Likelihood Methods for Beam Particle Identification at the COMPASS Experiment

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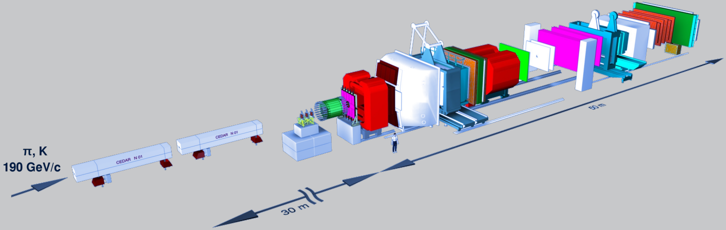
Outline

The COMPASS Experiment

- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Located at SPS at CERN



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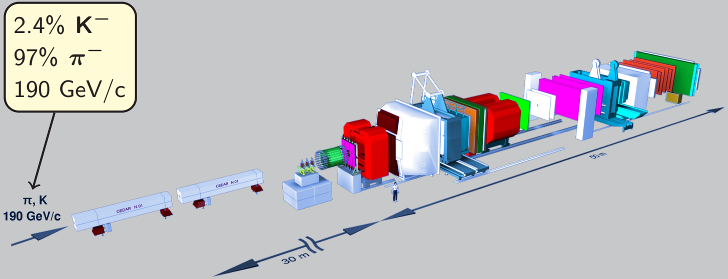

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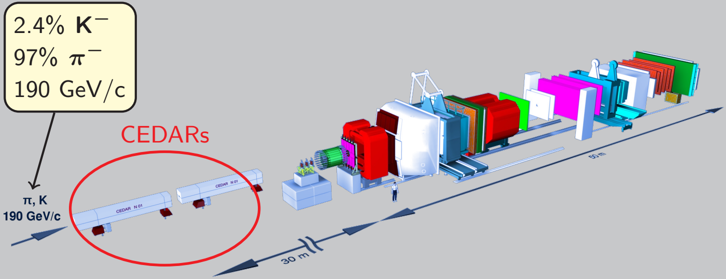

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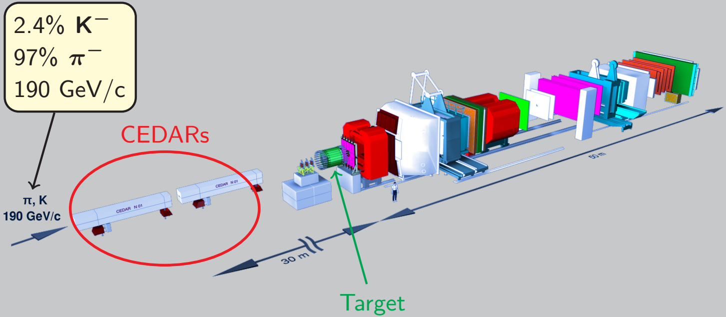

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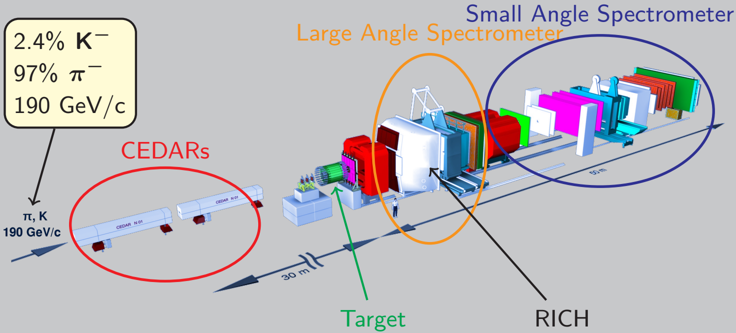

Hadron Physics @ COMPASS

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  - Different final states
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  - $\boldsymbol{\pi p \to \pi\gamma p}$
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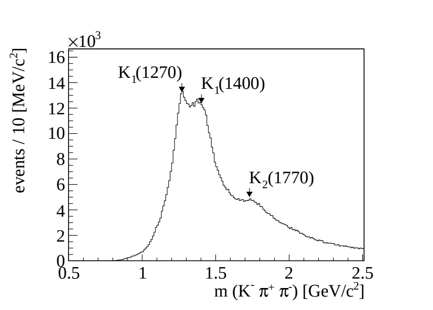
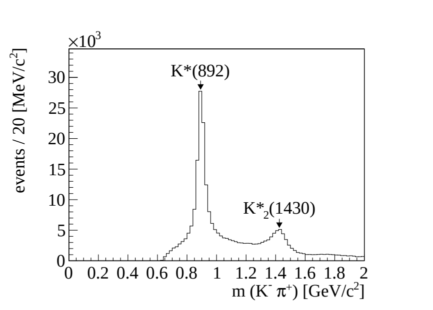
Example: $\mathbf{K\pi\pi}$ analysis

Analysis of diffractive dissociation of $\mathbf{K^-}$ into $\mathbf{K^-\pi^+\pi^-}$ on a liquid hydrogen target at the COMPASS spectrometer, PhD Thesis P. Jasinski (JGU Mainz)

Event Selection

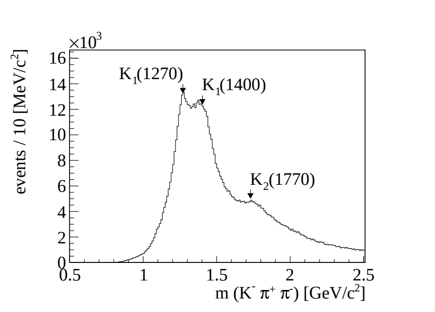
- Incoming kaon (majority cut)
- Primary vertex in target with 3 outgoing charged tracks
- Four momentum transfer $\mathbf{0.07 < t'[GeV^2/c^2] < 0.7}$
- One negative particle identified with RICH





Partial Wave Analysis

- disentangle $\mathbf{K}\pi\pi$ spectrum
- several resonances found
- further investigation needed (mass dependent fits)



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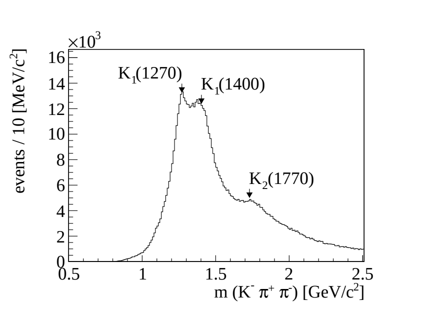

J^P	mass (GeV/c^2)	possible state
0^-	1.30	K(1460)
1^+	1.25	$K_1(1270)$
1^+	1.35	$K_1(1400)$
1^+	1.80	$K_1(1650)$
1^-	1.75	$K^*(1680)$
2^+	1.44	$K_2^*(1430)$
2^-	1.70	$K_2(1770)$
2^-	1.85	$K_2(1820)$
2^-	1.9 – 2.2	several

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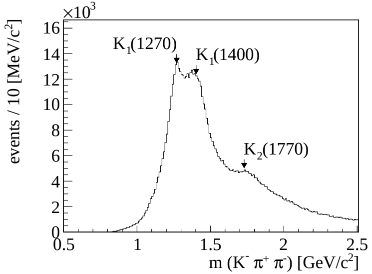

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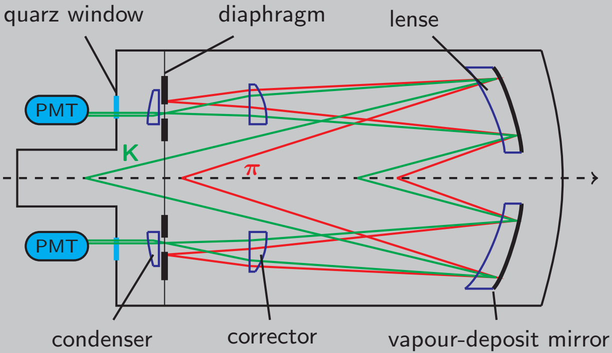
Only ≈ 50% of kaons used due to bad efficiency of beam particle identification.

Beam Particle Identification @ COMPASS

- Two CEDAR detectors
- $30\,\mathrm{m}$ upstream of the target

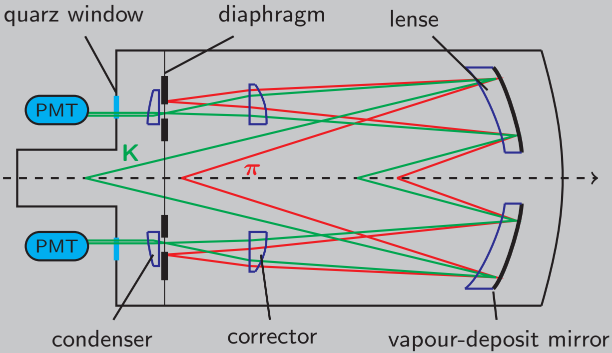
How does a CEDAR work?

- CEDAR = ČErenkov Differential counters with Acromatic Ring focus
- Fast charged particles emit Čerenkov light with angle $\mathbf{cos(\theta) = \frac{1}{n\beta}}$



How does a CEDAR work?

- Čerenkov light detected with 8 PMTs
- Particle identification using multiplicities, e.g. 6 of 8 PMTs



Influence of Beam Divergence

- beam tuned to traverse full spectrometer
- beam is not parallel in the CEDAR region

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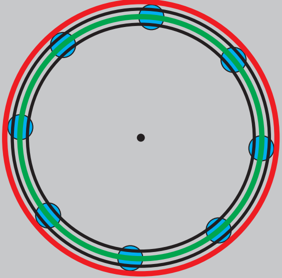
parallel beam



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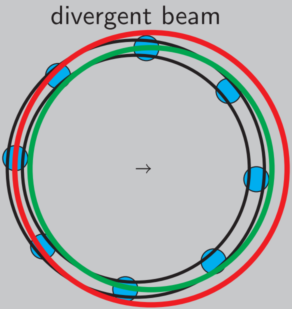

- Kaon ring leaves acceptance, pion ring enters
- Multiplicity method does not work for divergent beams

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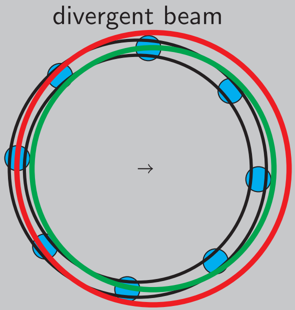

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↷ Find a method which takes divergence into account

General Idea

- Look at response of single PMTs for Kaon and Pion seperately
- Take care of beam divergence
- Identify beam particles using likelihoods

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- Take care of beam divergence
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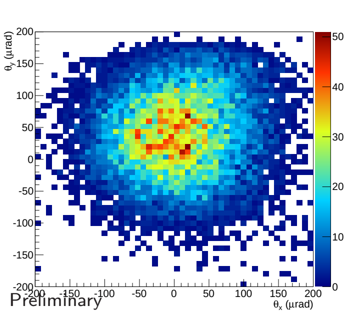
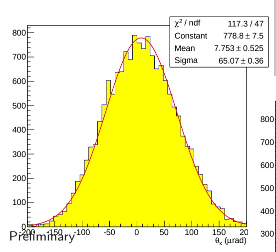
5 steps to take

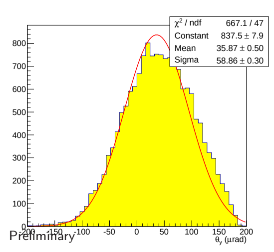
1. Measure beam divergence
2. Create a pure Kaonsample and a pure Pionsample
3. Determine probabilities to have hits in PMTs for Pion and Kaon
4. Calculate likelihoods from probabilities
5. Use likelihoods to identify particles

Step 1: Measure beam divergence

- Measure beam position in front of $(\mathbf{x_1}, \mathbf{y_1})$ and behind $(\mathbf{x_2}, \mathbf{y_2})$ CEDARs
- Calculate relative displacement $\mathbf{\Delta_x} = \frac{\mathbf{x_2 - x_1}}{\mathbf{1283{,}4\,cm}}$
- Divergence $\boldsymbol{\theta_x} = \mathbf{arctan(\Delta_x) \approx \Delta_x}$







Step 2: Create a pure Kaonsample and a pure Pionsample

Create a Kaonsample and a Pionsample

- Kaonsample

→ Use free Kaon decay $\mathbf{K}^- \rightarrow \pi^-\pi^-\pi^+$

  - 3 outgoing particles with correct charged
  - Primary vertex outside of the target
  - Cut on transverse momentum and Kaon mass

- Pionsample

→ Use diffractive production $\pi^-\mathbf{p} \rightarrow \pi^-\pi^-\pi^+\mathbf{p}$

  - 3 outgoing particles with correct charge
  - Primary vertex inside the target
  - Small angle to beam direction, similar momenta → same mass

In addition: Take a Beamsample without any filtering for testing the method

Step 3: Determine probabilities to have hits in PMTs for π and $\mathbf{K}$

Example: Particle with divergence θ_x, θ_y produces signal in PMT $\mathbf{i}$
Question: Is it a kaon?

$\rightarrow$ Use Bayes' Theorem:

$$\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Kaon}|\text{Signal}) = \frac{\cdot}{}$$

Here:

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Here:

$\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Signal}|\text{Kaon})$: Probability that Kaon at θ_x, θ_y produces signal in PMT $\mathbf{i}$ ($\rightarrow$ Kaonsample)

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$$\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Kaon}|\text{Signal}) = \frac{\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Signal}|\text{Kaon}) \cdot \mathbf{P}_{\theta_x,\theta_y}(\text{Kaon})}{}$$

Here:

$\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Signal}\|\text{Kaon})$:	Probability that Kaon at θ_x, θ_y produces signal in PMT $\mathbf{i}$	($\rightarrow$ Kaonsample)
$\mathbf{P}_{\theta_x,\theta_y}(\text{Kaon})$:	Probability that Kaon has divergence θ_x and θ_y	($\rightarrow$ Kaonsample)

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$\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Signal})$:	Probability that signal in PMT $\mathbf{i}$ ist produced at θ_x, θ_y	($\rightarrow$ Beamsample)

Step 3 continued

Pions and Kaons have the same divergence distribution:

$$\mathbf{P}_{\theta_x,\theta_y}(\text{Kaon}) = \mathbf{P}_{\theta_x,\theta_y}(\text{Pion}) = \mathbf{P}_{\theta_x,\theta_y}(\text{Beam})$$

$\Rightarrow \mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Kaon}|\text{Signal})$ and $\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Pion}|\text{Signal})$ have same normalization

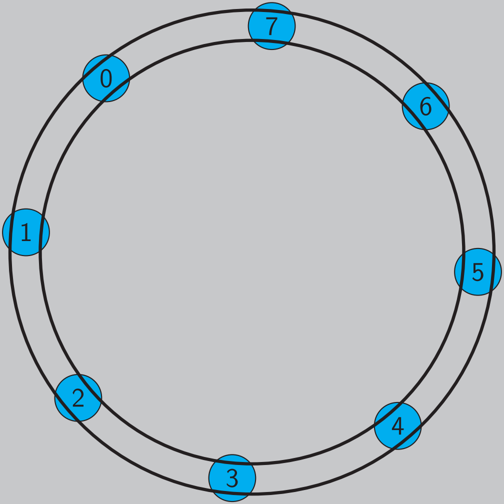
factor $\frac{\mathbf{P}_{\theta_x,\theta_y}(\text{Beam})}{\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Signal})}$, thus

$$\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Kaon}|\text{Signal}) \propto \mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Signal}|\text{Kaon})$$
$$\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Pion}|\text{Signal}) \propto \mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Signal}|\text{Pion})$$

Also calculate

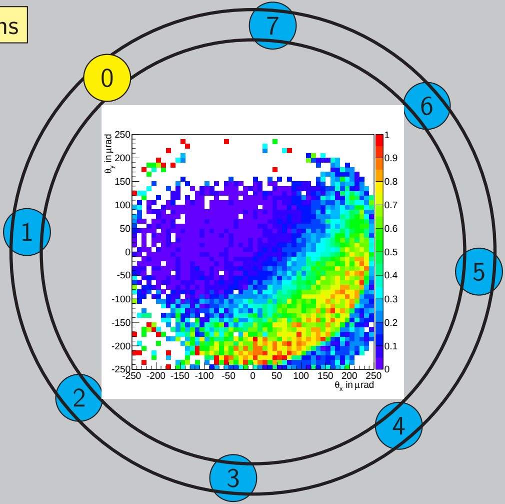
$$\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Kaon}|\overline{\text{Signal}}) \text{ and } \mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Pion}|\overline{\text{Signal}})$$

Probability Distributions



Probability Distributions

Pions



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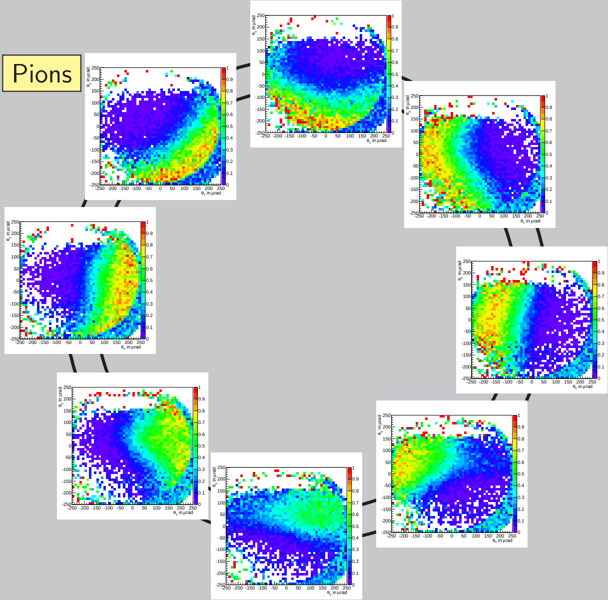
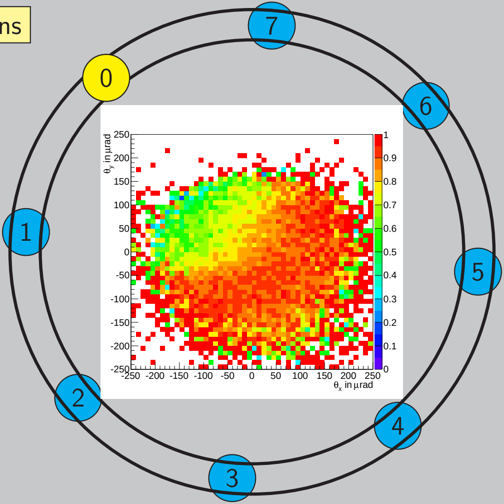
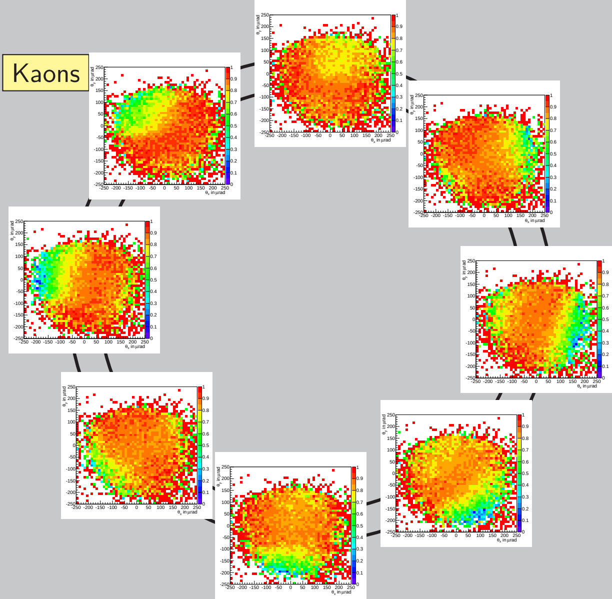


Probability Distributions

Kaons



Probability Distributions

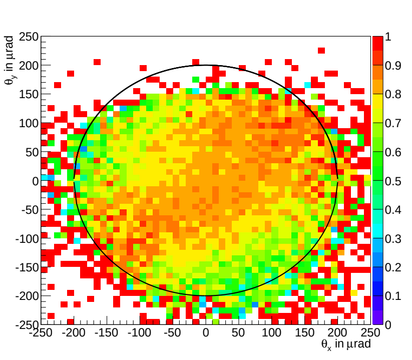


Additional Cut

- Statistics bad for large divergences
- Cut out events with

$$\mathbf{r} = \sqrt{\theta_x^2 + \theta_y^2} < \mathbf{200} \times \mathbf{10^{-6}}$$

- About 20% of all events are lost this way



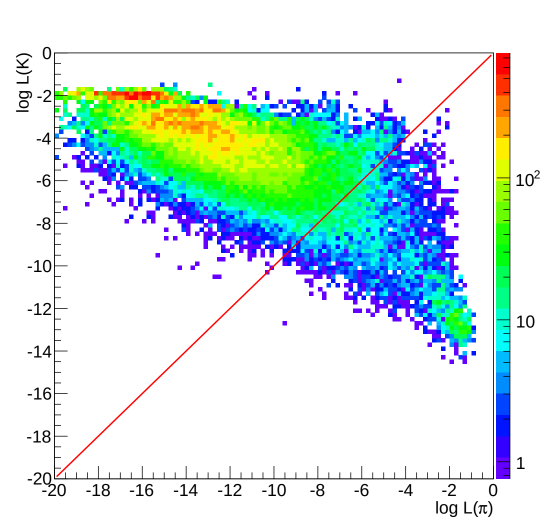
Step 4: Calculate likelihoods from probabilities

- To obtain the log likelihood just add logarithms of probabilities

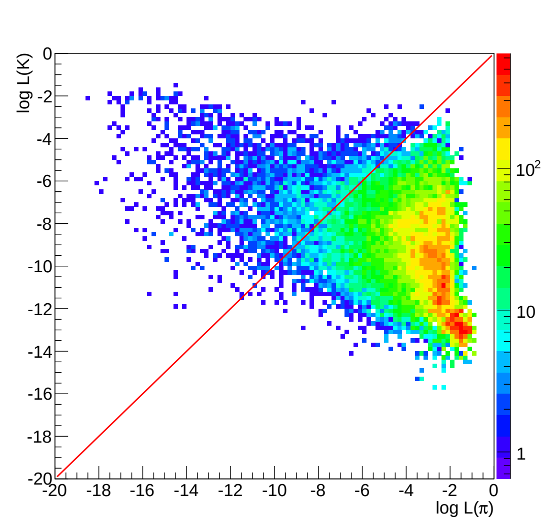
$$\mathbf{\log L}(\mathrm{Kaon}) = \sum_{\mathbf{i} \in \mathrm{PMT\ with\ Signal}} \mathbf{\log P}^{\mathbf{i}}_{\theta_x, \theta_y}(\mathrm{Kaon}|\mathrm{Signal}) + \sum_{\mathbf{j} \in \mathrm{PMT\ without\ Signal}} \mathbf{\log P}^{\mathbf{j}}_{\theta_x, \theta_y}(\mathrm{Kaon}|\overline{\mathrm{Signal}})$$

- Calculate the same for Pions.
- Compare them

Kaonsample


log L(K)
log L(π)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0
10^2
10
1

Pionsample



Step 5: Use likelihoods to identify particles

- Compare log likelihoods to get an ID for each CEDAR:
  - $\mathbf{log\,L^{K}} > \mathbf{log\,L^{\pi}} + \mathbf{A} \Rightarrow$ PID **K**
  - $\mathbf{log\,L^{\pi}} > \mathbf{log\,L^{K}} + \mathbf{B} \Rightarrow$ PID $\boldsymbol{\pi}$
  - else no PID given
- Tune **A** and **B** due to efficiency/purity.

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- Compare log likelihoods to get an ID for each CEDAR:
  - $\mathbf{\log L^K > \log L^\pi + A} \Rightarrow$ PID **K**
  - $\mathbf{\log L^\pi > \log L^K + B} \Rightarrow$ PID π
  - else no PID given
- Tune **A** and **B** due to efficiency/purity.
- Combine CEDARs afterwards

C2 \ C1	?	π	**K**
?	?	π	**K**
π	π	π	?
K	**K**	?	**K**

Calculation of Purity

Look at

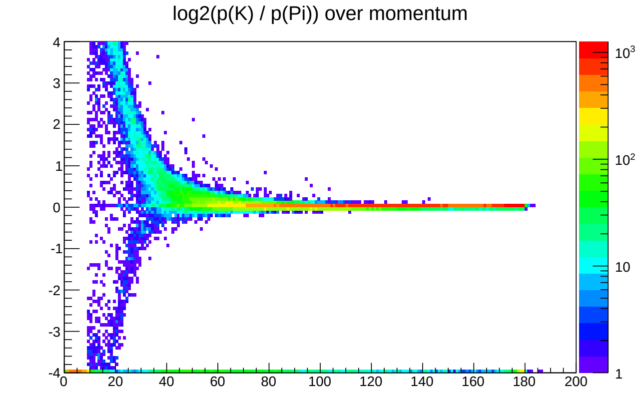
$$\mathbf{h^- p \to h'^- K^0_S p}$$

Then one knows (due to conservation of strangeness):

$\mathbf{h'^-}$	$\mathbf{h^-}$
$\mathbf{K^-}$	π^-
π^-	$\mathbf{K^-}$

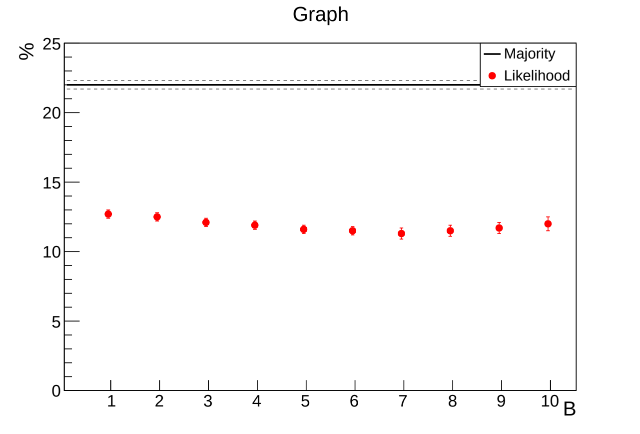
$\rightarrow$ Identify $\mathbf{h'^-}$ using the RICH and count the "wrong" particles

Select $\mathbf{h}^- = \pi^-$



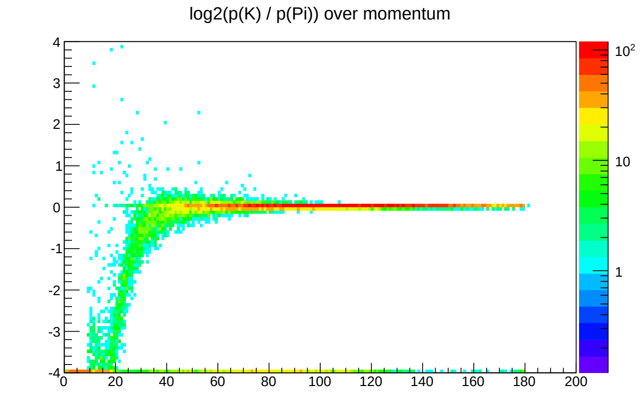
For CEDAR pions RICH should only see kaons ($\log_2\left(\mathbf{p(K)/p(\pi)}\right) > \mathbf{0}$)
Look at Events with $\mathbf{p} < \mathbf{50}\,\mathrm{GeV}$, cut out $\pm\mathbf{0}$ and $-\mathbf{4}$

Purity of Pion Selection



- Independent of likelihood cut
- $\approx$ 40% better than majority

Select $\mathbf{h^- = K^-}$



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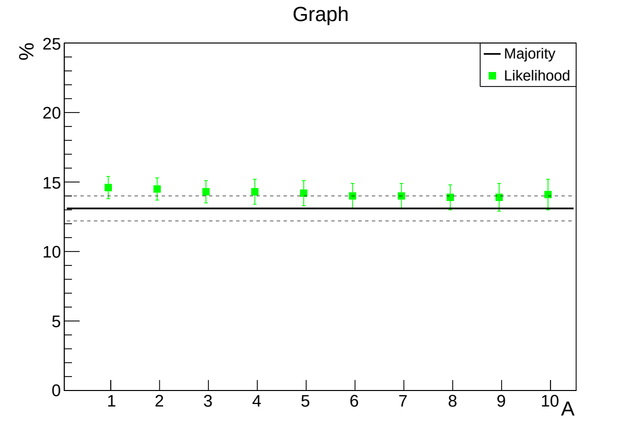
Purity of Kaon Selection

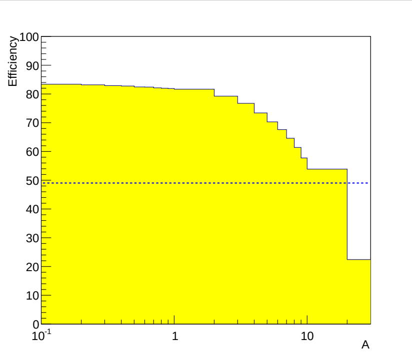


- Independent of likelihood cut
- Compatible with majority method
- Compatible with pion purity

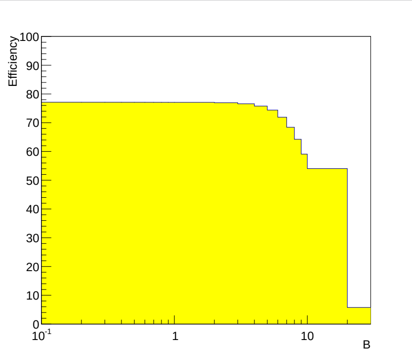
Calculation of Efficiency

Look at expected number of particles in the beam
2.4% kaons, 97% pions

Kaons

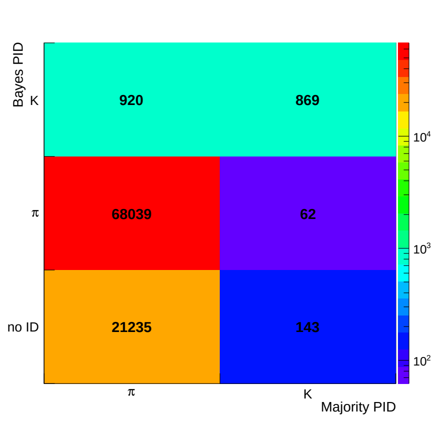


Pions



⇒ Efficiency of around 80% for pions and kaons
Efficiency for kaons ≈ 60% better than for majority method

Direct Comparison with Majority Method



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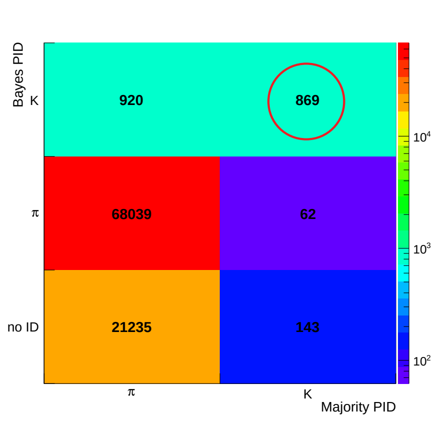

- Most of majority Kaons reproduced as Kaons (896 of 1074, 83%)

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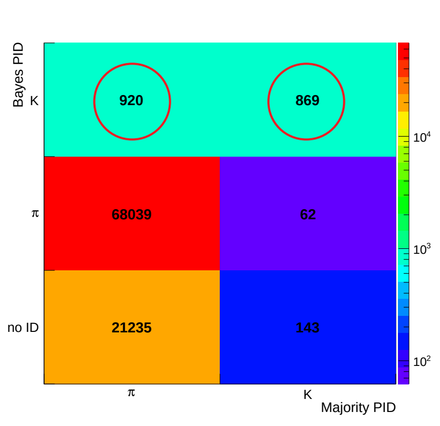

- Most of majority Kaons reproduced as Kaons (896 of 1074, 83%)
- 920 additional Kaons from majority Pions

Summary

- COMPASS hadron beam consists of 97% Pions and 2.4% Kaons
- Pions and kaons have to be identified for analyses
- Majority method only identifies ≈ **50%** of the Kaons
  - Problems with divergent beams
- Likelihood method improves identification for divergent beams
  - Identifies 80% of the kaons with 87% purity.

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Outlook

- Adapt methods to 2009/2012 data taking
- Do finetuning using existing hadron analyses