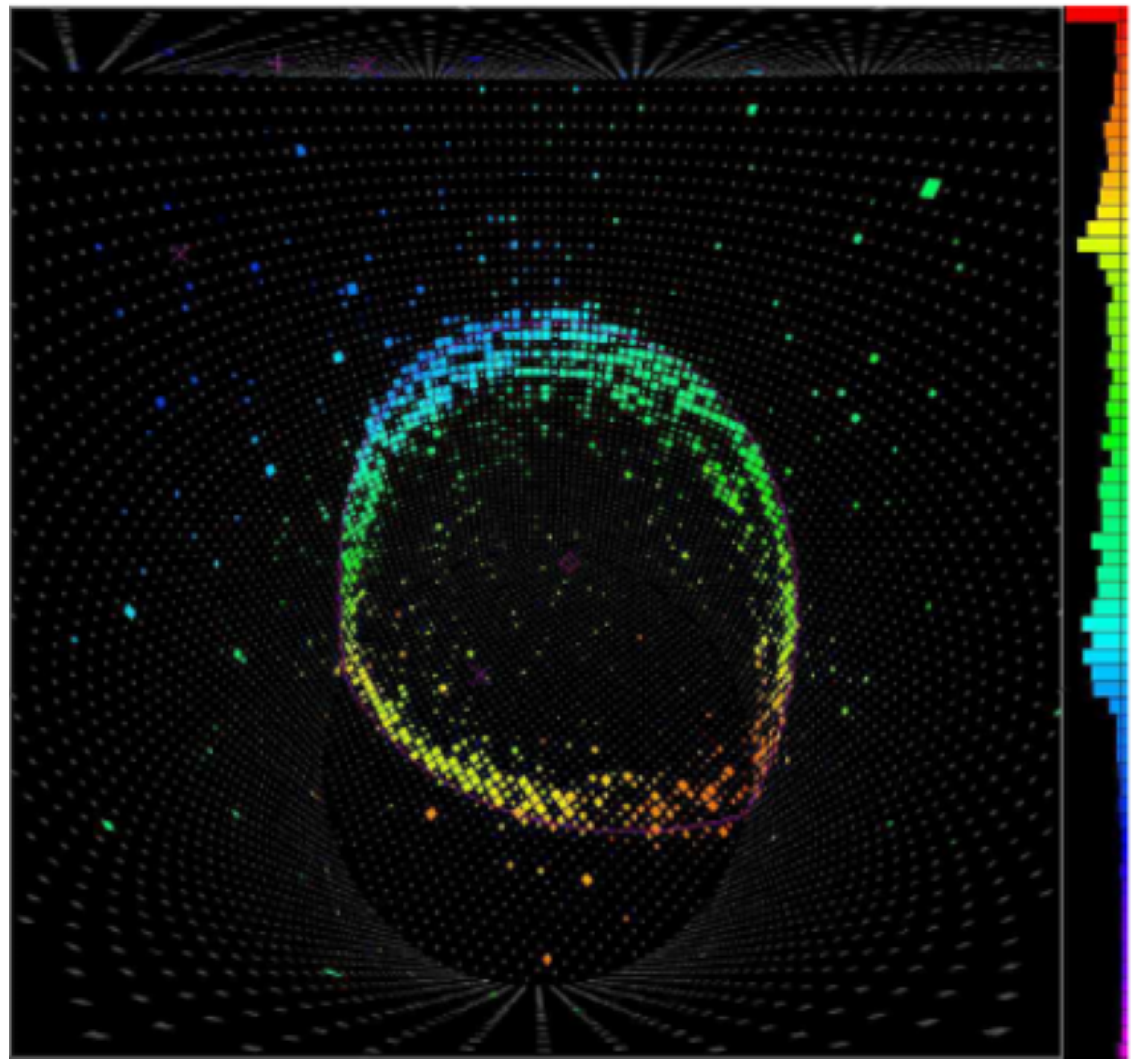
A. Key Challenges in PID

B. Adapting BDT Algorithm for High Energy Neutrinos

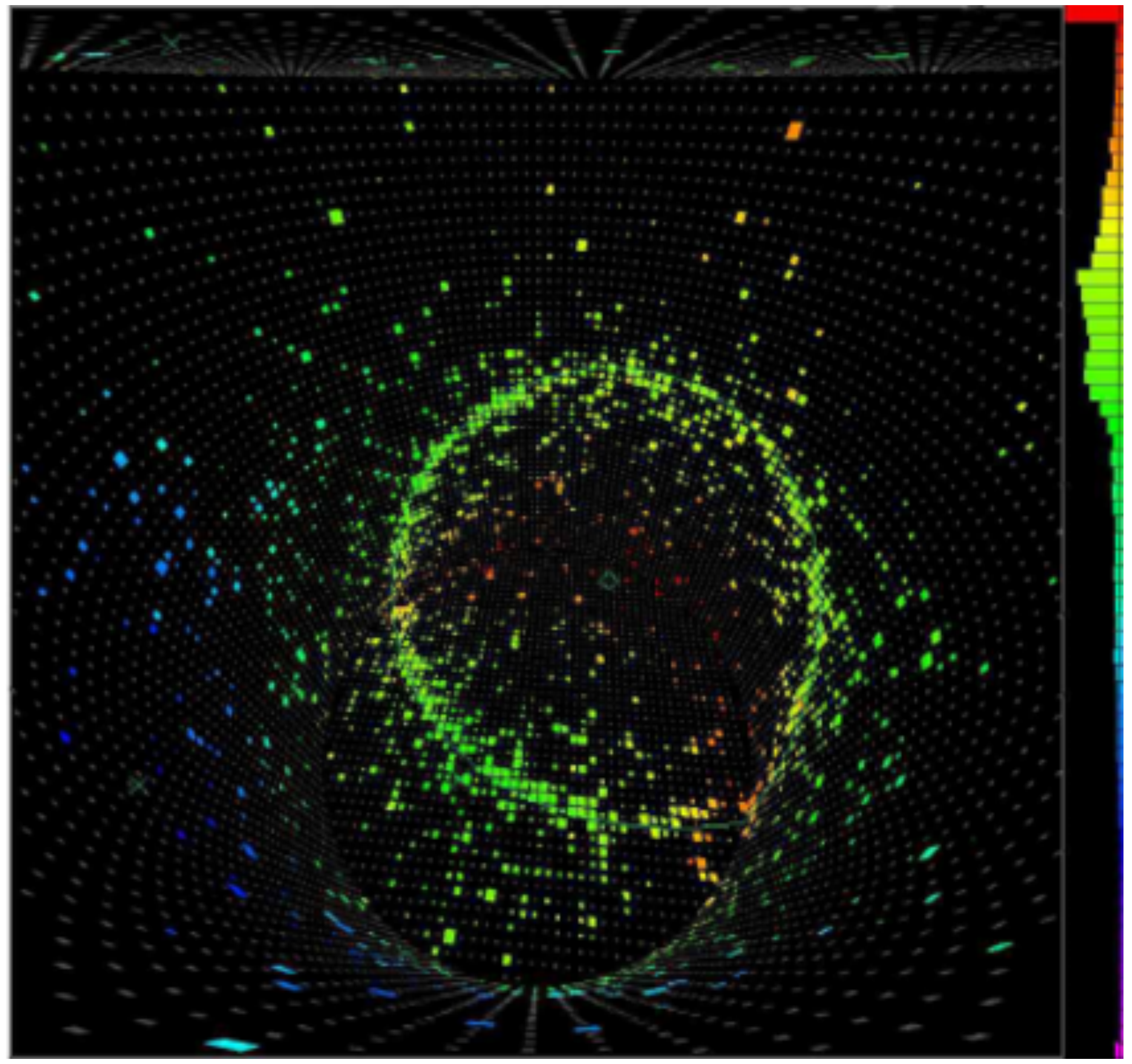
C. Adapting GNN Algorithm for High Energy Neutrinos

Identification of particles in levels of difficulties

- e/mu particle identification
- e/gamma particle identification
- e/pi0 particle identification
- mu/pi+ particle identification
- Multiple ring fit



Muon (Sharp)



Electron (Blurry)

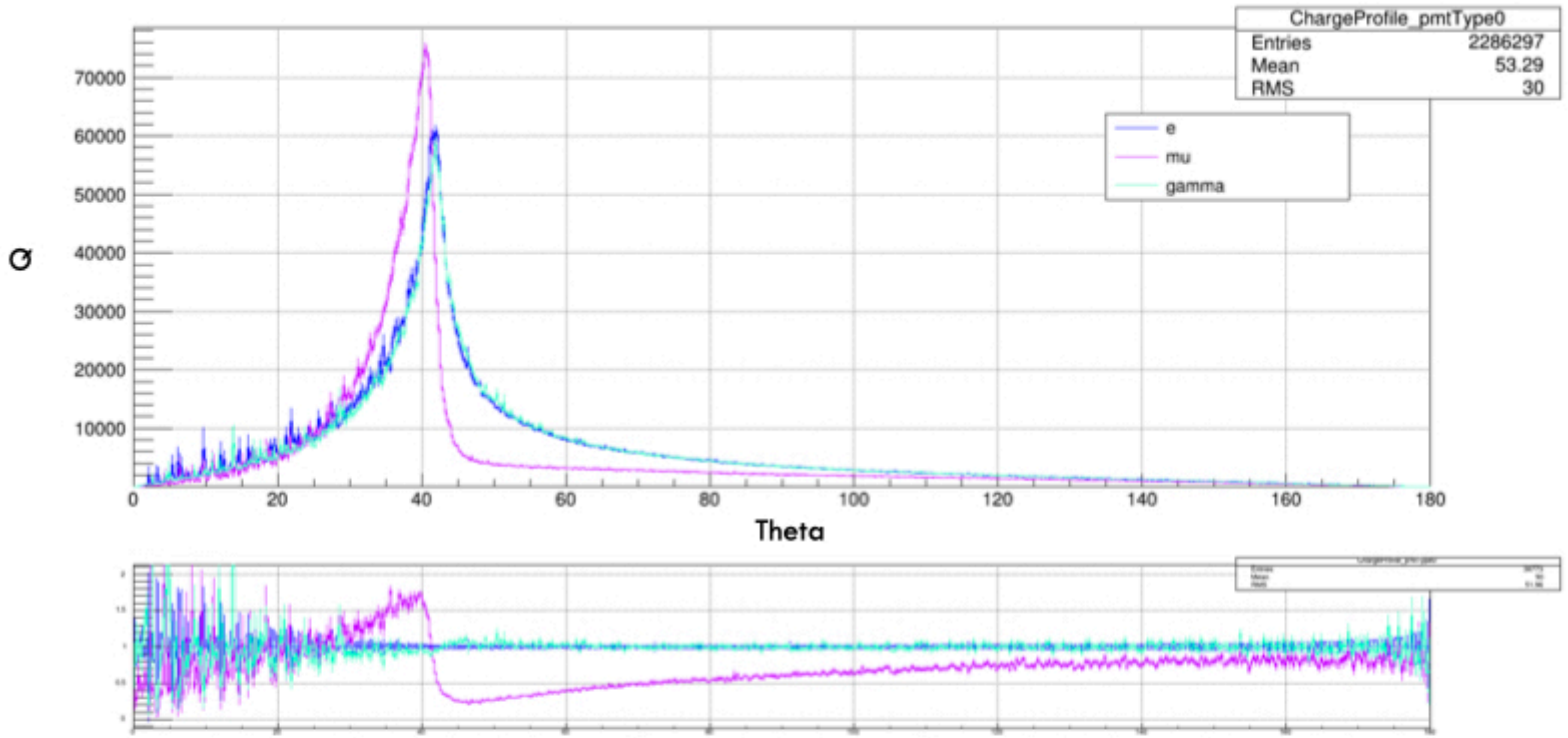
Distribution of Discriminating Variables

I. DISTRIBUTION OF DISCRIMINANT VARIABLES

TO SEE IF THERE ARE ANY RELEVANT TH1D VARIABLES

Distribution of Discriminating Variables

Charge Profile



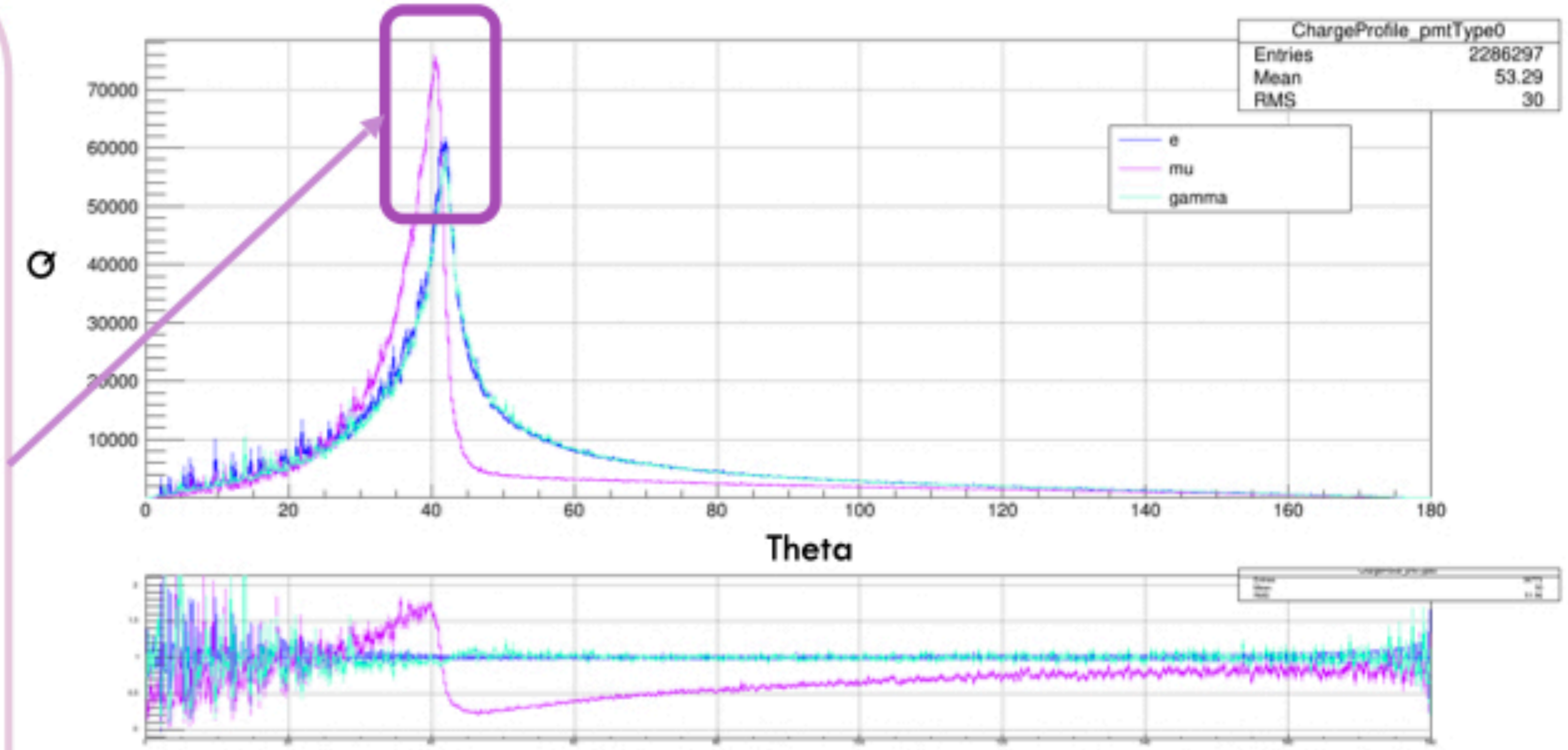
Distribution of Discriminating Variables

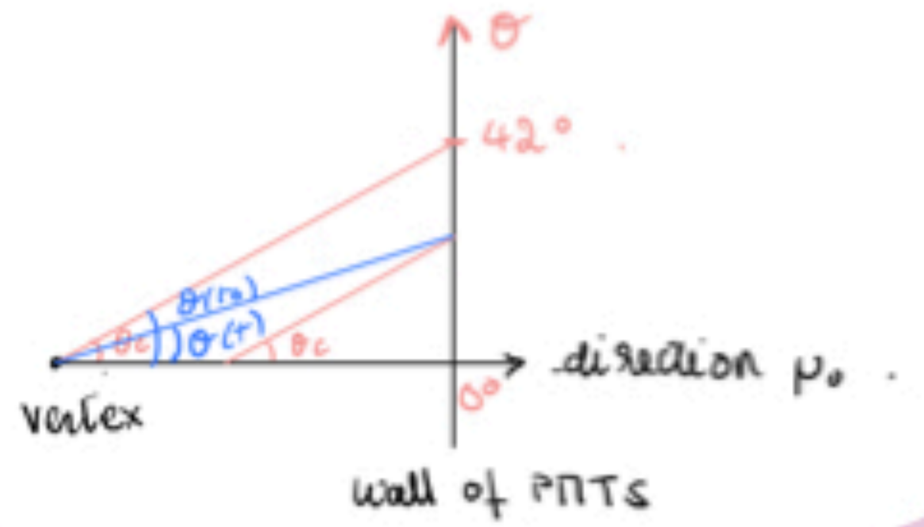
Charge Profile

Muon

<u>Explication pour le mu :</u>

- Broadening within the ring (see diagram) Hence, the peak shift is not exactly at 42°
- And thus, as the standard deviation is lower (compared to electron and gamma which are also broadened externally), the maximum value is higher.
- Charge per unit angle is higher for muons, dominating over the total charge since they are less scattered.





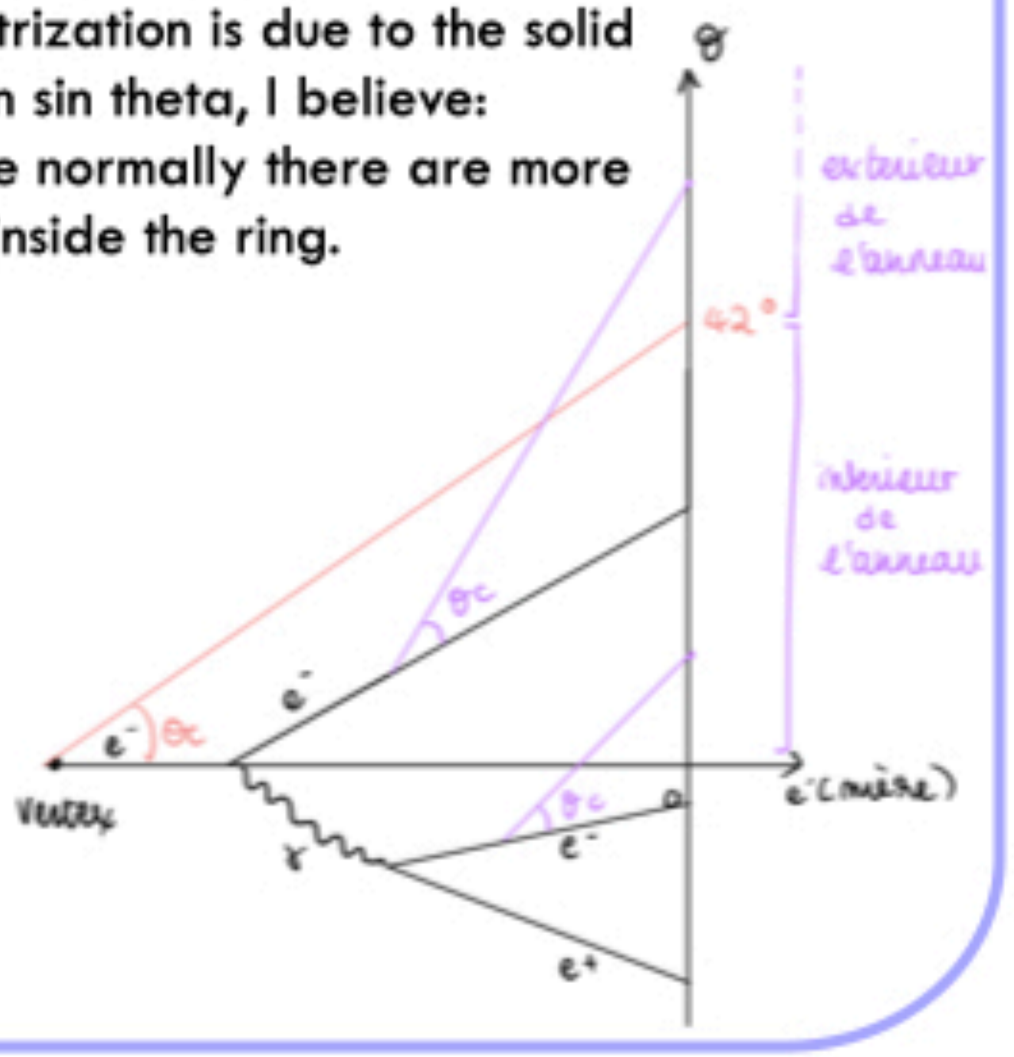
Distribution of Discriminating Variables

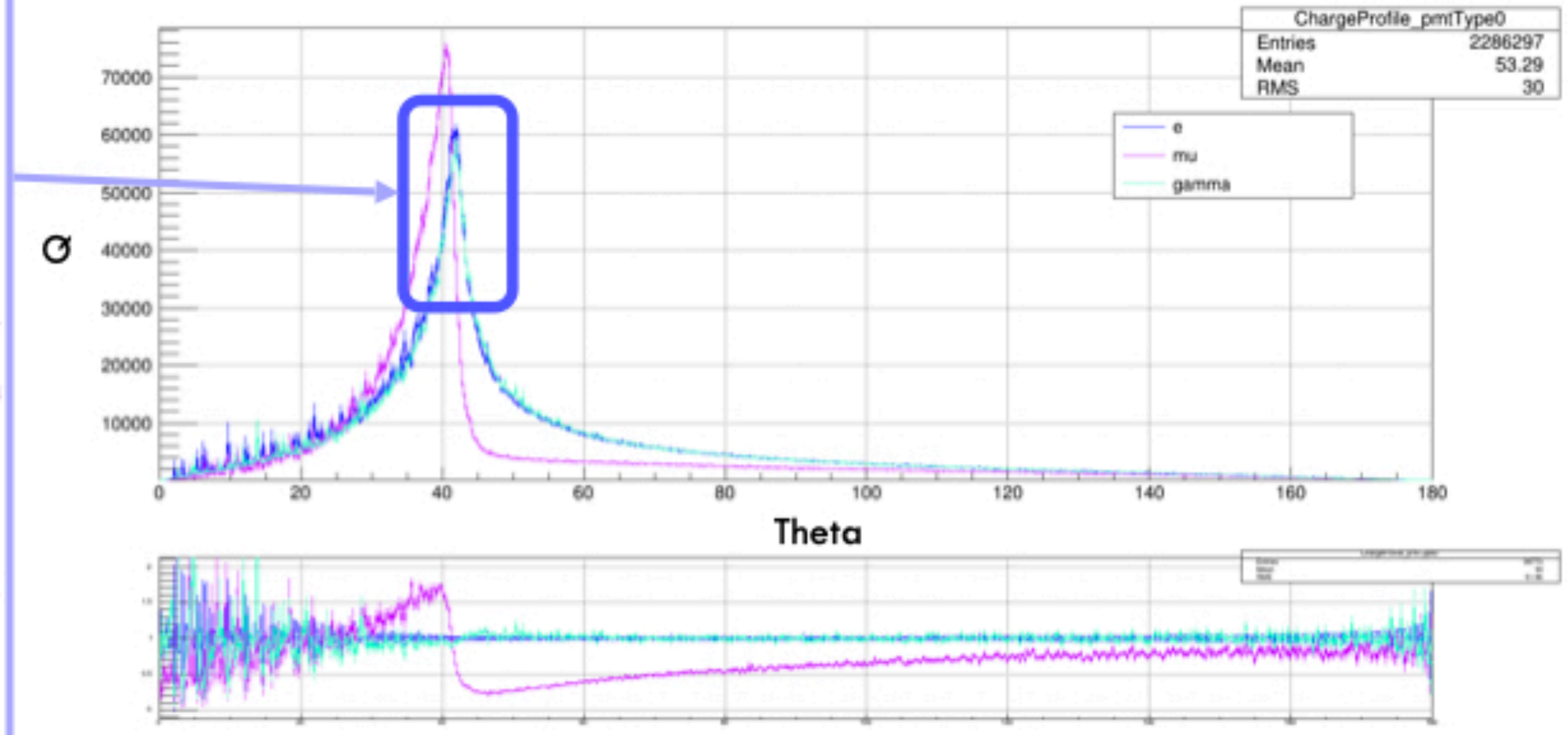
Charge Profile

Electron

<u>Explication pour l'électron :</u>

- A similar phenomenon as for muon, but with an additional factor:
- The electromagnetic cascade.
- Distribution broadened both inside and outside the ring
- Symmetrization is due to the solid angle in sin theta, I believe: because normally there are more events inside the ring.





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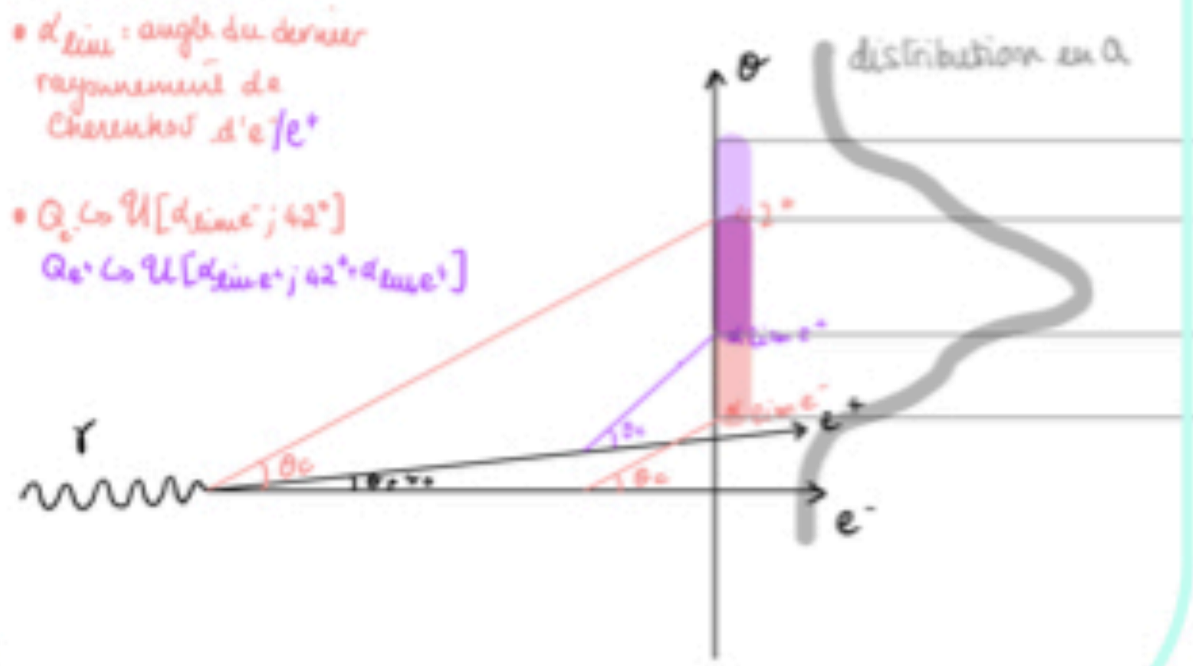
Distribution of Discriminating Variables

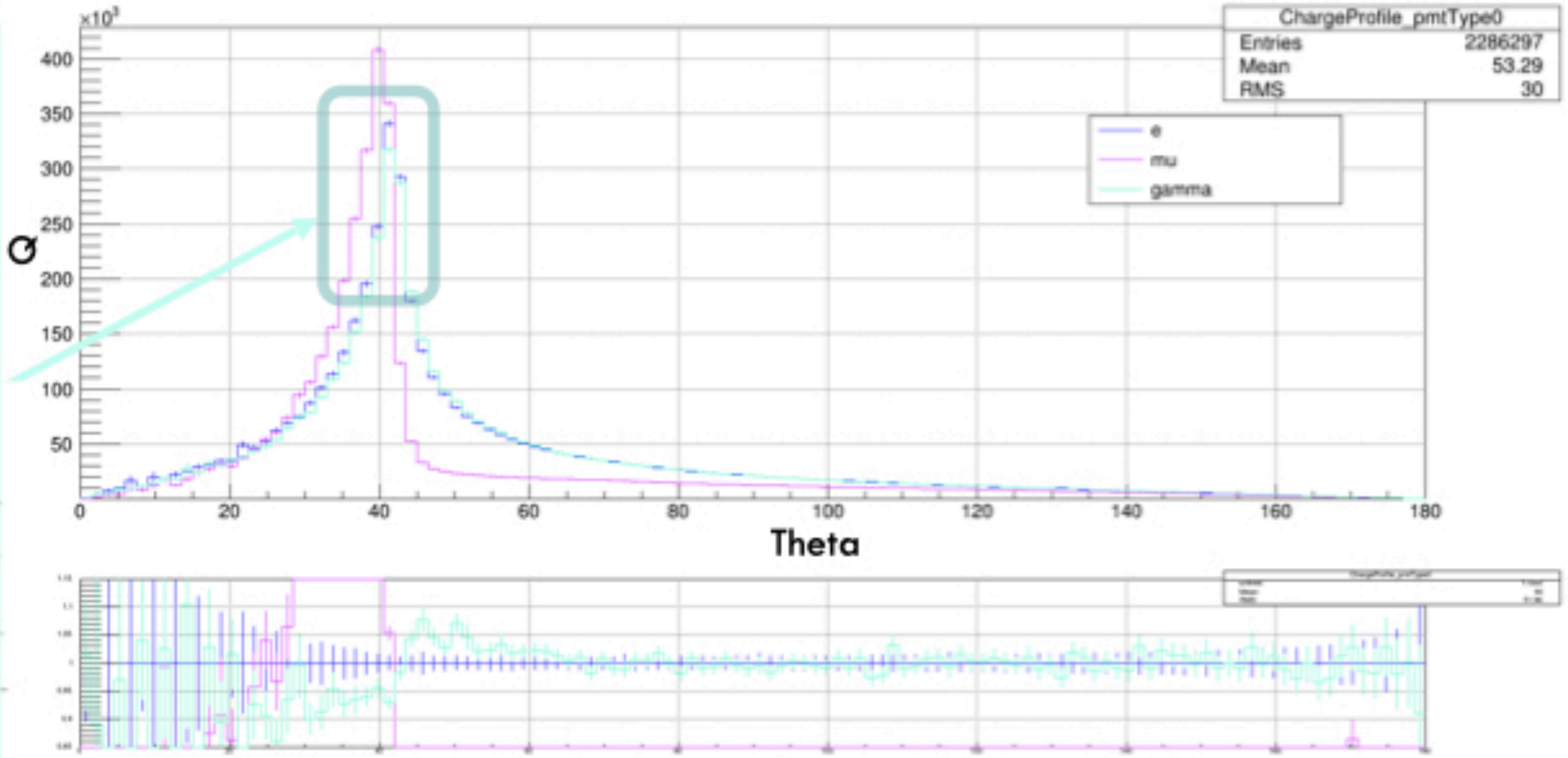
Charge Profile

Gamma

<u>Explication pour gamma :</u>

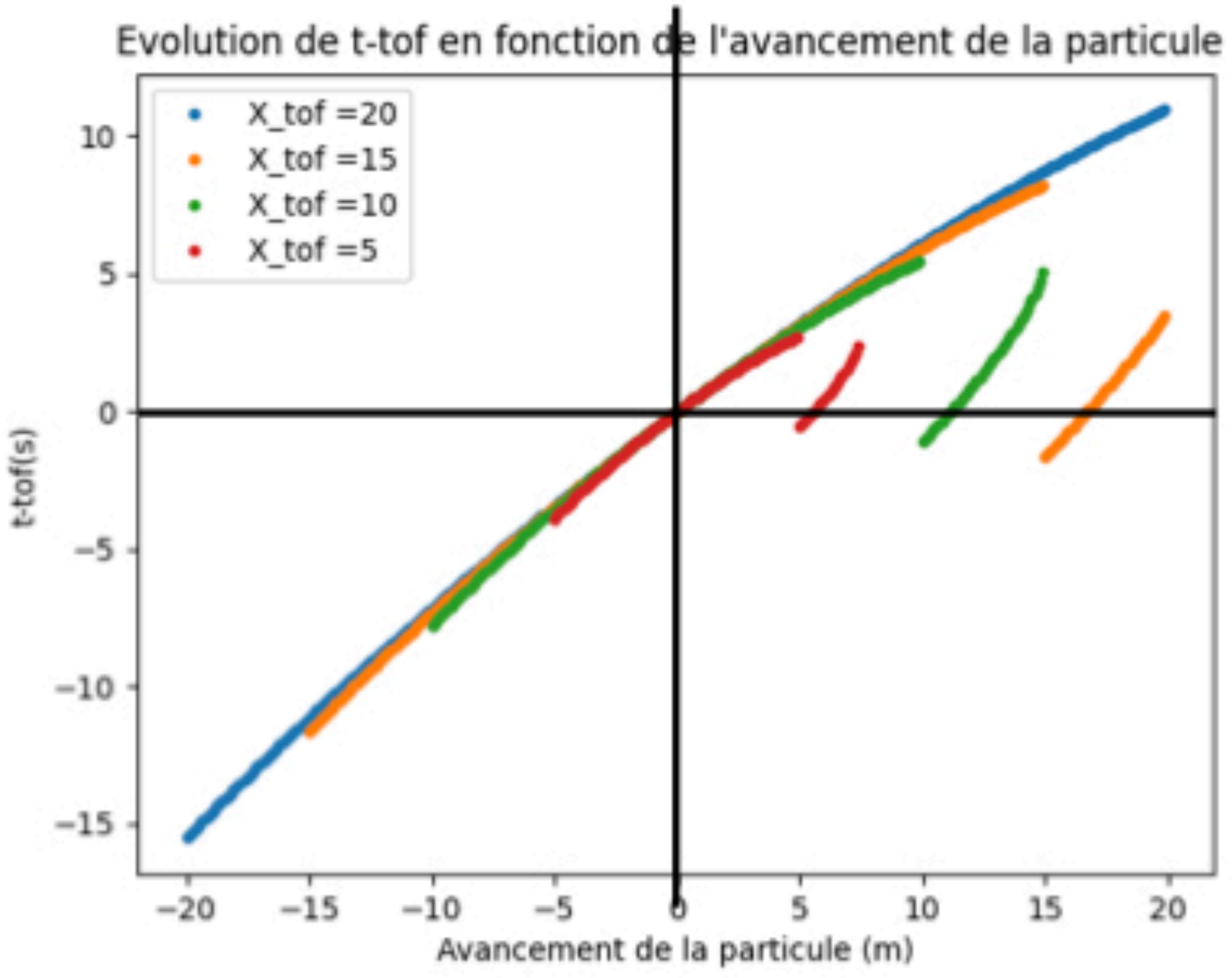
- (As for electrons): Compton effect and electromagnetic cascade also need to be taken into account.
- The dominant process at high energy: pair production of positron and electron
- Impact on the width of the distribution around the peak (but low impact)





Distribution of Discriminating Variables

Explanations t-TOF



Calculation of t-tof as a function of particle progress x:

Théorème d'Al Kashi:

$$AC^2 = AB^2 + BC^2 - 2AB\times BC\cos(\pi-\theta_c)$$

D'où:

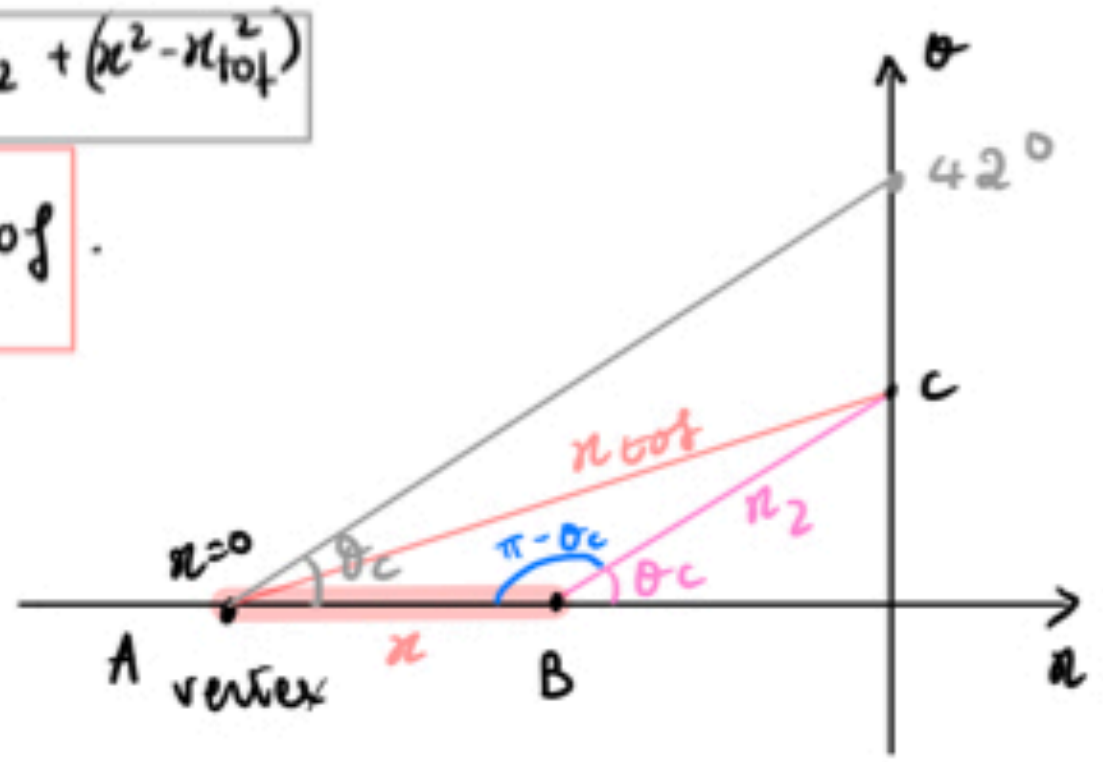
$$x_{tof}^2 = x^2 + x_2^2 - 2x\times x_2\cos(\pi-\theta_c)$$

x_2 solution de (P)

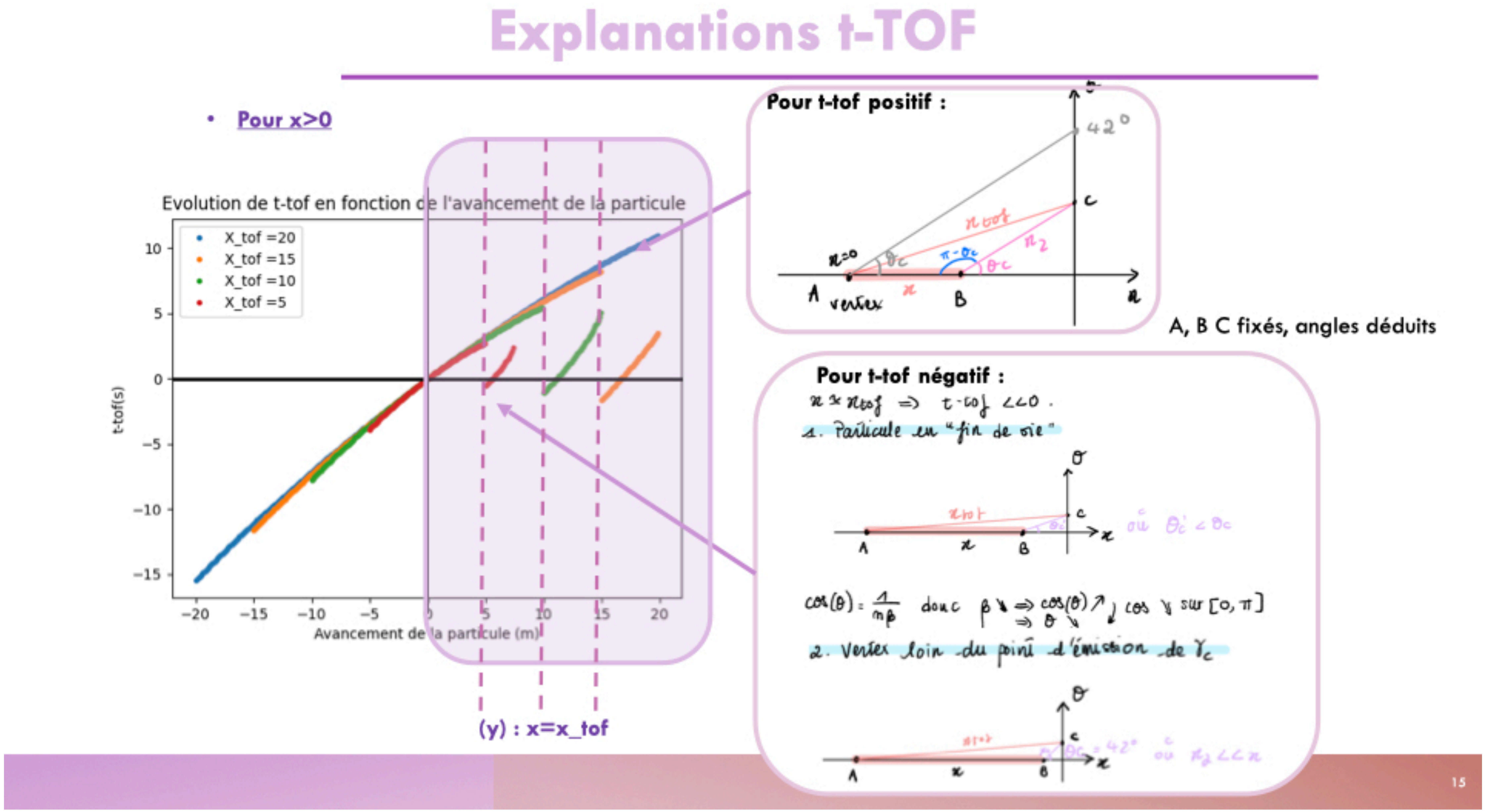
$$(P):\ x_2^2 - 2x\cos(\pi-\theta_c)\,x_2 + (x^2 - x_{tof}^2)$$

$$t\text{-}tof = \frac{x}{c} + \frac{n}{c}x_2(x) - tof$$

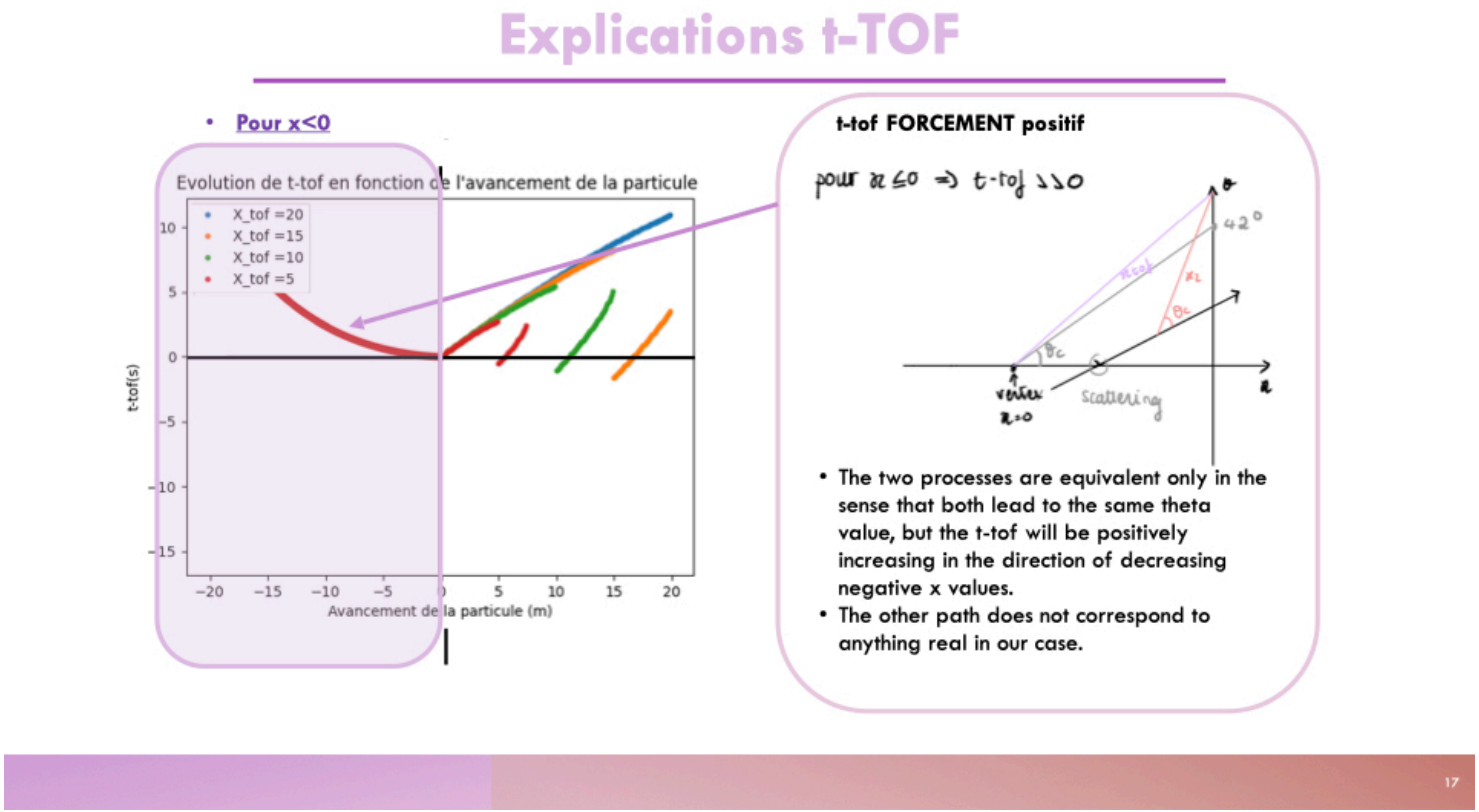
x_2 fct° de x



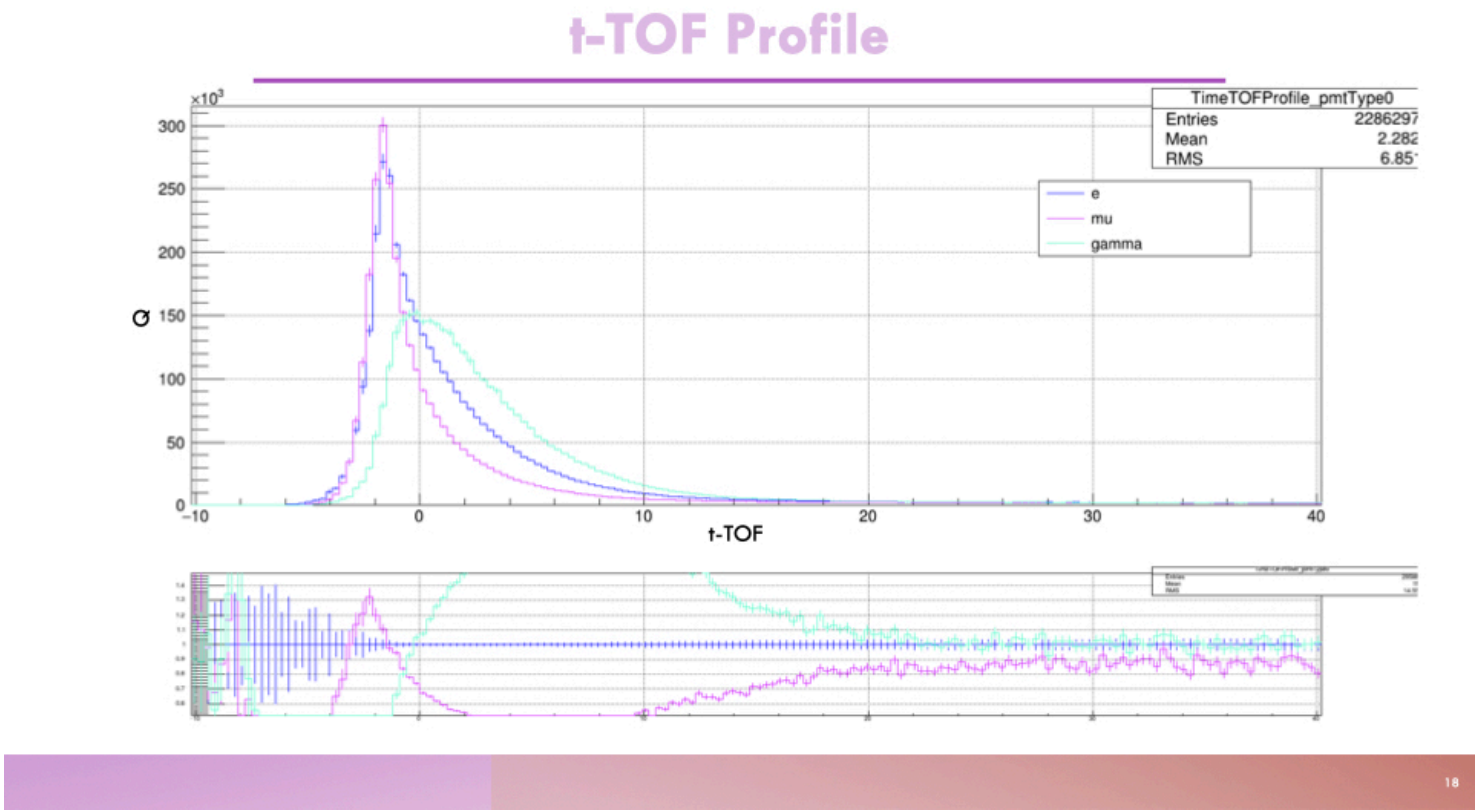
Distribution of Discriminating Variables



Distribution of Discriminating Variables



Distribution of Discriminating Variables



Distribution of Discriminating Variables

t-TOF Profile

Explication pour le mu :

Shifted peak:

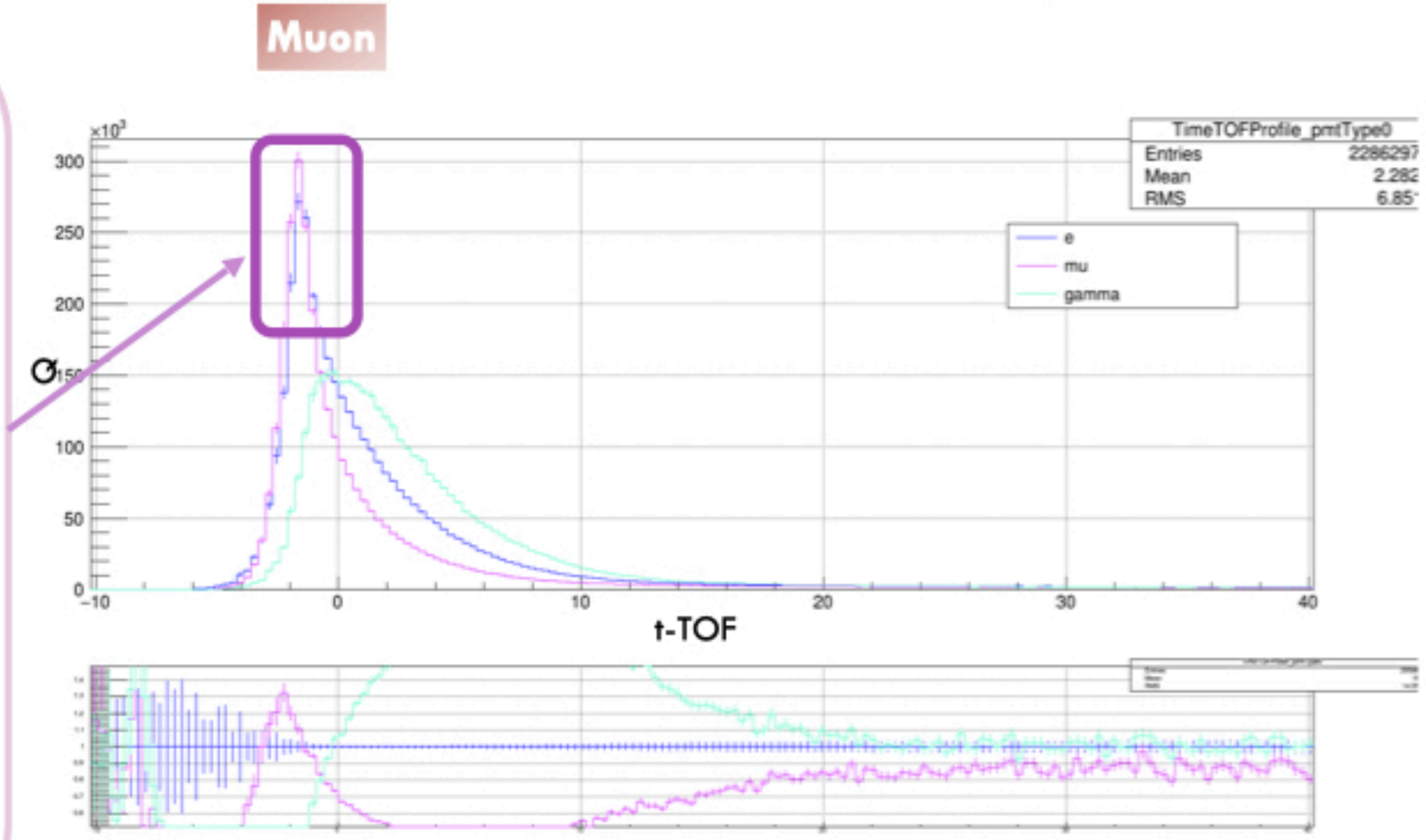
- Muon is about 2 times more energetic than each particle of the positron-electron pair, it will pass through the Cherenkov threshold later, so statistically, there is a higher chance that theta will be small, hence x = x_tof, resulting in negative t-tof. This shifts the peak.

Decreasing part:

- This corresponds to Cherenkov photons produced by the parent particle moving in its direction, after creation at the vertex.
- We see that Q decreases more quickly than for electrons. This is because muon passes through the Cherenkov threshold more rapidly than electrons.

Increasing part:

- Very steep, so few Cherenkov photons coming from charged particles whose trajectory is positively deviated.



Distribution of Discriminating Variables

t-TOF Profile

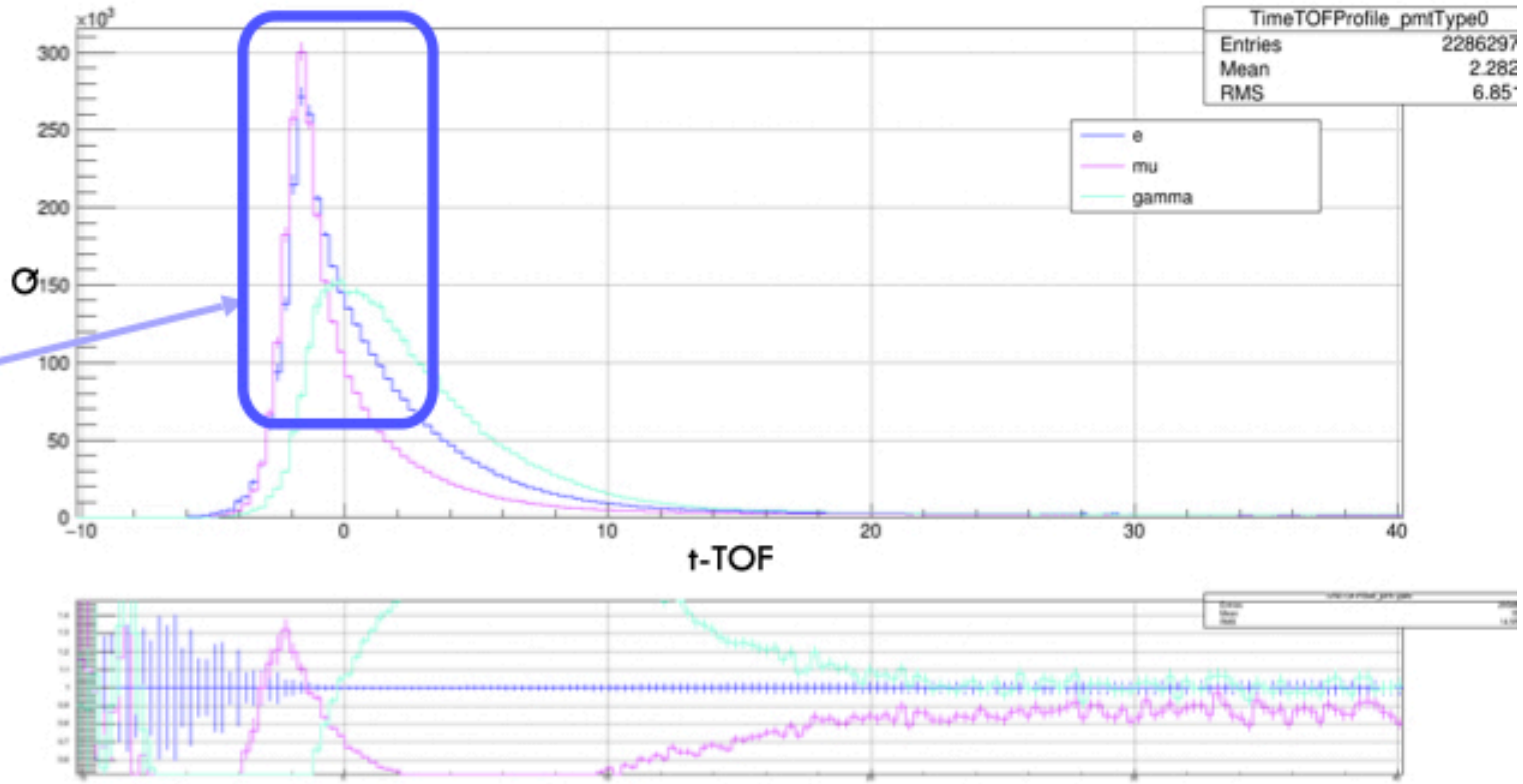
Electron

<u>Explication pour l'électron :</u>

Shifted peak:
- Same as for muon.

Decreasing part:
- This corresponds to Cherenkov photons produced by the parent particle moving in its direction, after creation at the vertex.
- We see that Q decreases more quickly than for electron. This is due to the fact that muon passes through the Cherenkov threshold more rapidly than electron.

Increasing and decreasing parts:
- Increasing part slightly less steep than for muon. Electromagnetic cascade populates both sides of the peak, so the decreasing part is also less steep.



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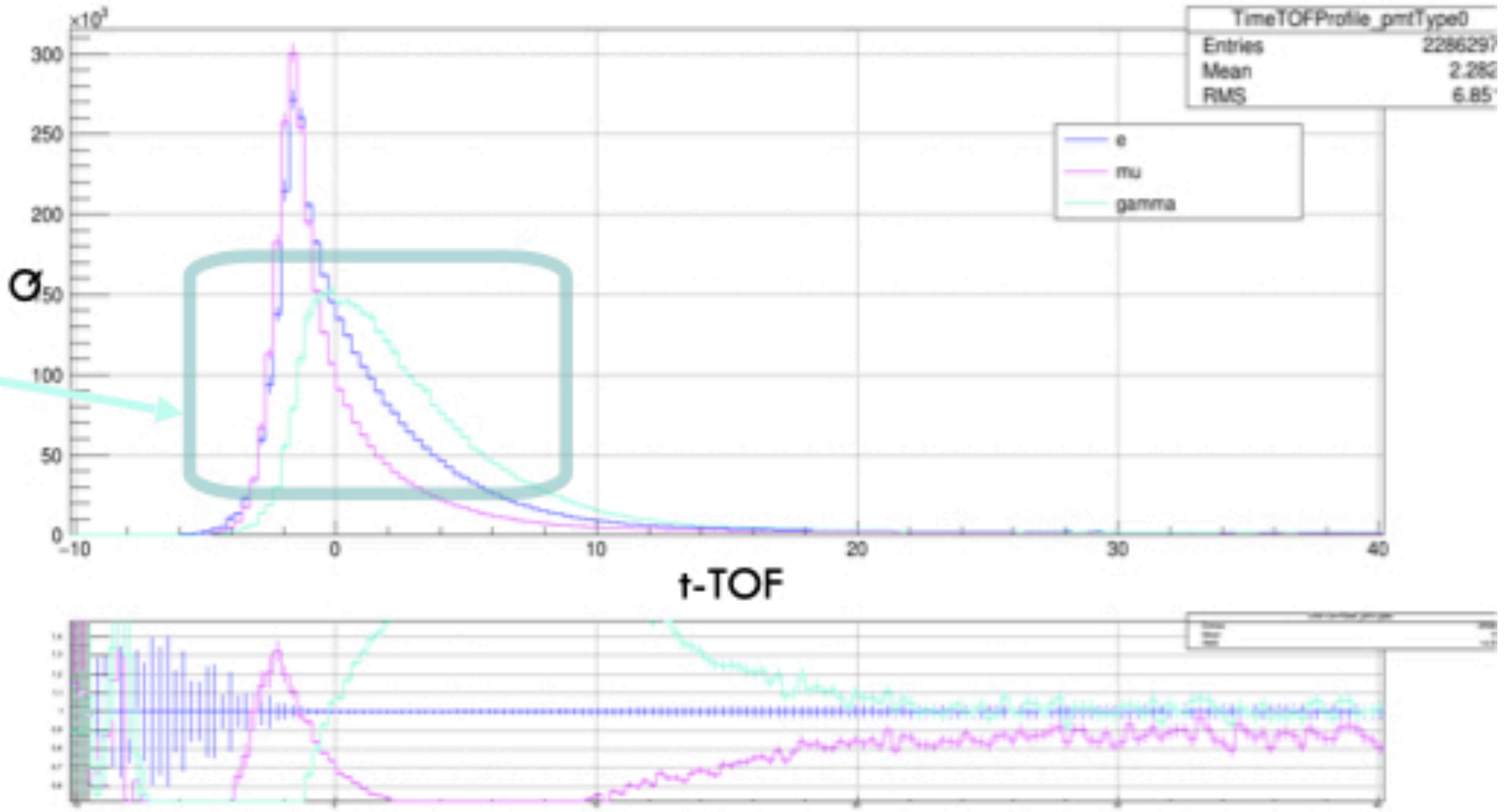
Distribution of Discriminating Variables

t-TOF Profile

Gamma

<u>Explication pour gamma :</u>

- **Overall**: distribution is much broader than for e-.
- **Maximum charge per PMT**: For the e+/e- pair, 2 times smaller than for e- and mu-. The maximum is found at t=tof. This seems consistent with the fact that when e+ and e- are very close to the vertex, the two generated photons are more likely to hit the same PMT. (The maximum charge per PMT does not allow for differentiation between e- and mu- because at the vertex there is no electromagnetic cascade effect, whereas, for the pair production, there is already a deviation in trajectory.)
- **In the increasing part**, the same as for the electron.
- **Wider distribution:** for t-tof on either side of the peak, less steep rise and fall due to electromagnetic shower effect AND ADDITIONALLY angle between e+/e- direction.
- **Conclusion**: the difference between e- and e+/e- appears more pronounced concerning the charge profile because t-TOF is a variable equivalent to a length, unlike theta, thus we can better see the energy difference of the pair production.



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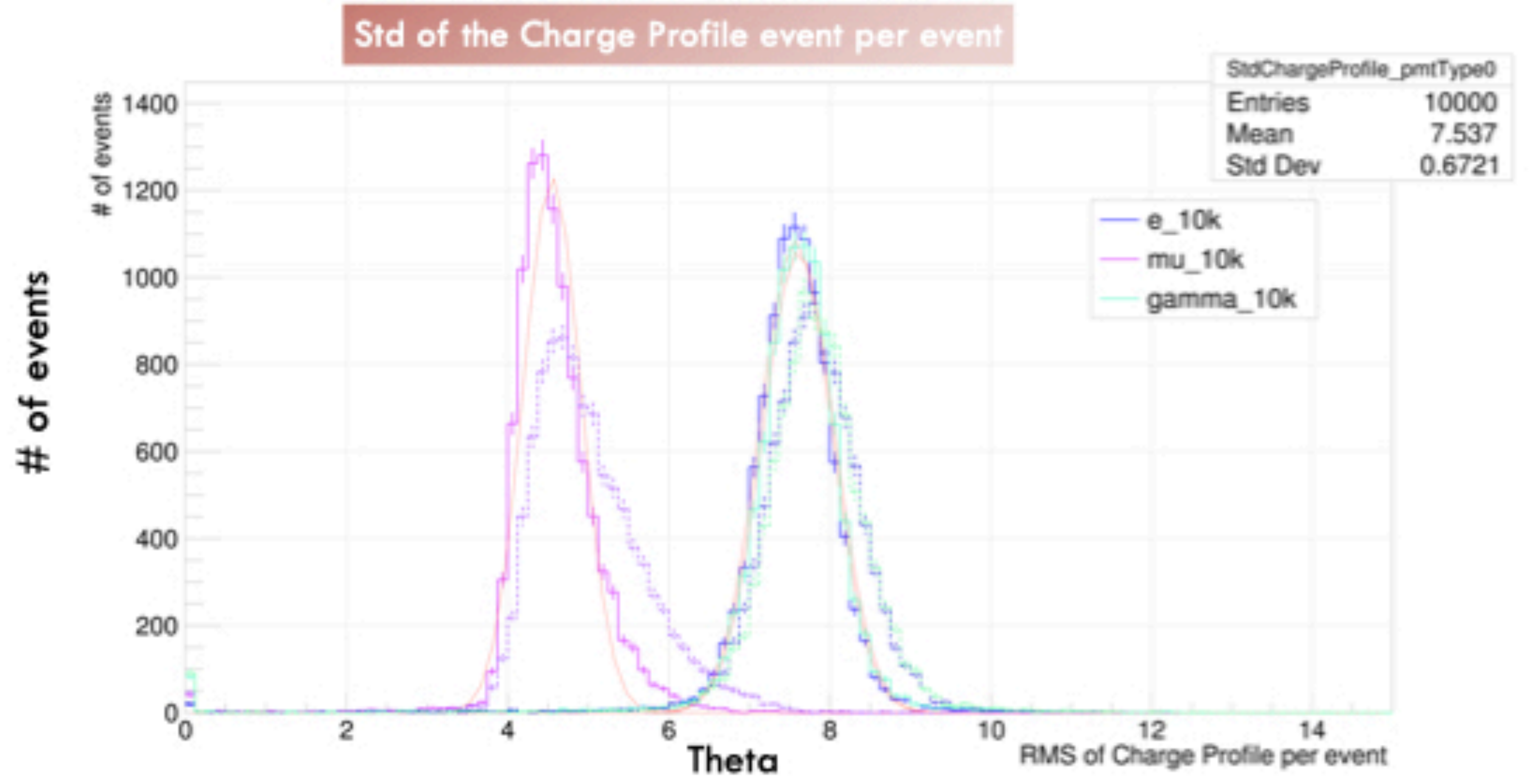
Distribution of Discriminating Variables

Reconstruction – Charge Profile



Without randomization:
- Mu is less scattered, so lower average std.
- Event by event: the std of gamma is larger than that of e because event by event gamma is more random due to pair production.
- The std of mu is generally larger because it fits Gaussian, and mu is skewed.

With random:
- Difficult to distinguish particles from each other… maybe try another fit?

	E	Mu	Gamma	Erreur
	Mean = 7.57311e+00 Sigma = 4.47620e-01 **Sig/mean = 0.05910649653**	Mean = 4.55252e+00 Sigma = 3.59515e-01 **Sig/mean = 0.07897054817** **Ecart : 33.607222228 %**	Mean = 7.61257e+00 Sigma = 4.50241e-01 **Sig/mean =0.05914441509** **Ecart : 0.06415294802 %**	Mean : 4.54 e-03, 5.23 e-03, 4.61 e-03 Sigma : 3.84 e-03, 3.55 e-03, 3.95 e-03
Rdm	Mean = 7.80574e+00 Sigma = 5.58229e-01 **Sig/mean = 0.07151519266**	Mean = 4.96763e+00 Sigma = 5.57641e-01 **Sig/mean =0.11225493847** **Ecart : 56.9665609428%**	Mean = 7.84185e+00 Sigma = 5.47913e-01 **Sig/mean =0.06987037497** **Ecart : 2.29995561617%**	Mean : 5.61 e-03, 8.67 e-03, 5.64 e-03 Sigma : 4.61 e-03, 5.82 e-03, 4.85 e-03

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Distribution of Discriminating Variables

Distribution of Discriminating Variables

II. STUDY OF THE CORRELATION BETWEEN DISCRIMINANT VARIABLES

C'EST DES TH2D ICI DU COUP

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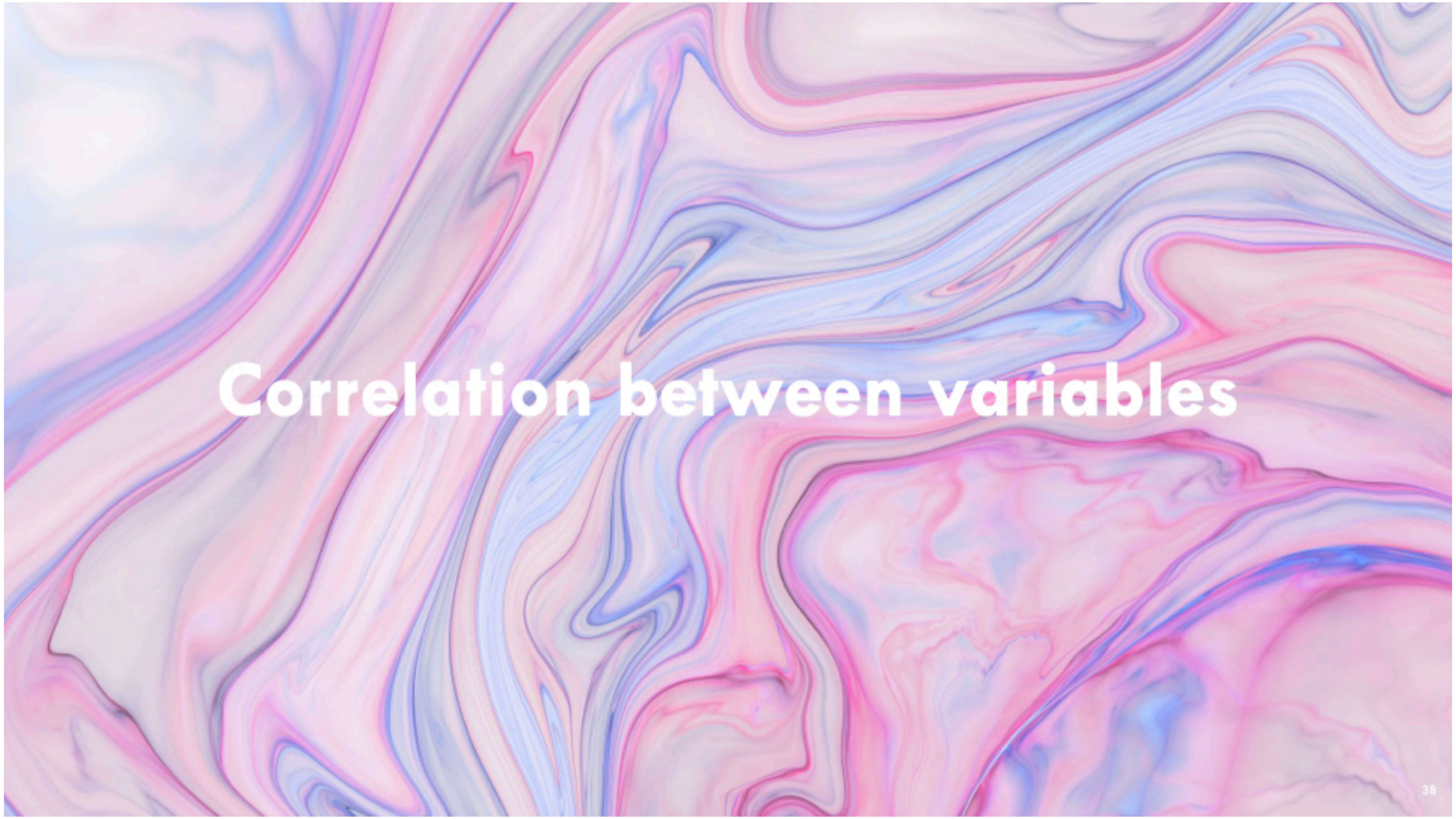
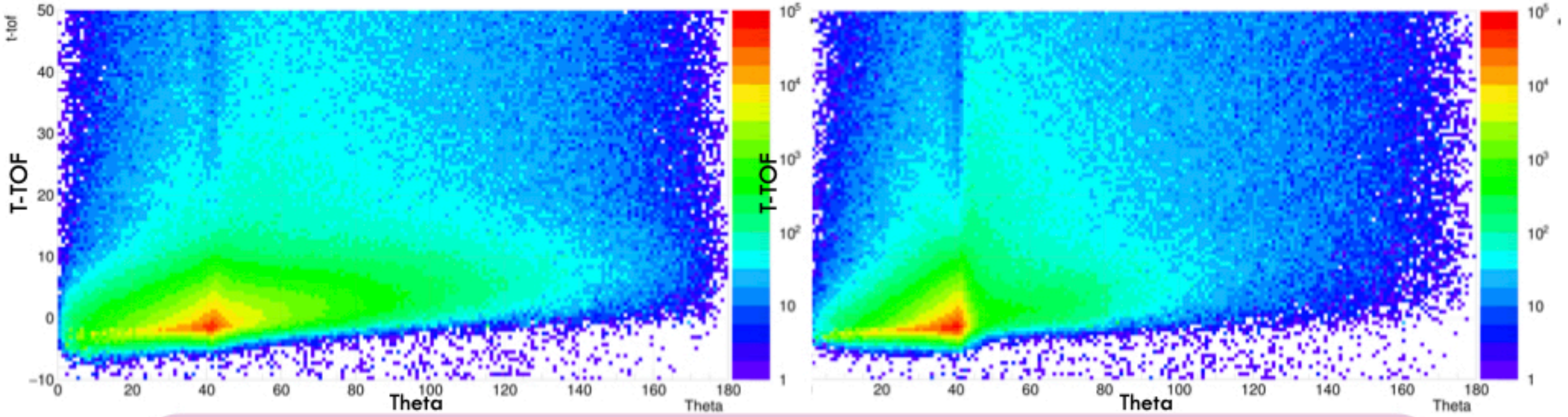
Distribution of Discriminating Variables



Distribution of Discriminating Variables

Q(Theta, t-tof)

Electron | Muon



- **Mu**

More concentrated near 42°, few events at small t-tof after 42°. No scattering effect or electromagnetic shower, resulting in a very clear break.
Charge peak at t-tof<0, but near 40°.

- **Electron**

The charge is more scattered at a given t-tof, due to electromagnetic cascade. The peak at t-tof<0, near 42°.
Distributed more or less uniformly around 42°, with a preferential direction.

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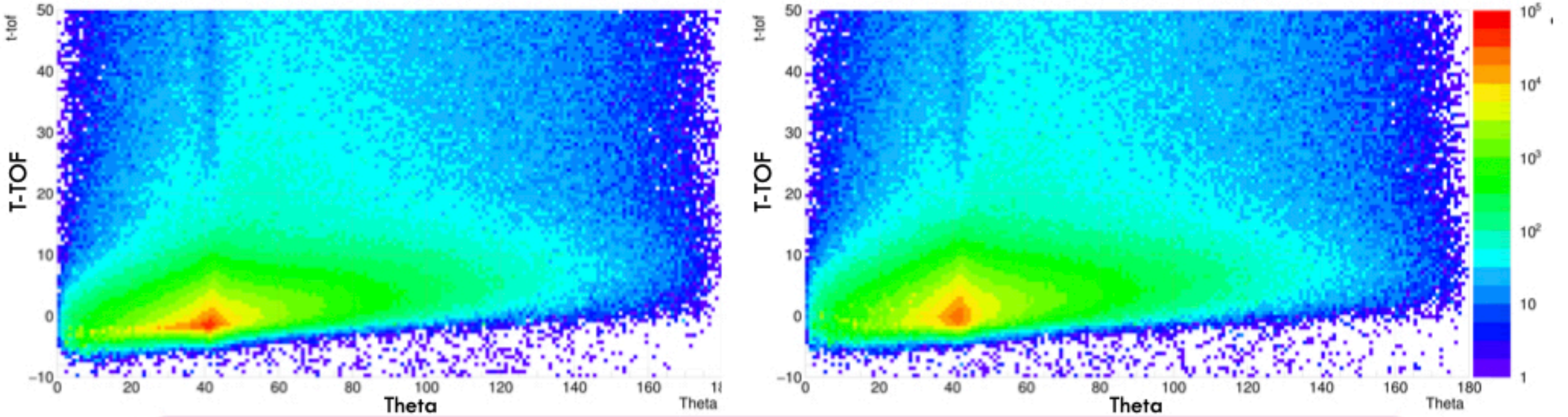
Distribution of Discriminating Variables

Q(Theta, t-tof)

Electron **Gamma**



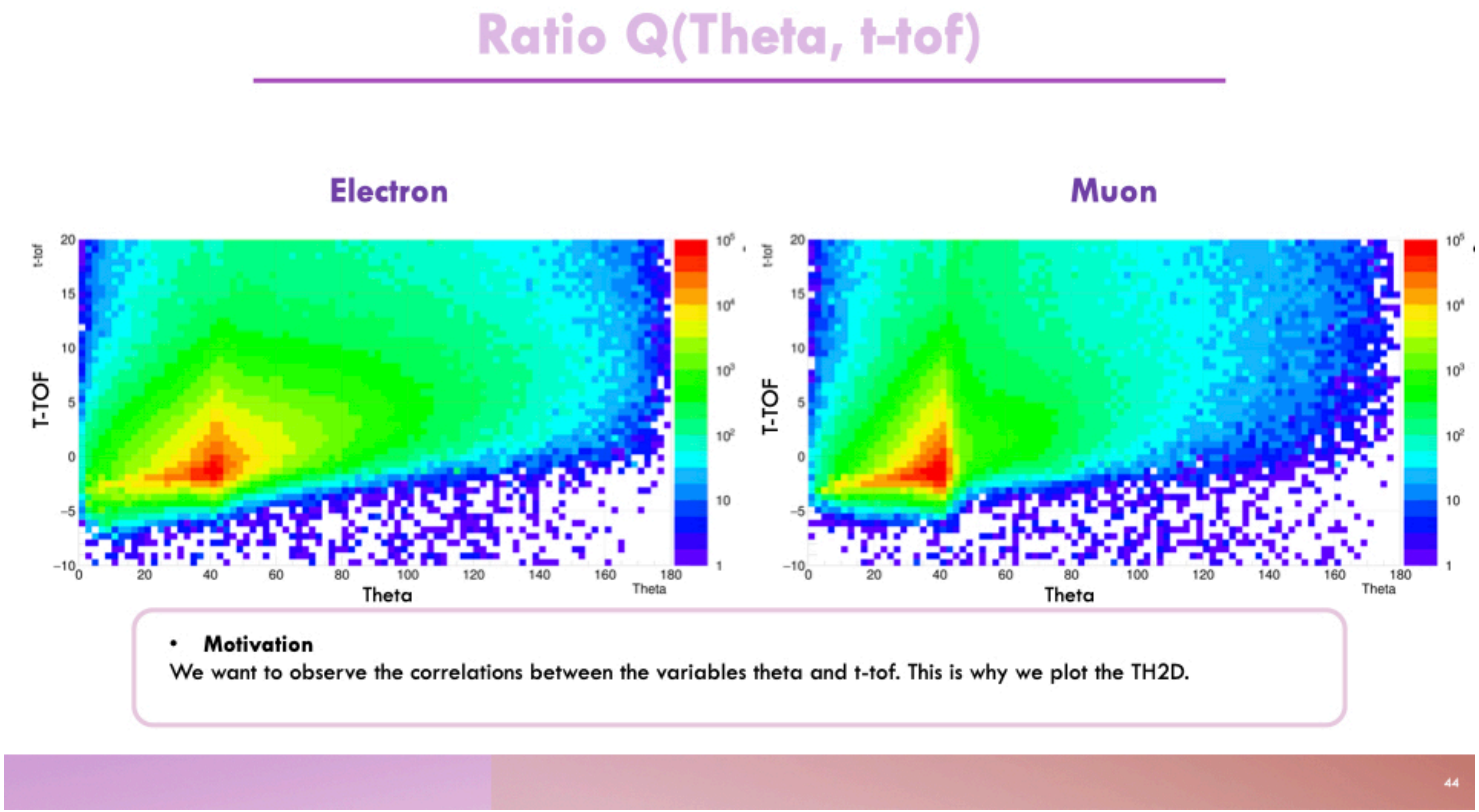
- **Gamma**

Significantly weaker charge. At t-tof=0, highly scattered, and has no real preferential direction.

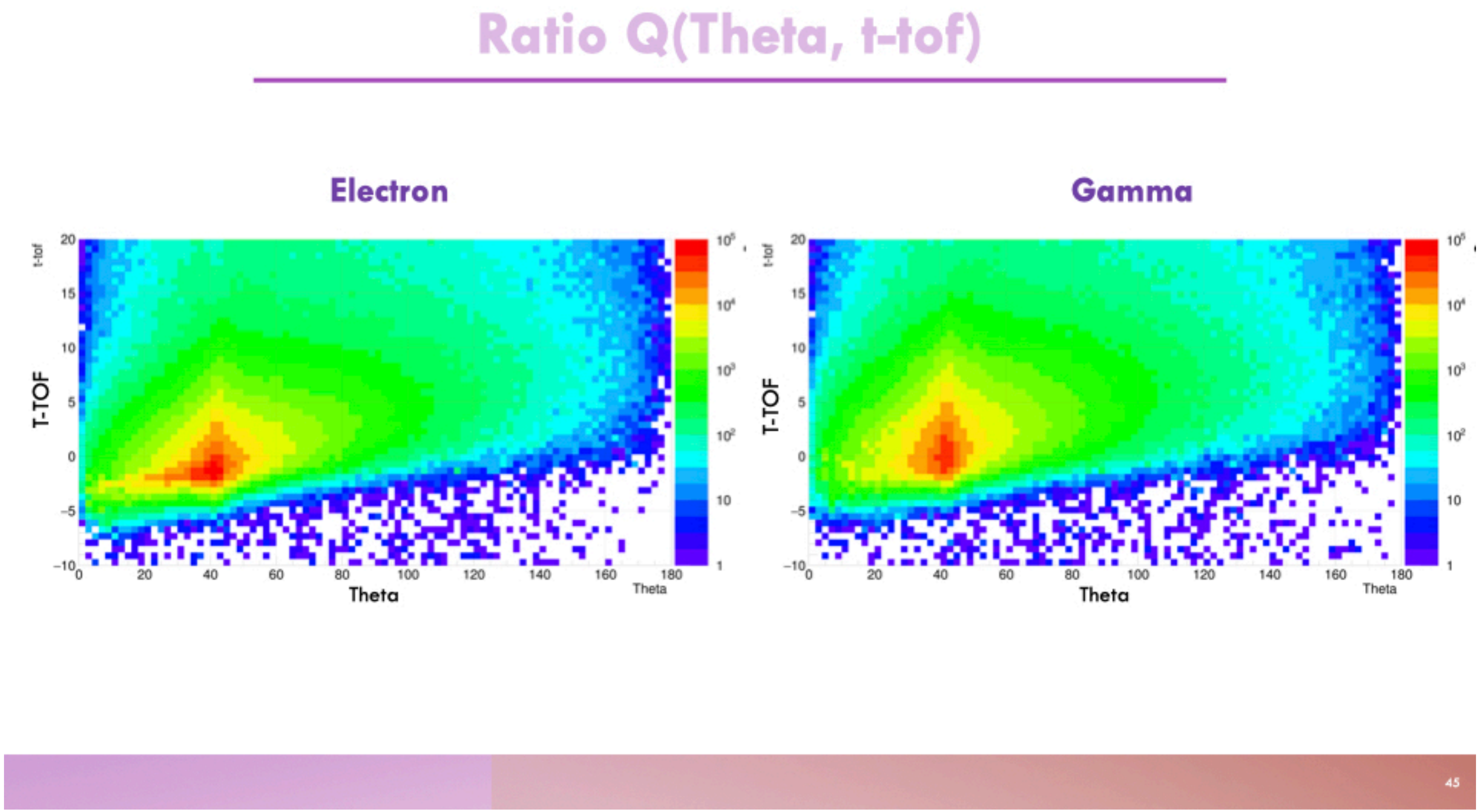
- **Electron**

The charge is more scattered at a given t-tof, due to electromagnetic cascade. The peak at t-tof<0, near 42°. Distributed more or less uniformly around 42°, with a preferential direction.

Distribution of Discriminating Variables

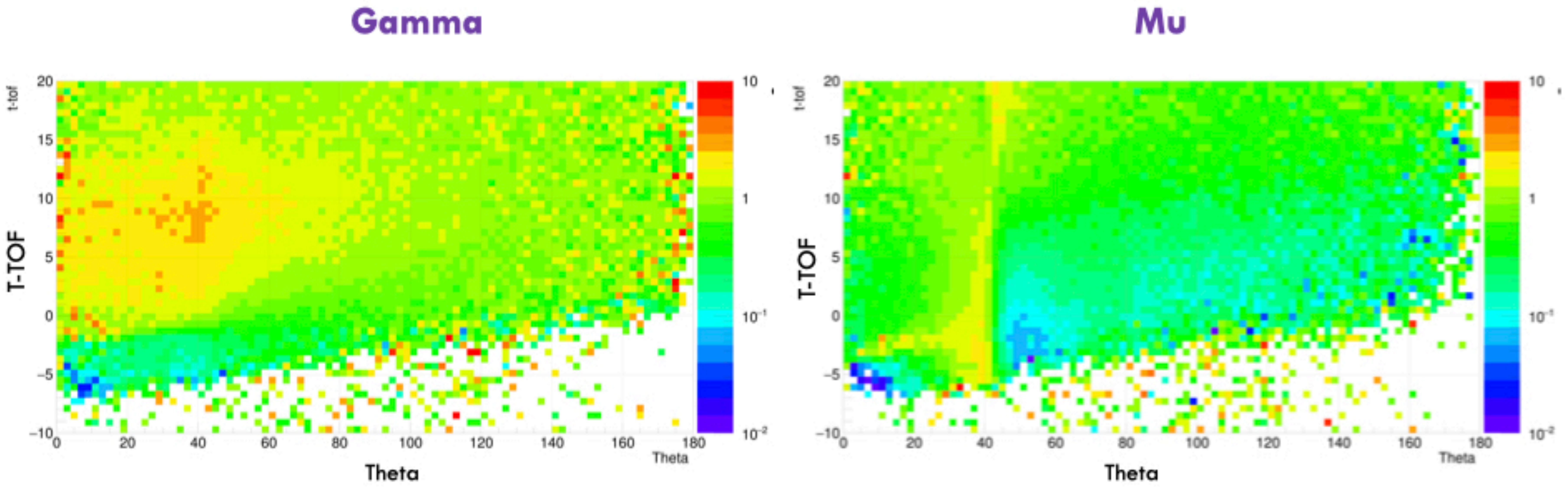


Distribution of Discriminating Variables



Distribution of Discriminating Variables

Ratio Q(Theta, t-tof)



Distribution of Discriminating Variables

III. STUDY OF THE IMPACT OF DETECTOR EFFECTS

RECONSTRUCTION EFFECT, WATER ABSORPTION EFFECT, AND RAYLEIGH SCATTERING EFFECT

Distribution of Discriminating Variables

Distribution of Discriminating Variables

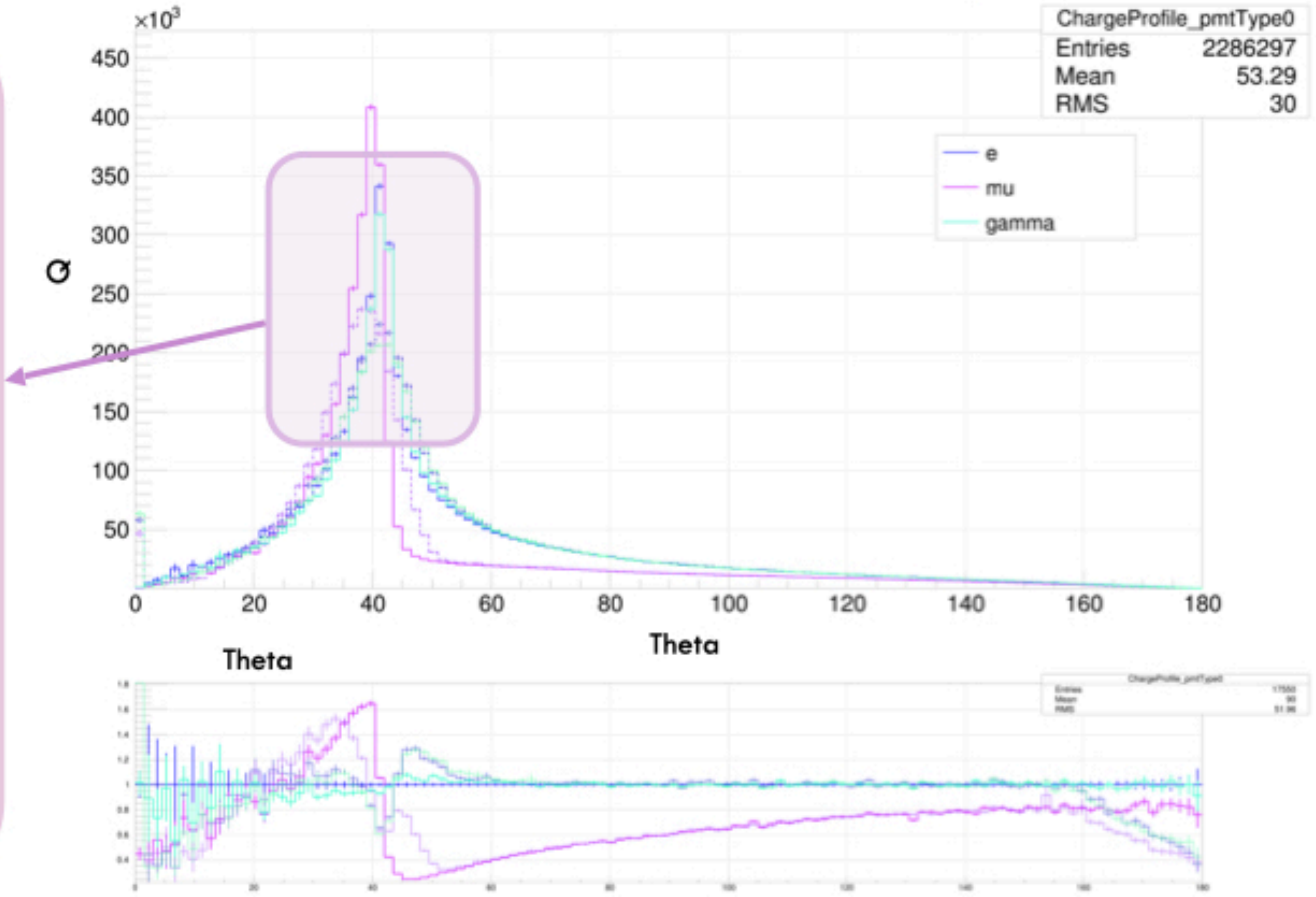
Q(theta) – Reconstruction Error

We study the **influence of the reconstruction error** on the charge profile with an error of:

- 20 cm on the reconstruction of the vertex position
- 2.5 degrees in the direction

Expected effect
We would expect the overall amplitude to be attenuated because changing the initial vertex position results in a more scattered distribution, thus decreased amplitude, increased standard deviation, and unchanged integral.

Observation
The charge profile, which takes this error into account, has a lower amplitude, but the mean is preserved: we can still distinguish between a mu and an e. The distinction between e and gamma is more difficult to make after randomization.



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Distribution of Discriminating Variables

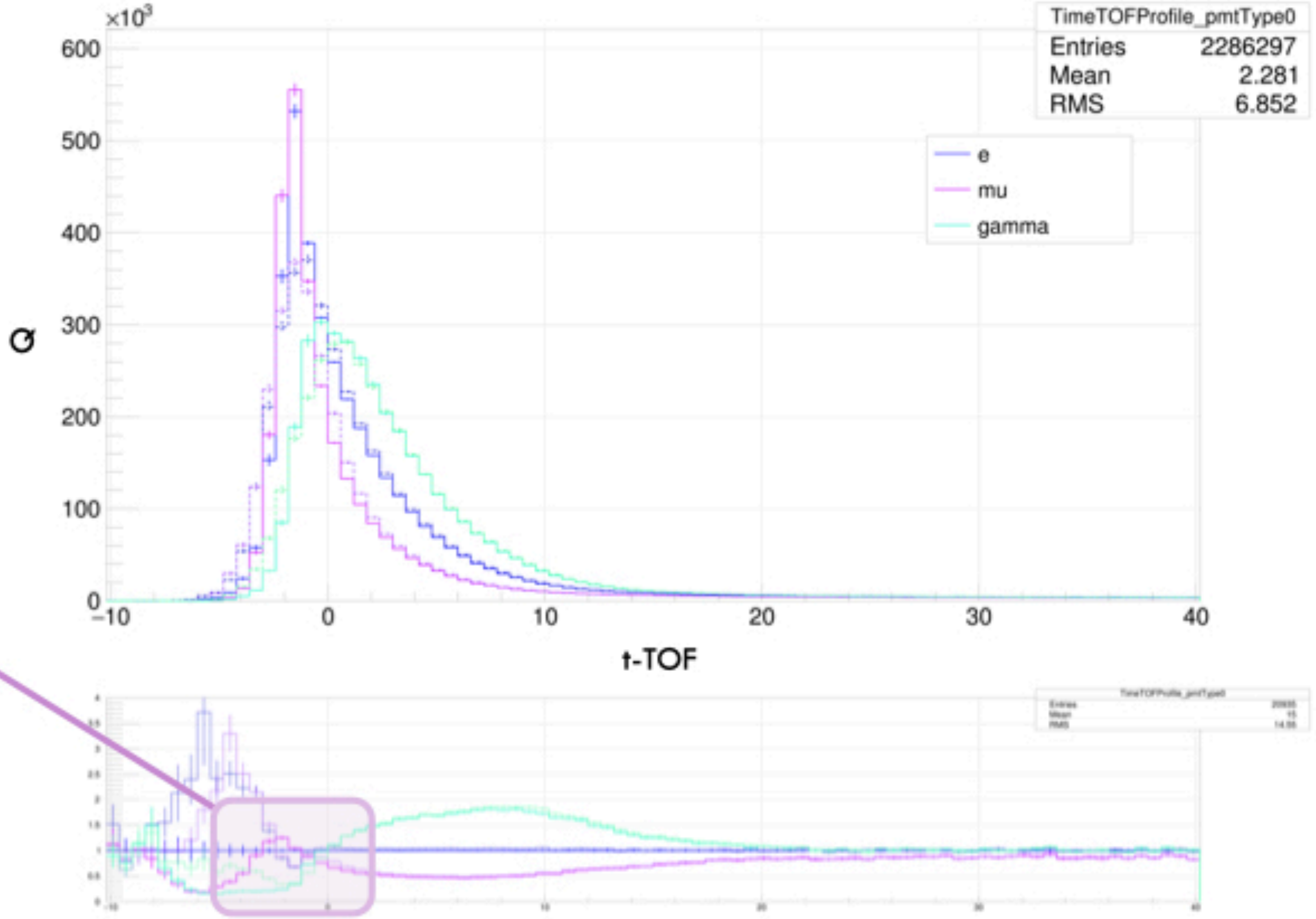
Q(TOF) – Reconstruction Error

We study the **influence of the reconstruction error** on the charge profile with an error of:

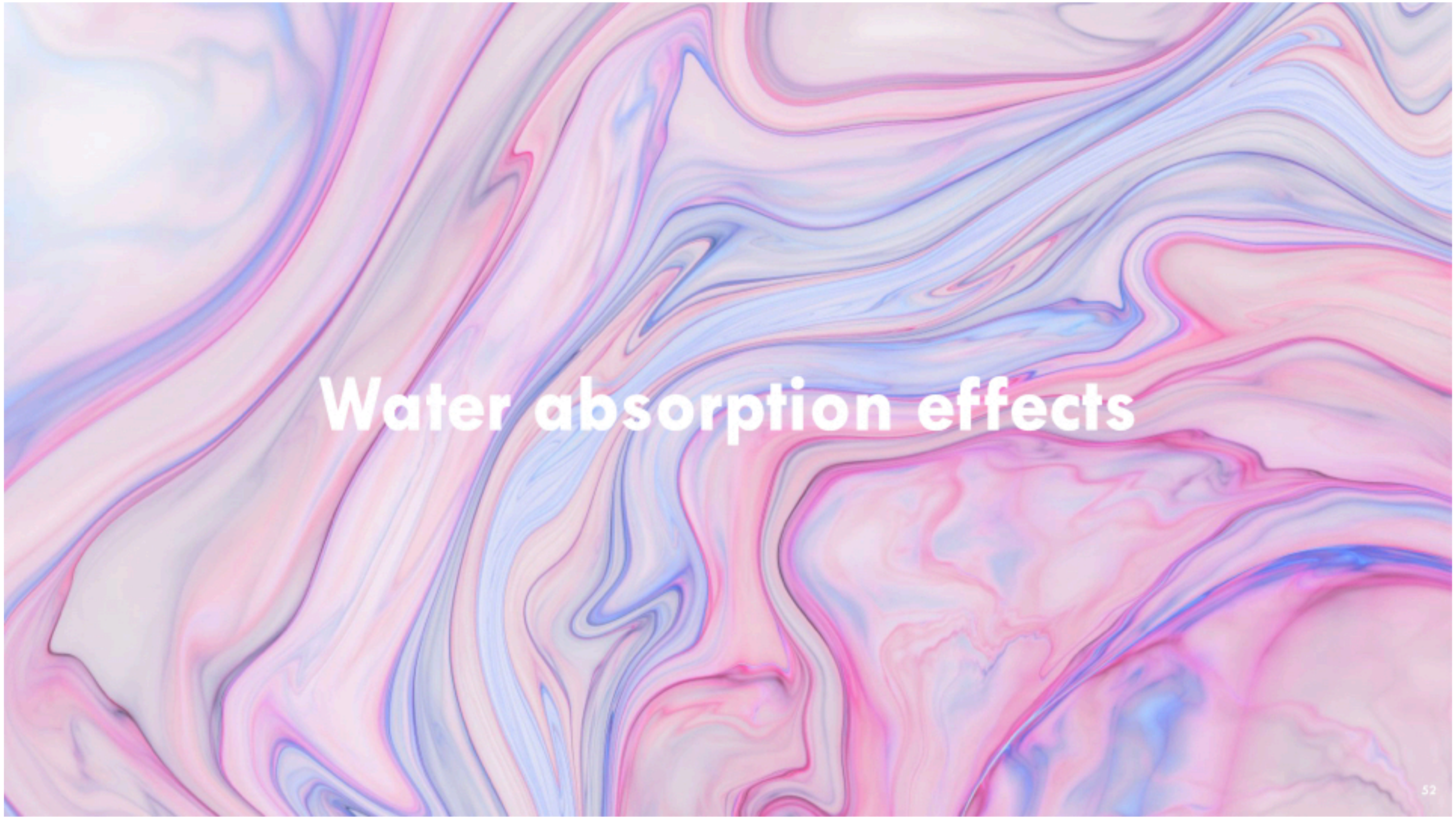
- 20 cm on the reconstruction of the vertex position
- 2.5 degrees in the direction

Expected effect
We would expect the overall amplitude to be attenuated, with less effect on long-time photons because the further away from the vertex, the less the initial position has an impact.

Observation
Amplitude attenuation on Q. No shift of the mean (ratio plot). We can still distinguish between gamma and e.



Distribution of Discriminating Variables



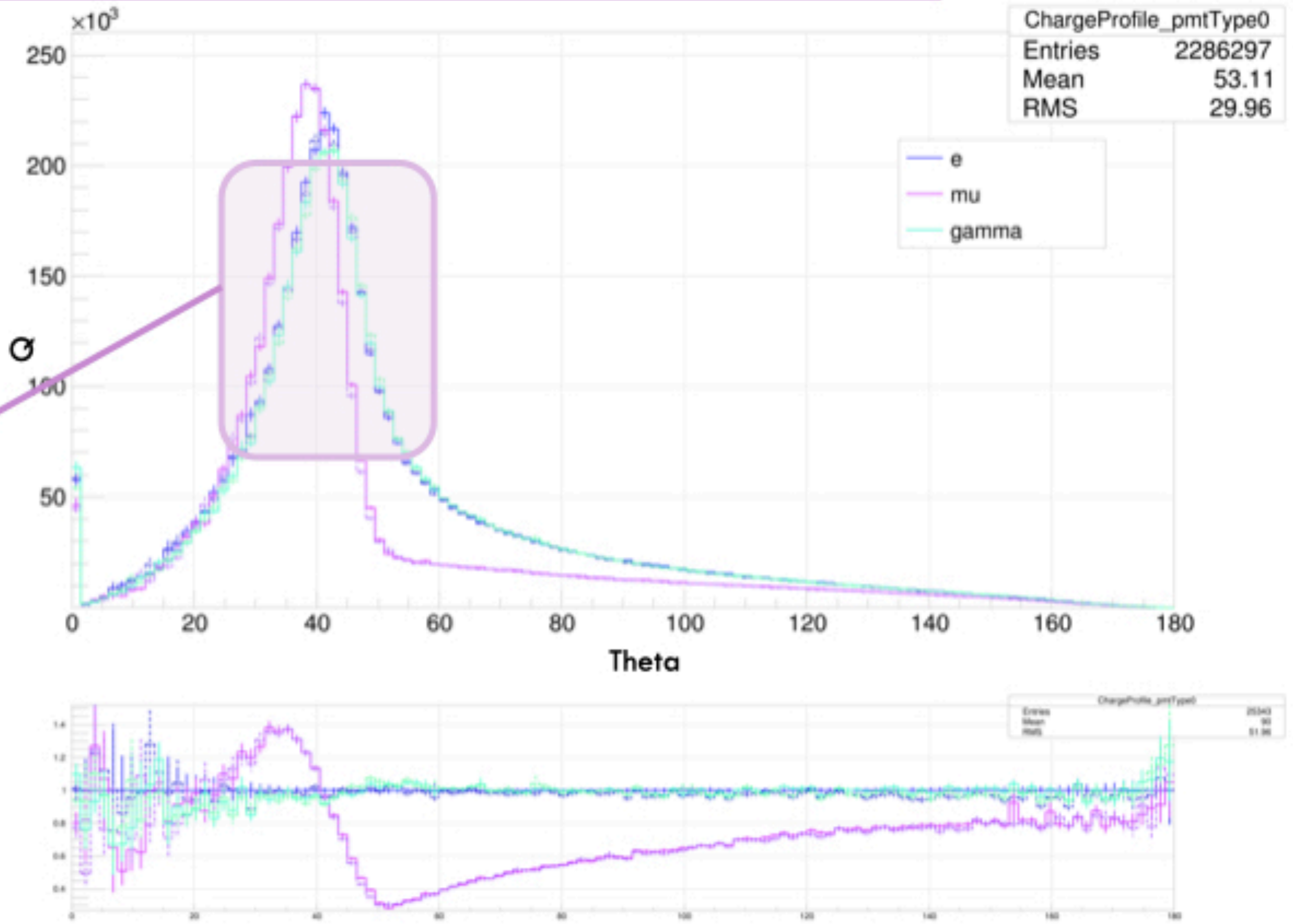
Distribution of Discriminating Variables

Q(theta) – Water absorption

Study of the influence of water absorption:
The characteristic length of 1.3 minus 1 sigma = 0.07.

The effect of water absorption
We would expect a major influence/ decrease on long-time photons populating the outer ring because those that pass through more material have a higher absorption probability. And less impact on gamma, more on mu and e.

Observations
No major changes, a small shift for the muon, because less in the outer ring.



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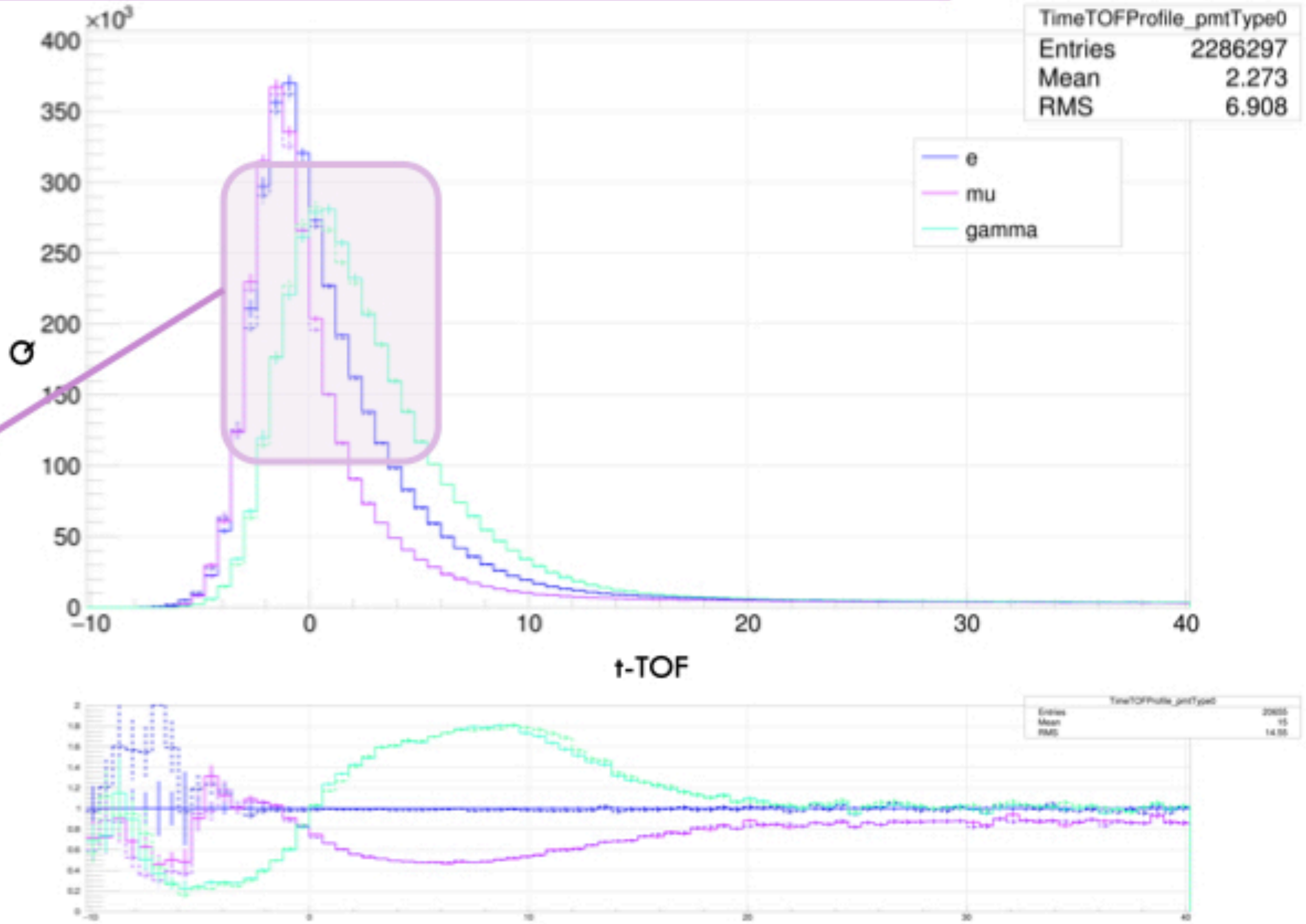
Distribution of Discriminating Variables

Q(TOF) – Water absorption

Study of the influence of water absorption:
The characteristic length of 1.3 minus 1 sigma = 0.07.

The effect of water absorption
We expect less population in the long-time, i.e., outer ring for mu and e (a little for gamma), and internal/ external for e and gamma due to the shower.

Observations
Weaker overall impact. Still, presence of a shift for mu and e and a slight shift to the left of gamma, so the distinction is possible between e and gamma.



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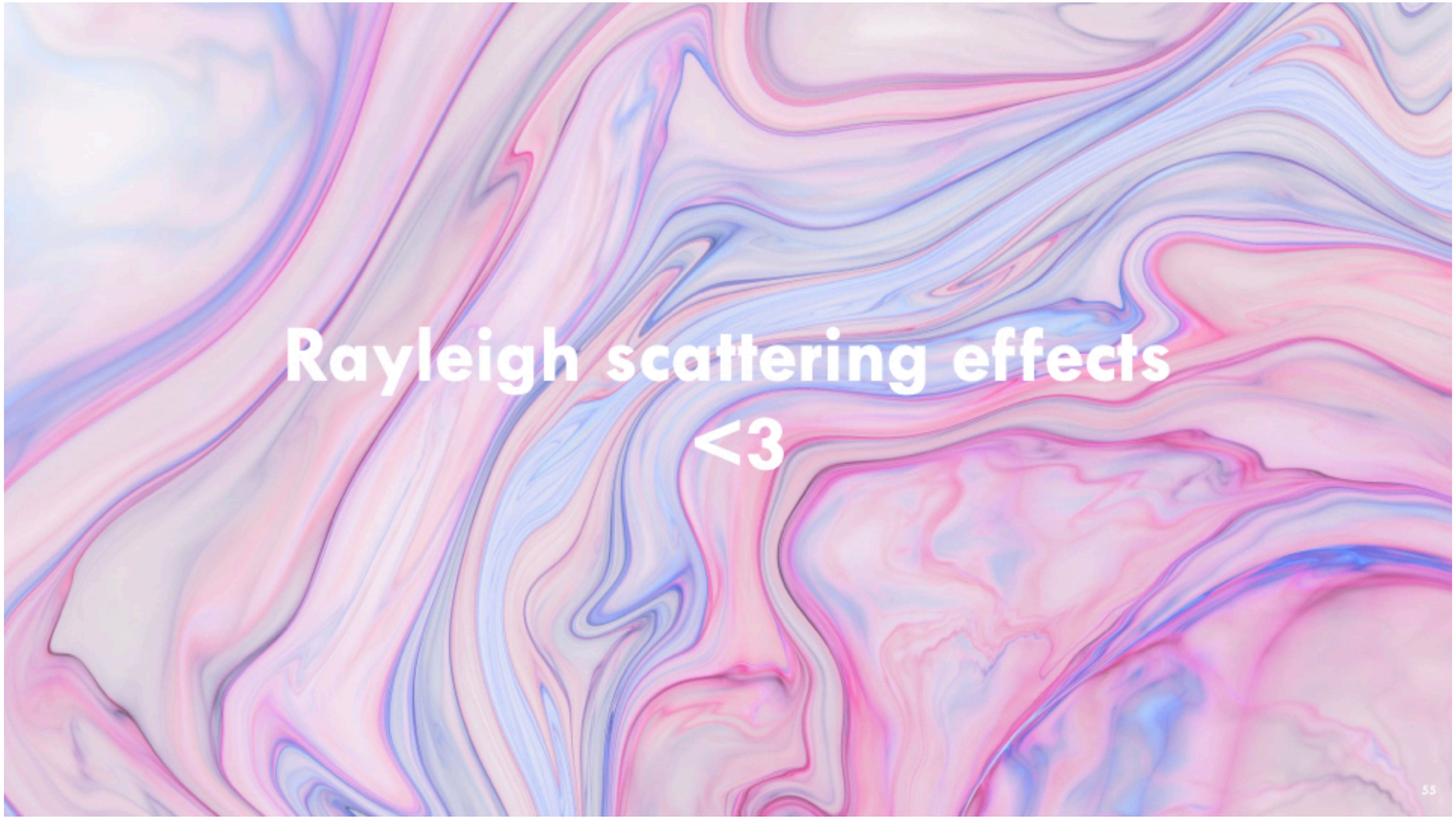
Distribution of Discriminating Variables



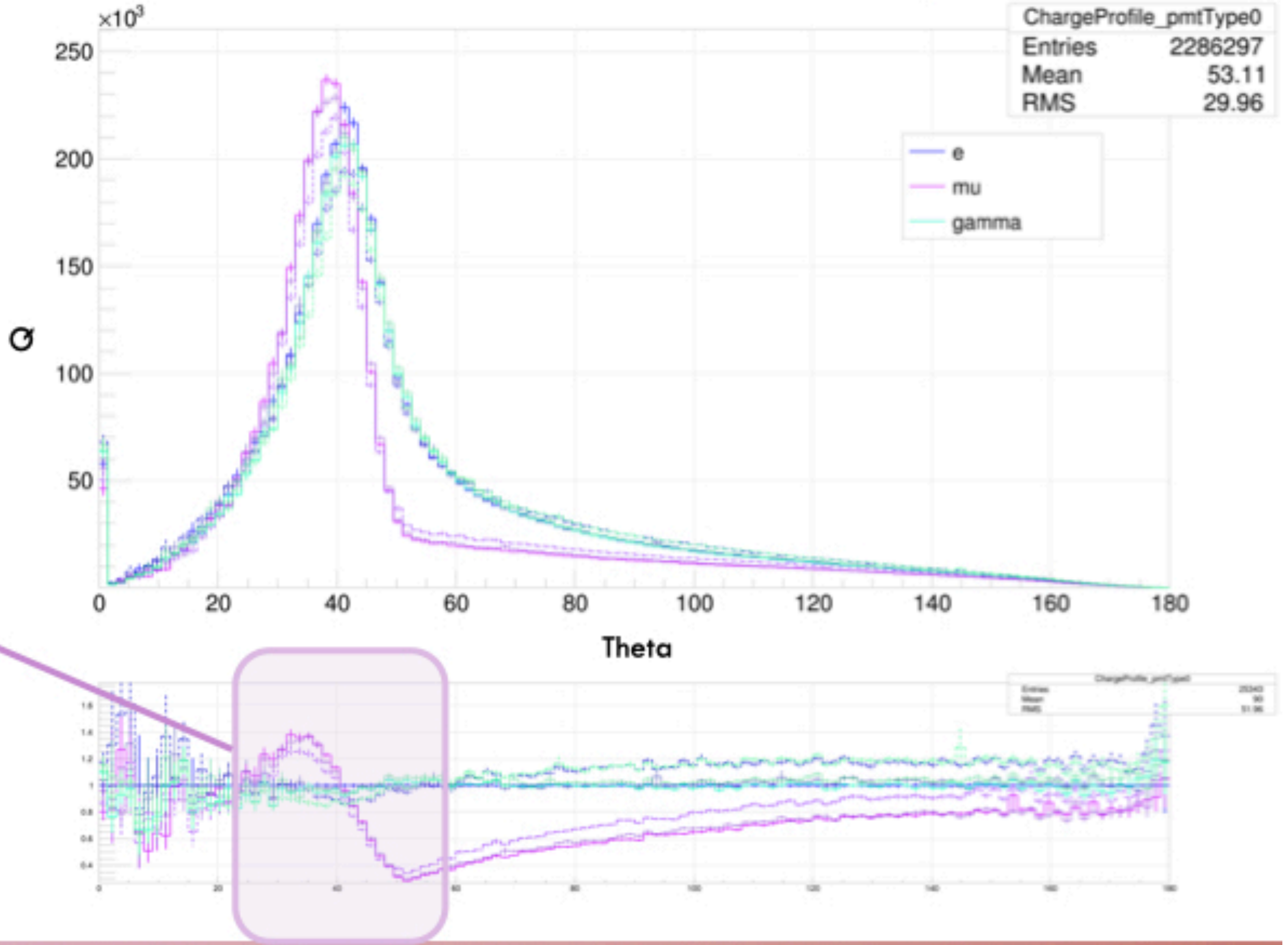
Distribution of Discriminating Variables

Q(theta) – Rayleigh scattering

Study of Rayleigh scattering:
0.75 characteristic length minus 1 sigma = 0.42 and at 0.1.

Effect of Rayleigh scattering
It is expected that the photons that travel the most will be more scattered, especially those at the outer edge of the ring for mu, int/ext for e, and more for gamma.

Observations
The greater the effect of Rayleigh scattering, the more the amplitude is attenuated. The distribution appears wider for mu. But by looking at the ratio plot, e can still be distinguished from mu.



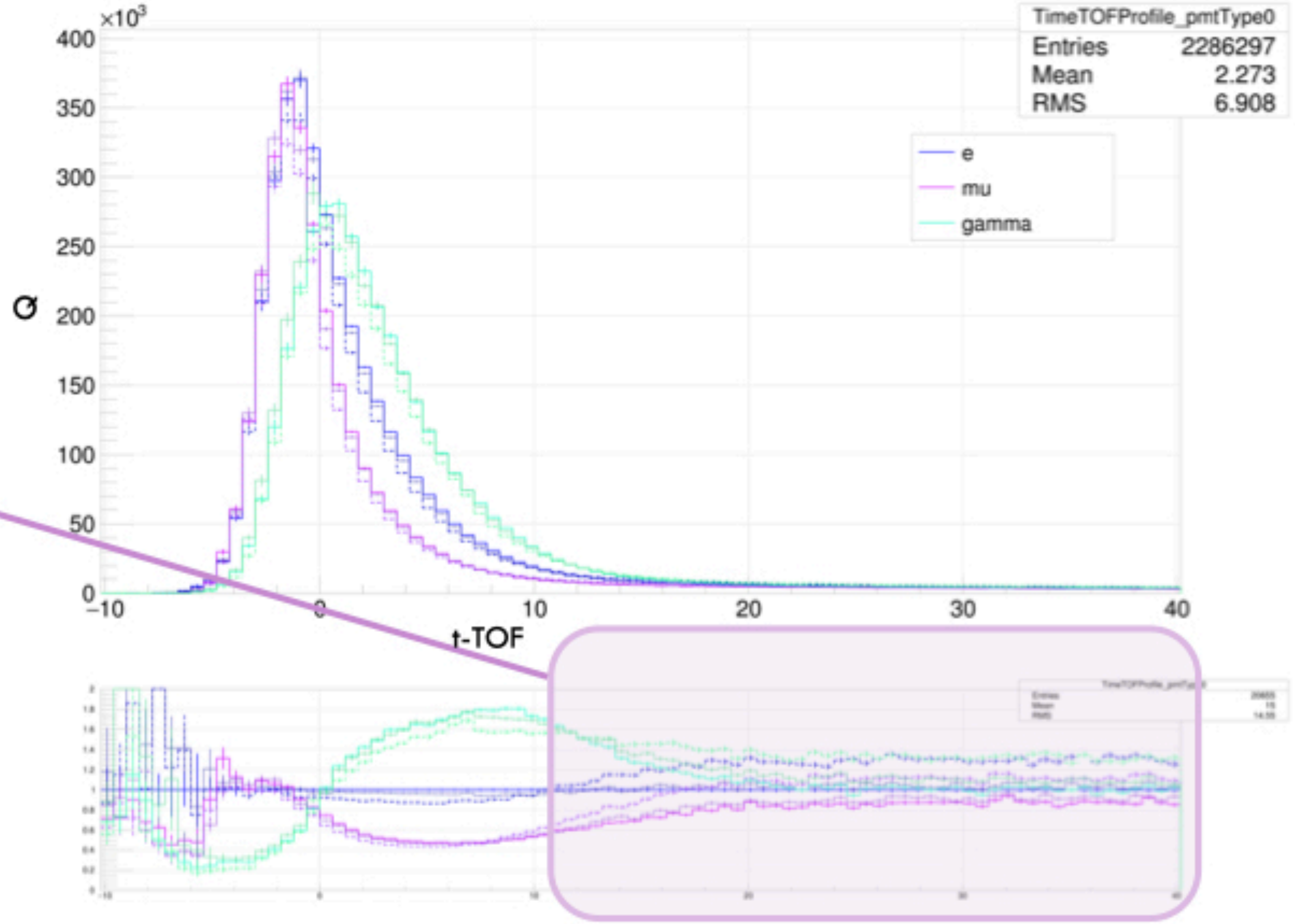
Distribution of Discriminating Variables

Q(TOF) – Rayleigh scattering

Study of Rayleigh scattering:
- 0.7 characteristic length minus 1 sigma = 0.42 and at 0.1.

Expected effect
- It is expected that there will be fewer populations in the long/ positive time, resulting in a shift to the left.

Observations
- Shift to the left for all distributions, so it's okay, but e can still be distinguished from gamma.
- On the ratio plot, after 15 ns. It moves the peak.



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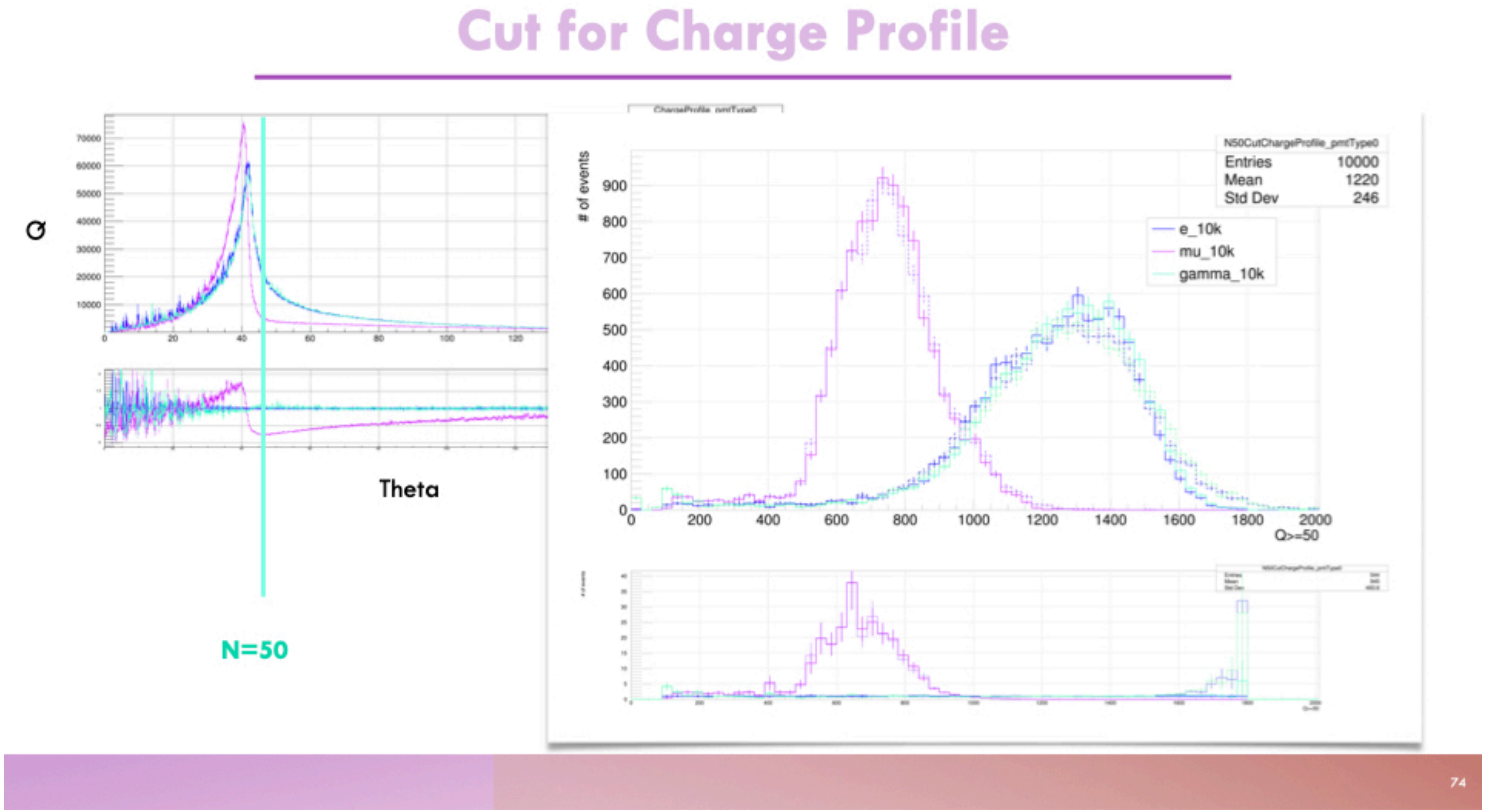
Distribution of Discriminating Variables

Distribution of Discriminating Variables



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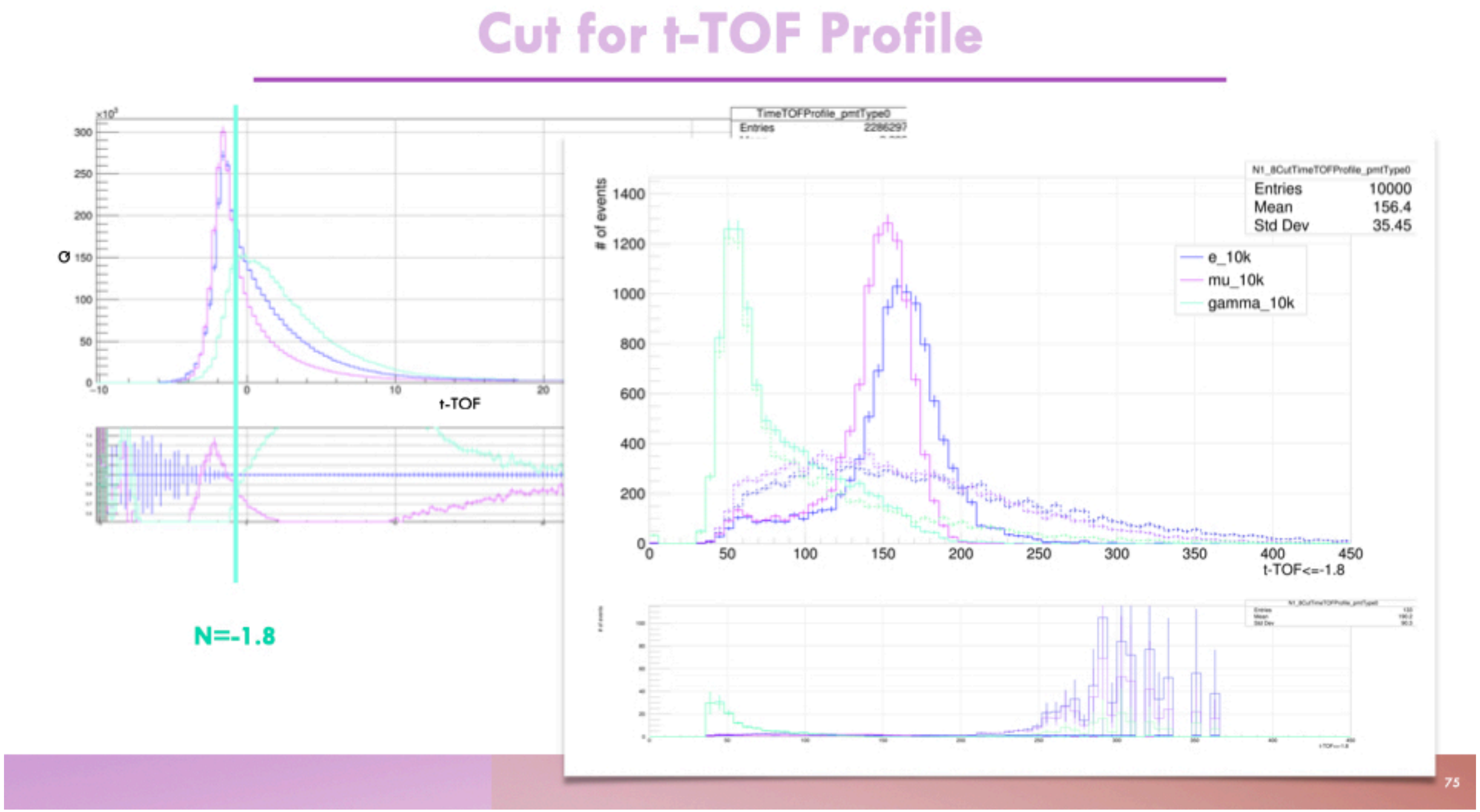
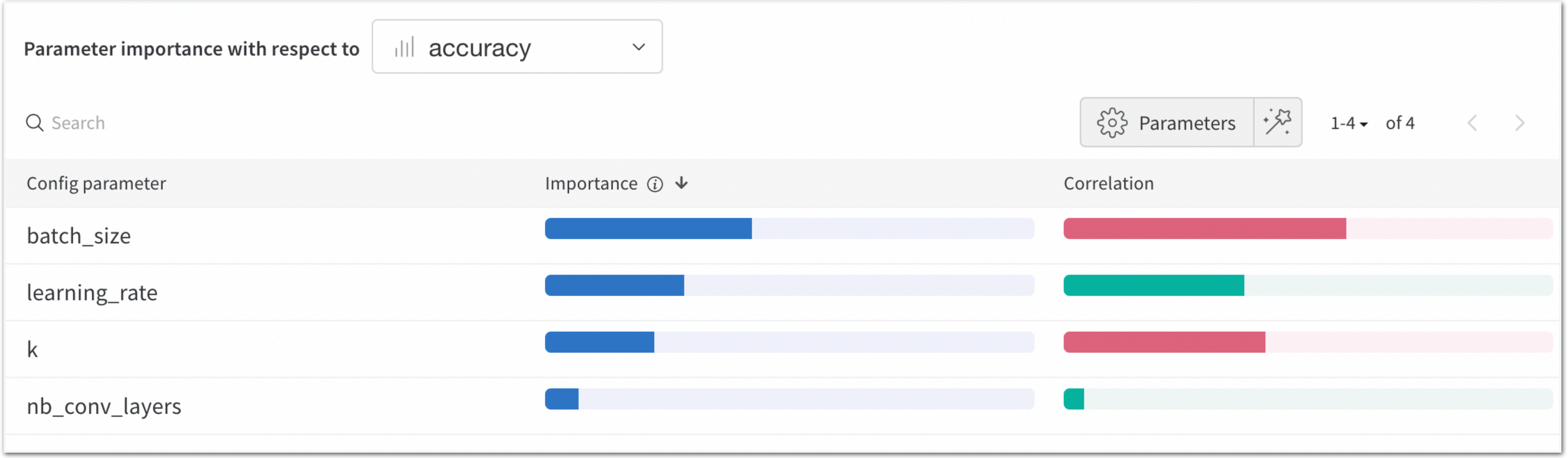
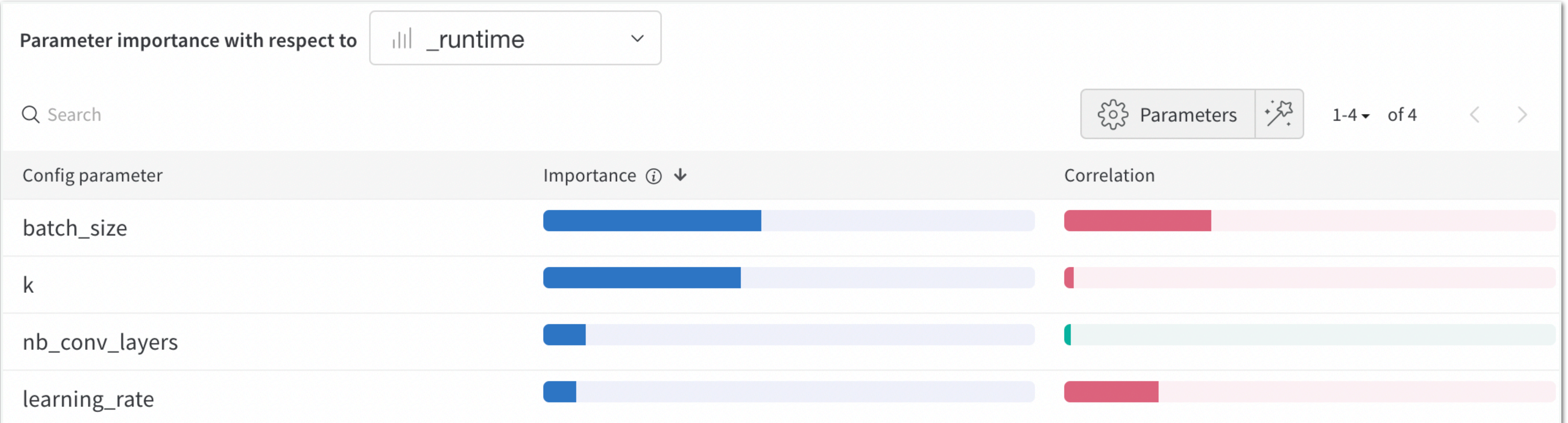
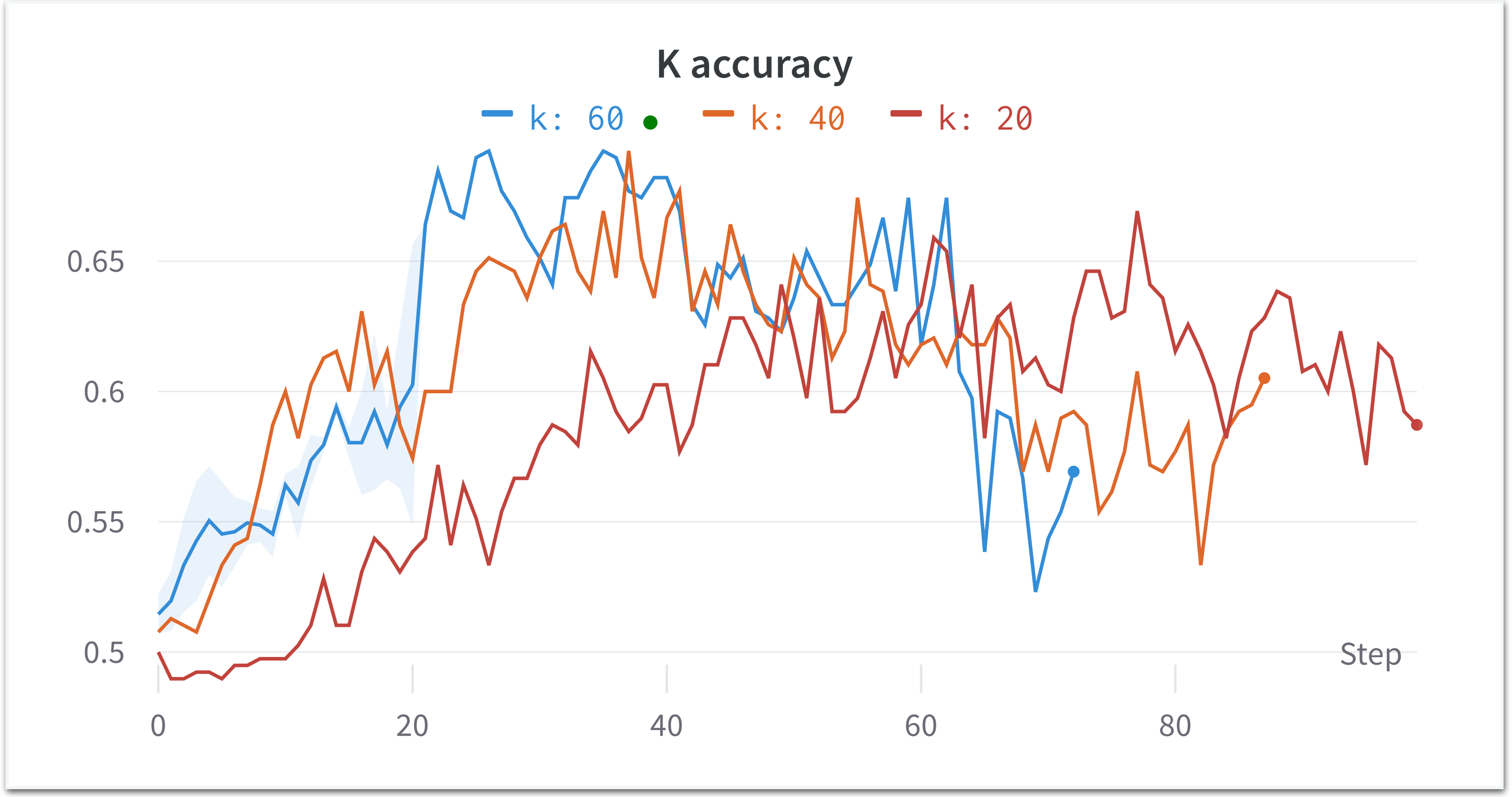


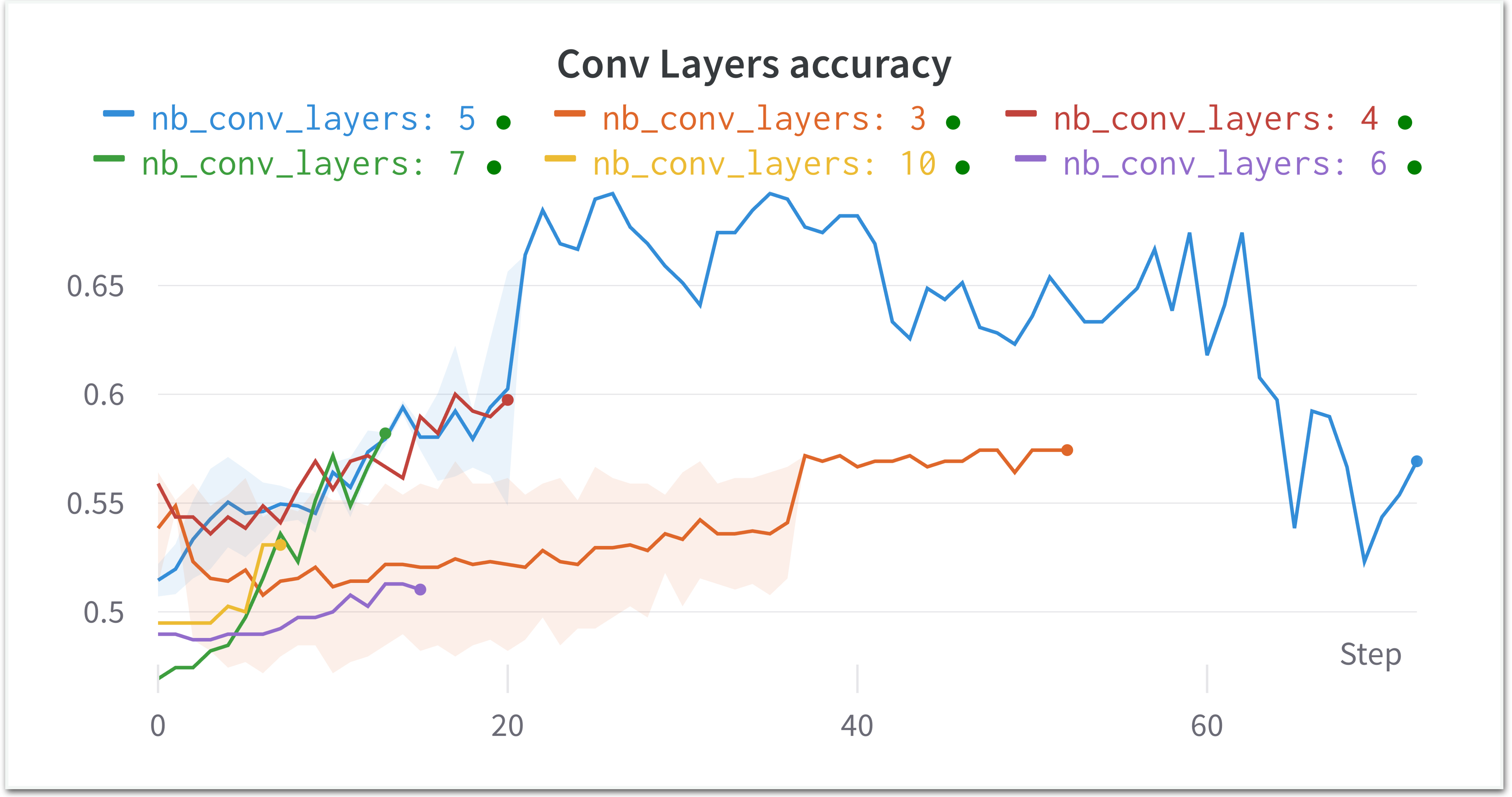
Hyper Parameters optimization





Hyper Parameters optimization





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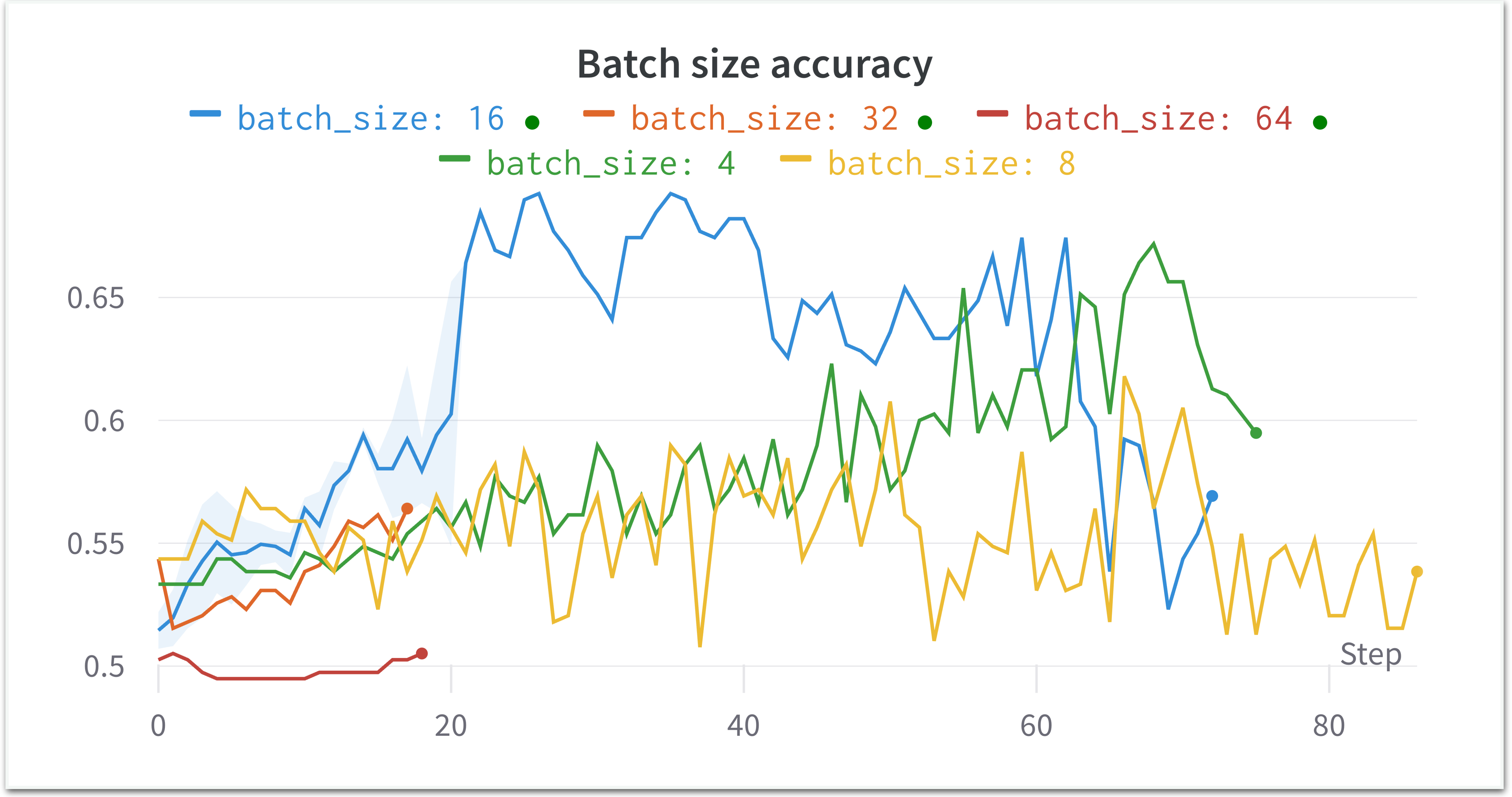
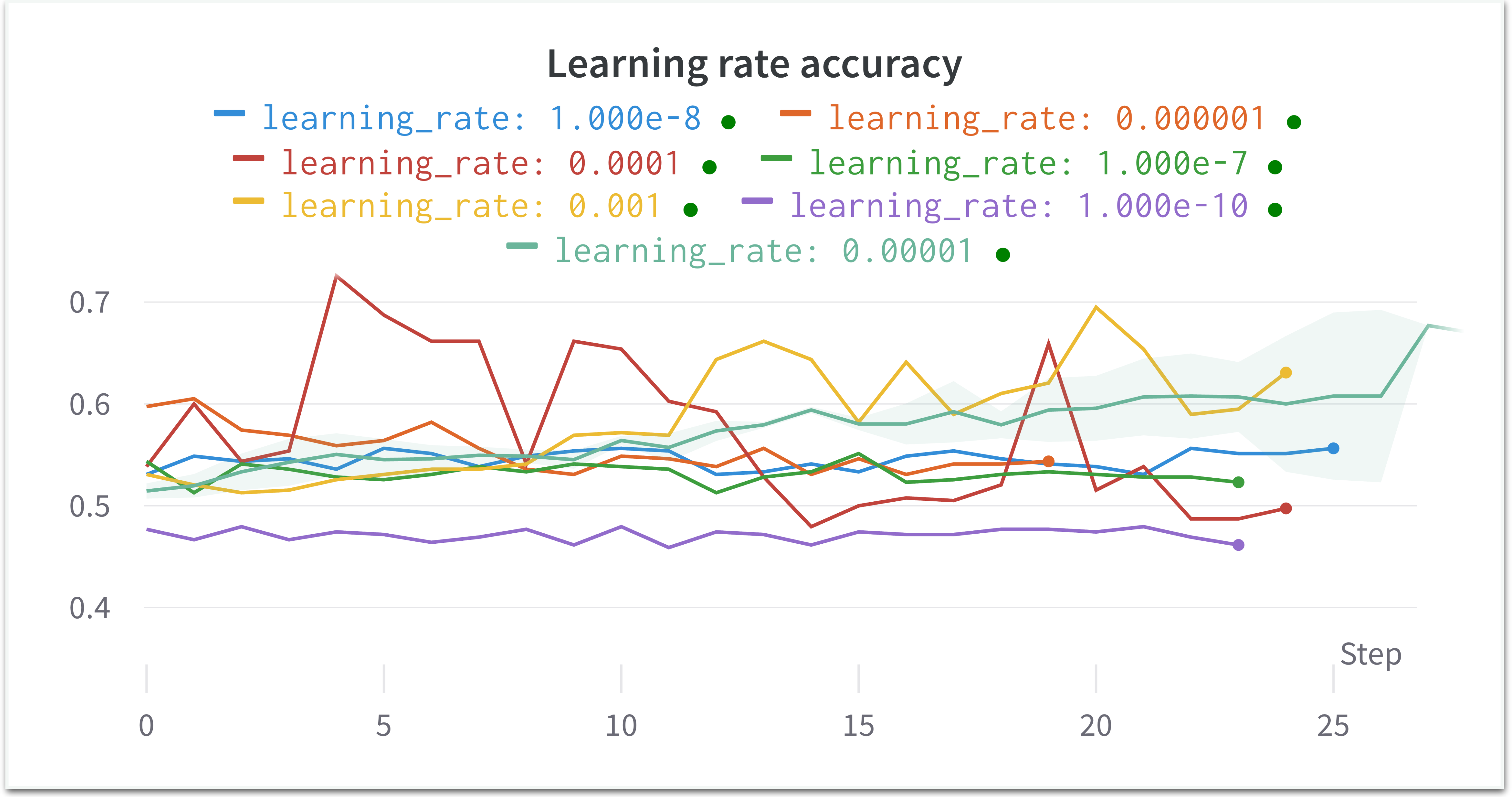
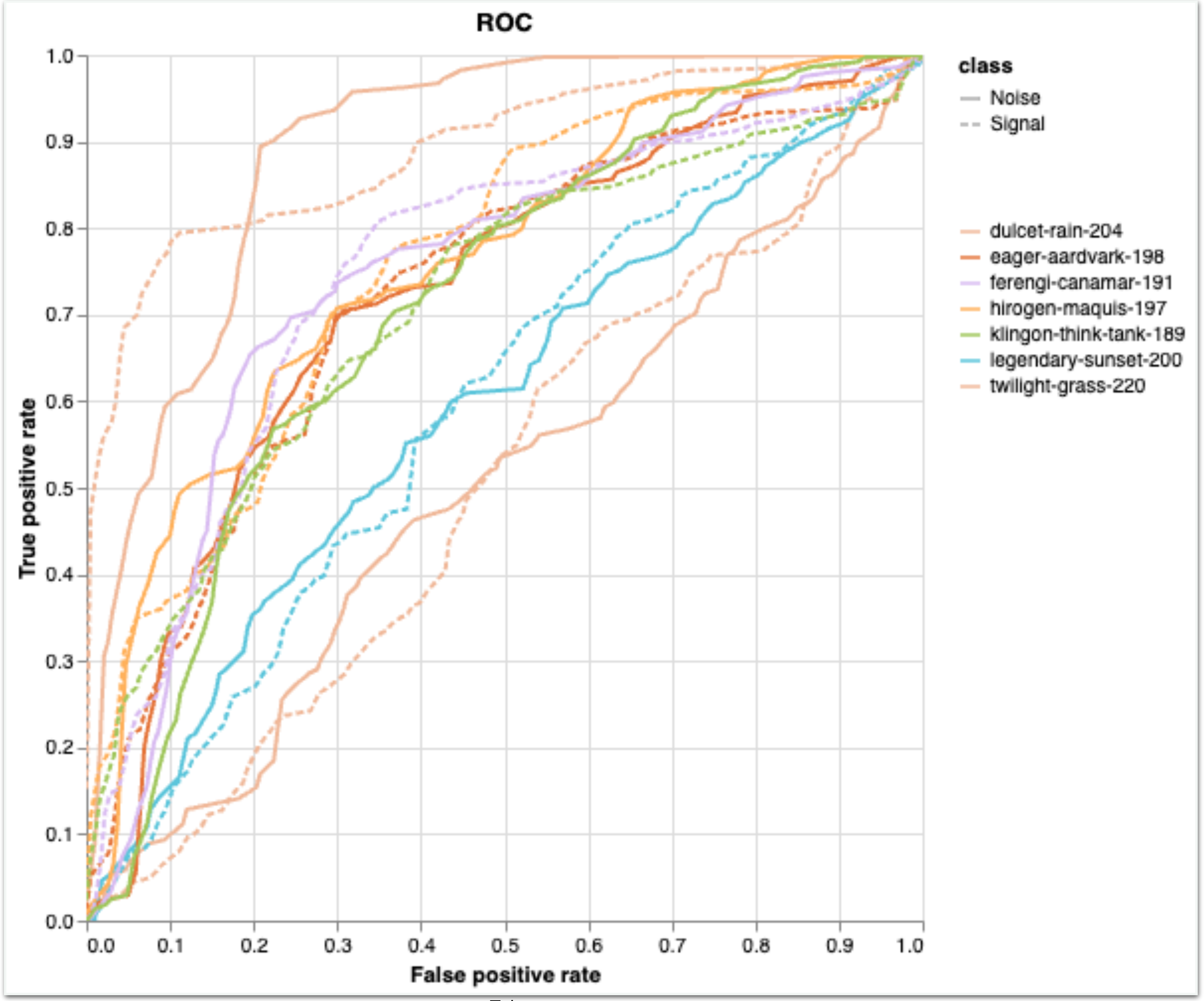
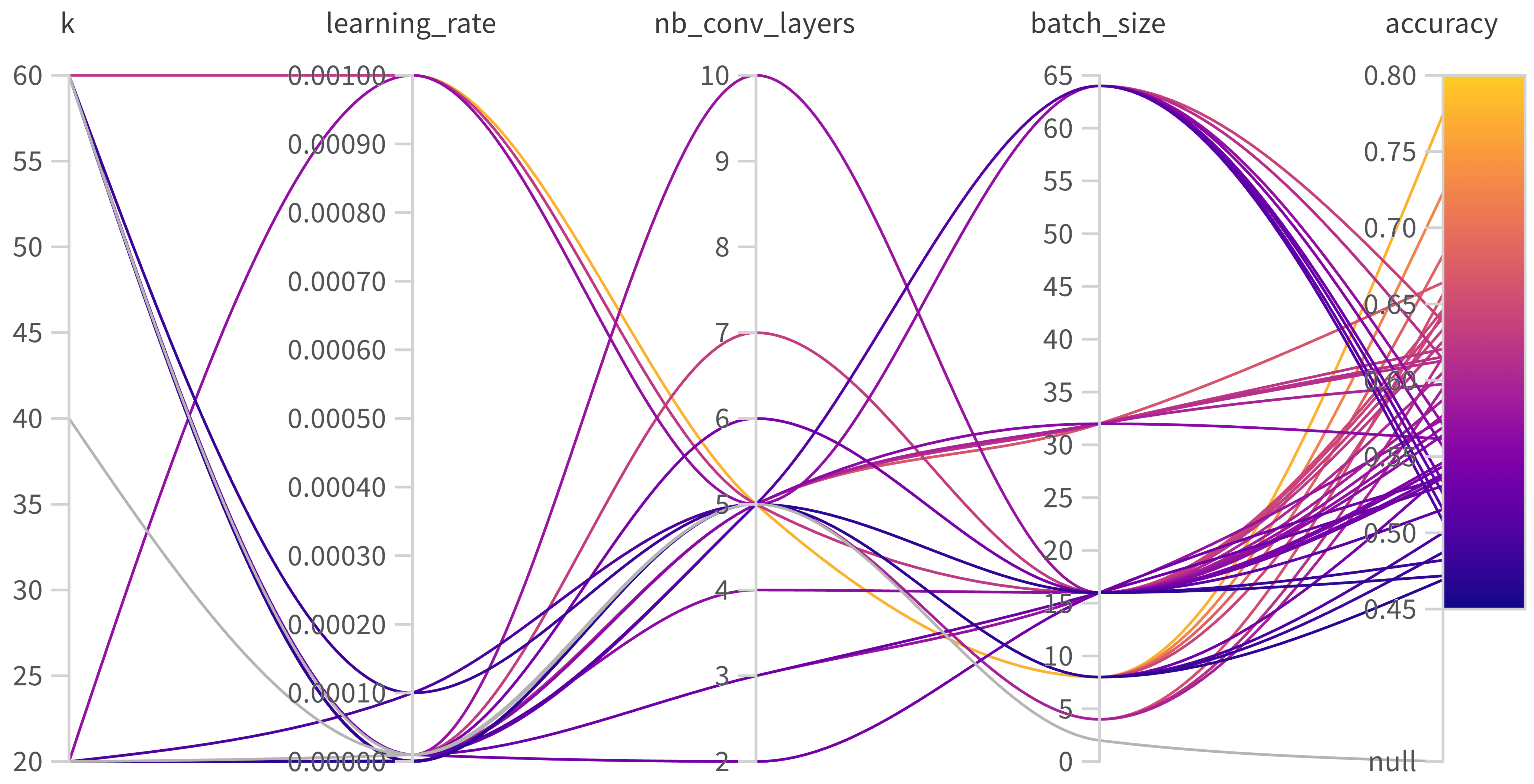




Hyper Parameters optimization



Hyper Parameters optimization



3 What’s next?

A. GNN : ideas for improvement

B. BDT : ideas for improvement

GNN

- Finishing the Optimization the hyperparameters of the GNN
- Quantify the efficiency and precision of the GNN classification mu/e then identify the physical parameters of the GNN by comparing the distributions
- Do the same for e/gamma separation
- Optimize the parameters of the GNN at variable energy.
- Parallelization of the GNN training

BDT

- Finding better cuts and study the correlation between built distributions
- Take GNN's output parameters as inputs for the BDT

Fin