PID studies with proto-TORCH testbeam
TORCH meeting

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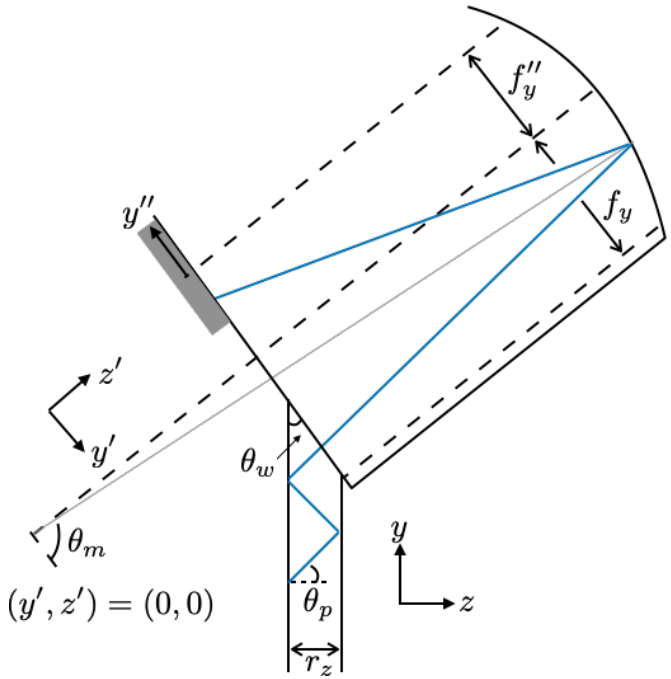
Introduction

- 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 reoconstruction 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

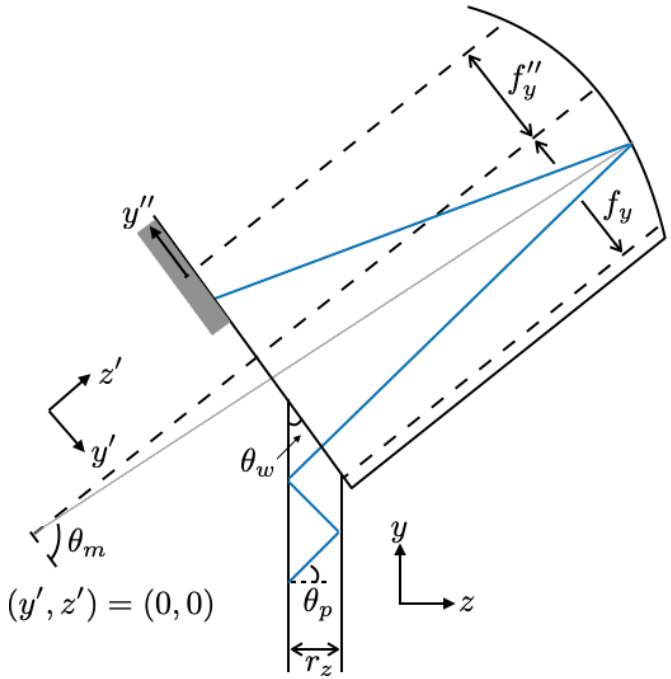
- Forwards propagation:
  1. Trace emitted photon through quartz bar
  2. Reflect in cylindrical mirror
  3. MCP hit!



- Reconstruction described in LHCb-PUB-2022-007

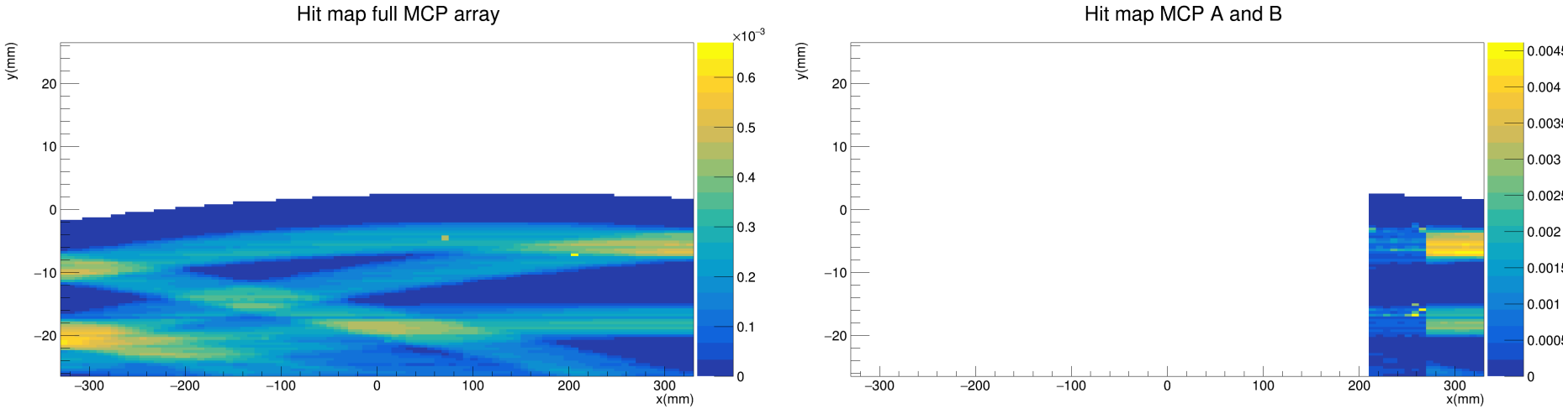
Introduction to reconstruction code

- Reconstruction:
  1. Reconstruct photon direction from vertical MCP pixel position
  2. From photon direction, calculate $\theta_c \rightarrow n_{\text{phase}} \rightarrow n_{\text{group}}$
  3. Reconstruct propagation time!



- Reconstruction described in LHCb-PUB-2022-007

Simulated hit maps

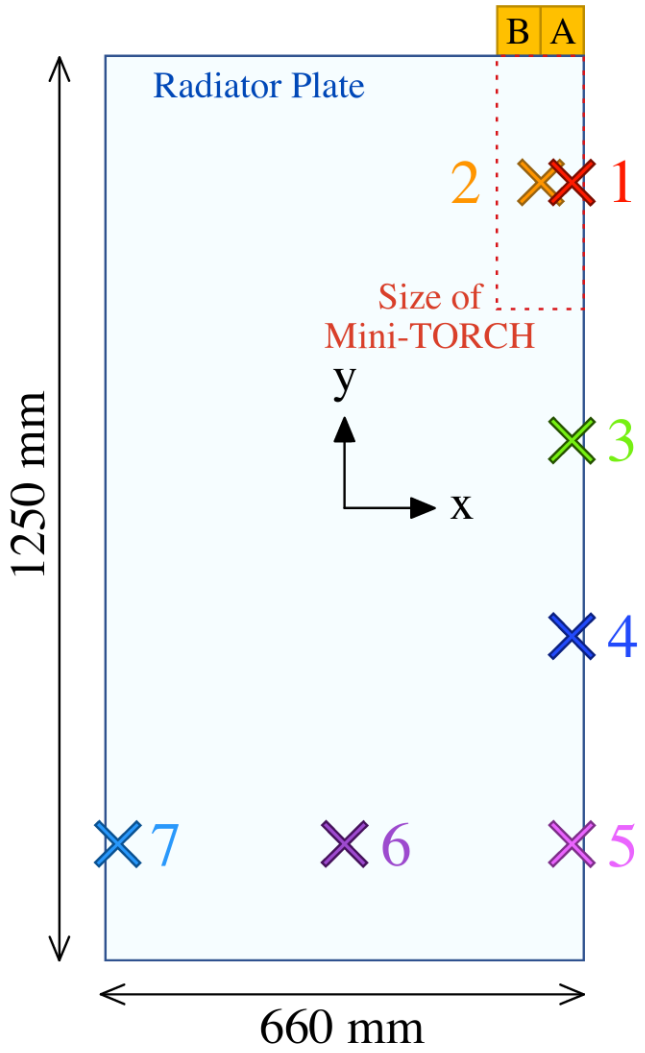


(a) Full MCP array, nominal QE

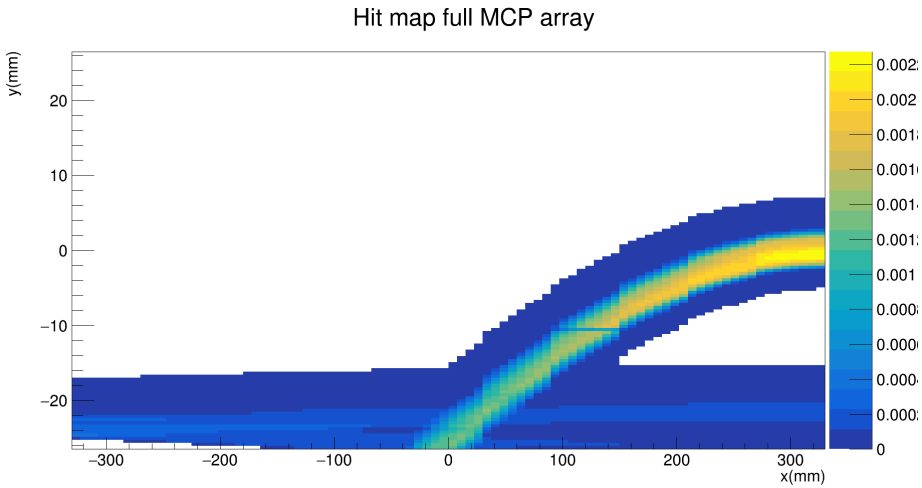
(b) MCP (reduced QE) A and B

Figure 1: Track incident 1 m from top

Beam position



Simulated hit maps



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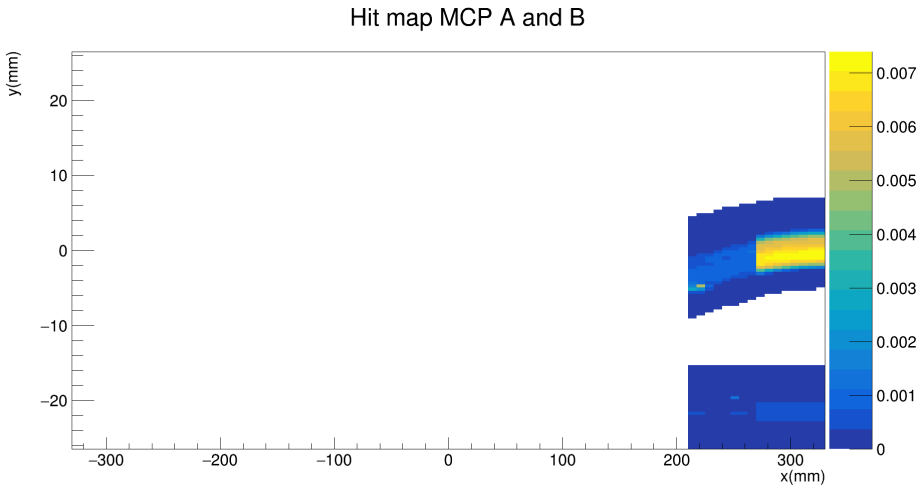


(b) MCP (reduced QE) A and B

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):

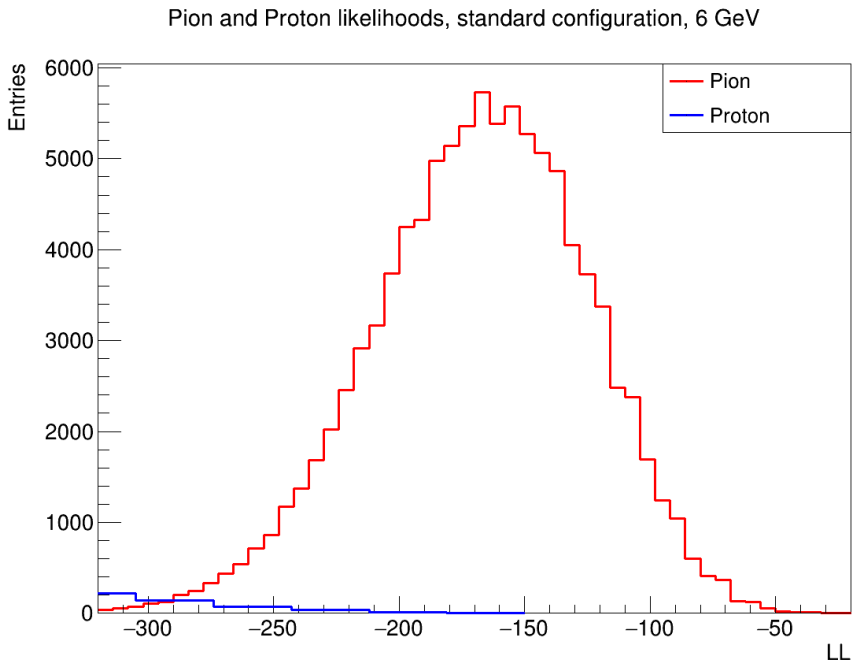
$$P(x_d, y_d, t_d) = P(E_\gamma, \phi_c, t_0)/|J|, \quad |J| = \left|\frac{\partial y_d}{\partial E_\gamma}\frac{\partial x_d}{\partial \phi_c} - \frac{\partial x_d}{\partial E_\gamma}\frac{\partial y_d}{\partial \phi_c}\right|$$

- $P(t_0)$: Gaussian PDF with $\sim 70\,\text{ps}$ time resolution
- $P(E_\gamma)$: Frank-Tamm formula
- PID algorithm described in LHCb-PUB-2022-007

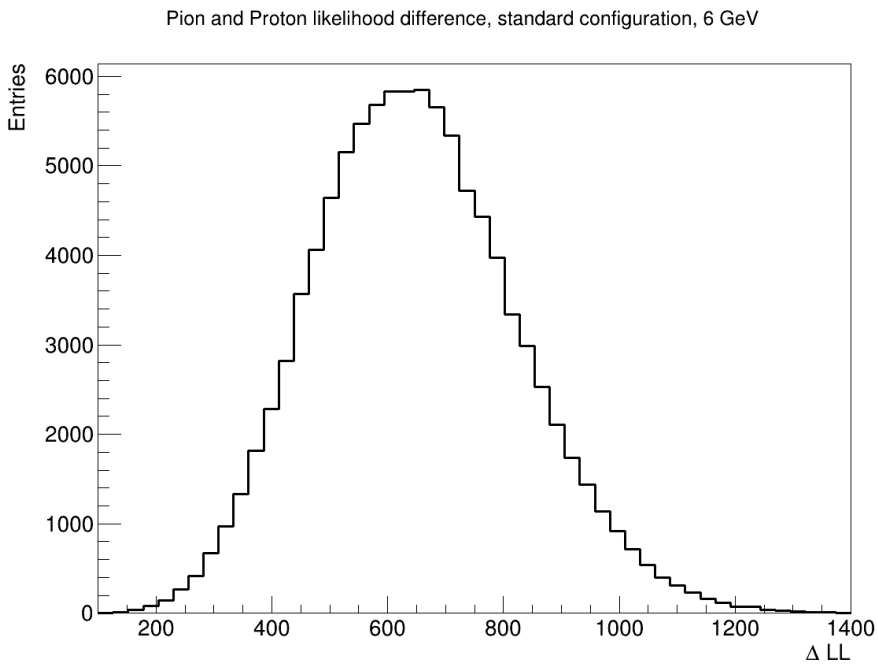
Test likelihood calculation on proto-TORCH

- 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



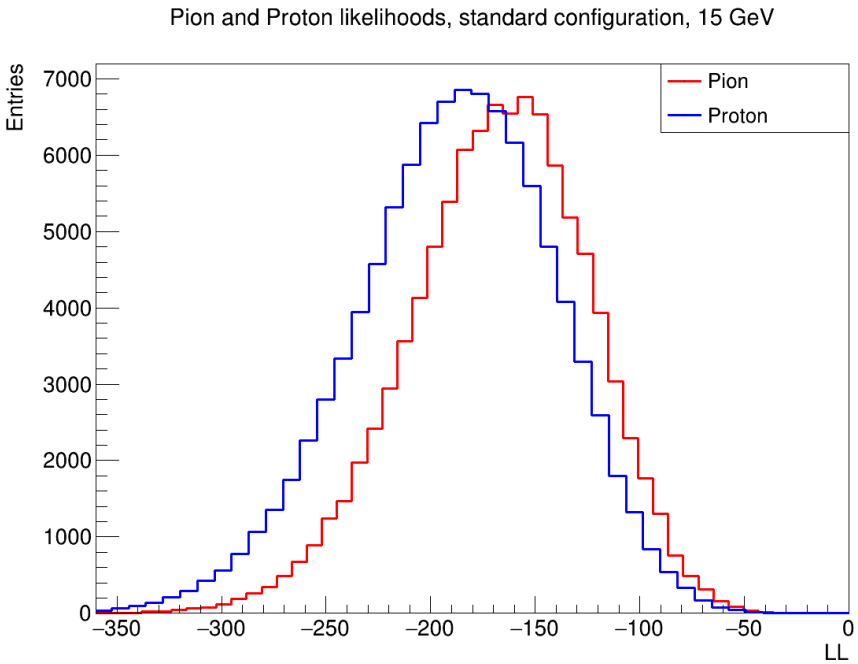
(a) Pion and proton hypotheses



(b) Pion-proton $\Delta\mathrm{LL}$

Figure 3: Log likelihood at 6 GeV/c

Pion-Proton likelihood simulations



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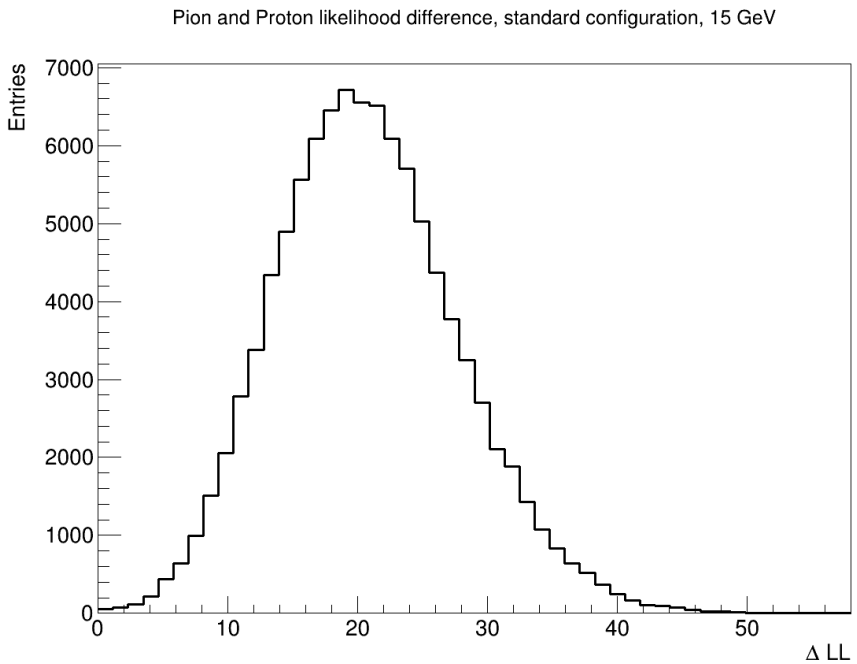
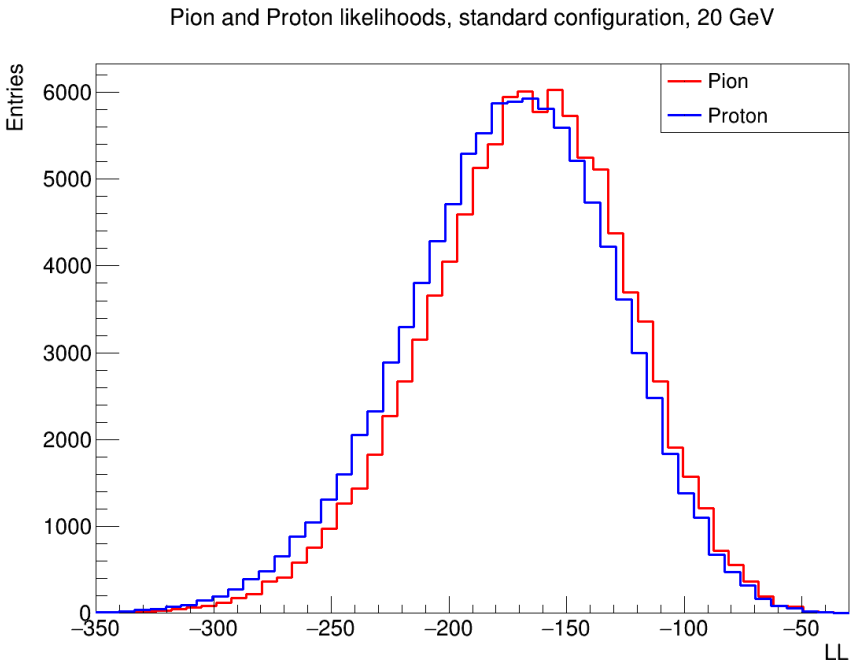


(b) Pion-proton $\Delta\mathrm{LL}$

Figure 4: Log likelihood at 15 GeV/c

Pion-Proton likelihood simulations



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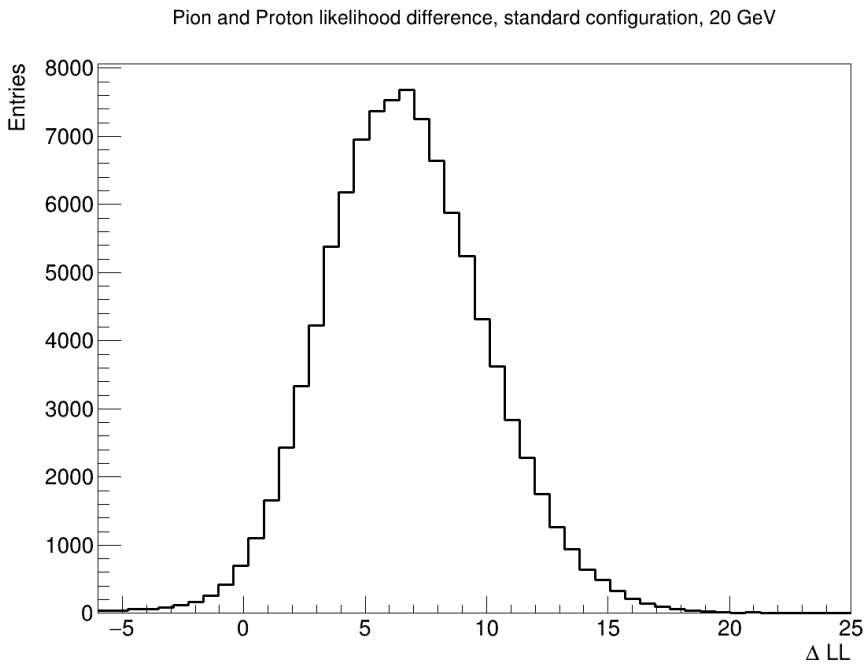
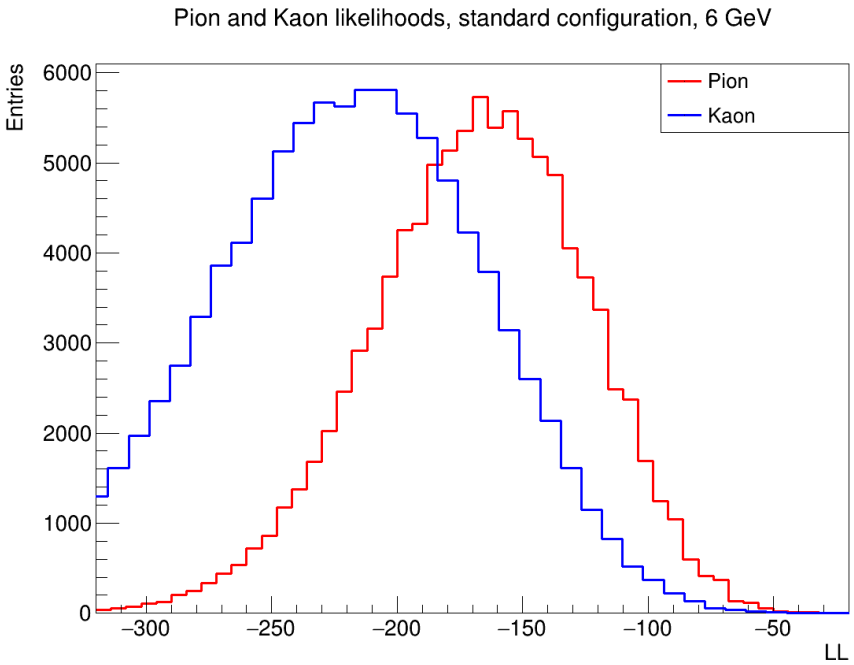


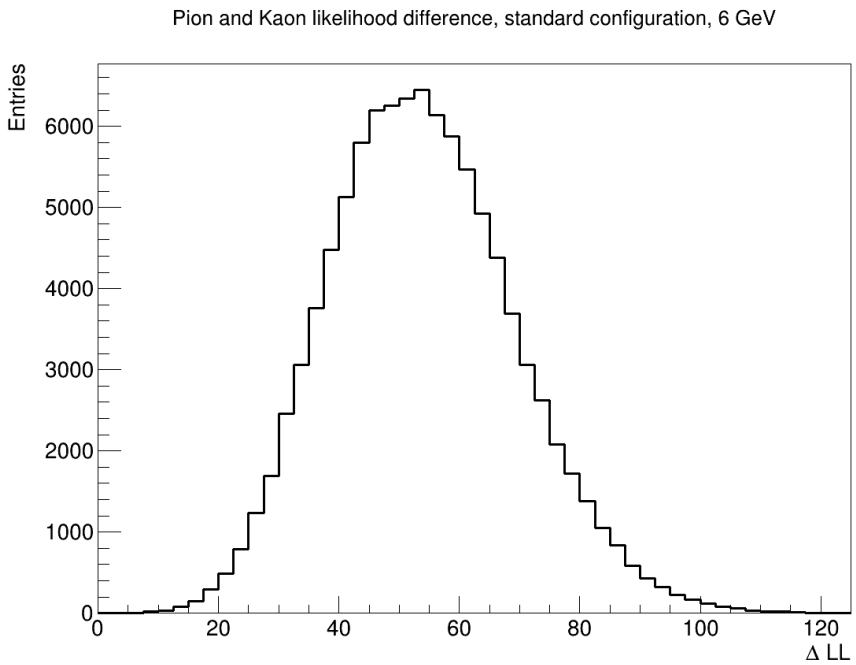
(b) Pion-proton $\Delta\mathrm{LL}$

Figure 5: Log likelihood at 20 GeV/c

Pion-Kaon likelihood simulations



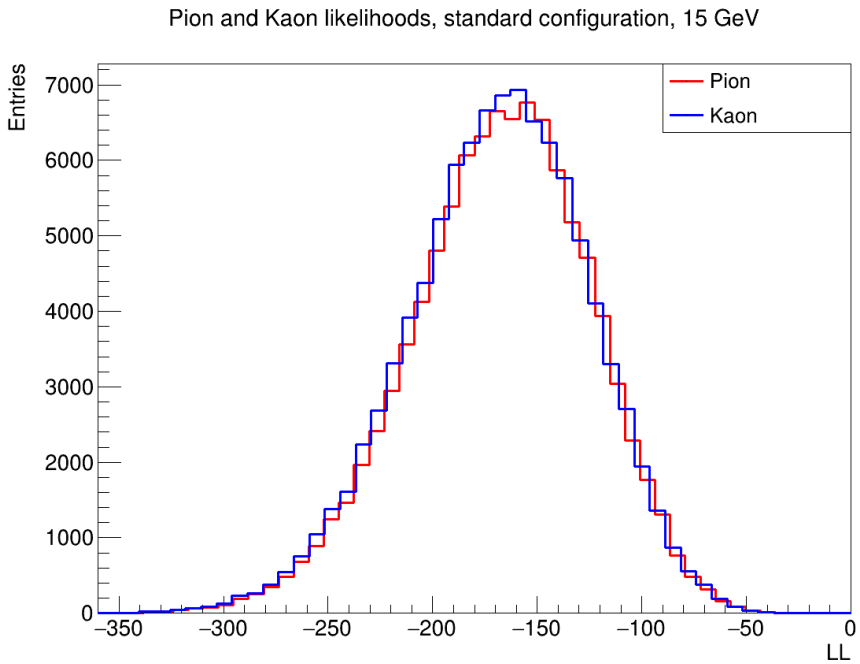
(a) Pion and kaon hypotheses



(b) Pion-kaon $\Delta\mathrm{LL}$

Figure 6: Log likelihood at 6 GeV/c

Pion-Kaon likelihood simulations



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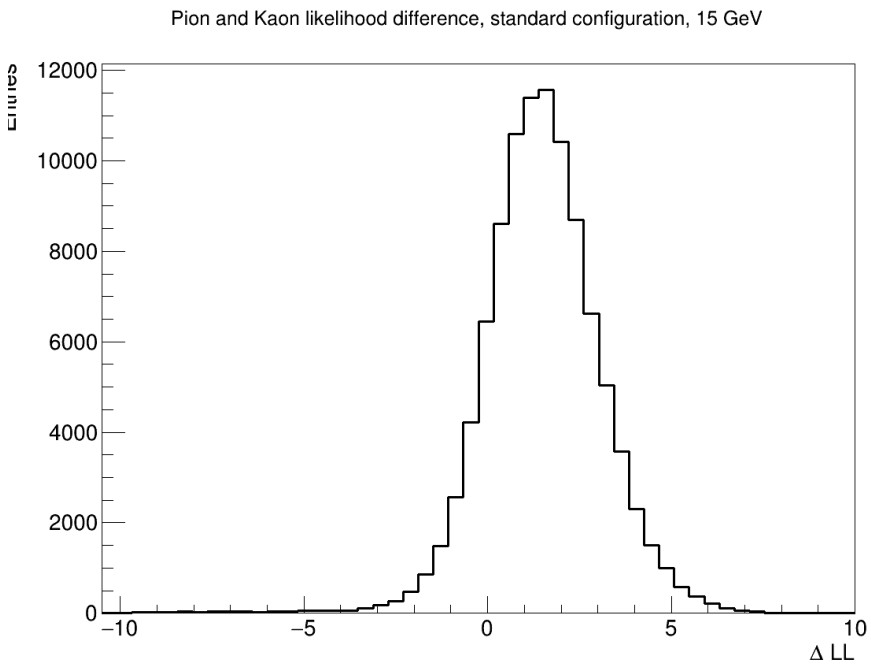
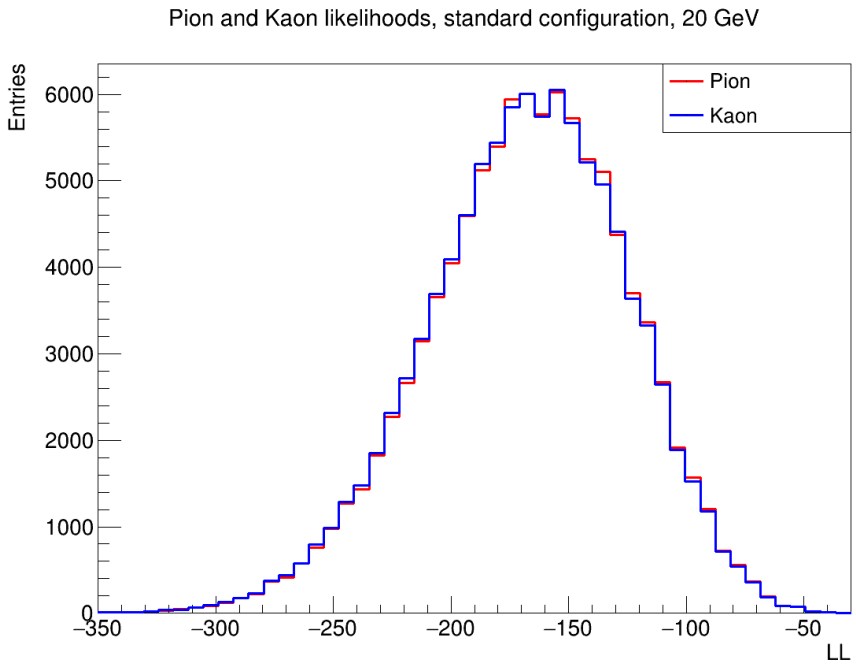


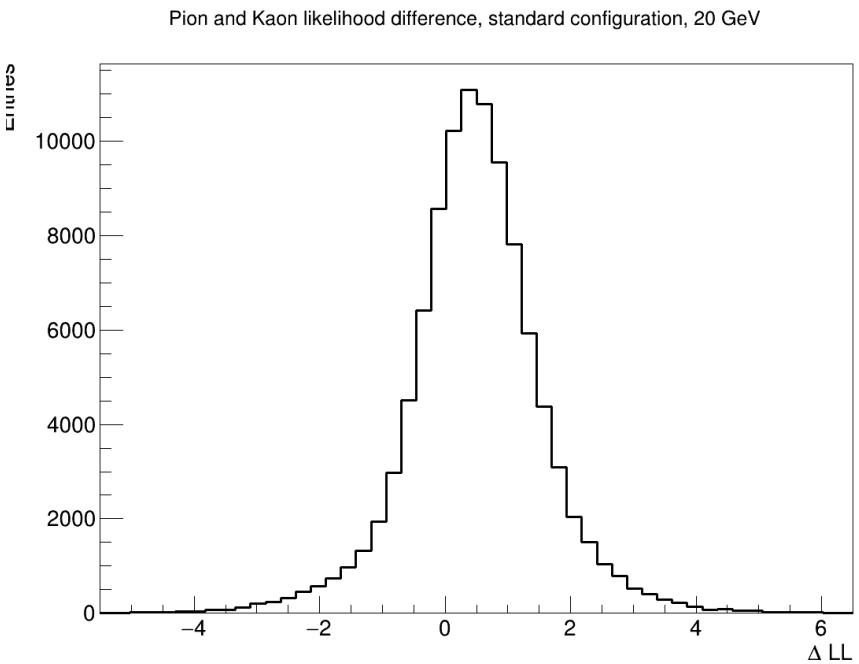
(b) Pion-kaon $\Delta\mathrm{LL}$

Figure 7: Log likelihood at 15 GeV/c

Pion-Kaon likelihood simulations



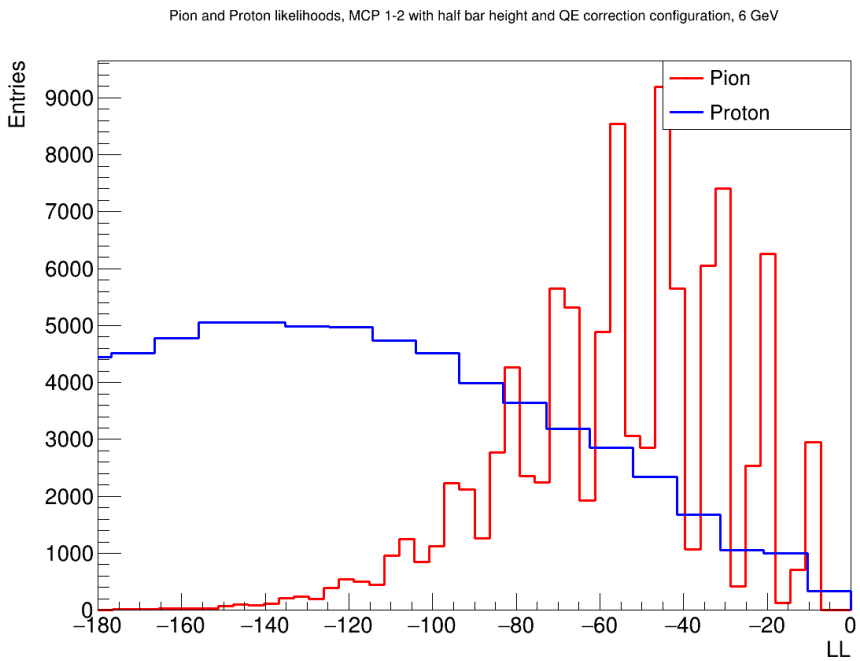
(a) Pion and kaon hypotheses



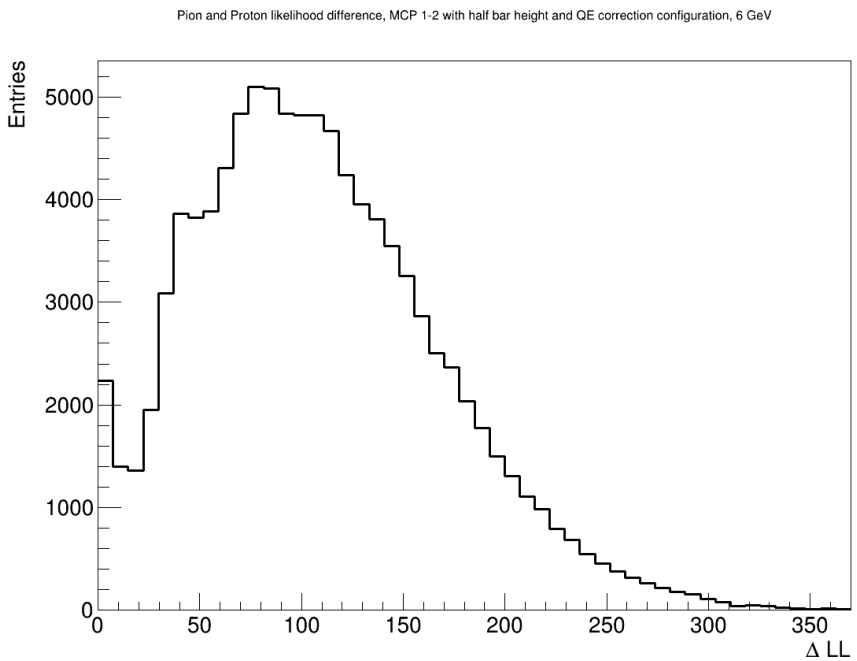
(b) Pion-kaon $\Delta\mathrm{LL}$

Figure 8: Log likelihood at 20 GeV/c

Pion-Proton likelihood simulations



(a) Pion and proton hypotheses

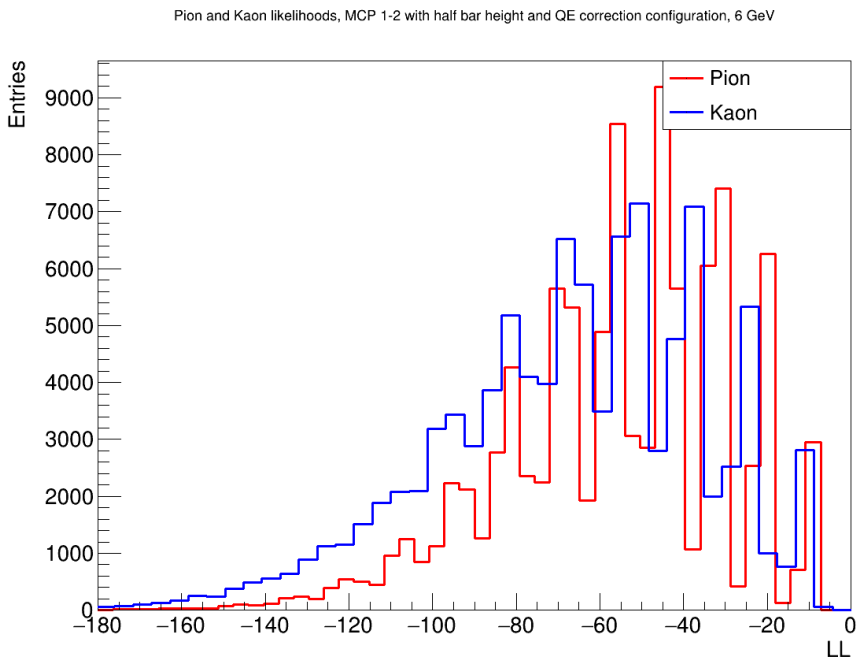


(b) Pion-proton $\Delta\mathrm{LL}$

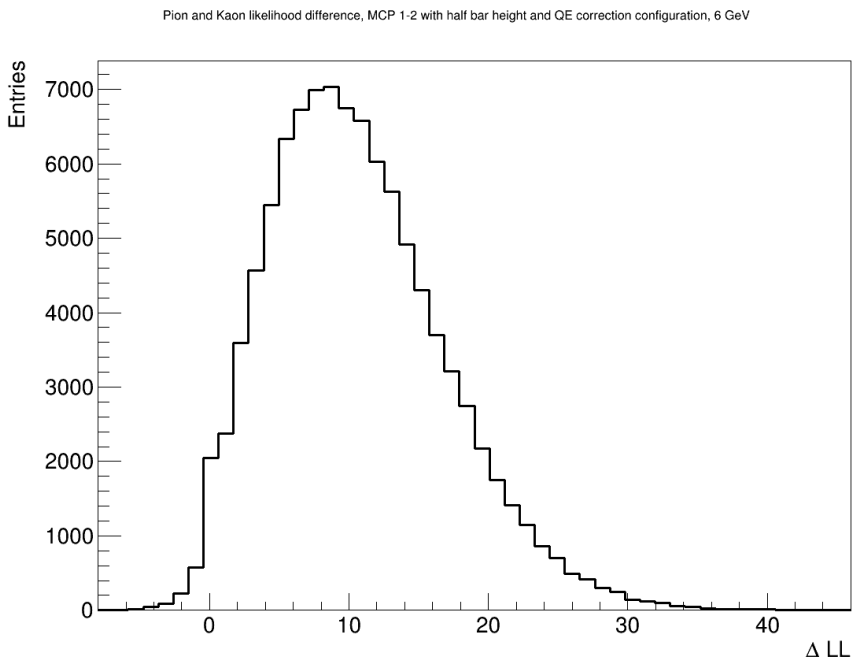
Figure 9: Log likelihood at 6 GeV/c

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



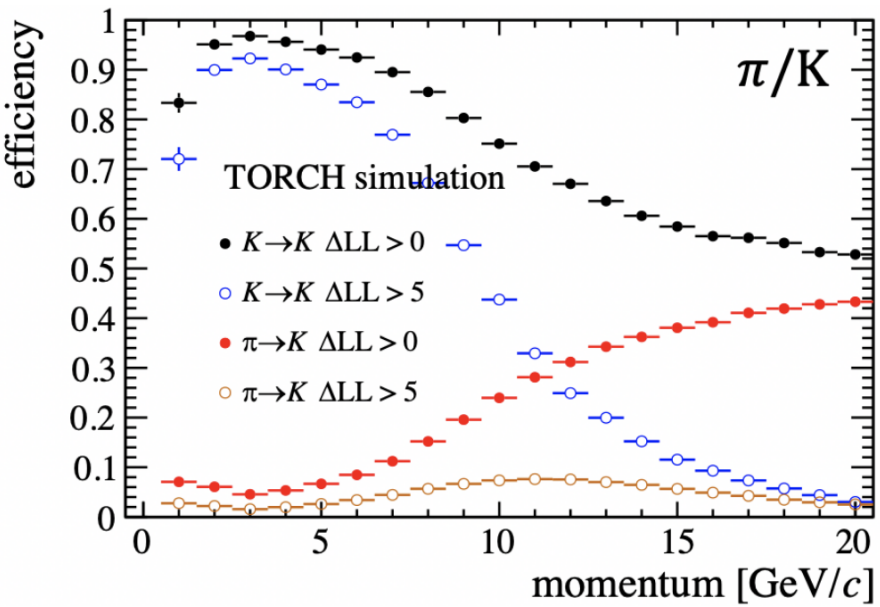
(b) Pion-kaon $\Delta\mathrm{LL}$

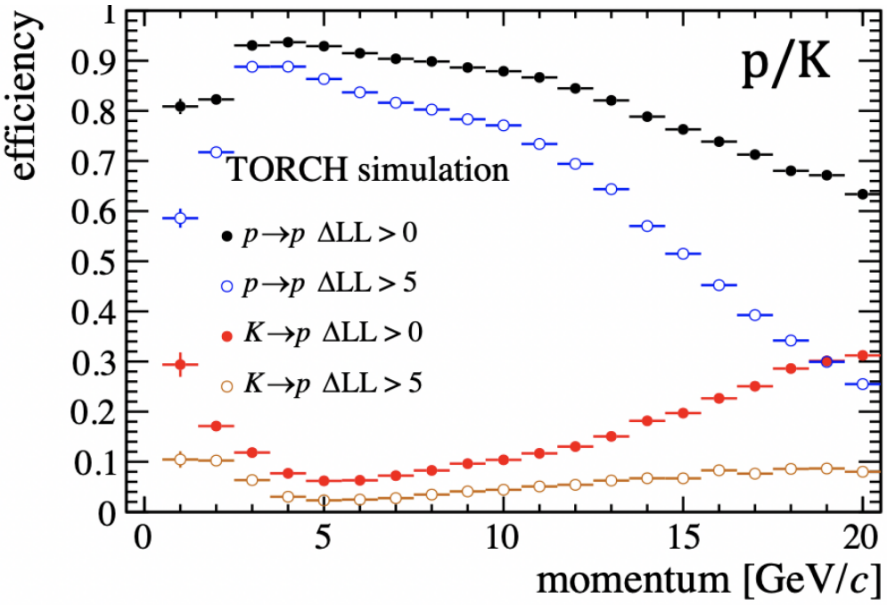
Figure 10: Log likelihood at 6 GeV/c

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

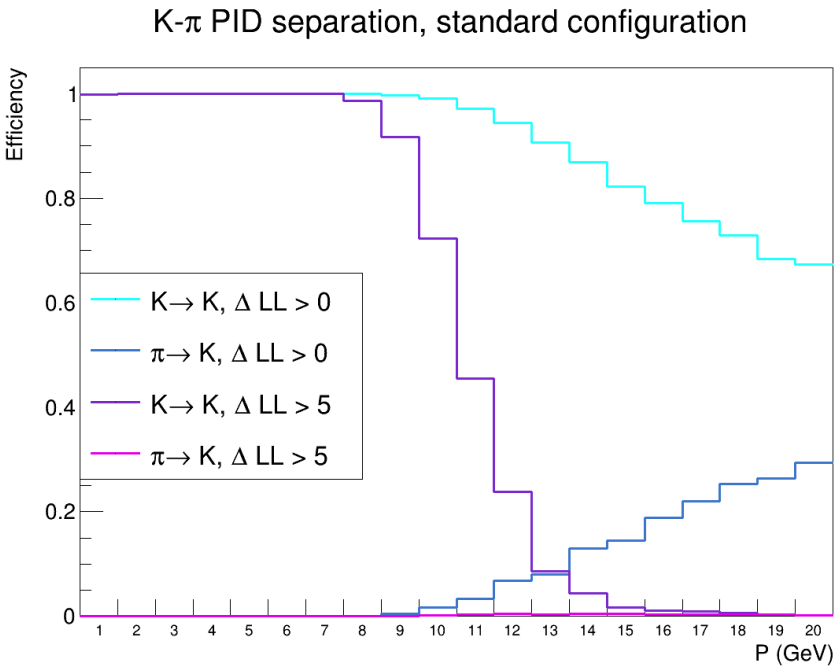
PID efficiency from FTDR

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

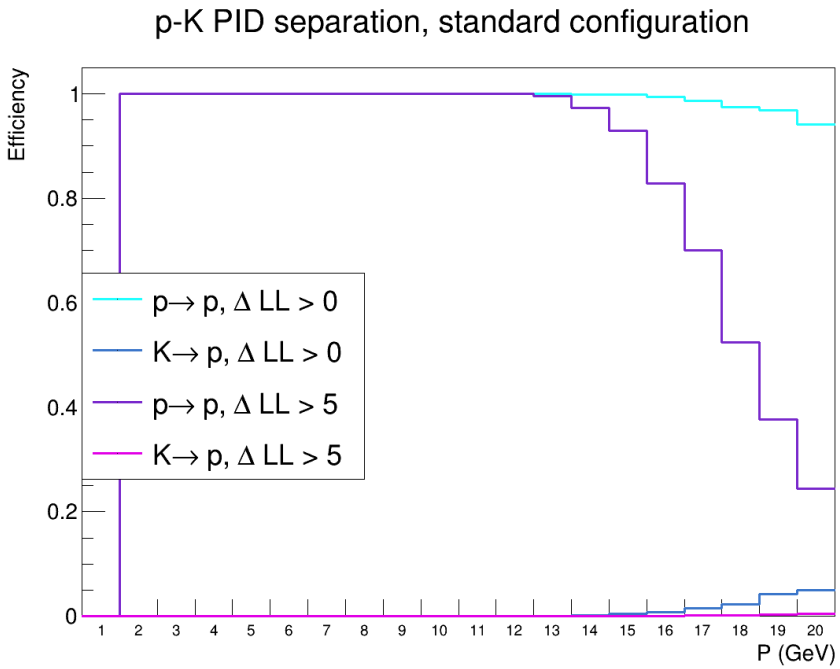




PID efficiency simulation



(a) Kaon-pion

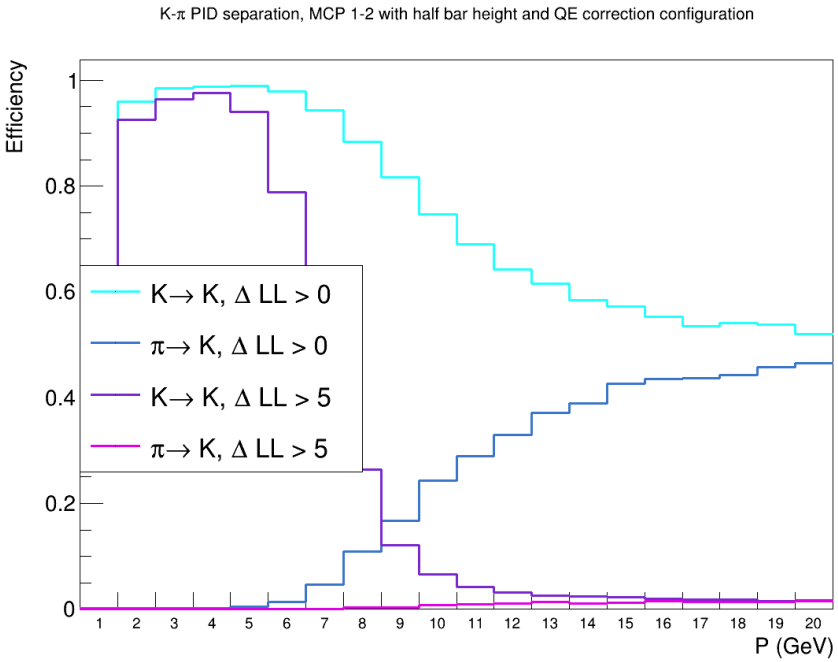


(b) Kaon-proton

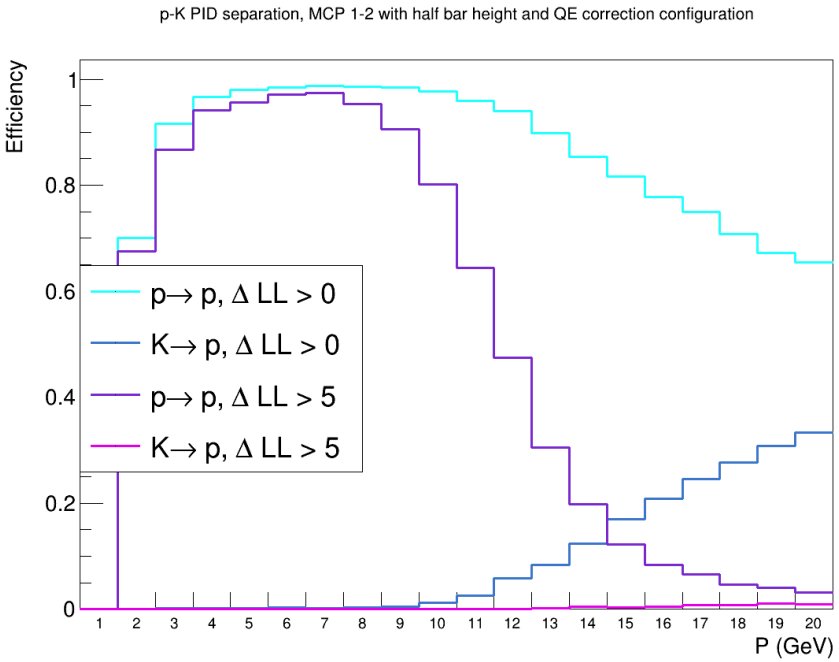
Figure 11: PID efficiency

Full array of MCPs with same QE

PID efficiency simulation



(a) Kaon-pion



(b) Kaon-proton

Figure 12: PID efficiency

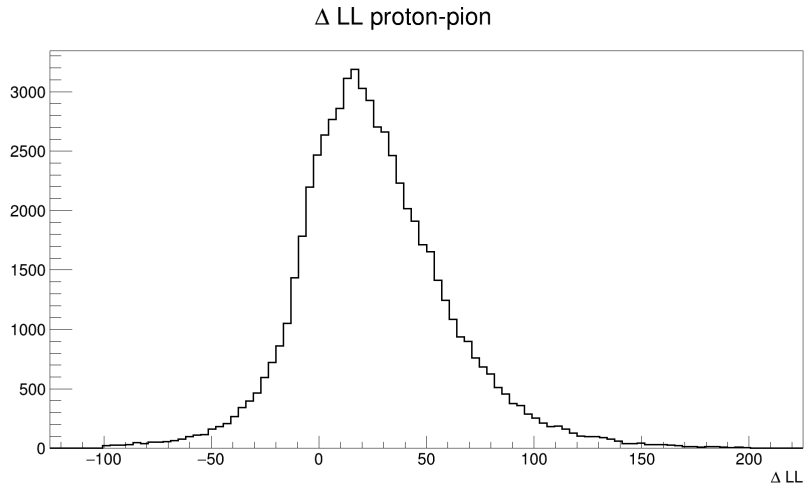
2 MCPs, one with lower QE

PID study of proto-TORCH testbeam data

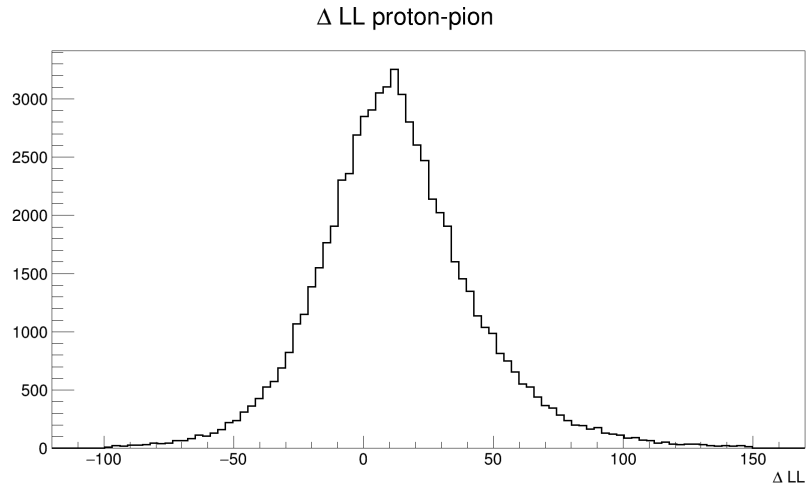
Obviously, more messy and challenging:

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

Likelihood in proto-TORCH testbeam data



(a) Pion sample



(b) Proton sample

Figure 13: $\Delta\mathrm{LL}$ 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%

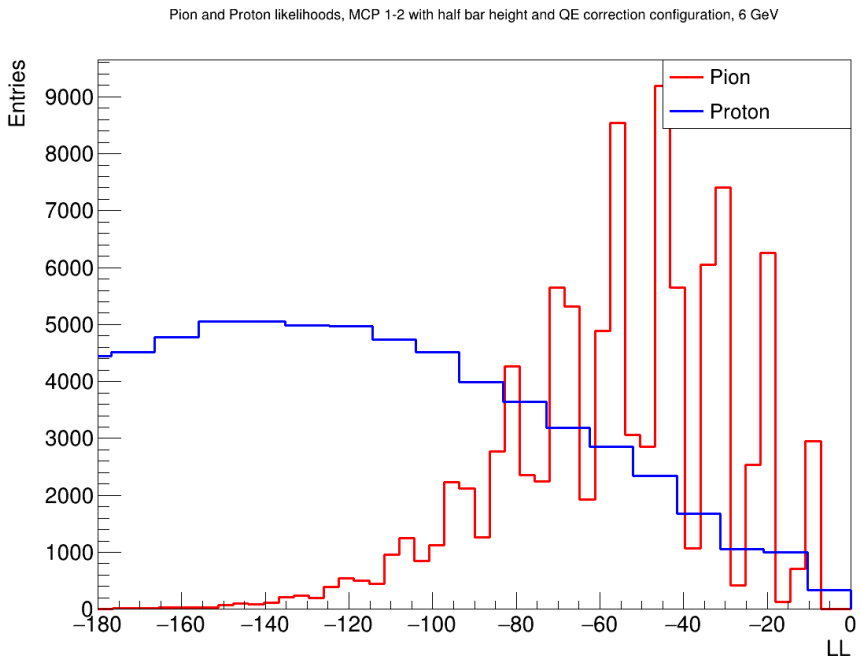
- Clearly this is work in progress:
  1. Time alignment not perfect! Needs to be understood...
     - Individual pixels
     - Overall t_0
  2. Proton sample has more backgrounds (kaons)?
  3. Likelihood calculation uses a "perfect" time resolution (~ 70 ps)
  4. MCPs in proto-TORCH have worse QE than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

Summary and next steps

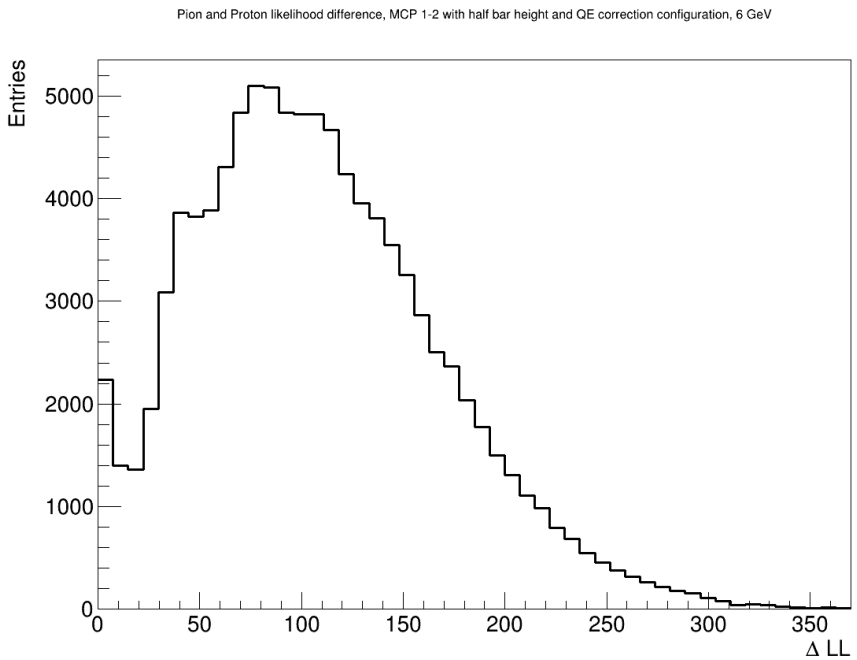
- Summary
  1. Likelihood calculation gives consistent results
  2. Single particle simulation shows very good PID separation power
  3. Testbeam data show some PID separation, not as good as simulation

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

Pion-Proton likelihood simulations



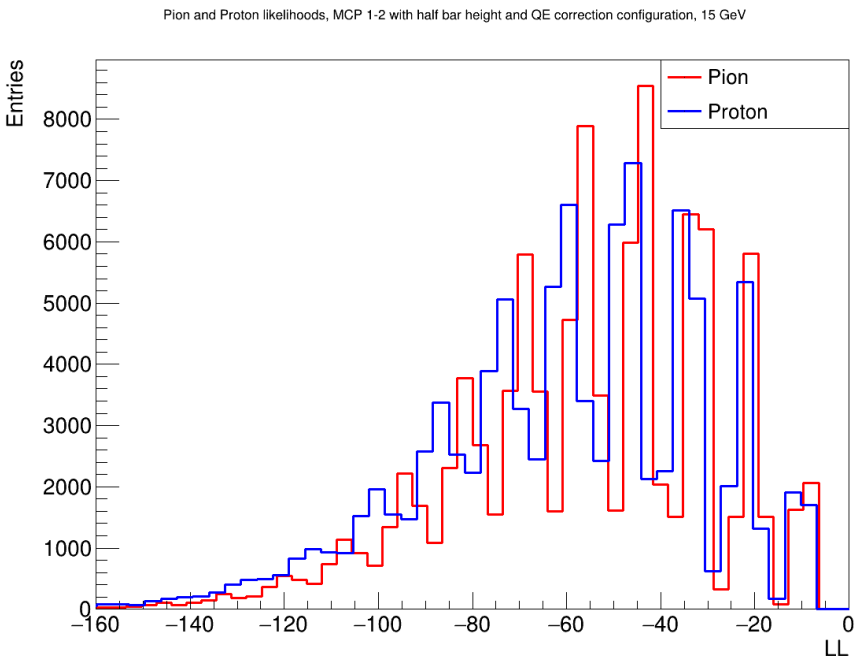
(a) Pion and proton hypotheses



(b) Pion-proton $\Delta\mathrm{LL}$

Figure 14: Log likelihood at 6 GeV/c

Pion-Proton likelihood simulations



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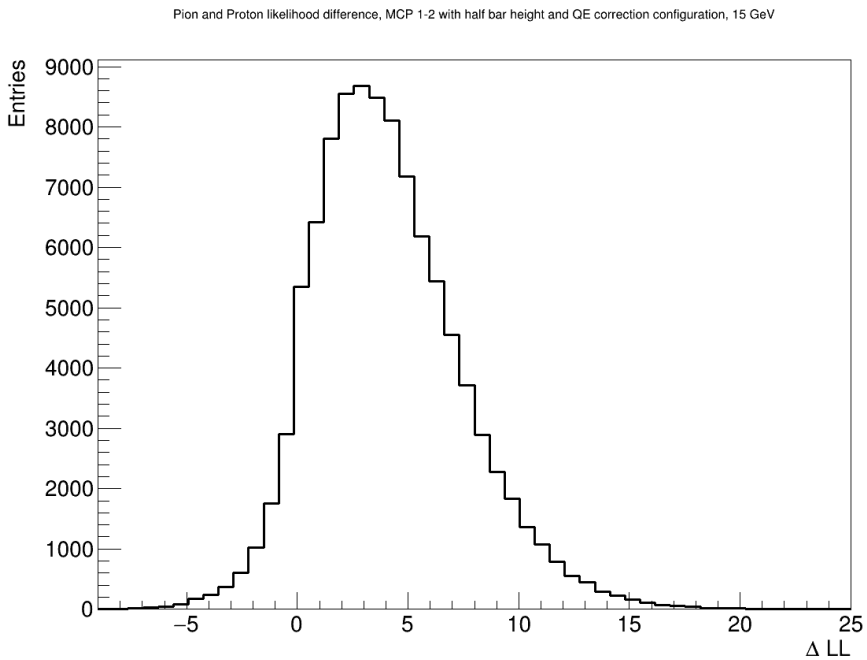
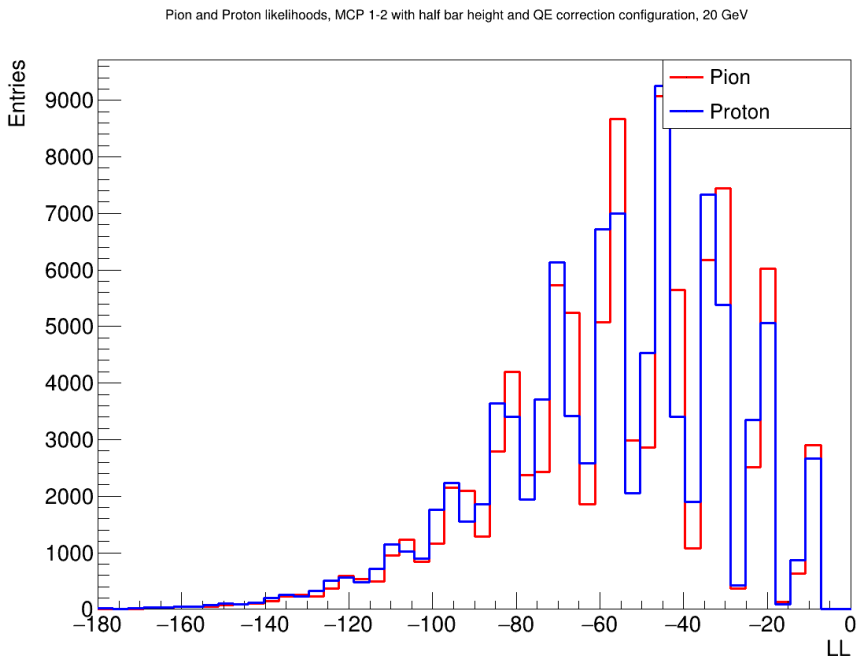


(b) Pion-proton $\Delta\mathrm{LL}$

Figure 15: Log likelihood at 15 GeV/c

Pion-Proton likelihood simulations



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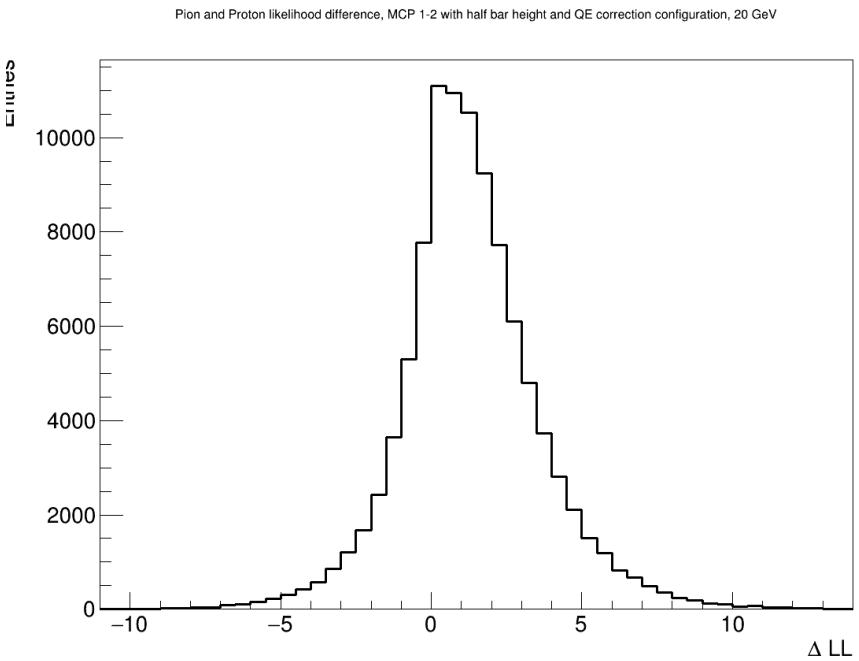
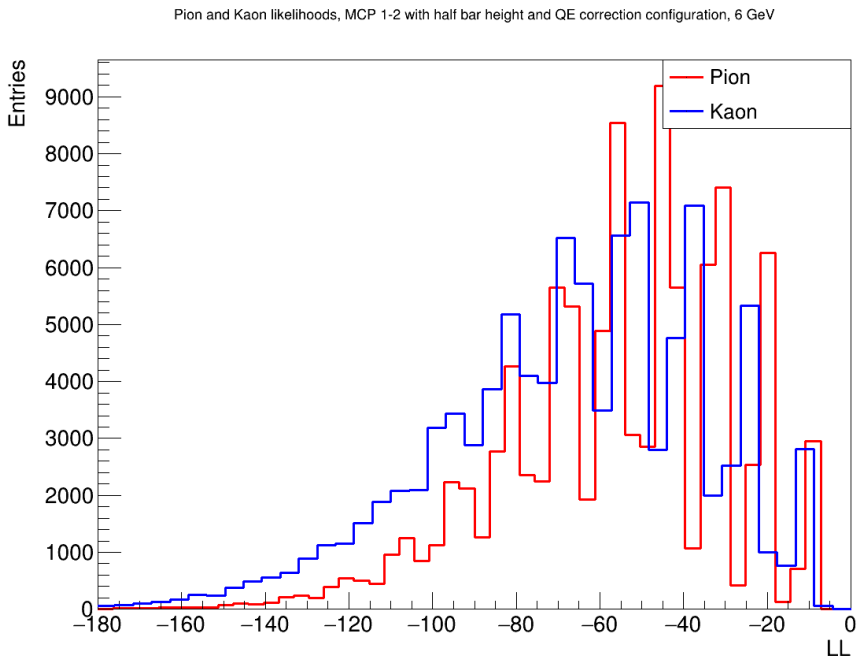


(b) Pion-proton $\Delta\mathrm{LL}$

Figure 16: Log likelihood at 20 GeV/c

Pion-Kaon likelihood simulations



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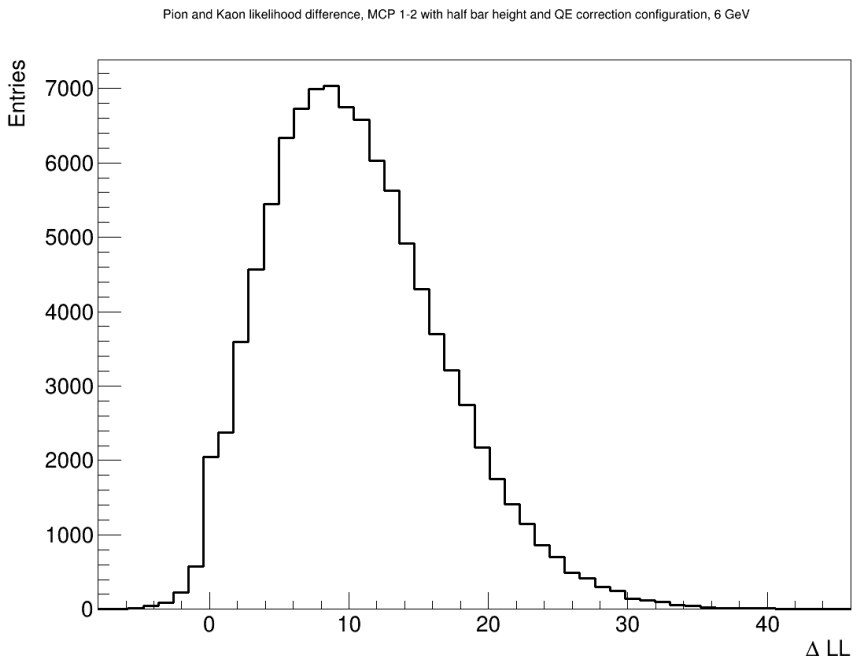
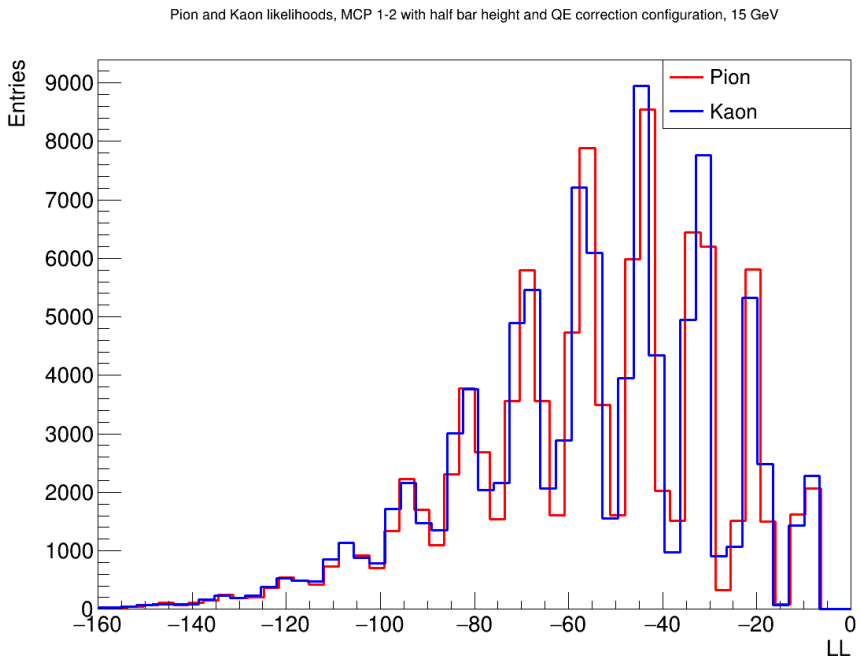


(b) Pion-kaon $\Delta\mathrm{LL}$

Figure 17: Log likelihood at 6 GeV/c

Pion-Kaon likelihood simulations



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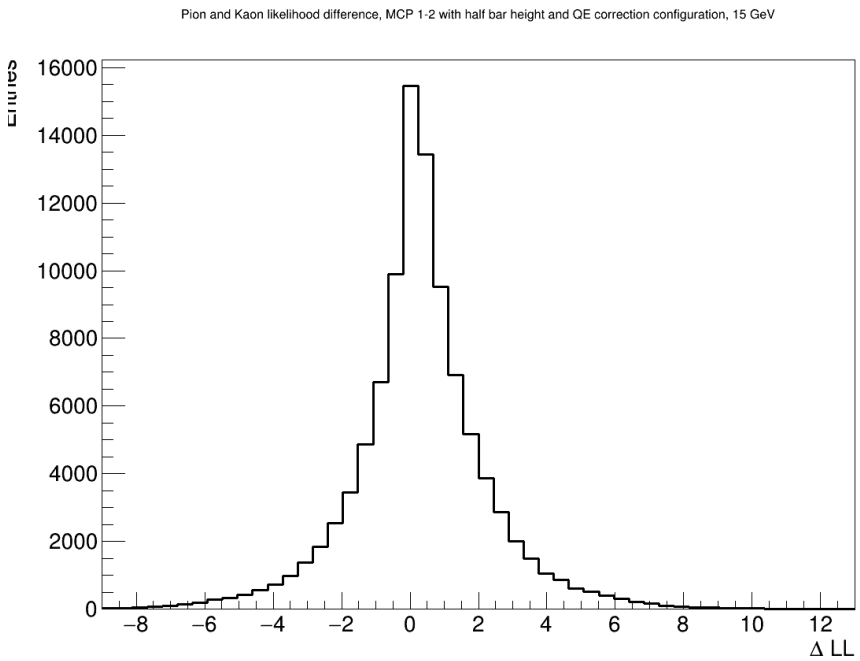
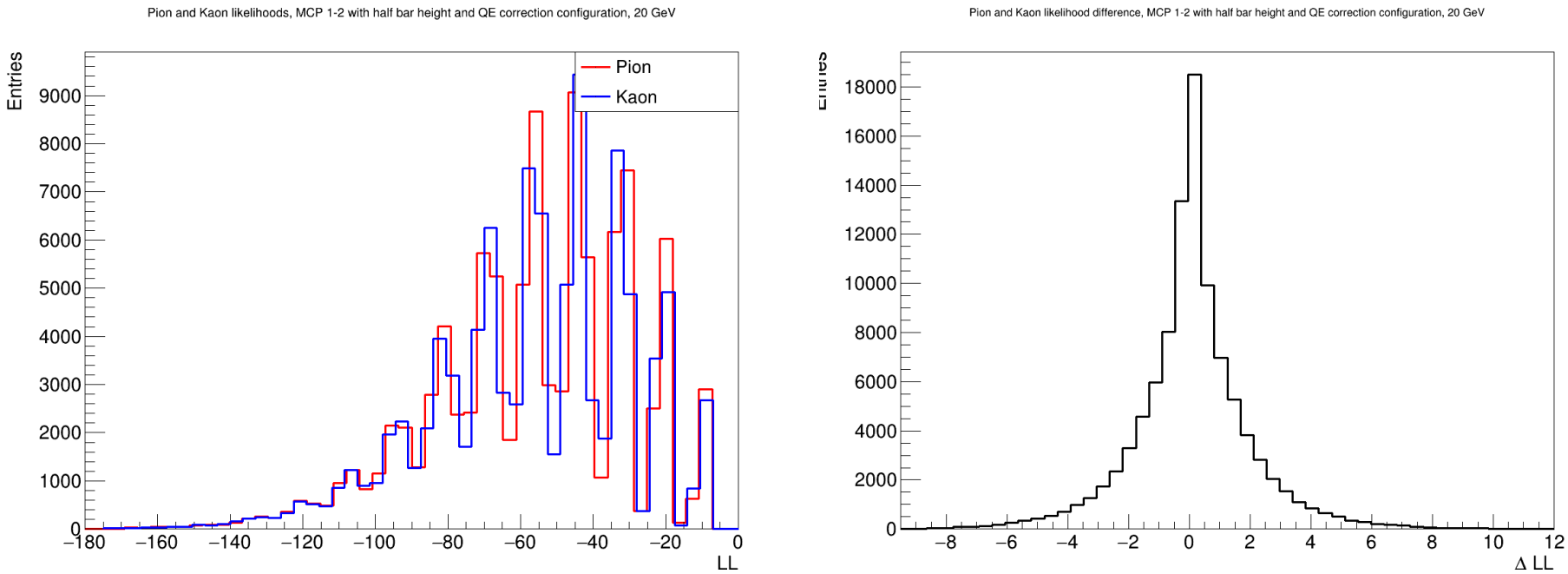


(b) Pion-kaon $\Delta\mathrm{LL}$

Figure 18: Log likelihood at 15 GeV/c

Pion-Kaon likelihood simulations



(a) Pion and kaon hypotheses

(b) Pion-kaon $\Delta\mathrm{LL}$

Figure 19: Log likelihood at 20 GeV/c