

PID studies with proto-TORCH testbeam TORCH meeting

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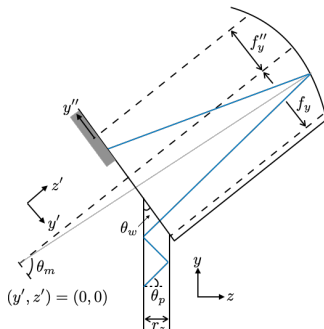
Introduction

- My work so far:
 - Study how photons are propagated through TORCH optics
 - Study analytical photon reconstruction from MCP hits
 - Understand likelihood calculation
- Long term goal:
 - Prepare for PID study of next testbeam data
 - Testing reconstruction code on real data
 - Build on Jenny's testbeam data analysis:
 - Jenny has focused on timing resolution studies
 - I will study PID separation power
- Thanks to:
 - Thomas Blake and Jonas Rademacker for providing LHCb reconstruction code
 - Jenny for providing testbeam data

Introduction to reconstruction code

- Forwards propagation:

- ① Trace emitted photon through quartz bar
- ② Reflect in cylindrical mirror
- ③ MCP hit!

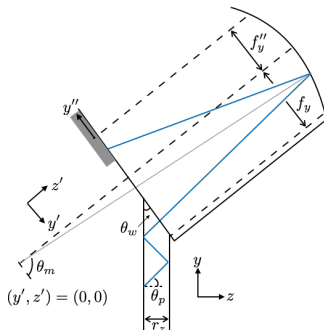


- Reconstruction described in [LHCb-PUB-2022-007](#)

Introduction to reconstruction code

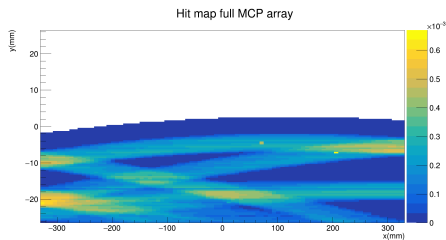
- Reconstruction:

- ➊ Reconstruct photon direction from vertical MCP pixel position
- ➋ From photon direction, calculate $\theta_c \rightarrow n_{\text{phase}} \rightarrow n_{\text{group}}$
- ➌ Reconstruct propagation time!

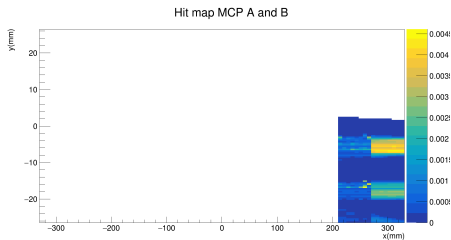


- Reconstruction described in [LHCb-PUB-2022-007](#)

Simulated hit maps



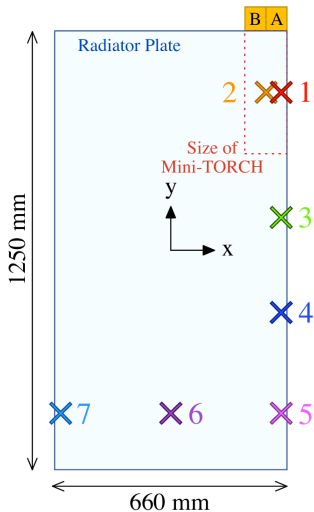
(a) Full MCP array, nominal QE



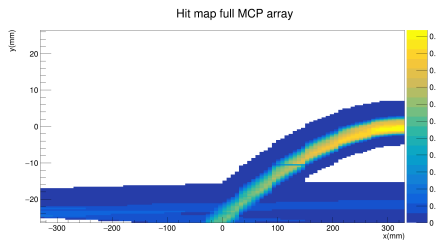
(b) MCP (reduced QE) A and B

Figure 1: Track incident 1 m from top

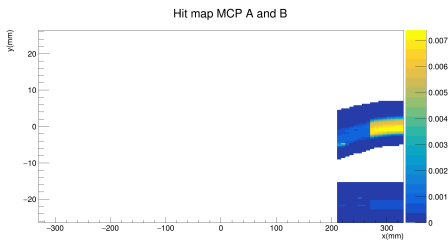
Beam position



Simulated hit maps



(a) Full MCP array, nominal QE



(b) MCP (reduced QE) A and B

Figure 2: Track incident on top right corner (position 1)

Likelihood calculation

- Probability of photon hit with energy E_γ , azimuthal angle ϕ_c , time t_0 :

$$\begin{aligned} P(E_\gamma, \phi_c, z, t_0) &= P(\phi_c)P(z)P(t_0)P(E_\gamma)\Theta(E_\gamma, \phi_c, z) \\ &= \frac{1}{2\pi} \frac{1}{r_z} P(E_\gamma)P(t_0)\Theta(E_\gamma, \phi_c, z) \end{aligned}$$

- Transform to detector coordinates (x_d, y_d) :

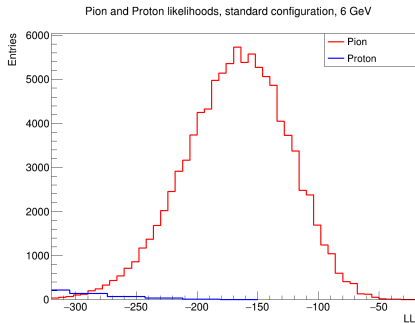
$$P(x_d, y_d, t_d) = P(E_\gamma, \phi_c, t_0)/|J|, \quad |J| = \left| \frac{\partial y_d}{\partial E_\gamma} \frac{\partial x_d}{\partial \phi_c} - \frac{\partial x_d}{\partial E_\gamma} \frac{\partial y_d}{\partial \phi_c} \right|$$

- $P(t_0)$: Gaussian PDF with ~ 70 ps time resolution
- $P(E_\gamma)$: Frank-Tamm formula
- PID algorithm described in [LHCb-PUB-2022-007](#)

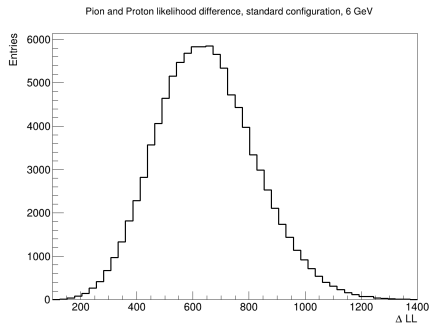
Test likelihood calculation on proto-TORCH

- Half height, 2 MCPs (one with reduced QE)
- Does PID separation still work?
- Set up single charged track simulation:
 - 1 Send single particle (pion, kaon, proton) through quartz
 - 2 Generate Cherenkov photons
 - 3 Propagate photons to MCPs
 - 4 Calculate likelihood from photon hits
 - 5 Start over from step 1
- No background hypothesis
- Turn on pixelisation, charge sharing, clustering

Pion-Proton likelihood simulations



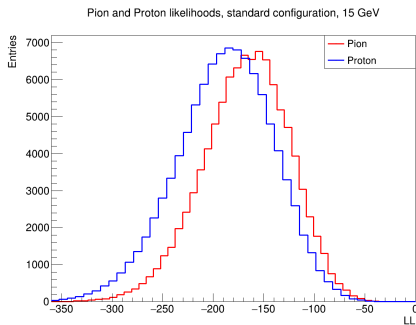
(a) Pion and proton hypotheses



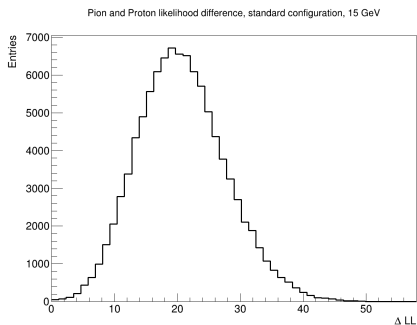
(b) Pion-proton ΔLL

Figure 3: Log likelihood at 6 GeV/c

Pion-Proton likelihood simulations



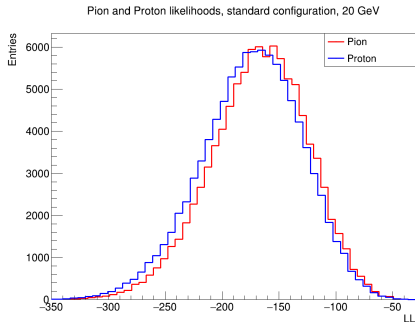
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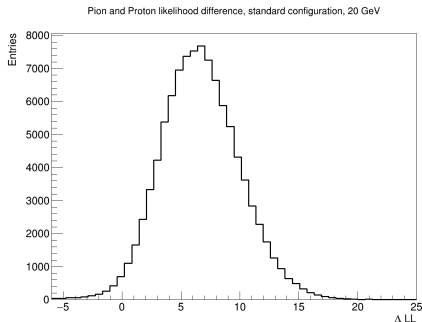
(b) Pion-proton ΔLL

Figure 4: Log likelihood at 15 GeV/c

Pion-Proton likelihood simulations



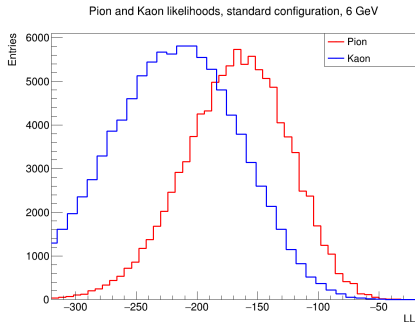
(a) Pion and proton hypotheses



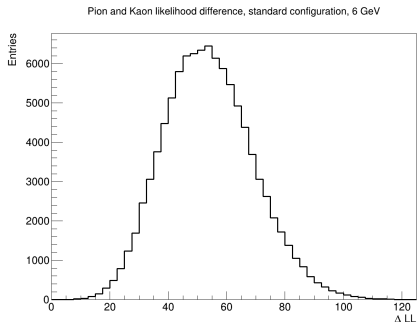
(b) Pion-proton ΔLL

Figure 5: Log likelihood at 20 GeV/c

Pion-Kaon likelihood simulations



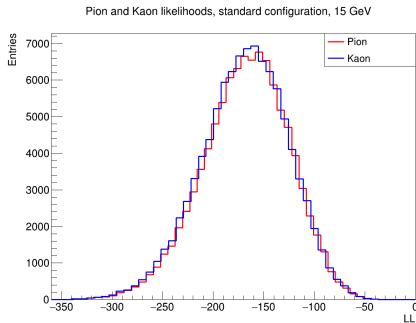
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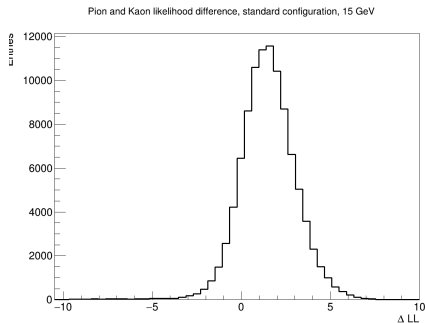
(b) Pion-kaon ΔLL

Figure 6: Log likelihood at 6 GeV/c

Pion-Kaon likelihood simulations



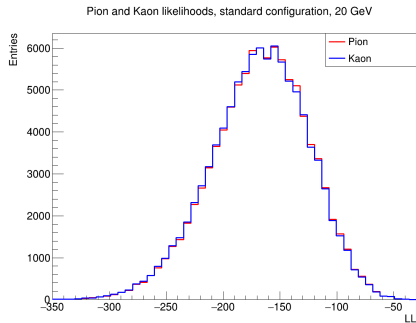
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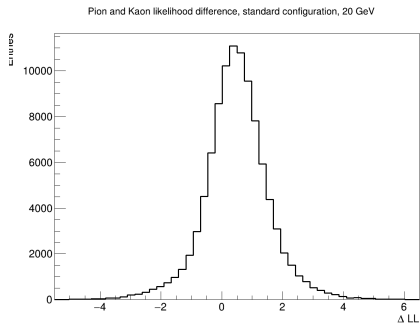
(b) Pion-kaon ΔLL

Figure 7: Log likelihood at 15 GeV/c

Pion-Kaon likelihood simulations



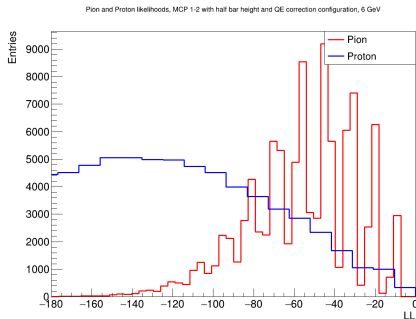
(a) Pion and kaon hypotheses



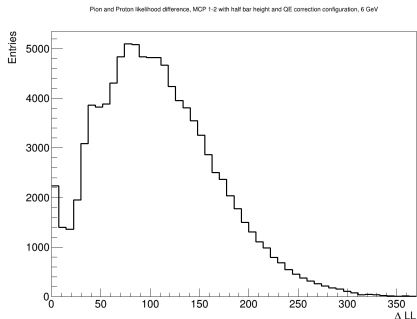
(b) Pion-kaon ΔLL

Figure 8: Log likelihood at 20 GeV/c

Pion-Proton likelihood simulations



(a) Pion and proton hypotheses

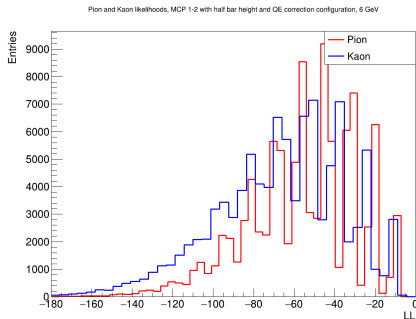


(b) Pion-proton ΔLL

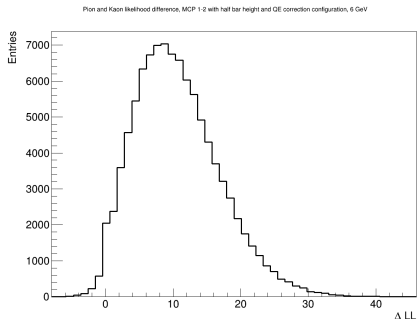
Figure 9: Log likelihood at 6 GeV/c

Adopt to testbeam setup: MCP A and B
Assume MCP A has QE that is 65% of MCP B

Pion-Kaon likelihood simulations



(a) Pion and kaon hypotheses



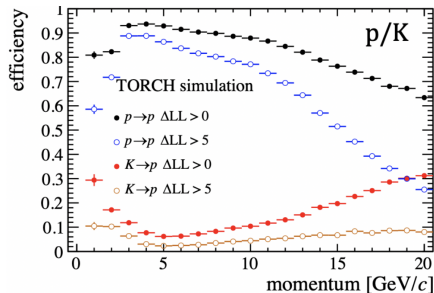
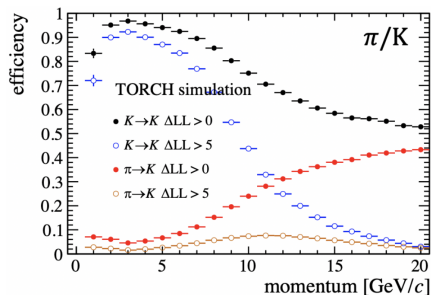
(b) Pion-kaon ΔLL

Figure 10: Log likelihood at 6 GeV/c

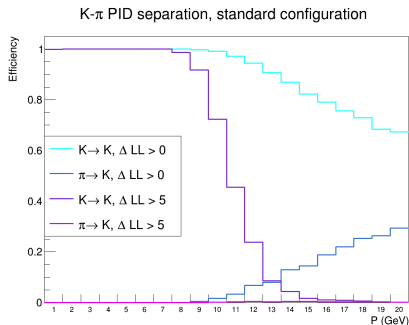
Adopt to testbeam setup: MCP A and B
Assume MCP A has QE that is 65% of MCP B

PID efficiency from FTDR

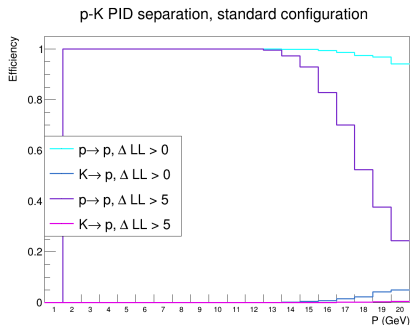
PID efficiency study from FTDR
Aim: Reproduce similar study with testbeam setup



PID efficiency simulation



(a) Kaon-pion

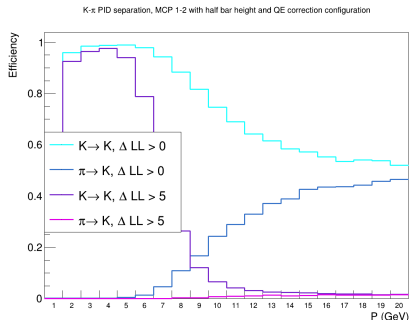


(b) Kaon-proton

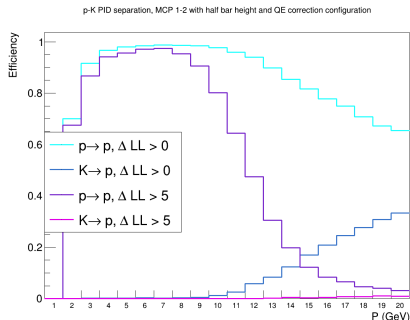
Figure 11: PID efficiency

Full array of MCPs with same QE

PID efficiency simulation



(a) Kaon-pion



(b) Kaon-proton

Figure 12: PID efficiency

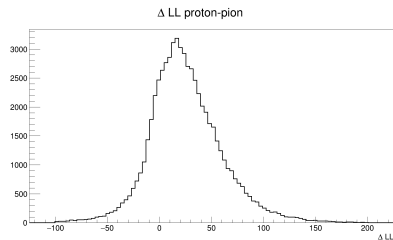
2 MCPs, one with lower QE

PID study of proto-TORCH testbeam data

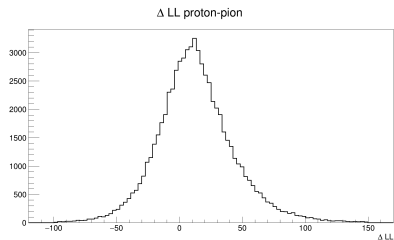
Obviously, more messy and challenging:

- ① Not many photons \implies Use position 1 only
- ② Backgrounds \implies For now, discard events where reconstruction fails
 - Photon hits do not match track sometimes...
- ③ T2 has an unknown offset \implies Align time distribution from simulation with that in data
 - There is probably a much better way...
- ④ No T1 \implies Introduce artificial 9500 mm offset to time information

Likelihood in proto-TORCH testbeam data



(a) Pion sample



(b) Proton sample

Figure 13: ΔLL of testbeam data

Results from testbeam data “out of the box”

- Estimate of testbeam momentum: 8.6 GeV/c

PID cut	$\Delta LL > 0$	$\Delta LL > 5$
8 GeV/c pion simulation	99.0%	97.9%
9 GeV/c pion simulation	98.9%	96.8%
Proto-TORCH testbeam pion sample	78.6%	72.9%
8 GeV/c proton simulation	98.7%	97.4%
9 GeV/c proton simulation	98.8%	96.5%
Proto-TORCH testbeam proton sample	66.9%	59.5%

- Clearly this is work in progress:
 - ① Time alignment not perfect! Needs to be understood...
 - Individual pixels
 - Overall t_0
 - ② Proton sample has more backgrounds (kaons)?
 - ③ Likelihood calculation uses a “perfect” time resolution (~ 70 ps)
 - ④ MCPs in proto-TORCH have worse QE than in simulation

Summary and next steps

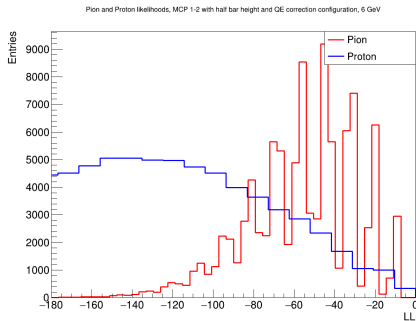
- Summary

- ① Likelihood calculation gives consistent results
- ② Single particle simulation shows very good PID separation power
- ③ Testbeam data show some PID separation, not as good as simulation

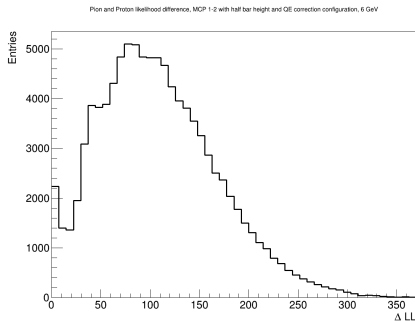
- Next steps:

- ① Need much more work to understand test beam data better
 - ① Time alignment
 - ② Background

Pion-Proton likelihood simulations



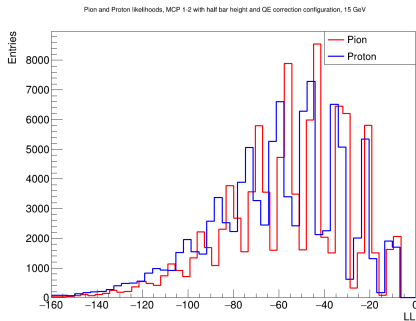
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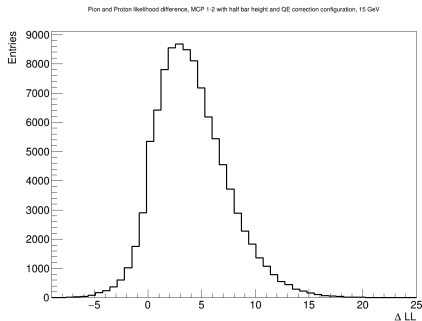
(b) Pion-proton ΔLL

Figure 14: Log likelihood at 6 GeV/c

Pion-Proton likelihood simulations



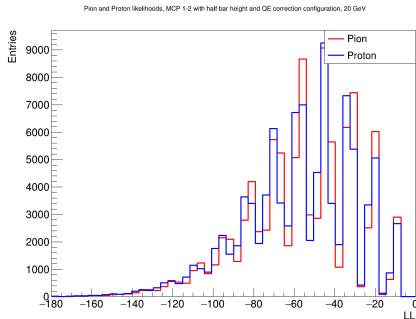
(a) Pion and proton hypotheses



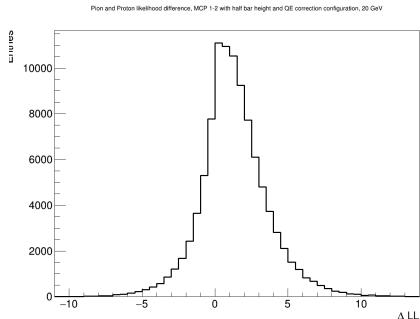
(b) Pion-proton ΔLL

Figure 15: Log likelihood at 15 GeV/c

Pion-Proton likelihood simulations



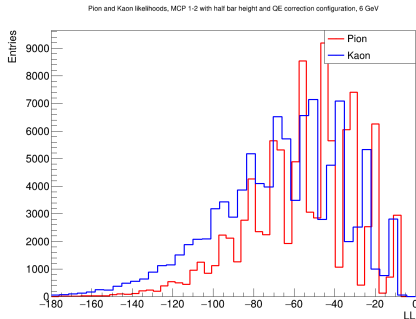
(a) Pion and proton hypotheses



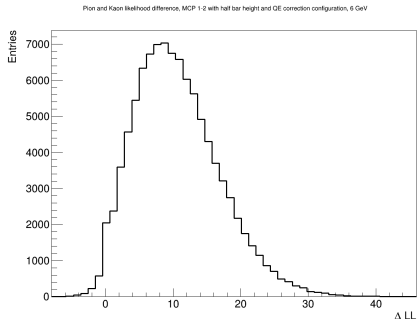
(b) Pion-proton ΔLL

Figure 16: Log likelihood at 20 GeV/c

Pion-Kaon likelihood simulations



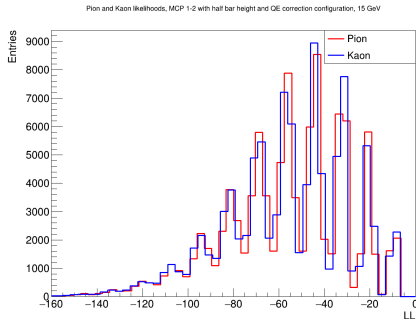
(a) Pion and kaon hypotheses



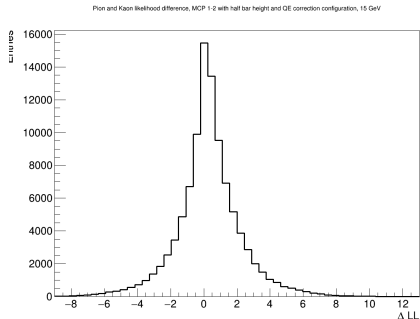
(b) Pion-kaon ΔLL

Figure 17: Log likelihood at 6 GeV/c

Pion-Kaon likelihood simulations



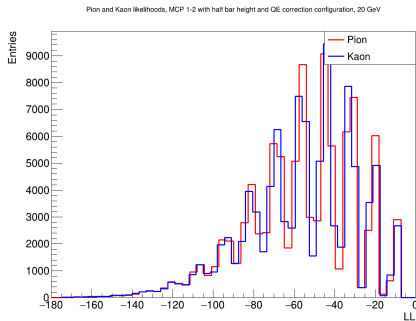
(a) Pion and kaon hypotheses



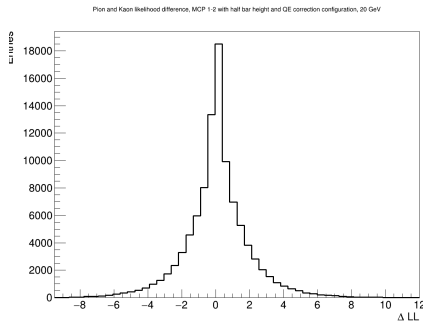
(b) Pion-kaon ΔLL

Figure 18: Log likelihood at 15 GeV/c

Pion-Kaon likelihood simulations



(a) Pion and kaon hypotheses



(b) Pion-kaon ΔLL

Figure 19: Log likelihood at 20 GeV/c

Pion-Kaon likelihood simulations

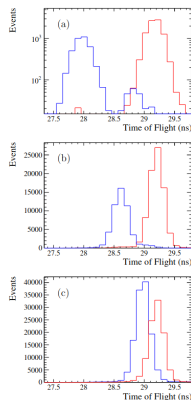


Figure 6.15: Particle times of flight measured in June 2018 at the nominal beam momenta of (a) 3.5 GeV/c, (b) 5 GeV/c, and (c) 8 GeV/c, coloured according to whether or not a signal was seen in the Cherenkov counters. Red indicates a signal was seen, and hence corresponds to pions; blue indicates no signal was seen, corresponding to protons. In (a), a second blue peak can be seen at 28.8 ns, corresponding to a small kaon signal. In (b), part of the upper tail of the proton peak may be attributed to kaons. In (c), any kaon signal is impossible to distinguish. Note the x-axis range is the same for all three plots for ease of comparison, however only (a) has a logarithmic y-axis.

Figure 20: From Thomas Hancock's thesis